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A spatial vulnerability analysis of urban populations during extreme heat events in Australian capital cities

Final Report

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ABBREVIATIONS AND ACRONYMS

°C	degrees Celsius
ABS	Australian Bureau of Statistics
ACF	aged-care facilities
ACT	Australian Capital Territory
AHO	adverse health outcomes
AMI	acute myocardial infarction
AOGCM	atmosphere–ocean global circulation model
ARN	Adaptation Research Network
AT	apparent temperature
BCP	basic community profile
BoM	Bureau of Meteorology
CALD	culturally and linguistically diverse
CBD	central business district
CCAM	conformal cubic atmospheric model
CCD	collection census data
CMG	climate modelling grid
CSIRO	Commonwealth Scientific and Industrial Research Organisation
ED	emergency department
EHA	emergency hospital admission
EPA	Environment Protection Authority
EMS	emergency medical service
GCM	general circulation models
GIS	geographic information systems
HadCM3	Hadley Centre coupled model version 3
HHWS	heat health warning system
IOA	Index Of Agreement
IPCC	Intergovernmental Panel on Climate Change
IRSD	Index of Relative Socio-economic Disadvantage
LGA	local government area
LST	land–surface temperature
MeanT	mean temperature
NARP	National Adaptation Research Plan
NCCARF	National Climate Change Adaptation Research Facility
PCA	principal components analysis

POA	postal area
RMSE	root mean square error
SD	statistical division
SEIFA	socio-economic indexes for areas
SES	socio-economic status
SLA	statistical local area
SREX	Special Report 'Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation'
Tmax	maximum temperature
Tmin	minimum temperature
UHI	urban heat island
VI	vulnerability index
WHO	World Health Organization

Note: where plurals exist in the text, no 's' is added to the acronym

ABSTRACT

Extreme heat events pose a risk to the health of all individuals, especially the elderly and the chronically ill, and are associated with an increased demand for healthcare services. In order to address this problem, policy makers' need information about temperatures above which mortality and morbidity of the exposed population is likely to increase, where the vulnerable groups in the community are located, and how the risks from extreme heat events are likely to change in the future.

This study identified threshold temperatures for all Australian capital cities, developed a spatial index of population vulnerability, and used climate model output to predict changes in the number of days exceeding temperature thresholds in the future, as well as changes in risk related to changes in urban density and an ageing population.

The study has shown that daily maximum and minimum temperatures from the Bureau of Meteorology forecasts can be used to calculate temperature thresholds for heat alert days. The key risk factors related to adverse health outcomes were found to be areas with intense urban heat islands, areas with higher proportions of older people, and areas with ethnic communities.

Maps of spatial vulnerability have been developed to provide information to assist emergency managers, healthcare professionals, and ancillary services develop heatwave preparedness plans at a local scale that target vulnerable groups and address heat-related health risks. The numbers of days exceeding current heat thresholds are predicted to increase over the next 20 to 40 years in all Australian capital cities.

EXECUTIVE SUMMARY

Heatwaves in Australia have a greater negative impact on population health than any other natural hazard. As climate change progresses heat exposure stands to cause additional heat-related illness and death, especially for the most vulnerable groups such as older people, young children, people with chronic disease and those living in built-up areas in cities. As a result, the demand for emergency services such as ambulances will increase during hot weather. Community engagement and the ability to enact proactive as well as reactive strategies to cope with increased risk are important components of emergency service heatwave planning. Communities can adapt to extreme heat events by engaging with emergency managers, local governments and non-government organisations to reduce heat exposures during periods of extreme summer temperatures. This can be done by 1. Changing their behaviors' and living environments. 2. Building resilience facilitated by understanding the nature and location of high-risk areas and developing targeted heatwave adaptation planning.

Service providers need specific information to develop heat-related emergency plans for urban centres and to provide guidance for governments and communities on the adaptation of the local environment. This information includes; who the high-risk groups are, where they live, and how risk will change in the future. This study has developed a 'tool' to map population vulnerability to extreme heat events in large urban areas. That will assist emergency managers and public health authorities develop adaptation strategies to cope with extreme heat. By identifying areas that show a high-risk of heat-related illnesses and increased service demands during extreme heat events, and by providing a decision making framework to guide future adaptation planning.

Developing the tool required three steps.

1. Identification of the daily temperatures at which excess heat-related illnesses and deaths occurred. This was done using daily temperature data from 1999 to 2011. Days that showed an increase in heat-related illness were selected and maps were drawn to show areas within the cities where these events occurred.
2. Development of an index of population vulnerability to extreme heat using readily accessible data. The local environment, the health status of a population and the demographic structure of a population all contribute to vulnerability. All three aspects were included in the index of vulnerability. When complete the index was used to create a vulnerability map for each capital city providing a visual representation of risk during extreme heat events. The maps can be used to inform discussion between government departments, local governments non-government organizations, community liaison groups and provide advice for adaptation and heatwave response strategies.
3. To develop effective medium-term to longer-term adaptation plans, we need to know how heat-related risk is going to change in the future. The temperatures identified in step 1 were modelled for two future time slices (2020-2040 and 2060-2080). This provided an indication of how many extremely hot days we can expect each year in the future. In addition, population projections for each area were used to identify areas where urban density was predicted to increase and areas where the proportion of older residents was predicted to increase. Areas of high urban density require careful planning to offset the urban heat island effect which intensifies heat exposures during hot weather in built-up areas. To help people adapt to hot weather and minimize the risk of heat exposures, information about adaptive behaviors should be made available to

high risk groups such as the elderly. This group may also need some modification to the local environment such as shading from vegetation or access to cool places.

Each step of the study provided information to support specific climate change adaptation measures, and collectively to advise heatwave policy and planning for emergency management.

Key findings for heat-health thresholds

- Threshold temperatures have been specifically developed for emergency mangers to identify increased service demands for each capital city.
- Bureau of meteorology weather forecasts for daily maximum and minimum temperature can be used to calculate heat alerts for each city based on these thresholds. These can be issued to relevant emergency services two or three days prior to the event and updated on a daily basis. Heat alerts can be used by emergency managers and public health practioners to anticipate and prepare for corresponding increases in service demands and save lives.

Key findings for spatial indices of population vulnerability.

- Variables featuring strongly in the vulnerability indices across all cities are; the presence of an urban heat island, areas with high numbers of older residents, and people who required assistance with daily activities (disabilities). Older people and people with disabilities often live in the higher density (hotter) areas of the city. We need to understand people and place in exposure assessments and developing specific responses to area specific problems.
- Ethnicity was also an important factor with higher risk noted in non-English speaking homes i.e. people living in culturally and linguistically diverse communities. Stressing the need to provide culturally appropriate information systems. A vital step to help migrant communities manage the heat during Australian summers.
- Areas of high vulnerability tended to cluster beyond the inner city areas, with several cities showing an increase in risk along the urban fringe.

Key findings from future projections.

- Heat extremes are projected to increase substantially in all cities over the coming decades, emphasizing the need to act now to reduce adverse health impacts.
- There are areas within all cities that currently show high levels of risk and this is predicted to continue into the future. These are key areas for adaptation and heat-health planning strategies. In the absence of adaptation, heat-related mortality and morbidity will increase.

Vulnerability indices are useful tools to inform adaptation and increase community and organizational resilience to natural hazards such as heatwaves. We recommend that emergency managers, local governments, and public health authorities use these maps to initiate discourse and engage collaborative adaptation policies. This research has provided a ‘tool’ to guide short-term, medium-term and longer-term heatwave adaptation policy. However it is the judicious application of this new knowledge that will determine whether heat-related mortality and morbidity can be reduced.

1. OBJECTIVES OF THE RESEARCH

1.1 *Introduction*

Evidence that increases in greenhouse gas emissions from human activity are causing global average temperatures to rise, and the Earth's climate to change, is now unequivocal (IPCC, 2007). Climate models indicate that the global climate is likely to become more variable; and extreme weather events, including floods, storms, heatwaves and drought, to become more frequent and severe (IPCC, 2012). Such changes are a major threat to the health and wellbeing of human populations (Costello, 2009), and indeed, climate change is already contributing to the global burden of disease and health impacts are likely to increase in all countries and regions (IPCC, 2007). An assessment by the World Health Organization (WHO), that took into account only a subset of possible health impacts, concluded that the modest warming that has occurred since the 1970s has already caused over 140,000 extra deaths annually to the year 2004 (WHO, 2008).

Extreme heat events, also known as 'heatwaves', are expected to occur more frequently and become more severe over most land areas of the globe during the 21st century (IPCC, 2012). Heatwaves are an underrated hazard; not only is hot weather in Australia part of the culture of a 'sunburnt country' (MacKellar, 1911), heatwaves are silent killers, less dramatic than floods and storms, and claiming the lives of those who are less visible in society — older people, the sick and socially isolated (Klinenberg, 2002).

Heatwaves are a major environmental hazard, having caused more deaths in Australia over the past 200 years than any other natural hazard except disease (Coates, 1996). More than 4000 deaths have been attributed to heatwaves in Australia since 1800, twice the number of deaths due to either flood or cyclones. In 2003, unprecedented heatwaves killed an estimated 70,000 people across Western Europe (Robine *et al.,* 2008), and in south-eastern Australia 374 deaths were associated with a severe heatwave that included peak temperatures of over 45°C (Victorian Government Department of Human Services, 2009).

The experience of these recent extreme heat events, and information that has come from analyses of their impact, has highlighted factors that contribute to community vulnerability, and the need for adaptive strategies. Vulnerability is defined as the 'propensity or predisposition to be adversely affected' (IPCC, 2012). In the context of climate change, it is 'the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes' (IPCC, 2007). Vulnerability is influenced by a combination of environmental, economic and social factors, and is a function of the level of exposure, sensitivity of the exposed population, and capacity to adapt (Australian Greenhouse Office, 2005).

Not only are heatwaves very likely to become more frequent in the future, but the number of people at risk of harm will increase as a result of demographic changes, increased urbanisation and the increasing trends of social isolation. Older people, particularly those who are dependent on others for care, are disproportionately represented in mortality and morbidity statistics. Cities are sites of high heat exposure with heat-absorbing building materials and a lack of vegetation generating urban heat islands (UHI) that are hotter than surrounding areas, particularly at night. Heatwaves are sudden events and their impacts are swift. For disasters to be averted in the future, extreme heat event adaptation strategies must include elements of pre-summer planning and preparation, education, early warning systems, and targeting of prevention and response strategies to vulnerable groups. For strategies to efficiently and effectively allocate resources, they must have an understanding of the vulnerable groups and where they are located.

The National Climate Change Adaptation Research Plan for Emergency Management has identified 'understanding the nature and location of the risks from climate change related natural disasters' as a priority for research. Knowledge generated will inform the emergency management sector, government agencies and communities to allow effective targeting of resources and enable improved community resilience to risks posed by climate change (NCCARF, 2009). This project will address that priority through investigation of the spatial distribution of risk to extreme heat events for the populations in Australian capital cities.

1.2 *Study objectives*

The overall aim of the following study is to provide an analysis of the spatial distribution of vulnerability of urban populations to extreme heat events in Australian capital cities at the present time, and to estimate future vulnerability in relation to projected climate changes. In particular, this study will:

- identify threshold weather conditions associated with increased emergency service demand in Australian capital cities
- describe spatial distributions of human vulnerability to extreme heat, and provide evidence to develop adaptive measures and information to target emergency responses during heatwaves
- predict and map changes in future heat extremes for Australian capital cities in order to understand the vulnerability of different populations in the future.

1.3 *Report structure*

This study has the following four main components:

1. A review of literature that addresses human vulnerability to heat for the Australian states and territories, as well as an overview of international literature
2. A determination of temperature thresholds above which mortality and morbidity is observed to increase for each Australian capital city
3. An analysis of demographic, environmental and health risks, and development of a spatial index of vulnerability to explain where people face the greatest risk from extreme heat events
4. An estimation of future vulnerability to harm of Australian populations through use of climate modelling and knowledge of existing baseline risk.

These are followed by an overview of research findings and a discussion of gaps in knowledge and future research directions.

2. LITERATURE REVIEW

2.1 *Introduction*

The overall aim of this study is to provide an analysis of the spatial distribution of vulnerability of urban populations to extreme heat events in Australian capital cities at the present time, and to estimate future vulnerability in relation to projected climate changes. The following literature review informs this process and provides a context for the research.

Peer-reviewed and grey literature relating to human heat vulnerability for each state and territory of Australia has been reviewed. The review also includes literature providing an overview of international research findings and activities.

The review commences with an overview of studies on the impact of extreme heat on human populations, and then explores human vulnerability to heat and factors that contribute to this.

2.2 *Method*

Peer-reviewed and grey literature relating to human heat vulnerability for each state and territory of Australia was retrieved, as well as that providing an overview of international research findings and activities.

Peer-reviewed literature

Bibliographic databases addressing the broad subject areas of medicine, geography and environmental science were searched, including Medline and Geobase. Journals accessed included those from the disciplines of medicine, public health, epidemiology, geography, environmental health, climatology, and biometeorology. Bibliographies of key articles were also scanned for other relevant publications.

Terms used in the search strategy were selected to locate literature addressing the domains of extreme hot weather (heatwave/extreme heat/hot weather), older people (older people/elderly), vulnerable population groups (including homeless/socio-economically deprived), risk factors (including: risk factors/risk assessment/urban heat island), health outcomes (mortality/morbidity/heat exhaustion/heat stress disorders/heat-related mortality and morbidity), study location (including: states and territories of Australia) and study design (including: spatial analysis/geographic information systems). The search was limited to publications written in English, and published between 1980 and the present.

Grey literature

Government and other agency reports addressing climate change and extreme weather events, human vulnerability to extreme heat, and relevant adaptation policy and strategies were identified and accessed through the World Wide Web, with particular attention given to publications by health departments from each of the Australian states and territories, Australian emergency services organisations, CSIRO and key international agencies.

Inclusion criteria

Publications were included in the review if they focused on: climate change and extreme heat events, human heat vulnerability including health effects of heatwave events, relationship between heat and health, vulnerable groups, risk factors for harm, spatial distribution of health impacts, adaptation strategies to minimise harm from extreme heat.

Exclusion criteria

Publications were excluded from review if they were written in a language other than English, were published before 1980, or focused on seasonal patterns or effects of cold weather on health.

2.3 *Results*

Background

What is an 'extreme heat event'?

An extreme heat event, also referred to as a 'heatwave', is a weather event characterised by ambient temperatures high enough to pose a serious risk to the health of exposed individuals and populations, as well as to public and private infrastructure (Cleugh *at al.* 2011).

Definitions of 'heatwave' differ between regions and countries so no one definition is universally applicable. This reflects both the influence of usual weather patterns in a particular area, as well as the characteristics of exposed populations, including environment and past opportunities for acclimatisation, on thresholds for harm.

The Australian Bureau of Meteorology (BoM) defines a heatwave in general terms as 'a period of abnormally hot weather lasting several days' (Bureau of Meteorology, 2012). Other definitions are used to more precisely characterise heatwave events through descriptions of exposure thresholds and duration above which morbidity and mortality of exposed populations increased. Thresholds may be based on measures of temperature (NHS, 2011), or more complex indices such as 'apparent temperature (AT)' (Kalkstein, 1986) and 'Tappmax' (D'Ippoliti *et al.,* 2010) that include a consideration of humidity, or 'temporal synoptic indices' (Vaneckova *et al.*, 2008b; Tan *et al.*, 2004) that incorporate additional variables including wind and cloud cover to estimate human health impact. These more precise definitions are used to investigate the relationship between temperature and health, and by government health departments and emergency management organisations as triggers for heat-health warning systems. Examples of extreme heat event definitions used in Australia and by international agencies and organisations are provided in **Table 1**.

Climate change and extreme heat events

The Intergovernmental Panel on Climate Change (IPCC) has concluded in its recent Special Report 'Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation' (SREX), that it is virtually certain that the frequency and magnitude of warm days and nights will increase, and the frequency and magnitude of cold extremes will decrease over the 21st century at a global scale. Furthermore, it is very likely that the length, frequency and/or intensity of heatwaves will increase over most land areas during this time (IPCC, 2012) .

For south-eastern Australia, climate model projections are for average temperatures to rise by 0.6 to 1.5°C by 2030 and by 1.0 to 5.0°C by 2070 when compared with temperatures for the period 1980 to 1999, if climate scenarios are within the range of those considered by the IPCC (IPCC, 2000). These changes will be experienced as an increased frequency of very hot days and warm nights, and an increased duration of extreme heat events (CSIRO, 2012; Alexander and Arblaster, 2009).

Table 1: Definitions of 'extreme heat event' used in Australia and internationally

State or territory of Australia	Definition of extreme heat event
Victoria	*General definition*: a period of abnormally and uncomfortably hot weather that could impact on human health, community infrastructure and services *Technical definition*: average temperature (average of the forecast daily maximum and overnight minimum temperatures) equal to, or exceeding heat-health thresholds determined for the nine forecast districts of Victoria (Victorian Government Department of Health, 2011)
South Australia	The Bureau of Meteorology South Australian Regional Office defines a heatwave for Adelaide as: five consecutive days at or above 35°C, or three consecutive days at or over 40°C (South Australian SES, 2012)
Western Australia	For the Perth metropolitan area: a mean temperature of 32°C or greater for one or more days (Government of Western Australia, 2010)
International examples	
United Kingdom	Threshold maximum day and night temperatures defined by the Met Office for each of nine regions (NHS, 2011).
Environment Canada	A period with more than three consecutive days of maximum temperatures at or above 32°C/90°F (Health Canada, 2008).
EuroHEAT research project	A period when maximum apparent temperature and minimum temperature are over the 90th percentile of the monthly distribution for at least two days (WHO - Europe, 2009).

Human response to heat

Human beings must regulate their internal body temperature to within a very narrow range (average body temperature is 37°C, with a normal range of 35.5 to 37.7°C) to protect vital body structures and allow normal body functioning (Unglaub Silverthorn, 2010). This is achieved through physiological and behavioural responses that influence the balance of heat gain and heat loss. Heat is gained as a by-product of metabolic processes, through muscle activity, and from the environment. In hot weather, physiological reflexes coordinated by the hypothalamus and mediated by the sympathetic nervous system promote heat loss through dilation of blood vessels in the skin and by sweating; a small increase in blood temperature also increases heart rate and cardiac output (Bouchama and Knochel, 2002).

Dilation of cutaneous blood vessels allows large volumes of blood to be shunted through the skin where heat can be lost to the environment through radiation and conduction (Lugo-Amador *et al.*, 2004). This process requires increased work by the heart and can be hindered in people with heart disease, peripheral vascular disease, or who are taking certain medications (WHO - Europe, 2009). Sweating achieves heat loss through evaporation, with the rate of evaporation influenced by the relative humidity of the air (Unglaub Silverthorn, 2010).

Behavioural responses to promote heat loss and minimise heat gain include seeking a cooler environment, removing clothing and reducing physical activity. These responses depend on awareness of hot environments, and capacity to move to cooler spaces and care for oneself, as well as access to shelter and resources.

Heat-related illnesses arise if heat gain from the environment or metabolic processes cannot be effectively dissipated through physiological or behavioural thermoregulatory processes. These illnesses range from mild to life-threatening, and include heat oedema, heat cramps, heat syncope, heat exhaustion and heat stroke (Coris *et al.,* 2004). Heat stroke is a medical emergency, leading to rapid death in 10 to 50% of cases and a poor outcome in a high proportion of survivors (WHO - Europe, 2009, Argaud *et al.*, 2007).

In addition, exposure to extreme heat is reported to exacerbate existing chronic illnesses, with cardiovascular disease, respiratory disease, cerebrovascular disease and metabolic disorders reported to account for a high proportion of excess deaths during extreme heat events (Michelozzi *et al.*, 2005; Rooney *et al.*, 1998).

Impact of extreme heat events on population health

Impact on mortality

A clear association between extreme environmental heat and mortality has been established through analysis of extreme heat events, and the relationship between heat and health over longer periods of time.

Extreme heat events are associated with marked short-term increases in mortality of exposed populations. Unprecedented heatwaves across Western Europe in 2003 led to between 50,000 and 70,000 excess deaths over three summer months (Brucker, 2005; Robine *et al.*, 2008) — 15,000 of these deaths occurring in France during a three-week period (Fouillet *et al.*, 2006). Other heatwave events in the northern hemisphere for which large losses of life have been reported include those in Athens (Katsouyanni, 1988), England and Wales (Rooney *et al.*, 1998; Johnson *et al.*, 2005b), Chicago (Whitman *et al.*, 1997), Portugal (Nogueira *et al.*, 2005), Netherlands (Garssen *et al.*, 2005), Spain (Simon *et al.*, 2005), California (Hoshiko *et al.*, 2010), and Russia (Agence France-Presse, August 6, 2010).

Analyses of these heatwave events have revealed that deaths occur quickly, on the same day or within one to four days of exposure (Hajat *et al.*, 2002; Whitman *et al.*, 1997; Michelozzi *et al.*, 2005), and occur most frequently among older age groups (D’Ippoliti *et al.*, 2010; Johnson *et al.*, 2005a, Pirard *et al.*, 2005). Mortality rates were higher among older women than men in Mediterranean cities affected by the 2003 European heatwaves (D’Ippoliti *et al.*, 2010), and in England and Wales (Rooney, 1998), but higher for older men during the 1995 heatwave in Chicago (Whitman *et al.*, 1997). This suggests that social factors are impacting on older men and women in addition to the physiological consequence of ageing. Evidence for a small proportion of excess deaths being attributed to forward displacement of deaths of frail individuals whose deaths were expected to occur in the short term has been noted for some heatwaves (Braga *et al.*, 2001), but not others (Hajat *et al.*, 2005; Le Tertre *et al.*, 2006), possibly reflecting different sensitivities of exposed populations.

Cardiovascular disease, respiratory disease and cerebrovascular disease have been reported to be prominent causes of death during extreme heat events, with a lesser proportion attributable to the direct impact of heat (D’Ippoliti *et al.*, 2010). This has not always been the case, with disease ‘directly linked to heat’ found to account for the largest proportion of deaths of older people in France during the 2003 event (Pirard *et al.*, 2005).

Some studies have investigated a possible confounding or effect modification of air pollution on the temperature–health relationship. This is an ongoing area of research. Studies report no effect, or confounding and synergistic effects of pollutants including ozone and fine particulates on the health impact of extreme heat (Ren *et al.*, 2011; Ren *et al.*, 2006; Rooney *et al.*, 1998; Johnson *et al.*, 2005a).

In Australia, heatwaves are estimated to have caused at least 4287 deaths over the period 1802 to 2003, twice the number of fatalities caused by floods or cyclones over the same time (Coates, 1996). In Queensland, 22 deaths and 350 injuries were reported following a heatwave in January 2000 (Auditor General of Queensland, 2004), and an estimated 75 excess deaths occurred in Brisbane during a heatwave in February 2004 (Tong *et al.*, 2010a). A severe heatwave across south-eastern Australia in late January 2009 led to a total estimated excess mortality of 32.4 in Adelaide (Nitschke *et al.*, 2011), and an estimated 374 excess deaths in Victoria (Victorian Government Department of Human Services, 2009) .

Older age groups have also consistently been reported to be more vulnerable to high summer temperatures in Australia (McMichael *et al.*, 2003; Gosling *et al.*, 2007; Vaneckova, 2008a; Vaneckova *et al.*, 2008b; Wang *et al.*, 2012; Guest *et al.*, 1999), however increased rates of mortality and morbidity among younger age groups have also been reported. During the 2009 heatwave in Victoria, there was a 55% increase in deaths of people aged 5 to 64 years compared to the same period during the previous five years (Victorian Government Department of Human Services, 2009); excess deaths of the population of Adelaide during the 2009 heatwave were predominantly people in the 15 to 64 years age group (Nitschke *et al.*, 2011); Hansen *et al.* (2008a) reported an increased number of deaths due to psychoactive substance use for females aged 15 to 64 years in heatwave periods compared to non-heatwave periods from 1993 to 2006; increased hospital admissions for acute myocardial infarction (Loughnan, 2010b) and ischaemic heart disease (Nitschke *et al.*, 2011) have been reported for the 15 to 64 year age group during heatwaves in Melbourne and Adelaide.

An estimated 59% of 110 excess deaths associated with a heatwave in Sydney in January 1994 were a consequence of mortality displacement (Gosling *et al.*, 2007). No evidence was found that the excess mortality in the 2004 Brisbane heatwave was a consequence of short-term mortality displacement (Tong *et al.*, 2010a).

A study of the time course of heat impacts on mortality for the population of Brisbane has shown that hot temperatures have an acute, short-term effect. For all-cause mortality, hot temperature effects were seen most strongly up to three days after heat exposure, with deaths of people aged over 85 years, and of people dying from cardiovascular disease being most pronounced within a lag of zero to one day (Yu *et al.*, 2011b). This early vulnerability to cardiovascular death was observed for all age groups (Yu *et al.*, 2011a). Another study investigating the impact of temperature on years of life lost, also of the Brisbane population, has reported that the greatest impacts of heat on mortality occurred on the day of exposure, returning to baseline level within two days (Huang *et al.*, 2012). These findings support the importance of the identification of vulnerable population subgroups prior to summer to allow targeted interventions and support in order to minimise the risk of heat-related morbidity and mortality.

Impact on morbidity

A number of Australian studies have reported the impacts of extreme heat on morbidity of exposed populations (see**Table 2**). Indicators of excess morbidity have included ambulance call-outs, hospital emergency department presentations, and hospital admissions.

Most notably, renal disease (Khalaj *et al.*, 2010; Wang *et al.*, 2012; Williams *et al.*, 2012b; Hansen *et al.*, 2008c; Nitschke *et al.*, 2007), ischaemic heart disease (Loughnan *et al.*, 2010b; Khalaj *et al.*, 2010; Victorian Government Department of Human Services, 2009; Nitschke *et al.*, 2011; Nitschke *et al.*, 2007), and mental health disorders (Khalaj *et al.*, 2010; Hansen *et al.*, 2008a; Nitschke *et al.*, 2007) have been observed to be more prevalent during episodes of extreme hot weather.

More males than females were admitted to hospital suffering from severe heat-related morbidity in New South Wales each year for the period 1993 to 2004 (Beggs and Vaneckova, 2008), but Vaneckova *et al.* (2008b) found women to be more vulnerable to oppressive synoptic weather conditions over the period 1993 to 2001 in Sydney. In Melbourne over the period 1999 to 2004, males were almost twice as likely to be admitted to hospital for acute myocardial infarction (AMI) during episodes of hot weather than females (Loughnan *et al.*, 2010b) .

Table 2: Australian studies reporting relationship between extreme heat and morbidity in Australian capital cities

Location (Author date)	Study period	Population	Exposure	Impact on morbidity
Brisbane (Wang *et al.*, 2009)	1996–2005	Population of Brisbane	Daily temperatures	Average daily emergency hospital admission (EHA) for primary intracerebral haemorrhagic stroke positively associated with summer temperature for the < 65 years age group
Brisbane (Wang *et al.*, 2009)	1996–2004	Patients aged ≥15 years	Heatwaves during this time, defined as daily maximum temperature ≥37°C for two or more days	Increased risk of EHA for all non-external causes for ≥65 year age group, and for EHA for renal disease for people aged 64–74 years during heatwaves
New South Wales (Beggs and Vaneckova, 2008)	1993–2004	All hospital admissions		An average of 91 hospital admissions each year with a principle diagnosis of the effects of heat and light. Consistently more males than females admitted.
Five regions of New South Wales (Khalaj *et al.*, 2010)	1993–2004	EHA	Extreme heat defined as ≥ 99th percentile for each temperature metric, for each region	EHA increased more for heat-related injuries, dehydration, and disorders of fluid and electrolyte balance than for any other conditions. People with underlying mental and behavioural, nervous system, cardiovascular, respiratory, and renal disorders, and neoplasms were described as more susceptible.
Perth (Williams *et al.*, 2012b)	1994–2008	ED presentations	Heatwave days, defined as three or more days ≥35°C	Compared with non-heatwave days, heatwave days were associated with a 3.4% increase in total ED presentations and a 10.9% increase in renal-related ED presentations. Hospital admissions decreased by 10%.
Melbourne (Loughnan *et al.*, 2010b)	1999–2004	All EHA of people aged ≥ 35, for acute myocardial infarction	24-hour average temperature ≥ 30°C, or three-day average temperature ≥ 27°C	Hospital admissions for acute myocardial infarction increased by 37.7% for three-day average temperatures ≥ 27°C and by 10% for a 24-hour average temperature ≥ 30°C. Twice as many males admitted than females, and the males were younger, with peak occurrence in the 60–64 years age group

Location (Author date)	Study period	Population	Exposure	Impact on morbidity
Victoria (Victorian Government Department of Human Services, 2009)	January 2009	Population of Victoria	Heatwave event: 26 January to 1 February 2009	12% overall increase in ED presentations, a 37% increase in 75+ age group, and an 8% increase in direct heat-related presentations, when compared with the same period for the previous five years. Emergency ambulance callouts increased by 25%, with a 46% increase over the three hottest days; the majority of cases were for the 75+ age group, and there was a threefold increase in cardiac arrest cases.
Adelaide (Nitschke *et al.*, 2007)	1993–2006	Population of metropolitan Adelaide	Daily maximum temperature ≥35°C for 3 or more consecutive days	During heatwaves, total hospital admissions, total mental health admissions, total renal admissions, and ischaemic heart disease admissions increased when compared with non-heatwave periods. Ambulance transports for assault-related conditions for people aged 15–64 years also increased significantly.
Adelaide (Hansen *et al.*, 2008c)	1995–2006	Population of metropolitan Adelaide	Daily maximum temperature ≥35°C for three or more consecutive days	Hospital admissions for renal disease and acute renal failure increased during heatwaves when compared to non-heatwave periods.
Adelaide (Hansen *et al.*, 2008a)	1993–2006	Population of metropolitan Adelaide	Daily maximum temperature ≥35°C for three or more consecutive days	Hospital admissions for mental and behavioural disorders increased by 7.3% in heatwave periods compared to non-heatwave periods.
Adelaide (Nitschke *et al.*, 2011)	1993–2008, and March 2008, Jan–Feb 2009	Population of metropolitan Adelaide	Heatwave periods defined as: daily maximum temperature ≥35°C for three or more consecutive days. Two heatwave events: 3–16 March 2008, 26 Jan to 7 Feb	Renal mortality of older people showed an increase in both the 2008 and 2009 heatwave events. Increase in ambulance callouts, hospital admissions, and ED presentations for ischaemic heart disease related disorders in 2009 heatwave, especially for 15–64 age group. Increased ED presentations for heat-related disorders of 75+ age group during 2009 heatwave.

Indirect impacts on population health

Extreme heat events often occur in association with power blackouts, infrastructure failure and fires leading to other impacts on population health. The January 2009 heatwave in Victoria was accompanied by major power outages leading to disruptions to public transport, and failure of air conditioners, lifts and water pumps in city buildings (ABC News, 2009). At least one aged-care facility (ACF) chose to evacuate residents to a cooler environment when air conditioning and power generators failed (Turner, 2010) . Subsequent catastrophic bushfires across Victoria claimed 173 lives (Teague, 2009). Klinenberg (2002) also described this phenomena of a 'disaster within a disaster' when power failures and disruptions to water supplies compounded the impact of the severe heatwave in Chicago in 1995.

Other indirect health impacts of hot weather reported in the literature include increased risks of violence (Auliciems and DiBartolo 1995), crime (LeBau and Corcoran, 1990), suicide (Page *et al.*, 2007), and injury in children (Hussain *et al.*, 2007) and adults (Pirard *et al.*, 2005). A study of the relationship between heat and morbidity from 1993 to 2006 in metropolitan Adelaide reported a significant increase in assault-related ambulance transports for the 15 to 64 years age group during heatwaves (Nitschke *et al.*, 2007).

Projections for future health impacts of extreme heat in Australia

The IPCC has reported that an increase in heat-related deaths is likely to be one of the most significant impacts of climate change for Australia in the future (Hennessy, 2007). A number of Australian studies have sought to predict the extent of this impact. One study concluded that the net impact of hot and cold extremes for the populations of Perth, Adelaide, Melbourne, Sydney and Brisbane combined will be negligible by 2030, as any increase in summer heat-related deaths would be offset by a reduction in winter cold-related deaths (Guest, 1999). Another study investigating Australia-wide hot and cold temperature-related mortality predicted an increase of 1250 deaths in 2070, and an increase of 8628 deaths by 2100, for an unmitigated emissions scenario when compared to a no climate change scenario. The projected impact was predominantly for Queensland, the Northern Territory and Western Australia, with a decrease in cold-related deaths leaving little net mortality in the other states (Bambrick, 2008).

Other studies have projected substantial rises in heat-related mortality. An investigation of temperate and tropical Australian cities has predicted that the annual heat-related death rates for Perth, Adelaide, Brisbane, Melbourne, Canberra and Sydney combined would increase to between 4300 and 6300 by 2050, but the impact on the tropical cities of Darwin, Townsville and Cairns would be considerably less (McMichael, 2003). Another study found that with no mitigation action, heat-related deaths of people aged 65 and over in all six Australian capital cities combined, will be in the range of 8000 to 15,000 per year by 2100, compared with 1100 per year for the baseline period of 1997 to 1999 (Woodruff, 2005). A 344% increase in heat-related mortality from a 1961 to 1990 baseline has been predicted for Sydney by the 2080s (Gosling, 2009).

One study has made projections for the frequency of dangerously hot days likely to cause hyperthermia if the worst scenario of 6°C warming for the city of Perth is realised. They found that for unacclimatised people, outdoor activity would be dangerous for up to 45 days a year, compared to 4 to 6 days at present, and for acclimatised people, outdoor manual work would be dangerous on 15 to 26 days per year compared to the current 1 per year (Maloney, 2011).

Inherent uncertainties in these studies relate to temperature projections, greenhouse gas emission scenarios, and factors that influence the relationship between temperature and health including air quality, demographic composition, population acclimatisation, incidence of chronic disease, and the effectiveness of heat adaptation strategies (Bi, 2011).

Vulnerability to harm from extreme heat events

Defining vulnerability

The health impacts of extreme heat events depends on the vulnerability of individuals and communities (Health Canada, 2011). In the context of climate change, vulnerability is defined as the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes (IPCC, 2007). Vulnerability is determined by a combination of environmental, economic and social factors, and is a function of the level of exposure, sensitivity of the exposed population, and capacity to adapt (Australian Greenhouse Office, 2005). These factors are outlined in the following discussion (see **Figure** 1).

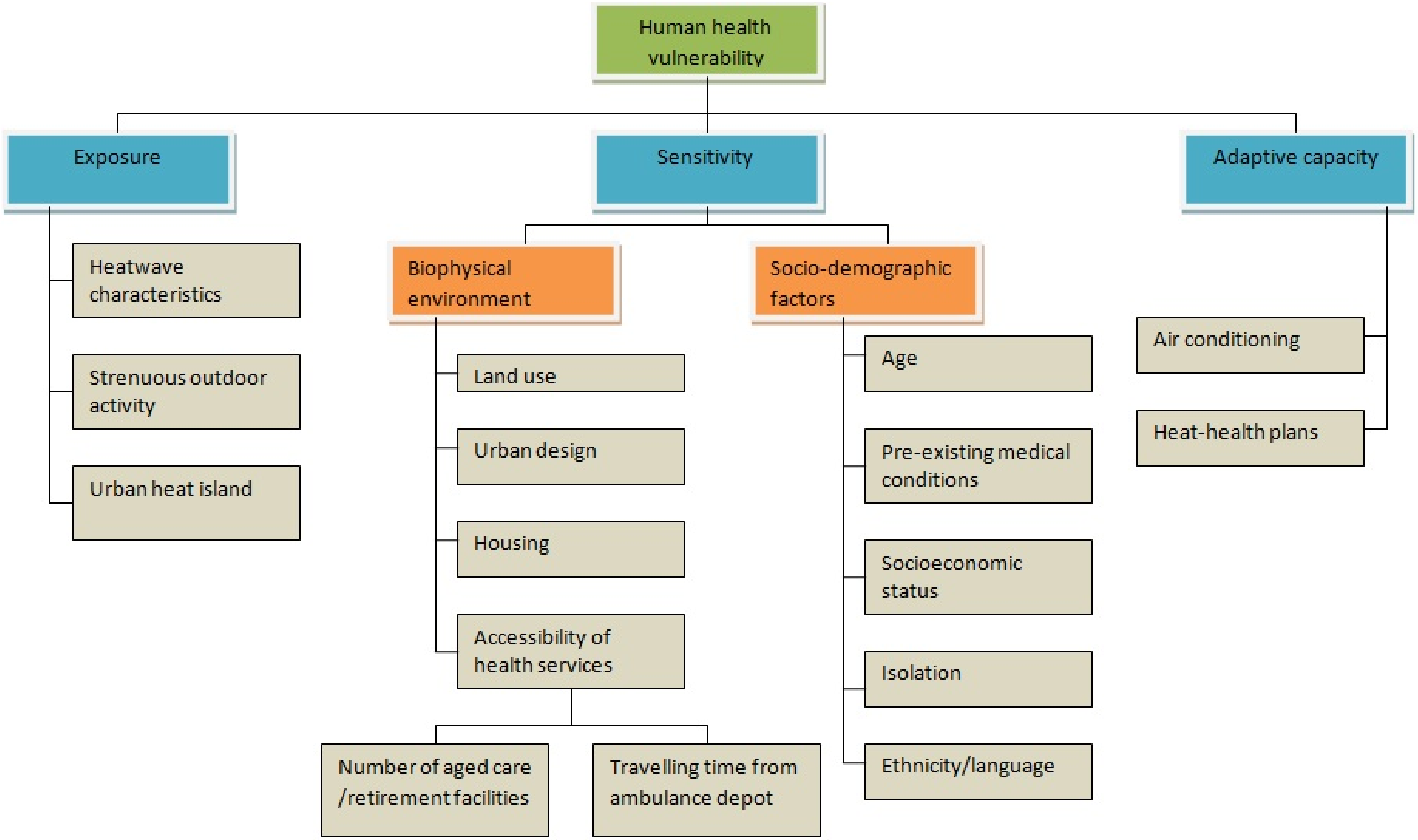

Figure 1: Factors influencing vulnerability to extreme heat events

Exposure to heat

Heatwave characteristics

A number of studies have found that heatwave intensity, duration and timing in the summer season influence the risk of mortality. Numerous international (McMichael, 2008, Basu, 2008, Hajat, 2002, Curriero, 2002) and Australian studies (Bi, 2008, Hu, 2008) have demonstrated a positive relationship between high ambient temperature and mortality. The heat-health relationship has consistently been represented as a J- or U- shaped curve demonstrating an optimum temperature at which mortality rate is lowest, and a steep increase in mortality when temperatures exceed a threshold value (Kovats, 2008). Temperature-mortality thresholds have been determined for a number of Australian capital cities (Gosling, 2007, Bambrick, 2008, Williams, 2012b, Williams, 2012a, Tong, 2010b, Nicholls, 2008, Vaneckova, 2008a, Guest, 1999) and regions (Loughnan, 2010a), and have been incorporated into heatwave plans in Victoria (Victorian Government Department of Health, 2011). **Table 3.** provides an outline of studies investigating temperature-mortality thresholds for Australian capital cities. A number of Australian studies have also investigated temperature-morbidity thresholds (Loughnan, 2010b, Tong, 2010b, Hansen, 2008a, Williams, 2012a); these are outlined in **Table 4**. In the northern hemisphere, higher heat thresholds have been observed for populations that experience relatively higher average temperatures and in settings located closer to the equator (Gosling, 2007, Curriero, 2002, Hajat and Kosatky, 2010), which is considered likely to reflect a range of adaptations to local climate conditions by exposed populations.

Studies of the relationship between heat and health have noted that the measure of daily mean temperature is a better predictor of health impact than maximum temperature alone. This suggests that high night-time temperatures may contribute to heat-related mortality as no cooling down period occurs in which people can recover from the heat of the day (Hajat, 2006). A study in Melbourne has found that the average daily mortality for people aged 65 years or over increases sharply to between 19 and 21% once overnight temperatures exceed 24°C (Nicholls, 2008).

A number of studies have reported a higher risk of mortality as heatwave duration increases (Anderson and Bell, 2011; Curriero *et al.*, 2002; D'Ippoliti *et al.*, 2010). Nitschke *et al*. (2011) reported that heatwaves of longer duration and intensity had a more marked impact on mortality and morbidity in Adelaide, particularly for ischaemic heart disease in the 15 to 64 years age group, and for renal disease and heat-related emergency department (ED) presentations of older people, placing considerable strain on health services.

The timing of extreme heat within the summer season has also been reported to increase health risks (Hajat, 2002, Smoyer, 1998). In a study of the impact of high temperatures on mortality for the population of Sydney, the greatest impact was seen at the beginning of each warm season (Vaneckova, 2008a).

Table 3: Studies investigating temperature-mortality thresholds for Australian capital cities

Reference	Location	Statistical analysis	Study period	Age group	Temperature-mortality threshold thresholds
Guest *et al*. (1999)	Sydney Melbourne Brisbane Adelaide Perth Sydney	Observed/expected analysis	1979–1990	All ages to 85 years	No obvious threshold was detected for any city, however for the five cities combined the greatest annual mean excess deaths attributable to temperature was evident for a threshold of 28°C (maximum temperature)
Bambrick *et al.* (2008)	Sydney Melbourne Brisbane Adelaide Perth Hobart Darwin Canberra	Poisson-regression model	1990–2005	45–75+ years	Temperature-mortality thresholds (daily maximum temperature): Sydney 27°C Melbourne 26°C Brisbane 28°C Adelaide 30°C Perth 29°C Hobart 26°C Darwin 33°C Canberra 33°C
Gosling *et al*. (2007)	Sydney	Observed/expected analysis	1988–2003	All ages	Temperature-mortality threshold of 26°C (daily maximum temperature)
Vaneckova *et al.* (2008a)	Sydney	Scatter plot smoothing	1993–2004	All ages	Mortality was observed to rise at temperatures over 24°C (maximum temperature)
Nicholls *et al*. (2008)	Melbourne	Time-series analysis	1979–2001	≥65 years	Mean daily temperature of 30°C, or daily minimum temperature of 24°C
Tong *et al*. (2010b)	Brisbane	Non-linear regression analysis	1996–2005	All ages	Mortality begins to rise at a maximum temperature threshold of about 27°C.
Williams *et al.* (2012a)	Adelaide	Observed/expected analysis	1993–2009	All ages	Maximum temperature threshold = 30°C Minimum temperature threshold = 16°C
Williams *et al.* (2012b)	Perth	Observed/expected analysis	1994–2008	All ages	Maximum temperature threshold = 34–36°C Minimum temperature threshold = 20°C

Table 4: Studies investigating temperature-morbidity thresholds for Australian capital cities

Reference	Location	Analysis method	Study period	Age Group	Temperature-morbidity thresholds
Loughnan et al. (2010b)	Melbourne	Time-series analysis	1999–2004	≥35 years	30°C daily average temperature and 27°C for three-day average temperature were identified as thresholds above which hospital admissions for acute myocardial infarction increased.
Tong *et al*. (2010b)	Brisbane	Non-linear regression analysis	1996–2005	All ages	Emergency hospital admissions begin to rise at a maximum temperature threshold of about 27°C.
Hansen *et al*. (2008a)	Adelaide	Poisson-regression model	1993–2006	All ages	Hospital admissions for mental and behavioural disorders increased over a temperature threshold of 26.7°C.
Williams *et al*. (2012a)	Adelaide	Observed/expected analysis	1993–2009	All ages (and ≥65 years)	Ambulance call-outs Maximum temperature threshold = 26°C (26°C) Minimum temperature threshold = 18°C (18°C) Heat-related ED presentations Maximum temperature threshold = 34°C (32°C) Minimum temperature threshold = 22°C (22°C)

Strenuous outdoor activity

Participating in either occupational working or recreational strenuous physical activity outdoors has been recognised as a risk for heat stress and heat-related illness (Yip, 2008). Muscle activity is an endogenous source of heat, increasing risk for people working or exercising outdoors, or within ‘uncooled’ indoor environments (Unglaub Silverthorn, 2010, Hanna, 2011).

Older people have been identified as the age group being predominantly affected by heatwaves, however excess deaths and illness also occur within younger age groups during heat events in France and Arizona, particularly for men. This leads to suggestions of occupational or recreational exposure as a potential cause. A study in Maricopa county, Arizona found that 66% of heat-related mortality occurred in outdoor workers (Yip, 2008). The majority of these outdoor deaths were in people younger than 65 years (77%).

A study of hospital admissions for renal disease in Adelaide over a 12-year period noted an association between hospital admissions for acute renal disease and heatwave periods, with the risk for admission being greatest for males aged 15 to 64 years (Hansen, 2008b). In Melbourne, a 55% increase in the death rate was reported for the 5 to 64 year age group, corresponding to 64 excess deaths during the 2009 heatwave (Victorian Government Department of Human Services, 2009). Worker characteristics span all age groups, health status and fitness levels; current trends for an ageing workforce, as well as an increased incidence of obesity and chronic illness may contribute to an increasing risk profile for this group.

Urban heat island effect

The UHI effect is a phenomenon in which ambient air temperatures are higher in urban areas than surrounding rural areas (United States Environmental Protection Agency, 2012). Urban heat islands have been measured for many cities including Melbourne, where a peak temperature differential of up to 7°C has been observed in the central business district (Torok, 2001).

Urban heat islands arise through characteristics of cities that include replacement of vegetation and soil with impervious, heat-absorbing surfaces such as concrete and bitumen, installation of tall buildings that reduce airflow and ventilation, and generation of heat and greenhouse gases through human activities (Huang, 2011, Coutts, 2007). The UHI effect is particularly pronounced overnight when heat stored in buildings and hard surfaces during the day is slowly released overnight, and varies both spatially and temporally depending on the local microclimates, geography and urban development (Coutts, 2010).

A number of studies have shown a greater impact of extreme heat on mortality in urban areas than surrounding regions (Kunkel, 1996, Rooney, 1998, Fouillet, 2006, Smoyer, 2000). One explanation is that the UHI allows little relief from the heat overnight, causing extra heat stress for susceptible individuals (Kovats, 2008). This is potentially a significant issue for Australia where the proportion of the population living in large cities is projected to increase to 67% by 2056 (Australian Bureau of Statistics, 2008).

Sensitivity: Biophysical environment

Land use

Reports indicate that urban green space reduces the risk of heat-related mortality and illness. Kilbourne et al. (1982) conducted a case control study investigating risk factors for heat stroke during the 1980 heatwave in St. Louis and Kansas City, Missouri, and found an inverse relationship between the risk of non-fatal heat stroke and the extent of tree and shrubbery growth around residences. An increased area of urban green spaces in Shanghai was deemed to be an important factor in reducing the health impact of heatwaves from 1998 to 2003 in Shanghai (Tan, 2007). Urban vegetation can reduce temperatures in urban areas by providing shade, evaporative cooling through evapotranspiration, and reduced heat storage capacity compared to bricks and other building material (Aniello, 1995, Jonsson, 2004, Tan, 2007, City of Melbourne, 2012).

Urban design

Urban sprawl may increase vulnerability to a heat hazard by reducing the accessibility of residents in some areas to emergency response services and increase human discomfort in urban areas (Coutts et al., 2012). Towbridge et al. (2009) found urban sprawl of metropolitan counties in the US (measured as a county-based composite index incorporating measures including residential density, segregation of land use, and accessibility of the street network) to be strongly correlated with increased emergency medical service (EMS) response time and a higher probability of delayed ambulance arrival (≥ 8 minutes) following motor-vehicle crashes.

Housing

Older residential buildings arguably pose the greatest challenge to the management of indoor thermal conditions and energy demand, since they are more likely to be poorly insulated and make management of indoor temperatures challenging (White-Newsome, 2012). The spatial location of buildings is likely to influence intensity and duration of exposure to increased temperature. It has been reported that the risk is higher for city dwellers than those living in non-urban areas (Smoyer, 2000). Adaptive measures such as the installation of insulation and passive solar building design, heat-reducing urban planning, and the use of air conditioners for high-risk groups are likely to influence heat-related mortality rates (Woodruff, 2005).

Accessibility of health services

Recent analysis of single visits by patients to emergency departments (ED) in the US from 2002 to 2003 found that geographical location and travel distance play an important role in ED attendance characteristics (Henneman, 2011). The majority of patients were found to live within 12 miles[1] of the ED. Sicker people were willing to travel further to attend an ED, and people were more willing to travel during the day than the night. Spatial analysis of patient volume showed that visit volume decreased with increasing distance from the ED. Barriers to ED visits included the presence of a state border, a major drive and the presence of another ED within one mile of home. The accessibility to emergency services can be quantified as the number of health services within a postcode area or the travelling time from ambulance stations to a patient's home address.

Sensitivity: Socio-demographic factors

Age

Studies of the relationship between hot temperatures and mortality consistently show that older people are at most risk of harm. Young children are also at greater risk of

[1] 1 mile = 1.6 km

heat-related illness compared to adults as they have a greater surface-to-volume ratio, higher metabolic rate, less responsive cardiovascular system and produce less sweat (Grubenhoff, 2007). Non-ambulatory children are dependent on others to move them to cooler environments and to provide them with liquids. Being left in a hot car is a potentially lethal situation (CDC, 2005).

A combination of factors diminishes the older person's ability to maintain a normal body temperature and adequate hydration in the face of high ambient heat, leaving them vulnerable to illness and death. Ageing affects the physiological process of thermoregulation. Older people have been found to have reduced sweat production, decreased cutaneous blood flow, and reduced cardiac output during heat stress when compared to younger individuals (Kenny and Munce, 2003). These factors all contribute to the less efficient dissipation of heat through evaporation, conduction and convection.

The sensation of thirst and ability to satiate thirst may also be altered for older people. Age-related changes to the hypothalamus alter the sensation of thirst satiation in older individuals, leading to earlier thirst satiation for smaller volumes of water which may not be adequate to combat dehydration (Farrell, 2008). In addition, reduced mobility, vision, cognitive function and fitness, or inadequate carer support, as well as concerns about urinary continence may lead to voluntary or involuntary reduced fluid intake and predisposition to dehydration during hot weather.

A number of chronic illnesses associated with an increased risk of death during heatwaves, including cardiovascular disease, respiratory disease, diabetes, cancer and neurological disorders, are more common in people aged over 65 years (Australian Institute of Health and Welfare, 2006). These illnesses as well as medication prescribed for their treatment, including diuretics and agents that affect the sympathetic nervous system, may increase vulnerability to death and illness during hot weather through compromising thermoregulation, and reducing the mobility, awareness and ability to adopt protective behaviours.

In addition, social isolation of older people is common (Australian Bureau of Statistics, 2006), and also a risk factor for death during heatwaves (Vandentorren, 2006). Social isolation can arise through loss of partner, chronic illness, being a 'carer', living in an isolated area, mental illness, language difficulties, inability to access social media, fear of assault, or lacking access to transportation (Findlay, 2002) .

Residents of nursing homes and institutions have been found to be particularly vulnerable to heat-related mortality (Hajat, 2007, Klenk, 2010). Factors that contribute to this vulnerability include old age, general frailty, chronic illness, use of medications, cognitive disorders and dependence on others for care. During the 2003 heatwave event in Europe, mortality rates are reported to have increased twofold in the 75+ age group for people living in retirement homes in France (Fouillet, 2006), and heat-related mortality in the Netherlands was most pronounced in nursing homes (Garssen, 2005).

Pre-existing medical conditions

Pre-existing illnesses including cardiovascular disease, respiratory disease, psychiatric illness, diabetes, neurological disease, obesity and cancer are known to predispose individuals to illness and death during extreme heat (Vandentorren, 2006, Basu, 2002b, Semenza, 1996, Naughton, 2002b). These illnesses and medication prescribed for their treatment may increase vulnerability through altering thermoregulatory capacity, mobility, awareness of hot environments, and ability to respond appropriately.

An increased vulnerability of people with mental illnesses is noted in a number of studies, included those from Australia (Khalaj, 2010, Hansen, 2008c, Nitschke, 2007). Reasons suggested for this increased vulnerability include effects of medication on the nervous system, increased agitation, poor social circumstances with lack of access to air conditioning or cool spaces, and lack of ability to make behavioural responses to heat (Bark, 1998).

Socio-economic status

Socio-economic status as a risk factor for heat-related mortality has been investigated by Australian and international researchers. An increased impact of extreme heat on disadvantaged population subgroups was observed for both the 1995 Chicago and 2003 European heatwaves. Poverty, a high proportion of older people, lack of vegetation and a high incidence of crime have been associated with disproportionately high heatwave mortality rates in areas of Chicago (Klinenberg, 2002). Excess mortality rates in Paris during the 2003 heatwave were found to be twofold higher in the most deprived cantons when compared to the least deprived, when assessed using a 'deprivation index' that incorporates measures of household income, education level, occupation and unemployment rates (Rey, 2009a, Rey, 2009b). Michelozzi (2005) reported the greatest excess mortality during this heatwave event occurred among those of low socio-economic status in Rome, and with lower education levels in Turin.

Socio-economic factors could feasibly have an impact on risk of heat-related illness or death through housing quality, access to domestic air conditioning, access to health care and social services, level of education, use of medications and individual behaviours (CDC, 2004, Johnson, 2009a, Smoyer, 2000). Older people, the sick and disabled people are less able to evacuate into cooler environments in hot day events (Woodruff, 2005). There is evidence that the most disadvantaged socio-economic groups in Australia are more likely to have multiple risk factors for cardiovascular disease, also a risk factor for heat-related death (AIHW, 2005). A study in the US has reported that lower socio-economic groups are more likely to live in hotter urban areas and are therefore vulnerable to greater heat stress (Harlan, 2006).

In contrast to these findings, a study of five large Australian cities over the period 1979 to 1990 found no modification of the temperature-mortality relationship by socio-economic status (Guest, 1999). A study by Vaneckova et al. (2010) investigating the spatial distribution of heat-related mortality for the older population of Sydney also found that socio-economic status, measured as indexes incorporating numerous indicators of income, educational attainment and occupation, was not a significant factor explaining increased mortality. Differences between these and the US and European findings may be related to the comparatively greater homogeneity of Australian populations with regards to extremes of wealth and poverty. In addition, heterogeneity of socio-economic status within study areas (e.g. the statistical local areas – SLA) may influence findings.

A spatial analysis study of the Melbourne population has identified an increased risk of hospital admission for AMI during hot weather for the most and least disadvantaged geographical areas (Loughnan, 2010c). However, for short periods of hot weather, differences in age explained these spatial differences better than socio-economic circumstances. Future research incorporating smaller spatial study areas and information regarding co-morbidities may help to refine these observations.

Social isolation and homelessness

Numerous studies have identified social isolation as increasing the risk of heat-related death. Living alone (Naughton, 2002b, Semenza, 1996), not leaving home each day (Semenza, 1996), being a widow or widower (Stafoggia, 2006), and not having social contacts (Vandentorren, 2006) are strongly associated with an increased risk of death during heatwaves.

Research shows that homeless populations are vulnerable during extreme heat events. In the 2006 Phoenix, Arizona heatwave, there were 13 heat stroke deaths, 11 of which were homeless people (Kovats, 2008). Factors contributing to increased vulnerability of people who are homeless, or who have insecure housing, include lack of access to cool shelter, information and drinking water. In addition, pre-existing psychiatric illness, cardiovascular disease, pulmonary disease, alcoholism and drug abuse, all more prevalent in homeless populations, further exacerbate risk (Ramin, 2009). During the severe heatwave and subsequent Black Saturday bushfires in Victoria, January and February 2009, more homeless people came to use the available healthcare services, food, water, clothing, toiletries, shower and laundry facilities provided in Living Room, a not-for-profit agency located in the centre of Melbourne (Raymond, 2009).

Heatwaves and bushfires are inextricably linked and persons made homeless by fire are at a higher risk of exposure to heat while living in overcrowded or temporary accommodation. When interviewed, homeless individuals described their plight during this time. They reported being 'moved on or turned away from anywhere air-conditioned: Melbourne Central, the State Library, fast-food outlets and public toilets. Even in shaded areas, they said they were harassed by hot and cranky passers-by and questioned by police. Fountains and many taps in the city are turned off or the water is hot, so access to any water, let alone cold water is difficult. Those with a room in a hostel reported paying around $160 a week for a room with no fan or windows' (Raymond, 2009).

Ethnicity and language

Ethnicity has been linked to an increased risk of heat-related deaths (Basu, 2008, Harlan, 2006). People from a non-English speaking background might have difficulty understanding instructions for using household appliances, such as air conditioners or electric fans, as well as in understanding heat response guidelines and factsheets from state and local government which increases their vulnerability and highlights the need for multilingual communication strategies (Hoy, 2010). A qualitative study of heatwave understanding in culturally and linguistically diverse (CALD) communities in Adelaide has identified two high-risk groups: ageing migrants in established communities, and refugees and asylum seekers in new and emerging communities (Hansen et al., 2012). Unequal access to heat-health information and limited adaptation opportunity linked to socio-economic circumstance were identified as key barriers to adaptation.

Adaptive capacity

Adaptive capacity is defined in the IPCC Fourth Assessment Report (Working Group II Report, 17.3) as 'the ability or potential of a system to respond successfully to climate variability and change, and includes adjustments in both behaviour and in resources and technologies' (IPCC, 2007). Adaptive capacity is influenced by the complexity of interacting factors including socio-economic conditions, political systems and institutions, access to and the use of technology, access to information, skills, and infrastructure (Australian Greenhouse Office, 2005). Factors discussed in the literature that influence adaptive capacity include use of air conditioning, and the development of heat-health plans.

Air conditioning

Having a working air conditioner, or being able to visit other air-conditioned environments have been identified as protective against heat-related death by a number of studies (Naughton, 2002a, Semenza, 1996, Bouchama, 2007). Other studies have identified lack of access to air conditioning as a risk factor for death and illness during heatwaves (Rooney, 1998, Nunes, 2011, Semenza, 1996, McGeehin and Mirabelli, 2001). This leads to the conclusion that access to air conditioning is an important adaptive behaviour.

During the July 2006 California extreme heat event, 13% of heat stroke victims, most of whom were elderly and living alone, had not used their functioning air conditioning (Margolis, 2008). O'Neill et al. (2005) found a lower prevalence of central air conditioning in African–American residences in four US cities. These subgroups were also found to have higher heat-related mortality rates than other ethnic groups (O'Neill, 2003). A decrease in heat-related mortality between 1998 and 2003 in Shanghai was also partially attributed to the increased use of air conditioners (Tan, 2007). In developing a county-based heat vulnerability index (VI) across the US, Reid et al. (2009) found that the prevalence of air conditioning correlates with lower cumulative heat vulnerability. Similarly, a case-control study in St Louis and Kansas City, Missouri found a decreased risk of heat stroke for people living in houses with air conditioning and for persons spending more time in air-conditioned places (Smoyer, 1998).

Other studies have expressed concern that increased use of air conditioners will reduce the opportunities of populations to acclimatise to heat, contribute to greenhouse gas emissions and to anthropogenic urban heat loading, as well as bring about power blackouts during heatwaves due to peak usage (Maller, 2011). For these reasons, a number of commentators have encouraged other solutions to the protection of residents in urban areas from heat extremes. These include improved urban planning, housing design, use of vegetation to allow passive cooling, and better access to shared cool spaces, rather than an increasing dependence on air conditioners (Bambrick, 2011, Younger, 2008, Farbotko, 2011, Woodruff, 2005).

Heat-health plans

In response to major heatwave events, many large cities and regions in the United Kingdom (NHS, 2011), Europe, US and Canada now have heat plans such as the heat health warning systems (HHWS) in which short-term interventions aimed at vulnerable population groups are triggered by forecasts of hot weather. Core elements of these plans include: community education and engagement, an alert protocol, a community response plan, and an evaluation plan (Health Canada, 2012).

Heatwave response plans are now available, supported by a range of web-based materials for Victoria (Victorian Government Department of Health, 2011), South Australia (South Australian SES, 2012), and Western Australia (Government of Western Australia, 2010). These organisations also provide web-based support materials for the community and health professional, as do the health departments of Queensland (Queensland Government, 2011) New South Wales (NSW Ministry of Health, 2011), the Australian Capital Territory (ACT Health, 2011), and the Northern Territory (Northern Territory Government, 2011).

2.4 *Conclusion*

This review has explored the Australian and international literature addressing aspects of human vulnerability to extreme heat events. The review shows that extreme heat events are associated with large increases in short-term mortality and morbidity of the exposed population, and are therefore a major hazard for human health. While all people are vulnerable to harm from these extreme weather events, some groups within the community have consistently been shown to be more vulnerable to harm than others — in particular older people, the very young, those who have chronic illnesses, and those who are socially isolated and have limited means to care for themselves. Only a small proportion of deaths in heatwaves represent forward displacement of the deaths of people expected to die in the short term. Heatwave deaths are largely avoidable. This information supports the importance of implementing preventive measures, such as earlier planning, and the identification of vulnerable groups to minimise harm. Additionally it highlights the need to build individual, community, and organisational resilience to disasters such as heatwaves. The following three chapters will describe the research steps that were taken to develop the spatial vulnerability assessment and the implications for vulnerability in the future under two different climate change scenarios. Firstly threshold temperatures were identified for each capital city using a nationally consistent methodology in an attempt to overcome some of the inconsistencies noted in the extant literature. This will be described and discussed in the next chapter.

3. THRESHOLD TEMPERATURES AND HUMAN HEALTH

3.1 *Introduction*

Extremes of temperature, particularly extreme heat events, pose significant risk to human health and consequently make considerable demands on public health and emergency services. Evidence from the published literature indicates that temperature thresholds or tipping points exist above which mortality and morbidity of exposed populations increases (McMichael, 2008, Curriero, 2002). This study identified threshold temperatures related to emergency service demands on hot days using readily available Bureau of meteorology forecasts. This information can be used to identify high-risk days and to trigger implementation strategies to minimise the adverse health effects of extreme heat.

Temperature thresholds have been identified in many regions around the world including Australia (Williams, 2012a, Gomez-Acebo, 2012, Hajat, 2002, Guest, 1999, Nicholls, 2008, Loughnan, 2010a). There are several statistical approaches frequently used to identify threshold temperatures. The choice of a statistical approach will depend on the type of data used but all rely on identifying the temperature at which excess mortality and morbidity occur. Care must be taken when interpreting the results as different time slices and the use of different diagnostic disease categories may yield different threshold temperatures as demonstrated in the previous chapter (see Tables 3 and 4).

A notable latitudinal effect has been observed, with higher thresholds occurring at lower latitudes, that is, in 'hotter' regions (Gosling, 2007, Keatinge, 2000, Curriero, 2002). Whether or not this latitudinal variation exists across Australia is at present unknown. Global and regional climate change models predict an increase in the frequency, duration, and intensity of extreme heat events in Australia and elsewhere (CSIRO, 2012, Alexander, 2009, IPCC, 2012). This translates to an increased demand for healthcare services including the ambulance service, hospital emergency departments and hospitals. This increased demand may be unsustainable in the future unless the adaptation and mitigation capacity of communities, service providers, and infrastructure is improved. In addition to the predicted increase in heat events, there are predicted increases in populations deemed 'vulnerable' such as the elderly and chronically ill, as well as increased urban population densities adding to UHIs as cities grow. These changes will further exacerbate the impact of heat events as age and chronic illness are known to be linked with lower socio-economic circumstance (Australian Institute of Health and Welfare, 2010) and higher density poorer neighbourhoods are often situated in hotter parts of the city (Harlan, 2006).

The IPCC Special Report Managing the Risks of Extreme Events and Disasters to Advance Climate Adaptation (SREX) broadly describes vulnerability as exposure versus adaptive capacity, or the rate, magnitude and character of the change, the sensitivity to climate change, and the adaptive capacity of the community exposed (IPCC, 2012). However, it must be acknowledged that climate change will occur differently in different locations — the direct and indirect effects of climate change will be mitigated by the differences in exposure, the differences in preparedness, response, and resilience across different regions. To improve a community's resilience it is important to either reduce its exposure to extreme weather events, or to increase preparedness and response capacity through extreme event warning systems.

Extreme heat events in Australia are predicted to increase in intensity, duration, and frequency (Alexander, 2009). Heat events in Australia are responsible for the deaths of more Australians than any other natural hazard (Coates, 1996). Unlike catastrophic natural hazards such as floods and earthquakes, heatwaves are silent — we do not see or hear them, they do not result in broad scale evacuations, but hit each household individually and unequally, leaving older, poorer, and socially isolated residents at risk of greater harm. The 2009 heatwave in south-eastern Australia resulted in hundreds of deaths mostly of people over 65 years, highlighting the vulnerability of older people to natural hazards (Victorian Government Department of Human Services, 2009). Insufficient warning about the severity of this heatwave limited the ability of emergency services to prepare for, and respond to the event. The gravity of the situation was further compounded by electricity blackouts, public transport failure, and occupational health and safety restrictions on working conditions for home and community care workers. This limited the services normally supplied to the aged and chronically ill. In addition, there was a lack of knowledge about behavioural and technological adaptations to minimise the effects of heat on health.

The review of current literature highlights the importance of communication and early warning systems enabled by weather monitoring and assessment for reducing harm from extreme heat events. (Fouillet, 2008, Ebi, 2005, Kovats, 2008, Kovats, 2006). Currently there are no national approaches for determining a threshold for hazardous heat events. Each Australian state and territory employs a different heatwave alert system or definition and enacts different heatwave action plans. For example the information from published Australian studies provided in Tables 3 and 4 show a range of thresholds for each city. In many cases different disease categories were analysed across different age groups using different data periods. Some studies examined all ages together some only the older population aged 45+ years (Bambrick *et al.2008)* or 65+ years (Nicholls *et al,* 2008). Some studies used mortality data (Table 3) and Table 4 used various measures of morbidity such as ED presentations, ambulance calls (Williams *et al.,* 2012a) and emergency hospital admissions (Tong *et al.,* 2010). A threshold for emergency hospital admission cannot be used to predict emergency service demand for ambulances. The thresholds identified in some instances are very close to average summertime temperatures in the cities studied. To use these for heat-health alerts would mean issuing many alerts over the summer period potentially leading to warning fatigue. There are also gaps in the information available, there are no internationally peer-reviewed published studies describing thresholds in Canberra, Hobart or Darwin.

The purpose of the following study has been to use a nationally consistent approach to identify threshold temperatures above which mortality and morbidity increases in each Australian capital city. This information can be used to develop a national approach for advising emergency managers and healthcare services of impending heat events and their potential magnitude in terms of mortality and morbidity.

3.2 *Research methods and activities*

Study areas

The Australian Geographical Standard Classification of statistical division (SD) for each capital city was used to define the study area (Australian Bureau of Statistics, 2011). For each capital city this includes the central business district (CBD) as well as the greater metropolitan area.

Meteorological data

Daily temperature data were obtained from the Australian Bureau of Meteorology (BoM) including daily maximum and minimum temperatures, and daily maximum and minimum dewpoint temperatures for the period 1999 to 2009. Maximum temperature was the highest temperature measured in the 24 hours after 9am, and minimum temperature the lowest measured in the 24 hours before 9am, in degrees Celsius. Dewpoint temperature, a measure of the moisture content of the air (i.e. the temperature to which air must be cooled for dew to form), was also measured using this time frame (Bureau of Meteorology, 2012). From the data, daily mean temperatures (the average of the daily maximum and following overnight minimum temperatures), and daily apparent temperature (AT) were calculated. Apparent temperature includes a measure of humidity and is a measure of the impact of 'oppressive' weather on health (Kalkstein, 1986). It is calculated as shown in **Equation** 1.

Equation 1: Calculation of apparent temperature (AT)

$$AT = -2.653 + (0.994 \times \text{temperature °C}) + 0.0153 \times (\text{dewpoint temperature °C})^2$$

Mortality and morbidity data

Mortality data were obtained from the Australian Bureau of Statistics (ABS) and included the daily total number of deaths in each SD of Melbourne, Sydney, Adelaide, Brisbane, and Perth from 1999 to 2009. The small number of daily deaths in Hobart, Canberra, and Darwin meant the ABS could only provide second-daily numbers of deaths (deaths over a 48-hour period) for Hobart and Canberra, and weekly death totals for Darwin. The ABS is restricted from publishing information in situations where fewer than five deaths occur.

Morbidity data were obtained from state ambulance services and state health departments. Three morbidity measures were used depending on data availability: 1) emergency ambulance call-outs, 2) ED presentations and corresponding triage category, and 3) emergency hospital admissions (EHA). Emergency ambulance call-out data included all callouts other than those for patient transfers. Emergency hospital admissions included all admissions other than those for elective procedures.

Ambulance call-out data were not available for each city, therefore daily number of ED presentations and corresponding triage category, and daily number of emergency hospital admissions were obtained from state health departments where required. The South Australian Department of Health provided daily totals of ED presentations at Adelaide hospitals by triage category 1 to 5. Only triage categories 1 to 3 were considered in the analysis as these include presentations requiring immediate treatment[2]. The Australian Capital Territory Ambulance service provided daily totals of ambulance call-outs by four levels of emergency responses (A1 to A4) and by resource dispatched to emergency incident. Unique emergency incidents were used in the analysis. Emergency responses (graded as A1 and A2) were considered in this analysis as they required immediate emergency response [3]. The daily numbers of EHA were provided for Sydney. **Table 5** outlines the mortality and morbidity measures used in threshold calculations for each capital city.

[2] Triage category according to urgency of need for medical or nursing care, using the National Triage Scale (Australasian College for Emergency Medicine) 1 = resuscitation, 2 = emergency, 3 = urgent, 4 = semi-urgent, 5 = non-urgent, 6 = dead on arrival

[3] Emergency incident response graded as A1: Emergency response-Lights and sirens-Life threatening, A2: Emergency response-Non life threatening, A3: Non emergency patient transport requiring intensive care paramedics and intensive care ambulance, A4: Non emergency patient transport

Table 5: Mortality and morbidity measures used in threshold temperature calculations for each capital city

City	Mortality measure (1999–2009)	Morbidity measure	Duration of morbidity dataset
Adelaide	Daily number of deaths	Daily ED presentations for triage categories 1, 2 and 3	1/1/2004 – 31/12/2010
Brisbane	Daily number of deaths	Daily emergency ambulance call-outs	1/7/2003 – 4/8/2011
Canberra	Second-daily death totals (deaths over 48-hour period)	Daily emergency ambulance call-outs	17/8/2004 – 10/4/2011
Darwin	Weekly death totals	Daily ED presentations reported as 'heat related'	24/1/2005 – 8/10/2011
Hobart	Second-daily death totals (deaths over 48-hour period)	Daily emergency ambulance call-outs	1/7/2003 – 31/7/2011
Melbourne	Daily number of deaths	Daily emergency ambulance call-outs	1/1/2002 – 31/12/2010
Perth	Daily number of deaths	Daily emergency ambulance call-outs	1/1/2006 – 30/6/2011
Sydney	Daily number of deaths	Daily emergency hospital admissions	1/1/2000 – 30/6/2010

Data analysis

A simple method based on daily forecasts from BoM was used to identify the temperature on days when the median mortality and morbidity increased from the expected or baseline number, for each of the Australian capital cities. The methodology used is similar to that previously devised to identify threshold temperatures for ten regional Victorian areas and for metropolitan Melbourne (Nicholls, 2008, Loughnan, 2010a).

Time-series mortality and morbidity data respond to short- and longer-term trends and cycles that are not related to weather, and these need to be removed before the data can be analysed. This was done using a multiplicative seasonal decomposition model (deaths = trend-cycle × seasonal factor × anomaly) described in **Equation 2** (SPSS, 2011). This procedure produced a new variable for mortality or morbidity which measured the observed deviance from the expected mortality/morbidity on each day in the time series. This variable is referred to as the mortality or morbidity anomaly. Box-and- whisker plots show the median, interquartile points and ranges for mortality/morbidity anomalies for each 1 or 2 degree Celsius temperature band. We used a non-parametric measure as health outcomes are not normally distributed within each temperature bin.

Equation 2: Estimation of seasonal component of mortality and morbidity data

$$Xt = TCt \times St \times It, \quad T = 1,......n$$

Where: *TCt* is the 'trend-cycle' component.

St is the 'seasonal' component.

It is the 'irregular' or 'random' component.

The procedure for estimating the seasonal component is:

(1) Smooth the series by the moving average method; the moving average series reflects the trend-cycle component.

(2) Obtain the seasonal-irregular component by dividing the original series by the smoothed values. (SPSS, 2011)

The relationship between maximum temperature (Tmax), minimum temperature (Tmin), mean temperature (meanT), and apparent temperature (AT) were assessed for daily, second-daily and weekly mortality, and for daily morbidity. Second-daily mortality was investigated against the maximum temperature experienced over the 48-hour period. This was considered appropriate, as there is often a lag effect of one to four days in heat-related mortality and morbidity (Conti, 2005, Basu, 2002b). For weekly mortality in Darwin, this was the highest Tmax, Tmin, meanT, and AT during the corresponding week. Lag effects of one to three days were examined in this analysis for all daily data. However, the increase in excess mortality or morbidity was smaller than that of the 'hottest' day or disappeared completely. This indicated that the impact of heat exposure was greatest on the hottest day and that the shift in excess mortality and morbidity was immediate. Therefore this report addresses only the peak mortality or morbidity periods associated with the hottest days.

Temperature data were assembled in 1°C and 2°C bins and box plots were prepared for Tmax, Tmin, meanT, AT and daily, second-daily and weekly mortality, and daily morbidity. The median, upper, and lower quartiles, and range for mortality and morbidity were displayed for each of the 1°C and 2°C increments.

3.3 *Results*

Overall, mortality and morbidity in Australian capital cities shows a wide 'U' shape relationship. Increased mortality and morbidity occur at the highest and lowest range of daily temperatures, and there is a broad comfort zone between. Results are presented for all capital cities then interpreted individually. **Table 6** presents the threshold temperatures for each capital city for both mortality and morbidity, (the number of episodes exceeding the threshold in each area), and the percentage increase in median mortality or morbidity associated with exceedence of each threshold value. Also included is the number of days in each time-series data set on which calculations were based.

Table 18 and Table 19 (Appendix) show the median and interquartile points for the lowest and highest thresholds, for mortality and morbidity respectively. These tables indicate the percentage increase in excess adverse health outcomes (AHO) for temperatures that exceed the thresholds.

Table 6: Threshold temperature derived from analyses of daily all-cause mortality, daily emergency hospital admissions, daily ambulance call-outs or emergency department presentations in Australian capital cities (number of days exceeding the temperature threshold over the record period are in parenthesis)

City	Number of days of data	Tmax	% increase in median	Tmin	% increase in median	meanT	% increase in median	AT	% increase in median
Brisbane									
Morbidity	2956	36 (55)	2.5–12%	26 (7)	2.5%	34 (2)	9%	40(25)	4–11%
Mortality	4007	36(58)	12%	25(11)	5%	31(6)	15%	40(9)	8%
Canberra									
Morbidity	2320	37 (33)	5–10%	20 (30)	5%	28 (28)	5-8%	38(11)	8-10%
Mortality	4007	33(179)	5%	20(43)	2%	28(16)	2%	41(4)	5%
Darwin									
Morbidity	1826	36 (4)	5%	28 (17)	5%	31 (19)	7%	35(5)	5%
Mortality	4007	37(11)	5%	29(19)	8%	31(94)	3%	47(5)	10–20%
Hobart									
Morbidity	2953	NA		18 (28)	5–20%	27 (3)	5%	36(5)	4–10%
Mortality	4007	35(13)	11%	20(5)	2%	28(5)	6%	37(6)	5–20%
Melbourne									
Morbidity	3287	44 (5)	3%	26 (6)	3%	34 (6)	3%	42(10)	2–3%
Mortality	4007	39(23)	2–65%	26(9)	5%	28(112)	3–13%	36(68)	4%
Perth									
Morbidity	2007	43 (3)	14%	26 (4)	4%	NA		43(8)	2–5%
Mortality	4007	44(3)	30%	NA		32(20)	3–10%	45(3)	10%
Adelaide									
Morbidity	3045	NA		31(4)	5%	39(1)	24%	NA	
Mortality	4007	42(21)	2–8%	NA		34(2)	8%	43(16)	2–10%
Sydney									
Morbidity	4162	41(3)	5–38%	25(5)	4%	31(5)	2%	41(3)	5%
Mortality	4007	38(3)	2–18%	25(3)	5%	30(12)	5%	37(27)	2–24%

The extant literature for each city shows inconsistencies in threshold temperatures for mortality and morbidity, with a tendency to focus on mortality and hospitalisations and less on emergency service demands. Also the use of temperature metrics has largely been limited to daily maximum temperature and in some cities relative humidity. The importance of high overnight temperatures has not been considered. The uses of heat stress indices such as AT is also lacking in the Australian literature. This lack of knowledge limits the development of a national approach to adaptation. In this study we have used the same methodology for mortality and morbidity analyses in each city, this incorporates overnight (minimum temperature) as well as AT a heat stress index. However there are city specific differences in morbidity measures due to data availability issues. Nevertheless this study provides a more cohesive picture of heat-related emergency service demand in our capital cities.

Brisbane

The mortality and morbidity thresholds for Brisbane are quite consistent across temperature groups. A threshold of 36°C for Tmax, 25°C for overnight Tmin, 31°C for daily meanT, and 40°C for AT would identify periods of increased risk for mortality and increased demand for ambulance services. Maximum temperatures above 36°C occur most frequently and are associated with a substantial increase in mortality and morbidity. This threshold can be easily determined from BoM weather forecasts and would be useful as a heat-health alert threshold.

The published literature available for temperature thresholds in Brisbane differs from current study. Using data from pre 2006 Bambrick *et al.,* (2008) identified a temperature-mortality threshold at 28°C and Tong *et al.,* (2010) showed an increase in mortality at 27°C during the summer season December to February with an increased relative risk at lag day 1. Only maximum daily temperature and relative humidity were considered, but these were not used in an index such as AT. The increased mortality lag day1 suggests that high overnight minimum temperatures were contributing to the mortality, but this was not measured. Emergency hospital admissions were examined as a morbidity measure with similar results. These cannot be compared with the ambulance callout data presented in this study.

Canberra

The overnight Tmin and daily meanT provide a clear indication of increased mortality and health service demand in Canberra. An overnight Tmin of 20°C and daily meanT of 28°C could be applied as a threshold for this region. The overnight Tmin of 20°C appears to be quite a low threshold but nights in Canberra are usually cool due to the small population and low building density. These factors in combination with clear skies overnight, elevation and a valley location would reduce temperatures even in the urban environment. Bambrick *et al.* (2008) identified a mortality threshold of 33°C daily maximum temperature for Canberra. This is consistent with the results presented here.

Darwin

The threshold temperatures for mortality and increased numbers of ED presentations coded as heat-related in Darwin are quite consistent across three of the four temperature measures used. A daily Tmax of 36°C, an overnight Tmin of 28°C, and a meanT of 31°C all result in an increase in mortality and morbidity. However, for AT there is a considerable difference between the thresholds identified for mortality (47°C) and morbidity (35°C). This may result from using weekly data for mortality calculations, the shorter time-series of the morbidity data set, or the fact that only 8% of days recorded a heat-related ED presentation. Bambrick *et al.* (2008) showed a threshold of 33°C for Darwin using data from 1990 to 2005. Using a more recent time slice 1999 to 2009 this study identified a threshold of 37°C for mortality. The more recent time slice may have allowed for a level of adaptation in the population, air-conditioning use has been shown to have increased over time. There are not published studies detailing morbidity in Darwin.

Hobart

Threshold temperatures for Hobart were identified for mortality and morbidity across all temperature groups with the exception of daily Tmax for morbidity. This suggests that there is no increase in emergency ambulance call-outs as the daily Tmax increases. However, there is a threshold for increased service demand when the overnight Tmin exceeds 18°C, and when daily mean temperature exceeds 27°C. This indicates that the warmer overnight temperatures and the 'lack of relief' do have an impact on the health of Hobart residents. These may provide useful thresholds for a heat-health warning system for Hobart. Apparent temperatures of 36°C and 37°C have a notable impact on both ambulance call-outs and mortality. Bambrick *et al*. (2008) showed a mortality threshold of 26°C for Hobart, whereas this study indicated it was 35°C. Again the higher threshold may be related to adaptive behaviours and the increase in the occurrence of hot weather during the latter part of the last decade. Bambrick *et al.* (2008) did not consider minimum temperatures.

Melbourne

Threshold temperatures were identified in Melbourne across all temperature groups for both mortality and emergency ambulance callouts. Thresholds for overnight Tmin are the same for both mortality and morbidity. The percentage increase in median mortality is largest for daily Tmax, with a 65% increase in mortality noted when the temperature exceeded 44°C during the severe 2009 heatwave. The severe health impacts of that heatwave have been well documented (Victorian Government Department of Human Services, 2009). This threshold differs from the published thresholds in Loughnan *et al.* (2010) and Nicholls *et al.* (2008) due to differences in the age cohorts and diagnostic groups of the data sets used, despite using the same methodology.

An interesting pattern appears in the observed median mortality for Melbourne data as temperatures increase, as seen in **Figure 2.**

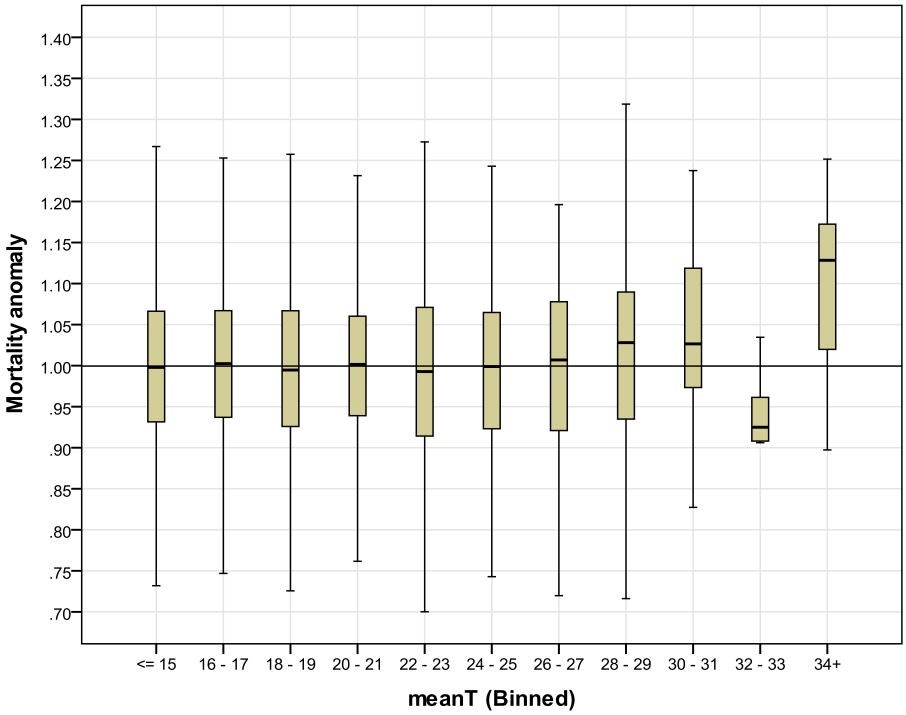

Figure 2: Changes in median mortality per 2°C temperature bin for mean temperature (meanT) Melbourne

Median mortality increases consistently from baseline mortality at 28°C until 30–31°C, but decreases notably at 32–33°C, followed by marked increase as temperatures increase to 34°C or above. A similar pattern is noted for AT (see **Figure 3**).

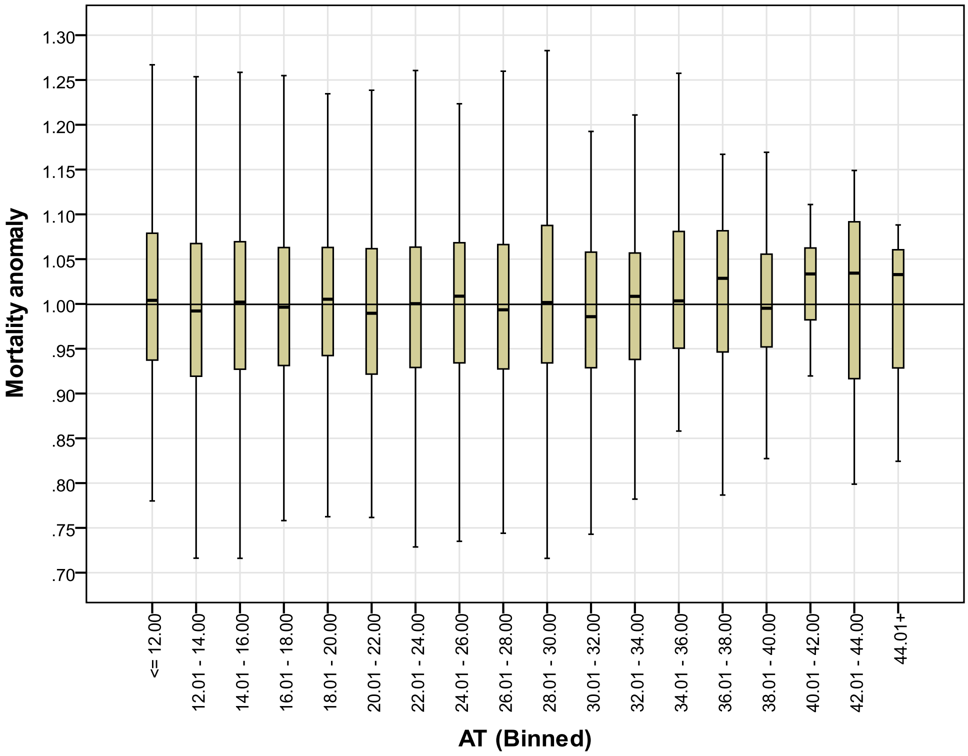

Figure 3: Changes in median mortality per 2°C temperature bin for apparent temperature (AT) Melbourne

Again, mortality shows small increases at 36–38°C, returns to baseline at 38–40°C, and increases as temperatures increase thereafter. This is possibly related to seasonal timing of hot weather or behavioural adaptation as temperatures increase. Potentially, as people begin to feel uncomfortable they implement all available behavioural and technological adaptations such as using the air conditioner, restricting exposure to heat, and limiting physical activity. However, as the temperatures continue to increase, the limits of adaptation are reached and the mortality rate rises. It is not possible to determine the actual cause of this pattern from the data set used in this analysis but these results do suggest a better understanding of the response of humans to hot environments is required.

This pattern of health impact also makes it difficult to determine an appropriate threshold for heat-health warning systems. This study has chosen the first increase in mortality as the threshold; we feel this raises heat awareness and should signal the need to engage heat avoidance strategies. However, for service provision the later threshold may be a more appropriate as it coincides with a greater demand on service provision.

Perth

Daily Tmax and AT provide the clearest thresholds for identifying days with increased heat-related mortality and morbidity in Perth. Mortality and emergency ambulance calls were found to increase by 14% and 30% respectively when the daily Tmax reached 43°C and 44°C respectively. When the AT reached 43°C and 45°C respectively, there was an increase of 2 to 5% in emergency ambulance calls and an increase of 10% in daily median mortality. A daily Tmax of 44°C would provide a useful threshold for heat-health warnings and be an indicator that demand for ambulance services will increase. Bambrick *et al. (2008)* and Williams *et al. (2012)* have shown lower thresholds for mortality in Perth see Table 3. Both studies use a different time slice and analytical approach to this study. Over time adaptive behaviours and changes in health care amongst other environmental, economic and socio-political developments influence population vulnerability. Higher thresholds identified using a very recent time slice may indicate adaptation in this population. There are no other studies describing morbidity thresholds for Perth.

Adelaide

An increase in mortality of between 2 and 10% was noted in Adelaide during hot weather. An increase in mortality of 2 to 8% was observed when daily Tmax exceeded 42°C. Mortality increased by 8% when meanT exceeded 34°C, and an increase of 2 to10% was observed when AT reached 43°C.

An increase in ED visits for triage categories 1, 2 and 3 were noted when the overnight Tmin was equal to, or greater than, 31°C, with an overall increase in median number of presentations of 5%. When each triage category was examined separately, different thresholds became apparent. Triage 3 accounted for 34%, Triage 2 for 11% and Triage 1 accounted for 1% of all ED presentations. These differences in percentage do not reflect the demand on staff or resources as Triage 1 patients require immediate and intensive resuscitation exerting considerable demand on hospital services.

There was an increase in Triage 3 presentations of 5% and 3% respectively when the overnight Tmin exceeded 28°C and when the meanT exceeded 39°C. There were no discernible threshold temperatures for Triage 2 presentations. Triage 1 presentations increased by 15% when the overnight Tmin exceeded 31°C, and a 20% increase in presentations was noted when the meanT exceeded 39°C. Bambrick *et al.* (2008) and Williams *et al.* (2012) again show different thresholds. This may be due to the use of specific age categories and disease groups. This study includes all cause mortality across all age groups.

Sydney

Threshold temperatures were identified across all temperature measures in Sydney for both mortality and morbidity. Daily Tmax of 38°C and 43°C result in substantial increases in mortality and morbidity (ranging up to 18% and 38% respectively). Daily AT also shows a notable increase in mortality above 37°C, and there is a marked (24%) increase in mortality above 45°C demonstrating the impact of 'oppressive' hot weather in Sydney. Two earlier studies of mortality and heat in Sydney (Gosling,2007; Bambrick, 2008) indicate that deaths increase above 26-27°C using age specific groups representing the older population. This analysis found no evidence to support these thresholds using a whole population approach. There are no other studies of morbidity for Sydney.

3.4 *Conclusions*

Overall, there is a clear indication that extreme heat events result in an increase in mortality and morbidity in all eight Australian capital cities. This information can be used to determine heat-health warnings as well as advise emergency services of impending increase in service demand related to hot weather. **Table 7** and **Table 8** present the recommended thresholds for morbidity and mortality in each city. Apparent temperature was not included in the recommendations as this cannot be forecast using BoM information.

Table 7 and **Table 8** suggest that daily Tmax provides a suitable threshold in most capital cities. In Melbourne, either daily Tmax or meanT would provide a suitable threshold based on ambulance call-outs, but the recommended heat-health warning would be based on meanT. In Adelaide, meanT provided the highest percentage increase in ED presentations but this was a single event during the 2009 heatwave. Daily Tmin may also be used as this threshold was exceeded four times during the study period. Mean temperature was also the recommended threshold for Darwin, demonstrating the effect of a hot day followed by a very hot night.

Daily Tmax and Tmin can be easily obtained from the BoM website for each city. Mean temperature can be simply calculated from the BoM daily forecasts by determining the arithmetic average of today's Tmax and the forecast overnight temperature. That is, a hot day followed by a hot night will result in a high mean T. The Bureau issues forecasts of daily Tmax and Tmin five days in advance, allowing time for preparation of heat-health warnings and an opportunity for emergency services to prepare for increased service demand.

Days exceeding the temperature thresholds based on increased service demand (morbidity) in each city were extracted from the data set and mapped at a postal area (POA) level. This provides a spatial representation of increased risk in urban areas during extreme heat events as well as a guide for provision of emergency services during extreme heat events. Excess emergency demand has also been mapped to serve as a guide to direct emergency preparedness for heat events in urban areas thereby increasing resilience in the highest risk areas. Predicted changes in risk for the most vulnerable group (persons over the age of 65 years) have also been incorporated into the study. To increase our understanding of the impacts of climate change on the frequency of extreme temperatures in each capital city, the predicted increase in days that exceed the temperature thresholds can be modelled using regionally downscaled global climate models such as the conformal cubic atmospheric model (CCAM). These works will be described in detail in the following chapters.

Table 7: Recommended temperature thresholds for each capital city based on city-specific morbidity measures

City	Threshold	Frequency of occurrence over 11-year reference period	% increase in morbidity	Health measure used to determine threshold
Adelaide	MeanT 39°C Tmin 31°C	1 day 4 days	24 5 (15 Triage 1)	ED presentations
Brisbane	Tmax 36°C	55 days	2.5–12	Ambulance call-outs
Canberra	Tmax 37°C	33 days	5–10	Ambulance call-outs
Darwin	MeanT 31°C	19 days	7	Heat-related ED presentations
Hobart	Tmin 18°C	28 days	5–20	Ambulance call-outs
Melbourne	Tmax 44°C MeanT 34°C	5 days 6 days	3 3	Ambulance call-outs Ambulance call-outs
Perth	Tmax 43°C	3 days	14	Ambulance call-outs
Sydney	Tmax 41°C	3 days	5–38	EHA

Table 8: Recommended temperature thresholds for each capital city based on city-specific mortality measures

City	Threshold	Frequency of occurrence over 11-year reference period	% increase in mortality	Health measure used to determine threshold
Adelaide	Tmax 42°C	21 days	2–8	Daily mortality
Brisbane	MeanT 31°C	6 days	15	Daily mortality
Canberra	Tmax 33°C	179 days	5	Second daily mortality
Darwin	Tmin 29°C	19 days	8	Weekly mortality
Hobart	Tmax 35°C	13 days	11	Second daily mortality
Melbourne	MeanT 28°C	112 days	3–13	Daily mortality
Perth	Tmax 44°C	21 days	30	Daily mortality
Sydney	Tmax 38°C	3 days	2–18	Daily mortality

4. MAPPING VULNERABILITY IN AUSTRALIAN CAPITAL CITIES

4.1 *Introduction*

Periods of extreme heat pose a risk to the health of individuals especially the elderly, very young, and the chronically ill. Risk factors can also include housing characteristics, and socio-economic factors, or environmental risk factors such as UHIs. This study developed an index of population vulnerability in urban settings using known environmental, demographic and health-related risk factors for heat stress. This method was based on a spatial index of heatwave risk developed for Melbourne (Loughnan *et al., 2012)*. In the current project, the spatial variations in risk factors were correlated with spatial variation in ambulance calls or emergency presentation or emergency admission to hospital in all Australian capital cities. The spatial index was weighted using one of the aforementioned health outcomes during heatwave periods. The maps of spatial vulnerability provide information to target heat-related health risks by aiding emergency management, policy advisors, urban planners, healthcare professionals, and ancillary services to develop heatwave preparedness plans at a local scale and increase community and organisational resilience.

A few published articles have described social or environmental factors that influence an individual's vulnerability over and above biophysical risk factors (Reid *et al.*, 2009; Stafoggia *et al.*, 2006; Cutter *et al.*, 2003; Few, 2007). Studies resulting in maps of population vulnerability to heat are much fewer in number. Vescovi *et al*. (2005) present maps of population vulnerability to heat and projected population vulnerability for Quebec. Harlan *et al*. (2006) used socio-economic and environmental variables and human thermal comfort to quantify the relationship between socio-economic status and environmental heat. Reid *et al*. (2009) developed an index for population vulnerability to heat events in the US. This included identifying which of the known risk factors best explained vulnerability. The study provided a template for local and regional heat maps to guide interventions aimed at mitigating the effects of heatwaves (Reid *et al.*, 2009). In Britain, Lindley *et al.* (2011) describe how climate change, vulnerability, and social justice affect health and wellbeing of people living in Britain. They apply a framework of vulnerability to aid policy makers address current inequalities.

This work draws on the information provided in previous studies to expand the methodology by using temporal and spatial morbidity data to describe the spatial distribution of AHO during hot weather. In addition, this will develop an index of the spatial variation of vulnerability based on a number of factors reported in the literature as having an influence on population health during periods of extreme heat. Information on factors reflecting health, demographic and environmental contributions to vulnerability were obtained and are listed in Table 20, Appendix.

Two methods were used to assess the spatial variations in these factors, and their relationship to excess morbidity in eight Australian capital cities during 'hot' weather. These were a weighted VI and a simple VI using principal component analysis (PCA). The ability of the different variables in the vulnerability indices to identify the spatial variations in vulnerability across a city will provide useful information to assist with public health initiatives to reduce heat-related mortality and morbidity. Ethics approval for this study was granted from the Monash University Standing Committee on Ethical Research Involving Humans.

4.2 *Research methods and activities*

Eleven variables or factors for use in developing a VI were identified *a priori* from a literature review and the appropriate data sources for these variables were identified as shown in **Table 20** (Appendix). The index comprised three main groups of variables: environmental, health and demographic. The demographic variables included information about the population distribution of high-risk age groups, the numbers of aged-care facilities (ACF), socio-economic status, persons living alone, and the prevalence of ethnic groups, in each area. The environmental variables included information about dwelling type, population density per square kilometre, land cover, and the intensity of the UHI. The health variables included were the proportion of residents with a disability and accessibility to emergency service. The following section provides a description of the variables included in the indices.

Developing the vulnerability index: Demographic variables

Age groups, numbers of ACF, socio-economic circumstance, aged persons living alone and prevalence of ethnic groups were included as demographic variables. Age has been identified as an important risk factor associated with heat-related mortality and morbidity. Specific age groups (persons aged less than 4 years, and persons aged 65 years and older) within the population defined population vulnerability. This does not mean that persons outside these groups are not vulnerable, simply that people within these groups are more vulnerable than other members of the community. Aged care facilities were identified during the European heatwave in 2003 as having high rates of heat-related mortality and morbidity. Aged-care facilities are not evenly distributed around cities. Therefore it is important to identify areas with ACF as these may constitute areas of increased risk.

Analysis of the Chicago 1995 and European 2003 heatwaves demonstrated that living alone and not leaving the house regularly contributed to the risk of mortality during a heatwave and married couples were less likely to be affected by heatwaves in Italy and France (Harlan *et al.*, 2006; Kalkstein and Valimont, 1989; O'Neill *et al.*, 2003; Basu and Samet, 2002a; Donaldson *et al.* 2003; Fouillet *et al.*, 2006; Schwartz, 2005; Smoyer-Tomic, 1998; Kovats and Hajat 2008). However Hajat *et al.* (2007) found that living alone did not modify the risk in England. Whether living alone increases risk during hot weather in Australia has yet to be established. Socio-economic circumstance has also been described as a risk factor that moderates the heat-health relationship (Kalkstein *et al.*, 2008; Klinenberg, 2002; Laaidi *et al.*, 2006; Semenza *et al.*, 1996; Vandentorren *et al.*, 2006; Vandentorren *et al.*, 2004) as does belonging to a racial or ethnic subgroup (Adcock *et al.*, 2000; Johnson *et al.*, 2009b; Smoyer-Tomic *et al.*, 2003; Stafoggia *et al.*, 2008; Vandentorren *et al.*, 2004; Fouillet *et al.*, 2006). Demographic variables were obtained from the ABS Basic Community Profile (BCP) based on the data from the 2006 census. A list of all the ACF in Australian capital cities were downloaded from the Department of Health and Ageing website (Australian Government Department of Health and Ageing, 2010). This data set includes the ACF by the location where the service is based.

Developing the vulnerability index: Environmental variables

High-density urban development and the presence of a UHI have been shown to increase the heat load experienced by urban populations. The UHI is a phenomenon that occurs in urbanised landscapes where built areas are warmer, especially during the night, than surrounding environment. This is due to the high thermal heat capacity and heat storage of urban surfaces, and added sources of heat from anthropogenic surfaces. People often restrict travelling and spend most of their time indoors when weather conditions are extreme and as such are exposed to local urban micro-climates. Evidence from the French heatwave in 2003 indicates that multi-dwelling structures were associated with an increased risk of mortality (Vandentorren *et al.*, 2006). Hajat *et al*. (2007) demonstrated that the relative risk of dying during a heatwave was higher in urban than in rural areas, and other authors have also suggested that increased numbers of urban deaths were attributable to higher temperatures in urban areas (Coutts *et al.*, 2007, Clarke, 1972).

For the calculation of the UHI effect within cities, satellite-based measurements from the MODIS/Terra Land Surface Temperature and Emissivity Monthly L3 Global 0.05Deg CMG (climate modelling grid) satellite MOD11C3 (5.6 km) in geographic coordinate system WGS 84 (lat/long) have been used. Monthly average temperatures (2005–2010) were downloaded, pre-processed into degrees Celsius and then extracted for all Australian cities.

Green space can assist in reducing the UHI effect, thus reducing the level of exposure to heat by urban communities (Aniello *et al.*, 1995, Jonsson *et al.*, 2004). To measure the area of green space in each POA, Mesh Block land use data were downloaded from the ABS (http://www.abs.gov.au/websitedbs/D3310114.nsf/home/Seifa_entry_page, 2008). The total area of green space (measured as a sum of parkland and agricultural land areas) in each POA and the total area in squared kilometres of each POA defined the proportion of area in POA covered by green space.

To estimate accessibility to emergency services, Berke and Shi (2009) compared four methods of estimating travelling time of people in the same ZIP code to a cancer centre in two cities in the USA. They found that there is little difference between geometric centroid (the point at the geometric centre of the area) of a ZIP code and the census-based population centroid of a ZIP code, especially in urban areas. Another study found that there is an inverse relationship between attendance rates and distance from the clinic to the location of patients (Henneman *et al.*, 2011). We used the geometric centroid of each POA in determining travelling distance and time to hospital ED. This method assumes that people in the same POA live at the geometric centre of the POA and thus all have the same travelling time and travelling distance to the nearest public hospital with an emergency department. The number of public hospital EDs included in each city is listed in **Table 9**.

Driving distance and driving time from each POA to ED were extracted from Google Maps (http://maps.google.com) using SAS 9.2. It is noted that the shortest driving time from each POA to each ED were selected first, followed by driving distance associated with the driving time. The shortest driving distance and driving time from each POA to the ED were included in the indices. The driving distance is measured in metres and the driving time is measured in seconds.

Table 9: Number of public hospital emergency departments included for each capital city

Cities	Number of public hospitals/emergency departments
Adelaide	8
Brisbane	15
Canberra	2
Darwin	1
Hobart	1
Melbourne	39
Perth	15
Sydney	41

Data sources: The geographical information system (GIS) layer of public hospitals was provided by the department of health in New South Wales, Western Australia and Victoria. For other states and territories, lists of public hospitals were acquired from their respective departments of health and were geocoded into GIS using Google Earth and ArcGIS 9.3.

Developing the vulnerability index: Health variable

Chronic disease has been shown to increase susceptibility to heat-related mortality and morbidity (Basu, 2009; Bouchama *et al.* 2007; Semenza *et al.*, 1996). Similarly, persons with a disability have been deemed more vulnerable than the wider population (Vandentorren *et al.*, 2006). Disabled persons have limited mobility and therefore limited ability to respond to their ambient conditions. It was therefore important to include the number of persons with a disability who required assistance with daily activity; these data were obtained from the ABS 2006 census.

Developing the vulnerability index: Study areas

The SD for each capital city defined the study area; this includes the CBD as well as the greater metropolitan area (Australian Bureau of Statistics, 2011). The spatial VI is mapped by the POA unit. This is the finest scale at which heat-related outcomes (i.e. emergency presentations or ambulance call-outs) can be accessed. The social demographic data from ABS is also available at this level. Therefore, it allows integrating different data sets to map vulnerability of urban populations in all major cities in Australia.

For each city, we selected all POA falling within the city SD for analysis. For Darwin and Hobart, there are some POA which comprise multiple features and their areas are much bigger, but only a small proportion of POA fall within the city SD. For these POAs, the areas included in the analysis are an aggregation of collection census districts (CCD) from the area within each POA for the Darwin or Hobart SD. This allows the extraction of census data from CCD, and then aggregating to POA level. Exclusion of the area of POA outside the city SD will also ensure the UHI variables, derived from average of MODIS grid value within POA, represent the land–surface temperature (LST) of areas within the city SD. The relevant data were extracted from the databases at the smallest spatial scale practicable, risk factors and data sources are described in **Table 20** (Appendix).

Management of the morbidity dataset

We used daily recorded morbidity data for each POA in each of the cities to describe the spatial distribution of health outcomes during heat events (hot days), and on all summer days not identified as heat events (non-hot days). We measured the daily AHO as the number of ambulance call-outs, the ED presentation rate or the EHA rate in each POA. The postcode associated with ambulance call-outs shows the location where patients needed the ambulance service, but not the patient's residence location. Therefore, AHO using ambulance call-out data sets are measured as a count variable. The AHO incident rate (i.e. ED presentation rate or EHA rate based on where patient lives) is calculated as the number of AHO per 10,000 persons in each POA. **Table 24** (Appendix) summarises the temporal scale and attributes morbidity data sets that are used in validating the VI.

Statistical analysis

All statistical analyses were conducted in SPSS version 19 (SPSS, 2011). Results were then transformed into ArcGIS 9.3 to map the VIs for urban communities in Australia cities.

A Pearson correlation was conducted for *a priori* vulnerability variables and morbidity outcomes on hot days. Hot days in each city were defined using city-specific threshold temperatures as shown in **Table 6** of the previous chapter. A Pearson correlation (Pearsons *r)* is used to measure the strength of a relationship between two continuous variables. An *r* value of +1 indicates a perfect correlation, whereas an *r* value of -1 perfect negative correlation a value close to zero indicates no association. Correlation does not imply causation, but suggests that values closer to +1or -1 show a stronger relationship than values closer to zero.

We used stepwise regression to select the 'best' variables to represent the morbidity during hot days. Co-linearity is a problem when the variables in the regression are not independent. A condition index greater than 15 indicates a possible problem and an index greater than 30 suggests a serious problem with co-linearity (Pallant, 2004). The model producing the highest r^2 values that show no indication of co-linearity was selected. The un-standardised coefficients of selected variables are used as weights in a multiplicative model to determine the composite VI (weighted VI) see **Table 21** (Appendix)

Principal component analysis (PCA) was used to find underlying components that may explain the correlations and spatial variability among the variables defined from the literature. PCA is a mathematical method that transforms a given data set to a smaller number of uncorrelated variables called principal components. The first principal component accounts for as much of the variability in the data as possible, and each succeeding component accounts for as much of the remaining variability as possible. Varimax rotation was performed on the results of the PCA to maximise the variance accounted for by the components. Only components with eigenvalues > 1 were included in the analysis. This method is similar to that used in a previous study by Cutter *et al*. (2003). An additive model of principal components was then used to map the composite VI (PCA). The VI (PCA) map (presented by decile) is then visually examined with the map of AHO on hot days (also presented by decile). Maps were also created in the larger cities with sufficient data to indicate areas where the VIs are either over or under predicting vulnerability compared with the AHO measured. To examine whether the additive model VI (PCA) or weighted VI maps could predict the vulnerability of communities equally well, we did a Spearman correlation between number of AHO and VI and between AHO and VI (PCA). The results are shown in **Table 24** (Appendix). A Spearman Rank Order Correlation (*RHO)* is also a statistical measure of association between two variables and similar to a Pearson correlation. However, if one or both of the variables are ordinal then a Pearson correlation cannot be used and a Spearman correlation is appropriate. As with a Pearson correlation a value of *RHO* +1 indicates a perfect correlation and a value of *RHO* -1 indicates perfect negative correlation a value close to zero indicates no association. As the VI used deciles as ranked values a Spearman correlation was used for this part of the analysis.

Mapping future heat-related vulnerability

This study compiled data from extreme heat events identified using the threshold temperatures for each city, and created decile maps of emergency service demand during the extreme events, Areas marked as decile 8 and above on vulnerability maps constitute higher emergency service usage during heat events.

There are many factors influencing community risk, such as climate change, changes in socio-demographic structures, as well as the application of adaptation and mitigation activities. The changes in overall risk are complex, as are the complex interactions among risk factors. Therefore not all risk factors included in vulnerability indices can be successfully modelled. Given that advancing age has been identified as a primary risk factor around the world, it was selected to represent the changes in risk in each city into the future. Additionally not all *a priori* vulnerability variables were available at the spatial unit the researchers required.

All Australian cities have projected population (by total population and by age group) up to 2021, 2026 or 2032 (**Table 24**, Appendix). The finest spatial units available for these data are the statistical local area (SLA), local government area (LGA) (e.g. Hobart, Perth), region (defined by the city as in the case of Canberra) or the statistical reporting regions of the Northern Territory. Thus, changes in risk profiles for communities based on changes in aged population (65+ years) distributions and predicted changes in population density were used as surrogates for changes in the intensity of the UHI, an important indicator of increased risk of exposure to hot weather in each city.

In the next section we present maps of the predicted changes in vulnerability for seven cities (maps could not be produced for region-based projections in Darwin) and then discuss the maps' implications for the changes in community risk profiles based on changes in socio-demographic factors associated with an ageing population.

4.3 *Results*

Brisbane

Summary

The distribution of vulnerability in the Brisbane region appears to be highest for Bribie Island, Redcliffe, Redland Bay and Stradbroke Island. These areas are also predicted to experience increasing total population density, including an increase in the elderly population. Heatwave policy and planning in these regions should be reviewed to implement short- and longer-term adaptation strategies to minimise risk and build resilience. In addition, emergency services can be alerted to the increased risk and demand in these areas during periods of hot weather and incorporate this information into preparedness and response plans.

Development of vulnerability indices for Brisbane

Queensland Ambulance service provided data between 1/7/2003 and 4/8/2011. There are two days where mean temperature equalled or exceeded the threshold temperature of 34°C. During this period, there is an increase in emergency ambulance calls of 9% on hot days compared with ambulance call-outs on non-hot summer days.

Table 25 (Appendix) shows that there is a significant correlation between AHO and 9 of the 11 variables used in the index. These are: age, need for assistance, accessibility to emergency services, urban design, ACF, single-person households where persons are aged over 65 years, population density, night-time LST (night time UHI) and land cover. A meanT threshold of 34°C was used to define hot days in summer (see **Table 6** in Chapter 3) and the AHO for these days were extracted and used in a stepwise regression. The results indicate that three variables from the index: ACF, single person aged over 65 and urban design were the best predictors of vulnerability in Brisbane city ($r^2 = 0.31$). The condition index for this model was between 2 and 4.8, indicating that multi-colinearity was not a problem. The unstandardised coefficients from the regression analysis for these variables were used to weight the composite VI for Brisbane city as the following model (see **Equation 3**):

Equation 3: Derivation of vulnerability index (VI) for Brisbane

Weighted VI = 2.450 * ACF + 1.248 * single-person households (65+) + 0.083*urban design

Table 22 (Appendix) shows that overall, the weighted VI map explains 61.7% of the spatial variability in ambulance calls on hot days in Brisbane. High levels of vulnerability (red areas marked as above decile 8) (see **Figure 4C**) are seen in areas north of Brisbane along Bribie Island, as well as north and south-east of Brisbane city. These areas should be a focus for the development of heatwave planning policy and provision of emergency service response. Lower levels of vulnerability (green areas) are seen in the outer areas of Brisbane. Four POAs in the outer west and south of Brisbane show moderate vulnerability (yellow to orange areas), however they also have low numbers of ambulance call-outs (green areas) (see **Figure 4B)**. Although these areas may have high-risk attributes such as more ACF and older people living alone and higher urban densities, they do not increase the demand on ambulance services during hot weather. This may be due to recognition that older people are more vulnerable and that current heatwave planning policy is effective.

By contrast, areas to the east of Brisbane, around Redland Bay, and to the west of Redcliffe, indicate a lower level of vulnerability (see **Figure 4C**) but higher demand for service during hot weather (see **Figure 4B**). One consideration may be heat exposure in the workplace and recreational areas as opposed to areas where people live, or an increased reliance on emergency services such as ambulances. Emergency managers need to be aware of these differences and focus on adaptation, and mitigation plans to increase resilience in these areas. Interestingly, the decile values of ambulance call-outs on non-hot days (not shown) in these areas also show moderate to high decile values.

Principal components analysis or factor analysis was also used to determine the influence of groups of closely related variables and whether this could be used to explain spatial patterns in ambulance calls during hot weather. The analysis yielded five components or groups that explained 79.6% of the spatial variability in the *a priori* vulnerability variables (see **Table 26**, Appendix). **Table 27** (Appendix) indicates that UHI, density of vulnerable age groups, ethnicity and land cover variables listed in component 1 and 2 play an important role in defining risk. Visually, the VI (PCA) map in **Figure 4A** predicts high levels of vulnerability in Brisbane city centre and low levels of vulnerability in the city fringe areas. This also corresponds to the spatial distribution of ambulance call-outs on hot days (see **Figure 4B**). The Spearman correlation of the additive model of vulnerability using factor analysis (VI PCA) and the ambulance calls on hot days is *rho* = 0.547, $p < 0.001$, indicating that this model explains 54.7% of the spatial variability in ambulance calls.

Figure 4D indicates an interesting pattern of relative change in AHO between non-hot days and hot days. While POA in the outer suburbs of southern Brisbane and around the city of Brisbane generally are reported with increased ambulance call-outs, POA in the northern part of Brisbane are generally reported with decreased ambulance call-outs. Such an uneven distribution of emergency service demand on hot days among POA in the city highlights the need to prioritise areas for emergency service provision. A Spearman correlation including the number of ambulance call-outs on hot days and VI (see **Table 22**, Appendix) indicates that weighted VI better predicts vulnerability for Brisbane communities than VI (PCA). **Table 25** to **27** (Appendix) show Pearson correlations and PCA results for Brisbane.

Projected changes in population distribution in Brisbane from 2006 to 2031 (presented as quintiles for population density – persons per km^2), and the changes in proportion of people aged over 65 years are shown in **Figure 5** and **Figure 6** respectively. Increased population density and potentially increased UHIs are shown in red and are predominantly in the north, west and southern outer suburban areas, such as Caboolture South, Mango Hill, Bowen Hills, and Beenleigh. Increased numbers of older residents shows that the areas around Bribie Island and to the west of Redcliffe as well as the eastern part of Brisbane near Redland Bay and the South Stradbroke Island region are projected to have the biggest increase in the rate of elderly people. These areas as indicated in **Figure 4B** and **Figure 4C** are prone to high levels of heat-related vulnerability as well as high numbers of ambulance call-outs on hot days.

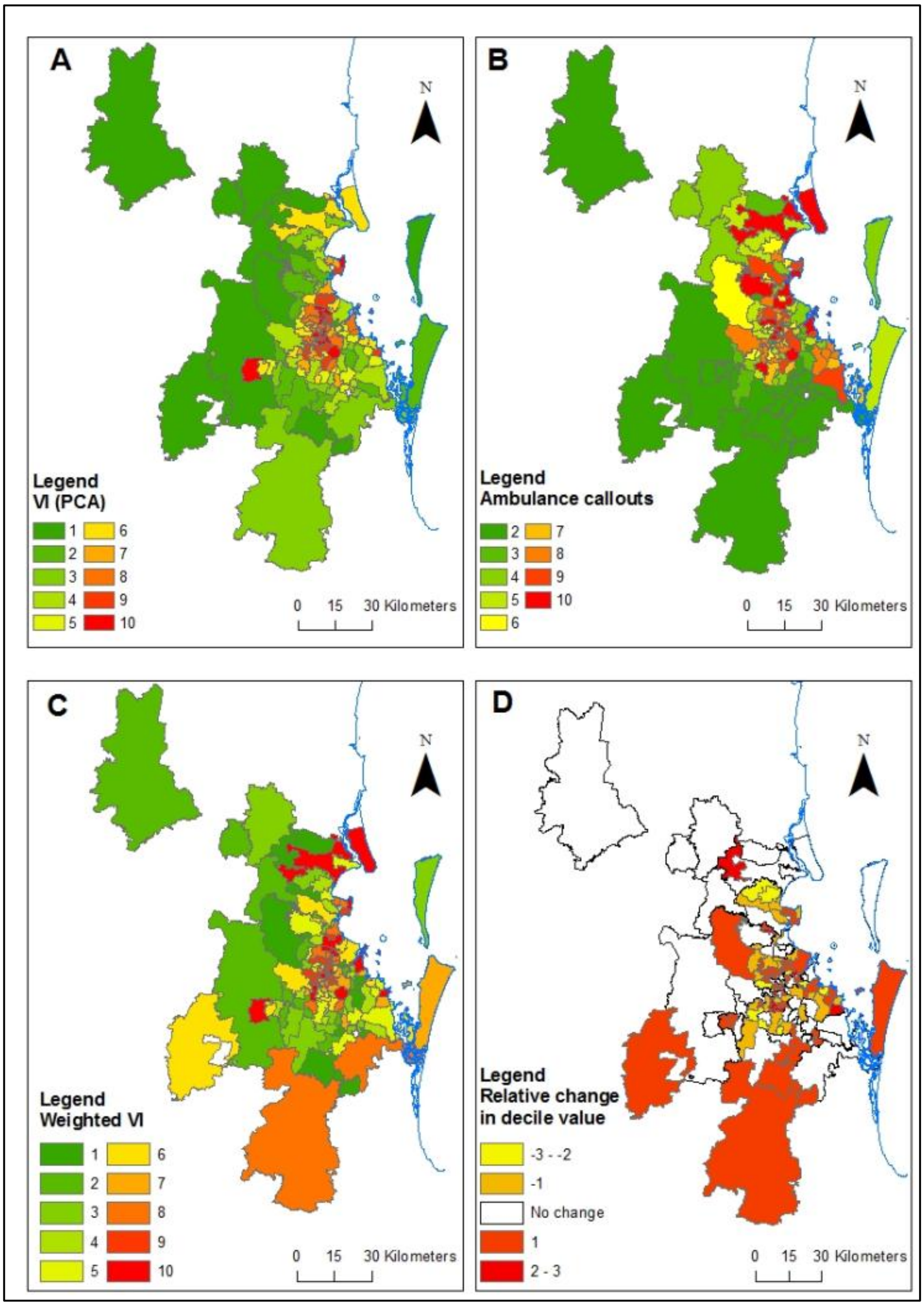

Figure 4: Brisbane – Spatial distribution of the vulnerability indices (VI) (A, C) and ambulance call-outs on hot days (using mean temperature threshold of 34°C) (B) by decile; and relative change in decile value of adverse health outcomes between baseline (summer non-hot days) and hot days (D)

In **Figure 4D**, a blank (white) POA indicates there was no difference in AHO decile value, whereas yellow and orange POA indicate a lower AHO decile value on hot days as compared with summer non-hot days. Red indicates an increase in demand for ambulance services on hot days.

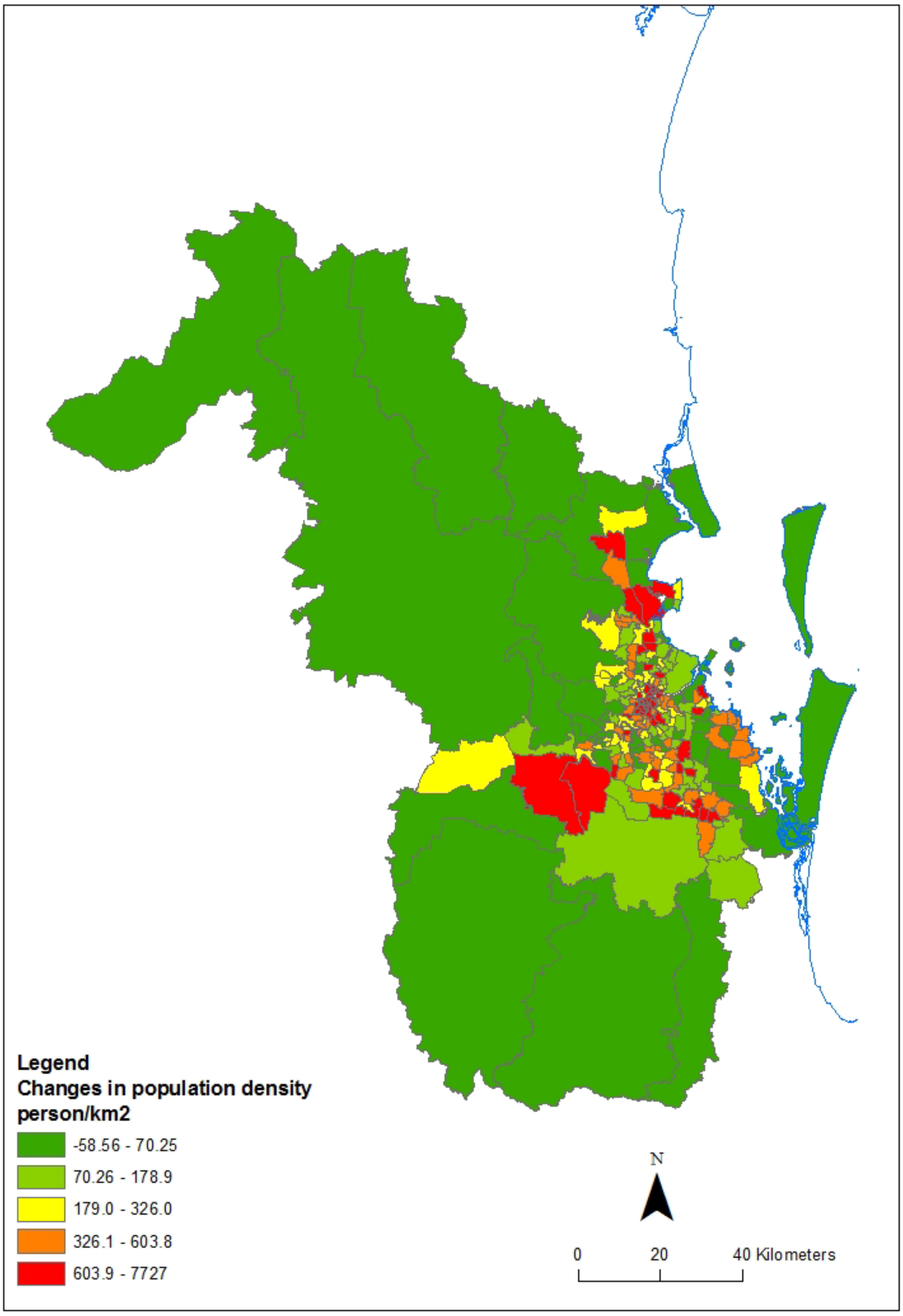

Figure 5: Change in population density (shown as quintiles for persons per km^2) between 2006 and 2031 by statistical local area in Brisbane

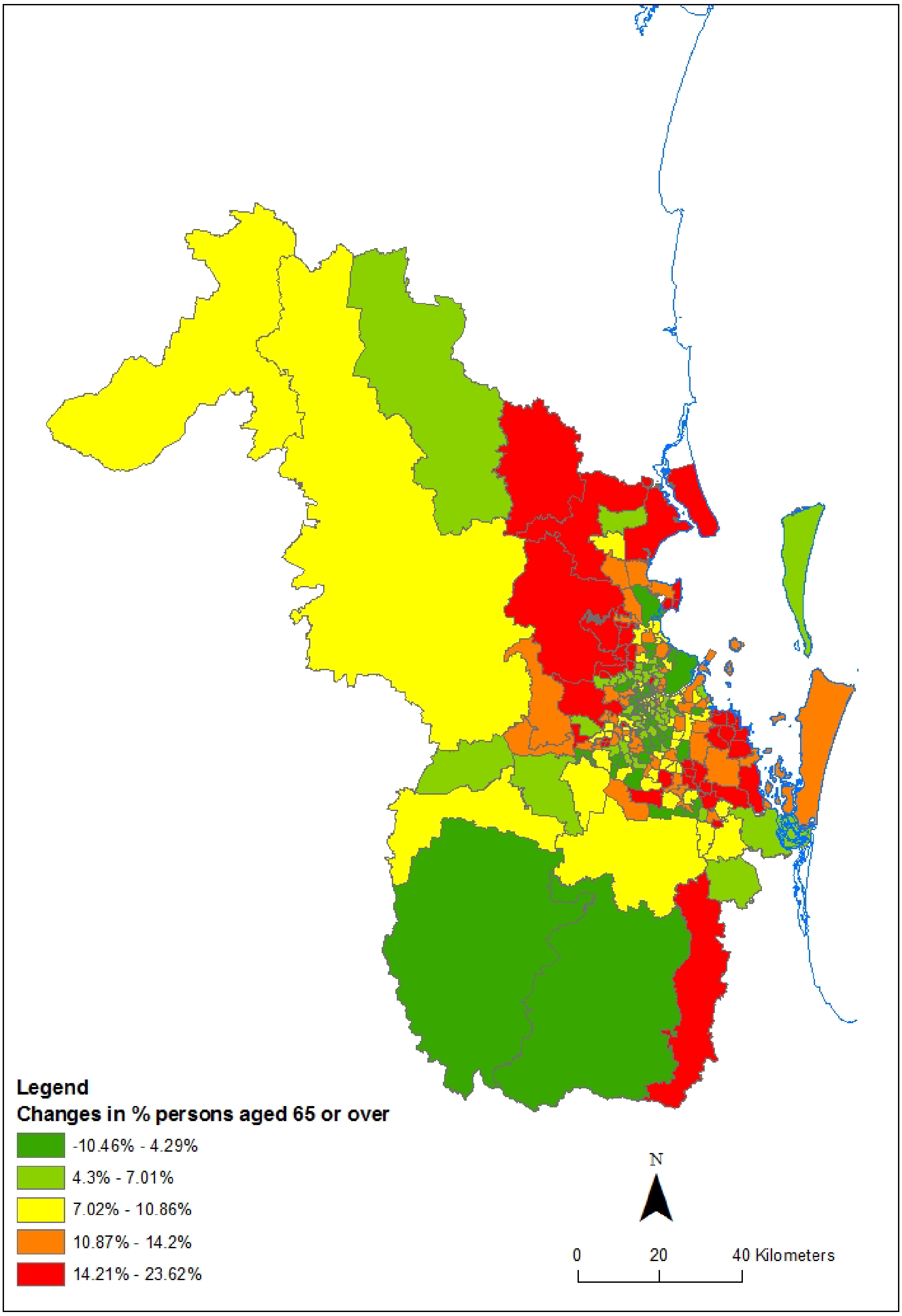

Figure 6: Changes in proportion of elderly people (aged 65 or over) between 2006 and 2031 by statistical local area in Brisbane

Canberra

Summary

Increased vulnerability and increased service demand is noted in the suburbs north of the city, and the VI (PCA) model, which incorporates three components, is a better predictor of vulnerability in Canberra during hot weather. The predicted increase in population density corresponds with current known areas of higher vulnerability; however the areas with the greatest predicted increase in older people do not correspond with current higher risk areas.

Development of vulnerability indices for Canberra

The Australian Capital Territory (ACT) Ambulance Service provided ambulance call-out data between 17/8/2004 and 10/4/2011, amounting to 2310 days of data. If multiple responses were dispatched, these were counted as one incident. Only emergency dispatches A1 and A2) were included in the analyses.

Hot days were defined as days equalling or exceeding a meanT threshold of 28°C (see **Table 6**, Chapter 3). There are 28 days that equalled or exceeded the threshold during the study period. This resulted in 1567 emergency calls on these hot days. On average, there were 56 AHO on hot days compared with 53 AHO on non-hot summer days. This represents an increase of 5.6% in AHO on hot days in summer.

Table 28 (Appendix) shows that AHO correlates significantly with the proportion of ACF and UHI (day time). Including both variables in the model violates the condition index suggesting multi-colinearity. Stepwise regression analysis (see **Equation 4**) showed that ACF was the best predictor of VI, however it only explains 18.2% ($r^2 = 0.182$) variability of emergency responses in Canberra. The condition index of the selected model is 2.02, indicating that multi-colinearity is not a problem.

Equation 4: Derivation of vulnerability index (VI) for Canberra

Weighted VI = 3.713*Aged-care facility

Map of the weighted VI for Canberra (see **Figure 7C**) shows greater vulnerability in the northern suburbs. Similarly, maps of the ambulance calls during hot weather in Canberra also show high demand in these areas (see **Figure 7B)**. The Spearman correlation of the weighted model of vulnerability and the ambulance calls on hot days is *rho* = 0.430, p = 0.041, (see **Table 22**, Appendix) indicating that this model explains 43% of the spatial variability in ambulance calls. The Spearman correlation of the additive model of vulnerability VI (PCA) and the ambulance calls on hot days is *rho* = 0.522 (p = 0.011), indicating that this model explains 52.2% of the spatial variability in ambulance calls. Pearson correlations are listed in **Table 28** (Appendix). Principal components analysis for Canberra yielded three components that explained 73.5% of the spatial variability in *a priori* vulnerability (see **Table 29,** Appendix). Components 1 and 2 are primarily related to age and environmental factors including ACF, persons needing assistance, urban design, and areas with low socio-economic circumstance, single-person households aged 65+ years, travelling time to ED services, and UHI. Ethnicity and land cover (Component 3) play a smaller role in defining risk in Canberra. **Figure 7A** shows that VI (PCA) predicts a low level of vulnerability for fringe suburbs to the north-east, east and south of Canberra (green to lime areas), and high levels of vulnerability (red areas) to the north of the city. These areas also had low to high levels of ambulance calls on hot days respectively in Canberra (see **Figure 7B**).

The relative change in ambulance calls on hot days compared with non-hot days (see **Figure 7D**) indicates that two areas of suburbs incorporating Ngunnawal, Nicholls, Palmerston, Crace, Scullin, Page, Hawker Weetangera, Macquarie, Cook and Aranda to the north of the city and three areas of suburbs incorporating Kingston, Narrabundah, Fadden, Macarthur, Gowrie, Monash, Gordon, Conder and Banks to the south of the city show greater demand for services. The areas to the north are recognised as areas of higher vulnerability, however the areas to the south are not indicated as high risk. These areas should be noted as potential 'hotspots' during heat events. A closer examination of these areas may highlight the reason for increased service demands.

Projected changes for the total population (presented as quintiles for population density – persons per km^2) and the changes in proportion of people aged over 65 years in Canberra from 2006 to 2021 are shown in **Figure 8**. The projected changes in population density, a surrogate for increase in UHIs, are shown in red on **Figure 8A**. This area close to the CBD is also highlighted as an area with moderate to high ambulance calls during hot weather and high vulnerability. Conversely, the red area indicating an increased percentage of older people in **Figure 8B** in 2021 does not correspond with current areas of high vulnerability or increased demand for ambulance services during hot weather.

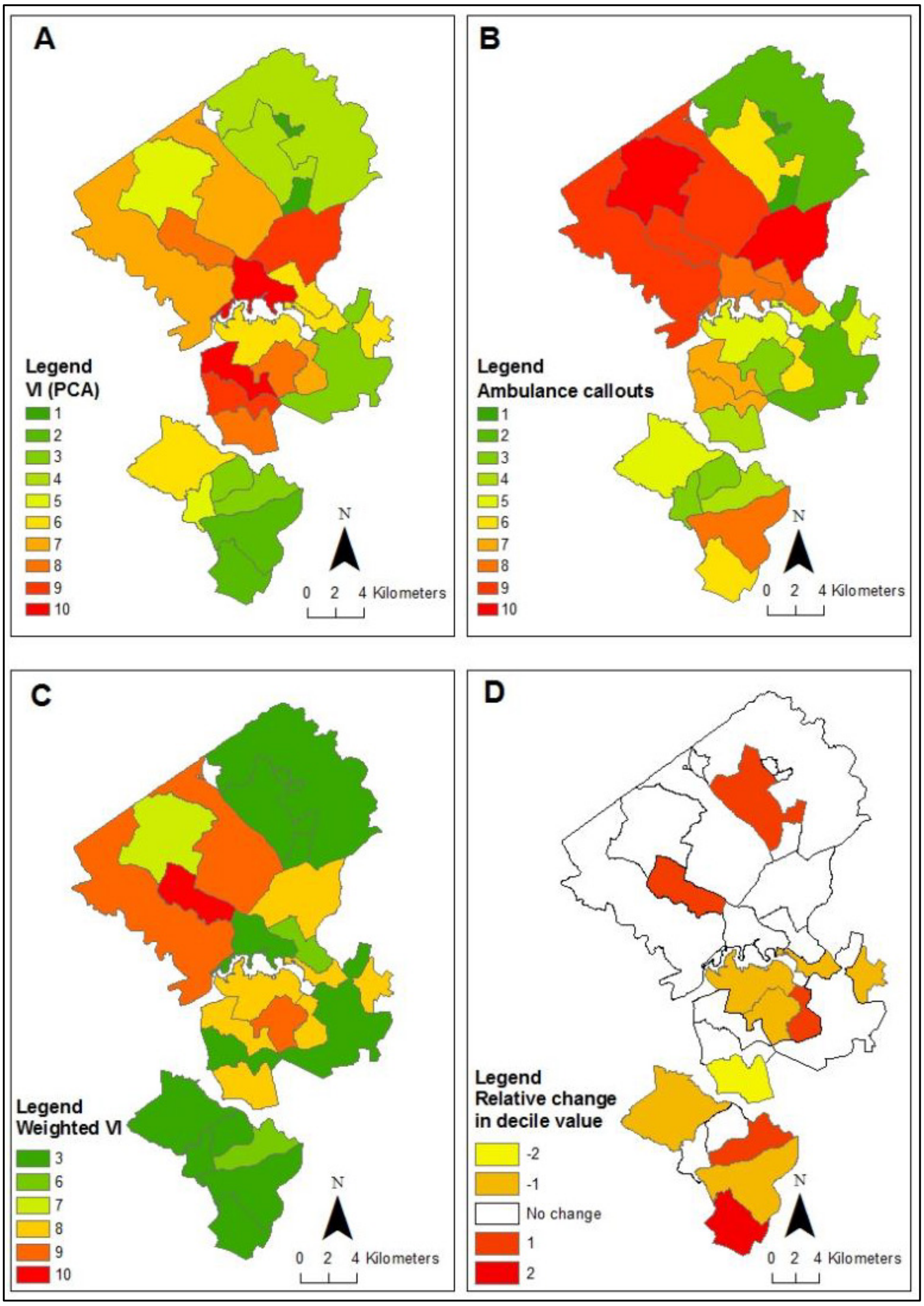

Figure 7: Spatial distribution of the vulnerability indices (VI) (A, C) and ambulance call-outs during hot days (using meanT threshold of 28°C) (B) by decile; and relative change in decile value of ambulance call-outs between baseline (summer non-hot days) and hot days (D) in Canberra

In **Figure 7D,** Blank POA indicates there was no difference in AHO decile value, whereas yellow to orange POA indicates a lower AHO decile value on hot days as compared with summer non-hot days. Red indicates increased demand on hot days in Canberra.

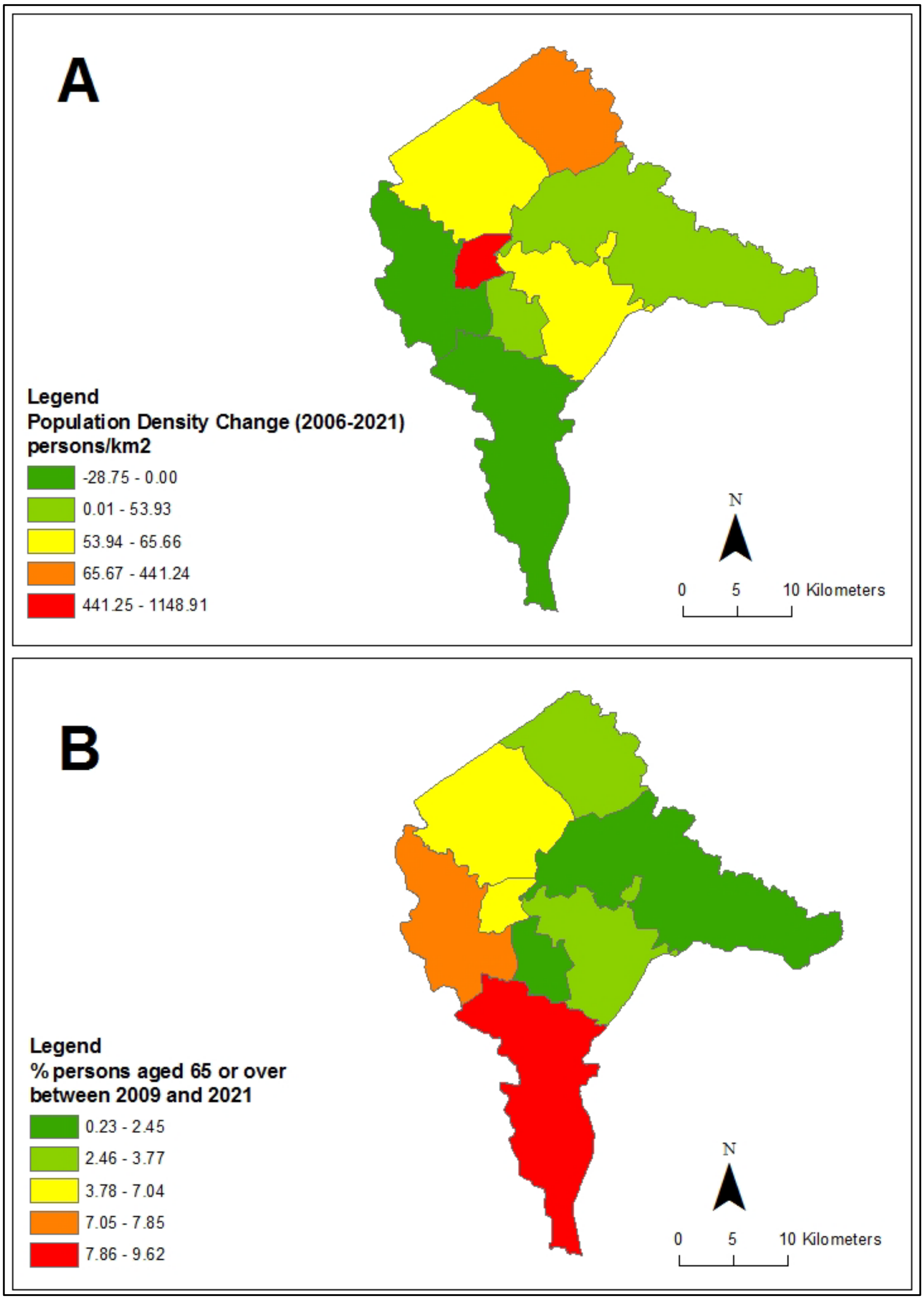

Figure 8: Changes in population density (shown as quintiles for persons per km^2) (A), and proportion of elderly people (aged 65 or over) (B) between 2006/09 and 2021 by district in Canberra.

Hobart

Summary

The weighted VI map indicates that there is higher vulnerability in areas to the north-west of the city; this also corresponds with areas of increased demand for ambulance services during hot weather. The relative change in ambulances calls during hot days and non-hot days suggests that there are areas south of Hobart city that notably increase service demand during hot weather. These areas do not appear as high risk using either the weighted VI or the VI (PCA). Further work should be undertaken to understand heat-related risk in these areas. Projected population changes in Hobart indicate that there will be increased density in the inner city and Brighton to the north, and an increase in older people living in the north-east and north-west suburbs. These northern suburbs are areas noted as high vulnerability under our current climate. The predicted changes in these areas could enhance this risk and short- and longer-term adaptation strategies should be developed to minimise adverse heat-related outcomes.

Development of vulnerability indices for Hobart

Ambulance call-out data were provided by the Tasmanian Ambulance Service for the period between 1/7/2003 and 31/7/2011. During these 2953 consecutive days, there were 121,166 ambulance call-outs. During summer, 49,398 call-outs were recorded. On average, there were 40 call-outs on non-hot days as compared with 51 call-outs on hot days (days equal to or exceeding meanT 28°C). This represents a 27.5% increase in ambulance call-outs during hot weather over summer.

Table 31 (Appendix) shows that six out of eleven variables are significantly correlated with AHO, namely socio-economic, measure of disability, accessibility to ED, urban design, and ACF. However, only the number of ACF and socio-economic circumstance (Index of Relative Socio-economic Disadvantage – IRSD score) are deemed independent and make a significant contribution to the regression equation ($r^2 = 0.54$). The condition index of a selected model is between 1 and 2.94 indicating that multi-colinearity is not a problem. Therefore, these variables were used to determine weighted VI using **Equation 5**.

Equation 5: Derivation of weighted vulnerability index (VI) for Hobart

Weighted VI = 1.843* percentage ACF + (–0.034) * IRSD score

Figure 9A shows the mapped VI using PCA. **Table 32** (Appendix) show that four principal components explained 83.76% variability in vulnerability variables. Components 1 and 2 are highly loaded by UHI. Component 3 is greatly impacted by accessibility to ED, population density of vulnerable groups, urban design, and ethnicity. Age, measure of disability, and single-person households aged 65 or over loaded the highest in Component 4. Visual examination between **Figure 9A** and **Figure 9B** reveals the VI (PCA) map does not correspond well with spatial distribution of ambulance calls during hot weather. This relationship was not statistically significant (Spearman correlation *rho* = 0.034, p = 0.854).

The weighted VI maps for Hobart (see **Figure 9C**) indicate that there is greater vulnerability in the inner city area and areas of Magra and Molesworth to the north-west of the city. This fits well with the mapped ambulance calls during hot weather (see **Figure 9B)**. The weighted index explains 80.7% (see **Table 22,** Appendix) of the spatial variability in ambulance calls during hot weather.

The relative change in AHO between non-hot summer days and hot summer days (see **Figure 9D**) indicates that there is a notable increased demand in southern suburbs (i.e. Cambridge, Acton Park, Sanford, Clifton Beach, Margate, Oyster Cove, Tinderbox, Leslie Vale, Fern Tree and Ridgeway) that are not indicated as high vulnerability. Increased demand and high vulnerability are consistent in the north-east suburbs but areas to the north and outer eastern suburbs (with moderate to high vulnerability) show decreased demand during hot weather.

Population projections based on populations as of 30 June 2007 were used to map changes in population density and proportion of elderly people (aged 65 or over) in Hobart in 2032. These maps (see **Figure 10**) are projected to the finest scale at LGA in 2032. Projected population changes in Hobart indicate that there will be increased density in the inner city and Brighton to the north (see **Figure 10A)** and an increase in older people living in the north-east and north-west suburbs (see **Figure 10B)**.

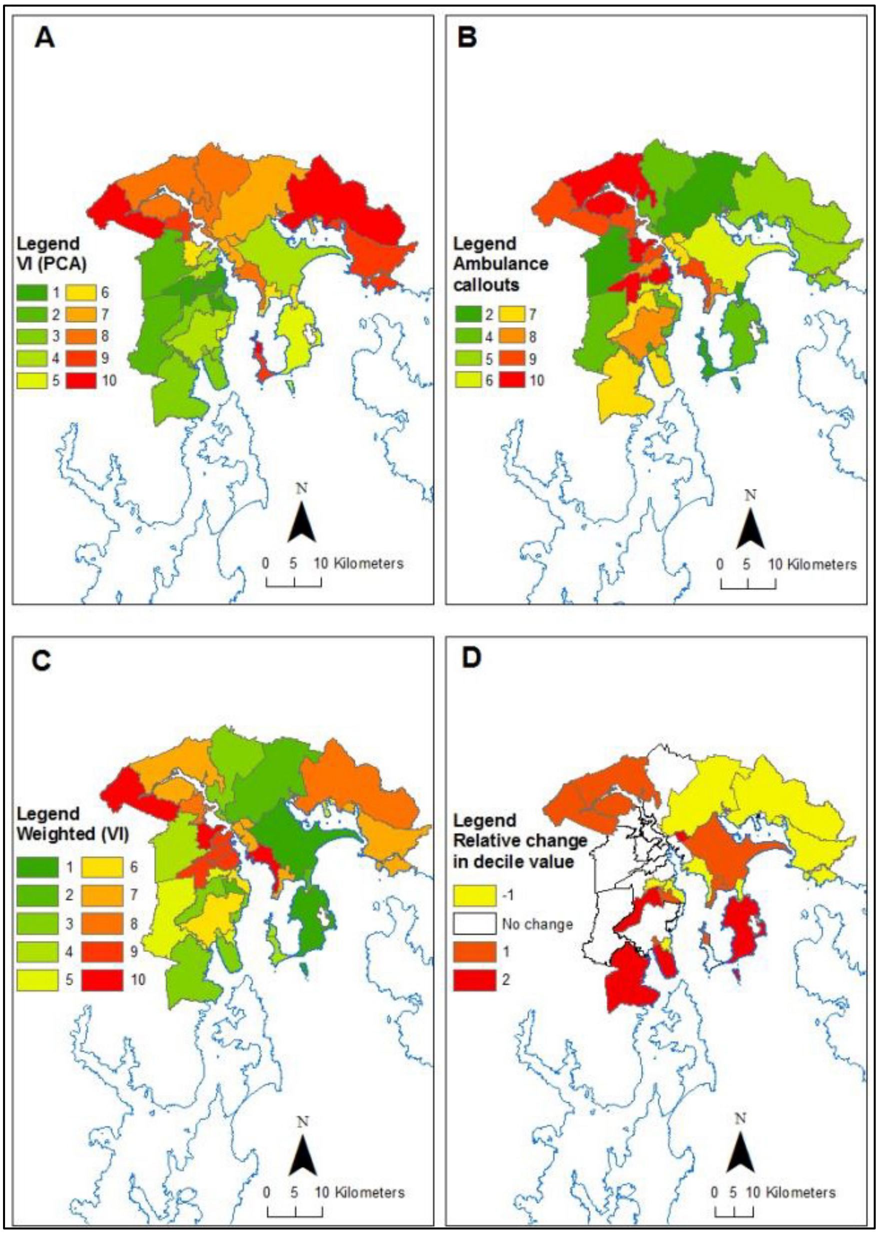

Figure 9: Spatial distribution of the vulnerability indices (VI) (A and C), and ambulance call-outs on hot days (using meanT threshold of 18°C) (B) by decile; and relative change in decile value of ambulance call-outs between baseline (summer non-hot days) and hot days (D) in Hobart

In **Figure 9D**, blank (white) POA indicates no difference in AHO decile value, whereas yellow POA indicates a lower AHO decile value on hot days as compared with summer non-hot days. Orange through to red indicates an increase in demand for ambulance services on hot days. This map indicates that there was a decrease in AHO decile value on hot days in POAs in the east and in the centre of Hobart, whereas there was an increase in AHO decile value for POAs in the south and the south-west of Hobart.

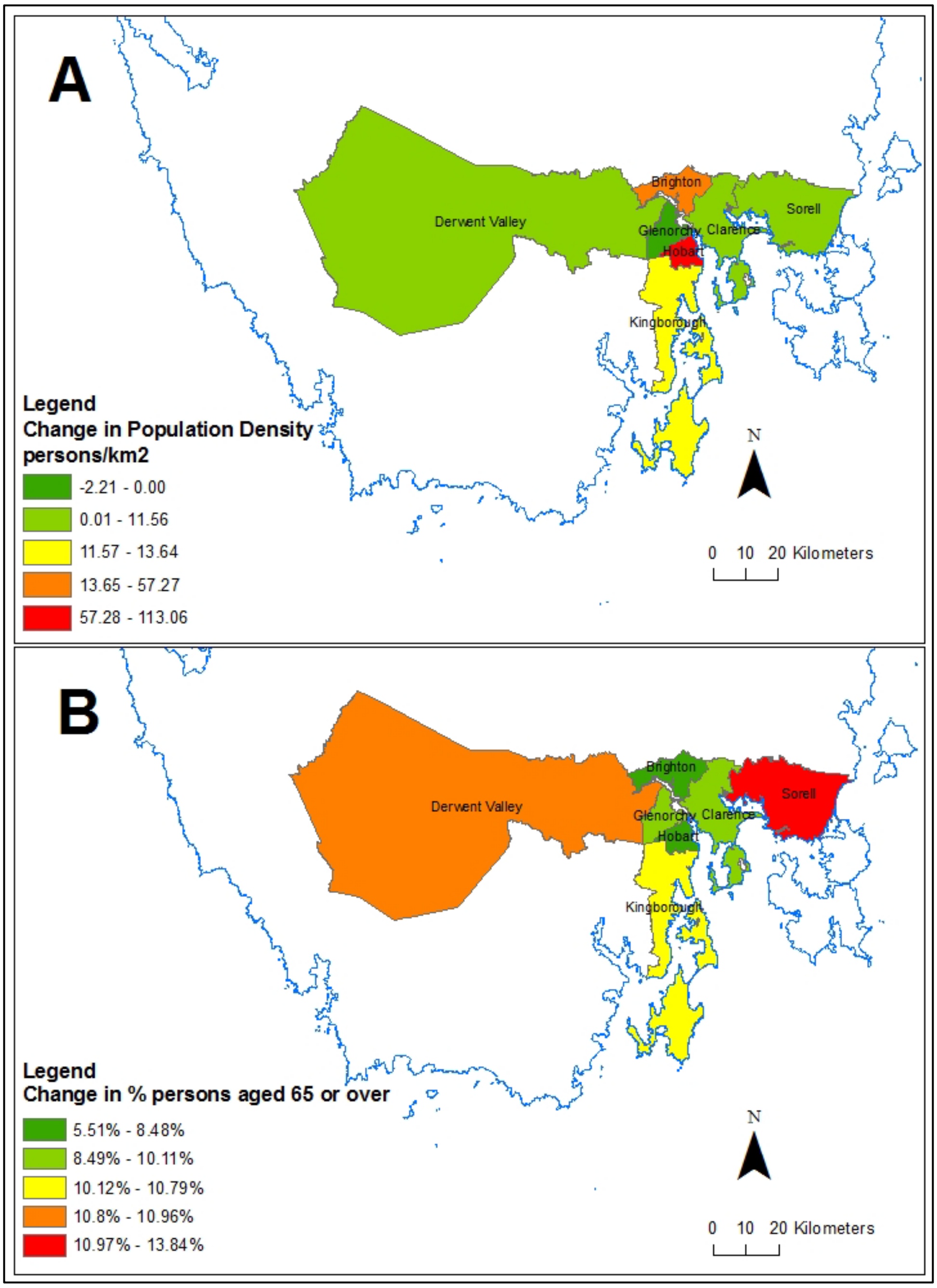

Figure 10: Changes in population density (shown as quintiles for persons per km^2) (A), and proportion of older people (B) in Hobart by local government area between 2007 and 2032

Melbourne

Summary

The weighted VI in Melbourne correlated well with ambulance class during hot weather. Increased vulnerability and increased service demand are noted in the western and south-eastern regions. The same pattern is observed for relative changes in service demand between hot days and non-hot days over summer. There is also a notable increase in service demand in the outer eastern suburbs and Dandenong Ranges areas. Changes in population density are predicted in the inner city areas and areas to the west and south of the city. A change in the proportion of older people living in the western and southern suburbs is also predicted but most notably there is large area to the north-east of Melbourne where the proportion of older people is predicted to rise dramatically.

Development of vulnerability indices for Melbourne

Ambulance call-out data were provided for Melbourne between 1/1/2002 to 31/12/2010. There are six days that exceeded the meanT threshold during the study period. This resulted in on average of 944 ambulance call-outs on hot days. On average, there were 944 AHO on hot days as compared with 687 AHO on other summer days. This represents an increase of 37.5% in service demand on hot days in summer.

Hot summer days were defined as days where the meanT equalled or exceeded 34°C. There were six occasions during the study period when this threshold was reached, three consecutive days were during the 2009 heatwave.

Table 34 (Appendix) shows that all variables in the VI except the variable for socio-economic circumstance (IRSD) are significantly correlated with the AHO on hot days. Only variables that make a unique contribution to the regression equation were included in the index. Three vulnerability variables were included: ACF, ethnicity, and single-person households aged over 65 years ($r^2 = 0.46$, the condition index of selected model is between 1 and 5). The chosen model is shown in **Equation 6**.

Equation 6: Derivation of weighted vulnerability index (VI) for Melbourne

Weighted VI = 19.052 * % ACF + 0.337 * ethnicity + 1.954 * single-person households (65+).

Figure 11A shows the mapped VI using PCA. **Table 35** to **36** (Appendix) show that four principal components explained 79.13% variability in vulnerability variables. Components 1 and 2 are highly impacted by UHI, accessibility to ED, population density of vulnerable groups, urban design, ethnicity, and land cover. Component 3 is greatly impacted by single-person households aged over 65, measure of disability, and age variables see **Table 36** (Appendix). Aged care facilities equally influence components 3 and 4. The socio-economic variable is high for Component 4 (see **Table 36**, Appendix). **Figure 11A** shows a high level of vulnerability (red areas) in the inner city areas, whereas a low to medium level of vulnerability is predicted for the south-east regions and the western areas of Melbourne. The VI using PCA method explains 61.3% spatial variability of AHO on hot days (Spearman correlation value between AHO on hot days and VI (PCA) was *rho* = 0.613, $p < 0.001$) (see **Table 22**).

Maps of the weighted VI for Melbourne (see **Figure 11C**) indicate that the highest vulnerability surrounds but does not include the inner city area, with some areas of higher vulnerability extending to the western and south-eastern bayside suburbs. This correlates quite well with the AHO on hot days (see **Figure 11B)** (Spearman correlation *rho* = 0.747, p = < 0.001).

It is clear from **Figure 11D** that the relative change in AHO decile value on hot days, shows increased AHO decile values for a number of POA across the Melbourne metropolitan area from both the west, along Port Phillip Bay to the south of Mornington Peninsula and to the outer eastern region of metropolitan area. The western plains region of Melbourne is an area of relatively new development and rapid urbanisation. The southern peninsula and Westernport Bay areas are areas where the 'resident' population increases dramatically over summer since these are both busy tourist destinations. These areas recorded high ambulance call-outs on hot days (see **Figure 11B**) and therefore they should be targeted for heatwave preparedness and response, particularly the western areas where there was increased demand for ambulance services on hot days as compared to other summer days (see **Figure 11D)**.

Population projections for the Melbourne region show increased population density in the inner Melbourne area (see **Figure 12A**) this will enhance the UHI in these areas and contribute to population risk. The predicted increase in older persons (see **Figure 12B**) living in the outer western suburbs, Mornington Peninsula, and the eastern fringe suburbs will add to the increased demand for ambulance services already noted in these areas.

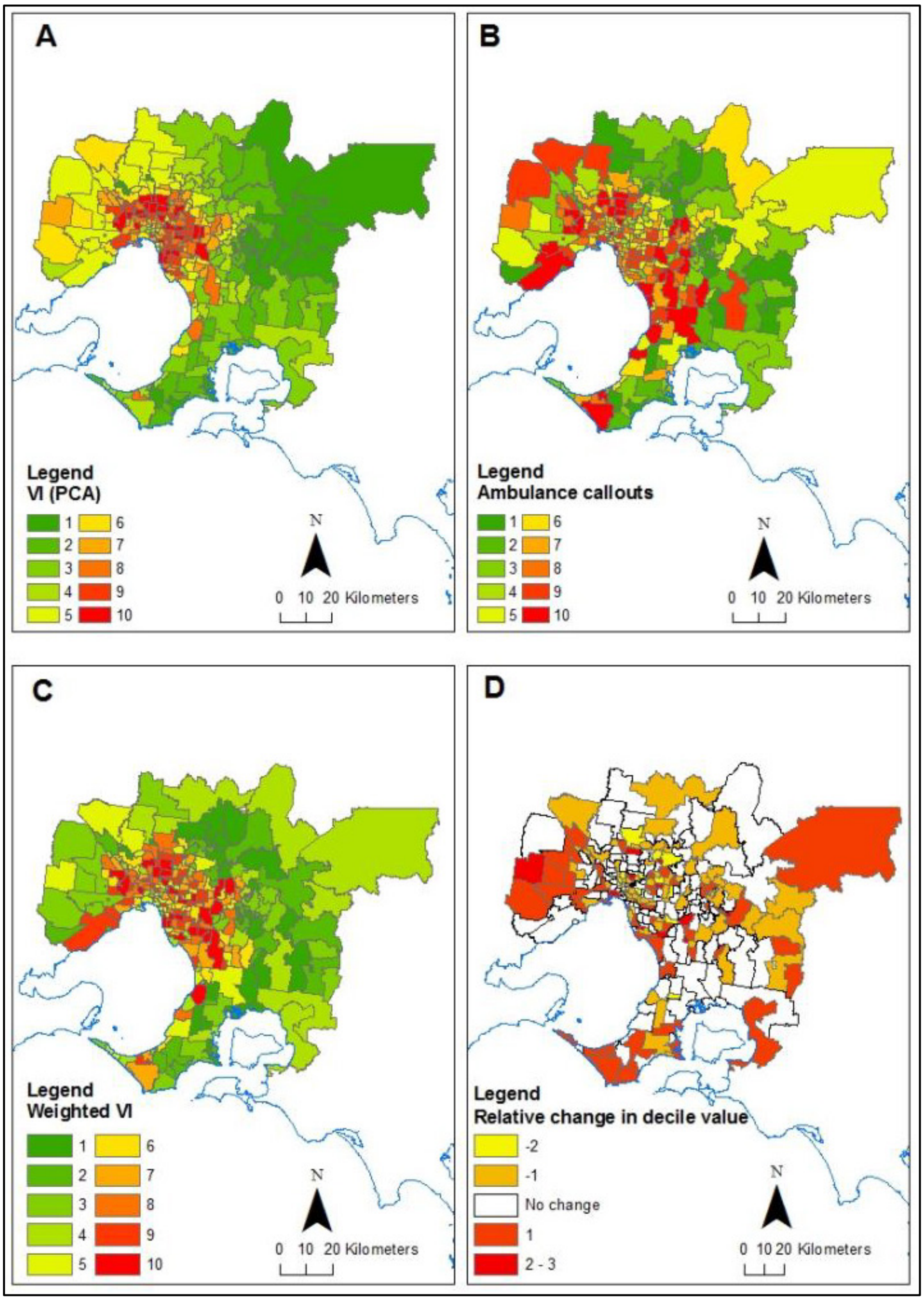

Figure 11: Spatial distribution of the vulnerability indices (VI) (A,C), and ambulance call-outs on hot days (using meanT threshold of 34°C) (B) by decile; and relative change in decile value of ambulance call-outs between baseline (summer non-hot days) and hot days (D) in Melbourne

In **Figure 11D**, blank (white) POAs indicate there was no difference in AHO decile value, whereas a yellow POA indicates a lower AHO decile value on hot days as compared with summer non-hot days. Orange through to red indicates an increase in demand for ambulance services on hot days.

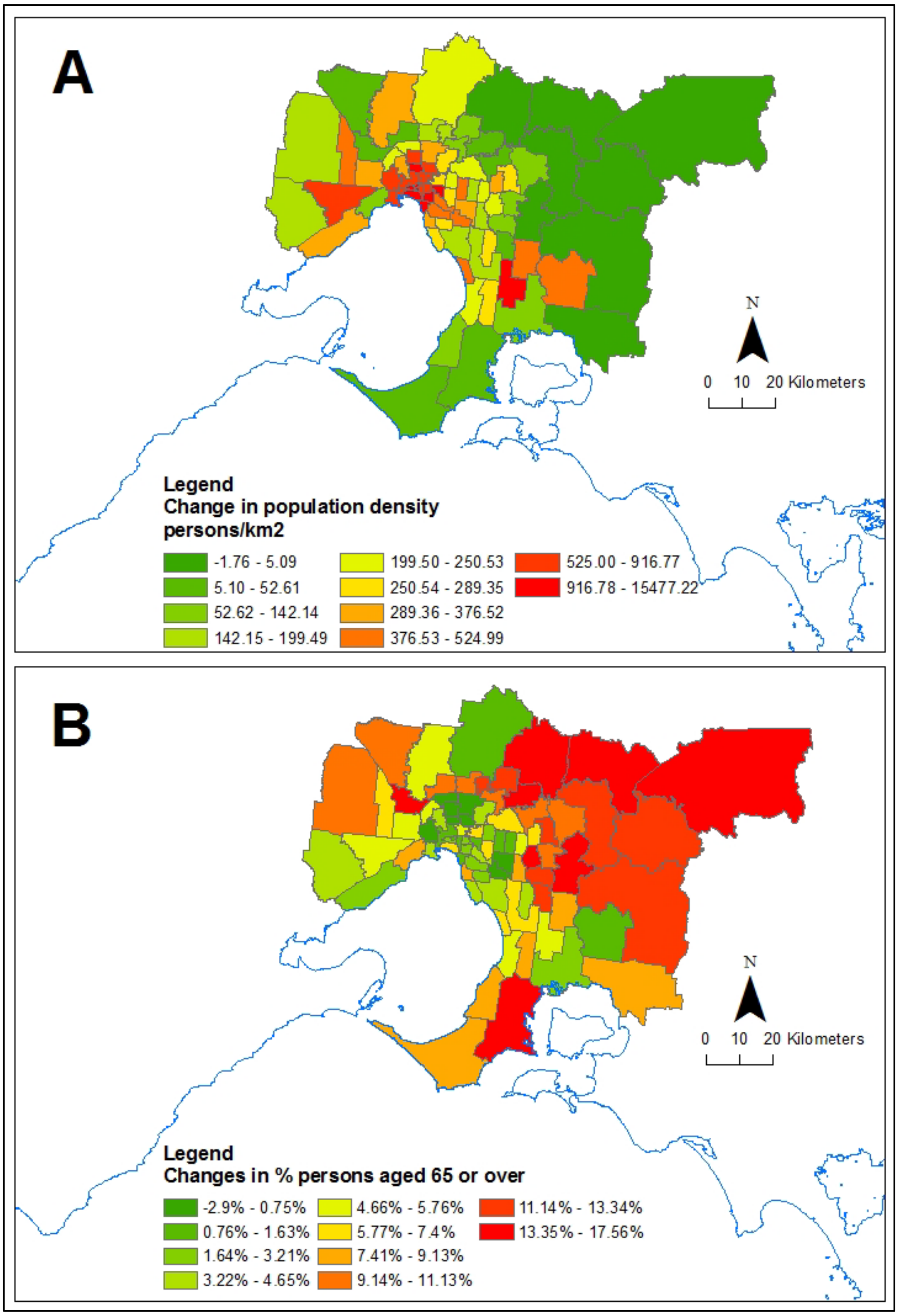

Figure 12: Changes in population density (shown as deciles for persons per km^2) (A), and proportion of elderly people (aged 65 or over) (B) in Melbourne by statistical local area between 2006 and 2026

Perth

Summary

Increased vulnerability in Perth is noted in the inner city suburbs, north of the city and south along the Swan River, there was good agreement between the weighted VI and VI (PCA). The relative change in service demand between hot days and non-hot days show increases in the outer suburbs especially north-west of the city. These areas are not indicated as high vulnerability by either index. Further study into factors influencing increased service demands during hot weather is needed especially as the proportion of older people living in these areas is predicted to increase in coming decades. Adaptation strategies should be developed to counteract what is potentially a high-risk area.

Development of vulnerability indices for Perth

Ambulance call-out data were provided by the Australian Ambulance Service for 2007 consecutive days (from 1/1/2006 to 30/6/2011). Using a threshold of Tmax of 43°C there were three days that exceeded the threshold during the study period. There was a total of 373 ambulance call-outs on these three hot days. On average, there were 124 AHO on hot days compared with 113 AHO on other summer days. This represents an increase of 9.7% AHO on hot days in summer.

Table 37 (Appendix) show that except for socio-economic and daytime UHI variables, vulnerability variables statistically associate with AHO on hot days. All variables were entered into a stepwise regression. The best model (shown in **Equation 7**) included two variables, the percentage of ACF and ethnicity ($r^2 = 0.26$). The condition index of the selected model was 3.6, suggesting no multi-colinearity in the model.

Equation 7: Derivation of vulnerability index (VI) for Perth

$$VI = 1.265*percentageACF+0.071*Ethnicity$$

The weighted VI map for Perth (see **Figure 13C**) shows increased vulnerability in the inner Perth suburbs, north of the city and south along the Swan River. The weighted index explains 59.1% of the spatial variability in AHO during hot weather (Spearman correlation *rho* = 0.591, $p < 0.001$). A similar pattern results from mapping the principal components from the factor analysis (see **Figure 13A**). However, this method explains slightly less (41%) of the spatial variability in AHO Perth (Spearman correlation *rho* = 0.410, $p < 0.001$). **Table 38** (Appendix) shows that four principal components explain 78.92% of variability in vulnerability variables. **Table 39** (Appendix) reveals that UHI and accessibility to ED variables load highest in components 1 and 2, whereas demographic and health variables load high in components 3 and 4.

The relative change in AHO between non-hot days and hot days during summer (see **Figure 13D**) shows larger increases in demand for ambulance services in the outer suburbs (e.g. Morangup, Gidgegannup, Parkerville or Stoneville) especially to the north-west of the city (e.g. Jindalee, Butler) during hot weather.

Projected changes in population density (presented as quintiles for population density – persons per sq km) (see **Figure 14A**) in Perth are predominantly in the inner city regions, but predicted changes in the proportion of older people (aged 65 or over) (see **Figure 14B)** show some increases in the inner city area but also in the northwest.

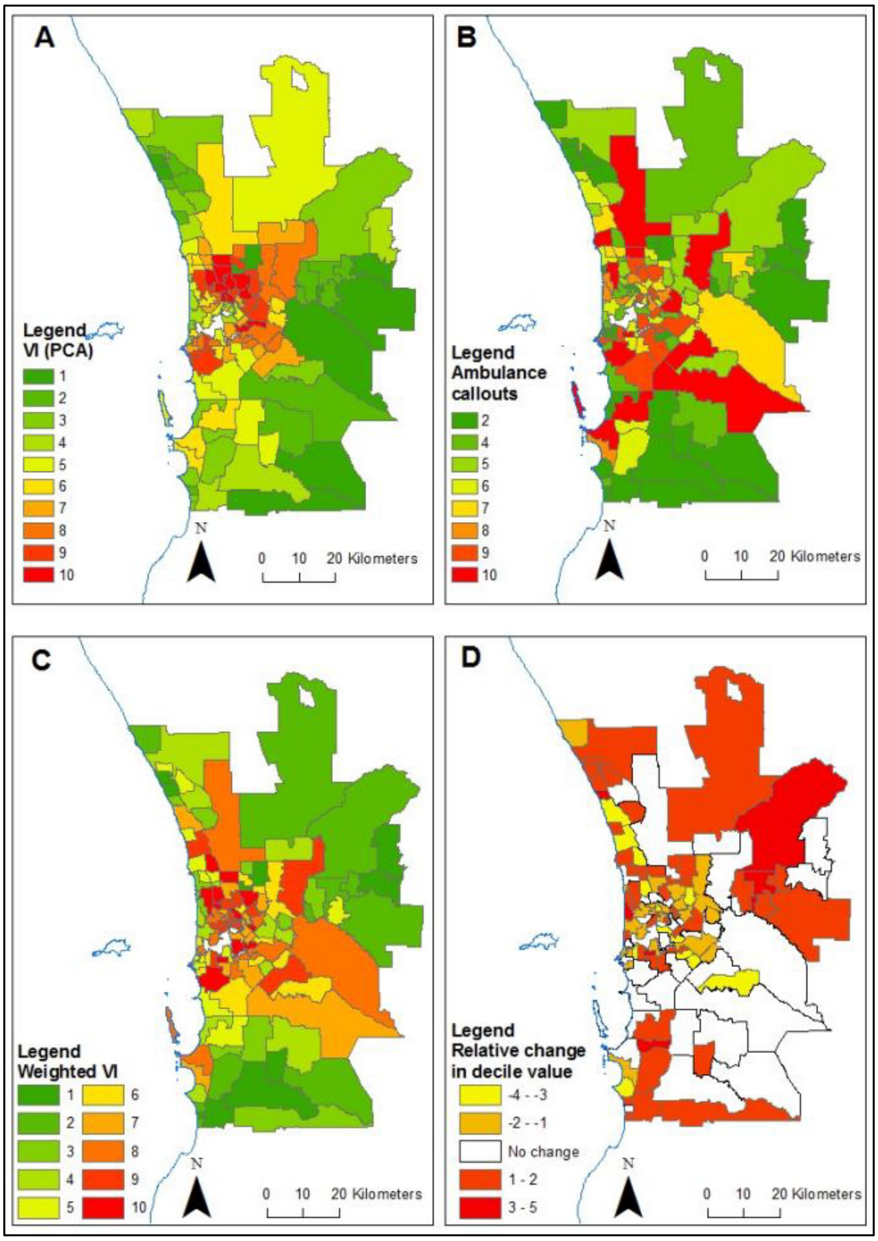

Figure 13: Spatial distribution of the vulnerability indices (VI) (A, C) and ambulance call-outs on hot days (using Tmax threshold of 43°C) (B); and relative change in decile value of ambulance call-outs between baseline (summer non-hot days) and hot days (D) in Perth

In **Figure 13D**, blank (white) POA indicates there was no difference in AHO decile values, whereas yellow POA indicate a lower AHO decile value on hot days as compared with summer non-hot days. Orange to red indicates an increase in demand for ambulance services during on hot days.

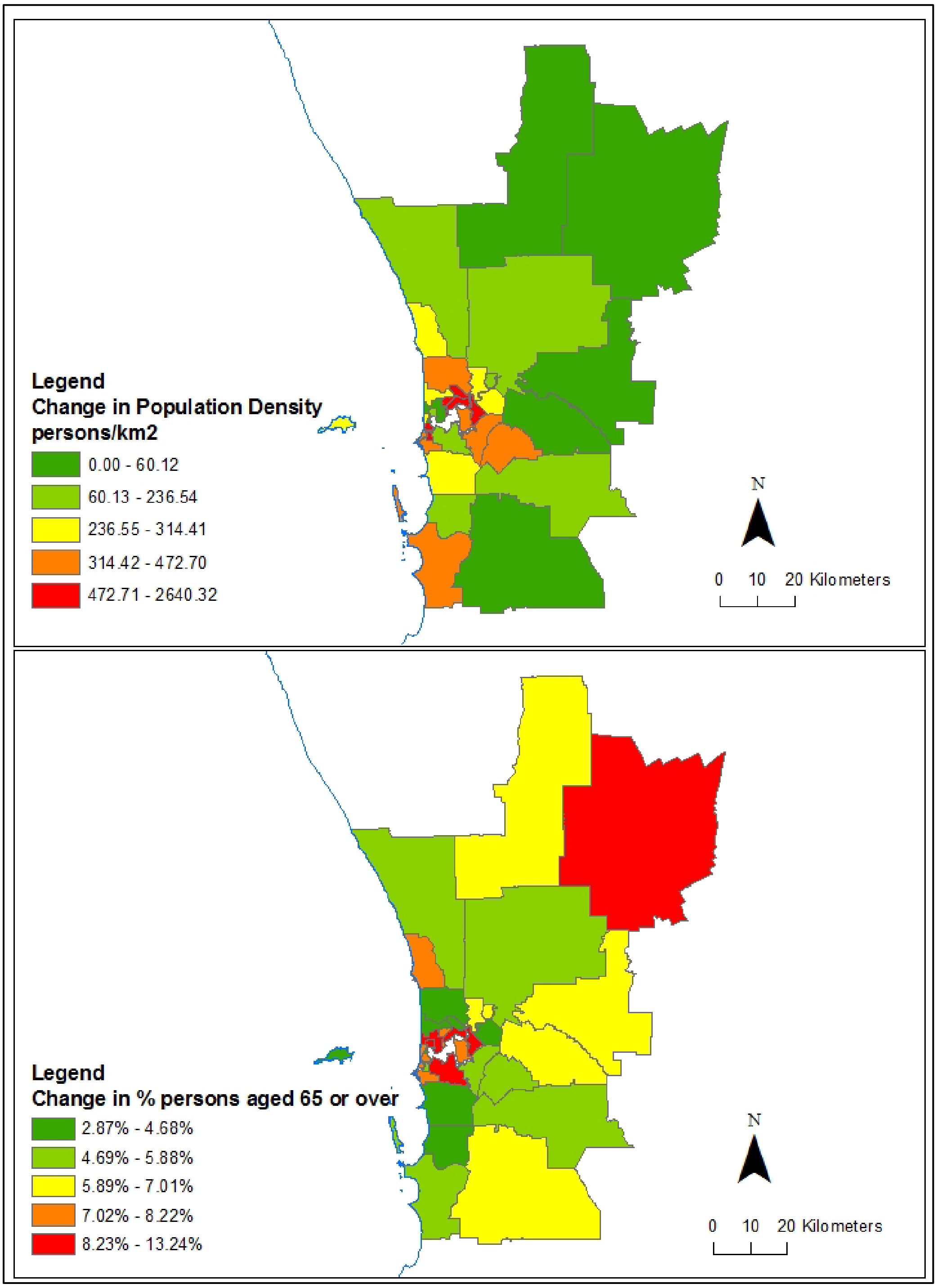

Figure 14: Changes in population density (shown as quintiles for persons per km^2) (A), and proportion of elder people (aged 65 or over) (B) by local government areas between 2006 and 2026 in Perth

Adelaide

Summary

Emergency department presentation rate for all persons categorised as either triage 1, 2 or 3 were used to measure AHO during periods of hot weather in Adelaide. The spatial distribution of AHO in Adelaide suggests increased vulnerability in the outer northern and southern suburbs. The weighted VI predicts this quite well. The relative change in presentation rates between hot days and non-hot days suggests that there is increased vulnerability in the northern suburbs and an area in the Adelaide hills. The total population in the northern suburbs is predicted to increase in coming years and the proportion of older person living in the outer suburbs is predicted to increase.

Development of vulnerability indices for Adelaide

The South Australian Department of Health provided data for patients from the Adelaide Statistical Division attending metropolitan ED from 1/1/2004 to 31/12/2010. Analyses of threshold temperatures for ED presentations indicated that meanT would be the most suitable value (see **Table 6**, Chapter 3). However, when using a meanT threshold of 39°C, more than 20% of POA (27 out of 126 POA) were not reported with any cases of ED presentation for any of three triage groups (1–3) examined. Such a high proportion of POA with zero value may influence the results of the stepwise regression analysis. Therefore, the Tmin threshold of 31°C was used to define hot days. This is a useful measure as hot nights are always preceded by hot days. At Tmin threshold of 31°C, there were 17 out of 126 POA without any cases of emergency department presentations for any of three triage groups (1–3). There are four days where Tmin equalled or exceeded the threshold temperature of 31°C. On hot days, there is a 6% increase in ED presentations for triage 1 to 3 when compared with number of ED presentations on non-hot summer days.

The AHO in Adelaide were measured as the number of persons presenting to ED and categorised as triage 1 to 3. This was defined for each POA during hot days as the ED presentations per 10,000 population. The total populations for each POA as of 2006 census data were used, as this is the latest census data set that was available.

Stepwise regression analysis shows that the measure of disability and accessibility to emergency service by travelling time are good predictors of vulnerability for urban communities in Adelaide ($r^2 = 0.63$). The weighted VI was calculated using the following formula (**Equation 8**). The weighted VI formula indicates that there is positive association between VI and measure of disability, but a negative association between VI and accessibility to ED. This suggests that the people presenting to ED on hot days are more likely to live in areas close to the hospital. It may be that people who are unwell live close to medical services[4]. This was measured as distance by road to ED, not as a measure of ED coverage by radius.

Equation 8: Derivation of weighted vulnerability index (VI) for Adelaide

Weighted VI = 1.949 * Need assistance – 0.005 * Accessibility to ED (time travel)

Principal components analyses for Adelaide yielded four components that together explained explain 83.1% of spatial variability in the *a priori* index variables (see **Table 40** and **Table 41,** Appendix). The rotated component matrix indicates that variables loading high value on Component 1 include land cover, accessibility to emergency

[4] Note also that all POA in Adelaide are within 15 km of an ED.

services and night-time LST (see **Table 42**, Appendix). However, Component 2 is loaded high with daytime LST. Loading high in Component 3 includes variables measuring urban design and elderly population (i.e. ACF, vulnerable age groups, single person, and people needing assistance and population density). Component 4 includes variables measuring ethnicity and socio-economic circumstance. The maps of VI PCA (see **Figure 15A**) show increased risk concentrated in the inner city region, whereas the maps of ED presentations (see **Figure 15B**) suggest that the outer suburbs to the north and south of the city area have higher incidence rates. The Spearman correlation of the additive model of vulnerability using factor analysis and the ED presentations on hot days is *rho* = 0.43, $p < 0.001$, indicating that this model explains 43% of the spatial variability in ED presentation rate.

The maps of the weighted VI (see **Figure 15C**) and ED presentations (see **Figure 15B**) indicate the highest vulnerability north and south of the city. This is quite consistent with the spatial pattern shown in ED presentations on hot days. The Spearman correlation between the weighted VI and ED presentations on hot days is *rho* = 0.60, $p < 0.001$, indicating that this model explains 60% of the spatial variability in ED presentations.

The relative change in AHO between hot days and non-hot days in summer is shown in **Figure 15D**. Areas shown as yellow indicate that the incidence rate of ED presentations decreases during hot weather, whereas areas shown in orange and red indicate that the incidence rate of ED presentations increases during hot weather. There are several areas in the inner Adelaide suburbs that show increased incidence rates and three areas in the outer north, east, and south of the city.

Projected changes in population distribution for total population from 2006 to 2026 (presented as quintiles for population density – persons per sq km) (see **Figure 16A**) and the changes in proportion of people aged over 65 years in Adelaide (see **Figure 16B**) indicate that population density will increase in the inner city region. In this regard increased proportions of older people are shown in the outer suburban areas to the east in particular.

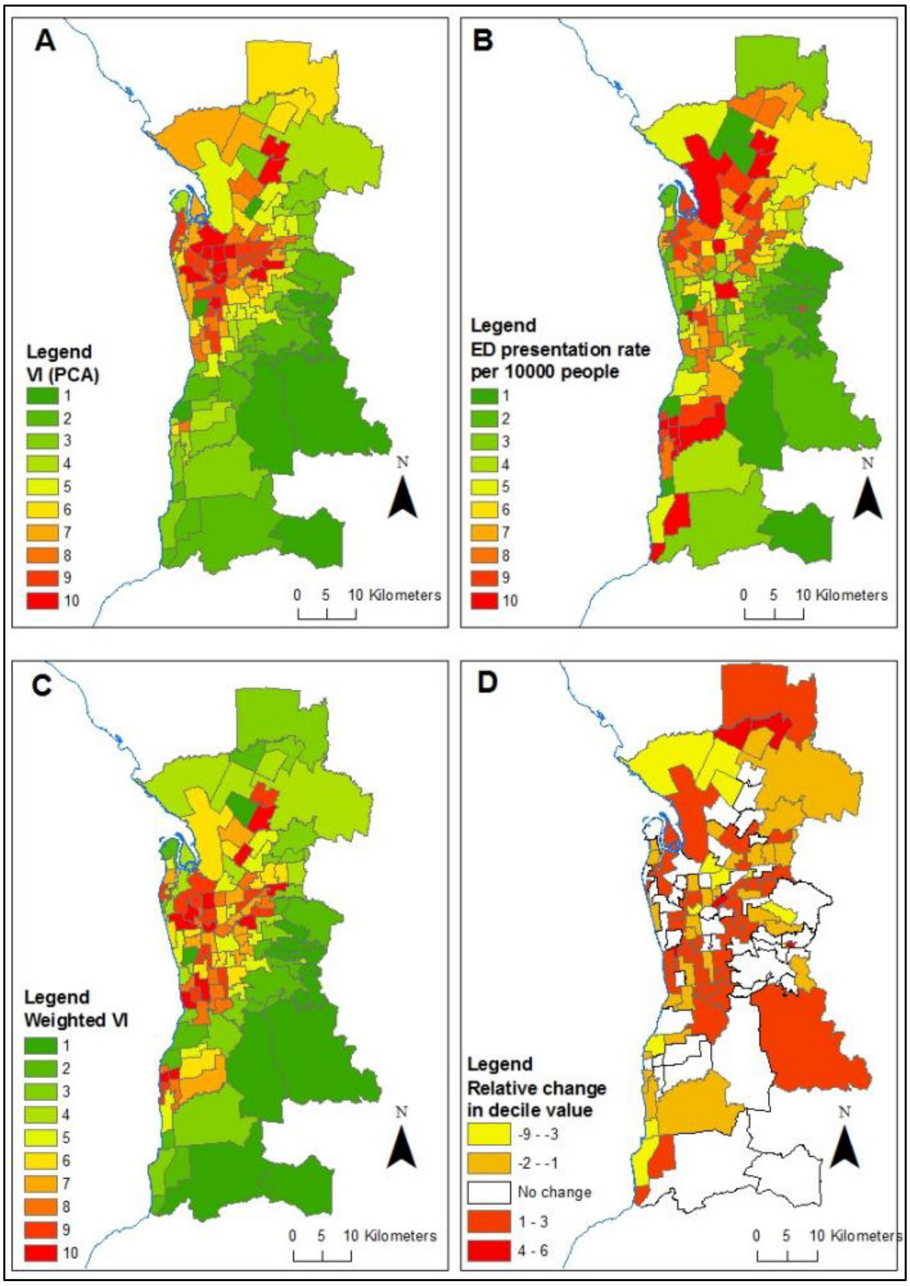

Figure 15: Spatial distribution of the vulnerability indices (VI) (A, C) and emergency department (ED) presentations (per 10,000 population) on hot days (using Tmin threshold of 31˚C) (B) by decile; and relative change in ED presentations between baseline (summer non-hot days) and hot days (D) in Adelaide

In **Figure 15D,** blank POA indicates there was no difference in AHO decile value, whereas yellow to orange POA indicates a lower AHO decile value on hot days as compared with summer non-hot days. Red indicates increased demand on hot days in Adelaide.

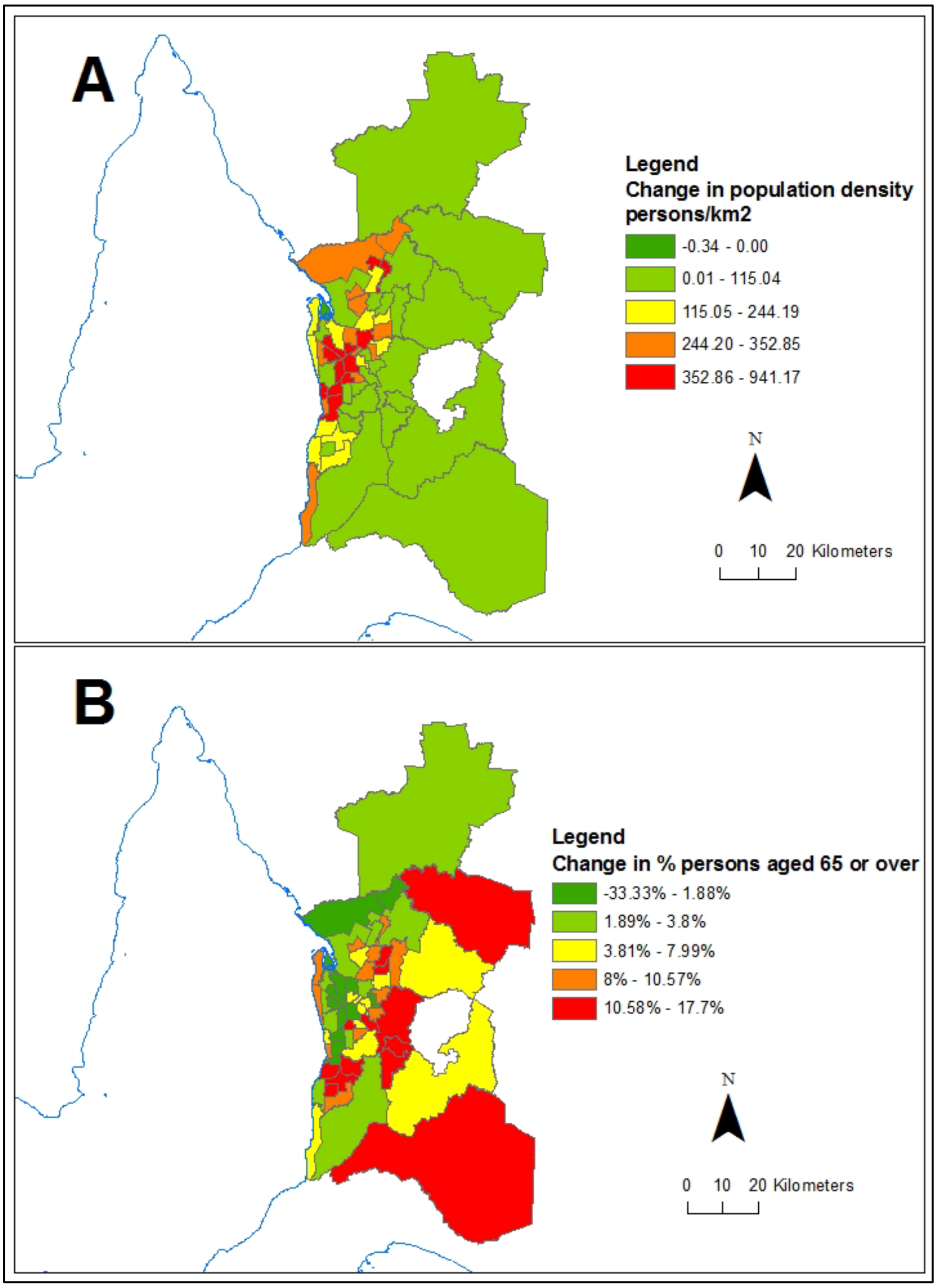

Figure 16: Change in the population density (shown as quintiles for persons per km^2) (A) and proportion of elderly people (aged 65 or over) (B) between 2006 and 2026 by statistical local area in Adelaide

The white area belongs to an SLA that has most its area outside the study area and is therefore not included.

Darwin

Summary

Emergency department presentations recorded as heat related were used to measure AHO in Darwin during hot weather. The spatial distribution of heat-related presentations is highest in Darwin city and in the eastern suburbs. The VI (PCA) was the best method to predict vulnerability in the Darwin area. The relative change in ED presentations between hot days and non-hot days supported the VI PCA model. The projected population growth in the Darwin region from 2006 to 2021 indicates an increase in both total population and the proportion of older people in the community. This will potentially increase risk in some areas and steps must be taken to provide opportunities for adaptation.

Development of vulnerability indices for Darwin

The Northern Territory provided daily emergency presentations reported as ‘heat related’ for every patient admitted to hospital in the Northern Territory between 24/1/2005 and 8/10/2011. Patients residences were recorded by locality and therefore the POA for each ED presentation was updated based on locality name. If the spatial boundary of locality intersects with multiple POA, the locality was assigned to the POA where its area occupies the biggest proportion in the locality polygon. Only ED presentations from Darwin were selected to determine the weight-to-map VI. Satellite imagery could not be obtained for Darwin due to cloud cover during the summer months; UHI variables are not included in the vulnerability variable list for Darwin.

A threshold meanT of 31°C was used to define hot days, on those days there were 5 out of 13 POAs with ED presentations. The total population of each POA in 2006 was used to determine the ED presentation rate. The ED presentation rate was determined for each POA as the rate per 10,000 population.

Table 43 (Appendix) shows that only the urban design variable correlates with AHO ($p < 0.05$). Stepwise regression analysis shows that urban design is found to be a good predictor of ED presentation rate in Darwin ($r^2 = 0.45$) see **Equation 9**, and the condition index for this model was 2.4, indicating mullti-colinearity is not a problem.

Equation 9: Derivation of weighted vulnerability index (VI) for Darwin

Weighted VI = 0.029*urban design

Principal components analysis shows that four components can explain 83.6% of variability among vulnerability variables (see **Table 44**, Appendix). **Table 45** (Appendix) shows that 7 out of 11 vulnerability variables load highly in Component 1 including accessibility to ED, ethnicity, single people aged 65 or over, urban design, population density and ACF. For Component 2, variables loading high include land cover and measure of disability. Socio-economic circumstance and age variables load high in components 3 and 4 respectively. The map of VI (PCA) in **Figure 17A** shows predicted vulnerability is highest in Darwin city, the surrounding suburbs, and suburbs to the east of the city. The Spearman correlation of the additive model of vulnerability using factor analysis and the ED presentations on hot days is *rho* = 0.725, $p < 0.005$, indicating that this model explains 72.5% of the spatial variability in ED presentation rate.

The maps of the weighted VI and AHO for Darwin (**Figure 17C**) indicate that the highest presentation rate is in the city of Darwin and high decile values in Holtze and Howard Springs to the south-east of the city. The Spearman correlation for the weighted VI and AHO in Darwin is *rho* = 0.186, $p = 0.543$, this result is not statistically significant.

The relative changes in ED presentation rate between hot days and non-hot days in Darwin are shown in Figure 17**D**. This figure shows increased presentation rates in suburbs to the north and east of Darwin city and one suburb on the southern fringe. These areas are also noted as increased vulnerability in the VI (PCA).

Projected population in the Northern Territory is available for the whole state as well as for six Northern Territory Government Statistical Reporting regions (Northern Territory Government, 2011). For Darwin, SD the finest scale of projected population is the greater Darwin statistical reporting region. **Table 10** shows that the proportion of elderly people in Darwin is predicted to increase by nearly 4% between 2006 and 2021. The total population of Darwin in 2006 was 114,361 persons, the projected population for 2021 is 153,393. This is an increase of 39,032 or 34.13%. Maps could not be generated for this area because of the large spatial scale relating to the projected population changes.

Table 10: Total population and proportion of elderly people in the Greater Darwin in 2006 and its projection in 2021

	2006		**2021**	
	Total	% of total	Total	% of total
Persons aged 65+	5970	5.22	13,912	9.07

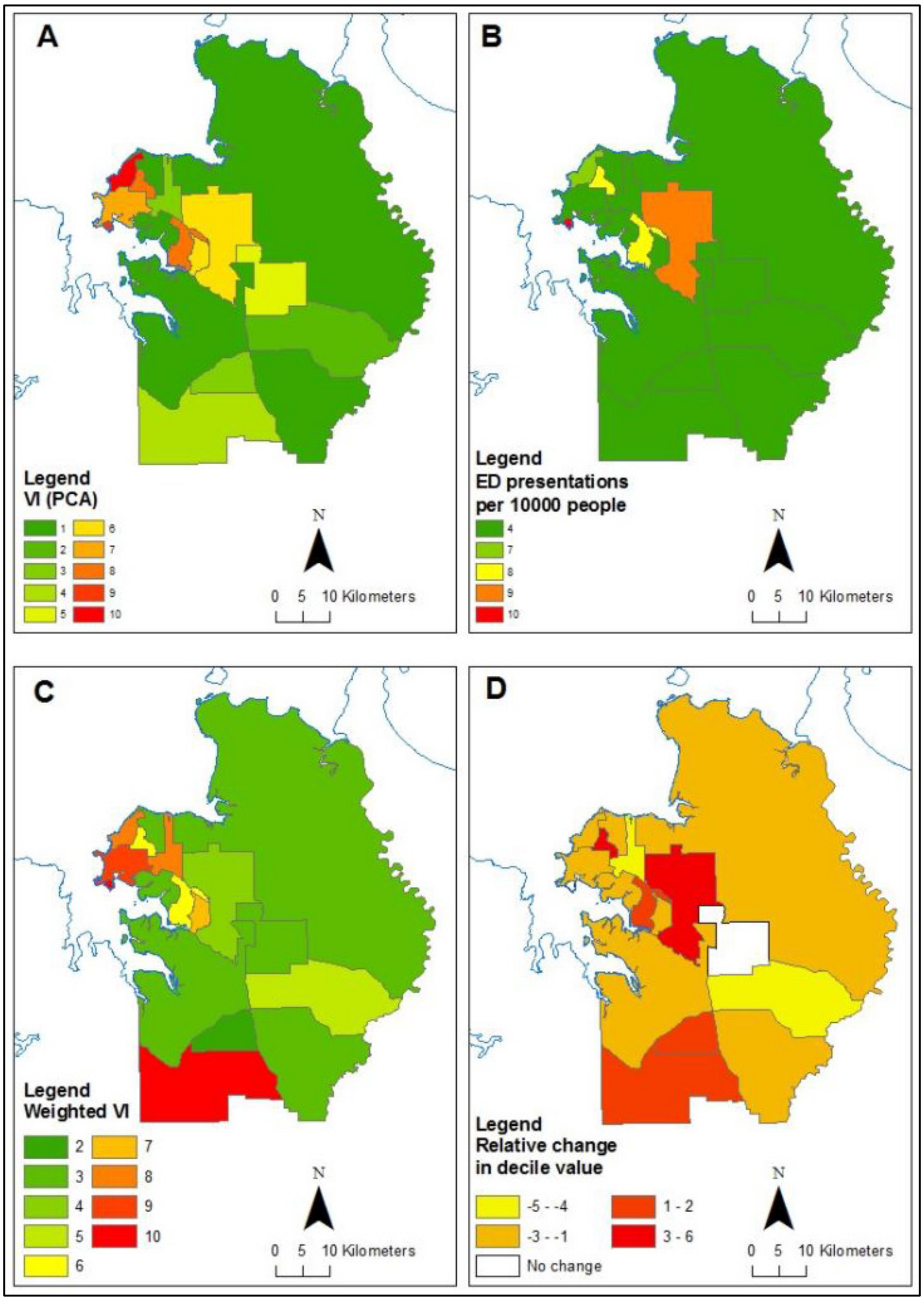

Figure 17: Spatial distribution of the vulnerability indices (VI) (A,C) and heat-related emergency department (ED) presentations (per 10,000 population) (B) by decile; and relative change in ED presentations between baseline (summer non-hot days) and hot days (D) in Darwin

In **Figure 17**, blank POA indicates there was no difference in AHO decile value, whereas yellow to orange POA indicates a lower AHO decile value on hot days as compared with summer non-hot days. Red indicates increased demand on hot days in Darwin.

Sydney

Summary

Emergency hospital admissions were used to measure the health outcomes in Sydney during hot weather. The spatial distribution of hospital admissions on hot days is concentrated in areas to the north, south, and west of the city. The weighted VI used only one variable ‘age’. This provided the best model for vulnerability to heat in Sydney. Areas to the south of the city in particular reported increased admission during hot weather compared with the admission rates during non-hot days. The predicted change in future total population shows greater densities in the inner suburban area. This is likely to have an impact on the UHI in Sydney in the future. The projected increase in the proportion of older people is greatest in the outer suburban areas, especially in western Sydney. This area is already highlighted as high vulnerability. An ageing population in this area will increase demand on hospital services on hot days, therefore it is vital that adaptation strategies are developed to increase resilience and minimise AHO in this population during heat events.

Development of vulnerability indices for Sydney

The Department of Health, New South Wales provided emergency admissions to hospital for residents in the Sydney SD by postcode and age groups (0–64 and 65 years or over) between 1/1/2000 and 30/6/2010. The threshold temperature used to define hot days in Sydney was a meanT 31°C. There were five occasions when this threshold was reached.

Table 46 (Appendix) shows that land cover, accessibility to hospitals, age, single-person households, night-time UHI, and population density of vulnerable groups were all significantly correlated with AHO on hot days. However, these correlations are small. Stepwise regression analysis produced two models. Model 2, including age and UHI (night time) variables, was not selected because of a high condition index value of 42. Model 1 (shown in **Equation 10**) indicates that age can be a good predictor of AHO, but the model has a low r^2 (0.04).

Equation 10: Derivation of vulnerability index (VI) for Sydney

Weighted VI = 0.23*Age

Principal components analysis shows that four components are created and can explain 78% of variability among *a priori* variables (see **Table 47**, Appendix).

Table 48 shows that UHI (night time) and accessibility to hospital variables load highest in Component 1, accounting for 26.4% of variability of vulnerability variables. Variables loading high values in Component 2 (accounting for 24.8% of variability) include socio- economic circumstance, ethnicity and UHI (daytime). Component 3 relates to 'density' of urban environment, which records high loading values for land cover, urban design and population density variables. Finally, high loading values include 'elderly related' variables, namely ACF, age, single person aged 65 or over, and measure of disability only accounting for 12.3% of the variability within the *a priori* variables. Figure 18 shows that the predicted vulnerability using the PCA model is largely concentrated in the areas surrounding the city. Visually the mapped VI (PCA Fig 18A) and mapped AHO(Figure 18B) on hot days (see Figure 18**A**) are quite different. The Spearman correlation is *rho* = 0.239, $p < 0.001$ suggesting this model explains 24% of the variability in AHO on hot days.

The map of the weighted VI for Sydney (see Figure 18**C**) indicates that increased vulnerability exists in the suburbs surrounding the city, extending along the northern coastal suburbs and inland through to western Sydney. There appears to quite good agreement with the mapped admission rates however the Spearman correlation is *rho* = 0.28, $p < 0.001$. This suggests that the VI explains 28% of the spatial variability, although the model used only includes one variable 'age'. Therefore, we can imply that age alone explains the observed spatial patterns.

The relative change in AHO on hot days (see Figure 18**D**) shows an increase in admissions from the suburbs north and south of the city region and extending west onto western Sydney. It is also possible that the heat intensity in areas away from the coast and in western Sydney exacerbated the morbidity in these areas. Heatwave plans for these areas should be developed or revised to help reduce the increased morbidity during hot weather that is apparent from the map.

Projected changes in population distribution for total population from 2006 to 2026 (presented as quintiles for population density – persons per km^2) (see **Figure 19A**) and the changes in proportion of people aged over 65 years in Sydney (see **Figure 19B**) indicate that changes in total population are greatest in the immediate areas surrounding the city. Changes in the proportion of older people are more pronounced in the outer suburban areas.

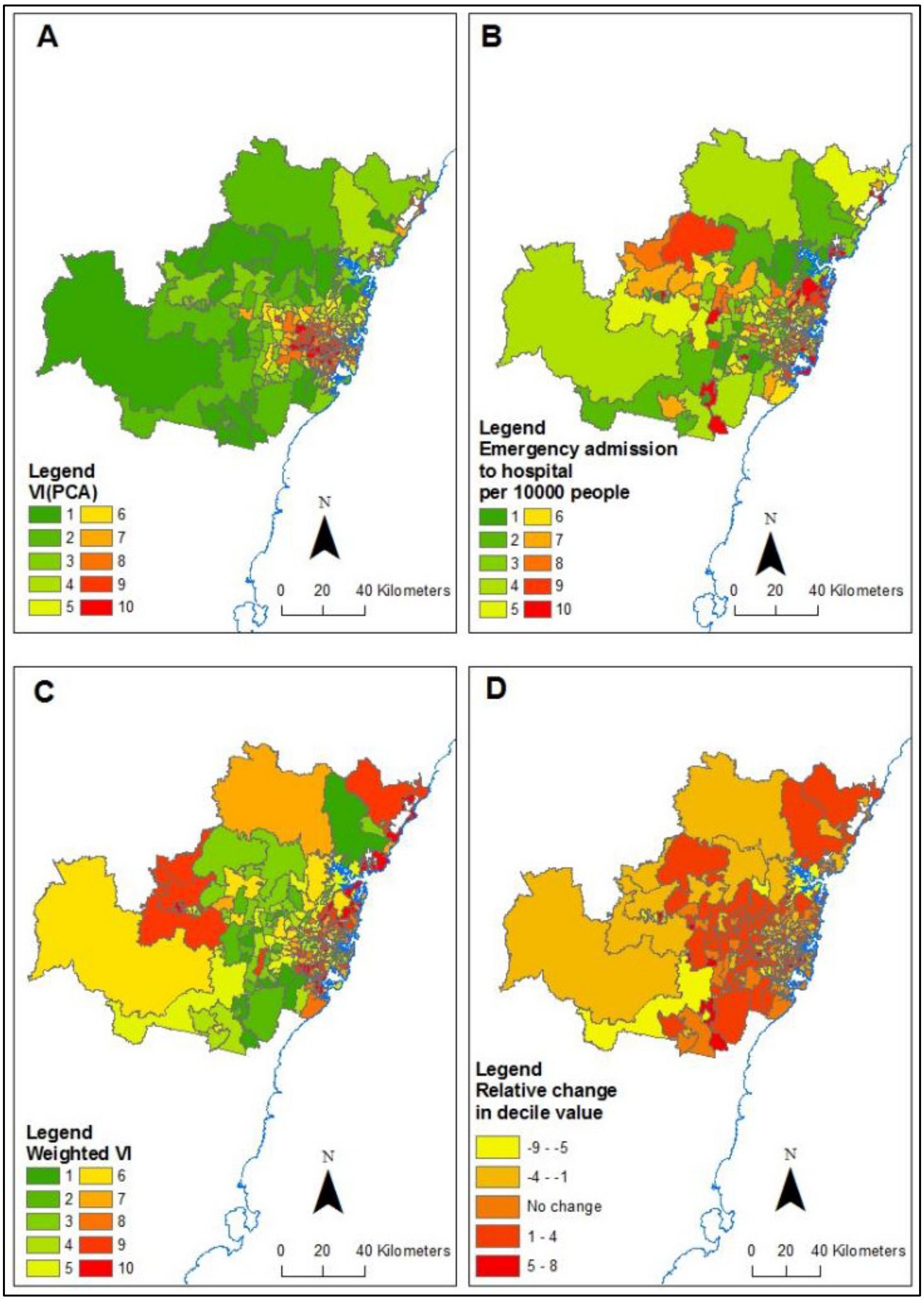

Figure 18: Spatial distribution of the vulnerability indices (VI) (A, C) and emergency hospital admission (EHA) to (per 10,000 population) (B) on hot days by decile; and relative change in decile value of emergency admission to hospital between baseline (summer non-hot days) and hot days (D) in Sydney.

In **Figure 18**, blank POA indicates there was no difference in AHO decile value, whereas yellow to orange POA indicates a lower AHO decile value on hot days as compared with summer non-hot days. Red indicates increased admissions on hot days in Sydney.

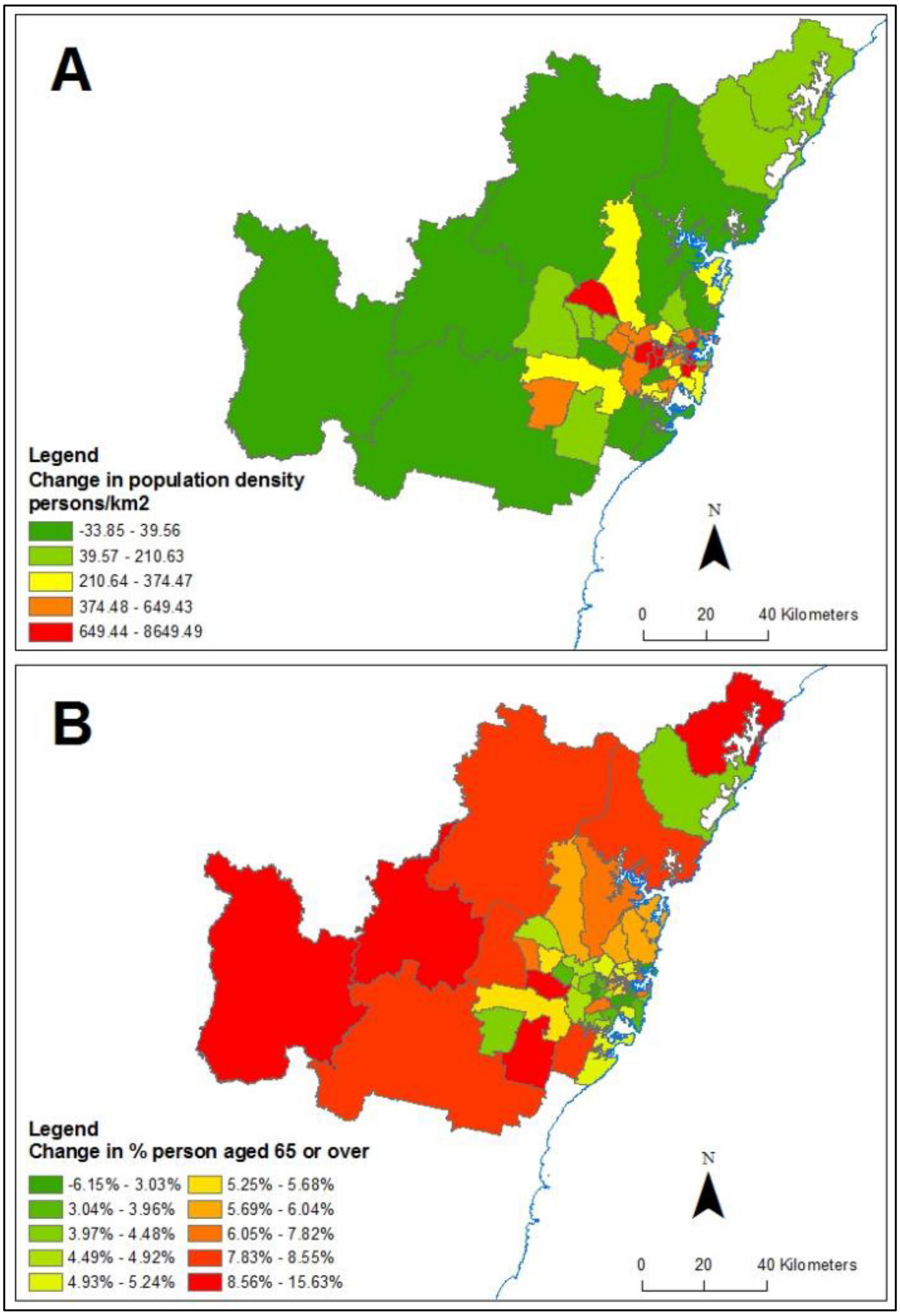

Figure 19: Changes in population density (shown as quintiles for persons per km^2) (A), and the proportion of older people (B) between 2006 and 2026 by statistical local area in Sydney

4.4 *Discussion*

The key purpose of this research was to identify areas that are classified as 'high risk' for Australia capital cities in terms of AHO related to heat events, and increase our understanding of how this risk may change in the future. Four variables features strongly in the assessment of heat related AHO, these were age, disability, UHI and ethnicity. It was also noted that higher risk areas clustered outside of the central city areas. We used a three-phase research approach to develop information for emergency managers, Australian governments, and communities. Firstly, health data and climate data were collected and analysed to identify threshold temperatures where the mortality and morbidity in each capital city increased in response to ambient temperatures. This provided information about exposure-related risk. Secondly, we defined demographic, environmental and health risks from the existing literature and developed a spatial index of vulnerability to explain where people face the greatest risk. Thirdly, we identified how future regional climate change will affect the number of days exceeding the health thresholds in each city. This novel and triangulated approach will critically inform the way that the emergency management sector can respond to climate change in large urban areas in terms of prevention, preparedness, response, and recovery. It will also inform government agencies and communities and thereby target the areas in most need of help in developing resilience to known triggers such as heat events.

Risk analysis is an integral part of emergency management. Risk can be defined as 'a function of the hazard, exposure to that hazard, the vulnerability, or susceptibility to harm, and the ability to recover' (NCCARF, 2009). To date however, knowledge of the risks related to heatwaves has largely been limited to identifying and defining heatwaves. Tools that aid in vulnerability assessment are still in the early stages of development, especially those that show how vulnerability translates into AHO during heat events. As such, these studies have made limited contribution to heatwave policy development, or informing emergency management and public health sectors.

Mapping population vulnerability that is directly related to AHO during heat events enables this study to present a more accurate picture of heat-related risk in the urban environment and the demands experienced by emergency services and the health sector. It also highlights the areas with the greatest need for adaptation.

By aggregating known factors of environmental, demographic and health risks 'hotspots' have been identified in each of the capital cities and these have been validated against AHO during heat events. The vulnerability indices developed in the study meets the follow criteria as outlined by Wolf *et al.* (2009):

- significance – identifies areas with elevated vulnerability compared with surrounding areas
- relevance – corresponds with areas of increased mortality and morbidity during heat events
- feasibility – the data used to compile the index is available, reliable and collected a suitable spatial resolution
- transferability to all larger urban areas.

We used two approaches to examine spatial vulnerability. A PCA grouped the *a priori* variables into uncorrelated components (factors). We created an additive index and then mapped to predict vulnerability in each city (Cutter *et al.*, 2003; Reid *et al.*, 2009). We used a second method that regressed the index variables against the AHO to identify which variables made a significant contribution to the health outcome during hot weather. The selected variables were then used to create a weighted index. We then mapped the weighted index to predict vulnerability in each city and also generated maps of the spatial distribution of AHO on hot days. We performed a Spearman rank order correlation to determine which model best described vulnerability in relation to AHO. For the capital cities except Darwin and Canberra, the results indicated that the weighted index provides a better explanation of spatial vulnerability than the PCA model. Why Darwin is different is unclear, it may be that the smaller data sets for Darwin and Canberra were unsuitable for regression analysis.

We also generated maps of the spatial distribution of AHO (using decile values) on hot days in summer. This provides emergency services with information about service demand. To clarify this relationship further we also mapped the relative change in AHO on hot days during summer. This allows emergency services to plan for increased demand in service provision, as well as areas where adaptation and heatwave planning is needed. The variable used to measure UHI featured strongly in both models of vulnerability. This is because the primary characterisation of vulnerability on hot days is the outdoor (ambient) temperature. This is heavily influenced by urban density, lack of vegetation, and the UHI in larger cities. Furthermore, residences with high 'inside' heat load due to age of the building, building height, quality of thermo-isolation and ventilation and exposure are associated with a higher risk of adverse health effects from hot weather (Wolf *et al.*, 2009). Redesigning cities to increase green infrastructure, water availability, and sustainable housing design will help moderate this effect.

Age also features strongly in both models of vulnerability. This includes the number of ACF, the age structure of the population at risk (the proportion of older people and children), and the proportion of older people who live alone. The number of people who need assistance with daily tasks was also an important indicator of vulnerability that undoubtedly increases with advancing age. Ethnicity is also indicated as a risk factor. This is not surprising as a recent study has indicated that people in CALD (culturally and linguistically diverse) communities experience barriers to heatwave adaptation (Hansen *et al*., 2012). These barriers include living within lower socio-economic circumstances and facing linguistic problems in trying to understand heatwave risks in the Australian climate. This experience is true for both recent migrants and older or longer term migrants. These issues highlight the need for culturally specific risk communication strategies for CALD communities and some research into low-cost adaptive behaviours that are also culturally appropriate. Heatwave planning guides prepared by public health authorities and local governments would help develop resilience in these groups. These approaches need to be integrated as often the most vulnerable people live in the areas with the highest heat exposure during hot weather. It is therefore important to ensure that short-term, and longer-term technological and behavioural adaptation is accounted for in heatwave planning and preparedness.

We also mapped the difference between predicted vulnerability and AHO on hot days to indicate areas where the index either over predicts or under predicts vulnerability. This was done for the larger cities of Brisbane, Melbourne, Adelaide, Sydney and Perth. Areas where vulnerability is under predicted are of particular concern, as these will need further research and targeted interventions to determine the main drivers of vulnerability.

Interestingly when the relative change in AHO was compared with the predicted vulnerability in each city area there were some discrepancies, or areas predicted as high vulnerability that showed a decrease in service demand on hot days. Conversely some areas predicted as lower vulnerability experienced an increase in service demand on hot days. Some areas consistently demonstrate a high demand for emergency services and high numbers of hospital attendances irrespective of weather, whereas other areas that ordinarily have lower AHO show a marked increase in vulnerability during hot weather. It is difficult to determine what is driving this observation given the level of data used in the study, but for cities where the AHO were ambulance calls it may be because the VI was based on demographic factors for areas where people live and ambulances may be responding to workplaces, or recreation areas. For example, Bassil *et al*. (2009) found excess emergency calls from recreation areas along the waterfront in Toronto during summer.

As UHI and urban density featured quite strongly in predicting vulnerability, it is important to know how these patterns may change in the future. Changes in predicted total population were used as a proxy for changes in urban density, which would imply changes in UHIs within cities. Maps of the predicted changes highlighted areas with the greatest changes; these areas need to be considered from an urban planning perspective to ensure that urban development is sustainable and provides as cool an environment as possible. Maps of predicted changes in the proportion of older people living in each region indicate that ageing communities will (a) generally be located in the outer or fringe suburbs and (b) are associated with areas that show increased vulnerability under current conditions. Again, this provides information for policy development and infrastructure planning to ensure that adaptation can be enacted in a timely fashion.

Using spatially based indices of vulnerability to forecast heat health outcomes and corresponding emergency service demands has a number of limitations that end-users need to keep in mind when using the maps. We used satellite imagery to determine mean summer daytime or night-time LST, but this is not the only factor that influences ambient temperature or exposure. Air temperature, solar radiation, wind speed and humidity all influence exposure. However, the satellite imagery allows us to identify 'hotspots' within regions. Surface temperature may not represent indoor exposures. This is important as most people remain indoors when temperatures are extreme, although surface temperatures do indicate areas where the thermal mass of buildings may inhibit night-time cooling. For five of the eight capital cities, ambulance call-out data allowed us to map the area where AHO were occurring, the remaining three cities showed vulnerability in relation to where people lived. This may not represent where the greatest exposures are occurring, heat-related health outcomes in the workplace cannot be accounted for. Unfortunately, useful data sets for heat-related illness and workplace characteristics would be difficult to obtain. Using a composite index may appear to oversimplify the problem and lead to misinterpretation of risks. Absolute index values (deciles) are ranked from 1 to 10 with 1 representing lower vulnerability end of the scale and 10 the highest vulnerability. These rankings are city specific and cannot be compared between cities, as they depend on the distribution of the data sets across each city.

The usefulness of VI as tools to inform adaptation policy is at present untested. Translating scientific theory to adaptation policy and then initiating action at a grassroots level is a very difficult process. Does uncertainty in vulnerability predictions lead to inaction in policy development? How accurate does predicted vulnerability need to be to initiate action? In areas where predicted vulnerability reflects social and environmental injustice, can adaptation policy be enacted in a timely fashion? Therefore, the question remains of how best to translate science into policy and lead to change at an individual, community, organisational and national level.

The final stage of this study involved using a global climate model regionally downscaled to cover the area of Australian capital cities to determine the likely changes in the numbers of days exceeding the temperature thresholds described in Chapter 3. Two time slices were examined, 2020-2040 and 2060-2080. The 2020-2040 time slice is of particular interest as this aligns with the projected population changes and maps showing projected changes in risk for areas with increased urban density and greater proportions of older people.

5. PROJECTED CHANGES IN HEAT EXTREMES ASSOCIATED WITH CLIMATE CHANGE

5.1 *Introduction*

As a consequence of climate change, average temperatures in Australia are projected to rise by between 1.0 and 5.0°C by 2070 when compared with temperatures of the period 1980 to 1999 (CSIRO, 2012), and extreme heat events are likely to become longer and more severe (Alexander and Arblaster, 2009). The results of this study support this finding. The IPCC has reported that an increase in heat-related deaths is likely to be one of the most significant impacts of climate change for Australia in the future (IPCC, 2007). Therefore it is crucial to prepare for extreme heat events and protect Australian communities. Estimations of likely numbers of heat-related deaths in Australian capital cities, such as that of Woodruff *et al*. (2005) of up to 15,000 deaths per year by 2100, highlight the public health significance of this issue.

Even with the most stringent mitigation efforts, continuing climate change is 'locked in' for centuries to come as a consequence of current greenhouse gases emissions and inertia in the climate system (Solomon *et al.*, 2009; Cleugh *et al.*, 2011). Adaptation strategies are therefore essential to minimise health impacts.

Health planners and policy makers need information about likely future climate exposures in order to develop adaptation and emergency management strategies. Climate models provide information about the future climate. The challenge for climate scientists is to provide climate projections on useful spatial and temporal scales. Much of the research that has been conducted to estimate future climate has been done at global or continental scales. However, it is well documented that vulnerability to extreme heat varies considerably across populations and between geographical areas (Rey *et al.*, 2009a; D'Ippoliti *et al.*, 2010; Rooney *et al.*, 1998); more detailed regional projections are required to assess potential local impacts and inform targeted heat adaptation strategies.

Global climate models (GCM), also referred to as general circulation models, are mathematical representations of the Earth's climate used to project future climate over large geographical areas for decades and into the future (CSIRO, 2012). In order to generate projections at a finer scale, downscaling methods are used over an area of interest. One approach is to use a 'dynamic approach' in which data from a GCM is fed into a regional climate model that takes into account local weather conditions (Cooney, 2012).

CSIRO Marine and Atmospheric Research have been modelling regional climates for several decades. Data from the CSIRO regional modelling program using the CCAM has been made available to this research. This model is a full atmospheric GCM based on a conformal-cubic grid that covers the globe but can be stretched to provide dynamical downscaling output from global climate models for many regions of the world (McGregor, 2005). The regional downscaling improves on GCM mean values of climate variables, spatial patterns of climate variables and seasonal variability of climate variables (Nguyen and McGregor, 2009).

The CCAM had been run at 60-km resolution over Australia using a number of host GCMs. Simulations using the Hadley Centre Model ver.3 (HadCM3) data set were chosen on the basis of this model's ability to predict future climate over Australia. HadCM3 is a coupled atmosphere–ocean global circulation model (AOGCM) developed at the Hadley Centre in the United Kingdom (Gordon *et al.*, 2000). HadCM3 has a resolution of 3.75° (longitude) x 2.5° (latitude) or ~300 km x 300 km (Reichler and Kim, 2008). The downscaling process reduces the GCM to a grid with a resolution of 0.5° (longitude) x 0.5° (latitude) or ~60 km x 60 km. This represents an enormous improvement in horizontal resolution of the climate forecasts and makes the data more suitable for an application that assesses heat extremes over isolated areas in the future.

Most projections of future climate over Australia have been made for two very broad regions: north and south (e.g. see figures SPM.4A and SPM.4B in IPCC, 2012). Consequently there remains considerable uncertainty associated with projections for more localised areas such as capital cities.

The aim of this study is to use data from the CSIRO regional modelling program CCAM to predict changes in future heat extremes for broad Australian capital city locations in order to understand the vulnerability of different populations in the future.

5.2 *Method*

Overview

This study has focused on climate projections for eight Australian capital cities: Adelaide, Brisbane, Canberra, Darwin, Hobart, Melbourne, Perth and Sydney. These are the most populous capital cities, accounting for approximately 63% of the Australian population, including 59.5% of those aged 65 years or older (Australian Bureau of Statistics, 2010) .

We made projections of numbers of days exceeding previously determined thresholds for heat-related mortality for each of the cities, for two future time periods, 2020 to 2040 and 2060 to 2080, using the dynamic downscaling climate model system.

The suitability of the climate model was initially verified by comparison with relevant meteorological data for the period 1999 to 2010 for the regions in question. Details of the data used, and methods used for climate model verification and temperature projections are provided below.

Data

Data used in this part of study included meteorological data collected for the purpose of validating the climate model, simulated data generated by the climate model, and data regarding temperature thresholds for heat-related mortality in Australian capital cities.

Meteorological data

We obtained daily meteorological data for temperature, relative humidity, and dewpoint temperature for the period 1990 to 2010 from the Australian BoM for one weather station from each of the eight capital cities (see **Table 11**.)

Stations were selected on the basis of location and data availability for the entire reference period. These locations increased the likelihood of observations being applicable to a large portion of the population on any given day. For example, we selected sites as close to the CBD as possible to capture the influence of built environments, and avoided frequently cooler coastal sites.

The data for all three parameters were provided six times daily, from which we calculated daily maximum, minimum and mean values. This was then compared to climate model data using a range of statistical methods.

Table 11: Bureau of Meteorology weather observation stations from which six-times daily data were provided for the period 1990 to 2010 (http://www.bom.gov.au)

City	Site name	Site number	Latitude	Longitude	Elevation (meters)
Adelaide	Adelaide (Kent Town)	023090	34.92° S	138.62° E	51
Brisbane	Brisbane	040913	27.48° S	153.04° E	8
Canberra	Canberra Airport Comparison	070014	35.30 °S	149.20 °E	578
Darwin	Darwin Airport	014015	12.42 °S	130.89 °E	30
Hobart	Hobart (Ellerslie Road)	094029	42.89 °S	147.33 °E	51
Melbourne	Melbourne Regional Office	086071	37.81 °S	144.97 °E	31
Perth	Perth Airport	009021	31.93° S	115.98° E	15
Sydney	Sydney (Observatory Hill)	066062	33.86 °S	151.21 °E	39

Climate simulation data

Data from the HadCM3 climate model are available for a range of greenhouse gas emission scenarios. In order to generate projections of most use to policy makers, and to take into account inherent uncertainties in scenario assumptions, we selected model output data for two emission scenarios spanning the range of high to low emissions. The two emission scenarios chosen from the IPCC SRES (Special Report on Emissions Scenarios) were B1, to represent the lowest emissions scenario, and A2 to represent the high emissions scenario (IPCC, 2000). There is evidence to suggest current emission levels are tracking at or above those suggested for the A2 scenario (Leggett and Logan 2008). By selecting two emission scenarios with broad differences in driving forces, a range of outcomes will be projected for the consideration of policy makers.

Climate model outputs of interest were temperature and relative humidity for the reference period (1990 to 2010) and two future time periods 2020 to 2040, and 2060 to 2080. These time slices were chosen to capture the current climate and the future climate change signal. We used the reference period data to validate the model through comparison with BoM data, and used the data from the future time periods to make predictions about future heat extremes and potential health impacts.

Temperature threshold data

The threshold values above which heat-related mortality has been observed to increase in Australian capital cities are taken from the work described in Chapter 3 (See **Table 6**)

Assessment of the performance of CCAM

An assessment of the regional climate model's ability to reproduce present-day climate over the regions of interest is necessary, not only to have confidence in the results, but also to improve our understanding of them. The assessment of CCAM output was conducted by comparing BoM observations for the reference period with CCAM output for the same period. We employed a number of statistical methods to validate the CCAM output of temperature and relative humidity, including the generation of frequency distributions to provide visual confirmation of CCAM's ability to reproduce climate statistics over the 20-year reference period. Statistical techniques employed to establish similarity between CCAM and BoM data sets were

- the correlation coefficient (r)
- the coefficient of determination (R^2)
- the index of agreement (IOA)
- the root mean square error (RMSE).

The correlation coefficient, r, was considered because a test of statistical significance is possible for these values.

R^2 is a commonly used statistical tool, particularly for models that predict future outcomes on the basis of other related information. R^2 represents the proportion of variability in a data set that is accounted for by the statistical model.

The IOA measures the degree to which the observed data are approached by the predicted data. The IOA overcomes the insensitivity of R^2 to the differences in the observed means and variances. An IOA of 0 shows no agreement between observed and modelled values, whereas a value of 1 shows perfect agreement between the two data sets.

The RMSE is a good measure of precision, used commonly in the atmospheric sciences to assess how effectively models predict the behaviour of the atmosphere. It aggregates individual differences into a single measure of predictive power. The smaller the RMSE the closer the modelled data are to BoM observations.

Identifying changes in the frequency of extremely hot days

The threshold temperatures above which heat-related mortality is observed to rise have been provided by work described in Chapter 3. These measures include daily Tmax, daily Tmin and, 24-hour (9am–9am) mean temperature referred to as meanT.

5.3 *Results*

Assessment of the performance of CCAM

We created frequency distribution curves for each climate parameter for all cities, but only a selection is provided in this chapter as an example of the results shown.

From **Figure 20** and **Figure 21** we can see that while the broad distributions are similar, CCAM tends to overestimate or under estimate both Tmax and minimum relative humidity in Hobart through different parts of the distribution. Although the statistical analyses in the following section demonstrate the overall degree of error in simulated data, these distributions can offer some insight into the reason for those errors. For example, we can gain insight into the location of the model grid points in comparison to the BoM observation station in each city.

Figure 20: Frequency distribution of maximum temperature for conformal cubic atmospheric model (CCAM) output and Bureau of Meteorology (BoM) observations in Hobart (Ellerslie Road) for the period 1990–2010

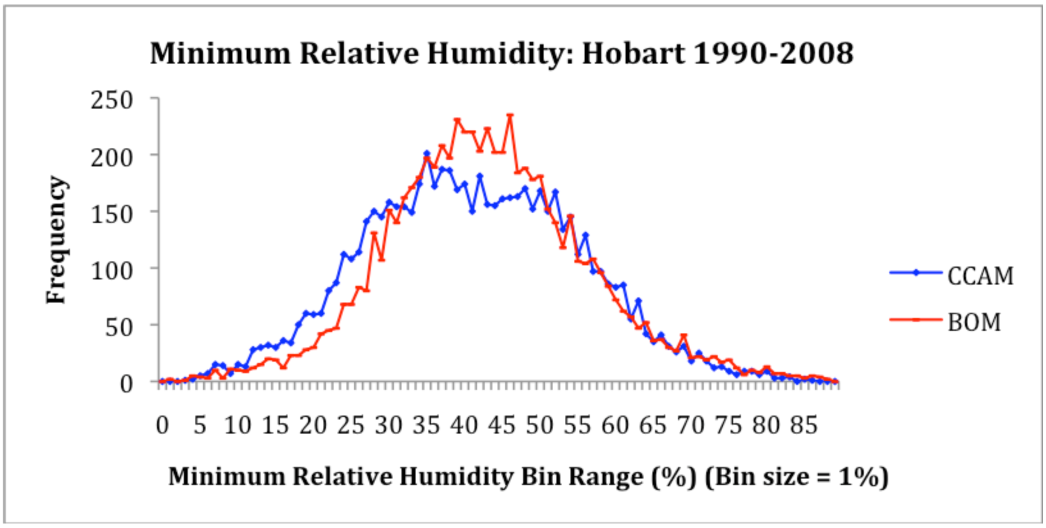

Figure 21: Frequency distribution of relative humidity for CCAM output and BoM observations in Hobart

Statistical analyses

Daily data from CCAM have been compared to BoM data for a number of measures of model performance (**Table 12** and **Table 13**). In Table 12, R2 is shown for daily meanT, Tmin, Tmax and mean, minimum and maximum relative humidity. R2 values are between 0 and 1. A value closer to 1 is ideal. Values of R2 are derived directly from r, the correlation coefficient. Relationships where the values of r are not statistically significant are indicated with **bold type**; all other relationships are significant at the 0.01 level. The CCAM and BoM variables are strongly linearly related except those for relative humidity in Sydney and maximum relative humidity in Brisbane.

Table 12: Coefficient of determination (R^2) values of CCAM

City	meanT R^2	Tmin R^2	Tmax R^2	Mean relative humidity R^2	Minimum relative humidity R^2	Maximum relative humidity R^2
Adelaide	0.3611	0.2505	0.3518	0.1534	0.1625	0.0608
Brisbane	0.5576	0.5053	0.3453	0.0136	0.0117	**0.0007**
Canberra	0.5440	0.3793	0.5062	0.0941	0.0786	0.0174
Darwin	0.1038	0.2476	0.0484	0.2922	0.3347	0.0830
Hobart	0.2997	0.1826	0.2551	0.0469	0.0564	0.0028
Melbourne	0.3546	0.2466	0.3077	0.0542	0.0686	0.0031
Perth	0.5375	0.3941	0.4525	0.1201	0.0931	0.0529
Sydney	0.4783	0.4817	0.2909	**0.0001**	**0.0000**	**0.0000**

Table 12 overall shows much higher R^2 values for temperature than relative humidity. The R^2 values for temperature confirm that stronger correlations are seen for Adelaide, Brisbane, Canberra, Perth and Sydney.

The IOA measures the degree to which the observed data are approached by the predicted data. The IOA overcomes the insensitivity of R^2 to the differences in the observed means and variances. An IOA of 0 shows no agreement between observed and modelled values, whereas a value of 1 shows perfect agreement between the two data sets.

In **Table 13** the IOA is shown for daily meanT, Tmin and Tmax and mean, minimum and maximum relative humidity. IOA values are between 0 and 1. A value closer to 1 is ideal.

Table 13: Index of Agreement (IOA) values of CCAM

City	MeanT	Tmin	Tmax	Mean relative humidity	Minimum relative humidity	Maximum relative humidity
Adelaide	0.616	0.544	0.618	0.867	0.503	0.496
Brisbane	0.708	0.679	0.589	0.961	0.359	0.432
Canberra	0.695	0.618	0.900	0.961	0.453	0.450
Darwin	0.421	0.558	0.360	0.894	0.595	0.472
Hobart	0.573	0.495	0.571	0.981	0.463	0.409
Melbourne	0.608	0.531	0.601	0.950	0.439	0.413
Perth	0.689	0.613	0.658	0.862	0.482	0.475
Sydney	0.655	0.619	0.592	0.940	0.347	0.430

Similar to results for the R^2 values presented in **Table 13**, IOA values tend to be higher for temperature than relative humidity but lower for those cities (Darwin and Perth) that had poorer frequency distribution results (not shown). One notable observation in the IOA values shown in **Table 13** is the mean relative humidity values. These values are exceptionally good, above 0.86 for all eight capital cities.

In **Table 14** the RMSE is shown for daily meanT, Tmin and Tmax and mean, minimum and maximum relative humidity. A lower value is best.

Table 14: Root mean squared error (RMSE) values of CCAM

City	MeanT RMSE	Tmin RMSE	Tmax RMSE	Mean relative humidity RMSE	Minimum relative humidity RMSE	Maximum relative humidity RMSE
Adelaide	5.413	5.497	6.434	18.995	20.6	20.854
Brisbane	3.008	3.663	3.934	15.110	23.479	11.153
Canberra	4.487	5.241	5.452	15.734	23.125	13.451
Darwin	2.802	2.480	3.796	16.206	19.838	15.915
Hobart	4.101	4.517	5.083	12.888	16.839	12.717
Melbourne	4.937	4.957	6.322	16.107	20.877	15.838
Perth	4.661	5.202	5.668	19.784	22.291	21.140
Sydney	4.226	4.475	5.825	19.911	27.361	15.947

While results for temperature are largely consistent across most cities, a point of difference is noted — Darwin has the lowest RMSE values (a good relationship between modelled and observed values) for temperature. This is somewhat contrary to the other performance statistics for that location and variable. RMSE is a good predictor of precision. Because Darwin has a small annual temperature range, the deviation of simulated values from observed values is lower than that of other cities. This also explains the lower RMSE values observed for Brisbane compared to the more southerly cities.

RMSE values for relative humidity are quite high in comparison to temperature values, particularly for minimum relative humidity in all eight cities, indicating large daily differences between observed and simulated values on a daily basis. The poorer correlation results for relative humidity for all statistical analyses are expected. It is well known that processes involving moisture are typically harder to simulate in climate models, particularly in coastal locations subject to maritime air incursions.

Given the issues with humidity prediction, the results presented in this chapter only take temperature predictions into account (i.e. we do not consider daily AT thresholds). However, the correspondence between the BoM observations and CCAM outputs shown are believed to be satisfactory for the purpose of this research.

An important consideration when assessing of the skill of a climate model is that these simulations reproduce statistics of mean climate. Global circulation model simulations provide an independent time series of the climate record. Global circulation model output for weather on a particular day (or for a particular week or month) is not expected to be the same as the observed weather on that day or over that period. However, models are expected to reproduce the typical range of weather and climate variations that are observed, and CCAM has done this in all cities except Darwin. In the case of Darwin, we believe that the model grid point used is not fully representative of the location of the BoM weather station. For this reason and until a solution to the issue can be found, Darwin has been removed from further consideration. For most cities, CCAM output produced a thermal climate similar to observed data over the reference period and that is unlikely to have occurred by chance.

Changes in threshold days

The number of days equal to and exceeding the threshold temperatures (Chapter 3: **Table 6**) under current conditions in each city was identified from CCAM data and also projected for each future time period and emission scenario. Note that the thresholds for increased mortality for each city are calculated from current data so the results and discussion below assume no adaptations or changes in socio-economic conditions that would modify the threshold response.

Number of threshold days

Using CCAM output, the change in number of days exceeding thresholds between the reference period (1990–2010) and the respective future periods and emissions was calculated. This number was then added to the observed (BoM) threshold exceedences to derive the number of days exceeding the thresholds for all future periods and emissions scenarios. This determines the expected number of days above threshold temperatures for the two future time periods under two emission scenarios, and allows us to apply the climate change signal from the CCAM results to the BoM data.

Table 15**,** Table 16 and Table 17 report threshold exceedences for Tmax, Tmin and meanT for the baseline period and for the future time periods for the B1 and A2 emission scenarios. Broadly, the future projections show an increased number of days above the thresholds and for A2 projections versus B1 projections, but not in all cases. Model skill (indicated by BoM vs CCAM exceedences) varies between sites, largely because of difficulty reconciling the model grid point with the BoM site observations.

Table 15: Average number of days per year when temperature exceeds the threshold for maximum temperature (Tmax) [The first period of data (1990–2010) is taken from BoM observations and CCAM projections and the future periods (2020–2040 and 2060–2080) are BoM observations added to the CCAM projections.]

Tmax threshold						
			Emission scenario			
	BoM	**CCAM**	**B1**	**A2**	**B1**	**A2**
	1990–2010		**2020–2040**		**2060–2080**	
Days per year temperature exceeds Tmax threshold						
Adelaide	0.81	0.81	1.76	2.33	2.95	2.9
Brisbane	1.08	5.33	9.51	9.84	10.12	17.78
Canberra	11.47	10.60	26.42	24.94	28.09	32.47
Hobart	0.86	0.67	1.19	1.77	2.76	2.91
Melbourne	1.81	2.62	5.33	5.67	7.67	8.23
Perth	0.57	2.29	2.76	2.81	5.47	6.38
Sydney	0.24	6.09	9.62	8.72	9.47	11.34

Table 16: Average number of days per year where temperature exceeds the threshold for minimum temperature (Tmin) [The first period of data (1990–2010) is taken from BoM observations and CCAM projections and the future periods (2020–2040 and 2060–2080) are BoM observations added to the CCAM projections.]

Tmin threshold						
			Emission scenario			
	BoM	**CCAM**	**B1**	**A2**	**B1**	**A2**
	1990–2010		**2020–2040**		**2060–2080**	
Days per year temperature exceeds Tmin threshold						
Adelaide	1.23	0.67	2.04	2.13	3.09	3.52
Brisbane	3.50	0.58	5.59	5.07	7.07	14.2
Canberra	1.14	5.42	10.95	10.99	13.43	19
Hobart	0.33	0.24	1.09	1.14	2.56	2
Melbourne	0.14	0.48	1	0.76	1.24	1.85
Perth	1.71	5.14	7.99	7.28	12.8	16.47
Sydney	0.14	2.52	4.09	4.42	5.38	6.9

Table 17: Average number of days per year where temperature exceeds the threshold for meanT [The first period of data (1990–2010) is taken from BoM observations and CCAM projections and the future periods (2020–2040 and 2060–2080) are BoM observations added to the CCAM projections.]

MeanT threshold						
			Emission scenario			
	BoM	**CCAM**	**B1**	**A2**	**B1**	**A2**
	1990–2010		**2020–2040**		**2060–2080**	
Days per year temperature exceeds meanT threshold						
Adelaide	1.048	0.62	1.38	1.29	2.53	2.81
Brisbane	0.50	1.71	4.02	3.83	3.93	7.55
Canberra	1.14	2.47	11.69	4.38	5.52	6.76
Hobart	0.38	1.14	0.71	0.61	1.19	2.28
Melbourne	1.19	2.90	3.09	2.29	5.05	5.52
Perth	1.48	6.29	5.81	5.62	10.91	14.72
Sydney	0.29	9.14	13.05	14.67	14.81	19.48

5.4 *Discussion*

This emergency management project is focused on mapping vulnerability of Australian populations in the immediate future, and for which there are also good socio-economic projections. The results from Section 5.3 show the approximate number of days per year we can expect to see increased mortality in Australian cities in the future for two different scenarios and for two different time slices. Although there are always uncertainties with model projections, in most cases there is an increase in threshold exceedences of 0 to 5 days per year from the reference period to the mid-century time period (2020–2040) where we can expect to see increased mortality.

There is generally little difference in the expected number of hot days between emission scenarios A2 and B1 during 2020–2040 because the A2 and B1 scenarios' greenhouse gas emissions remaining largely uniform until 2020. Beyond 2030, uncertainties in emission levels increase significantly among the entire spectrum of the 40 SRES scenarios. The result of this divergence in atmospheric concentrations is not observed immediately because of the long residence time of greenhouse gases in the atmosphere.

In some cases and contrary to expectation, the A2 scenario presents fewer threshold days than the B1 scenario. Reasons for this remain unclear and may relate to local inter-decadal climate variability. It is beyond the scope of this project to investigate this apparent anomaly further.

The results for the end-of-century time period (2060–2080) are less relevant to this emergency management project that concentrates on the 2020–2040 period. For the earlier period we have good population projections, but the longer-term projections highlight a concerning upward trend in dangerously hot days. These results are consistent with global and regional modelling studies that generally confirm that heatwave events will intensify, be longer lasting and become more frequent as mean global temperature increases over the current century. Our results substantiate the findings of other Australian climate change reviews that predict heat extremes to increase substantially over the next 20 to 60 years.

What distinguishes this study from other heat extreme studies is the use of location-specific thresholds to quantify risk. Most Australian climate change reviews treat heatwaves in a cursory manner, usually citing the number of arbitrarily defined hot days and warm nights per year as a measure of heatwaves. This study uses location-specific temperatures that are known to elicit a response from existing populations in Australian cities.

The urban influence is not included in the land-surface component of CCAM. The model does not yet encompass the structural and heat-generation characteristics of cities and the local effects of humidity, which ultimately limit the adaptation response of many communities and organisations in very built-up areas or those near water bodies. This means the numbers of future extreme heat days presented in these results are conservative estimates. This is because the model does not factor in the influence of increased urbanisation or urban consolidation, which is known to increase heat stress in cities, particularly at night time.

Observed data were obtained from BoM for the purpose of validating CCAM output during a reference period. Establishing a degree of correlation between CCAM output and BoM data over the same time period gives confidence in the CCAM projections, so they can be directly applied to focus on the impact of climate change on heat-related mortality.

5.5 *Conclusions*

Through the improved resolution of the climate forecasts, the risk associated with heat-related mortality in each Australian city can be treated uniquely. All cities in Table 15, Table 16 and Table 17 show an increase in median mortality to 2040, although some cities show particularly marked increases in exceedences. In particular, Brisbane and Sydney for Tmax; Canberra, Perth and Sydney for Tmin; and Brisbane, Canberra and Sydney for meanT. Brisbane will see the number of days exceeding its Tmax threshold (for which there is a 12% increase in mean mortality) increase from ~1 day per year to up to ~10 days per year between 2020 and 2040. Similarly, Brisbane's mean daily temperature threshold of 31°C for a mortality increase of 15% will increase from ~0.5 days per year to up to ~4 days per year between 2020 and 2040. Results such as these should be considered alongside socio-economic data providing information, in particular, about the likelihood of adaptation and the impact of an ageing population in Australia. With careful planning and effective response systems that address the needs of the most vulnerable groups heatwave mortality and morbidity can be reduced.

6. GAPS AND FUTURE RESEARCH DIRECTIONS

Presenting and evaluating vulnerability for natural hazard risk assessment, communication and management is an important issue in environmental hazards and climate change research. This study provides preliminary information to initiate discussion between government agencies, emergency services, and communities and direct adaptation. This study has highlighted gaps in our current knowledge and areas for future research that will enhance our capabilities to cope with heat events and impending climate change. This research has developed the VI as a tool for identifying 'areas of need', and how this is applied should be followed by an evaluation therefore enabling the refinement of the tool if necessary.

1. By developing a VI and relating it to measures AHO, it has become apparent that the tool to identify heat-related vulnerability may also indicate health-related vulnerability in general. Several cities showed that some areas within the metropolitan regions demonstrated high demand for emergency services or hospital attendances regardless of weather; Reid *et al*. (2012) also noted this using a similar method. Therefore, an opportunity exists for incorporating preventative healthcare and health-promotion agencies as high-risk areas have now been identified. There may also be an opportunity to use this approach to identify areas where cold-related AHO occur. Mortality and morbidity during the colder months is also a significant public health problem that will continue in the coming years.

2. This study used a national approach but this was limited to the capital cities. Reid *et al*. (2012) also used a national approach including areas outside major cities and found that vulnerability to heat events also exists outside metropolitan areas. This is most likely true for Australia as well, considering the burden of disease is known to be greater in regional and rural areas than in cities. Additionally, the rate of ageing of rural communities may make the higher risk.

3. We note higher rates of mortality and morbidity during hot days and association with vulnerability. We used an all-of-summer approach, however, heatwaves are known to be more hazardous if occurring early in the summer season (Anderson and Bell, 2011). It may be possible to look at seasonal demands on emergency services, anomalous weather and service demands, as well as exploring links with electricity usage and risk of exposure.

4. The main drivers of vulnerability in cities are age, and exposure (UHI); this appears to be consistent nationally. We have drawn on research into past heatwave events with the aim of identifying vulnerability relative to future conditions, the temperature (in terms of level and duration) likely to trigger an increase in morbidity and mortality. As a result, this has placed pressures on service organisations, generating a need to reshape infrastructure and develop adaptations that are more receptive to heatwave threats such as supporting water sensitive urban design (Coutts *et al*., 2012). This was also identified by Oven *et al*. (2012). What do we need to change in urban environments to improve adaptation and reduce heatwave risks? Is expanding the availability of air conditioning the answer?

5. We identified suburban areas where health risks are greatest during hot weather. Some of these areas already have heatwave response plans. What are the barriers to modifying and enhancing their adaptation strategies and resilience planning to cope with future conditions? Vulnerability assessment is a new found area of research and how to transfer information efficiently has not

been trialled. Which channels are best to facilitate information? How do we transfer knowledge from bottom-up to top-down strategies? The next step of this research might be to deliver the tool to stakeholders via web-based learning. One area that needs special attention is CALD communities. What information is needed to protect new migrants and ethnic groups who may have little knowledge of the harshness of Australian climates or the links that can be made to provide assistance?

6. To what extent are heatwave vulnerabilities related to vulnerabilities from other natural hazards (e.g. floods). Can flood-related vulnerability be modelled using the VI approach?

7. The development of GCM over recent years has provided us with an excellent range of predictive models for future climate scenarios, but models of future changes to urban growth are not as well developed. There is a need to improve modelling of the impact of UHI under known climate change scenarios. A further issue is the requirement for downscaling to provide climate projections at a spatial scale that is appropriate for work such as this. Provision of data for one grid point representative of each capital city is not ideal.

8. Which road is the best road? Our findings suggest that, ideally, risk to built infrastructure and organisational support for older people's care should be assessed in terms of multiple facets of hazard and vulnerability, including heatwaves. This may be difficult for local governments and care organisations with limited resources attempting to produce resilient environments and people.

9. This study examined AHO in relation to days that exceeded heat thresholds; however, there is a known relationship between health outcomes and ozone during summer. Future analysis should include a measure of air quality to account for synergistic effects of heat and air pollution.

10. Several smaller components of this project could be teased out such as.

    (a) Understanding the UHI and LST during average summers and during extremes — how does this phenomenon behave?

    (b) Urban heat islands, LST, and land-use categories — what are the relationships.

    (c) How effective is green infrastructure in reducing LST and heat exposure in urban areas?

    (d) Understanding the relationship between land use, the urban form, and public health.

11. Vulnerability indices have only taken ambient outdoor temperature into consideration. How well this measure correlates with indoor exposures is not well understood.

12. There is some potential to include AHO and workplace characteristics, thereby providing evidence for occupational health and safety reform for heat-related workplace policy.

13. There are many factors framed in vulnerability analysis. However, as in many other studies, mapping vulnerability in this project was limited to three major

components: demographic, environment and health. This was largely based on available data and resources. The opportunity for organisations to link data sources needs to be explored. The mapping exercise can be updated once additional risk factor data can be acquired or shared by other organisations.

14. While regression analysis can provide some knowledge about the contribution of individual vulnerability variables to the composite VI, more work still needs to be undertaken to understand the contribution of the weighted variable to the dimension of vulnerability. This is especially important for predicting future vulnerability as weights derived from regression analysis using past events might not be the same as the weight required for future events. Such uncertainties can be minimised by incorporating knowledge from stakeholders through workshop or community engagement and then undertaking scenario-based analysis to examine the change of weights on composite VI.

15. The spatial scale of analysis in this study is POA. Improvement in data provision, such as recording the spatial location of ambulance call-outs and spatial location of patients' residences, can provide opportunities for a finer scale of analysis. This was seen in the Canadian study by Rinner *et al.* (2011) Local government areas can incorporate this method into their GIS frameworks using the weighted variables identified for each city to guide smaller-scale inspections of high-risk POA.

This list of gaps and future recommendations for research is by no means exhaustive and many more points for inclusion will be raised as this VI is incorporated into emergency management planning and practice.

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8. APPENDIX

Note: For acronyms used in tables refer to the list on pages xii–xiii.

Table 18: City, threshold range (degrees Celsius) median and interquartile points for mortality (*interquartile points for the lowest and highest threshold listed*)

City	Tmax threshold interquartile range			Tmin threshold interquartile range			MeanT threshold interquartile range			AT threshold interquartile range		
Percentile	**25th**	**50th**	**75th**	**25th**	**50th**	**75th**	**25th**	**50th**	**75th**	**25th**	**50th**	**75th**
Brisbane	36°C			25°C			31–33°C			40°C		
Mortality	0.9	1.14	1.16	0.86	1.05	1.15	0.96 1.05	1.02 1.15	1.11 1.29	0.9	1.08	1.12
Canberra	33–39+ °C			20°C			28°C			41–43°C		
Mortality	0.84 0.70	1.05 1.05	1.18 1.10	0.93	1.04	1.22	0.82	1.03	1.12	1.0	1.05 1.10#	1.20
Darwin	37°C			29°C			31°C			47°C		
Mortality	0.85	1.05	1.20	0.98	1.08	1.20	0.84	1.05	1.18	1.08	1.10	1.20
Hobart	33°C			20°C			28°C			37°C		
Mortality	0.99	1.03	1.10	0.97	1.01	1.10	0.99	1.05	1.08		1.22#	
Melbourne	39–44+ °C			26–28°C			28–34°C			36–44°C		
Mortality	0.92 0.99	1.02 1.08	1.05 1.18	1.05	1.08 1.03#	1.12	0.95 1.03	1.04 1.12	1.10 1.18	0.93 1.03	1.02 1.05	1.09 1.10
Perth	44°C			NA			32–34+ °C			45°C		
Mortality		1.30#					0.98	1.03 1.11#	1.08	1.02	1.10	1.20
Adelaide	42°C			NA			34–38°C			43°C		
Mortality	0.92	1.06	1.26				0.92	1.01 1.08#	1.18			
Sydney	38–42+ °C			25°C			30–32°C			37–47°C		
Mortality	0.97	1.04 1.18#	1.11	0.97	1.05	1.15	1.02 0.80	1.05 0.94	1.08 1.05	0.98	1.08 1.18#	1.11

Median mortality greater than 1 indicates an increase in mortality at the population level

 # shows a single event

Threshold range for increased mortality rate in degrees Celsius

Table 19: City, threshold range (degrees Celsius) median and interquartile points for morbidity *(interquartile points for the lowest and highest threshold listed)*

City	Tmax threshold and interquartile points for morbidity			Tmin threshold and interquartile points for morbidity			MeanT threshold and Interquartile points for morbidity			AT threshold and interquartile points for morbidity		
Percentile	**25th**	**50th**	**75th**	**25th**	**50th**	**75th**	**25th**	**50th**	**75th**	**25th**	**50th**	**75th**
Brisbane	35–41°C			26°C			31–33°C			40°C		
Morbidity	0.99 1.05	1.02 1.12	1.06 1.18	0.97	1.02	1.03	1.00	1.09	1.18	0.9	1.08	1.12
Canberra	37–39 °C			20–22°C			28–30°C			41–43°C		
Morbidity	0.94 1.03	1.04 1.10	1.10 1.15	0.97 0.94	1.04 1.05	1.09 1.06	0.89 0.98	1.05 1.06	1.09 1.10	1.0	1.05 1.10#	1.20
Darwin	36°C			29°C			31°C			47°C		
Morbidity	1.02	1.07	1.41	0.99	1.01	1.02	0.99	1.00	1.36	1.02	1.12	1.14
Hobart	NA			18–20°C			28°C			36–38°C		
Morbidity				0.92	1.04	1.14	1.01	1.04	1.14	0.87	1.04 1.10#	1.20
Melbourne	44 °C			26°C			34°C			40°C		
Morbidity	1.004	1.016	1.034	0.995	1.02	1.03	0.099	1.02	1.03	0.96	1.04	1.08
Perth	43°C			26°C			NA			43°C		
Morbidity	1.08	1.14	1.17	0.89	1.02	1.18				1.02	1.11	1.21
Adelaide	NA			31°C			39°C			NA		
Morbidity				0.965	1.02	1.03		1.035				
Sydney	41 °C			25°C			31°C			37–45°C		
Morbidity	0.99	1.05	1.11	0.99	1.04	1.09	0.985	1.02	1.04	0.98	1.06 1.20#	1.11

Median morbidity greater than 1 indicates an increase in morbidity at the population level

 # shows a single event

Threshold range for increased morbidity rate in degrees Celsius

Table 20: Risk factors and their respective data sources

Risk factor	Data sources
Age (0–4, 65+)	ABS BCP Table 1
Aged care facilities (ACF)	Department of Health and Ageing
SES	ABS SEIFA Table 3
Urban design (non-single dwellings)	ABS BCP Table 31
Single-person households	ABS BCP Table 22
Need for assistance (measure of disability)	ABS BCP Table 17
Population density	ABS BCP Table 1
Ethnicity	ABS BCP Table 12
UHI	MODIS (Terra) Land surface Temperature & Emissivity Monthly L3 Global 0.05° CMG
Land cover	ABS Meshblock
Accessibility to emergency service	Google maps

Table 21: Stepwise regression analysis between AHO and vulnerability variables in Australian cities

City	Number of POAs	r^2 of selected model	Significant variables
Adelaide	126	0.62	Persons in need of assistance, shortest travelling time to ED
Brisbane	131	0.31	ACF, single person aged over 65 and urban design
Canberra	23	0.18	ACF
Darwin	13	0.45	Urban design
Hobart	32	0.54	ACF and social economic factor
Melbourne	267	0.46	ACF, ethnicity and single lone person aged over 65
Perth	117	0.26	ACF and ethnicity
Sydney	259	0.04	Age

Table 22: Summary of Spearman correlation values between adverse health outcomes on hot days and vulnerability indices (VI)

City	Weighted VI		VI (PCA)	
	Rho	*P* value	Rho	*P* value
Adelaide	0.599	0.000***	0.429	0.000***
Brisbane	0.617	0.000***	0.547	0.000**
Canberra	0.430	0.041*	0.522	0.011*
Darwin	0.186	0.543	0.725	0.005
Hobart	0.807	0.000***	0.034	0.854
Melbourne	0.747	0.000***	0.613	0.000***
Perth	0.591	0.000***	0.410	0.000***
Sydney	0.283	0.000***	0.239	0.000***

*** Correlation at $p \leq 0.001$

** Correlation at $p < 0.01$
* Correlation at $p < 0.05$

Table 23: Summary of projections of population in Australian cities

City	Spatial unit	Baseline data	Projection year
Adelaide	SLA	2006	2026
Brisbane	SLA	2006	2031
Canberra	District	2006	2021
Darwin	Statistical reporting region	2006	2021
Hobart	LGA	2006	2032
Melbourne	SLA	2006	2026
Perth	LGA	2006	2026
Sydney	SLA	2006	2031

Data sources: (NSW Government Planning & Infrastucture, 2011, South Australian SES, 2012, Queensland Government, 2011, ACT Government, 2011, Northern Territory Government, 2011, Demographic Change Advisory Council Tasmania, , Department of Planning and Community Development, 2008, Planning Western Australia, 2005)

Table 24: Morbidity measures used in validating the vulnerability index

City	Duration	Morbidity measure	AHO
Adelaide	1/1/2004 to 31/12/2010	Daily ED presentations for triage categories 1, 2 and 3	ED presentation rate
Brisbane	1/7/2003 to 4/8/2011	Daily ambulance call-outs (emergency calls)	Number of ambulance call-outs
Canberra	17/8/2004 to 10/4/2011	Daily ambulance callo-uts (emergency calls)	Number of ambulance call-outs
Darwin	24/1/2005 to 8/10/2011	Daily ED presentations reported as ‘heat related’	‘Heat-related’ ED presentation rate
Hobart	1/7/2003 to 31/7/2011	Daily ambulance call-outs (emergency calls)	Number of ambulance call-outs
Melbourne	1/1/2002 to 31/12/2010	Daily ambulance call-outs (emergency calls)	Number of ambulance call-outs
Perth	1/1/2006 to 30/6/2011	Daily ambulance call-outs (emergency calls)	Number of ambulance call-outs
Sydney	1/1/2000 to 30/6/2010	Daily emergency admissions to hospital	Emergency admissions to hospital rate

Table 25: Pearson correlation values between vulnerability variables and adverse health outcomes (Brisbane) (N = 131)

Variables	Pearson correlation	p-value
ACF	.425	.000***
Single-person households 65+	.420	.000***
Night-time UHI summer 09	.388	.000***
Population density	.379	.000***
Urban design	.347	.000***
Night-time UHI summer 08	.300	.001***
Vulnerable age groups	.295	.001***
Night-time UHI summer 07	.268	.002**
Night-time UHI summer 06	.211	.016**
Needs assistance	.191	.029*
Daytime UHI summer 08	.141	.109
Daytime UHI summer 09	.138	.115
Ethnicity	.105	.234
Daytime UHI summer 06	.050	.573
Socio-economic	.043	.623
Daytime UHI summer 07	–.081	.355
Land use/land cover	–.190	.030*
Access to ED (time)	–.194	.026*
Access to ED (distance)	–.257	.003**

*** Correlation at $p \leq 0.001$

** Correlation at $p < 0.01$

* Correlation at $p < 0.05$

Table 26: Total variance explained by principal components (Brisbane)

Component	Initial eigenvalues			Rotation sums of squared loadings		
	Total	% of variance	Cumulative %	Total	% of variance	Cumulative %
1	8.132	42.801	42.801	4.811	25.323	25.323
2	2.788	14.674	57.475	4.628	24.358	49.680
3	1.949	10.256	67.732	2.617	13.771	63.451
4	1.213	6.383	74.115	1.868	9.833	73.285
5	1.036	5.455	79.570	1.194	6.285	79.570

Table 27: Varimax Rotated Component Matrix (Brisbane)

Variables	Component				
	1	2	3	4	5
UHI (night-time) 09	.904	.144	.066	.122	.015
UHI (night-time) 08	.892	.286	–.031	.129	.027
UHI (night-time) 06	.808	.301	.142	.042	–.112
UHI (night-time) 07	.797	.486	.027	.100	.005
UHI (daytime) 09	.455	.840	.038	.127	–.025
UHI (daytime) 08	.485	.794	.004	.069	–.018
UHI (daytime) 07	–.007	.953	.041	–.021	–.107
UHI (daytime) 06	.225	.944	–.004	.110	–.029
Urban design	.469	.207	–.049	.425	.267
Population density (vulnerable groups)	.466	.414	.259	.348	.417
Single-person households 65+	.357	.036	.806	.153	.134
Ethnicity	.115	.555	–.151	.149	.113
Age	.050	–.106	.939	–.012	.168
Socio-economic	–.071	–.072	.062	–.004	.916
Needs assistance (measure of disability)	–.126	–.001	.886	.037	–.153
ACF	–.157	.085	.407	.683	–.024
Land cover	–.425	–.685	–.022	–.134	–.028
Accessibility to ED (time travel)	–.447	–.137	.093	–.747	–.011
Accessibility to ED (network distance)	–.641	–.166	–.006	–.633	.006

Table 28: Pearson correlation values between vulnerability variables and adverse health outcomes (Canberra) (N = 23)

Variables	Pearson correlation	p-value
Land cover	–.109	.622
Urban design	–.214	.328
ACF	.427	.042*
Accessibility to ED (distance)	–.373	.080
Accessibility to ED (time travel)	–.256	.238
Age	.218	.318
Socio-economic	.255	.240
Ethnicity	.196	.371
Measure of disability	.374	.078
Single-person households 65+	.135	.540
Population density (vulnerable groups)	.363	.088
Daytime UHI summer 06	–0.252	0.247
Night-time UHI summer 06	–0.062	0.777
Daytime UHI summer 07	–.232	.286
Night-time UHI summer 07	.404	.056
Daytime UHI summer 08	–0.520	0.011*
Night-time UHI summer 08	0.322	0.134
Daytime UHI summer 09	–0.119	0.589
Night-time UHI summer 09	0.081	0.714

*correlation is significant at 0.05 level (2-tailed)

Table 29: Total variance explained by principal components (Canberra)

Component	Initial eigenvalues			Rotation sums of squared loadings		
	Total	% of variance	Cumulative %	Total	% of variance	Cumulative %
1	4.895	37.654	37.654	3.971	30.545	30.545
2	2.845	21.884	59.538	3.727	28.672	59.218
3	1.817	13.977	73.515	1.859	14.298	73.515

Table 30: Varimax rotated component matrix (Canberra)

Variables	Component		
	1	2	3
Age	.884	.206	.015
Needs assistance (measure of disability)	.841	.382	–.114
Population density (vulnerable groups)	.797	–.040	–.233
Urban design	–.686	.442	–.035
Socio-economic	.659	–.026	.650
Aged-care facilities	.603	.435	–.064
Single-person households 65+	.504	.620	–.231
Land cover	–.437	–.096	.695
Accessibility to ED (time travel)	–.237	–.712	–.030
Accessibility to ED (network distance)	–.236	–.914	–.108
UHI (night-time)	–.125	.838	.109
UHI (daytime)	.055	–.843	.200
Ethnicity	–.045	.058	.873

Table 31: Pearson correlation values between vulnerability variables and adverse health outcomes for Hobart (N = 32)

Variables	Pearson correlation	p-value
Age	0.187	0.305
SES	–0.520	0.002**
Need for assistance (measure of disability)	0.462	0.008**
Accessibility to ED (distance)	–0.379	0.032*
Accessibility to ED (travelling time)	–0.436	0.013*
Urban design	0.517	0.002**
ACF	0.568	0.001**
Single-person households 65+	0.344	0.054
Ethnicity	0.204	0.262
Population density (vulnerable groups)	0.280	0.121
UHI (daytime) 06	–0.021	0.908
UHI (night-time) 06	–0.191	0.295
Land cover	–0.078	0.670

*correlation is significant at 0.05 level (2-tailed)

**correlation is significant at 0.01 level (2-tailed)

Table 32: Total variance explained by principal components (Hobart)

	Initial eigenvalues			**Rotation sums of squared loadings**		
Component	Total	% of variance	Cumulative %	Total	% of variance	Cumulative %
1	7.497	39.455	39.455	4.399	23.153	23.153
2	4.525	23.814	63.270	4.229	22.258	45.412
3	2.475	13.029	76.299	3.912	20.588	65.999
4	1.417	7.458	83.757	3.374	17.757	83.757

Table 33: Varimax rotated component matrix (Hobart)

Variables	Component			
	1	2	3	4
Age	.033	.124	–.143	.894
Ethnicity	–.391	–.262	–.629	.166
Needs assistance (measure of disability)	.262	–.005	–.114	.892
Single-person households 65+	–.058	.103	–.348	.852
Urban design	–.261	–.372	–.649	.384
Land cover	.185	–.381	.753	–.168
Accessibility to ED (network distance)	.137	.384	.846	–.066
Accessibility to ED (time travel)	.049	.431	.828	–.098
ACF	–.143	–.221	–.340	.668
Population density (vulnerable groups)	–.110	.108	–.815	.404
Socio-economic	–.355	–.019	–.049	–.451
UHI (daytime) 05	.924	.315	.132	.057
UHI (night-time)	.446	.853	.013	.047
UHI (daytime) 06	.960	.119	.168	.098
UHI (night-time)	.287	.896	.116	–.006
UHI (daytime) 07	.950	.178	.197	.075
UHI (night-time)	.209	.928	.153	.065
UHI (daytime) 08	.943	.229	.188	.016
UHI (night-time)	.034	.931	.182	–.005

Table 34: Pearson correlation values between vulnerability variables and adverse health outcomes for Melbourne (N = 267)

Variables	Pearson correlation	p-value
Age	0.162	0.008**
Socio-economic	0.02	0.976
Measure of disability	0.298	0.000***
Accessibility to ED (distance)	–0.280	0.000***
Accessibility to ED (travelling time)	–0.266	0.000***
Urban design	0.189	0.002**
ACF	0.606	0.000***
Single-person households 65+	0.309	0.000***
Ethnicity	0.403	0.000***
Population density (vulnerable groups)	0.377	0.000***
UHI (daytime) 06	0.195	0.001**
UHI (night-time) 06	0.163	0.007**
Land cover	–0.344	0.000***

*Correlation is significant at 0.05 level (2-tailed)

**Correlation is significant at 0.01 level (2-tailed)

*** Correlation significant at < 0.001 (2-tailed)

Table 35: Total variance explained by principal components (Melbourne)

	Initial eigenvalues			Rotation sums of squared loadings		
Component	Total	% of variance	Cumulative %	Total	% of variance	Cumulative %
1	8.168	42.989	42.989	6.850	36.051	36.051
2	3.536	18.611	61.599	4.427	23.298	59.349
3	2.197	11.566	73.165	2.534	13.339	72.687
4	1.134	5.966	79.131	1.224	6.444	**79.131**

Table 36: Varimax rotated component matrix (Melbourne)

Variables	Component			
	1	2	3	4
1	2	3	4	5
UHI (night-time) 06	.948	.089	.048	.065
UHI (night-time) 05	.945	.108	–.003	.038
UHI (night-time) 07	.929	.149	.037	.100
UHI (night-time) 08	.927	.156	.064	.024
Population density (vulnerable groups)	.745	.148	.368	.260
Urban design	.721	.069	–.184	.162
Ethnicity	.415	.575	.211	–.143
Single-person households 65+	.283	–.212	.727	.328
Aged-care facilities	.272	.164	.358	.307
UHI (daytime) 05	.272	.945	–.010	–.020
UHI (daytime) 08	.206	.965	–.025	–.030
UHI (daytime) 07	.200	.967	–.017	–.005
Needs assistance (measure of disability)	.028	.152	.859	–.206
UHI (daytime)06	–.009	.983	–.076	–.025
Socio-economic	–.023	–.122	–.022	.891
Age	–.029	–.114	.896	–.016
Land cover	–.746	–.146	–.249	.075
Accessibility to ED (time travel)	–.750	–.275	–.178	.167
Accessibility to ED (network distance)	–.809	–.244	–.120	.143

Table 37: Pearson correlation values between vulnerability variables and adverse health outcomes for Perth (N = 117)

Variables	Pearson correlation	p-value
Age	0.273	0.003**
Socio-economic	0.132	0.154
Need for assistance measure of disability	0.278	0.002**
Accessibility to ED (distance)	–0.313	0.001**
Accessibility to ED (travelling time)	–.0.295	0.001**
Urban design	0.227	0.014*
Aged-care facilities	0.474	0.000**
Single-person households 65+	0.030	0.751
Ethnicity	0.340	0.000**
Population density (vulnerable groups)	0.239	0.009**
UHI (daytime) 2006	–0.022	0.812
UHI (night-time) 2006	0.271	0.003**
Land cover	–0.206	0.026*

*Correlation is significant at 0.05 level (2-tailed)

**Correlation is significant at 0.01 level (2-tailed)

*** Correlation significant at < 0.001(2-tailed)

UHI variables for the years 2005, 2007–2009 were strongly correlated ($r^2 > 0.9$) this violates the assumption of independence, therefore these variables were not entered into the regression analysis.

Table 38: Total variance explained by principal components (Perth)

Component	Initial eigenvalues			Rotation sums of squared loadings		
	Total	% of variance	Cumulative %	Total	% of variance	Cumulative %
1	7.916	41.662	41.662	7.186	37.820	37.820
2	3.997	21.038	62.700	3.980	20.946	58.767
3	1.790	9.422	72.123	2.376	12.504	71.270
4	1.291	6.796	78.918	1.453	7.648	78.918

Table 39: Varimax Rotated Component Matrix (Perth).

Variables	Component			
	1	2	3	4
Urban design	.699	–.140	.270	–.105
Aged-care facilities	.435	–.107	.552	.041
Accessibility to ED (network distance)	–.803	–.048	–.121	–.123
Accessibility to ED (time travel)	–.789	–.070	–.128	–.128
Age	.212	–.098	.694	.589
Socio-economic	–.009	–.130	.738	–.240
Single-person households 65+	.176	–.013	–.107	.945
Ethnicity	.614	.266	.302	.199
Needs assistance (measure of disability)	.267	.054	.796	.063
Land cover	–.566	–.145	–.208	–.222
UHI (daytime) 05	.147	.978	–.046	.028
UHI (daytime) 06	–.245	.949	–.022	–.001
UHI (daytime) 07	–.025	.988	–.077	–.010
UHI (daytime) 08	.067	.981	–.051	–.030
UHI (night-time) 05	.960	–.083	.043	.057
UHI (night-time) 06	.964	–.074	.044	.057
UHI (night-time) 07	.963	–.043	.065	.067
UHI (night-time) 08	.957	–.095	.035	.069
Population density (vulnerable groups)	.785	.027	.377	.015

Table 40: Pearson correlation values between vulnerability variables and adverse health outcomes for Adelaide (N = 126)

Variables	Pearson correlation	p-value
Land cover	–.127	.157
ACF	.092	.307
Accessibility to ED (distance)	–.307	.000***
Accessibility to ED (travelling time)	–.366	.000***
Age	.401	.000***
Ethnicity	.280	.002**
Single-person households 65+	.290	.001**
Need for assistance measure of disability	.769	.000***
UHI (daytime) 05	.312	.000***
UHI (daytime) 06	.320	.000***
UHI (daytime) 07	.307	.000***
UHI (daytime) 08	.334	.000***
UHI (night-time) 05	.318	.000***
UHI (night-time) 06	.309	.000***
UHI (night-time) 07	.304	.001**
UHI (night-time) 08	.339	.000***
Urban design	.116	.197
Population density (vulnerable groups)	.114	.204
Socio-economic	–.693	.000***

*Correlation is significant at 0.05 level (2-tailed)

**Correlation is significant at 0.01 level (2-tailed)

*** Correlation significant at < 0.001(2-tailed)

Initially the stepwise regression analysis was completed with all vulnerability variables. However, the inclusion of social economic factors resulted in a very high condition index of the model, indicating the presence of multi-colinearity in the model. This is probably due to the significant correlations between social economic factors and most of the other vulnerability variables (significance value $P < 0.001$). As a result, the socio-economic variable was not included in the stepwise regression.

Table 41: Total variance explained by principal components (Adelaide)

Component	Initial eigenvalues			Rotation sums of squared loadings		
	Total	% of variance	Cumulative %	Total	% of variance	Cumulative %
1	9.830	51.736	51.736	5.228	27.516	27.516
2	3.337	17.562	69.298	4.425	23.290	50.806
3	1.563	8.224	77.522	4.193	22.071	72.877
4	1.059	5.574	83.097	1.942	10.219	83.097

Table 42: Varimax Rotated Component Matrix (Adelaide)

Variables	Component			
	1	2	3	4
Land cover	–.689	–.014	–.521	–.121
ACF	.186	.112	.703	–.136
Accessibility to ED (network distance)	–.829	–.076	–.349	.024
Accessibility to ED (time travel)	–.734	–.198	–.338	.074
Age	.124	.008	.856	.182
Urban design	.433	.074	.538	.237
Ethnicity	.407	.040	.130	.709
Single-person households 65+	.256	.006	.870	.200
Needs assistance (measure of disability)	.140	.214	.762	.442
UHI (daytime) 05	.378	.879	.109	.184
UHI (daytime) 06	.094	.986	.008	.071
UHI (daytime) 07	.194	.966	.038	.056
UHI (daytime) 08	.221	.933	.106	.167
UHI (night-time) 05	.775	.428	.132	.385
UHI (night-time) 06	.833	.338	.214	.304
UHI (night-time) 07	.813	.342	.187	.361
UHI (night-time) 08	.765	.409	.192	.385
Population density (vulnerable groups)	.505	.027	.776	–.001
Socio-economic	–.065	–.430	–.230	–.697

Table 43: Pearson correlation values between vulnerability variables and adverse health outcomes for Darwin (N = 13)

Variables	Pearson correlation	p-value
Age	.042	.891
Accessibility to ED (distance)	–.308	.306
Accessibility to ED (travelling time)	–.130	.672
Socio-economic	.294	.329
Ethnicity	.045	.885
Need for assistance measure of disability	.550	.051
Single-person households 65+	.140	.647
Urban design	.669	.012*
ACF	.236	.437
Population density (vulnerable groups)	.331	.269
Land cover	–.130	.672

*correlation at $p < 0.05$

Table 44: Total variance explained by principal components (Darwin)

Component	Initial eigenvalues			Rotation sums of squared loadings		
	Total	% of variance	Cumulative %	Total	% of variance	Cumulative %
1	5.122	46.565	46.565	4.159	37.807	37.807
2	1.796	16.331	62.896	1.855	16.865	54.672
3	1.230	11.179	74.075	1.620	14.729	69.401
4	1.046	9.508	83.583	1.560	14.182	83.583

Table 45: Varimax Rotated Component Matrix (Darwin)

Variables	Component			
	1	2	3	4
Age	.122	.013	.029	.949
Accessibility to ED (network distance)	–.781	.183	–.422	–.338
Accessibility to ED (time travel)	–.775	.120	–.456	–.338
Land cover	.172	–.838	–.076	.272
Socio-economic	.110	.171	.942	.037
Ethnicity	.872	–.094	.126	–.079
Needs assistance (measure of disability)	.190	.854	.108	.288
Single-person households 65+	.839	.084	–.277	.162
Urban design	.666	.073	.414	–.044
ACF	.691	.451	–.049	.241
Population density (vulnerable groups)	.688	.350	.249	.423

Table 46: Pearson correlation values between vulnerability variables and adverse health outcomes for Sydney (N = 259)

Variables	Pearson correlation	p-value
Land cover	–.158	.011*
Urban design	.107	.085
ACF	.036	.567
Accessibility to ED (distance)	–.148	.017*
Accessibility to ED (travelling time)	–.146	.019*
Age	.208	.001**
Socio-economic	.045	.466
Single-person households 65+	.192	.002**
Ethnicity	.073	.244
Need for assistance measure of disability	.088	.160
UHI (daytime) 06	–.043	.493
UHI (night-time) 06	.188	.002**
Population density (vulnerable groups)	.146	.018*

*correlation at $p < 0.05$

**correlation at $p < 0.01$

Table 47: Total variance explained by principal components (Sydney)

Component	**Initial eigenvalues**			**Rotation sums of squared loadings**		
	Total	% of variance	Cumulative %	Total	% of variance	Cumulative %
1	8.350	43.945	43.945	5.027	26.456	26.456
2	3.377	17.773	61.718	4.704	24.757	51.214
3	2.020	10.634	72.352	2.766	14.556	65.769
4	1.096	5.769	78.121	2.347	12.352	78.121

Table 48: Varimax Rotated Component Matrix for Sydney

Variables	Component			
	1	2	3	4
Land cover	–.492	–.333	–.607	–.138
Urban design	.284	.032	.848	–.012
ACF	–.023	.087	.198	.436
Accessibility to ED (network distance)	–.656	–.141	–.457	–.043
Accessibility to ED (time travel)	–.607	–.113	–.466	–.062
Age	.213	–.251	–.100	.829
Socio-economic	.056	–.546	.136	–.217
Single-person households 65+	.171	–.400	.292	.761
Ethnicity	.328	.767	.119	.142
Needs assistance (Measure of disability)	–.003	.363	–.138	.833
UHI (daytime) 05	.422	.838	.240	–.100
UHI (daytime) 06	.064	.944	.102	–.157
UHI (daytime) 07	.417	.819	.286	–.058
UHI (daytime) 08	.226	.933	.121	–.106
UHI (night-time) 05	.864	.217	.305	.012
UHI (night-time) 06	.931	.207	.164	.094
UHI (night-time) 07	.839	.238	.369	.030
UHI (night-time) 08	.919	.129	.049	.128
Population density (vulnerable groups)	.388	.113	.801	.169

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