‘Hot Spots’ Project: Spatial vulnerability to heat events in Melbourne Australia
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**Abstract**

In Australia heat waves claim more lives than any other natural hazard. To direct population adaptation strategies for a changing climate, it is necessary to be able to identify the location of groups within our population who are most vulnerable to adverse health outcomes associated with extremely hot weather, and to understand factors that influence this vulnerability. This project used multiple social, health and environmental sources of information to create an index of vulnerability. This index has been mapped to create a spatial representation of vulnerability in the city Melbourne. The tool itself is not Melbourne specific and can be transferred to other Australian cities provided threshold temperatures for these regions can be determined. By providing information about the population most vulnerable to heat exposure, this study created the ability to target behavioral adaptation, implement heat wave response plans within the communities with the highest risk. In addition, the spatial distribution of population vulnerability to heat events provided specific information for urban planners about health risks in relation to Urban Heat Islands.
Introduction

Rationale

The global climate is changing; this is well documented. The potential impact of climate change on human health in Australia is a growing concern. Climate change projections for south-eastern Australia include an increase in the number of warm nights and an increase in heat wave frequency and duration (Alexander & Arbalster, 2008). The effects of heat waves on human health can be disastrous (Vandentorren et al., 2004). These effects are determined by biophysical and social vulnerability, modulated by environmental exposure and urban design (McMichael, Woodruff, & Hales, 2006; Menne & Matthies, 2009). Lessons learned from several heat waves in the US over the last decade and the European heat wave in 2003, when over 45,000 people died, have indicated that there are common themes in population vulnerability during heat events. In brief, the greatest risks appear to be for urban populations, the very young and elderly, persons with chronic disease or disability, and persons living in a built environment that enhances the effects of local weather during heat waves (Smoyer-Tomic, Kuhn, & Hudson, 2003). Furthermore, people who are socially isolated are at a greater risk, as are people living in areas of lower socioeconomic circumstance. High urban and population density also contributes to the increased risk. Taking all this information into consideration it is reasonable to expect that population vulnerability to heat waves will be unevenly distributed in space.

The aim of this research project was to integrate and gather information that defined population vulnerability to periods of extreme heat. Information was selected to describe health, demographic and environmental vulnerabilities and this information was used to develop a
unique methodological design to map population vulnerability. Such maps could provide government and healthcare agencies with a tool for the development of targeted heat-health action plans, and to indicate changes in building design and urban planning that could help minimise the effects of climate change on the health of urban populations. Data relating to the city of Melbourne was used to develop the vulnerability index, and used to map the geographic variations in vulnerability across the City.

**Background**

**Population health risks**

There is no universal definition of a heat wave. The Australian Bureau of Meteorology defines a heat wave as ‘a prolonged period of excessive heat’. The impacts of heat events are determined by environmental, behavioural and physiological adaptations. Human responses to the high ambient temperatures experienced during heat waves are determined by bio-physiological responses and behavioural adaptations. Persons with pre-existing illness, either acute infections or chronic disease, are at a greater risk of heat related illness (Kovats & Hajat, 2008). Understanding the environmental risk factors affecting vulnerability to heat waves may lead to actions that minimize the adverse effects of heat on urban populations.

**Environmental risk factors**

Population risk factors are often categorised as compositional (age, disability, chronic disease) and contextual (housing, human behaviour). Contextual and compositional factors are linked and population risk factors tend to vary according to location and contextual adaptations to local climate. People spend most of their time indoors especially if weather conditions are extreme.
Evidence from the French heat wave in 2003 has indicated that brick houses (high thermal mass), houses with poor or no insulation, aspect (north facing in Australia), poor ventilation, multi-dwelling structures, living above the second floor, and no green space/vegetation around dwelling were associated with increased risk of mortality/morbidity during heat waves (Vandentorren et al., 2004). Similarly, living in areas that demonstrate urban heat island (UHI) effects such as the inner city, areas of high urban density and industry has been shown to increase health risks ("U.S. Environmental Protection Agency. Heat Island Effect. What can be done?," 2008).

Studies from the US indicate that air-conditioning is a protective factor for heat related mortality/morbidity (Davis, Knappenberger, Michaels, & Novicoff, 2003). A decrease in heat related mortality/morbidity over the past two decades was attributed to increased use of air-conditioning (Davis, Knappenberger, Michaels et al., 2003; Davis, Knappenberger, Novicoff, & Michaels, 2003). Lack of air-conditioning was proposed to explain the increased risk of mortality in inner urban poor Americans during the Chicago heatwaves in 1995 and 1999 (Davis, Knappenberger, Novicoff et al., 2003). There are two concerns regarding reliance upon air-conditioning; firstly, power failures either partial or complete are common during heat waves due to an inability for energy providers to meet the increased demand. Secondly, reliance on air-conditioning may alter physiological acclimatisation and increase the susceptibility of some people to heat waves.
Urban design and Urban Heat Island

The temperature gradient across urban areas may represent a change in ambient air temperature of several degrees (Coutts, Beringer, & Tapper, 2007; Morris & Simmonds, 2000; Walker, 2004) and (Oke, 1973). The intensity of the urban heat island is affected by several factors, such as the reduction of green space, low wind velocity due to high building density and change of street surface coating materials. The main contributing factors are changes in the characteristics of the urban surface (albedo, thermal capacity, and heat conductivity), replacement of vegetation by asphalt and concrete, and the decrease of surface moisture available for evapotranspiration. Modification of land cover in urban areas can cause the local air and surface temperatures to rise several degrees higher than the temperature of the surrounding rural areas.

Environmental design strategies for cool cities.

Cities can mitigate the effects of extreme temperatures by engaging in efforts to reduce the UHI effect created primarily by the lack of vegetation and the high thermal absorbance of engineered urban surfaces. These “cool cities” initiatives to reduce the UHI effect are gaining in importance because of their potential not only to reduce heat-related illness and mortality, but also to reduce energy demand, greenhouse gas emissions, air-conditioning costs, and air pollution (U.S. Global Change Research Program, 2004). A “whole building” approach to energy efficiency and sustainability is promoted by the U.S. Green Buildings Council through their Leadership in Energy and Environmental Design (LEEDS) certification program. LEEDS buildings make use of numerous design features, including high albedo surfaces and green roofs, to minimize a building’s thermal capacity and reduce energy consumption. Additional strategies to promote cool cities include increasing tree plantings, especially to shade buildings, as well as increasing the relative amount of green spaces, and reintroducing water into urban areas.
To reduce costs, cities could promote policies of replacing low-albedo surfaces with high-albedo surfaces during routine maintenance of roads and buildings (Akbari, Pomerantz, & Taha, 2001).

**Risk factors defining the effects of “place” on health during heat events.**

**Socio-economic factors**

To date our understanding of the effect of heat waves on different social groups is incomplete. The physical environment and area characteristics such as air and noise pollution, high concentrations of industry, high-density housing, and reduced green space are characteristic of many urban spaces in rapidly expanding cities. These can all have a negative impact on health and health behaviour.

**Socioeconomic status and heat events**

Whilst there is an extensive body of literature reporting consistent results relating to socioeconomic status and health, as well as socioeconomic status and particular health outcomes, there is less available information addressing environmental extremes such as heat waves and health in relation to socioeconomic status.

Results from US studies indicate that population density, lack of vegetation, substandard housing, and lower socioeconomic status, were risk factors in heat-related death (Kinney, O'Neill, Bell, & Schwartz, 2008). The identification of characteristics within populations that consistently increase vulnerability to temperature extremes across many regions of the world indicates that further research is required to assess how populations will adapt to changes in local climate, either by
physiological adaptation, behavioural changes, or by institutional interventions such as weather alerts or changes to urban planning (Medina-Ramon, Zanobetti, Cavanagh, & Schwartz, 2006; Michelozzi et al., 2003; Michelozzi et al., 2006; Schwartz, 2005).

**Population vulnerability**

Social vulnerability is interconnected with social inequality and environmental justice. The social factors that influence or shape the vulnerability of social groups also governs their ability to respond to environmental threats or hazards. Furthermore, the quality of human settlements including dwelling size, housing density, housing type, housing structure, orientation, roadways, and green space, all contribute to place vulnerability (Cutter, Boruff, & Shirley, 2003).

During heat events there is only a limited ability to improve the physiological adaptive capacity of humans; however responses to extreme heat can be better met through technological and behavioural adaptation (Menne & Matthies, 2009). These measures are more effective when combined with changes to building design and urban planning.

**Social vulnerability indices.**

The first steps in any exposure reduction plan are identifying and quantifying population vulnerability. The main clusters of vulnerability in space can be defined by developing an index of vulnerability that includes evidence of population sensitivity, environmental hazards and health risks. This information can then be used to develop a targeted approach to comprehensive heat-health action plans.
Vulnerability mapping

One important finding of epidemiologic investigations of heat-related morbidity and mortality is that poor and minority populations, located in urban neighbourhoods, are disproportionately affected.

In Melbourne the extent of population vulnerability, and the spatial distribution of vulnerable populations, is unknown. Predicted climate change for south-eastern Australia suggests that heat events will increase in intensity and duration (Alexander & Arbalster, 2008). Public health systems in Melbourne should be prepared for future health impacts of climate change.

Information relating population vulnerability to geographical location is essential for the development and implementation of heat adaptation and mitigation strategies. The provision of this information creates the ability to target behavioural adaptation strategies and heat wave response plans in the communities with the highest risk of adverse responses to extreme heat.

Methods

The basis of this research was to develop a vulnerability index that was not only relevant to the Australian situation but was comprehensive in its ability to identify vulnerability to heat events at a local population level of analysis, and was simple enough to allow easy replication at various locations. It was also important to appreciate that populations are not static and so indices that may be used to drive policy decisions at a given point in time must also be simple enough to accommodate change. To achieve this goal a multi-variable index was constructed to represent population vulnerability. Many of the variables included in the index were selected from the
ABS 2006 census data because this information is comprehensive for the Australian population, it is updated every 5 years, and is readily available to researchers. This index was subsequently tested using known thresholds for heat related mortality and morbidity in Melbourne (Loughnan, 2008; Nicholls, Skinner, Loughnan, & Tapper, 2008), for different population types and different areas. The index was then mapped to provide a spatial guide to heat related vulnerability in the metropolitan area.

**Design**

A simple and easily replicable design was constructed to create the vulnerability index, as shown in Figure 1. This incorporated assembling known risk factors into three main groups; health, environmental, and population demography. The main index categories in each of the three groups were then selected.

(Insert Figure 1 here)

**Index categories**

The first step was to define the index categories and the appropriate data sources as shown in Table 1. The relevant data was extracted from the databases at the smallest spatial scale practicable; in this case the geographic scale chosen to represent vulnerability was Postal Areas (POA). Whilst census data and environmental data are available at a very small spatial scale, the corresponding health data requires a higher level of confidentiality and hence aggregation at a larger spatial scale such as POA is required. The proportion of people each area (number of people in the index category/number of people in the POA) for each index category was calculated. Each POA in Melbourne was ascribed to a decile rank with the lowest 10% as decile
1 and the highest 10% as decile 10. The decile ranks for each index category in each POA were then summed to produce an index value for each spatial area in this case each POA. This was subsequently mapped using MapInfo (MapInfo, 2005). To validate the index a composite variable was created which included all emergency hospital admissions and deaths in each POA on each day in summer. A stepwise regression was conducted to predict which of the independent variables in the vulnerability index best predict the distribution of the adverse health outcomes (dependent variable).

(Insert Table 1 here).

(Insert Figure 2 here)

**Results**

**The Vulnerability Index**

The regression analysis used identified which of the variables within the index best explained the spatial distribution of hospital admissions and deaths on days exceeding the threshold or on ‘hot’ days. Variables entered into the stepwise regression were the incidence rate of AHO per POA as the dependent variable. The independent variables entered were the variables used to construct the vulnerability index (V1 to V10) see Table 1. This analysis identified the best predictors of vulnerability, and at the same time controlled for co-linearity. The individual variables that best predicted vulnerability in each POA were, the number of aged care facilities, ethnicity, population density of the elderly and very young, single people aged over 65 years and living alone, dwelling structure (separate houses) and UHI. Individual variables in the index identified as strong predictors of health outcomes were weighted using the un-standardised coefficients.
from the regression analysis. The new weighted variables were used to recalculate the vulnerability index. This was subsequently mapped using MapInfo software (MapInfo, 2005).

The map of the vulnerability index shown in Figure 2 demonstrates a clear picture of increased vulnerability in the inner urban POA on a northwest to southeast axis, which transects the inner city region. There are also several areas of increased vulnerability on the southern Mornington Peninsula, an area with large numbers of retirees. Figure 3 shows the relationship between the night-time UHI and population vulnerability in Melbourne. The areas with medium (blue) and high (red) vulnerability are predominantly clustered in the inner city (warmer) regions and regions to the immediate north and northwest of the city. Having identified regions with the greatest vulnerability, researchers can extract information about these areas relevant to addressing extreme heat events. This includes aspects of the built environment not included in the index such as building size, orientation, numbers of windows, external shading, and access to open space, buildings having bedrooms under the roof, small living spaces, poor ventilation and reliance on air-conditioning for climate control can be identified. In the broader context this also allows community groups and health care organisations to designate the placement of cooling centres and dissemination points for welfare that are located in the areas of greatest need, thereby increasing efficiency of response plans. (Insert Figure 3 here)

**Discussion and conclusions**

Identification and localisation of the most vulnerable people in communities such as the elderly and infirmed is an important step towards strengthening the public health response to these high risk groups during hot weather. During heat events the UHI within cities puts an additional heat load on human beings, by reducing thermal comfort inside buildings. At night indoor
temperatures are more relevant for thermal comfort as this lack of relief from the heat further compromises people with a poor physiological heat response and may affect the quality and duration of sleep which in turn adds to physical exhaustion. Appropriate planning and building measures can reduce the impact of the UHI on human health.

This project was the first in Australia aimed at developing a spatial index of population vulnerability to heat events. This has been done for the Melbourne metropolitan area at a small spatial scale and has incorporated environmental, health and demographic vulnerabilities. By mapping the vulnerability index a visual guide has been provided to direct public health adaptation, mitigation and response plans. Statistical analysis identified key five aspects of communities that contribute to vulnerability during heat events. These included areas with large numbers of elderly persons either living alone or in aged care facilities, areas with large ethnic populations, Melbourne suburbs and industrial areas affected by the night-time UHI, and persons living in separate houses. In Melbourne there is considerable urban sprawl, and high density housing is concentrated in the inner city suburbs. These areas have undergone recent gentrification and are now areas with a younger professional population. A visual display of the data also identifies clusters of high risk areas such as the inner urban areas, and industrial areas, both of which are subject to UHI effects, and areas with high numbers of retirees (see Figure 2). Visualisation of the index also shows relationships with known environmental risks such as the night-time UHI in Melbourne shown in Figure 3. There is a well known relationship between elevated night-time temperature and increased mortality and morbidity during periods of hot weather in Melbourne (Nicholls et al., 2008). It was therefore important to be able to provide further evidence for this relationship in a spatial context as was done in Figure 3. Areas of
intense UHI and high vulnerability can now be identified providing information for a public health response through a heat-health action plan. Areas of increased risk within each POA can be identified using local knowledge or by re-examination of the data at a census collection district (CCD) level. This would require using census data to develop a small scale index for CCD within high risk POA.

This research implies that mitigation of Melbourne’s UHI in the medium and longer term would provide significant health benefits. The areas of risk highlighted in this project will allow local governments in these areas to identify specific problems and plan their remediation. In addition, the result of this research directs the development of longer term action plans. This may include renovating buildings to improve their thermal properties, and aid urban planners develop sustainable efficient urban communities. The longer term plan should also include protection for those described as vulnerable within communities as well as including urban design that contributes to public amenity and maintaining health and wellbeing in the face of a changing climate.

The public health effects of heat waves are largely preventable through the development and implementation of heat-health actions plans in large cities and regional areas. It is very important to raise awareness of the dangers of heat events and inform the population of how to minimise the risk of heat-related mortality and morbidity. In Europe the EUROHEAT Project has identified heat waves as a serious health problem for both present and future communities (Matthies, Bickler, Cardenosa Marin, & Hales, 2008; Menne, Apfel, Kovats, & Racioppi, 2008;
Menne & Matthies, 2009). The aim of heat-health plans is to predict, prevent and provide short term emergency measures for populations to reduce heat related risks to health.

Heat-health action plans are becoming a necessity for many cities due to changing weather patterns associated with climate change. Heat events cause illness and death; hot weather outside of heat waves also has adverse health impacts. The adverse health effects of ambient heat are largely preventable, but this requires a robust public health response, which is based on sound trans-disciplinary research capable of informing the development of a comprehensive heat-health action plan. By developing a spatial index of vulnerability this research provides the first step in this process. As this was also the first spatially based vulnerability index describing the effects of heat on urban populations to be developed in Australia it provides a unique opportunity for the development of a heat-health action plan and opens the door for the development of broader scale change in urban environments in the medium to longer term.
Figure 1 Methodological framework for variable selection and index construction.
Table 1 Index variables, risk factors and data sources.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Risk factor</th>
<th>Data source (census data from the 2006 census)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Age (65+,0-4)</td>
<td>ABS (Basic Community Profile (BCP) , Table B01)</td>
</tr>
<tr>
<td>3</td>
<td>Aged care facilities Nursing homes</td>
<td>Dept Health and Ageing (DHS) numbers and location of Aged care facilities in Melbourne</td>
</tr>
<tr>
<td>4</td>
<td>SES</td>
<td>ABS SEIFA (Socioeconomic Index for Areas)</td>
</tr>
<tr>
<td>5</td>
<td>Urban design (non-single dwellings)</td>
<td>ABS BCP (census data, Table 31)</td>
</tr>
<tr>
<td>6</td>
<td>Single person households</td>
<td>ABS , BCP (census data, Table B22)</td>
</tr>
<tr>
<td>7</td>
<td>Measure of disability</td>
<td>ABS, BCP ( census data, Table B17)</td>
</tr>
<tr>
<td>8</td>
<td>Population density</td>
<td>ABS, BCP (census data, Table B01, and land area square Kilometres)</td>
</tr>
<tr>
<td>9</td>
<td>Ethnicity</td>
<td>ABS, BCP (census data, Table B12)</td>
</tr>
<tr>
<td>10</td>
<td>UHI</td>
<td>MODIS (Terra) Land Surface Temperature &amp; Emissivity Monthly L3 Global 0.05Deg CMG</td>
</tr>
</tbody>
</table>
Figure 2. Map of Melbourne metropolitan area showing the Vulnerability Index for each POA.

Index is the sum of ranked deciles for variables 1 to 10 shown in Table 1.
Figure 3. The association between the night-time UHI and the vulnerability index. Melbourne night-time UHI (red = 13-14°C, orange = 12-13°C, yellow = 11-12°C, green <11°C) with the vulnerability index. Vulnerability index (bars; Black = high, Grey = medium, White = low).
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