Journal of Cleaner Production 92 (2015) 1–12

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Review

Impacts of heat waves and corresponding measures: a review

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ARTICLE INFO

Article history:
Received 8 May 2014
Received in revised form
15 December 2014
Accepted 20 December 2014
Available online 27 December 2014

Keywords:
Heat waves
Built environment
Mechanisms
Resilience

ABSTRACT

Heat waves have significant impacts on both ecosystems and human beings. This is compounded by future climate scenarios which indicate more frequent and severe heat waves in certain locations. There are members of communities that are more vulnerable to the effects of heat waves such as the elderly and infants and this presents particular challenges for the future. Hence it is timely to undertake a critical and systematic review of the effects of heat waves and mechanisms to mitigate their effects. There are significant implications associated with heat waves such as extra power consumption, community health, water consumption and quality, and additional costs within the natural and built environments. One of the critical issues is peak electricity demand which is closely linked with factors such as building occupant health and costs to consumers. Utilization of renewable and sustainable energy helps to mitigate this specific issue. Common policy instruments to deal with risks associated with heat waves include heat impact assessment and heat warning system. Similarly, building design should take impacts of heat waves into consideration such as dwelling adaptation. This review provides useful inputs to both policy making and industry practice on improving the resilience of urban and regional areas in the event of extreme weather conditions such as heat waves in the future.

1. Introduction

The last decades have witnessed more frequent and severe occurrences of extreme weather such as heat waves that are likely to be linked to global climate change (Keellings and Waylen, 2014; Benhelal et al., 2013; Beermann, 2011; Dieleman, 2013; Zhao et al., 2012; Yau and Hasbi, 2013). This has attracted an increasingly level of concern from both public and government (Wamsler et al., 2013; Duan and Hu, 2014). The duration and intensity of a heat wave will have a bearing on its impact and the World Meteorological Organization (WMO) provided a snapshot of extreme events over the last decade (2001–2010) (WMO, 2011). It is identified in the WMO report that Australia is one of the regions which is particularly susceptible to heat waves and drought conditions.

There have been a number of record-breaking heat waves in Australia in recent years. In March 2008 a prolonged heat wave hit southern Australia during which Adelaide had a 15 day period with temperatures over 35 °C. This was followed in 2009 with a heatwave in January–February where many places experienced their highest recorded maxima. In Victoria this culminated in the Black Saturday bushfires that claimed 173 lives. In late December 2012 and early January 2013, the heat wave events occurred in vast area of Australia with 70% of population was affected (Steffen, 2013). More than one third of number of days with an average maximum temperature exceeding 39 °C during the last century of Australia occurred in the last summer (BoM, 2013). This includes 7 consecutive days above 37 °C in Perth, 17 consecutive days of 40 °C or above in Alice Springs, and five consecutive days of 48 °C in some areas of South Australia.

Nguyen et al. (2010) analysed 153 years of climate data for Melbourne and found that, while there has not been an increase in the overall number of days over 35 °C or 40 °C there has been an increase in the number of 2–3 day hot spells. This is significant as there is evidence to suggest that, in terms of its impact, the duration of a heat wave may be more important than intensity (D'Ippoliti et al., 2010). Recent heat waves in other states such as Western Australia and South Australia were also well documented in both academic studies and industry reports (e.g. Pezza et al., 2012; Bi et al., 2011; Williams et al., 2012a,b; Ibrahim et al., 2012; Granger and Berechree, 2009; PwC, 2011). The vast majority of these

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http://dx.doi.org/10.1016/j.jclepro.2014.12.078
0959-6526/

studies placed a focus on the health impacts of heat waves and appropriate policy responses. There has been very limited research on building design as a mechanism to respond to challenges and risks associated with heat waves.

According to the predictions from the Intergovernmental Panel on Climate Change (IPCC), the length, intensity and frequency of heat waves will very likely increase in many countries in the future (Field et al., 2012). This is also echoed in a number of academic studies across Europe and North America (e.g. Beaulant et al., 2012; Lau and Nath, 2012; Sheridan et al., 2012). The phenomenon is supported by National Climate Change Adaptation Research Facility (NCCARF) which forecasted the number of very hot days in major cities will double by 2070 (ISR, 2010). The modelling of the global climate over the 21st century by the International Panel on Climate Change is well known (IPCC, 2000, 2007) and includes a warming effect of between 1.4 °C and 5.8 °C over the period 1990 to 2100. In particular, the recently released IPCC report predicted that the global mean surface temperatures for 2081–2100 will increase up to 4.8 °C compared to that of 1986–2005 (IPCC, 2014). The new IPCC reports also projected that the global mean sea level rise could be as high as 0.82 m. In Australia, the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and Bureau of Meteorology have developed climate change projections (CSIRO, 2007) that are based on the possible future scenarios for emissions defined by the IPCC. Table 1 gives data for current conditions, and projections for 2030 and 2070 based on two emissions scenarios.

The data indicates an increase in number of days over 35 °C over the next 20–50 years ranging from moderate to substantial. What is not shown is whether the projected increases in number of hotter days will be consecutive or sporadic.

A recent report by the Climate Commission of the Department of Climate Change and Energy Efficiency predicted that "… (it) is highly likely that extreme hot weather (such as heat waves) will become even more frequent and severe in Australia and around the globe over the coming decades" (Steffen, 2013). The significant impacts of heat waves on both the natural and built environment have gained growing public awareness. As a result, there is an increasingly level of research focusing on the mitigation of the impacts of heat waves although much less on adaptation (VijayaVenkataRaman et al., 2012).

There is not lack of studies on heat waves considering its significant impacts on human health and environment. However, there are very few studies focusing on a systematic review of the effects of heat waves and mechanisms to mitigate these effects in Australia context. Following the record breaking hot weather in last summers of Australia, there are predictions that the heat waves will remain a significant risk of coming years. Therefore, it is a timely study to review the existing body of knowledge related to heat waves systematically. This will provide useful inputs for policy making and industry practice to improve the resilience of urban and regional areas to deal with extreme weather conditions such as heat waves. Another contribution of this study is the identification of the implications following the extensive review of literature related to heat waves. This includes the improvement of building design of dwellings by considering the changing climatic conditions in Australia.

This paper reports on a critical literature review which covers the following main aspects: (1) the definition of heat waves; (2) the impacts of heat waves on health, ecosystems and the built environment; (3) the current mechanisms to deal with impacts of heat waves. The knowledge gap is identified as a result of which a future research agenda has been suggested.

The organization of this paper is as follows. The second chapter provides the methodology employed in this paper to identify and analyse literature related to heat waves. This is followed by a review of various definitions of heat waves. The fourth chapter reveals impacts of heat waves on human health and ecosystems. The fifth chapter reviews the mechanisms available to deal with these impacts. The sixth chapter identifies the implications of the extensive review conducted in this study, particularly for the building design of dwellings. Finally, the conclusions are drawn together with the identification of future research directions.

Table 1
Number of days over 35 °C for various Australian population centres, current and projected (Source: CSIRO, 2007), unit: days per year.

	Current	2030 medium emissions scenario	2070 low emissions scenario	2070 high emissions scenario
Adelaide	17	23	26	36
Alice Springs	90	109	122	155
Brisbane (airport)	1.0	2.0	3.0	7.6
Canberra	5	8	10	18
Darwin	11	44	89	227
Melbourne	9	12	14	20
Perth (airport)	28	35	41	54
Sydney	3.5	4.4	5.3	8

2. Methodology

The aim of this research is to present a critical review of impacts of heat waves and corresponding mechanisms. The main sources of literature include:

- International organizations such as: World Meteorological Organization, the Intergovernmental Panel on Climate Change, and World Health Organization
- Major databases of scientific journals such as: Scopus, ScienceDirect, Oxford Journals, and Springer
- Government Authorities such as: Department of Environment, Water, Heritage and the Arts of Australian Government, Department of Climate Change and Energy Efficiency of Australian Government
- National research institute such as: National Institutes of Health of US, National Climate Change Adaptation Research Facility of Australia, the Commonwealth Scientific and Industrial Research Organization

A list of keywords was used to search related papers and reports. These keywords include: extreme weather conditions; heat waves; hot spell; health; overheating; mechanisms; building, etc. As a result, 173 papers and reports were selected to be critically reviewed in this study. Majority of these are sourced from international journals, conference proceedings and books (132); followed by reports from governmental authorities in Australia (19); reports from research institutes (12); and reports from international organizations (10). The papers published in international journals and conference proceedings covered the heat wave related studies in both Australia and overseas. It is also very common that the reports from research institutes and international organizations (e.g. WHO and WMO) used Australia as one of cases for dealing with heat waves.

3. Definition of heat waves

Heat waves are climatic events that are by nature unpredictable, short term and uncomfortable. The Intergovernmental Panel on Climate Change classified heat waves as one of the extreme weather events associated with climate change and one that has a number of risks associated with it (Field et al., 2012). There is no *common* definition of a heat wave although it is generally understood to be a ‘prolonged period of excessive heat’ (BoM, 2011) which is usually associated with atmosphere-related heat stress (Roetzel et al., 2010; Streimikiene, 2010). There are also locational variations to definitions of heat wave. Indeed, it is difficult to define a heat wave due to “establishing an acceptable threshold and duration of an event, and relating it to the climatology of the area under investigation” (Granger and Berechree, 2009; page 1). The length of the period that constitutes ‘prolonged’ and the conditions that equate to ‘excessive heat’ will vary with location. Robinson points out that: “there are two facets to a heat wave, which may be called somewhat loosely, the “physiological” and the “sociological” aspects. The former centers on the general thermoregulation of the human body, the latter on local adaptations to the climate” (Robinson, 2001, p. 763).

It is well recognised that the definition of heat waves may vary by regions as “notions of what constitutes extreme heat is different” (Bobb et al., 2011). People who live in Darwin are likely to have a different appreciation of heat than those who live in Hobart, and capital city residents are likely to have a different definition from those who live in rural parts the country. Thus the definitions of a heat wave often involve a combination of environmental factors (such as temperature, humidity, radiation and wind speed) and social or cultural factors (such as acclimatization) (see Matzarakis and Nastos, 2011).

Definitions may vary according to why people are concerned about heat waves. For example, many organisations are monitoring global changes in climatic extremes, including heat waves, and they require a common definition. It is proposed that the Heat Wave Duration Index (HWDI) should be adopted for this purpose (Frich et al., 2002, p. 195). The HWDI, measured in days, is defined as:

$$\begin{aligned}&\textit{maximum period} > 5 \textit{ consecutive days with } T_{max} > 5^{\circ}C\\ &\qquad\qquad \textit{above the } 1961-1990 \textit{ daily } T_{max} \textit{ normal}\end{aligned}$$

This approach using an absolute threshold (e.g. 5 °C) has been criticized for not taking into account climatic variability (De Boeck et al., 2010). To compensate for this issue, a relative cut-off has been proposed by some scholars. For instance, De Boeck et al. (2010) used the 90th percentile of daily maximum temperature in a European study.

On a local level the definition of a heat wave is often linked to concerns about heat-related health issues. Tong et al. (2012) investigated 10 different definitions of a heat wave and the relationship to health outcomes in Brisbane and found that “*even a small change in heatwave definition had an appreciable effect on the estimated health impact*” (p.1). Indeed, Radinović and Mladjen Ćurić (2012) pointed out that the HWDI should “be based on climatic features that permit the comparison of results across climatic zones” (p.505). They further suggested using statistical thresholds derived from the normal frequency distribution of maximum daily temperature values rather than the constant value employed by the IPCC approach in calculating HWDI.

Currently the Bureau of Meteorology (BOM) has definitions which differ with location. For Adelaide a heatwave is defined as 5 days with a maximum air temperature over 35 °C or 3 days over 40 °C, and for Perth, 3 days over 35 °C. In south-east Queensland, the BOM combines both air temperature and humidity in a measure known as the ‘Heat Index’. A *heat warning* is declared when the heat index is forecast to exceed 36 °C for Brisbane for 2 days or more; an *extreme heat warning* when the heat index is expected to exceed 40 °C for Brisbane for 2 days or more (Qld Health, 2004).

In South Australia, the Department of Families and Communities Extreme Weather Plan (DFC, 2010) defines the thresholds for different levels of alerts or warnings about heat waves based on Average Daily Temperature (ADT) which is the (maximum + minimum temperature)/2. An extreme warning is triggered when Adelaide's forecast temperatures for the following 5 days are for maximums of greater than 40 °C for 3 or more consecutive days and minimum of greater than 24 °C for 3 or more consecutive nights (ADT 32 °C).

Similarly, some researchers proposed to use the mortality rate as a reference cut off point to define heat waves (Zhang et al., 2014a; Tong et al., 2014). This is an alternative to the absolute threshold definition such as HWDI and percentile. It is also worth noting that there are a wide range of weather metrics being used to investigate the health–heat association such as temperature, relative humidity, solar radiation, barometric pressure, and wind speed (Barnett et al., 2010; Zhang et al., 2014a). However, there is no universal standard for the metric of heat exposures yet. Furthermore, the impacts of heat on health may vary according to geographical locations.

The Bureau of Meteorology is proposing a more universal definition based on an analysis of the long-term weather in the location and allowing for the influence of the weather immediately preceding the heat event (CAWCR, 2013). The suggestion is that this definition will be adopted for use in the heat wave plans that are being developed in states and local council areas around the country (e.g. Qld Health, 2004; DFC, 2010; SA SES, 2010). These plans include strategies for issuing warnings and alerts about forthcoming heat waves, provision of information about what to do in a heat wave and mobilization plans for various government agencies.

4. Impacts of heat waves: health, ecosystems and human systems

Heat waves have significant impacts on a number of issues such as health, infrastructure performance, energy demand, building design, water quality and cost (see Fig. 1). These impacts are significant and some of them are even interacted (e.g. cost and power consumption). It is estimated that the 2009 heat wave in southern Australia negatively affected more than one million people in some way (Kiem et al., 2010). These include: more than 420 casualties due to the high heat; and estimated A$800 million of financial losses derived from power outages, disruptions to public transport and response expenditure (Kiem et al., 2010). As shown in Fig. 1, heat waves have significant impacts on health, power consumption, buildings and infrastructures, and costs, etc. Similarly, policies and plans, building design, behaviour and cultural change play critical role to mitigate these impacts to improve the resilience of community and built environment to heat wave events.

4.1. Heat and health

One of the major concerns about heat waves is their impact on health, particularly for vulnerable sections of the community such as the young, elderly, homeless and socially disadvantaged (Vandentorren et al., 2006; Vaneckova et al., 2010; Oudin Åström et al., 2011a; Wilson et al., 2011; Peng et al., 2011). Therefore, it is imperative to conduct health impact assessment for the consequences associated with climate change related events (Haines et al., 2006a,b). This also helps to identify vulnerable groups (Spickett et al., 2011a,b). Health impacts associated with heatwaves range from sunburn, heat stress and heat exhaustion to kidney failure and heart attacks (WHO, 2004; Matzarakis and Nastos, 2011; Thomas et al., 2012). Heat waves can lead to increased hospital emergency admission, ambulance call-outs, as well as increased morbidity and mortality (Nitschke et al., 2011; Wang et al., 2012). Heat waves are a major source of weather-related fatalities in

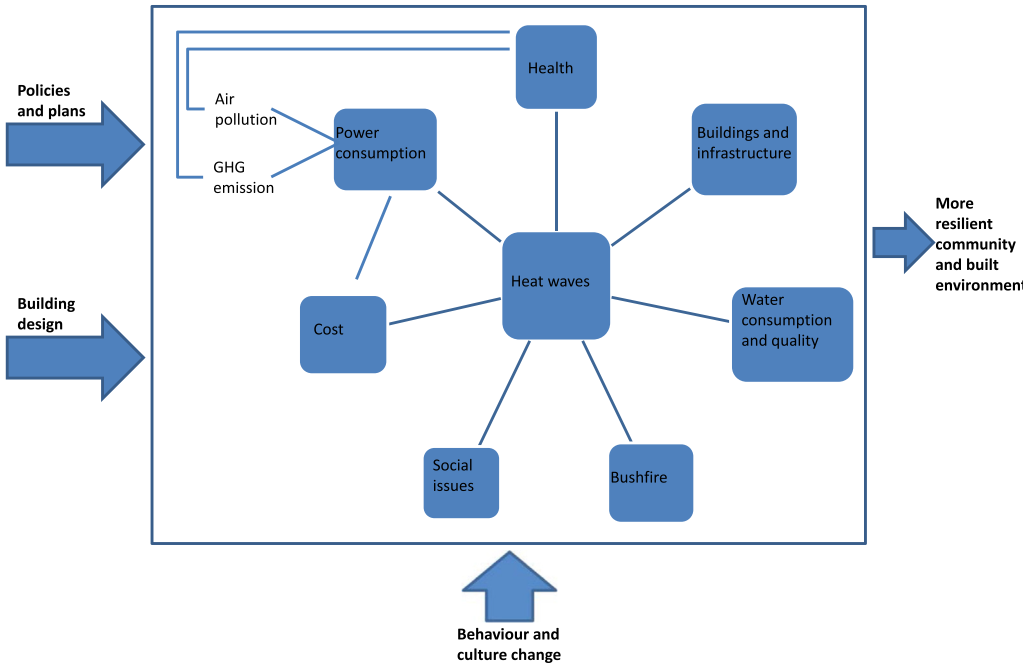

Fig. 1. Effects and mechanisms for heat waves.

Australia (BoM, 2011) and the United States (Robinson, 2001). During the 2009 heat wave in Australia there was a 62% increase in mortality in Melbourne and 10% increase in Adelaide (Nitschke et al., 2011) and it is estimated that 500 deaths can be attributed to the heat wave (Kiem et al., 2010). In 2003 heat waves in southern Europe had a devastating impact with estimates of nearly 15,000 deaths in France alone (Vandentorren et al., 2006) and between 25,000–70,000 throughout Europe (Chaineux and Charlier, 2008; D'Ippoliti et al., 2010). Díaz et al. (2002) modelled the heat waves in Madrid 1986–1997 and found that "a mortality increase up to 28.4% for every degree the temperature rises above 36.5 °C, with particular effect in women over the age of 75 years and circulatory-cause mortality". They also pointed out that low level of humidity will increase the impacts of extreme temperature, "linking dryness to air pollutants, ozone in particular" (see also Spickett et al., 2011a,b). It is worth noting that high level of humidity also exacerbates the impact of extreme weather. This is due to its significant impacts on the ability of human beings to relieve heat stress by means of sweating (Lee, 2014). In addition, it is well recognized that high humidity leads to the decline of both physical strength and mental capacity (Zanobetti et al., 2014). Together with high temperature, high level of humidity increases the feeling of discomfort and heat stress (Halonen et al., 2011).

Heat waves also have impacts on the mental health of human beings (Williams et al., 2012a,b). People with mental disorders are more vulnerable to the heat waves (Cusack et al., 2011) and the physiological heat stress derived from heat wave events should not be overlooked. Pre-existing mental and physical ailments can be exacerbated (Hansen, 2010; Cusack et al., 2011; Gupta et al., 2012). People may have trouble sleeping during a heat wave and this can cause fatigue, a lack of concentration and lead to accidents (Hansen, 2010; Sakka et al., 2012).

Access to air conditioning is reported frequently as a 'protective' factor in reports of morbidity or mortality associated with heat events (Smoyer, 1998; O'Neill et al., 2003; Vandentorren et al., 2006; D'Ippoliti et al., 2010) and consequently some researchers advocate increasing the use of air conditioners to address heat-related health issues (WHO, 2004; Harlan et al., 2006). However, Maller and Strengers (2011) caution against the suggestion that increased air conditioning is the best way to address heat-related health problems. They maintain this 'techno-fix' may mean other strategies (such as passive design measures) are ignored. This can increase problems if power outages occur during heat waves and air conditioning is the only means of mitigation. There is a suggestion that increased reliance on air conditioning may reduce acclimatization (Institute of Sustainable Resources, 2010).

4.2. Power consumption, peak loads

There has been a rapid increase in the penetration of residential air conditioning, which was virtually static through to the 1990s and then increased rapidly from 1999. EES 2008 predicts that air conditioner use will continue to increase and that by 2020 nearly 80% of Australian dwellings will have some form of air conditioning. There are a number of suggested reasons for this growth:

- Significant decline in the capital cost of air conditioners
- Relatively low fuel costs
- Changes to house designs – increased density, reduced eaves, increased number of 2-storey houses with uncomfortable upper (bedroom) levels
- A number of years with very hot summers from 2000 to 2010 (EES, 2008)

Maller and Strengers (2011) suggest that, even if air conditioning is installed, higher energy costs may mean that vulnerable groups may not be able to maintain it. The inability of people to meet their energy needs and the problems that arise as a result is known as fuel poverty and there is considerable evidence that this phenomenon is occurring in Australia (VCOSS, 2005). The causes of fuel poverty include inadequate income, poor thermal performance of housing, inefficient appliances and regressive tariff structures. The inability to pay electricity, gas and telephone bills on time is reported by 18.4% of people in the lowest income quintile, 13.5% in the second and 16.4% in the third quintile in Victoria (VCOSS, 2005). It is likely that the section of the community who are susceptible to fuel poverty will be more vulnerable in the future given the combined effect of more extreme climate events and higher energy costs. The fuel poverty is also one of significant social issues associated with heat wave events.

The average price of electricity in Australia was roughly constant between 2002 and 2007 but then increased up until 2011 by approximately 40% in real terms (Mountain, 2012). The Australian Energy Markets Commission (AEMC) expects that by 2013/14 household electricity prices will rise by another 20–33% (AEMC, 2011). On an international basis, the price of electricity is higher than many OECD countries; 20% higher than the EU, 70% higher than the U.S. and 130% higher than Canada. Given overseas and local trends in price increases, these differences are predicted to be significantly greater by 2013/14 (Mountain, 2012). The use of electric fans, which is less energy demanding than refrigerative air conditioning, may help to reduce the adverse health impacts associated with heat waves (Gupta et al., 2012). Similarly, renewable and sustainable energy resources, such as solar power and wind power can be utilized in buildings to help reduce the electricity demand and cut greenhouse gas emissions (Panwar et al., 2011; Baniyounes et al., 2012). Indeed, the public policies on renewable energy play a critical role of the intervention of climate change to promote healthy and resilient communities (Kravchenko et al., 2013). This is achieved by means of control of air pollution (Haines et al., 2006a,b).

Peak demand has become a particular problem in many developed countries as electricity use increases. Power plant capacity is required to cover times of peak demand even though these times occur for a very short period (Saman and Halawa, 2009). There is an increasing level of air conditioner usage for space cooling purpose which has significant implications on peak electricity demand (Yau and Hasbi, 2013; Rübbelke and Vögele, 2013; Strengers, 2012). In Australia, peak demand for power occurs during the hottest weather even for Victoria where peak demand shifted from winter to summer by late 1990s (EES, 2004). Hot conditions cause problems with both power generation and transmission, leading to associated increases in greenhouse gas emissions per unit of energy consumed (Matzarakis and Nastos, 2011). Electricity transmission systems are vulnerable to high temperatures, particularly when night-time temperatures are high as this reduces the ability of the system to shed excess heat (Institute of Sustainable Resources, 2010). Resultant power outages are common during severe heat waves. During the 2009 heat wave in southern Australia a number of households in Adelaide and Melbourne were without power during the extreme heat either due to direct failure of the system or controlled load shedding designed to avert system breakdown. A number of deaths were connected to a lack of air conditioning either due to power cuts or because the household did not have an air conditioner (Son et al., 2012). In Melbourne, the 2009 heat wave events had significant impacts on the peak load which is responsible for the explosion of a supply transformer of the power grid (Boston, 2013).

4.3. Buildings and infrastructure

Heat waves also have significant impacts on built environment such as urban infrastructure (Smith and Lawson, 2012; Depietri et al., 2012). A heat wave event may cause damage to transport infrastructure, e.g. buckling of rail tracks, damage to roads, and failure of systems such as traffic lights (Institute of Sustainable Resources, 2010; Thom et al., 2010). McEvoy et al. (2012) examined the impacts of 2009 heat wave on the urban infrastructure at Melbourne, Australia. Their study found that the heat waves have major impacts on the electricity infrastructure; moderate impacts on roads and rail whereas water, telecommunications and airports are relatively less vulnerable.

Similarly, heat waves may cause problems with building materials, e.g. expansion stress in concrete and steel structures, problems with protective finishes, and stress in large sections of insulated glass units (PwC, 2011). In addition, the extensive exposure to ultraviolet radiation could bring damage to building materials and coatings which affects their durability (Yau and Hasbi, 2013).

Another critical aspect of heat wave is urban bioclimatology (WHO, 2004). The health impacts of heat waves are exacerbated in cities and built-up areas due to the urban heat island (UHI) effect (Rosenzweig et al., 2005). Of the 8.3 billion global population projected for 2030, approximately 60% will live in cities, up from 30% about 50 years ago. This amounts to an increase of approximately 67 million people a year seeking a living in urban environments (UN, 2006). The development of urban areas reduces vegetation and free water and increases non-evaporative surfaces such as concrete and asphalt (Shimoda, 2003; Tremeac et al., 2012). This causes greater absorption of solar energy with a consequent increase in ambient temperature (Allegrini et al., 2012). Based on meteorological records at Shanghai, Tan et al. (2010) concluded that urban heat island is directly responsible for enhancing the intensity of heat waves and adverse health impacts such as heat related mortality. The effect is amplified by an increase in heat output due to human activities through the use of various forms of energy and adds to the cooling loads of buildings in cities (Ashtiani et al., 2014).

The urban heat island effect has been studied for decades in cities around the world. A review of literature on heat island research in Europe by Santamouris (2007) revealed various temperature differentials between city centres and outlying areas. Typical differentials were several degrees although the maximum heat island intensity in Athens was measured to be 16 °C (Santamouris, 2007). Low thermal mass dwellings are more vulnerable to heat waves due to overheating risks (Peacock et al., 2010; Gupta and Gregg, 2013). The high thermal mass of tall buildings and lack of air movement within urban 'canyons' is a major factor in creating these temperature differentials of between 1 °C and 6 °C according to Luber and McGeehin (2008). Furthermore, heat is absorbed during the day and released slowly at night, known as the hysteresis lag effect (Golden, 2004) which raises the minimum temperatures. Impervious surfaces and materials with high heat capacity can reduce night-time cooling (Harlan et al., 2006; Harlan and Ruddell, 2011) and this may be combined with poorer air quality from many sources including vehicle emissions. An urban heat island has significant impacts on mortality rate, heat related diseases and climate change resilience of a city (Mirzaei et al., 2012; Emmanuel and Krüger, 2012).

Heat waves intensify the urban heat island effect causing an amplification of heat stress and associated problems, especially where there is little vegetation and dense urban form. Planting vegetation and increasing areas of urban parks and gardens is proposed as a longer term factor that can mitigate the combined effects of urban heat island and heat waves (Golden, 2004; WHO, 2004). Gill et al. (2007) modelled the effect of green cover in Greater Manchester, UK, on changes to surface temperature resulting from future climate change. They found that the effect of a 10% green cover to areas of little green, such as town centres and high density residential areas, was to maintain those surface temperatures at or below the 1961–1990 baseline as far in to the future as the 2080s. A further compensating factor is to increase the albedo effect of urban infrastructure; that is to increase the amount of solar radiation that is reflected rather than absorbed by the application of more suitable finishes and colours. Cool (green) roofs are also proposed as a means of reducing the heat island effect by either increasing the albedo effect or by establishing green plantings (Spanaki et al., 2011; Santamouris, 2014; Bianchini and Hewage, 2012).

4.4. Other aspects

The correlation between heat waves and fire occurrences has been documented in a number of locations including western Turkey (Unal et al., 2012) and Australia (CSIRO, 2007; Wilson et al., 2010; McLennan and Handmer, 2012). During a heat wave event, the relative humidity can drop 1% and the drying out of vegetation significantly increased the occurrence probability of catastrophic bushfires (Pezza et al., 2012). Known as Black Saturday, the bushfire event occurred in the state of Victoria in 2007 is devastated with a causality of 173 and substantial economic damage (at least $1.02 billion Australian in insurance claims) (Cai et al., 2009). As the worst bushfire in the recorded history of Australia, Black Saturday was preceded by a record-breaking heat wave in Victoria with a maximum temperature of near 49 °C (Cordner et al., 2011).

Similarly, heat wave events are associated with increased water consumption and problems with water quality. Indeed, Rinaudo et al. (2012)'s study confirmed a statistically significant positive correlation between the heat wave events and water usage. For instance, during the 2009 heat wave in Victoria the water treatment plants were affected by increased evaporation, algal blooms and the breakdown of pumps and other equipment. Wetz and Yoskowitz (2013) found that extreme weather events such as heat waves affect the water quality of estuarine which is related to nutrients and organic matter. The degraded water quality will consequently impact the human health (English et al., 2009). Access to the reliable water service also presents one of significant social risks associated with heat wave events (Yardley et al., 2011). Extreme heat led to damage to the urban water infrastructure such as pipelines which interrupted the water services. The quality of water, especially the drinking water affects the health condition of human beings significantly.

There are also social issues associated with climate change related events such as heat wave. The PwC study found that the increase in crime is correlated with heat waves, e.g. domestic violence and road rage (PwC, 2011). Doherty and Clayton (2011) attributed these issues such as increased homicide and suicide to the psychological impacts of climate change. Huang et al.'s study (2011) found that the land surface temperature is statistically significantly correlated with high poverty and low education as well as higher crime level. Therefore, the heat wave has significant social implications. They further suggested these specific areas should be assigned higher priority in terms of heat prevention and intervention so that the social risks can be reduced. Indeed, Yardley et al. (2011) argued that the social and community factors should be taken into consideration in health planning to mitigate risks associated with heat waves. These factors include: social isolation, income level, education level, socio-economic status, ethnicity, housing, access to air conditioning and transportation. They further revealed that the top down approach which is commonly adopted for heat health planning is not able to accommodate the diverse demands of different communities. As a result, Yardley et al. (2011) suggested that the cultural, physical, and social diversity of communities into consideration during the policy making process. Similarly, Oudin Åström et al. (2011b) revealed that women is one of most vulnerable groups to heat wave events however the risk could be mitigated by means of social conditions, e.g. living with the family rather than alone.

In addition, there are significant cost implications of heat waves. The financial costs include: reduced economic activity, losses to agricultural and horticultural enterprises through damaged crops, cost of the power outages (including food spoilage), disruption to services, reduced outdoor work activities (CSIRO, 2010; Kiem et al., 2010; PwC, 2011). Significant amount of expenditure is needed for both pre- and post-heat wave events. Extra cost is required for electricity consumption to deal with prolonged hot period and this can present a particular issue to low income families (Sakka et al., 2012). There are financial barriers to cooling mechanisms such as using air conditioner or attending cooling centre (Sampson et al., 2013). Similarly, there are costs related to human health issues, social issues and environmental issues discussed in above sections. These non-financial costs should not be overlooked if taking a broader perspective for the economics of climate change.

In summary, there are a range of impacts associated with heat waves. The impacts can be inter-related. For example, disruptions to transport can have a flow-on impact on business activity and productivity; power outages may increase the difficulty of dealing with bushfires, smoke from bushfires can affect electricity grid insulator capacity. Matzarakis and Nastos (2011) asserted that the "synergetic effects of extreme heat conditions, air pollution, and other environmental factors, like noise and UV radiation" are unknown and warrant further research.

5. Mechanisms to deal with heat waves

There are a number of mechanisms for dealing with the effects of heat waves that broadly fall into the following categories:

- Structural/institutional
- Technological
- Cultural/behavioural

The effectiveness of these interventions varies from country to country. However, in general the building design as the mechanism was largely overlooked, particularly in the residential sector. Similarly, these mechanisms can be classified into mitigation or adaptation categories. Ultimately, these mechanisms aim to improve the resilience of urban and built environment to climate change.

5.1. Structural/institutional

Since the 2003 heat waves in Europe, efforts have been made by various governments to mitigate the impacts of heat waves. The heat wave warning system related to public health has been a most common approach worldwide (Zhang et al., 2012). Indeed, heat wave warning systems is an important action plan to reduce heat-related health effects. It provides the useful information and inputs for the decision making process during the heat wave period (Antics et al., 2013). The effectiveness of heat wave warning system is determined by a number of factors such as awareness of public on heat wave and its consequences, communication measures, and socio-demographic factors (Toloo et al., 2013). Knowledge of local conditions should be incorporated into the heat wave and health warning system so that an accurate prediction can be achieved (Zhang et al., 2014b). Similarly, such warning system should be simple and reliable (Pascal et al., 2013). Public may lost faith in the system following false warning or alerts.

However, Kovats and Ebi (2006) argued that "Passive dissemination of heat avoidance advice is likely to be ineffective given the current knowledge of high-risk groups … Populations in regions where extremely hot weather is relatively infrequent are most vulnerable to heatwaves owing to a lack of behavioural adaptations and inappropriate housing". The elderly are one of the groups most vulnerable to the effects of heat waves. Harvison et al. (2011) maintain that the conjunction of an ageing population and the impact of aspects of climate change, such as increasing heat waves, introduces particular concerns in relation to the built environment.

The majority of older Australians live in private dwellings and it is anticipated that this will be the case in the future. Recent Government policy aims to support older people staying in their own homes (Department of Health and Ageing, 2012). Harvison suggest that while new housing should be designed for passive cooling and to have a low carbon footprint, the majority of the current housing stock was built before the Building Code of Australia (BCA) energy efficiency provisions were introduced in 2003 and is likely to need retro-fitting including shading, changing roof colour, insulation and installing ceiling fans or air conditioners (Harvison et al., 2011: p. 48).

Many researchers point out that mitigation is not enough. For instance, Kwok and Rajkovich (2010) maintain that:

> “Even if greenhouse gas concentrations are stabilized in the atmosphere, extreme climatic events and seal level rise will continue for several centuries due to the inertia of the atmosphere. Therefore, adaptation will be a necessary complement to carbon dioxide mitigation efforts” (p 18).

They maintain that policy needs to address both mitigation and adaptation at the regional planning, urban design and building design levels.

In recent years the range of impacts associated with heat waves has been well-researched. Less clear is the connection between residential buildings, the increased heat waves anticipated in the future and the impact on the occupants. It has been suggested that new buildings in Australia that comply with the energy efficiency requirements of the National Construction Code, Building Code of Australia (NCC BCA) are reasonably resilient to the *average* changes expected with climate change. However they may not be so resilient to extremes such as heat waves. Furthermore, dwellings constructed before the introduction of the energy efficiency provisions of the BCA, the bulk of the current building stock, have far less resilience (BRANZ, 2007).

The performance of buildings is affected by a combination of government policy (at federal, state and local level), standards and codes (PC, 2012; BRANZ, 2007). The National Climate Change Adaptation Framework, endorsed in 2007, specifically refers to the need for building codes, standards and guides to increase resilience to climate change and the need for the Australian Building Codes Board (ABCB) to consider climate change as part of their periodic reviews of the BCA (COAG, 2007). In 2010 the ABCB released a study of possible adaptation measures for climate change that could be incorporated into the BCA (ABCB, 2010). The study considers a wide range of climate change impacts including extreme temperatures. As with the BRANZ study, the report finds that, “by and large, the bulk of the BCA's energy provisions will contribute to positive adaptation outcomes” (ABCB, 2010, p. 24). However, when discussing heat waves it maintains that;

> despite heat waves posing a clear health and life safety risk, it remains unclear the role buildings have played; relative to other factors such as age and health of those persons affected… Clearly a buildings ability to maintain stable internal temperatures will reduce some of the health risks associated with heat waves; however the BCA does not currently address issues of thermal comfort directly. Rather, energy efficiency requirements effecting material selection, passive solar design and minimum levels of insulation serve to regulate a buildings internal temperature and therefore reduce risks during heatwaves (ibid: 61)

The recent Productivity Commission draft report “Barriers to effective climate change adaptation” (PC, 2012), notes that although there have been numerous requests that climate change be addressed in the BCA, to date this has not happened. One important consideration is that the BCA is based on historical weather and climate data and that this needs to be reviewed and updated. On the other hand, the Commission notes that the BCA deals with new buildings. However, existing buildings pose a greater problem as they are not required to keep abreast of the requirements of the BCA and there are issues regarding lack of information, costs associated with adaptation measures, and ‘split incentives’ for rental properties.

There have been suggestions that the current National House Energy Rating Scheme (NatHERS) should be supplemented by a measure of a dwelling's performance during days of peak electricity demand (generally days of extreme heat). Different approaches have been investigated. Woolcock et al. (2007) compared the NatHERS ratings and performance on a peak load day for twelve dwelling types of various construction materials and orientations. They found a relatively strong and significant linear relationship between the peak load and star rating of the cases. However for a given star rating there was a $\pm$30% variation in peak load values. Hence, the thermal performance of houses with a given star rating does not directly relate to performance under peak load conditions caused by heat waves. Saman and Halawa (2009) investigated a different approach based on heating and cooling appliances. Neither these two studies progressed beyond the initial research.

Land-use planning needs to work in conjunction with standards and codes (PC, 2012; BRANZ, 2007). Many of the recent planning reviews undertaken by state and territory governments to guide growth in the coming decades refer to climate change mitigation and adaptation measures (see for example Dept of Sustainability and Environment 2005; Dept of Planning and Local Government, 2010; City of Sydney, undated).

5.2. Technological

The World Health Organisation advice regarding building design and heat waves is that “climate-adapted building and energy-efficient design should be stressed over air-conditioning” (WHO, 2004: p 93) partly because of the greenhouse impact of power use and also to guard against energy cuts during heat waves. Many publications about climate change and/or heat waves and health include general comments about using passive design for cooling (WHO, 2004; Snow and Prasad, 2011).

One recent publication that specifically looks at building design in relation to heat waves is, “An investigation of extreme heat wave events and their effects on buildings and infrastructure” (Nguyen et al., 2010). This paper investigates the likelihood of increased hot days and hot spells for different locations in Australia and the impact of hot spells on building thermal performance. The researchers found that the longer the hot spell the more cooling was required. A 3-bedroom house required 32% more cooling energy during a 4 day hot spell than that required for 4 individual hot days.

In 2005 the report, ‘Climate change and the indoor environment’ was published in England (CIBSE, 2005). This presents 13 case studies of residential and commercial buildings that were simulated using synthetic weather years for 2020, 2050 and 2080. The study found that many of the buildings investigated would overheat under these future weather scenarios, particularly those of lightweight construction. Various improvements to the construction are modelled and the likelihood of those designs that may require mechanical cooling in the future. The report lists the principles of adaptation strategies as: switch off (to reduce unnecessary heat gains); absorb (to increase thermal mass); blow away (to introduce an intelligent ventilation strategy); and cool (to introduce active cooling) (CIBSE, 2005).

Using natural ventilation has been recommended by some studies in order to minimize the power consumption; to reduce the greenhouse gas emission; and to improve indoor air quality (Chan et al., 2010; Xing et al., 2011). However, other studies have revealed there is certain level of overheating risks associated with naturally ventilated buildings due to elevated night temperature and internal heat gain (Lomas and Ji, 2009). They have suggested complementing the use of glazing, building orientation and external shading to minimize the risks.

Porritt et al. (2011) examined the effectiveness of interventions to the adapation of dwellings in the UK focusing on terrace houses to cope with future heat waves by means of dynamic thermal simulation. Their findings showed the most effective interventions are wall insulation (where external performs better than internal) and measures to reduce solar heat gain (e.g. external window shutters and painting the external walls a lighter colour). Other interventions such as a lighter coloured roof and increased levels of loft insulation were found less effective (see also Porritt et al., 2012). Porritt et al. (2012) asserted that the most appropriate interventions depend on a variety of factors such as: the type of occupants and their corresponding occupancy profiles as well as the dwelling construction details.

5.3. Cultural/behavioural

Awareness, attitude, behaviour and knowledge of building occupants on heat waves and countermeasures (adaptation), e.g. using air conditioning system (Chatzidiakou et al., 2012) are important factors. The way occupants use their buildings and their willingness to adapt to heat waves play a vital role. In many cases design for heat waves may be different from designing for climates that are generally hot. The period of discomfort may be brief but intense and design solutions that focus on adaptation may involve not just changes to the building stock but also to the way spaces are occupied and to design practices and cultural attitudes. The adaptive behaviour of households is crucial. For instance, Yu et al. (2012) argued that prolonged exposure to static air-conditioned environments may weaken resident's physiological thermal adaptability and natural ability to deal with heat waves in addition to increasing the energy consumption.

The awareness and knowledge of building professionals with regard to heat waves is equally important. Gul and Menzies (2012)'s study found that the UK housing sector is still using “traditional designing methods where overheating, whether current or future, is not considered a serious concern”. The emphasis of this traditional approach is “to fulfil client requirements, to meet minimum standards and regulations and to lower capital costs”. Despite a growing level of awareness on low energy and zero carbon homes, the study found that no proper overheating assessments were considered during house design with an aim to reduce room air-conditioner sales.

Adaptive comfort theory provides a less static approach to understanding thermal comfort, recognising that thermal perception is not limited to factors measurable through the physical and physiological sciences. In general, there are three forms of adaptation from the social perspective as per the thermal comfort model, i.e. psychological adaptation, physiological adaptation and behavioural thermoregulation (Peeters et al., 2009). Both the physiological and psychological categories highlight the relationship between people's perception of a comfortable temperature and their past experience, acclimatisation and heritage (genetic and cultural). The occupants of buildings with a constant internal environment “detached from the diurnal, synoptic and seasonal drifts outdoors” (Jendritzky and de Dear, 2009, p. 27) tend to have a fixed and narrow comfort range. Occupants in buildings that are not air-conditioned are reported to be comfortable across a greater range of temperatures (de Dear and Brager, 2002; van Hoof et al., 2010) with their responses more closely linked to the external temperature.

In previous times (and other cultures) there were many adaptive behaviours for coping with heat. These ranged from changing clothes, reducing activity and drinking more water to ‘manipulating’ the building, by changing floor coverings and opening or closing screens and blinds (Roetzel et al., 2010; Schweiker et al., 2013). One strategy for dealing with heat is to move – either within a building, from the building to more pleasant outdoor areas or to another location (Coley et al., 2012). In many parts of the colonial world, summers were spent in the cooler mountainous regions.

6. Implications for building design of dwellings

Building design is an important consideration in relation to climate change and heat waves both in terms of mitigation and adaptation. Until recently much of the information related to building design and climate change has been concerned with mitigating the effects of climate change through reducing CO_2 emissions associated with the building sector across the building life cycle. According to statistics from the World Business Council for Sustainable Development, buildings contributed to more than 40% of energy consumption in most countries (WBCSD, 2007). Indeed, the building sector is one of the biggest energy consumers and carbon emitters (Zuo et al., 2012). There are many publications aimed at a wide readership that provide information about the relationship between building design and climate change (e.g. Roaf et al., 2005; Smith, 2005; Simon, 2008; Williams et al., 2012a,b; Steenbergen et al., 2012). This is due to the fact that the heat waves not only affect the building (e.g. overheating) but also occupants. Indeed, building design contributes toward the long-term policies and programs to address public health issues associated with heat waves (Bi et al., 2011). The vast majority of these studies focused on the commercial sector. For example, Henze et al. (2007) found that building thermal mass control helps to save energy and cost during heat wave events, even higher than what can be offered by using adaptive comfort criteria in commercial building operation. Peacock et al. (2010) argued that “… thermal comfort (…) is an amalgam of physiological and mental response to a climatic condition. Our mental state at home and the range of adaptive behaviour possible is distinct to that in the office and therefore perceptions of comfort are likely to be quite different”. Pfafferott et al. (2007) pointed out that one of effective approaches to adapt office building during summer period is to utilize “building's thermal storage activated by natural heat sinks (e.g. ambient air, ground water or soil) through night ventilation or thermally activated building systems (TABS)”. Their study found that passive cooling design provides reasonable level of thermal comfort during typical summer climate in Germany however is not enough to deal with long duration heat waves.

Studies on adapting residential buildings are comparatively limited. However, these limited number of studies have highlighted the importance of dwelling adaptation for heat waves. For instance, Mavrogianni et al. (2012) modelled 3456 dwellings in London to investigate the indoor overheating issues using the current and future climate data. Four factors were considered, i.e. dwelling archetype (combination of built form and construction age); morphology of the external environment; orientation; retrofitting of the floor, walls, windows and roof/loft (which affects thermal conductivity and the associated U-values). Their study found that dwelling types and insultation affect the overheating risks. Combined insulation measures (roof/loft and window) help to decrease internal temperatures. However, internal solid wall insulation and floor retrofitting may increase overheating if no night time ventilation is provided as the daytime living room temperature tends to increase with these retrofitting features in place.

Ren et al. (2011) investigated the impacts of global warming on energy consumption and CO_2 emissions for two residential house designs in a number of Australian locations. They considered fixed appliance use and water heating as well as space heating and cooling energy use although they noted that lighting and appliances are 'relatively insensitive to global warming" (p. 2403). The house designs are modelled using AccuRate software with weather files adjusted to represent future temperature increases up to 6 °C. They recommend adapting new and existing houses so that energy use remains the same with future temperature increases. For existing houses in heating dominated climate zones retrofitting from 2 stars (taken as the base case) to 5 stars is required. In climates where there is a balance between heating and cooling, increasing the star rating is required plus increasing the energy efficiency of air conditioning and appliances. In cooling-dominated Darwin all these measures are required plus the installation of an on-site solar photo-voltaic system.

Housing and house design is an important consideration in relation to heat waves and health. The majority of people spend most of their time indoors (WHO, 2004) and the link between health and housing is well-established (Maller and Strengers, 2011). Therefore, the connection between building design and thermal comfort during heat waves is an important area of research. Gul and Menzies (2012) claimed that conventional domestic building design approaches inadequately address future overheating risk derived from climate change. They asserted "A dwelling design should take account of both passive and active measures to reduce the risk of overheating, and the ability of additional measures to be adapted in the future".

There is little information about specific aspects of building design and the heat-related health of the occupants. At a general level, studies have shown that most heat-related deaths are likely to occur in the home or in nursing homes (O'Neill et al., 2003; Dhainaut et al., 2004; Bi et al., 2011). Bedrooms have been singled out as an area of particular concern as "this is often where an occupant will find adaptation difficult, particularly at night" (Patidar et al., 2011, p.273). Patidar et al. (2014) modelled the heat wave duration and probability of overheating using a typical 3-bedroom at future times, i.e. 2030s, 2050s and 2080s. Their study found that the night temperature in the bedroom will increase in the future (30° plus at 2080s during the summer heat wave period) and the overheating duration will increase accordingly (up to 40%). Lack of sleep is one of the factors that pre-disposes people to heat-related illness (WHO, 2004: p. 21) and increased heat-related morbidity and mortality has been identified after a second night of elevated minimum temperature (Loughnan et al., 2010; Nitschke et al., 2011). A study of risk factors associated with deaths during the 2003 heat wave in France highlights two that relate to bedrooms: having a bedroom directly under an un-insulated roof and the number of hours that the bedroom receives sunlight (Vandentorren et al., 2006). Other building-related risk factors identified are a lack of insulation, internal heat gains, greater number of windows per floor area, building orientation, occupancy schedule and smaller dwellings (Porritt et al., 2012).

Dwelling design needs to encourage an increased engagement with adaptive behaviours and promote building solutions employing 'silent technologies' which enable these to occur (Wilkins, 2007). One such solution is the design of 'cool retreats' to provide increased thermal choice and achieve an appropriate level of comfort during heat wave periods within a portion of the dwelling. The cool retreat draws upon the experiences of 'summer rooms' in both Australian and international precedents. At least two distinct cool retreat models are possible; one which draws upon the experiences of sub ground or basement construction employing mass materials and another utilising above ground space featuring thermal control capabilities greater than the remainder of the building.

7. Conclusions

Heat waves have significant implications for human beings and environment. This is compounded by the increased frequency, length and intensity of heat waves in the future predicted by a number of organizations such as the Intergovernmental Panel on Climate Change. This paper has reported a critical review of literature related to the consequences and strategies to respond to heat waves. It is found that even though there are a number of definitions of heat waves, it is well recognized that a heat wave will often involve a combination of environmental factors (such as temperature, humidity, radiation and wind speed) and social or cultural factors. With a projection of increased frequency, length and intensity of heat waves in the future, the traditional definition of heat waves need to be revisited, followed by the re-consideration of associated impacts and measures.

In terms of impacts of heat waves, the review shows that vast majority of existing studies played more focus on environmental issues such as water quality, power consumption, peak demand and pollution; and health issues. Cost and social issues derived from heat waves are comparatively overlooked. Future studies are required to provide more evidence of cost and social impacts of heat waves to inform decision making.

The common mechanisms to deal with heat waves and the associated consequences include: structural/institutional, technological and cultural/behavioural. This study found that structural/institutional and technological are two categories that attracted most attention in the literature whereas cultural/behavioural was paid less attention. This may attribute to the significant amount of resources (e.g. time) required to change the behaviour of residents and somewhat perceived intangible benefits. It is worth noting that these mechanisms are complementary with an ultimate goal to improve the resilience of urban and built environment to the climate change. Indeed, a proper combination of these mechanisms may lead to more effective measures to deal with heat waves and its associated impacts. Effectiveness of these measures varies and is subject to the contextual factors such as cultural background, economic development level, etc. Future research opportunities exist to conduct empirical studies to develop a model for matching measures with contextual factors with a consideration of dynamic relationship amongst these factors.

It is well recognized that heat waves have significant impacts on buildings and infrastructures. Residential buildings should be given more focus in heat waves related research considering the amount of time residents stay at home. This is particular important for those groups more vulnerable to heat waves such as elder people and infants due to health implications. This review shows that there are limited studies on dwelling adaptation for heat waves. Indeed, it is highlighted in this study that the dwelling design plays a critical role for mitigating effects of heat waves. Future research opportunities exist to investigate the design options for dwellings as a response to heat waves in future. Modelling the effectiveness of various design options with future climatic data will provide a useful reference to the future policy making and industry practice. This modelling exercise needs to take various factors into consideration such as: location, local climatic conditions, design modifications and type of dwellings. Similarly, measures need to be taken into consideration for both those suitable for retro-fitting to an existing house and those that could be incorporated into a new house design. The cool retreat is proposed in this study as a critical component of modelling houses for future climate scenarios.

In addition, future research opportunity exists to prioritize the large number of risks associated with heat waves that are reported in this paper. One of common approaches is to analyse the probability and severity of each individual risks (vide Martins et al., 2011). This helps policy makers to assign more resources to those risks with higher level of probability and severity.

Acknowledgement

This research is part of a project at the University of South Australia entitled “A Framework for Adaptation of Australian Households to Heat waves” and supported by the Australian Government's National Climate Change Adaptation Research Facility (NCCARF).

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