Vulnerability of Australia to heatwaves: a systematic review on influencing factors, impacts, and mitigation options

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Abstract

Background: Heatwaves have received major attention globally due to their detrimental effects on human health and the environment. The frequency, duration, and severity of heatwaves have increased recently due to changes in climatic conditions, anthropogenic forcing, and rapid urbanization. Australia is highly vulnerable to this hazard. Although there have been an increasing number of studies conducted in Australia related to the heatwave phenomena, a systematic review of heatwave vulnerability has rarely been reported in the literature.

Objectives: This study aims to provide a systematic and overarching review of the different components of heatwave vulnerability (e.g., exposure, sensitivity, and adaptive capacity) in Australia.

Methods: A systematic review was conducted using the PRISMA protocol. Peer-reviewed English language articles published between January 2000 and December 2021 were selected using a combination of search keywords in Web of Science, Scopus, and PubMed. Articles were critically analyzed based on three specific heatwave vulnerability components: exposure, sensitivity, and adaptive capacity.

Results and discussion: A total of 107 articles meeting all search criteria were chosen. Although there has been an increasing trend of heat-related studies in Australia, most of these studies have concentrated on exposure and adaptive capacity components. Evidence suggests that the frequency, severity, and duration of heatwaves in Australian cities has been increasing, and that this is likely to continue under current climate change scenarios. This study noted that heatwave vulnerability is associated with geographical and climatic factors, space, time, socioeconomic and demographic factors, as well as the

physiological condition of people. Various heat mitigation and adaptation measures implemented around the globe have proven to be efficient in reducing the impacts of heatwaves.
Conclusion: This study provides increased clarity regarding the various drivers of heatwave vulnerability in Australia. Such knowledge is crucial in informing extreme heat adaptation and mitigation planning.

Keywords: heatwaves; exposure; sensitivity; adaptive capacity; PRISMA protocol; Australia

1. Introduction

1.1. Background

It is widely accepted that heatwaves have detrimental effects on human health (morbidity and mortality rates), agriculture, and urban and natural systems (Bi et al., 2011; Campbell et al., 2018; Jyoteeshkumar reddy et al., 2021; Li et al., 2018; Tong et al., 2015). In recent decades many regions worldwide have experienced frequent and intense heatwaves, with severe impacts on residents (Jyoteeshkumar reddy et al., 2021). More than 35,000 deaths were reported during the European heatwave in 2003 (Hintz et al., 2018) and evidence of the damaging effects of heatwaves on human health was also observed in other events such as those that occurred in Chicago, USA in 1995 (Whitman et al., 1997), South-East Australia in 2009 (Nitschke et al., 2011), Russia in 2010 (Barriopedro et al., 2011), China in 2003 (Ding and Qian, 2011) and 2013 (Sun et al., 2014), and India in 2017 (Pattanaik et al., 2017). It appears, however, that the association between heatwaves and mortality across different regions is essentially nonlinear over time as the relationships yield U, V, and J shapes indicate that the threshold temperature varies among cities (Lu et al., 2021). Global temperatures have increased significantly over the last two decades, so the frequency, severity, and duration of extreme heat events are also likely to increase (Cowan et al., 2014; Orimoloye et al., 2019). The average global temperature is projected to increase by approximately 2.6 °C – 4.8 °C by the end of the 21st century due to the increased greenhouse gas concentration in the atmosphere, as well as enhanced radiative forcing effects (Jyoteeshkumar reddy et al., 2021). The 2021 IPCC report (IPCC, 2021) indicated that heat stress resulting from the increase in global temperature would decrease labor productivity and cause significant economic damage in many regions of the world. Elevated ambient air temperatures also increase levels of air pollution and greenhouse gas emissions (Livada et al., 2019).

Australia is a heterogeneous climatic region with the northern parts of the continent characterized by summer monsoonal features and the Inter-tropical Convergence Zone (ITCZ), while the central and southern parts are dominated by subtropical climatic conditions (Herold et al., 2018). Most of the major capital cities are located along the coast (Tong et al., 2014). Due to the high climatic variability, Australia is recognized as one of the major heatwave hotspot regions on earth. Extreme heat events can occur in all seasons (Cowan et al., 2014; Davis and Hanna, 2020), and are particularly prevalent during the summer and autumn (Jacobs et al., 2014; Sharifi et al., 2016). Heatwaves cause a greater number of deaths than all other natural hazards combined (Hatvani-Kovacs et al., 2016b; Jyoteeshkumar reddy et al., 2021; Nairn and Fawcett, 2015; Oppermann et al., 2018; Trancoso et al., 2020; Xiao et al., 2017; Zander et al., 2019). Extreme heat events were responsible for 5332 deaths in Australia between 1844 and 2010 (Coates et al., 2014). The average land temperature of the country has increased over the last half a century and is projected to increase a further 1 °C by 2030 (Banwell et al., 2012). In southern Australia, the temperatures reached during heatwaves can be 15 °C warmer than the climatological maximum. More than one-third of the total Australian population lives in this region and the area also produces a large share of the country's agricultural products. Extreme heat events, therefore, pose a serious threat to the population and food security (Cowan et al., 2014). Heatwaves are also reportedly associated with increasing bushfires (Jyoteeshkumar reddy et al., 2021), decreasing agricultural yields (Herold et al., 2018), and damage to ecosystems, infrastructure, health, and social life (Hatvani-Kovacs et al., 2016b). The variability noted with high temperatures is also associated with high mortality risk in Australia (Cheng et al., 2019). Extreme heat events, and the associated severe impacts they can have on Australian towns and cities, are projected to increase due to: (1) an increase in the frequency, duration, and severity of summer heatwaves and the increasing winter warm spells associated with climate change (Cowan et al., 2014; Hatvani-Kovacs et al., 2016a; Huang et al., 2012; Jyoteeshkumar reddy et al., 2021; Ossola et al., 2021; Trancoso et al., 2020; Xiao et al., 2017), (2) a projected increase in anthropogenic forcing (Chapman et al., 2016; Khan et al., 2021; Nishant et al., 2022), (3) a projected increase in the elderly population (Loughnan et al., 2015; Xiao et al., 2017), and (4) rapid urban growth (Chapman et al., 2019; Coutts et al., 2010; Livada et al., 2019).

The research carried out on heatwaves in Australia is substantial and increasing (Iping et al., 2019). Heatwave-related studies in Australia have been conducted to investigate: (1) climatological heatwave intensity and severity (Cowan et al., 2014; Jyoteeshkumar reddy et al., 2021; Nairn and Fawcett, 2015; Pezza et al., 2012), (2) the epidemiological effects of heatwaves (Campbell et al., 2019; Cheng et al., 2019; Lu et al., 2021; Wondmagegn et al., 2021; Xu et al., 2019a; Xu et al., 2019b), (3) the economic consequences of heatwaves (Varghese et al., 2019a), and (4) the potential value of various heatwave mitigation measures (Haddad et al., 2020a; Iping et al., 2019; Ossola et al., 2021; Santamouris et al., 2020). Heatwave intensity varies over different regions of the continent. In general, the mean daily temperature in the southern continental coastline is higher than in the tropical north (Nairn and Fawcett, 2015). Heat exposure (person-days) is projected to increase by ~42 times under the RCP8.5-SSP5 climate change scenario. Important capital cities and regional centers such as Melbourne, Adelaide, Sydney, and Perth are particularly vulnerable to high heat exposure (Nishant et al., 2022; Pezza et al., 2012).

Heatwave vulnerability in Australia also varies across different demographic groups (Varghese et al., 2019a; Xiao et al., 2017), geographical locations (Davis and Hanna, 2020; Varghese et al., 2019a), as well as socioeconomic status (Lu et al., 2021), and health condition (Lu et al., 2021; Xu et al., 2021b). The minimum mortality temperature also varies from city to city (Cheng et al., 2019). Despite the significant negative health effects caused by heatwaves, they tend to receive less attention from researchers and policymakers than other natural hazards (Xiao et al., 2017). Many regions in Australia have created emergency management plans in response to heatwaves, however, there is a lack of understanding regarding the spatial distribution of heatwave risk, and mitigation plans are generally based on research conducted in other countries (Xiao et al., 2017). Current approaches to the monitoring, forecasting, and mitigation of heatwaves also tend to vary across the country (Ambrey et al., 2017; Bartesaghi-Koc et al., 2021; Haddad et al., 2020b; Nairn and Fawcett, 2015). The potential efficacy of the different heat mitigation measures is also not very well understood due to the geographical variation in heatwave vulnerability. A clearer understanding of heatwave vulnerability is required to improve hazard forecasting (Pezza et al., 2012).

In this review, we aim to critically analyze heatwave vulnerability in Australia by identifying: (1) the existing state of heatwave intensity and exposure; (2) factors associated with heatwave sensitivity; and (3) heatwave mitigation and adaptation measures practiced in the various regions.

1.2. Conceptualizing heatwave vulnerability

There is no universal definition of a heatwave due to the diversity of world climatic conditions, and the varying socio-demographic and acclimatization characteristics of the world population. Countries define heatwaves according to differing environmental and anthropogenic conditions (Hintz et al., 2018; Jyoteeshkumar reddy et al., 2021; Marx et al., 2021; Tong et al., 2015; Xiao et al., 2017). Researchers have commonly used a combination of duration and intensity to define a heatwave event (Davis and Hanna, 2020; Jacobs et al., 2018; Varghese et al., 2019c; Xu et al., 2019a; Xu et al., 2019b). According to Perkins and Alexander (2013), for example, heatwaves are extended periods of excessively hot weather. In the tropical region where maximum daily summer temperatures are high (more than 35 °C), heatwave events tend to be approximately 2-4 °C warmer than the climatological maximum temperature (Banwell et al., 2012; Cowan et al., 2014). A heatwave definition is generally based on climatic parameters such as maximum temperature, minimum temperature, and relative humidity. In health-related studies, mean temperature has proven to be a better indicator than other climatic parameters in defining a heatwave condition (Xu et al., 2019a). Thresholds of such variables can be used in both absolute and relative terms (Jyoteeshkumar reddy et al., 2021). For instance, the United Kingdom definition of a heatwave is when the daily average maximum temperature is exceeded by 5 °C for a minimum of five consecutive days. In Germany, heatwave events are those days when the daily temperature exceeds 30 °C for at least five consecutive days (Hintz et al., 2018).

In Australia, the Bureau of Meteorology defines heatwave based on a temperature threshold (Oppermann et al., 2018). A heatwave event is a period of three or more consecutive hot days when the temperature exceeds a relative threshold based on a region's recent climate history (Cowan et al., 2014; Jyoteeshkumar reddy et al., 2021; Tong et al., 2010; Xiang et al., 2014). Herold et al. (2018) used 30 °C as a threshold temperature to define heatwave days in Australia. Xiang et al. (2014) considered a threshold of >35 °C. Sharifi et al. (2016) reported that human activities tend to decline once the outdoor temperature reaches 28-30 °C in South Australia. According to Pezza et al. (2012), heatwaves events are those when the maximum temperature is above the 90th percentile for three consecutive days. During the second and third days, the minimum temperature is also above the 90th percentile. While analyzing biological and atmospheric factors associated with heat stress in Melbourne, Jacobs et al. (2014) determined that air temperature exceeding 27 °C creates thermal discomfort for people. A study by Kenawy and Elkadi (2018) estimated that the thermal acceptability rate for Melbourne ranges between 20 and 24.9 °C. Extreme heatwaves usually occur in mid-summer, however, a few severe or low-intense heatwaves can also occur during spring and early autumn (Jacobs et al., 2014; Nairn and Fawcett, 2015).

Conceptually, the effects of heatwave on public health depend on three factors, i.e., exposure, sensitivity, and adaptive capacity (Bi et al., 2011; Buzási, 2022; Hatvani-Kovacs et al., 2016b; Mac and McCauley, 2017; Wilhelmi and Hayden, 2010; Xu et al., 2019b). Exposure represents the extent to which heatwaves pose a threat to the population, infrastructure, environmental services and resources, economic, social, and cultural assets (Mac and McCauley, 2017). Exposure depends on the timing, frequency, intensity, and duration of hot weather (Hatvani-Kovacs et al., 2016b). The second element of vulnerability is susceptibility or sensitivity. An individual's resilience to heatwave conditions depends on various factors such as the demographic profile (e.g., age, body composition, gender) of the exposed population, degree of acclimatization, pre-existing medical conditions and certain medications, and socioeconomic status (Aubrecht and Özceylan, 2013; Azhar et al., 2017; Inostroza et al., 2016; Mac and McCauley, 2017). Adaptive capacity is the final component of vulnerability. This refers to the ability of an individual, family, community, or city to respond or adapt to the adverse effects of heatwaves (Inostroza et al., 2016; Mac and McCauley, 2017; Raja et al., 2021). Figure 1 presents a framework of heatwave vulnerability as used in this study.

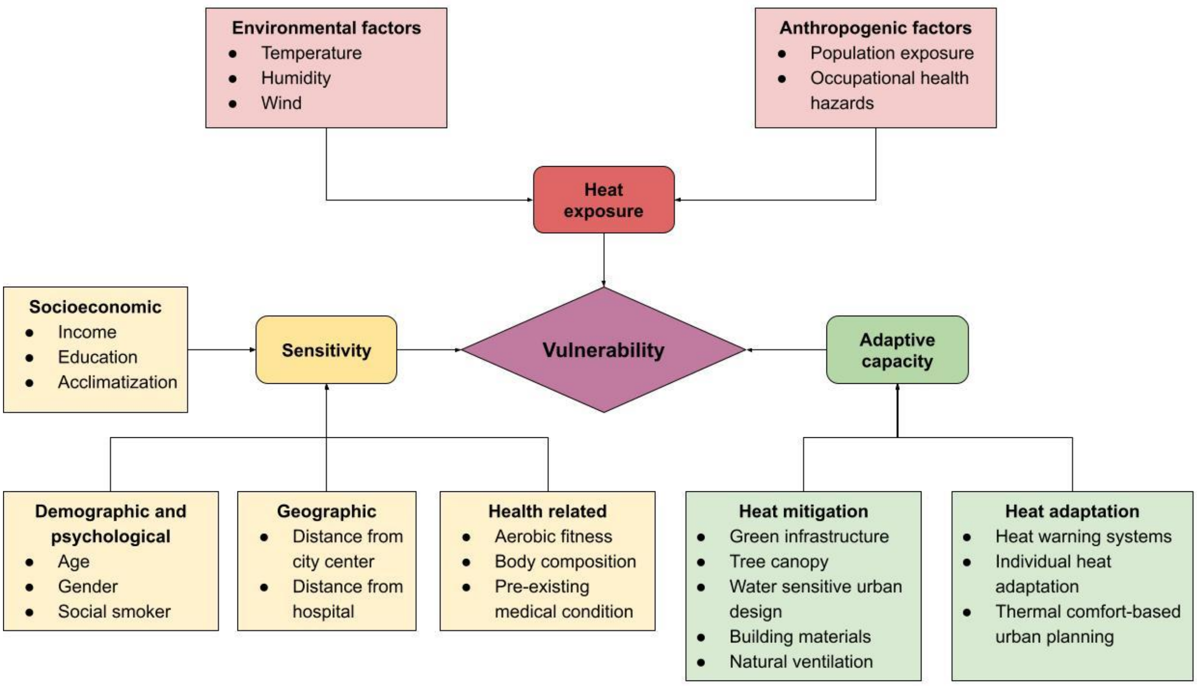

Figure 1 Synergies between three components of heatwave vulnerability: exposure, sensitivity, and adaptive capacity

2. Methodology

This review adhered to the guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol (Liberati et al., 2009). Peer-reviewed English language articles published between 01 January 2000 and 31 December 2021 were examined. Several online databases such as Web of Science, Scopus, and PubMed were used in the initial article search phase using various combinations of keywords under four different themes — heatwave, vulnerability, mitigation, and location (Table 1). The keywords were selected so that the search results covered all articles of relevance, thereby limiting the retrieval of irrelevant information (Pullin and Stewart, 2006). The Boolean operators "AND" and "OR" were used, but followed various keyword combinations. The search strings used to perform the search in all three databases (including the relevant keywords and Boolean operators) are provided in the supplementary Table S1.

The initial search identified a total of 811 articles. After removing 167 duplicate records, a two-stage screening process was followed to select articles for full-text evaluation. During the first stage, articles were evaluated based on their title, abstract, and keywords. A total of 479 articles that did not meet the inclusion criteria were excluded. The remaining 163 articles were reviewed in detail. Those articles provided references to two additional articles (i.e., snowballing method) (Chapman et al., 2017) for full-text review. Following this review, a total of 107 articles were assessed as suitable for inclusion in this study. Figure 2 shows a flowchart of the screening process used in this work, including the number of articles at each stage of the review process. Across the two-stage screening process, the following exclusion criteria were used to remove articles:

- Articles did not meet the objectives of this study (based on title, abstract, or keywords).
- Studies relating to heatwave vulnerability of animal, bird, plant species, and marine habitats.
- Review papers.
- Studies conducted outside Australia.
- Studies at the global and individual building scales.

Table 1 Keyword combination for searching the literature

Heatwave related	Vulnerability related	Mitigation related	Location related
Heatwave	Vulnerability index	Urban heat mitigation	Australia
Heat wave	Vulnerability mapping	Green infrastructure	Australian cities
Temperature	Heat stress	Heat mitigation	
Extreme heat	Human health	Heat adaptation	
Urban heat island	Health hazards	Greenspace	
Urban temperature	Health effects	Urban greening	
	Population health	Evaporative cooling	
	Morbidity	Albedo	
	Mortality	Shading	
		Thermal comfort	

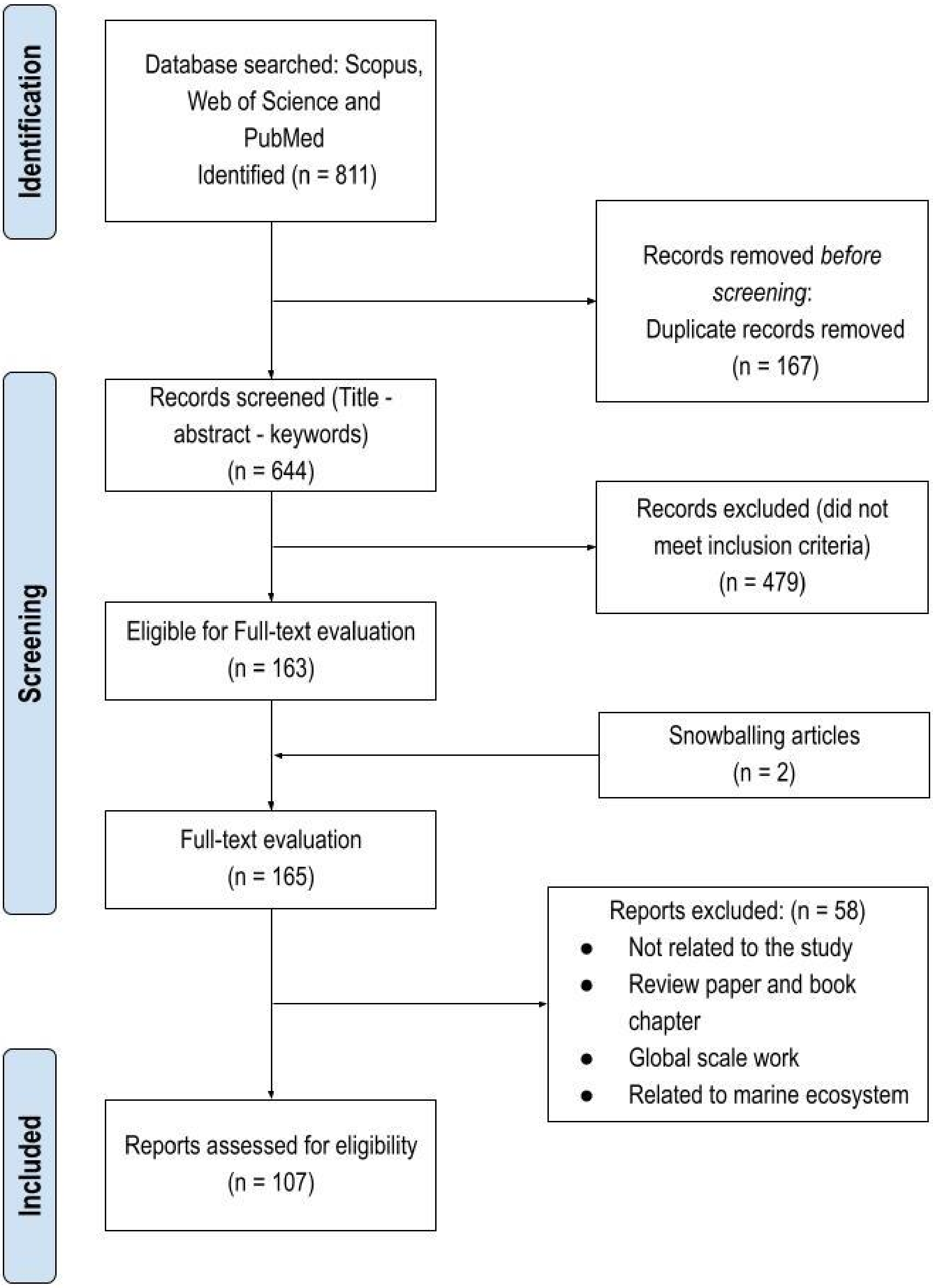

Figure 2 Flowchart of the systematic review (e.g., article screening) process

3. Results and discussion

3.1. Overview of the selected articles

Research on heatwave vulnerability in Australia has been increasing since the beginning of the last decade. All 107 articles selected for this study were published between 2010 and 2021. Figure 3a exhibits an increasing trend of published articles. About 20% (n = 19) of studies reviewed were published between 2020 and 2021. The articles reviewed were obtained from

55 different journals. Most of these journals were published in the subject areas of environmental science, social science, medicine, and earth and planetary sciences (Figure 3c). The social science-related journals include subject matter such as geography, planning and development, sociology and political science, urban studies, and safety research. A detailed list of journals, the number of articles, and the subject areas are given in the supplementary Table S2.

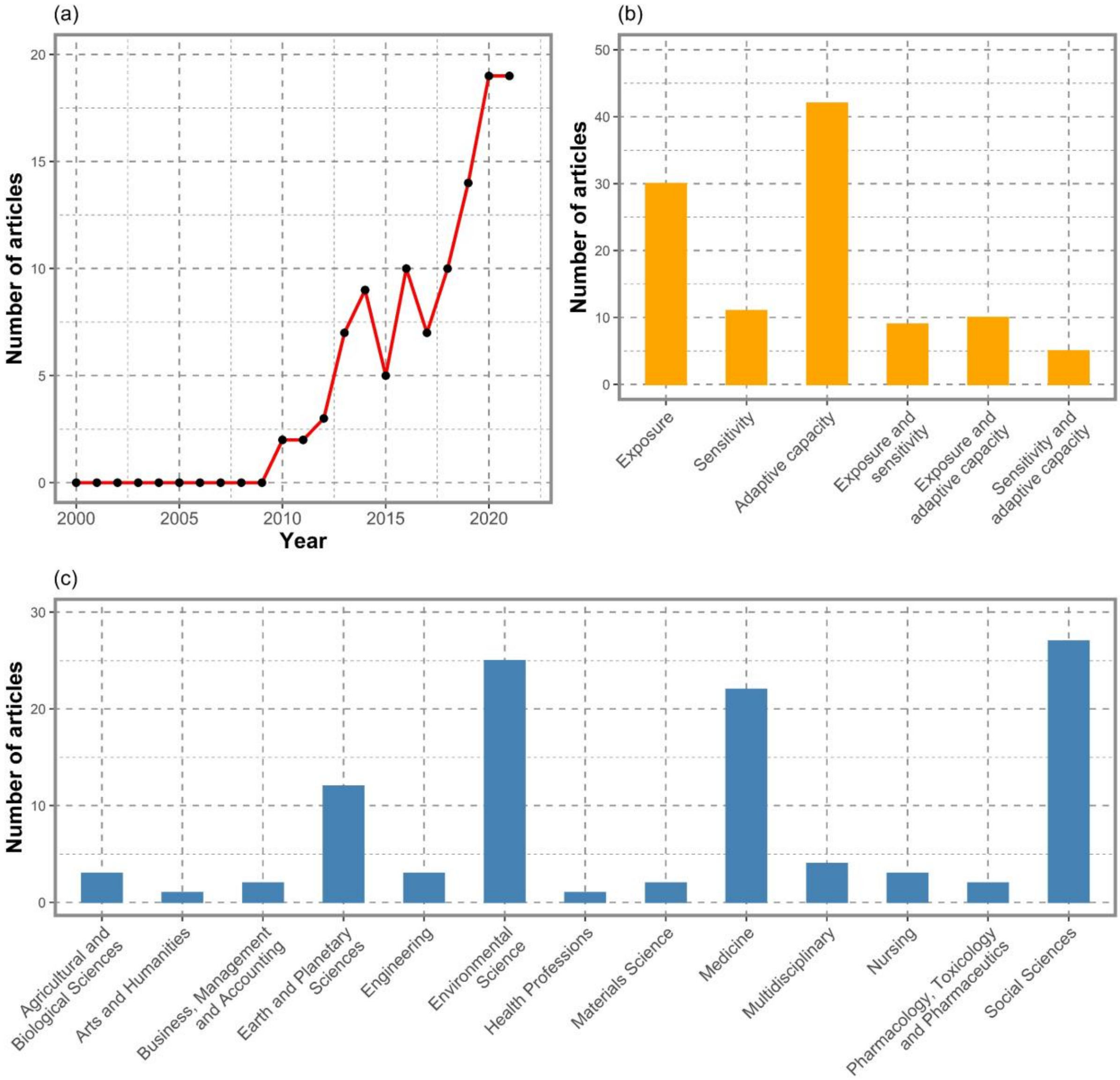

Figure 3 An overview of the reviewed articles based on: (a) year of publication; (b) components of heatwave vulnerability; and (c) subject areas

The majority of the articles (*n* = 42) focused on heat adaptation and mitigations strategies. A substantial proportion (28%) of the reviewed articles addressed heat exposure. A total of 24 articles were found that focused on multiple components such as exposure and sensitivity, exposure and adaptive capacity, and sensitivity and adaptive capacity. Only a limited number of studies concentrated purely on the sensitivity aspect (Figure 3b). The low number of heatwave sensitivity-related studies could be attributed to: (1) challenges associated with quantifying the epidemiological effects of heatwaves (Li et al., 2018); (2) the limited amount of data available regarding the health impacts of heatwaves of various age groups (Nitschke et al., 2013; Xu et al., 2017); and (3) the difficulty in understanding the effects of different heat adaptation techniques on public health based on differing demographic and socioeconomic backgrounds (Hansen et al., 2013; Hansen et al., 2011; Hansen et al., 2014; Hatvani-Kovacs et al., 2016a; Williams et al., 2013).

3.2. Heat exposure

3.2.1. Heatwave intensity

Heatwave peak temperatures have been increasing in Australia at the rate of 0.14 ± 0.22 °C/decade over 67 years (1950-2016) (Trancoso et al., 2020). These peaks have also been shifting from coastal areas to more inland areas. More heatwaves are now observed and felt in eastern Victoria, southern New South Wales, and central Western Australia, while less are felt in the north coastal regions (Trancoso et al., 2020; Zander et al., 2017). In the recent past, extreme heatwave events tended to last six to nine days in the central and northern parts of the country and three to six days in the south (Herold et al., 2018). Sadeghi et al. (2021) developed a biometeorological matric based on the Universal Thermal Climate Index (UTCI) to quantify urban heat exposure during the 2017 heatwave event in Sydney. The highest UTCI value was estimated to be 35.6 °C, with a mean exceedance of heat stress threshold of 6 °C. In Queensland, the daily mean temperature increased by 0.6 °C in 17 years (1997-2013) (Sadeghi et al., 2021). In Brisbane, the maximum temperature observed was 41.5 °C between 1996 and 2006. Coastal regions of Australia have also experienced the greatest warming between 1911 and 1917, particularly in the dry season. From 1981 to 2010, Northern Australian regions experienced extreme temperature readings for seven months a year (on average) (Davis and Hanna, 2020). In Sydney, a significant, increasing trend in ambient air temperature was found for the years 1970-2016, primarily due to changes in both global and local climates (Livada et al., 2019). In some areas (e.g., Perth during the period 2000 to 2009), temperature variability has caused more deaths than heat (Cheng et al., 2019).

Heatwaves are projected to increase both in the short term (2020–2039) and the long term (2060–2079) (Cowan et al., 2014; Herold et al., 2018). Research indicates that global temperature increases beyond 2 °C could cause significant warming-related loss of lives in Australia (Huang et al., 2012). In the northern areas of the country, the number of heatwaves and associated heatwave days is predicted to double in the near future and triple in the longer term. Such changes in the frequency and duration of heatwaves associated with climate change have also resulted in decreased precipitation and soil moisture values (Cowan et al., 2014; Herold et al., 2018). However, it appears the maximum temperature increase will be higher in southern Australia when compared to the more northerly regions (Cowan et al., 2014). A decrease in urban vegetation coverage as a result of development activities would also cause an increase in the ambient temperature (Xu et al., 2021b). Higher energy consumption resulting from anthropogenic activities also contributes to increasing urban heat. In four Australian capital cities — Brisbane, Sydney, Melbourne, and Adelaide — the day-time population density is significantly higher than the night-time population density due to a large influx of commuting workers, resulting in increased energy use (and heat) from vehicles. Energy emissions from buildings due to heating, cooling, ventilation, lighting, use of appliances, and even human metabolic activities all contribute to the general increase in the temperature of urban areas within Australian cities (Chapman et al., 2016; Coutts et al., 2010). Chapman et al. (2019) estimated that the number of hot days and nights could double in the urban and rural areas of Brisbane during 2041 to 2050 compared to the 1991–2000 period under the RCP8.5 scenario. Both climate change and urban growth were considered to be the main contributing factors behind this increasing temperature (Chapman et al., 2019; Coutts et al., 2010).

3.2.2. Population heat exposure

Heatwave events in Australia cause an increase in ambulance dispatches, hospital emergency department presentations, length of hospital stay, health expenses, and deaths (Campbell et al., 2019; Huang et al., 2012; Lu et al., 2020; Toloo et al., 2015; Tong et al., 2021b; Tong et al., 2015; Tong et al., 2010; Turner et al., 2013; Wondmagegn et al., 2021; Xu et al., 2019b). Various studies have found a strong association between heatwaves and mortality in the major cities of Brisbane, Melbourne, and Sydney (Tong et al., 2015; Tong et al., 2014). Both the young and the elderly people are at increased risk of heat exposure-induced morbidity and mortality (Tong et al., 2015; Turner et al., 2013; Xu et al., 2019b). In Brisbane, for the period 2000-2007, a 9.5 °C increase in temperature above a threshold temperature of 29 °C, caused an increase in total ambulance attendances by 50.6% (Turner et al., 2013). There were a total of 907 hospitalizations for Alzheimer's disease between 2005 and 2014, of which 307 patients died within two months of being discharged (Xu et al., 2019b). Besides, a significant number of fatalities was recorded due to acute myocardial infarction between 2005 and 2013 associated with heat exposure (Xu et al., 2021a). Toloo et al. (2015) projected an additional increase in hot days[1] hospital visits by the young and the old in 2060, the numbers ranging between 229–2300 for the young and 145–1188 for older citizens. These excess emergency admissions would cost taxpayers AU$120,000–1,200,000 and AU$96,000–786,000, respectively. In Adelaide, a total of 3,915 hospital admissions between 2010 and 2015 were attributed to high temperature conditions (temperature ranged between 6.7 and 37.7 °C), resulting in 99,766 days of hospitalization and costing AU$ 159.1 million (Wondmagegn et al., 2021). In Perth, heat-related hospital healthcare is projected to increase from AU$ 79.5 in 2006-2012 to AU$ 125.8-129.1 m during 2026-2032 under future climate change scenarios (Tong et al., 2021a) (Tong et al., 2021a). In Queensland, from 1995 to 2016, the rate of hospitalizations for cardiovascular diseases had shown an increase, with a strong association with temperature (Lu et al., 2020). While exposure to heat is associated with an elevated risk of emergency department visits in Australia, the risk profile does vary between cities. Spatial heterogeneity of heat exposure is related to risk triggering temperature that causes detrimental heat effects (Bolleter et al., 2021; Cheng et al., 2018).

Heat-related mortality is significantly associated with extreme temperatures in the warmer climatic zones of Australia. Most of the capital cities and important regional centers show evidence of the impact of extreme heat on mortality (Longden, 2019). A complex relationship exists between heat-related mortality and temperature, differing due to location, inhabitants' degree of acclimatization, local biophysical, structural and behavioral adjustments, as well as underlying population characteristics such as levels of chronic disease (Banwell et al., 2012; Longden, 2019). Global warming is likely to increase the rate of heat-related hospital admissions, length of hospital stays, and associated healthcare expenses in the future. Hospitals, therefore, face significant challenges in providing consistent, high-level healthcare services (Lu et al., 2020; Wondmagegn et al., 2021). There is also an underlying fear by citizens that increased environmental heating creates an uncertain future (Zander et al., 2019)

[1] The number of hot summer days (maximum temperature ≥ 35 °C) ranges between 2 and 13 days in 2060 (Toloo et al., 2015)

3.2.3. Heatwaves' impact on work-related injuries

Heat poses a significant occupational hazard in the workplace. Prolonged physical work in hot and humid environments leads to increasing heat stress on the individual (Carter et al., 2020; Hansen et al., 2020; Varghese et al., 2019b; Varghese et al., 2020a; Varghese et al., 2020b; Zander and Garnett, 2020). Extreme heat events negatively impact productivity by disrupting working hours and causing heat-related injuries. Beggs et al. (2021) reported that moderate heat stress risk would have resulted in significant work disruptions in Brisbane (115 days) and Alice Springs (95 days) in 2019. Various studies have found a strong association between ambient temperature and heat-related injuries (Carter et al., 2020; Varghese et al., 2019a). While investigating the cost of productivity loss resulting from heat stress at work in Australia during 2013-2014, Zander et al. (2015) reported that work absenteeism and reductions in work performance caused an annual economic loss of around US$6.2 billion, i.e., 0.33-0.47% of the country's GDP, however, the pattern varies between cities (Varghese et al., 2019a). Both in Northern and Southern Australia, chronic heat stress symptoms are more evident in outdoor workers who are exposed to direct sunlight and hot surfaces (Carter et al., 2020; Xiang et al., 2014). While workers in Melbourne have a low risk of exposure to elevated temperatures, traumatic injuries during hot days have increased in other parts of the country such as in Brisbane and Perth (Varghese et al., 2019a; Varghese et al., 2019b). Men are more likely to be affected by heat stress due to the higher proportion of men working outdoors. (Zander et al., 2015).

Various studies have reported that workers' exposure to heat is associated with different types of injuries (both major and minor) including burns and blistered hands, lacerations, and falls. Exposure to heat results in various health issues such as heat exhaustion, musculoskeletal injuries, nausea, severe dehydration, vomiting, headache, dizziness, loss of focus and concentration, light-headedness, sunburn, loss of consciousness or collapse, heat rashes and brain injury (Carter et al., 2020; Hansen et al., 2020; Varghese et al., 2020a; Varghese et al., 2020b). Heat stress to workers also reduces labor productivity (Beggs et al., 2021; Zander and Garnett, 2020). In Australian cities such as Melbourne and Perth, a 14% increase in workers' work-related injuries and illness compensation claims were associated with workers' exposure to high ambient temperatures for the period 2005 to 2016 (Varghese et al., 2019a). In Adelaide, for the period 2003 to 2013, new workers, workers in medium-sized enterprises, indoor industries, and laborers claimed compensation during moderate heatwave events (Varghese et al., 2019c). Mechanical injuries, such as those caused by moving objects, chemicals, various substances, and electricity, all increased during heatwave days (Xiang et al., 2014)

The heat stress felt by workers is also strongly associated with the type of activity being undertaken. The indoor environment of a workplace is a causative factor for heat-related injuries to workers especially if the workplace normally has elevated temperatures. For this reason, tradespersons and related workers are more susceptible to heat stress compared to people employed in public administration and safety (Carter et al., 2020; Zander et al., 2015). Similarly, in industries such as underground mining, transport, and manufacturing, the presence of heat-generating machinery is a major source of heat exposure (Hansen et al., 2020). In the case of outdoor workers, male people aged over 55 years, particularly those who are employed in "agriculture, forestry and fishing" and "electricity, gas and water" sectors are more vulnerable to heat (Xiang et al., 2014). At the individual level, acclimatization, concentration lapses, poor decision making, language barrier, dehydration and fatigue, and age are reportedly associated with higher rates of heat-related injuries to workers. At the interpersonal level, attitudes concerning self-presentation can be a contributing factor (Hansen et al., 2020; Varghese et al., 2020a; Varghese et al., 2020b; Zander et al., 2015). A lack of access to shade, the wearing of personal protective equipment (PPE) leading to higher body temperature, and rushed activity are commonly reported work-related factors associated with injuries (Varghese et al., 2020a; Varghese et al., 2020b).

3.3. Sensitivity

3.3.1. Risk awareness and acclimatization to high temperature

The heat vulnerability of an individual could also be related to personal risk awareness and the ability of the individual to adapt to high temperatures (Haynes et al., 2021; Oppermann et al., 2018; Varghese et al., 2019a; Zander et al., 2017). In Melbourne, for instance, a lowered occupational risk to outdoor workers is associated with a greater awareness of possible risks posed by hot weather conditions, as well as a better acclimatization status. A lack of significant association was also found between hot temperatures and occupational injuries in Brisbane, primarily due to the workers acclimatizing to a hot and humid environment (Varghese et al., 2019a). Zander et al. (2017) found that people who lacked awareness of climate change effects (and the associated increase in temperature) were more susceptible to heat stress impacts. Many communities in South Australia are accustomed to a hot environment and they have adequate knowledge and the experience to cope with possible adverse heat effects (Hansen et al., 2011;

Williams et al., 2017). Hatvani-Kovacs et al. (2016a) found that people who have heat-stress related physical conditions are more conscious of, and adaptive to, hot weather and therefore undertake various adaptation measures such as regularly monitoring weather forecasts when planning activities, using showers for cooling purposes, wearing light-colored and loose-fitting clothes, and keeping windows shut during warm days.

3.3.2. Physical factors

People with pre-existing health conditions are highly vulnerable to heatwaves (Beggs et al., 2021; Hatvani-Kovacs et al., 2016a; Zander et al., 2017). Older people generally suffer a physiological decline in health as a result of their age, making them more susceptible to the effects of heat than younger people (Hansen et al., 2011). Cardiovascular diseases are one of the biggest public health problems in Australia with about 27% of all deaths in 2017 caused by cardiovascular system diseases. In Queensland, cardiovascular diseases were responsible for 147,238 deaths during 1997-2013 (Lu et al., 2021). The increasing frequency and severity of hot temperatures have been associated with a higher risk of cardiovascular mortality (Bi et al., 2011; Lu et al., 2021; Xu et al., 2021b), especially in individuals with pre-existing hyperlipidemia (Xu et al., 2021b). High ambient temperatures also pose an elevated risk of acute kidney injury (AKI) in many countries, including in Australia. High temperatures induce sweating which can lead to dehydration, lower extracellular fluid, and blood volume. This can eventually result in AKI (Bi et al., 2011; Xu et al., 2020). Intense heat also increases hospital admission and mortality rates of patients with Alzheimer, primarily due to changes in thermoregulation capacity, hyperthermia, and a decreased cognitive awareness of hostile environments (Xu et al., 2019b). The older population (over 65 years of age), as well as working-class people, tend to be more vulnerable to heat-induced cardiovascular diseases, AKI, and Alzheimer’s disease (Bi et al., 2011; Hatvani-Kovacs et al., 2016b; Turner et al., 2013; Xu et al., 2020; Xu et al., 2019b).

High ambient temperature conditions also pose a risk of stillbirth and preterm birth. While analyzing the impacts of ambient temperature on preterm birth and stillbirth in Brisbane, Li et al. (2018) found that exposure to high temperature during the second and third trimester of pregnancy increased the risk of stillbirth, while heat exposure during the third trimester of pregnancy is associated with increased preterm birth rates. High heat exposure increases the risk of heat stress among pregnant women, causes dehydration, and leads to decreased uterine blood flow. All these physiological processes may lead to preterm birth and stillbirth (Li et al., 2018).

3.3.3. Sociodemographic and psychological factors

Age and gender appear associated with heat-related injuries (Zander et al., 2017). Generally, extreme heats pose a greater threat to men than women in Australia (Lu et al., 2020; Lu et al., 2021; Xu et al., 2017). Children aged 15 years and under, and the older population aged over 65 years, are more vulnerable to heat-induced diseases and more prone to emergency department presentations (Beggs et al., 2021; Campbell et al., 2019; Hansen et al., 2014; Lu et al., 2020; Nitschke et al., 2013; Xu et al., 2020). For instance, in Brisbane, the mortality rate of people aged over 65 years increases by 7% with every increase of 1 °C in mean summer daytime temperature (Bi et al., 2011). The mortality rate due to heatwaves in this age group is projected to increase by an additional 3.5% in the short term, and 11.9% in the longer term (Herold et al., 2018). It has also been found that infants in Brisbane are extremely susceptible to adverse health impacts of heatwaves due to their less-developed thermoregulation and immune systems (Xu et al., 2017). The older population is more vulnerable to work-related injuries during hotter days, however many young and female industrial workers also appear to have higher rates of injury due to a lowered perception of risk (Hansen et al., 2020; Varghese et al., 2019a). Older citizens are more conscious of the heat than younger people and normally take suitable measures to mitigate any elevated temperature effects (Hatvani-Kovacs et al., 2016a; Nitschke et al., 2013). Their "heat health" behavior includes wearing summer clothing, taking additional cool showers, reducing sun exposure by closing blinds and curtains, opening up the house in the evening, and drinking more fluids (Nitschke et al., 2013).

The review also reveals that there is a relationship between socioeconomic status and heatwave vulnerability. People with high socioeconomic status, and from warmer regions, are more adaptive to high temperatures (Lu et al., 2021). In various regions of Australia, income level has been found to be inversely correlated with heat stress (Hansen et al., 2014; Hatvani-Kovacs et al., 2016a; Lu et al., 2021; Rajagopalan et al., 2020; Xu et al., 2021b; Zander et al., 2017). The male population, particularly those living in suburbs with low and middle socioeconomic status, are more vulnerable to heat (Lu et al., 2021; Xu et al., 2021b). Higher-income levels are associated with ownership of more heat-stress-resistant homes, generally achieved with the use of air-conditioning (Hatvani-Kovacs et al., 2016a). In some cases, older people are reluctant to use cooling devices in their homes due to the associated energy costs (Hansen et al., 2011).

Hansen et al. (2014) reported that some migrants and refugees faced difficulties in adapting to heatwaves due to various cultural factors such as wearing unsuitable garments, inadequate drinking of water, as well as a lack of information on heat-protective measures.

Behavioral and psychological factors can be associated with heat stress. Social smokers and heavy smokers are likely to be more affected by hot temperatures compared to non-smokers (Zander et al., 2017). Literacy skills, language barriers, and a lack of knowledge regarding transport and health options are also found to be associated with heatwave vulnerability (Hansen et al., 2013; Hansen et al., 2014). In rural communities, peoples' age, health, housing conditions, and cooling methods are attributed to individual heat vulnerability. Limited public transport services can potentially restrict the rural population from receiving emergency support during extreme heat events (Williams et al., 2013). Extreme heat events can cause various psychological issues in older people such as panic, anxiety, and fear. Hansen et al. (2011) reported that water restrictions, bushfires, and extensive media coverage during the 2009 heatwave, created anxiety and fear in the older population.

3.4. Adaptive capacity

3.4.1. Urban heat mitigation strategies

Table 2 provides an overview of various heat mitigation options available for Australian cities. This includes green infrastructures, shading, water sensitive urban design (WSUD), increased albedo, use of cooling materials, spray systems, and natural ventilation. Green infrastructure is regarded as a natural cooling measure that promotes evapotranspiration. It also reduces atmospheric CO_2 (Ambrey et al., 2017; Coutts et al., 2010). Outdoor activity patterns in areas where urban greenery exists are usually more resistant to heat stress effects when compared to activities in hard-landscaped areas (Sharifi et al., 2016). Areas with a higher percentage of green cover could potentially lower the effect of heatwaves on hospitalizations for Alzheimer's disease (Xu et al., 2019b). Several urban heat mitigation studies have also assessed the potential of urban water management for improving urban cooling. The WSUD strategy has been shown to be effective in reducing urban heat by enhancing evaporation processes. This allows retention of water in the urban environment (Broadbent et al., 2018; Coutts et al., 2010; Fogarty et al., 2021; Lam et al., 2020). Higher canopy cover, green space, green roofs and walls, and open space all assist evaporation (Coutts et al., 2010; Qi et al., 2021; Sanusi et al., 2016). Heat storage in urban areas can also be reduced by using a high albedo (reflective) surface (Bartesaghi-Koc et al., 2021; Coutts et al., 2010). A study by Santamouris et al. (2020)

demonstrated that reflective roofs and pavements have the ability to reduce the peak ambient temperature by 1–2.5 °C in Sydney. In Melbourne, the use of a highly reflective surface was also found to be influential in reducing urban heat. Areas with darker rooftop surfaces absorb more solar radiation, resulting in lower surface albedo and higher ambient temperature so a rooftop constructed using highly reflective materials would be beneficial in reducing solar absorption, and hence heating potential (Coutts et al., 2010).

Recent studies have also shown that the combined use of different heat mitigation strategies can result in a substantial reduction in urban temperature (Haddad et al., 2020b; Qi et al., 2021; Santamouris et al., 2020). According to Brown et al. (2018), increasing urban vegetation patches and high albedo in built up areas could reduce air temperature by between 1 °C and 7 °C. Better acclimatization to the local climate can be achieved by introducing measures such as green space, low population density, and improved building design; all features which would help to minimize heatwave risk (Cheng et al., 2018). While quantifying the potentials of various heat mitigation measures in the northern Australian city of Darwin, Haddad et al. (2020b) found that the combined application of cooling materials, shading, and greenery reduced the peak ambient temperature by 2.7 °C, significantly decreasing peak electricity demand and the total annual cooling load.

Utilizing the natural airflow (breezes) can improve urban ventilation efficiency and reduce the overall urban temperature (He et al., 2020; Jacobs et al., 2014; Zhou et al., 2019). In research conducted in Melbourne by Jacobs et al. (2014), it was found that cooling winds significantly affect the elevated air temperatures associated with heat stress. He et al. (2020) quantified the potential of wind speed to reduce the air temperature in Sydney. They concluded that both solar radiation and wind speed influence air temperature. Lower temperatures are generally associated with low sky view factor (SVF) areas and those exposed to sea breezes. Zhou et al. (2019) found that building density (quantified using the frontal area index) and diversity of building heights (quantified using the terrain ruggedness index) can influence sea breeze cooling effects in urban areas. These studies suggest that a mix of high-density and high-rise buildings is necessary to maximize the cooling potential of wind.

Table 2 Overview of various heat mitigation measures applied in Australian cities

Heat mitigation strategies	Description	Sources
Urban green infrastructure	Green infrastructure can be defined as a network of green spaces such as urban forests, parks, street trees, tree covers, vegetation patches, green roofs and walls, intentionally managed both in private and public lands to benefit humans.	(Abdollahzadeh and Biloria, 2021; Ambrey et al., 2017; Bartesaghi-Koc et al., 2021; Beggs et al., 2021; Brown et al., 2018; Chen et al., 2014; Coutts et al., 2010; Coutts et al., 2013; Coutts et al., 2016; Douglas et al., 2021; Feitosa and Wilkinson, 2018; Feitosa and Wilkinson, 2020; Haddad et al., 2020b; Imran et al., 2019; Jacobs et al., 2018; Jamei and Rajagopalan, 2017; Ma et al., 2018; Motazedian et al., 2020; Ossola et al., 2021; Santamouris et al., 2020; Sharifi et al., 2020; Thom et al., 2016; Zhang et al., 2021)
Tree canopy cover	Tree canopy cover can provide shading, reduce local air temperatures and create a cooler and more comfortable environment for the city dwellers, particularly pedestrians.	(Bartesaghi-Koc et al., 2021; Coutts et al., 2013; Coutts et al., 2016; Haddad et al., 2020b; Qi et al., 2021; Sanusi et al., 2016)
Water Sensitive Urban Design (WSUD)	WSUD aims to retain water within the urban landscape by reducing stormwater runoff. This form of urban design employs irrigated open space, bio-filtration systems, open water bodies, wetlands, rainwater tanks, rain gardens,	(Broadbent et al., 2018; Coutts et al., 2010; Coutts et al., 2013; Fogarty et al., 2021; Lam et al., 2020; Ma et al., 2018; Santamouris et al., 2020)

	and stormwater harvesting systems.	
Increased albedo	The albedo of a surface determines the amount of reflected solar radiation. Greater use of reflective surfaces in urban areas reflects higher amounts of radiation, which reduces heat storage.	(Bartesaghi-Koc et al., 2021; Coutts et al., 2010; Ma et al., 2017; Qi et al., 2021; Santamouris et al., 2020)
Cooling materials	Reflective and radiative cooling materials such as cellulose nanofiber can have a great response to changes in ambient radiation.	(Bartesaghi-Koc et al., 2021; Haddad et al., 2020b; Qi et al., 2021)
Spray systems	Evaporative cooling can be increased by installing outdoor misting fan systems.	(Bartesaghi-Koc et al., 2021; Haddad et al., 2020b)
Improving natural ventilation	Natural ventilation such as sea breezes can reduce air temperatures, especially in coastal cities. Sea breezes are mostly available on clear days.	(He et al., 2020; Zhou et al., 2019)

3.4.2. Heat adaptation measures

Seasonally elevated temperatures have profoundly influenced the Australian environment and become an integral part of the normal Australian "way of life" (Banwell et al., 2012). Various cities have implemented adaptation measures in response to extreme heat events arising as a result of the Australian climate. Many recent studies have attempted to evaluate the effectiveness of these differing heat adaption measures (Table 3). Heatwave response plans, including "heat warning systems" or "heat health warning systems", are designed to predict hot weather, ensure preparedness, and take necessary actions during the hot days to minimize, as much as possible, the risks to the health of the affected populations during heatwave events (Akompab et al., 2013b; Toloo et al., 2013). Such plans have also been developed in many cities across the globe (Akompab et al., 2013b). In the south Australian city of Adelaide, heat warning systems were introduced before the extreme heating event which occurred in 2014. As a result, heat-related morbidity was significantly reduced compared to an event that occurred previously in 2009 (Nitschke et al., 2016). Varghese et al. (2019a) noted that the presence of heat stress policies in Melbourne limits the occurrence of occupational injuries.

At the individual level, people tend to have different approaches in regard to handling hot weather conditions (Haynes et al., 2021). For example, heat-induced emigration is a type of adaptation measure that people practice, or are willing to practice, in different regions of Australia (Zander and Garnett, 2020; Zander et al., 2016). However, such adaptation measures have a strong age association. While younger people in Australia primarily move from one region to another due to employment opportunities, inhabitants over the age of 50 tend to emigrate to avoid parts of the country that experience seasonally high temperatures (Zander and Garnett, 2020). Other forms of individual heat adaptation include the use of air conditioners and fans, wearing cool light clothing, reducing physical activities, staying inside, and drinking more fluids (Akompab et al., 2013a; Banwell et al., 2012; Hansen et al., 2015; Hatvani-Kovacs et al., 2016a; Hatvani-Kovacs et al., 2016b; Loughnan et al., 2014; Williams et al., 2019; Zander et al., 2021; Zografos et al., 2016). However, the adaptation of individuals to heatwaves varies between socioeconomic and demographic groups (Haynes et al., 2021). Besides, an increasing reliance on adaptation measures such as air-conditioning, however, generally increases energy demands, with associated increases in energy (e.g., electricity and gas) costs (Loughnan et al., 2015).

Thermal comfort-based urban planning can assist in reducing the effects of elevated temperatures. Improved pedestrian thermal comfort can be achieved in streets with a higher aspect ratio and an orientation aligned with the normal wind flow. Aspect ratio is defined as the ratio between building height and the width of the street. Streets with a higher aspect ratio receive less solar radiation and have relatively cooler outdoor temperatures (Abdollahzadeh and Biloria, 2021). Street orientation can have a significant impact on the airflow that determines thermal comfort with streets oriented parallel to the direction of airflow experiencing the greatest wind velocity and hence most heat dissipation (Abdollahzadeh and Biloria, 2021; Sanusi et al., 2016). Compact development can also improve the thermal efficiency of a city. Increased building height generally means a greater ratio of open space, a factor that helps to reduce ambient temperatures. While investigating the effects of proposed future structural planning on the city of Melbourne, Jamei and Rajagopalan (2017) found that the largest reduction in mean air temperature could be achieved by increasing the building heights as proposed in the plan.

Building heat-resistant houses is a common practice in Australia. In South Australia, the use of brick veneer and double brick to build their houses, installation of central air-conditioning systems, roof insulations, and targeted retrofitting of the existing residential building stock has proved to be effective in reducing both heat stress in the built environment, as well as the associated greenhouse gas emissions (Hatvani-Kovacs et al., 2016b; Loughnan et al., 2015). Work-related injuries can be managed by various adaptation measures such as acclimatization, reductions in heat exposure, rotation of workers, improved access to hydration, an introduction of fitness programs, rescheduling working hours, and limiting work times to below a threshold temperature (Varghese et al., 2020a; Varghese et al., 2020b; Zander et al., 2015).

Table 3 Overview of individuals heat adaptation measures

Heat adaptation strategies	**Description**	**Sources**
Heat warning systems	Heat warning systems include early alerts and consultation services along with emergency public health measures.	(Akompab et al., 2013b; Bolleter et al., 2021; Nitschke et al., 2016)
Individual heat adaptation	Individual heat adaptation measures include using air conditioners and fans, wearing cool light clothing, reducing physical activities, staying inside, drinking more fluids, moving somewhere cooler (emigration).	(Akompab et al., 2013a; Banwell et al., 2012; Hansen et al., 2015; Hatvani-Kovacs et al., 2016a; Hatvani-Kovacs et al., 2016b; Haynes et al., 2021; Loughnan et al., 2014; Williams et al., 2019; Zander and Garnett, 2020; Zander et al., 2021; Zander et al., 2016; Zografos et al., 2016)

Thermal comfort-based urban planning	This approach includes various components such as street orientation, height control, aspect ratio, street hierarchy strategy (wider street).	(Abdollahzadeh and Biloria, 2021; Jamei and Rajagopalan, 2017; Sanusi et al., 2016)
Building retrofitting	Different types of building retrofitting such as changes in thermal insulation, solar transmittance of the windows, and ventilation and infiltration rate can make buildings adaptive to hot weather.	(Haddad et al., 2020a; Kumar et al., 2021; Zander et al., 2021)
Heat adaptation for workers	This approach includes acclimatization, rotation of work schedule, improved access to hydration, introduction of fitness programs, rescheduling working hours, limiting work within a threshold temperature.	(Oppermann et al., 2018; Varghese et al., 2020a; Varghese et al., 2020b; Zander et al., 2015).

4. Conclusion and the way forward

This study reviewed heatwave vulnerability-related studies in Australia to determine the existing state of heat intensity and exposure knowledge, identify all factors associated with heat sensitivity, and map the potential effects of differing heatwave mitigation and adaptation measures. Australia is generally a dry country with mean annual precipitation of less than 500 mm, apart from the coastal areas which border the continent (Pezza et al., 2012). It was found that heatwave vulnerability is highly context-specific, and varies according to climatic conditions, space, time, socioeconomic and demographic factors, as well as the physiological makeup of its citizens. Thermal discomfort perceptions tend to be associated with climatic parameters such as wind and humidity. As the definition of a heatwave varies globally, the ability to estimate vulnerability is not a straightforward task. Heat-related mortality estimated in previous studies shows that this is sensitive to location and the minimum mortality temperatures being considered. In Australia, both the frequency and severity of heatwaves are on the rise, therefore, it is surmised that ongoing climate change is likely to deteriorate natural and anthropogenic environments. Studies indicate that the peak temperatures recorded during heatwaves in Southern Australia are projected to be higher than those for the warmer northern parts of the country in the future. A significant proportion of the country's population is exposed to extreme heat and an increasing ratio of elderly citizens in the total population means they are at the greatest risk during hot weather. Occupational heat-related injuries are also a significant issue in Australia. Many studies have focused on the impacts of extreme heat on work-related injuries. This study has identified that people's awareness of, and acclimatization to, high temperature, pre-existing physical conditions, demographic characteristics, socioeconomic backgrounds, and psychological attributes are all intrinsically associated with heatwave vulnerability.

Studies show that various heat mitigation and adaptation measures at differing scales have proven to be efficient in reducing heat impacts. These also indicate that limiting global warming to between 1.5 and 2.0 °C may potentially limit the frequency and severity of heatwaves in Australia (Trancoso et al., 2020). Green infrastructures are regarded as a sustainable intervention in mitigating heatwave impacts due to their multifaceted benefits. The majority of heat adaptive capacity-related studies emphasized the differing elements of green infrastructures for use as potential heat mitigation measures. This study also identified that extreme temperature impacts in various Australian cities can be reduced by adopting water sensitive urban design (WSUD). This promotes evaporation by retaining existing water bodies. Several studies have shown that the use of high albedo surface areas (as well as reflective and radiative cooling materials), when used at the local (building construction) scale, can increase the reflectance of solar radiation, and hence mitigate any potential heating effects. In terms of heat adaptation, thermal comfort-based urban planning can enhance heat adaptation. High temperature warning systems have already proven to be efficient in limiting occupational injuries in various Australian cities. At the individual level, a number of adaptation measures are commonly practiced. People use air conditioners and fans, wear cool light clothing, reduce physical activities, and stay inside their houses in hot weather. If circumstances warrant it, people (particularly in the older age groups) can relocate to cooler climatic zones.

There have been a significant number of heat-related studies undertaken in Australia and elsewhere (Marx et al., 2021), however, there is still a general lack of understanding in regard to the spatiotemporal distribution of heatwave vulnerability. Future research can focus on several areas. Firstly, identified differences in the definition of heatwaves, methodology for estimating mortality, and population characteristics can cause variations in the heatwave-health relationship (Tong et al., 2015; Tong et al., 2014; Xu et al., 2017). It is imperative to use regional climatic and environmental conditions in the definition of heatwaves in order to define a regionally specific early warning system (Tong et al., 2015). It is also important to quantify the effects of various heat mitigation measures on risk-triggering temperatures (Cheng et al., 2018). Secondly, the impacts of heatwaves on the health of citizens with differing socioeconomic backgrounds (particularly migrants and minorities) have not been well documented (Hansen et al., 2014). Thirdly, heat stress can be apparent before clinical symptoms are evident, however, there has been limited research conducted on investigating the sub-clinical effects of heat (Zander et al., 2017). Fourthly, heat generated from anthropogenic activities and energy consumption can increase urban heat by 4.0°C (Chapman et al., 2016). Urban climate studies, however, often overlook anthropogenic heat generation estimation due to a lack of data, and the complexities involved in estimating this variable. The development of climate models at a finer scale than presently used could have the capacity to predict heatwaves more accurately (Gross et al., 2017). Lastly, a limited number of studies have focused on measuring resilience to heatwaves (Hatvani-Kovacs et al., 2016b; Sharifi et al., 2016). Future research should focus on more empirical studies to improve understanding of the effectiveness of various measures to improve heatwave resistance in Australian cities.

Heatwaves are increasing across Australia as a result of anthropogenic climate change. This review showed that heatwave has become an important research topic in environmental science, medicine, and social science domains, due to the detrimental effects that this hazard poses on both the physical and anthropogenic environments. The results of this study enhanced our understanding of the various drivers, leading to heatwave vulnerability. The findings of this work can be used to assist in the development of adaptation and mitigation measures to save people and properties from extreme heat both in Australia and elsewhere.

5. References

Abdollahzadeh, N., Biloria, N., 2021. Outdoor thermal comfort: Analyzing the impact of urban configurations on the thermal performance of street canyons in the humid subtropical climate of Sydney. Frontiers of Architectural Research. 10**,** 394-409.

Akompab, D. A., et al., 2013a. Heat waves and climate change: Applying the health belief model to identify predictors of risk perception and adaptive behaviours in Adelaide, Australia. International journal of environmental research and public health. 10**,** 2164-2184.

Akompab, D. A., et al., 2013b. Engaging stakeholders in an adaptation process: governance and institutional arrangements in heat-health policy development in Adelaide, Australia. Mitigation and Adaptation Strategies for Global Change. 18**,** 1001-1018.

Ambrey, C., et al., 2017. Cultivating climate justice: Green infrastructure and suburban disadvantage in Australia. Applied Geography. 89, 52-60.

Aubrecht, C., Özceylan, D., 2013. Identification of heat risk patterns in the US National Capital Region by integrating heat stress and related vulnerability. Environment international. 56, 65-77.

Azhar, G., et al., 2017. Heat wave vulnerability mapping for India. International journal of environmental research and public health. 14, 357.

Banwell, C., et al., 2012. Socio-cultural reflections on heat in Australia with implications for health and climate change adaptation. Global health action. 5, 19277.

Barriopedro, D., et al., 2011. The hot summer of 2010: redrawing the temperature record map of Europe. Science. 332, 220-224.

Bartesaghi-Koc, C., et al., 2021. Can urban heat be mitigated in a single urban street? Monitoring, strategies, and performance results from a real scale redevelopment project. Solar Energy. 216, 564-588.

Beggs, P. J., et al., 2021. The 2021 report of the MJA–Lancet Countdown on health and climate change: Australia increasingly out on a limb. Medical Journal of Australia. 215, 390-392. e22.

Bi, P., et al., 2011. The effects of extreme heat on human mortality and morbidity in Australia: implications for public health. Asia Pacific Journal of Public Health. 23, 27S-36S.

Bolleter, J., et al., 2021. Projected Extreme Heat Stress in Northern Australia and the Implications for Development Policy. Planning Practice & Research. 1-23.

Broadbent, A. M., et al., 2018. The microscale cooling effects of water sensitive urban design and irrigation in a suburban environment. Theoretical and Applied Climatology. 134, 1-23.

Brown, H., et al., 2018. Cool communities—Urban density, trees, and health. International journal of environmental research and public health. 15, 1547.

Buzási, A., 2022. Comparative assessment of heatwave vulnerability factors for the districts of Budapest, Hungary. Urban Climate. 42, 101127.

Campbell, S., et al., 2018. Heatwave and health impact research: A global review. Health & place. 53, 210-218.

Campbell, S. L., et al., 2019. The value of local heatwave impact assessment: a case-crossover analysis of hospital emergency department presentations in Tasmania, Australia. International journal of environmental research and public health. 16, 3715.

Carter, S., et al., 2020. The impact of perceived heat stress symptoms on work-related tasks and social factors: A cross-sectional survey of Australia's Monsoonal North. Applied ergonomics. 82, 102918.

Chapman, S., et al., 2019. The impact of climate change and urban growth on urban climate and heat stress in a subtropical city. International Journal of Climatology. 39, 3013-3030.

Chapman, S., et al., 2016. Large seasonal and diurnal anthropogenic heat flux across four Australian cities. Journal of Southern Hemisphere Earth Systems Science. 66, 342-360.

Chapman, S., et al., 2017. The impact of urbanization and climate change on urban temperatures: a systematic review. Landscape Ecology. 32, 1921-1935.

Chen, D., et al., 2014. Urban vegetation for reducing heat related mortality. Environmental pollution. 192, 275-284.

Cheng, J., et al., 2019. Impacts of heat, cold, and temperature variability on mortality in Australia, 2000–2009. Science of the Total Environment. 651, 2558-2565.

Cheng, J., et al., 2018. Assessment of heat-and cold-related emergency department visits in cities of China and Australia: population vulnerability and attributable burden. Environmental research. 166, 610-619.

Coates, L., et al., 2014. Exploring 167 years of vulnerability: An examination of extreme heat events in Australia 1844–2010. Environmental Science & Policy. 42, 33-44.

Coutts, A., et al., 2010. Changing urban climate and CO2 emissions: implications for the development of policies for sustainable cities. Urban policy and research. 28, 27-47.

Coutts, A. M., et al., 2013. Watering our cities: The capacity for Water Sensitive Urban Design to support urban cooling and improve human thermal comfort in the Australian context. Progress in physical geography. 37, 2-28.

Coutts, A. M., et al., 2016. Temperature and human thermal comfort effects of street trees across three contrasting street canyon environments. Theoretical and applied climatology. 124, 55-68.

Cowan, T., et al., 2014. More frequent, longer, and hotter heat waves for Australia in the twenty-first century. Journal of Climate. 27, 5851-5871.

Davis, C. J., Hanna, E. G., 2020. Seasonal temperature and rainfall extremes 1911–2017 for Northern Australian population centres: challenges for human activity. Regional Environmental Change. 20, 1-17.

Ding, T., Qian, W., 2011. Geographical patterns and temporal variations of regional dry and wet heatwave events in China during 1960–2008. Advances in Atmospheric Sciences. 28, 322-337.

Douglas, A. N., et al., 2021. Evaluating and comparing the green wall retrofit suitability across major Australian cities. Journal of environmental management. 298, 113417.

Feitosa, R. C., Wilkinson, S. J., 2018. Attenuating heat stress through green roof and green wall retrofit. Building and Environment. 140, 11-22.

Feitosa, R. C., Wilkinson, S. J., 2020. Small-scale experiments of seasonal heat stress attenuation through a combination of green roof and green walls. Journal of Cleaner Production. 250, 119443.

Fogarty, J., et al., 2021. Making waves: Creating water sensitive cities in Australia. Water Research. 202, 117456.

Gross, M. H., et al., 2017. The representation of health-relevant heatwave characteristics in a Regional Climate Model ensemble for New South Wales and the Australian Capital Territory, Australia. International Journal of Climatology. 37, 1195-1210.

Haddad, S., et al., 2020a. On the potential of building adaptation measures to counterbalance the impact of climatic change in the tropics. Energy and Buildings. 229, 110494.

Haddad, S., et al., 2020b. Holistic approach to assess co-benefits of local climate mitigation in a hot humid region of Australia. Scientific reports. 10, 1-17.

Hansen, A., et al., 2013. Vulnerability to extreme heat and climate change: is ethnicity a factor? Global health action. 6, 21364.

Hansen, A., et al., 2011. Perceptions of heat-susceptibility in older persons: Barriers to adaptation. International journal of environmental research and public health. 8, 4714-4728.

Hansen, A., et al., 2015. Heat-health behaviours of older people in two Australian states. Australasian journal on ageing. 34, E19-E25.

Hansen, A., et al., 2014. Extreme heat and cultural and linguistic minorities in Australia: perceptions of stakeholders. BMC public health. 14, 1-12.

Hansen, A. L., et al., 2020. Using a qualitative phenomenological approach to inform the etiology and prevention of occupational heat-related injuries in Australia. International journal of environmental research and public health. 17, 846.

Hatvani-Kovacs, G., et al., 2016a. Drivers and barriers to heat stress resilience. Science of the Total Environment. 571, 603-614.

Hatvani-Kovacs, G., et al., 2016b. Heat stress risk and resilience in the urban environment. Sustainable Cities and Society. 26, 278-288.

Haynes, V., et al., 2021. The future of our suburbs: Analyses of heatwave vulnerability in a planned estate. Geographical Research. 60, 152-167.

He, B.-J., et al., 2020. Outdoor thermal environment of an open space under sea breeze: A mobile experience in a coastal city of Sydney, Australia. Urban Climate. 31, 100567.

Herold, N., et al., 2018. Australian climate extremes in the 21st century according to a regional climate model ensemble: Implications for health and agriculture. Weather and climate extremes. 20, 54-68.

Hintz, M. J., et al., 2018. Facing the heat: A systematic literature review exploring the transferability of solutions to cope with urban heat waves. Urban climate. 24, 714-727.

Huang, C., et al., 2012. The impact of temperature on years of life lost in Brisbane, Australia. Nature Climate Change. 2, 265-270.

Imran, H. M., et al., 2019. Effectiveness of vegetated patches as Green Infrastructure in mitigating Urban Heat Island effects during a heatwave event in the city of Melbourne. Weather and Climate Extremes. 25, 100217.

Inostroza, L., et al., 2016. A heat vulnerability index: spatial patterns of exposure, sensitivity and adaptive capacity for Santiago de Chile. PLOS one. 11, e0162464.

IPCC, 2021. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Iping, A., et al., 2019. (Re) presenting urban heat islands in Australian cities: A study of media reporting and implications for urban heat and climate change debates. Urban Climate. 27, 420-429.

Jacobs, S. J., et al., 2018. Use of cool roofs and vegetation to mitigate urban heat and improve human thermal stress in Melbourne, Australia. Journal of Applied Meteorology and Climatology. 57, 1747-1764.

Jacobs, S. J., et al., 2014. A new 'bio-comfort'perspective for Melbourne based on heat stress, air pollution and pollen. International journal of biometeorology. 58, 263-275.

Jamei, E., Rajagopalan, P., 2017. Urban development and pedestrian thermal comfort in Melbourne. Solar Energy. 144, 681-698.

Jyoteeshkumar reddy, P., et al., 2021. Intensifying Australian heatwave trends and their sensitivity to observational data. Earth's Future. 9, e2020EF001924.

Kenawy, I., Elkadi, H., 2018. The outdoor thermal benchmarks in Melbourne urban climate. Sustainable cities and society. 43, 587-600.

Khan, H. S., et al., 2021. Analyzing the local and climatic conditions affecting the urban overheating magnitude during the Heatwaves (HWs) in a coastal city: A case study of the greater Sydney region. Science of The Total Environment. 755, 142515.

Kumar, D., et al., 2021. Retrofitting Building Envelope Using Phase Change Materials and Aerogel Render for Adaptation to Extreme Heatwave: A Multi-Objective Analysis Considering Heat Stress, Energy, Environment, and Cost. Sustainability. 13, 10716.

Lam, C. K. C., et al., 2020. Does irrigation cooling effect intensify during heatwaves? A case study in the Melbourne botanic gardens. Urban Forestry & Urban Greening. 55, 126815.

Li, S., et al., 2018. Temporal change in the impacts of ambient temperature on preterm birth and stillbirth: Brisbane, 1994–2013. Science of the Total Environment. 634, 579-585.

Liberati, A., et al., 2009. The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate health care interventions: explanation and elaboration. Journal of clinical epidemiology. 62, e1-e34.

Livada, I., et al., 2019. Time series analysis of ambient air-temperature during the period 1970–2016 over Sydney, Australia. Science of the Total Environment. 648, 1627-1638.

Longden, T., 2019. The impact of temperature on mortality across different climate zones. Climatic Change. 157, 221-242.

Loughnan, M., et al., 2015. The relationship between housing and heat wave resilience in older people. International journal of biometeorology. 59, 1291-1298.

Loughnan, M. E., et al., 2014. Learning from our older people: Pilot study findings on responding to heat. Australasian journal on ageing. 33, 271-277.

Lu, P., et al., 2020. Temporal trends of the association between ambient temperature and hospitalisations for cardiovascular diseases in Queensland, Australia from 1995 to 2016: A time-stratified case-crossover study. PLoS medicine. 17, e1003176.

Lu, P., et al., 2021. Temporal trends of the association between ambient temperature and cardiovascular mortality: a 17-year case-crossover study. Environmental Research Letters. 16, 045004.

Ma, S., et al., 2017. Pricing the urban cooling benefits of solar panel deployment in Sydney, Australia. Scientific reports. 7, 1-6.

Ma, S., et al., 2018. Evaluating the effectiveness of mitigation options on heat stress for Sydney, Australia. Journal of applied meteorology and climatology. 57, 209-220.

Mac, V. V. T., McCauley, L. A., 2017. Farmworker vulnerability to heat hazards: a conceptual framework. Journal of nursing scholarship. 49, 617-624.

Marx, W., et al., 2021. Heat waves: a hot topic in climate change research. Theoretical and Applied Climatology. 146, 781-800.

Motazedian, A., et al., 2020. The microclimatic interaction of a small urban park in central Melbourne with its surrounding urban environment during heat events. Urban Forestry & Urban Greening. 52, 126688.

Nairn, J. R., Fawcett, R. J., 2015. The excess heat factor: a metric for heatwave intensity and its use in classifying heatwave severity. International journal of environmental research and public health. 12, 227-253.
Nishant, N., et al., 2022. Future population exposure to Australian heatwaves. Environmental Research Letters.
Nitschke, M., et al., 2013. Risk factors, health effects and behaviour in older people during extreme heat: a survey in South Australia. International journal of environmental research and public health. 10, 6721-6733.
Nitschke, M., et al., 2016. Evaluation of a heat warning system in Adelaide, South Australia, using case-series analysis. BMJ open. 6, e012125.
Nitschke, M., et al., 2011. Impact of two recent extreme heat episodes on morbidity and mortality in Adelaide, South Australia: a case-series analysis. Environmental Health. 10, 1-9.
Oppermann, E., et al., 2018. Beyond threshold approaches to extreme heat: repositioning adaptation as everyday practice. Weather, Climate, and Society. 10, 885-898.
Orimoloye, I. R., et al., 2019. Implications of climate variability and change on urban and human health: A review. Cities. 91, 213-223.
Ossola, A., et al., 2021. Small vegetated patches greatly reduce urban surface temperature during a summer heatwave in Adelaide, Australia. Landscape and Urban Planning. 209, 104046.
Pattanaik, D., et al., 2017. Heat wave over India during summer 2015: an assessment of real time extended range forecast. Meteorology and Atmospheric Physics. 129, 375-393.
Perkins, S. E., Alexander, L. V., 2013. On the measurement of heat waves. Journal of climate. 26, 4500-4517.
Pezza, A. B., et al., 2012. Severe heat waves in Southern Australia: synoptic climatology and large scale connections. Climate Dynamics. 38, 209-224.
Pullin, A. S., Stewart, G. B., 2006. Guidelines for systematic review in conservation and environmental management. Conservation biology. 20, 1647-1656.
Qi, J., et al., 2021. Toward cool cities and communities: A sensitivity analysis method to identify the key planning and design variables for urban heat mitigation techniques. Sustainable Cities and Society. 75, 103377.
Raja, D. R., et al., 2021. Spatial distribution of heatwave vulnerability in a coastal city of Bangladesh. Environmental Challenges. 4, 100122.
Rajagopalan, P., et al., 2020. Investigating thermal comfort and energy impact through microclimate monitoring-a citizen science approach. Energy and Buildings. 229, 110526.
Sadeghi, M., et al., 2021. Development of a heat stress exposure metric–Impact of intensity and duration of exposure to heat on physiological thermal regulation. Building and Environment. 200, 107947.
Santamouris, M., et al., 2020. Heat mitigation technologies can improve sustainability in cities. An holistic experimental and numerical impact assessment of urban overheating and related heat mitigation strategies on energy consumption, indoor comfort, vulnerability and heat-related mortality and morbidity in cities. Energy and Buildings. 217, 110002.
Sanusi, R., et al., 2016. Street orientation and side of the street greatly influence the microclimatic benefits street trees can provide in summer. Journal of Environmental Quality. 45, 167-174.
Sharifi, E., et al., 2020. Climate change adaptation and carbon emissions in green urban spaces: Case study of Adelaide. Journal of Cleaner Production. 254, 120035.
Sharifi, E., et al., 2016. Resilience to heat in public space: a case study of Adelaide, South Australia. Journal of Environmental Planning and Management. 59, 1833-1854.
Sun, Y., et al., 2014. Rapid increase in the risk of extreme summer heat in Eastern China. Nature Climate Change. 4, 1082-1085.
Thom, J. K., et al., 2016. The influence of increasing tree cover on mean radiant temperature across a mixed development suburb in Adelaide, Australia. Urban forestry & urban greening. 20, 233-242.
Toloo, G., et al., 2013. Evaluating the effectiveness of heat warning systems: systematic review of epidemiological evidence. International journal of public health. 58, 667-681.

Toloo, G. S., et al., 2015. Projecting excess emergency department visits and associated costs in Brisbane, Australia, under population growth and climate change scenarios. Scientific reports. 5, 1-9.
Tong, M. X., et al., 2021a. Hospital healthcare costs attributable to heat and future estimations in the context of climate change in Perth, Western Australia. Advances in Climate Change Research. 12, 638-648.
Tong, M. X., et al., 2021b. Emergency department visits and associated healthcare costs attributable to increasing temperature in the context of climate change in Perth, Western Australia, 2012–2019. Environmental Research Letters. 16, 065011.
Tong, S., et al., 2015. Exploration of the health risk-based definition for heatwave: A multi-city study. Environmental research. 142, 696-702.
Tong, S., et al., 2010. Assessment of heat-related health impacts in Brisbane, Australia: comparison of different heatwave definitions. PloS one. 5, e12155.
Tong, S., et al., 2014. The impact of heatwaves on mortality in Australia: a multicity study. BMJ open. 4, e003579.
Trancoso, R., et al., 2020. Heatwaves intensification in Australia: A consistent trajectory across past, present and future. Science of The Total Environment. 742, 140521.
Turner, L. R., et al., 2013. The effect of heat waves on ambulance attendances in Brisbane, Australia. Prehospital and disaster medicine. 28, 482-487.
Varghese, B. M., et al., 2019a. Geographical variation in risk of work-related injuries and illnesses associated with ambient temperatures: A multi-city case-crossover study in Australia, 2005–2016. Science of the total environment. 687, 898-906.
Varghese, B. M., et al., 2019b. Characterising the impact of heatwaves on work-related injuries and illnesses in three Australian cities using a standard heatwave definition-Excess Heat Factor (EHF). Journal of exposure science & environmental epidemiology. 29, 821-830.
Varghese, B. M., et al., 2019c. Heatwave and work-related injuries and illnesses in Adelaide, Australia: a case-crossover analysis using the Excess Heat Factor (EHF) as a universal heatwave index. International archives of occupational and environmental health. 92, 263-272.
Varghese, B. M., et al., 2020a. Determinants of heat-related injuries in Australian workplaces: Perceptions of health and safety professionals. Science of the total environment. 718, 137138.
Varghese, B. M., et al., 2020b. Heat-related injuries in Australian workplaces: Perspectives from health and safety representatives. Safety science. 126, 104651.
Whitman, S., et al., 1997. Mortality in Chicago attributed to the July 1995 heat wave. American Journal of public health. 87, 1515-1518.
Wilhelmi, O. V., Hayden, M. H., 2010. Connecting people and place: a new framework for reducing urban vulnerability to extreme heat. Environmental Research Letters. 5, 014021.
Williams, S., et al., 2013. Extreme heat and health: perspectives from health service providers in rural and remote communities in South Australia. International journal of environmental research and public health. 10, 5565-5583.
Williams, S., et al., 2019. Heat-health warnings in regional Australia: examining public perceptions and responses. Environmental Hazards. 18, 287-310.
Williams, S., et al., 2017. Heat adaptation and place: Experiences in South Australian rural communities. Regional Environmental Change. 17, 273-283.
Wondmagegn, B. Y., et al., 2021. Increasing impacts of temperature on hospital admissions, length of stay, and related healthcare costs in the context of climate change in Adelaide, South Australia. Science of The Total Environment. 773, 145656.
Xiang, J., et al., 2014. The impact of heatwaves on workers′ health and safety in Adelaide, South Australia. Environmental research. 133, 90-95.
Xiao, J., et al., 2017. Variation in population vulnerability to heat wave in Western Australia. Frontiers in public health. 5, 64.
Xu, Z., et al., 2017. Heatwave and infants' hospital admissions under different heatwave definitions. Environmental pollution. 229, 525-530.
Xu, Z., et al., 2019a. Assessing heatwave impacts on cause-specific emergency department visits in urban and rural communities of Queensland, Australia. Environmental research. 168, 414-419.

Xu, Z., et al., 2020. Heat and risk of acute kidney injury: An hourly-level case-crossover study in queensland, Australia. Environmental research. 182, 109058.
Xu, Z., et al., 2019b. Heatwaves, hospitalizations for Alzheimer's disease, and postdischarge deaths: A population-based cohort study. Environmental research. 178, 108714.
Xu, Z., et al., 2021a. Associations of heat and cold with hospitalizations and post-discharge deaths due to acute myocardial infarction: what is the role of pre-existing diabetes? International Journal of Epidemiology. 51, 134-143.
Xu, Z., et al., 2021b. Associations of extreme temperatures with hospitalizations and post-discharge deaths for stroke: What is the role of pre-existing hyperlipidemia? Environmental Research. 193, 110391.
Zander, K. K., et al., 2015. Heat stress causes substantial labour productivity loss in Australia. Nature climate change. 5, 647-651.
Zander, K. K., Garnett, S. T., 2020. The importance of climate to emigration intentions from a tropical city in Australia. Sustainable Cities and Society. 63, 102465.
Zander, K. K., et al., 2019. Climate change–related heat stress and subjective well-being in Australia. Weather, climate, and society. 11, 505-520.
Zander, K. K., et al., 2017. Drivers of self-reported heat stress in the Australian labour force. Environmental research. 152, 272-279.
Zander, K. K., et al., 2021. "Run air-conditioning all day": Adaptation pathways to increasing heat in the Northern Territory of Australia. Sustainable Cities and Society. 74, 103194.
Zander, K. K., et al., 2016. Exploring the effect of heat on stated intentions to move. Climatic Change. 138, 297-308.
Zhang, J., et al., 2021. Outdoor thermal environments and related planning factors for subtropical urban parks. Indoor and Built Environment. 30, 363-374.
Zhou, Y., et al., 2019. Sea breeze cooling capacity and its influencing factors in a coastal city. Building and Environment. 166, 106408.
Zografos, C., et al., 2016. When exposure to climate change is not enough: Exploring heatwave adaptive capacity of a multi-ethnic, low-income urban community in Australia. Urban Climate. 17, 248-265.