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Research Article

Mapping Heat Health Risks in Urban Areas

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Periods of extreme heat pose a risk to the health of individuals, especially the elderly, the very young, and the chronically ill. Risk factors include housing characteristics, and socioeconomic factors, or environmental risk factors such as urban heat islands. This study developed an index of population vulnerability in an urban setting using known environmental, demographic, and health-related risk factors for heat stress. The spatial variations in risk factors were correlated with spatial variation in heat-related health outcomes in urban Melbourne. The index was weighted using measured health outcomes during heatwave periods. The index was then mapped to produce a spatial representation of risk. The key risk factors were identified as areas with aged care facilities, higher proportions of older people living alone, living in suburban rather than inner city areas, and areas with larger proportions of people who spoke a language other than English at home. The maps of spatial vulnerability provide information to target heat-related health risks by aiding policy advisors, urban planners, healthcare professionals, and ancillary services to develop heatwave preparedness plans at a local scale.

1. Introduction

Climate change projections for south eastern Australia include an increase in the number of warm nights, and heatwave duration, both of which are significant for human health, potentially the impacts of climate change on the health of Australia's population is of growing concern [1]. Recent extreme heatwaves have caused serious health, economic and social problems in Europe, USA, and southeast Australia, particularly in urban areas. Such events will continue to pose additional challenges to health risk management, emergency response systems, and to the reliability of the power supplies and other infrastructure [2]. Important lessons can be learned from many of the public health outcomes experienced during the recent American and European heatwaves, and the actions that followed. Specifically adverse health effects resulting from hot weather and heatwaves are largely preventable under current climate conditions, if heat-health preparedness plans can be implemented [3, 4].

Heatwaves in the USA over the last decade and the European heatwave in 2003 (when over 45,000 people died [5, 6]) have indicated that there are commonalities in population vulnerability during heat events. The greatest risks appear to be for urban populations, the very young, the elderly, persons with chronic disease or disability, and persons living in a built environment that increases the effects of local temperatures during heatwaves [6], people who are socially isolated are at a greater risk, as are people living in areas of lower socioeconomic circumstance and some ethnic groups [7, 8], high urban and population density also contributes to the increased risk [6, 9]. It is reasonable to expect that population vulnerability to heatwaves will be unevenly distributed making it more difficult to identify high risk groups and apply adaptation strategies.

In Australian cities similar effects are noted in response to hot weather, this highlights the need to understand the impacts of heat on public health, to build resilience, and to develop adaptation strategies [10]. In Melbourne, a simple heat-health warning system has been developed for use by public health authorities to advise older people when hot weather may be hazardous to their health [11, 12]. This system is based on a threshold temperature above which mortality in the elderly increases. The approach was

extended to include 10 regional centres across Victoria [12]. This enables the Victorian Department of Health to issue state wide alerts when hot weather is forecast.

Persons with preexisting cardiovascular disease have an increased risk of heat related mortality and morbidity. However, little information is available describing cardiovascular morbidity and heat relationships. Two Australian studies have highlighted increased risk in Melbourne and defined threshold temperatures above which acute myocardial infarction (AMI) admissions to hospital increase [13, 14]. This study uses the same method as described in Nicholls et al. [11]. The second study expands the use of threshold temperatures to prepare public health warnings by including a place-based analysis of how age and socioeconomic status influence AMI hospital admission rates during hot weather [13]. This approach allows targeted warning systems and adaptation strategies to be developed in required areas. Understanding the contribution of age and social circumstance to heat-health outcomes only describes part of what we now know contributes to population vulnerability and more detailed studies are emerging in the literature.

A few published articles (some noted above) have described social or environmental factors that influence an individual's vulnerability over and above biophysical risk factors [15–19]. Studies resulting in maps of population vulnerability to heat are much fewer in number. Maps of population vulnerability to heat and projected population vulnerability for Quebec were presented by Vescovi et al. (2005) [15–19]. Harlan et al. [7] used socioeconomic and environmental variables and human thermal comfort to quantify this relationship [7]. Chow et al. (2012) developed a spatial index of vulnerability for Phoenix Arizona for two time periods using an equally weighted spatial index [20]. The results indicate that ethnic groups and the elderly were concentrated in areas of higher risk [20]. A heat index was used to identify heat-related health outcomes in Chicago which indicated that callouts were concentrated in the central business areas but also occurred throughout the suburban areas [21]. Reid et al. (2009) developed an index for population vulnerability to heat events in the USA. This included identifying which of the known risk factors best-explained vulnerability and provided a template for local and regional heat maps to guide interventions aimed at mitigating the effects of heatwaves [17]. In Britain, Lindley et al. (2011) describes how climate change, vulnerability, and social justice affect health and wellbeing of people living in Britain and applies a framework of vulnerability to aid policy makers in addressing current inequalities [22]. Oven et al. (2012) have reviewed the links between weather extremes, older people, and support services. They have developed operational definitions of extreme weather likely to affect older people and their care providers and relate these to the latest climate change predictions for regions in the UK [23].

The aim of the current study was to draw on the information provided in previous studies from Melbourne and expand the methodology by using temporal and spatial mortality and morbidity data to delineate the spatial distribution of adverse health outcomes during hot weather. An additional aim was to develop an index of the spatial variation of vulnerability based on numerous factors reportedly influencing population health during periods of extreme heat. Vulnerability in this study can be defined as the propensity or predisposition to be adversely affected [24]. 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" [25]. 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 [26]. Information on factors reflecting health, demographic, and environmental contributions to vulnerability were obtained. Spatial variations in these factors were then correlated with the spatial variations in mortality and morbidity across Melbourne, on hot days (days that exceed the temperature thresholds). A vulnerability index, which could be mapped, was then developed to provide a visual guide to vulnerability. The relative ability of the different variables in the vulnerability index to assist in identifying the spatial variations in vulnerability across the city will assist the public health initiatives to reduce heat-related mortality/morbidity. Ethics approval for this study was granted from the Monash Standing Committee on Ethical Research Involving Humans.

2. Materials and Methods

The city of Melbourne and greater metropolitan area is the second largest city in Australia. During the study period the population of Melbourne was estimated at 4,137,432 persons. Melbourne is a multicultural city with 35.8% of its residents born overseas. Like many cities in Australia, Melbourne has an ageing population and they reside in the older more established suburban areas [27]. Melbourne is located in southeastern Australia and the city is located around Port Phillip Bay with the Great Dividing Range to the northeast and basalt plains to the west. Melbourne has a warm temperate climate with hot summers and relatively mild winters. Rainfall is relatively uniform throughout the year. A feature of Melbourne summers is the occasional incursion of extreme heat from central Australia that can push temperatures well above 40°C.

Hot weather in Melbourne was defined as days exceeding the Melbourne threshold temperature of 30°C (mean 24-hour temperature from 9 am to 9 am), above which, previous studies had demonstrated substantial increases in excess mortality [11]. The Bureau of Meteorology provided daily data on observed maximum and minimum temperatures for Melbourne, from 1/1/2001 to 31/12/2006. From this dataset, the daily maximum and minimum temperatures recorded at Melbourne Regional weather station in the central city area were selected and daily mean temperature (meanT) was determined by averaging the recorded maximum and minimum temperature between 9 am one day and 9 am the following day. Threshold temperatures were determined for daily maximum, minimum, and daily mean T using the method described in Nicholls et al., 2008 [11].

Daily records of mortality and morbidity for each postal area (POA) in the Melbourne metropolitan region were

used to determine the spatial distribution of adverse health outcomes during heat events, (i.e., where the threshold temperature of 30°C was exceeded) and also on all summer days not identified as heat events. Mortality included deaths from "all causes," but the morbidity data were selected for several key disease groups. A search of the published literature revealed these groups as important heat-related illnesses. 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 [28]. Heat stroke is a medical emergency, leading to rapid death in 10–50% of cases and a poor outcome in a high proportion of survivors [29]. In addition, exposure to extreme heat is reported to exacerbate existing chronic illnesses, with cardiovascular disease, respiratory disease, cerebrovascular disease, mental illnesses, and metabolic disorders reported to account for a high proportion of excess deaths during extreme heat events [30, 31].

Daily mortality and morbidity data were obtained for each year of the study period (2001–2006). The morbidity data set used was the Victorian Admitted Episodes Database (VAED) provided by the Victorian Department of Health (DoH). This data set consisted of 465,868 emergency admissions to hospital on 2185 consecutive days. The daily mortality data were provided by the Department of Justice, Registry for Births Deaths and Marriages. This data set included the numbers of deaths on each day in each POA in the Melbourne statistical division (SD) during the period from 01/01/2001 to 31/12/2006. The data set consisted of 2185 consecutive days and 202,944 deaths. The morbidity data set used was the Victorian Admitted Episodes Database (VAED) provided by the Victorian Department of Health (DoH) see Table 1. That is, the AHO for a specific POA on a specific day was the sum of emergency admissions and the number of deaths. All data sets used included a patient spatial identifier which was "place of residence" recorded as a postcode (POA). The age group, sex, postcode of usual residence, and principal diagnosis for each admission were selected from the VAED. A multiplicative decomposition model was used to remove the trend, the seasonal variation, and any cyclic behaviour in the mortality/morbidity time series. The mortality/morbidity time series was decomposed using exponential smoothing in SPSS [32]. The smoothed time series that resulted from this procedure provided an estimate of the expected or average AHO (smoothed or expected AHO = trend × cycle × seasonal factor), for each day during the period of record. The AHO anomaly for each day over the period of record was then calculated as the deviation of the actual AHO for that day from the smoothed AHO (AHO anomaly = actual AHO/smoothed AHO).

2.1. Index Variables. Ten variables/factors potentially of use in developing a vulnerability index were identified *a priori* from a literature review and the appropriate data sources for these variables were identified as shown in Table 2. The index was composed of three main groups of variables: environmental, health, and demographic. The demographic variables contained information about the population distribution of high-risk age groups, the numbers of aged care facilities, socioeconomic status for areas (SEIFA), persons living alone, and the prevalence of ethnic groups, in each area. The environmental variables contained information about dwelling type, population density per square kilometre, and the intensity of the urban heat island (UHI). Health variables were measures of the burden of disease in each area and the proportion of residents with a disability. The variables selected to be included in the index are discussed in more detail below.

Table 1: ICD-10 codes used in selection of data from the *Victorian Admitted Episodes Dataset (VAED).

Disease category	ICD-10 codes
Circulatory system	I00-I79, I95, I97, I99
Endocrine	E00-07, E09-14, E20-35, E66, E84, E86-87
Respiratory	J00-84, J96-98
Mental health/behaviour	F00-99
Chronic renal disease	N00-N39
Diseases of nervous system	G00-09, G10-13, G20-26, G30-32, G35-37, G40, G41, G43, G44, G45, G70-73, G80-83
Neoplasm	C00-96
Pregnancy	O00-16
Other disease	X30, X32, T67, L55-56, and R50.9

* The VAED comprises a minimum data set containing (deidentified) demographic, administrative, and clinical data. The VAED is audited internally every two years and has a published error rate of 0.9% [27].

2.2. Demographic Variables/Factors. Age groups, numbers of aged care facilities, socioeconomic 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 [33–38]. Aged care during the European heatwave in 2003 aged care facilities reported high rates of heat-related mortality and morbidity [9, 38, 39], therefore areas containing these facilities are important to identify. 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 [40–42] and married couples were less likely to be affected by heatwaves in Italy [18] and France [35]. However, Hajat et al. [43] found that living alone did not modify the risk in England [43]. Socioeconomic circumstance has also been described as a risk factor that moderates the heat-health relationship [6, 9, 44, 45], as does belonging to a racial or ethnic subgroup [7, 46–49]. Specific age groups within the population were selected to define population vulnerability. People within these groups have been shown to be more vulnerable than other members of the community. Age categories 0–4, 65–74, 75–84, and 85 years and older were extracted from the Australian Bureau of Statistics (ABS)

Table 2: Risk factors and their respective data sources.

Variable	Risk factor	Data source
1	Aged care facilities Nursing homes	Department Health and Ageing (DoH 2006)
2	Ethnicity	ABS BCP census data (2006 census)
3	Single person households	ABS-BCP census data (2006 census)
4	Urban density (nonsingle dwellings)	ABS-BCP census data (2006 census)
5	SocioEconomic Status	ABS SEIFA census data (2006 census)
6	Age (number of persons aged 65+, 0–4)	Australian Bureau Statistics Basic Community Profile (census data (2006 census))
7	Measure of disability	ABS-BCP census data (assistance with core activities) (2006 census)
8	UHI	Modis/Landsat
9	Burden of disease	Department of Health
10	Population density (per km^2)	ABS BCP census data (2006 census)

* Australian Bureau Statistics (ABS).
* Basic Community Profile (BCP).
* SEIFA Socioeconomic Index for Areas.

Basic Community Profile (BCP) for each Melbourne POA. Identification of the number of elderly persons living alone in each POA was completed using the Household Characteristics table within the BCP. Data for the total number of households in each POA were extracted. Data for single-person households (persons aged 65 years and older) were also extracted. The proportion of single person households with occupants aged 65 years and older was calculated from the total number of households in each POA. The location of each aged care facility in the SD of Melbourne was obtained from the Victorian Department of Health, and the number of aged care facilities in each POA was calculated, along with the number of aged care facilities in the Melbourne SD. The proportion of aged care facilities in each POA was calculated using the Melbourne SD total.

The Australian Bureau of Statistics (ABS) socioeconomic index (SEIFA) [27] was used to describe socioeconomic circumstance in areas; SEIFA has been constructed so that areas of relative disadvantage have low index values. Low scores on the Index of Relative Social Disadvantage (IRSD) occur in areas where there are many families with low income, and many people with little training or considerable employment in unskilled occupations. A high SEIFA score reflects lack of disadvantage, not a high proportion of advantage. The BCP was also used to identify areas where families spoke a language other than English at home. The total number of persons speaking a language other than English at home was extracted for each POA, as well as the total number of persons in each POA. The percentage of persons speaking a language other than English at home in each POA was then calculated.

2.3. Environmental Variables/Factors. High density urban development and the presence of an UHI have been shown to increase the heat load experienced by urban populations [9, 50]. People spend most of their time indoors when weather conditions are extreme. Evidence from the French heatwave in 2003 indicates that multidwelling structures were associated with an increased risk of mortality [42]. Hajat et al. (2007) demonstrated that the relative risk of death during a heatwave was higher in urban than in rural areas [43] and Clarke (1972) also suggested that increased numbers of urban deaths were attributable to higher temperatures in urban areas [51].

Information relating to urban density was obtained from the ABS as either an independent house (single-dwelling structures) or multidwelling structures. Multidwelling structures included apartments, blocks of housing units and townhouses as well as flats above shops, mobile homes, improvised dwellings, and houseboats. This provided information to identify areas where there were larger numbers of multidwelling structures indicating higher density living arrangements. Areas of high population density often correspond to areas of high urban density and a potentially high UHI effect. To incorporate areas of high population density the land area in square kilometres of each POA was obtained from the ABS. Population density was measured as the number of persons per square kilometre. The method assumes that population is evenly distributed across each POA, but nonetheless will give an estimation of high-density, medium-density and low-density areas for the vulnerable age groups.

For the mapping of the Urban Heat Island effect in Melbourne, satellite-based measurements from the MODIS/Terra Land Surface Temperature and Emissivity Monthly L3 Global 0.05 Deg CMG (climate modelling grid) satellites have been used. The Land Surface Temperature & Emissivity Monthly L3 Global 0.05 Deg CMG product was downloaded from the NASA land processes distributed active archive centre. Data from the MODIS/Terra Land Surface Temperature and Emissivity (LST/E) products provided per-pixel temperature and emissivity values in a sequence of swath-based to grid-based global products. The MODIS/Terra LST/E 8-Day L3 Global 0.05 Deg climate modelling grid is configured on a 0.05° latitude/longitude [52]. The satellite data for the period from November to March were chosen for analysis, as these months are the warmest for the Melbourne metropolitan region. Monthly images and data for the reference period

from November 2000 to March 2006 were downloaded, georeferenced, and then clipped for the Melbourne region. The day and night image data were multiplied by the scale factor of 0.02 and temperature units were converted from Kelvin to Celsius. This data set provided temperature data at a much higher spatial resolution than was available from weather stations. Although LST does not translate directly to air temperature, there is a strong coupling between the two resulting in strong positive correlations that are to an extent modulated by land cover [53].

2.4. Health Variables/Factors. Chronic disease has been shown to increase susceptibility of heat-related mortality and morbidity [54, 55]. Similarly, persons with a disability have been deemed more vulnerable than the wider population [42]. Disabled persons have limited mobility and limited ability to respond to their ambient conditions and therefore they are important to include. Specifically, the number of persons with a disability who required assistance with daily activities was calculated. The Victorian Department of Health (DoH) collates data on population status for health services planning. The total burden estimates portray the relative ranking of the importance of the major diseases confronting the populations in Local Government Areas (LGA). Cancers, cardiovascular disease, mental disorders, neurological and sense disorders, and chronic respiratory disease are the major causes of ill-health identified [56]. The Burden of Disease (BoD) data were supplied by the DoH at an LGA level. In order to include this information in the index, the BoD for each POA was determined by calculating the BoD as the incidence per 100 persons in each LGA. The incidence in each POA was then estimated based on the total population in each POA of each LGA. Data relating to persons with a disability were accessed from the ABS BCP. Questions relating to "core activity need for assistance" are used to measure the number of persons with a profound or severe disability. People with a profound or severe disability are defined as people needing help and assistance in one or more of the three core activity areas of self-care, mobility, and communication because of a disability, long-term health condition (lasting six months or more), or old age. The proportion of persons with a "core activity need for assistance" in each POA was calculated.

2.5. Index Development. The relevant data were extracted from the databases at the smallest spatial scale practicable, namely, postal areas (POA). The risk factors and data sources are described in Table 2. The total number of persons relating to each variable for each POA, and total persons in each POA was extracted. The proportion of the population for each variable in each area was calculated (e.g., the proportion of people in each POA aged 65 or above or aged under four years). This data provided a theoretical representation of vulnerability in each POA. Whilst the risk factors were assembled in the index for each POA, and AHO were based on persons place of residence, it must be noted that this method cannot account for individuals' location when the heat exposure took place. To account for possible outdoor occupational exposures, this study used an area based index of socioeconomic circumstance. This will include areas with high numbers of unskilled workers and manual labourers who may be at risk of heat exposure. It is possible that they were not at home, although during extreme heat events most people will remain indoors wherever possible. This study uses population level data as this is an ecological design, to try to attribute this information to individuals would be an ecological fallacy.

2.6. Statistical Analysis. The incidence rate of AHO per POA was calculated as the number of AHO per 1000 persons separately for both hot days (i.e., days exceeding the heat threshold) and nonhot days (all other summer days). The AHO incidence rates in each POA were imported into SPSS [32] for analysis. The association between the variables to be considered for inclusion in the vulnerability index and AHO was examined first by calculating linear correlations between the variables/factors and AHO. Table 3 lists the correlations between AHO and the variables. Two variables (burden of disease and population density) did not show a significant correlation with AHO and were not considered further for inclusion in the vulnerability index. The other eight variables whose spatial variations across Melbourne exhibited statistically significant correlations with AHO were then considered for inclusion in the vulnerability index (these are variables 1–8 in Table 2). A condition index was also generated to identify possible colinearity between index variables. 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 [57].

A stepwise linear multiple regression between AHO and the remaining variables was then calculated. The weighted values were calculated for each variable in each POA in the index, the weighted variable values were then summed in each POA. Each POA was given a decile rank (relative to all the other POAs) with the lowest 10% as decile 1 and the highest 10% as decile 10. This was done by exporting the data into SPSS [32] where they were transformed using the visual banding function into bands with a width of 10%. The ranks for each variable were calculated so an increase in rank should indicate an increase in vulnerability. This was subsequently mapped using MapInfo software [58] (see Figure 1).

The AHO were calculated for each POA for each day within the study period. To examine differences between AHO on hot days and on nonhot days in each POA the data set was split into days that exceeded the predetermined heat thresholds and days that did not. Decile values for the AHO in each POA on hot days and on nonhot days were calculated. However, these data cannot be presented here as there are privacy considerations relating to areas with small numbers of deaths. To understand the change in vulnerability in each POA during heat events the difference in AHO in each POA from baseline (nonhot days) and hot days was determined by subtracting the decile value on baseline days from the decile value hot days. This difference in decile values of AHO

Table 3

Correlations	Vulnerable age groups	Burden of disease	Aged care facilities	IRSD	Urban design	Single person households (65+ years)	Persons with disability	Population density (sq km)	Ethnicity	AHO (incidence 1000 persons)	UHI
Vulnerable age groups	1	−0.022	0.103	−0.103	−0.319**	0.635**	0.408**	−0.029	0.036	0.435**	−0.094
Burden of disease		1	−0.159**	0.067	−0.182**	−0.088	−0.089	−0.237**	−0.168**	0.033	−0.231**
Aged care facilities			1	−0.048	0.190**	0.261**	0.063	0.586**	0.251**	0.459**	0.188**
IRSD				1	−0.04	−0.053	−0.190**	−0.053	−0.351**	−0.212**	−0.175**
Urban design					1	0.406**	−0.066	0.745**	0.277**	−0.265**	0.284**
Single person households (65+ years)						1	0.271**	0.311**	0.05	0.352**	−0.066
Persons with disability							1	0.012	0.052	0.116*	0.107
Population density (sq km)								1	0.426**	0.087	0.349**
Ethnicity									1	0.453**	0.605**
AHO (incidence 1000 persons)										1	0.206**
UHI											1

*Correlation is significant at the 0.05 level.
**Correlation is significant at the 0.01 level (2-tailed).

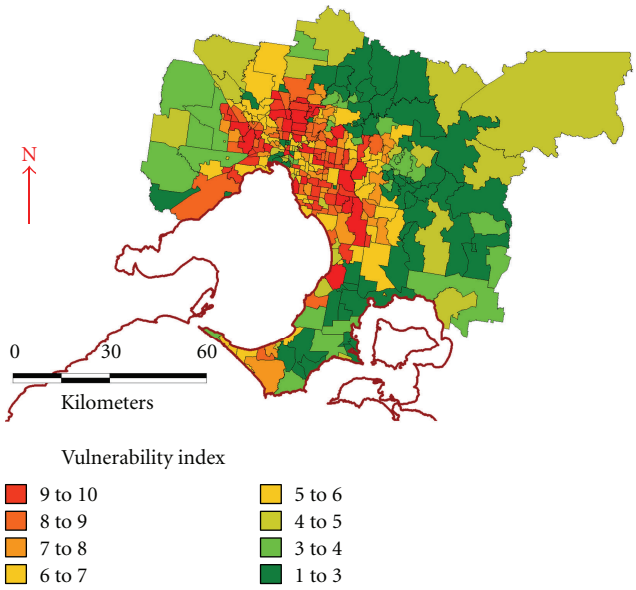

Figure 1: A map of the statistical district of Melbourne showing the weighted vulnerability index for each POA, on hot days.

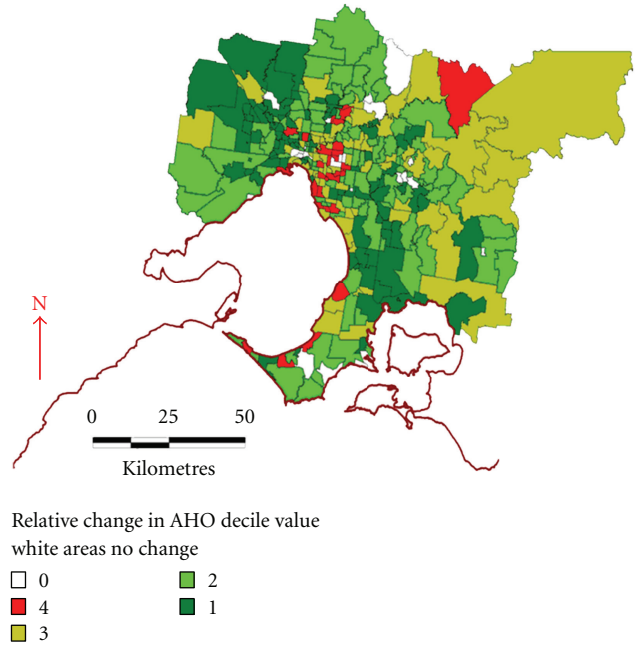

Figure 2: A map of the statistical district of Melbourne showing the relative change in AHO for each POA between baseline (nonhot days) and hot days.

in each POA was then mapped using MapInfo software [58], Figure 2. The difference between absolute and relative vulnerability was also examined by determining the change in health outcomes for each POA between hot days and nonhot days. Here we define "absolute vulnerability" as areas where AHO are generally higher than the overall Melbourne average on nonhot days throughout the summer. These areas have generally poorer health and further increases in AHO are apparent during periods of hot weather. In these areas, the population presents high mortality rates and morbidity rates during summer but increase further during hot weather.

Areas of "relative vulnerability" are defined as areas where AHO are average or below average on nonhot days throughout the summer period but where during periods of hot weather there is a notable increase in AHO. In these areas, mortality and morbidity rates are typically low during summer (compared with the Melbourne average) but during hot weather these rates markedly increase, indicating that these populations are still vulnerable during hot weather despite having low rates of AHO on nonhot summer days.

3. Results

The threshold temperature defining hot days for the Melbourne region during the study period was a mean T of 30°C, based on previous work [11]. There were 26 days that exceed this threshold during the study period. There was an average of 327 AHO per day in Melbourne on hot days, compared with 279 AHO per day on nonhot days. This represents a 17% increase in AHO on hot days in summer. This is consistent with results presented in Nicholls et al. [11].

3.1. Regression Analysis. Eight of the ten variables initially examined were significantly correlated with AHO; these are variables 1–8 in Table 2. Five of the eight variables, namely, proportion of aged care facilities, ethnicity, and households with single persons over 65 years of age, areas with large proportion of persons in the vulnerable age groups 0–4 years and 65 years and older, and urban density, made significant contributions to the spatial distribution of the vulnerability index. A model with these five variables included explained 47% of the spatial variability of relative AHO on hot days. The proportion of aged care facilities and the location of ethnic groups together explain 40.9% of the spatial distribution of AHO on hot days. A condition index of 7.2 was not suggestive of multicolinearity between the variables in this model.

A map of the weighted vulnerability index demonstrates a clear picture of increased vulnerability (areas shown as orange to red in Figure 1) mainly in the inner urban POAs on a northwest to southeast axis, which transects the inner city region. There does not appear to be increased vulnerability in areas within the CBD.

Maps were also generated for the actual AHO on hot days and for the relative change in AHO in each POA between hot days and nonhot days, but these cannot be shown due to confidentiality restraints necessary when using potentially identifiable health data. The pattern of AHO on hot days broadly resembles that of the predicted vulnerability as shown by the map of the vulnerability index in Figure 1. However, there is an interesting anomaly in the northeast suburbs where the predicted vulnerability is high (decile 8–10), but the AHO on hot days is average or just above average (deciles 5–7). Some of this variation is explained by calculating the relative change in AHO from baseline (nonhot days) and hot days (see Figure 2). Some areas in Melbourne show

a substantial increase in AHO on hot days compared to nonhot days but the decile rank for AHO still does not reach the high decile category, because AHO on nonhot days in these areas is low relative to other parts of Melbourne.

Thus, the vulnerability index is accurately predicting increased vulnerability in these regions, even though the vulnerability is still low relative to other parts of the city. This difference in absolute and relative vulnerability should be taken into account when interpreting and reproducing the index.

4. Discussion

Heat-related mortality, and morbidity are among the primary health concerns that are expected to increase as a function of climate change [45]. Population vulnerability is an active process with some people being more vulnerable to heatwaves than others based on their health, location, culture, or occupation. It is therefore useful to identify populations at risk and to plan and target interventions accordingly. The public health outcomes of heat-waves depend on the level of exposure (timing, frequency, intensity, and duration of the heat-wave), the extent of the event, and the demographic profile of the exposed population, population sensitivity and the prevention measures in place [2].

This research project gathered information that defined population vulnerability to periods of extreme heat in Melbourne, Australia. Mapping population vulnerability provided government and healthcare agencies with a "tool" for the development of targeted heat-health action plans and to help minimize the adverse effects of climate change on the health of urban populations. The spatial index of vulnerability was developed using spatially matched data for morbidity and mortality on days exceeding the predetermined heat thresholds in Melbourne. Five variables were identified that together explained 47% of the spatial variability in heat related vulnerability. A weighted index was created and is shown in Figure 1. The five variables that best-explained population vulnerability were the percentage of aged care facilities in each POA, ethnicity or households where a the primary language spoken at home was NOT English, elderly people living alone, people living in single dwellings, and areas with a high proportion of elderly and very young citizens. The index represents the spatial variations in vulnerability on days exceeding the 30°C threshold in Melbourne. However, it may not accurately represent the spatial distribution of vulnerability during extreme heatwaves that continue over a number of days. Another consideration is that the vulnerability index represents absolute vulnerability, that is, areas with high AHO outcomes on hot days. It is possible that vulnerability may be relative to the underlying health status of the population and that the change in vulnerability between hot days and nonhot days in each POA may also be important. For example, POA that are recorded as decile 1-2 on nonhot days may be decile 5–7 on hot days. This would represent a considerable increase in risk, although it is not necessarily associated with high absolute decile values of AHO. Therefore, we are presenting two types of vulnerability: absolute vulnerability where on nonhot days AHO are high and the AHO on hot days are also high. There is also a relative vulnerability in areas where AHO on nonhot days are average/below average, but the AHO on hot day's increases markedly. This change may not result in high decile values but does indicate increased vulnerability in the population in these areas.

The number of aged care facilities in each POA (as a proportion of all aged care facilities in Melbourne) explained 31% of the spatial variability in the AHO on hot days. This highlights the vulnerability of elderly persons in the community to extreme heat despite being cared for by professionals. The increased vulnerability for the persons living in aged care facilities in Melbourne corresponds with the literature from Europe where the greatest numbers of deaths in the elderly during the 2003 heatwaves were within institutions [37, 59]. Some of the most vulnerable persons live within an institutional situation. In France the mortality rate in the 75 years and older group doubled for persons living in retirement homes [35]. Similar situations occurred in Italy, and the UK [4, 60]. Furthermore, within the aged care cohort often victims were those who were less frail. Personal care in institutions was targeted towards the most vulnerable (frail) but less frail patients made the largest contribution to mortality [9, 36, 38, 42]. There were several explanations for the observed increase in mortality in aged care facilities. Firstly there was no mandatory air-conditioning in care facilities; therefore, in some facilities there were no areas within the buildings for respite from the heat as the duration and intensity of the heatwave progressed. Persons who were identified as most frail commanded more intense care. Secondly, the European heatwave occurred during the summer vacation period that left many institutions running on minimal "holiday" staff numbers. This meant that not only were relatives and friends on holiday and unable to assist with the care of elderly relatives, but that the remaining staff were also affected by the heat and the increased workload; this affected their ability to care for residents [35]. These patterns were not observed in the USA during heatwaves except when air-conditioning failure occurred [61].

Aged care facilities in Melbourne have air-conditioning within the communal living areas but not generally in resident's bedrooms. This will provide some respite for people who are able to move into the communal areas throughout the day but little relief during the night or for people who are bedridden. Ceiling fans in bedrooms may help in these areas by providing ventilation (air motion over the skin produces some cooling effect). Broadly, it would be expected that living in an aged care facility would be protective unless air-conditioning failed, but this may not be the case. A short but intense heatwave occurred in Melbourne in January 2009; the Chief Health Officer's report indicated that there was a considerable impact on the elderly, particularly for persons aged 75 years and older [62]. Ambulance callouts and doctor's visits to aged care facilities increased considerably with 61% of ambulance callouts being for persons aged 75 years or older and 42% of locum doctor's visits were in aged care facilities, respectively, [62]. As heatwaves are likely to occur during summer holiday periods maintaining staff-resident

ratios and relying on support from relatives could be a problem faced by Australian facilities. The increased level of risk observed for residents of aged care facilities in Melbourne suggests they should be targeted when developing adaptation and heatwave mitigation strategies. The number of households in each POA where large numbers of persons speak a language other than English at home explained a further 10% of the spatial variability in AHO on hot days. There is a well-recognized relationship between migrant populations, area deprivation and poor population health [63, 64]. This is the result of multiple factors including limited access to facilities or characteristics of the local environment such as increased air pollution, noise pollution, high-density housing, and industry, limited green space, and overcrowded living conditions. Epidemiological examination of mortality and morbidity during heatwaves in Europe, USA, Canada, and the UK indicates that racial minorities living in areas of lower socioeconomic status are at a greater risk [49, 65, 66]. One notable exception was a decreased risk of heat related mortality in the Latino population in Chicago during the 1995 heatwave [67]. This may have been due to increased social connectedness in this community. There is some evidence that lower income groups in urban areas were more at risk of heat wave-related mortality in the Europe 2003 heatwave, but many studies also show that there was no modification of the temperature-mortality relationship by socioeconomic status in Europe [4]. Therefore, it is not clear that poor urban populations are more at risk from heat-related mortality in Europe. This corresponds with the results of this study where ethnicity, which is often used as a surrogate for low socioeconomic status, is suggestive of increased vulnerability, but measures of socioeconomic circumstance alone were not strong predictors of increased vulnerability. It is suggested that there are multifaceted aspects of ethnicity beyond socioeconomic status that determine vulnerability within ethnic groups.

Level of education may be a moderating factor. A study in several Italian cities used level of education as an indicator of socioeconomic status as this information is available on individual death certificates. Excess mortality in Rome during the summer of 2003 was 6% in persons with the highest level of education and 18% in persons with the lowest level of education, and a similar pattern was observed in Milan [30]. Level of educational attainment may be related to occupational exposure, as blue-collar workers and manual labourers may experience direct exposure to environmental heat. A measure of educational attainment was not included in this study but could warrant inclusion in future indices. It is also possible that being a member of an ethnic minority group could increase vulnerability.

People are advised to spend most of their time indoors during periods of extreme heat. Therefore, urban density was incorporated into the vulnerability index based on evidence from the European 2003 heatwave that indicated building type, structure, and orientation were important risk factors in heat-related mortality and morbidity [42]. In Europe the risk was greater in regions with high-density housing. The urban density variable in this analysis included the proportion of dwellings in each POA that were considered high density. Melbourne is a city with considerable urban sprawl with high-density housing limited to the inner city and inner suburbs. These areas have undergone considerable gentrification in the recent past and are now areas with a younger professional population. This was supported by the statistical analysis that found a significant correlation between the proportion of vulnerable age groups and urban density ($r = -.319$, $P = 0.01$). This relationship was significant but weak and negative, indicating that as urban density increased the percentage of residents in the vulnerable age groups decreased. The relationship between urban density and AHO on hot days was also negative and significant in this analysis ($r = -.265$, $P = 0.01$). This result indicates that mortality and morbidity on hot days in Melbourne is occurring in suburban areas where people live in houses/single dwelling structures rather than city apartments and flats.

Evidence from the French heatwave in 2003 has indicated that brick houses (high thermal mass), houses with poor or no insulation, a south facing aspect, reduced ventilation, multidwelling structures, living above the second floor, bedrooms under the roof, and no green space/vegetation around dwelling were associated with increased risk of mortality/morbidity during heatwaves [9]. Whether or not this was the case for persons suffering heat-related mortality and morbidity in Melbourne could not be established by this study.

Air conditioning may be a protective factor for people living in areas with higher density housing in Melbourne. Studies from the USA have indicated that air-conditioning is a protective factor for heat-related mortality/morbidity [68]. A decrease in heat-related mortality/morbidity over the past two decades was attributed to increased use of air-conditioning [69]. Lack of air-conditioning was proposed to explain the increased risk of mortality in inner urban poor Americans during the Chicago heatwaves in 1995 [21, 40, 67] and 1999 and the European heatwave in 2003 [42]. Increased reliance upon air-conditioning may also become a feature in both Europe and Australia over the coming decades [37, 40]. There are three concerns regarding reliance upon air-conditioning; firstly, power failures either partial or complete are common during heatwaves due to 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 heatwaves. Thirdly, excessive reliance on air-conditioning and the associated energy has implications for fossil fuel consumption and its contribution to the increased effects of UHI locally, and climate change globally.

This study examined the AHO recorded as a place of residence; it therefore does not reflect the possibility of heat-related morbidity or mortality in the workplace or in transit. It is possible that occupational exposure to heat and disruptions to the transportation system will increase the risk of heat-related mortality and morbidity in susceptible people. To mitigate the effects of an intensified UHI associated with climate change, "cool city" designs that are not reliant on air-conditioned buildings should be incorporated into longer-term urban design and urban planning strategies [37].

Some secondary characteristics of heatwaves often overlooked are increased rates of injury, trauma, crime, and

domestic violence. Heat exposure may also be a secondary risk factor for people made homeless by other weather hazards such as floods and bushfires. These secondary characteristics are currently underrepresented in the literature, hence should be the focus of future research. There is limited opportunity to improve the biophysical thermal capacity of humans. However, exposure to extreme heat can be mitigated through behavioural adaptation and technological change. How to implement these measures and determine their effectiveness should be a focus for research in the future.

A limitation of this study included not being able to determine where the heat exposure occurred. This may be different to the place of residence, however by including place of residence we can match this to spatial areas with larger numbers of unskilled workers and manual labourers based on socioeconomic information.

5. Conclusion

Elderly persons living in aged care facilities and the elderly living alone are at a greater risk of heat related mortality and morbidity. In addition to biophysical reasons for increased risk, social factors are important. Other factors that increase the risk of heat stress are; living in areas of low socioeconomic status [70, 71], homelessness [72], and poor English language skills [67]. In urban areas, the urban heat island reflects an increased a sensible heat load to the atmosphere; this may be enhanced by poor building design and urban planning resulting in high-density housing with limited green space [73–75]. The spatial vulnerability index developed in this study provides critical information for policy makers and planners, healthcare professionals, and ancillary services. Each of the local government areas in Melbourne can now identify POA in its jurisdictions that are most at risk. Areas of increased risk within each POA can be identified using local knowledge or by reexamination of the data at a census collection district level. Such information can then be used to direct services such as community education, emergency management, heat-health adaptation strategies, and direct short-term and longer-term redevelopment and refurbishment of existing dwellings to mitigate the effects of heat in urban areas.

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