Heat and Work, Health, and Safety in Australia: Intra-urban risk assessment, future projections, and workplace policy analysis

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A thesis submitted in fulfillment of the requirements for the degree of Doctor of Philosophy



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With profound gratitude and admiration, I dedicate this dissertation to my beloved parents,
Colonel (R) Syed Asad Abdullah Zaidi (Late) and Begum Syeda Najma Batool.
This gesture is a humble tribute, expressing my deep respect and appreciation for you both.

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LIST OF ABBREVIATIONS

ABS:	Australian Bureau of Statistics
AF:	Attributable Fraction
ANZSIC:	Australian and New Zealand Standard Industrial Classification
ANZSCO:	Australian and New Zealand Standard Classification of Occupations
ATR:	Absolute Temperature Risk Effect
BLUP:	Best Linear Unbiased Prediction/s
CI:	Confidence Interval
CMIP:	Coupled Model Intercomparison Project
CSIRO:	Commonwealth Scientific and Industrial Research Organisation
DLNM:	Distributed Lag Non-Linear Model/s
ES:	Effect Sizes
EHF:	Excess Heat Factor
GCCSA:	Greater Capital City Statistical Area/s
GHG:	Greenhouse Gases
GIS:	Geographical Information System/s
HI:	Heat Index
HSR:	Health Safety Representative/s
ICD-9-CM:	International Classification of Diseases, Ninth Revision, Clinical Modification
IEO:	Index for Education and Occupation
IRSAD:	Index of Relative Socio-Economic Advantage and Disadvantage
IPCC:	Intergovernmental Panel on Climate Change
LCI:	Lower Confidence Intervals
LMIC:	Low- and Middle-Income Country
LST:	Land Surface Temperature
NDS:	National Dataset for Compensation-Based Statistics
NDVI:	Normalised Difference Vegetation Index
NGO:	Non-governmental Organisations
OI:	Occupational Injuries and Illnesses
OR:	Odds Ratio
OSHA:	Occupational Safety and Health Administration

Phd:	Doctor of Philosophy
PMOI:	Percentile of Minimum Occupational Injuries and Illnesses
POA:	Postal Areas
PPE:	Personal Protective Equipment
QAIC:	Quasi Akaike Information Criterion
RCP:	Representative Concentration Pathways
RR:	Relative Risk
SA2:	Statistical Area 2
SA3:	Statistical Area 3
SWA:	Safe Work Australia
SWSA:	Safe Work South Australia
Tavg:	Average Air Temperature
Tmax:	Maximum Air Temperature
Tmean:	Mean Air Temperature
Tmin:	Minimum Air Temperature
TOOCS:	Type of Occurrence Classification System
TS:	Time Series
UCI:	Upper Confidence Intervals
US:	United States of America
WBGT:	Wet-Bulb Globe Temperature
WHO:	World Health Organisation
WHS:	Work, Health, and Safety

DECLARATION

I certify that this work contains no material which has been accepted for the award of any other degree or diploma in my name, in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. In addition, I certify that no part of this work will, in the future, be used in a submission in my name, for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Adelaide and where applicable, any partner institution responsible for the joint award of this degree.

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Syeda Hira Fatima

5 September, 2023

COVID-19 IMPACTS

This journey has been a testament to my endurance and patience. In February 2020, I urgently returned to my home country due to my father's terminal illness. Little did I know that the COVID-19 pandemic would soon disrupt the world, and I found myself stranded there due to the international border closure in Australia. I remained in my home country for one year and ten months, navigating the uncertainties of the pandemic and personal challenges. During this time, I also grappled with decreased efficiency due to technical glitches associated with working remotely with large datasets. I finally managed to return to Australia in late November 2021.

During this prolonged period, my academic journey encountered numerous obstacles and adaptations. I took a leave of absence, received a 3-month COVID-19 scholarship extension, and adjusted my attendance status to part-time to accommodate my circumstances.

ACKNOWLEDGMENTS

In the name of Allah, the most beneficent and merciful, who granted me the strength, courage, and wisdom to complete my doctoral dissertation, I am humbled as I reflect on this profound journey.

This thesis is far more than the result of solitary toil at my desk. It represents a collective effort, and I am filled with immense gratitude towards the many individuals who played pivotal roles in guiding and supporting me throughout its compilation.

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PUBLICATIONS DURING CANDIDATURE

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2. Fatima, S. H., Rothmore, P., Giles, L. C., & Bi, P. (2023). Intra-urban risk assessment of occupational injuries and illnesses associated with current and projected climate: Evidence from three largest Australian cities. *Environmental Research*, *228*, 115855. https://doi.org/10.1016/j.envres.2023.115855.
3. Fatima, S. H., Rothmore, P., Giles, L. C., & Bi, P. (2022). Outdoor ambient temperatures and occupational injuries and illnesses: Are there risk differences in various regions within a city? *Science of the Total Environment*, 826, 153945. https://doi.org/10.1016/j.scitotenv.2022.153945.
4. Fatima, S. H., Rothmore, P., Giles, L. C., Varghese, B. M., & Bi, P., (2021). Extreme heat and Occupational Injuries in different climate zones: a systematic review and meta-analysis of epidemiological evidence. *Environmental International*, 148(2021) 106384. https://doi.org/10.1016/j.envint.2021.106384.

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MEDIA COVERAGE

Research findings from one of my studies "Extreme heat and occupational Injuries in different climate zones: A systematic review and meta-analysis of epidemiological evidence" are cited in "As heatwaves become more extreme, which jobs are riskiest?" by The Conversation and Australian Broadcasting Corporation (ABC) News, January 2021.

1. https://theconversation.com/as-heatwaves-become-more-extreme-which-jobs-are-riskiest-151841
2. https://www.abc.net.au/news/2021-01-26/as-heatwaves-become-more-extreme-which-jobs-are-riskiest/13088750?utm_campaign=abc_news_web&utm_content=link&utm_medium=content_shared&utm_source=abc_news_web

AWARDS AND ACHIEVEMENTS

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THESIS ABSTRACT

High ambient temperatures pose significant challenges for Work, Health, and Safety (WHS) with increased risk of occupational injuries and illnesses (OI). Previous studies provide evidence on the impacts of heat on OI at broader scales. However, such heat exposure may vary at an intra-urban scale. Analysing the location-specific heat-related OI risk within cities is crucial for tailored risk reduction. Therefore, this thesis aimed to understand the multifaceted impacts of heat on WHS at intra-urban scale, with the main objectives:1. Conducting such intra-urban risk assessments in diverse climates of Australia, 2. Identifying vulnerable groups of workers, 3. Projecting future OI risk under climate change scenarios, 4. Assessing the efficacy of existing heat-related policies in high-risk industries.

A mixed method approach was utilised. In the quantitative part, the associated impacts of heat on OI were estimated in four cities of Australia including Greater Adelaide, Greater Brisbane, Greater Melbourne, and Greater Sydney. The epidemiological assessments were conducted using time series study design coupled with distributed lag non-linear models using quasi-poison distribution at statistical area level 3. Vulnerable groups of workers were identified based on their environmental, personal and workplace characteristics. Risk of OI and attributable fraction (AF) associated with projected climate change scenarios were also predicted for the four cities. In the qualitative part, WHS policy documents were assessed thematically using a framework of analysis approach in high risk construction industry. The policy documents were acquired from one large commercial construction company and its sub-contractors.

The risk of OI varied geographically within cities. Typically, areas characterized by consistently hot weather conditions posed a heightened OI risk for workers. In Greater Adelaide, it was the northern and western regions that exhibited greater vulnerability among workers. In Greater Brisbane and Greater Sydney, workers in the western inland areas had a higher burden of heat-related OI compared to eastern coastal areas. In Greater Melbourne, workers in densely populated inner-city regions were vulnerable to the impacts of heat. Overall, younger workers (aged < 45 years), male workers, those engaged in heavy physical work, and those working predominantly outdoors were at elevated risk of OI. The complex interactions between environmental and socio-

economic factors played an essential role in the spatial patterns of heat-related OI risk dynamics. Regions with less vegetation and lower socio-economic status were found to be more vulnerable. Such risk is predicted to increase due to climate change. Cities with warm baseline climates, such as Greater Brisbane and Greater Sydney, will face a higher risk.

Policy document analysis suggests that the development and implementation of heat-related policies are still in their early stages. Priorities for heat-related policy development include an increased emphasis on preparation and planning for hot weather and considering localised workplace and individual risk factors in assessing the heat hazards.

Research findings with location-specific risk identification will have implications for OI risk prevention by relevant stakeholders. Outcomes form this study will be helpful for WHS field to identify vulnerability, plan for better WHS measurements such as advocacy, urban planning, infrastructure development, emergency preparedness, and community engagement.

CHAPTER 1

INTRODUCTION

Preface

Chapter 1 provides evidence regarding the effects of heat on work, health, and safety (WHS). The unfolding impacts of climate change have brought to light the significance of heat as a critical occupational health concern. Section 1.1 lays the groundwork for understanding the influence of climate change on human health. Section 1.2 explores the association between heat and its implications on WHS. The association between occupational injuries and illnesses (OI) and heat is presented in Section 1.3. Section 1.4 examines a policy framework about heat and its implications on WHS. To establish the foundation of the thesis, Section 1.5 presents the thesis aims, while Section 1.6 outlines the structure and content organisation of the thesis.

1.1 Climate Change and Global Health

Climate change is unequivocally the biggest global health threat of the 21st century (1). The unparalleled shifts in climate are a result of the emissions of greenhouse gases (GHG) from human activities. The last four decades (1980-2020) were successively warmer than any preceding decade since 1850 (2). The global surface temperature was found to be 1.09ºC higher in the decade spanning 2011-2020 than in the second half of the 19th century. Under a range of GHG emission scenarios, the Intergovernmental Panel on Climate Change (IPCC) predicts that by 2081-2100, the global surface temperature will be 1.0 to 1.8ºC hotter than current temperatures under the low GHG emission scenarios, 2.1 to 3.5ºC hotter under intermediate GHG emission scenarios, and more than 3.3 to 5.7ºC hotter under high GHG emission scenarios (2).

Climate change affects human health in multifaceted ways (3). The direct and indirect effects of climate change are mediated through several exposure pathways such as extreme weather events, heat stress, air quality, food and water insecurity, and vector distribution and ecology (1, 4, 5). The often-interrelated health consequences include injuries and mortalities from extreme weather conditions, heat-related illness, respiratory disorders, water-borne diseases, zoonoses and vector-borne diseases, malnutrition and food-borne diseases, noncommunicable diseases such as cardiovascular diseases, mental and psychosocial disorders, and work-related injuries and illnesses (3, 5).

The impacts of climate change vary geographically and impact communities differently in various parts of the world (6, 7). Climate-related risks are higher for lower latitudes and low- and middle-income countries (LMIC) (8). Further, extreme temperatures are projected to increase more often than global mean temperatures, with some regions more vulnerable to the impacts of heat (9). Figure 1.1 illustrates the geographical variations in maximum temperature over 120 years.

Projected climate change will further aggravate heat-related morbidity and mortality, worsen poverty and socio-economic disparities, and widen the existing health inequalities between and within populations (1). IPCC has concluded that the world must curtail temperature rise to 1.5ºC by the end of this century. Global warming of even 1.5ºC is not safe, given that every additional 0.1ºC rise in temperature can potentially have a severe toll on human health (10).

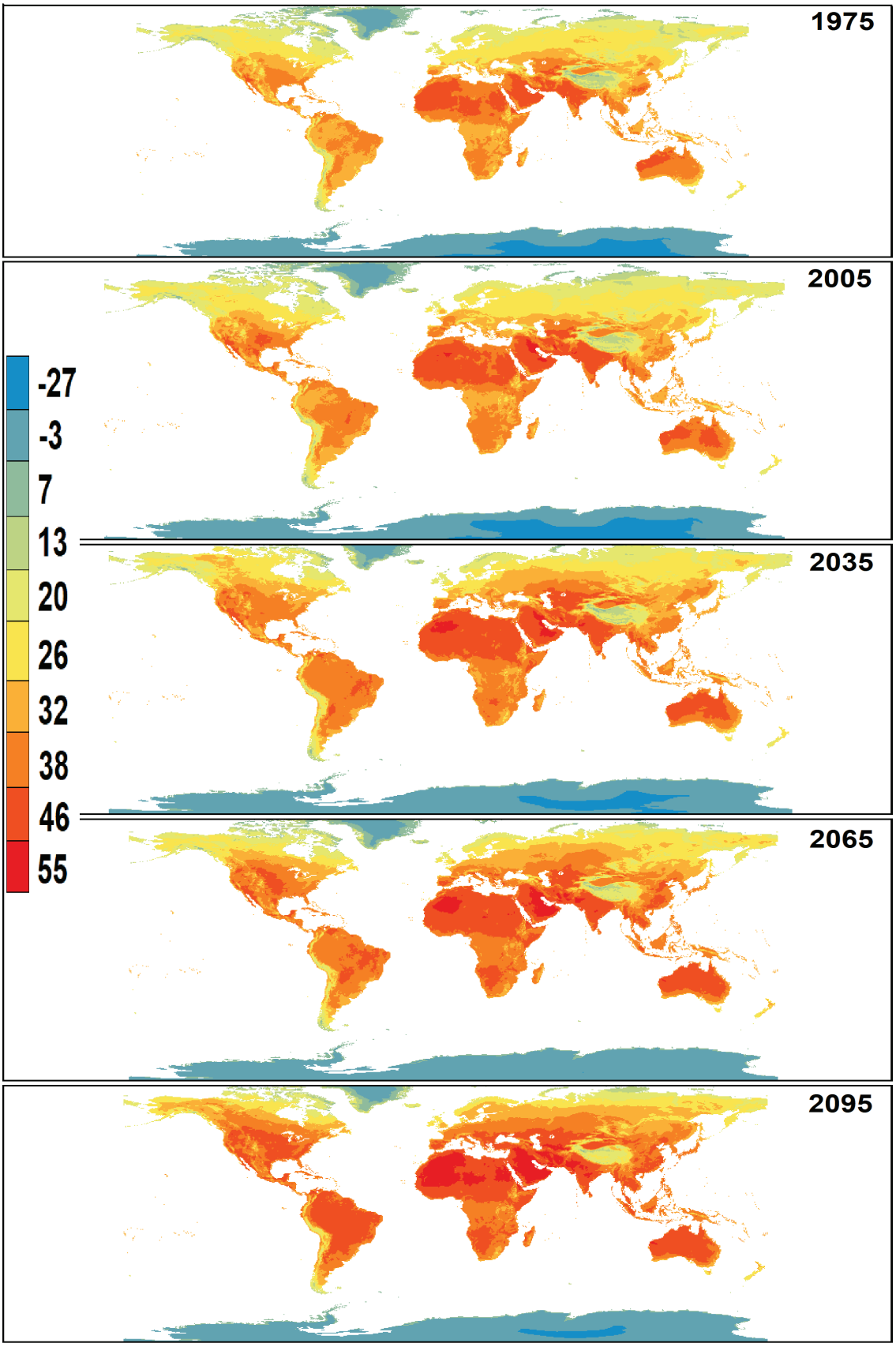

Figure 1.1 Global maps of maximum temperature (ºC) of the warmest month acquired from global bioclimatic indicators derived from climatic projections (11).

The maps indicate values for 30-year increments: 1975, 2005, 2035, 2065, and 2095, respectively.

1.1.1 Increasing Temperatures and Frequent Extreme Heat Events

One of the most significant challenges for climate change associated health burdens is increasing temperatures and frequent extreme heat events (12-14). Population exposure to heat is increasing, which will continue due to climate change. From 2000 to 2016, the count of susceptible individuals exposed to heatwave occurrences rose by approximately 125 million. Notably, there was a peak increase of 175 million people exposed to heatwaves in 2015 (15). It has been estimated that around 30% of the global population experiences climatic conditions that exceed dangerous temperature thresholds for at least 20 days annually. By 2100, this proportion of the population affected is estimated to rise to approximately 48% under low GHG scenarios and up to 74% under high GHG scenarios (16).

The impacts of increasing temperature on human health are spatially heterogeneous (17, 18). For example, Tropical regions near the equator experience higher temperatures and frequent heatwaves, which can be especially intense due to their already warm climate. South Asian countries like Pakistan and India are home to some of the densest human populations and experience severe heatwaves during summer months.

Many countries in Sub-Saharan Africa are particularly vulnerable to the impacts of heat, which can have adverse effects on human health, particularly in areas with limited access to healthcare and resources. Under climate change scenarios, these regions may potentially exceed human biophysical capacity, regardless of local acclimatization (19, 20). Arid and Semi-Arid dry climates, such as deserts and arid landscapes in Middle East and North Africa, are susceptible to extreme heat events, as they lack the moderating effect of large water bodies. Similarly, countries in Mediterranean regions, such as Spain, Italy, and Greece, have been experiencing prolonged and intense heatwaves, leading to severe impacts on human health. The Southwestern United States (US) and many regions in Australia, are characterised by hot and dry climate and they experience frequent and intense heatwaves, leading to heat-related illnesses and strain on the healthcare system. Temperate climates will most likely be affected by periodic extreme heat events (21).

Moreover, urban environments are characterised by micro-climates and exhibit the urban heat island effect. This phenomenon occurs because of the dense presence of concrete and asphalt, leading to heat trapping and retention. Consequently, these areas experience

higher temperatures than the surrounding rural areas. This situation renders residents in mega-cities susceptible to the adverse impacts of heat.

The spatial heterogeneity in global trends is not only attributed to underlying climate conditions but is also influenced by factors such as population characteristics, health equity, and socio-economic resilience that affect human susceptibility to heat effects (22). Geographical variations in exposure patterns highlight an urgent need for highly localised risk estimation and predicting future patterns for developing tailored interventions and early warning systems across the planet's diverse urban settlements (14, 23).

Australia is particularly vulnerable to the impacts of heat, as most parts of the country experience hot summers and frequent heatwaves. According to the Australian Bureau of Meteorology, the average temperature in Australia has risen significantly, with an average increase of 1.4°C since the commencement of national records in 1910, notably more pronounced after the year 1950 (24). Every decade since 1950 has been warmer than the preceding decades. Very high monthly maximums that occurred around 2% of the time previously (1960-1989) now occur over 11% of the time (2007-2021) (Figure 1.2). Extreme heat has caused more deaths in Australia than any other natural hazard (24).

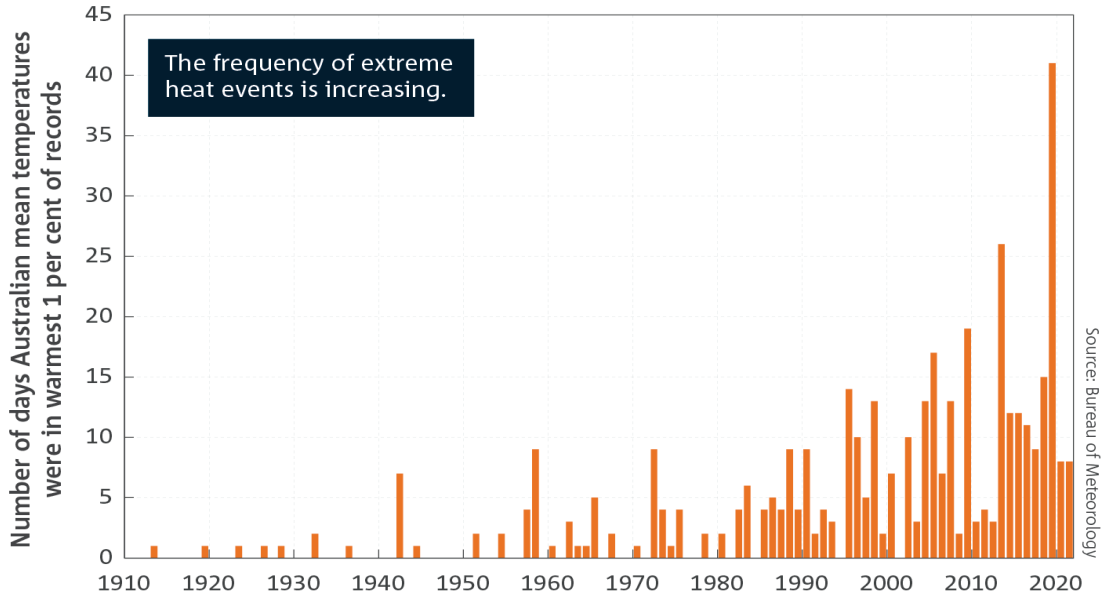

Figure 1.2 Number of hottest days (when area-weighted average of daily mean temperature for each month is extreme) for the period of 1910 to 2021.

(Source: Bureau of Meteorology, Australia (24)).

Rising global ambient temperatures have a wide range of physiological and psychosocial impacts on all populations, often amplifying existing comorbidities, premature deaths, and disabilities (25-28). However, some populations face a higher level of exposure to or are physiologically or socio-economically vulnerable to heat stress, exacerbated illness, and an increased risk of death from exposure to excess heat. These include the elderly, infants and children, pregnant women, athletes, people from a lower socio-economic position, and workers - particularly those working outside and in manual work (29).

1.2 Heat and Work, Health, and Safety (WHS)

Workers in many industries have to work under direct exposure to high ambient temperatures for long periods due to their job requirements (30). Many factors contribute to increased heat stress and consequent health burden in workplaces, including external/environmental factors, workplace factors, and workers' personal characteristics (31, 32).

Environmental factors such as ambient temperature, humidity, and wind speed influence the body's thermoregulation (33). For example, in hot and particularly humid conditions, the heat transfer from the body is limited, leading to an increase in core body temperature (21). Conversely, the body loses heat faster in cold environments, which can drop the core body temperature. Other environmental factors such as the absence of green spaces, heat emissivity from surfaces, solar radiation, the urban heat island effect, extreme weather events such as heatwaves, and atmospheric pollution may also contribute to the overall impacts of heat.

Workplace factors such as the type and nature of work, such as that involving the use of heavy personal protective equipment (PPE) or strenuous physical activities, affect sweat loss and heat convection from the body and add to personal heat exposure (34, 35). Radiant heat from hot objects/machinery, process-generated heat at workplaces (for example, in boiler rooms, steel mills, foundries, and other manufacturing industries), and poor workplace infrastructure with a lack of cooling, ventilation, and confined spaces are some of the work-related indoor sources that can potentially expose workers to heat stress and associated health impacts in workplaces.

Personal factors such as gender, age, safety motivation, health status (for example, pregnancy, obesity, and existing comorbidities such as heart conditions and diabetes, intake of medication, among others), alcohol consumption, socio-economic status, experience, and acclimatization to hot working conditions are some of the important predisposing factors that can affect a person's adaptability to heat and consequent heat impacts.

Exposure to extreme heat can lead to heat stress and heat-related illnesses. If these conditions are not promptly treated, they can potentially result in tissue or organ damage and, in severe cases, even lead to fatalities among workers (36). Furthermore, the resultant fatigue and acute impairment of work capacity can lead to loss of productivity and diminished performance and may further lead to an increased risk of injuries and illnesses in the workplace, as illustrated in Figure 1.3 (21, 37, 38).

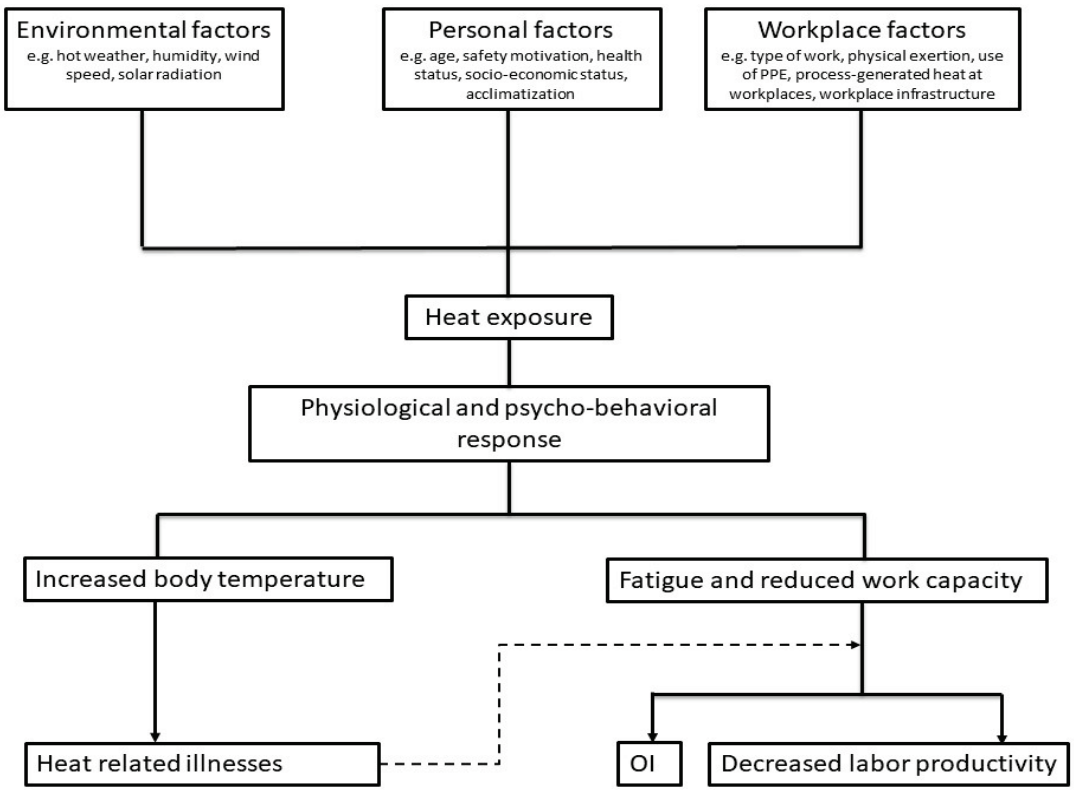

Figure 1.3 Diagrammatic illustration of impacts of heat exposure on WHS.

Adapted from Varghese et al., Borg et al., and Kjellstrom et al. (32, 39, 40).

1.2.1 Occupational Injuries and Illnesses (OI)

An occupational injury is defined as *"...any personal injury, disease or death resulting from an occupational accident."* and occupational illness is defined as *"...a disease contracted as a result of an exposure over a period of time to risk factors arising from work activity." (41)*. OI contribute to a significant global health burden and pose a threat to workers' health, the workplace, and the community. Across the globe, approximately 2.3 million deaths occur annually for reasons attributed to work (42). The numbers will continue to rise in climate change scenarios, hindering health, economic and social development, and aggravating productivity loss in many countries. Figure 1.4 shows global estimates of OI incidence for seven regions classified by the World Health Organisation (WHO) based on income structures. The estimates are compiled from various studies (43-46). This figure demonstrates that communicable diseases, digestive disorders, and occupational injuries are higher in LMIC, while neuropsychiatric disorders and neoplasms are more common in high-income countries. High-income countries also show a greater incidence of circulatory and genitourinary diseases among OI.

OI are increasing in LMIC but are declining in high-income countries, although the overall effect of globalization on OI is mixed (47). The steady decline in Australia, North America, and Western Europe is partly attributed to the export of labour-intensive industrial productions to regions with lower economic costs and less stringent workplace regulations. However, small firms and informal sectors have markedly increased in these countries. These firms and jobs are underserved by WHS regulations enforcement and have a greater but underreported burden of OI (47).

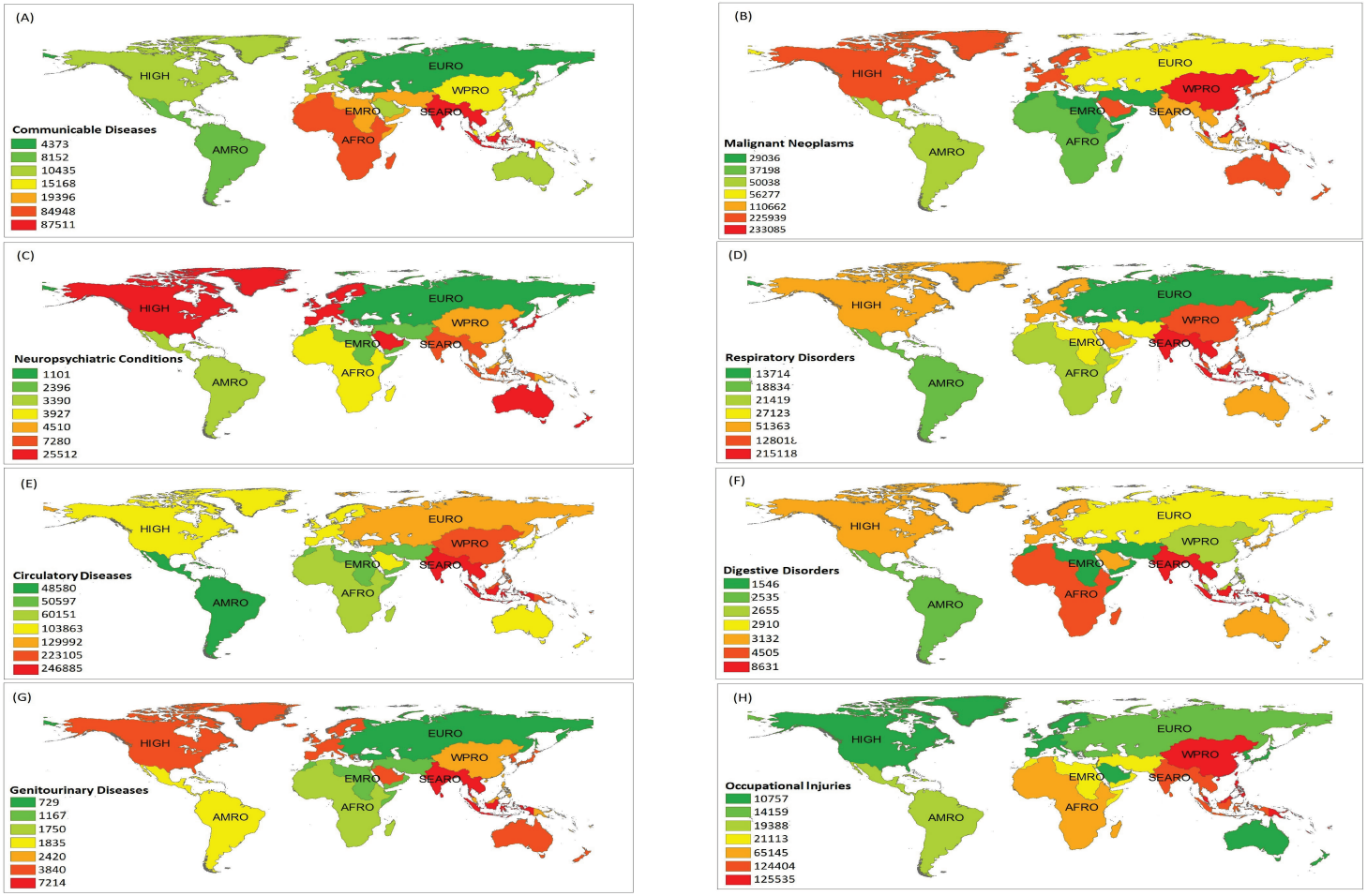

Figure 1.4 Choropleth maps of global estimates of the incidence of Occupational Diseases and Injuries, 2017.

The conditions are classified as A. Communicable Diseases, B. Malignant Neoplasms, C. Neuropsychiatric Conditions, D. Respiratory Disorders, E. Circulatory Diseases, F. Digestive Disorders, G. Genitourinary Diseases, H. Occupational Injuries. Datasets are acquired from (43-46).

1.2.2 OI Burden in Australia

In Australia, 120,355 serious claims of OI that resulted in one week of absence from work and 194 fatalities at workplaces were reported in 2020 (48). The frequency of serious claims per million hours worked decreased by 23% from 2009-2010 to 2018-2019 (49). The majority of OI burden is attributable to traumatic injuries and musculoskeletal disorders. Generally, the high-risk workers for OI are labourers, community and personal service workers, machinery operators and drivers, technicians, and trade workers. The most common causes of OI include body stress (37%), falls, trips, and slips of a person (23%), being hit by moving objects (16%), mental stress (8%), and hitting objects with a part of the body (7%), and others (8%) (48).

The national regulatory authority Safe Work Australia (SWA) compiles the case-level compensable injuries and illnesses made under the state, territory, and Australian Government compensation acts in the National Dataset for Compensation-Based Statistics (NDS) (50). The NDS is supported by several classification systems, including the Australian and New Zealand Standard Industrial Classification (ANZSIC), the Australian and New Zealand Standard Classification of Occupations (ANZSCO), and the Type of Occurrence Classification System (TOOCS)

1.3 Heat and OI

Exposure to hot weather conditions increases the risk of OI (34, 51-53). Exposure to extreme heat can lead to heat stress, which causes heat-related illnesses such as heat stroke, heat exhaustion, rhabdomyolysis, heat syncope, and heat cramps. Further, workers become lethargic and fatigued in hot weather, which results in the reduction of fine motor skills, coordination, alertness, and performance (38, 54, 55). These effects lead to loss of concentration and increase the rate of mistakes, resulting in injuries such as falls, trips, or slips (56). The risk of injuries also increases due to sweaty palms, fogged-up safety glasses, or when workers do not use PPE due to hot weather (57, 58). For example, sweaty palms can reduce grip strength and control, making it more challenging for workers to hold onto tools, equipment, or surfaces. In situations where a firm grip is essential, such as construction work, handling machinery, or working at heights, sweaty palms can increase the likelihood of accidents and injuries. In high-

temperature and humid conditions, safety glasses and goggles may fog up due to temperature differences between the inside and outside of the lenses. Foggy eyewear can obstruct vision and reduce visibility, potentially leading to accidents, tripping hazards, or improper use of machinery. In hot weather, some workers might be tempted to forego wearing PPE, such as hard hats, gloves, or safety vests, due to discomfort. This non-compliance can expose them to severe injuries, as the protective equipment are specifically designed to protect workers from potential hazards and accidents in the workplace. Further, recurrent exposure to heat may increase the risk of kidney diseases, cardiovascular diseases, mental problems, and other health problems (59, 60). For example, prolonged heat exposure can lead to dehydration and an increased loss of bodily fluids through sweating. This can strain the kidneys to filter waste and regulate electrolyte balance, which can lead to heat-related acute kidney injury. Similarly, high temperatures cause increased heart rate and blood pressure and chronic exposure can lead to additional stress on cardiovascular system, potentially contributing to cardiovascular diseases including hypertension, heart attacks, and strokes. Recurrent heat exposure can also cause mental issues like heat exhaustion and heatstroke leading to confusion, anxiety and in severe cases delirium.

Recent studies have focused on enhancing our comprehension of the links between occupational health and exposure to environmental risks. Many studies have explored the associations between higher temperatures and OI, identified the most vulnerable occupations and workers, and examined the threshold temperatures in different geographical regions (61-65). These studies have utilised retrospective national workers' compensation claims databases for OI and meteorological data from local weather stations to evaluate the relationship between exposure and response (66-68).

Studies published in the past decade suggest that the risk of OI increases between 0.2% and 6% with each 1°C increase in temperature above optimum conditions in various locations across the world (61, 65, 66, 69-76). The heterogeneity in risk distribution depends on environmental, workplace, and personal factors (31). The association between temperatures and OI is usually J-, V-, or U-shaped, with the increased risk associated with hot weather conditions (31). Some studies found a reduced risk of OI related to extreme temperatures, indicating populations' adaptability or prevention and mitigation measures at the workplace towards extreme weather conditions (62, 65).

The risk of OI linked to heat exposure tends to be more pronounced in Humid Subtropical climates. This observation aligns with earlier research on general population mortality and morbidity (17). Additionally, workers in temperate Oceanic and Mediterranean climates face an elevated risk of OI due to high ambient temperatures (31). For a comprehensive understanding of the climate-dependent risk assessment, further insights can be found in Chapter 2, Section 2.2. There is a lack of evidence on the risk assessment of OI associated with heat from Tropical climates. A recent study (77) carried out in Kuwait, characterised by a Subtropical Desert climate, suggests that 40ºC and 41ºC were associated with a relative risk of 1.48 (95%CI: 1.39, 1.59) and 1.44 (95%CI: 1.27, 1.63), respectively.

Specific industries and occupations are particularly vulnerable to the impacts of heat because of the type of work being carried out. For example, workers in outdoor-intensive industries such as agriculture, forestry, fishing, and construction and indoor industries with process-generated heat, such as manufacturing, kitchens, and foundries, are generally more vulnerable to heat impacts. Similarly, labour-intensive work carried out by labourers, drivers, and machinery operators or involving heavy PPE use is also found to be particularly at higher risk of OI. Personal factors also contribute to the ability to develop heat stress and increased risk of OI. For example, few studies suggest that risk is notably higher in young workers who are usually inexperienced or not acclimatised to the impacts of heat (65, 78, 79). Men are found to be at higher risk of OI because most of the labour-intensive occupations are male-dominant (80). Recent evidence suggests that both males and females are vulnerable to the impacts of heat (67). Unacclimatised workers are particularly at higher risk of OI. Tustin et al. suggest that most heat-related incidents occur in the first week of the job as workers are acclimatised to outdoor heat stress (81).

1.3.1 Fine-Scale Risk Assessment of OI Associated with Heat

The availability of national databases on daily occurrences of OI has significantly improved the efficacy of evidence-based studies. Strong evidence has been established on the natural history of temperature-related mortality and morbidity in general and working populations. However, significant questions remain regarding the location-specific association between heat and OI. Previous studies have primarily relied on

aggregated data on broad spatial resolution such as city, state, or province level using meteorological data from a single weather station or multiple weather stations (61-63, 65, 67-69, 72, 82).

Recent advances in remote sensing and geographical information system (GIS) offer high-resolution geospatial datasets that can provide location-specific information on exposure variables such as temperature, humidity, and other meteorological variables. The air temperature may vary significantly at a local scale within cities. Cities have temperature gradients due to the urban heat island effect, lack of green spaces, and air pollution. Studies indicate that air temperature in urban areas is much higher than in surrounding rural areas (83-85). On the other hand, rural areas usually have poorer access to primary healthcare services, which may make rural communities more vulnerable to heat impacts (86). The heat patterns within urban areas and temperature fluctuations across various geographical locations are additionally influenced by natural land morphology, including differences in elevation and the impacts of proximity to the sea in coastal regions (85). These variations cannot be fully captured by unevenly distributed weather station datasets. Geospatial data can potentially help to identify local patterns in exposure variables and can be used to estimate location-specific temperature-related risk of OI.

Fine-scale risk assessment is crucial to categorise geographical differences in heat impacts and identify high-risk areas to inform targeted interventions for risk prevention. Findings from such studies also provide insights into urban planning, better healthcare provision for extreme heat events, and resource allocation for mitigation and adaptation, particularly in climate change scenarios (23). Such information can help industrial entities, civil society organisations, and policy-making organisations to understand the risk of extreme heat and prepare appropriate policies and guidelines for heat events.

Previously, the National Integrated Heat Health Information System initiated in the US used geospatial datasets to map county-level heat vulnerability. These tools are developed to protect communities from the health impacts of warming temperatures. They are proven effective for reducing health, economic, and infrastructural effects of heat (https://www.heat.gov/). Similarly, the European Heat-Shield project is developed to address the negative impacts of increased workplace heat stress on the health and productivity of five European industries: manufacturing, construction, transportation,

tourism, and agriculture. They have developed a comprehensive heat-shield weather platform that forecasts the location-specific heat stress conditions (https://www.heat-shield.eu/).

1.4 Heat and WHS in the Existing Policy Framework

Several countries like Canada, Australia, the US, and some European countries have developed heat action plans to minimize harm to vulnerable groups at the community level (87-89). However, only a few countries have proposed heat-related labour protection programs. Most of them are disseminated as recommendations and guidelines rather than strict policies (90). For example, the US National Institute for Occupational Safety and Health has developed heat standards for managing occupational heat stress. It includes recommendations for employers about how to prevent heat-related illness. They have also developed heat safety tools for planning outdoor work based on weather conditions. It has real-time heat index and hourly location-specific forecasts. It also provides WHS recommendations from the Occupational Safety and Health Administration (OSHA) and National Institute for Occupational Safety and Health (NIOSH).

The Chinese government issued the first national regulation, "Administrative Measures for Heatstroke Prevention and Cooling" (AMHP), 2012 on the prevention of heatstroke in outdoor and indoor labourers in 2012 (91). According to this policy, all outdoor work activities will halt when the temperature exceeds 40°C. Furthermore, outdoor work will not be carried out during the three hottest hours on days when the temperature is between 37 and 40°C, and workers cannot work overtime if the temperature is between 35 and 37°C. Employers are also required to pay high-temperature subsidies to outdoor workers when the temperature exceeds 35°C (92). A recent study evaluated the effectiveness of this policy and suggested that AMHP contributed to the reduction in the heat-related risk of OI by 13% (90).

Similarly, in southern Italy, the region of Puglia enacted an ordinance to protect the health of outdoor workers in the agricultural industry in 2020. The ordinance prohibits workers from working during the hottest hours (12:30 to 16:00) for high-risk days.

The Australian WHS laws protect workers from workplace hazards, including heat exposure. SWA, the national regulatory authority for WHS, provides guidelines for

working in heat. All Australian states and territory regulators also provide detailed guidelines and resources regarding the hazards of working in heat on their websites. SWA's guidelines for working in heat do not recommend any stop-work temperature but suggest that employers identify heat hazards, carry out risk assessments, implement control measures and review their effectiveness. SWA also provides an infographic, fact sheet, and checklist for managing the risks of heat in the workplace.

1.5 Thesis Aims

The overall aim of this research was to contribute towards an improved understanding of the multifaceted impacts of ambient heat on WHS and provide recommendations for policy and practical implications, particularly in the face of a warming climate. The specific research objectives and research questions are presented in Chapter 3.

1.6 Thesis Structure and Outline

This thesis is presented in the "thesis by publication" format and is categorised into seven main chapters. Chapter 1 introduces the thesis topic and identifies the main aim of this research project. Chapter 2 presents a comprehensive systematic literature review of the association between heat and OI, followed by a literature review on the existing heat-related policies established at workplaces and gaps in the existing literature that will be addressed in subsequent chapters. Chapter 3 outlines the research objectives developed from the gap analysis and the specific research questions, the study design, and the overarching methodology of the thesis with a detailed theoretical framework. The next three chapters present the main studies of the thesis. Chapter 4 covers the detailed epidemiology of heat-related risk of OI at the spatiotemporal scale, and the estimation of the risk of OI in future projected scenarios in Greater Adelaide. Chapter 5 presents more comprehensive evidence from three large cities of Australia, including Greater Brisbane, Greater Melbourne, and Greater Sydney. Chapter 6 details the review of existing heat-related policies being implemented at the organisational level in accordance with the national guidelines. Chapter 7 brings together the emerging evidence from the previous chapters to highlight the key findings in terms of research questions and presents the main conclusions to be drawn from this thesis.

CHAPTER 2

LITERATURE REVIEW

Preface

Chapter 2 explores the current body of literature concerning the impacts of heat on WHS. In Section 2.1, the authorship of the published article is stated. Section 2.2 details the systematic review of literature conducted to evaluate the effects of heat, including hot temperatures and heatwaves, on OI in various workplace settings worldwide. The studies are categorised to assess the diverse impacts of heat on WHS in different climate zones across the globe. The review encompasses 24 studies from 2005 to 2020. This work was published in Environmental International in 2021.

Fatima, S. H., Rothmore, P., Giles, L. C., Varghese, B. M., & Bi, P. (2021). Extreme heat and occupational injuries in different climate zones: A systematic review and meta-analysis of epidemiological evidence. *Environment International*, *148*, 106384. https://doi.org/10.1016/j.envint.2021.106384

Additional nine studies published between June 2020 and June 2023 are incorporated in an updated search, detailed in Section 2.3. Section 2.4 delves into the literature review on existing heat and WHS policies in high-risk industries within Australia. Section 2.5 identifies the primary research gaps evident in the present literature.

2.1 Statement of Authorship

Title of Paper	Extreme heat and occupational injuries in different climate zones: A systematic review and meta-analysis of epidemiological evidence.
Publication Status	☑ Published ☐ Accepted for Publication ☐ Submitted for Publication ☐ Unpublished or unsubmitted work written in manuscript style
Publication Details	Fatima, S. H., Rothmore, P., Giles, L. C., Varghese, B. M., Bi, P., (2021). Extreme heat and Occupational Injuries in different climate zones: a systematic review and meta-analysis of epidemiological evidence. *Environmental International*, 148(2021) 106384. https://doi.org/10.1016/j.envint.2021.106384

Principal Author

Name of Principal Author (Candidate)	Syeda Hira Fatima
Contribution to the Paper	Conceptualization, Methodology, Software, Formal Analysis, Validation, Writing - Original Draft
Overall percentage (%)	75%
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.
Signature	Date 25\08\2023

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);

ii. permission is granted for the candidate in include the publication in the thesis; and

iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

Name of Co-Author	Paul Rothmore
Contribution to the Paper	Conceptualization, Writing - Review & Editing, Supervision
Signature	Date 25/8/23

Name of Co-Author	Lynne C. Giles
Contribution to the Paper	Conceptualization, Writing - Review & Editing, Supervision
Signature	Date 25/8/23

Name of Co-Author	Blesson M. Varghese		
Contribution to the Paper	Conceptualization, Methodology, Software, Formal analysis, Validation, Writing - Review & Editing		
Signature		Date	25/8/23

Name of Co-Author	Peng Bi		
Contribution to the Paper	Conceptualization, Writing - Review & Editing, Supervision		
Signature		Date	25/08/2023

2.2 Extreme Heat and Occupational Injuries in Different Climate Zones: A Systematic Review and Meta-Analysis of Epidemiological Evidence

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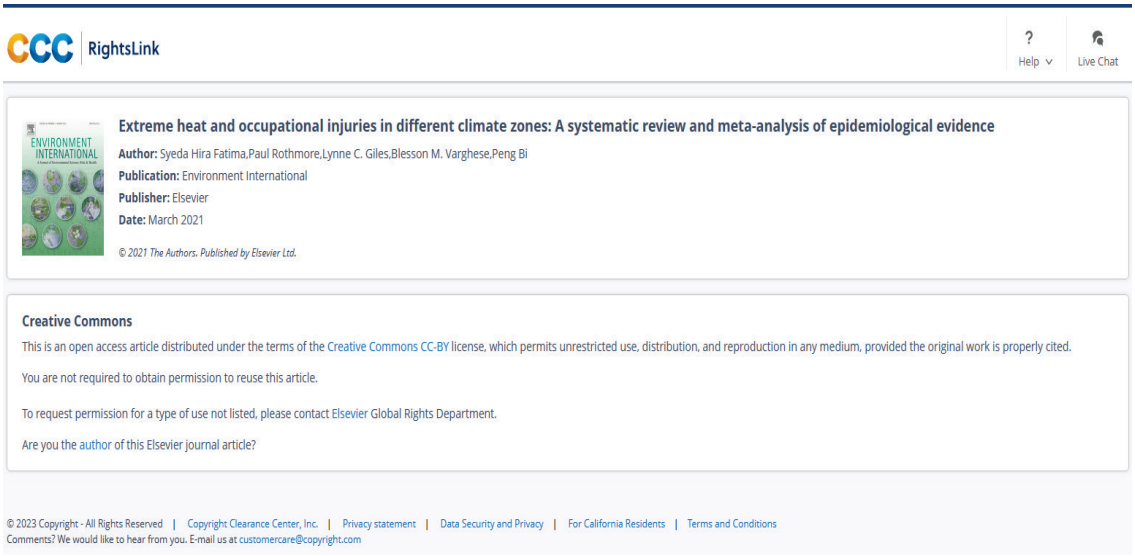

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Review article

Extreme heat and occupational injuries in different climate zones: A systematic review and meta-analysis of epidemiological evidence

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ABSTRACT

Background: The link between heat exposure and adverse health outcomes in workers is well documented and a growing body of epidemiological evidence from various countries suggests that extreme heat may also contribute to increased risk of occupational injuries (OI). Previously, there have been no comparative reviews assessing the risk of OI due to extreme heat within a wide range of global climate zones. The present review therefore aims to summarise the existing epidemiological evidence on the impact of extreme heat (hot temperatures and heatwaves (HW)) on OI in different climate zones and to assess the individual risk factors associated with workers and workplace that contribute to heat-associated OI risks.

Methods: A systematic review of published peer-reviewed articles that assessed the effects of extreme heat on OI among non-military workers was undertaken using three databases (PubMed, Embase and Scopus) without temporal or geographical limits from database inception until July 2020. Extreme heat exposure was assessed in terms of hot temperatures and HW periods. For hot temperatures, the effect estimates were converted to relative risks (RR) associated with 1 °C increase in temperature above reference values, while for HW, effect estimates were RR comparing heatwave with non-heatwave periods. The patterns of heat associated OI risk were investigated in different climate zones (according to Köppen Geiger classification) based on the study locations and were estimated using random-effects meta-analysis models.

Subgroup analyses according to workers' characteristics (e.g. gender, age group, experience), nature of work (e.g. physical demands, location of work i.e. indoor/outdoor) and workplace characteristics (e.g. industries, business size) were also conducted.

Results: A total of 24 studies published between 2005 and 2020 were included in the review. Among these, 22 studies met the eligibility criteria, representing almost 22 million OI across six countries (Australia, Canada, China, Italy, Spain, and USA) and were included in the meta-analysis. The pooled results suggested that the overall risk of OI increased by 1% (RR 1.010, 95% CI: 1.009–1.011) for 1 °C increase in temperature above reference values and 17.4% (RR 1.174, 95% CI: 1.057–1.291) during HW.

Among different climate zones, the highest risk of OI during hot temperatures was identified in Humid Subtropical Climates (RR 1.017, 95% CI: 1.014–1.020) followed by Oceanic (RR 1.010, 95% CI: 1.008–1.012) and Hot Mediterranean Climates (RR 1.009, 95% CI: 1.008–1.011). Similarly, Oceanic (RR 1.218, 95% CI: 1.093–1.343) and Humid Subtropical Climates (RR 1.213, 95% CI: 0.995–1.431) had the highest risk of OI during HW periods. No studies assessing the risk of OI in Tropical regions were found. The effects of hot temperatures on the risk of OI were acute with a lag effect of 1–2 days in all climate zones. Young workers (age < 35 years), male workers and workers in agriculture, forestry or fishing, construction and manufacturing industries were at high risk of OI during hot temperatures. Further young workers (age < 35 years), male workers and those working in electricity, gas and water and manufacturing industries were found to be at high risk of OI during HW.

Conclusions: This review strengthens the evidence on the risk of heat-associated OI in different climate zones. The risk of OI associated with extreme heat is not evenly distributed and is dependent on underlying climatic conditions, workers' attributes, the nature of work and workplace characteristics. The differences in the risk of OI across different climate zones and worker subgroups warrant further investigation along with the development of climate and work-specific intervention strategies.

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1. Introduction

Climate change has led to a significant rise of 0.8 °C–0.9 °C in global mean temperature, leading to frequent and severe heatwaves (HW) (Glaser et al., 2016). Increasing temperatures and HW have and will continue to pose adverse effects on human health, ranging from minor discomfort to death, as documented in numerous epidemiological studies across the world (Amegah et al., 2016; Åström et al., 2011; Azongo et al., 2012; Song et al., 2017). It is predicted that the trend of increasing temperatures and frequent occurrences of HW will continue into the future placing populations at further risk. Recent studies have raised serious concerns about the impacts of extreme heat on workers' health (Kjellstrom et al., 2016; Yang et al., 2017). Workers, as opposed to the general public are usually required to work under exposed conditions for extended periods. The combined effects of prolonged exposure to heat and hot environments, physical work demands and work uniform requirements contribute to heat stress experienced by workers in several occupations and industries (Gao et al., 2018; McCarthy et al., 2018). Thermal exposure can elicit heat stress, acute impairment of work capacity, heat-related illness, loss of productivity and even death among workers (Cheung et al., 2016). Diminished performance and work capacity may further lead to an increased risk of occupational injuries (OI) in the workplace (Binazzi et al., 2019).

A growing body of epidemiological evidence suggests that the risk of OI increases at hot temperatures as compared to an intermediate 'comfortable' temperature range (Adam-Poupart et al., 2015; Ricco, 2018; Tawatsupa et al., 2013). A majority of studies assessing the risk of heat-related OI have found a curvilinear response with a steeper slope at higher temperature thresholds (Marinaccio et al., 2019; Martínez-Solanas et al., 2018; Varghese et al., 2019). Most of these studies were conducted in developed countries with Temperate Climates (Marinaccio et al., 2019; Spector et al., 2016; McInnes et al., 2017; Xiang et al., 2014), while two studies were from developing countries with Humid Subtropical Climates (Guangzhou, China) (Sheng et al., 2018; Ma et al., 2019). However, the thermal exposure thresholds at which the risk of OI increases varies from region to region because of the underlying climate. For example a study from Adelaide, Australia with a dry Warm Mediterranean Climate showed that 1 °C increase in maximum temperature (Tmax) above 14.2 °C and below 37 °C was associated with an increased risk of OI (Xiang et al., 2014), while in Guangzhou, China, Tmax above 30 °C was found to be linearly associated with an increased risk of OI (Sheng et al., 2018). Particularly noteworthy here are the differences in thermal exposure limits. It appears that the threshold above which the risk of OI increases is higher in Guangzhou than Adelaide, suggesting that the heat impacts vary. This geographic variability is due to the underlying local climatic conditions because human health is primarily affected by the long-term climate and seasonal trends rather than daily weather variability (Kalkstein et al., 1996). People are largely adapted to the local climate, in their physiology, culture and engineered supporting infrastructure (Nairn and Fawcett, 2015).

Previously conducted reviews have explored the risk of OI associated with heat exposure (Binazzi et al., 2019; Bonafede et al., 2016; Levi et al., 2018; Spector et al., 2019; Varghese et al., 2018; Xiang et al., 2013). Three comprehensive reviews of the literature (Spector et al., 2019; Varghese et al., 2018; Xiang et al., 2013) published until December 2019, provided evidence on the relationship between heat exposure and the risk of OI and identified specific individual and occupational characteristics that contribute to the vulnerability of workers. These reviews of ecological observational studies have indicated that a linear relationship exists between hot weather and the risk of OI. Further, male workers and young workers (age < 25 years) and those working in outdoor intensive industries such as agriculture, forestry and fishing and construction were found to be at high risk (Binazzi et al., 2019; Xiang et al., 2013).

Occupational injuries including both serious and traumatic injuries arising from slips, trips and falls, exposure to harmful objects, blunt forces and hitting objects, wounds, lacerations and amputations, burns and minor cuts etc. have been reported to increase in hot weather conditions (Bonafede et al., 2016; Spector et al., 2019; Varghese et al., 2018). Varghese et al. (2018) shed light on the potential mechanisms of heat-associated risk of OI involving a combination of physiological and psycho-behavioral responses which upon interaction with other workplace hazards result in OI. Further, a systematic review (Bonafede et al., 2016) explored the associations between extreme weather conditions (both heat and cold) and OI. This systematic review included eight studies published till November 2014 in the qualitative synthesis and showed an association between high temperatures/HW and risk of work-related injuries. More recently, Binazzi et al. (2019) carried out a meta-analysis to summarize the evidence on the heat associated risk of OI and identified specific subgroups of workers at higher risk. A total of eight studies published till October 2018 were included in this meta-analysis and estimated an increased risk of 0.5% (RR 1.005, 95% CI: 1.001–1.009) of OI associated with heat exposure. However, Binazzi et al. (2019) pooled estimates from eight studies irrespective of underlying climates and exposures variables (hot temperatures and HW). For example, the estimates from four city-based (Garzon-Villalba et al., 2016; McInnes et al., 2017; Xiang et al., 2014; Sheng et al., 2018) and three province/state-based studies (Adam-Poupart et al., 2015; Ricco, 2018; Spector et al., 2016) were pooled with that from a whole country based study (Martínez-Solanas et al., 2018), without considering the possible geographical variability of the effect estimates across different locations. Subgroup analyses based on a limited number of variables such as gender, age and industries revealed increased risk for male workers, young workers (with age < 25 years) and those working in the agricultural industry. Other characteristics such as work experience, physical demands of the occupation, business size and industries where heat has been shown previously to be problematic (e.g. electricity, gas, and water, transport etc.) were not considered.

Between 2018 and early 2020, multiple studies have been published concerning the heat-associated risk of OI and covering a range of occupations and geographical locations with diverse climates. While both previous systematic reviews (Binazzi et al., 2019; Bonafede et al., 2016) assessed the risk of bias in individual studies, the strength and quality of their synthesized evidence were not systematically assessed. We therefore systematically reviewed observational ecological studies regarding heat exposure, considering both hot temperatures and HW, and OI risk including more recent studies and undertook an extended meta-analysis using location-specific estimates at the city/province-level classified by Köppen Geiger climate zones. Our primary research question in terms of Population, Exposure, Comparator, Outcome and Study design (PECOS) (Morgan et al., 2018) was:

Among non-military workers (Population) what is the effect of extreme heat assessed in terms of hot temperatures and heatwaves (Exposure) estimated per 1 °C increase in temperature or HW vs non-HW periods (Comparator) on the incidence of Occupational Injuries (Outcome) in observational ecological studies (Study design)?

Further, we also aimed to address the following two specific research questions:

1. How does the risk of OI associated with extreme heat vary in different climate zones of the world?
2. Which workers are at high risk of OI associated with extreme heat in terms of workers' characteristics, nature of work and workplace characteristics?

2. Methods

2.1. Search strategy and selection criteria

A systematic review of published literature for studies that assessed the effects of extreme heat on OI was undertaken using three databases (PubMed, Embase and Scopus). A comprehensive search strategy

focused on "Extreme Heat" and "Occupational Injuries" was developed in consultation with the University librarian (Tables A1–A3, Appendix A of Supplementary Material - SM). The search strategy was designed using the PECOS framework (Morgan et al., 2018; Moola et al., 2015). Briefly, it included keywords such as "hot temperatures" and "heat-waves", "occupations" and "industries", "occupational injuries", "risk assessment" and "epidemiological studies". The study selection criteria based on our PECOS statement is presented in Table 1. Studies were considered eligible after full-text evaluation, if: (a) they explicitly examined and quantitatively reported a risk estimate including odds ratios (OR), incidence rate ratios (IRR) or relative risks (RR) for the relationship between heat exposure (hot temperatures and HW) and OI in non-military workers and (b) they were peer-reviewed publications in English (Table 1). Studies were excluded if: (a) they examined the risk in military workers (b) they addressed process-generated heat, (c) they qualitatively evaluated heat exposure, for example in a questionnaire survey and (d) they were conference abstracts without full-text or non-English articles, editorials, or review articles. No additional filter was applied for publication date.

The search was initially run on November 23, 2019 and was last updated on July 20, 2020 before the finalization of this review.

2.2. Study selection process

Studies retrieved from the three electronic databases were imported into the Endnote X9 reference management system and duplicates were subsequently removed. The study selection process is shown in Fig. 1. All retrieved studies were then identified by initial screening of titles followed by abstract screening. If the information in titles or abstracts was not sufficient to decide on inclusion or exclusion of the study, then the full text was reviewed for eligibility. The studies were screened against inclusion exclusion criteria by two authors independently (SHF and BMV). Inconsistencies between the two authors were discussed for clarification and agreement on final reporting with the other authors. References in each of the identified papers were also examined for any additional studies that may have been missed in our electronic database searches. As the health impacts of HW are different from that of a single hot day, evidence available on the risk of OI associated with extreme heat were categorized into studies assessing the risk at hot temperature and studies assessing the risk during HW periods.

Table 1
Studies eligibility criteria.

Studies eligibility criteria based on PECOS elements	
Population	*All epidemiological studies assessing the risk of occupational injuries among non-military workers associated with extreme heat, published from database inception until July 20, 2020 were eligible for inclusion.*
Exposure	*All epidemiological studies where extreme heat was quantified in terms of hot temperature and HW. The following heat exposure metrics were considered: maximum temperature (Tmax), minimum temperature (Tmin), mean temperature (Tmean) or composite measures of the thermal indices that take into account additional atmospheric variables such as humidity, wind speed, and solar exposure (e.g. Wet Bulb Globe Temperature (WBGT), apparent temperature (AT), Humidex) and HW classifications. HW have been previously defined as extended periods of hot temperatures with three or more days above 35 °C or using indices such as Excess Heat Factor (EHF) to measure intensity, load and duration of HW events (Nairn and Fawcett, 2015).*
Comparator	*Study design did not use any comparators, however the risk is estimated with reference to lower level of exposure. For example for hot temperatures studies there are generally- reference temperatures or thresholds beyond which there is an increase in risk or is a comparison between temperature percentiles while for heatwave studies the reference is made to non-heatwave periods.*
Outcome	*"Occupational Injuries" were defined as any personal injury (injury, illness or death) taking place at the workplace as the result of an occupational accident (ABS, 2018). Occupational illnesses with long latency periods, symptoms of heat stress and loss of productivity were excluded.*
Study Design	*Observational studies including ecological studies, prospective and retrospective cohort studies and case-control studies were considered for inclusion.*

2.3. Data extraction

Relevant study characteristics were extracted from eligible hot temperature and HW studies into a Microsoft Excel spreadsheet. The characteristics included: authors, year of publication, location, (where the study was conducted), climate zones, region (Asia, Australia, Europe and North America), type of industry (agriculture, construction etc.) study population (smelter workers, disaster relief workers etc.), exposure metrics (Tmax, Tmin, Tmean, Humidex or WBGT etc.), minimum reference temperature, highest threshold temperature associated with risk, study design (time series or case crossover), type of statistical models (examples such as Distributed Lag Nonlinear Models or Generalized Additive Models etc.), number of injury records, study duration, time span (short < 5 years or long > 5 years), yearly trend (i.e. whole year or warm season only), effect estimates (RR/OR/IRR) and confidence intervals or mean difference and standard deviation.

Climate zones were extracted for each study location (city, state or provinces) from the 1 Km resolution Köppen Geiger climate classification maps (Beck et al., 2018) and was verified with the climate data developed for cities across the world (Climate-Data.org. Climate data for cities worldwide, 2020). To enable investigation of heat associated risk of OI in different climate zones, location-specific risk estimates were extracted at city, state or province level from the published studies. For studies reporting regional-level results (i.e. province or state level) or national level results, location-specific estimates were obtained from published tables, through textual/graphical descriptions and supplementary materials. When information from figures seemed imprecise, or when data seemed available but was not given in the articles, the relevant studies' authors were contacted at least twice to request for additional data. A unique combination of authors, year of publication and location was used to identify the location-specific effect estimates which were further classified into nine Köppen Geiger climate zones (Humid and Warm Continental, Warm Mediterranean, Hot Mediterranean, Oceanic, Humid Subtropical, Hot Semi-arid, Cold Semi-arid, Subarctic, Hot Deserts Climates) based on Köppen Geiger classification (Köppen and Geiger, 1930).

For hot temperature studies, the effect estimates were reported either as "1°C increase in temperature" (Adam-Poupart et al., 2015; Spector et al., 2016; McInnes et al., 2017; Xiang et al., 2014; Sheng et al., 2018) or as a "comparison between temperature percentiles" (e.g. 90th percentile vs 50th percentile (Varghese et al., 2019; Schifano et al., 2019) or as a "comparison between extreme heat and the reference value where the injury risk was minimal" (e.g. 99th percentile vs. the minimum injury temperature percentile (Marinaccio et al., 2019; Martínez-Solanas et al., 2018; Varghese et al., 2019). Different estimates of effect sizes (e.g. OR, RR, IRR and percent change) have been used to quantify the risk of OI in the reference studies. In studies where ORs were reported, (Ricco, 2018; Spector et al., 2016; McInnes et al., 2017; Schifano et al., 2019; Calkins et al., 2019; Ricco et al., 2020; Ricco et al., 2019) the effect estimates were converted to RR under the assumption that OR approximate RR when the outcome is rare (Diaz-Quijano, 2012). In one study (Rameezdeen and Elmualim, 2017), results were presented as effect sizes and p-values. The method of Altman and Bland (2011) was used to estimate the risk confidence intervals for that study. In another study by Martínez-Solanas et al. (2018) effect estimate sizes were not available numerically at the provincial level. The percentage change was manually estimated from the exposure–response graphs for each province from the study's supplementary material and was converted to RR and 95% confidence intervals.

All effect estimates for hot temperature studies were converted into a common exposure unit of 1 °C increase above reference temperature to quantitatively pool the estimates following the approach of Luo et al.

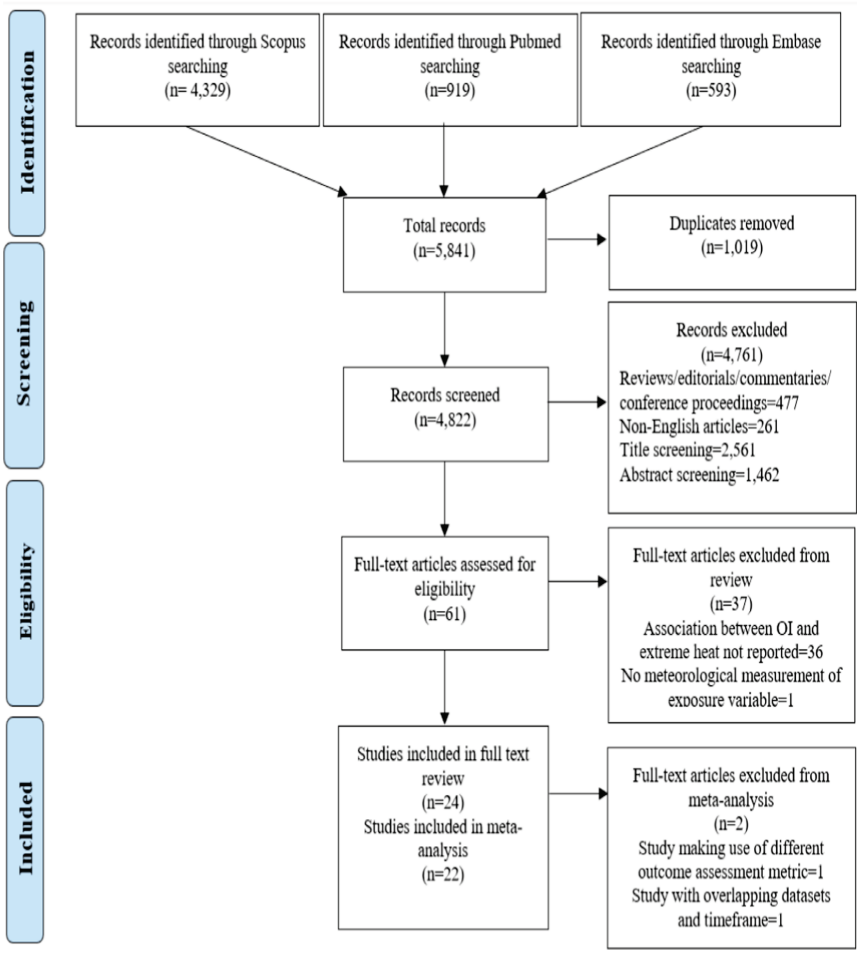

Fig. 1. Flow chart of the selection process to retrieve relevant studies (n = 24).

(2019). For studies assessing the risk using 1 °C increase in temperature, we recorded the reference temperature values and effect estimates associated with each 1 °C increase above the reference values. When percentile-based RR were given, we recorded the temperature values at the reference percentiles (e.g. 25th or 50th percentiles) and maximum percentiles (e.g. 75th, 95th or 99th) and the effect estimates between those percentile ranges. To quantify the effect estimates associated with a 1 °C increase in temperature above the reference value, we calculated the effect as the log RR divided by the range of temperature values at reference percentiles and maximum percentile in each city assuming a log-linear association of OI and heat beyond reference temperature (Luo et al., 2019; Ma et al., 2014; Sun et al., 2018). For HW studies, the effect estimates were extracted as RR and no conversion was performed as they compared the risk of OI in HW versus non-HW periods. For studies that focused on the same city during the same time period but stratified their analysis based on subgroups (e.g. one study assessing the impacts of heat on migrants workers (Ricco et al., 2019) and stratified their analysis into Islamic and non-Islamic holiday periods), we pooled the RRs using fixed-effect models to arrive at one estimate for city and time specific period.

2.4. Assessment of evidence

We used the Navigation Guide framework (Johnson et al., 2014; Johnson et al., 2016) to assess the strength of evidence in the reviewed articles. This framework offers a rigorous and transparent methodology for translating environmental studies including separate guidelines specifically for observational studies (Johnson et al., 2014; Johnson et al., 2016; Goodman et al., 2017; Woodruff and Sutton, 2014). The assessment of evidence was carried out in three steps for both hot temperatures studies and HW studies: Step 1: Assessment of risk of bias in individual studies, Step 2: Assessment of quality of evidence across the studies and Step 3: Assessment of the strength of evidence across the studies for each outcome type.

Each stage of assessment was carried out by two authors independently (SHF and BMV) resolving any disagreement through discussion.

2.4.1. Step 1: Assessment of risk of bias in individual studies

The risk of bias across individual studies was assessed in the following domains: exposure assessment, outcome assessment, recruitment/selection strategy, confounding bias, incomplete outcome data, selective reporting and conflict of interest based on the predefined criteria. A predefined, unequivocal criteria was developed in each of the domains, modified from (Johnson et al., 2014; Woodruff and Sutton, 2014; Achilleos et al., 2017) (Appendix B of SM). Each study was rated as having "Low" (L), "Probably Low" (PL), "Probably High" (PH) or "High" (H) probability of bias. Any disagreements among the reviewers were resolved through discussions until a consensus on quality was reached.

2.4.2. Step 2: Assessment of quality of evidence across the studies

The Navigation Guide framework follows the approach developed by the Grading of recommendations, assessment, development and evaluation methods (GRADE), i.e. first assigning a pre-specified rating to the body of evidence and then considering adjustments (upgrading and

downgrading) based on the characteristics of the included studies (Johnson et al., 2016; Balshem et al., 2011). The quality ratings are not additive scores but serve as qualitative guidance in assessing the overall quality of evidence (Johnson et al., 2016). GRADE guidelines evaluate clinical interventions and experimental human studies i.e. randomized control trials as "high" quality of evidence (Guyatt et al., 2011) and assign "low" quality to observational studies (Balshem et al., 2011). However, not all observational studies are of low quality (Johnson et al., 2014; Viswanathan et al., 2013) and the decision in the context of environmental health is primarily dependent on human observational data (Johnson et al., 2014). Therefore, in line with other methodological reviews (Johnson et al., 2014; Viswanathan et al., 2013) we initially assigned "moderate" quality to the overall body of evidence across all observational studies, in recognition of the value and limitations of such data in examining the associations between environmental exposures and health outcomes.

The upgrading and downgrading of the overall body of evidence is based on eight specific factors including: (1) risk of bias, (2) indirectness, (3) inconsistency, (4) imprecision, (5) publication bias, (6) large magnitude of effect, (7) dose response and (8) whether confounding minimizes the effect. These eight factors are based on GRADE guidelines (Johnson et al., 2014; Balshem et al., 2011) and their criteria for evaluation of the quality of evidence is detailed in Table C1, Appendix C of SM. Various statistical tests were performed to check the overall quality of evidence for risk of bias across the studies, inconsistencies (measured in terms of heterogeneity) and risk of publication bias (Higgins et al., 2003; Higgins and Green, 2008). As a result, the possible ratings were 0 (no change from initial quality rating), −1 (1 level downgrade) or −2 (2 level downgrade); +1 (1 level upgrade) or +2 (2 level upgrade).

Each reviewer independently evaluated the quality of evidence and then compared the ratings and rational for each quality factor. The downgrading and upgrading were conservative, and only when there was a compelling evidence to do so. The weighting of downgrades and upgrades in the overall quality assessment was done after thorough judgements and evidence from statistical tests.

2.4.3. Step 3: Assessment of strength of evidence across the studies

We rated the strength of the body of evidence provided in reviewed papers based on four considerations: (1) "quality of the body of evidence" (i.e. the study ratings from steps 1 and 2 of the assessment); (2) "direction of effect" (i.e. consistency in findings across studies on the risk of OI associated with hot temperatures or HW); (3) "confidence in the effects" (i.e. the likelihood of a new study changing our conclusions); and (4) "any other attributes that affect certainty", as highlighted by Johnson and colleagues (Johnson et al., 2016; Johnson et al., 2014; Woodruff & Sutton, 2014). We used these considerations to assign the overall strength rating, according to the definitions specified in the Navigation Guide for "sufficient evidence", "limited evidence", "inadequate evidence" or "lack of evidence" (Table C2, Appendix C of SM).

2.5. Synthesis of results

Quantitative synthesis was conducted in the form of meta-analysis and forest plots for studies assessing the risk during hot temperatures and HW periods. The meta-analyses were further classified into different climate zones for both categories of heat exposures (where possible). In case of studies not suitable for inclusion in the meta-analysis, we synthesized the study findings narratively and added these to the relevant climate zone results section.

2.5.1. Meta-analyses

There were two steps in the statistical analysis to meet the specific research questions of the study: (1) separately pooling estimates for hot temperatures and HW overall and by climate zones using random-effects models; and (2) performing subgroups analysis.

We estimated the pooled RR of OI associated with exposure to hot temperature overall and separately for each of the climate zones where possible (when total number of city/province-specific effect estimates (K) were greater than equal to two i.e. $K \geq 2$). While different temperature metrics were used in the included studies, we pooled the RR regardless of the exposure metric due to the strong correlation between different measurements of temperature which suggests that on average, they have the similar predictive ability (Varghese et al., 2019).

For HW studies separate meta-analyses were conducted to pool RR of OI during HW compared to non-HW periods overall and in each climate zone where possible (i.e. $K \geq 2$). The studies included in this review used different definitions of HW. In some studies, HW were defined as Tmax $\geq$ 35 °C for three or more consecutive days (Ricco, 2018; Ricco et al., 2020; Ricco et al., 2019; Rameezdeen and Elmualim, 2017; McInnes et al., 2018; Xiang et al., 2014). Varghese et al. (2019, 2018) used the dimensionless location-specific EHF index to assess HW, developed by Nairn and Fawcett (2015). EHF accounts for both short-term and long-term temperature anomalies by comparing the location specific three day Tmean with the 95th percentile of Tmean and the preceding 30 days Tmean (Nairn and Fawcett, 2015; Scalley et al., 2015). EHF is thus a potentially useful indicator to assess the effect of HW at a local population level on health outcomes.

While the HW definitions used in these studies differ, they quantify the risk of heat-related OI in relation to temperatures above the 95th percentile (i.e. 35 °C) (Rameezdeen and Elmualim, 2017; McInnes et al., 2018; Xiang et al., 2014). That is also captured by the studies using the EHF definition (Varghese et al., 2019; Varghese et al., 2018). Hence, we combined all the HW studies together for meta-analysis and presented them separately for different climate zones (where possible). It should be noted that for HW studies temperature variable was not included in the models and all studies modelled HW as the lagged effect of three or more days of hot temperatures. A random-effects meta-analysis was performed to obtain pooled results in different climate zones for both hot temperatures and HW studies considering the heterogeneity in included studies (for example based on different study designs, geographical locations, workforce characteristics etc.). Random-effects models assume that there may be different underlying true effects estimated in each trial which are distributed about an overall mean and are appropriate when heterogeneity between studies is anticipated. The I^2 statistic was calculated to quantify the degree of heterogeneity (Higgins et al., 2003). I^2 values of 0–25%, 25–50% and >50% were taken as indicative of low, moderate and high heterogeneity, respectively (Higgins et al., 2003).

In addition to I^2, we also used the 80% prediction intervals (PI) to assess heterogeneity between studies in line with previous systematic reviews (Orellano et al., 2020; Lee et al., 2020). We considered severe heterogeneity when the 80% PI contained unity and was twice the width of confidence intervals. A series of sensitivity analyses were conducted to explore the potential causes of heterogeneity using overall pooled estimates from all studies. Leave-one-out analysis was performed by iteratively removing one study at a time to confirm that our findings were not driven by any single study. Further, a set of sensitivity analyses were also conducted to calculate the pooled estimates for hot temperature studies based on different exposure metrics (Tmax, Tmean, thermal indices), exposure assessment datasets (single/multiple weather station data vs gridded, geolocated or satellite data) and unit of estimate (1 °C increase in temperature vs comparing percentiles). For HW studies sensitivity analysis was carried out based on exposure assessment datasets and different definitions of HW. Publication bias was evaluated for both hot temperature and HW studies (where possible) using Funnel plots, Begg's and Egger's tests (Egger et al., 1997). We further used Duval and Tweedie's Trim and Fill procedure (Duval and Tweedie, 2000) with random-effects model to recompute the pooled effect sizes after adjusting for small study bias.

2.5.2. Subgroup analyses

Subgroup analyses were conducted by workers characteristics (such

as gender, age, experienced vs new workers), nature of work (such as physical demands and location of work outdoors and indoors) and workplace characteristics (such as type of industries and business size). Additional subgroup analysis based on study characteristics (such as region, study design and modelling techniques) was also carried out. To accommodate the different age group categories across included studies, we stratified pooled estimates for different age groups as age below 35 years and above 35 years and excluded Adam-Poupart et al. (2015) and Ricco et al. (2020) as the age groups did not match with other studies. Subgroup analysis by workers, nature of work, and workplace characteristics was not conducted in different climate zones because of limited number of studies ($K < 2$).

All analyses were performed using 'Metan' command in Stata version 15 (Stata Corp 2013, Harris et al., 2008).

3. Results

3.1. Included studies

Our search retrieved a total of 5841 records. After eliminating duplicate records, 4822 unique records remained. Another 738 articles were excluded because they were either reviews, editorials, conference papers or in other languages. A total of 4023 articles out of the remaining 4084 were excluded as a result of initial screening of titles and abstracts based on inclusion and exclusion criteria. The remaining 61 articles were assessed for full-text eligibility. Thirty-seven articles were excluded because they did not report an association between extreme heat and risk of OI or did not use a direct measure of extreme heat to quantify the risk. The remaining 24 articles were selected for the full-text review as shown in Fig. 1.

3.2. Characteristics of included studies

All studies included in the full text review were published in the past fifteen years between January 2005 and July 2020, although no date restriction was applied to the search. All studies used either a time series ($n = 14$) or case-crossover ($n = 10$) study designs. Two nationwide studies (Marinaccio et al., 2019; Martínez-Solanas et al., 2018) estimated the location-specific risk in all provinces of Italy and Spain. Three studies from Italy and Australia were multi-city studies representative of different climates, and 19 studies were representative of only one city/state/province from various countries such as Australia, Canada, USA, and China. Together, all studies encompass nine climate zones, with a majority of studies representative of mid-latitude temperate climatic zones. Fig. 2 shows the geographic distribution of studies within different climate zones. Sixteen studies were focused on all workers, whereas, eight studies were focused on specific group of workers such as agriculture workers (Ricco, 2018; Spector et al., 2016), construction workers (Calkins et al., 2019; Ricco et al., 2020; Rameezdeen and Elmualim, 2017), aluminum smelter workers (Fogleman et al., 2005), disaster relief workers (Garzon-Villalba et al., 2016) and migrant workers (Ricco et al., 2019).

Sixteen studies assessed the risk of OI in hot temperatures only, while three studies estimated the risk in both hot temperatures and HW periods, and five studies assessed the risk exclusively during HW. In total, 19 studies were used to assess the risk of OI associated with hot temperatures. The study characteristics are given in Table 2. Eight studies were used to assess the risk of OI during HW periods, and their study characteristics are presented in Table 3.

3.3. Assessment of evidence

3.3.1. Assessment of risk of bias in individual studies

The risk of bias assessment of the included studies (hot temperature and HW studies) is summarized in Figs. 3 and 4. Detailed risk of bias assessment of all individual studies is presented in Tables D1–D24, Appendix D of SM.

3.3.1.1. Hot temperature studies. Two out of 19 (11%) hot temperature studies (Sheng et al., 2018; Ma et al., 2019) assessing the risk of OI had a "probably high" risk of bias in recruitment/selection strategy, as the baseline data were representative of only 54% of the workers'

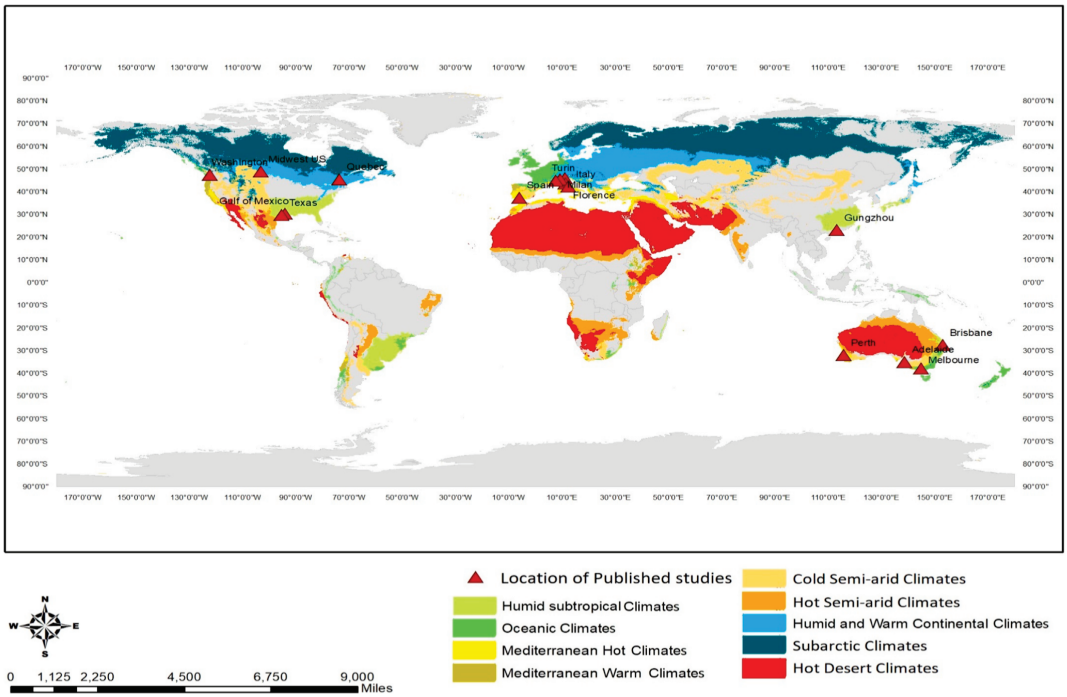

Fig. 2. Geographic distribution of published studies included in the review ($n = 24$) within nine climate zones.

Table 2
Study characteristics and key findings of all studies assessing the risk of OI in hot temperature conditions (n = 19).

First Author, Year	Location	Climate	Study Population	Study Design	Exposure metric and source	Key findings ES(CI)
Fogleman et al., 2005	Midwest US	**Humid and Warm Continental Climates**	Aluminum smelter workers	TS	Daily Heat Index Comparing Percentiles: Ref Heat Index: 13.5 Threshold Heat Index: 38	RR: 1.050 (1.024–1.076)
Morabito et al., 2006	Tuscany, Italy	**Hot Mediterranean Climates**	All occupations	TS	Daily maximum AT Daily average AT Maximum AT ≥ 31.1 °C	$X^2 = 9.3$ P-value = 0.025 *Reversed U shape response*
Xiang et al., 2014	Adelaide, Australia	**Warm Mediterranean Climates**	All occupations	TS	1 °C increase in Tmax	IRR: 1.002 (1.001–1.004) *Gender* M: 1.004 (1.002–1.006) F: 0.998 (0.994–1.001) *Age* ≤24: 1.005 (1.002–1.008) 25–34: 1.002 (0.999–1.003) 35–54: 1.001 (0.999–1.003) ≥55: 1.000 (0.997–1.003) *Industries* Agriculture: 1.007 (1.001–1.013) Construction: 1.006 (1.002–1.011) *Reverse U shaped response with no lagged effect*
Adam-Poupart et al., 2015	Quebec, Canada	**Humid and Warm Continental Climates:** Bas-Saint Laurent, Capitale Nationale, Maurice, Estrie, Montreal, Outaoais, Abitibi-Temiscamingue, Chaudere-Appalaches, Laval, Lanaudiere, Laurentides, Montrege **Subarctic:** Sanguenay-Lac-Saint_Jaen, Cote-Nord, Nord-du-Quebec, Gaspesia-lies-de-la-Madeleine	All occupations	TS	1 °C increase in Tmax	IRR: 1.002 (1.001–1.003) *Gender* M: 1.003 (1.002–1.005) F: 1.000 (0.998–1.003) *Age* 15–24: 1.008 (1.005–1.010) 25–44: 1.003 (1.001–1.004) ≥45: 1.000 (0.999–1.001) *Industries* Forestry and logging: 1.011 (1.001–1.020) Construction: 1.003 (1.000–1.006) *Linear and lagged response*
Garzon-Villalba et al., 2016	Gulf of Mexico, US	**Humid Subtropical Climates**	Disaster relief workers	TS	1 °C increase in WBGTmax	RR: 1.060 (1.040–1.070) *No delayed effect for acute injuries*
Spector et al., 2016	Washington, US	**Warm Mediterranean Climates**	Agriculture Workers	CCO	1 °C increase in Humidex	OR: 1.010 (1.010–1.020) *Reverse U shaped curve*
Martínez-Solanas et al., 2018	Spain	**Oceanic:** Alava, Asturias, Burgos, Cantabria, Guipzcoa, Huesca, La Rioja, Leon, Lugo, Navarra, Palencia, Soria, Teruel, Vallodoid, Vizcaya**Warm Mediterranean:** A coruna, Avila, Pontevedra, Salamanca, Segovia, **Hot Mediterranean:** Badajoz, Barcelona, Caceres, Cadiz, Cordoba, Cuenca, Granada, Girona, Guadalajara, Huelva, Jaen, Madrid, Malaga, Ourense, Sevilla, Tarragona **Hot Semi-arid:** Alicante, Murcia, Santa Cruz de Tenerife, **Cold Semi-arid:** Albacante, Almeria, Castellon, Ciudad Real, Illes Balears, Lleida, Toledo, Valencia, Zamora, Zaragoza**. Hot Desert:** Las Palmas	All occupations	CCO	Comparing percentiles: Average Ref Tmax: 14.98 °C Average Threshold Tmax: 34.9 °C	Overall RR: 1.004 (1.003–1.005) *Gender* M: 1.004 (1.003–1.005) F: 1.002 (1.000–1.003) *Age* ≤24: 1.005 (1.003–1.006) 25–34: 1.003 (1.002–1.004) 35–54: 1.003 (1.002–1.004) ≥55: 1.002 (1.001–1.004) *Industries* Agriculture: 1.012 (1.010–1.015) Construction: 1.004 (1.002–1.005) *U shaped trend and lag effect of 1 or 2 days and to less extent 3and 4 days*
McInnes et al., 2017	Melbourne, Australia	**Oceanic Climates**	All occupations	CCO	1 °C increase in Tmax	OR: 1.002 (0.999–1.004) *Gender* M: 1.003 (1.000–1.006) F: 0.999 (0.994–1.005) *Age* <25: 1.008 (1.001–1.015)

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Table 2 (*continued*)

First Author, Year	Location	Climate	Study Population	Study Design	Exposure metric and source	Key findings ES(CI)
						25–34: 1.002 (0.996–1.007) 35–44: 1.004 (0.999–1.009) 45–54: 0.999 (0.994–1.003) ≥55: 0.998 (0.987–1.002)
Sheng et al., 2018	Guangzhou, China	**Humid Subtropical Climates**	All occupations	CCO	1 °C increase in daily Tmax and Tmin	RR: 1.014 (1.012–1.017) *Gender* M: 1.014 (1.011–1.016) F: 1.015 (1.008–1.021) *Age* ≤24: 1.005 (0.998–1.012) 25–34: 1.018 (1.013–1.024) 35–44: 1.021 (1.017–1.024) 45–54:1.009 (1.001–1.016) ≥55: 0.989 (-) *Industries* Manufacturing: 1.019 (1.015–1.022) Finance, property and business: 1.014 (1.009–1.019)
Ricco, 2018	Trento, Italy	**Humid Subtropical Climates**	Agricultural workers	TS	Comparing percentiles, Ref Tmax: 33.2 °C Threshold Tmax > 37.1 °C	RR: 1.034 (1.007–1.060) *Lagged effect and linear increase*
Calkins et al., 2019	Washington, US	**Warm Mediterranean Climates**	Construction Workers	CCO	1 °C increase in dry bulb temperature	OR: 1.007 (1.005–1.009) *Age* 18–24: 1.008 (1.004–1.014) 25–34: 1.005 (1.002–1.008) 35–44: 1.003 (0.98–1.005) 45–54: 1.004 (0.99–1.008) ≥55: 1.010 (1.002–1.080) *Linear increase in risk*
Dillender, 2019	Texas, US	**Humid Subtropical Climates**	All occupations	TS	Comparing percentiles, Ref Tmax: 15.5 °C Threshold Tmax > 37.7 °C	RR: 1.019 (1.009–1.027) *Age* Statistically significant risk in workers younger then 40 years of age at 37.7 °C
Ma et al., 2019	Guangzhou, China	**Humid Subtropical Climates**	All occupations	TS	Comparing percentiles, Ref WBGTmax: 24 °C Threshold WBGTmax > 30 °C	RR: 1.023 (1.008–1.033) *Gender* M: 1.023 (1.015–1.034) F: 1.021 (1.001–1.042) *Age* <35: 1.021 (1.006–1.035) 35–44: 1.024 (1.009–1.041) >44: 1.023 (0.998–1.046) *No evidence of delayed effect between WBGTmax and OI*
Marinaccio et al., 2019	All provinces of Italy (110)	**Oceanic:** Aosta, Arezzo, Belluno, Biella, Bolzano, Campobasso, Como, Cuneo, L'Aquilla, Varese, Verbano-Cusio-Ossola, **Warm Mediterranean:** Ogliastra, Potenza, **Humid Subtropical:** Alessandria, Ancona, Ascoli Piceno, Asti, Barletta-Andria-Trani, Bergamo, Bologna, Brescia, Chieti, Cremona, Fermo, Ferrara, Foggia, Forlì-Cesena, Genova, Gorizia, Macerata, Lecco, Mantova, Milano, Modena, Monza e della, Brianza, Novara, Padova, Parma, Pavia, Perugia, Pesaro e Urbino, Pescara, Piacenza, Pordenone, Ravenna, Reggio nell'Emilia, Rieti, Rimini, Rovigo, Sondrio, Teramo, Trento, Torino, Treviso, Trieste, Venezia, Udine, Vercelli, Verona, Vicenza **Hot Mediterranean:** Agrigento, Avellino, Bari, Benevento, Brindisi, Cagliari, Caltanissetta, Carbonia-Iglesias, Caserta, Catania, Catanzaro,	Specific occupations	TS	Comparing percentiles: Average Ref Tmean (25th Percentile): 11.5 °C Average Threshold Tmean (75th Percentile): 20.5 °C	Overall RR: 1.017 (1.015–1.020) *Gender* M: 1.019 (1.015–1.023) F: 1.007 (1.002–1.013) *Age* 15–34: 1.023 (1.017–1.027) 35–60: 1.013 (1.009–1.060) >60: 0.989 (0.974–1.007) *Industries* Construction: 1.027 (1.020–1.033) *Lag effect up to 2 days and U shaped relationship between daily mean temperature and OI*

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Table 2 (*continued*)

First Author, Year	Location	Climate	Study Population	Study Design	Exposure metric and source	Key findings ES(CI)
		Cosenza, Crotone, Enna, Firenze, Frosinone, Grosseto, Imperia, Isernia, La Spezia Latina Lecce Livorno, Lodi, Lucca, Massa Carrara, Matera, Medio Campidano Messina, Napoli Nuoro Olbia-Tempio Oristano Palermo Pistoia, Prato,Pisa, Ragusa, Reggio di Calabria, Roma, Salerno, Sassari Savona Siena Siracusa Terni, Trapani, Vibo Valentia, Viterbo, **Cold Semi Arid**: Tarranto,				
Ricco et al., 2019	Trento, Italy	**Humid Subtropical Climates**	All occupations in Migrant workers in comparison to local workers	TS	Pooled the estimates for Islamic and non-Islamic holiday periods for warm season Ref Tmax: 21.4 °C Threshold Tmax > 25 °C	RR: 0.965 (0.871–1.035)
Schifano et al., 2019	Turin, Milan and Rome, Italy	**Humid Subtropical:** Turin and Milan **Hot Mediterranean:** Rome	All occupations	CCO	Comparing percentiles, Turin: Ref Tmax:26 °C Threshold Tmax:33 °C Milan: Ref Tmax:21 °C Threshold Tmax:34 °C Rome: Ref Tmax:24 °C Threshold Tmax:32 °C	**Turin** RR: 1.002 (0.998–1.008) *Industries* Agriculture: 0.976 (0.927–1.063) Construction: 1.009 (0.992–1.027) Electricity: 1.063 (0.992–1.135) Transportation: 1.000 (0.983–1.017) **Milan** RR: 1.000 (0.998–1.003) *Industries* Agriculture: 0.998 (0.946–1.067) Construction: 1.005 (0.997–1.021) Electricity: 1.034 (1.002–1.066) Transportation: 1.003 (0.996–1.010) **Rome** RR: 1.000 (0.998–1.002) *Industries* Agriculture: 1.004 (0.975–1.035) Construction: 1.007 (1.001–1.014) Electricity: 1.000 (0.979–1.020) Transportation: 1.004 (1.000–1.016)
Varghese et al., 2019	Adelaide, Australia	**Warm Mediterranean Climates**	All occupations	CCO	Comparing percentiles, Ref Tmax: 25 °C Threshold Tmax: 40.6 °C	RR: 1.016 (1.010–1.023) *Gender* M: 1.015 (1.007–1.023) F: 1.019 (1.008–1.030) *Age* 15–24: 1.026 (1.011–1.041) 25–34: 1.004 (0.990–1.018) 35–54: 1.021 (1.011–1.030) >55: 1.011 (0.993–1.028) *Industries* Agriculture: 1.091 (1.014–1.169) Electricity: 1.141 (1.067–1.215) *Non-Linear Increase in risk (J shaped curve)*
Varghese et al., 2019	Melbourne Brisbane Perth, Australia	**Oceanic:** Melbourne **Humid Subtropical:** Brisbane **Hot Mediterranean:** Perth	All occupations	CCO	Comparing percentiles, Melbourne: Ref Tmax: 20 °C Threshold Tmax > 38.9 °C Brisbane:	**Melbourne** RR: 1.006 (1.001–1.011) *Gender* M: 1.003 (0.996–1.010) F: 1.012 (1.003–1.021) *Age*

(*continued on next page*)

Table 2 (*continued*)

First Author, Year	Location	Climate	Study Population	Study Design	Exposure metric and source	Key findings ES(CI)
					Ref Tmax: 26.7 °C Threshold Tmax > 34.7 °C Perth: Ref Tmax: 23.7 °C Threshold Tmax > 40.1 °C	15–24: 1.007 (0.992–1.022) 25–34: 1.011 (1.000–1.023) 35–54: 1.005 (0.998–1.013) >55: 1.002 (0.989–1.015) *Industries* Transport and warehousing: 1.024 (1.008–1.040) **Brisbane** RR: 0.997 (0.985–1.010) *Gender* M: 1.001 (0.985–1.016) F: 0.992 (0.972–1.013) *Age* 15–24: 1.018 (0.986–1.049) 25–34: 1.006 (0.978–1.031) 35–54: 0.998 (0.981–1.016) >55: 0.962 (0.929–0.993) *Industries* Agriculture: 1.080 (0.958–1.201) **Perth** RR: 1.009 (1.001–1.018) (Traumatic injuries only) *Gender* M: 1.004 (0.997–1.010) F: 0.994 (0.985–1.004) *Age* 15–24: 1.008 (0.996–1.020) 25–34: 0.994 (0.983–1.005) 35–54: 1.001 (0.993–1.009) >55: 0.998 (0.984–1.013) *Industries* Electricity, gas and water: 1.025 (0.978–1.074) *Non-Linear relationship and the impacts of hot temperatures on OI were acute*
Ricco et al., 2020	Trento, Italy	**Humid Subtropical Climates**	Construction workers	TS	Comparing percentiles, Ref Tmean: 21 °C Threshold Tmax > 25.3	RR: 1.031 (1.013–1.040) *Age* <20: 1.115 (1.016–1.213) 20–29: 1.088 (1.042–1.134) 30–39: 1.046 (1.000–1.092) 40–49: 1.057 (1.006–1.107) ≥50: 0.983 (0.910–1.057) *Lagged effect and linear increase*

Note: All values are converted to increase in risk associated with 1 °C increase in temperature above reference value. Risk is estimated in terms of overall risk and risk in subgroups such as age, gender and type of industries where available. * Two studies (Marinaccio et al., 2019; Martínez-Solanas et al., 2018) are representative of nationwide estimates. The results given in this table represent the overall estimates. Risk is measured in terms of effect sizes and confidence intervals ES(CI). For exposure metrics, following abbreviations were used: AT (Apparent temperature), WBGT (Wet Bulb Globe Temperature) and study design TS (Time Series), CCO (case crossover).

population. Sixty eight percent of the hot temperature studies (Adam-Poupart et al., 2015; Ricco, 2018; Martínez-Solanas et al., 2018; Varghese et al., 2019; Garzon-Villalba et al., 2016; Schifano et al., 2019; Varghese et al., 2019; Fogleman et al., 2005; Morabito et al., 2006; McInnes et al., 2017; Xiang et al., 2014; Sheng et al., 2018; Ma et al., 2019) had "probably high" risk in exposure assessment. A majority of the studies used meteorological data from a single weather station or an average of multiple stations. Relatively few studies used gridded data (Spector et al., 2016; Calkins et al., 2019; Dillender, 2019) or satellite data (Marinaccio et al., 2019) or geolocated data (Ricco et al., 2020; Ricco et al., 2019) for exposure assessment. For outcome assessment, all studies had "probably low" to "low" risk of bias because of the use of national or regional databases that used standard measures of OI, although underreporting is possible. Around 32% of the studies (Ricco,

Table 3
Study characteristics and key findings of all studies assessing the risk of OI during HW periods.

First Author, Year	Location	Climate	Study Population	Study Design	Exposure metric and source	Key findings ES(CI)
Xiang et al., 2014	Adelaide, Australia	**Warm Mediterranean Climates**	All occupations	TS	HW (3 consecutive days Tmax ≥ 35 °C)	IRR: 0.983 (0.943–1.024) *Gender* M: 1.001 (0.947–1.012) F: 0.935 (0.897–0.974) *Age* ≤ 24 1.035 (0.981–1.091) 25–34 0.973 (0.928–1.019) 35–54 0.951 (0.898–1.007) ≥55 1.024 (0.940–1.115) *Industries* Agriculture 1.447 (1.125–1.861) Electricity, gas and water 1.297 (1.049–1.604)
Rameezdeen and Elmualim, 2017	Adelaide, Australia	**Warm Mediterranean Climates**	Construction workers	TS	HW (3 consecutive days Tmax ≥ 35 °C)	IRR: 0.970 (0.960–1.010)
McInnes et al., 2018	Melbourne, Australia	**Oceanic Climates**	All occupations	CCO	HW (3 consecutive days Tmax ≥ 35 °C)	OR: 1.090 (0.870–1.360) *Gender* M: 1.170 (0.900–1.510) F: 0.930 (0.610–1.420) *Age* <35: 0.970 (0.650–1.450) 35–49: 1.280 (0.930–1.780) ≥50: 0.940 (0.590–1.480)
Ricco, 2018	Trento, Italy	**Humid Subtropical Climates**	Agriculture workers	TS	HW (3 consecutive days Tmax ≥ 35 °C)	OR: 1.090 (1.020–1.170)
Varghese et al., 2018	Adelaide, Australia	**Warm Mediterranean Climates**	All occupations	CCO	EHF (moderate/high-severity HW days)	RR: 1.080 (1.010–1.160) *Gender* M: 1.130 (1.030–1.230) F: 0.990 (0.870–1.130) *Age* 15–24: 1.150 (0.970–1.360) 25–34: 1.110 (0.950–1.300) 35–54: 1.080 (0.970–1.200) >55: 0.970 (0.78–1.18)
Ricco et al., 2019	Trento, Italy	**Humid Subtropical Climates**	All occupations in migrant workers	TS	Risk of OI in migrant workers during HW (3 consecutive days Tmax ≥ 35 °C)	OR: 1.749 (1.014–3.017)
Varghese et al., 2019	Melbourne, Australia Brisbane, Australia Perth, Australia	**Oceanic:** Melbourne **Humid Subtropical:** Brisbane **Hot Mediterranean:** Perth	All occupations	CCO	EHF (moderate/high-severity HW days)	**Melbourne** RR: 1.250 (1.220–1.280) *Gender* M: 1.290 (1.250–1.330) F: 1.180 (1.150–1.230) *Age* 15–24: 1.270 (1.190–1.350) 25–34: 1.310 (1.240–1.370) 35–54: 1.260 (1.220–1.300) >55: 1.180 (1.120–1.240) **Brisbane** RR: 1.450 (1.420–1.480) *Gender* M: 1.500 (1.460–1.540) F: 1.350 (1.300–1.400) *Age* 15–24: 1.550 (1.470–1.630) 25–34: 1.560 (1.490–1.630) 35–54: 1.420 (1.370–1.460) >55: 1.300 (1.230–1.370) **Perth** RR: 1.260 (1.240–1.290) *Gender*

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Table 3 (*continued*)

First Author, Year	Location	Climate	Study Population	Study Design	Exposure metric and source	Key findings ES(CI)
						M: 1.290 (1.260–1.320) F: 1.200 (1.160–1.240) *Age* 15–24: 1.290 (1.230–1.350) 25–34: 1.270 (1.220–1.330) 35–54: 1.260 (1.220–1.300) >55: 1.210 (1.150–1.280)
Ricco et al., 2020	Trento, Italy	**Humid Subtropical Climates**	Construction workers	TS	HW (3 consecutive days Tmax ≥ 35 °C)	OR: 1.230 (1.144–1.322) *Age* < 20: 1.892 (1.449–2.470) 20–29: 1.125 (1.971–1.305) 30–39: 1.168 (1.020–1.337) 40–49: 1.323 (1.146–1.527) ≥50: 1.156 (0.958–1.396)

Note: Risk is estimated in terms of overall risk and risk in subgroups such as age, gender and type of industries where available. Risk is measured in terms of effect sizes and confidence intervals ES(CI).

2018; Xiang et al., 2014; Ma et al., 2019; Garzon-Villalba et al., 2016; Fogleman et al., 2005; Morabito et al., 2006) had "probably high" risk of confounding bias because some of the critical confounders (Peng et al., 2006) such as seasonality, time trends, day of the week, size of the workforce and additional confounders such as weather parameters and holidays were not taken into account. All studies had a "probably low"

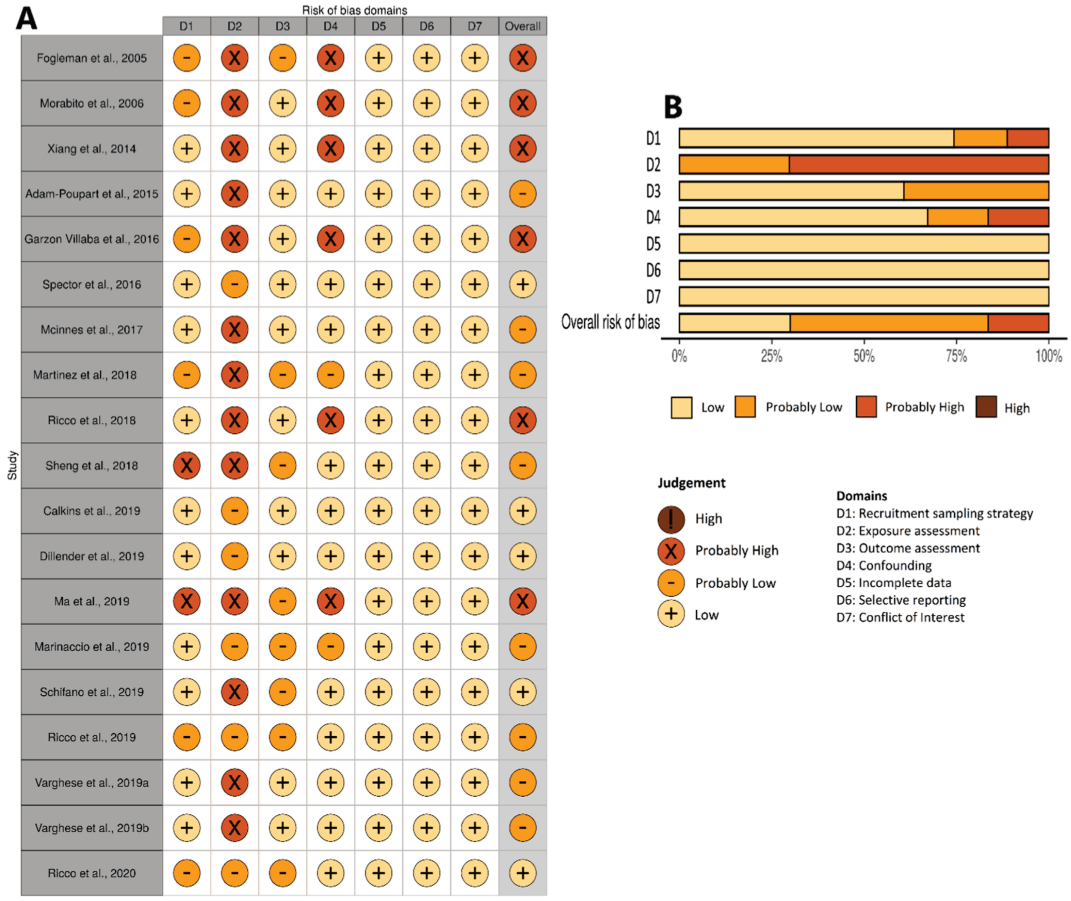

Fig. 3. Summary of the risk of bias assessment in the individual studies (hot temperatures studies n = 19) (A) shows the traffic plot of individual assessments and (B) shows the percentage plot given as percentages across all included hot temperature studies). Note: The probability of bias is assessed as High (H), Probably High (PH), Probably Low (PL) and low (L). The plots were created using Risk of Bias Visualization (ROBVIS) tool (McGuinness and Higgins, 2020).

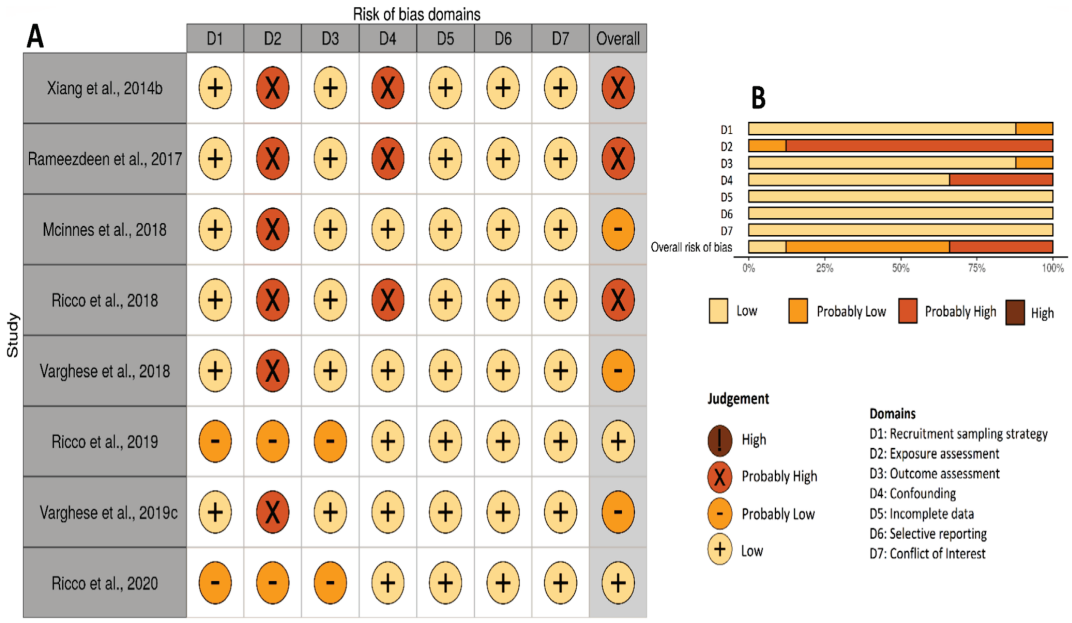

Fig. 4. Summary of the risk of bias assessment in the individual studies (HW studies n = 8) (A) shows the traffic plot and (B) shows the percentage plot given as percentages across all included HW studies. Note: The probability of bias is assessed as High (H), Probably High (PH), Probably Low (PL) and low (L). The plots were created using Risk of Bias Visualization (ROBVIS) tool (McGuinness and Higgins, 2020).

risk of bias in other domains i.e. incomplete datasets, selective reporting and conflict of interest.

3.3.1.2. Heatwave studies. All HW studies were found to be at "low" risk of recruitment/selection bias. Seventy five percent of HW studies (Ricco, 2018; Rameezdeen and Elmualim, 2017; McInnes et al., 2018; Xiang et al., 2014; Varghese et al., 2019; Varghese et al., 2018) had "probably high" risk in exposure assessment. For outcome assessment, all studies had "low" to "probably low" risk of bias. Thirty eight percent of HW studies (Ricco, 2018; Rameezdeen and Elmualim, 2017; Xiang et al., 2014) had "probably high" risk of confounding bias because some of the critical confounders such as seasonality, time trends, day of the week, size of the workforce and additional confounders such as weather parameters and holidays were not taken into account. All studies had a "low" probability of bias in other domains: incomplete datasets, selective reporting and conflict of interest.

3.3.2. Assessment of quality of evidence across the studies

The description and rationale of the assessment of the overall certainty of evidence assessing the risk of OI associated with extreme heat (hot temperatures and HW) is given in Table 4.

3.3.2.1. Hot temperature studies. The certainty of evidence for hot temperature studies was not downgraded for any of the downgrading factors but was upgraded for dose response category as all studies suggested an exposure response gradient. The overall certainty of evidence was therefore upgraded to "high" for the observational studies assessing the risk of OI associated with hot temperatures.

3.3.2.2. Heatwave studies. We downgraded the certainty of evidence for HW studies for high risk of bias and inconsistencies and upgraded the certainty of evidence for dose response category. The overall quality of evidence was therefore downgraded to "low" for the observational studies assessing the risk of OI associated with heatwaves.

3.3.3. Assessment of strength of evidence across the studies

The quality of the body of evidence was found to be "high" for hot temperature studies and "low" for HW studies (Table 4).

3.3.3.1. Hot temperature studies. The direction of the effect estimates indicated an increase in the risk of OI with exposure to hot temperatures. There is high confidence in effect estimates and it is unlikely that a new study would make the results of the meta-analysis null or statistically insignificant for evidence. The assessment of strength of evidence suggested that there was "sufficient" evidence that exposure to hot temperatures affect OI in non-military workers.

3.3.3.2. Heatwave studies. The direction of the effect estimates indicated an increase in the risk of OI with exposure to HW. However, the assessment of strength of evidence suggested that there was "limited" evidence that exposure to HW affects OI in non-military workers.

3.4. Synthesis of findings on extreme heat exposure on OI

Extreme heat exposure were assessed in terms of hot temperatures and HW. The following sections synthesize the evidence for hot temperature and HW studies in different climate zones (where possible).

3.4.1. Hot temperatures and the risk of OI

In total, 194 observations from 17 studies were considered for the meta-analysis in nine different climate zones. Two studies were excluded from the meta-analysis; Morabito et al., (Morabito et al., 2006) used a different outcome assessment metric and Ma et al., (Ma et al., 2019) was excluded because of the use of overlapping datasets. A summary of our meta-analysis results for all included hot temperature studies is presented in Table 5. For every 1 °C increase above reference temperature (mean reference temperature across all observations = 20.9 °C), the heat associated risk of OI increased by 1% (RR 1.010, 95% CI: 1.009–1.011). The results of meta-analyses by each climate zone are further presented in next sections.

3.4.1.1. Humid Subtropical Climates. Based on 56 effect estimates from nine studies (Ricco, 2018; Marinaccio et al., 2019; Varghese et al., 2019; Sheng et al., 2018; Garzon-Villalba et al., 2016; Schifano et al., 2019;

Table 4
Summary of findings, quality of evidence and strength of evidence for hot temperature exposure (n = 19) and HW periods (n = 8) and the risk of OI.

Quality factor Categories	Hot temperature studies (n = 19) Ratings	Rationale	Heatwave studies (n = 8) Ratings	
Downgrade considerations				
Risk of Bias across studies	(0)	We have found "probably high risk of bias" for 32% of the studies. The sensitivity analysis of high risk of bias studies revealed statistical differences between studies with low/probably low versus probably high risk of bias, but majority of studies showing high risk of bias had small weight on the results, therefore we did not downgrade for risk of bias (Fig. E1, Appendix E of SM).	(−1)	We have found "probably high risk of bias" in 38% of studies in overall risk of bias. The sensitivity analysis of high risk of bias studies revealed significant statistical differences between studies with low/probably low versus probably high risk of bias (Fig. F1, Appendix F of SM). Therefore we downgraded the rating based on risk of bias assessment.
Indirectness	(0)	Most studies are representative of appropriate proportion of population of interest. OI were identified under standard definitions in most studies. Direct measures of exposure are used in most studies.	(0)	Most studies are representative of appropriate proportion of population of interest. OI were identified under standard definitions in most studies. Direct measures of exposure are used in most studies.
Inconsistency	(0)	The evidence of quality was not downgraded for inconsistencies. The I^2 value of heterogeneity was found to be $I^2 = 95.1\%$ for overall all hot temperatures studies but 80% prediction intervals did not contain unity and were narrow as compared to confidence intervals (Fig. E2, Appendix E of SM).Further, "Leave One Out Analysis" also showed that the risk estimates were not significantly affected by individual studies (Table E1, Appendix E of SM).Sensitivity analysis based on exposure metrics (such as Tmax, Tmin, or thermal indices) indicated slightly higher estimates for studies that used heat indices instead of Tmax and Tmean. Different exposure assessment datasets (such as single or average weather station data or gridded/geolocated or satellite data) or the unit of estimate (i.e. 1 °C increase in temperature or comparing percentiles) (Table E2, Appendix E of SM) did not reveal major differences.It should also be noted that the I^2 value of heterogeneity reduced to 89.3% after classifying the studies into different climate zones and standardizing the data and conversion to increase in risk per 1 °C temperature (Table E3, Appendix E of SM).	(−1)	Considerable heterogeneity was found across the studies, $I^2 = 98.9\%$. Moreover, prediction intervals contain unity and are double of confidence intervals (Fig. F2, Appendix F of SM). Therefore we downgraded the quality of evidence for heterogeneity.Leave One Out Analysis and Sensitivity analysis based on different exposure assessment datasets (such as single or average weather station data or gridded/geolocated or satellite data) and different HW definitions (i.e. three or more days of Tmax $\geq$ 35 °C or heat indices such as EHF) are given in Table F1 and F2, Appendix F of SM. The results indicated higher estimates for studies using EHF definition of HW.
Imprecision	(0)	Most studies had sufficiently narrow confidence intervals.	(0)	Most studies had sufficiently narrow confidence intervals.
Publication Bias	(0)	Funnel plots of hot temperature studies (Fig. E3, Appendix E of SM) showed an asymmetrical distribution and Egger's test were significant ($p = 0.015$), indicating a potential risk of publication bias. The Trim and Fill method was carried out imputing three studies adding to a total of 21 hot temperature studies (Fig. E4, Appendix E of SM) to adjust for pooled RR from small study bias. The observed pooled RR was 1.010 (95% CI: 1.007–1.013) and the imputed point RR was very similar (1.009, 95% CI: 1.006–1.012). Therefore we did not downgrade the quality of evidence for potential risk of publication bias.	(0)	Number of studies included in the meta-analysis were too small (<10) for a statistical evaluation of potential publication bias.
Upgrade considerations				
Large effect magnitude	(0)	Overall effect magnitude (RR) was below 2 (RR < 2) times increase in the outcome prevalence in all studies.	(0)	Overall effect magnitude (RR) was below 2 (RR < 2) times increase in the outcome prevalence in all studies.
Dose response	(1)	All of the studies suggested an exposure–response gradient, i.e. exposure to high temperatures increases the risk of OI in most instances.	(1)	All of the studies suggested an exposure–response gradient, i.e. exposure to HW increases or decreases the risk of OI.
Confounding minimizes effect	(0)	Time series and case crossover study design take into account the potential confounders by modeling and by design. However, we identified some studies that might have residual confounding because they did not account for all potential confounders. We do not expect that omission of any of these confounders would have led to underestimating our meta-analysis association estimate and therefore did not upgrade for this consideration.	(0)	We identified some studies that might have residual confounding because they did not account for all potential confounders. However, we do not expect that omission of any of these confounders would have led to underestimating our meta-analysis association estimate and therefore we did not upgrade for this consideration.
Summary of Quality Assessment				
Overall quality of evidence	High	Moderate+(0)+(0)+(0)+(+1) = High - Downgrading and upgrading, brought the quality of studies to "high".	Low	Moderate+(0)+(−1)+(−1)+(+1) = Low - Downgrading and upgrading, brought the quality of studies to "low".
Summary of findings for Meta-analysis	NA	Studies included in meta-analysis provided consistent results i.e. the risk of OI increases with hot temperatures.	NA	Studies included in meta-analysis provided consistent results i.e. the risk of OI increases during HW periods.
Strength of evidence assessment				
Quality of evidence	NA	High	NA	Low
Direction of effect estimates	NA	Risk of OI increase among workers with increasing exposure to hot temperatures.	NA	Risk of OI increase among workers with increasing exposure to HW.
Confidence in effect estimates	NA	It is unlikely that a new study would have an effect estimate that would make the results of the meta-analysis null or insignificant.	NA	The evidence is limited
Other aspects	NA	None	NA	None
Overall strength of evidence	Sufficient	Overall, we rated the strength of evidence as "sufficient". We found that that there is a positive association between hot	Limited	Overall, we rated the strength of evidence as "limited". A causal interpretation of the positive association observed in the body of

(continued on next page)

Table 4 (*continued*)

Quality factor Categories	Hot temperature studies (n = 19) Ratings	Rationale	Heatwave studies (n = 8) Ratings
		temperatures and OI, and conclude with reasonable confidence that chance, bias and confounding could be ruled out as an explanation for the association. The available evidence included results from one or more well-designed, well-conducted studies, and we believe that our conclusion is unlikely to be strongly affected by the results of future studies	evidence on exposure and the outcome is credible, but chance, bias, or confounding could not be ruled out with reasonable confidence.

Note: Two studies (Ma et al., 2019; Morabito et al., 2006) were removed from the meta-analysis and therefore were not included in heterogeneity and publication bias tests.

Ricco et al., 2020; Ricco et al., 2019; Dillender, 2019) included in the meta-analysis, Humid Subtropical Climates had the highest risk of OI during warm periods. An increased risk of 1.7% (RR 1.017, 95% CI: 1.014–1.020) was found to be associated with 1 °C increase in temperature above reference value (Table 5 and Fig. G1, Appendix G of SM). The results were consistent across various studies with risk of OI ranging from 1% to 1.7% in majority of instances. However, Dillender (2019) and Marinaccio et al. (2019) estimated slightly increased risk in Texas (1.6%) and a few provinces of Italy (up to 6.6%) respectively. Garzon-Villalba et al. (2016) found a particularly higher risk (around 6%) for disaster relief workers. One study Morabito et al. (2006) was not included in the meta-analysis but also suggested an increased incidence in occupational accidents on days characterized by hot weather conditions in Tuscany Italy.

The exposure response relationship was found to be linear (Ma et al., 2019; Garzon-Villalba et al., 2016) and delayed with lag effect of up to two days (Ricco, 2018; Ricco et al., 2020).

3.4.1.2. Oceanic Climates. In temperate Oceanic Climates, 28 effect estimates from four studies (McInnes et al., 2017; Marinaccio et al., 2019; Martínez-Solanas et al., 2018; Varghese et al., 2019) were used to estimate the pooled RR. An overall 1% increased risk of heat-related OI (RR 1.010, 95% CI: 1.008–1.012) was noted for each 1 °C increase in temperature above reference value (Table 5 and Fig. G2, Appendix G of SM). All studies reported an increased risk of OI associated with hot temperatures ranging from 0.1% to 4.8%. For instance in Melbourne, Australia, Varghese et al. (2019) reported a 0.6% increased risk of OI (above Tmax 20 °C) and McInnes et al. (2017) discovered a 0.2% increased risk with each 1 °C increase in temperature above Tmax of 14 °C (Table 2). Consistent with this, Martínez-Solanas et al. (2018) found an increased risk ranging between 0.3 and 0.9% (above Tmax 12 °C) in various provinces of Spain. Marinaccio et al. (2019) particularly found an increased risk above 1.4% in most provinces of Italy (above Tmean 7.5 °C). Studies (Martínez-Solanas et al., 2018; Varghese et al., 2019) that assessed the exposure–response curve in oceanic climates found a linear increase in the risk and the effects were found to be acute (Varghese et al., 2019).

3.4.1.3. Hot Mediterranean Climates. Sixty seven effect estimates from four studies (Schifano et al., 2019; Marinaccio et al., 2019; Martínez-Solanas et al., 2018; Varghese et al., 2019) were included in the meta-analysis. The pooled RR of heat-attributable OI was estimated to be 0.9% (RR 1.009, 95% CI: 1.008–1.011) with each 1 °C increase in temperature above reference value in these regions (Table 5 and Fig. G3, Appendix G of SM). All four studies reported positive associations between extreme heat and OI. The risk of OI varied between 0.1 and 0.9% in most instances in three studies (Martínez-Solanas et al., 2018; Varghese et al., 2019; Schifano et al., 2019), while Marinaccio et al. (2019) estimated a higher effect of OI up to 9% in many Provinces of Italy including Rome. All four studies indicated a linear increase in the risk of injuries in Hot Mediterranean Climates. Two nation-wide studies predominantly from Hot Mediterranean Climates revealed a lag effect up to two days (Marinaccio et al., 2019; Martínez-Solanas et al., 2018) and up to four days in some instances (Martínez-Solanas et al., 2018).

3.4.1.4. Warm Mediterranean Climates. Our pooled estimates of 11 effect estimates from six studies (Marinaccio et al., 2019; Martínez-Solanas et al., 2018; Spector et al., 2016; Xiang et al., 2014; Varghese et al., 2019; Calkins et al., 2019) in Warm Mediterranean Climates suggested an increased risk of 0.6% (RR 1.006, 95% CI: 1.004–1.007) for OI for each 1 °C increase in temperature above reference value (Table 5 and Fig. G4, Appendix G of SM). All studies reported an increased risk of OI (ranging between 0.1% – 1.7%) and the results were consistent across the studies. For example, in Adelaide, Australia, a time-series study by Xiang et al. (2014) reported 0.2% increased risk of OI with every 1 °C increase in Tmax (above 14 °C) during warm periods. Similarly, Varghese et al. (2019) observed an increase in the OI risk of 1.7% during hot summers (above Tmax 25 °C). In Washington State, Spector et al. (2016) reported an increased risk of OI (1% per 1 °C increase in humidex) for agricultural workers; while Calkins et al. (2019) noted an increased risk of 0.7% per 1 °C increase in dry temperature for construction workers.

Five studies (Martínez-Solanas et al., 2018; Spector et al., 2016; Xiang et al., 2014; Varghese et al., 2019; Calkins et al., 2019) assessed the exposure–response curve in Warm Mediterranean Climates and reported mixed results. All studies reported a linear increase in risk above reference temperatures during warm seasons; however two studies (Spector et al., 2016; Xiang et al., 2014) reported a decline in the risk of OI at extremely hot temperatures indicating a reverse U-shaped curve.

3.4.1.5. Hot Semi-Arid Climates. One nation-wide study from Spain (Martínez-Solanas et al., 2018) provided three effect estimates for meta-analysis in Hot Semi-arid Climates. The results suggested a statistically significant risk of OI (RR 1.005, 95% CI: 1.004–1.007) with each 1 °C increase in hot temperatures above reference temperatures (Table 5 and Fig. G5, Appendix G of SM). The exposure–response relationship assessed by Martínez-Solanas et al. (2018) in various semi-arid provinces of Spain indicated a linear increase in the risk of OI.

3.4.1.6. Cold Semi-arid Climates. Eleven estimates from Italy and Spain (Marinaccio et al., 2019; Martínez-Solanas et al., 2018) were used in meta-analysis of Cold Semi-arid climates. An increased risk of 0.5% (RR 1.005, 95% CI: 1.004–1.005) associated with 1 °C increase in temperature above reference values was found in these climates (Table 5 and Fig. G6, Appendix G of SM). The exposure response relationship was found to be linear in all instances.

3.4.1.7. Humid and Warm Continental Climates. Our meta-analysis results of 13 effect estimates from two studies (Adam-Poupart et al., 2015; Fogleman et al., 2005) identified a 0.3% increase in OI (RR 1.003, 95% CI: 1.001–1.004) in Humid and Warm Continental Climates with 1 °C increase above reference temperature (Table 5 and Fig. G7, Appendix G of SM). Adam-Poupart et al., (Adam-Poupart et al., 2015) assessed the exposure–response curve and observed a linear and lagged effect of up to

Table 5
Random-effects meta-analysis estimates of RR and (95% CI) for risk of OI at hot temperatures (n = 17*).

Climate Zones (Studies)	Risk of OI RR(95% CI)	
Humid Subtropical Climates (Ricco, 2018; Marinaccio et al., 2019; Varghese et al., 2019; Sheng et al., 2018; Garzon-Villalba et al., 2016; Schifano et al., 2019; Ricco et al., 2020; Ricco et al., 2019; Dillender, 2019)	1.017 (1.014–1.020)	K = 56 I^2 = 89.8% P < 0.001 N = 2,352,778**
Oceanic Climates (McInnes et al., 2017; Marinaccio et al., 2019; Martínez-Solanas et al., 2018; Varghese et al., 2019)	1.010 (1.008–1.012)	K = 28 I^2 = 91.3% P < 0.001 N = 2,842,807**
Hot Mediterranean Climates (Schifano et al., 2019; Marinaccio et al., 2019; Martínez-Solanas et al., 2018; Varghese et al., 2019)	1.009 (1.008–1.011)	K = 67 I^2 = 86.5% P < 0.001 N = 10,716,074**
Warm Mediterranean Climates (Marinaccio et al., 2019; Martínez-Solanas et al., 2018; Spector et al., 2016; Xiang et al., 2014; Varghese et al., 2019; Calkins et al., 2019)	1.006 (1.004–1.007)	K = 11 I^2 = 75.3% P < 0.001 N = 1,262,274**
Hot Semi-arid Climates (Martínez-Solanas et al., 2018)	1.005 (1.004–1.007)	K = 3 I^2 0.0% P = 0.918 N = 1,347,551
Cold Semi-arid Climates (Marinaccio et al., 2019; Martínez-Solanas et al., 2018)	1.005 (1.004–1.005)	K = 11 I^2 = 0.0% P = 0.816 N = 2,958,103**
Humid and Warm Continental Climates (Adam-Poupart et al., 2015; Fogleman et al., 2005)	1.003 (1.001–1.004)	K = 13 I^2 = 53.1% P = 0.012 N = 350,196**
Subarctic Climates (Adam-Poupart et al., 2015)	1.000 (0.996–1.005)	K = 4 I^2 = 20.8% P = 0.286 N = 24,439
Hot Desert Climates (Martínez-Solanas et al., 2018)	1.004 (1.001–1.008)	K = 1 – – N = 416,609
Overall	1.010 (1.009–1.011)	K = 194 I^2 = 89.3% P < 0.001 N = 22,270,831

Note: *Two studies were (Ma et al., 2019; Morabito et al., 2006) not included in meta-analyses. K represents the number of city/province-specific estimates, and meta-analysis is conducted when K ≥ 2. I^2 is the heterogeneity score. P is the P-value of X^2 test of heterogeneity. N represents the total number of injury records. **The sample size was not obtainable for province specific observations for two studies; Schifano et al. (2019) and Marinaccio et al. (2019) representative of different climate zones.

two days in the risk of OI associated with hot temperatures.

3.4.1.8. Subarctic Climates. One study (Adam-Poupart et al., 2015) conducted in sixteen health regions of Quebec Province, Canada provided four estimates of risk of OI associated with hot temperatures in Subarctic Climates. No association was found between OI and hot temperatures in these mild to cool summer regions (RR 1.000, 95% CI: 0.996–1.005) (Table 5 and Fig. G8, Appendix G of SM).

3.4.2. Heatwaves and the risk of OI

The impacts of heat exposure on the risk of OI were pronounced during HW periods. Ten effect estimates from eight studies were used to estimate the risk of OI during HW (Ricco, 2018; Ricco et al., 2020; Ricco et al., 2019; Rameezdeen and Elmualim, 2017; McInnes et al., 2018; Xiang et al., 2014; Varghese et al., 2019; Varghese et al., 2018). The overall effect estimate was 17.4% (RR 1.174, 95% CI: 1.057–1.291) during HW periods. Further, among climate zones, the risk of OI was found to be highest in Oceanic Climates and Humid Subtropical Climates (Table 6 and Figs. H1–H3, Appendix H of SM).

3.5. Subgroup analyses

3.5.1. Subgroup analysis of hot temperatures

Subgroup analyses of workers' characteristics, nature of work and workplace characteristics identified specific group of workers which are at high risk during hot weather conditions. Summary of the subgroup analysis is given in Table 7. Male workers and young workers (age < 35 years) were found to be at high risk of OI during high temperatures. Outdoor intensive industries including: agriculture and construction were found to be at highest risk of OI although indoor industries such as manufacturing industries also had significant risk of OI associated with hot temperatures. Physical workload was also an important factor contributing towards increased risk of OI in hot weather conditions. Among various types of businesses, small and medium sized businesses were at high risk of OI associated with hot temperatures.

Further, subgroup analysis based on study characteristics (Table I1, Appendix I of SM) revealed that workers in North America and Asia were at higher risk of OI, however caution must be taken in interpreting the results because of small number of studies. Time series study design estimated higher values for heat attributable risk of OI. Studies using Distributed lag nonlinear models (n = 6) and those using other models (n = 11) (such as generalized linear models, condition logistics regression, generalized estimated equation) estimated similar risk of OI (Table I1, Appendix I of SM).

3.5.2. Subgroup analysis of heatwaves studies

Male workers, young workers (age < 35 years) and new workers were found to be at higher risk of OI associated with HW periods. Moreover, indoor industries had higher effect estimates for the risk of OI as compared to outdoor industries, high risk industries during HW included: Electricity gas and water and manufacturing. A summary of the subgroup analysis of HW studies is given in Table 8.

4. Discussions

4.1. Summary of research findings

Our systematic evaluation of the available literature representing around 22 millions of OI showed that the risk of OI associated with extreme heat has been extensively studied across different countries in nine climate zones. All studies suggested that working in hot environmental conditions increased the likelihood of experiencing OI (overall 1% increase in risk with 1 °C increase in temperature above reference value). Furthermore during extended periods of HW the risk of OI significantly increased by 17.4%. The additional classification of the available literature into different climate zones suggested that the risk of OI is not uniformly distributed and showed a geographic pattern associated with underlying local climate conditions. The heat associated risk of OI was highest in temperate climates with hot summers (for example Humid Subtropical Climates and Hot Mediterranean Climates) and in temperate climates with warm summers (for example Oceanic Climates). Subgroup analysis further revealed that male workers and young workers were at highest risk of OI during hot weather conditions. Among various industries; outdoor intensive industries such as agriculture and construction were at high risk during high temperatures, while electricity, gas and water supply, and manufacturing industries were at high risk during HW. The available evidence includes results from one or more well-designed and well-conducted studies. Overall, the strength of evidence across the studies was found to be sufficient for hot temperature studies but limited for HW studies.

4.2. Main findings in different climate zones

The results from the statistical analyses from various climate zones indicate that the risk of OI increased by 1.7% with 1 °C increase in temperature above reference value in Humid Subtropical Climates. Average reference temperature associated with risk of OI was found to be 13.3 °C (Ricco, 2018; Marinaccio et al., 2019; Varghese et al., 2019; Ricco et al., 2020; Ricco et al., 2019; Dillender, 2019). High humidity during warm periods plays a significant role in the risk of OI in these climates. Humidity limits bodily heat loss at hot temperatures, which leads to heat stress and an increased risk of OI (Xiang et al., 2014; Lucas et al., 2014). Similarly, temperate Hot Mediterranean Climates with hot summers and Oceanic Climates with warm summers were also found to be at increased risk of OI, ranging from 0.9 to 1% with 1 °C increase above reference temperature. Previously conducted multi-country analyses (Di Napoli et al., 2018; Gasparrini et al., 2015) on temperature and health associations from similar climates (for example from Spain, UK, France) also indicated increased risk of health outcomes associated with heat stress in these climate zones. Mediterranean climates are characterized by dry summers with several extremely hot days. Studies revealed that these regions are vulnerable to an increasing number of hot days under the climate change scenarios which can potentially contribute to increased risk in future (Hanna et al., 2011). The evidence is limited from Hot Semi-arid and Hot Desert Climates but our results indicate a high risk in these climate zones and warrant further investigations.

The impacts of hot temperatures on OI were estimated to be acute with a lag effect of 1 or 2 days and to a lesser extent 3–4 days (Ricco, 2018; Marinaccio et al., 2019; Martínez-Solanas et al., 2018). Understanding such lagged effects is important as it would help local Occupational Health Safety regulators and industries to take preventative actions. The exposure–response relationship was found to be linear or curvilinear in the majority of the studies (Adam-Poupart et al., 2015; Marinaccio et al., 2019; Martínez-Solanas et al., 2018; Varghese et al., 2019; Varghese et al., 2019; Calkins et al., 2019; Ricco et al., 2020) while two studies from dry summer Warm Mediterraean Climates (Spector et al., 2016; Xiang et al., 2014) and one from Oceanic Climates (McInnes et al., 2017) found a non-linear response with a reversal of effects at extremely hot temperatures. Some studies (Ricco, 2018; McInnes et al., 2017; Calkins et al., 2019) suggested that the observed differences can be attributed to different prevention and control measured adapted in different countries to limit the occurrence of OI. Further investigation of the effectiveness of preventative strategies is needed. It has been observed that the methodological differences between studies also led to conflicting results in some regions. For example, in Adelaide, Australia, Xiang et al. (2014) noted that the potential decrease in risk at extremely hot temperatures was due to the exclusion of the total workforce population as the denominator. The association between temperature and OI appears to be curvilinear (with a linear response during warm seasons) when the denominator information is taken into account because it partly captures the extent of short-term adaptation to temperature through a reduction of units worked. Varghese et al. (2019) confirmed the observation of Xiang et al. (2014) as a J-shaped non-linear response was reported for the association between heat and OI in Adelaide, Australia, using a time-stratified case-crossover study design.

Table 6
Random-effects meta-analytic estimates of RR and (95% CI) for risk of OI during HW (n = 8).

Climate Zones (Studies)	Risk of OI RR(95%CI)	
Oceanic Climate (McInnes et al., 2018; Varghese et al., 2019)	1.218 (1.093–1.343)	K = 2 I^2 = 38.0% P = 0.204 N = 155,734
Humid Subtropical Climates (Ricco, 2018; Ricco et al., 2020; Ricco et al., 2019; Varghese et al., 2019)	1.213 (0.995–1.431)	K = 4 I^2 = 96.9% P < 0.001 N = 180,114
Warm Mediterranean Climates (Rameezdeen and Elmualim, 2017; Xiang et al., 2014; Varghese et al., 2018)	1.088 (0.860–1.316)	K = 3 I^2 = 99.4% P < 0.001 N = 392,875
Hot Mediterranean Climates (Varghese et al., 2019)	1.260 (1.235–1.283)	K = 1 – – N = 12,207
Overall	1.174 (1.057–1.291)	K = 10 I^2 = 98.9% P < 0.001 N = 740,930

Note: K represents the number of city/province-specific observations, and meta-analysis is conducted when K ≥ 2. I^2 is the heterogeneity score. P is the P-value of X^2 test of heterogeneity. N represents the total number of injury records.

Table 7
Summary of subgroup analysis of hot temperature studies (n = 17*) conducted by workers' characteristics, nature of work and workplace characteristics.

Subgroups	N	K	RR	LCI	UCI	I^2	P value
Workers characteristics							
Gender							
Male	8	10	1.018	1.010	1.026	95.2%	<0.001
Female	8	10	1.008	1.000	1.016	85.2%	<0.001
Age							
<35 years old	8	10	1.009	1.005	1.013	89.9%	<0.001
≥35 years old	8	10	1.006	1.002	1.010	93.3%	<0.001
Experience							
New workers	3	5	1.008	1.004	1.012	0.0%	0.844
Experienced	3	5	1.007	1.000	1.014	75.5%	0.018
Type of workers							
Specific workers	5	5	1.032	1.003	1.061	91.8%	<0.001
All workers	12	12	1.008	1.005	1.011	95.6%	<0.001
Nature of Work							
Physical Demands							
Heavy and Manual work with MET > 5	6	9	1.003	1.002	1.004	12.9%	0.327
Location of work							
Outdoor	13	17	1.009	1.005	1.012	80.4%	<0.001
Indoor	8	12	1.005	1.002	1.008	92.6%	<0.001
Workplace characteristics							
Type of Industries							
Construction	10	14	1.009	1.006	1.013	81.9%	<0.001
Agriculture	9	13	1.010	1.006	1.014	28.8%	0.155
Manufacturing	6	8	1.007	1.001	1.012	92.0%	<0.001
Transport	8	12	1.005	1.003	1.008	20.7%	0.241
Electricity, Gas and Water	7	11	1.005	0.995	1.014	58.7%	0.007
Business size							
Small	5	5	1.011	1.005	1.016	90.2%	<0.001
Medium	5	5	1.012	1.006	1.018	91.7%	<0.001
Large	5	5	1.005	1.000	1.010	79.7%	0.001

Note: *Two studies (Ma et al., 2019; Morabito et al., 2006) were not included in the meta-analysis. N is the total number of studies. K is the total number of location-specific observations (where available) from each study. LCI is the low confidence interval and UCI is the upper confidence interval.

Table 8
Summary of subgroup analysis of HW studies (n = 8) conducted by workers characteristics and workplace characteristics.

Subgroups	N	K	RR	LCI	UCI	I^2	P value
Workers characteristics							
Gender							
Male	4	6	1.270	1.120	1.430	98.8%	<0.001
Female	4	6	1.160	1.030	1.290	97.5%	<0.001
Age							
<35 years old	4	6	1.260	1.090	1.440	98.6%	<0.001
≥35 years old	4	6	1.220	1.110	1.330	97.4%	<0.001
Experience*							
New workers	2	4	1.450	1.280	1.610	75.1%	0.007
Experienced	2	4	1.310	1.230	1.400	96.9%	<0.001
Nature of Work							
Location of work							
Outdoor	6	8	1.170	1.060	1.290	94.5%	<0.001
Indoor	3	5	1.240	1.120	1.360	98.5%	<0.001
Workplace characteristics							
Type of Industries							
Construction	4	6	1.300	1.150	1.440	93.3%	<0.001
Agriculture	4	6	1.380	1.150	1.610	75.0%	0.001
Manufacturing	3	5	1.410	1.210	1.600	97.2%	<0.001
Transport	3	5	1.270	1.070	1.460	95.1%	<0.001
Electricity, Gas and Water	3	5	1.500	1.340	1.660	20.1%	0.286

Note: *Caution in interpreting results because of fewer number of studies. N is the total number of studies. K is the total number of location-specific observations (where available) from each study. LCI is the low confidence interval and UCI is the upper confidence interval.

A significant cumulative association was found (RR 1.174, 95% CI: 1.057–1.291) between OI and HW in various studies. This is in contrast to three studies that suggested the risk of OI reduced during extended periods of extremely hot conditions (Rameezdeen and Elmualim, 2017; McInnes et al., 2018; Xiang et al., 2014). These differences may attribute to varying definitions of HW (Varghese et al., 2019). For example in Adelaide three studies were conducted; two studies (Rameezdeen and Elmualim, 2017; Xiang et al., 2014) defined HW as three or more consecutive days of daily maximum temperature of 35 °C or above and Varghese et al. (2018) used EHF index to define HW and the studies found statistically varying results. Varghese et al. (2018) argued that three days of Tmax ≥ 35 °C is a stringent measure of HW and it does not take into account the minimum temperature variations when considering impacts of HW on human health (Nairn and Fawcett, 2015). Further, the differences can possibly be due to the methodological variations (Hajat et al., 2006) and due to prevention and control measured adapted to reduce the risk. For example Xiang et al. (2014) suggested that preventive measures adapted in the workplace or workers may stop work or self-pace if the ambient temperature is extremely high, can result in the unexpected decline in the number of injuries.

The effect of HW was assessed in three climate zones and risk was found to be highest in Oceanic and Humid Subtropical Climates. However, caution should be taken in interpreting these results, as these estimates are based on fewer number of observations and require further evidence to increase the statistical power of the estimates to quantify the risk of HW in different climate zones. It is also pertinent to note that all studies characterizing the impacts of HW were conducted in mid-latitude, high-income countries with low to medium population density. Regions most at risk of experiencing extreme HW such as Tropical regions (Campbell et al., 2018) were under-represented.

4.3. Subgroup analyses

Subgroups analysis based on workers' characteristics revealed that male workers and young workers (<35 years of age) were found to be at higher risk of OI during hot weather conditions, although the risk was statistically significant in both genders and different age groups. The higher risk of OI in men (1.8% with 1 °C increase in hot temperatures above reference point and 27% increased risk during HW) could be attributed to gender-based differences in the workforce, because males usually represent a higher proportion of workers performing heavy, outdoor labour (Adam-Poupart et al., 2015; Xiang et al., 2014). In Australia, for example, most temperature-sensitive industries that mostly involve outdoor work are male dominated (less than 40% representation of females) (Australian Bureau of Statistics, 2018). Females are usually more represented in indoor, regulated environments but are still found to be at increased risk of OI (0.8% increased risk associated with hot temperature and 16% increased risk during HW) (Varghese et al., 2019; Sheng et al., 2018; Ma et al., 2019). Poor acclimatization, insufficient training, low competency in performing assigned tasks, low compliance with preventive measures, the strenous nature of jobs assigned and peer pressure are important factors contributing towards the risk of OI in young workers (0.9%) and new workers (0.8%) (Adam-Poupart et al., 2015; McInnes et al., 2017; Xiang et al., 2014). Our findings suggested that workers above the age of 35 years were also at increased risk (0.6%). Evidence from a recent physiological study (Flouris et al., 2018) indicated that the risk of heat stress during hot weather conditions is higher among older workers particularly because of the comorbidities (Kenny et al., 2010) and the loss of cooling mechnaisms that are more likely in elderly (Barnett et al., 2010).

We also found that experienced workers (i.e. with more than one year of experience) were at increased risk of OI at high temperatures (0.7%). The increased risk can possibly be attributed to their increased self-confidence due to which they ignore, underestimate or misjudge any hazards irrespective of their age (Dumrak et al., 2013).

When assessing the nature of work, we found that workers engaged in outdoor work were particularly at high risk to the impacts of hot temperatures (0.9% increased risk of OI vs 0.5% risk in indoor industries with 1 °C increase in temperature above reference value). Outdoor intensive industries mainly include agriculture, forestry, fishing, construction, and utilities supplies where workers are likely to do intense physical work in direct exposure to sunlight and high humidity (Xiang et al., 2014; Acharya et al., 2018; Moda and Minhas, 2019). Recently it has been suggested that direct exposure to solar radiation can potentially impair motor-cognitive performance (Piil et al., 2020) and therefore a combination of high ambient temperature and solar radiation increases the overall thermal stress experienced by outdoor workers leading to increased risk of OI. Furthermore, there is a high prevalence of hypo-hydration in occupations with elevated heat stress, affecting combined motor tasks (Piil et al., 2018). During HW the risk was higher in indoor industries (24% vs 17% in outdoor settings) mainly in manufacturing industries (41% increased risk of OI). These differences in risk of OI in outdoor and indoor settings warrant further investigations. Previous studies suggest that the effects on indoor workers are less clear and the impact more complex as industrial heat production and building architecture become factors of importance (Ciuha et al., 2019). Indoor workers in settings with high industrial heat production are exposed to significant thermal stress that may increase during HW. Moreover, the exposure to overall heat (outside working hours) is also an important contributing factor. During HW (when the minimum temperature is also significantly high) the workers do not adequately recover the impacts of heat stress between their work shifts which increases the risk of OI (Ciuha et al., 2019). Therefore, the exposure to heat during the day as well as night is important in assessing the risk of OI associated with HW. Workers with social disadvantage would be at higher risk of extreme periods of HW, particularly if there are financial impediments in maintaining thermal comfort (Hansen et al., 2013). Identifying high risk industries is particularly important for target-based interventions designed to reduce exposure to occupational hazards associated with heat stress. Although the underlying explanations behind the occurrence of injuries in non-optimal thermal conditions is

complex, the increased risk is likely to be related to physiological mechanisms, where the body is unable to cool itself to maintain the internal temperature (Parsons, 2014) resulting in adverse behavioral effects such as disorientation, impaired judgement, loss of concentration, reduced vigilance, carelessness and fatigue (Varghese et al., 2018). This may affect workers' physical, cognitive and psychomotor performance and may reduce their ability to take protective measures such as staying hydrated or moving to shaded areas. This reduced performance and the inability to follow protective measures can increase the risk of OI (McInnes et al., 2017; Varghese et al., 2019). In addition, we also found that heavy physical workload was also positively associated with high risk of OI (0.3%) during hot weather conditions. Intense physical work can further contribute to internally generated body heat which poses an additional risk of heat stress and associated health effects (Adam-Poupart et al., 2015; Varghese et al., 2019; McInnes et al., 2017).

Only one study assessed the risk of OI in migrant workers (Ricco et al., 2019). Migrant workers are known to be a vulnerable subgroup with language and cultural barriers, extended work hours, demanding jobs, limited safety training and lack of acclimatization (Ricco et al., 2019; Messeri et al., 2019). Future research should be carried out to assess the impacts of hot weather conditions in migrant workers and explore relevant adaptation mechanism.

4.4. Validity of findings/Certainty assessment of available evidence

Risk of bias assessment in individual studies clearly indicated that the quality of studies on this topic was generally high because all studies (100%) (both hot temperature and HW studies) used an appropriate and standard measure of OI outcome provided by national or regional databases. For observational studies, the existence of unmeasured confounders always impacts the quality of the evidence, however we identified that the majority of studies (68% of hot temperature studies and 62% of HW studies) accounted for potential confounders (e.g. time trends, seasonality, day of the week, size of the workforce, holidays and weather parameters (Peng et al., 2006). Exposure assessment was however, a critical point of bias as many studies; 68% of hot temperature studies used single station data or an average of several weather stations' data. This may lead to an underestimation of the local or individual risk level as weather station data fails to account for spatial variations in the exposure (Xiang et al., 2014; Varghese et al., 2019). Sensitivity analysis based on different exposure assessment datasets indicated that studies using satellite, gridded or geo-located metrological data for exposure assessment, estimated stronger effects for the risk of OI. This implies that the relationship between temperature and OI appears to be stronger when using exposure data with more spatial variability than using exposure data based on single weather station data (Lee et al., 2016).

Inter-study heterogeneity (I^2) was generally high (I^2 scores ranging from 0.0% to 91.3% in different climate zones and overall (I^2 89.3%) but as the 80% prediction intervals did not include unity and were sufficiently narrow, we did not downgrade the quality of evidence for the hot temperature studies (Orellano et al., 2020). Heterogeneity is likely and can be attributed to several factors including differences in location, exposure variable, exposure metrics, modelling preferences, type of population, health outcomes etc. In the present systematic review we classified the studies based on different exposure variables i.e. hot temperatures and HW, study locations and climatic zones. We standardized all the estimates to one unit of analysis i.e. assessing the risk per 1 °C increase in temperatures above a reference point. The I^2 value of heterogeneity reduced after classifying the evidence based on climate zones (For I^2 = 95.1% to 89.3%) and standardizing the data and conversion to increase in risk per 1 °C temperature (Table E3, Appendix E of SM). However, studies using different exposure metrics (Tmax, Tmean or Thermal indices) were combined based on the assumptions that the strong correlation between different exposure measures of temperature means that on average they have the same predictive ability in estimating mortality and potentially injuries (Varghese et al., 2019; Barnett et al., 2010). Exposure characterization is one of the most significant sources of heterogeneity in environmental epidemiology studies (Blair et al., 1995). The sensitivity analyses carried out for studies using different exposure metrics (for example Tmax, Tmean and Thermal indices) (Table E2, Appendix E of SM) revealed statistically significant risks of OI (0.8% for studies using Tmax, 1.2% for studies using Tmean and 2.6% for studies using thermal indices) indicating similar predictive ability of various exposure metrics. The risk was estimated to be slightly higher for studies that used thermal indices (Spector et al., 2016; Garzon-Villalba et al., 2016; Schifano et al., 2019; Fogleman et al., 2005), however it should be noted that three of these studies (Spector et al., 2016; Garzon-Villalba et al., 2016; Fogleman et al., 2005) were carried out for highly exposed occupations (agricultural workers, aluminum smelter workers and disaster relief workers), which can be attributed to higher risk estimates. To date, a large number of exposure metrics have been used to assess the temperature associated health effects. One study assessing the predictive ability of several temperature indices suggested that there is no best exposure metric and the selection of exposure metric should depend on the availability of reliable and complete datasets (Barnett et al., 2010). The effects of humidity are secondary to the effects of temperature and may be incorporated in the models when data is from regions characterized by hot and humid summers.

Funnel plots and Egger's test were indicative of risk of publication bias for hot temperature studies. However, caution must be taken in interpreting the results from funnel plots and other tests. There could be other possible sources of asymmetry in funnel plots such as high heterogeneity (Egger et al., 1997). Moreover, the Trim and Fill test suggested that any new hypothetical study with effects in the opposite direction would be unlikely to change the effects of our meta-analysis. Therefore, we did not downgrade the quality of evidence of hot temperature studies based on asymmetric funnel plots. Overall, the quality of evidence on the risk of OI associated with hot temperatures was "high" suggesting the results of our meta-analyses were sourced from well-designed and well-conducted studies.

The existing quality of studies on the effects of HW on OI was "low" primarily because of high heterogeneity in the evidence and high risk of bias across the studies. The high risk of bias is found to be attributable to unmeasured confounding variables in various studies and the risk of exposure misclassification because majority of the studies used single or average of multiple weather station data. Significant heterogeneity among studies can be attributed to the use of different definitions of heatwaves, which may vary in terms of duration, intensity and temperature metric (Hajat et al., 2006). Different study designs and statistical approaches used may contribute to high heterogeneity. Further, a study (Xu et al., 2016) suggested that different climates in study sites may play a significant role in driving the variability, because location-specific climatic variations are important in assessing the risk of HW. The present systematic review of literature suggests that more research is required to strengthen the existing evidence on the risk of OI during HW in different climate zones.

4.5. Gaps and future work

There is limited evidence from Tropical Climates on the potential risk of OI due to a lack of studies in these regions. Tropical Climates are inhabited by the majority of the world's population and are at the highest risk of extreme heat events. Most of the countries in hot Tropical Climates are low and middle-income countries, where national data on OI are either unavailable or underreported (Hämäläinen et al., 2017). Studies conducted in these regions have mostly focused on heat stress symptoms or productivity loss in various industries. Evidence from empirical studies suggested that the occupational burden is very high in tropical developing countries (Tawatsupa et al., 2013; Kjellstrom et al., 2009; Quiller et al., 2017; Sahu et al., 2013; Spector and Sheffield,

2014). The level of summer heat exposure reported at outdoor occupational sites in the tropics is also significantly higher than international thresholds. Thus, there is a need for future studies to determine the risk of OI in these regions so that effective intervention strategies can be developed (Moda and Minhas, 2019). Hot Semi-arid and Hot Desert Climates in the Middle East host millions of unacclimatized migrant workers, evidence is required from these regions to assess the impacts of hot temperatures on OI particularly in migrant workers. Furthermore, as the number of HW are predicted to increase there is an urgent need to understand the local impacts of HW on occupational health in different climate zones, which is currently an underexplored area of research and require crucial attention.

4.6. Strengths and limitations

We adapted a standardized and comprehensive search approaches for the identification, screening and extraction of evidence, in this systematic review, which we believe is the first comprehensive review to comparatively estimate the risk of OI associated with both hot temperatures and HW. Furthermore, we classified the location-specific studies into different climate zones. We have introduced a geographical breakdown in identifying the heat associated risk of OI, and propose that future work should consider geographical and global climatic variations as both are important factors in contextualizing the risk associated with temperature related mortality and morbidity. This has been largely neglected to date.

The present study has some limitations. We limited our search for language and considered only English language articles. Studies conducted for athletes and military personals were not included as their health and job requirements vary significantly from regular workers. Further, to combine estimates from different type of studies for example those assessing the risk per 1 °C increase in temperature and those using minimum reference temperature and maximum temperature values (or percentiles) we standardized the data to 1 °C increase in risk above reference temperature. For standardization, we assumed a log-linear relationship for studies that used temperature percentiles to assess the risk, this may have resulted in overestimation or underestimation of the results. However, sensitivity analysis (Table E2, Appendix E of SM) did not reveal any major differences in the results. It should be noted that we used location-specific estimates from various studies instead of pooled estimates and in some cases the data (both effect estimates and reference temperatures) was extracted manually from the textual/graphical descriptions if it was not available directly in the studies so the datasets were susceptible to imprecision. Nonetheless, the study used the best available data and contacted the authors of relevant studies twice to get the required data. It is also worth mentioning that the risk is estimated at city, state or province level in all studies, therefore we also assumed one type of climate in each location and did not take into account local climatic variations at intra-city level. This is not a limitation of the present study, but rather a shortcoming of research in this field and warrant future investigation at a finer spatial scale. Further, it should be noted that the critical appraisal of individual studies was carried out quite thoroughly by two authors independently following Johnson et al. (2014) however, the contextual support for each judgement is missing from the present systematic review and should be addressed in future work.

5. Conclusions

Our findings clearly suggest that the risk of OI increases with exposure to hot weather conditions. There is an urgent need to mitigate the impacts of occupational heat stress in the context of climate change and the anticipated rise in environmental heat stress. The risk of OI associated with extreme heat is not evenly distributed and is dependent on underlying climatic conditions, workers' characteristics, nature of work, and workplace characteristics. The differences in the risk of OI across different climate zones and worker subgroups warrants further investigation along with the development of climate- and work-specific intervention strategies. With this knowledge, relevant policies and ensuing actions can then be taken to mitigate the risk of OI.

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CRediT authorship contribution statement

Syeda Hira Fatima: Conceptualization, Methodology, Software, Formal analysis, Validation, Writing - original draft. **Paul Rothmore:** Conceptualization, Writing - review & editing, Supervision. **Lynne C. Giles:** Conceptualization, Writing - review & editing, Supervision. **Blesson M. Varghese:** Conceptualization, Methodology, Software, Formal analysis, Validation, Writing - review & editing. **Peng Bi:** Conceptualization, Writing - review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2021.106384.

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2.3 Update to Literature Review

In June 2023, an update of the literature search was carried out using the search strategy mentioned in Tables A1–A3, which can be found in Supplementary Materials for Chapter 2 – Appendix II. Nine studies were identified as published after this systematic review. The characteristics of these studies are presented below in Table 2.1 and Table 2.2.

Nine studies provide evidence of the association between hot weather and OI, and two studies estimated the risk of OI associated with heatwaves (77, 90, 93-99). All studies used a time series study design. Two nationwide studies estimated the region-specific OI risk due to extreme heat in Italy and South Korea (93, 95). Two more nationwide studies from Italy and Korea estimated the cumulative risk of OI at the country level (94, 99). All other studies were representative of one city/state/province from various countries such as Italy, the US, China and Mexico. Most studies are representative of mid-latitude temperate climatic zones; one study represents Tropical Rainforest climate (96) and one study represents Subtropical Desert climate (77). One study estimates the variation in risk with respect to average hourly daily temperature variations (96). Five studies (77, 90, 95, 97, 99) were focused on all workers, whereas four studies were focused on a specific group of workers such as agriculture workers, sugarcane harvesters and construction workers (93, 94, 96, 98). One study compared the risk of OI associated with hot weather before and after the implementation of labour protection policies and suggested a 13% drop in the risk of OI associated with hot weather (90). Such findings highlight the importance of adequate heat-related policies established in WHS and suggest adaptation for hot weather.

One study estimating the risk of OI associated with heatwaves suggests a significant increase in the risk of OI (26.6%) in agricultural workers during heatwaves (98). A similar study estimating the risk of OI from across Italy suggested an overall increase of 6% during heatwaves (94).

The evidence from these studies is consistent with previous findings that the risk of OI increases with an increase in hot weather conditions. However, geographical variations in risk estimation could be attributed to local climate conditions, workers' characteristics, and workplace characteristics. The variations could also be due to different study designs,

modelling techniques, and the datasets used. Further studies are required to understand the location-specific epidemiology of OI associated with hot weather conditions.

Table 2.1 Study characteristics and key findings of all studies assessing the risk of OI in hot temperature conditions (n = 6).

First Author, Year	Location	Climate	Study Population	Study Design	Exposure metric and source	Key findings ES(CI)
Ricco et al. **(98)**	Po River Valley, Italy	**Predominantly Humid Subtropical Climate**	Agricultural workers	TS	Comparing neutral vs. summer days, Reference Tmax: 12ºC Summer day Tmax >25	OR: 1.010 (1.009, 1.011) *Age* <20: 1.010 (1.009, 1.011) 20-29: 1.009 (1.008, 1.011) 30-39: 1.015 (1.012, 1.018) 40-49: 1.009 (1.008, 1.011) 50-59: 1.016 (1.012, 1.019) ≥60: 1.020 (1.014, 1.026)
Gariazzo et al. **(93)**	Italy	**Oceanic Climate:** Piemonte, Umbria **Warm humid Continental Climate:** Trentino A.A., Valle D'Aosta **Humid Subtropical Climate:** Abruzzi, Emilia Romagna, Friuli V. G., Lombardia, Marche, Veneto, **Hot Mediterranean climate:** Campania, Lazio, Liguria, Sicilia, Toscana **Cold desert climate:** Basilicata, Calabria, Molise, Puglie, Sardegna	Construction workers	TS	Comparing percentiles: Average Reference Tmean (25th Percentile): 11.5ºC Average Threshold Tmean (75th Percentile): 20.5ºC	RR: 1.020 (1.009, 1.032) Age: 15-34: 1.023 (1.005, 1.042) 36-60: 1.022 (1.013, 1.031) >60: 0.994 (0.954, 1.035)
Evoy et al. (97)	Oregon, US	**Warm Mediterranean Climate**	All workers	TS	Comparing heat index (ºF) with a reference value. 64ºF vs. 77ºF	IRR: 1.003 (1.001, 1.005) Construction workers: 1.010 (1.006, 1.015)
Su et al. **(90)**	Guangzhou, China	**Humid Subtropical Climate**	All workers	TS	Comparing the risk of OI pre and post-labour protection policy implementation	RR: 1.023 (1.000, 1.052) 13% reduction in the risk of OI after the implementation of public health policy.
Yoon et al. **(99)**	Korea	**Predominantly Humid and hot continental climate**	All workers	TS	Increase in hospital visits and deaths among	Association with Tmax *Total deaths*

					workers for injury, poisoning and certain other consequences of external causes associated with an increase in Tmax, Tavg, and HI	0.009 (with P value < 0.05) *Deaths outdoors* 0.005 (with P value < 0.05) *Infectious and Parasitic diseases* 0.005 (with P value < 0.05) *Cardio and cerebrovascular diseases* 0.003 (with P value < 0.05)
Choi et al. (95)	South Korea	**Humid and hot continental climate**: Chungcheong-bukdo, Chungcheong-namdo, Daegu, Gangwon-do, Gyeonggi-do, Gyeongsang-bukdo, Incheon, Jeolla-bukdo, Seoul **Humid Subtropical climate:** Busan, Daejeon, Gwanju, Gyeongsang-namdo, Jeolla-namdo, Jeju, Ulsan	All workers	TS	Comparing risk at Tmax (33ºC) with respect to a reference value (30ºC)	ATR: 1.011 (0.990, 1.031) *Gender* M: 1.017 (0.985, 1.050) F: 0.998 (0.949, 1.049) *Age* 20-29: 0.990 (0.950, 1.031) 30-39: 1.053 (0.991, 1.115) 40-49: 1.055 (1.011, 1.099) 50-59: 1.008 (0.959, 1.057) 60-69: 1.010 (0.966, 1.055) 70-79: 0.981 (0.941, 1.020) *Industries* Manufacturing: 1.031 (0.996, 1.065) Construction: 1.040 (1.003, 1.077) Others: 0.971 (0.936, 1.007)
Dally et al. (96)	Southwest Guatemala	**Tropical Rainforest Climate**	Sugarcane Harvesters	TS	One-degree increase in the hourly average WBGT above the daily mean WBGT	OR: 1.02 (0.96, 1.08)

Alahmed et al. (77)	Kuwait	**Subtropical Desert Climate**	All workers	TS	Comparing risk at 39.4°C, 40°C, 41°C, and 42°C with Average Reference Tmean: (10th percentile: 37°C)	RR: 1.44 (1.34, 1.53) RR: 1.48 (1.39, 1.59) RR: 1.44 (1.27, 1.63) RR: 1.21 (0.93, 1.57)
Blasi et al. (94)	Italy	**Predominantly Humid Subtropical Climate**	Agriculture workers		Comparing percentiles between 75th and 99th percentile	RR: 1.13 (1.08, 1.18) *Age* 15-34: 1.23 (1.14, 1.34) 35-60: 1.10 (1.02, 1.18) 61+: 1.16 (0.97, 1.38) *Professional qualification* Labourer 1.01 (0.83, 1.22) Occasional 1.25 (1.03, 1.52) Self-employed 1.15 (1.08, 1.23)

Note: Risk of OI is estimated in terms of overall risk and risk in subgroups such as age, gender and type of industries where available. Risk of OI is measured in terms of effect sizes and confidence intervals ES(CI). TS: Time series, Tmax: Maximum Temperature, Tavg: Average Temperature, Tmean: Mean Temperature, HI: Heat Index, RR: Relative Risk, OR: Odds Ratio, ATR: Absolute Temperature Risk effect, WBGT: Wet-Bulb Globe Temperature. All risk values are estimated as one-degree increase in temperature above reference values, as explained in the methods section.

Table 2.2 Study characteristics and key findings of all studies assessing the risk of OI in heatwave conditions (n = 2).

First Author, Year	Location	Climate	Study Population	Study Design	Exposure metric and source	Key findings ES(CI)
Ricco et al. **(98)**	Po River Valley, Italy	**Predominantly Humid Subtropical Climate**	Agricultural workers	TS	HW (3 consecutive days Tmax ≥35°C)	OR: 1.266 (1.206, 1.330)
Blasi et al. (94)	Italy	**Predominantly Humid Subtropical Climate**	Agriculture workers	TS	HW (3 consecutive days Tmean > 90th percentile of municipality-specific temperature)	RR: 1.06 (1.03, 1.08)

Note: Risk of OI is estimated in terms of overall risk and risk in subgroups such as age, gender and type of industries where available. Risk of OI is measured in terms of effect sizes and confidence intervals ES(CI). TS: Time Series, Tmax: Maximum Temperature, Tmean: Mean Temperature, RR: Relative Risk, OR: Odds Ratio.

2.4 Literature Review on Existing Policies in Relation to Heat and WHS in High-Risk Industries in Australia

As we are transitioning to a hot and more intense climate and are expected to observe more hot days and frequent heatwaves, workers in many industries are more likely to be affected by the impacts of heat. Therefore, it is crucial to implement effective heat prevention strategies to protect WHS against hot weather conditions. Effective heat stress management policies will not only protect workers from the impacts of heat but will also reduce the associated costs to organisations' benefits. A rationale for the preparation, analysis, and interpretation of study methods is given in Chapter 6.

A literature search of existing studies evaluating the efficacy of hot weather policies was carried out. The search strategy used for the review of literature was the same as those described in Section 2.1. Some key terms such as 'policies', 'guidelines', 'legislation', 'safety advisory', 'prevention' and 'standards' were added to the study type category. The search revealed that literature specific to the evaluation of hot weather policies has received little attention.

One study, reviewed the OSHA's heat enforcement cases to identify the limitations of heat illness prevention programs (100). The study found that over 80% of enforcement cases did not rely on national standard approaches for heat illness prevention. Work-rest cycle, acclimatization and training are amongst the most important missed-out components of prevention programs.

Another study assessed the effectiveness of the Australian government's WHS standards in safeguarding workers from the effects of heat (101). The study suggests that although hot weather is a significant occupational health issue in Australia, it is not a priority of Australian WHS policy. There are no mandatory requirements about working in hot weather in Australia. However, all Australian states and territories have regulatory bodies providing guidelines and resources regarding heat hazards on their websites. The study further suggests the need to review and evaluate prevention programs and develop evidence-based prevention strategies.

Both studies reveal the inadequacy of heat protection programs and standards to protect workers from workplace heat hazards. A major obstacle in implementing national and

regional environmental and occupational health recommendations/regulations is limited knowledge about the local ability to identify, prevent, and control the impacts of harmful heat exposure on WHS. Detailed investigations are thus warranted, which may include: 1. Location-specific prediction and evaluation of the heat-related effects on WHS in the light of increasing average temperatures and frequent extreme heat events. Such assessments will help us identify the high-risk areas and the factors potentially contributing to the high risk in those locations. 2. Evaluation of existing prevention procedures at the industrial level in accordance with the national guidelines. Such studies will provide much-needed scientific evidence for WHS regulators, industries, unions, and workers to design and implement location-specific measures. They can help promote effective work practices and interventions to protect workers in the warming climate.

2.5 Gaps in the Existing Literature

All of the previously published studies have been conducted at the city, state/province, or national levels. However, none of these studies offer evidence on an intra-urban scale. Conducting a more detailed risk assessment could potentially aid in identifying patterns and trends in risk distribution. This approach would also allow for the inclusion of more precise exposure classifications.

To ensure the applicability of results and to provide recommendations for improved adaptation, mitigation, and risk prevention, it is necessary to gather more evidence from various climate zones.

No published studies have predicted the risk of heat-related OI in the context of climate change scenarios. Assessing the future projected risk of OI is especially crucial given our transition towards warmer climates.

Until now, no research has been conducted to evaluate the effectiveness of heat-related policies implemented by organisations to mitigate heat-related risks. Such assessments could be valuable in identifying barriers to implementing heat management programs within organisations. Moreover, these evaluations could suggest ways to enhance WHS efforts. Additionally, they would help pinpoint areas needing improvement and offer insights for future studies on heat hazards and the most effective management practices.

The gap analysis has enabled us to pinpoint the research objectives this study aims to address. Based on these gaps and identified research objectives, specific research questions were formulated that guide the investigations in Chapters 4, 5, and 6. These research objectives and specific questions are presented comprehensively in Chapter 3.

CHAPTER 3

STUDY DESIGN AND METHODS

Preface

Chapter 3 provides a comprehensive overview of the methodological framework of the thesis, starting with clearly defined research objectives in Section 3.1, followed by the specific research questions presented in Section 3.2. The detailed study design, which includes study settings and the theoretical framework of the thesis, is thoroughly elucidated in Section 3.3 and Section 3.4, respectively. Section 3.5 encompasses detailed information about data collection and analysis in quantitative studies, providing epidemiological evidence of the association between OI and heat exposure.

Subsequently, Section 3.6 details the qualitative aspect of the research project, offering further insights into the policy documents collected and the analyses conducted to assess the efficacy of existing hot weather policies in terms of national guidelines. Section 3.7 provides the details on ethical approvals sought while preparing for this research project.

While the following three chapters (4, 5, and 6) include their standalone methodological descriptions, this chapter provides the overarching methodological details, offering a cohesive view of the study design for the entire thesis. It outlines the types of datasets collected, their pre-processing, and the analytical approaches employed to achieve the research goals effectively.

This thesis was completed as part of the Australian Research Council (ARC) funded project (ARC Discovery Project Scheme 2019 Grant – DP 200102571) and was led by the University of Adelaide.

3.1 Research Objectives

The specific research objectives encompassing the overall aim of the thesis are:

1. To systematically examine the location-specific effects of heat on the risk of OI in urban environments with diverse climates in Australia.
2. To identify characteristics of workers at risk during hot weather conditions.
3. To predict the risk of OI associated with future projected climate.
4. To assess the efficacy of existing heat-related policies institutionalised in high-risk industries to protect workers from ambient heat.

3.2 Research Questions

The main research questions to be addressed in this thesis are:

1. What is the association between ambient temperatures and the risk of OI and the heat-attributable burden of OI at the intra-urban scale in four large cities of Australia, including Adelaide, Brisbane, Melbourne, and Sydney?
2. What are the environmental, personal, and workplace characteristics of the workers at risk during hot weather?
3. What is the predicted future risk of OI associated with projected climate change scenarios (Representative Concentration Pathways (RCP) 4.5 and 8.5) in four major cities of Australia?
4. How well are the heat-related policies institutionalised in the high-risk construction industry in accordance with the Australian national guidelines to protect workers from ambient heat?

3.3 Study Settings

The research was conducted in four capital cities of Australia, including Greater Adelaide, Greater Brisbane, Greater Melbourne, and Greater Sydney at Statistical Area level 3 (SA3). The metropolitan areas of the cities were identified as Greater Capital City Statistical Areas (GCCSA) as defined by the Australian Bureau of Statistics (ABS). Together, these cities represent more than 80% of the urban population in Australia (102). Greater Sydney is the most populous city in terms of total and working-age population,

followed by Greater Melbourne, Greater Brisbane, and Greater Adelaide. Health care and social assistance, education and training, retail trade, and construction are the four largest industries representing a major proportion of the labour population in all cities. Table 3.1 gives the labour statistics of Australia's four cities. Figure 3.1 illustrates an overview of the labour population statistics across different industries in the four cities. In Figure 3.2, detailed labour statistics are presented, highlighting the distribution of workers' population based on their occupations.

Table 3.1 Descriptive summary statistics of workers' population in four cities of Australia for 2016 (102).

Description	Greater Adelaide	Greater Brisbane	Greater Melbourne	Greater Sydney
Estimated resident population (no.)	1324057	2362672	4714387	5024923
Working age population (aged 15-64 years) (no.)	868679	1589612	3203460	3399764
Employed (no.)	587057	1073783	2115493	2272715
Unemployed (no.)	49051	85643	153627	146187
Labour force (no.)	636107	1159426	2269121	2418898

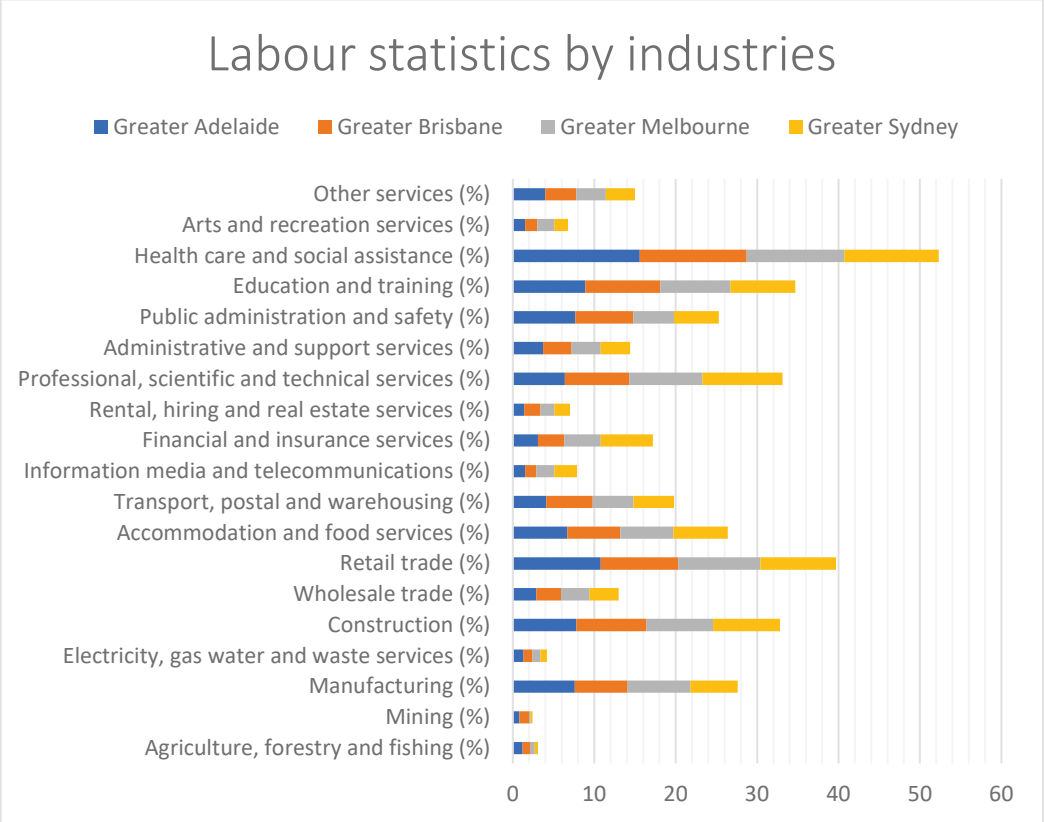

Figure 3.1 Labour statistics of workers' population with respect to industries in the four cities of Australia. (102).

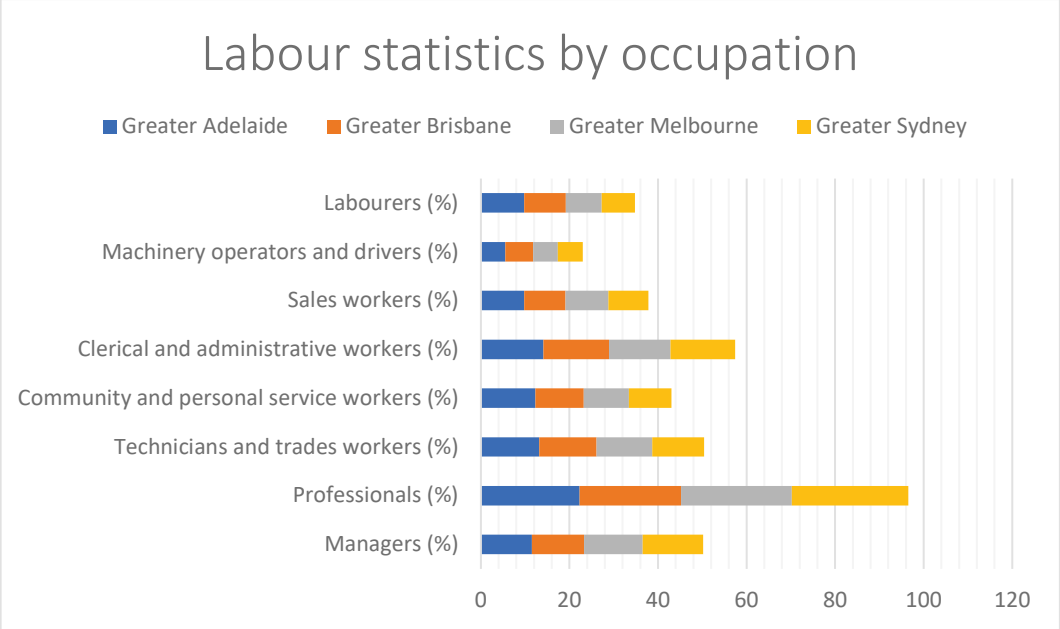

Figure 3.2 Labour statistics of workers' population with respect to occupations in the four cities of Australia (102).

All four cities are coastal, and the local climate of these cities is regulated by many geographical factors such as regional weather patterns, oceanic climate, latitude, and prevailing winds. The environmental and socio-economic profiles of the four cities are presented in Figures 3.3-3.6. In Greater Brisbane and Greater Sydney, the coastal areas are generally cooler as compared to inland peripheries of the cities (except Blue Mountains in Western Sydney) because the cooling impact of coastal winds does not penetrate deep into the inland regions (85). The impacts of heat are further exacerbated by the rapid urbanization in Greater Sydney, causing areas on the peripheries, such as those in the foothills of the Blue Mountains, to experience higher temperatures compared to their surroundings. (103). In terms of local climatic conditions identified by the Koppen Geiger Classification (104), Greater Adelaide is characterised by Semi-Arid climate in the north and a warm Mediterranean climate in the south-eastern parts of the city (Figure 3.3). Greater Brisbane is characterised by a Humid Subtropical climate (Figure 3.4). Greater Melbourne is mainly characterised by an Oceanic climate, while some western regions have a Cold Semi-Arid climate (Figure 3.5). Greater Sydney has a Humid Subtropical climate in the city's eastern parts, while an Oceanic climate in the western Blue Mountains (Figure 3.6).

It has been observed that all four cities generally have lower Normalised Difference Vegetation Index (NDVI) and higher land surface temperature (LST) in the inner-city

areas. A lower NDVI and higher LST in the central city areas are attributed to rapid urbanization and the heat island effect (105, 106). Further many of the inner city SA3 regions are also characterised by higher Relative Socio-Economic Advantage and Disadvantage Index (IRSAD) and Index for Education and Occupation (IEO), as shown in the figures below.

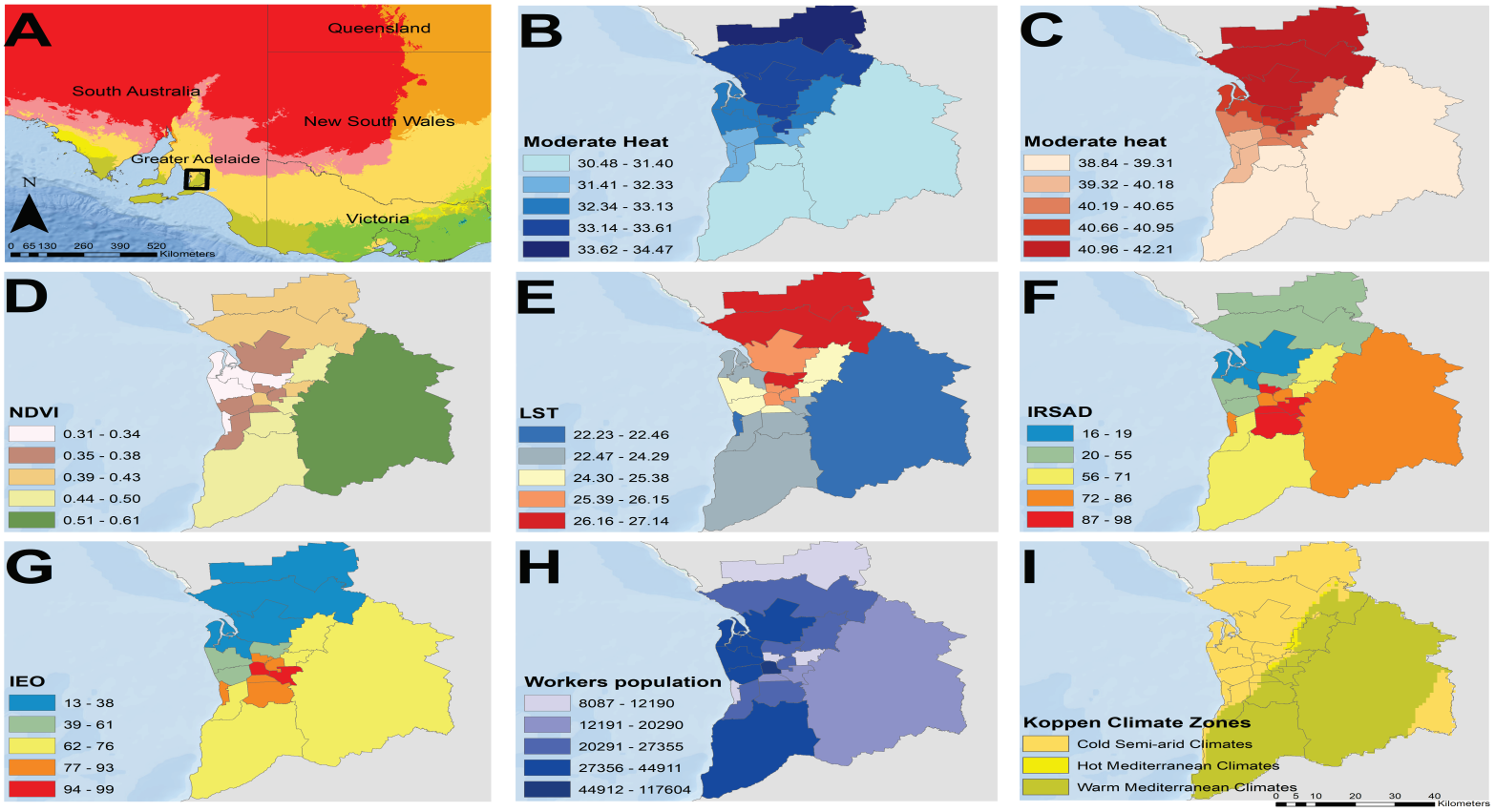

Figure 3.3 Environmental and socio-economic profile of Greater Adelaide at statistical area level 3.

A. Location of Greater Adelaide in the south-eastern part of the Australian coast B. Moderate Heat map of Greater Adelaide estimated at 90th percentile of maximum temperature for the study period from July 2005 to June 2018. C. Extreme Heat map of Greater Adelaide estimated at 99th percentile of maximum temperature for the study period. D. Averaged NDVI estimated over the study period. E. Average LST estimated over the study period for Greater Adelaide. F. Relative Socioeconomic Index for Areas acquired from the ABS. G. Index of Education and Occupation acquired from the ABS. H. Workers' population based on their place of work for 2016 acquired at the SA3 level. I. Climate distribution at the SA3 level in Greater Adelaide following Beck et al. (104). The map is created in ArcMap 10.5.

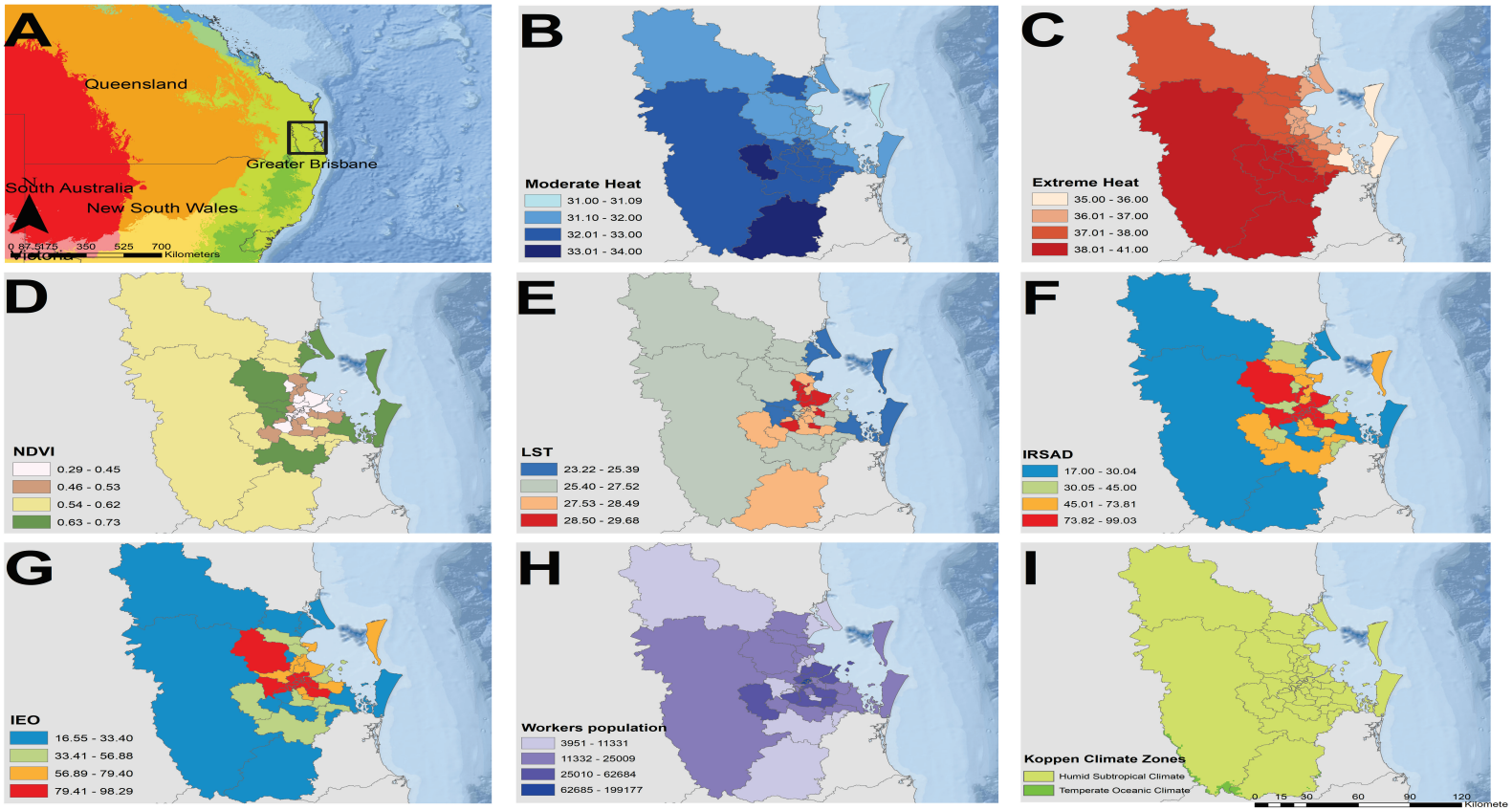

Figure 3.4 Environmental and socio-economic profile of Greater Brisbane at statistical area level 3.

A. Location of Greater Brisbane on the east coast of Australia B. Moderate Heat map of Greater Brisbane estimated at 90th percentile of maximum temperature for the study period from July 2005 to June 2018. C. Extreme Heat map of Greater Brisbane estimated at 99th percentile of maximum temperature for the study period. D. Averaged NDVI estimated over the study period. E. Average LST estimated over the study period for Greater Brisbane. F. Relative Socioeconomic Index for Areas acquired from the ABS. G. Index of Education and Occupation acquired from the ABS. H. Workers' population based on their place of work for 2016 acquired at the SA3 level. I. Climate distribution at the SA3 level in Greater Brisbane following Beck et al. (104). The map is created in ArcMap 10.5.

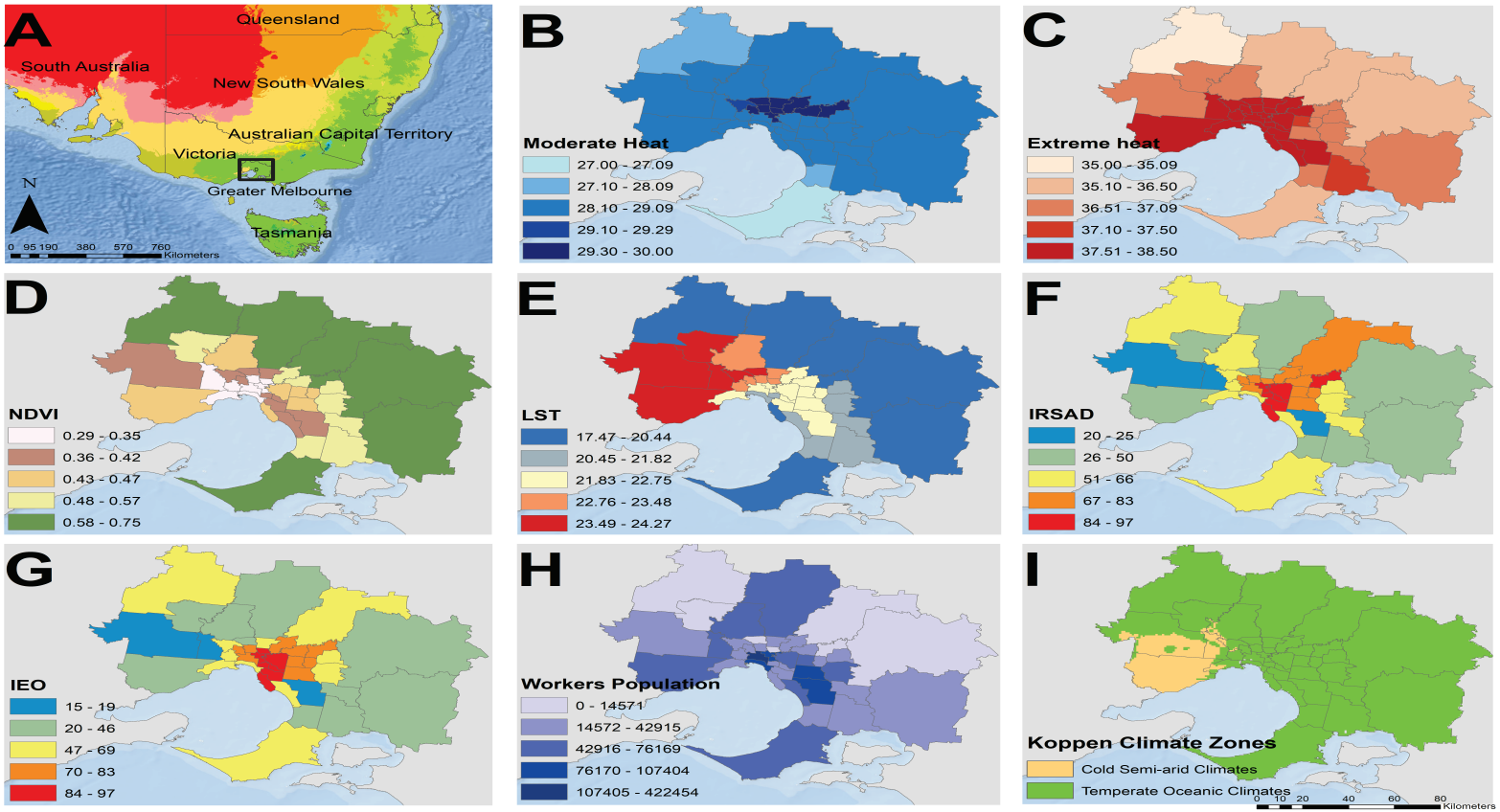

Figure 3.5 Environmental and socio-economic profile of Greater Melbourne at statistical area level 3.

A. Location of Greater Melbourne depicted on the south-eastern coast of Australia B. Moderate Heat map of Greater Melbourne estimated at 90th percentile of maximum temperature for the study period from July 2005 to June 2018. C. Extreme Heat map of Greater Melbourne estimated at 99th percentile of maximum temperature for the study period. D. Averaged NDVI estimated over the study period. E. Average LST estimated over the study period for Greater Melbourne. F. Relative Socioeconomic Index for Areas acquired from the ABS. G. Index of Education and Occupation acquired from the ABS. H. Workers' population based on their place of work for 2016 acquired at the SA3 level. I. Climate distribution at the SA3 level in Greater Melbourne following Beck et al. (104). The map is created in ArcMap 10.5.

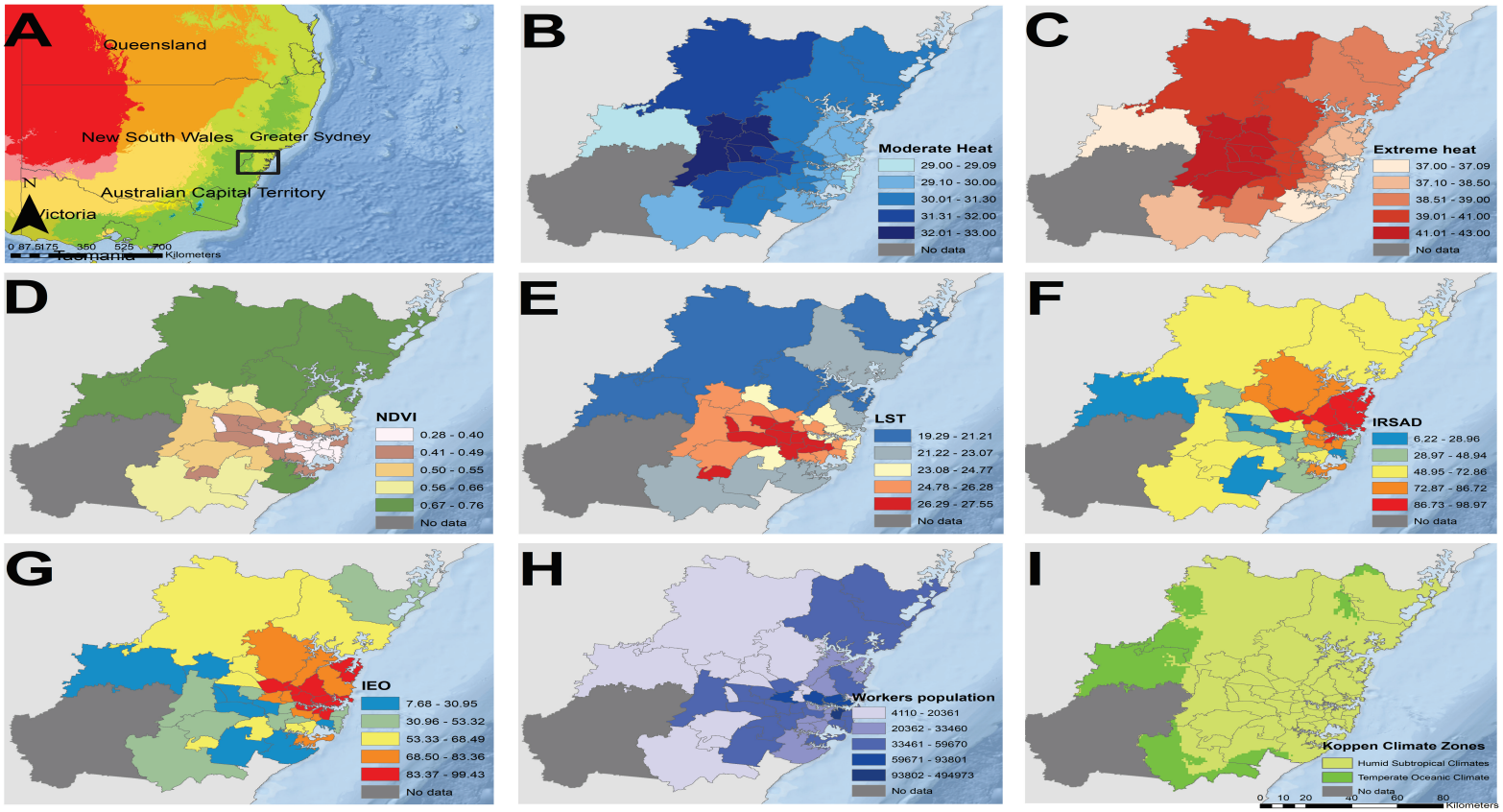

Figure 3.6 Environmental and socio-economic profile of Greater Sydney at statistical area level 3.

A. Location of Greater Sydney depicted on Australia's east coast B. Moderate Heat map of Greater Sydney estimated at 90th percentile of maximum temperature for the study period from July 2005 to June 2018. C. Extreme Heat map of Greater Sydney estimated at 99th percentile of maximum temperature for the study period. D. Averaged NDVI estimated over the study period. E. Average LST estimated over the study period for Greater Sydney. F. Relative Socioeconomic Index for Areas acquired from the ABS. G. Index of Education and Occupation acquired from the ABS. H. Workers' population based on their place of work for 2016 acquired at the SA3 level. I. Climate distribution at the SA3 level in Greater Sydney following Beck et al. (104). The map is created in ArcMap 10.5.

3.4 Theoretical Framework of the Thesis

A mixed method approach was adopted to address the overall research aim and the specific research objectives. In addition to the systematic literature review, the first part of the research pertaining to Chapters 4 and 5 was predominantly quantitative. It provides a comprehensive epidemiology of OI associated with hot weather conditions in present and future scenarios in the study cities. Depending on the availability of datasets, the first study was carried out in Greater Adelaide (Chapter 4), followed by a more comprehensive analysis providing evidence from three large cities including Greater Brisbane, Greater Melbourne, and Greater Sydney (Chapter 5). Chapter 6 was predominantly qualitative and addressed this thesis's fourth research question.

The quantitative studies (Chapters 4 and 5) addressed this thesis's first three research questions.

1. To examine the association between heat exposure and the risk of OI, an intra-urban risk assessment was carried out at Statistical Area Level 3 (SA3) in the four cities. For this purpose, the location of the workplace where the accidents occurred was considered. The workers' compensation claims data records the postal areas (POA) of workplaces where accidents occurred, but POA was not used as the spatial unit of analysis for two reasons. First, POA are non-ABS structures, which means they are spatially inconsistent and dynamic over time, and this can lead to temporal misalignment issues in the analysis (107). Second, workers' compensation claims data dispersed in several POA within the cities could lead to excess zeroes in the data and small sample size issues across space and time (108, 109). A similar issue is also prevalent for Statistical Area Level 2 (SA2), a consistent ABS geographical structure that is geographically similar to POA but will lead to small sample size issues. For the spatiotemporal feasibility of the analysis, SA3 was used as the unit of spatial analysis. SA3s are medium-sized general-purpose geographical regions as determined by the ABS (110) (The geographical structure of SA3 vs. SA2 is presented in Figure S1 in Appendix IV – Supplementary Materials for Chapter 5). Generally, they have a

population between 30,000 and 130,000 people. These regions are designed to represent a community that interacts socially and economically.

2. The environmental, personal, and workplace characteristics of workers associated with heat-related risk of OI were identified in the subgroup analyses. To evaluate personal factors, indicators such as age, gender, and claim type were utilised. For characterising workplace attributes, indicators such as occupation type, physical work demands, and various types of exposure were considered. In the second study carried out in three cities (Chapter 5); the environmental characteristics of the workplace were further explored, contingent upon findings from Chapter 4. The environmental characteristics considered in the analysis included hot vs. cold regions based on LST, vegetated vs. less vegetated regions based on NDVI, higher vs. lower IRSAD, and higher vs. lower IEO.
3. The heat-related risk of OI was estimated in the future projected periods for two climate change scenarios, i.e. RCP 4.5 and 8.5 at the GCCSA level in the four cities. Future predictions of risk of heat-related OI were not carried out at the SA3 level because future predictions are inherently uncertain, and spatial risk assessments must consider a range of localised demographic factors as these changes are pronounced at a local scale. These data were not available based on workers' place of work at the SA3 level for future projected periods.

Chapter 6 qualitatively assessed the existing heat-related policies institutionalised in high-risk construction industry addressing this thesis's fourth research question.

4. Heat-related policy documents were assessed qualitatively using the construction industry as a case study. These documents were evaluated based on the guidelines established at the national level by SWA to ensure the protection of workers from ambient heat exposure.

Together, these studies provide insight into the multifaceted impacts of heat on workers' health and safety burden, particularly in the face of climate change. This research, conducted from different perspectives, facilitated an in-depth understanding of the overall aim of this thesis.

3.5 Part I: Quantitative Analysis

3.5.1 Datasets

3.5.1.1 Environmental Data

Daily gridded meteorological data over the study period of July 2005 to June 2018 were acquired at a spatial resolution of 5 km. These datasets are publicly available from the Science and Technology Division of the Queensland Department of Environment and Science (111). These datasets are ready-to-use, gap-free, and have comprehensive spatiotemporal coverage. Further, the spatial resolution is reasonable for SA3-level analysis. A set of environmental variables, including maximum temperature, minimum temperature, solar radiation, and relative humidity were acquired. In the first study in Greater Adelaide (Chapter 4), maximum temperature was used as the exposure variable, adjusting for humidity in the models. Maximum temperature is a common metric used in heat-related studies because it is a proxy for the maximum thermal stress on the body (61, 63, 65-69, 71, 76). In particular, workers are most exposed and active at maximum temperature, which usually occurs a few hours after peak sunlight intensity (67, 112). In the study carried out in three cities in Australia (Chapter 5), the heat index was used as the primary exposure metric. The heat index is a composite metric estimated from maximum temperature and relative humidity, following Anderson et al. (113). Heat index includes humidity on the basis that the amount of air moisture plays an important role in the effectiveness of human thermoregulation in hot weather conditions. In temperate climates such as Greater Adelaide, thermoregulation is generally achieved by radiation and convection (114). As ambient temperature increases, the gradient for radiant heat loss diminishes, so the body relies significantly on the evaporation of sweat to limit the increase in body temperature. However, in hot and humid climates, predominantly in Greater Brisbane and Greater Sydney, water vapour pressure reduces the evaporative capacity of the environment. As such, hot and moist conditions not only limit the body's heat radiation and convection but also curtail the evaporative heat loss. In this regard, hot ambient temperatures combined with high humidity present a challenge for thermoregulation and how hot conditions are perceived by the human body (21, 114).

Additionally, NDVI was used as a covariate in the analysis. NDVI is associated with perceived vulnerability to heat effects (115). 16-day NDVI with a spatial resolution of 1*1 km resolution was acquired from Google Earth Engine (116). According to Didan et al. (117), each NDVI value in the time series represents the value for the entire 16-day period. To create daily time series data, the "last observation carried forward" approach was employed, which is considered an acceptable method for this purpose. An average of 16-day NDVI was used to identify vegetated versus less vegetated SA3 regions.

Additional variables were acquired for data stratification to identify the location-specific characteristics of the regions. They include:

1. An average of 8-day LST acquired from Google Earth Engine to identify hot vs. cool areas. LST is a reliable remote sensing product for classifying spatial variability in urban climates (118).
2. The socio-economic status of the regions was identified using IRSAD and IEO at the SA3 level acquired from the ABS (119).

The 75th percentile was used as a cut-off to create the binary variables. Previous studies have also used this cut-off for the separability of features (120).

3.5.1.2 Future Projected Data

Future projected daily meteorological data were obtained from two sources. Different data sources were used based on their availability at the time of research.

1. For the first study carried out in Greater Adelaide, a downscaled South Australian regional climate change projections dataset was acquired for the six "better performing" general circulation models (GCMs) under two RCP (4.5 and 8.5) (121). This is the most comprehensive set of downscaled climate projection data available in South Australia (122). The dataset encompasses the historical period from 1961 to 2005 and a projection period from 2006 to 2100.
2. For the second study carried out in the other three cities, nationally available 5 km application-ready daily gridded metrological data were obtained from Climate Change

in Australia (123, 124). These datasets were acquired for a set of two environmental variables, including maximum temperature and relative humidity at the SA2 level, for two 30-year projected periods from 2016 to 2045 and 2036 to 2065.

Data Pre-processing

The daily values for all the environmental variables were extracted using centroid points at SA2 in each GCCSA. Then, using the area-weighted approach, the daily values were aggregated at SA3 level. In this way, each value at the SA2 level was given a weighting based on its geographical covered area within SA3. Similarly, for future projected gridded datasets for the study carried out in three cities (Chapter 5), the area-weighted approach was used to aggregate SA2 level values at the GCCSA level. This approach is based on the concept of spatial dependence, as environmental variables such as temperature, humidity, among others, exhibit spatial dependence in the geographical space (125). This approach is computationally efficient for extracting very large daily gridded datasets at administrative level. The extraction and pre-processing of environmental variables was performed using R packages *raster, ncdf4*.

3.5.1.3 Workers' Compensation Claims Data

The Australian workers' compensation claims data are compiled by SWA as the NDS (50). These datasets are supplied by workers' compensation authorities from each State, Territory, and the Commonwealth government. There are eleven workers' compensation claim schemes in Australia. Eight primary schemes represent states and territories, and three Commonwealth government schemes are for government employees (Commonwealth Comcare), defence force personnel (Commonwealth Department of Veteran's Affairs), and seafarers (Commonwealth Sea Care) (126). Collectively, these schemes represent 90% of the Australian Workforce (127). Daily workers' compensation claims data was acquired from SWA pertaining to four compensation schemes representing four GCCSA: Greater Adelaide, Greater Brisbane, Greater Melbourne and Greater Sydney.

The third and the most recent version of NDS (i.e. NDS3) from 1 July 2005 to 30 June 2018 was acquired. NDS comprises de-identified data on cases of accepted and compensated OI.

NDS3 includes claimant details, occurrence details, and claims outcomes. Claimant information includes the industry of employer, size of employer, gender of claimant, age of claimant, occupation, labour hire indicator, apprentice/trainee indicator, and number of hours usually worked. Details on occurrence include date of injury/illness, postal area code of workplace where the accident occurred, nature of injury/illness, body location of injury/illness, mechanism of injury/illness, agency of injury/illness, and time of injury/illness. The claim outcome suggests the time lost from work. The occupational and industrial characteristics are coded as the ANZSIC and ANZSCO. The injury details, encompassing the nature or type of injury, the event or exposure that caused the injury (mechanism of injury), the affected body part or site, and the primary/secondary source of injury, are encoded following the Type of Occurrence Classifications System, Version 3.1. (TOOCS 3.1) codes (128). Thus, this dataset is a comprehensive and robust source for collecting information on OI and the locations where the accidents occurred in respective jurisdictions across Australia.

NDS3 includes all physical injuries, illnesses, and aggravated pre-existing injuries arising out of or in the course of the worker's employment. Data for all types of OI for which a claim was made was included in line with previous studies (65-67). The inclusion of all claims as the outcome variable may possibly include illnesses resulting from long-term exposure, which may potentially lead to exposure misclassification. However, 87% of all claims in Australia are due to injuries and musculoskeletal disorders, while 13% of claims can be attributed to diseases with short-term or long-term latency periods (129).

For the study carried out in Greater Adelaide, additional workers' compensation claims data was acquired from Safe Work South Australia (SWSA), the data custodian at the time of data acquisition (at the time of writing, the data custodian is Return to Work SA). The additional jurisdictional dataset provided information on any missing postal codes of the workplace where the accident occurred.

Data Pre-processing

Prior to data analysis, data cleaning was carried out. Briefly, claims were included irrespective of their severity (fatal or not) and duty status (for example, injury occurred at the workplace or during commuting). Claims were excluded only if:

1. Age of workers was <15 years or >80 years.
2. The location of the accident, which is recorded using the workplace's POA codes, was either missing or beyond the GCCSA or if the POA code provided was a PO box number rather than an actual physical address.
3. Some claims were excluded as a result of data transformations from the POA to the SA3 level. This ensured that the datasets were aligned with the SA3 geographical granularity.

The individual claimant's data were transformed into daily counts of OI at the SA3 level. The datasets were also stratified based on several indicators required for the subgroup analyses, such as date of injury/illness, industry of employer, gender, age, location, occupation, apprentice/trainee indicator, nature of injury/illness, mechanism of injury/illness, agency of injury/illness, time of injury/illness. Some additional variables were generated for subgroup analyses. They include claim type (occupational injuries only vs. occupational illnesses only), outdoor vs. indoor industries, type of work based on physical demands (limited, light, medium, heavy), and type of exposure (regulated and unregulated indoor, outdoor, multiple locations). Type of work based on physical demands and type of exposure were classified by merging ANZCO codes with Canadian occupational codes developed by Human Resources and Skills Development Canada (HRSDC) (130), using a common coding scheme - The International Standard Classification ISCO-88 (131). By utilising these coding schemes, the physical demands and the type of temperature exposure associated with each occupational title could be matched with the ANZCO-coded occupation title of each claimant. The process has been validated previously in the Australian context (66, 67, 132). The data pre-processing was performed using Stata 15 and R packages *dplyr, haven, lubridate, stringr, tidyverse*.

Spatial Transformation of Workers Compensation Claims Data from POA to SA3 Level

To carry out an intra-urban scale risk assessment at the SA3 level, all workers' compensation claims data (2005 to 2018) were initially transformed to POA 2016 geographical boundaries using ABS population-weighted correspondences (POA 2006 to POA 2016 and POA 2011 to POA 2016) available from the ABS (110). Subsequently, the ABS correspondences (POA 2016 to SA3 2016) were used to recode workers' compensation claims data recorded at the POA level to the SA3 level. All correspondences used to carry out transformations have been proven valid and reliable (110). Aggregated workers' compensation claims data was used at the GCCSA level to estimate the future projected risk of OI.

3.5.1.4 Population Data and Public Holidays

Workers' population data were acquired from the ABS census data. The ABS census is conducted every 5 years in Australia, and it is compulsory for all Australian households to take part (with stratification for employees in August 2006, 2011, and 2016). This is the only data that provides workers' population based on their "place of work" at the SA3 level.

Public holidays are potential confounders in the relationship between environmental exposure and health outcomes. Table 3.2 shows the list of public holidays included in the analysis as a binary variable (133, 134).

Table 3.2 List of national and jurisdiction-specific public holidays in Australia.

Public Holiday	Greater Adelaide	Greater Brisbane	Greater Melbourne	Greater Sydney
New Year's Day	1	1	1	1
Australia Day	1	1	1	1
Adelaide Cup	1			
Good Friday	1	1	1	1
Easter Saturday	1	1	1	1
Easter Monday	1	1	1	1
ANZAC Day	1	1	1	1
Queen's Birthday	1	1	1	1
Royal Queensland Show		1		
Labour Day	1	1	1	1
Melbourne Cup			1	
Christmas Day	1	1	1	1
Boxing Day	1	1	1	1

3.5.2 Overview of the Statistical Analysis

The effect of temperature on OI has been reported by others to be non-linear and delayed (61, 75, 93, 135). To account for these complex two-dimensional interactions, i.e. non-linearity and delayed effect, Distributed Lag Non-Linear Models (DLNM) were used. Time series designs capture long-term trends, seasonality, and other temporal patterns, which can help identify systematic variations in health outcomes associated with temperature (136, 137). While time-stratified case-crossover study design is advantageous for controlling for individual-level confounders and thus controlling for workers' populations by design, it is known for more strict control over seasonality and long-term trends (134). To control for workers' population, the population of workers based on their place of work was included as a logarithmic offset in the models. To capture the short-term fluctuations in workforces occurring over a few days, public holidays were included (61). Generalised linear models with quasi-Poisson distribution were used to model the count data of OI to account for over-dispersion in the datasets (61, 138).

Furthermore, to account for spatial heterogeneity at the intra-urban scale and to provide location-specific estimates, two-staged DLNM were used (139). The first stage estimated the temperature effects within each SA3, and the second stage pooled these estimates using

multivariate meta-regression to obtain cumulative estimates across the cities. This approach offers a flexible and comprehensive framework to analyse the association between heat exposure and OI (17, 61, 140-142). It allows the exploration of effect modifiers such as population characteristics or study-specific factors and potential sources of heterogeneity in effect estimates. The fitted models were used to obtain the best linear unbiased predictions (BLUP) of the overall cumulative associations between temperature and OI, as observed in the case of OI counts. This approach is advantageous when small daily counts exist in various SA3 regions. It allows areas with small daily counts to borrow information from larger populations with similar characteristics (141, 143). The BLUP curve was used to define the optimum temperature at which the risk is estimated to be zero; this temperature is referred to as the temperature "Percentile of Minimum OI" (PMOI) (61). The results were then summarised by computing the relative risk at the 1st percentile (cold), 90th percentile (moderate heat) and 99th percentile (extreme heat), using PMOI as a reference in each location in line with previous studies (61, 67, 142). The second-stage meta-analysis was performed with the R package *mvmeta* (143). Subgroup analysis based on workers' characteristics, nature of work, and workplace characteristics was carried out. Region-wise subgroup analyses were undertaken for gender, age, types of industries, and type of claims only. Sensitivity analyses were carried out to evaluate the robustness of modelling choices, including varying degrees of freedom for temperature and lag dimensions and varying exposure metrics such as maximum temperature, minimum temperature, and mean temperature.

The attributable fraction (AF) of OI was estimated as the ratio between the attributable number of OI and the total number of OI following Gasparrini and Leone (144). Heat and cold-related AF were estimated as the range between PMOI and maximum/minimum percentile of temperature, respectively. Values that fell between PMOI and the 90th percentile were defined as AF at moderate heat, and values beyond this range were defined as AF at extreme heat.

Log-linear extrapolation with spline functions was used for predicting future risk based on historical data. This method allows for flexible modelling of non-linear relationships and provides a framework for projecting risk beyond the observed data range (145).

3.6 Part II: Qualitative Analysis

3.6.1 Datasets

This part of the study focused on assessing the existing heat-related policies implemented at the organisational level in the high-risk construction industry as a case study. Snowball sampling was used to acquire policy documents from one company and its sub-contractors. Due to the complex nature of work and interactions within construction companies, snowball sampling was chosen as this is beneficial to identify the key players, which further helps to identify the related connections. Policy documents were acquired from the primary contracted company and five of its subcontractors, including civil contractor, electrical contractor, structural steel contractor, mechanical contractor, and height safety contractor.

3.6.2 Overview of Framework Analysis

The "framework analysis approach" (146, 147) was used to assess the policy documents thematically. This systematic and rigorous approach is used to analyse qualitative data, including policy documents (148). It provides a structured framework for organising and analysing textual information, thus allowing researchers to identify patterns, themes, and relationships within the documents (146).

The framework analysis of the policy documents was carried out in five main steps:

1. Familiarization with the documents by thorough reading and understanding the objectives, content and context of the policy documents.
2. Creating an analytical framework that guided the analysis. The main themes and categories were defined deductively by using SWA guidelines for working in heat. SWA's guidelines were used to guide the analysis, because SWA provides the model WHS framework and national guidelines. The states/territories are responsible for ensuring that the practical measures translated into the industry are in accordance with the national guidelines. Six main categories were identified from the guidelines of SWA: "preparedness", "identify hazards", "assess risks", "control risks" (by

elimination, substitution, isolation, engineering, administrative, and PPE), "review control measures" and "response".

3. The relevant data from the policy documents were extracted into the matrix of predefined framework of analysis.
4. All the textual data in categories and themes were interpreted and summarised to identify key patterns and gaps and to allow comparisons.
5. To give a descriptive overview of the existing policies, the findings in each category were summarised and presented in a summary table.

3.7 Ethical Approval

Ethics approval was obtained from the University of Adelaide Human Research Ethics Committee to carry out this research work (Approval numbers: H-2019-219 and H-2016-085). All the data obtained from SWA and SWSA were de-identified to maintain privacy and confidentiality. Data storage of all data was compliant with the university's policy. Workers' compensation claims data were stored on the password-protected university computer in the School of Public Health located in a restricted access area.

CHAPTER 4

HEAT AND OI: EPIDEMIOLOGICAL EVIDENCE FROM GREATER ADELAIDE

Preface

Chapter 4 focuses on evaluating the impacts of heat on OI at the intra-urban scale in Greater Adelaide. This chapter sought to address the first three specific research questions, providing evidence from Greater Adelaide.

In Section 4.1, the authorship of the published article is stated. Section 4.2 details the published study assessing the impacts of heat on OI in Greater Adelaide at an intra-urban scale. This study was published in Science of the Total Environment in 2022.

Fatima, S. H., Rothmore, P., Giles, L. C., & Bi, P. (2022). Outdoor ambient temperatures and occupational injuries and illnesses: Are there risk differences in various regions within a city?. *Science of the total environment*, *826*, 153945. https://doi.org/10.1016/j.scitotenv.2022.153945

The study identified characteristic spatial patterns in the distribution of the risk of OI associated with heat. Hotter regions in northern and western parts of the city were typically at elevated risk of OI for workers. Based on these findings, a more comprehensive study was carried out in three major cities in Australia, representing different climate zones (Chapter 5).

This study serves as a crucial steppingstone to comprehensively understand the intricate relationship between heat and OI, paving the way for further exploration and insights in the subsequent stages of the research project.

4.1 Statement of Authorship

Title of Paper	Outdoor ambient temperatures and occupational injuries and illnesses: Are there risk differences in various regions within a city?
Publication Status	☑ Published ☐ Accepted for Publication ☐ Submitted for Publication ☐ Unpublished or unsubmitted work written in manuscript style
Publication Details	*Fatima, S. H., Rothmore, P., Giles, L. C., & Bi, P.* (2022). Outdoor ambient temperatures and occupational injuries and illnesses: Are there risk differences in various regions within a city?. *Science of the total environment, 826*, 153945. https://doi.org/10.1016/j.scitotenv.2022.153945

Principal Author

Name of Principal Author (Candidate)	Syeda Hira Fatima		
Contribution to the Paper	Conceptualization, Methodology, Software, Formal Analysis, Writing - Original Draft		
Overall percentage (%)	75%		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
Signature		Date	25\08\2023

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);
ii. permission is granted for the candidate in include the publication in the thesis; and
iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

Name of Co-Author	Paul Rothmore		
Contribution to the Paper	Conceptualization, Writing - Review & Editing, Supervision		
Signature		Date	25/8/23

Name of Co-Author	Lynne C. Giles		
Contribution to the Paper	Conceptualization, Writing - Review & Editing, Supervision		
Signature		Date	25/8/23

Name of Co-Author	Peng Bi		
Contribution to the Paper	Conceptualization, Writing - Review & Editing, Supervision		
Signature		Date	25/08/2023

4.2 Outdoor Ambient Temperatures and Occupational Injuries and Illnesses: Are there Risk Differences in Various Regions Within a City?

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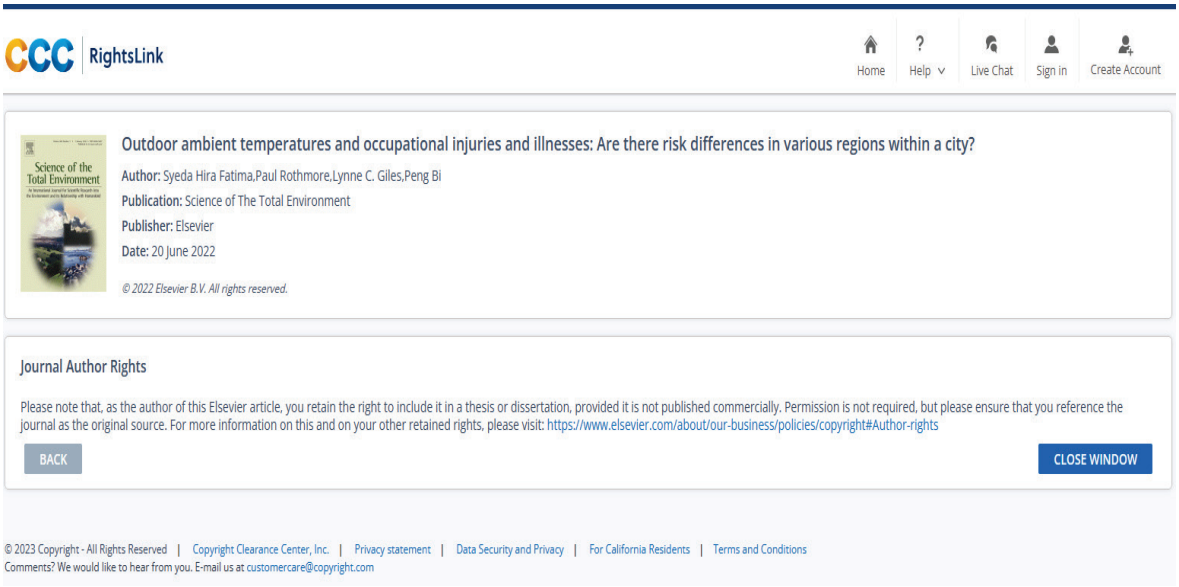

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Outdoor ambient temperatures and occupational injuries and illnesses: Are there risk differences in various regions within a city?

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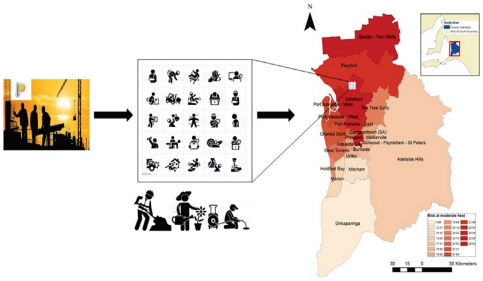
HIGHLIGHTS

- The risk of OI varies spatio-temporally in Greater Adelaide.
- Greater burden of OI is associated with moderate heat than extreme heat.
- The risk of OI is projected to increase in Adelaide in the face of climate change.
- Spatial risk assessment has significant implications in targeted interventions.

GRAPHICAL ABSTRACT



Exposure to hot weather conditions leads to the increased risk of Occupational Injuries and Illnesses and the risk varies spatially at intra-urban level and in different industries and occupations

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ABSTRACT

Increased risk of occupational injuries and illnesses (OI) is associated with hot ambient temperatures. However, the existing evidence of risk estimation is limited to large regions at the city or provincial scales. For effective and localized occupational health risk management, spatio-temporal analysis should be carried out at the intra-city level to identify high-risk areas within cities. This study examined the exposure-response relationship between ambient temperatures and OI at the intra-city scale in Greater Adelaide, Australia. Vulnerable groups of workers, in terms of workers' characteristics, the nature of their work, and workplace characteristics were identified. Further, the projected risk of OI was quantified in various climate change scenarios.

The temperature-OI association was estimated using a time-series study design combined with Distributed Lag Non-linear Models. Daily workers' compensation claims (2005–2018) were merged with 5 km gridded meteorological data of maximum temperature (°C) at Statistical Area Level 3 in Greater Adelaide. Region-wise subgroup analyses were conducted to identify vulnerable groups of workers. Future projections (2006–2100) were conducted using downscaled climate projections and the risk was quantified using log-linear extrapolation. The analyses were performed in R 4.1.0.

The overall OI risk was 16.7% (95%CI: 10.8–23.0) at moderate heat (90th percentile) and increased to 25.0% (95%CI: 16.4–34.2) at extreme heat (99th percentile). Northern Adelaide had a higher risk of OI for all types of workers at moderate heat, while western regions had a high risk for indoor industries. Southern and eastern regions had a higher OI risk for males, older workers, and outdoor industries at extreme heat. The projected risk of OI is estimated to increase from 20.8% (95%CI: −0.2–46.3) in 2010s to 22.9% (95%CI: −8.0–64.1) by 2050s. Spatio-temporal risk assessment at the intra-city scale can help us identify high-risk areas, where targeted interventions can be efficiently employed to reduce the socio-economic burden of OI.

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1. Introduction

Many studies have quantified the risk of occupational injuries and illnesses (OI) associated with ambient temperatures in different parts of the world (Adam-Poupart et al., 2015; Marinaccio et al., 2019; Martínez-Solanas et al., 2018; Morabito et al., 2006; Riccò, 2018; Sheng et al., 2018; Spector et al., 2016). The exposure-response curve of OI associated with ambient temperatures appears to be curvilinear with steeper slopes at higher temperature thresholds, whereby the risk increases progressively above or below optimal temperature range (Marinaccio et al., 2019; Martínez-Solanas et al., 2018; Varghese et al., 2019a). A recent systematic review and meta-analysis (Fatima et al., 2021) indicated that the risk of OI increases by 1.0% with each 1 °C increase in temperature above optimal ranges. Possible impacts of low ambient temperatures on the increased risk of OI have also been emphasized (Marinaccio et al., 2019; Morabito et al., 2014). One study (Bell et al., 2000) found a near doubling of risk below freezing point in outdoor settings, although another study found a non-significant risk reduction of OI associated with cold days, in cities characterized by moderate winters (Varghese et al., 2019b). The thermal exposure thresholds at which the risk of OI increases, exhibit geographical variations due to underlying differences in local climate conditions, as well as type of workers, their physiological conditions and workplace characteristics (Varghese et al., 2019b).

Evidence from various cities in Australia suggests that cities characterized by temperate Mediterranean climates for example Adelaide or Oceanic climates such as Melbourne had a higher risk of OI associated with extremely hot weather conditions (McInnes et al., 2017; Varghese et al., 2019a; Varghese et al., 2019b; Xiang et al., 2014a). However, non-significant effects were estimated in Brisbane characterized by Humid Subtropical climate (Varghese et al., 2019b). In Perth, the risk of traumatic injuries increased by 17% during extremely high temperatures (Varghese et al., 2019b). Furthermore, younger workers (age < 45 years), male workers, and workers in outdoor intensive industries such as agriculture, forestry or fishing, construction, and manufacturing were at high risk of OI during high temperatures in many occupational settings (Fatima et al., 2021; Marinaccio et al., 2019; Varghese et al., 2019a; Xiang et al., 2014a; Xiang et al., 2014b).

Cumulative exposure to hot weather conditions has direct negative consequences for workers such as heat-induced illnesses, work stress, physical discomfort, and loss of work capacity and productivity (Cheung et al., 2016). The physiological and psychological changes associated with heat exposure potentially reduce workers' performance, increase distractibility and increase fatigue which in turn increases the risk of OI (Kjellstrom et al., 2018; Varghese et al., 2018). In cold environments, thermal discomfort, hypothermia, and decreased dexterity can also trigger OI (Schulte and Chun, 2009). The most common types of OI include body stressing, slips, trips or falls, being hit by objects, hitting objects with a part of the body or vehicle incidents, etc. (Varghese et al., 2019a). Besides the specific health burden, OI have significant economic consequences, including direct costs of work-related incidents and indirect economic costs such as loss of productivity, loss of income, and quality of life (Borg et al., 2021).

The heat-related occupational health impact is a matter of great public health concern, especially in the context of climate change (Huang et al., 2011). The latest reports from the Intergovernmental Panel on Climate Change (IPCC) suggest that the number of hot days and heatwaves will increase in frequency, intensity, and duration (IPCC, 2021). In temperate latitudes, for example in Mediterranean regions of Australia, the number of hot working days is projected to increase by 15 to 26 days per year by 2070, which may increase the risk of OI (Kjellstrom et al., 2016). The number of “unsafe days” particularly for physical labor work is projected to increase from 31 days in 2009 to 94 days per year in 2070 (Maloney and Forbes, 2011). The global trend of sprawling cities and the associated urban heat island effect is likely to further intensify extreme climatic events and health-associated risks including OI within cities (Patz et al., 2005).

Most published studies concerned with the OI risk due to hot ambient temperatures have been conducted at the city, state, or province level while spatial variations at a localized intra-city scale are often ignored (Fatima et al., 2021). Given the considerable variations in environmental conditions within a city, such estimates at finer levels will provide valuable information for the development of precision preventative measurements to mitigate the impacts of heat stress related health risks for workers (Guerri et al., 2022). Furthermore, the allocation of resources, adaptation planning, and project management require localized analysis so that targeted actions can be taken. Previously, spatial analysis has been undertaken to develop interventions and mitigation strategies for different occupational sectors at regional and local scales, for example, the HEAT-SHIELD project in Europe (Morabito et al., 2019) or mapping the Wet Bulb Globe Temperature heat stress index across South-East Asia (Kjellstrom et al., 2013).

With recent advances in statistical modeling techniques, remote technologies, and the availability of high-resolution meteorological data, there are new opportunities to examine the exposure-response relationship at finer detail than was possible previously. In this study, we examined the exposure-response relationship between ambient temperatures and OI by considering the environmental and demographic variability at an intra-city level. Our overall aim was to identify highly vulnerable regions in Greater Adelaide, Australia. We also aimed to identify vulnerable groups of workers in terms of workers' characteristics, the nature of their work, and workplace characteristics and to project the future risks of OI associated with ambient temperature in the context of climate change.

2. Methods

The associations between ambient temperatures and OI were examined by using workers' compensation claims data for the study period of 1st July 2005 to 30th June 2018. We used a time-series study design combined with Distributed Lag Non-linear Models (DLNMs) to estimate the relationship between the count of daily OI and daily maximum temperatures Tmax (°C) (Gasparrini et al., 2010; Gasparrini, 2014; Gasparrini et al., 2015; Martínez-Solanas et al., 2018). Ethical approval was obtained from the University of Adelaide Human Research Ethics Committee (H-2019-219 and H-2016-085) and the study was carried out in 2021.

2.1. Study settings

This study was conducted in Greater Adelaide at the spatial scale of Statistical Area level 3 (SA3). SA3 is designed for regional outputs in Australia, with similar regional characteristics, administrative boundaries, and labor markets, and generally have a population of between 30,000 and 130,000 people. The northern and western SA3 regions of Adelaide are characterized by a Cold Semi-Arid climate. The eastern and southern SA3 regions have a Warm Mediterranean climate in general as shown in Fig. 1.

2.2. Data sources

2.2.1. Environmental data

Daily gridded meteorological data at a spatial resolution of 5 km were obtained from the Queensland Department of Environment and Science (Jeffrey et al., 2001). For the present study, a set of environmental variables were acquired including maximum temperature (Tmax), minimum temperature (Tmin), solar radiation, and relative humidity. The temperature values were extracted from the daily datasets using centroid points of SA2, which were then aggregated to the SA3 level using area weighted ratios of SA2 within SA3. This approach gives extracted temperature values a weightage based on the geographic area of SA2 within SA3. This is a simple approach of raster data aggregation at an administrative level and is computationally efficient for large datasets.

One additional environmental covariate was included in data analysis: Normalized Difference Vegetation Index (NDVI). The MOD13A2.006 product derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite data, provides NDVI at 1 km and 16-day spatio-temporal resolution. We extracted the NDVI values for the study period

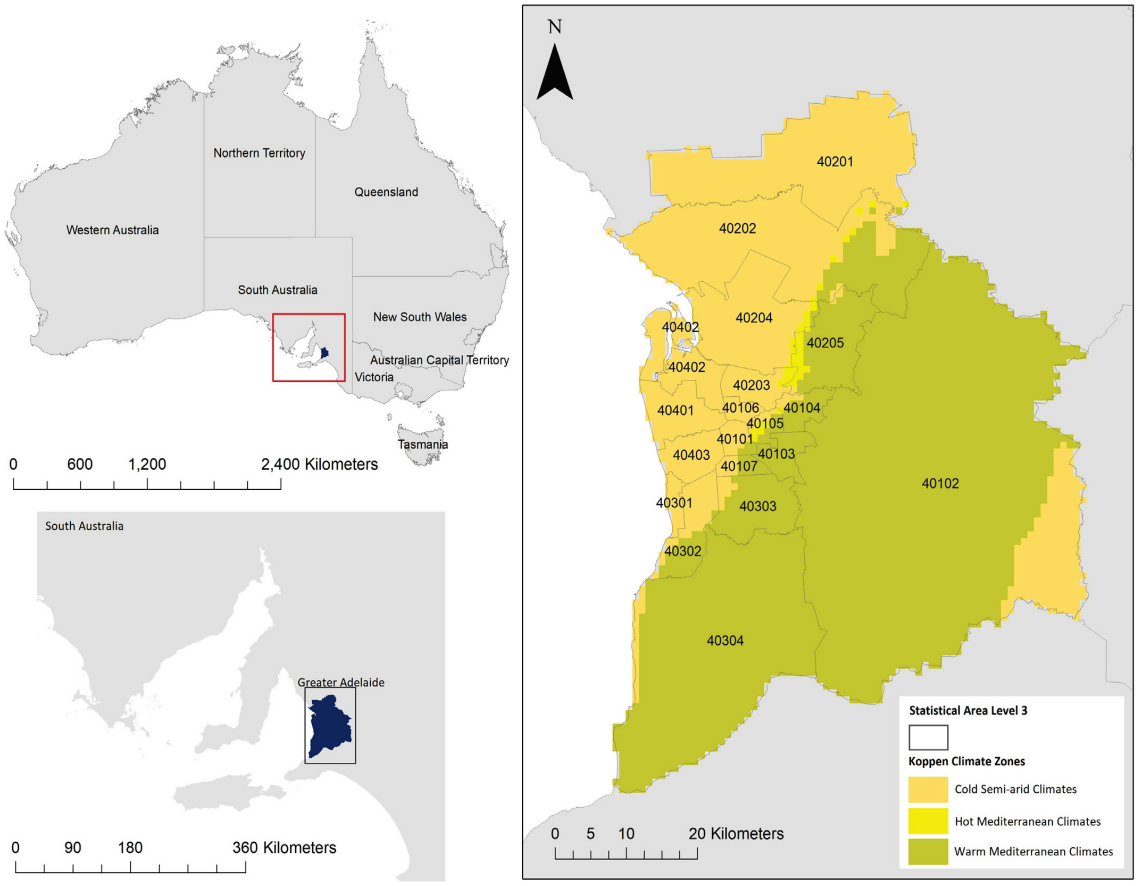


Fig. 1. Map of Greater Adelaide with Australia showing characteristic Köppen climate zones (Beck et al., 2018).The regions are labeled using SA3 five-digit code convention which is as follows: 40101 – Adelaide City, 40102 – Adelaide Hills, 40103 – Burnside, 40104 – Campbelltown (SA), 40105 – Norwood – Payneham – St Peters, 40106 – Prospect – Walkerville, 40107 – Unley, 40201 – Gawler – Two Wells, 40202 – Playford, 40203 – Port Adelaide – East, 40204 – Salisbury, 40205 – Tea Tree Gully, 40301 – Holdfast Bay, 40302 – Marion, 40303 – Mitcham, 40304 – Onkaparinga, 40401 – Charles Sturt, 40402 – Port Adelaide – West, 40403 – West Torrens.

using SA2 geographic centroids. Each NDVI value in the time series is representative of an entire 16 day time period (Didan et al., 2015). We used the last observation carried forward method to create a daily time series for NDVI datasets. Data aggregation to the SA3 level was done using methodology consistent with that as described above.

2.2.2. Climate projected data

The future risk of OI was estimated using downscaled South Australian regional climate change projections data (Goyder Institute for Water Research, 2015). This dataset represents the most comprehensive set of climate projections ever available for South Australia. The data encompass the historical period from 1961 to 2005 and a projection period from 2006 to 2100. We used data from six "better performing" general circulation models under two Representative Concentration Pathways (RCP) 4.5 and 8.5 (Charles and Fu, 2015).

2.2.3. Workers' compensation claims data

Daily compensation claims lodged by workers for their medical expenses and/or loss of wages for all types of injuries and illnesses were compiled for the study period. These datasets were acquired from two sources: i. State Regulatory authority (Return to Work SA) and ii. National Regulatory Authority using the National Dataset for Compensation Based Statistics (NDS3) collected by SafeWork Australia.

Workers' compensation claims data records the postal areas (POA) of the workplace where the accident occurred. POA are non-ABS structures and are known to change over time. Moreover, workers' compensation claims data dispersed in several POA within the cities have excess zeroes for daily claims. We, therefore, aggregated the data to SA3 level, which are more stable and purpose-built standard geographic structures (Australian Bureau of Statistics, 2016).

We included claims irrespective of their severity (fatal or not) and duty status (for example injury occurred at the workplace or during commuting). We excluded claims if 1. The age of workers was < 15 years or > 80 years. 2. The POA of the accident was missing, beyond South Australia or when the POA was a PO Box number and not an actual address. 3. Some claims were excluded because of data transformations from POA level to SA3 level. 4. Claims at the SA3 level were beyond the defined Greater Adelaide area (as shown in Fig. 2).

The workers' compensation claims data were classified based on age, gender, claim type (injuries or illnesses), types of occupations, physical work demands (limited, light, medium, or heavy work), location of work (indoor, outdoor, or multiple locations) and type of industries (indoor industries or outdoor industries). Claim types were identified according to the Type of Occurrence Classification System (TOOCS 3.1) (SafeWork Australia, 2018). The outdoor and indoor industries were classified following Xiang et al., 2014a. Physical work demands and location of work were categorized at the occupational

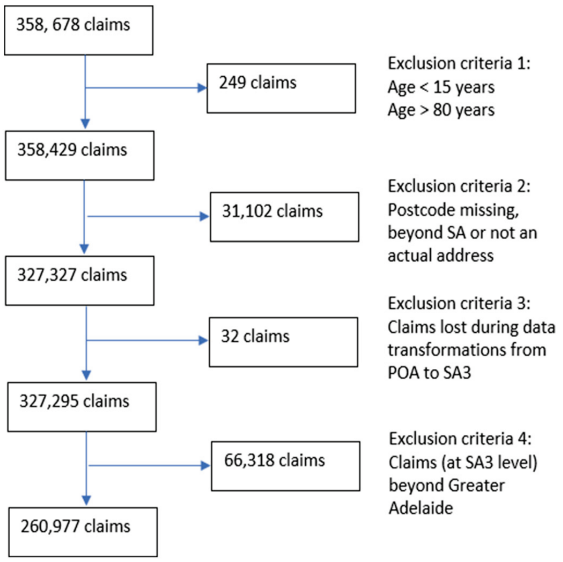


Fig. 2. Flow chart of the number of claims dropped based on defined eligibility criteria.

level using the cross-walk approach, described elsewhere (McInnes et al., 2017).

2.3. Statistical analyses

The DLNM approach used in this study involves a two-staged analysis to investigate the exposure-response relationship between OI and Tmax in multiple localities (Gasparrini et al., 2012). In the first stage, we used time-series regression based on generalized linear models with a Quasi-Poisson family to derive estimates of location-specific temperature–OI associations. Separate models were fitted in each SA3 and the effect estimates were reported as a percent difference. In these models, the cross basis was defined using B-splines with one internal knot placed at the 50th percentile (Martínez-Solanas et al., 2018). Long-term trends and seasonality were accounted for by including the natural cubic spline of time with four degrees of freedom per year. A variable corresponding to the day of the week and an indicator variable denoting public holidays were also included in the models. These adjustments controlled for a reduction in workers' population on weekends and holidays. The workers' population in their place of work in each SA3 was also included as an offset term to account for the number of workers potentially exposed to injuries (Martínez-Solanas et al., 2018). We extended the lag period to up to seven days to include possible lagged effects of the temperature exposure and OI. Cumulative results were obtained for all lags to estimate an overall temperature-injury association in each SA3.

In the second stage, the estimated location-specific associations were pooled using multivariate meta-regression models. The fitted models were used to obtain the best linear unbiased prediction of the overall cumulative associations between temperature and OI. The best linear unbiased prediction curve was used to define the optimum temperature at which the risk is estimated to be zero referred to as the temperature "Percentile of Minimum Occupational Injuries" (PMOI) (Martínez-Solanas et al., 2018). The results were then summarized by computing the relative risk at the 1st percentile (cold), 90th percentile (moderate heat), and the 99th percentile (extreme heat) using PMOI as a reference in each location (Gasparrini et al., 2015; Martínez-Solanas et al., 2018; Varghese et al., 2019a). The analyses were performed with R 4.1.0 using *dlnm* and *mvmeta* packages (Gasparrini, 2011; Gasparrini et al., 2012).

Overall subgroup analyses were based on workers' characteristics (age, gender, and type of claims), nature of work (type of work, physical demands), and workplace characteristics (location of work). Region-wise subgroup analyses were undertaken for gender, age, and types of industries only. Sensitivity analyses were also conducted to evaluate model choices based on Akaike Information Criterion, percent difference (%) at extreme heat, the fraction (%) of OI attributable to high temperatures (moderate heat and extreme heat).

2.3.1. Temperature-related attributable fraction of occupational injuries and illnesses

The heat and cold attributable fraction of OI, defined as the ratio between the attributable number of OI and the total number of OI, was estimated following a previously defined method (Gasparrini and Leone, 2014). The attributable components for heat were further separated by moderate and extreme impacts using the cutoff value of 90th percentile within the temperature range in each location (Gasparrini et al., 2015; Martínez-Solanas et al., 2018). Empirical confidence intervals (eCI) were generated using Monte Carlo simulations.

2.3.2. Future projections

We estimated the risk of OI at the city level in Greater Adelaide for the baseline period (2005–2018). This baseline period was used to estimate the exposure-response curve in the future using a log-linear extrapolation with a B-spline function (Vicedo-Cabrera et al., 2019). These projections are based on two assumptions: 1. The exposure-response association observed over the current range remains unchanged in the future; 2. The extrapolation appropriately represents the risk over the unobserved range (Vicedo-Cabrera et al., 2019). The effects of projected daily Tmax on future heat-related OI were estimated for each day and summed up for the whole projection period. The results were then presented in four timeframes including the current timeframe 2010s (2010–2019) and the future timeframes including 2030s (2030–2039), 2050s (2050–2059), and 2090s (2090–2099) for the two RCP scenarios (RCP 4.5 and RCP 8.5) and six "better performing models" (Charles and Fu, 2015). Heat and cold attributable fractions (relative to the observed period) were estimated along with the 95% empirical confidence intervals (95% eCI) (Gasparrini and Leone, 2014).

3. Results

3.1. Descriptive statistics

A total of 260,977 workers' compensation claims of OI were reported from Greater Adelaide between the years 2005 and 2018 based on our eligibility criteria. Table 1 provides the number of cases in each SA3 along with the maximum temperature (Tmax) profile. A large proportion of claims was reported from Adelaide city (40101) (21.9%), followed by Port-Adelaide West (40402) (8.9%), Charles Sturt (40401) (8.4%), West Torrens (40403) (8.3%), and Salisbury (40204) (7.2%). Over the study period, maximum Tmax was reported from Gawler – Two Wells (40201) (46.3 °C), and minimum Tmax was reported from Adelaide Hills (40102) (7.4 °C).

Descriptive statistics of workers' compensation claims are given in Supplementary Table S1. The claimants were predominantly males (65%) aged between 25 and 54 years (68%). The industries with the largest number of claims were manufacturing (14%), health care and social assistance (12%), and transport, postal, and warehousing (7%), and the most affected occupations included technicians and trade workers (22%), laborers (21%) and service workers (14%). Approximately 70% of claims were injury-related while 24% were related to illnesses. Body stressing (35%) was a predominant mechanism of injury followed by hits (16%) and falls (15%).

3.2. Overall risk estimates

The overall risk of OI in Greater Adelaide was estimated to be 16.7% (95%CI: 10.8–23.0) at moderate heat (90th percentile: 32.3 °C) and

Table 1
Summary statistics of workers' compensation claims and temperature (Tmax) profile in SA3 regions of Greater Adelaide for 13 years from 2005 to 2018.

SA3 regions	N (%)	Minimum value of Tmax (°C)	Maximum value of Tmax (°C)	Minimum Occupational Injuries Temperature	Moderate Heat (90th percentile)	Extreme Heat (99th percentile)
Adelaide City (40101)	57,181 (21.9)	9.8	45.3	16.7	32.9	40.6
Adelaide Hills (40102)	6391 (2.4)	7.4	43.9	18.4	31.3	39.0
Burnside (40103)	4694 (1.8)	9.0	44.9	17.5	32.3	40.3
Campbelltown (SA) (40104)	3602 (1.4)	9.1	45.3	17.7	32.8	40.7
Charles Sturt (40401)	21,813 (8.4)	10.1	44.6	12.9	32.6	40.0
Gawler - Two Wells (40201)	3955 (1.5)	9.9	46.3	18.2	34.5	42.2
Holdfast Bay (40301)	3900 (1.5)	10.0	44.2	12.8	31.8	39.8
Marion (40302)	7814 (3.0)	9.6	44.4	13.6	31.7	39.7
Mitcham (40303)	9036 (3.5)	8.8	44.2	17.6	31.4	39.3
Norwood - Payneham - St Peters (40105)	6259 (2.4)	9.6	45.7	17.7	33.3	41.2
Onkaparinga (40304)	16,862 (6.5)	9.1	44.2	17.7	30.5	38.8
Playford (40202)	14,440 (5.5)	9.5	45.7	17.5	33.5	41.3
Port Adelaide – East (40203)	17,386 (6.7)	9.6	45.5	17.3	33.4	41.3
Port Adelaide – West (40402)	23,336 (8.9)	10.1	44.8	12.9	32.9	40.8
Prospect – Walkerville (40106)	3015 (1.1)	9.9	45.4	16.9	33.1	40.9
Salisbury (40204)	18,919 (7.2)	9.8	45.4	17.1	33.6	41.4
Tea Tree Gully (40205)	7086 (2.7)	8.9	45.3	17.9	33.0	40.6
Unley (40107)	13,642 (5.2)	9.8	45.2	16.7	32.8	40.5
West Torrens (40403)	21,646 (8.3)	10.0	44.4	12.8	32.3	40.2

25.0% (95%CI: 16.4–34.2) at extreme heat (99th percentile: 40.2 °C), as compared to the reference PMOI (27th percentile: 17.3 °C). The risk of OI associated with cold (12.8 °C) was 3.2% (95%CI: −1.3-8.0). A J-shaped exposure-response curve was observed between Tmax and OI with a linear increase in risk at higher temperatures (Fig. 3). Lag-response curves (Fig. 3A and B) indicate that the effects of cold on OI were delayed with the highest effects observed after three days. In contrast, the effects of heat were acute and immediate, with the greatest effects observed at lag 0.

Cumulative risk estimates from subgroup analyses stratified by workers' characteristics, nature of work, and workplace characteristics are given in Supplementary Table S2. Overall, male workers, young workers (age < 45 years), technicians, machinery operators, those in "heavy demanding" occupations, and workers predominantly in outdoor environments were found to be at high risk at moderate heat, and the risk of OI increased significantly during extreme heat. Sensitivity analyses are given in Supplementary Table S3 and show similar results for a range of model choices. However, when the minimum temperature (Tmin) was used as the exposure metric, we found that the risk of OI was not statistically significant.

3.3. Region-wise risk estimates

Many SA3 regions in northern Greater Adelaide including Gawler – Two Wells (40201), Playford (40202), and Salisbury (40204), and western regions including Charles Sturt (40401), Port Adelaide – West (40402), and West Torrens (40403) were particularly at higher risk of OI at moderate heat (90th percentile) (Fig. 4). At extreme heat (99th Percentile) the eastern regions of the city including Adelaide Hills (40102), Burnside (40103), Campbelltown (SA) (40104), Norwood – Payneham – St Peters (40105), and Tea Tree Gully (40205) and southern regions including Mitcham (40303) and Onkaparinga (40304) were particularly at higher risk of OI (Fig. 4A). Northern and western parts of Adelaide are characterized by a Cold-Semi Arid climate. The northern regions include Adelaide City (40101), Gawler – Two Wells

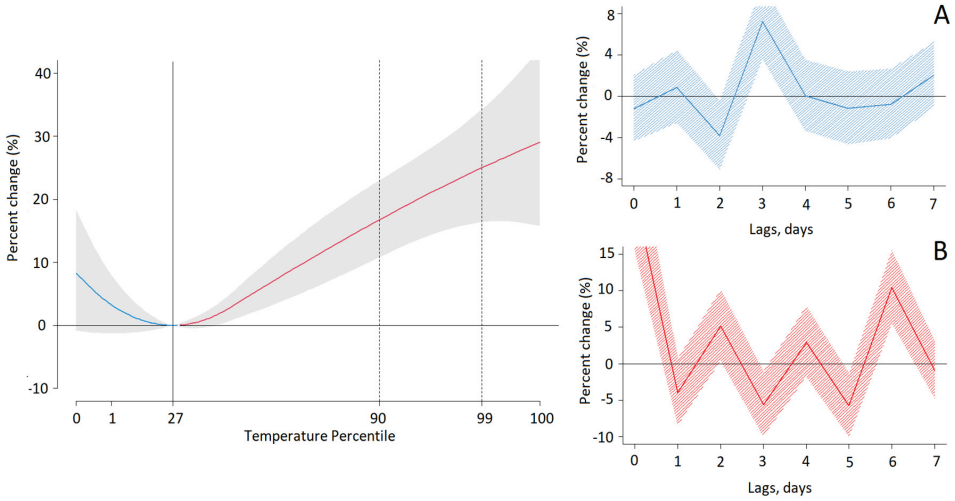


Fig. 3. Overall Cumulative Tmax-OI curve in percent difference [with 95% confidence intervals (CI) – shaded areas] in 19 statistical area level 3 divisions in Greater Adelaide from 2005 to 2018. The relationship considers 7 days of lag. The solid line represents the PMOI temperature (27th percentile – 17.3 °C) and the dashed lines are temperature in the 90th percentile (32.3 °C; moderate heat) and 99th percentile (40.2 °C; extreme heat). Fig. 3A and B, Lag-response relationship between temperature and OI for cold effects (days with temperatures in the 1st percentile) and heat effects (days with temperatures in the 99th percentile), respectively. Shaded areas represent 95% confidence intervals (CI).

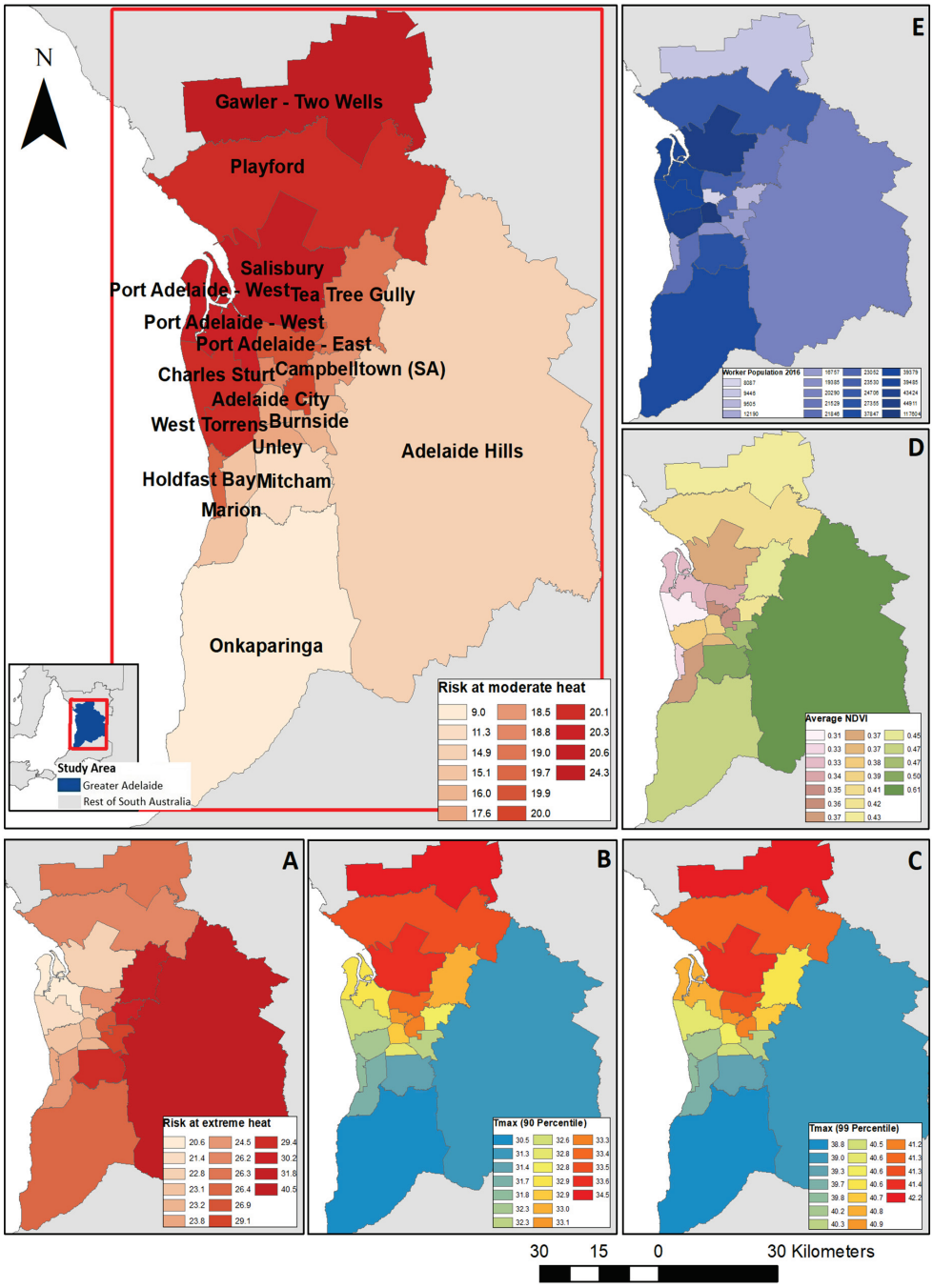


Fig. 4. Overall cumulative Exposure–Response in 19 SA3 of Greater Adelaide. Risk (percentage change) is estimated at moderate heat (90th percentile of Tmax). Fig. 4A shows the risk (percentage change) estimated at extreme heat (99th percentile of Tmax). Fig. 4B indicates the 90th percentile of Tmax estimated from gridded metrological data. Fig. 4C presents the 99th percentile of Tmax estimated from gridded metrological data. Fig. 4D corresponds to the averaged Normalized Vegetation Difference Index estimated for the study period. Fig. 4E indicates the total workforce population of Greater Adelaide by respective SA3 for the year 2016, data acquired from ABS, Australia. The maps were created in ArcGIS 10.5.

(40201), Playford (40202), Port-Adelaide East (40203), Prospect – Walkerville (40106), and Salisbury (40204). Fig. 4B and C show that these regions have characteristic high ambient temperatures ranging between 33.0 and 42.2 °C and are characterized by lower vegetation content (Fig. 4D). Western regions including Charles Sturt (40401), Holdfast Bay (40301), Port Adelaide – West (40402), and West Torrens (40403) have moderately high temperatures and a low vegetation content (Fig. 4B, C, and D). Eastern and southern regions of Greater

Adelaide have Warm Mediterranean climates. Eastern regions include Adelaide Hills (40102), Burnside (40103), Campbelltown (SA) (40104), Norwood – Payneham – St Peters (40105), and Tea Tree Gully (40205) while southern regions include Mitcham (40303), Marion (40302), Onkaparinga (40304), and Unley (40107). The majority of eastern and southern regions including Adelaide Hills (40102), Burnside (40103), Mitcham (40303), Marion (40302), and Onkaparinga (40304) have comparatively low ambient temperatures (30.0–40.0 °C). They are usually characterized by greater vegetation content (Fig. 4B, C, and D). Workers' population with respect to their place of work was concentrated mostly in Adelaide City (40101), Charles Sturt (40401), Mitcham (40303), Onkaparinga (40304), Playford (40202), Port Adelaide – West (40402), Salisbury (40204), and West Torrens (40403) as of the year 2016 (Fig. 4E). Region-wise predictions of the risk of OI associated with moderate heat and extreme heat in each SA3 are presented in Table 2.

Region-wise exposure-response curves (Supplementary Fig. S2) suggest a slight curvilinear response in hotter northern regions of Greater Adelaide, with a subtle increase in risk at extreme heat. In eastern and southern SA3 of Greater Adelaide, a characteristic J-shaped curve with a pronounced increase in the risk of OI at extreme heat was observed.

Subgroup analysis based on gender, age, and types of industries in different SA3 also indicates geographic differences in the risk of OI associated with moderate and extreme heat. The hotter northern SA3 including Gawler – Two Wells (40201), Salisbury (40204), and Port Adelaide – West (40402) were particularly at higher risk of OI for females. Male workers and older workers (age ≥ 45 years) were at higher risk of OI in northern and western regions of the city at moderate heat in Charles Sturt (40401), Gawler – Two Wells (40201), Salisbury (40204), Port Adelaide – West (40402), and West Torrens (40403). However, at extreme heat eastern and southern SA3 including Adelaide Hills (40102), Mitcham (40303), and Onkaparinga (40304) were particularly at higher risk of OI. Younger workers (age < 45 years) had a higher risk of OI in Gawler – Two Wells (40201), Salisbury (40204), and Adelaide Hills (40102) (Fig. 5 A, B, C, D, E, F, G, and H). Fig. 6A, B, C, and D indicate that eastern and southern SA3 regions had a higher risk of OI for outdoor industries and western regions were particularly at higher risk for indoor industries at both moderate and extreme heat.

Table 2
The percentage change in risk of OI associated with moderate and extreme heat in SA3 regions of Greater Adelaide.

Statistical Area Level 3 – Greater Adelaide (3–5 digit codes)	Percent Change associated with Moderate Heat (90th percentile)	Percent Change associated with Extreme Heat (99th percentile)
Adelaide City (40101)	17.6(10.8–24.9)	23.2(14.3–32.8)
Adelaide Hills (40102)	14.9(0.9–30.9)	40.5(13.3–74.1)
Burnside (40103)	16.0(8.1–24.4)	29.1(17.1–42.3)
Campbelltown (SA) (40104)	18.5(9.3–28.4)	30.2(16.5–45.5)
Charles Sturt (40401)	20.1(7.1–34.7)	21.4(4.3–41.4)
Gawler - Two Wells (40201)	24.3(9.0–41.7)	26.3(5.1–51.7)
Holdfast Bay (40301)	19.7(3.7–38.2)	23.8(2.8–49.2)
Marion (40302)	15.1(3.6–27.9)	24.5(8.3–43.0)
Mitcham (40303)	11.3(0.4–23.2)	29.4(11.1–50.8)
Norwood - Payneham - St Peters (40105)	20.0(10.4–30.4)	26.9(13.5–41.9)
Onkaparinga (40304)	9.0(−2.3–21.6)	26.4(8.4–47.5)
Playford (40202)	20.1(11.1–29.7)	26.2(13.7–40.2)
Port Adelaide – East (40203)	19.9(11.3–29.3)	24.5(12.6–37.6)
Port Adelaide – West (40402)	20.3(7.6–34.6)	20.6(3.9–39.9)
Prospect – Walkerville (40106)	18.8(11.3–26.8)	23.1(13.2–33.8)
Salisbury (40204)	20.6(11.5–30.6)	22.8(10.5–36.6)
Tea Tree Gully (40205)	19.0(8.6–30.3)	31.8(16.0–49.8)
Unley (40107)	17.6(11.0–24.5)	23.2(14.7–32.4)
West Torrens (40403)	20.1(6.0–36.0)	23.1(4.5–44.9)

3.4. Temperature-related attributable fraction of occupational injuries and illnesses

The total temperature-related attributable fraction of OI was estimated to be 6.37% (95%eCI: 4.96–7.12) in Greater Adelaide, while 6.10% (95% eCI: 4.73–6.87) was attributed to heat and 0.27% (95%eCI: 0.07–0.38) was attributed to cold. For hot temperatures, the attributable fraction of OI associated with extreme heat was 1.73% (95%eCI: 1.48–1.86), while 4.37% (95%eCI: 3.20–5.10) of OI in Greater Adelaide was attributable to moderate heat.

Region-wise estimates of the total attributable fraction of OI attributable to temperature are reported in Table 3. Results suggest that the highest attributable fractions for moderate heat were coming from northern and western Adelaide SA3 characterized by Cold Semi-Arid climates such as Charles Sturt (40401), Gawler – Two Wells (40201), Holdfast Bay (40301), Port Adelaide – West (40402), and West Torrens (40403). For extreme heat, the highest attributable fractions corresponded to Adelaide Hills (40102), Burnside (40103), Gawler – Two Wells (40201), Norwood – Payneham – St Peters (40105), and Port Adelaide – East (40203).

3.5. Future projections

3.5.1. Exposure-response association

Under the RCP 8.5 scenario the risk of OI is projected to increase from 20.8% (95%CI: −0.2 − 46.3) in the 2010s to 22.9% (95%CI: −8.0 − 64.1) in the 2050s. These results are based on GFDL-ESM2M general circulation model. The predicted exposure-response curve (red dotted line) indicates a slight increase in the risk of OI over the projected time (Fig. 7). Projected risk estimates for all six general circulation models under two RCP 4.5 and 8.5 are given in Supplementary Table S4. Similar results were observed for all general circulation models and two RCP scenarios.

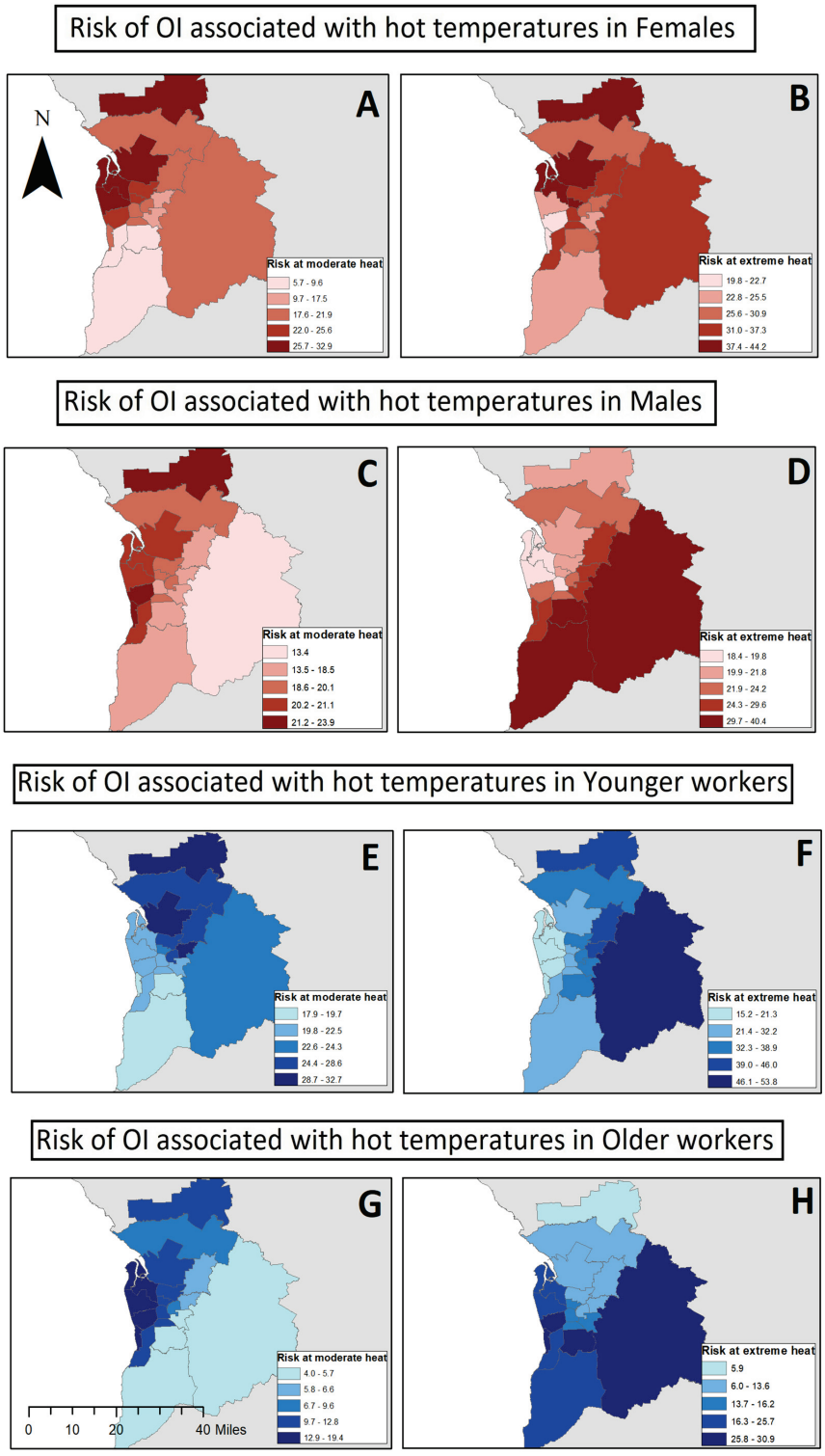
3.5.2. Future prediction of temperature attributable fraction of occupational injuries and illnesses

Temperature-related attributable fraction of OI is given in Table 4. For RCP 4.5, we found a 0.35% increase in heat attributable fraction of OI in the 2030s relative to the 2010s. The attributable fraction further increased by 0.63% by the 2050s and 1.05% by the end of the century. For RCP 8.5 the heat attributable fraction was predicted to increase by 0.48% by the 2030s, 1.07% by the 2050s, and 2.44% by the 2090s. We noted a gradual reduction in the cold-related attributable fraction over time.

4. Discussions

To our best knowledge, this is the first study identifying the risk of occupational injuries and illnesses associated with ambient temperatures at an intra-city level. Our results suggest that both heat and cold have significant impacts on OI, but the impacts from the heat were far stronger and more intense in Greater Adelaide. The risk of OI varied spatially within Greater Adelaide and the regions with characteristic hot weather conditions were at higher risk of OI. The complex interaction of thermal patterns and the greenness of a region may play an important role in the spatial dynamics of the risk and recent studies support this evidence at a very local scale (Guerri et al., 2022). Further, the risk of OI was predicted to increase across the 21st century under various climate change projection scenarios.

Consistent with the previous findings from Adelaide city (Varghese et al., 2019a), we found that the cumulative risk of OI increased up to 25.0% at 40.2 °C. The overall cumulative exposure-response suggested a J-shaped curve with a prominent linear increase in the risk of OI associated with higher temperatures. We observed that the effects of heat were immediate and acute, while that of cold were greatest after a 3-days lag. Overall, younger workers (age < 45 years), male workers, those engaged in heavy physical work, and those working predominantly in outdoor locations were found to be at higher risk of OI during moderate and extreme heat. These findings are in line with previous studies (Adam-Poupart et al., 2015; Calkins et al., 2019; Marinaccio et al., 2019; Martínez-Solanas


Risk of OI associated with hot temperatures in Females
A
N
Risk at moderate heat
5.7 - 9.6
9.7 - 17.5
17.6 - 21.9
22.0 - 25.6
25.7 - 32.9
B
Risk at extreme heat
19.8 - 22.7
22.8 - 25.5
25.6 - 30.9
31.0 - 37.3
37.4 - 44.2
Risk of OI associated with hot temperatures in Males
C
Risk at moderate heat
13.4
13.5 - 18.5
18.6 - 20.1
20.2 - 21.1
21.2 - 23.9
D
Risk at extreme heat
18.4 - 19.8
19.9 - 21.8
21.9 - 24.2
24.3 - 29.6
29.7 - 40.4
Risk of OI associated with hot temperatures in Younger workers
E
Risk at moderate heat
17.9 - 19.7
19.8 - 22.5
22.6 - 24.3
24.4 - 28.6
28.7 - 32.7
F
Risk at extreme heat
15.2 - 21.3
21.4 - 32.2
32.3 - 38.9
39.0 - 46.0
46.1 - 53.8
Risk of OI associated with hot temperatures in Older workers
G
Risk at moderate heat
4.0 - 5.7
5.8 - 6.6
6.7 - 9.6
9.7 - 12.8
12.9 - 19.4
0 10 20 40 Miles
H
Risk at extreme heat
5.9
6.0 - 13.6
13.7 - 16.2
16.3 - 25.7
25.8 - 30.9

et al., 2018; Varghese et al., 2019a; Varghese et al., 2019b; Xiang et al., 2014a).

We observed spatial variations in the risk of OI attributable to temperatures in Greater Adelaide. Region-wise estimates suggested that northern and western SA3 of Greater Adelaide were found to be more vulnerable to moderate heat. These regions are characterized by Cold Semi-Arid climatic, with typical hot weather conditions and less greenery. Most of the burden of heat-related OI was attributable to these regions. Further, the exposure-response curves were slightly curvilinear indicating that the risk of OI did not increase significantly at extreme heat. It is possible that at extreme heat some protective measures, such as taking breaks or relocating work shifts, are in place in these regions, as suggested in one of the previous studies from Adelaide (Xiang et al., 2014a; Xiang et al., 2016).

It should be noted that many suburbs of northern Adelaide have been previously identified as vulnerable regions to heat stress in the general population as well (Loughnan et al., 2012; Navi, 2018). These areas are characterized by newer settlements and are socio-economically less developed (Department of Planning, Transport, and Infrastructure, 2017; Navi, 2018). These indicators have been previously associated with heat-related mortality in general populations (Xu et al., 2013). These factors may also contribute to spatial differences in the OI risk. Further, these regions are generally characterized by lower NDVI as compared to southern and eastern regions (Barnett et al., 2013), such comparisons indicate that vegetation content may also contribute to local temperature conditions and the overall risk of OI. Green spaces in the cities can potentially reduce urban heat island effect and protect the health and well-being of human beings including working population (Guerri et al., 2022).

Interestingly, we found that majority of southern and eastern regions of Greater Adelaide were at higher risk of OI during extreme heat. These regions have moderate temperatures with a Warm Mediterranean climate and greater vegetation content. The high risk of OI during extremely hot days when the temperature exceeds 37.0 °C suggests that the working populations in these areas may work at unsafe temperature limits or that they are less adapted to extreme heat.

In addition to environmental factors, demographics and occupational characteristics also play an important role in the geographic differences. For example, western regions were particularly at higher risk for indoor industries. Western Adelaide including Port Adelaide – West and West Torrens have some of the main industrial hubs for example warehousing and industrial hubs in Royal Park and Adelaide Airport (Department of Planning, Transport, and Infrastructure, 2017). On the other hand, southern and eastern regions were at higher risk of OI particularly for male workers and older workers (age ≥ 45 years) and those in outdoor industries. Both Adelaide Hills and Onkaparinga are characterized by rural areas and are agriculture intensive (Department of Planning, Transport, and Infrastructure, 2017). In these regions, the workers are possibly required to work outdoors beyond safe temperature limits due to the nature of their occupation and are therefore at higher risk of OI. These findings suggest that localized preventative measurements should be developed in different regions within a city for tailored and precise actions.

Previous studies (Guo et al., 2017; Marinaccio et al., 2019; Varghese et al., 2019b) explained that the geographical differences in risk are also attributed to personal adaptive strategies to keep cool, acclimatization, and local policies and practices. In-depth analyses should be carried out to identify underlying factors related to workers' adaptability, heat perceptions, and interventions in workplaces.

The impacts of heat on OI were stronger and more intense (attributable fraction: 6.10%) than the impacts of cold (attributable fraction: 0.27%). Most of the burden was attributable to moderate heat, which is expected because the majority of the days in the time series are characterized by moderate heat (Gasparrini and Leone, 2014). Such results indicate that routine preventative measurements should be developed and implemented before and during moderate heat to minimize OI risks.

The risk of OI associated with future climate change is predicted to increase. We estimated an increase in the risk of OI up to 2.1% (for RCP 8.5) by mid-century. In addition, the heat attributable fraction of OI increased by 1.07% (till 2050-RCP 8.5) and the cold-related attributable fraction of OI was reduced by 0.39% (2050- RCP 8.5). Similar statistics were observed for heat attributable hospital admissions from Adelaide (Wondmagegn et al., 2021). Of note, projecting occupational health burdens associated with specific environmental stressors is a challenging task because of the complex risk patterns and the inherent uncertainty of future climate scenarios. Projections suggest that the cold-related attributable fraction of OI would drop slightly, but this would not completely mitigate the increases in the heat-related attributable fraction of OI.

5. Study limitations

Mapping spatial variability at an intra-city scale using health outcome data presents methodological challenges such as temporal boundary misalignment issues or small sample sizes across space and time (Hund et al., 2012; Hondula et al., 2013). The workers' compensation claims data are available at the POA level in Greater Adelaide. POA changed frequently over the study period and had small sample sizes across space and time. We, therefore, transformed the data from POA to a larger administrative level i.e. the SA3 level. This is a trade-off between high spatial and temporal resolution and is a potential limitation. We used daily meteorological data with 5 km resolution which offers low spatial resolution but is computationally more efficient to handle at the SA3 level. High-resolution remote sensing data could be used in future studies to investigate the risk of OI at a very local scale within cities.

Projections of the risk of OI associated with temperature were carried out at the city level as climate projections at a finer spatial level, such as SA3, are not presently available. We used downscaled projected data which are available at the weather station level. The Kent Town weather station has been previously used as representative of Adelaide city weather dynamics (Xiang et al., 2014a; Varghese et al., 2019a). While downscaled data has its caveats for use and relies on certain assumptions, such data are frequently used for regional/city-scale analyses. It should also be noted that we did not consider the changes in workforce population size over the projected periods, which may potentially contribute an important source of uncertainty in our projection estimates. Changes in demographic structure and the size of the workers' population may have a strong influence on future health impacts, both by increasing the population at risk and by shifting it towards more susceptible groups with higher associated risks of OI. Therefore, the overall impact of heat is likely to be underestimated in the current study. While the “stable populations” approach is built on simplistic assumptions and cannot provide a realistic representation of future excess burdens, it offers a more straightforward interpretation as it separates the impact of global warming from other changes, such as those related to demographic variations, that would occur anyway even in a stable climate. There are other potential sources of uncertainty. For example, climate change may also increase the number and intensity of events such as floods and bushfires, which may compound the heat effects on occupational health. Other factors, such as patterns of urbanization, the nature of built environments, the development of early warning systems, the quality and accessibility of health care services, and population health status were not considered in estimating future risk. Finally, adaptation strategies or technological advancements such as improved architecture, green spaces, lifestyle changes, and health care

Fig. 5. Subgroup analysis of the risk of OI associated with moderate heat and extreme heat based on different gender and age groups. Fig. 5A and B represent the risk of OI in females associated with moderate heat and extreme heat, respectively. Fig. 5C and D present the risk of OI in males associated with moderate and extreme heat, respectively. Fig. 5E and F indicate the risk of OI in younger workers with age < 45 years associated with moderate and extreme heat, respectively. Fig. 5G and H show the risk of OI in older workers (age ≥ 45 years) at moderate and extreme heat, respectively.

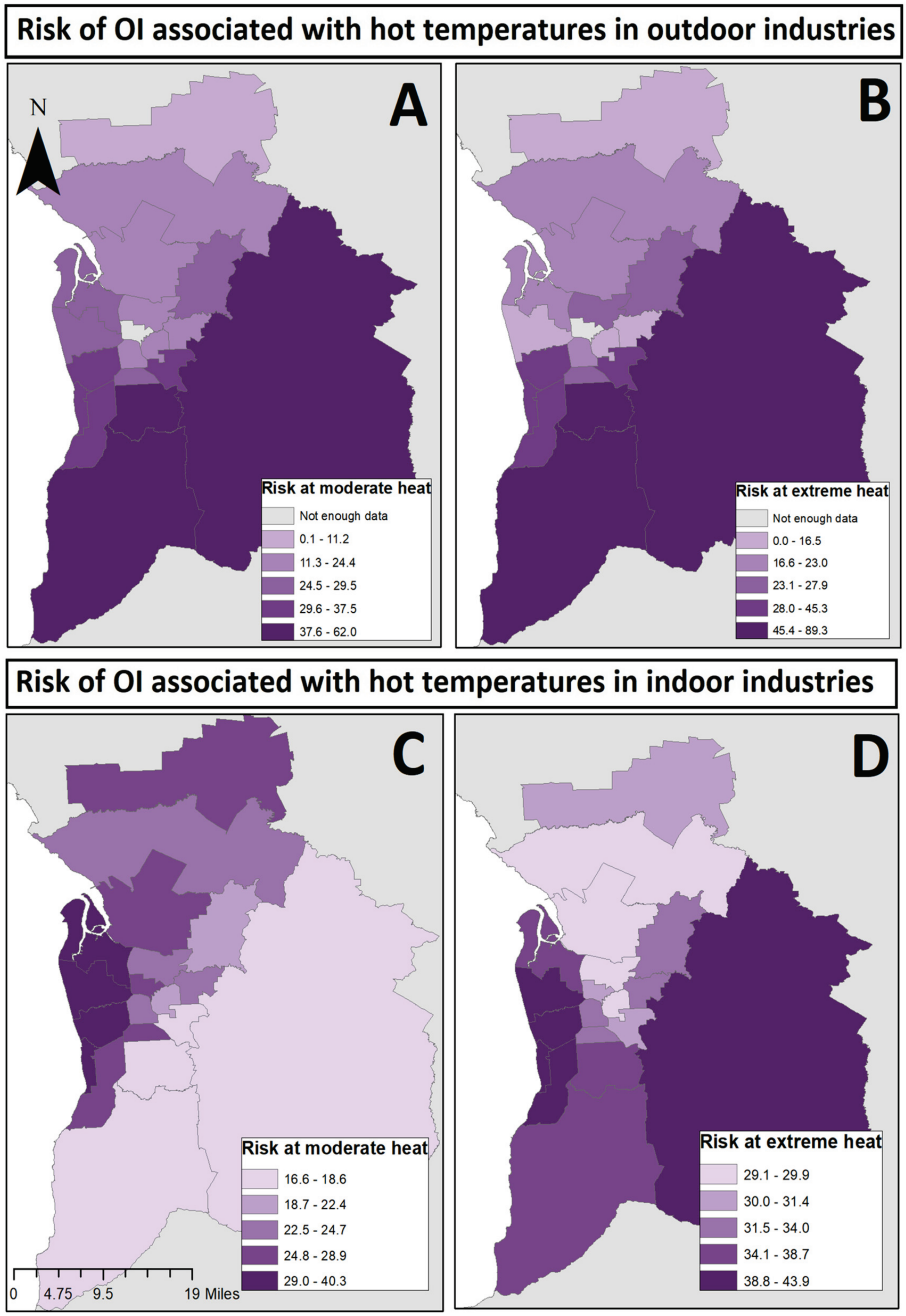


Fig. 6. Subgroup analysis of the risk of OI associated with moderate heat and extreme heat in various industries. Fig. 6A and B represent the risk of OI associated with moderate heat and extreme heat in outdoor industries. Fig. 6C and D indicate the risk of OI in indoor industries associated with moderate and extreme heat, respectively.

delivery advancements may alter the health effects of heat and hence the projections of risk of OI.

6. Conclusions

Our study suggests that the overall risk of OI significantly increases at high temperatures with a greater burden of OI associated with moderate heat than extreme heat in Greater Adelaide. Furthermore, the risk of OI varies spatially within a city due to underlying local climate conditions, workers' demographic characteristics, occupational characteristics, personal acclimatization, policies and practices in place, and adaptive strategies.

Spatial representation of risk assessment has significant implications for targeted interventions, development of policies, and precision guidelines.

Table 3
The attributable fraction of occupational injuries computed as separate components for cold and heat, defined on various temperature percentiles of Tmax in SA3 regions of Greater Adelaide.

Statistical Area Level 3 – Greater Adelaide	Cold (%) (below PMOI)	Moderate heat (%) (between 27th – 90th percentile)	Extreme heat (%) (above 90th percentile)
Adelaide City (40101)	0.12(−0.28–0.36)	3.92(1.93–5.05)	1.72(1.21–2.06)
Adelaide Hills (40102)	2.04(−0.93–3.87)	1.58(−1.27–3.49)	1.98(0.72–2.68)
Burnside (40103)	0.62(−0.24–1.17)	2.74(0.79–3.91)	1.86(1.18–2.25)
Campbelltown (SA) (40104)	0.93(−0.21–1.63)	3.26(1.05–4.63)	1.81(1.15–2.22)
Charles Sturt (40401)	0.00(−0.02–0.01)	6.45(0.11–10.55)	1.69(0.61–2.30)
Gawler - Two Wells (40201)	0.95(−0.45–1.91)	5.20(1.43–7.36)	2.09(0.83–2.76)
Holdfast Bay (40301)	−0.01(−0.02–0.00)	7.45(−0.23–12.96)	1.77(0.41–2.53)
Marion (40302)	0.00(−0.02–0.01)	4.23(−1.91–8.08)	1.61(0.61–2.20)
Mitcham (40303)	0.33(−1.39–1.37)	1.31(−1.34–2.97)	1.54(0.49–2.16)
Norwood - Payneham - St Peters (40105)	0.59(−0.31–1.17)	4.04(1.62–5.52)	1.96(1.20–2.44)
Onkaparinga (40304)	0.15(−1.37–1.13)	1.01(−2.13–2.77)	1.35(0.28–1.94)
Playford (40202)	0.65(−0.31–1.23)	3.98(1.78–5.36)	1.73(1.05–2.10)
Port Adelaide – East (40203)	0.38(−0.35–0.78)	4.31(2.04–5.69)	1.85(1.18–2.25)
Port Adelaide – West (40402)	0.00(−0.02–0.01)	6.17(−1.11–10.28)	1.71(0.63–2.34)
Prospect – Walkerville (40106)	0.19(−0.31–0.48)	4.27(2.14–5.50)	1.77(1.14–2.14)
Salisbury (40204)	0.33(−0.36–0.77)	4.62(2.11–6.05)	1.75(1.06–2.13)
Tea Tree Gully (40205)	1.20(−0.29–2.12)	3.13(0.84–4.70)	1.83(1.10–2.33)
Unley (40107)	0.14(−0.23–0.41)	3.90(2.19–4.97)	1.76(1.23–2.07)
West Torrens (40403)	−0.01(−0.02–0.01)	7.09(−0.30–11.77)	1.77(0.61–2.43)

This study has identified vulnerable regions and populations at an intra-city level in Greater Adelaide. Northern and western Adelaide were particularly at high risk for all types of workers during periods of moderate heat. This is of particular concern as most of the burden of OI arises from moderately high temperatures. Existing occupational policies (such as stopping work at extremely high temperatures) focus on extremely hot and heatwave periods. Adaptive strategies, such as the ability to keep cool and stay hydrated, particularly at moderately high temperatures, are important to reduce the risk of OI associated with moderate heat in these regions. Southern and eastern regions of Greater Adelaide including Adelaide Hills and Onkaparinga are characterized by Warm Mediterranean climates and rural settings and have predominant agricultural and forestry industries. These regions are found to be at high risk of OI in outdoor industries, particularly during extremely hot days. Furthermore, males and older workers (age ≥ 45 years) are at high risk in these regions at extreme heat. These areas should be prioritized by policymakers, service providers, and industries to design and implement targeted interventions particularly for outdoor workers to reduce the risk of OI during extremely hot days. This is particularly important in the context of climate change with projected increases in the number of hot days each year. Furthermore, in-depth analyses should be carried out to identify underlying factors related to workers' adaptability, heat perceptions, behavior, and interventions in workplaces (Xiang et al., 2016) that are contributing towards the geographic disparities in the risk. It is also important to develop region-specific heat-related health interventions and optimize healthcare resources to minimize OI risks in the face of climate change.

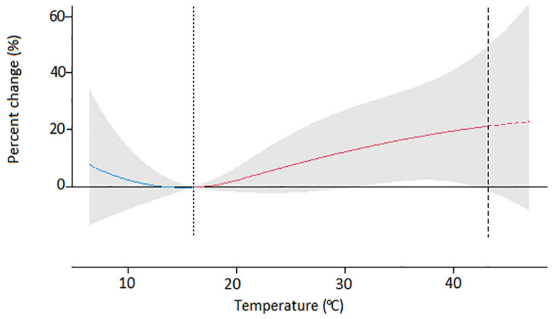


Fig. 7. Exposure-response curve represented as risk of OI across Tmax (°C) [with 95% CI – shaded area]. The dotted line represents the PMOI. The dashed part of the curve represents the extrapolated risk beyond the observed Tmax (using GFDL-ES2M model with RCP 8.5) till mid-century (2050s).

Table 4
Temperature-related attributable fraction for observed period the 2010s and three future timeframes (the 2030s, the 2050s and the 2090s).

RCP scenarios	Heat	Cold
2010s		
RCP 4.5	8.14 (−1.54–13.96)	1.38 (−0.46–2.59)
RCP 8.5	7.88 (−1.57–13.58)	1.32 (−0.45–2.49)
2030s		
RCP 4.5	8.49 (−1.55–14.51)	1.24 (−0.40–2.35)
RCP 8.5	8.36 (−1.58–14.36)	1.14 (−0.37–2.15)
2050s		
RCP 4.5	8.77 (−1.53–14.93)	1.15 (−0.36–2.18)
RCP 8.5	8.95 (−1.63–15.27)	0.93 (−0.30–1.76)
2090s		
RCP 4.5	9.19 (−1.60–15.64)	1.00 (−0.31–1.88)
RCP 8.5	10.32 (−1.62–17.54)	0.48 (−0.14–0.97)

CRediT authorship contribution statement

Syeda Hira Fatima: Conceptualization, Methodology, Software, Formal Analysis, Writing-original draft preparation.

Paul Rothmore: Conceptualization, Writing-reviewing and editing, Supervision.

Lynne C Giles: Conceptualization, Writing-reviewing and editing, Supervision.

Peng Bi: Conceptualization, Writing-reviewing and editing, Supervision.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2022.153945.

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CHAPTER 5

HEAT AND OI: EPIDEMIOLOGICAL EVIDENCE FROM THREE LARGE AUSTRALIAN CITIES

Preface

Chapter 5 provides a comprehensive assessment of the impacts of heat on OI at the intra-urban scale, offering concrete evidence from three major Australian cities: Greater Brisbane, Greater Melbourne, and Greater Sydney.

Section 5.1 presents the statement of authorship form. Section 5.1 details the study assessing the impacts of heat on OI in three large cities in Australia – addressing the first three research questions of this thesis. This study is published in Environmental Research in 2023.

Fatima, S. H., Rothmore, P., Giles, L. C., & Bi, P. (2023). Intra-urban risk assessment of occupational injuries and illnesses associated with current and projected climate: Evidence from three largest Australian cities. *Environmental Research*, *228*, 115855. https://doi.org/10.1016/j.envres.2023.115855

Building on the previous work in Chapter 4, this study reaffirmed that regions characterised by hotter climate conditions generally exhibited higher risk levels. To augment these findings, additional subgroup analyses were incorporated, considering spatial variations in NDVI, LST, IRSAD, and IEO. The study highlighted that regions with lower NDVI, higher LST, lower IRSAD, and lower IEO were more susceptible to the impacts of heat.

By expanding the investigation to multiple cities and considering various factors, this chapter significantly enhanced our understanding of the complexities surrounding the relationship between heat and OI. The insights gained from this study offer valuable implications for

improving WHS and informing policy measures to safeguard workers' well-being in heat-prone urban environments.

5.1 Statement of Authorship

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Principal Author

Name of Principal Author (Candidate)	Syeda Hira Fatima		
Contribution to the Paper	Conceptualization, Methodology, Formal Analysis, Writing - Original Draft		
Overall percentage (%)	75%		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
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By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);
ii. permission is granted for the candidate in include the publication in the thesis; and
iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

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Contribution to the Paper	Conceptualization, Writing - Review & Editing, Supervision		
Signature		Date	25\08\2023

5.2 Intra-Urban Risk Assessment of Occupational Injuries and Illnesses Associated with Current and Projected Climate: Evidence from Three Largest Australian Cities

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Intra-urban risk assessment of occupational injuries and illnesses associated with current and projected climate: Evidence from three largest Australian cities

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Intra-urban risk assessment of occupational injuries and illnesses associated with current and projected climate: Evidence from three largest Australian cities

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ABSTRACT

Background: Increased risk of occupational injuries and illnesses (OI) is associated with ambient temperature. However, most studies have reported the average impacts within cities, states, or provinces at broader scales.
Methods: We assessed the intra-urban risk of OI associated with ambient temperature in three Australian cities at statistical area level 3 (SA3). We collected daily workers' compensation claims data and gridded meteorological data from July 1, 2005, to June 30, 2018. Heat index was used as the primary temperature metric. We performed a two-stage time series analysis: we generated location-specific estimates using Distributed Lag Non-Linear Models (DLNM) and estimated the cumulative effects with multivariate meta-analysis. The risk was estimated at moderate heat (90th percentile) and extreme heat (99th percentile). Subgroup analyses were conducted to identify vulnerable groups of workers. Further, the OI risk in the future was estimated for two projected periods: 2016–2045 and 2036–2065.
Results: The cumulative risk of OI was 3.4% in Greater Brisbane, 9.5% in Greater Melbourne, and 8.9% in Greater Sydney at extreme heat. The western inland regions in Greater Brisbane (17.4%) and Greater Sydney (32.3%) had higher risk of OI for younger workers, workers in outdoor and indoor industries, and workers reporting injury claims. The urbanized SA3 regions posed a higher risk (19.3%) for workers in Greater Melbourne. The regions were generally at high risk for young workers and illness-related claims. The projected risk of OI increased with time in climate change scenarios.
Conclusions: This study provides a comprehensive spatial profile of OI risk associated with hot weather conditions across three cities in Australia. Risk assessment at the intra-urban level revealed strong spatial patterns in OI risk distribution due to heat exposure. These findings provide much-needed scientific evidence for work, health, and safety regulators, industries, unions, and workers to design and implement location-specific preventative measures.

1. Introduction

Many epidemiological studies have assessed the association between occupational injuries and illnesses (OI) and ambient temperatures in different regions of the world (Calkins et al., 2019; Dillender, 2021; McInnes et al., 2017a; Marinaccio et al., 2019; Martínez-Solanas et al., 2018; Sheng et al., 2018; Varghese et al., 2019). These studies have suggested that the risk of OI increases at non-optimal ambient temperatures, however, geographical variations have been observed in the risk assessments (Fatima et al., 2021). For example; an increased risk of OI (0.7%) associated with a 1 °C increase in temperature was reported for construction workers in Washington State, US (Calkins et al., 2019) while the risk was 1.9% for all workers in Texas, US (Dillender, 2021), 1.4% in Guangzhou, China (Sheng et al., 2018), and 0.6% in Melbourne, Australia (Varghese et al., 2019). No significant association was detected in Brisbane, Australia (Varghese et al., 2019). Nationwide studies from Italy and Spain respectively noted such associations varied in different provinces of these countries (Marinaccio et al., 2019; Martínez-Solanas et al., 2018). This spatial heterogeneity is potentially attributed to underlying local climate characteristics and workplace-specific characteristics such as type of work, industries, and workers' demographics (Varghese et al., 2019; Fatima et al., 2021).

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In this study, we intend to provide a detailed profile of the exposure-response association between OI and hot weather conditions at an intra-urban scale in three major cities of Australia namely Greater Brisbane, Greater Melbourne, and Greater Sydney. Previous studies have mainly provided evidence from broad-scale risk assessments at the city, state, or province level but were not able to reflect the localized spatial variations within the cities. A recent study carried out in Adelaide, Australia found that the geographical variations in the heat-related risk of OI are profound within the cities at a local scale (Fatima et al., 2022). Location-specific research is needed to quantify the work, health, and safety (WHS) impacts associated with climatic conditions to provide localized information for tailored decision-making, protect workers from the impacts of warming temperatures, and reduce the WHS and economic impacts from extreme heat (McInnes et al., 2017b).

The availability of high-resolution spatio-temporal datasets and recent advancements in statistical methods allow us to estimate temperature-related health associations at a localized scale within rapidly urbanizing cities. Previously, geospatial datasets have been used to develop localized heat stress vulnerability maps and location-specific vulnerability forecasts. Such datasets have been implemented at national levels to help governments and communities prepare for and respond to extreme heat events (The National Integrated Heat Health Information System (NIHHIS), 2018). The evidence from such localized studies will also provide valuable evidence for policy-makers and urban planners in mitigation, planning, and resource allocation (Fatima et al., 2022).

We will also estimate the burden of OI associated with projected climate change scenarios. Projection of occupational burden in future predicted scenarios is increasingly crucial as we are transitioning to hot and more intense climate conditions. The findings will have implications for a better policy framework for heat-related risk prevention and adaptation to warming climatic conditions.

2. Methods

A time-series study design coupled with Distributed Lag Non-Linear Models (DLNM) (Gasparrini et al., 2010) was used to estimate the effects of hot weather on the risk of OI in three cities in Australia. The analyses were carried out at an intra-urban spatial scale at Statistical Area Level 3 (SA3), although the future projected risk was only estimated at the greater city level. SA3s are medium-sized general-purpose geographical regions as determined by the Australian Bureau of Statistics (Australian Bureau of Statistics, 2016a) (Supplementary Figure S1). Generally, they have a population between 30,000 and 130,000 people. These regions are designed to represent a community that interacts together socially and economically.

The daily count of workers' compensation claims data from July 1, 2005, to June 30, 2018, was the response used in the models of the exposure-response associations. The heat index (^{o}C) was used as the exposure temperature metric for the three cities: Greater Brisbane, Greater Melbourne, and Greater Sydney. A major proportion of these regions (particularly Greater Brisbane and Greater Sydney) is characterized by a humid subtropical climate.

Ethics approval for this study was obtained from The University of Adelaide's Office of Research Ethics, Compliance, and Integrity Human Research Ethics Committee (approval number H-2019-219).

2.1. Data sources

2.1.1. Environmental data

For weather metrics, we used daily gridded meteorological data at 5 km spatial resolution (Jeffrey et al., 2001). The set of weather metrics included; maximum temperature (Tmax ^{o}C), minimum temperature (Tmin ^{o}C), solar radiation (MJ/m^{2}), and relative humidity (%). Additionally, we acquired 16-day Normalized Difference Vegetation Index (NDVI) from Google Earth Engine (Gorelick et al., 2017). The NDVI values represent an entire 16-day time period in the time series (Didan and Munoz, 2019).

For future climatic projections, we used 5 km daily gridded "application-ready" data (Craig and Clarke, 2021; CSIRO and Australian Bureau of, 2015). The data are available for eight selected general circulation models: Access 1.0, CESM1-CAM5, CNRM-CM5, GFDL-ESM2M, HadGEM2-CC, CanESM2, MIROC5, NorESM1-M. We acquired the data for two representative concentration pathways (RCP) (4.5 and 8.5) for a set of two environmental variables, including Tmax and average relative humidity for a projected period from 2016 to 2045 and 2036–2065. Heat index projections were estimated from Tmax and relative humidity following Anderson et al. (2013).

All datasets were extracted for the three cities using centroid points at Statistical Area Level 2 (SA2), and the values were then aggregated to the SA3 level using an area-weighted average of SA2 within SA3 regions. For future climatic projection, all data extracted at the SA2 level were aggregated to the greater city level using an area-weighted average of SA2 within the greater city region. This approach is computationally efficient and weights values based on the geographic area of SA2 within the broader spatial unit (SA3 and greater city) (Fatima et al., 2022).

Additional variables were acquired to define the location-specific characteristics of the regions. We identified hot versus cool SA3 regions based on an average value of 8-day land surface temperature (LST) acquired from Google Earth Engine (Gorelick et al., 2017). LST derived from remote sensing is a reliable and practical variable to classify spatial variability in urban climates (do Nascimento et al., 2022; Geletič et al., 2016). Vegetated versus less vegetated SA3 regions were identified using the average of all 16-day NDVI values in the time series. Similarly, we identified the socioeconomic status, education, and occupation status of the regions based on Indices for relative socio-economic advantage and disadvantage (IRSAD) and education and occupation (IEO) at the SA3 level acquired from the Australian Bureau of Statistics (Australian Bureau of Statistics, 2016b). For each of these additional variables, binary variables were created using the 75th percentile as a cut-point value. Previous studies have also used this cut-off for the separability of features (Cao et al., 2021). The variables were used for stratification purposes only, based on their location-specific characteristics.

2.1.2. Workers' compensation claims data

Daily compensation claims data were acquired from Safe Work Australia, an Australian government statutory agency that compiles the Australian National Dataset for Compensation-Based Statistics (NDS3) from all jurisdictions. The data represents 90% of all Australian workers (Safe Work Australia, 2020a).

Workers' compensation claims data records the location of the claims according to the postal areas (POA) of the workplace where the accidents occurred. For spatial feasibility of the analysis i.e., to cater to the temporal misalignment issue inherent in POA and small sample size across space and time, we aggregated the daily claims' location data to SA3.

Workers' compensation claims between July 1, 2005, and June 30, 2018, were included irrespective of their severity. However, claims were excluded if the POA of the location of the accident was not given, was beyond the greater city area, or when the POA was not an actual address. Claims were also excluded if the claimants were not in the working age group (15–80 years). For subgroup analyses, the workers' compensation claims were stratified based on age, gender, claim type (injury-related claims and illness-related claims), types of occupation (technicians, service workers, laborers, and drivers and machinery operators), physical demands (limited, light, medium, and heavy work), types of exposure (regulated and unregulated indoor, outdoor, and multiple locations), and types of industries (outdoor and indoor). Claim types were identified according to the Type of Occurrence Classification System (TOOCS 3.1) (Safe Work Australia, 2022). The outdoor and indoor industries were classified following Xiang et al. (2014). Industrial

sectors including "agriculture, forestry, and fishing", "construction", and "electricity, gas, and water" were categorized as outdoor industries, the remaining industries were combined as indoor industries (Xiang et al., 2014). The type of work based on physical demands and types of exposure was categorized based on the Australian and New Zealand Standard Classification of Occupations (ANZSCO) codes assigned to each claimant. The classification system to assign the physical demand and potential workplace exposure to occupations was initially developed by human resources and skills development Canada (HRSDC) (Government of Canada, 2011). This was done by trained occupational analysts in modified Delphi procedure (Government of Canada, 2011). HRSDC was associated with ANZSCO using a common coding structure: The International Standard Classification Occupations (ISCO – 88) (International Labour Organization (ILO), 1988). The systems have been validated in previous studies (Smith and Berecki-Gisolf, 2014; Smith et al., 2014).

2.2. Statistical analyses

A two-stage approach was used for this multi-location time series study (Martínez-Solanas et al., 2018; Gasparrini et al., 2015). First, we implemented generalized linear models with Quasi-Poisson distribution to estimate the associations between hot weather conditions and OI in each SA3 region in three greater cities.

$$\mathrm{Log}[\mathrm{E}(y)] = \beta_0 + \beta_1 \mathrm{cb} + \beta_2 \mathrm{dow} + \beta_3 \mathrm{holidays} + \beta_4 \mathrm{NDVI} + f_1(\mathrm{time}) + f_2(\mathrm{solar\ radiation}) + \log(\mathrm{population})$$

Where [E(y)] is the expected daily count of the OI, cb is the crossbasis for the two dimensions of predictor (heat index) and lags (Gasparrini et al., 2010), with quadratic B-splines with one internal knot placed at the 50th percentile to estimate the crossbasis for the exposure-response association. The statistical models also included a variable corresponding to the day of the week (dow) and an indicator variable denoting public holidays. NDVI was used as an additional covariate in the analysis. B_i represent the regression coefficients for these terms. A lag period of up to seven days was included to estimate the delayed effects of hot weather. Natural cubic splines (f_i (X_i)) were used to flexibly model the effects of time (with 6 df) and solar radiation (with 3 df). Workers' population at SA3 region level was acquired from census data (Australian Bureau of Statistics, 2016c) and log (population) was included as an offset term to account for population exposure. Solar radiation and NDVI were included as covariates because they have been linked previously with the perceived vulnerability to heat effects (Arifwidodo and Chandrasiri, 2020; Otani et al., 2019).

In the second stage of analysis, we pooled the location-specific coefficients estimated from the first stage using multivariate meta-regression models. This approach provided us with the best linear unbiased predictions (BLUPs). The BLUPs were used in the quantification of heat-related impacts of OI (Gasparrini et al., 2015). The overall risk of OI was estimated at moderate heat (90th percentile of heat index metric) and extreme heat (99th percentile) using the heat index percentile of minimum occupational injuries and illness (PMOI) (10th percentile) as the reference value (Martínez-Solanas et al., 2018; Fatima et al., 2022; Gasparrini et al., 2015). Region-wise risk estimates were also presented at moderate heat and extreme heat with respect to location-specific PMOI. The cumulative risk of OI in the three greater cities and the region-wise effect estimates were reported as percent differences. Heat-related attributable fractions (AF) of OI with empirical confidence intervals were estimated following the method outlined by Gasparrini and Leone (2014). Sensitivity analyses were conducted to evaluate model choices, based on: degree of freedom per year for seasonal control, knots for exposure and response and exposure variable (heat index, Tmax, Tmean, and Tmin).

For future projections, the risk of OI was estimated at the greater city level. The baseline data (2005–2018) were used to predict the risk in the future for two 30-year time-series datasets: 2016–2045 and 2036–2065 using log-linear extrapolation with a natural cubic spline function (Vicedo-Cabrera et al., 2019). These predictions are based on the assumptions that the risk of OI observed over the current period remains unchanged in the future and that the extrapolation appropriately represents the risk over the unobserved range (Vicedo-Cabrera et al., 2019). The results are presented at extreme heat (99th percentile of heat index) for the two projected timeframes: 2016–2045 and 2036–2065 for two RCP scenarios RCP 4.5 and RCP 8.5 and eight selected general circulation models. Absolute heat-related AF and empirical confidence intervals were also estimated (Gasparrini and Leone, 2014). All analyses were performed in the R software environment (R 4.1.0) using *dlnm* and *mvmeta* packages (Gasparrini, 2011).

Cumulative subgroup analyses were stratified based on personal factors (age, gender, claim type), workplace characteristics (types of occupation, type of work, and types of exposure), and location-specific characteristics (hot vs cool regions, high vs less vegetated regions, high vs low IRSAD, and high vs low IEO regions). Region-wise subgroup analyses were undertaken for age (younger (<45 years) vs older workers (≥45 years)), gender (males and females), types of industries (outdoor and indoor industries), and claims types (injuries and illnesses).

3. Results

The total number of OI claims was 263,260 in Greater Brisbane, 468,658 in Greater Melbourne, and 924,679 in Greater Sydney. The workers' population based on their place of work was 1.0 million in Greater Brisbane, 2.0 million in Greater Melbourne, and 2.2 million in Greater Sydney as of the 2016 census. Males had a high proportion of claims (>62%) in all three cities. Similarly, a higher proportion of claims were from Indoor industries (>85%) as compared to outdoor industries. Injury-related claims were dominant in Greater Brisbane and Greater Sydney (82 and 85% respectively), whereas illness-related claims were higher (51%) in Greater Melbourne. Particularly, musculoskeletal and connective tissue disorders had a significant proportion of claims in Greater Melbourne (37%). The descriptive statistics for workers' compensation claims are presented in Supplementary Table S1.

3.1. Risk assessment of OI in three major cities of Australia

The estimated OI risk was strongly associated with hot weather conditions in the three cities. In Greater Brisbane, the overall risk of OI was −0.4% (95%CI: 5.6, 5.0) at moderate heat (32.6 °C) and 3.4% (95% CI: 3.8, 11.1) at extreme heat (38.1 °C) (Fig. 1) relative to the 10th percentile (20.3 °C). Although the overall cumulative risk was minimal in Greater Brisbane, many SA3 regions were found to be at high risk of OI for example in Forest Lake - Oxley the risk was estimated to be 13.3% at 33.0 °C and 17.4% at 39.5 °C with reference to 17 °C (Supplementary Table S2).

Similarly, in Greater Sydney, the overall risk of OI associated with heat increased from 4.4% (95%CI: 1.3, 7.6) at 30.9 °C to 8.9% (95%CI: 4.1, 13.9) at 39.4 °C with respect to 10th percentile (15.8 °C) (Fig. 1). Region-wise risk estimates indicated a higher risk of OI in various SA3. For example, the risk increased up to 19.2% at 31.0 °C and up to 32.3% at 40.0 °C with reference to 13 °C in Auburn (Supplementary Table S2).

In Greater Melbourne, the risk of OI associated with heat index was 8.9% (95%CI: 4.6, 13.3) at 29 °C (Fig. 1). At extreme heat, it increased up to 9.5% (95%CI: 4.0, 15.4) at 37.5 °C with respect to 12.1 °C. Location-specific risk estimates were higher for SA3 regions in Greater Melbourne. For example; in Darebin – North the risk of OI associated with heat index increased up to 19.3% at 30.0 °C and 20.5% at 38.0 °C with respect to 9.0 °C (Supplementary Table S2). Summary statistics of the three cities with an estimated location-specific PMOI, 90% percentile, and 99th percentile of heat index are provided in Supplementary Table S3.

The impacts of heat on OI aggravate with an increase in heat index in

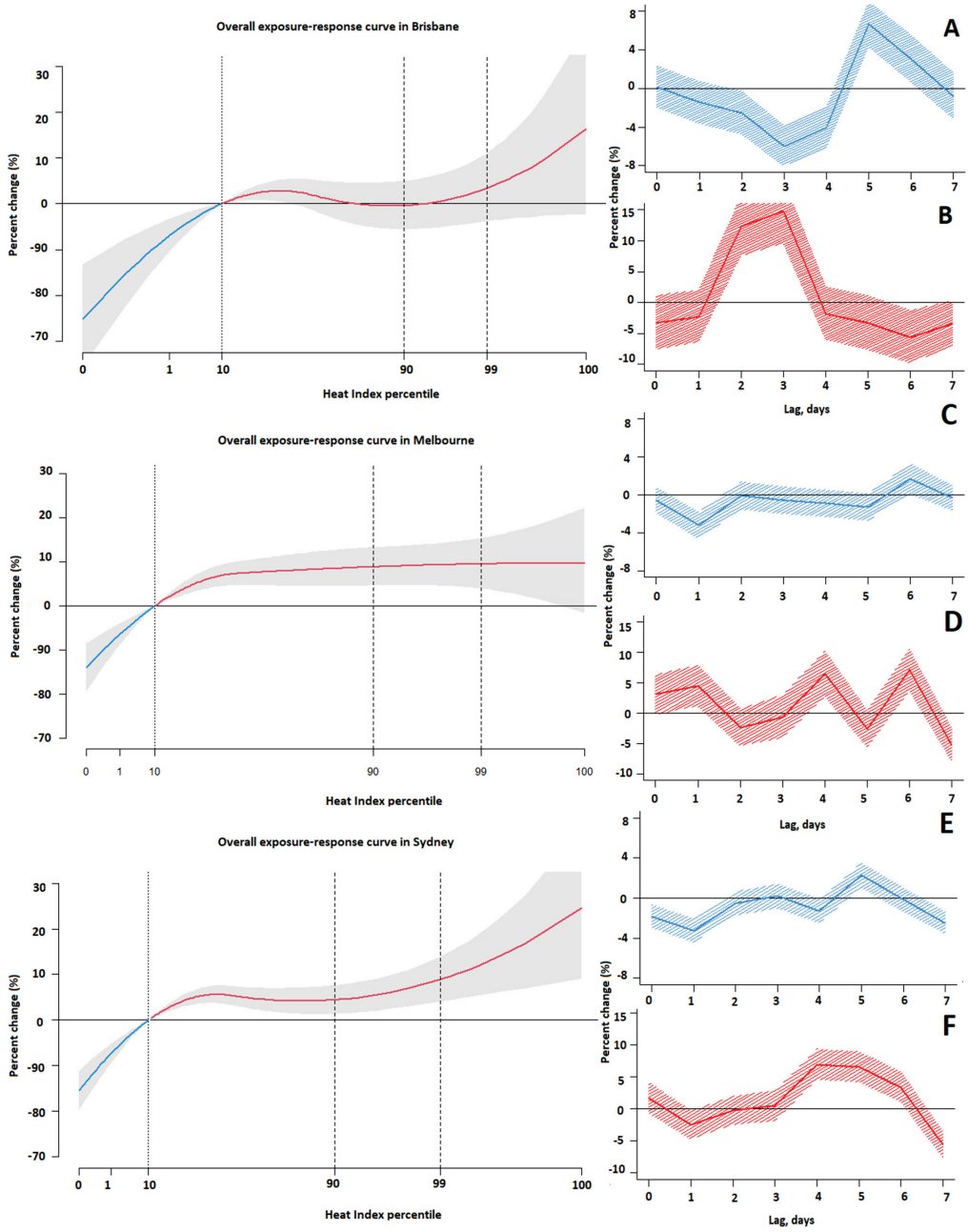

Fig. 1. Overall Cumulative exposure-response curve of OI associated with hot weather conditions given in percent difference [with 95% confidence intervals (CI) – shaded areas] in three major cities of Australia. The dotted line represents the PMOI (10th percentile). The dashed lines represent the moderate heat (90th percentile) and extreme heat (99th percentile) of the heat index. Fig. 1A and B, Lag-response relationship between heat index and OI for cold effects (estimated at 1st percentile) and heat effects (estimated at 99th percentile) respectively for Greater Brisbane. Fig. 1C and D, Lag-response relationship between heat index and OI for cold effects (estimated at 1st percentile) and heat effects (estimated at 99th percentile) respectively for Greater Melbourne. Fig. 1E and F, Lag-response relationship between heat index and OI for cold effects (estimated at 1st percentile) and heat effects (estimated at 99th percentile) respectively for Greater Sydney.

all three cities. Particularly, the exposure-response curve shows an exponential increase in the risk of OI associated with heat in Greater Brisbane and Greater Sydney, while in Melbourne the exposure-response curve remains comparatively stable (Fig. 1). The cold-related effects of the heat index metric (presented at 1st percentile) were delayed in all instances (Fig. 1A, 1C, 1E). The heat-related effects (99th percentile) were slightly delayed in Greater Brisbane and Greater Sydney but were immediate in Greater Melbourne (Fig. 1B, 1D, 1F). Region-wise exposure-response curves for the three greater cities are presented in Supplementary Figures S2, S3, and S4. Spatial maps of various

environmental variables for the three cities are presented in Supplementary Figures S5, S6, and S7. Sensitivity analysis for the three cities suggested that the models generally performed well with the selected modelling choices (Supplementary Table S4).

3.1.1. Spatial distribution of the risk of OI associated with heat index

In Greater Brisbane and Greater Sydney, the western inland regions were found to be at higher risk of OI at both moderate and extreme heat (Fig. 2). In Greater Brisbane, Beaudesert, Brown Plains, Centenary, Forest Lake, Ipswich Inner, Ipswich Hinterland, Jimboomba, Kenmore – Brookfield - Moggill, and Springfield-Redbank were regions, particularly at higher risk of OI (up to 25.9%) (Fig. 2A and 2D). Similar, patterns were observed in Greater Sydney. The inland western SA3 regions: Auburn, Bankstown, Blacktown, Blacktown North, Camden, Bringelly – Green Valley, Fairfield, Liverpool, Merryland – Guildford, Mount Druitt, Parramatta, Penrith, Richmond – Windsor, Rouse Hill – McGraths Hill, and St Marys were most vulnerable (up to 32.3%) to the effects of both moderate and extreme heat (Fig. 2C and 2F). While, in Greater Melbourne, Bayside, Darebin – North, Glen Eira, Manningham – East, Monash, Port Phillip, Stonnington – East, Stonnington – West, Whitehorse – East, Whitehorse – West were particularly at high risk of OI (up to 19.3%) at moderate heat (Fig. 2B). Darebin – East, Hobson Bay, Monash, Port Phillip, Whitehorse – East, and Whitehorse – West were particularly at high risk (up to 20.5%) at extreme heat (Fig. 2E).

3.2. Attributable fraction of OI associated with heat index

In Greater Brisbane, the total AF of OI associated with heat (20.3–44.8 °C) was 8.52% (95%CI: 6.84, 10.02). The AF of OI associated with extreme heat was 0.96% (95%CI: 0.72, 1.20), while 7.86% (95%CI: 6.22, 9.30) of the OI burden was attributable to moderate heat. The city's western outskirts had higher AF for OI (>11.5%) (Table 1).

In Greater Melbourne, the total AF of OI 11.15% (95%CI: 9.49, 11.82) was attributable to heat (12.1–45.6 °C). The AF of OI associated with extreme heat was 1.57% (95%CI: 1.36, 1.66), while 9.91% (95%CI: 8.54, 10.51) of OI burden was attributable to moderate heat. In Greater Melbourne, urbanized SA3 regions had a higher burden (>11.0%) of OI associated with heat index (Table 1).

In Greater Sydney, an overall AF of 11.02% (95%CI: 9.95, 11.96) was observed for heat (15.8–50.8 °C). The AF of OI associated with extreme heat was 1.43% (95%CI: 1.29, 1.56), whereas 9.78% (95%CI: 8.77, 10.68) of OI was attributable to moderate heat. The western outskirts of the city had a higher AF of OI burden (>13.0%) (Table 1).

3.3. Risk assessment of OI stratified by various subgroups

The overall subgroup risk estimates suggest that among personal and workplace factors, young workers (15–25 years) and middle-aged workers (35–44 years and 45–54 years), males, workers reporting injury claims, and drivers and machinery operators were more

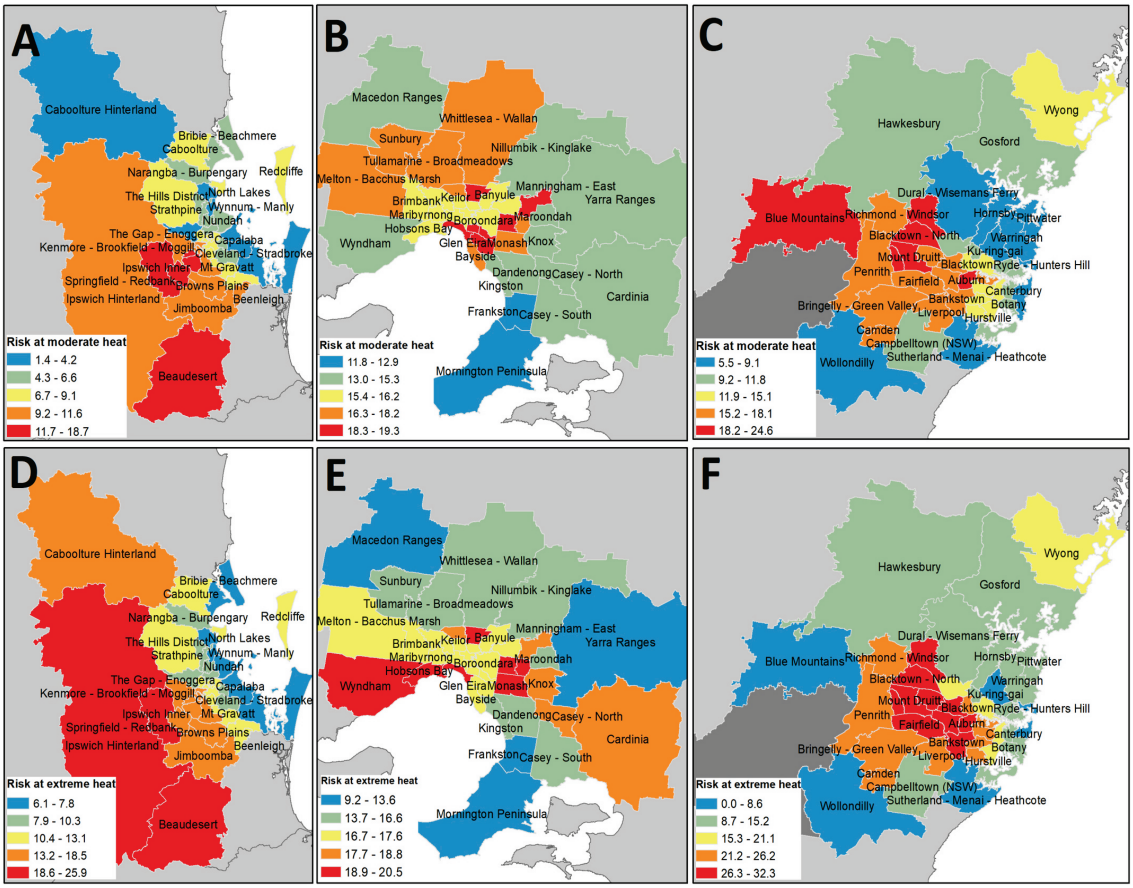

Fig. 2. The spatial distribution of the risk of OI associated with moderate heat for A. Greater Brisbane, B. Greater Melbourne, and C. Greater Sydney and extreme heat for D. Greater Brisbane, E. Greater Melbourne, and F. Greater Sydney.

Table 1
The attributable fraction with 95% confidence intervals of OI for overall heat component for SA3 regions of Greater Brisbane, Greater Melbourne and Greater Sydney from 2005 to 2018.

Greater Brisbane - SA3 Regions	Heat-related AF (95% CI)	Greater Melbourne - SA3 Regions	Heat-related AF (95% CI)	Greater Sydney – SA3 Region	Heat-related AF (95% CI)
Bald Hills - Everton Park	6.3 (-0.4, 12.2)	Banyule	10.9 (5.1, 14.3)	Auburn	14.8 (9.2, 20.3)
Beaudesert	18.7 (-1.4, 33.2)	Bayside	12.4 (4.0, 17.0)	Bankstown	13.8 (9.0, 18.6)
Beenleigh	10.1 (0.5, 19.6)	Boroondara	10.9 (6.1, 13.3)	Baulkham Hills	9.0 (6.3, 11.7)
Bribie - Beachmere	4.9 (-2.2, 11.4)	Brimbank	10.7 (5.9, 13.3)	Blacktown	13.9 (9.6, 18.1)
Greater Brisbane Inner	9.2 (3.5, 14.2)	Brunswick - Coburg	11.0 (5.1, 14.2)	Blacktown - North	15.3 (8.2, 22.5)
Greater Brisbane Inner-East	8.6 (3.5, 13.7)	Cardinia	10.3 (−2.8, 16.9)	Blue Mountains	−0.1 (-0.1, 0.0)
Greater Brisbane Inner-North	7.0 (2.0, 11.9)	Casey - North	10.6 (−1.8, 15.8)	Botany	9.8 (5.8, 13.8)
Greater Brisbane Inner-West	8.8 (3.4, 14.3)	Casey - South	9.9 (5.1, 12.6)	Bringelly - Green Valley	13.9 (6.9, 20.3)
Browns Plains	12.6 (6.0, 18.1)	Dandenong	10.3 (6.0, 12.6)	Camden	13.2 (7.8, 18.0)
Caboolture	9.5 (3.7, 14.4)	Darebin - North	13.2 (7.2, 16.4)	Campbelltown (NSW)	8.4 (5.5, 11.2)
Caboolture Hinterland	1.1 (-2.8, 4.6)	Darebin - South	10.9 (5.1, 13.6)	Canada Bay	12.8 (9.1, 16.2)
Capalaba	4.4 (-1.6, 10.1)	Essendon	11.1 (4.9, 14.5)	Canterbury	11.7 (6.2, 16.4)
Carindale	6.3 (1.0, 11.7)	Frankston	8.1 (2.0, 11.2)	Carlingford	10.5 (7.0, 13.6)
Centenary	13.9 (6.0, 21.3)	Glen Eira	12.4 (3.2, 16.7)	Chatswood - Lane Cove	9.2 (5.3, 13.2)
Chermside	6.1 (-0.9, 12.5)	Hobsons Bay	10.9 (2.0, 15.3)	Cronulla - Miranda - Caringbah	8.6 (4.3, 12.6)
Cleveland - Stradbroke	0.9 (-3.0, 4.7)	Keilor	10.8 (5.8, 13.6)	Dural - Wisemans Ferry	7.8 (3.0, 12.1)
Forest Lake - Oxley	14.1 (6.5, 21.2)	Kingston	10.1 (5.8, 12.2)	Eastern Suburbs – North	7.3 (2.3, 12.4)
Holland Park - Yeronga	9.5 (3.4, 15.1)	Knox	10.4 (−0.7, 15.8)	Eastern Suburbs – South	7.5 (2.8, 12.0)
Ipswich Hinterland	12.6 (-7.1, 27.4)	Macedon Ranges	10.9 (−14.3, 21.3)	Fairfield	14.2 (8.5, 19.2)
Ipswich Inner	16.2 (4.3, 26.7)	Manningham - East	12.8 (3.0, 17.4)	Gosford	8.7 (4.8, 12.3)
Jimboomba	11.4 (3.5, 17.8)	Manningham - West	10.8 (5.1, 13.6)	Hawkesbury	10.4 (-0.5, 19.0)
Kenmore - Brookfield - Moggill	11.8 (6.2, 17.5)	Maribyrnong	11.1 (5.0, 14.1)	Hornsby	7.4 (3.6, 10.6)
Loganlea - Carbrook	8.2 (-2.2, 17.6)	Maroondah	10.6 (6.0, 12.9)	Hurstville	11.6 (6.5, 16.3)
Mt Gravatt	5.9 (0.2, 11.1)	Greater Melbourne City	11.2 (5.1, 14.7)	Kogarah - Rockdale	10.6 (6.2, 14.8)
Narangba - Burpengary	5.6 (-1.2, 12.3)	Melton - Bacchus Marsh	12.4 (4.1, 16.5)	Ku-ring-gai	6.7 (2.4, 10.8)
Nathan	8.2 (2.8, 13.2)	Monash	12.6 (7.0, 15.2)	Leichhardt	10.6 (6.3, 14.6)
North Lakes	3.0 (-6.1, 10.8)	Moreland - North	12.0 (6.4, 14.8)	Liverpool	14.2 (10.3, 17.8)
Nundah	5.2 (-2.5, 12.1)	Mornington Peninsula	9.5 (−4.7, 16.2)	Manly	7.3 (1.5, 11.9)
Redcliffe	2.3 (-3.6, 7.1)	Nillumbik - Kinglake	10.2 (1.2, 15.1)	Marrickville - Sydenham - Petersham	10.8 (6.6, 15.1)
Rocklea - Acacia Ridge	11.6 (3.6, 18.8)	Port Phillip	12.9 (6.2, 16.6)	Merrylands - Guildford	13.4 (8.6, 17.8)
Sandgate	4.1 (-3.4, 10.8)	Stonnington - East	12.5 (3.0, 17.3)	Mount Druitt	14.9 (9.2, 20.3)
Sherwood - Indooroopilly	11.3 (4.2, 18.1)	Stonnington - West	12.9 (1.5, 18.9)	North Greater Sydney - Mosman	8.5 (4.2, 12.7)
Springfield - Redbank	14.2 (5.0, 22.9)	Sunbury	12.3 (3.4, 17.0)	Parramatta	13.2 (8.7, 17.6)
Springwood - Kingston	7.9 (2.3, 13.3)	Tullamarine - Broadmeadows	11.9 (4.5, 15.6)	Pennant Hills – Epping	8.4 (5.5, 11.3)
Strathpine	6.5 (0.1, 12.9)	Whitehorse - East	12.5 (7.1, 15.3)	Penrith	14.7 (5.5, 22.7)
Sunnybank	7.9 (2.4, 13.1)	Whitehorse - West	12.9 (7.6, 15.7)	Pittwater	7.6 (2.9, 12.2)
The Gap - Enoggera	0.5 (-0.8, 1.7)	Whittlesea - Wallan	11.6 (1.4, 16.3)	Richmond - Windsor	14.5 (4.8, 23.4)
The Hills District	8.2 (0.0, 15.5)	Wyndham	10.5 (1.8, 14.8)	Rouse Hill - McGraths Hill	14.7 (9.3, 19.9)
Wynnum - Manly	4.4 (-3.6, 11.0)	Yarra	11.2 (5.3, 14.4)	Ryde - Hunters Hill	12.0 (8.8, 15.2)
–	–	Yarra Ranges	10.1 (−0.3, 15.0)	St Marys	15.3 (7.9, 21.6)
–	–	–	–	Strathfield - Burwood – Ashfield	11.8 (6.6, 17.2)
–	–	–	–	Sutherland - Menai - Heathcote	5.7 (1.1, 9.6)
–	–	–	–	Greater Sydney Inner City	9.4 (5.4, 13.5)
–	–	–	–	Warringah	7.6 (2.9, 11.9)
–	–	–	–	Wollondilly	5.2 (-1.5, 10.9)
–	–	–	–	Wyong	10.8 (6.6, 14.9)

vulnerable to heat impacts. Among location-specific characteristics, workers were at increased risk of OI in regions with both high and low LST, low NDVI, low IRSAD, and low IEO (Supplementary Table S5). Although some variations were observed, for example in Greater Melbourne, workers in regions with high IEO were also vulnerable to theimpacts of heat.

Region-wise subgroup analysis revealed an evident spatial pattern in the distribution of the risk of OI stratified by various subgroups. In Greater Brisbane, a high risk of OI was seen for female workers, younger workers, workers with injury claims only, and outdoor and indoor industries at extreme heat in the inland western regions. In more crowded inner-city SA3 regions, male workers, older workers, and workers reporting illness-related claims only were at higher risk (Figs. 3 and 4). Female workers were at increased risk of OI particularly in the western regions in greater Brisbane, for example, a statistically significant increased risk of up to 60.5% (95%CI: 5.7, 143.6) was observed in The Gap Enogerra at 38.0 °C (Supplementary Table S6).

In Greater Melbourne, workers in urbanized SA3 regions of the city, including Bayside, Glen Eira, and Stonnington - East and Stonnington - West were particularly at high risk of OI at both moderate and extreme heat exposure. Essendon, Melbourne City, Port Phillip, Stonnington – West, and Yarra were generally at higher risk of OI for young workers and workers with illness-related claims. The city's outer fringes, including Macedon ranges, Nillumbik Kinglake, Sunbury, Whittlesea Wallan, and Yarra ranges were at higher risk of OI for older workers and workers reporting injury-related claims (Figs. 5 and 6). The highest risk of OI was recorded for outdoor industries in many SA3 regions including Bayside 50% (95%CI: 8.0, 108.2), Glen Eira 51.4% (95%CI: 7.4, 113.5), Manningham – East 52.3% (95%CI: 9.0, 112.9), Melton – Bacchus Marsh 44.1% (95%CI: 9.3, 90.2), Stonnington – East 52.8% (95%CI: 6.8, 118.7), Stonnington – West 57.6% (95%CI: 4.3, 138.2) at extreme heat (37.0–38.0 °C) (Supplementary Table S7).

In Greater Sydney, a higher risk of OI was calculated for male workers, younger workers, outdoor industries, and injury-related claims in the inland western regions including Auburn, Blacktown, Blacktown North, Blue Mountains, Bringelly - Green Valley, Camden, Fairfield,

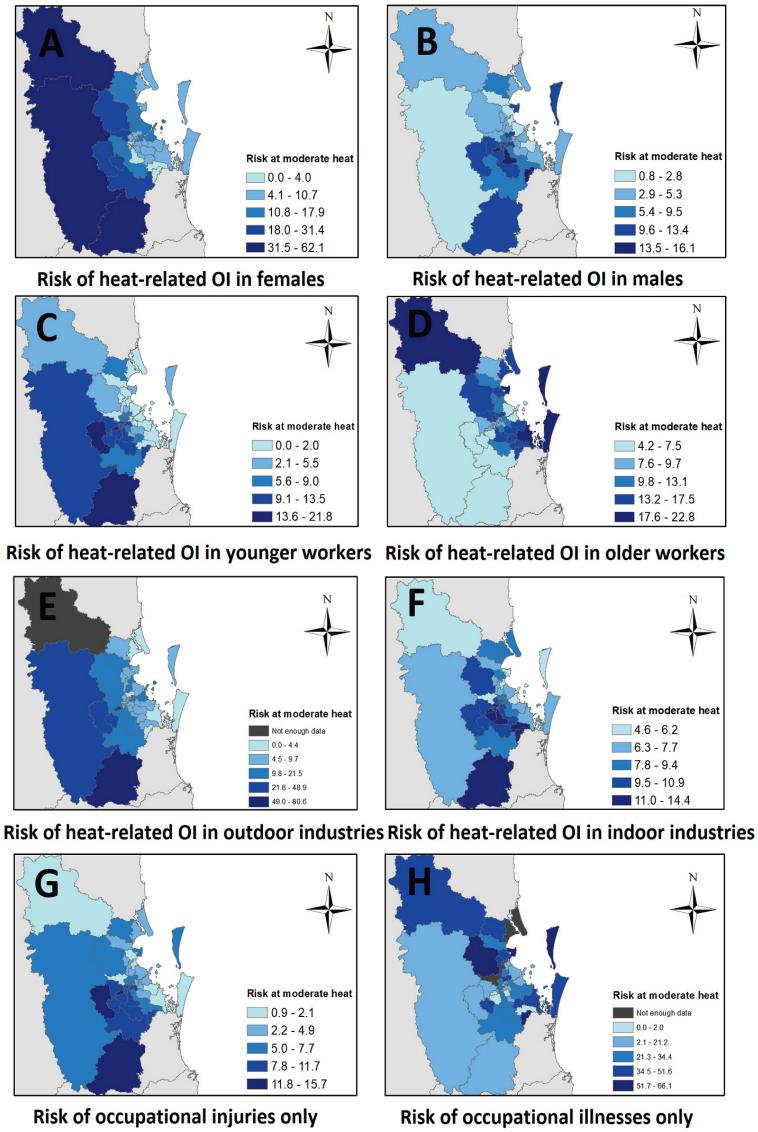

Fig. 3. Risk assessment of OI associated with moderate heat stratified by gender: A. females, B. males, by age C. younger (age <45) and D. older (age ≥45), types of industries E. outdoor industries and F. indoor industries and types of claims G. injury-related claims only and H. illness-related claims only in Greater Brisbane.

Merrylands - Guildford, Mount Druitt, Parramatta, Penrith, Richmond - Windsor, Rouse Hill - McGarths Hill, and St Marys (Figs. 7 and 8). More urbanized regions including Canada Bay, Canterbury, Hurstville, Kogarah-Rockdale, Strathfield-Burwood-Ashfield, and Greater Sydney Inner City were predominantly associated with higher risk for female workers, older workers, and workers with illness-related claims. Statistically high risk of OI associated with extreme heat was found for various subgroups, for example, in St Marys, an increased risk of OI 42.8% (95% CI: 22.5, 66.5) was estimated for male workers and 49.0% (95%CI: 26.7, 75.3) for younger workers at 43.0 °C. Workers in outdoor industries were particularly at high risk for most regions. In Richmond - Windsor, the risk increased up to 54.3% (95%CI: 1.7, 134.2) at 43.0 °C for workers in outdoor industries (Supplementary Table S8).

3.4. Risk assessment of OI associated with the projected heat index

The risk estimates of OI at extreme heat for two 30-year projected periods (2016-2045 and 2036-2065) for Greater Brisbane, Greater Melbourne, and Greater Sydney are presented in Table 2. The estimates are based on the NorESM1-M general circulation models, as the model is known to perform well in representing the range of projected changes in the climate from all models (CSIRO and Australian Bureau of, 2015). The risk of OI increased in future projected scenarios (2016–2045 and 2036–2065) as compared to the baseline period particularly for Greater Sydney (6.5%) and Greater Brisbane (4.5%) at extreme heat in the projected period 2036–2065 (RCP 8.5), while for Melbourne we observed a slight reduction in the risk of OI (0.1%).

Projected risk estimates for other general circulation models are presented in Supplementary Table S9. Similar estimates were observed

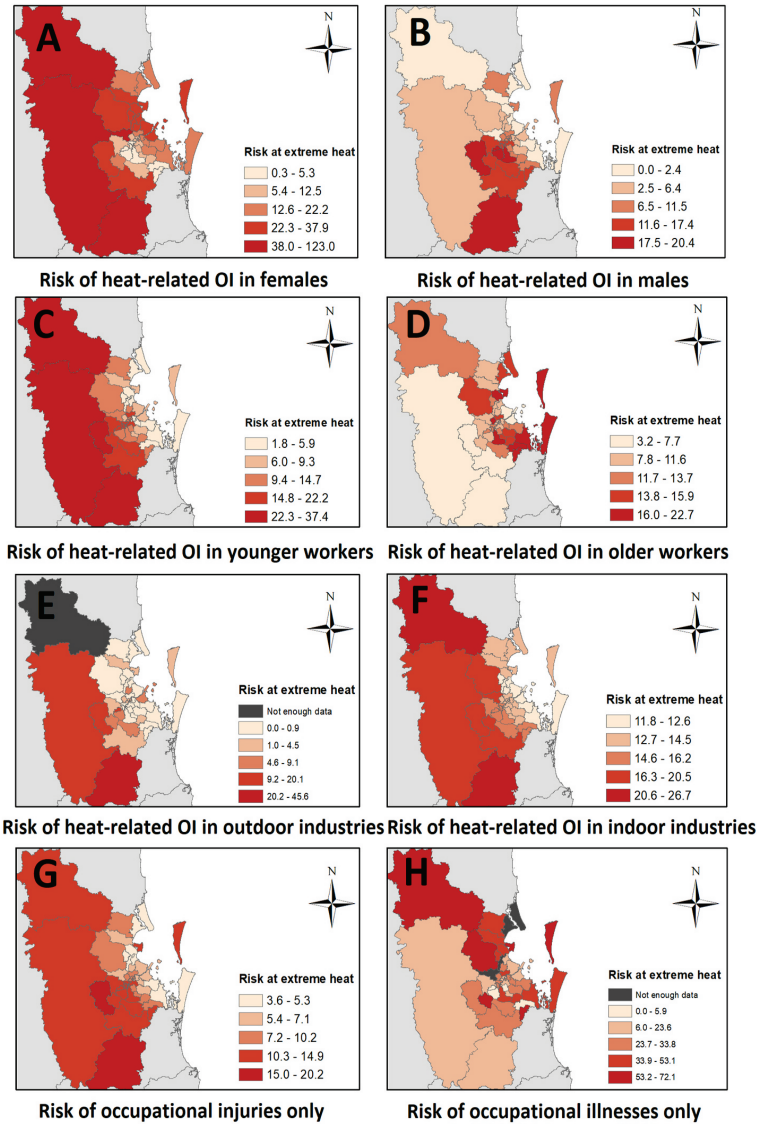

Fig. 4. Risk assessment of OI associated with extreme heat stratified by gender: A. females, B. males, by age C. younger (age <45) and D. older (age ≥45), types of industries E. outdoor industries and F. indoor industries and types of claims G. injury-related claims only and H. illness-related claims only in Greater Brisbane.

for all general circulation models and RCP scenarios. The absolute AF of OI for baseline and projected periods associated with heat is given in Supplementary Table S10. We observed that AF increased for all three cities.

4. Discussions

In this study, we have undertaken a risk assessment of OI associated with hot weather conditions at an intra-urban scale to identify high-risk areas in three large Australian cities. In Greater Brisbane and Greater Sydney, we found that the inland western regions were at higher risk of OI at both moderate and extreme heat. In Greater Melbourne, the urbanized coastal areas were particularly at higher risk of OI during moderate heat and extreme heat. In terms of the types of industries and claims, the risk of OI was typically high for workers in outdoor industries and workers with injury-related claims, in the outer fringes of the three cities. In contrast, workers in the more crowded inner-city regions were at high risk for illness-related claims. Future projection analysis indicates that the risk of OI is predicted to increase.

Fine-scale risk assessment offers valuable information in the development of targeted interventions in high-risk areas. Risk assessment at the intra-urban level quantifies the risk more accurately, by considering local exposure differences (Gasparrini, 2022). These variations are often overlooked in broad-scale risk assessments, i.e., risk assessments at the city level. For example, workers in some SA3 regions in Greater Brisbane were particularly vulnerable (risk of OI > 15%) to the effects of extreme heat, which was not reflected in the cumulative risk of OI 3.4 (95%CI: 3.8-11.1). Therefore, such assessments at a finer level can help to develop location-specific tailored interventions.

Many location-specific factors could play an important role in the

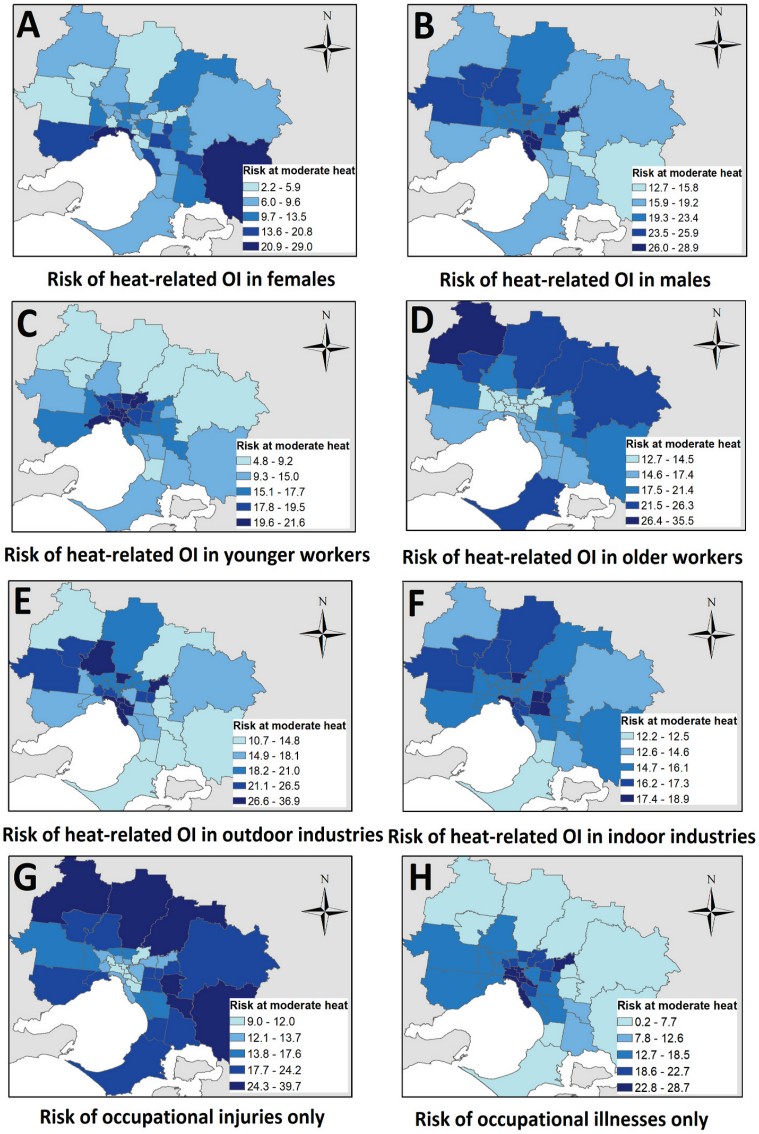

Fig. 5. Risk assessment of OI associated with moderate heat stratified by gender: A. females, B. males, by age C. younger (age <45) and D. older (age ≥45), types of industries E. outdoor industries and F. indoor industries and types of claims G. injury-related claims only and H. illness-related claims only in Greater Melbourne.

spatial distribution of the heat-related risk of OI. We found that regions with low NDVI, low IRSAD, and IEO had a higher risk of OI. For example, Blacktown North, Fairfield, Mount Druitt, Penrith, Richmond – Windsor are some of the western inland regions in Greater Sydney characterized by lower NDVI, IRSAD, and IEO (Supplementary Figure S7). These regions were particularly vulnerable to the impacts of heat on WHS. Similarly, Centenary, Forest Lake – Oxley, Ipswich Inner, Kenmore – Brookfield – Moggil are some of the low socio-economic indexed regions highly vulnerable to the impacts of heat in Greater Brisbane (Supplementary Figure S5). The high risk of OI in regions with low socioeconomic status and low index of education and occupation suggests that workers are generally less adaptive and more sensitive to heat exposure because of limited resources to stay cool and usually have low awareness and education, as suggested in previous studies (Gronlund, 2014). The results suggest that urban policymakers and employers should consider targeted mitigation responses, implement heat-related injury and illness reduction strategies in socio-economically vulnerable regions and promote green spaces in lower-income neighbourhoods. Previous studies have also identified, that these factors are associated with the impacts of hot temperatures on both workers and the general population (Gasparrini et al., 2022; Guerri et al., 2022).

In Greater Sydney and Greater Brisbane, workers in the hotter western inland regions were at higher risk of OI and had higher heat-related AF, as compared to more crowded inner-city areas where workers were also vulnerable to heat exposure. The western inland regions of these two cities were generally 4–6 °C hotter than other regions (Supplementary Figures S5 and S7), potentially because coastal winds keep the coastal areas cool but could not penetrate inland (Santamouris et al., 2017). In Greater Sydney, the impacts are further compounded by rapid urbanization, the destruction of bushland, and their replacement

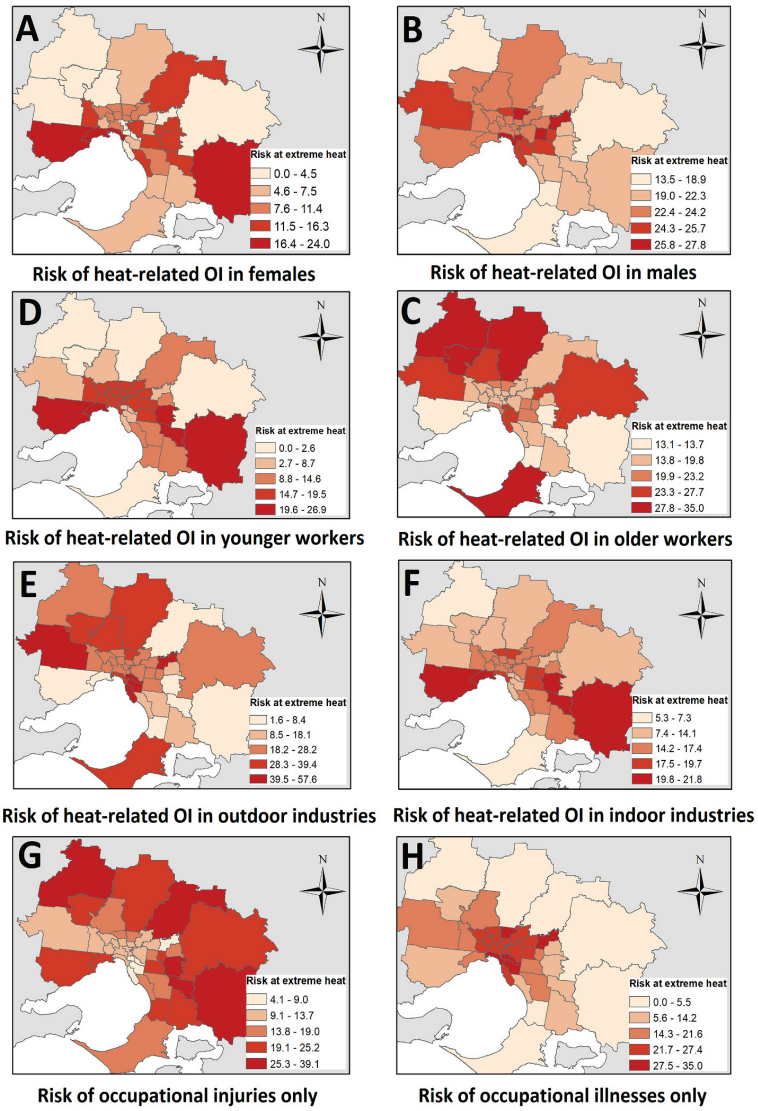

Fig. 6. Risk assessment of OI associated with extreme heat stratified by gender: A. females, B. males, by age C. younger (age <45) and D. older (age ≥45), types of industries E. outdoor industries and F. indoor industries and types of claims G. injury-related claims only and H. illness-related claims only in Greater Melbourne.

by buildings and roads. These activities contribute to urban heat island effects in many suburbs and consequently higher temperatures in the western foothills of the Blue Mountains (Santamouris et al., 2017; Pfautsch et al., 2020).

In Greater Melbourne, workers in coastal areas were at higher risk of OI associated with moderate heat. Regions including Bayside, Darebin – North, Glen Eira, Manningham – East, Monash, Port Phillip, Stonnington - East, Stonnington - West, Whitehorse – East and Whitehorse – West were characterized by high IRSAD and IEO, but were vulnerable to the impacts of heat (Supplementary Figure S6). Although the coastal areas are generally characterized by relatively cool weather conditions and lower LST, many of these SA3 regions have a major proportion of workforce from occupations such as technicians and trade workers, machinery operators, and drivers and laborers. These occupations are generally more vulnerable to heat effects as workers are required to do heavy work outside (Li et al., 2016). In addition, construction and manufacturing are among the major industries in many of these SA3 (Australian Bureau of Statistics, 2016c). Further, the risk of OI was consistently higher for workers at moderate heat in these regions, similar results were also found in a previous study from Melbourne (McInnes et al., 2018). In oceanic climates, characterized by cool and temperate weather conditions, people are generally less acclimatized to hot weather and a sudden increase in temperature can put workers at acute risk of OI. These findings suggest that heat preventive measures should be implemented at moderate heat well before extreme weather conditions are approaching (McInnes et al., 2018). This is an important finding in terms of implementing heat-related policies at the onset of hot weather conditions. Some previous studies suggested a higher risk at extreme heat when city-level risk assessments were undertaken (McInnes et al., 2017a; Varghese et al., 2019). The discrepancies with our findings could be due to different geographical levels of assessment or the use of different statistical models.

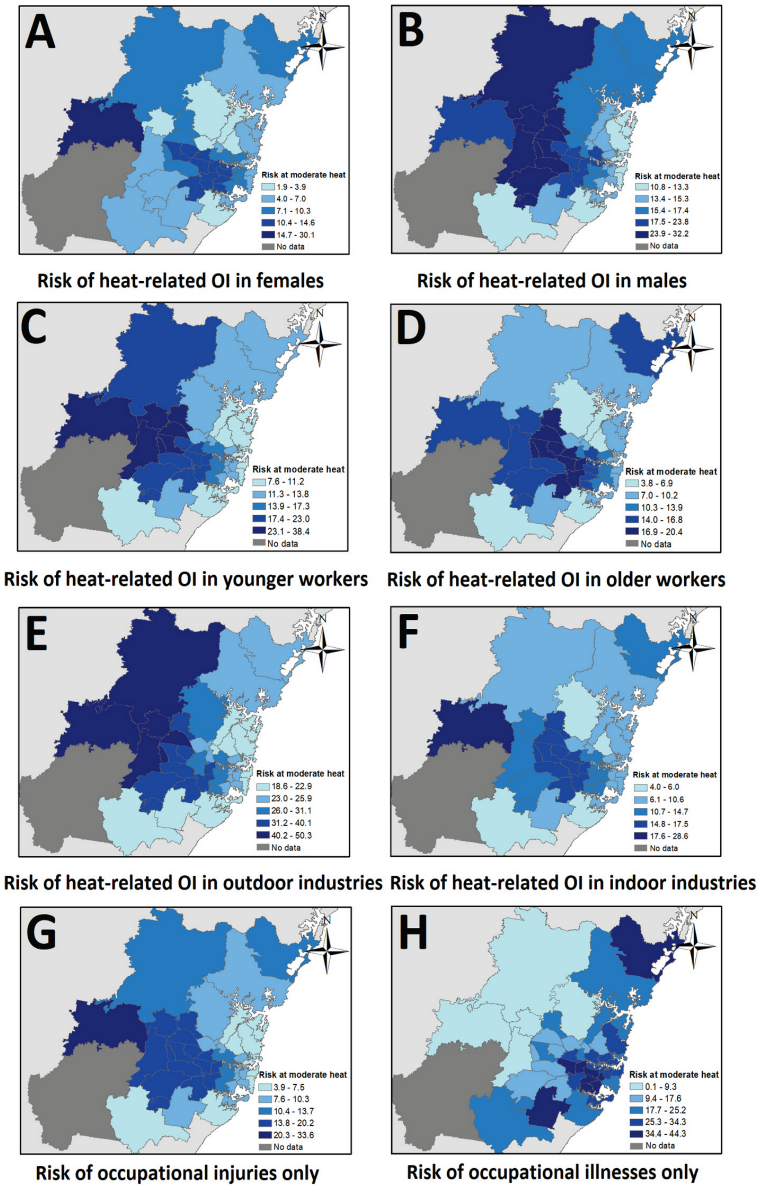

Fig. 7. Risk assessment of OI associated with moderate heat stratified by gender: A. females, B. males, by age C. younger (age <45) and D. older (age ≥45), types of industries E. outdoor industries and F. indoor industries and types of claims G. injury-related claims only and H. illness-related claims only in Greater Sydney.

Based on regional climatic conditions we can infer that workers in humid subtropical climates were generally at high risk of OI during extreme heat and the curve showed an exponential increase, as compared to workers in oceanic climates. A higher risk of OI was predicted in many SA3 regions of Greater Sydney (up to 32.3% increase) and Greater Brisbane (up to 25.9%) as compared to Greater Melbourne (20.5%). These findings support the existing evidence from the literature that revealed spatial heterogeneity in heat-related risk of OI across different climate zones (Fatima et al., 2021). In addition, hot and humid regions in Greater Brisbane and Greater Sydney had lagged effects (2–6 days) of hot weather conditions on OI, whereas in Greater Melbourne the effects were immediate (0–1 days) (Fig. 1). In humid subtropical climates, people are generally acclimatized to hot weather conditions but at extreme heat, humidity plays a significant role in the thermoregulatory response of the human body (Oppermann et al., 2017).

The risk of OI associated with heat index was ubiquitously high for outdoor industries particularly in outer SA3 regions in all three greater cities. Many SA3 regions vulnerable to the impacts of hot weather conditions for workers in outdoor industries, had a workforce predominantly employed in the construction sector (Australian Bureau of Statistics, 2016c). This finding suggests that relevant adaptive policies, guidelines, and codes of practice should be developed and adequate resourcing should be provided in the outdoor industrial sector where workers are required to do heavy work outside in unsafe thermal conditions at both moderate and extreme heat. Workers in indoor industries in hotter SA3 regions were also at high risk. In western regions of

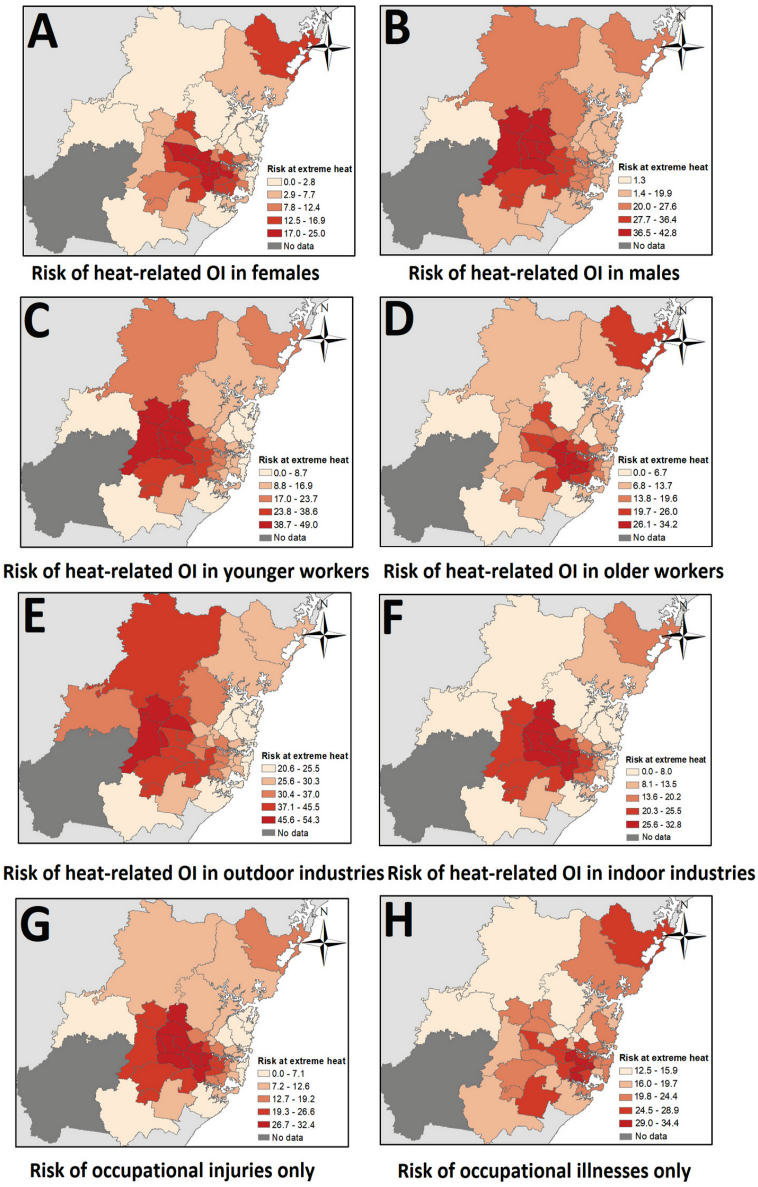

Fig. 8. Risk assessment of OI associated with extreme heat stratified by gender: A. females, B. males, by age C. younger (age <45) and D. older (age ≥45), types of industries E. outdoor industries and F. indoor industries and types of claims G. injury-related claims only and H. illness-related claims only in Greater Sydney.

Greater Brisbane, females were particularly at higher risk of OI. Some of the major indoor industries such as retail trade, education and training, and health care and social assistance are female-dominated sectors (Australian Bureau of Statistics, 2016c). These findings suggest that workers are also vulnerable to heat effects in regulated indoor workplaces. Industries and various levels of government need to deploy standards for heat management, in all industrial sectors, to help workers cope better with hot climate (Zander et al., 2018). Resource allocation should be prioritized in high-risk areas.

We also found a significant association between illness-related claims and hot weather conditions. The risk of occupational illnesses in workers was consistently high in the crowded city areas in all three cities. Recent literature provides evidence of the increased risk of illness and conditions associated with hot weather conditions in the general population (Liu et al., 2021, 2022). These findings have important implications for current and future healthcare prevention strategies which should be focused on both injuries and illnesses in occupational health and safety.

The risk of OI and AF associated with heat is predicted to increase in the projected periods: 2016–2045 and 2036–2065 in the three cities. Previous studies from multiple locations suggested an increase in heat-related health burden associated with warming climates (Gasparrini et al., 2017; Martínez-Solanas et al., 2021). Although, there are geographical variations in the impacts based on local climatic conditions and socio-economic factors (Gasparrini et al., 2017). Consistent with previous findings we observed that regions characterized by warm

Table 2
The risk estimates of OI associated with projected heat index (extreme heat - 99th percentile) for two timeframes (2016–2045, 2036–2065) and two RCP scenarios (4.5 and 8.5) for the NorESM1-M general circulation model in the three cities of Australia.

City	Prediction Period	RCP Scenario	Heat Effects (95% CI)
Greater Brisbane	Baseline	NA	2.7 (−10.0, 17.2)
	2016–2045	RCP 4.5	7.1 (−19.7, 42.9)
		RCP 8.5	6.8 (−19.1, 41.2)
	2036–2065	RCP 4.5	7.8 (−21.6, 48.1)
		RCP 8.5	7.2 (−20.5, 44.5)
Greater Melbourne	Baseline	NA	7.6 (−7.4, 24.9)
	2016–2045	RCP 4.5	7.5 (−17.4, 39.7)
		RCP 8.5	7.5 (−16.1, 37.8)
	2036–2065	RCP 4.5	7.5 (17.4, 39.7)
		RCP 8.5	7.5 (−17.4, 39.7)
Greater Sydney	Baseline	NA	11.3 (−5.5, 31.2)
	2016–2045	RCP 4.5	16.9 (−10.2, 52.1)
		RCP 8.5	16.9 (−10.2, 52.1)
	2036–2065	RCP 4.5	18.7 (−11.6, 59.2)
		RCP 8.5	17.8 (−10.8, 55.5)

baseline climates i.e. Greater Brisbane and Greater Sydney are particularly at higher risk of OI associated with the projected hot weather. Further investigations are warranted to assess the magnitude of the impacts of projected climate change on OI by considering factors like adaptations and changes in workforce size and composition (Arbuthnott et al., 2016; Petkova et al., 2014).

Exposure to extreme heat can result in a greater risk of OI and the impacts are disproportionate on a local scale. Therefore, it is of prime importance to issue localized warnings of hot weather conditions for timely preparedness and response. The national and state regulatory authorities should develop a holistic response to minimize the impacts of persistent hot weather conditions. These may include 1. Identifying vulnerable areas and implementing location-specific targeted interventions and resource allocation; 2. Promoting green spaces in urban planning will curb heat impacts, provide cool spaces, and help prevent the long-run impacts of climate change; and 3. Providing cooling assistance in socio-economically vulnerable regions.

4.1. Strength and limitations

Fine-scale assessment of the risk of OI associated with hot weather provides much-needed scientific evidence for WHS regulators, industries, unions, and workers. It will help them identify high-risk areas within a city and implement location-specific preventative measures to reduce the occupational health impacts associated with hot climate. The findings from this study will provide a valuable resource for policymakers in WHS and planning in integrating effective occupational health and climate policies at both local and national scales. Safe Work Australia has extensive information on working in heat (Safe Work Australia, 2020b). The findings from this study could add significantly to the existing information. The results are based on modelling choices that performed consistently well in the three cities as shown in the sensitivity analysis. The use of heat index improved the models' performance as compared to maximum temperature. As the heat index considers the combined effect of air temperature and relative humidity, it is a more reliable exposure metric, particularly in regions characterized by high humidity (Edirisinghe and Andamon, 2019).

This study has some limitations. First of all, to estimate the risk of OI at a finer geographical scale within cities, we have used SA3 as our spatial unit of analysis instead of POA, the geographical unit at which workers' compensation claims data is collected. The selection of SA3 was necessary to avoid methodological challenges such as the temporal boundary misalignment issue, which is inherent in POA, and the small sample size issue across space and time. SA3 regions are known to have similar labour market characteristics. Second, the results from this study were based only on workers' compensation claims data from Safe Work Australia. These data capture information on compensation claims only and do not reflect the additional burden associated with workplace incidents that do not progress to formal claims (McInnes et al., 2014). As such, our results are likely to be an underestimate of the total burden associated with injuries and illnesses of this nature. Third, in this study, we only considered workplace and location-specific characteristics. Many other factors related to workers' adaptability, personal risk factors, heat perceptions, and interventions in workplaces may significantly contribute to the geographic disparities in the risk, but these variables were not assessed due to the lack of availability of the datasets. Fourth, we have not adjusted for air pollutants in the models to estimate the association between OI and heat. While this could be considered as a limitation, previous studies have argued the need for such adjustments in heat-related studies (Buckley et al., 2014), as air pollutants act as a mediator rather than a confounder (Xu et al., 2019; Varghese, 2019). Furthermore, previous studies suggest that adjustments for air pollutants are likely to have a minimal effect on the heat-health associations (Zhao et al., 2019; Schifano et al., 2019). Fifth, we did not consider the potential for demographic changes over the projected periods. Although this could potentially lead to an underestimate of the overall impact of heat, it offers a straightforward interpretation of the results as it separates the impacts of global warming from other changes that may occur anyway even in a stable climate scenario (Vicedo-Cabrera et al., 2019). Finally, the indirect impacts on workers' health such as those arising due to more frequent extreme weather events such as excessive bushfires, floods, or droughts were also not considered in the future predictions.

5. Conclusions

This study provides a comprehensive spatial profile of the risk of occupational injuries and illnesses (OI) associated with hot weather conditions across three major cities in Australia. Risk assessment at the intra-urban city level revealed strong spatial patterns in the distribution of risk in all greater cities. The inland western regions in Greater Sydney and Greater Brisbane were at higher risk of OI. In Greater Melbourne, urbanized coastal areas were more vulnerable to heat effects. Regions characterized by lower vegetation, and lower socio-economic status were generally at higher heat-related risk of OI. Further, analysis stratified by various subgroups identified vulnerable groups of workers at a local level within the cities. These findings provide a strong base for policymakers and urban planners to implement location-specific risk prevention and mitigation strategies that should consider both climatic and workplace characteristics to mitigate the impacts of heat. Future projections suggest that Greater Sydney is the most vulnerable of the three cities in climate change scenarios.

Credit author statement

Syeda Hira Fatima: Conceptualization, Formal Analysis, Methodology, Writing-original draft preparation, **Paul Rothmore:** Conceptualization, Writing-reviewing and editing, Supervision, **Lynne C Giles:** Conceptualization, Writing-reviewing and editing, Supervision, **Peng Bi:** Conceptualization, Writing-reviewing and editing, Supervision.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence

the work reported in this paper.

Data availability

The authors do not have permission to share data.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2023.115855.

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CHAPTER 6

HEAT AND WHS: EVIDENCE FROM EXISTING HOT WEATHER POLICIES

Preface

Chapter 6 delves into an in-depth assessment of the effectiveness of the existing policy framework for WHS concerning the impacts of heat. This chapter addresses the last research question in this thesis, aimed at assessing the efficacy of existing heat-related policies institutionalised in high-risk industries to protect workers from ambient heat.

Section 6.1 of this chapter provides the authorship statement of the published article. Section 6.2 details the conducted systematic policy review to assess the existing hot weather policies implemented in the high-risk construction industry. This study is published in Safety Science in 2023.

Fatima, S. H., Rothmore, P., Giles, L. C., & Bi, P. (2023). Impacts of hot climatic conditions on work, health, and safety in Australia: A case study of policies in practice in the construction industry. *Safety Science*, *165*, 106197. https://doi.org/10.1016/j.ssci.2023.106197

Safe Work Australia has developed comprehensive guidelines aimed at managing the risks associated with working in hot weather. These guidelines are based on a robust risk management framework for addressing WHS risks.

Despite the availability of detailed guidelines, previous studies have identified organisational-level challenges in implementing them effectively. Contingent upon previous studies (Chapters 4 and 5), this chapter evaluates the policy implications of heat on WHS in the high-risk outdoor industry - the construction industry.

By approaching the assessment from a different perspective, this study sheds light on the impacts of heat on WHS in a unique context. This review is instrumental in gauging the efficacy and implementation of current policies, facilitating insights for enhancing WHS in the face of heat-related challenges.

6.1 Statement of Authorship

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Overall percentage (%)	75%		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
Signature		Date	25\08\2023

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);
ii. permission is granted for the candidate in include the publication in the thesis; and
iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

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6.2 Impacts of Hot Climatic Conditions on Work, Health, and Safety in Australia: A Case Study of Policies in Practice in the Construction Industry

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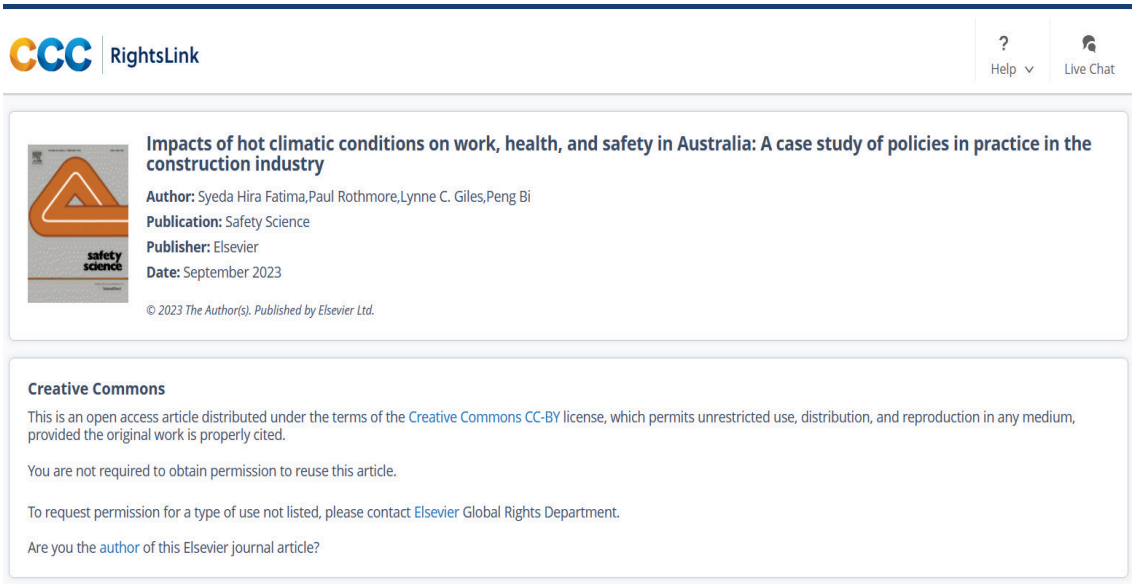

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Impacts of hot climatic conditions on work, health, and safety in Australia: A case study of policies in practice in the construction industry

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ABSTRACT

Workers in many industries are frequently exposed to hot weather conditions. To protect workers' health and safety, it is important to evaluate the existing heat-related policies practiced in workplaces in accordance with national guidelines. We used a case study design to evaluate the existing heat-related policies of a large construction company and five of its subcontractors according to the guidelines provided by safe work Australia (SWA). We used snowball sampling to acquire documents from the companies. The retrieved documents were analysed thematically using the framework approach. The main guidance themes and categories were developed deductively based on *"the guide for working in heat"* provided by SWA. The data was interpreted and summarized. Our results suggest that all policies advised on some administrative control measures, safe work practices for workers, use of personal protective equipment, and emergency response plans. The majority of policies focus on administrative control measures, which may not be practicable at all times and are not a high level of health and safety control if implemented alone. The policies do not comprehensively cover some most important aspects of heat stress management such as consultation with workers, risk assessment of heat hazard, promoting training and awareness programs among workers, and reviewing and evaluating control measures and heat stress incidents. Priorities for heat-related policy development include an increased emphasis on preparation and planning for hot weather in consultation with workers, along with considering location-specific, workplace, and individual risk factors in assessing the heat hazard at the workplace.

1. Introduction

In Australia, workers in many outdoor industries are frequently exposed to hot ambient conditions, as most parts of the country experience hot summers and frequent heatwaves that can last for a week or longer (Coates et al., 2014). Exposure to hot temperatures leads to a reduction in physical capacity, impaired mental alertness, and altered behaviour among workers (Varghese et al., 2018; Fatima et al., 2021; Parsons, 2014), which compromises work, health, and safety (WHS), labour productivity, and economic yield in occupational settings (Kjellstrom et al., 2009, Zander et al., 2015). Australian studies focusing on heat-related health impacts have found a significant association between the rate of occupational injury claims and higher ambient temperatures and heatwaves (Fatima et al., 2022; Mcinnes et al., 2017a; Varghese et al., 2019; Xiang et al., 2015a). For example; Xiang et al., found that the risk of occupational heat illnesses increased by 12.7% with each one-degree increase in maximum temperature above 35.5 °C (Xiang et al., 2015a). The risk of all occupational injuries and illnesses was estimated to increase by 16% above 32.3 °C in Adelaide (Fatima et al., 2022), and 14% at 38.9 °C in Melbourne (Varghese et al., 2019). Loss of productivity is also a major consequence of heat stress. In the 2013–2014 financial year, productivity loss in Australia due to climate-related heat stress was estimated at 6 billion dollars (0.33 to 0.47% of GDP) (Zander et al., 2015). In 2019, Australians working outdoors in the construction industry lost over 67,500 potential work hours due to heat stress, which was more than double the 1991–2000 average of 25,240 h (Beggs et al., 2021).

Increasing global temperatures and frequent, longer, and more intense heatwaves (Trancoso et al., 2020) will further jeopardize WHS, especially in high-risk outdoor industries (Humphrys et al., 2020; Levy and Roelofs, 2019; Moda et al., 2019). Other factors such as the aging workforce and increasing obesity may also contribute to the future burden of heat strain (Kenny et al., 2010; Mcinnes et al., 2017b). Without adequate interventions, climate change will exacerbate the

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burden of heat-related occupational injuries and illnesses, loss of productivity, and economic losses in vulnerable industries (Moda et al., 2019).

1.1. Heat risk in the construction industry

Among vulnerable working populations, those employed in the construction industry are the most susceptible to heat impacts because of the dynamic and informal nature of the industry (Rowlinson et al., 2014). Safe Work Australia (SWA), the Australian national WHS regulator has identified the construction industry as a national priority to reduce the number and rate of fatalities and serious claims in the *Australian Work Health and Safety Strategy 2023–2033* (Safe Work Australia, 2023). Exposure to heat in the construction industry varies greatly with the geographic location, nature of work, and stage of the project life-cycle (Rowlinson et al., 2014). For example, construction work is often performed outdoors with direct sunlight exposure on roofs and roadways, during the hottest times of the year (Acharya et al., 2018) or indoors in non-climate-controlled spaces, such as attics and crawlspaces. Other construction jobs may expose workers to process-generated heat, for example from welding and cutting torches or hot asphalt and paving machines, etc. (Echt et al., 2020). In addition to hot temperatures, high humidity, and low air movement may limit the body's heat loss (Hanna et al., 2011). Construction work also involves heavy physical labour work and the use of personal protective equipment (PPE). The most commonly used PPE in construction industries such as safety helmets, reflective vests, and hard boots, often increase workers' heat strain (Rowlinson et al., 2014). A study found that when the environmental temperature was 32.2 °C, the air temperature inside the workers' helmets was 43.7 °C (Jia et al., 2016). In these circumstances, workers will naturally get rid of PPE from time to time to reduce thermal discomfort but will be exposed to other workplace hazards as a result (Rowlinson et al., 2014). Furthermore, personal risk factors such as underlying medical conditions, lack of acclimatization, age, body weight, socio-economic status, use of alcohol and recreational drugs, and restricted fluid intake may also increase heat risk (Cramer & Jay, 2016; Nerbass et al., 2017; Taylor & Cotter, 2006).

1.2. Heat risk management in the construction industry

Previous studies have reviewed the methods of heat risk management in construction industries (Edirisinghe & Andamon, 2019; Rowlinson et al., 2014). Various heat indices have been suggested for environmental heat identification, including air temperature, heat index, Wet Bulb Globe Temperature (WBGT), physiological strain index, perceptual heat strain, thermal work limit, etc (American Conference of Governmental Industrial Hygienists, 2017; Al-Bouwarthan et al., 2019; Bates & Miller, 2002; Chan et al., 2013; Miller & Bates, 2007; Occupational Safety and Health Administration, 2017; Parsons, 2006; Australian Institute of Occupational Hygienists, 2013). However, there is little consensus on which index best fits the observed injuries and illnesses data in selected conditions and locations (Epstein & Moran, 2006; Goldie et al., 2017; Edirisinghe & Andamon, 2019). The American Conference of Governmental Industrial Hygienists (ACGIH) provides international guidelines for heat risk management at workplaces. ACGIH specifies the thresholds for heat stress based on a combination of environmental heat (measured as WBGT) and metabolic heat (i.e. workload) (American Conference of Governmental Industrial Hygienists, 2017). Workers with predisposing personal risk factors, or are unacclimatized or those who wear PPE have lowered exposure limits (American Conference of Governmental Industrial Hygienists, 2017).

Based on these indices, various strategies are recommended for workplace heat risk management globally, including engineering and administrative controls (Edirisinghe & Andamon, 2019). Some of the most effective strategies as suggested by previous research include mandatory work-rest arrangements and self-pacing, increased fluid intake, enhancing heat tolerance (acclimatization), ensuring regular screening of workers, setting up heat alerts, and supervision and training (Edirisinghe & Andamon, 2019; Morrissey et al., 2021; Morris et al., 2021; Rowlinson et al., 2014).

A few countries have also proposed heat-related labour protection guidelines. For example, SWA has developed its guidelines for managing the risk of working in heat, and the US National Institute for Occupational Safety and Health (NIOSH) has also developed heat standards for managing occupational heat stress and provides recommendations for employers on how to prevent heat-related illness (Safe Work Australia, 2020a, National Institute for Occupational Safety and Health, 2016). Similarly, the Chinese government also issued the first national regulation "Administrative Measures for Heatstroke Prevention and Cooling" (AMHP 2012) on the prevention of heatstroke in outdoor and indoor labourers in 2012 (Zhao et al., 2016). According to this policy outdoor work activities will halt when the temperature exceeds 40 °C (Han et al., 2021). Furthermore, some hot weather policies have been implemented in the construction industry. For example, the Enterprise Bargaining Agreement (EBA) of the Australian Construction, Forestry, Mining, and Energy Union (also known as CFMEU) states that workers will stop work and leave the site at 35 °C (Construction, Forestry, Mining, and Energy Union, 2016).

1.3. Overview of Australia's current WHS legislation and protection of workers from heat exposure

The Australian WHS legislation framework consists of legislated acts that set out health and safety principles in occupational settings, supported by WHS regulations that prescribe mandatory requirements. Codes of practice further explain the practical measures required for compliance with laws (Safe Work Australia, 2022a; Mcinnes et al., 2017b). Approved codes of practice are not mandatory but can be used in a court of law as evidence for reasonable workplace practices. For WHS acts, regulations, and codes of practice to have effect in jurisdictions they must be implemented in that jurisdiction. Australian standards, New Zealand standards, International standards, and other industry standards guide many workplace activities, processes, and procedures relating to health and safety issues (Mining and Quarrying Occupational Health and Safety Committee, 2017). Standards are not mandatory, however, if there is a law that refers to a specific standard for the performance of particular activities in the industry then the duty holder must conform to those standards (Safe Work Australia, 2020b). Other types of non-mandatory guidance materials and resources are also available to assist with the management of hazards in workplaces (Mining and Quarrying Occupational Health and Safety Committee, 2017). SWA is the national WHS regulator, responsible for the development and evaluation of the model WHS legislation to achieve nationwide consistent WHS laws in Australia. The Commonwealth, States, and Territories are responsible for implementing, regulating, and enforcing WHS legislation in their jurisdictions. Model WHS legislation has been implemented by the Commonwealth government and all Australian states and territories except Victoria, which has its legislation in practice (Safe Work Australia, 2022a).

Australian WHS laws require *"the working environment to be safe and without risks to health and safety of workers, so far as is reasonably practicable"* (Safe Work Australia, 2022b). This applies to health and safety risks, including occupational injuries and illnesses arising from working in non-optimum temperatures. Model WHS regulations given by SWA also specified "working in extreme heat or cold" as a workplace hazard. Thirteen out of twenty-six model codes of practice given by SWA identified heat as a potential hazard in workplaces, however, none of these specifically addressed the management of risks associated with working in the heat.

SWA has developed detailed guidelines for managing the risk of working in heat, which is based on the risk management framework for managing WHS risks (Safe Work Australia, 2018; Safe Work Australia,

2020a). All Australian state and territory regulators also provide detailed guidelines and resources regarding the hazard of working in heat on their websites (Northern Territory WorkSafe, 2022; SafeWork South Australia, 2023; WorkCover New South Wales, 2023; Workplace health and safety Queensland, 2018; WorkSafe Australian Capital Authority, 2023; WorkSafe Tasmania, 2012; WorkSafe Victoria, 2012; WorkSafe Western Australia, 2020). The guidelines provided by the states and territories broadly correspond with the "Guide for Managing the Risks of Working in Heat" provided by SWA (Mcinnes et al., 2017b). Risk management of heat in workplaces is a holistic process (Singh et al., 2015) and involves various steps to control and manage the risk of working in heat (Safe Work Australia, 2020a). The workers and their health and safety representatives (HSRs) must be consulted when managing the risks of working in the heat. The risk management framework includes steps such as: identifying the hazard, risk assessment, controlling risk using the hierarchy of controls (Safe Work Australia, 2020a), and reviewing controls (Safe Work Australia, 2020a; WorkCover New South Wales, 2023). The SWA guidelines also provide information on preparedness for working in heat and response to heat-related incidents. SWA suggests that the most effective control measures that are reasonably practicable in the circumstances should be implemented. Examples of control measures include eliminating the risk by stopping the work or by removing workers from the hot environment based on preliminary risk assessment; using mechanical equipment and automation of processes to reduce the need for strenuous physical work. Engineering controls such as the provision of fans or air misters, where possible, air-conditioned sheds or rest areas for outdoor workers; maintaining thermal comfort in an indoor office environment where practicable, provision of cool drinking water can be adapted. Administrative controls can be established further to minimize remaining risks and examples of these include: reorganizing work, rotating jobs, and relocating work to cooler areas, etc with adequate supervision, awareness, and training, encouraging safe work behaviour, and the use of PPE.

1.4. Organizational-level issues in the implementation of heat-related standards

Despite the existence of heat-related safety standards, programs, and regulatory requirements that have been developed for the protection of workers (American Conference of Governmental Industrial Hygienists, 2017; National Institute for Occupational Safety and Health, 2016; Safe Work Australia, 2020a; Australian Institute of Occupational Hygienists, 2013), there has been a reported increase in heat-related morbidity and mortality in workplaces (Gubernot et al., 2015). Various studies have identified organizational-level issues contributing to heat-related health impacts in different industries and occupations (Jia et al., 2019; Rowlinson & Jia, 2015; Varghese et al., 2020a; Varghese et al., 2020b; Lao et al., 2016; Oswald et al., 2018; Weber et al., 2018). An investigation of Occupational Safety and Health Administration (OSHA) heat enforcement cases found that 80% of employers do not comply with national guidelines for heat illness prevention (Arbury et al., 2014). They are usually perceived as a regulative burden to many businesses that affect productivity rather than effective tools to improve safety (Hale et al., 2015). A case study assessing the institutional factors contributing to heat stress in mega-construction project in Australia found that senior management is often reported to be unaware of the heat risk and does not change productivity expectations (Jia et al., 2019). Various exploratory studies suggested that informal rules and practices such as self-pacing are almost always overshadowed by progress pressure (Jia et al., 2019; Singh et al., 2015; Rowlinson et al., 2014). One study exploring workers' experiences with heat stress suggested that workers' heat perceptions vary from person to person. The reluctance of many workers to undertake protective behaviour may be related to peer pressure and accultured stereotypical attitudes due to lack of awareness and training (Lao et al., 2016). It has also been suggested that heat safety in the construction industry is not the responsibility of one person or the organization at an isolated level rather it involves the participation of all those who work and interact across all levels of the system (Woolley et al., 2020). Furthermore, evidence-based studies suggested that heat impacts may aggravate at moderately hot weather conditions before the onset of extremely hot weather (Fatima et al., 2022), but there is little focus on heat stress prevention in moderately hot weather conditions in occupational settings (Varghese et al., 2018). One study reviewed the Australian WHS acts, regulations, and other relevant material available to protect workers from the impacts of heat and suggested that location-specific research is required to quantify health impacts in occupational settings to determine what is actually happening in workplaces (Mcinnes et al., 2017b).

In the light of existing literature, it is also crucial to assess the effectiveness of existing heat-related policies implemented at the organizational level and how well they are aligned with the national standards. To the best of our knowledge, there is no study that has assessed the efficacy of heat-related policies that are in place in organizations for heat risk prevention. Such assessments will help to identify impediments in the implementation of heat management programs within the organizations and provide recommendations to enhance organizations' WHS actions and performance. Such assessments will also help to inform areas for improvement and will guide future research into heat hazards and the best practices to manage heat hazards.

In this study, we aimed to evaluate the existing policies of a large construction company and five of its subcontractors in Australia in accordance with the national guidelines provided by SWA, identify the existing gaps in the heat-related policies implemented by the construction companies, and propose recommendations.

2. Methods

Using a case study design (Yin, 2009), this analysis focused on a large construction company to assess its existing heat-related policies in accordance with the national standards of Australia. A snowball sampling (Ishak & Abu Bakar, 2014) was adopted to acquire the policy documents from the company and its subcontractors. The company provided us with its heat-related policy documents and the heat-related policy documents of five of its existing subcontractors, such as civil contractor, electrical contractor, structural steel contractor, mechanical contractor, and height safety contractor. As per the company's policy, all subcontractors should have their hot weather policy, which covers the workers under their control. However, regardless of subcontractors' policies, the company has the authority to change activities at its discretion to ensure the safety of workers. We acquired six heat-related policies, two sun protection policies, and one Quality, WHS, and environmental systems integrated management plan from the construction company and its subcontractors (Table 1). All these documents provide information on practical measures or standards that are adopted by the companies for heat risk management.

We analysed all policy documents thematically using the "framework analysis approach" (Pope et al., 2000; Goldsmith, 2021). Framework analysis is a commonly used qualitative research approach in applied policy (Srivastava and Thomson, 2009). SWA provides the model WHS framework and the state regulatory authorities that enforce WHS laws in their respective states, follow the guidelines given by SWA. It is the responsibility of State/Territory regulatory authorities to ensure that the practical measures translated in the industry are in accordance with the national guidelines. Therefore, we have assessed the heat-related policies of the construction company and its subcontractors in accordance with the guidelines for managing the risks of working in heat provided by SWA. Framework analysis consists of two main components: developing the framework of analysis and charting, sorting, and interpreting the data according to the developed framework. The main guidance themes and categories in the framework of analysis were identified deductively based on SWA's guidelines for working in the heat. To ensure the inclusion of all guidance and recommendation

Table 1
Policy/procedures document characteristics.

Industry type	Type of work	Document Type
Construction Company	*Commercial builders*	*Hot Weather Policy*
		Sun Protection Policy
Subcontractors		
Civil Contractor	*Civil works, demolition work*	*Working in Heat Policy*
Electrical Contractor	*Industrial electrical installation*	*Hot works Policy*
		Quality, WHS, and Environmental Systems Integrated Management Plan
Structural Steel Contractor	*Structural steel fabrication and erection works*	*Extreme Temperature Policy*
Mechanical Contractor	*Mechanical construction and services*	*Fatigue and Working in Heat Management Policy*
Height Safety Contractor	*Height safety solutions*	*Working in heat and cold*
		Sun safety

themes, six main categories were identified from the guidelines given by SWA. They are "preparedness", "identify hazards", "assess risks", "control risks" (by elimination, substitution, isolation, engineering, administrative, and PPE) "review control measures" and "response".

All policy documents were read thoroughly and the relevant data was extracted into the matrix of our predefined framework of analysis. To identify key patterns and gaps and to allow comparisons, all textual data in categories and themes were interpreted and summarized (Goldsmith, 2021). To give a descriptive overview of the existing policies, the frequency of recommended actions in each category was counted and presented in a summary table.

3. Results

Table 2 presents the summary of recommendations given in the hot weather policies of the construction company and its subcontractors against the set criteria of SWA's guidelines for working in the heat. The contents of the documents were summarized in terms of six main categories based on guidelines from SWA: "preparedness", "identification of heat hazard", "risk assessment", "control measures", "review controls", and "response plan".

Preparedness: Quantitative distribution of content in each category reveals that four policies suggested preparing for the minimization of heat-related risk at workplaces for example by *"arranging toolbox meetings"* and *"by informing the work plan at the beginning of each work shift where excessive heat is likely to be a problem"*. Only one policy suggested consultation with workers in the risk management process. No policy suggested the use of checklists or other supporting documents to assist preparedness.

Identification of heat hazard: Four policies identified heat as a hazard at workplaces such as *"Working outside on day of extreme heat is a safety issue recognized by the management team"* and *"…environmental conditions that may affect the health of the individual workers; working in high temperatures, minimal air movement, humidity, and around hot machinery"*. Although three policies explicitly defined extreme heat or hot weather conditions as a WHS risk for their businesses, there are discrepancies in the temperature threshold. For example, one policy identified temperatures over 35 °C as hot while one used 36 °C as their threshold, and one identified 38 °C as extreme temperature. Other climatic factors (such as humidity or air flow) were not used in any of the hot weather definitions. In terms of the hazard identification process, one policy suggested the involvement of stakeholders.

Risk assessment: Three policies suggested carrying out a risk assessment for undertaking work in hot weather conditions and identified the risk factors associated with heat stress such as; climatic factors, personal factors, and workplace factors. One document further explained the risk assessment process which will be carried out by identifying the seriousness of the hazard and how likely it is to cause harm and the type of control measures required to minimize the risk. No policy suggested the use of a heat stress calculator or expert advice for carrying out a risk assessment.

Control measures: Among controls, two policies suggested stopping work during hot weather conditions and one policy suggested eliminating workers from extreme temperatures. One policy suggested stopping work at a defined temperature i.e. 36 °C. Further, two policies explicitly discussed the financial implications of stopping work. One policy stated that salaried workers will be paid for the remainder of the day if they stop work during a hot day (when the temperature is above 36 °C). However, the policy does not apply to office and depot workers. Casual workers will only be paid for hours worked. The other policy states that *"if the employee feels unable to continue with his/her work duties he/she must notify supervisors prior to leaving workplace. Any lost work hours can be paid from employee's available annual leave entitlements"*.

Recommendations on using isolation or substitution as a control for reducing harm from the heat were usually lacking in the documents, only one policy recommended the use of mechanical aids to reduce physical exertion during hot weather.

Engineering controls such as the installation of cooling equipment and provision of rest areas and shades were mentioned in two to three policies. One policy provided further details advising that *"if there is no natural shade, physical barriers should be provided by installing temporary shade structures (awnings and shade cloths), if reasonably practicable"*. Four policies advised on the provision of cool drinking water for employees.

All policies provided some advice on using administrative controls such as *"rescheduling work to cooler parts of the day"* and *"job rotation"* (four policies), *"involving more people"*, *"providing frequent rest breaks"*, and *"reducing work load"* (two policies). Five policies advised on encouraging workers to keep hydrated. None of the policies advised the supervision of workers particularly new or young workers during hot weather conditions. Further, the policies did not advise acclimatization to hot working conditions. Only two policies explicitly mentioned the provision of training and information to workers about working in the heat. Four policies advised on some generic safe work practices for employees for example *"employees should take regular breaks"*, *"avoid heavy exertion"*, *"work at a sensible pace"*, *"avoid drinking coffee, tea, alcohol, and caffeinated soft drinks"* *"workers will Be responsible for their own sun protective practices at work"* and *"employees working in direct sunlight should ensure they are wearing the appropriate PPE"*.

All policies provided information on PPE and advised on the use of appropriate PPE to protect workers from heat-related risks such as loose clothing, covering arms and legs, wide-brimmed hats, and sunblock. However, most of the policies did not advise on assessing the heat-related risks associated with heavy protective gear used in many industrial operations. Only one policy mentioned that government-mandated instructions on wearing masks in close contact with others may increase the risk of heat stress and should be discussed with operation managers before making any decision.

Review controls: Two policies suggested, reviewing the control measures or the related policy documents on annual basis or when for example introducing new plants, equipment, or high-risk activities at the workplace. Only one policy suggested reporting and reviewing heat stress incidents.

Response plan: All policies suggested that if a worker reports symptoms of heat illness, immediate medical attention should be sought and first aid should be performed.

4. Discussion

This study reviews and assesses the existing policies in place in the construction industry and its subcontractors in accordance with

Table 2
Recommendations of the six hot weather policies against the set criteria of working in heat guidelines provided by SWA.

SWA Guidelines	Construction Company	Civil Contractor	Electrical Contractor	Structural Steel Contractor	Mechanical Contractor	Height safety Contractor	Summary
Preparedness							
deciding on how to manage the risks/consultation with workers or HSRs/preparing checklists	1	1	1	1	–	–	4
Identification of heat hazard							
monitoring weather conditions/involving stakeholders	1	1	1	1	–	–	4
Risk assessment							
Carrying out risk assessment/Identifying and assessing the risk factors/considering the impacts of hazards and the likelihood of causing harm	1	1	1	–	–	–	3
use of heat stress calculator/seeking expert advice for risk assessment	–	–	–	–	–	–	0
Control measures							
Elimination							
stopping work/eliminating workers from high-risk locations	1	1	1	–	–	–	3
Substitution and mechanical aids							
replacing manual work with automated tasks	–	–	–	–	–	1	1
Isolation							
separating workers from hot sources	–	–	–	–	–	–	0
Engineering							
Installation of cooling equipment and maintaining thermal comfort/shades/rest areas	1	1	1	–	–	–	3
Installation of insulation/ventilation	–	–	–	–	–	–	0
Reducing radiant heat	–	–	–	–	–	–	0
Availability of cool and clean drinking water	1	1	1	1	–	–	4
Administrative							
modifying targets and reorganizing work: regular breaks, relocation, rotation, avoid physical work during hot parts of the day	1	1	1	1	1	1	6
adequate supervision	–	–	–	–	–	–	0
allowing acclimatization	–	–	–	–	–	–	0
monitoring dehydration and hydration advice	–	1	1	1	1	1	5
information and training of workers	1	–	1	–	–	–	2
Advice for employees on safe work practices: take regular breaks and avoid exertion, prevent heat illness, call for assistance, look out for each other, avoid diuretic drinks, understand individual risk factors, avoid working alone	–	1	1	–	1	1	4
Use of PPE	1	1	1	1	1	1	6
assessing the risk of using PPE in extreme weather conditions	–	1	–	–	–	–	1
Review controls							
Review the control measures in consultation with workers	–	–	1	1	–	–	2
Review and report heat-related incidents	–	–	–	–	1	–	1
Response plan							
immediate medical assistance	1	1	1	1	1	1	6
ease of access to support services (Provision of the first aid fact sheet, which is easily accessible and understood by all workers)	1	–	1	–	–	–	2

Australia's national guidelines and recommendations for managing the risks of working in the heat. Our results identified the most common gaps in the existing heat-related policy framework, implemented in the construction company and its subcontractors. Such assessment will help to develop consistent and effective heat-related policies, which is crucial to protect workers from the growing impacts of working in the heat.

We found that the construction company and its five subcontractors have hot weather policies in place, and each policy provided recommendations on heat controls. However, the policies do not comprehensively cover some of the most important aspects of heat risk management. Consultation with workers or their HSRs about heat-related risk management is not reflected in a majority of policies. Many policies do not provide adequate information about carrying out risk assessments. Among control measures, stop work has been recommended with a majority of policies relying on administrative controls such as rescheduling work to cooler parts of the day, rotating jobs during hot weather, and use of PPE. The provision of training and information to workers, acclimatization, and reviewing and reporting of heat stress incidents are some of the important components of heat risk management, which are absent in the policy documents.

The majority of the policies broadly suggested preparing for working in heat. However, the policies do not suggest a consultation with workers or their HSRs when deciding on how to manage the risks of working in the heat. The guidelines from SWA and the regulatory bodies from Australian states and territories suggest that the employer must consult with workers who are likely to be directly impacted by heat hazards, when possible. To effectively manage the risks of heat stress in workers exposed to hot weather conditions, heat risk management plans

should be discussed, developed, and implemented in consultation with workers and their HSRs (Safe Work Australia, 2020a). Toolbox meetings are a good forum to get workers' feedback in the decision-making process (WorkSafe Western Australia, 2020; WorkCover New South Wales, 2023).

The risk assessment should be carried out where necessary by considering the impacts of heat and how likely it is to cause harm (Safe Work Australia, 2020a). Occupational hygienists can be engaged when required. Information on formal workplace risk assessment during hot weather conditions is not adequate in the reviewed policy documents. Some policies relied only on predetermined 'stop work' temperatures to enforce controls. The guidelines by SWA or other jurisdictions do not specify a 'stop work' temperature. It is important to understand that the prevention of heat-related injuries/illnesses is a complex process and there is no workplace exposure standard or limit for heat stress (SafeWork South Australia, 2023). Setting a safe/unsafe limit based only on temperature metrics is not appropriate and has been criticized previously (Workplace Health and Safety Queensland, 2017; Bates & Miller, 2002; Montazer et al., 2013; Edirisinghe & Andamon, 2019). Further, it is not a practical control measure when several hot days with temperatures above the threshold are forecasted.

Some of the important location-specific, workplace, and personal factors that should be considered when implementing heat controls include climatic factors such as humidity, wind speed, and solar radiation, in addition to air temperature, the nature of work i.e. physical workload and use of PPE, radiant heat from other sources, and individual factors such as acclimatization and physical fitness (Morrissey et al., 2021; Rowlinson et al., 2014). Heat indices can be used to assess the physiological strain associated with heat in construction industries (National Institute for Occupational Safety and Health, 2016; American Conference of Governmental Industrial Hygienists, 2017). Work Safe Queensland provides extensive details on the risk assessment process and suggests the use of a heat stress calculator, which can potentially provide a good start to assess the location-specific risk of heat stress at the workplace. A heat stress calculator considers many of the above-mentioned risk factors and can be used for preliminary assessment by people with limited technical expertise (WorkSafe Western Australia, 2020; Workplace Health and Safety Queensland, 2017). If the calculator determines an unacceptable level of heat stress and the work involves physical labour and the use of PPE then heat indices such as predicted heat strain, thermal work limit, and physiological monitoring can be used. These assessment procedures require a range of measuring equipment and expertise (Australian Institute of Occupational Hygienists, 2013; WorkSafe Western Australia, 2020; Workplace Health and Safety Queensland, 2017; WorkSafe Victoria, 2012). Due to frequent changes in working environments in the construction industry, site supervision staff needs to make instant managerial decisions to mitigate heat risks. It is, therefore, crucial to have a set of localized, simplified, and realistic thresholds to implement heat controls for heat risk management (Rowlinson et al., 2014).

Further, stopping work has financial implications. Although employers and employees are often motivated to combat heat stress in workplaces, potential conflicts of interest can arise in desired outcomes (Singh et al., 2015). For example, stopping work at a certain temperature can impact the progress of the planned activities and increase the overall cost and payments involved. A common WHS barrier reported in previous studies is that employers tend to prioritize their project goals over the health and safety of workers and therefore would not want to stop work even when the heat stress risk is very high (Jia et al., 2019; Morris et al., 2021; Singh et al., 2015; Weber et al., 2018; Williams et al., 2020; Xiang et al., 2015b). Workers who are employed on a casual basis may wish to keep working irrespective of heat conditions to preserve their income. Not paying workers for the lost hours will push them to work even in heat-stress conditions, which can potentially increase the risk of occupational heat stress (Varghese et al., 2020a).

The majority of policies advised administrative controls for the management of heat risks. However, some of the administrative controls may not be practical at all times (Morris et al., 2021; Singh et al., 2015). For example, rescheduling work to cooler parts of the day and providing shades can potentially help in reducing injuries but may not be practicable in all instances due to the nature and requirements of job tasks (Varghese et al., 2020a; Uejio et al., 2018). Further research is required to investigate the feasibility and trade-offs of shifting tasks to reduce heat exposure (Uejio et al., 2018).

Previous studies have also argued that some safety rules lead to counter-safety behaviours and outcomes (Singh et al., 2015). For example, PPE standards to protect workers from sun and heat require workers to use long-sleeved PPE, however, employees sometimes do not comply with PPE requirements stating that it is too hot to wear long-sleeved shirts in summer, resulting in more heat-related complaints (Singh et al., 2015). Moreover, heavy protective gear, certain fabrics, hard hats and materials frequently used in construction industries block airflow and can make workers feel hotter and lead to an increased risk of heat stress (Rowlinson & Jia, 2015; Rowlinson et al., 2014; Safe Work Australia, 2020a). Exploratory studies also suggested that workers want safety rules related to PPE to be more flexible so that their actions are not perceived as unsafe violations (Oswald et al., 2018). While all policies advised on using PPE, it is also important to assess the risks involved in using PPE in tasks being performed. We found that there is a lack of information on the assessment of PPE used for certain tasks in the majority of policy documents. Previous studies have also highlighted this issue (Lao et al., 2016; Williams et al., 2020). It is necessary to find a practical solution to deal with this challenge which may need multi-sectoral collaboration. For example, PPE with new fabric and technology for better airflow might be welcomed by workers in construction industries.

Many administrative control strategies are effective, economically viable for organizations to adopt, and feasible for workers to implement to manage heat stress, but require adequate planning, supervision, and training (Safe Work Australia, 2020a). For example; job rotation, self-hydration, and adequate work-rest periods are found to be quite effective in managing heat stress (Rowlinson et al., 2014; Yi & Chan, 2013; Varghese et al., 2020b). Job rotation accommodates work-rest periods and the use of cooling strategies to expedite heat dissipation. A work schedule is required for rotating duties, with the allocation of adequate time and sufficient workers to allow the completion of tasks (Urban Utilities, 2022). Physically demanding tasks should be regularly rotated among workers to prevent heat illness. Job rotation can also help workers in developing acclimatization (Urban Utilities, 2022). Studies suggested that adequate work-rest schedules optimize productivity and safeguard the health and safety of construction workers (Acharya et al., 2018; Yi & Chan, 2013). However, they should be formally mandated in heat risk management policies and must be carried out under adequate supervision and training (Rowlinson et al., 2014). Self-pacing is also reported to be an effective way of preventing heat illness in the construction industry (Bates & Schneider, 2008). Previous studies suggested that although workers are generally aware of protective measures such as work-rest schedules and self-pacing, pressure for work progress imposed by supervisors does not allow workers to reduce their work rate (Williams et al., 2020; Xiang et al., 2016). The employer's perception of the so-called reduction in productivity associated with regular rest breaks and self-pacing may be fallacious (Rowlinson et al., 2014). It is likely that a fatigued worker makes more mistakes and has to redo work or is vulnerable to an accident, which will involve more costs (Rowlinson et al., 2014). Indeed, it is employers' responsibility to consider environmental conditions in planning and costing work.

We found that the policies we reviewed from the construction company and its subcontractors lack information on adequate supervision of employers and training and information for workers. Effective implementation of heat management controls requires supervision, effective communication and information, and appropriate training of workers to ensure workers are adequately prepared, particularly

inexperienced and young workers (Safe Work Australia, 2020a). Training and information would provide workers with the necessary understanding of the risks of heat exposure, potential risk factors and predisposing factors, acclimatization, safe work practices, and work-rest regulation which are critical elements of managing heat risk (Workplace Health and Safety Queensland, 2017, Purohit et al., 2018). Trained and educated workers will be well aware of the heat impacts and will be able to adopt safe work practices such as self-pacing and hydration without excessive peer pressure, task completion pressure, and monetary incentives (Rowlinson et al., 2014).

Acclimatization is an important aspect of heat risk management which was missing from all policies. Acclimatization is the physiological adaptation of the human body to heat (National Institute for Occupational Safety and Health, 2016). Human populations are naturally acclimatized to their local climates, in physiological, behavioural, and cultural terms (Edirisinghe & Andamon, 2019). In occupational settings, excessive exposure to hot conditions can significantly increase the risk of heat stress, particularly in new, young, migrant, fly-in/fly-out workers and those returning from long leaves as their body is not acclimatized to hot environments (Safe Work Australia, 2020a). Evidence from previous studies suggests that around 73% of heat-related incidents occur in the first week of work (Tustin et al., 2018). An analysis of OSHA heat-related illness reports in the US suggests that 99% of employers failed to: develop heat tolerance among workers, monitor environmental conditions, enforce mandatory rest breaks during hot weather, and provide shade, and fluid replacement strategies (Tustin et al., 2018). Acclimatization can be achieved by gradually increasing controlled exposure to heat over 3–7 days (Rowlinson et al., 2014). The NIOSH standards also emphasize the importance of enhancing heat tolerance, which has been successfully implemented in other industries (Edirisinghe & Andamon, 2019). Acclimatization protocols can be practically and feasibly adapted in the construction industry and can be incorporated as mandatory programs in existing heat prevention policies. It should be noted that there is a limit to the body's physiological adaptation to heat, therefore acclimatization programs should be developed in consultation with occupational hygienists (Safe Work Australia, 2020a).

The policies broadly encouraged some safe work practices, but most of the policies did not articulate how employers can ensure that workers are complying with these safe work practices. The text in the majority of policies relies on advising employees rather than setting strict measures, which suggests that the locus of responsibility for coping with heat lies with the individuals, rather than the employers. It is noteworthy that occupational health risk associated with heat is not only the responsibility of individual workers but should be implemented as a systematic WHS intervention, where the principal responsibility lies with the employers (Safe Work Australia, 2020a; Singh et al., 2015).

Reviewing the control measures is a fundamental step in the heat management process but is missing from the policies (Safe Work Australia, 2020a). Reporting and reviewing hazards are important processes to assist in assessing the effectiveness of control measures and maintaining a safe working environment. They provide baseline data essential to develop evidence-based prevention strategies. Previous studies suggested that under-reporting of heat incidents is widespread in workplaces (Singh et al., 2015). SWA also advises that workers should be able to identify and report hazards and employers should review near misses, incidents, and injury records (Safe Work Australia, 2020a). Our study has shown that while heat-related policies were in place at the organizational-level in the construction industry that we were able to access, there were important omissions in the policies in terms of managing heat risks. As well, a unified framework to assess such policies was lacking. Policy assessments will improve implementation of heat management programs within organizations and could also be of benefit in enhancing organizations' WHS culture and performance. Such assessments will also help to inform areas for improvement and shape best practices to manage heat hazards in organizations.

4.1. Limitations

Limitations of this study include a small sample size of policy documents gathered from one company and its subcontractors in one industry, so we advise caution in the generalizability of results. While the documents were gathered from different types of contractors (for example civil works, height safety, electrical workers, etc.), it is likely that only those companies who have heat stress policies in place provided the documents. The policy documents were acquired from one construction company and its subcontractors so we cannot compare the findings across different companies, different industries, or different jurisdictions in Australia. We focused on policy documents only and these documents do not generally provide details on operational procedures and how the issue is being managed in the workplace. Finally, this review does not comment on how the policies are being enforced in workplaces and their effectiveness.

5. Conclusions

Hot weather conditions present a serious hazard for WHS. As we are transitioning to a hotter and more intense climate, it is important to have well-developed and readily accessible heat-related policies at workplaces. This review of existing policy documents from a construction company suggests that the development and implementation of heat-related policies is still in its infancy and needs further improvements. SWA guidelines serve as a good reference model for companies to structure their heat-related policies. Priorities for heat-related policy development include an increased emphasis on preparation and planning for hot weather in consultation with workers, along with considering location-specific, workplace, and individual risk factors in assessing the heat hazards at the workplace. Pursuing these priorities could lead to the implementation of practical control measures in a timely and effective manner. Mandating work-rest regimens and self-pacing, promoting awareness, and introducing training, acclimatization, and fitness programs among workers may also mitigate some of the risks of heat stress. Adequate supervision, review, and evaluation of control measures, heat stress incidents, and near misses at the workplace, and the development of practical and effective response plans must be prioritized in the development and revision of policy documents.

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CRediT authorship contribution statement

Syeda Hira Fatima: Conceptualization, Formal analysis, Methodology, Writing – original draft. **Paul Rothmore:** Conceptualization, Writing – review & editing, Supervision. **Lynne C. Giles:** Conceptualization, Writing – review & editing, Supervision. **Peng Bi:** Conceptualization, Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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CHAPTER 7

DISCUSSIONS AND CONCLUSIONS

Preface

The thesis explored the impacts of heat on OI and the efficacy of heat-related WHS policies implemented at workplaces in Australia. It involved a systematic review of previous literature and a meta-analysis that assessed the impacts of heat on OI in different climate zones of the world and identified the existing research gaps (Chapter 2). Chapter 3 describes the methodological framework utilised in this thesis. The thesis aimed to address the following research questions:

1. What is the association between ambient temperatures and the risk of OI and the heat-attributable burden of OI at the intra-urban scale in four large cities of Australia, including Adelaide, Brisbane, Melbourne, and Sydney?
2. What are the environmental, personal, and workplace characteristics of the workers at risk during hot weather?
3. What is the predicted future risk of OI associated with projected climate change scenarios (RCP 4.5 and 8.5) in four major cities of Australia?
4. How well are the heat-related policies institutionalised in the high-risk construction industry in accordance with the Australian national guidelines to protect workers from ambient heat?

Chapters 4, 5, and 6 collectively addressed the above-mentioned research questions. Chapters 4 and 5 focused on fine-scale intra-urban risk assessment of heat-related OI using gridded meteorological datasets, identifying the associated risk factors, and estimating the future projected risk in four large cities in Australia. Chapter 6 evaluated the existing heat exposure policy framework established in a high-risk industry. This study was carried out to identify gaps in existing heat-related policies and their implementation and to provide recommendations.

Chapter 7 summarizes the key findings concerning the research questions in Section 7.1. The significance of the thesis is discussed further in Section 7.2, followed by overall limitations and future directions in Sections 7.3 and 7.4, respectively. The chapter will be concluded with conclusions in Section 7.5.

7.1 Key Findings

7.1.1 Spatiotemporal Association between Heat and OI

7.1.1.1 Overall and Regions-Wise Risk Estimates

The association between heat and OI is complex. The risk of OI varies spatially, even within a city, and the regions with characteristic hot weather conditions are generally at higher risk of OI.

In Greater Adelaide (Chapter 4), the cumulative risk of heat-related OI was estimated to be 16.7% at moderate heat (90th percentile of maximum temperature) and 25.0% at extreme heat (99th percentile of maximum temperature). The city is characterised by a combination of Cold Semi-Arid and Mediterranean climates. Regions characterised by a Cold Semi-Arid Climate in the northern and western parts of the city were particularly at higher risk of OI for workers at moderate heat (up to 24.3%). Regions with cool Mediterranean climates in the southern and eastern parts of the city were at higher risk of OI at extreme heat (up to 40.5%).

In Greater Brisbane and Greater Sydney (Chapter 5), workers in western regions of the cities were characteristically at higher risk of heat-related OI, particularly at extreme heat (up to 25.9% and 32.3%, respectively). Greater Brisbane and Greater Sydney have Humid Subtropical climates, although coastal areas near the central business district are generally cooler than inland western regions due to the maritime effect and land morphology. The local climate in Greater Sydney is also significantly influenced by the urban heat island effect, resulting in a significant temperature gradient between coastal areas and western parts of the city (in the foothills of Blue Mountains). Greater Melbourne has a temperate Oceanic climate. The inner-city areas near the central business district are generally at high risk of heat-related OI for workers (up to 20.5%), as previously noted in Chapter 5.

In temperate climates like Greater Adelaide and Greater Melbourne, the effect of heat on OI was immediate, while Greater Brisbane and Greater Sydney had lagged effects of hot weather conditions on OI.

7.1.1.2 Heat-Related Attributable Fractions (AF) of OI

The overall cumulative heat-related AF of OI for all four cities is given in Table 7.1. Most of the heat-attributable OI were attributed to moderate heat (4-9%). The attributable fraction of OI associated with extreme heat was relatively small. SA3 regions characterised by warmer conditions generally had higher heat-related AF of OI, for example, the north-western hot regions of Greater Adelaide, the western outskirts in Greater Brisbane and Greater Sydney, and the inner urbanised areas in Greater Melbourne.

Table 7.1 Cumulative AF of OI associated with heat in four large cities in Australia.

Location	AF associated with moderate heat	AF associated with extreme heat
Greater Adelaide	4.37 (3.20, 5.10)	1.73 (1.48, 1.86)
Greater Brisbane	7.86 (6.22, 9.30)	0.96 (0.72, 1.20)
Greater Melbourne	9.91 (8.54, 10.51)	1.57 (1.36, 1.66)
Greater Sydney	9.78 (8.77, 10.68)	1.43 (1.29, 1.56)

7.1.2 Environmental, Personal, and Workplace Characteristics of the Workers at Risk

The association between heat and OI does not only depend on temperature conditions but also on personal characteristics of workers (for example, age and gender), workplace characteristics (for example, types of occupation, type of work, and types of exposure), and location-specific characteristics (i.e. hot vs. cool regions, high vs. less vegetated regions, high vs. low socio-economic index). Overall, younger workers (age < 45 years), male workers, those engaged in heavy physical work, and those working predominantly in outdoor locations were at higher risk of OI at both moderate and extreme heat in the four cities (Chapters 4 and 5). The complex interactions between the local climate and the built environment play an important role in the spatial patterns of heat-related OI risk. Workers in regions with less vegetation and of lower socio-economic status were found to be vulnerable to the impacts of heat.

SA3 region-wise subgroup analysis based on gender, age, type of industries (indoor and outdoor), and type of claims (occupational illnesses only and occupational injuries only) reveal significant geographic variations within cities. Outskirts of the cities were consistently

more vulnerable to the impacts of heat for workers in outdoor industries. These areas also posed a higher risk for occupational injuries only. In all four cities, inner-city SA3 regions demonstrated a consistent pattern of increased vulnerability for workers in indoor industries and those suffering from occupational illnesses only (Chapters 4 and 5). Workers' responses to heat, in terms of their age and gender, varied across different cities.

7.1.3 Predicted Future Risk of OI Associated with Projected Climate Change Scenarios (RCP 4.5 and 8.5)

The risk of OI and AF associated with projected climate change scenarios RCP 4.5 and 8.5 is predicted to increase by mid-century. In Greater Adelaide, the risk is projected to increase by 1.3% by the 2050s (RCP 8.5, CANESM2).

For Greater Brisbane and Greater Sydney, the risk of OI is projected to increase by 4.5% and 6.5%, respectively, in the 2036-2065 projected period in the RCP 8.5 scenario (NorESM1-M). The heat effects were found to be consistent for Melbourne, without any significant change. These findings suggest that the impacts differ across geographical regions due to variations in local climatic conditions. There are geographical variations in the impacts based on local climatic conditions. It was found that regions with warm baseline climates, for example, Greater Sydney and Greater Brisbane, were more vulnerable to the impacts of heat and showed a higher increase in the risk of OI in projected climate change scenarios. Previous studies also indicated similar patterns in multi-location assessments (17, 149). The comparisons of AF of heat-related OI associated with heat in different projected time periods suggest that it will increase rapidly by mid-century for both RCP 4.5 and 8.5. For example, the AF of heat-related OI in Greater Brisbane is projected to increase from 0.12 to 0.57% by the 2030s and up to 0.75% by the 2050s under RCP 8.5. Similarly, in Greater Sydney, the AF of OI will increase from 1.76 to 2.40% by the 2030s and up to 2.85% by mid-century.

7.1.4 Heat-Related Policies Institutionalised in the High-Risk Construction Industry in Accordance with the National Guidelines to Protect Workers from Ambient Heat

In the face of climate change, the increasing severity of hot weather conditions poses a significant risk to WHS. To adapt to climate change, it is crucial to have well-established and easily accessible heat-related policies at workplaces. The heat-related policies of one construction company and its five subcontractors were used as a case study in accordance with SWA's national guidelines for working in the heat. Although the hot weather policies included guidance for heat control measures, they lacked comprehensive coverage of crucial aspects related to managing heat risks. One major gap identified was the absence of consultation with workers or their health safety representatives (HSR) regarding heat-related risk management.

Additionally, many policies failed to provide sufficient information on the performance of risk assessments and relied on stop-work temperatures to halt work activities. Such approaches are unlikely to protect workers adequately and may become impractical due to productivity pressure. Several policies suggested the implementation of administrative controls, such as adjusting work schedules to cooler times of the day, rotating job tasks during hot weather, and utilising PPE. However, the policy documents lacked essential components of heat risk management, such as offering training and information to workers, implementing acclimatization measures, and establishing protocols for reviewing and reporting heat stress incidents.

The findings suggest that the development and implementation of heat-related policies are still in their early stages and require further improvement. The guidelines provided by SWA serve as an excellent framework for companies to structure their heat-related policies. The guidelines suggest that workplaces should consider location-specific, workplace, and individual risk factors in assessing heat hazards at the workplace.

7.2 Significance of the Thesis

To my best knowledge, this is the first study to assess the risk of OI associated with hot weather conditions at an intra-urban scale to provide location-specific risk assessment with accurate exposure assessment (Chapters 4 and 5). The existing policy framework was evaluated in a case study, within the high-risk construction industry (Chapter 6). Such studies provide the needed scientific evidence for the development of location-specific heat health interventions in the workplace.

Integrating geospatial environmental datasets with workers' compensation claims data makes it possible to obtain valid and reliable epidemiological evidence that helps identify the effects of hot weather conditions on WHS at a localised level. This approach is particularly valuable in urban settings, where temperature gradients exist due to the influence of local climate patterns and anthropogenic activities.

The intra-urban epidemiological assessments of OI associated with heat provide valuable insights into the spatial variability of heat-related health impacts on WHS based on environmental conditions such as heat intensity, humidity, urban heat island effect, the availability of green spaces, and social determinants. The findings also helped to identify high-risk areas for OI and vulnerable groups of workers based on age, gender, type of industry, and type of claims, who are likely to be at higher risk of heat-related OI in different regions within cities. The findings will have implications for OI risk prevention and mitigation by local governments and state authorities. These areas can be targeted for tailored WHS interventions and resource allocation. A time series study design incorporating temporal trends in the datasets helped to identify long-term health effects of heat exposure, providing insights into long-term adaptation strategies and informing preventive measures.

The policy review revealed gaps in the current heat risk management policies within the high-risk construction industry. Through this process, we have also developed recommendations that can support policymakers, employers, and public health officials in making well-informed and practical choices for implementing heat controls, thus enhancing risk management at workplaces.

Such comprehensive studies have significant implications for the most vulnerable areas, including WHS planning and healthcare provision, WHS advocacy, urban planning, and infrastructure development. They also contribute to preparedness in addressing the impacts of climate change, identifying social determinants of vulnerability, emergency preparedness efforts, insurance and financial risk management, as well as fostering community engagement and education.

WHS Planning and Healthcare Provision: Intra-urban risk assessment can help local governments, WHS representatives, unions, and industries to develop and implement targeted interventions to protect the health and well-being of workers related to hot weather. This information can guide the development of targeted interventions such as heatwave response plans, early warning systems, and the deployment of resources where they are most needed. The findings can support the development of policies and guidelines to protect workers from heat-related health risks, for example, by developing heat vulnerability maps, or they can serve as the baseline for developing heat health information systems.

WHS Advisory: The findings have implications for improvements in WHS advisory and heat stress management guidelines. Specifically, the investigation in Chapters 4 and 5 underscores that workers face notable risks of OI even during moderately hot weather conditions. This risk arises due to a complex interplay of environmental, workplace, and personal factors. Notably, these contributing factors are not currently considered in the prevailing temperature thresholds that dictate when work should cease due to heat. A range of additional variables, including humidity levels, the nature of the tasks being performed, and personal factors such as underlying health conditions, can significantly amplify workers' susceptibility to heat-related issues at different temperature levels. The findings can have significant implications in terms of risk reduction, as most of the burden of OI is associated with moderate heat. Moreover, the analysis of policy documents (Chapter 6) reveals that construction companies often rely on stop-work temperatures instead of a formal risk assessment to implement heat controls. This observation underscores the importance of transitioning toward location-specific risk assessments as we confront increasingly hot and intense climatic conditions. Predefined high-temperature thresholds, which may not be practical and might not safeguard all workers even under moderate conditions, need to be

replaced by comprehensive and customised evaluation tools. These findings have implications within Australia as well as internationally as many heat-related policies for workers rely on stop-work temperature, for example, China's 2012 regulation "Administrative measures for prevention and cooling" (AMHP) (150).

Urban Planning and Infrastructure Development: Understanding the spatial patterns of heat-related health impacts can also inform urban planning and infrastructure development strategies for local governments. For example, highly vulnerable suburbs could be targeted for the development of green spaces, incorporating green infrastructure and green building design, installation of cooling stations and shaded structures for better adaptation and heat mitigation, improving the built environment, and updating building codes to improve thermal comfort. These measures can mitigate the health risks associated with heat exposure and create healthier working environments. The study identified that some areas are typically at higher risk of OI for heat-related health impacts, for example, Western regions of Greater Sydney. Studies suggest that Western Sydney is generally 5°C hotter than Eastern suburbs because of the natural land morphology, limited greenspace, and urban heat island effect (85, 103). Addressing heat vulnerability in these regions requires a comprehensive and multi-faceted approach involving various stakeholders.

Impacts of Climate Change: By estimating the future burden, such assessments can help identify vulnerable groups of populations and geographic areas at high risk of OI in future projected scenarios. The research findings highlight the importance of planning and preparedness for more intense conditions and provide guidance for health and safety advisors in the development of health and safety protocols and regulations to protect workers from heat stress and extremely hot weather events due to changing climate conditions.

Identifying Social Determinants of Vulnerability: These assessments also helped to understand the social determinants of vulnerability, such as socio-economic status and co-morbidity to hot weather and how they interact with occupational health outcomes. Integrating these considerations in the epidemiological assessments can help to identify disparities in the availability of resources for vulnerable populations and inform that interventions should be tailored to the needs of local populations.

Emergency Preparedness Efforts: Findings from these studies can help prepare for extreme weather events. Heatwaves are amongst the deadliest natural hazards (151, 152). They have claimed more lives than any other natural disaster in Australia (152). Location-specific epidemiological risk assessments can aid emergency response agencies in developing effective plans and protocols to address these events, particularly in highly vulnerable regions, and address community needs promptly.

Insurance and Financial Risk Management: Occupational heat stress has serious financial implications. Health insurers (for example, workers' compensation schemes in Australia) can utilize the information from epidemiological risk assessment to assess risk accurately by considering potential risk factors, determining premiums, and developing policies that incentivize heat resilient measures. Further, the policy review suggests that heat stress is a major issue in vulnerable industries. Some employers do not comply with the heat prevention guidelines as they perceive them as a regulatory burden affecting productivity rather than a tool to improve safety. Not paying workers for the lost hours during extremely hot weather conditions will push them to work even in heat-stress conditions, potentially increasing the risk of occupational heat stress (153). Implementing location-specific and workplace-specific heat controls can reduce the impacts of heat and will reduce the financial implications involved in stopping work at a threshold temperature.

Community Engagement and Education: Communicating these findings to workers' groups, unions, HSRs, government regulators, and other stakeholders can raise awareness amongst workers, foster community engagement and promote proactive measures across the board. Risk assessment can be used to develop educational campaigns and behavioural interventions that encourage workers to adopt climate-resilient behaviours and take necessary precautions to protect their health.

Overall, these studies evaluating the occupational health impacts associated with hot weather conditions at a spatiotemporal scale can facilitate heat-related risk prevention, planning, targeted intervention and informed decision-making to protect WHS and increase WHS resilience in the face of heat-related challenges. In-depth policy reviews provide practical implications for improving existing policies to help adapt to hot weather conditions in the face of climate change.

7.3 Overall Limitations

The epidemiological assessments of OI associated with heat impacts relied only on workers' compensation claims data. Although this dataset represents 90% of the workforce in Australia (127), it only includes reported OI claims, and employees may not report the incidents to their supervisors/line managers, WHS representatives, or employers. The reasons could be that they feel it is unnecessary to report mild OI, are unwilling to undertake the compensation process, are unaware of their eligibility, or are apprehensive about the process and its impact on their employment. The workers' compensation claims data do not include workers not covered by the state compensation schemes, excluding self-employed workers, employees with separate private schemes that partially or completely cover payments, and workers with national compensation schemes. Some claims were excluded during the analysis, when POA was not given, beyond the study area, or during data transformation. Therefore, potential underreporting should be acknowledged.

The workers' compensation claims data does indicate the individuals' medical history, any existing comorbidities, migration status, or level of heat acclimatization, which are known risk factors for heat stress. Other factors related to heat perception and behaviours and any intervention strategies in places were also not considered in the population-level risk assessments.

The analysis was carried out at the SA3 level, which represents a regional population between 30,000 and 130,000 and required data transformation from POA based location of the workplace where the accident occurred. A smaller spatial unit of analysis, for example, SA2 or POA, was not chosen because of methodological challenges such as excess zero issues, which can potentially reduce the statistical power of the models (108, 109) or a temporal misalignment issue inherent in case of POA (107).

Some degree of exposure misclassification is likely to exist as the individuals' personal heat exposure was not identified, for example, due to process-generated heat sources or the confounding impact of air conditioning. However, localised exposure data was considered by utilising gridded data and assessing risk at the SA3 level. This sets our studies apart from

previous research that typically relied on weather station data or the average of gridded meteorological data at broader city or province levels (61, 65-67, 75). The exposure data were acquired at the SA2 level from gridded meteorological data and were transformed to SA3 using an area-weighted approach.

Further, maximum temperature was used as the primary exposure metric in Greater Adelaide (Chapter 4) and the Heat Index as the exposure metric in the other three cities (Chapter 5). No consensus exists in the literature on the best exposure metric (154). In the study conducted in Greater Brisbane, Greater Melbourne, and Greater Sydney, the heat index was employed due to the prevalence of Humid Subtropical climates in many areas within these cities. Therefore, a composite metric that considers the combined effect of temperature and humidity was required (114). Sensitivity analyses were carried out to assess the impacts of different exposure metrics. The results were consistent, with all risk estimates indicating a positive increase in risk estimates with different exposure metrices (maximum temperature, minimum temperature, and mean temperature).

Further, the effect of air pollution on temperature was not considered. Previous studies show that adjusting for air pollution may lead to biased results instead of improved estimates because air pollution potentially acts as a mediator rather than a confounder (155). Further, adjustments for air pollution have minimal effect on the heat-health associations (82, 156).

Future predictions of the heat-related risk of OI associated with climate change were carried out at the city level instead of SA3 because future predictions are inherently uncertain, and the spatial risk assessments must consider a range of localised demographic factors as these changes are more pronounced at the local scale. These datasets were not available. Although not considering demographic changes in future projections could potentially lead to an underestimation of the overall impacts of heat, it offers a straightforward interpretation of the results, as it separates the impacts of global warming from other changes that may occur anyway, even in stable climate change scenarios (145).

It should also be noted that future projected datasets used Coupled Model Intercomparison Project (CMIP) 5 instead of the newer CMIP6 scenarios that incorporate Shared Socio-

economic Pathways. To my knowledge, no CMIP6 data with sufficient resolution exists to represent Australian cities. When these data become available, an investigation of the projected values using the newer scenarios should be undertaken to capitalize on the contemporary data.

For policy reviews (Chapter 6), the main limitation of the study was a small sample of policy documents gathered from one company and its subcontractors in the construction industry. Therefore, the results cannot be compared across different industries, workplace settings, or different states in Australia. In addition, the focus in this study, was on policy documents, and these documents generally do not provide details on how the issue is being addressed and enforced in the workplace.

7.4 Future Directions

This research has covered some of the most important aspects of heat impacts on workers' health and its prevention and mitigation. It has also opened new areas of research for further exploration.

7.4.1 Advancing Research on Heat-Related Health Impacts in WHS: Role of Environmental and Socio-economic Factors, Advanced Spatiotemporal Risk Assessments, Real-Time Heat Risk Assessments and Global Implications

Heat-related health impacts disproportionately affect vulnerable workers' populations, including low-income communities and marginalised groups of workers. The complex interplay of environmental and socio-economic factors plays a significant role in shaping this vulnerability to heat-related health impacts. Future research should be directed towards understanding these complex associations and their impacts on workers' health, particularly in the face of climate change. For example, in-depth epidemiological assessments should consider factors such as workers' access to greenspaces, availability of cooling infrastructure at workplaces, transportation options, and factors related to health equity such as access to healthcare facilities, housing conditions, and other socio-economic indicators. By considering these multilayered impacts of environment and social determinants on

vulnerability to heat, future research can inform targeted WHS interventions and policies to reduce health disparities. These studies will also ensure that interventions and policies are inclusive and targeted towards those who are most affected.

Location-specific epidemiological risk assessment can be used as baseline information to create heat health information systems tailored to local temperature conditions, the nature of work being performed, and workers' individual characteristics, which can help employers better prepare and plan for heat events at their workplaces and implement control measures in a timely and effective manner. These information systems can also help identify vulnerable groups and high-risk areas where response resources such as the availability of cooling equipment, shades, and emergency services are most needed. The interactive tools, data visualization tools, and user-friendly interfaces can facilitate the dissemination of information, aid decision-making processes, and foster community engagement.

There is a need to understand the individual level workers' perceptions and their behavioural strategies that are implemented to minimize heat impacts at workplaces. This information will have crucial implications for adaptive and prevention measures, especially for vulnerable working populations such as young workers, older workers, those undertaking outdoor work and those in high physical demand jobs. Furthermore, a major proportion of the labour force in Australia is represented by migrant (temporary or permanent) workers (26.3%) (157) who are more likely to be underpaid and overburdened (158). Previous studies from other countries highlighted the impacts of heat on migrant workers (159-161). Further, it is essential to address organisational-level issues and perceptions of employers, industrial associations, and unions about heat-related issues at workplaces. There is also a need to assess the detailed operational procedures to evaluate how heat policies are implemented at workplaces.

Rapid advances in data collection methods and modelling techniques can enhance the accuracy and resolution of spatiotemporal risk assessments. This includes incorporating high-resolution climate data and integrating more detailed information on population characteristics, health outcomes, and vulnerability factors. For example, we can develop and update urban heat maps by using high-resolution remote sensing technologies such as

satellite imagery, aerial imagery, and ground-based surveys. Further, by deploying sensor networks, including wearable devices and environmental sensors, investigators can acquire real-time data on individuals' physiological responses to heat stress and ambient temperature conditions. The sensor networks can provide real-time measurements for body temperature, heart rate, electrodermal activity, respiration rate and activity, and ambient environmental conditions. This information is not only crucial for research purposes but also for developing strategies to address heat stress at workplaces.

Future efforts should also be directed towards the development of biomarkers and technologies for early detection and monitoring of heat stress and physical demands in labour-intensive occupations, including hydration and electrolyte imbalance biomarkers, sweat analysis and genetic factors. Early detection biomarkers can provide valuable insights into an individual's physiological responses and susceptibility to heat stress and help identify the early signs and prevention of heat-related problems. They allow for identifying physiological changes that occur before the symptoms of heat stress appear, thus enabling timely interventions. Each individual worker responds to heat stress differently, and this personalised information can help employers and occupational health professionals develop tailored measures for individual workers, such as adjusting their workload and rest breaks.

Integrating the Internet of technologies with epidemiological studies will provide more accurate and granular assessments of heat impacts on health. Strengthening existing health surveillance systems to capture and monitor heat-related injuries and illnesses and mortality records is crucial. Integrating digital health records, emergency department visits, hospital admissions, and mortality data can help establish an association between heat exposure and health outcomes. Social media is another effective digital platform for real-time data assessment. These platforms offer valuable insights into how individuals perceive, behave, and are affected during heatwaves. Analysing this data can potentially help identify vulnerable groups, understand the community's response to heat warnings, and improve communication strategies for heat-related health risks. Artificial intelligence and machine learning can be used to uncover the complex interactions between heat exposure, individual susceptibility, and health outcomes. Artificial intelligence tools can also be used to predict potential heat stress incidents and pre-emptively implement cooling strategies.

Due to the increased uncertainty in projecting the risk of OI related to heat and its association with climate change, further evidence is needed to assess the potential impact of heat-related OI in the context of climate change. This could be done in countries with larger populations or by analysing and pooling results across multiple countries to provide evidence from larger datasets. This information can potentially enhance our understanding of projected heat impacts caused by climate change and will help to navigate towards more resilient and adaptive workplaces.

For more accurate future projections of heat-related risks, it is crucial to utilize the latest CMIP6 future scenarios that integrate socio-economic pathways. These pathways provide a nuanced understanding of how economic and societal factors interplay with climate change, shaping vulnerability and adaptive capacity. Integrating socio-economic dimensions into risk assessments enables a comprehensive evaluation of potential impacts, aiding in the formulation of more effective mitigation and adaptation strategies. By accounting for socio-economic disparities, these projections can yield insights into differential impacts on diverse communities, fostering the development of equitable resilience strategies and informed policy decisions.

In a global narrative, it is also crucial to assess the impacts of heat in other regions of the world, particularly in developing and underdeveloped countries, which represent a major proportion of the world's population who are more vulnerable to the impacts of heat. Evidence is required from these regions to fully understand the global impacts of heat in present and future projected scenarios and make informed decisions.

7.4.2 Advancing Heat-Related WHS Policies: Integrating Technology and Multifaceted Strategies for Effective Heat Stress Mitigation

Despite the abundance of evidence regarding the adverse effects of heat on WHS, there is a lack of effort in developing and implementing policies at workplaces, particularly at the organisational level. Key areas of focus for policy development regarding heat-related issues include placing greater emphasis on preparing for and planning during hot weather,

consulting with workers and their HSRs, and considering location-specific, workplace-specific, and individual risk factors when assessing heat hazards at the workplace.

By using recent advances in technologies, initial risk assessment can be done effectively using real-time heat strain monitoring wearable devices and mobile apps. These applications will allow the investigators to use a set of factors to carry out an initial risk assessment of the work scenario's potential risks and controls without requiring expensive equipment and expertise. These apps utilize factors such as temperature, humidity, solar radiation, work intensity, physiological indicators such as heart rate, core body temperature, and workers' individual factors to develop heat strain index specific to individuals. This can enable workers and supervisors to monitor their heat exposure levels and make informed decisions about work-related schedules, hydration and other preventive measures. By prioritising these aspects, practical control measures can be implemented promptly and effectively. The heat health information systems and mobile apps could be used to issue alerts and warnings based on specific thresholds and criteria. This will help to raise awareness and facilitate proactive measures to mitigate heat-related health impacts.

Mandating work-rest schedules and self-regulation, raising awareness, providing training, and implementing acclimatization and fitness programs for workers to help mitigate the risks of heat stress, particularly for vulnerable groups of workers. It is also important to ensure adequate supervision, review, and evaluation of control measures, heat stress incidents, and near misses in the workplace, as well as developing practical and effective response plans. These aspects should be given priority during the creation and revision of policy documents.

7.4.3 Advancing WHS in High-Risk Industries: Innovations in Engineering Controls and Protective Measures

In order to improve heat risk management in high-risk industries, future research should focus on developing more effective engineering controls. For example, technological advancements are crucial in several areas:

Smart Cooling Systems – Integrating smart sensors and data analytics to regulate cooling systems based on real-time weather conditions and workers' potential heat exposure levels, ensuring optimal cooling efficiency.

Improved Personal Protective Equipment (PPE): providing appropriate heat-resistant and breathable PPE, for example, lightweight, moisture-wicking clothing, the use of phase change materials that absorb and release heat to help in regulating body temperature or the provision of personalised cooling devices such as vests or wristbands.

Providing Shading Structures: Shading structures should be introduced in high-risk industrial zones, preferably solar-powered shades, that can automatically adjust angles to provide maximum shade during peak hours and minimize heat gain.

Developing Heat-Resistant Construction Materials: Heat-resistant construction materials have improved thermal properties, reducing heat absorption and minimising surface temperatures in buildings and equipment.

Drone Technology: Using drone technology equipped with infrared cameras to monitor heat exposure in real-time and identify areas of concern in large industrial sites or agricultural fields.

Integrating Heat-Responsive Automation Systems: Automatic heating control systems can adjust work processes or machinery operations to reduce heat exposure during hot conditions.

Future studies also need to comprehensively evaluate the effectiveness of these innovative engineering controls and heat mitigation measures. This could be done through various methods such as experimental studies, comparative analyses, perception insights through surveys and interviews, and cost-benefit evaluations. These evaluations will offer critical insights for creating evidence-based strategies to create safer and more productive work environments. By comprehensively gauging the impact of these measures, researchers can inform well-informed decisions aimed at optimising workplace safety and well-being.

7.4.4 Fostering Integration of Expertise for WHS

Future research work should aim to foster multi-sectoral collaborations. Integrating expertise from various disciplines such as public health experts, WHS professionals, urban planners, climate scientists, government, and WHS policy advisors who can help to develop more comprehensive and effective heat management strategies for detection, prevention, and management of heat-related occupational outcomes. Employers, healthcare workers, and government bodies will play a crucial role in promoting awareness, instigating behavioural adaptations, and implementing preventative measures at workplaces. These collaborations can further facilitate the development of industry-specific interventions, improving personal protective equipment, refining heat mitigation policies and the practical implementation of control measures in workplaces. Effective collaboration among unions, frontline workers, and managers is also essential in organisations. Unions can advocate for policies, offer training, and represent workers' interests. Frontline workers should practice self-care, communicate challenges, and follow safety measures. Managers play a pivotal role in risk assessment, implementing preventive measures, providing training, and maintaining open communication. This collective effort ensures a comprehensive approach to addressing heat-related challenges and promoting safer working conditions.

7.5 Conclusions

The impact of heat on OI is a significant concern that is projected to intensify with the effects of climate change. This issue is particularly noteworthy due to the varying risk distribution of OI among industries and types of workers within urban areas. Some regions within cities are consistently exposed to higher OI risks, which can be attributed to a combination of factors, including hot local climate, socio-economic vulnerability, demographic factors, type of industries, and environmental factors like lack of greenspaces and elevated LST.

These areas with heightened susceptibility to OI should be the primary focus of resource allocation and targeted interventions by industries, unions, and state and national WHS authorities. By identifying these high-risk zones, authorities can tailor strategies and allocate resources effectively to mitigate the impact of heat-related injuries. Such interventions could

include the establishment of cooling centres, improved access to shade, enhanced medical services, and outreach programs to raise awareness about heat-related risks among employers and workers.

Despite the abundance of scientific evidence detailing the detrimental effects of heat on WHS, the policies in place for safeguarding workers are still developing. To address this gap, policy initiatives should concentrate on two main areas:

Preparedness and Planning During Hot Weather: Policies need to emphasize the importance of proactive planning and preparation for periods of elevated temperatures. This involves establishing guidelines for employers to follow, such as implementing shorter work shifts during the hottest parts of the day, providing regular breaks, ensuring access to hydration, and promoting the use of appropriate protective clothing and gear.

Consultation, Risk Assessment, and Evaluation: Policies should advocate for inclusive decision-making processes that involve consulting with workers and their HSRs. This collaboration ensures that the perspectives and needs of those directly affected by heat-related risks are considered. Furthermore, policies should stress the significance of location-specific, workplace-specific, and individual risk factors in assessing heat hazards. This includes considering local climatic conditions, the nature of job tasks, and the vulnerabilities of individual workers. Evaluations of the effectiveness of these risk assessment measures are needed to inform evidence-based decisions for creating a safer and more productive work environment.

In conclusion, the impact of heat on WHS is a multifaceted challenge that demands targeted interventions and policy development. By identifying high-risk areas and involving workers and their representatives in the policymaking process, it is possible to enhance protection against heat-related OI and promote safer working conditions, especially as the effects of climate change continue to unfold.

APPENDICES

APPENDIX I – Ethics Approvals

THE UNIVERSITY of ADELAIDE

RESEARCH SERVICES
OFFICE OF RESEARCH ETHICS, COMPLIANCE AND INTEGRITY
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CRICOS Provider Number 00123M

Our reference 34024

30 January 2023

Professor Peng Bi
Public Health

Dear Professor Bi

ETHICS APPROVAL No: H-2019-219
PROJECT TITLE: The role of heat-related environmental stressors in occupational health and safety in urban settings of Australia: a mixed method study

Thank you for the Annual Report on Project Status (dated 30/11/2022) requesting an extension for further data collection. The extension request has been approved.

The ethics amendment for the above project has been reviewed by the Low Risk Human Research Ethics Review Group (Faculty of Health and Medical Sciences) and is deemed to meet the requirements of the *National Statement on Ethical Conduct in Human Research 2007 (Updated 2018)* involving no more than low risk for research participants.

You are authorised to commence your research on: 12/11/2019
The ethics expiry date for this project is: 30/11/2025

NAMED INVESTIGATORS:

Chief Investigator:	Professor Peng Bi
Student - Postgraduate Doctorate by Research (PhD):	Ms Syeda Hira Fatima
Associate Investigator:	Associate Professor Lynne Giles
Associate Investigator:	Associate Professor Paul Rothmore

Ethics approval is granted for three years and is subject to satisfactory annual reporting. The form titled Annual Report on Project Status is to be used when reporting annual progress and project completion and can be downloaded at http://www.adelaide.edu.au/research-services/oreci/human/reporting/. Prior to expiry, ethics approval may be extended for a further period.

Participants in the study are to be given a copy of the information sheet and the signed consent form to retain. It is also a condition of approval that you immediately report anything which might warrant review of ethical approval including:

- serious or unexpected adverse effects on participants,
- previously unforeseen events which might affect continued ethical acceptability of the project,
- proposed changes to the protocol or project investigators; and
- the project is discontinued before the expected date of completion.

Yours sincerely,

Mrs Alexia Jane Adhikari
Secretary

The University of Adelaide

THE UNIVERSITY of ADELAIDE

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CRICOS Provider Number 00123M

Our reference 0000021589

01 February 2022

Professor Dino Pisaniello
Public Health

Dear Professor Pisaniello

ETHICS APPROVAL No: H-2016-085
PROJECT TITLE: Workers' health and safety at high temperatures: New perspectives on injury prevention

Thank you for the Annual Report on Project Status provided by Blesson Varghese on 1 February 2022. It is noted data collection is complete and the writing up stage for PhD students Matthew Borg and Hira Fatima is continuing. The extension request to cover the writing up stage has been approved.

The ethics amendment for the above project has been reviewed by the Secretariat, Human Research Ethics Committee and is deemed to meet the requirements of the *National Statement on Ethical Conduct in Human Research 2007 (Updated 2018)* involving no more than low risk for research participants.

You are authorised to commence your research on: 02/05/2016
The ethics expiry date for this project is: 31/05/2025

NAMED INVESTIGATORS:

Chief Investigator:	Professor Dino Pisaniello
Student - Postgraduate Doctorate by Research (PhD):	Dr Blesson Mathew Varghese
Associate Investigator:	Professor Peng Bi
Associate Investigator:	Associate Professor Adrian Barnett
Associate Investigator:	J S Heyworth
Associate Investigator:	Dr Scott Hanson-Easey
Associate Investigator:	Shelley Rowett
Associate Investigator:	Dr Monika Nitschke
Associate Investigator:	Dr Alana Hansen
Associate Investigator:	Professor M R Sim
Associate Investigator:	Dr Susan Williams
Student - Postgraduate Doctorate by Research (PhD):	Dr Matthew Anthony Borg
Student - Postgraduate Doctorate by Research (PhD):	Ms Syeda Hira Fatima

Ethics approval is granted for three years and is subject to satisfactory annual reporting. The form titled Annual Report on Project Status is to be used when reporting annual progress and project completion and can be downloaded at http://www.adelaide.edu.au/research-services/oreci/human/reporting/. Prior to expiry, ethics approval may be extended for a further period.

Participants in the study are to be given a copy of the information sheet and the signed consent form to retain. It is also a condition of approval that you immediately report anything which might warrant review of ethical approval including:

- serious or unexpected adverse effects on participants,
- previously unforeseen events which might affect continued ethical acceptability of the project,
- proposed changes to the protocol or project investigators; and
- the project is discontinued before the expected date of completion.

Yours sincerely,

Ms Amy Lehmann
Secretary

The University of Adelaide

APPENDIX II – Supplementary Material for Chapter 2

Appendix A – Search Strategy

Table A1 PubMed search strategy search by most recent articles (n = 919)

Environmental factors	**Occupations**	**Impacts**	**Study type**
hot temperature [mh] OR heat [ti] OR hot weather [ti] OR hot temperature*[ti] OR warm temperature* [ti] OR ambient temperature* [ti] OR heatwave* [ti] OR heat wave* [ti] OR climate change [mh] OR global warming [mh] OR sun exposure [tiab] OR metereolog* [tiab] OR high temperature* [ti] OR low temperature* [ti] OR temperature extreme* [ti] OR maximum temperature* [ti] OR minimum temperature* [tiab] OR moderate temperature* [ti] OR mean temperature* [tiab] OR humidity [tiab] OR urbanization [mh] OR urban heat island [tiab] OR excess heat factor [tiab] OR apparent temperature* [tiab] OR Wet Bulb Globe Temperature [tiab] OR Humidex [tiab]	Industry[mh:noexp] OR Industr* [tiab] OR Industrial[tw] OR Work[ti] OR workplace[ti] OR work-related[tw] OR workplace[mh] OR employment[tw] OR employment[mh] OR occupation*[ti] OR employee*[tw] OR company*[tw] OR occupational groups [mh] OR agriculture industry[mh:noexp] OR forestry[mh] OR Forestry[tiab] OR building site*[tiab] OR WORKER*[TW] OR farmer* [tw] OR salesman [tw] OR indoor worker* [tw] OR outdoor worker* [ti] OR frontline worker* [ti] OR staff [tw] OR health care worker* [tiab] OR trainer* [tiab] OR technicians [tiab] OR daily governance [tiab] OR policemen [ti] OR OR construction worker* [ti] OR veterinarian* [tiab] OR non-military personals [tiab]	Heat stress disorders [mh] OR Heat stress [tiab] OR Workers' compensation [mh] OR OR occupational health [mh] OR adverse effects [Subheading] OR wounds and injuries[mh] OR Accidental falls [mh] OR Accidents, occupational[mh] OR heat stroke [tiab] OR occupational injuries [mh] OR occupational injuries [ti] OR occupational diseases [mh] OR injur*[tw] OR accident* [tiab] OR injuries [Subheading] OR heat exhaustion [mh] OR heat injuries [tw] OR work-related stress* [tw] OR work-related injuries and illnesses [ti] OR work-related injuries [ti] OR mortality [mh] OR Morbidity [mh]	epidemiology [mh] OR risk [tiab] OR risk assessment [tiab] OR case control [tiab] OR cohort [tiab] OR population based [tiab] OR spatial analysis [tiab] OR GIS [tiab] OR case comparison [tiab] OR follow-up [tiab] OR longitudinal stud* [tiab] OR time series [tiab] OR ecological studies [tiab] OR case crossover [tiab]

Table A2 Scopus search strategy search by most recent articles (n = 4329)

Environmental factors/exposure	**Occupations/population**	**Impacts/outcome**	**Study type**
TITLE-ABS-KEY (“hot temperature*” OR heat OR “hot weather” OR “warm temperature*” OR “ambient temperature*” OR “heatwave*” OR “heat wave*” OR “climate change” OR “global warming” OR “sun exposure” OR “metereolog*” OR “high temperature*” OR “temperature extreme*” OR “maximum temperature*” OR “minimum temperature*” OR “moderate temperature*” OR “mean temperature*” OR “humidity” OR “urbanization” OR “urban heat island” OR “urban green space*” OR “excess heat factor” OR “apparent temperature*” OR “Wet Bulb Globe Temperature” OR Humidex)	TITLE-ABS-KEY (“Industry” OR “Industrial” OR “work” OR “workplace” OR “work-related” OR “employment” OR “occupation*” OR “employee*” OR “company” OR “occupational groups” OR “agriculture” OR “forestry” OR “building site*” OR “worker*” OR “farmer*” OR “salesman” OR “indoor worker” OR “outdoor worker” OR “frontline worker” OR “staff” OR “health care worker” OR “trainer*” OR “technicians” OR “daily governance” OR “policemen” OR “construction worker” OR “veterinarian” OR “non-military”)	TITLE-ABS-KEY “heat stress disorders” OR “heat stress” OR “workers compensation” OR “wounds and injuries” OR “accidental falls” OR “occupational health” OR “adverse effect*” OR “occupational accidents” OR “heat stroke” OR “occupational injury” OR “occupational disease” OR “injur*” OR “accident*” OR “heat exhaustion” OR “heat injuries” OR ”work-related stress” OR “work-related injur* and illness*” OR “work-related injur*” OR “mortality” OR “morbidity”	TITLE-ABS-KEY “epidemiology” OR “risk” OR “risk assessment” OR “case control” OR “cohort” OR “population based” OR “spatial analysis” OR “case comparison” OR “follow-up” OR “longitudinal studies” OR “ecological study” OR “time series” OR “case crossover”

Table A3 Embase search strategy search by most recent articles (n = 593).

Environmental factors	Occupations	Impacts	Study type
'high temperature'/de OR 'heat':ti OR 'hot weather':ti OR 'hot temperature*':ti OR 'warm temperature*':ti OR 'ambient temperature*':ti OR 'heatwave*':ti OR 'heat wave*':ti OR 'climate change'/exp OR 'global warming'/de OR 'sun exposure':ti,ab OR 'metereolog*':ti,ab OR 'high temperature*':ti OR 'low temperature*':ti OR 'temperature extreme*':ti OR 'maximum temperature*':ti OR 'minimum temperature*':ti,ab OR 'moderate temperature*':ti OR 'mean temperature*':ti,ab OR 'humidity':ti,ab OR 'urban heat island':ti,ab OR 'excess heat factor':ti,ab OR apparent temperature*:ti,ab OR 'Wet Bulb Globe Temperature':ti,ab OR 'humidex':ti,ab	'Industry'/de OR 'Industr*':ti,ab OR 'Industrial' OR 'work':ti OR 'workplace':ti OR 'work-related' OR 'workplace'/de OR 'employment' OR 'employment'/de OR 'occupation*':ti OR 'employee*' OR 'compan*' OR 'named groups by occupation'/exp OR 'agriculture industry'/de OR 'building site*':ti,ab OR 'WORKER*' OR 'forestry':ti,ab OR 'farmer*' OR 'salesman' OR 'indoor worker*' OR 'outdoor worker*':ti OR 'frontline worker*':ti OR 'staff' OR 'health care worker*':ti,ab OR 'trainer*':ti,ab OR 'technicians':ti,ab OR 'daily governance':ti,ab OR 'policemen':ti OR 'construction worker*':ti OR 'veterinarian*':ti,ab OR 'non-military personals':ti,ab	'Heat stress disorders'/de OR 'Workers compensation'/de OR 'wound*' OR 'injury'/exp OR 'occupation health'/de OR 'adverse effects*':ti,ab OR 'occupational accident'/exp OR 'falling'/de OR 'falls' OR 'occupational injur*' OR 'occupational disease*'/de OR 'injur*' OR 'accident*':ti,ab OR 'heat stroke*' OR 'heat stress':ti,ab OR 'heat exhaustion':ti,ab OR 'work-related stress*' OR 'work-related injuries and illnesses':ti OR 'work-related injuries':ti OR 'thermal exposure'/de OR 'heat injury'/de OR 'mortality'/exp OR 'morbidity'/exp	'epidemiology'/de OR 'risk':ti,ab OR 'risk assessment':ti,ab OR 'case control':ti,ab OR 'cohort':ti,ab OR 'population based':ti,ab OR 'spatial analysis':ti,ab OR 'case comparison':ti,ab OR 'follow-up':ti,ab OR 'longitudinal stud*':ti,ab OR 'time series':ti,ab OR 'case crossover':ti,ab OR 'ecological study':ti,ab

Appendix B – Criteria for "Risk of Bias" Assessment

Note 1. Instructions for the Risk of Bias Assessment in individual studies, modified from Woodruff and Sutton. (162), Johnson et al. (163) and Achilleos et al. (164)

Exposure assessment: ***Were exposure assessment methods robust?***

Criteria for a judgement 'low risk of bias'

'*Low risk of bias*' is judged when there is low risk of exposure misclassification and the following criteria were met:

When there is high confidence in the accuracy of exposure assessment methods.

Well established and direct exposure measurements were used in the published studies (e.g., Personalised heat exposure measures estimated at the workers or workplace level (165).

Criteria for a judgement 'probably low risk of bias'

'Probably low risk of bias' is judged when:

There is insufficient evidence on measuring direct heat exposure, instead high-resolution proxy indicators were used to suffice the impact of exposure misclassification (e.g. using remote sensing data or gridded metrological data)

Criteria for a judgement 'probably high risk of bias'

'Probably High risk of bias' is judged when:

There is insufficient information on exposure assessment methods to permit a judgment '*high risk of bias*'

The methods adapted rely on imprecise exposure data and are likely to introduce exposure bias, e.g. use of meteorological data from a single weather station data or average across multiple weather stations, as described by the criteria for a judgment '*high risk of bias*'.

Criteria for a judgement 'high risk of bias'

'High risk of bias' is judged when any one of the following criteria are met:

There is low confidence in the accuracy of the exposure assessment methods that is likely to introduce exposure misclassification,

Less established or less direct exposure measurements that are not validated against well-established direct methods

Reported by the study participants retrospectively, which is subjected to recall bias,

There is lack of information on exposure assessment methods.

Outcome assessment: ***Were the outcome assessment methods robust?***

Criteria for a judgement 'low risk of bias'

'Low risk of bias' is judged in the outcome assessment when following criteria were met:

Study used an appropriate and standard measure of occupational injuries outcome based on diagnosis standard criteria and provided by national or regional database. (e.g. Workers compensation claims data based on standard codes of injury detection for example ICD 9)

Criteria for a judgement 'probably low risk of bias'

'probably low risk of bias' is assigned when:

There is insufficient evidence on methods of outcome assessment to permit a judgment '*low risk of bias*', but indirect evidence suggests that the study assessed the outcome based on standard criteria and the data are collected by researcher.

Criteria for a judgement 'probably high risk of bias'

'*probably high risk of bias*' is judged when:

The methods of outcome were not assessed based on standard diagnosis criteria but is accompanied by sensitivity analysis to suggest risk is minimum.

Criteria for a judgement 'high risk of bias'

'*High risk of bias'* is judged in the outcome assessment, if the study:

Outcomes were based on self-reports and data collected by researchers.

Lacked information on how the outcome information was obtained.

Recruitment/selection strategy: ***Was the strategy for recruiting participants consistent across study groups, adequately representing the study population?***

Criteria for a judgement 'low risk of bias'

'*Low risk of bias'* is judged in the recruitment strategy, if:

Recruitment or selection of study individuals adequately represented the study population (e.g. use of national structured databases such as workers' compensation claims of occupational injuries with a good coverage of the working population due to the mandatory requirements for companies to register occupational injuries).

In a study using control groups, there is no difference in the selection strategy of individuals among the exposed and unexposed and no difference in the underlying characteristics of these groups.

There is adequate representation of subgroups of population where required (e.g. migrant workers).

The selection time frame adequately represents the seasonal variations where required.

Criteria for a judgement 'probably low risk of bias'

'Probably low risk of bias' was assigned when:

There is insufficient information about individuals sampling to permit a judgment '*low risk of bias*', but there is evidence suggesting that individuals sampling process was consistent and covers a good proportion of workforce population, as described by the criteria for a judgment '*low risk of bias*'.

Criteria for a judgement 'probably high risk of bias'

'Probably high risk of bias' is assigned when:

There is insufficient information about participant sampling to permit a judgment '*high risk of bias*', but there is indirect evidence suggesting that participant recruitment or sampling was not adequately representative of the study population as described by the criteria for a judgment '*high risk of bias*'.

Criteria for a judgement 'high risk of bias'

'*High risk of bias*' in the sampling and recruitment strategy judged, if:

Study individuals were sampled and recruited so that the sample was not representative of the study population

Inadequate representation of subgroup populations where required.

The selection time frame doesn't adequately represent the seasonal variations.

Confounding: ***Was confounding adequately addressed?***

Criteria for a judgement 'low risk of bias'

'*Low risk of bias*' is predicted if:

All critical* and additional** confounders are considered or adjusted for in the models.

*Critical confounders include: Seasonality, long term and short term temporal trends, day of the week, size of the workforce (166)

**Additional confounders include: Humidity and other weather parameters, holidays

Criteria for a judgement 'probably low risk of bias'

'Probably low risk of bias' is assigned, when:

All critical and some additional confounders are considered or adjusted for in the models.

Criteria for a judgement 'probably high risk of bias'

'Probably high risk of bias' is assigned when:

A combination of critical and additional confounders are not taken into account.

Criteria for a judgement 'high risk of bias'

'*High risk of bias*' is judged if:

If no confounders are taken into account.

Incomplete outcome data: ***Were incomplete outcome data adequately addressed?***

Criteria for a judgement 'low risk of bias'

'*Low risk of bias*' is assigned if the study reports:

No missing outcome data.

Missing data has no impact on true outcome.

Missing data have been imputed using appropriate methods.

Criteria for a judgement 'probably low risk of bias'

'Probably low risk of bias' is judged, when:

The study provides insufficient evidence on incomplete outcome data to permit a judgment '*low risk of bias*', but there is indirect evidence suggesting incomplete outcome data were adequately addressed, as described by the criteria for a judgment '*low risk of bias*'.

Criteria for a judgement 'probably high risk of bias'

'Probably high risk of bias' is judged, when:

There is insufficient information about incomplete outcome data to permit a judgment '*high risk of bias*', but there is indirect evidence suggesting incomplete outcome data were not adequately addressed, as described by the criteria for a judgment '*high risk of bias*'.

Criteria for a judgement 'high risk of bias'

'*High risk of bias*' is judged in relation to incomplete data, if:

> There is evidence of missing outcome data, which may have potential impact on true outcome.
>
> The incomplete data were not adequately addressed or inappropriate application of imputation was noted.

Selective reporting: ***Are reports of the study free of the suggestion of selective outcome reporting?***

Criteria for a judgement 'low risk of bias'

'Low risk of bias' is assigned, when:

> All of the study's pre-specified outcomes and objectives have been clearly reported in abstract and/or introduction, methods and results sections that are of interest in the current review.

Criteria for a judgement 'probably low risk of bias'

'Probably low risk of bias' is judged, when:

> There is insufficient information about selective outcome reporting to permit a judgment '*low risk of bias*', but there is indirect evidence suggesting that the study was free of selective reporting, as described by the criteria for a judgment '*low risk of bias*'.

Criteria for a judgement 'probably high risk of bias'

'Probably high risk of bias' is judged, when:

> There is insufficient information about selective outcome reporting to permit a judgment '*high risk of bias*', but there is indirect evidence suggesting that the study was not free of selective reporting, as described by the criteria for a judgment '*high risk of bias*'.

Criteria for a judgement 'high risk of bias'

'*High risk of bias*' is judged in relation to selective outcome reporting, if:

The study's pre-specified primary outcomes (as outlined in the protocol, methods, abstract, and/or introduction) have not been reported adequately.

One or more primary outcomes are reported using measurements, analysis methods or subsets of the data (e.g., subscales) that were not pre-specified.

One or more of the reported primary outcomes were not pre-specified (unless clear justification for their reporting without pre-specification is provided, such as an unexpected effect).

Conflict of interest: ***Was the study free of support from the study author or any other entity having a financial interest in exposures/ outcomes studied?***

Criteria for a judgement 'low risk of bias'

'*Low risk of bias*' is judged if:

The study is financially supported by entities that have no financial interests in the study outcomes e.g. Governmental or academic research institutes.

If the authors are not employees of or affiliated with a company/government/non-governmental/NGO that may have financial interests in the outcomes of the study.

A company/government/NGO with a financial interest in the outcome of the study was not involved in the design, conduct, analysis, or reporting of the study and authors had complete access to the data.

Study authors make a claim denying the conflict of interest.

Criteria for a judgement 'probably low risk of bias'

'*Probably low risk of bias*'is judged if:

There is insufficient information to permit a judgment '*low risk of bias*', but there is indirect evidence suggesting that the study was free of support from a company, study author, or other entity having a financial interest in the outcome of the study, as described by the criteria for '*low risk of bias*'.

Criteria for a judgement 'probably high risk of bias'

'*Probably high risk of bias*' is judged, when:

> There is insufficient information to permit a judgment '*high risk of bias*', but there is indirect evidence suggesting that the study was not free of support from a company, study author, or other entity having a financial interest in the outcome of the study, as described by the criteria for a judgment '*high risk of bias*'.

Criteria for a judgement 'high risk of bias'

'*High risk of bias*' is judged if:

> There is evidence that the study received support from the study author or any other entity having financial interest in the outcome of the study, (e.g. research funds provided by relevant industries, materials provided at no cost, writing services).
>
> An author/staff from the study was an employee or otherwise affiliated with an entity with financial interest in the study outcome.
>
> An entity with financial interest in the study outcome was involved in the design, conduct, analysis, or reporting of the study or limited authors' access to the data.
>
> The study authors make a claim of conflict of interest.

Appendix C – Evaluation of the Quality of the Body of Evidence

Table C1 Factors for evaluating the quality of body of evidence. Adapted from Johnson et al. (163)

Downgrading Factors	**Summary of criteria for downgrading**
Risk of bias	A substantial risk of bias across body of evidence. Risk of bias was assessed using sensitivity analyses (Appendix E of SM) between studies showing high verses probably low or low risk of bias following (167). The quality of body of evidence was downgraded if there was substantial difference between values of sensitivity analysis. We also assessed the type of studies which were contributing towards high risk. For example, if the majority of the studies that are contributing towards high risk are small studies with low weightage in meta-analysis, then the evidence was not downgraded.
Indirectness	Evidence was not directly comparable to the question of interest (i.e., population, exposure, comparator, outcome).
Inconsistency	Widely different estimates of effect in similar populations (high heterogeneity I^2 or variability in results). An additional criteria was used to assess severe heterogeneity following (167). The evidence was downgraded if the precision interval included unity and was more than twice the random effects meta-analysis confidence interval.
Imprecision	Studies had few participants and few events (wide confidence intervals as judged by reviewers).
Publication Bias	Studies missing from body of evidence, resulting in an over or underestimate of true effects from exposure. The evidence of publication bias was inspected visually in the funnel plots and egger's test. Further Trim and fill methods was used to estimate potentially missing studies.

Upgrading Factors	**Summary of criteria for upgrading**
Large magnitude of effect	Upgraded if modelling suggested confounding alone unlikely to explain associations with large effect estimate as judged by reviewers.
Dose response	Upgraded if consistent relationship between dose and response in one or multiple studies, and/or dose response across studies.
Confounding minimizes effect	Upgraded if consideration of all plausible residual confounders or biases would underestimate the effect or suggest a spurious effect when results show no effect.

Table C2 Factors for evaluating the strength of body of evidence. Adapted from Johnson et al. (163).

Rating factors	**Criteria for rating factors**
Sufficient	A causal association between the exposure and the outcome has been established. That is, a positive association has been observed in the body of evidence on exposure and the outcome in studies in which chance, bias, and confounding were ruled out with reasonable confidence.
Limited	A causal interpretation of the positive association observed in the body of evidence on exposure and the outcome is credible, but chance, bias, or confounding could not be ruled out with reasonable confidence.
Inadequate	The available studies are of insufficient quality, consistency, or statistical precision to permit a conclusion to be drawn about the presence or the absence of a causal association between exposure and the outcome.
Evidence of lack of effect	There are several high-quality studies covering the full range of levels of exposure of interest, which are mutually consistent in not showing a positive association between exposure and the studied outcome at any observed level.

Appendix D – Assessment of Risk of Bias in Individual Studies

Risk of bias assessment among hot temperature studies (n = 19)

Table D1 Risk of bias assessment of Fogleman et al. (73).

# 1 Fogleman et al. (73)		
Design	Time Series	
Population and Time	Aluminum Smelter workers, 1997-1999	
Exposure	Heat Index, weather station	
Outcomes	Work-related injuries and illness	
Risk of Bias Assessment		
Bias Domain	**Author's judgement**	**Criterion supportive response**
Selection/recruitment strategy	Probably low	Used Occupational health data consisting of 1097 cases of occupational injuries and illness from Aluminum smelter. Occupational health data of the company is assumed to cover majority of the cases.
Exposure Assessment	Probably high	Used exposure data from one weather station.
Outcome Assessment	Probably low	Included daily counts of work-related occupational health data. The company based health data is assumed to be based on standard injury classification codes.
Confounding	Probably high	Potential confounders considered: Time trends, day of the week, size of the workforce and humidity. Potential confounder not considered: Seasonality.
Incomplete outcome data	Low	Daily counts for occupational health data were obtained. However, any potential errors or missing data does not depend on air-temperature levels.
Selective outcome reporting	Low	All pre-specified outcomes reported in the pre-specified way.
Conflict of interest	Low	Authors declared no conflicts of interest.
Other sources of bias	Low	No other potential sources of bias identified.

Table D2 Risk of bias assessment of Morabito et al. (62).

# 2 Morabito et al. (62)		
Design	Ecological correlation	
Population and Time	All workers, 1998-2003, June-September	
Exposure	Daily Apparent temperature, weather station	
Outcomes	Work-related hospitalization	
Risk of Bias Assessment		
Bias Domain	**Author's judgement**	**Criterion supportive response**
Selection/recruitment strategy	Probably low	Study included inpatient discharge data for work-related accidents recorded in the five hospitals between 1 June- 30th September 1998-2003. Inpatient hospital discharge data is assumed to cover majority of the work-related cases.
Exposure Assessment	Probably high	Used exposure data from one weather station.
Outcome Assessment	Low	Included daily counts of work-related hospital admissions which were coded based on ICD-9-CM.
Confounding	Probably high	Potential confounders considered: Seasonality, holidays and humidity. Potential confounders not adjusted for: Workforce estimates and time trends.
Incomplete outcome data	Low	Daily counts for hospitalised work injuries were obtained. However, any potential errors or missing data does not depend on air-temperature levels.
Selective outcome reporting	Low	All pre-specified outcomes reported in the pre-specified way.
Conflict of interest	Low	Authors declared no conflicts of interest.
Other sources of bias	Low	No other potential sources of bias identified.

Table D3 Risk of bias assessment of Xiang et al. (65).

# 3 Xiang et al. (65)		
Design	Time-series	
Participants	All workers in Adelaide, 2001-2010	
Exposure	Daily Tmax, weather station	
Outcomes	All injuries, workers' compensation claims	
Risk of Bias Assessment		
Bias Domain	**Author's judgement**	**Criterion supportive response**
Selection/recruitment strategy	Low	Study included workers who got injured and compensated between 1 July 2001-30 June 2010.Occupational injuries sourced from workers' compensation claims with 85% coverage of insured workers (168).
Exposure Assessment	Probably high	Exposure data sourced from one weather station.
Outcome Assessment	Low	Included daily injuries reported according to the TOOCS.
Confounding	Probably high	Potential confounders considered: Time trends, day of the week and seasonality. Potential confounders not adjusted for: Size of workforce.
Incomplete outcome data	Low	Daily counts for injuries were obtained, excludes claims that were rejected and not submitted. However, any potential errors or missing data does not depend on air-temperature levels.
Selective outcome reporting	Low	All pre-specified outcomes reported in the pre-specified way.
Conflict of interest	Low	Authors declared no conflicts of interest.
Other sources of bias	Low	No other potential sources of bias identified.

Table D4 Risk of bias assessment of Adam-Poupart et al. (69).

# 4 Adam-Poupart et al. (69)		
Design	Time-series	
Participants	All workers in 16 health regions of Quebec, 2003-2010	
Exposure	Tmax, one weather station per province	
Outcomes	All occupational injuries, workers' compensation claims	
Risk of Bias Assessment		
Bias Domain	**Author's judgement**	**Criterion supportive response**
Selection/recruitment strategy	Low	Study included workers who got injured and compensated between 1 May- 30th September 2003-2010. Occupational injuries sourced from Workers compensation board of Quebec covers upto 92% of worker force in Quebec.
Exposure Assessment	Probably high	Used one monitoring station per health region.
Outcome Assessment	Low	Included daily counts of work-related injury compensations which were coded based on Canadian Standard Association - Standard Z795.
Confounding	Low	All critical and additional confounders taken into account. Adjusted for seasonality, day, month, year, two-week holiday of the construction sector and public holiday periods, monthly working population, and relative humidity.
Incomplete outcome data	Low	Daily counts for injuries were obtained, excludes claims that were rejected and not submitted. However, any potential errors or missing data does not depend on air-temperature levels.
Selective outcome reporting	Low	All pre-specified outcomes reported in the pre-specified way.
Conflict of interest	Low	Authors declared no conflicts of interest.
Other sources of bias	Low	No other potential sources of bias identified.

Table D5 Risk of bias assessment of Garzon-Villalba et al. (72).

# 5 Garzon-Villalba et al. (72)		
Design	Time-series	
Population and Time	Disaster relief workers, 2010-2011	
Exposure	Daily Maximum WBGT (WBGTmax)	
Outcomes	All acute injuries, British Petroleum Database of reportable injuries	
Risk of Bias Assessment		
Bias Domain	**Author's judgement**	**Criterion supportive response**
Selection/recruitment strategy	Probably low	Study included acute injuries recorded in the BP database between May 2010- March 2011. The data was collected by British petroleum. The employer generated data collection was based on standard occupational safety and health practice (72) and is therefore assumed to cover majority of workforce.
Exposure Assessment	Probably high	WBGTmax was sourced from weather stations averaged to be representative.
Outcome Assessment	Low	Daily acute injury data from the incident database identified using Bureau of Labour Statistics Occupational Injury and Illness Classification System, v1.01.
Confounding	Probably high	Potential confounders considered: size of the workforce and humidity. Potential confounders not considered: Seasonality and time trends.
Incomplete outcome data	Low	Daily rates of work injuries were obtained. However, any potential errors or missing data does not depend on air-temperature levels.
Selective outcome reporting	Low	All pre-specified outcomes reported in the pre-specified way.
Conflict of interest	Low	Authors declared no conflicts of interest.
Other sources of bias	Low	No other potential sources of bias identified.

Table D6 Risk of bias assessment of Spector et al. (64).

# 6 Spector et al. (64)		
Design	Time-stratified case-crossover	
Participants	Agriculture workers in Eastern Washington State, USA, 2000-2012, May-September	
Exposure	Maximum humidex modelled grid from weather stations	
Outcomes	All traumatic injuries, workers' compensation claims	
Risk of Bias Assessment		
Bias Domain	**Author's judgement**	**Criterion supportive response**
Selection/recruitment strategy	Low	Study included workers who got injured and compensated between 1 March-31 October 2000-2012. Traumatic injuries sourced from Washington State Department of Labour and Industries covers two-thirds of the state's workforce (64).
Exposure Assessment	Probably low	Exposure data obtained from high-resolution meteorological data spatiotemporally joined with injury location.
Outcome Assessment	Low	Traumatic injuries defined using American National Standards Institute (ANSI) and Occupational Injury and Illness Classification System (OIICS) codes.
Confounding	Low	All potential confounders adjusted for in the models. Seasonality, workforce and day of week controlled by design, excluded major holidays and included humidex in the models.
Incomplete outcome data	Low	Daily counts for injuries were obtained, excludes claims that were rejected and not submitted. However, any potential errors or missing data does not depend on air-temperature levels.
Selective outcome reporting	Low	All pre-specified outcomes reported in the pre-specified way.
Conflict of interest	Low	Authors declared no conflicts of interest.
Other sources of bias	Low	No other potential sources of bias identified.

Table D7 Risk of bias assessment of McInnes et al. (68).

# 7 McInnes et al. (68)		
Design	Time-stratified case-crossover	
Participants	All workers in Melbourne, 2002-2012	
Exposure	Daily Tmax and Tmin, averaged across weather stations	
Outcomes	All acute-injuries; workers' compensation claims	
Risk of Bias Assessment		
Bias Domain	**Author's judgement**	**Criterion supportive response**
Selection/recruitment strategy	Low	Study included workers aged 15 years or over who got injured and compensated during the months of November to March (inclusive) over the period of 1 July 2002 to 30 June 2012. Occupational injuries sourced from workers' compensation claims system (covers about 85% of workers) (168).
Exposure Assessment	Probably high	Used exposure data from eight weather stations and assigned them to each of the local government area in a way that each LGA was allocated the data from one weather station only.
Outcome Assessment	Low	Workers' compensation claim administrative data was used to identify cases of acute work-related injury coded according to the Nature of Injury/Disease Classification System for Victoria (VCODE). The study only included most serious injuries (i.e. those with at least a 10-day absence from work, or where the incurred health care expenses exceed a specified threshold).
Confounding	Low	All potential confounders were taken into account. Seasonality, workforce and day of week controlled by design. Excluded public holidays and adjusted for relative humidity.
Incomplete outcome data	Low	Daily counts for injuries were obtained, excludes claims that were rejected and not submitted. However, any potential errors or missing data does not depend on air-temperature levels.
Selective outcome reporting	Low	All pre-specified outcomes reported in the pre-specified way.
Conflict of interest	Low	Authors declared no conflicts of interest.
Other sources of bias	Low	No other potential sources of bias identified.

Table D8 Risk of bias assessment of Martínez-Solanas et al. (61).

# 8 Martinez-Solanas et al. (61)		
Design	Time-series	
Population and Time	All workers in 50 provinces of Spain, 1994-2013	
Exposure	Daily Tmax and Tmin, weather station	
Outcomes	All injuries, workers' compensation claims	
Risk of Bias Assessment		
Bias Domain	**Author's judgement**	**Criterion supportive response**
Selection/recruitment strategy	Probably low	Study included workers who got injured and compensated between 1994 and 2013. Occupational injuries sourced from Spanish Labour Administration is assumed to cover majority of workforce population injury claims as it is mandatory for companies to register injuries.
Exposure Assessment	Probably high	Used exposure data from one weather station per province. Imputed missing values (0.01% of the data), however, results did not change if missing values were excluded.
Outcome Assessment	Probably low	Data obtained from the Spanish National System provided by the Spanish Labour Administration and assumed to be assessed using standard injury codes.
Confounding	Probably Low	Potential confounders taken into account: Seasonality, long-term trends, day of week, holidays, month and number of workers. Potential confounders not taken into account: Humidity
Incomplete outcome data	Low	Daily counts for injuries were obtained, excludes claims from relapses and commuting. However, any potential errors or missing data does not depend on air-temperature levels.
Selective outcome reporting	Low	All pre-specified outcomes reported in the pre-specified way.
Conflict of interest	Low	Authors declared no conflicts of interest.
Other sources of bias	Low	No other potential sources of bias identified.

Table D9 Risk of bias assessment of Ricco et al. (76).

# 9 Ricco et al. (76)		
Design	Time Series	
Population	Agricultural workers in Trento Province, Italy	
Exposure	Maximum temperatures and heatwave periods	
Outcomes	Occupational Injuries	
Risk of Bias Assessment		
Bias Domain	**Author's judgement**	**Criterion supportive response**
Selection/recruitment strategy	Low	Study included workers who got injured and compensated between January 1, 2000 to December 31, 2013 during hot temperatures, heatwave periods (exposure) and non-heatwave (non-exposure) periods. The INAIL insurance is compulsory in risky workplace environments to ensure workers safety and covers 85% of Italian workforce data (75).
Exposure Assessment	Probably high	Exposure data obtained from one weather station per municipality in Trento Province.
Outcome Assessment	Low	Data retrieved from Institutional database of the National Insurance for Occupational Illness and Injuries (INAIL). National datasets have standard criterion of assessing type of injuries.
Confounding	Probably High	Potential confounders adjusted for: Day of the week, holidays and seasonality. Potential confounders not adjusted for: Size of workforce and humidity.
Incomplete outcome data	Low	Daily counts of injuries were obtained. Any potential errors or missing data does not depend on air temperature levels.
Selective outcome reporting	Low	All pre-specified outcomes reported in the pre-specified way.
Conflict of interest	Low	Authors declared no conflicts of interest.

Table D10 Risk of bias assessment of Sheng et al. (63).

# 10 Sheng et al. (63)		
Design	Time-stratified case-crossover	
Population and Time	All workers, Guangzhou, 2011-2012	
Exposure	Daily Tmax and Tmin, weather station	
Outcomes	All injuries, workers' compensation claims	
Risk of Bias Assessment		
Bias Domain	**Author's judgement**	**Criterion supportive response**
Selection/recruitment strategy	Probably high	Study included workers who got injured and compensated between January 1, 2011 to December 31, 2012. Occupational injuries sourced from a relatively new workers' compensation claims system (not universal and covers about 54% of workers) (63). Study only used two years of data.
Exposure Assessment	Probably high	Used exposure data from weather station (not clear if from a single station or several stations).
Outcome Assessment	Probably low	Data obtained from workers' compensation claims (according to the Regulations on Work Injury Insurance scheme) and are assumed to assess using standard injury codes.
Confounding	Low	All potential confounders were taken into account. Seasonality, workforce and day of week controlled by design. Excluded public holidays and adjusted for relative humidity.
Incomplete outcome data	Low	Daily counts for injuries were obtained, excludes claims that were rejected and not submitted. However, any potential errors or missing data does not depend on air-temperature levels.
Selective outcome reporting	Low	All pre-specified outcomes reported in the pre-specified way.
Conflict of interest	Low	Authors declared no conflicts of interest.

Table D11 Risk of bias assessment of Calkins et al. (70).

# 11 Calkins et al. (70)		
Design	Time-stratified case-crossover	
Population and Time	All construction workers, 2000-2012, June-September	
Exposure	Daily Maximum Humidex,	
Outcomes	Traumatic injuries, workers' compensation claims	
Risk of Bias Assessment		
Bias Domain	**Author's judgement**	**Criterion supportive response**
Selection/recruitment strategy	Low	Study included workers who got injured and compensated between 1 March-31 October 2000-2012. Traumatic injuries sourced from Washington State Department of Labour and Industries which covers two-thirds of the state's workforce (64).
Exposure Assessment	Probably low	Exposure data obtained from high-resolution meteorological data spatiotemporally joined with injury location.
Outcome Assessment	Low	Traumatic injuries defined using American National Standards Institute (ANSI) and Occupational Injury and Illness Classification System (OIICS) codes.
Confounding	Low	All potential confounders were taken into account. Seasonality, workforce and day of week controlled by design. Excluded public holidays and adjusted for relative humidity.
Incomplete outcome data	Low	Daily counts for injuries were obtained, excludes claims that were rejected and not submitted. However, any potential errors or missing data does not depend on air-temperature levels.
Selective outcome reporting	Low	All pre-specified outcomes reported in the pre-specified way.
Conflict of interest	Low	Authors declared no conflicts of interest.
Other sources of bias	Low	No other potential sources of bias identified.

Table D12 Risk of bias assessment of Dillender et al. (71).

# 12 Dillender et al. (71)		
Design	Time series study design	
Population and Time	All workers in Texas, US	
Exposure	Data from multiple weather stations converted to daily grids using inverse weighted distance tool.	
Outcomes	Occupational Injuries	
Risk of Bias Assessment		
Bias Domain	**Author's judgement**	**Criterion supportive response**
Selection/recruitment strategy	Low	Accepted workers' daily compensation claims for work related injuries and illness lodged from 2006 to 2014 are maintained by Texas Workers Compensation Medical Claims Data, in Texas US. 81% of Texas workers work for firms with WC insurance as of 2012 (71).
Exposure Assessment	Probably Low	Exposure measured at metropolitan statistical area level using inverse distance weighted average of multiple weather station data which estimates values at unknown locations.
Outcome Assessment	Low	Details of each claim are recorded according to the International Classification of Diseases (ICD-9) code
Confounding	Low	All potential confounders were taken into account. Seasonality, workforce and day of week controlled by design. Excluded public holidays and adjusted for precipitation.
Incomplete outcome data	Low	Daily counts for injuries were obtained. However, any potential errors or missing data does not depend on air-temperature levels.
Selective outcome reporting	Low	All pre-specified outcomes reported in the pre-specified way.
Conflict of interest	Low	Authors declared no conflicts of interest.

Table D13 Risk of bias assessment of Ma et al. (74).

# 13 Ma et al. (74)		
Design	Time-series	
Population and Time	All workers, Guangzhou, 2011-2012	
Exposure	Daily WBGT, weather station	
Outcomes	All injuries, workers' compensation claims	
Risk of Bias Assessment		
Bias Domain	**Author's judgement**	**Criterion supportive response**
Selection/recruitment strategy	Probably high	Study included workers who got injured and compensated between January 1, 2011 to December 31, 2012. Occupational injuries sourced from a relatively new workers' compensation claims system (not universal and covers about 54% of workers)(63). Study only used two years of data.
Exposure Assessment	Probably high	Used exposure data from weather station (not clear if from a single station or several stations).
Outcome Assessment	Probably low	Data obtained from workers' compensation claims (according to the Regulations on Work Injury Insurance scheme) and is assumed to be assessed using standard injury codes.
Confounding	Probably High	Potential confounders considered: Seasonality, time trends, public holidays and day of the week. Potential confounders not considered: Size of the workforce.
Incomplete outcome data	Low	Daily counts for injuries were obtained, excludes claims that were rejected and not submitted. However, any potential errors or missing data does not depend on air-temperature levels.
Selective outcome reporting	Low	All pre-specified outcomes reported in the pre-specified way.
Conflict of interest	Low	Authors declared no conflicts of interest.

Table D14 Risk of bias assessment of Marinaccio et al. (75).

#14 Marinaccio et al. (75)		
Design	Time Series	
Population	All workers at national level in Italy	
Exposure	Mean Temperatures	
Outcomes	Occupational Injuries	
Risk of Bias Assessment		
Bias Domain	**Author's judgement**	**Criterion supportive response**
Selection/recruitment strategy	Low	The study considers occupational injuries at national level in Italy from period of 2006-2010. Data was retrieved from INAIL archives which covers 80% of Italian workforce (75).
Exposure Assessment	Probably low	Daily air temperature data were obtained at 1k X 1k resolution from satellite data to estimate the risk at municipality level in Italy.
Outcome Assessment	Probably low	Data retrieved from Institutional database of the National Insurance for Occupational Illness and Injuries (INAIL). National datasets are assumed to have standard criterion for assessing type of injuries.
Confounding	Probably low	Potential confounders adjusted for: Seasonality, time trends, day of the week, two-week holiday of the construction sector and public holiday periods and monthly working population. Potential confounders not adjusted for: Humidity.
Incomplete outcome data	Low	Daily counts for injuries were obtained, excludes claims that were rejected and not submitted. However, any potential errors or missing data does not depend on air-temperature levels.
Selective outcome reporting	Low	All pre-specified outcomes reported in the pre-specified way.
Conflict of interest	Low	Authors declared no conflicts of interest.

Table D15 Risk of bias assessment of Schifano et al. (82)

# 15 Schifano et al. (82)		
Design	Time Stratified Case Crossover	
Population	All workers in three cities of Italy including Milan, Turin and Rome	
Exposure	Apparent temperature and air pollution	
Outcomes	Occupational Injuries	
Risk of Bias Assessment		
Bias Domain	**Author's judgement**	**Criterion supportive response**
Selection/recruitment strategy	Low	The study researched the risk of occupational injuries in three cities of Italy including Milan, Turin and Rome. Data were retrieved from INAIL archives which covers 85% of Italian workforce (75).
Exposure Assessment	Probably high	City-specific single weather station data were used.
Outcome Assessment	Probably low	Data retrieved from Institutional database of the National Insurance for Occupational Illness and Injuries (INAIL) which is assumed to be assessed using standard injury codes.
Confounding	Low	All potential confounders were taken into account. Seasonality, workforce and day of week controlled by design. Excluded public holidays and adjusted for relative humidity.
Incomplete outcome data	Low	Daily counts for injuries were obtained. However, any potential errors or missing data does not depend on air-temperature levels.
Selective outcome reporting	Low	All pre-specified outcomes reported in the pre-specified way.
Conflict of interest	Low	Authors declared no conflicts of interest.

Table D16 Risk of bias assessment of Ricco et al. (161).

# 16 Ricco et al. (161)		
Design	Time series	
Population and Time	Migrant workers from the Eastern-Mediterranean Region (EMRO)	
Exposure	Hot temperatures and Heatwave periods	
Outcomes	Occupational injuries risk differentials between EMRO migrant workers and EURO natives	
Risk of Bias Assessment		
Bias Domain	**Author's judgement**	**Criterion supportive response**
Selection/recruitment strategy	Probably low	Data on occupational injuries for Trento from 2000 – 2013 were retrieved from archives of operational Unit for Health and safety in Workplaces. The data were collected from different sources such as local emergency department, local safety authorities and national insurance for occupational illness and injuries and is assumed to have reasonable coverage of occupational injuries.
Exposure Assessment	Probably low	Used exposure data from 214 weather stations to directly link with the geographical site of the injury with air temperature at the time of accident. Local exposure assessed using the nearest weather station data.
Outcome Assessment	Probably low	The data were retrieved from archives of operational Unit for Health and safety in Workplaces. The data is assumed to be based on standard criterion.
Confounding	Low	All potential confounders were taken into account. Adjusted for: seasonality, day of the week, time trends, workforce numbers. Adjusted for: Humidity, windspeed solar radiation and holidays.
Incomplete outcome data	Low	Daily counts for injuries were obtained. However, any potential errors or missing data does not depend on air-temperature levels.
Selective outcome reporting	Low	All pre-specified outcomes reported in the pre-specified way.
Conflict of interest	Low	Authors declared no conflicts of interest.

Table D17 Risk of bias assessment of Varghese et al. (66).

# 17 Varghese et al. (66)		
Design	Time Stratified Cass crossover study design	
Population and Time	All workers in Adelaide, Australia	
Exposure	Maximum temperatures	
Outcomes	Work related injuries and illness in Adelaide Metropolitan Area	
Risk of Bias Assessment		
Bias Domain	**Author's judgement**	**Criterion supportive response**
Selection/recruitment strategy	Low	Accepted workers' daily compensation claims for work related injuries and illness lodged between 1 July 2003 to 30 June 2013 are maintained by Return to Work SA, the state jurisdiction of South Australia. Occupational injuries sourced from workers' compensation claims with 85% coverage of insured workers (168).
Exposure Assessment	Probably high	Exposure data sourced from one weather station.
Outcome Assessment	Low	Details of each claim are recorded according to the Type of Occurrence Classification System (TOOCS 3.1).
Confounding	Low	All potential confounders were taken into account. Seasonality, workforce and long term trends are controlled by design. Weekly strata of 7 days also take into account the week-to-week variations such as labour strikes, power outages, change in work settings etc. Other environmental variables such as humidity was adjusted for in the models.
Incomplete outcome data	Low	Daily counts for injuries were obtained. However, any potential errors or missing data does not depend on air-temperature levels.
Selective outcome reporting	Low	All pre-specified outcomes reported in the pre-specified way.
Conflict of interest	Low	Authors declared no conflicts of interest.

Table D18 Risk of bias assessment of Varghese et al. (67).

# 18 Varghese et al. (67)		
Design	Time Stratified Cass crossover study design	
Population and Time	All workers in Melbourne, Perth and Brisbane	
Exposure	Maximum temperature	
Outcomes	Work related injuries and illness in three major Metropolitan Area of Australia	
Risk of Bias Assessment		
Bias Domain	**Author's judgement**	**Criterion supportive response**
Selection/recruitment strategy	Low	Accepted workers' daily compensation claims for work related injuries and illness lodged between 1 July 2005 to 30 June 2016 were included. These data were extracted from the National Dataset for Compensation Based Statistics (NDS3) collected by Safe Work Australia (SWA). Occupational injuries sourced from workers' compensation claims with 85% coverage of insured workers (168).
Exposure Assessment	Probably high	Exposure data sourced from one weather station.
Outcome Assessment	Low	Details of each claim are recorded according to the Type of Occurrence Classification System (TOOCS 3.1).
Confounding	Low	All potential confounders were considered. Seasonality, workforce and long term trends are controlled by design. Weekly strata of 7 days also take into account the week-to-week variations such as labour strikes, power outages, change in work settings etc. Other environmental variables such as humidity was adjusted for in the models.
Incomplete outcome data	Low	Daily counts for injuries were obtained. However, any potential errors or missing data does not depend on air-temperature levels.
Selective outcome reporting	Low	All pre-specified outcomes reported in the pre-specified way.
Conflict of interest	Low	Authors declared no conflicts of interest.

Table D19 Risk of bias assessment of Ricco et al. 2020 (169)

# 19 Ricco et al. 2020 (169)		
Design	Time series	
Population and Time	Construction workers in Trento Province Italy	
Exposure	Maximum temperatures and Heatwave periods	
Outcomes	Occupational injuries	
Risk of Bias Assessment		
Bias Domain	**Author's judgement**	**Criterion supportive response**
Selection/recruitment strategy	Probably low	Data on occupational injuries for Trento from 2000 – 2013 were retrieved from archives of operational Unit for Health and safety in Workplaces. The institutional service representing the local governmental structure for the management and prevention of occupational injuries, occupational diseases and work-related diseases in workplace.
Exposure Assessment	Probably low	Used exposure data from 214 weather stations to directly link with the geographical site of the injury with air temperature at the time of accident. Local exposure assessed using the nearest weather station data.
Outcome Assessment	Probably low	The data were retrieved from archives of operational Unit for Health and safety in Workplaces. The data is assumed to be based on standard criterion.
Confounding	Low	All potential confounders were considered. The study adjusted for seasonality, day of the week, month, long-term trends. Relative humidity was used as a covariate in the analysis. The analysis also included the number of workers employed by calendar year.
Incomplete outcome data	Low	Daily counts for injuries were obtained. However, any potential errors or missing data does not depend on air-temperature levels.
Selective outcome reporting	Low	All pre-specified outcomes reported in the pre-specified way.
Conflict of interest	Low	Authors declared no conflicts of interest.

Risk of bias assessment among HW studies (n = 8)

Table D20 Risk of bias assessment of Xiang et al. 2014 (58).

# 20 Xiang et al. 2014b (58)		
Design	Time-series	
Population and Time	All workers in Adelaide, 2001-2010	
Exposure	Daily Tmax with three consecutive days above 35ºC identified as Heatwaves, weather station	
Outcomes	All injuries, workers' compensation claims	
Risk of Bias Assessment		
Bias Domain	**Author's judgement**	**Criterion supportive response**
Selection/recruitment strategy	Low	Study included workers who got injured and compensated between 1 July 2001-30 June 2010. Occupational injuries sourced from workers' compensation claims with 85% coverage of insured workers (168).
Exposure Assessment	Probably high	Exposure data sourced from one weather station.
Outcome Assessment	Low	Included daily injuries reported according to the TOOCS criteria from Safe Work Australia.
Confounding	Probably high	Potential confounders adjusted for: Seasonality, day of the week, time trend and public holidays. Potential confounders not adjusted for: Size of workforce
Incomplete outcome data	Low	Daily counts for injuries were obtained, excludes claims that were rejected and not submitted. However, any potential errors or missing data does not depend on air-temperature levels.
Selective outcome reporting	Low	All pre-specified outcomes reported in the pre-specified way.
Conflict of interest	Low	Authors declared no conflicts of interest.
Other sources of bias	Low	No other potential sources of bias identified.

Table D21 Risk of bias assessment of Rameezdeen et al. 2017 (170)

# 21 Rameezdeen et al. 2017 (170)		
Design	Ecological correlation	
Population and Time	Construction workers, 2002-2013	
Exposure	Daily Tmax with three consecutive days above 35ºC identified as Heatwaves, weather station	
Outcomes	All injuries, workers' compensation claims	
Risk of Bias Assessment		
Bias Domain	**Author's judgement**	**Criterion supportive response**
Selection/recruitment strategy	Low	Study included workers who got injured and compensated between 1 July 2002–31 June 2013. Occupational injuries sourced from workers' compensation claims with 85% coverage of insured workers (168).
Exposure Assessment	Probably high	Used exposure data from one weather station.
Outcome Assessment	Low	Included daily injuries reported according to the Type of Occurrence Classification System (TOOCS2) criteria from Safe Work Australia.
Confounding	Probably High	Potential confounders adjusted for: Seasonality, day of the week, time trend and public holidays. Potential confounders not adjusted for: size of workforce
Incomplete outcome data	Low	Daily counts for injuries were obtained, excludes claims that were rejected and not submitted. However, any potential errors or missing data does not depend on air-temperature levels.
Selective outcome reporting	Low	All pre-specified outcomes reported in the pre-specified way.
Conflict of interest	Low	Authors declared no conflicts of interest.
Other sources of bias	Low	No other potential sources of bias identified.

Table D22 Risk of bias assessment of McInnes et al. (171)

# 22 McInnes et al. (171)		
Design	Time-stratified case-crossover	
Participants	All workers in Melbourne, 2002-2012	
Exposure	Daily Tmax and Tmin, weather station	
Outcomes	All acute-injuries; workers' compensation claims	
Risk of Bias Assessment		
Bias Domain	**Author's judgement**	**Criterion supportive response**
Selection/recruitment strategy	Low	Study included workers aged 15 years or over who got injured and compensated during the months of November to March (inclusive) over the period of 1 July 2002 to 30 June 2012. Occupational injuries sourced from workers' compensation claims system (covers about 85% of workers, (168)). The study only included most serious injuries (i.e. those with at least a 10-day absence from work, or where the incurred health care expenses exceed a specified threshold).
Exposure Assessment	Probably high	Used exposure data from eight weather stations and assigned them to each of the local government area in a way that each LGA was allocated the data from one weather station only.
Outcome Assessment	Low	Workers' compensation claim administrative data was used to identify cases of acute work-related injury coded according to the Nature of Injury/Disease Classification System for Victoria (VCODE).
Confounding	Low	All potential confounders were taken into account. Seasonality, workforce and day of week controlled by design. Excluded public holidays and adjusted for relative humidity.
Incomplete outcome data	Low	Daily counts for injuries were obtained, excludes claims that were rejected and not submitted. However, any potential errors or missing data does not depend on air-temperature levels.
Selective outcome reporting	Low	All pre-specified outcomes reported in the pre-specified way.
Conflict of interest	Low	Authors declared no conflicts of interest.
Other sources of bias	Low	No other potential sources of bias identified.

Table D23 Risk of bias assessment of Varghese et al. (172).

# 23 Varghese et al. (172)		
Design	Time Stratified Cass crossover study design	
Population and Time(172)	All workers in Adelaide Australia, Ambulance call-outs	
Exposure	Heatwaves using Excess Heat Factor	
Outcomes	Work related injuries and illness and work-related/industrial ambulance call outs	
Risk of Bias Assessment		
Bias Domain	**Author's judgement**	**Criterion supportive response**
Selection/recruitment strategy	Low	Accepted workers' daily compensation claims for work related injuries and illness lodged between 1 July 2003 to 30 June 2013 are maintained by Return to Work SA, the state jurisdiction of South Australia. Occupational injuries sourced from workers' compensation claims with 85% coverage of insured workers (168). Ambulance call-outs from 1 July 2003 to 30 June 2013 were retrieved from South Australian Ambulance Service (SAAS). SAAS call-outs coded as work-related/industrial were selected only.
Exposure Assessment	Probably high	Heatwave data were obtained from Excess heat factor index developed by Bureau of Meteorology, Australia. City-level values were extracted from gridded datasets.
Outcome Assessment	Low	Details of each claim are recorded according to the Type of Occurrence Classification System (TOOCS 3.1).
Confounding	Low	All potential confounders were taken into account. Seasonality, workforce and long-term trends are controlled by design. Weekly strata of 7 days also take into account the week-to-week variations such as labour strikes, power outages, change in work settings etc. Other environmental variables such as humidity was adjusted for in the models.
Incomplete outcome data	Low	Daily counts for injuries were obtained. However, any potential errors or missing data does not depend on air-temperature levels.
Selective outcome reporting	Low	All pre-specified outcomes reported in the pre-specified way.
Conflict of interest	Low	Authors declared no conflicts of interest.

Table D24 Risk of bias assessment of Varghese et al. (173).

#24 Varghese et al. (173)		
Design	Time Stratified Cass crossover study design	
Population and Time	All workers in three metropolitans of Australia	
Exposure	Heatwaves using Excess Heat Factor	
Outcomes	Work related injuries and illness in Melbourne, Perth and Brisbane	
Risk of Bias Assessment		
Bias Domain	**Author's judgement**	**Criterion supportive response**
Selection/recruitment strategy	Probably low	All accepted workers' compensation claims (as determined by the insurer) that occurred in the three Australian states (Qld, Vic and WA) between 1 January 2006 and 30 March 2016 were extracted from the national dataset 3 archived by SafeWork Australia. Occupational injuries sourced from workers' compensation claims with 85% coverage of insured workers (168).
Exposure Assessment	Probably high	Heatwave data were obtained from Excess heat factor index developed by Bureau of Meteorology, Australia. City-level values were extracted from gridded datasets.
Outcome Assessment	Low	Details of each claim are recorded according to the Type of Occurrence Classification System (TOOCS 3.1).
Confounding	Low	All potential confounders were taken into account. Seasonality, workforce and long-term trends are controlled by design. Weekly strata of 7 days also take into account the week-to-week variations such as labour strikes, power outages, change in work settings etc. Other environmental variables such as humidity was adjusted for in the models.
Incomplete outcome data	Low	Daily counts for injuries were obtained. However, any potential errors or missing data does not depend on air-temperature levels.
Selective outcome reporting	Low	All pre-specified outcomes reported in the pre-specified way.
Conflict of interest	Low	Authors declared no conflicts of interest.

Appendix E – Sensitivity Analyses to Check the Quality of Evidence in Hot Temperature Studies (n = 17)

Risk of Bias Assessment Across hot temperature studies (n = 17)

Sensitivity analysis was carried out to check the statistical difference between "probably high" vs."probably low" and "low" studies.

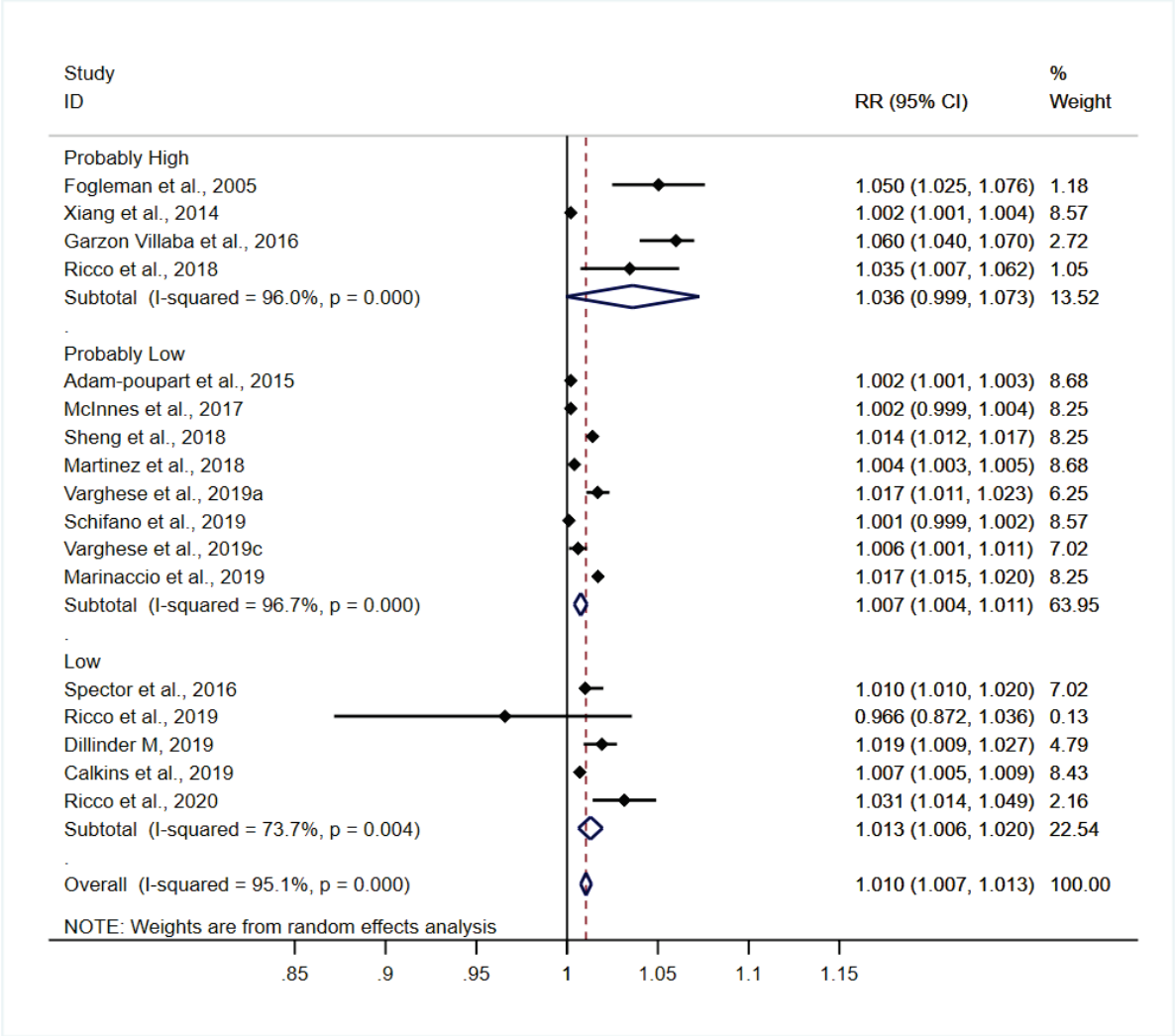


Figure E1 Forest plots for overall Risk of Bias assessment across hot temperature studies (n = 17)

Forest Plots with Prediction Intervals

Meta-analyses were conducted for overall estimated for hot temperature studies (n = 17) and HW studies (n = 8), prediction intervals were estimated to check the inconsistencies in the dataset for certainty assessment

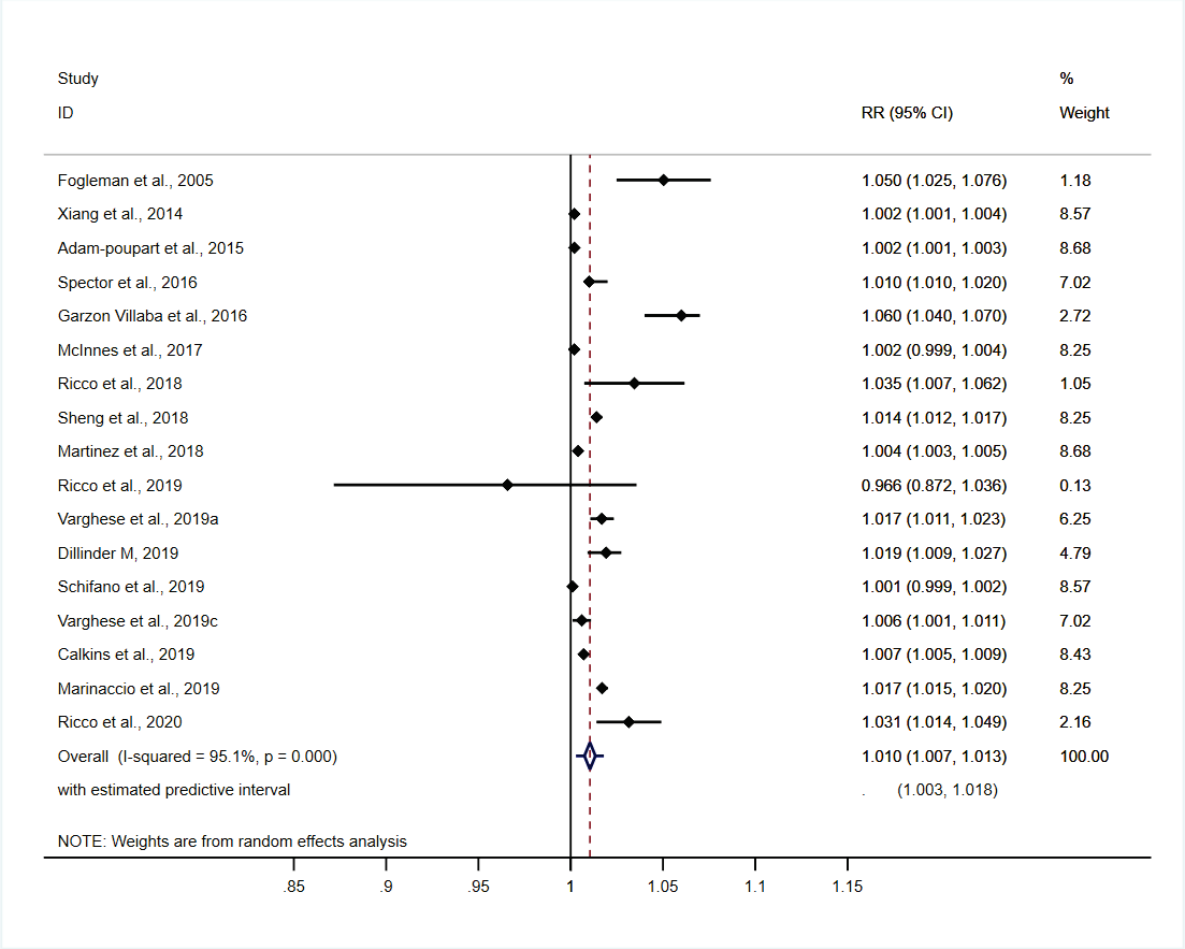


Figure E2 Forest plots of hot temperature studies with prediction interval estimated

Sensitivity Analyses to test for potential sources of heterogeneity

Leave one out analysis was carried out to test for the sources of heterogeneity from individual studies. The results indicate that omitting each study from the analysis does not significantly impact the results.

Table E1 Influence meta-analysis of aggregated hot temperature using Random effects inverse-variance model with DerSimonian-Laird estimate of tau^2

Authors omitted	RR	LCI	UCI	% weights
Fogleman et al. (73)	1.010	1.007	1.013	102.04
Xiang et al. (65)	1.011	1.008	1.015	81.37
Adam-poupart et al. (69)	1.012	1.008	1.015	74.01
Spector et al. (64)	1.010	1.007	1.014	92.79
Garzon Villalba et al. (72)	1.009	1.006	1.012	113.86
McInnes et al. (68)	1.011	1.008	1.014	87.67
Ricco et al. (76)	1.010	1.007	1.013	99.94
Sheng et al. (63)	1.010	1.007	1.013	104.18

Martinez et al. (61)	1.012	1.008	1.015	68.41
Ricco et al. (161)	1.010	1.007	1.013	99.82
Varghese et al. (66)	1.010	1.007	1.013	96.74
Dillender et al. (71)	1.010	1.007	1.013	97.34
Schifano et al. (82)	1.012	1.008	1.015	83.94
Varghese et al. (67)	1.011	1.008	1.014	91.62
Calkins et al. (70)	1.011	1.008	1.014	85.96
Marinaccio et al. (75)	1.009	1.006	1.012	121.98
Ricco et al. (169)	1.010	1.007	1.013	100.03
Overall effect	**1.010**	**1.007**	**1.013**	**100.00**

Test of overall effect = 0: z=665.467 p=0.000

Heterogeneity measures

	Value	**df**	**p-VALUE**
Cochrane's Q	326.18	16	<0.001
I^2(%)	95.1%		
Modified H^2	19.386		
Tau^2	0.0000		

Note I^2 = between study variance (tau^2) as a percentage of total variance Modified H^2 = ratio of tau^2 to typical within-study variance. LCI is the lower confidence interval and UCI is the upper confidence interval

Table E2 Sensitivity analysis using different exposure metrics, different exposure assessment data and unit of estimate for hot temperature studies

Type of sensitivity analysis	**N**	**RR**	**LCI**	**UCI**	**I^2(%)**	**p-VALUE (hetero)**
Exposure Metrics						
Tmax	11	1.008	1.005	1.011	92.1%	<0.001
Tmean	2*	1.012	1.002	1.022	97.3%	<0.001
Thermal Indices (WBGT, Humidex, MAT)	4	1.026	1.010	1.043	96.4%	<0.001
Overall	**17**	**1.010**	**1.007**	**1.013**	**95.1%**	**<0.001**
Exposure assessment dataset						
Single/average of weather station data	11	1.008	1.005	1.011	94.5%	<0.001
Gridded/satellite/geolocated data	6	1.014	1.008	1.021	89.4%	<0.001
Overall	**17**	**1.010**	**1.007**	**1.013**	**95.1%**	**<0.001**
Unit of Estimate						
1ºC increase in temperature	7	1.009	1.004	1.013	96.6%	<0.001
Comparing percentiles	10	1.013	1.008	1.018	94.2%	<0.001
Overall	**17**	**1.010**	**1.007**	**1.013**	**95.1%**	**<0.001**

Note n is the total number of studies. Caution should be taken in interpreting the results from limited number of studies/observations. I^2 is the heterogeneity. RR is the risk estimate, LCI is the low confidence interval and UCI is the upper confidence interval. Two studies (62, 74) were excluded from the meta-analysis of hot temperature studies.

Table E3 Heterogeneity in different climate zones before and after standardising results

Climate zones	k	RR	LCL	UCL	p-VALUE (hetero)	AFTER standardising RR	BEFORE standardising RR
Humid Subtropical	56	1.017	1.014	1.020	<0.001	89.8%	93.7%
Oceanic	28	1.010	1.008	1.012	<0.001	91.3%	95.2%
Hot Mediterranean	67	1.009	1.008	1.011	<0.001	86.5%	87.5%
Warm Mediterranean	11	1.006	1.004	1.007	<0.001	75.3%	92.4%
Hot Semi-Arid	3	1.005	1.004	1.007	0.918	0.0%	61.8%
Cold Semi-Arid	11	1.005	1.004	1.005	0.816	0.0%	0.0%
Humid and Warm Continental	13	1.003	1.001	1.004	0.012	53.1%	26.2%
Subarctic	4	1.000	0.996	1.005	0.286	20.8%	20.8%
Hot Desert	1	1.004	1.001	1.008			
Overall	**194**	**1.010**	**1.009**	**1.011**	**<0.001**	**89.3%**	**93.0%**

Funnel Plots and Egger's test to check risk of publication bias

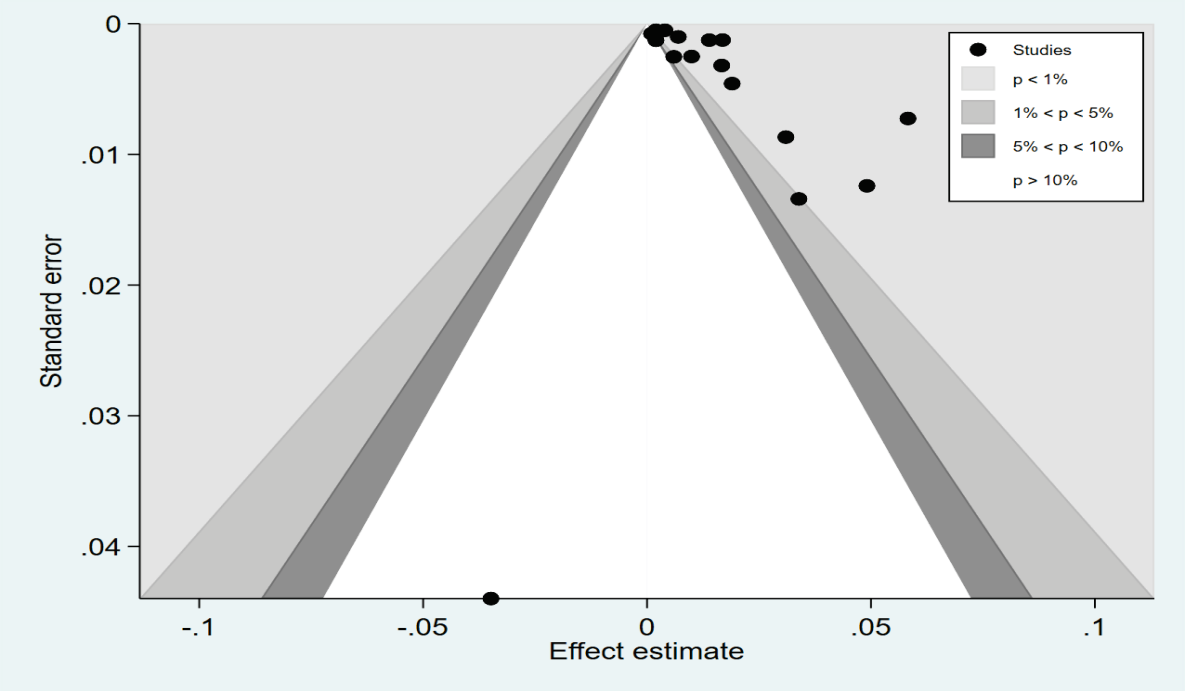


Figure E3 Funnel plot with Egger's test for detecting publication bias in meta-analysis in studies assessing the risk of OI associated with hot temperatures (n = 17). Note Two studies (62, 74) were removed from meta-analyses.

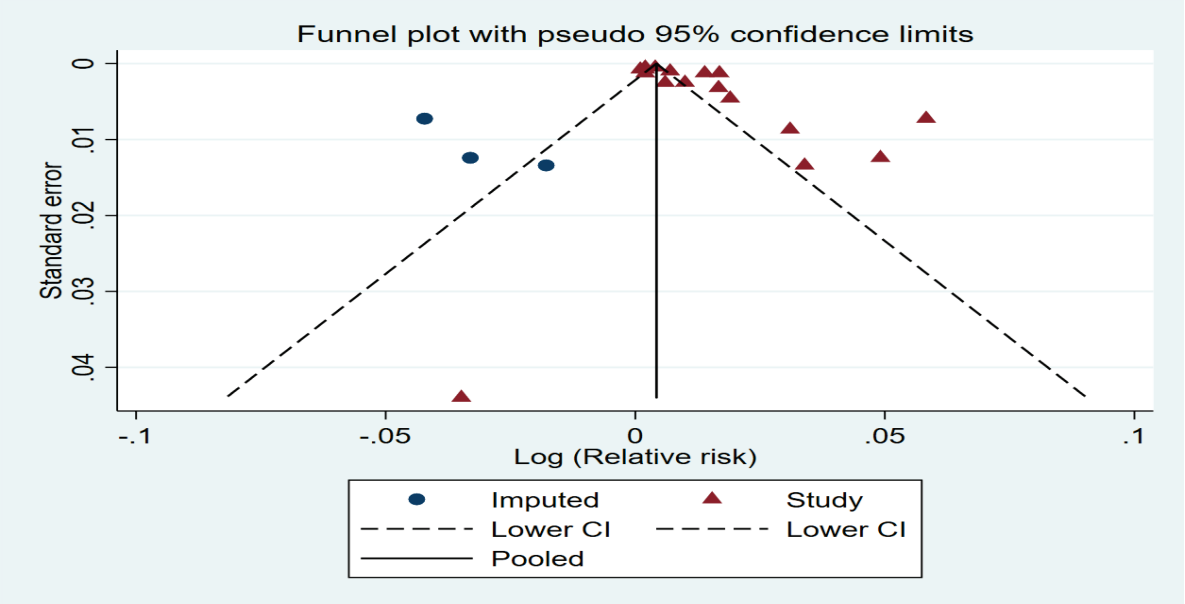


Figure E4 Funnel plot with Egger's test after imputing three studies using Trim and Fill method for detecting publication bias in meta-analysis in studies assessing the risk of OI associated with hot temperatures (n = 17). Two studies (62, 74) were removed from meta-analyses.

Appendix F – Sensitivity Analyses to Check the Quality of Evidence in Heatwave Studies (n = 8)

Risk of Bias Assessment Across HW studies (n = 8)

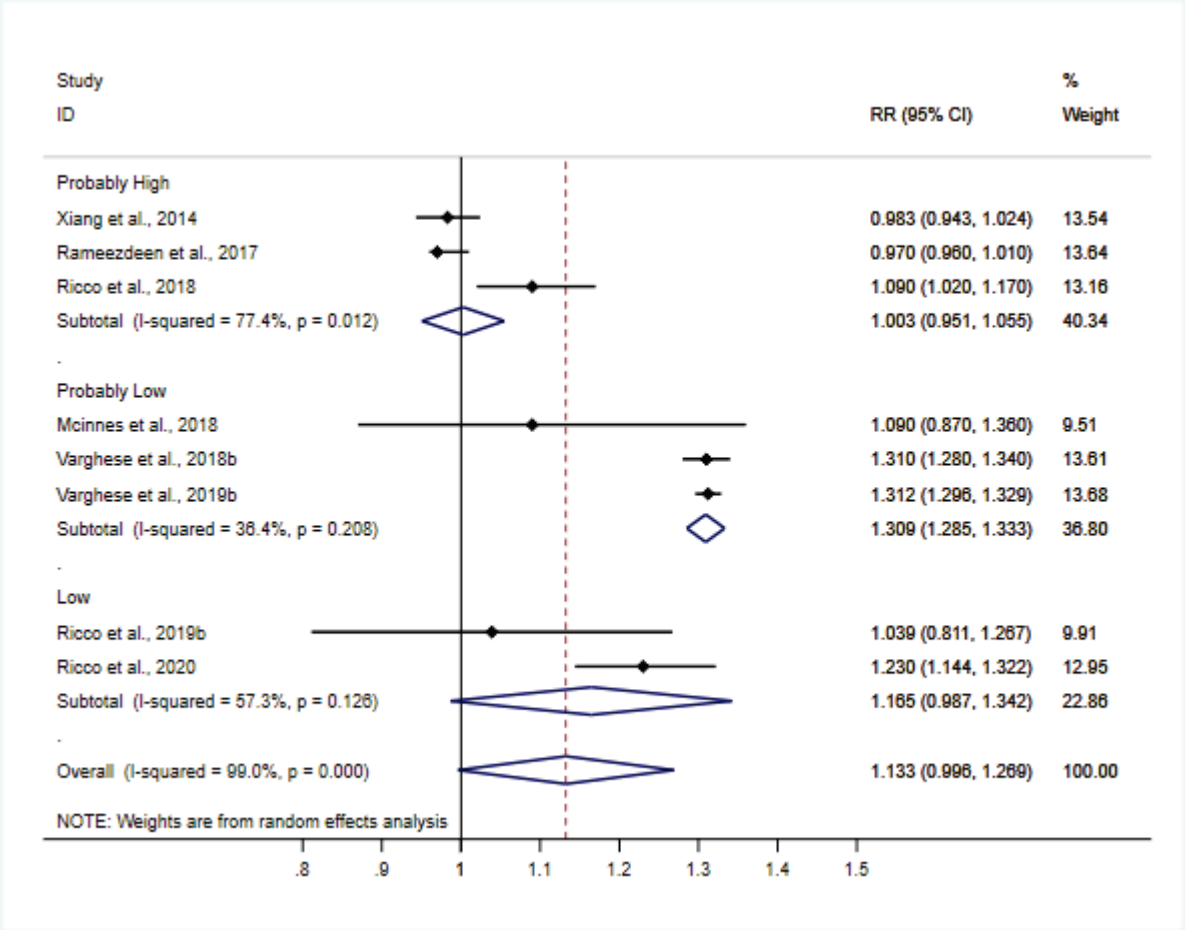


Figure F1 Forest plots for overall Risk of Bias assessment of HW studies (n = 8)

Forest Plots with Prediction Intervals

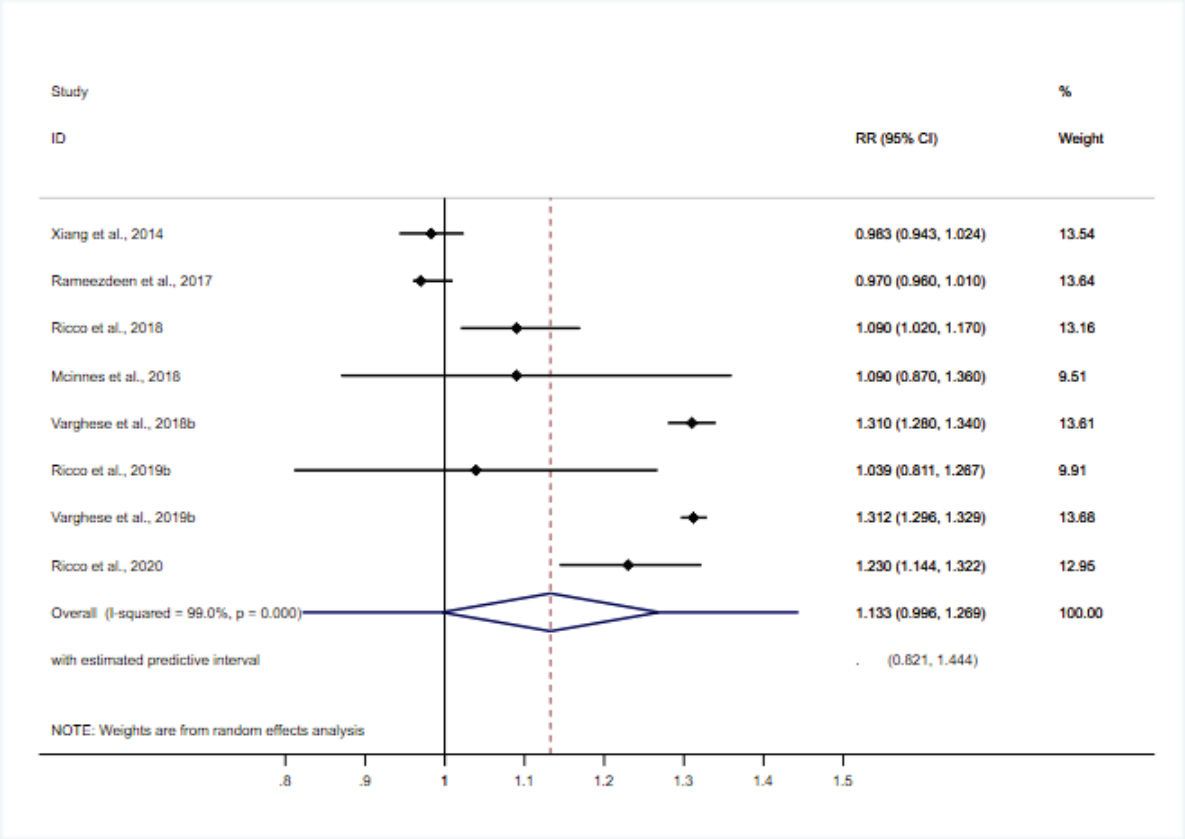


Figure F2 Forest Plots of HW studies (n = 8) with prediction intervals estimated

Influence Analysis to test for heterogeneity

Leave one out analysis was carried out to test for the sources of heterogeneity from individual studies. The results indicate that omitting each study from the analysis does not significantly impact the results.

Table F1 Influence meta-analysis of aggregated HW studies using Random effects inverse-variance model with DerSimonian-Laird estimate of tau^2

Authors omitted	RR	LCI	UCI	% weights
Xiang et al. (58)	1.156	1.011	1.301	88.80
Rameezdeen et al. (170)	1.162	1.046	1.277	139.40
Ricco et al. (76)	1.139	0.990	1.288	83.93
Mcinnes et al. (171)	1.137	0.993	1.281	90.08
Varghese et al. (172)	1.104	0.941	1.267	69.97
Ricco et al. (161)	1.143	0.999	1.287	89.77
Varghese et al. (173)	1.118	0.969	1.267	84.25
Ricco et al. (169)	1.104	0.960	1.248	90.04
Overall	**1.133**	**0.996**	**1.269**	**100.00**

Test of overall effect = 0: z=16.267 p=0.000

Heterogeneity measures

	Value	df	p-VALUE
Cochrane's Q	675.37	7	<0.001
I^2(%)	99.0%		
Modified H^2	95.482		
Tau^2	0.0354		

Note I^2 = between study variance (tau^2) as a percentage of total variance Modified H^2 = ratio of tau^2 to typical within-study variance. LCI is the lower confidence interval and UCI is the upper confidence interval

Table F2 Sensitivity analysis using different exposure assessment data in HW studies (n = 8)

Type of sensitivity analysis	N	RR	LCI	UCI	I^2 (%)	p-VALUE (hetero)
Exposure assessment dataset						
Single/average of weather station data	6	1.128	0.970	1.286	99.3%	<0.001
Gridded/satellite/geolocated data	2	1.165	0.987	1.342	57.3%	0.126
Overall	**8**	**1.133**	**0.996**	**1.269**	**99.0%**	**<0.001**
Different definitions of HWs						
HW Tmax ≥ 35°C for three or more consecutive days	6	1.059	0.982	1.135	86.8%	<0.001
EHF-Moderate/High severity HW days	2	1.312	1.297	1.326	0.0%	0.909
Overall	**8**	**1.133**	**0.996**	**1.269**	**99.0%**	**<0.001**

Note N is the total number of studies. Caution should be taken in interpreting the results from limited number of studies/observations. I^2 is the heterogeneity. RR is the risk estimate, LCI is the low confidence interval and UCI is the upper confidence interval. One study Varghese et al (173) had estimates for multiple cities, pooled estimate was used for this analysis.

Appendix G – Meta-Analysis Results for Hot Temperature Studies in Different Climate Zones

Hot Temperature studies (n = 17)

Humid Subtropical Climates

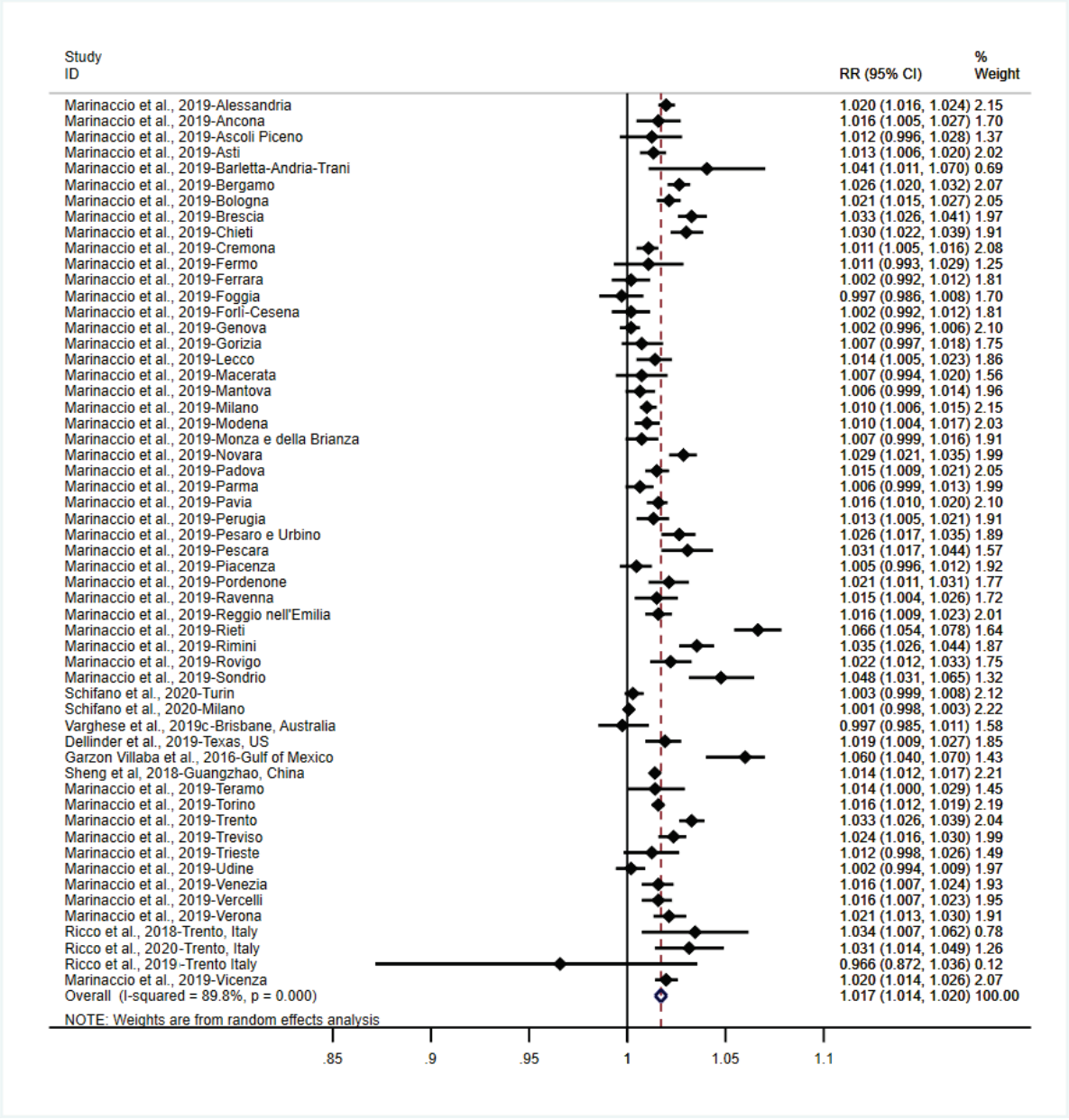


Figure G1 Estimated Risk of OI associated with 1ºC increase in temperatures in Humid Subtropical Climates

Oceanic Climates

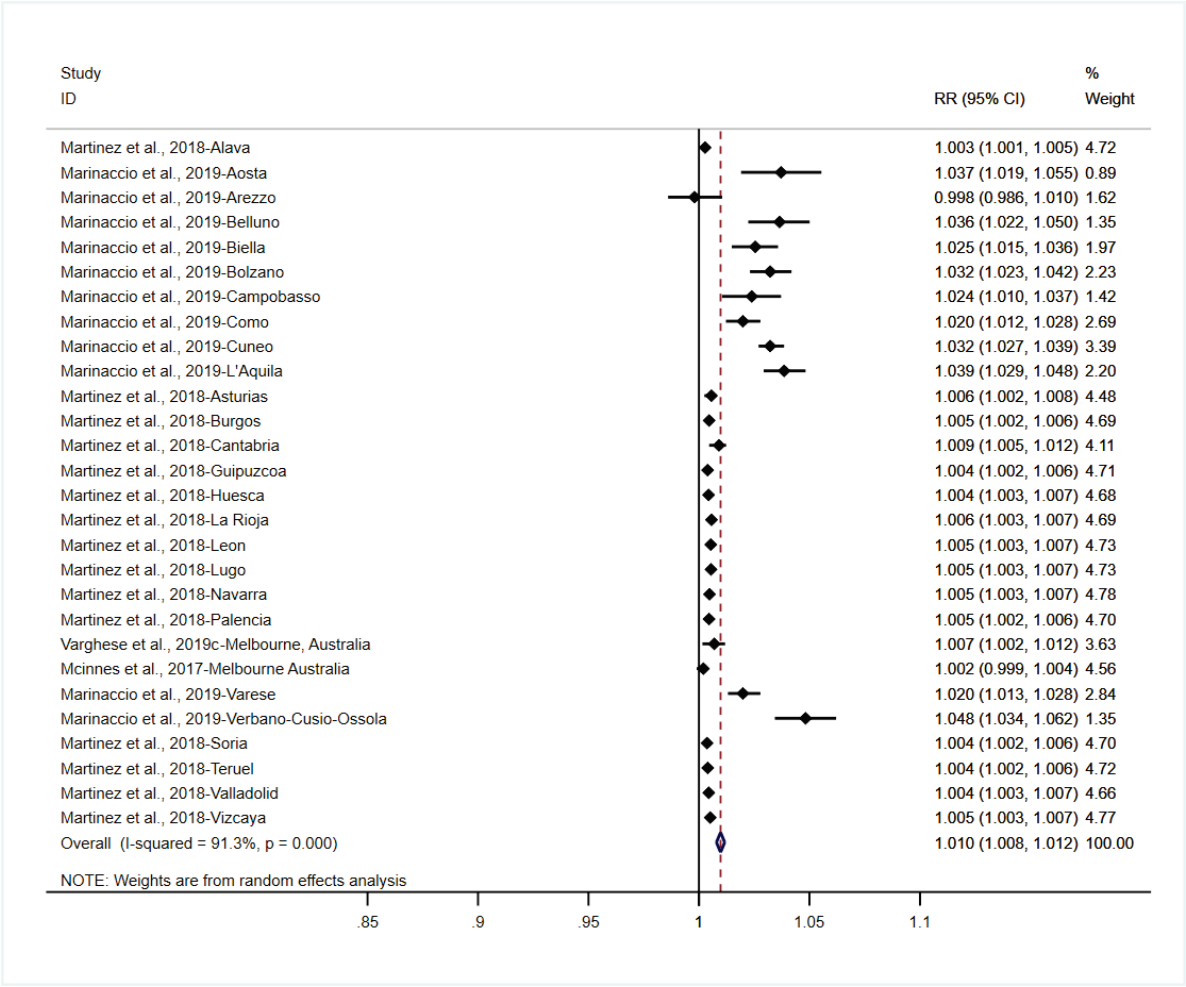


Figure G2 Estimated Risk of OI associated with 1ºC increase in temperatures in Oceanic Climates

Hot Mediterranean Climates

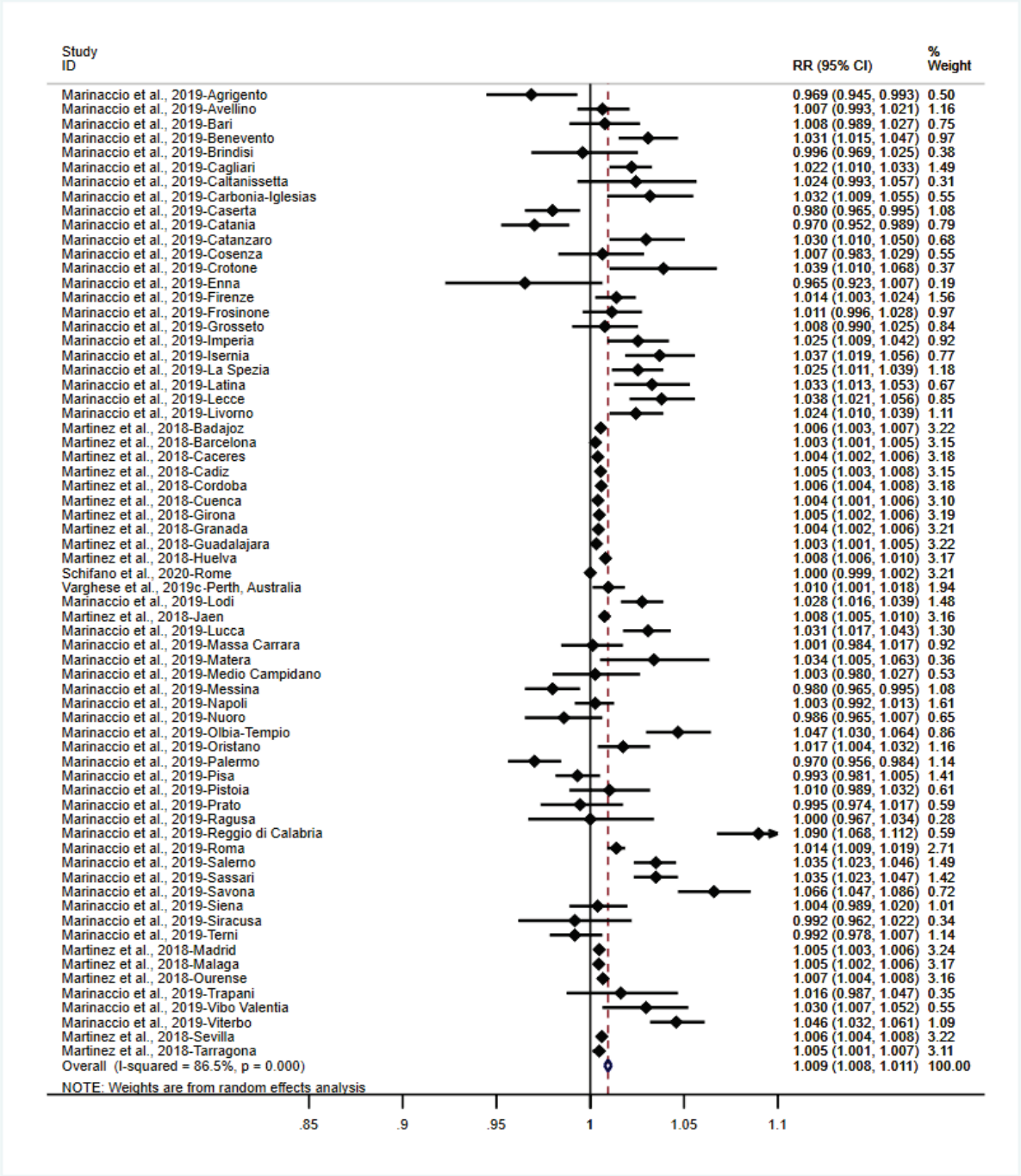


Figure G3 Estimated Risk of OI associated with 1ºC increase in temperatures in Hot Mediterranean Climates

Warm Mediterranean Climates

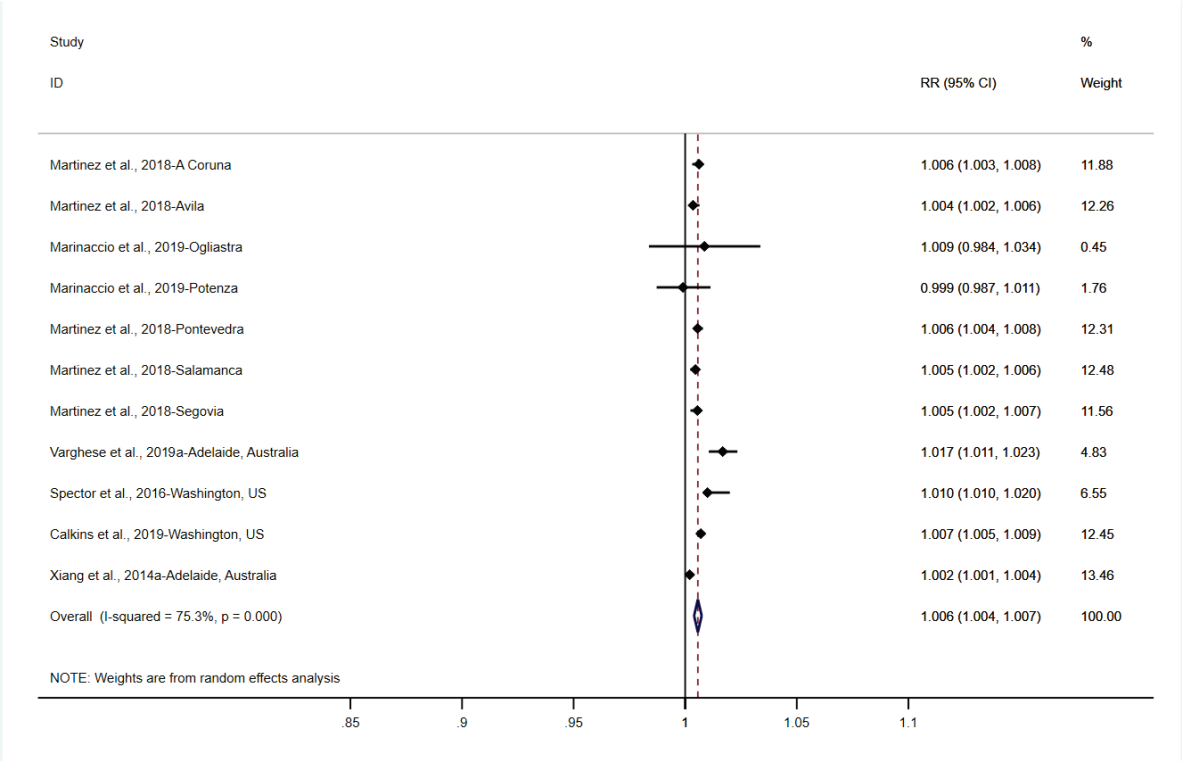


Figure G4 Estimated Risk of OI associated with 1ºC increase in temperatures in Warm Mediterranean Climates

Hot Semi-Arid Climates

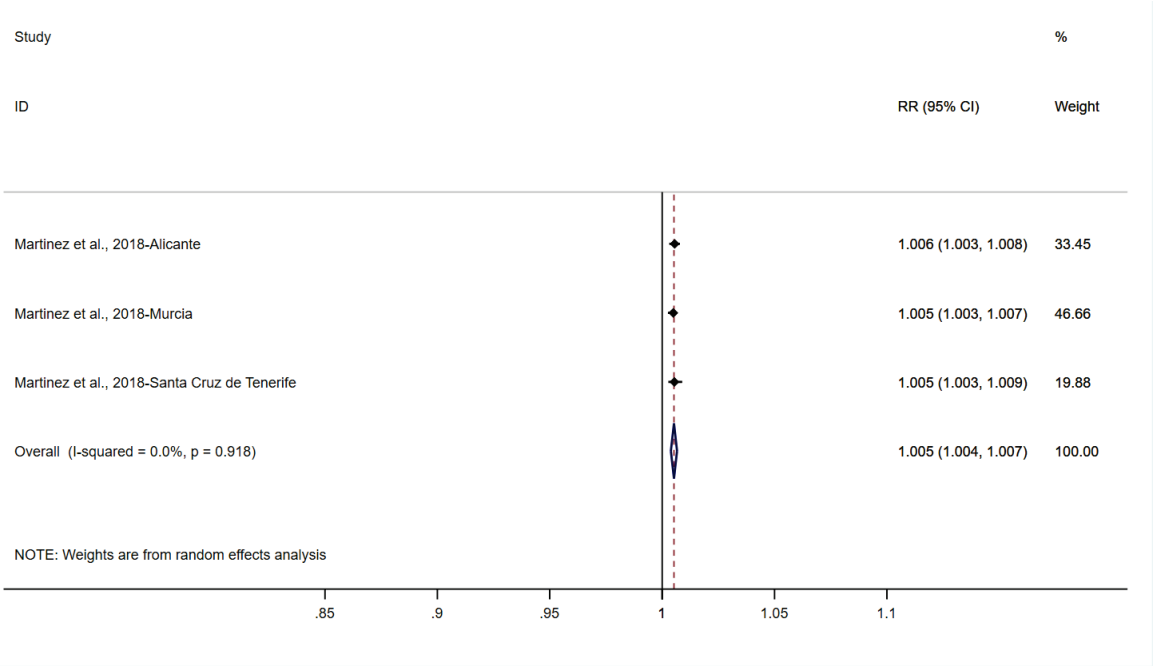


Figure G5 Estimated Risk of OI associated with 1ºC increase in temperatures in Hot Semi-Arid Climates

Cold Semi-Arid Climates

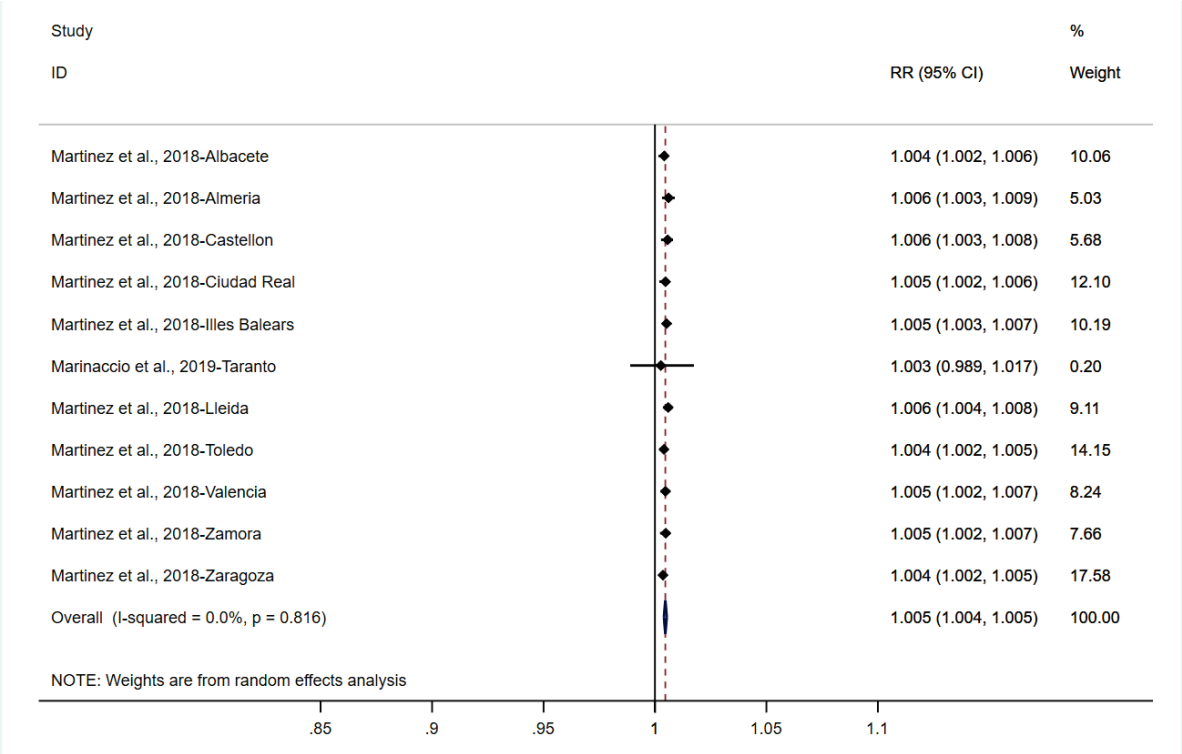


Figure G6 Estimated Risk of OI associated with 1ºC increase in temperatures in Cold Semi-Arid Climates

Humid and Warm Continental Climates

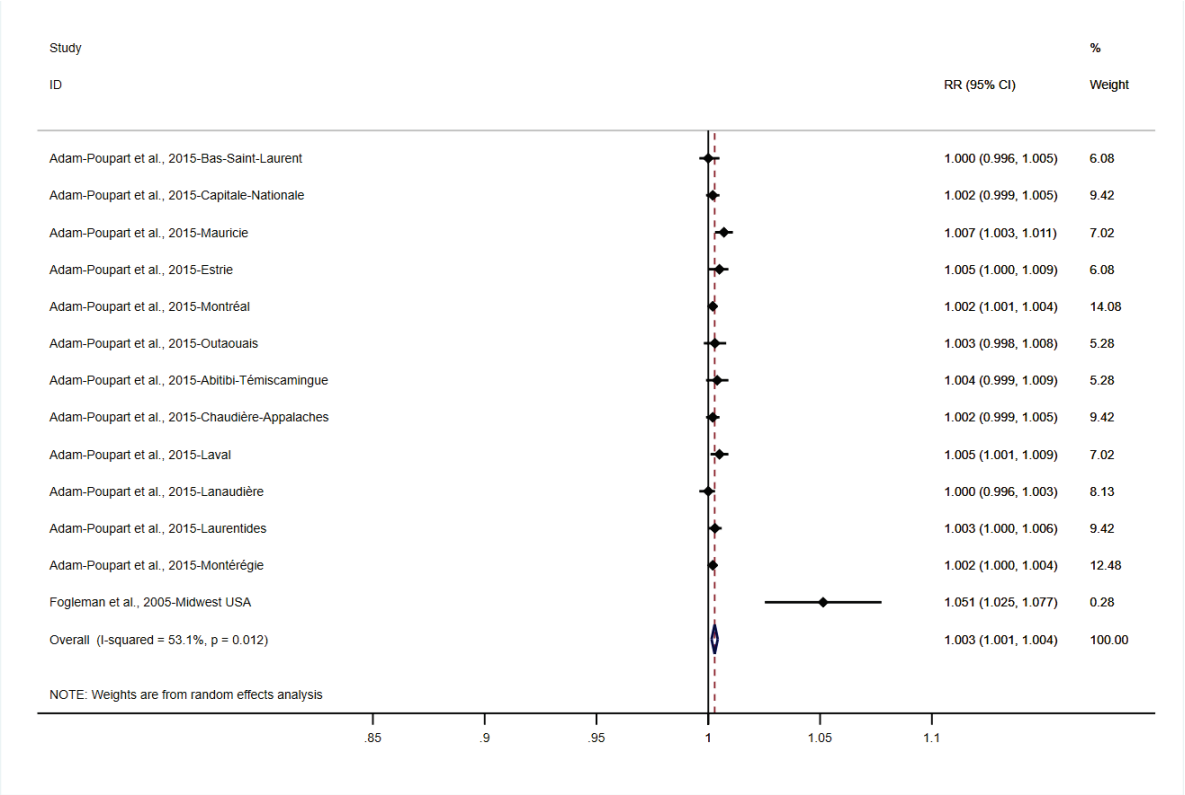


Figure G7 Estimated Risk of OI associated with 1ºC increase in temperatures in Humid and Warm Continental Climates

Subarctic climates

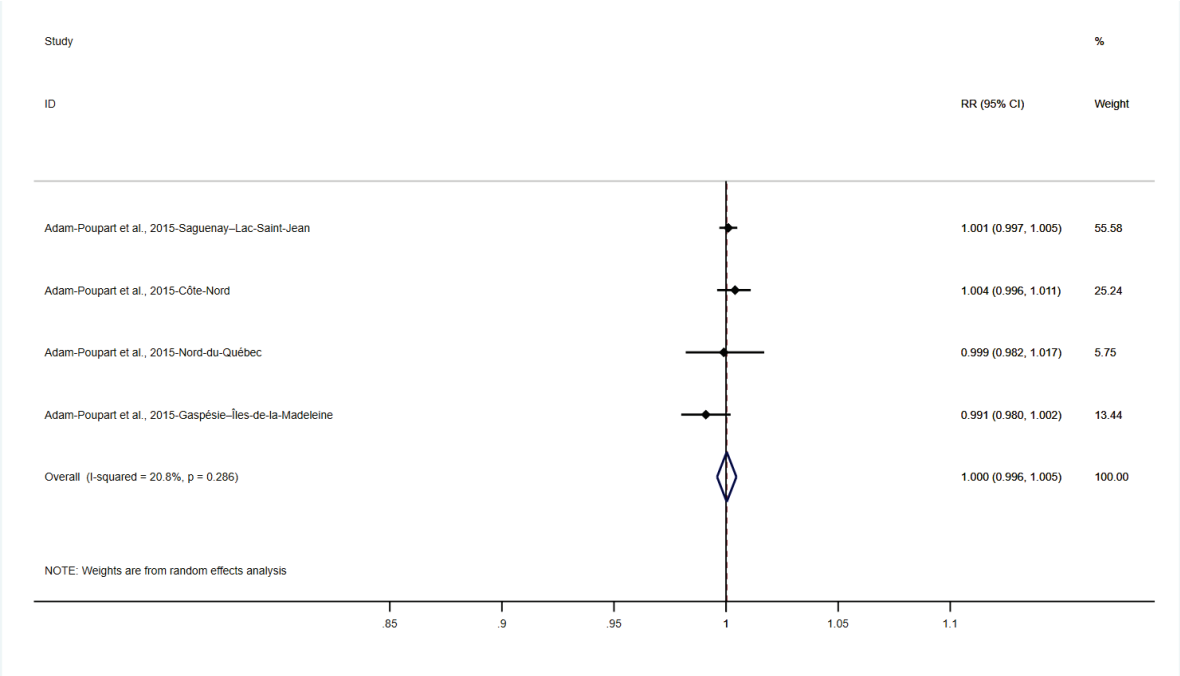


Figure G8 Estimated Risk of OI associated with 1ºC increase in temperatures in Subarctic climates

Appendix H – Meta-Analysis Results for Heatwave Studies in Different Climate Zones

Heatwave studies (n = 8)

Oceanic Climates

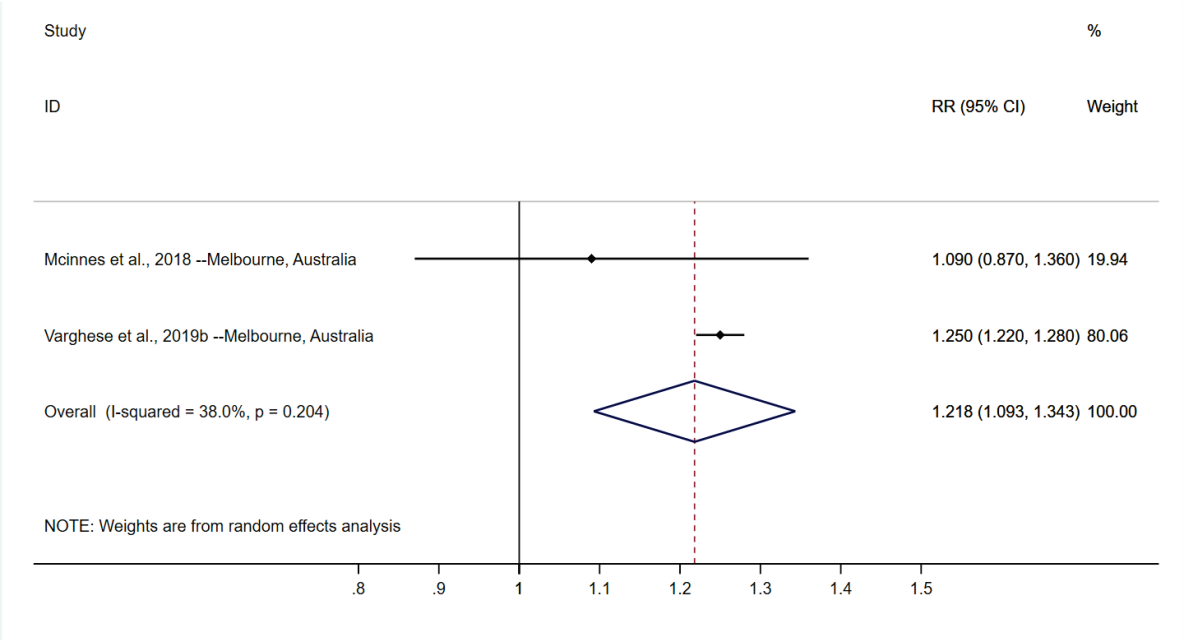


Figure H1 Estimated Risk of OI associated with HW periods in Oceanic Climates

Humid Subtropical Climates

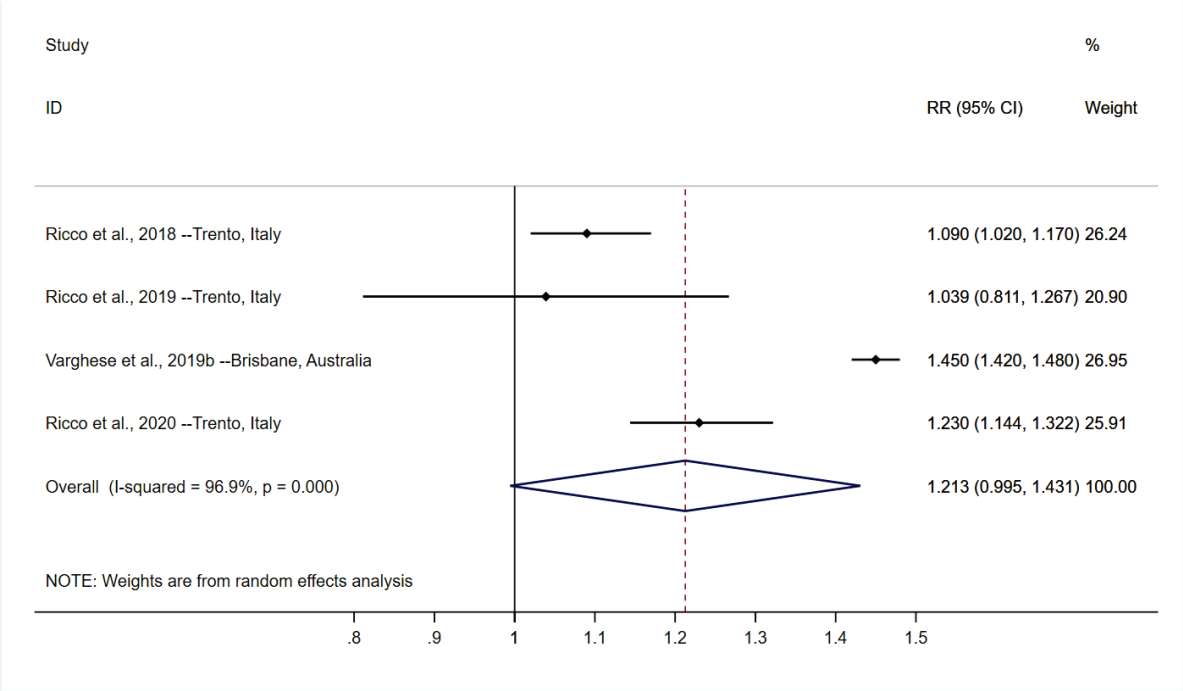


Figure H2 Estimated Risk of OI associated with HW periods in Humid Subtropical Climates

Warm Mediterranean Climates

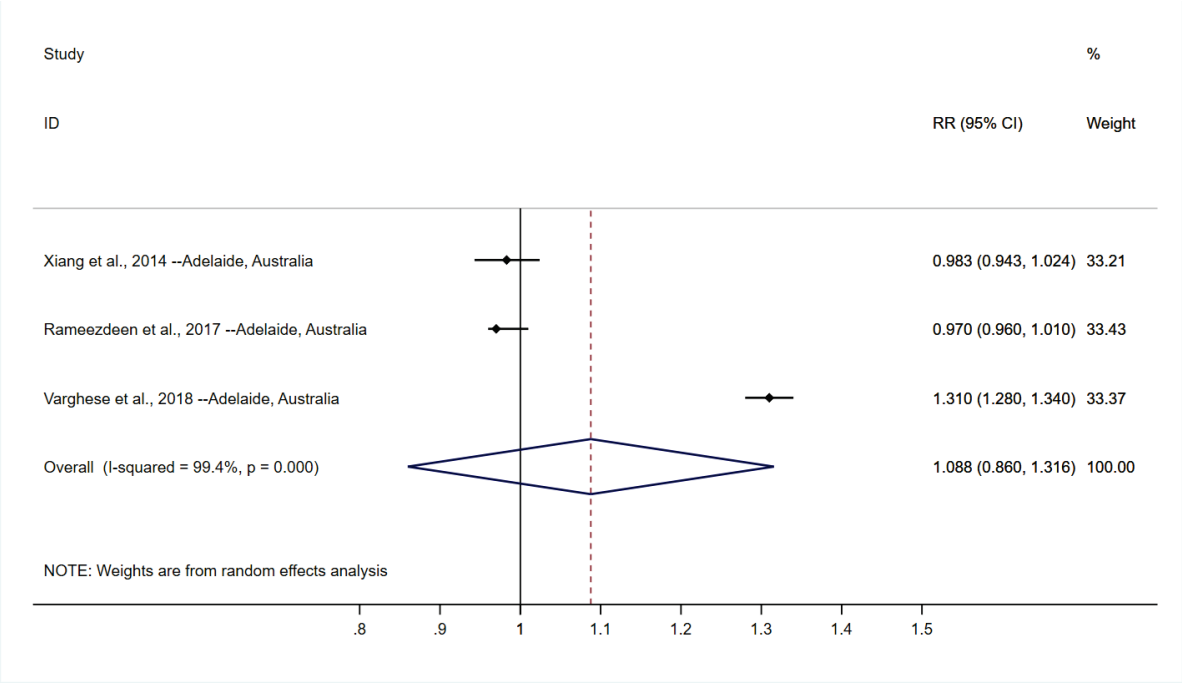


Figure H3 Estimated Risk of OI associated with HW periods in Warm Mediterranean Climates

Appendix I – Subgroup Analysis

Additional Subgroup Analyses based on study characteristics (n = 17).

Subgroup analysis are based on overall results from all studies.

Table I1 Subgroup analysis based on study characteristics for hot temperature studies (n = 17).

Subgroups	N	RR	LCI	UCI	I^2	P value
Study Characteristics						
Region	**17**	**1.010**	**1.007**	**1.013**	**95.1%**	**<0.001**
North America/Canada	6	1.017	1.010	1.024	95.3%	<0.001
Australia	4	1.006	1.001	1.010	86.1%	<0.001
Europe	6	1.011	1.004	1.017	96.2%	<0.001
Asia	1*	1.014	1.012	1.017		0.153
Study Design	**17**	**1.010**	**1.007**	**1.013**	**95.1%**	**<0.001**
TS	10	1.014	1.009	1.019	95.9%	<0.001
CCO	7	1.008	1.003	1.012	94.2%	<0.001
Modeling techniques	**17**	**1.010**	**1.007**	**1.013**	**95.1%**	**<0.001**
DLNMs	6	1.010	1.004	1.015	97.2%	<0.001
Non-DLNMs Models	11	1.011	1.007	1.015	92.0%	<0.001

Note n is the number of studies included in the analysis, I^2 is the heterogeneity value in percentage. LCI is the lower confidence interval and UCI is the upper confidence interval

APPENDIX III – Supplementary Material for Chapter 4

Table S1 Descriptive statistics of Workers' Compensation Claims in Greater Adelaide, 2005-2018.

Classification	**Greater Adelaide N (%)**
All claims	260,977
Gender	
Female	91,366 (35.0)
Male	169,616 (65.0)
Age group (years)	
15-24	38,332 (14.7)
25-34	52,279 (20.0)
35-44	59,205 (22.7)
45-54	66,326 (25.4)
55 and above	44,849 (17.2)
Worker Experience	
Apprentice/trainee	5,317 (2.0)
Other workers	255,660 (98.0)
Industry	
Agriculture, Forestry & Fishing	1,952 (0.7)
Mining	1,047 (0.4)
Manufacturing	35,418 (13.6)
Electricity, gas, water and waste services	3,320 (1.3)
Construction	17,234 (6.6)
Wholesale Trade	9,555 (3.7)
Retail trade	18,867 (7.2)
Accommodation & Food Services	6,575 (2.5)
Transport, Postal & Warehousing	19,578 (7.5)
Education & Training	19,552 (7.5)
Health Care & Social Assistance	31,502 (12.1)
Other Services	35,353 (13.5)
Miscellaneous**	61,031 (23.4)
Occupations	
Managers	8,635 (3.3)
Professionals	21,893 (8.4)
Technicians & Trade Workers	56,525 (21.7)
Service Workers	36,244 (13.9)
Administrative Workers	13,455 (5.1)
Sales Workers	13,746 (5.3)
Machinery Operators & Drivers	34,081 (13.1)
Labourers	54,201 (20.8)
Miscellaneous*	22,203 (8.5)
Mechanism of Injury	
Falls	39,851 (15.3)
Hitting objects	27,147 (10.4)
Being hit	41,868 (16.0)
Sound and pressure	4,794 (1.8)
Body stressing	91,448 (35.0)
Heat and electricity	6,010 (2.3)
Chemical agents	5,435 (2.1)
Biological agents	976 (0.4)

Mental	12,174 (4.7)
Vehicle	24,830 (9.5)
Miscellaneous**	6,458 (2.5)
Nature of Injury	
Intracranial injuries	1,754 (0.7)
Fractures	12,164 (4.7)
Wounds and lacerations	45,134 (17.3)
Burns	4,902 (1.9)
Nerves and spinal cord injuries	402 (0.1)
Traumatic injuries	100,792 (38.6)
Other injuries	16,388 (6.9)
Musculoskeletal and other connective tissue disorders	33,067 (12.7)
Mental disorders	12,388 (4.7)
Digestive system disorders	2,490 (0.9)
Skin disorders	2,793 (1.1)
Nervous system and sense organ disorders	8,616 (3.3)
Respiratory disorders	675 (0.3)
Circulatory disorders	504 (0.2)
Infections	621 (0.2)
Neoplasms	134 (0.1)
Other diseases	285 (0.1)
Miscellaneous*	17, 879 (6.8)

Note: The total number of claims for each category vary slightly due to data transformations (from POA to SA3) for all the respective categories. * include claims from smaller categories and where the data is missing or unavailable.

Table S2 Subgroup Analysis of the estimation of cumulative risk of OI based on age, gender, type of claims, type of workers, physical demands, and location of work.

Subgroup Analysis	Percent Change (1st percentile)	Percent Change (90th percentile)	Percent Change (99th percentile)
Age			
15-24 years	5.6 (-3.4-15.4)	26.7 (13.9-41.1)	32.7 (14.8-53.4)
25-34 years	5.2 (-3.8-14.9)	23.1 (11.8-35.7)	33.8 (17.4-52.5)
35-44 years	5.8 (-2.5-14.8)	20.3 (9.7-32.0)	27.1 (11.8-44.5)
45-54 years	0.0 (-4.3-4.6)	13.1 (2.2-25.2)	22.0 (6.6-39.5)
55+ years	-1.8 (-6.9-3.6)	2.0 (-7.8-14.9)	7.2 (-8.7-25.8)
Gender			
Females	-0.9 (-4.6- 3.0)	14.2 (4.8-24.5)	25.1 (10.8-41.2)
Males	5.2 (-0.4-11.1)	18.4 (11.3-26.0)	25.1 (14.9-36.2)
Type of claims			
Injuries-only	6.6 (0.8-12.7)	21.2 (14.3-28.5)	25.5 (15.9-35.8)
Illness-only	-1.1 (-5.6-3.5)	15.3 (3.9-27.9)	28.4 (11.8-47.6)
Type of workers			
Technicians	4.4 (-4.3-13.8)	20.7 (9.1-33.5)	29.0 (13.5-46.7)
Labourers	4.1 (-4.0-12.8)	18.9 (7.9-30.9)	23.8 (8.0-41.9)
Service workers	-1.9 (-7.2-3.6)	8.0 (-4.5-22.2)	19.8 (1.8-41.1)
Drivers and Machinery operators	2.0 (-5.5-10.1)	33.5 (17.1-52.2)	37.9 (15.2-64.9)
Physical Demands			
Limited	0.5 (-5.6-7.1)	21.5 (7.9-36.7)	29.8 (7.7-56.4)
Light	5.4 (-3.2-14.8)	10.9 (-0.6-23.0)	7.1 (-5.6-21.7)
Medium	0.8 (-4.1-5.8)	20.6 (9.3-33.0)	31.5 (16.1-48.8)
Heavy	4.1 (-3.3-12.2)	21.9 (10.2-35.0)	29.8 (14.8-46.7)
Location of Work			
Indoor (regulated and Unregulated)	2.3 (-2.5-7.4)	15.6 (8.7-22.9)	20.1 (10.2-31.0)
Outdoor (Outdoor and In Vehicles or Cabs)	-3.8 (-12.0-5.1)	28.9 (4.4-59.1)	38.8 (0.4-91.7)
Multiple Locations	5.9 (-3.1-15.8)	25.2 (14.4-37.0)	34.1 (18.7-51.5)

Table S3 Sensitivity analysis of the risk estimates computed as the percent difference (%), based on four criteria 1. Quasi Akaike Information Criterion (QAIC), 2. Risk of OI estimated at 99th percentile, 3. Attributable fraction (AF) at moderate heat, 4. Attributable fraction (AF) at extreme heat by varying modelling choices, fitting the models to all OI.

Sensitivity Analysis	**QAIC**	**99th Percentile heat effects**	**AF at moderate heat**	**AF at Extreme heat**
Long-term trend smoothening				
4df/year	24973.29	25.0 (16.4-34.2)	4.37%	1.73%
5df/year	25000.34	25.1 (16.2-34.7)	6.24%	1.92%
6df/year	25004.18	28.3 (18.5-38.9)	8.54%	2.09%
7df/year	25037.20	32.5 (22.0-43.9)	9.19%	2.28%
8df/year	25003.98	24.0 (14.2-34.6)	8.36%	1.92%
9df/year	25065.60	27.0 (16.8-38.1)	8.81%	2.02%
Knots for exposure-response				
50th percentile	24973.29	25.0 (16.4-34.2)	4.37%	1.73%
10th percentile	24975.91	28.6 (19.3-38.6)	4.97%	1.80%
10th and 90th percentiles	24978.01	-8.7 (-15.5- -1.5)	3.66%	1.77%
25th and 75th percentiles	24983.74	11.9 (2.2-22.5)	3.81%	1.66%
33th and 66th percentiles	24987.47	15.3 (5.5-26.1)	4.05%	1.68%
25th 50th and 75th percentiles	24990.91	-11.4 (-18.0- -4.3)	4.19%	1.90%
10th 50th and 90th percentiles	24993.94	-10.4 (-17.1- -3.1)	3.69%	1.88%
Exposure				
Tmin	24953.08	-8.2 (-16.3-0.5)	5.21%	1.44%
Tmean	24963.82	21.3 (11.9-31.4)	5.20%	1.74%

Table S4 Risk estimates at maximum Tmax estimated using various general circulation models under two RCP (4.5 and 8.5) for four timeframes (2010s, 2030s, 2050s, and 2090s).

	CANESM2	MIROC5	GFDL-ESM2M	CNRM5	IPSL-CM5B-LR	MRI-CGCM3
2010						
RCP 4.5	21.9 (-9.0-63.3)	21.6 (-9.3-63.0)	20.7 (-5.7-54. 6)	21.9 (-8.9-63.2)	22.5 (-8.3-63.6)	21.1 (-4.9-54.1)
RCP 8.5	21.3 (-0.2-50.0)	21.4 (-3.8-53.3)	20.8 (-0.2-46.3)	21.4 (-9.4-62.7)	21.7 (-6.4-58.1)	21.7 (-9.2-63.2)
2030						
RCP 4.5	21.1 (-4.7-53. 9)	21.4 (-8.2-60.7)	21.4 (-9.4-62.7)	21.4 (-6.0-56.8)	21.9 (-4.9-56.1)	21.8 (-9.0-63.1)
RCP 8.5	22.7 (-8.1-63.8)	22.3 (-8.6-63.7)	22.8 (-8.1-64.1)	20.5 (-4.5-52.2)	22.1(-8.8-63.3)	21.7 (-9.2-63.2)
2050						
RCP 4.5	22.9 (-8.0-64.2)	21.4 (-1.4-64.2)	21.4 (-9.3-62. 7)	21.4 (-3.5-63. 6)	22.7 (-8.1-63.7)	22.7 (-8.1-63.7)
RCP 8.5	22.6 (-8.1-63.7)	22.0 (-8.9-63.5)	22.9 (-8.0-64.1)	21.7 (-9.0-63.1)	22.8 (-8.0-64.1)	22.6 (-8.1-63.7)
2090						
RCP 4.5	22.6 (-8.2-63.7)	22.9 (-8.0-64.1)	21.5 (-9.2-62.7)	22.1 (-6.7-63.6)	22.2 (-8.6-63.3)	22.0 (-0.9-63.3)
RCP 8.5	23.1 (-7.7-64.2)	21.4 (-5.5-56.0)	21.2 (-9.7-62.5)	22.4 (-8.5-63.5)	21.8 (-9.0-63.1)	22.8 (-8.0-63.9)

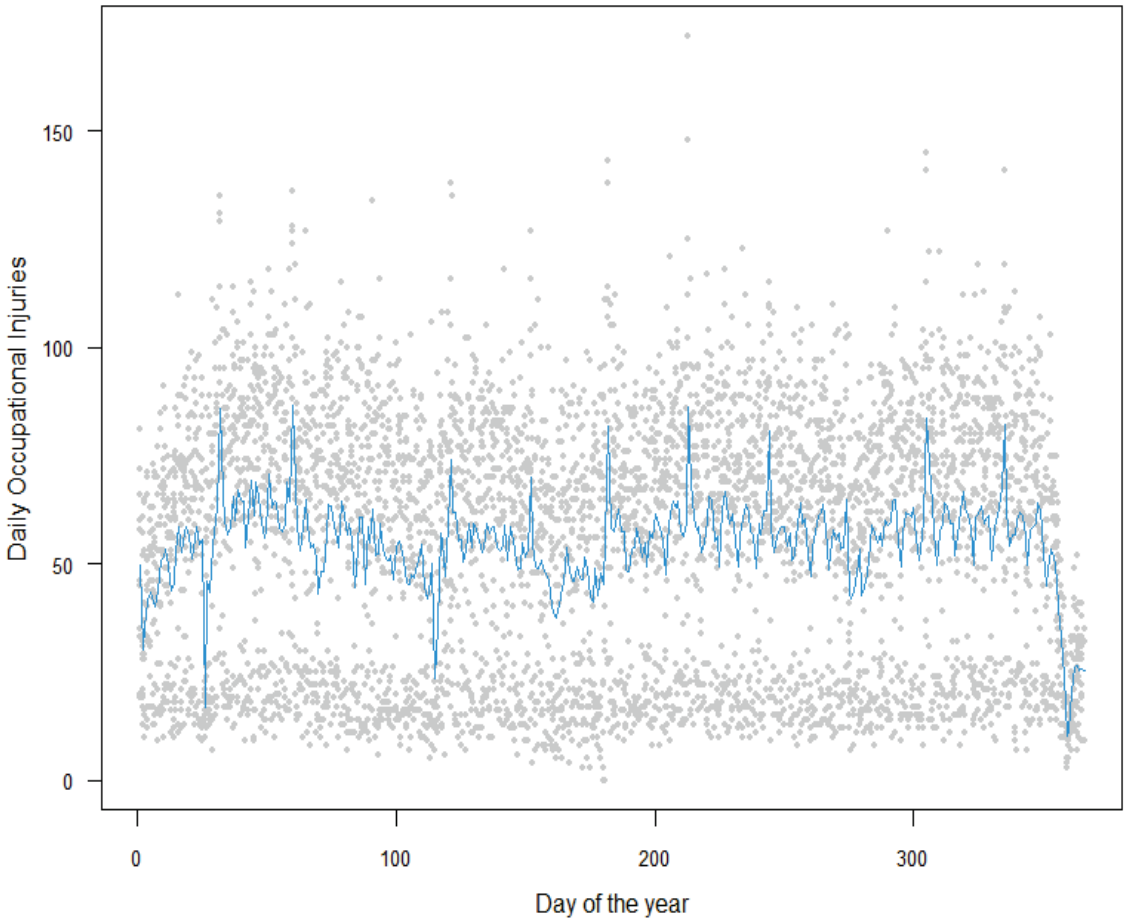


Figure S1 Seasonal trends of OI in Greater Adelaide, Australia. Grey dots correspond to the observed daily OI counts registered in each day of the year between 2005 and 2018. The blue line depicts the mean number of OI per day of the year.

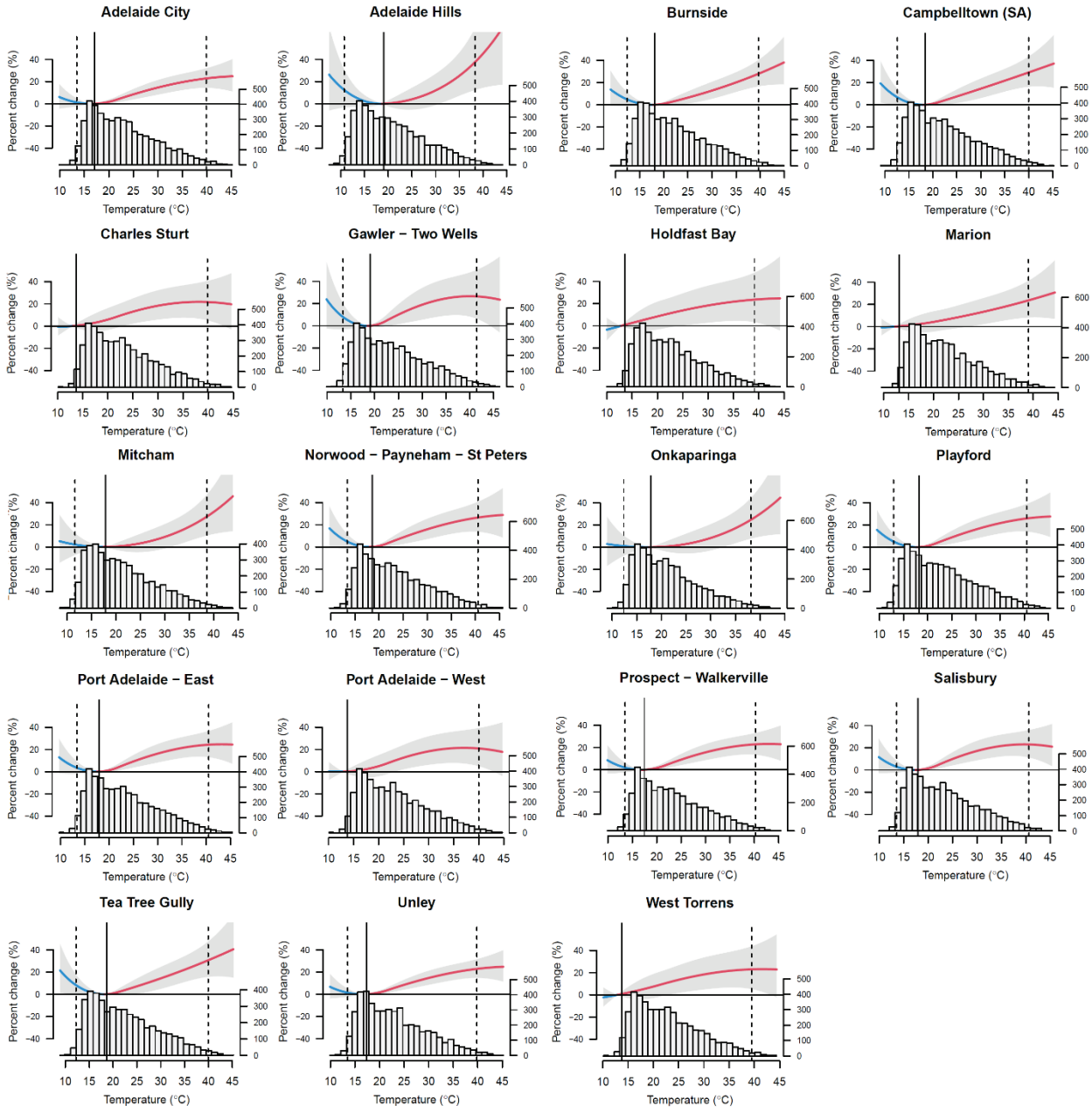


Figure S2 Region-wise exposure-response curves estimated as percent difference [with 95% confidence intervals (CI) – shaded areas] for OI associated with Tmax (ºC) in 19 SA3 regions in Greater Adelaide from 2005 to 2018.

The relationship considers 7 days of lag. The solid line represents the PMOI, and dashed lines are temperatures in the 1st and 99th percentile characterised as cold and heat effects, respectively.

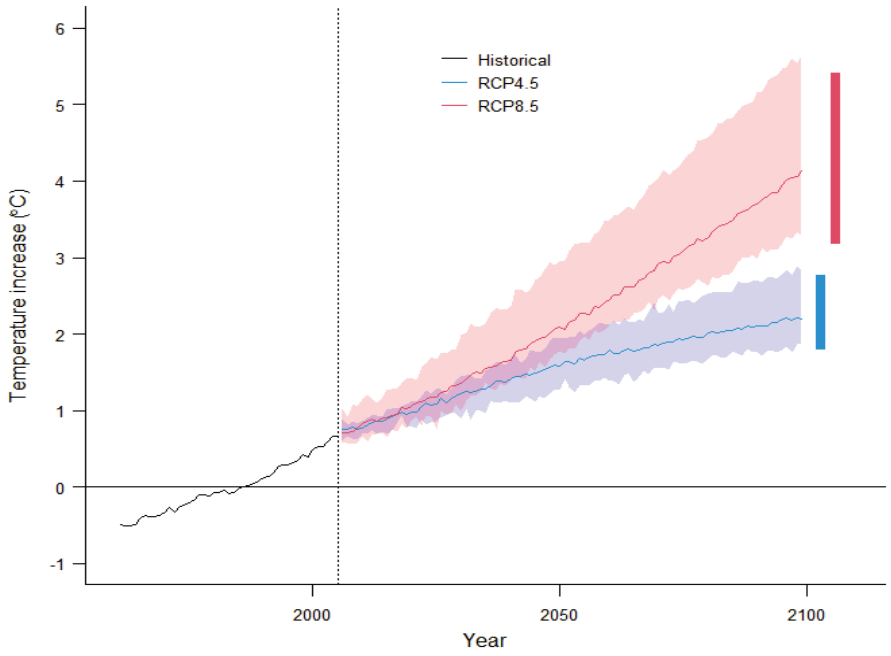


Figure S3 Temporal trends in the projected Tmax for the historical period (1961–2005) and projected period (2006–2100) in Greater Adelaide, Australia.

Solid lines respond to the mean annual temperatures estimated across the six general circulation model series [variability in the range for each year - shaded areas]. The vertical bars in the right show the average annual maximum and minimum for each modelled temperature series.

APPENDIX IV – Supplementary Material for Chapter 5

Classification of the Australian hierarchy of statistical areas for publication and analysis of official data

"The Australian statistical geography standards (ASGS) is a classification of Australia into hierarchy of statistical areas. It is a social geography, developed to reflect the location of people and communities. It is used for the publication and analysis of official statistics and other data. The ASGS is updated every 5 years to account for growth and change in Australia's population, economy and infrastructure." (Source: Australian Bureau of Statistics, (174))

Statistical area level 3 (SA3) is designed for an output of regional data, with a population of about 30,000 to 130,000 people. Most of the health data have a granularity of SA3 (Figure S1 – A).

Statistical area level 2 (SA2) is a smaller subunit of SA3, which are medium-sized general-purpose areas built to represent communities that interact socially and economically. They have a population range of about 3,000 to 25,000 people. (Figure S1 – B).

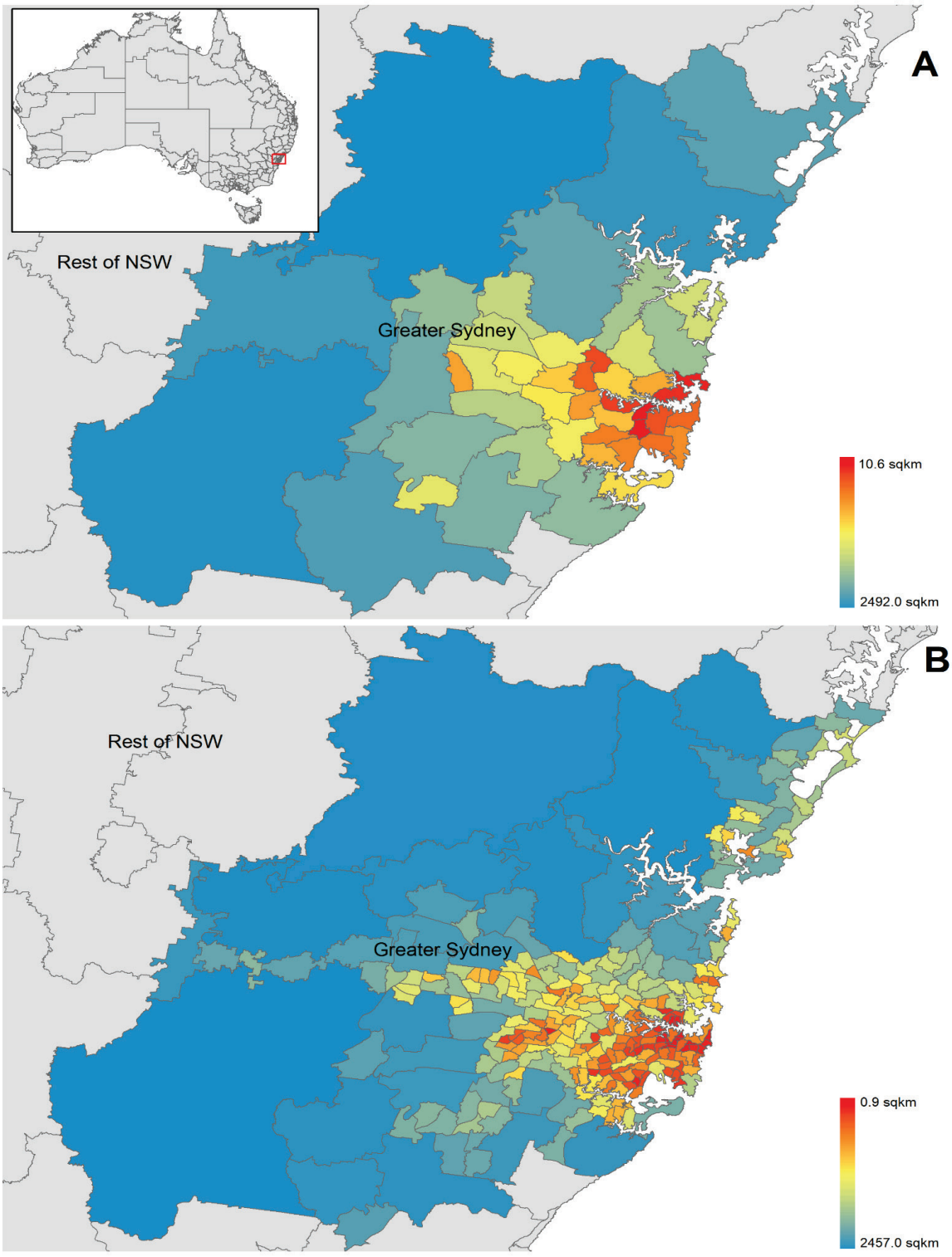


Figure S1 Australian statistical geography standard (ASGS), Structures. A - Statistical area level 3, B - Statistical area level 2.

Table S1 Descriptive statistics of Workers' Compensation Claims in Greater Brisbane, Greater Melbourne, and Greater Sydney respectively from the year 2005 to 2018.

Classification	Greater Brisbane N (%)	Greater Melbourne N (%)	Greater Sydney N (%)
All claims	263260	468658	924679
Gender			
Female	88404 (33.6)	164217 (35.0)	347515 (37.6)
Male	174856 (66.4)	304441 (65.0)	577164 (62.4)
Age Group (years)			
15-24y	50652 (19.2)	50612 (10.8)	128410 (13.9)
25-34y	57847 (22.0)	94731 (20.2)	207817 (22.5)
35-44y	57630 (21.9)	107112 (22.8)	208897 (22.6)
45-54y	57704 (21.9)	125995 (26.9)	219032 (23.7)
55+y	39427 (15.0)	90209 (19.2)	160523 (17.4)
Types of occupation			
Managers	6853 (2.6)	24846 (5.3)	52605 (5.7)
Professionals	16394 (6.2)	59706 (12.7)	151670 (16.4)
Technicians & trade workers	56936 (21.6)	80767 (17.2)	145742 (15.8)
Service workers	32207 (12.2)	62013 (13.2)	146491 (15.8)
Administrative workers	13088 (5.0)	18520 (3.9)	63181 (6.8)
Seles workers	15339 (5.8)	38622 (8.2)	58241 (6.3)
Machinery operators & drivers	39507 (15.0)	65804 (14.0)	116897 (12.6)
Labourer	78297 (29.7)	97652 (20.8)	187216 (20.2)
Others*	4638 (1.8)	20728 (4.4)	2636 (0.3)
Nature of Injury			
Intracranial injuries	1247 (0.5)	4271 (0.9)	5077 (0.5)
Fractures	20467 (7.8)	29684 (6.3)	49783 (5.4)
Wounds & Lacerations	46358 (17.6)	91638 (19.6)	204768 (22.1)
Burns	5349 (2.0)	6397 (1.4)	16739 (1.8)
Nerves and spinal cord injuries	519 (0.2)	132 (0.0)	795 (0.1)
Traumatic injuries	132689 (50.4)	80384 (17.2)	459991 (49.7)
Other injuries	11619 (4.4)	14440 (3.1)	48897 (5.3)
Musculoskeletal and other connective tissue diseases	22276 (8.5)	173374 (37.0)	44879 (4.9)
Mental disorders	4997 (1.9)	32296 (6.9)	44101 (4.8)
Digestive system diseases	4605 (1.7)	9450 (2.0)	9986 (1.1)
Skin & subcutaneous diseases	1693 (0.6)	2650 (0.6)	4082 (0.4)
Nervous system & sense organ diseases	8614 (3.3)	17532 (3.7)	19259 (2.1)
Respiratory system diseases	655 (0.2)	1595 (0.3)	2265 (0.2)

Circulatory system diseases	213 (0.1)	1191 (0.3)	1165 (0.1)
Infectious & parasitic diseases	538 (0.2)	749 (0.2)	1470 (0.2)
Neoplasm	490 (0.2)	220 (0.0)	638 (0.1)
Other diseases	151 (0.1)	648 (0.1)	1856 (0.2)
Others*	779 (0.3)	2006 (0.4)	8929 (1.0)
Mechanism of Injuries			
Falls	49240 (18.7)	91254 (19.5)	181581 (19.6)
Hitting objects	26940 (10.2)	29144 (6.2)	94191 (10.2)
Being hit	37590 (14.3)	79777 (17.0)	152421 (16.5)
Sound & pressure	5528 (2.1)	11449 (2.4)	14896 (1.6)
Body stressing	93154 (35.4)	193115 (41.2)	315764 (34.1)
Heat & electricity	5504 (2.1)	6637 (1.4)	18071 (2.0)
Chemicals	3464 (1.3)	6658 (1.4)	16694 (1.8)
Biological	872 (0.3)	1898 (0.4)	5509 (0.6)
Mental	4637 (1.8)	1882 (0.4)	42309 (4.6)
Vehicle	36332 (13.8)	19608 (4.2)	83233 (9.0)
Others*	0 (0.0)	27236 (5.8)	9 (0.0)
Industries			
Agriculture, forestry & fishing	3080 (1.2)	2419 (0.5)	6360 (0.7)
Mining	3961 (1.5)	917 (0.2)	5517 (0.6)
Manufacturing	56272 (21.4)	85000 (18.1)	127299 (13.8)
Electricity, gas & water	2682 (1.0)	4728 (1.0)	12533 (1.4)
Construction	29643 (11.3)	47587 (10.2)	80597 (8.7)
Wholesale trade	12051 (4.6)	35052 (7.5)	42583 (4.6)
Retail trade	24162 (9.2)	37156 (7.9)	83907 (9.1)
Accommodation & food services	13180 (5.0)	15909 (3.4)	54104 (5.9)
Transport, postal & warehousing	23306 (8.9)	42121 (9.0)	83972 (9.1)
Information, media & telecommunication	518 (0.2)	3346 (0.7)	9843 (1.1)
Financial & insurance services	1356 (0.5)	4658 (1.0)	17834 (1.9)
Rental hiring and retail services	2766 (1.1)	5407 (1.2)	8454 (0.9)
Professional, scientific & technical services	3745 (1.4)	12672 (2.7)	30260 (3.3)
Administrative & support services	13725 (5.2)	16482 (3.5)	33105 (3.6)
Public administration & safety	9999 (3.8)	31709 (6.8)	87570 (9.5)
Education & training	6407 (2.4)	33341 (7.1)	75310 (8.1)
Health care & social assistance	44880 (17.0)	58424 (12.5)	112979 (12.2)
Arts & recreational services	2981 (1.1)	17585 (3.8)	19375 (2.1)
Others*	8547 (3.2)	14143 (3.0)	33077 (3.6)
Types of workers based on experience			
Apprentice	9827 (1.1)	9062 (1.9)	13520 (1.5)
Experiences	253433 (98.9)	459596 (98.1)	911159 (98.5)
Physical work			
Limited	45555 (17.3)	113821 (24.3)	298154 (32.2)
Light	57668 (21.9)	79953 (17.1)	186861 (20.2)
Medium	73535 (27.9)	95846 (20.5)	221032 (23.9)

Heavy	81654 (31.0)	102478 (21.9)	213718 (23.1)
Others*	4848 (1.8)	76559 (16.3)	4916 (0.5)
Types of exposure			
Regulated inside	170595 (64.8)	272497 (58.1)	660353 (71.4)
Unregulated inside	1921 (0.7)	580 (0.1)	1346 (0.1)
Outside	1961 (0.7)	2116 (0.5)	8658 (0.9)
Vehicle or cab	17034 (6.5)	24708 (5.3)	44337 (4.8)
Multiple locations	66901 (25.4)	92197 (19.7)	205072 (22.2)
Others*	4848 (1.8)	76559 (16.3)	4916 (0.5)
Age group (based on younger a& older stratification)			
Younger (< 45 years)	166128 (63.1)	252454 (53.9)	545125 (59.0)
Older (≥ 45 years)	97132 (36.9)	216204 (46.1)	379554 (41.0)
Industries (based on outdoor & indoor industries)			
Outdoor Industries	35406 (13.4)	54734 (11.7)	99490 (10.8)
Indoor Industries	227854 (86.5)	412560 (88.0)	824725 (89.2)
Others*	-	1364 (0.3)	464 (0.1)
Types of Claims (based on injuries & diseases)			
Injury-related claims	218249 (82.9)	226947 (48.4)	786049 (85.0)
Disease-related claims	44233 (16.8)	239705 (51.1)	129701 (14.0)
Others*	778 (0.3)	2006 (0.4)	8929 (1.0)

Note: * include claims from smaller categories and where the data is missing or unavailable.

Table S2 Region-wise risk estimates of OI associated with moderate heat and extreme heat respectively in three cities of Australia.

Greater Brisbane -SA3 Regions	Percent Change at moderate heat (95% CI)	Percent Change at extreme heat (95% CI)	Greater Melbourne -SA3 Regions	Percent Change at moderate heat (95% CI)	Percent Change at extreme heat (95% CI)	Greater Sydney - SA3 Regions	Percent Change at moderate heat (95% CI)	Percent Change at extreme heat (95% CI)
Bald Hills - Everton Park	5.5 (-3.3, 15.2)	8.6 (-1.7, 20.1)	Banyule	16.2 (7.7, 25.3)	17.3 (6.8, 28.9)	Auburn	19.2 (10.2, 28.8)	32.3 (19.7, 46.1)
Beaudesert	18.7 (-8.5, 53.8)	25.9 (-8.2, 72.7)	Bayside	18.2 (6.4, 31.4)	17.2 (2.9, 33.4)	Bankstown	17.8 (10.4, 25.6)	28.7 (18.4, 39.9)
Beenleigh	10.7 (-3.7, 27.1)	13.1 (-5.2, 35.0)	Boroondara	15.8 (8.8, 23.2)	17.1 (8.4, 26.5)	Baulkham Hills	10.6 (6.3, 15.1)	18.9 (11.9, 26.3)
Bribie - Beachmere	5.0 (-4.1, 14.9)	7.8 (-3.0, 19.9)	Brimbank	15.7 (9.2, 22.5)	17.0 (8.9, 25.7)	Blacktown	17.5 (10.1, 25.4)	31.7 (20.3, 44.0)
Greater Brisbane Inner	8.8 (0.4, 17.9)	11.7 (1.6, 22.9)	Brunswick - Coburg	16.1 (8.0, 24.8)	17.3 (7.2, 28.2)	Blacktown - North	18.9 (8.0, 31.0)	30.2 (14.3, 48.4)
Greater Brisbane Inner - East	7.7 (0.1, 15.8)	11.4 (2.0, 21.6)	Cardinia	14.9 (-0.3, 32.4)	18.0 (-0.7, 40.3)	Blue Mountains	24.6 (-1.1, 57.1)	0.0 (0.0, 0.0)
Greater Brisbane Inner - North	6.6 (-0.8, 14.6)	10.3 (0.8, 20.7)	Casey - North	15.1 (1.6, 30.5)	18.3 (1.6, 37.9)	Botany	11.8 (6.2, 17.8)	15.2 (8.1, 22.8)
Greater Brisbane Inner - West	8.4 (0.3, 17.1)	11.5 (1.6, 22.3)	Casey - South	14.3 (7.8, 21.2)	15.5 (7.4, 24.2)	Bringelly - Green Valley	16.5 (5.5, 28.6)	22.8 (8.0, 39.6)
Browns Plains	11.6 (1.5, 22.8)	15.5 (2.5, 30.2)	Dandenong	15.3 (9.4, 21.6)	16.6 (9.1, 24.6)	Camden	15.9 (7.4, 25.1)	22.6 (11.4, 34.9)
Caboolture	8.6 (1.0, 16.7)	12.0 (2.8, 22.0)	Darebin - North	19.3 (11.1, 28.2)	20.5 (10.6, 31.4)	Campbelltown (NSW)	10.0 (5.7, 14.5)	13.7 (7.4, 20.2)
Caboolture Hinterland	3.5 (-8.9, 17.5)	15.6 (-20.8, 68.8)	Darebin - South	16.1 (8.3, 24.4)	17.2 (7.6, 27.7)	Canada Bay	16.0 (10.3, 22.0)	22.9 (15.4, 30.9)
Capalaba	4.2 (-3.9, 13.1)	7.5 (-2.7, 18.8)	Essendon	16.2 (7.7, 25.2)	17.3 (6.9, 28.7)	Canterbury	15.1 (7.6, 23.1)	23.3 (13.1, 34.5)
Carindale	6.0 (-1.6, 14.2)	9.9 (0.1, 20.7)	Frankston	11.8 (3.0, 21.3)	13.0 (1.8, 25.5)	Carlingford	13.1 (8.0, 18.4)	22.2 (14.5, 30.5)
Centenary	13.1 (0.9, 26.7)	16.5 (1.0, 34.5)	Glen Eira	18.3 (6.0, 32.1)	17.3 (2.4, 34.3)	Chatswood - Lane Cove	11.2 (5.6, 17.1)	14.6 (7.1, 22.6)

Chermside	5.3 (-3.8, 15.2)	8.4 (-2.2, 20.3)	Hobsons Bay	15.6 (4.6, 27.8)	19.1 (5.4, 34.6)	Cronulla - Miranda - Caringbah	10.3 (4.5, 16.3)	12.1 (5.0, 19.7)
Cleveland - Stradbroke	3.0 (-7.2, 14.3)	6.1 (-8.3, 22.6)	Keilor	15.9 (8.6, 23.6)	17.1 (8.1, 27.0)	Dural - Wisemans Ferry	8.4 (1.5, 15.7)	10.1 (0.7, 20.4)
Forest Lake - Oxley	13.3 (0.8, 27.3)	17.4 (0.7, 36.9)	Kingston	14.5 (8.8, 20.5)	15.8 (8.3, 23.7)	Eastern Suburbs – North	8.5 (1.8, 15.6)	8.6 (0.5, 17.3)
Holland Park - Yeronga	9.1 (0.4, 18.5)	12.0 (1.5, 23.5)	Knox	15.1 (1.6, 30.4)	18.3 (1.6, 37.8)	Eastern Suburbs – South	8.7 (2.2, 15.7)	9.1 (1.2, 17.6)
Ipswich Hinterland	10.8 (-13.5, 41.9)	19.2 (-12.5, 62.4)	Macedon Ranges	14.8 (-12.2, 50.0)	11.1 (-20.5, 55.4)	Fairfield	17.3 (8.8, 26.6)	28.0 (15.7, 41.5)
Ipswich Inner	14.6 (-4.5, 37.6)	19.8 (-4.8, 50.7)	Manningham - East	18.9 (6.4, 32.9)	17.9 (3.3, 34.6)	Gosford	10.2 (4.7, 16.0)	12.1 (4.7, 20.0)
Jimboomba	10.1 (-1.8, 23.5)	16.4 (-0.1, 35.7)	Manningham - West	16.1 (8.1, 24.7)	17.3 (7.4, 28.1)	Hawkesbury	11.1 (-3.0, 27.2)	9.5 (-8.0, 30.3)
Kenmore - Brookfield - Moggill	11.0 (1.7, 21.2)	15.1 (3.1, 28.5)	Maribyrnong	15.9 (7.9, 24.5)	17.3 (7.3, 28.2)	Hornsby	8.5 (3.3, 14.0)	10.1 (2.9, 17.8)
Loganlea - Carbrook	8.8 (-4.3, 23.7)	10.9 (-4.9, 29.3)	Maroondah	15.3 (9.0, 22.0)	16.5 (8.6, 25.0)	Hurstville	15.0 (7.6, 23.0)	21.7 (12.2, 32.0)
Mt Gravatt	5.6 (-2.2, 14.0)	9.6 (-0.6, 20.8)	Greater Melbourne City	16.0 (7.5, 25.2)	17.3 (6.7, 29.0)	Kogarah - Rockdale	13.1 (6.9, 19.7)	19.4 (10.5, 27.8)
Narangba - Burpengary	4.9 (-4.6, 15.3)	9.4 (-2.6, 22.9)	Melton - Bacchus Marsh	17.9 (7.4, 29.4)	16.8 (4.3, 30.8)	Ku-ring-gai	7.6 (1.5, 14.1)	7.6 (-0.4, 16.2)
Nathan	7.9 (0.1, 16.3)	11.1 (1.5, 21.6)	Monash	18.0 (11.0, 25.4)	19.2 (10.9, 28.1)	Leichhardt	13.1 (6.9, 19.6)	18.8 (10.5, 27.7)
North Lakes	3.2 (-7.6, 15.3)	6.5 (-6.6, 21.4)	Moreland - North	17.6 (10.3, 25.4)	18.8 (9.9, 28.5)	Liverpool	18.1 (11.9, 24.5)	26.2 (18.2, 34.7)
Nundah	4.4 (-5.6, 15.5)	7.8 (-3.9, 21.0)	Mornington Peninsula	12.9 (-4.0, 32.8)	9.2 (-11.4, 34.6)	Manly	8.4 (1.7, 15.6)	8.5 (0.5, 17.3)

Redcliffe	7.1 (-8.3, 25.1)	12.0 (-10.3, 39.8)	Nillumbik - Kinglake	15.2 (2.3, 29.7)	16.2 (0.8, 34.0)	Marrickville - Sydenham - Petersham	13.3 (7.0, 20.0)	19.3 (10.8, 28.4)
Rocklea - Acacia Ridge	11.1 (-0.2, 23.8)	14.5 (-0.3, 31.6)	Port Phillip	18.6 (9.8, 28.1)	20.0 (9.4, 31.5)	Merrylands - Guildford	17.2 (9.8, 25.1)	31.7 (20.4, 43.9)
Sandgate	3.5 (-6.7, 14.8)	7.2 (-5.2, 21.3)	Stonnington - East	18.4 (5.6, 32.8)	17.3 (1.9, 35.1)	Mount Druitt	19.0 (9.9, 28.8)	31.2 (18.2, 45.5)
Sherwood - Indooroopilly	10.9 (-0.1, 23.0)	14.4 (0.0, 30.7)	Stonnington - West	18.7 (4.1, 35.4)	17.6 (0.0, 38.3)	North Greater Sydney - Mosman	10.0 (4.2, 16.1)	11.7 (4.6, 19.4)
Springfield - Redbank	13.1 (-0.6, 28.6)	18.5 (-0.2, 40.6)	Sunbury	17.7 (6.2, 30.5)	16.5 (2.6, 32.2)	Parramatta	16.9 (9.9, 24.4)	30.7 (20.0, 42.3)
Springwood - Kingston	7.6 (-0.1, 15.8)	10.9 (1.4, 21.2)	Tullamarine - Broadmeadows	17.5 (7.4, 28.6)	16.5 (4.5, 29.9)	Pennant Hills – Epping	10.1 (5.8, 14.6)	13.9 (7.7, 20.4)
Strathpine	5.7 (-3.0, 15.2)	8.7 (-1.5, 20.0)	Whitehorse - East	18.0 (11.1, 25.4)	19.2 (10.9, 28.1)	Penrith	17.6 (4.0, 33.0)	22.8 (5.2, 43.3)
Sunnybank	7.7 (0.0, 16.0)	10.9 (1.5, 21.3)	Whitehorse - West	18.8 (11.8, 26.2)	20.1 (11.7, 29.1)	Pittwater	8.9 (2.5, 15.8)	9.8 (1.6, 18.6)
The Gap - Enoggera	1.4 (-3.2, 6.3)	8.7 (-10.0, 31.3)	Whittlesea - Wallan	17.4 (4.1, 32.3)	16.3 (0.8, 34.0)	Richmond - Windsor	16.9 (2.3, 33.7)	25.0 (4.8, 49.2)
The Hills District	7.7 (-2.8, 19.3)	12.3 (-0.7, 26.9)	Wyndham	15.3 (3.8, 28.1)	19.1 (4.3, 36.0)	Rouse Hill - McGraths Hill	18.8 (9.8, 28.5)	30.7 (17.9, 44.9)
Wynnum - Manly	3.7 (-6.2, 14.6)	7.4 (-4.6, 20.9)	Yarra	16.2 (7.5, 25.7)	17.4 (6.6, 29.3)	Ryde - Hunters Hill	15.1 (9.9, 20.5)	20.9 (14.1, 28.0)
-	-	-	Yarra Ranges	14.8 (1.7, 29.5)	13.6 (-1.9, 31.6)	St Marys	19.0 (8.1, 31.1)	30.5 (14.5, 48.7)
-	-	-	-	-	-	Strathfield - Burwood - Ashfield	14.9 (7.3, 23.0)	23.9 (13.3, 35.4)
-	-	-	-	-	-	Sutherland - Menai - Heathcote	6.6 (0.5, 13.1)	6.7 (-1.0, 14.9)

-	-	-	-	-	-	Greater Sydney Inner City	11.4 (5.7, 17.3)	14.3 (7.3, 21.8)
-	-	-	-	-	-	Warringah	9.1 (2.7, 15.8)	10.0 (1.9, 18.8)
-	-	-	-	-	-	Wollondilly	5.5 (-2.9, 14.7)	3.1 (-7.9, 15.5)
-	-	-	-	-	-	Wyong	13.9 (7.4, 20.9)	21.1 (11.7, 31.2)

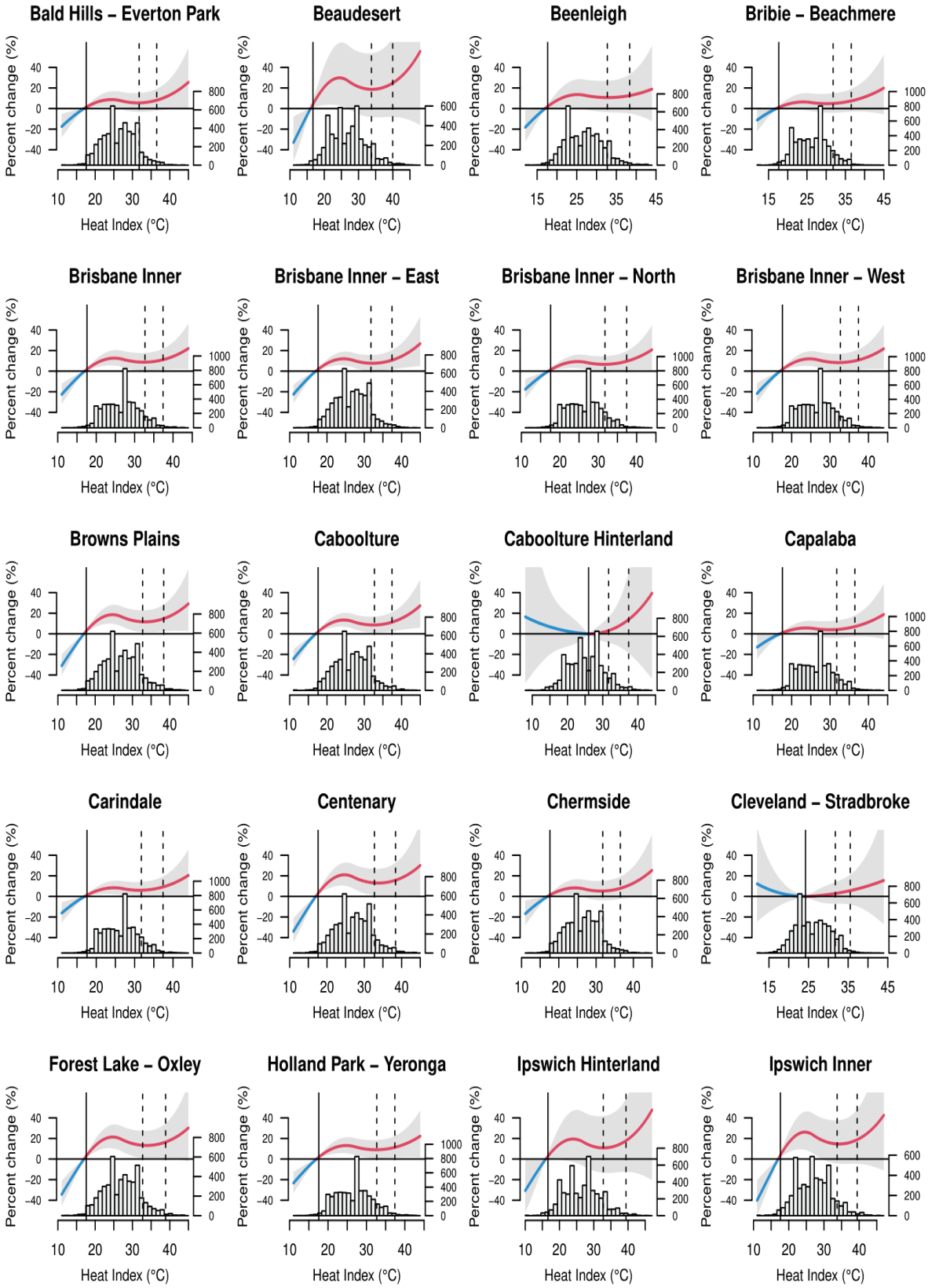
Table S3 Summary statistics of workers' compensation claims and temperature metrics (heat index) profile in Greater Brisbane, Greater Melbourne, and Greater Sydney in different SA3 for 13 years from 2005 to 2018.

Greater Brisbane - SA3 Regions	**N (%)**	**PMOI**	**90th %**	**99th %**	**Greater Melbourne -SA3 Regions**	**N(%)**	**PMOI**	**90th %**	**99th%**	**Greater Sydney - SA3 Regions**	**N(%)**	**PMOI**	**90th %**	**99th %**
Bald Hills - Everton Park	1676(0.6)	16.0	32.0	37.0	Banyule	9161(1.9)	10.0	30.0	38.0	Auburn	24602(2.7)	13.0	31.0	40.0
Beaudesert	666(0.2)	17.0	34.0	40.5	Bayside	4064(0.9)	10.0	29.0	38.0	Bankstown	35413(3.8)	13.0	31.0	40.0
Beenleigh	6884(2.6)	17.0	33.0	39.0	Boroondara	9478(2.0)	10.0	29.0	38.0	Baulkham Hills	16968(1.8)	13.0	31.0	41.0
Bribie - Beachmere	669(0.2)	17.0	32.0	37.0	Brimbank	12920(2.7)	10.0	29.0	38.0	Blacktown	36043(3.9)	13.0	32.0	42.0
Brisbane Inner	47194(17.9)	17.0	33.0	38.0	Brunswick - Coburg	5115(1.1)	10.0	30	38.0	Blacktown - North	4497(0.5)	13.0	33.0	43.0
Brisbane Inner - East	5459(2.1)	17.0	32.0	38.0	Cardinia	4474(0.9)	9.0	29.0	37.0	Blue Mountains	5790(0.6)	37.0	29.0	37.0
Brisbane Inner - North	18741(7.1)	17.0	32.0	38.0	Casey - North	9097(1.9)	9.0	29.0	37.0	Botany	32850(3.6)	13.0	30.0	37.0
Brisbane Inner - West	10650(4.0)	17.0	33.0	38.0	Casey - South	6352(1.3)	10.0	29.0	37.5	Bringelly - Green Valley	5699(0.6)	13.0	32.0	42.0
Browns Plains	4711(1.8)	17.0	33.0	39.0	Dandenong	37344(8.0)	10.0	29.0	38.0	Camden	8777(0.9)	13.0	32.0	41.0
Caboolture	3040(1.1)	17.0	33.0	38.0	Darebin - North	8835(1.9)	9.0	30.0	38.0	Campbelltown (NSW)	23465(2.5)	13.0	31.0	39.0
Caboolture Hinterland	871(0.3)	26.0	32.0	38.0	Darebin - South	4045(0.9)	10.0	30.0	38.0	Canada Bay	9820(1.1)	13.0	31.0	39.0
Capalaba	3066(1.2)	17.0	32.0	37.0	Essendon	4606(1.0)	10.0	30.0	38.0	Canterbury	8469(0.9)	13.0	31.0	39.0
Carindale	2151(0.8)	17.0	32.0	38.0	Frankston	11331(2.4)	10.0	28.0	37	Carlingford	8869(1.0)	13.0	31.0	40.0
Centenary	3663(1.4)	17.0	33.0	39.0	Glen Eira	7050(1.5)	10.0	29.0	38.0	Chatswood - Lane Cove	22337(2.4)	13.0	30.0	38.0

Chermside	5356(2.0)	17.0	32.0	37.0	Hobsons Bay	16485(3.5)	10.0	29.0	38.0	Cronulla - Miranda - Caringbah	13602(1.5)	13.0	30.0	37.0
Cleveland - Stradbroke	4776(1.8)	24.0	32.0	36.0	Keilor	5450(1.2)	10.0	29.3	38.0	Dural - Wisemans Ferry	2959(0.3)	13.0	31.0	40.0
Forest Lake - Oxley	5778(2.2)	17.0	33.0	39.5	Kingston	16376(3.5)	10.0	29.0	38.0	Eastern Suburbs – North	13803(1.5)	13.0	29.0	37.0
Holland Park - Yeronga	9767(3.7)	17.0	33.0	38.0	Knox	18635(4.0)	9.0	29.0	37.0	Eastern Suburbs – South	20720(2.2)	13.0	29.0	37.0
Ipswich Hinterland	2428(0.9)	16.0	33.0	40.0	Macedon Ranges	1583(0.3)	6.0	28	35.0	Fairfield	39788(4.3)	13.0	32.0	42.0
Ipswich Inner	10859(4.1)	17.0	34.0	40.0	Manningham - East	996(0.2)	9.0	30.0	37.0	Gosford	27299(3.0)	12.5	31.0	39.0
Jimboomba	2728(1.0)	17.0	33.0	40.0	Manningham - West	3900(0.8)	10.0	30.0	38.0	Hawkesbury	2982(0.3)	12.0	32.0	41.0
Kenmore - Brookfield - Moggill	1971(0.7)	17.0	33.0	39.0	Maribyrnong	15181(3.2)	10.0	29.0	38.0	Hornsby	11497(1.2)	13.0	30.0	39.0
Loganlea - Carbrook	8159(3.1)	17.0	33.0	38.0	Maroondah	11586(2.5)	9.0	29.0	37.0	Hurstville	12128(1.3)	13.0	31.0	38.0
Mt Gravatt	7559(2.9)	17.0	32.0	38.0	Melbourne City	54696(11.7)	10.0	29.0	38	Kogarah - Rockdale	14065(1.5)	13.0	30.0	38.0
Narangba - Burpengary	2915(1.1)	17.0	32.0	38.0	Melton - Bacchus Marsh	6682(1.4)	9.0	29.0	37.0	Ku-ring-gai	9669(1.0)	13.0	30.0	38.5
Nathan	12309(4.7)	17.0	33.0	38.0	Monash	27137(5.8)	9.0	29.0	37.0	Leichhardt	9857(1.1)	13.0	30.0	38.0
North Lakes	2599(1.0)	17.0	32.0	37.0	Moreland - North	5352(1.1)	9.5	30.0	38.0	Liverpool	25745(2.8)	13.0	31.3	40.0
Nundah	16548(6.3)	17.0	32.0	37.0	Mornington Peninsula	10737(2.3)	9.0	27.0	36.0	Manly	3513(0.4)	13.0	29.0	37.0
Redcliffe	3166(1.2)	24.0	31.0	35.0	Nillumbik - Kinglake	3125(0.7)	8.0	29.0	36.0	Marrickville -	9635(1.0)	13.0	30.0	38.0

										Sydenham - Petersham				
Rocklea - Acacia Ridge	14567(5.5)	17.0	33.0	39.0	Port Phillip	22850(4.9)	10.0	29.0	38.0	Merrylands - Guildford	25833(2.8)	13.0	32.0	41.0
Sandgate	1523(0.6)	17.0	32.0	37.0	Stonnington - East	2260(0.5)	10.0	29.0	38.0	Mount Druitt	24088(2.6)	13.0	33.0	42.0
Sherwood - Indooroopilly	2664(1.0)	17.0	33.0	39.0	Stonnington - West	5398(1.1)	10.0	29.0	38.0	North Sydney - Mosman	17274(1.9)	13.0	29.0	37.0
Springfield - Redbank	4230(1.6)	17.0	33.0	40.0	Sunbury	1938(0.4)	8.0	29.0	37.0	Parramatta	42752(4.6)	13.0	32.0	41.0
Springwood - Kingston	8690(3.3)	17.0	33.0	38.0	Tullamarine - Broadmeadows	31312(6.7)	9.0	29.0	37.0	Pennant Hills – Epping	4613(0.5)	13.0	31.0	39.0
Strathpine	4181(1.6)	17.0	32.0	37.0	Whitehorse - East	4595(1.0)	9.0	29.0	37.0	Penrith	22206(2.4)	13.0	33.0	42.0
Sunnybank	2466(0.9)	17.0	33.0	38.0	Whitehorse - West	10764(2.3)	9.0	29.0	37.5	Pittwater	6646(0.7)	13.0	30.0	38.0
The Gap - Enoggera	1275(0.5)	28.0	32.0	38.0	Whittlesea - Wallan	13195(2.8)	8.0	29.0	36.5	Richmond - Windsor	6180(0.7)	13.0	33.0	43.0
The Hills District	4467(1.7)	16.0	32.0	38.0	Wyndham	22438(4.8)	10.0	29.0	38.5	Rouse Hill - McGraths Hill	3211(0.3)	13.0	33.0	42.0
Wynnum - Manly	12837(4.9)	17.0	32.0	37.0	Yarra	12109(2.6)	10.0	30.0	38.0	Ryde - Hunters Hill	27609(3.0)	13.0	31.0	39.0
-	-	-	-	-	Yarra Ranges	10005(2.1)	8.0	29.0	36.0	St Marys	8029(0.9)	13.0	33.0	43.0
-	-	-	-	-	-	-	-	-	-	Strathfield - Burwood – Ashfield	22045(2.4)	13.0	30.0	39.0
-	-	-	-	-	-	-	-	-	-	Sutherland - Menai - Heathcote	8865(1.0)	13.0	30.0	37.0

-	-	-	-	-	-	-	-	-	-	Sydney Inner City	195533(21.1)	13.0	30.0	37.0
-	-	-	-	-	-	-	-	-	-	Warringah	20702(2.2)	13.0	30.0	38.0
-	-	-	-	-	-	-	-	-	-	Wollondilly	4810(0.5)	11.5	30.0	38.0
-	-	-	-	-	-	-	-	-	-	Wyong	23422(2.5)	13.0	31.0	39.0


Bald Hills – Everton Park
Beaudesert
Beenleigh
Bribie – Beachmere
Brisbane Inner
Brisbane Inner – East
Brisbane Inner – North
Brisbane Inner – West
Browns Plains
Caboolture
Caboolture Hinterland
Capalaba
Carindale
Centenary
Chermside
Cleveland – Stradbroke
Forest Lake – Oxley
Holland Park – Yeronga
Ipswich Hinterland
Ipswich Inner
Percent change (%)
Heat Index (°C)

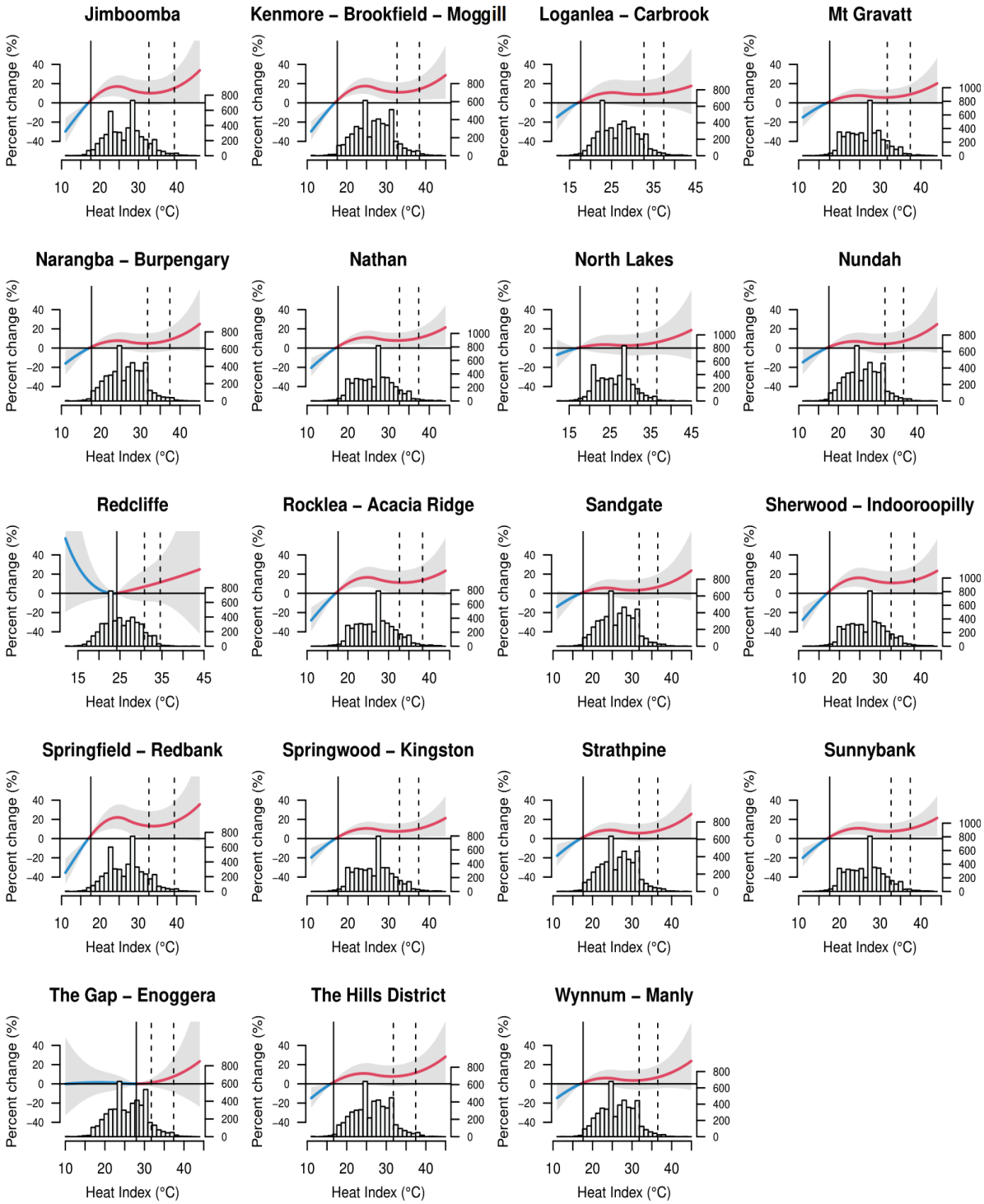
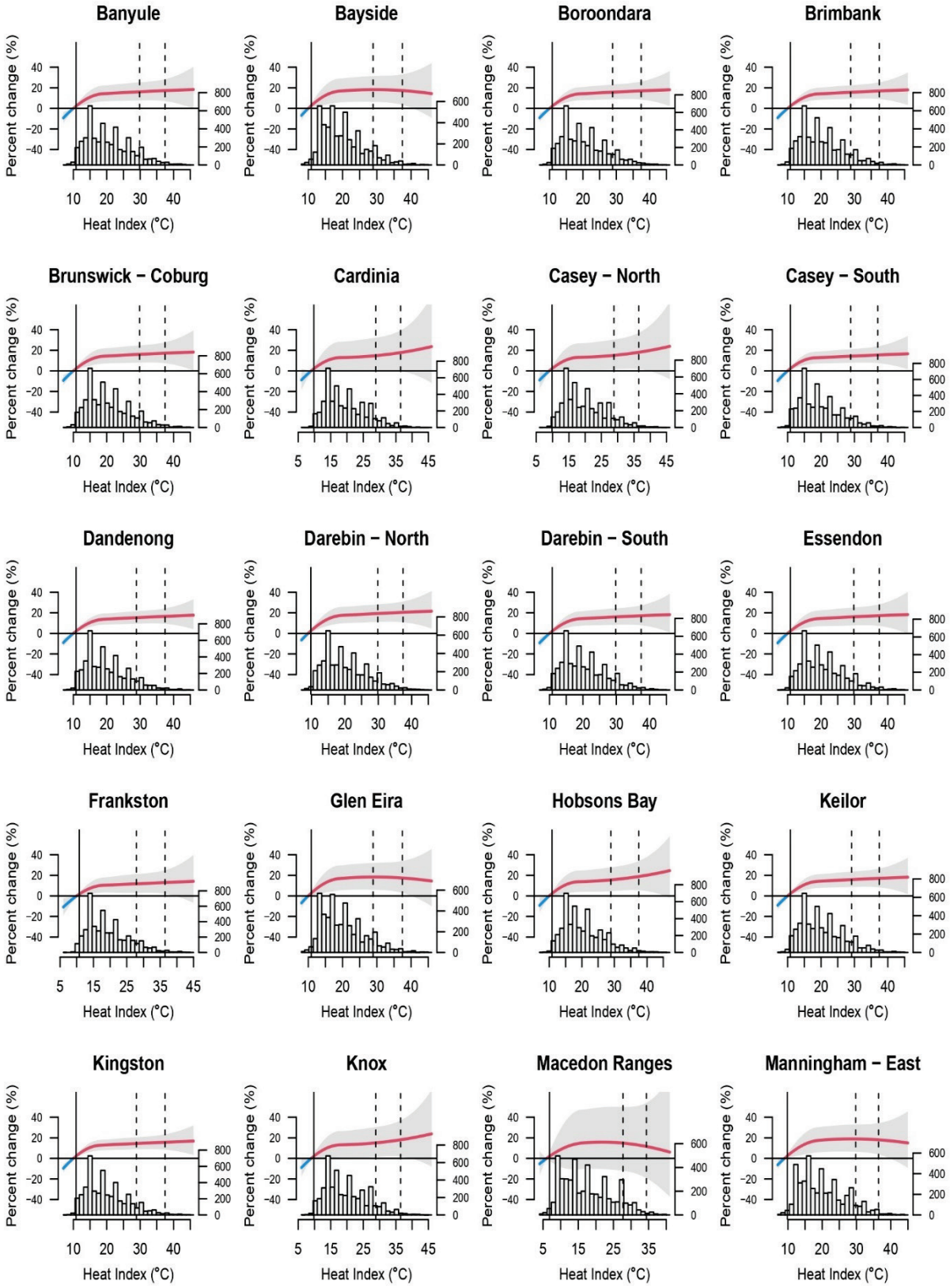


Figure S2 Region-wise exposure-response curves estimated as percent difference [with 95% confidence intervals (CI) - shaded areas] for OI associated with heat index (ºC) in 39 SA3 regions in Greater Brisbane from 2005 to 2018.


Banyule
Bayside
Boroondara
Brimbank
Brunswick – Coburg
Cardinia
Casey – North
Casey – South
Dandenong
Darebin – North
Darebin – South
Essendon
Frankston
Glen Eira
Hobsons Bay
Keilor
Kingston
Knox
Macedon Ranges
Manningham – East
Percent change (%)
Heat Index (°C)

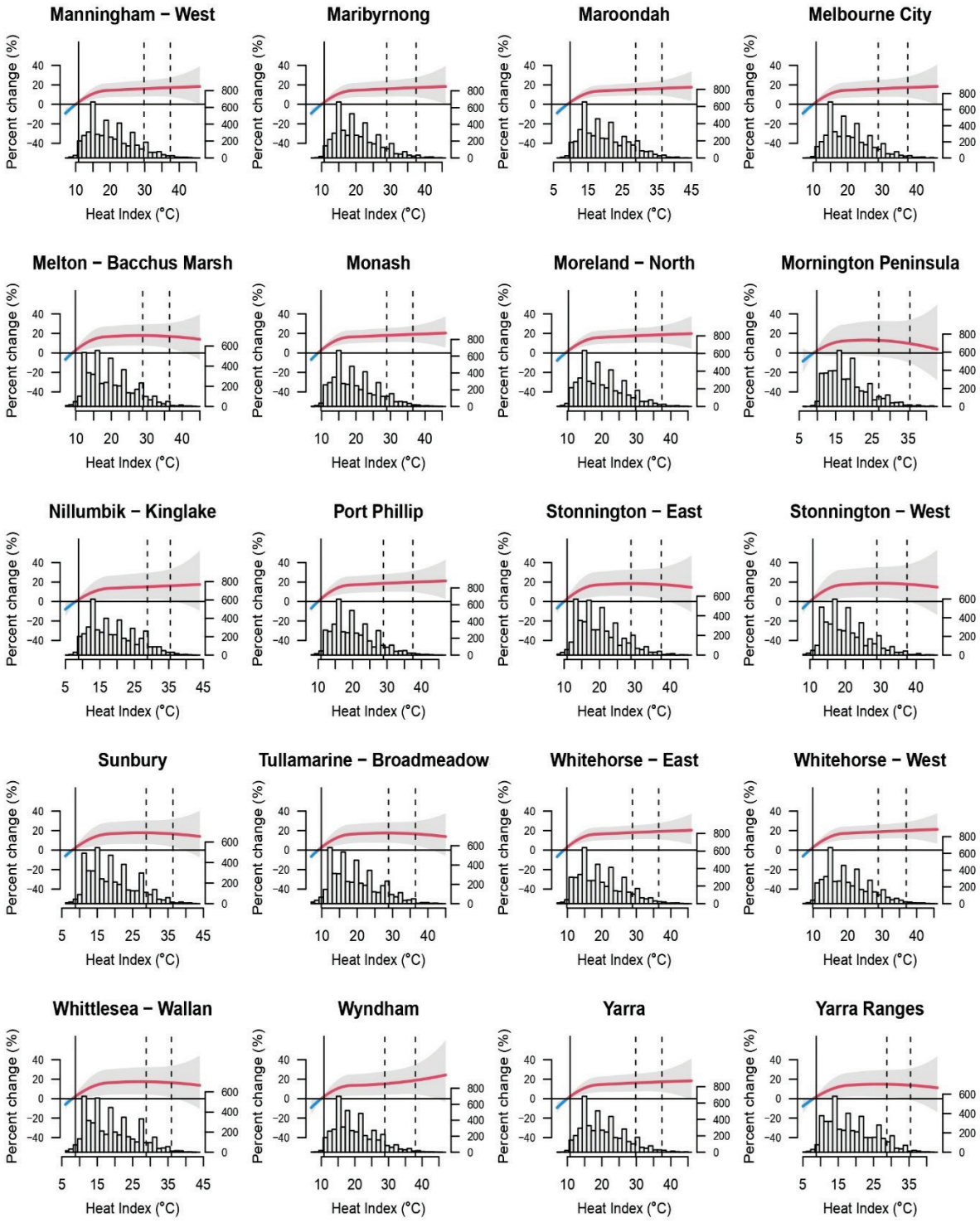
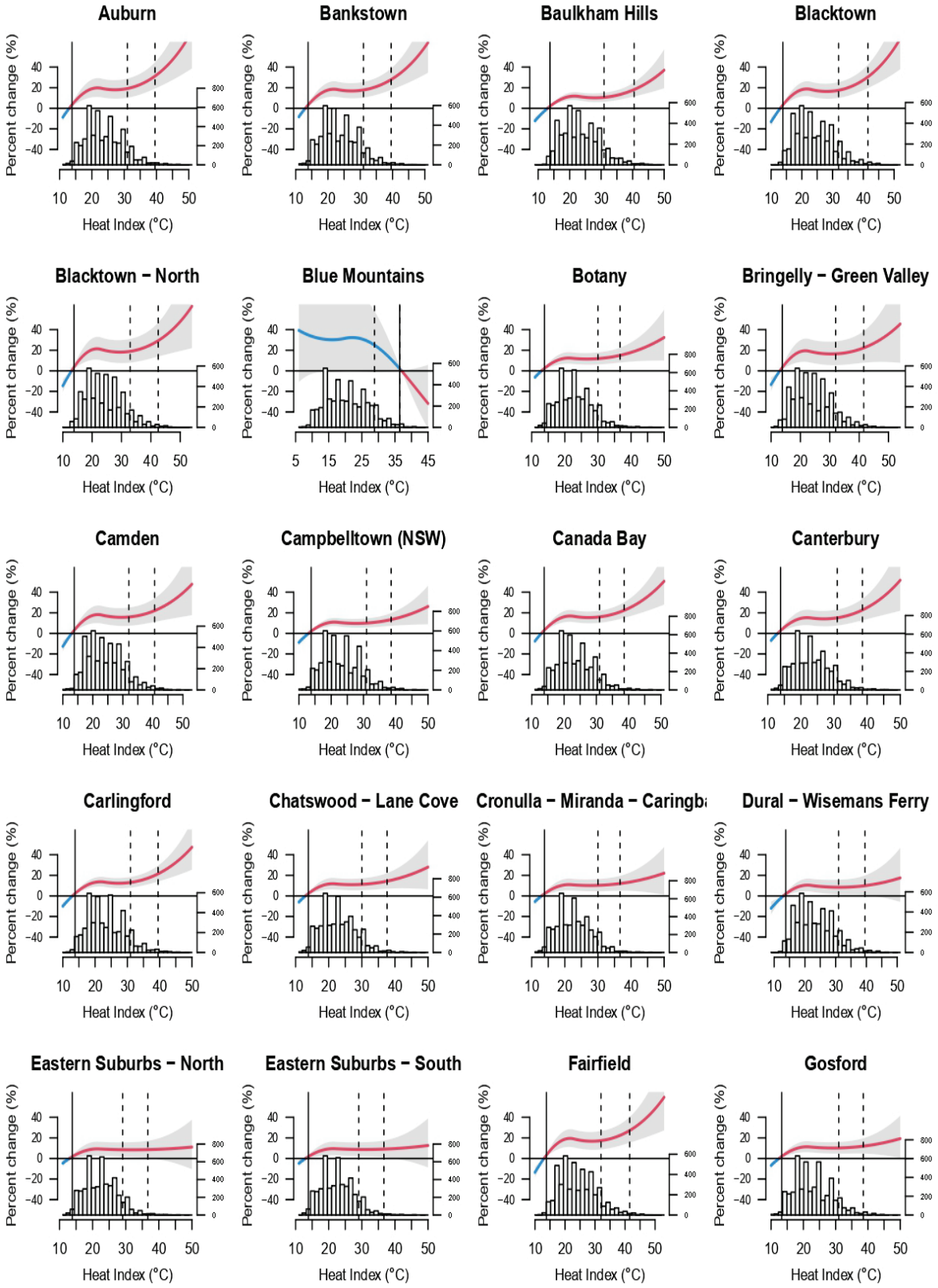
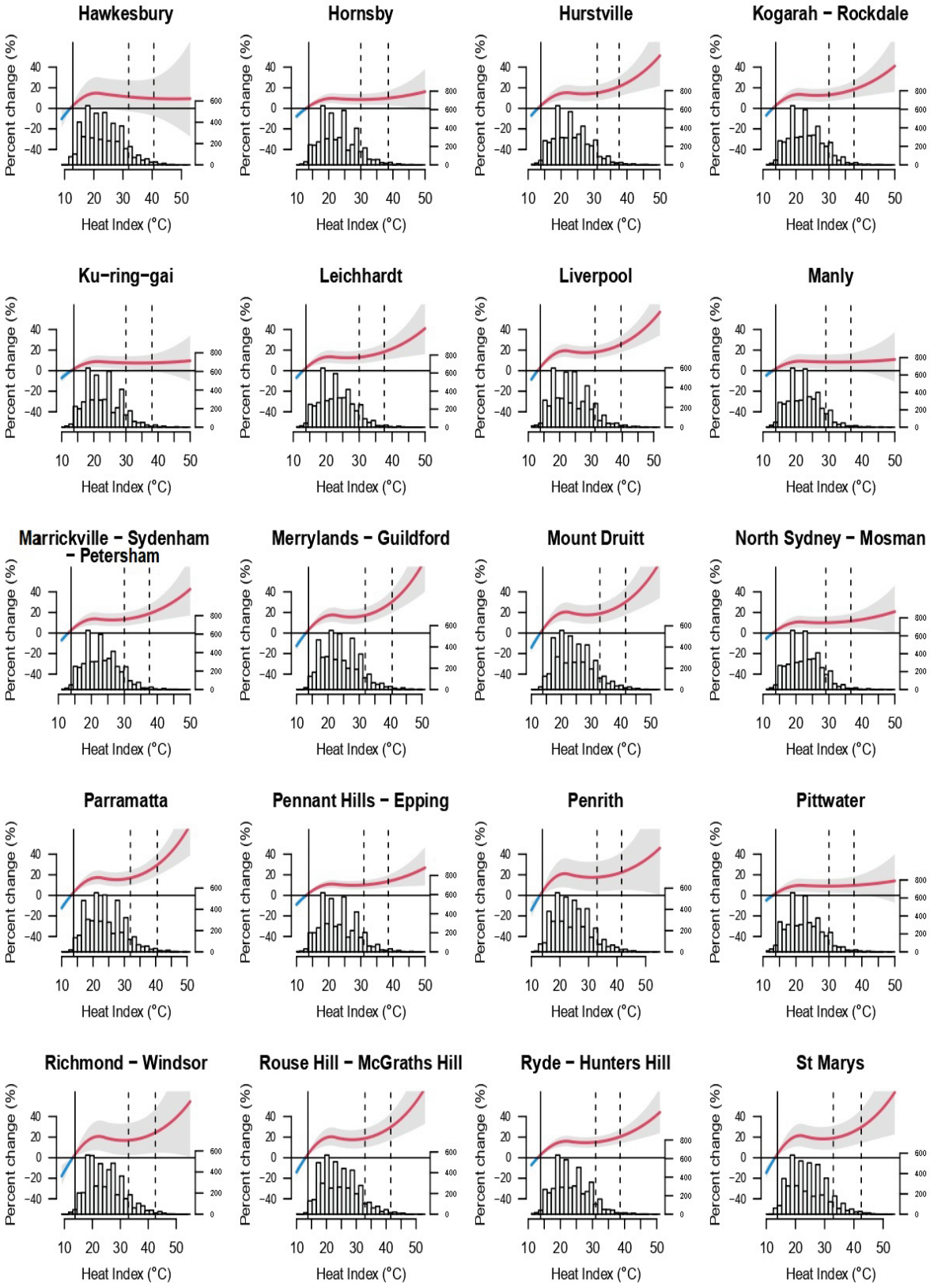


Figure S3 Region-wise exposure-response curves estimated as percent difference [with 95% confidence intervals (CI) - shaded areas] for OI associated with heat index (°C) in 40 SA3 regions in Greater Melbourne from 2005 to 2018.


Auburn
Bankstown
Baulkham Hills
Blacktown
Blacktown – North
Blue Mountains
Botany
Bringelly – Green Valley
Camden
Campbelltown (NSW)
Canada Bay
Canterbury
Carlingford
Chatswood – Lane Cove
Cronulla – Miranda – Caringbi
Dural – Wisemans Ferry
Eastern Suburbs – North
Eastern Suburbs – South
Fairfield
Gosford
Percent change (%)
Heat Index (°C)


Hawkesbury
Hornsby
Hurstville
Kogarah – Rockdale
Ku-ring-gai
Leichhardt
Liverpool
Manly
Marrickville – Sydenham – Petersham
Merrylands – Guildford
Mount Druitt
North Sydney – Mosman
Parramatta
Pennant Hills – Epping
Penrith
Pittwater
Richmond – Windsor
Rouse Hill – McGraths Hill
Ryde – Hunters Hill
St Marys
Percent change (%)
Heat Index (°C)

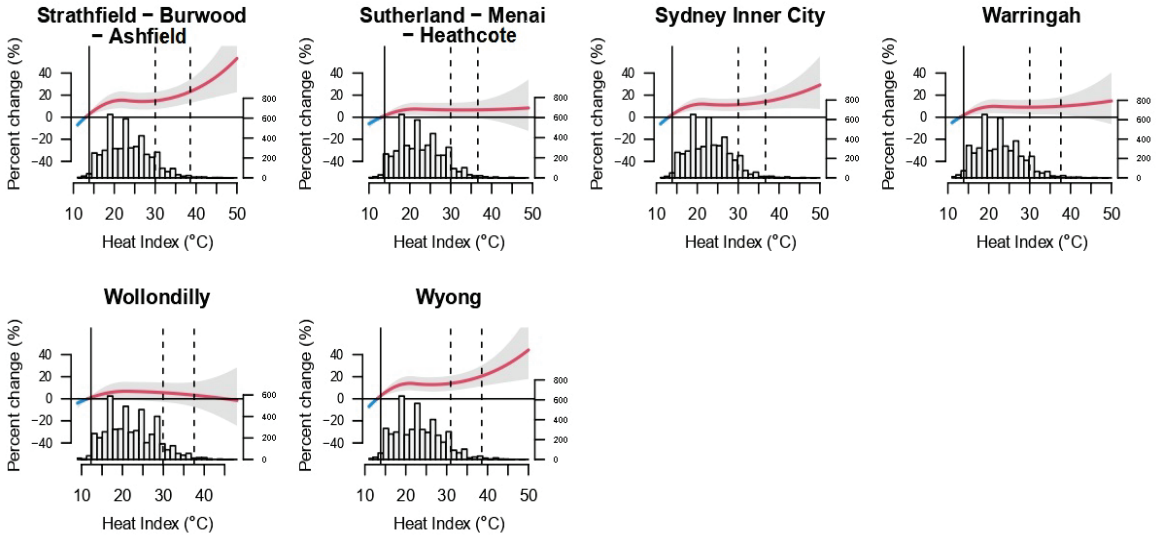


Figure S4 Region-wise exposure-response curves estimated as percent difference [with 95% confidence intervals (CI) - shaded areas] for OI associated with heat index (°C) in 46 SA3 regions in Greater Sydney from 2005 to 2018.

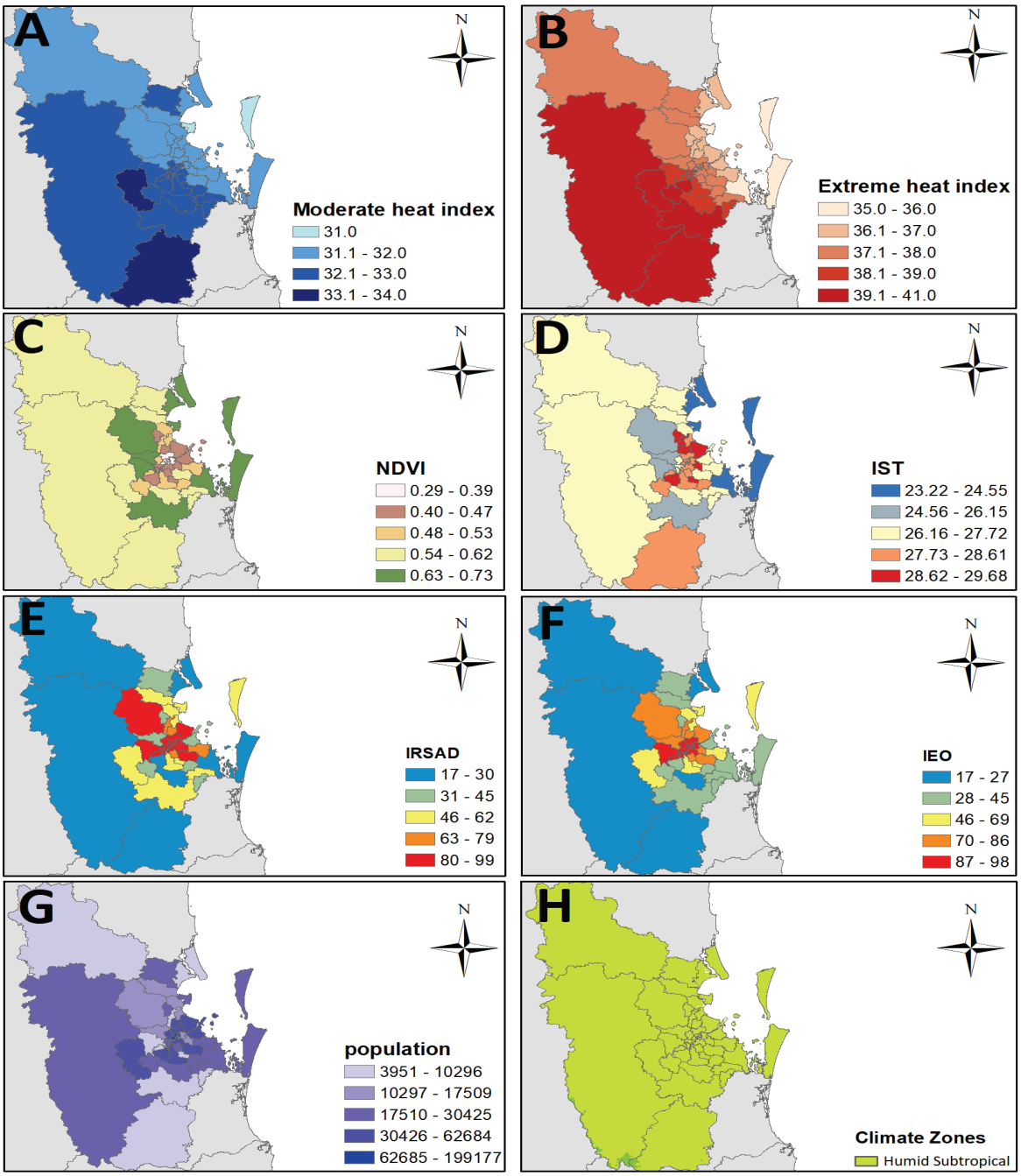


Figure S5 Environmental profile of Greater Brisbane.

A. Spatial distribution of moderate heat index across Greater Brisbane. B. Spatial distribution of extreme heat index across Greater Brisbane. C. Spatial profile of averaged NDVI estimated over the period of thirteen years. D. Spatial distribution of averaged LST. E. IRSAD available at the SA3 level. F. IEO available at the SA3 level. F. Workers' population based on their place of work for the year 2016 at the SA3 level. G. Climate distribution at the SA3 level in Greater Brisbane following Beck et al. (104).

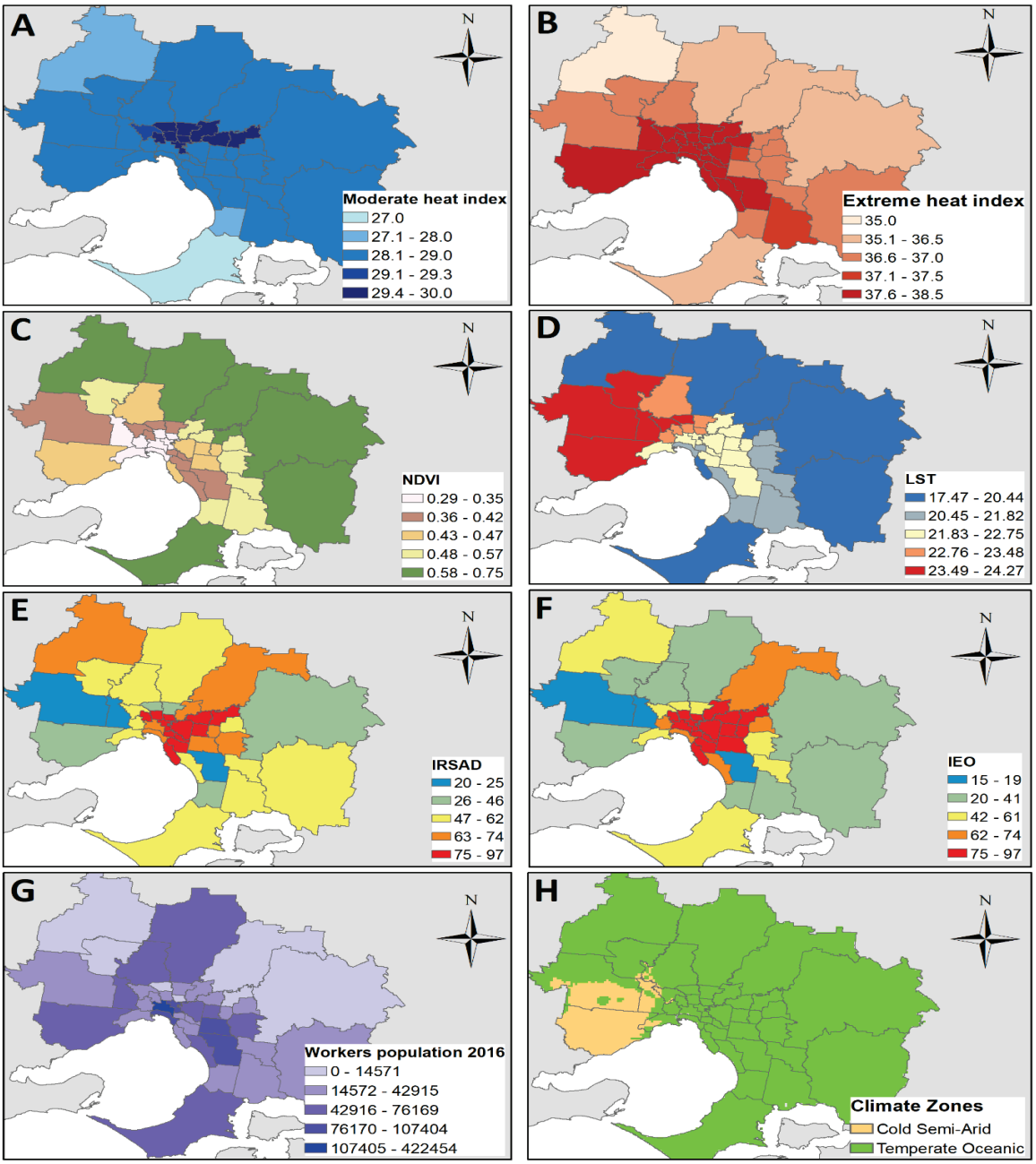


Figure S6 Environmental Profile of Greater Melbourne.

A. Spatial distribution of moderate heat index across Greater Melbourne. B. Spatial distribution of extreme heat index across Greater Melbourne. C. Spatial profile of averaged NDVI (NDVI) estimated over the period of thirteen years. D. Spatial distribution of averaged LST. E. IRSAD available at the SA3 level. F. IEO available at SA3 level. F. Workers' population based on their place of work for the year 2016 at the SA3 level. G. Climate distribution at the SA3 level in Greater Melbourne following Beck et al. (104).

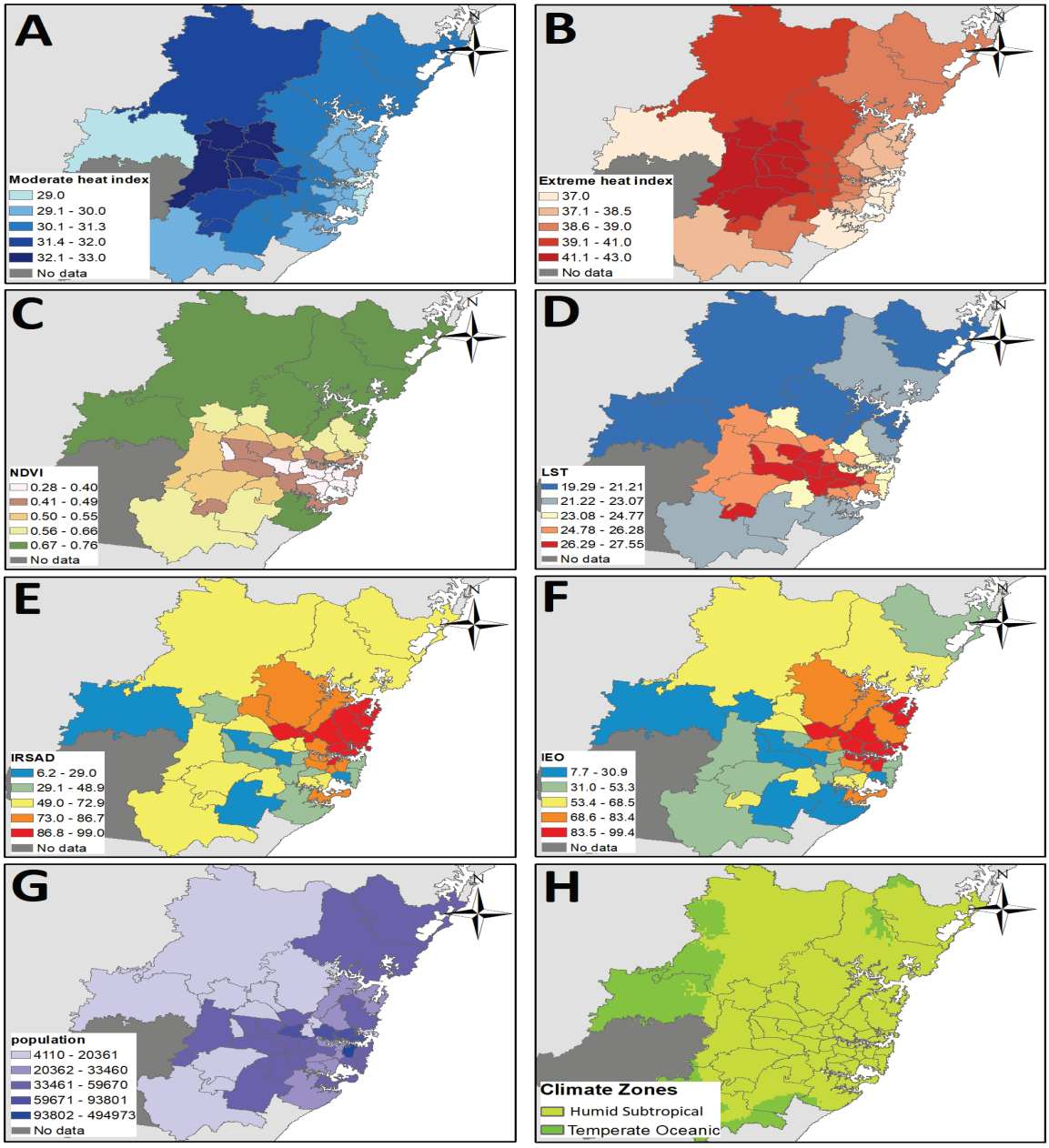


Figure S7 Environmental profile of Greater Sydney.

A. Spatial distribution of moderate heat index across Greater Sydney. B. Spatial distribution of extreme heat index across Greater Sydney. C. Spatial profile of averaged NDVI estimated over the period of thirteen years. D. Spatial distribution of averaged LST. E. IRSAD available at the SA3 level. F. IEO available at SA3 level. F. Workers' population based on their place of work for the year 2016 at the SA3 level. G. Climate distribution at the SA3 level in Greater Sydney following Beck et al. (104).

Table S4 Sensitivity analysis computed in the percent difference (%), based on two criteria 1. Quasi Akaike Information Criterion (QAIC) and 2. Risk of OI estimated at 99th percentile by varying modelling choices.

Sensitivity Analysis	**Greater Brisbane**		**Greater Melbourne**		**Greater Sydney**	
	QAIC	**99th Percentile hot effects**	**QAIC**	**99th Percentile hot effects**	**QAIC**	**99th Percentile hot effects**
Long-term trend smoothening						
4df/year	20798.2	-0.6 (-5.3, 4.3)	17900.0	9.8 (3.5, 16.6)	25234.1	8.9 (4.6, 13.6)
5df/year	20836.2	-2.8 (-7.7, 2.4)	17934.4	-3.5 (-7.3, 0.4)	25272.2	-1.2 (-4.6, 2.4)
6df/year	20797.2	3.4 (-3.8, 11.1)	17918.9	9.5 (4.0, 15.4)	25263.4	8.9 (4.1, 13.9)
7df/year	20856.0	0.6 (-6.5, 8.2)	17959.4	13.1 (7.1, 19.4)	25332.1	15.6 (10.3, 21.2)
8df/year	20842.5	-6.1 (-11.3, -0.6)	17937.1	7.7 (2.0, 13.7)	25278.9	9.3 (4.2, 14.7)
9df/year	20901.6	-4.0 (-9.3, 1.6)	17964.8	9.4 (3.5, 15.7)	25343.4	15.6 (10.1, 21.3)
Knots for exposure-response						
50th percentile	20797.2	3.4 (-3.8, 11.1)	17918.9	9.5 (4.0, 15.4)	25263.4	8.9 (4.1, 13.9)
10th percentile	20805.7	1.5 (-5.7, 9.2)	17916.9	6.7 (1.4, 12.3)	25261.3	5.9 (1.3, 10.6)
10th and 90th percentiles	20816.7	-2.0 (-9.6, 6.1)	17934.8	3.3 (-2.3, 9.3)	25266.9	6.3 (1.5, 11.3)
25th and 75th percentiles	20817.9	0.0 (-8.5, 7.4)	17938.9	4.1 (-1.8, 10.3)	25273.8	6.4 (1.5, 11.6)
33th and 66th percentiles	20818.1	0.1 (-7.5, 8.3)	17936.4	4.5 (-1.3, 10.8)	25277.6	6.6 (1.7, 11.8)
25th 50th and 75th percentiles	20835.6	-6.1 (-12.1, 0.3)	17954.6	4.6 (-1.3, 9.2)	25288.1	0.9 (-2.8, 4.9)
10th 50th and 90th percentiles	20830.0	-3.1 (-8.9, 3.1)	17947.3	-1.5 (-8.4, 0.2)	25284.7	3.1 (-0.6, 6.9)
Exposure						
Tmin	20781.9	14.6 (8.6, 21.0)	17906.9	9.3 (4.3, 14.6)	25271.6	13.3(9.3-17.5)
Tmean	20787.4	11.9 (6.4, 17.6)	17913.0	8.4 (2.8, 14.2)	25289.5	9.1(4.1-14.3)
Tmax	20800.9	0.9 (-6.0, 8.4)	17920.0	7.7 (1.4, 14.4)	25272.6	6.6(1.7-11.8)
Heat.index	20797.2	3.4 (-3.8, 11.1)	17918.9	9.5 (4.0, 15.4)	25263.4	8.9 (4.1, 13.9)

Table S5 Subgroup analysis of the estimation of cumulative risk of occupational injuries and illnesses (OI) based on personal factors: age, gender, claim types, workplace factors: types of occupation, physical demands, and types of exposure, and location-specific factors: hot vs. cold regions based on Land Surface Temperature (LST), and vegetated vs. less vegetated regions based on Normalised Difference Vegetation Index (NDVI), high vs. low Index of socio-economic advantage and disadvantage regions based on IRSAD.

	Brisbane		**Melbourne**		**Sydney**	
Subgroup Analysis	**Percent Change (90th percentile)**	**Percent Change (99th percentile)**	**Percent Change (90th percentile)**	**Percent Change (99th percentile)**	**Percent Change (90th percentile)**	**Percent Change (99th percentile)**
Age						
15, 24 years	4.9 (-5.6, 16.7)	2.4 (-11.6, 18.6)	20.3 (8.1, 33.9)	17.4 (1.1, 36.3)	8.1 (1.7, 14.8)	8.9 (-0.9, 19.5)
25, 34 years	-1.0 (-10.7, 9.6)	6.0 (-7.9, 21.9)	0.0 (0.0, 0.0)	-4.4 (-11.4, 3.1)	5.7 (0.1, 11.5)	5.7 (-2.8, 14.9)
35, 44 years	-8.5 (-17.9, 1.8)	-3.7 (-17.1, 11.9)	7.6 (0.2, 15.5)	4.5 (-5.3, 15.2)	7.8 (2.2, 13.7)	14.4 (5.6, 23.9)
45, 54 years	9.8 (-2.1, 23.1)	12.6 (-3.0, 30.7)	10.6 (3.5, 18.1)	10.3 (1.2, 20.3)	2.6 (-1.7, 8.0)	6.2 (-1.7, 14.7)
55+ years	0.0 (0.0, 0.0)	-11.0 (-21.5, 0.8)	4.2 (-4.3, 13.5)	9.0 (-1.5, 20.6)	2.4 (-3.7, 8.9)	4.2 (-5.3, 14.7)
Gender						
Females	0.6 (-8.1, 2.1)	8.3 (-4.3, 22.7)	6.5 (0.1, 13.2)	5.3 (-2.9, 14.2)	-1.0 (-5.4, 3.5)	-0.1 (-6.6, 6.9)
Males	-1.0 (-7.0, 5.4)	-0.6 (-8.7, 8.2)	10.9 (5.8, 16.3)	12.6 (5.9, 19.7)	8.9 (5.2, 12.8)	14.6 (8.7, 20.8)
Claim types						
Injuries-only	-0.9 (-6.4, 4.9)	1.9 (-5.7, 10.1)	11.2 (5.7, 17.0)	10.4 (3.3, 17.9)	3.9 (0.7, 7.2)	8.2 (3.2, 13.4)
Illness-only	7.7 (-5.1, 22.4)	11.4 (-6.0, 32.1)	6.1 (0.6, 12.0)	8.6 (1.4, 16.4)	7.3 (-0.8, 16.1)	6.0 (-4.7, 18.0)
Types of occupation						
Technicians	-7.9 (-17.0, 2.2)	-6.2 (-18.8, 8.2)	9.6 (1.2, 18.7)	2.4 (-7.7, 13.6)	10.5 (4.1, 17.3)	16.3 (6.4, 27.1)
Labourers	5.2 (-3.4, 14.6)	5.9 (-5.8, 19.0)	6.9 (-1.0, 15.4)	7.0 (-3.0, 17.9)	5.3 (-0.4, 11.3)	8.7 (-0.2, 18.4)
Service workers	4.0 (-9.9, 20.1)	2.4 (-17.0, 26.5)	-3.1 (-12.8, 7.7)	1.2 (-12.9, 17.6)	3.9 (-4.4, 12.8)	5.7 (-6.3, 19.1)
Drivers and Machinery operators	9.1 (-3.2, 23.0)	5.4 (-11.0, 24.7)	17.6 (5.7, 30.9)	13.5 (-0.3, 29.4)	10.6 (3.3, 18.5)	14.2 (3.0, 26.6)
Physical Demands						
Limited	-3.0 (-14.3, 9.9)	2.5 (-13.4, 21.4)	12.1 (4.3, 20.4)	9.9 (0.4, 20.4)	3.9 (-1.2, 9.3)	4.6 (-3.0, 12.7)
Light	1.2 (-8.5, 12.0)	0.1 (-13.2, 15.4)	5.9 (-2.6, 15.2)	7.7 (-5.1, 22.4)	4.4 (-0.7, 9.9)	5.6 (-2.1, 13.9)
Medium	0.6 (-9.3, 11.6)	-0.8 (-13.8, 14.2)	20.9 (12.2, 30.3)	15.8 (5.1, 27.6)	2.2 (-2.5, 7.5)	8.9 (1.0, 17.3)
Heavy	3.3 (-5.2, 12.5)	5.7 (-6.4, 19.4)	7.0 (-1.1, 15.7)	4.3 (-5.1, 14.7)	9.6 (4.0, 15.6)	14.8 (5.4, 25.0)
Types of exposure						

Indoor (regulated and unregulated)	2.0 (-4.4, 8.8)	8.7 (-0.4, 18.6)	10.9 (5.6, 16.4)	10.6 (3.7, 17.9)	3.3 (-0.1, 6.9)	6.4 (1.2, 11.8)
Outdoor (Outdoor and in vehicles and cabs)	--	--	22.6 (5.1, 43.0)	24.2 (3.5, 49.2)	14.0 (3.6, 25.5)	16.6 (0.9, 34.9)
Multiple locations	0.3 (-9.4, 11.0)	-2.9 (-15.5, 11.6)	10.8 (2.4, 19.8)	4.4 (-6.8, 17.0)	7.8 (2.2, 13.8)	12.9 (4.1, 22.3)
Hot vs. cold regions						
Hot regions	-1.4 (-10.0, 8.1)	4.6 (-7.6, 18.3)	2.1 (-5.7, 10.6)	6.5 (-4.0, 18.2)	5.9 (-0.1, 12.3)	15.5 (5.5, 26.4)
Cool regions	-0.5 (-7.1, 6.5)	2.3 (-6.8, 12.3)	11.0 (6.0, 16.3)	10.4 (3.9, 17.2)	4.0 (0.4, 7.7)	7.3 (1.8, 13.0)
Vegetated vs. less vegetated regions						
Vegetated areas	0.0 (0.0, 0.0)	-7.1 (-18.9, 6.4)	9.3 (-1.4, 21.1)	5.1 (-6.8, 18.4)	6.4 (-0.5, 13.9)	8.6 (-1.6, 19.9)
Less vegetated areas	0.5 (-4.8, 6.2)	7.0 (-0.6, 15.3)	8.9 (4.1, 13.8)	10.6 (4.4, 17.3)	3.9 (0.4, 7.4)	8.9 (3.5, 14.6)
Index of relative socio-economic advantage and disadvantage						
High IRSAD	-2.8 (-10.1, 5.1)	3.4 (-6.9, 14.9)	14.1 (4.4, 24.7)	8.3 (-3.7, 21.9)	2.2 (-3.0, 7.6)	3.8 (-4.0, 12.2)
Low IRSAD	0.3 (-6.7, 7.9)	2.1 (-7.4, 12.7)	8.1 (3.2, 13.1)	9.8 (3.5, 16.6)	5.7 (1.8, 9.7)	11.7 (5.7, 18.1)
Index of Education and Occupation						
High IEO	-2.0 (-8.8, 5.3)	2.1 (-7.6, 12.8)	12.3 (6.6, 22.5)	12.6 (2.7, 23.5)	2.0 (-2.9, 7.1)	4.2 (-3.4, 12.3)
Low IEO	0.9 (-7.2, 9.9)	4.4 (-7.0, 17.3)	6.9 (1.5, 12.7)	8.1 (1.2, 15.4)	5.9 (1.9, 10.0)	11.5 (5.4, 18.0)

Table S6 Region-wise subgroup analysis - Greater Brisbane

Greater Brisbane -SA3 Regions	Female workers at moderate risk	Female workers at extreme risk	Male workers at moderate heat	Male workers at extreme heat	Younger workers at moderate heat	Younger workers at extreme heat	Older workers at moderate heat	Older workers at extreme heat	Outdoor Industries at moderate heat	Outdoor industries at extreme heat	Indoor industries at moderate risk	Indoor industries at extreme risk	Injuries risk at moderate heat	Injuries risk at extreme heat	Illnesses risk at moderate heat	Illnesses risk at extreme heat
Bald Hills - Everton Park	17.2 (0.1, 37.2)	25.6 (4.9, 50.5)	3.8 (-9.7, 19.2)	3.4 (-11.1, 20.2)	0.0 (0.0, 0.0)	4.2 (-2.4, 11.2)	11.1 (-7.6, 33.5)	11.0 (-10.1, 36.9)	8.5 (-5.6, 24.7)	0.0 (0.0, 0.0)	7.5 (-2.3, 18.2)	12.3 (0.8, 25.3)	2.8 (-7.6, 14.4)	5.0 (-6.7, 18.3)	Not enough data	Not enough data
Beaudesert	62.1 (-0.1, 162.8)	65.1 (-8.3, 197.2)	11.7 (-19.6, 55.1)	18.0 (-20.1, 74.5)	21.8 (-14.9, 74.2)	37.4 (-11.4, 113.0)	4.4 (-32.7, 61.7)	3.8 (-38.7, 75.9)	80.6 (-16.5, 290.4)	45.6 (-43.6, 275.6)	13.2 (-14.5, 49.9)	24.1 (-11.9, 74.8)	15.7 (-13.9, 55.4)	20.2 (-15.8, 71.6)	12.1 (-54.6, 177.0)	21.4 (-54.8, 226.0)
Beenleigh	0.0 (0.0, 0.0)	2.2 (-14.1, 21.5)	16.1 (-4.6, 41.2)	16.4 (-8.6, 48.2)	9.9 (-11.1, 36.0)	10.9 (-16.3, 46.8)	16.8 (-8.5, 49.0)	20.4 (-10.1, 61.3)	3.1 (-21.5, 35.4)	0.0 (0.0, 0.0)	14.4 (-1.2, 32.4)	16.2 (-3.6, 40.2)	9.9 (-6.5, 29.1)	11.7 (-9.1, 37.1)	63.3 (-7.6, 188.5)	62.9 (-9.0, 191.6)
Bribie - Beachmere	10.7 (-4.7, 28.6)	20.3 (0.9, 43.5)	3.6 (-10.8, 20.4)	2.4 (-13.1, 20.8)	1.0 (-14.9, 19.9)	4.7 (-14.6, 28.4)	14.3 (-4.9, 37.4)	14.4 (-7.4, 41.4)	4.4 (-9.2, 19.9)	0.0 (0.0, 0.0)	9.2 (-0.9, 20.4)	13.5 (1.2, 27.3)	2.8 (-8.2, 15.2)	5.1 (-7.6, 19.5)	Not enough data	Not enough data
Brisbane Inner	5.8 (-6.2, 19.3)	8.3 (-6.1, 25.0)	9.3 (-3.4, 23.6)	10.5 (-4.1, 27.3)	7.3 (-6.2, 22.7)	10.5 (-6.8, 31.1)	8.6 (-7.4, 27.4)	10.4 (-7.3, 31.5)	5.9 (-17.8, 36.5)	3.1 (-25.8, 43.3)	10.7 (1.8, 20.5)	14.2 (3.3, 26.2)	7.2 (-2.3, 17.7)	9.2 (-2.4, 22.1)	16.4 (-15.8, 60.9)	19.9 (-14.5, 68.2)
Brisbane Inner - East	16.0 (2.0, 31.9)	22.2 (4.6, 42.8)	3.6 (-8.4, 17.1)	4.2 (-9.3, 19.7)	0.1 (-13.1, 15.3)	4.0 (-13.1, 24.3)	10.8 (-5.7, 30.2)	11.2 (-7.7, 33.9)	16.4 (0.0, 35.4)	0.0 (0.0, 0.0)	8.7 (0.5, 17.5)	14.2 (3.9, 25.5)	4.2 (-5.0, 14.2)	6.6 (-4.2, 18.6)	24.2 (-21.3, 96.1)	28.4 (-19.1, 103.8)
Brisbane Inner - North	7.0 (-4.3, 19.7)	15.2 (0.2, 32.4)	11.4 (-1.3, 25.6)	11.5 (-3.1, 28.3)	9.0 (-4.5, 24.4)	15.7 (-2.8, 37.8)	14.9 (-1.5, 34.0)	15.8 (-2.9, 38.1)	4.0 (-21.6, 37.9)	0.9 (-31.3, 48.2)	9.4 (1.3, 18.2)	14.4 (4.0, 26.0)	5.9 (-3.0, 15.6)	8.8 (-2.4, 21.1)	40.4 (-5.6, 108.8)	43.7 (-4.5, 116.2)
Brisbane Inner - West	6.1 (-5.5, 19.1)	9.6 (-4.5, 25.9)	8.5 (-4.4, 23.2)	9.4 (-5.5, 26.5)	6.0 (-8.1, 22.4)	9.3 (-9.2, 31.4)	15.8 (-1.9, 36.8)	17.4 (-1.9, 40.5)	5.3 (-22.0, 42.1)	2.5 (-31.2, 52.6)	10.5 (1.9, 19.9)	14.2 (3.7, 25.9)	6.3 (-3.1, 16.7)	8.3 (-3.1, 21.1)	27.3 (-17.3, 95.9)	30.2 (-16.1, 102.3)
Browns Plains	13.0 (-3.6, 32.5)	10.0 (-9.9, 34.4)	11.5 (-3.4, 28.6)	16.0 (-2.2, 37.6)	12.0 (-4.8, 31.8)	17.6 (-5.2, 45.8)	10.9 (-8.4, 34.2)	13.2 (-9.1, 41.0)	18.6 (-17.6, 70.8)	8.1 (-34.4, 78.0)	10.9 (0.3, 22.7)	15.5 (1.7, 31.1)	9.8 (-1.9, 22.8)	12.0 (-2.7, 28.9)	26.1 (-23.5, 107.9)	32.0 (-21.4, 121.8)
Caboolture	15.5 (1.7, 31.1)	19.6 (2.9, 39.0)	7.7 (-4.8, 21.8)	9.2 (-4.9, 25.3)	7.6 (-7.0, 24.5)	13.1 (-5.7, 35.6)	9.2 (-7.5, 28.8)	9.7 (-8.6, 31.7)	9.7 (-4.5, 25.9)	0.0 (0.0, 0.0)	9.3 (1.2, 18.2)	14.1 (4.1, 25.1)	6.8 (-2.5, 16.9)	9.1 (-1.9, 21.3)	38.9 (-14.3, 125.1)	43.2 (-12.1, 133.1)
Caboolture Hinterland	44.3 (-20.4, 161.6)	123.0 (-0.1, 397.6)	4.9 (-26.3, 49.4)	0.0 (0.0, 0.0)	2.9 (-5.6, 12.2)	28.9 (-16.3, 98.7)	21.8 (-21.7, 89.6)	12.3 (-42.4, 118.9)	Not enough data	Not enough data	4.6 (-6.9, 17.6)	26.7 (-15.8, 90.7)	1.9 (-7.8, 12.6)	12.2 (-24.9, 67.7)	51.6 (-43.1, 303.7)	61.2 (-53.0, 452.8)
Capalaba	7.4 (-6.0, 22.9)	18.1 (0.2, 39.2)	2.8 (-9.3, 16.5)	1.5 (-12.2, 17.5)	0.2 (-0.6, 1.0)	4.3 (-4.0, 13.2)	13.4 (-5.2, 35.6)	13.4 (-7.6, 39.2)	5.6 (-9.4, 23.2)	0.0 (0.0, 0.0)	7.7 (-1.4, 17.6)	12.6 (1.0, 25.4)	2.1 (-7.1, 12.2)	4.6 (-6.8, 17.3)	31.1 (-17.6, 108.5)	33.8 (-16.9, 115.6)
Carindale	7.4 (-4.4, 20.7)	17.2 (1.2, 35.8)	5.3 (-7.3, 19.6)	4.5 (-10.0, 21.4)	1.6 (-12.2, 17.5)	5.9 (-12.8, 28.6)	12.6 (-4.6, 32.8)	13.2 (-6.4, 36.8)	7.9 (-9.6, 28.9)	0.0 (0.0, 0.0)	9.1 (0.8, 18.1)	14.5 (3.6, 26.5)	3.5 (-5.7, 13.5)	6.2 (-5.3, 19.1)	25.1 (-25.1, 108.9)	28.4 (-23.8, 116.2)

Centenary	11.9 (-7.4, 35.2)	5.3 (-17.1, 33.8)	14.3 (-2.8, 34.2)	20.1 (-1.2, 46.0)	15.9 (-3.2, 38.7)	21.1 (-4.4, 53.4)	9.5 (-11.9, 35.9)	12.5 (-12.7, 45.0)	28.8 (-12.9, 90.4)	20.1 (-29.4, 104.5)	11.6 (-1.1, 26.0)	15.2 (-1.0, 34.2)	12.8 (-1.0, 28.6)	14.9 (-2.6, 35.5)	0.1 (-2.1, 2.4)	5.0 (-12.6, 26.2)
Chermside	17.4 (-0.2, 38.1)	26.3 (4.8, 52.3)	4.1 (-9.6, 19.8)	3.6 (-11.1, 20.7)	5.5 (-9.9, 23.6)	11.4 (-7.5, 34.2)	11.3 (-7.6, 34.2)	11.2 (-10.1, 37.6)	13.1 (-20.8, 61.6)	6.3 (-30.6, 62.9)	7.3 (-2.7, 18.4)	12.3 (0.4, 25.7)	4.9 (-6.0, 17.0)	7.1 (-5.1, 21.0)	29.2 (-21.5, 112.8)	33.0 (-19.7, 120.5)
Cleveland - Stradbroke	6.0 (-22.3, 44.8)	21.8 (-14.4, 73.4)	4.9 (-9.0, 20.9)	1.9 (-15.1, 22.2)	1.1 (-4.6, 7.2)	5.0 (-9.7, 22.1)	19.3 (-13.3, 64.1)	19.0 (-17.0, 70.6)	0.3 (-13.5, 16.2)	0.0 (-6.6, 7.2)	7.1 (-12.1, 30.4)	11.8 (-10.6, 39.8)	1.3 (-5.9, 9.2)	4.1 (-10.0, 20.4)	50.1 (-22.7, 191.6)	53.1 (-23.7, 206.9)
Forest Lake - Oxley	11.7 (-8.0, 35.7)	3.9 (-19.6, 34.3)	12.6 (-4.4, 32.6)	19.3 (-2.9, 46.7)	11.1 (-7.4, 33.2)	14.7 (-10.6, 47.0)	7.3 (-13.9, 33.7)	11.0 (-14.9, 44.9)	19.1 (-20.1, 77.5)	6.3 (-39.8, 87.4)	11.7 (-1.3, 26.5)	15.9 (-1.5, 36.5)	11.7 (-2.3, 27.6)	13.8 (-4.6, 35.7)	0.1 (-2.1, 2.4)	5.9 (-14.7, 31.4)
Holland Park - Yeronga	5.5 (-6.8, 19.5)	7.4 (-7.3, 24.4)	12.8 (-1.1, 28.6)	14.5 (-1.5, 33.2)	13.5 (-2.1, 31.6)	18.8 (-1.7, 43.6)	8.3 (-8.8, 28.7)	10.3 (-8.6, 33.0)	5.4 (-9.9, 23.3)	0.0 (0.0, 0.0)	10.9 (1.6, 20.9)	14.2 (3.0, 26.6)	9.8 (-0.4, 21.1)	12.2 (-0.2, 26.2)	20.5 (-22.2, 86.7)	23.6 (-21.0, 93.5)
Ipswich Hinterland	54.3 (-2.6, 144.4)	67.1 (-6.0, 197.0)	1.7 (-25.1, 38.1)	6.4 (-26.9, 54.9)	10.6 (-20.4, 53.8)	28.4 (-15.4, 94.9)	4.7 (-31.4, 59.8)	3.2 (-38.8, 74.2)	48.9 (-25.1, 196.1)	15.1 (-52.3, 178.0)	7.2 (-17.9, 40.1)	20.5 (-13.9, 68.5)	7.7 (-18.2, 41.9)	13.3 (-19.6, 59.6)	9.4 (-51.8, 148.3)	19.7 (-52.3, 200.5)
Ipswich Inner	31.4 (-6.1, 83.8)	24.4 (-18.3, 89.5)	12.4 (-10.4, 41.2)	20.4 (-9.0, 59.5)	17.5 (-8.4, 50.6)	27.8 (-6.9, 75.6)	4.2 (-24.3, 43.3)	5.5 (-28.4, 55.5)	40.5 (-16.5, 136.2)	16.2 (-40.6, 127.5)	10.1 (-9.6, 34.0)	16.9 (-8.8, 49.8)	13.4 (-7.4, 39.0)	16.5 (-9.7, 50.3)	21.2 (-32.0, 116.3)	29.8 (-32.4, 149.0)
Jimboomba	24.7 (0.7, 54.4)	28.7 (-3.2, 71.2)	9.5 (-6.7, 28.5)	14.7 (-6.3, 40.5)	9.0 (-9.1, 30.6)	20.0 (-6.3, 53.8)	7.1 (-14.1, 33.6)	7.7 (-18.1, 41.8)	21.5 (-18.7, 81.5)	2.1 (-41.8, 79.2)	8.8 (-3.8, 23.2)	17.8 (-0.2, 39.1)	9.0 (-4.6, 24.5)	13.4 (-4.9, 35.3)	24.6 (-28.3, 116.7)	33.2 (-26.5, 141.5)
Kenmore - Brookfield - Moggill	13.5 (-2.0, 31.5)	12.3 (-6.7, 35.2)	11.3 (-3.0, 27.7)	15.5 (-2.0, 36.1)	11.0 (-5.3, 30.0)	16.9 (-5.3, 44.4)	9.6 (-8.7, 31.5)	11.6 (-9.3, 37.4)	13.5 (-20.9, 63.0)	2.1 (-37.9, 67.8)	10.6 (0.8, 21.4)	15.6 (2.8, 29.9)	9.5 (-1.5, 21.6)	12.0 (-1.9, 27.8)	13.5 (-31.4, 87.9)	18.9 (-29.3, 99.8)
Loganlea - Carbrook	0.2 (-1.3, 1.7)	4.9 (-8.8, 20.8)	8.5 (-9.9, 30.7)	7.4 (-13.4, 33.1)	1.8 (-16.9, 24.8)	1.8 (-20.8, 30.8)	16.2 (-7.8, 46.4)	18.1 (-9.2, 53.6)	6.2 (-12.7, 29.2)	0.0 (0.0, 0.0)	13.3 (-1.1, 29.9)	15.5 (-1.8, 36.0)	6.9 (-8.1, 24.4)	8.5 (-9.4, 29.8)	2.0 (-11.1, 17.0)	3.1 (-18.0, 29.6)
Mt Gravatt	7.6 (-4.7, 21.6)	18.7 (1.7, 38.6)	5.2 (-7.4, 19.4)	4.2 (-10.3, 21.1)	2.4 (-11.2, 18.1)	7.6 (-10.9, 30.0)	15.4 (-2.1, 36.1)	15.9 (-4.3, 40.4)	7.3 (-10.1, 28.2)	0.0 (0.0, 0.0)	8.9 (0.3, 18.2)	14.5 (3.2, 27.1)	3.9 (-5.3, 14.1)	7.0 (-4.8, 20.2)	27.1 (-18.2, 97.6)	30.4 (-17.3, 105.6)
Narangba - Burpengary	17.6 (-0.8, 39.4)	31.0 (6.3, 61.5)	2.8 (-11.0, 18.8)	2.3 (-13.4, 20.9)	0.9 (-14.2, 18.6)	7.9 (-12.1, 32.4)	10.3 (-9.1, 33.9)	9.8 (-12.8, 38.2)	11.0 (-22.2, 58.5)	3.0 (-34.9, 63.0)	7.1 (-3.4, 18.7)	14.2 (0.7, 29.6)	3.0 (-8.0, 15.4)	6.4 (-7.1, 21.9)	34.4 (-20.7, 127.7)	39.5 (-19.0, 140.4)
Nathan	6.5 (-4.8, 19.2)	11.3 (-2.7, 27.3)	9.3 (-3.2, 23.5)	10.1 (-4.4, 26.7)	7.0 (-6.9, 23.0)	11.2 (-7.1, 33.1)	11.9 (-5.0, 31.7)	13.2 (-5.2, 35.2)	9.5 (-5.6, 27.1)	0.0 (0.0, 0.0)	10.3 (1.9, 19.3)	14.3 (4.0, 25.7)	7.7 (-1.6, 17.8)	10.2 (-1.1, 22.9)	0.4 (-3.0, 3.9)	2.7 (-10.2, 17.6)
North Lakes	12.1 (-7.2, 35.4)	25.0 (0.1, 56.2)	1.9 (-13.7, 20.5)	0.2 (-16.9, 20.8)	0.8 (-16.2, 21.4)	5.8 (-15.2, 31.8)	17.5 (-5.1, 45.4)	17.6 (-8.2, 50.7)	5.8 (-10.6, 25.1)	0.0 (0.0, 0.0)	8.2 (-4.1, 22.1)	13.3 (-1.7, 30.6)	1.0 (-11.6, 15.3)	3.6 (-11.0, 20.7)	45.4 (-17.2, 155.5)	49.0 (-16.5, 165.9)
Nundah	17.9	28.5	2.7	2.0	1.1	6.4	7.5	6.8	7.7	0.0 (0.0, 0.0)	6.8	12.2	3.4	5.9	12.5	16.5

	(-1.6, 41.2)	(4.4, 58.1)	(-11.2, 18.9)	(-13.2, 19.9)	(-14.1, 18.9)	(-12.0, 28.8)	(-11.8, 31.0)	(-14.9, 34.0)	(-7.6, 25.4)		(-4.3, 19.2)	(-1.0, 27.3)	(-8.1, 16.4)	(-7.2, 20.9)	(-27.6, 74.6)	(-26.1, 83.6)
Redcliffe	9.3 (-33.3, 79.1)	33.6 (-23.3, 132.9)	13.2 (-8.6, 40.3)	9.2 (-17.4, 44.4)	3.0 (-11.8, 20.3)	8.5 (-15.3, 39.1)	22.8 (-16.9, 81.6)	22.7 (-22.8, 95.0)	5.0 (-28.1, 53.3)	2.3 (-39.9, 74.2)	6.2 (-12.3, 28.6)	13.5 (-11.8, 46.0)	6.9 (-10.6, 27.8)	11.5 (-13.0, 42.9)	64.0 (-31.6, 293.2)	72.1 (-32.4, 338.4)
Rocklea - Acacia Ridge	3.8 (-12.2, 22.7)	0.3 (-19.2, 24.5)	15.0 (-1.3, 34.0)	19.5 (-1.3, 44.6)	10.0 (-6.8, 29.9)	12.3 (-10.5, 41.0)	13.4 (-7.5, 39.1)	17.4 (-7.6, 49.1)	13.3 (-12.7, 46.9)	0.0 (0.0, 0.0)	11.9 (-0.1, 25.3)	14.9 (-0.7, 33.0)	9.6 (-3.0, 23.8)	11.4 (-5.0, 30.6)	33.1 (-15.6, 110.1)	38.3 (-15.5, 126.5)
Sandgate	16.5 (-3.2, 40.2)	28.8 (3.3, 60.5)	0.8 (-6.6, 8.9)	0.0 (0.0, 0.0)	0.2 (-0.8, 1.1)	5.5 (-3.5, 15.5)	10.9 (-10.1, 36.9)	10.4 (-13.5, 41.0)	11.4 (-6.5, 32.7)	0.0 (0.0, 0.0)	6.0 (-5.3, 18.6)	12.0 (-2.0, 28.0)	1.3 (-10.0, 13.9)	4.1 (-9.3, 19.5)	14.7 (-31.0, 90.6)	18.8 (-29.8, 100.9)
Sherwood - Indooroopilly	4.0 (-11.4, 22.1)	1.3 (-17.7, 24.6)	13.4 (-2.7, 32.2)	17.4 (-3.0, 42.0)	13.0 (-4.8, 34.1)	17.2 (-7.5, 48.3)	9.7 (-10.4, 34.4)	13.7 (-10.0, 43.8)	7.2 (-17.3, 39.0)	0.0 (0.0, 0.0)	11.8 (0.2, 24.7)	15.0 (-0.1, 32.3)	9.7 (-2.7, 23.7)	11.8 (-4.4, 30.7)	26.7 (-24.5, 112.7)	31.9 (-23.7, 128.1)
Springfield - Redbank	22.4 (-3.0, 54.5)	17.0 (-14.1, 59.5)	9.5 (-7.9, 30.3)	16.4 (-6.7, 45.2)	13.3 (-6.7, 37.6)	22.2 (-6.3, 59.4)	6.4 (-16.1, 34.9)	8.4 (-19.4, 45.9)	28.5 (-16.0, 96.6)	8.0 (-40.4, 95.5)	10.4 (-3.9, 26.8)	17.3 (-2.5, 41.0)	10.5 (-4.7, 28.0)	13.4 (-6.7, 37.8)	48.1 (-13.6, 153.7)	57.8 (-12.4, 184.2)
Springwood - Kingston	6.8 (-4.4, 19.4)	12.5 (-1.6, 28.7)	9.2 (-3.4, 23.5)	9.8 (-4.8, 26.6)	7.7 (-6.5, 24.2)	12.6 (-6.3, 35.4)	14.1 (-3.2, 34.4)	15.2 (-3.6, 37.7)	6.3 (-21.4, 43.6)	4.5 (-30.2, 56.5)	10.1 (1.9, 19.0)	14.3 (4.1, 25.6)	6.3 (-2.8, 16.2)	8.7 (-2.5, 21.2)	38.8 (-11.3, 117.3)	42.1 (-10.0, 124.4)
Strathpine	17.1 (0.3, 36.8)	25.3 (4.9, 49.6)	3.3 (-9.7, 18.2)	3.0 (-11.1, 19.2)	0.9 (-13.2, 17.5)	5.3 (-11.9, 25.9)	13.1 (-5.5, 35.4)	13.3 (-7.8, 39.1)	9.1 (-4.6, 24.8)	0.0 (0.0, 0.0)	7.5 (-2.1, 18.1)	12.4 (1.0, 25.0)	3.1 (-7.2, 14.4)	5.3 (-6.3, 18.2)	42.6 (-12.5, 132.4)	46.3 (-10.7, 139.6)
Sunnybank	6.7 (-4.6, 19.3)	12.0 (-2.0, 28.1)	8.5 (-4.3, 23.0)	9.0 (-5.6, 26.0)	4.0 (-10.0, 20.3)	7.3 (-11.1, 29.6)	13.5 (-4.0, 34.1)	14.7 (-4.3, 37.4)	8.4 (-7.3, 26.8)	0.0 (0.0, 0.0)	10.2 (1.9, 19.1)	14.3 (4.0, 25.6)	6.2 (-3.0, 16.2)	8.5 (-2.8, 21.0)	17.5 (-27.5, 90.5)	20.3 (-26.3, 96.6)
The Gap - Enoggera	23.0 (-10.4, 68.7)	60.5 (5.7, 143.6)	3.6 (-13.9, 24.8)	0.0 (0.0, 0.0)	0.9 (-2.2, 4.1)	13.4 (-8.7, 41.0)	14.5 (-15.3, 54.9)	10.9 (-25.4, 64.9)	12.6 (-25.4, 69.9)	0.0 (0.0, 0.0)	4.9 (-13.6, 27.4)	17.4 (-9.2, 51.7)	0.9 (-3.3, 5.2)	7.0 (-12.4, 30.6)	Not enough data	Not enough data
The Hills District	24.6 (3.6, 49.9)	37.9 (10.6, 71.9)	4.8 (-11.7, 24.4)	4.5 (-13.7, 26.5)	4.6 (-13.7, 26.9)	11.8 (-11.4, 41.2)	14.8 (-5.8, 40.0)	14.6 (-9.2, 44.7)	13.5 (-6.0, 37.1)	0.0 (0.0, 0.0)	10.5 (-1.2, 23.5)	17.6 (3.0, 34.4)	5.3 (-8.0, 20.6)	8.7 (-6.9, 26.8)	66.1 (-12.1, 214.2)	71.9 (-10.2, 229.1)
Wynnum - Manly	16.3 (-2.8, 39.2)	28.0 (3.5, 58.4)	4.2 (-9.4, 20.0)	3.6 (-11.8, 21.6)	2.0 (-12.7, 19.2)	8.6 (-10.1, 31.1)	7.4 (-12.2, 31.3)	6.6 (-15.6, 34.8)	14.0 (-17.9, 58.2)	9.1 (-27.3, 64.0)	6.1 (-4.8, 18.3)	12.0 (-1.6, 27.4)	3.4 (-7.7, 15.9)	6.3 (-7.0, 21.4)	17.1 (-24.2, 81.0)	21.2 (-23.3, 91.4)

Table S7 Region-wise subgroup analysis - Greater Melbourne

Greater Melbourne, SA3 Regions	Female workers risk at moderate heat	Female workers risk at extreme heat	Male workers risk at moderate heat	Male workers at extreme heat	Younger workers risk at moderate heat	Younger workers risk at extreme heat	Older workers risk at moderate heat	Older workers risk at extreme heat	Outdoor industries risk at moderate heat	Outdoor industries risk at extreme heat	Indoor industries risk at moderate heat	Indoor industries risk at extreme heat	Injuries risk at moderate heat	injuries risk at extreme heat	Illness risk at moderate heat	Illness risk at extreme heat
Banyule	7.3 (-12.6, 31.9)	9.2 (-12.9, 36.8)	22.2 (11.6, 33.8)	23.7 (10.7, 38.3)	19.9 (9.2, 31.7)	17.0 (4.2, 31.4)	13.0 (1.8, 25.4)	18.4 (4.1, 34.7)	21.0 (-1.3, 48.4)	25.9 (-0.7, 59.8)	15.9 (7.0, 25.4)	16.5 (5.7, 28.5)	11.9 (1.6, 23.3)	10.2 (-2.2, 24.2)	19.4 (3.5, 37.8)	27.0 (12.0, 44.0)
Bayside	8.1 (-16.8, 40.5)	4.3 (-21.0, 37.7)	27.2 (12.0, 44.6)	25.4 (7.2, 46.7)	16.9 (2.6, 33.3)	7.1 (-8.9, 25.8)	17.4 (1.7, 35.6)	27.4 (6.7, 52.2)	30.4 (-2.6, 74.4)	50.0 (8.0, 108.2)	16.9 (4.7, 30.4)	13.5 (-0.9, 29.9)	12.7 (-1.6, 29.1)	8.6 (-8.1, 28.4)	24.9 (3.2, 51.2)	27.4 (7.3, 51.3)
Boroondara	12.6 (-7.5, 36.9)	13.1 (-8.4, 39.7)	21.1 (12.5, 30.3)	23.2 (12.4, 35.0)	18.3 (9.6, 27.7)	16.2 (5.6, 27.8)	13.9 (4.7, 23.9)	18.4 (6.5, 31.6)	17.8 (-1.3, 40.5)	24.1 (1.8, 51.2)	15.6 (8.4, 23.3)	16.6 (7.5, 26.3)	13.7 (5.1, 23.0)	12.6 (2.1, 24.2)	18.5 (3.5, 35.8)	23.2 (11.1, 36.5)
Brimbank	12.9 (-7.1, 37.1)	13.4 (-7.8, 39.5)	20.6 (12.8, 29.1)	23.0 (13.0, 33.8)	17.6 (9.6, 26.2)	15.8 (6.1, 26.5)	14.5 (5.9, 23.7)	18.4 (7.4, 30.5)	17.6 (-0.4, 38.8)	22.7 (2.3, 47.3)	15.6 (8.9, 22.7)	16.6 (8.2, 25.6)	14.6 (6.5, 23.2)	13.7 (3.8, 24.5)	14.0 (0.1, 29.9)	21.6 (10.6, 33.7)
Brunswick - Coburg	11.6 (-9.7, 37.9)	11.1 (-11.5, 39.4)	22.0 (11.9, 33.0)	23.6 (11.1, 37.4)	19.5 (9.3, 30.7)	16.8 (4.6, 30.4)	13.3 (2.6, 25.1)	18.4 (4.7, 33.8)	20.4 (-1.0, 46.6)	25.4 (-0.1, 57.4)	15.9 (7.4, 24.9)	16.5 (6.2, 27.9)	12.4 (2.5, 23.2)	10.8 (-1.1, 24.1)	20.7 (4.7, 39.2)	26.0 (11.8, 42.0)
Cardinia	22.6 (-8.1, 63.4)	21.7 (-11.7, 67.8)	14.7 (-3.0, 35.7)	21.6 (-0.8, 49.0)	13.5 (-4.6, 35.0)	22.8 (-0.6, 51.7)	20.1 (-0.8, 45.4)	13.7 (-10.0, 43.7)	13.0 (-11.0, 43.4)	1.9 (-27.5, 43.3)	16.0 (0.0, 34.5)	21.4 (1.4, 45.4)	28.7 (7.5, 54.1)	33.9 (7.5, 66.7)	3.9 (-16.6, 29.4)	3.6 (-17.3, 29.8)
Casey - North	20.8 (-7.3, 57.5)	16.3 (-13.3, 56.2)	15.8 (0.0, 34.1)	22.3 (2.3, 46.3)	15.4 (-1.0, 34.4)	23.9 (2.9, 49.3)	18.6 (0.3, 40.3)	13.5 (-7.6, 39.5)	11.7 (-11.8, 41.4)	2.7 (-24.9, 40.6)	16.1 (1.9, 32.3)	21.4 (3.6, 42.3)	26.1 (7.6, 47.7)	30.5 (7.5, 58.3)	9.4 (-10.2, 33.4)	7.6 (-11.8, 31.2)
Casey - South	10.5 (-8.4, 33.4)	4.8 (-14.6, 28.6)	17.3 (9.6, 25.6)	20.3 (10.5, 31.0)	12.9 (5.1, 21.3)	13.3 (3.6, 23.9)	16.4 (7.7, 25.8)	17.1 (6.2, 29.1)	14.8 (-1.2, 33.4)	14.2 (-3.7, 35.5)	14.5 (7.7, 21.7)	15.8 (7.3, 25.0)	19.0 (10.5, 28.1)	19.6 (9.0, 31.1)	12.6 (-0.7, 27.7)	11.1 (1.1, 22.2)
Dandenong	7.3 (-10.7, 28.9)	10.6 (-9.4, 34.9)	19.2 (12.1, 26.8)	22.1 (13.1, 31.9)	15.0 (7.9, 22.7)	14.6 (5.7, 24.2)	16.4 (8.5, 24.9)	18.4 (8.3, 29.4)	17.4 (1.3, 36.1)	18.1 (0.6, 38.6)	15.4 (9.2, 21.9)	16.6 (8.8, 24.9)	17.6 (10.0, 25.8)	17.6 (8.2, 27.9)	14.9 (1.8, 29.7)	15.8 (6.2, 26.2)
Darebin - North	11.6 (-11.5, 40.7)	10.6 (-12.7, 40.1)	25.9 (15.7, 37.0)	27.8 (15.5, 41.5)	21.2 (11.0, 32.3)	19.0 (7.1, 32.4)	18.8 (7.8, 31.0)	23.2 (9.5, 38.6)	28.3 (3.9, 58.5)	32.3 (6.5, 64.2)	18.9 (10.3, 28.1)	19.7 (9.4, 30.9)	15.5 (5.5, 26.5)	14.3 (2.5, 27.5)	22.6 (5.4, 42.8)	28.6 (14.6, 44.3)
Darebin - South	7.1 (-13.1, 31.9)	11.4 (-10.9, 39.3)	21.8 (12.2, 32.2)	23.5 (11.6, 36.7)	19.2 (9.4, 29.8)	16.6 (4.9, 29.6)	13.5 (3.3, 24.8)	18.4 (5.3, 33.1)	21.0 (0.2, 46.2)	24.5 (0.1, 54.8)	15.8 (7.8, 24.5)	16.5 (6.6, 27.4)	12.8 (3.3, 23.2)	11.3 (-0.1, 24.1)	17.7 (2.4, 35.4)	25.2 (11.7, 40.4)
Essendon	9.6 (-11.4, 35.5)	10.2 (-12.4, 38.6)	22.2 (11.7, 33.6)	23.7 (10.8, 38.1)	19.8 (9.2, 31.5)	16.9 (4.3, 31.1)	13.1 (2.0, 25.3)	18.4 (4.2, 34.5)	19.7 (-2.3, 46.7)	26.3 (-0.2, 59.9)	15.9 (7.1, 25.3)	16.5 (5.8, 28.4)	12.0 (1.8, 23.3)	10.4 (-1.9, 24.2)	21.2 (4.8, 40.3)	26.7 (11.9, 43.5)
Frankston	8.8 (-10.4, 32.0)	7.0 (-14.9, 34.4)	12.7 (2.2, 24.2)	16.6 (3.0, 32.1)	8.9 (-1.6, 20.5)	10.9 (-2.6, 26.3)	15.5 (3.5, 29.0)	13.6 (-1.4, 31.0)	10.7 (-8.6, 34.0)	8.4 (-15.1, 38.5)	12.2 (2.9, 22.3)	13.8 (1.9, 27.1)	20.4 (8.5, 33.7)	22.3 (7.0, 39.8)	3.5 (-10.3, 19.4)	3.2 (-10.3, 18.8)

Glen Eira	5.1 (-19.1, 36.5)	6.1 (-19.9, 40.5)	27.6 (11.7, 45.8)	25.6 (6.6, 47.9)	17.6 (2.6, 34.8)	7.4 (-9.2, 27.0)	17.0 (0.7, 35.9)	27.4 (5.8, 53.3)	29.5 (-4.3, 75.2)	51.4 (7.4, 113.5)	16.9 (4.3, 31.1)	13.4 (-1.5, 30.6)	12.0 (-2.8, 29.0)	7.7 (-9.6, 28.2)	21.9 (0.5, 47.9)	28.6 (7.5, 53.8)
Hobsons Bay	29.0 (1.5, 63.9)	24.0 (-4.3, 60.8)	18.0 (5.1, 32.6)	24.2 (7.7, 43.1)	19.7 (6.0, 35.2)	26.9 (9.4, 47.3)	15.2 (0.8, 31.6)	13.1 (-4.0, 33.3)	17.7 (-8.6, 51.5)	8.3 (-19.1, 44.9)	16.1 (4.6, 28.8)	21.4 (6.8, 37.9)	18.9 (4.7, 34.9)	22.0 (4.5, 42.4)	17.4 (-1.1, 39.3)	18.1 (0.7, 38.5)
Keilor	8.9 (-11.4, 33.8)	9.7 (-11.8, 36.6)	21.3 (12.4, 31.0)	23.3 (12.1, 35.6)	18.7 (9.6, 28.5)	16.4 (5.4, 28.5)	13.7 (4.1, 24.2)	18.4 (6.1, 32.2)	19.6 (-0.2, 43.4)	24.0 (1.0, 52.3)	15.7 (8.1, 23.7)	16.6 (7.2, 26.7)	13.4 (4.4, 23.1)	12.1 (1.2, 24.1)	17.1 (1.9, 34.5)	24.0 (11.4, 38.0)
Kingston	20.2 (0.3, 44.0)	13.2 (-7.4, 38.2)	18.1 (11.3, 25.4)	21.0 (12.0, 30.7)	14.2 (7.3, 21.7)	13.8 (5.0, 23.4)	15.4 (7.7, 23.6)	17.2 (7.3, 28.1)	18.1 (2.8, 35.6)	14.8 (-2.4, 35.1)	14.6 (8.6, 20.9)	15.8 (8.1, 24.1)	17.3 (9.9, 25.2)	17.3 (7.9, 27.5)	14.6 (2.0, 28.7)	14.1 (4.5, 24.5)
Knox	13.0 (-12.6, 46.1)	14.9 (-14.0, 53.4)	15.8 (0.1, 34.1)	22.3 (2.4, 46.2)	15.4 (-0.9, 34.4)	23.9 (2.9, 49.2)	18.6 (0.3, 40.2)	13.5 (-7.5, 39.4)	14.2 (-16.0, 55.4)	1.6 (-29.4, 46.2)	16.1 (2.0, 32.2)	21.4 (3.6, 42.2)	26.0 (7.6, 47.5)	30.4 (7.5, 58.1)	7.7 (-11.2, 30.6)	7.6 (-11.8, 31.1)
Macedon Ranges	9.2 (-20.7, 50.2)	0.0 (0.0, 0.0)	19.1 (-13.7, 64.4)	18.7 (-20.9, 77.9)	8.1 (-14.1, 36.0)	0.0 (0.0, 0.0)	35.5 (-5.8, 94.8)	35.0 (-14.7, 113.6)	13.7 (-36.7, 104.2)	28.2 (-37.8, 164.1)	13.8 (-14.4, 51.5)	7.3 (-25.0, 53.6)	39.7 (-1.4, 98.1)	39.1 (-9.9, 114.7)	6.4 (-20.7, 42.6)	0.0 (0.0, 0.0)
Manningham - East	4.9 (-20.4, 38.1)	2.7 (-22.8, 36.8)	28.3 (12.2, 46.8)	26.6 (7.9, 48.6)	16.8 (1.8, 34.1)	8.2 (-8.2, 27.5)	18.9 (2.2, 38.4)	27.7 (6.5, 53.0)	36.9 (1.2, 85.2)	52.3 (9.0, 112.9)	17.3 (4.4, 31.7)	14.1 (-0.6, 31.0)	12.6 (-2.4, 29.9)	9.0 (-8.1, 29.2)	24.1 (2.2, 50.7)	28.4 (7.7, 53.0)
Manningham - West	5.9 (-14.1, 30.5)	5.1 (-16.1, 31.7)	21.9 (12.0, 32.7)	23.6 (11.3, 37.2)	19.4 (9.4, 30.4)	16.7 (4.7, 30.1)	13.3 (2.8, 25.0)	18.4 (4.9, 33.6)	20.1 (-1.0, 45.9)	25.3 (0.1, 56.8)	15.8 (7.5, 24.8)	16.5 (6.3, 27.8)	12.5 (2.8, 23.2)	11.0 (-0.8, 24.1)	22.7 (6.4, 41.5)	25.6 (11.7, 41.3)
Maribyrnong	4.0 (-15.6, 28.1)	7.5 (-14.1, 34.5)	21.7 (11.8, 32.5)	23.6 (11.2, 37.4)	19.5 (9.4, 30.6)	16.8 (4.6, 30.3)	13.0 (2.5, 24.7)	18.4 (4.8, 33.8)	22.4 (0.4, 49.1)	24.7 (-0.6, 56.4)	15.7 (7.4, 24.7)	16.5 (6.2, 27.9)	12.3 (2.6, 23.0)	10.9 (-1.0, 24.1)	15.5 (0.2, 33.2)	26.1 (12.0, 42.0)
Maroondah	10.2 (-9.1, 33.5)	12.7 (-8.3, 38.4)	19.0 (11.4, 27.1)	21.8 (12.3, 32.2)	14.3 (6.7, 22.5)	14.1 (4.8, 24.4)	17.1 (8.6, 26.2)	18.4 (7.8, 30.1)	13.9 (-2.0, 32.3)	17.8 (-0.2, 39.0)	15.5 (8.9, 22.5)	16.6 (8.4, 25.5)	19.0 (10.8, 27.8)	19.0 (8.9, 30.1)	5.6 (-6.5, 19.4)	14.2 (4.2, 25.1)
Melbourne City	12.1 (-7.7, 36.1)	11.3 (-10.4, 38.2)	22.0 (11.4, 33.6)	23.8 (10.6, 38.5)	20.0 (9.3, 31.9)	17.0 (4.1, 31.5)	12.7 (1.5, 25.1)	18.4 (4.0, 34.8)	23.3 (0.4, 51.5)	25.3 (-1.4, 59.3)	15.7 (6.9, 25.3)	16.5 (5.6, 28.6)	11.8 (1.4, 23.1)	10.1 (-2.4, 24.2)	25.0 (8.6, 44.0)	26.9 (11.8, 44.1)
Melton - Bacchus Marsh	2.2 (-7.2, 12.5)	3.5 (-15.0, 26.1)	25.9 (12.4, 40.9)	24.6 (8.6, 42.9)	13.9 (1.4, 27.9)	5.8 (-8.2, 21.8)	19.8 (5.6, 36.0)	27.6 (9.4, 48.8)	26.5 (-1.5, 62.5)	44.1 (9.3, 90.2)	16.6 (5.8, 28.6)	13.5 (0.8, 27.8)	15.6 (2.5, 30.4)	12.3 (-3.0, 30.1)	15.7 (-2.3, 37.0)	21.1 (4.3, 40.6)
Monash	16.1 (-5.6, 42.7)	13.9 (-7.8, 40.8)	22.7 (14.3, 31.7)	25.4 (15.3, 36.3)	16.4 (8.0, 25.4)	16.3 (6.4, 27.0)	20.9 (11.5, 31.1)	22.3 (11.1, 34.8)	16.0 (-2.6, 38.1)	21.6 (2.6, 44.0)	18.0 (10.7, 25.7)	19.1 (10.5, 28.4)	20.3 (11.4, 30.0)	20.6 (10.1, 32.1)	16.8 (2.2, 33.6)	18.1 (7.3, 30.0)
Moreland - North	10.9 (-10.9, 38.0)	8.9 (-13.1, 36.3)	23.4 (14.4, 33.0)	25.4 (14.4, 37.5)	19.4 (10.3, 29.1)	17.4 (6.7, 29.2)	16.9 (7.1, 27.4)	20.9 (8.7, 34.4)	21.0 (0.5, 45.8)	27.3 (4.6, 54.9)	17.3 (9.8, 25.4)	18.2 (9.0, 28.2)	15.3 (6.3, 25.0)	14.2 (3.5, 26.1)	17.4 (2.0, 35.1)	24.8 (12.5, 38.4)
Mornington Peninsula	8.6 (-10.3, 31.5)	6.4 (-21.7, 44.5)	16.5 (-4.2, 41.7)	13.5 (-11.8, 46.1)	12.7 (-5.9, 34.9)	0.0 (0.0, 0.0)	22.6 (-1.5, 52.6)	29.4 (-2.5, 71.7)	13.3 (-21.1, 62.5)	32.7 (-16.0, 109.7)	12.5 (-5.3, 33.7)	5.3 (-15.6, 31.5)	19.5 (-3.3, 47.7)	15.7 (-11.7, 51.6)	7.1 (-15.7, 36.1)	0.0 (0.0, 0.0)
Nillumbik -	13.5 (-12.9, 47.8)	13.0 (-15.2, 50.5)	16.7 (1.2, 34.5)	20.5 (1.7, 42.8)	9.0 (-6.0, 26.3)	11.3 (-6.7, 32.8)	22.8 (4.5, 44.2)	19.8 (-1.3, 45.4)	13.4 (-14.3, 50.1)	8.0 (-21.8, 49.1)	15.9 (2.2, 31.3)	17.4 (1.0, 36.4)	28.3 (10.2, 49.4)	30.3 (8.6, 56.4)	0.2 (-3.0, 3.5)	2.7 (-14.2, 22.9)

Kinglake																
Port Phillip	23.5 (-1.5, 54.7)	18.3 (-6.2, 49.1)	25.2 (14.2, 37.2)	27.2 (14.1, 41.8)	21.6 (10.6, 33.8)	19.5 (6.8, 33.8)	16.9 (5.2, 30.0)	21.6 (7.2, 37.8)	28.9 (3.2, 60.9)	32.1 (4.9, 66.3)	18.1 (8.9, 28.0)	19.0 (8.2, 31.0)	13.5 (2.9, 25.3)	12.6 (0.2, 26.5)	27.5 (9.0, 49.0)	30.2 (15.1, 47.4)
Stonnington - East	6.7 (-18.8, 40.3)	2.1 (-23.7, 36.6)	27.9 (11.3, 46.9)	25.7 (6.1, 49.1)	18.2 (2.5, 36.2)	7.7 (-9.6, 28.3)	16.5 (-0.3, 36.3)	27.3 (5.0, 54.5)	31.7 (-3.8, 80.3)	52.8 (6.8, 118.7)	16.9 (3.8, 31.7)	13.4 (-2.1, 31.4)	11.3 (-3.9, 28.9)	6.8 (-10.9, 28.1)	24.5 (1.7, 52.3)	30.1 (8.0, 56.8)
Stonnington - West	2.6 (-22.8, 36.5)	3.7 (-24.1, 41.8)	28.9 (9.9, 51.2)	26.4 (3.9, 53.7)	20.2 (2.1, 41.5)	8.7 (-11.1, 32.9)	15.1 (-3.9, 37.9)	27.2 (1.8, 58.9)	35.0 (-5.5, 92.6)	57.6 (4.3, 138.2)	17.0 (2.1, 34.2)	13.4 (-4.2, 34.2)	9.0 (-8.0, 29.0)	4.1 (-15.5, 28.2)	28.7 (3.4, 60.0)	35.0 (8.9, 67.4)
Sunbury	4.5 (-8.3, 19.1)	3.8 (-16.6, 29.0)	24.2 (9.6, 40.6)	24.0 (6.4, 44.5)	9.1 (-4.2, 24.3)	2.6 (-12.5, 20.3)	24.6 (8.5, 43.2)	29.4 (9.1, 53.6)	23.3 (-4.1, 58.4)	36.2 (3.4, 79.3)	16.9 (4.7, 30.5)	13.7 (-0.6, 30.1)	23.2 (7.7, 41.1)	21.0 (2.7, 42.7)	7.1 (-10.9, 28.8)	10.5 (-6.6, 30.6)
Tullamarine - Broadmeadows	7.2 (-14.4, 34.5)	4.5 (-18.2, 33.5)	24.7 (11.9, 39.1)	23.9 (8.7, 41.3)	11.8 (-0.1, 25.2)	4.7 (-8.7, 19.9)	21.4 (7.5, 37.0)	27.7 (10.3, 48.0)	28.5 (2.1, 61.9)	39.4 (8.3, 79.6)	16.5 (6.0, 28.1)	13.6 (1.3, 27.4)	18.3 (5.2, 33.1)	15.6 (0.3, 33.1)	16.5 (-0.4, 36.3)	16.8 (1.2, 34.8)
Whitehorse - East	15.5 (-7.7, 44.6)	14.0 (-8.8, 42.4)	22.8 (14.4, 31.7)	25.4 (15.4, 36.3)	16.5 (8.2, 25.5)	16.3 (6.6, 27.0)	20.8 (11.4, 30.9)	22.3 (11.1, 34.6)	23.7 (3.5, 47.9)	22.6 (3.5, 45.2)	18.0 (10.7, 25.6)	19.1 (10.5, 28.4)	20.2 (11.3, 29.7)	20.4 (9.9, 31.8)	14.3 (-1.0, 32.0)	17.9 (7.1, 29.7)
Whitehorse - West	8.8 (-12.5, 35.5)	6.5 (-14.4, 32.7)	24.3 (15.8, 33.4)	26.9 (16.7, 38.0)	18.5 (10.1, 27.6)	17.7 (7.8, 28.5)	20.5 (11.1, 30.7)	23.2 (11.8, 35.7)	25.1 (3.4, 51.3)	26.7 (6.2, 51.0)	18.6 (11.3, 26.3)	19.7 (11.1, 29.0)	18.6 (9.9, 28.1)	18.4 (8.1, 29.7)	20.6 (4.2, 39.7)	22.8 (11.4, 35.2)
Whittlesea - Wallan	4.5 (-6.5, 16.9)	5.9 (-14.8, 31.6)	23.0 (6.4, 42.1)	23.3 (3.9, 46.4)	7.0 (-7.9, 24.5)	2.0 (-14.7, 22.0)	26.3 (7.5, 48.4)	29.2 (6.5, 56.7)	20.7 (-8.4, 59.0)	29.8 (-4.1, 75.7)	16.8 (2.8, 32.7)	14.1 (-2.0, 32.8)	26.5 (8.2, 47.9)	25.1 (4.0, 50.5)	3.7 (-14.7, 26.1)	5.5 (-12.7, 27.4)
Wyndham	18.3 (-6.8, 50.2)	23.3 (-5.9, 61.5)	17.0 (3.6, 32.2)	24.0 (6.3, 44.6)	17.7 (3.6, 33.7)	26.3 (7.5, 48.4)	16.6 (1.4, 34.2)	13.1 (-5.3, 35.1)	15.8 (-11.2, 50.9)	5.0 (-23.6, 44.2)	15.9 (4.0, 29.3)	21.8 (6.1, 39.8)	21.2 (6.2, 38.4)	25.2 (5.9, 48.0)	15.0 (-3.5, 37.0)	14.1 (-3.9, 35.5)
Yarra	8.5 (-12.1, 33.8)	3.4 (-17.8, 30.1)	22.3 (11.4, 34.3)	23.8 (10.4, 38.9)	20.2 (9.1, 32.4)	17.1 (3.9, 31.9)	12.8 (1.3, 25.6)	18.4 (3.7, 35.2)	19.3 (-3.2, 47.0)	27.1 (-0.5, 62.4)	15.9 (6.8, 25.8)	16.5 (5.4, 28.9)	11.6 (1.1, 23.3)	9.9 (-2.8, 24.2)	23.8 (7.1, 43.1)	27.4 (11.9, 45.0)
Yarra Ranges	8.6 (-16.0, 40.5)	2.8 (-23.1, 37.4)	18.2 (2.1, 36.7)	18.9 (-0.5, 42.0)	4.8 (-10.0, 22.1)	0.4 (-16.6, 20.8)	23.6 (5.0, 45.6)	25.3 (2.6, 53.0)	16.4 (-11.0, 52.1)	22.0 (-10.9, 67.2)	14.6 (0.7, 30.3)	12.0 (-4.3, 31.0)	24.2 (6.1, 45.4)	23.3 (1.9, 49.2)	6.7 (-11.7, 28.9)	1.8 (-16.4, 24.0)

Table S8 Region-wise subgroup analysis - Greater Sydney

Greater Sydney, SA3 Regions	Female workers risk at moderate heat	Female workers risk at extreme heat	Male workers risk at moderate heat	Male workers at extreme heat	Younger workers risk at moderate heat	Younger workers risk at extreme heat	Older workers risk at moderate heat	Older workers risk at extreme heat	Outdoor industries risk at moderate heat	Outdoor industries risk at extreme heat	Indoor industries risk at moderate heat	Indoor industries risk at extreme heat	Injuries risk at moderate heat	injuries risk at extreme heat	Illness risk at moderate heat	Illness risk at extreme heat
Auburn	14.6 (2.6, 28.1)	25.0 (7.9, 44.9)	21.7 (11.1, 33.2)	35.2 (20.4, 51.7)	19.6 (8.9, 31.3)	32.9 (17.9, 49.8)	20.4 (8.3, 33.9)	34.2 (17.2, 53.6)	34.5 (12.7, 60.4)	40.7 (12.3, 76.2)	17.5 (8.2, 27.6)	31.6 (18.4, 46.2)	16.4 (7.3, 26.2)	31.3 (18.3, 45.7)	44.3 (15.5, 80.3)	34.4 (6.0, 70.3)
Banksto wn	13.1 (3.2, 24.0)	21.8 (7.6, 38.0)	20.8 (12.2, 30.1)	32.5 (20.4, 45.8)	18.5 (9.8, 28.0)	29.3 (17.2, 42.8)	18.7 (8.8, 29.5)	30.3 (16.4, 45.8)	33.0 (15.1, 53.6)	38.6 (15.1, 67.0)	16.2 (8.6, 24.3)	27.8 (17.1, 39.5)	15.2 (7.7, 23.2)	27.4 (16.8, 39.0)	34.3 (10.5, 63.2)	28.4 (5.2, 56.9)
Baulkha m Hills	1.9 (-4.8, 9.1)	2.7 (-8.7, 15.6)	16.3 (11.1, 21.8)	25.8 (17.3, 35.0)	13.4 (8.1, 19.0)	23.2 (14.5, 32.5)	9.4 (3.4, 15.8)	15.7 (6.2, 26.1)	24.4 (13.6, 36.3)	29.7 (13.1, 48.7)	8.9 (4.3, 13.8)	18.2 (10.7, 26.3)	9.7 (5.3, 14.4)	18.1 (10.8, 25.8)	11.2 (-8.7, 35.5)	13.7 (-3.3, 33.8)
Blackto wn	10.6 (0.3, 21.9)	20.4 (4.0, 39.4)	23.8 (14.9, 33.4)	38.9 (25.3, 54.0)	20.8 (11.8, 30.7)	41.4 (26.9, 57.5)	17.4 (7.1, 28.6)	26.0 (11.1, 42.9)	33.2 (14.9, 54.5)	40.8 (14.9, 72.6)	15.9 (8.0, 24.4)	32.8 (20.4, 46.4)	16.9 (9.2, 25.1)	32.4 (20.5, 45.4)	11.2 (-10.1, 37.6)	17.3 (-5.5, 45.5)
Blackto wn - North	7.7 (-7.1, 24.8)	12.4 (-9.1, 38.9)	29.9 (16.0, 45.5)	42.6 (22.3, 66.2)	25.4 (11.3, 41.3)	48.7 (26.4, 74.9)	17.7 (2.0, 35.8)	18.2 (-2.7, 43.6)	41.9 (13.0, 78.2)	47.6 (8.8, 100.2)	16.5 (4.5, 29.9)	31.9 (13.8, 52.9)	20.1 (8.6, 32.9)	31.5 (14.7, 50.8)	14.5 (-14.8, 53.9)	22.7 (-11.9, 70.9)
Blue Mountai ns	30.1 (-6.6, 81.2)	0.0 (0.0, 0.0)	21.3 (-9.2, 62.1)	0.0 (0.0, 0.0)	38.4 (2.8, 86.3)	0.0 (0.0, 0.0)	16.8 (-15.8, 62.2)	0.0 (0.0, 0.0)	50.3 (2.2, 121.2)	32.8 (-31.0, 155.6)	28.6 (0.0, 65.2)	0.0 (0.0, 0.0)	33.6 (4.4, 71.0)	0.0 (0.0, 0.0)	0.1 (-3.8, 4.1)	13.6 (-38.3, 109.1)
Botany	8.2 (0.5, 16.5)	10.6 (0.4, 21.9)	14.6 (8.0, 21.6)	18.9 (10.6, 27.9)	12.3 (5.6, 19.3)	13.7 (5.4, 22.5)	12.1 (4.4, 20.4)	17.2 (7.4, 27.9)	24.4 (10.6, 39.9)	26.6 (9.7, 46.1)	10.6 (4.7, 16.8)	13.5 (6.2, 21.4)	9.0 (3.3, 15.1)	12.6 (5.4, 20.4)	21.9 (2.1, 45.6)	18.3 (-1.4, 41.9)
Bringell y - Green Valley	6.7 (-8.3, 24.1)	8.3 (-12.0, 33.4)	28.1 (13.9, 44.2)	36.4 (17.1, 58.9)	23.0 (8.6, 39.4)	38.6 (17.9, 62.9)	15.1 (-0.8, 33.6)	12.3 (-7.4, 36.2)	40.1 (10.6, 77.6)	45.5 (7.4, 97.1)	13.9 (1.8, 27.5)	22.9 (6.2, 42.3)	18.0 (6.3, 30.9)	23.4 (7.9, 41.2)	13.1 (-16.4, 52.9)	20.9 (-13.8, 69.6)
Camden	7.0 (-4.8, 20.2)	8.9 (-7.2, 27.8)	25.4 (14.6, 37.3)	33.7 (19.4, 49.8)	21.2 (10.2, 33.2)	34.1 (19.0, 51.1)	14.8 (2.5, 28.6)	15.2 (-0.2, 32.9)	36.5 (14.0, 63.6)	41.5 (13.0, 77.2)	13.7 (4.3, 23.9)	22.3 (9.7, 36.4)	16.4 (7.5, 26.1)	22.8 (11.1, 35.8)	19.5 (-7.3, 54.0)	23.0 (-5.4, 59.8)
Campbel ltown (NSW)	4.8 (-1.6, 11.6)	4.9 (-5.3, 16.2)	14.9 (9.5, 20.5)	19.8 (12.1, 28.0)	12.3 (7.0, 17.9)	14.6 (7.1, 22.6)	8.7 (2.8, 15.0)	13.1 (4.6, 22.3)	22.9 (11.9, 34.9)	26.2 (11.0, 43.5)	8.6 (4.1, 13.3)	12.0 (5.5, 18.8)	8.6 (4.1, 13.2)	12.0 (5.6, 18.7)	35.5 (12.7, 63.0)	27.4 (7.8, 50.5)
Canada Bay	11.4 (3.7, 19.7)	15.2 (4.6, 27.0)	19.7 (13.1, 26.8)	27.6 (18.8, 37.0)	17.3 (10.5, 24.4)	23.7 (14.9, 33.2)	16.5 (8.8, 24.7)	23.8 (13.8, 34.7)	31.1 (17.3, 46.6)	35.0 (17.5, 55.1)	14.5 (8.6, 20.7)	21.6 (13.9, 29.9)	13.7 (7.8, 19.8)	21.2 (13.5, 29.3)	31.7 (9.4, 58.6)	27.5 (7.0, 51.9)
Canterbu ry	11.6 (1.4, 22.8)	16.9 (2.6, 33.3)	16.9 (8.2, 26.3)	25.8 (13.8, 39.0)	14.7 (5.9, 24.3)	20.4 (8.5, 33.5)	16.1 (5.8, 27.4)	27.3 (13.0, 43.4)	28.1 (10.1, 49.1)	32.6 (9.1, 61.3)	13.7 (5.9, 22.1)	21.7 (11.0, 33.4)	11.8 (4.2, 19.9)	21.0 (10.5, 32.5)	40.3 (13.0, 74.1)	31.0 (5.3, 63.0)
Carlingf ord	8.1 (1.0, 15.8)	12.0 (-0.1, 25.7)	16.5 (10.6, 22.8)	26.7 (17.6, 36.4)	14.6 (8.6, 20.9)	23.0 (13.9, 32.8)	12.8 (6.1, 20.0)	22.8 (12.5, 34.1)	24.4 (12.4, 37.7)	30.1 (12.6, 50.4)	12.0 (6.7, 17.5)	21.4 (13.3, 30.0)	11.2 (6.0, 16.6)	21.1 (13.1, 29.7)	23.6 (1.1, 51.1)	19.7 (0.7, 42.3)

Chatswood - Lane Cove	7.6 (0.0, 15.7)	8.7 (-2.0, 20.4)	14.2 (7.6, 21.2)	18.8 (9.9, 28.4)	11.8 (5.2, 18.8)	12.5 (3.9, 21.8)	11.3 (3.7, 19.5)	17.0 (6.6, 28.3)	23.8 (10.0, 39.3)	26.6 (8.7, 47.5)	9.9 (4.2, 16.1)	12.6 (4.9, 20.9)	8.5 (2.8, 14.5)	11.9 (4.4, 20.1)	29.8 (8.4, 55.4)	24.2 (3.3, 49.3)
Cronulla - Miranda - Caringbah	6.6 (-1.2, 14.9)	6.7 (-3.5, 18.0)	13.7 (6.8, 21.0)	16.7 (8.1, 26.0)	11.1 (4.3, 18.4)	10.8 (2.4, 19.7)	10.2 (2.3, 18.7)	13.7 (3.8, 24.4)	22.9 (8.6, 39.2)	25.1 (7.6, 45.4)	9.0 (3.1, 15.3)	10.1 (2.8, 18.0)	7.7 (1.8, 13.9)	9.4 (2.2, 17.1)	27.8 (5.4, 55.0)	23.4 (1.4, 50.2)
Dural - Wisemans Ferry	2.6 (-4.9, 10.7)	0.1 (-2.8, 3.0)	17.4 (8.4, 27.2)	20.8 (8.2, 34.8)	12.6 (3.6, 22.4)	16.8 (4.2, 31.0)	6.0 (-3.8, 16.9)	4.2 (-8.9, 19.1)	29.7 (10.6, 52.1)	32.3 (6.7, 63.9)	5.5 (-2.0, 13.5)	8.0 (-2.3, 19.5)	8.4 (1.2, 16.1)	8.8 (-1.0, 19.6)	7.7 (-16.8, 39.5)	12.6 (-13.2, 46.0)
Eastern Suburbs – North	5.1 (-4.0, 15.1)	2.3 (-8.9, 14.8)	12.4 (4.1, 21.3)	14.2 (4.1, 25.3)	9.9 (1.7, 18.7)	7.5 (-2.2, 18.1)	8.1 (-1.1, 18.3)	9.6 (-1.6, 22.2)	20.8 (3.8, 40.6)	23.4 (2.8, 48.0)	7.5 (0.5, 14.9)	6.4 (-1.9, 15.4)	6.2 (-0.6, 13.5)	5.8 (-2.4, 14.7)	27.6 (3.5, 57.3)	23.1 (-1.5, 54.0)
Eastern Suburbs – South	5.7 (-3.2, 15.4)	1.6 (-9.2, 13.6)	12.5 (4.5, 21.2)	14.5 (4.7, 25.3)	10.0 (2.1, 18.6)	7.9 (-1.4, 18.2)	8.4 (-0.6, 18.3)	10.2 (-0.8, 22.4)	21.1 (4.6, 40.2)	23.6 (3.6, 47.4)	7.7 (0.9, 14.9)	6.9 (-1.2, 15.7)	6.4 (-0.2, 13.5)	6.3 (-1.7, 15.0)	25.2 (2.6, 52.8)	21.0 (-2.4, 49.9)
Fairfield	8.4 (-3.4, 21.7)	13.3 (-4.0, 33.7)	26.1 (15.4, 37.8)	38.2 (22.9, 55.4)	22.2 (11.3, 34.1)	41.1 (24.7, 59.7)	16.7 (4.4, 30.4)	19.6 (3.2, 38.7)	37.0 (14.7, 63.6)	43.1 (13.4, 80.7)	15.2 (5.8, 25.4)	28.8 (15.1, 44.2)	17.7 (8.7, 27.4)	28.7 (15.8, 43.0)	15.4 (-8.8, 46.0)	20.9 (-6.3, 56.0)
Gosford	5.1 (-2.4, 13.2)	4.2 (-6.5, 16.1)	15.8 (8.8, 23.3)	19.2 (9.7, 29.5)	12.8 (5.9, 20.1)	12.9 (3.8, 22.8)	9.0 (1.3, 17.3)	11.7 (1.4, 23.1)	24.9 (10.5, 41.2)	27.7 (8.7, 50.0)	8.7 (2.9, 14.8)	10.1 (2.3, 18.4)	8.7 (3.0, 14.7)	9.9 (2.3, 18.1)	23.4 (1.7, 49.8)	21.0 (0.1, 46.3)
Hawkesbury	7.3 (-9.0, 26.6)	0.0 (0.0, 0.0)	25.7 (6.5, 48.4)	25.8 (1.6, 55.8)	19.4 (0.4, 42.0)	23.6 (-1.2, 54.7)	8.9 (-7.0, 27.4)	0.0 (0.0, 0.0)	42.4 (12.1, 80.8)	43.5 (2.1, 101.8)	8.0 (-7.3, 25.7)	7.9 (-11.4, 31.5)	13.0 (-2.0, 30.3)	8.7 (-9.6, 30.7)	4.1 (-29.8, 54.4)	15.0 (-27.3, 82.0)
Hornsby	3.8 (-3.5, 11.7)	2.3 (-9.1, 15.2)	13.9 (7.3, 20.9)	17.1 (7.9, 27.2)	11.2 (4.7, 18.2)	11.0 (2.1, 20.7)	6.9 (-0.3, 14.7)	9.1 (-0.9, 20.1)	22.4 (8.8, 37.7)	25.5 (7.0, 47.1)	7.0 (1.5, 12.8)	7.9 (0.4, 16.0)	7.3 (1.9, 12.9)	8.0 (0.6, 16.0)	19.1 (-3.1, 46.4)	17.0 (-4.1, 42.7)
Hurstville	11.5 (1.4, 22.7)	15.8 (2.5, 30.8)	16.8 (8.2, 26.2)	24.0 (13.0, 36.2)	14.7 (5.9, 24.2)	19.3 (8.3, 31.5)	16.0 (5.8, 27.2)	25.0 (11.8, 39.7)	28.1 (10.2, 48.9)	31.2 (9.3, 57.6)	13.7 (5.9, 22.0)	20.2 (10.2, 31.0)	11.7 (4.2, 19.8)	19.2 (9.5, 29.7)	39.3 (12.7, 72.1)	31.8 (6.3, 63.3)
Kogarah - Rockdale	9.6 (1.1, 18.7)	14.6 (2.2, 27.6)	15.3 (8.2, 23.0)	22.6 (12.2, 32.4)	13.2 (5.9, 20.9)	16.8 (6.9, 26.9)	13.7 (5.2, 22.8)	22.7 (10.3, 34.5)	25.6 (10.7, 42.6)	29.2 (9.4, 51.4)	11.8 (5.4, 18.7)	17.7 (8.5, 26.5)	10.1 (3.8, 16.8)	17.0 (7.9, 25.5)	37.5 (13.8, 66.3)	28.9 (6.8, 57.2)
Ku-ring-gai	3.9 (-4.5, 13.1)	0.0 (0.0, 0.0)	13.5 (5.6, 22.0)	15.2 (4.8, 26.7)	10.6 (2.8, 19.0)	8.7 (-1.3, 19.7)	5.7 (-2.9, 14.9)	6.2 (-4.9, 18.5)	22.3 (6.1, 40.9)	25.0 (4.0, 50.2)	6.0 (-0.5, 12.8)	5.1 (-3.2, 14.1)	6.5 (0.1, 13.2)	5.4 (-2.8, 14.3)	12.6 (-10.3, 41.2)	12.5 (-10.4, 41.2)
Leichhardt	9.8 (1.3, 18.9)	11.2 (-0.6, 24.4)	15.3 (8.2, 23.0)	21.9 (12.2, 32.4)	13.2 (5.9, 20.9)	16.5 (6.9, 26.9)	13.7 (5.2, 22.8)	21.7 (10.3, 34.4)	25.6 (10.7, 42.5)	28.7 (9.4, 51.3)	11.8 (5.4, 18.6)	17.1 (8.5, 26.4)	10.1 (3.8, 16.7)	16.4 (7.9, 25.5)	32.5 (9.0, 61.0)	25.9 (3.5, 53.3)
Liverpool	12.9 (4.5, 22.0)	14.3 (3.4, 26.5)	23.4 (16.2, 31.2)	32.7 (23.2, 43.0)	20.7 (13.4, 28.6)	30.7 (21.0, 41.2)	18.3 (9.9, 27.3)	24.5 (13.8, 36.2)	35.0 (19.8, 52.1)	39.9 (20.9, 61.8)	16.5 (10.0, 23.3)	25.5 (17.0, 34.6)	16.6 (10.3, 23.3)	25.3 (17.1, 34.2)	17.3 (-1.9, 40.1)	18.8 (0.1, 41.0)
Manly	4.9	2.8	12.4	14.1	9.9	7.4	8.1	9.6	20.8 (3.7, 40.7)	23.3	7.4	6.3	6.2	5.7	23.6	19.7

	(-4.3, 14.9)	(-8.6, 15.5)	(4.0, 21.3)	(4.0, 25.3)	(1.6, 18.8)	(-2.3, 18.0)	(-1.2, 18.3)	(-1.7, 22.1)		(2.7, 48.1)	(0.4, 14.9)	(-2.0, 15.3)	(-0.7, 13.55256)	(-2.5, 14.6)	(-0.4, 53.4)	(-4.8, 50.5)
Marrickville - Sydenham - Petersham	9.8 (1.2, 19.2)	14.5 (2.1, 28.3)	15.5 (8.1, 23.3)	22.3 (12.4, 33.0)	13.3 (5.9, 21.3)	16.9 (7.2, 27.6)	13.9 (5.3, 23.3)	22.3 (10.6, 35.3)	25.8 (10.6, 43.2)	28.9 (9.3, 52.1)	12.0 (5.4, 19.0)	17.7 (8.8, 27.2)	10.3 (3.9, 17.1)	16.9 (8.3, 26.2)	38.7 (13.9, 68.8)	30.4 (6.8, 59.1)
Merrylands - Guildford	12.4 (2.0, 23.8)	24.1 (7.6, 43.1)	21.3 (12.5, 30.8)	36.3 (23.0, 51.1)	19.2 (10.3, 28.9)	36.8 (23.0, 52.1)	17.5 (7.5, 28.5)	29.8 (15.0, 46.5)	29.1 (11.5, 49.6)	37.0 (12.1, 67.5)	16.1 (8.4, 24.4)	32.3 (20.4, 45.4)	15.8 (8.2, 24.0)	32.0 (20.3, 44.9)	35.6 (9.3, 68.1)	27.7 (3.3, 57.9)
Mount Druitt	12.0 (-0.8, 26.4)	23.3 (4.0, 46.0)	27.5 (16.3, 39.8)	40.7 (24.7, 58.7)	23.9 (12.6, 36.5)	44.7 (27.4, 64.2)	18.3 (5.4, 32.6)	22.9 (5.7, 42.9)	37.9 (14.8, 65.7)	44.2 (13.5, 83.2)	17.1 (7.2, 27.8)	32.4 (18.0, 48.7)	19.2 (9.8, 29.5)	32.3 (18.6, 47.5)	25.2 (-2.1, 60.1)	26.5 (-2.5, 64.0)
North Sydney - Mosman	7.0 (-0.9, 15.5)	4.5 (-5.5, 15.6)	13.3 (6.3, 20.7)	16.4 (7.7, 25.9)	10.9 (4.0, 18.3)	10.4 (2.0, 19.5)	10.0 (2.0, 18.5)	13.2 (3.3, 24.1)	22.6 (8.2, 38.9)	24.9 (7.2, 45.5)	8.9 (2.9, 15.2)	9.7 (2.4, 17.6)	7.5 (1.6, 13.7)	9.0 (1.7, 16.8)	29.5 (7.5, 56.1)	24.4 (2.1, 51.4)
Parramatta	11.7 (1.9, 22.5)	22.3 (6.9, 40.0)	21.1 (12.8, 30.1)	35.6 (22.9, 49.5)	19.0 (10.5, 28.1)	35.7 (22.7, 50.2)	17.1 (7.6, 27.5)	28.7 (14.7, 44.5)	29.1 (12.3, 48.4)	36.7 (12.9, 65.5)	15.7 (8.4, 23.6)	31.2 (19.9, 43.6)	15.5 (8.2, 23.2)	30.9 (19.8, 43.1)	30.9 (7.2, 59.9)	25.4 (2.6, 53.3)
Pennant Hills – Epping	5.4 (-1.1, 12.3)	6.3 (-4.4, 18.2)	14.9 (9.6, 20.4)	19.9 (12.3, 28.1)	12.4 (7.1, 17.9)	14.8 (7.4, 22.8)	8.8 (2.9, 15.1)	13.4 (4.9, 22.5)	22.9 (12.0, 34.8)	26.3 (11.2, 43.4)	8.7 (4.2, 13.4)	12.2 (5.8, 19.1)	8.6 (4.2, 13.3)	12.2 (5.9, 18.9)	17.6 (-4.1, 44.0)	15.9 (-2.7, 38.1)
Penrith	6.2 (-12.0, 28.1)	7.7 (-15.6, 37.5)	31.7 (13.7, 52.5)	38.9 (15.5, 66.9)	25.9 (7.8, 47.0)	41.6 (16.5, 72.0)	15.5 (-4.0, 39.0)	10.7 (-12.3, 39.7)	45.2 (8.0, 95.0)	50.1 (4.1, 116.5)	14.7 (-0.3, 31.9)	22.7 (2.9, 46.4)	19.9 (5.3, 36.5)	24.0 (5.4, 45.8)	8.5 (-23.4, 53.7)	18.4 (-20.7, 76.8)
Pittwater	5.3 (-3.3, 14.8)	1.7 (-9.6, 14.4)	12.9 (5.0, 21.4)	15.2 (5.1, 26.4)	10.2 (2.4, 18.6)	7.9 (-1.8, 18.5)	8.6 (-0.3, 18.2)	11.5 (0.1, 24.3)	21.7 (5.4, 40.4)	24.2 (3.6, 48.7)	7.8 (1.1, 14.9)	7.4 (-1.0, 16.5)	6.6 (0.0, 13.6)	6.9 (-1.4, 15.9)	22.3 (-0.9, 51.1)	19.0 (-4.2, 47.8)
Richmond - Windsor	2.7 (-16.4, 26.2)	4.8 (-21.1, 39.3)	32.2 (12.8, 55.0)	42.4 (15.5, 75.6)	24.1 (5.0, 46.8)	47.9 (18.5, 84.7)	16.1 (-5.0, 41.9)	10.0 (-15.7, 43.5)	48.8 (8.1, 104.8)	54.3 (1.7, 134.2)	12.9 (-3.0, 31.4)	25.5 (2.6, 53.5)	19.5 (3.8, 37.5)	26.6 (5.2, 52.4)	9.3 (-25.8, 61.1)	21.9 (-22.8, 92.5)
Rouse Hill - McGraths Hill	8.5 (-3.9, 22.4)	13.8 (-4.1, 35.1)	27.4 (16.3, 39.6)	40.3 (24.5, 58.2)	23.8 (12.5, 36.3)	44.2 (27.1, 63.6)	18.0 (5.3, 32.3)	22.4 (5.4, 42.3)	37.9 (14.8, 65.5)	44.1 (13.6, 82.7)	16.9 (7.1, 27.5)	31.9 (17.6, 48.0)	19.1 (9.7, 29.3)	31.8 (18.3, 46.8)	20.8 (-7.0, 56.9)	23.9 (-4.8, 61.4)
Ryde - Hunters Hill	10.3 (3.4, 17.7)	14.0 (4.3, 24.5)	19.2 (13.2, 25.5)	26.1 (18.1, 34.58125)	16.6 (10.5, 23.0)	21.8 (13.8, 30.2)	15.4 (8.4, 22.7)	21.5 (12.5, 31.4)	30.1 (17.6, 44.0)	33.9 (17.8, 52.1)	13.6 (8.3, 19.2)	19.5 (12.5, 26.9)	12.9 (7.6, 18.4)	19.0 (12.1, 26.4)	33.1 (12.5, 57.5)	28.5 (9.5, 50.9)
St Marys	9.2 (-5.8, 26.6)	16.9 (-5.4, 44.5)	30.0 (16.1, 45.6)	42.8 (22.5, 66.5)	25.5 (11.4, 41.4)	49.0 (26.7, 75.3)	17.8 (2.2, 35.9)	18.5 (-2.4, 44.0)	41.9 (13.0, 78.2)	47.7 (8.9, 100.4)	16.6 (4.6, 30.0)	32.3 (14.1, 53.3)	20.2 (8.6, 33.0)	31.9 (15.0, 51.2)	12.3 (-16.1, 50.3)	21.4 (-12.7, 68.9)
Strathfield - Burwood	11.1 (0.7, 22.6)	18.8 (4.0, 35.7)	16.5 (7.7, 26.1)	26.2 (13.9, 39.8)	14.5 (5.5, 24.2)	20.9 (8.7, 34.4)	15.9 (5.5, 27.4)	27.9 (13.2, 44.5)	28.8 (10.4, 50.3)	32.9 (8.8, 62.4)	13.4 (5.4, 21.9)	22.2 (11.2, 34.3)	11.4 (3.7, 19.7)	21.6 (10.8, 33.4)	39.3 (13.5, 70.8)	29.9 (4.4, 61.6)

d - Ashfield																
Sutherland - Menai - Heathcote	3.1 (-5.5, 12.5)	1.1 (-10.8, 14.5)	10.8 (3.2, 19.1)	12.3 (2.6, 22.9)	8.7 (1.1, 16.8)	5.8 (-3.4, 15.9)	4.7 (-3.7, 13.9)	6.7 (-3.9, 18.5)	18.6 (3.0, 36.6)	20.7 (1.2, 43.9)	5.3 (-1.1, 12.1)	4.2 (-3.7, 12.8)	4.8 (-1.5, 11.5)	4.2 (-3.6, 12.7)	21.9 (-2.8, 52.9)	17.9 (-6.0, 47.9)
Sydney Inner City	7.9 (0.3, 16.1)	7.2 (-2.5, 17.9)	14.3 (7.7, 21.3)	18.3 (10.0, 27.2)	11.9 (5.3, 18.9)	12.8 (4.7, 21.5)	11.5 (3.9, 19.7)	16.1 (6.5, 26.7)	24.0 (10.2, 39.4)	26.1 (9.3, 45.5)	10.1 (4.3, 16.2)	12.5 (5.3, 20.2)	8.6 (2.9, 14.6)	11.7 (4.6, 19.3)	27.6 (9.1, 49.3)	23.1 (4.1, 45.6)
Warringah	5.4 (-3.1, 14.7)	2.5 (-8.6, 15.0)	13.0 (5.2, 21.3)	15.4 (5.4, 26.4)	10.3 (2.6, 18.5)	8.1 (-1.4, 18.6)	8.7 (0.0, 18.2)	11.8 (0.5, 24.4)	21.8 (5.7, 40.3)	24.3 (4.0, 48.5)	7.9 (1.3, 14.9)	7.7 (-0.6, 16.7)	6.7 (0.2, 13.6)	7.1 (-1.1, 16.0)	29.4 (5.6, 58.6)	24.2 (0.6, 53.4)
Wollondilly	5.9 (-5.3, 18.3)	0.0 (0.0, 0.0)	11.0 (0.3, 22.9)	10.2 (-4.1, 26.6)	7.6 (-2.9, 19.3)	0.3 (-12.9, 15.5)	3.8 (-7.8, 16.9)	4.9 (-10.6, 23.1)	19.8 (-2.1, 46.5)	20.6 (-7.9, 57.9)	4.0 (-3.8, 12.4)	0.0 (0.0, 0.0)	3.9 (-3.7, 12.2)	0.0 (0.0, 0.0)	21.4 (-7.5, 59.3)	18.2 (-11.7, 58.2)
Wyong	10.2 (1.3, 20.0)	13.3 (0.3, 28.0)	16.1 (8.5, 24.2)	24.1 (13.1, 36.0)	13.8 (6.1, 22.1)	18.1 (7.4, 29.9)	14.7 (5.7, 24.4)	24.9 (11.9, 39.4)	25.9 (10.1, 43.8)	30.3 (8.8, 56.1)	12.7 (5.8, 20.0)	19.4 (9.6, 30.0)	10.9 (4.3, 18.0)	18.8 (9.3, 29.2)	37.9 (13.5, 67.6)	28.8 (5.5, 57.1)

Description of CMIP models and reasons for their inclusion in Application ready data (Sourced from CSIRO and Bureau of Meteorology (124)).

ACCES 1.0: The model exhibited a high skill score with regard to historical climate.

CESM1-CAM5: This model was representative of a low change in an index of the Southern Annular Mode (per degree global warming). Further, the model has results representing all RCPs.

CNRM-CM5: This model was representative of low warming/dry sea surface temperature modes. It also has a good representation of extreme El Niño in CMIP5 evaluations.

GFDL-ESM2M: This model was representative of the hot/dry sea surface temperature mode. It also has a good representation of extreme El Niño in CMIP5 evaluations. Further, the model has results representing all RCPs.

HadGEM2-CC: This model has good representation of extreme El Niño in CMIP5 evaluations.

CanESM2: This model was representative of the hot/wet sea surface temperature. It also has a high skill score with regard to historical climate and it increased representation of the spread in genealogy of models. It also has good representation of extreme El Niño in CMIP5 evaluations.

MIROC5: This model was representative of a higher change in an index of the Southern Annular mode (per degree global warming). It also has good representation of extreme El Niño in CMIP5 evaluations. Further, the model has results representing all RCPs.

NorESM1-M: This model was representative of the low warming/wet sea surface temperature mode. The model also has results representing all RCPs.

Table S9 The risk estimates of OI associated with projected heat index (extreme heat - 99th percentile) as estimated by various General Circulation Models under the two RCP (4.5 and 8.5) for the study periods.

RCP Scenario	Access 1.0	CESM1-CAM5	CanESM2	CNRM-CM5	GFDL-ESM2M	HadGEM2-CC	MIROC5
Greater Brisbane							
2016-2045							
RCP 4.5	7.4 (-20.2, 44.7)	6.9 (-19.1, 41.2)	7.4 (-20.2, 44.7)	6.9 (-19.1, 41.2)	7.4 (-20.2, 44.7)	6.9 (-19.1, 41.2)	6.8 (-19.1, 41.2)
RCP 8.5	6.9 (-19.1, 41.2)	7.4 (-20.2, 44.7)	8.6 (-22.4, 51.9)	7.4 (-20.2, 44.7)	6.9 (-19.1, 41.2)	7.4 (-20.2, 44.7)	8.0 (-21.3, 48.2)
2036-2065							
RCP 4.5	7.2 (-20.5, 44.5)	7.8 (-21.6, 48.1)	8.9 (-23.7, 55.6)	7.2 (-20.5, 44.5)	10.1 (-25.8, 63.4)	7.8 (-21.6, 48.1)	7.8 (-21.6, 48.1)
RCP8.5	9.5 (-24.8, 59.5)	8.9 (-23.7, 55.6)	10.7 (-26.9, 67.5)	8.9 (-23.7, 55.6)	7.8 (-21.6, 48.1)	8.9 (-23.7, 55.6)	8.9 (-23.7, 55.6)
Greater Melbourne							
2016-2045							
RCP 4.5	7.6 (-14.9, 36.0)	7.5 (-16.1, 37.8)	7.5 (-17.3, 39.8)	7.6 (-14.9, 36.0)	7.5 (-16.1, 37.8)	7.6 (-14.9, 36.0)	7.5 (-17.3, 39.8)
RCP 8.5	7.5 (-16.1, 37.8)	7.5 (-16.1, 37.8)	7.4 (-18.6, 41.6)	7.5 (-16.1, 37.8)	7.6 (-14.9, 36.0)	7.6 (-14.9, 36.0)	7.5 (-16.1, 37.8)
2036-2065							
RCP 4.5	7.5 (-17.3, 39.8)	7.5 (-17.3, 39.8)	7.4 (-18.6, 41.6)	7.5 (-16.1, 37.8)	7.3 (-19.7, 43.5)	7.4 (-18.6, 41.6)	7.4 (-18.6, 41.6)
RCP 8.5	7.3 (-19.8, 43.5)	7.5 (-17.3, 39.8)	7.2 (-22.1, 47.6)	7.4 (-18.6, 41.6)	7.5 (-17.3, 39.8)	7.3 (-19.8, 43.5)	7.5 (-17.3, 39.8)
Greater Sydney							
2016-2045							
RCP 4.5	17.7 (-10.9, 55.6)	16.9 (-10.2, 52.1)	17.7 (-10.9, 55.6)	16.9 (-10.2, 52.1)	16.9 (-10.2, 52.1)	17.7 (-10.9, 55.6)	16.9 (-10.2, 52.1)
RCP 8.5	16.9 (-10.2, 52.1)	17.7 (-10.9, 55.6)	19.4 (-12.5, 62.9)	17.7 (-10.9, 55.6)	16.9 (-10.2, 52.1)	17.7 (-10.9, 55.6)	17.7 (-10.9, 55.6)
2036-2065							
RCP 4.5	17.8 (-10.8, 55.5)	18.7 (-11.6, 59.2)	19.5 (-12.3, 63.0)	17.8 (-10.8, 55.5)	23.1 (-15.5, 79.2)	19.5 (-12.3, 63.0)	18.7 (-11.6, 59.2)
RCP 8.5	22.3 (-13.9, 70.9)	19.5 (-12.3, 63.0)	22.2 (-14.7, 75.0)	20.4 (-13.1, 66.9)	18.7 (-11.6, 59.2)	20.4 (-13.1, 66.9)	19.5 (-12.3, 63.0)

Table S10 Attributable fraction (AF) [with 95% confidence intervals] of OI for overall heat component for the three cities including Greater Brisbane, Greater Melbourne, and Greater Sydney for two timeframes 2016-2045 and 2036-2065 and two RCP 4.5 and 8.5.

City	Prediction Period	RCP Scenario	Heat-related attributable fraction
Greater Brisbane	Baseline	NA	0.12 (-0.92, 1.13)
	2016-2045	RCP 4.5	0.54 (-2.59, 3.34)
		RCP 8.5	0.57 (-2.80, 3.57)
	2036-2065	RCP 4.5	0.68 (-3.35, 4.25)
		RCP 8.5	0.75 (-3.88, 4.87)
Greater Melbourne	Baseline	NA	2.51 (-0.87, 5.79)
	2016-2045	RCP 4.5	2.80 (-0.99, 6.28)
		RCP 8.5	2.86 (-1.00, 6.37)
	2036-2065	RCP 4.5	3.03 (-1.11, 6.79)
		RCP 8.5	3.18 (-1.18, 7.11)
Greater Sydney	Baseline	NA	1.76 (-1.30, 4.76)
	2016-2045	RCP 4.5	2.32 (-1.32, 5.61)
		RCP 8.5	2.40 (-1.35, 5.80)
	2036-2065	RCP 4.5	2.64 (-1.47, 6.33)
		RCP 8.5	2.85 (-1.59, 6.85)

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