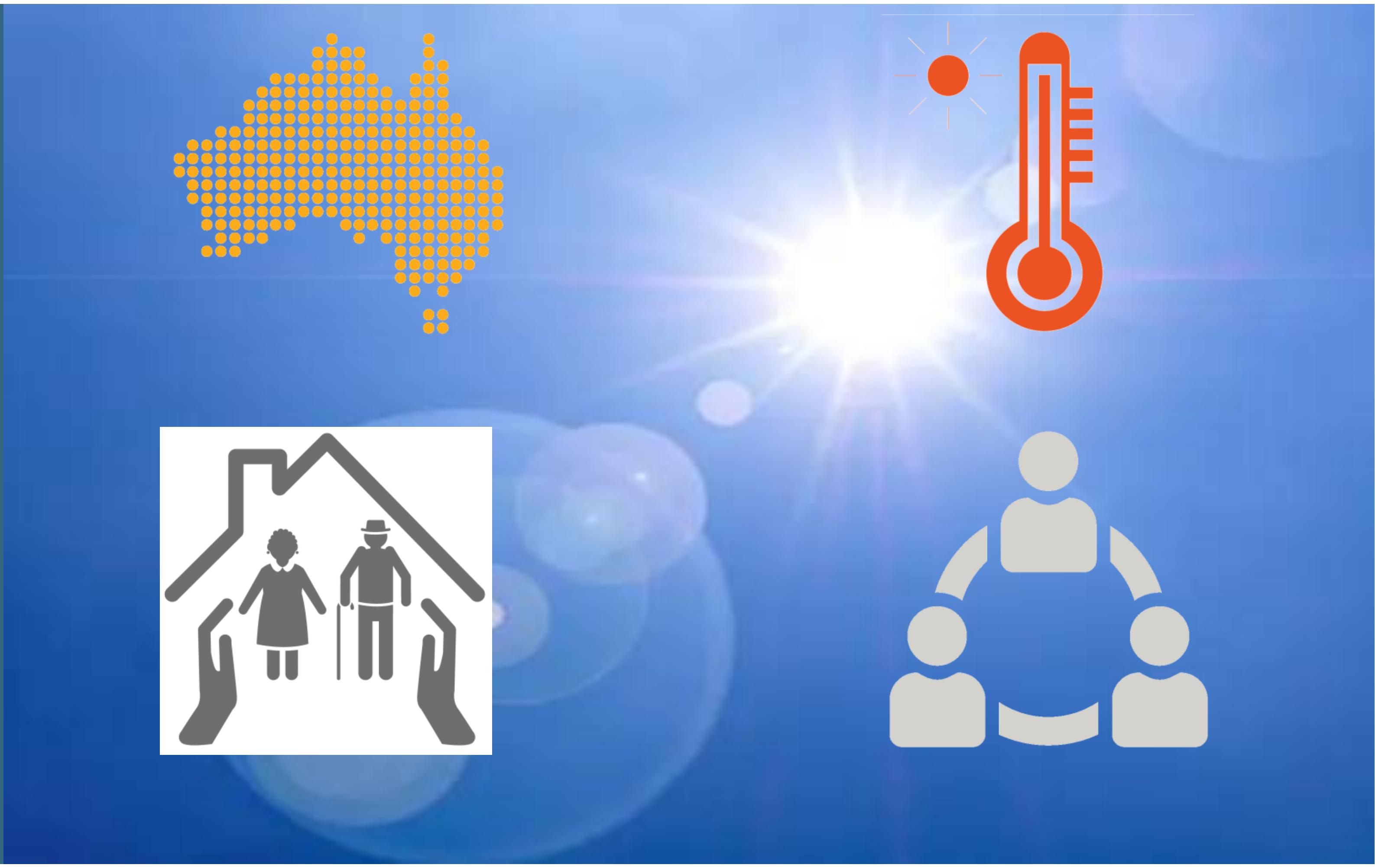
Australian Government
Bureau of Meteorology

Reducing Illness and Lives Lost from Heatwaves

Physical Environment Analysis Network (PEAN) 2019-21

Final Report - March 2021



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Suggested citation

Physical Environment Research Network. (2021). *Reducing Illness and Lives Lost from Heatwaves: Project Report*. Canberra, Australia: Australian Government Data Integration Partnership for Australia.

Acknowledgements

The RILLH project was funded by the Data Integrated Partnership for Australia (DIPA) and administered through the Physical Environment Analysis Network (PEAN). The Department of Agriculture, Water and Environment (DAWE) coordinated and facilitated the PEAN network.

Disclaimers

This report reflects the views of the authors and should not be construed to represent the agency views or policies.

Contents

Abbreviations used in this report

ABS	Australian Bureau of Statistics
ASGS	Australian Statistical Geography Standard
AWAP	Australian Water Availability Project
BARRA	BOM Atmospheric high-resolution Regional Reanalysis for Australia
BOM	Bureau of Meteorology
CDC	Centers for Disease Control and Prevention
CI	Confidence intervals
COPD	Chronic Obstructive Pulmonary Disease
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DEA	Digital Earth Australia
DOH	Department of Health
ED	Emergency Department
EHF	Excess Heat Factor
EMA	Emergency Management Australia
GA	Geoscience Australia
GCCSA	Greater Capital City Statistical Areas
GP	General Practitioners
HVI	Heat Vulnerability Index
IPCC	Intergovernmental Panel on Climate Change
LST	Land Surface Temperature
MADIP	Multi-Agency Data Integration Project
MBS	Medicare Benefits Schedule
MMM	Modified Monash Model
NEXIS	National Exposure Information System
NHS	National Health Survey
NHSD	National Health Services Directory
NPEDC	Non-admitted Patient Emergency Department Care Database
PBS	Pharmaceutical Benefits Scheme
PCA	Principal Component Analysis
PHIDU	Public Health Information Development Unit
RILLH	Reducing Illness and Lives Lost from Heatwaves
RR	Relative Risk
SA2	Statistical Areas 2
SVI	Social Vulnerability Index
UCL	Urban Centres and Localities Classification

Executive summary

Background

The Reducing Illness and Lives Lost from Heatwaves (RILLH) project is a multi-agency collaboration that assessed the utility of linked government data for understanding a significant, complex, and coupled social and environmental problem. Specifically, how do individual and neighbourhood characteristics influence health outcomes related to heatwaves?

Heatwaves are an enduring feature of Australia's climate and have significant social, health (physical and mental), and economic impacts on the Australian community. A primary motivation for the RILLH project was to address the complexity of heatwaves and their impacts with a nationally consistent approach using multiple mortality and morbidity measures assessed at different spatial scales.

By identifying which Australians are most at risk from heatwaves and exploring what can be learnt from large datasets about the key vulnerabilities to affect Australians during heatwaves, this project has laid the groundwork for improving warnings, emergency response, and health services for heatwaves.

The overall aims of this project were to:

- Use individual and neighbourhood level data to model the impact of heatwaves on human health (mortality/morbidity) in Australia and identify populations and places most at risk.
- Demonstrate the utility of linked social and environmental data from multiple agencies for understanding complex, coupled social and environmental problems.
- Engage with stakeholders to explore how project outputs and spatial analysis could inform heatwave warning services, and preparedness and response efforts for those most vulnerable to heatwave.

The RILLH project was led by the Australian Bureau of Meteorology (BOM) in collaboration with the Commonwealth Department of Health (DOH), Australian Bureau of Statistics (ABS) and Geoscience Australia (GA). Given the nature and complexity of heatwave vulnerability and health impacts, the project could not have been accomplished without the expertise, datasets and analytical skills drawn from the partner agencies.

Methods

Our methodology and analytical approaches focus on understanding how health outcomes relate to heatwaves and are modified by individual and neighbourhood characteristics. Two main analyses were conducted:

- Modelling of the relative risk of all cause and specific causes of mortality or morbidity (General Practice Attendances, and Ambulance callouts) during heatwaves of varying severity. Base models looked at each health outcome risk as related to heatwave days as defined by the BOM's Excess Heat Factor (EHF) heatwave metric. [78] Subsequent models were built that take into consideration individual (person level) and area (neighbourhood) level factors.
- Spatial analysis of heat-health risk (e.g., mapping and hotspot analysis) was conducted for the eight Greater Capital City Statistical Areas (GCCSA). This included analysis of each health outcome separately and, in relation to heat vulnerability indices (Overall vulnerability, Exposure, Sensitivity and Adaptive Capacity), derived from over 50 social, health, and environmental indicators.

These are large datasets with varying degrees of sensitivity and required the use of secure computing environments (Australian Bureau of Statistics DataLab and Department of Health servers).

Key findings and recommendations

The project demonstrates how existing data assets and emerging linked data can provide new opportunities for understanding complex social and environmental problems, particularly in the health domain. There are several key findings and recommendations from the RILLH project.

Key findings

- **Mortality and morbidity** – Mortality and morbidity increase during heatwaves across Australia with the magnitude of the increase varying by location.
- **Individuals and communities** – Individual and neighbourhood level factors are important in driving patterns of risk of dying and getting sick during heatwaves. Individuals are more susceptible if they have certain underlying health conditions, are from vulnerable groups or live in heat exposed neighbourhoods.
- **Spatial variation** – There is considerable spatial variation in heat vulnerability and health outcomes across Australia, especially within larger urban areas. Different factors drive these patterns including the degree to which communities can respond and adapt to heatwaves.

Recommendations

- **Cross-agency collaboration** - Cross-agency collaboration is vital for the sharing of expertise and diverse viewpoints to address complex problems. The RILLH project brought together expertise in the areas of extreme weather (forecasting and warnings), environmental epidemiology, health geography, and the built environment.

- **Evidence for planning and response** - As heatwave impacts vary between populations and locations, evidence concerning vulnerable people and places is critical for effective policy, planning, and interventions, especially in a warming climate.
- **Spatially targeted interventions** - Opportunities for spatial targeted interventions should be identified so warnings, targeted response plans, and other outreach methods can be customised for specific places and segments of the population.

Project background

1.1 Partner agencies

The Reducing Illness and Lives Lost from Heatwaves (RILLH) project is a multi-agency collaboration between the Australian Bureau of Meteorology ('the Bureau'), Commonwealth Department of Health (DOH), Australian Bureau of Statistics (ABS), and Geoscience Australia (GA). The project was funded for the 2019-20 Financial year through the Data Integrated Partnership for Australia (DIPA) which is a three-year $130.8 million investment to maximise the use and value of the Government's data assets. The project is one of several reporting to DIPA through the Physical Environment Analysis Network (PEAN) which is a collaboration between Commonwealth agencies who are custodians of data related to natural resources, the environment, water, agriculture, farms, and biodiversity. The Department of Agriculture, Water and Environment (DAWE) coordinated and facilitated the PEAN network.

1.2 Heatwaves and human health

Heatwaves have increased across much of the world as global average temperatures have increased.[1-5] Peak temperatures, frequency and duration of heatwave events have increased throughout Australia, consistent with historical and projected global trends in heatwave severity.[1, 5-8] Heatwaves vary in severity and duration and have significant social, health (physical and mental), and economic impacts on the Australian community (Table 1).[9,10] For example, heatwaves as extreme weather events have contributed to excess mortality in Australia more than all other natural hazards combined.[11] Much of the current understanding of heat-health risk relates to the role of heatwaves in mortality and morbidity at the city-scale [12-18] while limited evidence exists on the individual person level (e.g. physical and mental health, age) and local (e.g. neighbourhood) area factors (e.g. urban environment, dwelling type) that place populations most at risk.[19-21] A primary motivation for the RILLH project was to address this complexity with a nationally consistent approach using multiple mortality and morbidity measures assessed at different spatial scales.

Heat-health impacts are largely preventable [3,4] and heatwave warning systems and interventions addressing the public health risks have been developed by most Australian jurisdictions.[12] As climate change intensifies, the need to better warn, prepare for, respond to, and mitigate the impacts of heatwaves becomes more pressing. However, currently there is not a consistent approach to addressing heatwaves risk and impacts across Australia.[12, 22] States and territories have different portfolio responsibilities for heatwave management and warnings and their own heatwave metrics, plans, warnings thresholds, terminology, and processes. Because of this there are different levels of maturity of heatwave services across the nation in terms of warnings and public health interventions.[22] In 2019-20, the National Heatwave Warning Framework working group (NHWF, co-chaired by the Department of Home Affairs and Emergency Management Australia) was established to develop a national framework for consistent heatwave information and warnings. The RILLH project contributes information that will assist NHWF and other stakeholders to develop future impact-based heatwave warnings. It will also support products and services developed in partnerships between the Bureau, health and emergency service agencies.

Table 1- Heatwave severity as defined by Excess Heat Factor (EHF) and potential health impacts

Severity class[1]	Potential health impacts
Low intensity	Most people expected to have adequate capacity to cope with this level of heat.
Severe	Challenging for more vulnerable people, such as those over 65, pregnant women, babies, and young children, and those with a chronic illness.
Extreme	Will impact normally reliable infrastructure, such as power and transport and are a risk for anyone who does not take precautions to keep cool, even those who are healthy.

[1]Heatwaves are categorised by the Bureau of Meteorology as based on the excess heat factor (EHF) which provides a nationally consistent measure that includes local meteorological observations.

Source: Bureau of Meteorology http://www.bom.gov.au/australia/heatwave/about.shtml

For additional information about heatwaves and health impacts, readers are directed to the research and recent reviews in Table 2.

1.3 Linked social, health and environmental data

An additional motivation for the RILLH project was assessing the utility of linked government data for understanding a significant, complex, and coupled social and environmental problem. Specifically: how do individual and neighbourhood characteristics influence health outcomes related to heatwaves? Details of the datasets and scales of data linkage are described in detail below, and include linked data from the ABS's Multi-Agency Data Integration Project (MADIP) [62] asset (including mortality), Excess Heat Factor (EHF), and social and built environment attributes. These are all very large datasets which required the use of the secure computing environments at ABS DataLab [63] and DOH. Working with data across agencies will also contribute to the objective of providing evidence to support the development of improved government services that will prevent deaths from heatwaves (and other natural hazards) expected to increase as the climate changes.

Table 2 - Selected literature on heatwaves and health

Topics		**References**
Heatwave characteristics		[1, 6, 7]
Comprehensive reviews		[2, 23-25]
Mortality	All-cause deaths	[15-18, 26-39]
Morbidity	Ambulance calls	[32-34, 36, 38, 40-42]
	Emergency department visits	[13, 15, 28-36, 38, 40, 43, 44]
	Hospitalisations	[35, 45-47]
	Occupational injuries and Heat-illness	[48-53]
	Food-borne	[54, 55]
	Perinatal outcomes	[56]
Vulnerability	Area factors	[57-59]
	Vulnerability indices and mapping	[19-21]
Heat warning systems	General	[60, 61]
	Evaluation	[32]

1.4 Project objectives

The overall aims of this project were to:

- Use individual and neighbourhood level data to model the impact of heatwaves on human health (mortality/morbidity) in Australia and identify populations and places most at risk.
- Demonstrate the utility of linked social and environmental data from multiple agencies to understand complex, coupled, social and environmental problems.
- Engage with stakeholders to explore how project outputs and spatial analysis could inform impact warning services and preparedness and response efforts for those most vulnerable to heatwave.

Methodology

2.1 Data sources

An important aspect of this work is the use of datasets from a wide range of Commonwealth agencies, and allied sources. These datasets fall into six main categories, summarised here (See the Appendix for complete details):

- Heatwaves and climate - Excess Heat Factor (EHF), derived from Australian Water Availability Project (AWAP) and the Australian Bureau of Meteorology's Atmospheric High-Resolution Regional Reanalysis for Australia (BARRA), and Land Surface Temperature (LST) from the Commonwealth Scientific and Industrial Research Organisation (CSIRO).
- Built environment – Vegetation/bare earth cover (GA)/ Digital Earth Australia (DEA)); Housing (National Exposure information System (NEXIS) and ABS).
- Neighbourhood and community – ABS Population Census and National Health Survey (NHS); Chronic disease and risk factors (ABS NHS & Public Health Information Development Unit (PHIDU).
- Service and amenity locations – Health facilities and services (National Health Services Directory (NHSD).
- Individual level characteristics – Demographics (MADIP), Pre-existing conditions (MADIP Pharmaceutical Benefits Schedule (PBS).[62]
- Individual level health outcomes – Mortality (MADIP)[62], ambulance callouts (South Australia Health Department), ED presentations (National Non-admitted Patient Emergency Department Care Database (NNAPEDCD), medical attendances (MADIP Medicare Benefit Schedule (MBS)).

The time-period considered in this study is 2007-2018, but some of the health outcome datasets did not cover the entire period, and this is noted below. An important step in developing datasets for the analysis involved the linkage of social, health and environmental data. In some cases, these data have not been analysed together previously. Two forms of linked data were used:

- Person-level linkage – The ABS and partners have developed the MADIP data asset[62] that links existing government datasets at the person level. This includes demographic, census, health (MBS, PBS, and deaths), social services, and tax office data.
- Area linkage – All datasets considered in this study were aggregated or downscaled to a common geography/unit of analysis, the Australian Statistical Geography Standard (ASGS) Statistical Area Level 2 (SA2). In many cases, data were already available at the SA2 level while other data such as EHF were apportioned to SA2s from their native resolution (5 km).

2.2 Heat-health modelling

Relationships between heatwaves and human health outcomes are shaped by factors including the health status of individuals, their socioeconomic context and living conditions, and access to essential services. The project examined three health outcomes datasets each representing an increasing degree of severity for affected individuals – mortality (nationally), emergency department presentations, and general practice (GP) attendances (nationally). A multilevel approach was adopted as the conceptual framework for analysis, which involved analysis of the data from a highly aggregated (National) level to a finer geographic (neighbourhoods within cities) level. (see Figure 1).

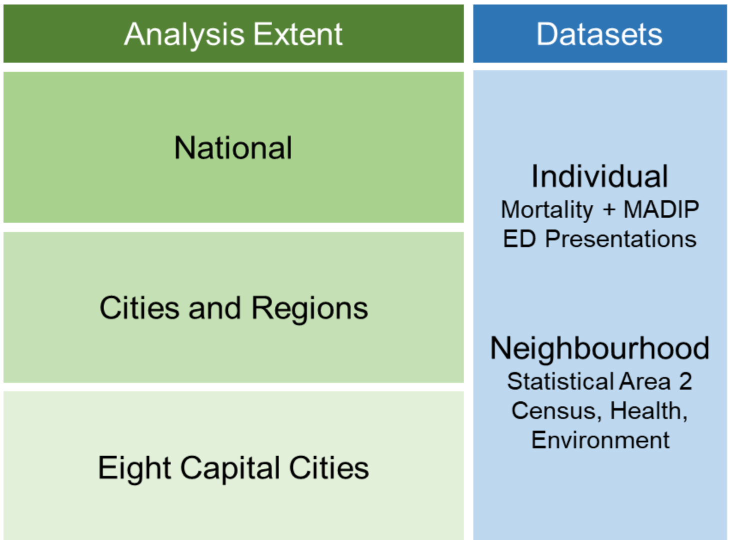

Figure 1 - Analysis scales and datasets used for heat-health modelling

A time-stratified case-crossover design with conditional logistic regression was used to quantify the effects of heatwaves on health outcomes (mortality and morbidity).[[59]] This commonly used approach in environmental epidemiological studies is suitable to assess the impacts of health outcomes arising from exposure to short-term events like heatwaves. The case-crossover models by design consider the influence of temporal trends (short/long-term) and other individual-level factors that do not change over a month, as each case acts as its own control. In other words, a person is compared to themselves during heatwave and non-heatwave conditions. Most data processing and statistical analysis were conducted using Stata 16 MP within the ABS's secure virtual-server DataLab environment [[63]] except for morbidity related to emergency department presentations which were analysed on DOH's secure server system.

For all analyses, the models estimate the relative risk (RR; Figure 2), for health outcomes during heatwave periods compared to non-heatwave periods during the warm season (October to

March). In simple terms, RR tells us "how much more, or less likely the outcome" is in the exposed group (heatwaves) compared to the non-exposed group (non-heatwaves). RRs are unit-less and range from 0 to infinity and is one of the 'safe measures' allowed to be released by the ABS from DataLab.[63] A RR of one means there is no difference in the risk of an event in the exposed and unexposed group, while a RR greater than one indicates an increased risk of an event in the exposed group compared with the unexposed group. Confidence intervals (CI) indicate the range in which the true estimate would fall 95% of the time (Figure 2).

For example, a RR of 1.60 from the mortality analysis means that the risk of death is 60% higher during heatwaves compared with non-heatwaves. If the RR is less than 1, then the risk of an event is less in the exposed group compared with the unexposed group. For example, a RR of 0.70 from the morbidity analysis means that the risk of renal outcomes was 30% lower during heatwaves compared with non-heatwaves. For ease of comparison, we have expressed RR as a percent change e.g., RR = 1.30 expressed as 30% increase.

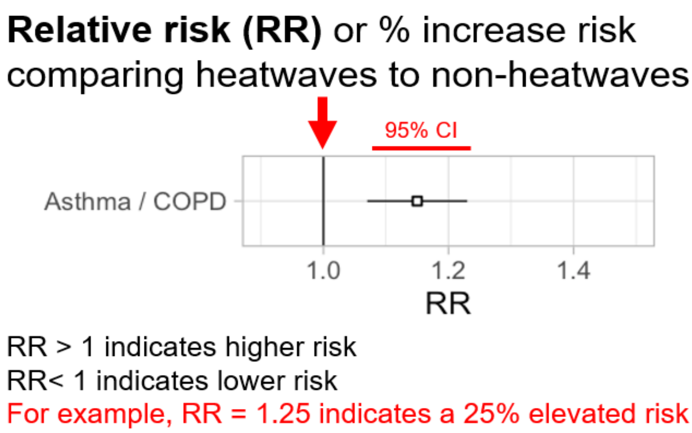

Figure 2 - Interpretation of Relative Risk and percent change in risk statistics

Following the approach of previous studies,[57,59,64-67] the modification of heat-health relationships by each of the neighbourhood level factors and individual-level factors was assessed using single-interaction models by including an interaction term between heatwaves and each potential modifier. Each of the neighbourhood-level indicators were categorised into quartiles (0-25th, 25th-50th, 50th-75th and >75th percentiles) and RRs were estimated for each of the four subgroups with the highest quartile considered as the most vulnerable during heatwaves. For example, RR modelling incorporating EHF and Disability produced four models: Quartile 1 (Least vulnerability) – Quartile 2 – Quartile 3 – Quartile 4 (Most vulnerable).

Individual-level factors were assessed using indicator variables for individuals with or without the characteristic, where those with a certain characteristic were considered as more vulnerable than others during heatwaves. For example, individuals who live alone compared to those who do not live alone.

Three general model forms were developed that included some combination of heatwave (Excess Heat Factor), individual (person) and/or neighbourhood (SA2) level variables.

Model 1: Baseline models predicting RR in relation to EHF alone.

Model 2: Base model with the addition of individual level variables.

Model 3: Base model with the addition of neighbourhood level variables.

Models were developed for each health outcome where applicable.

2.3 Heat vulnerability indices

To complement the health risk modelling and identify spatial variation in heatwave vulnerability and intervention options, a heat vulnerability index (HVI) was constructed, and neighbourhood level datasets compiled for the heat-health modelling. This approach furthered the assessment of spatial variability in heat-health risk but without some of the limitations related to the health data alone (See Discussion).

Two vulnerability assessment and mapping approaches were adapted for this project. The first is the Centres for Disease Control and Prevention's (CDC) Social Vulnerability Index (SVI).[68] The SVI is commonly used to map community vulnerability to natural and manmade health hazards, and it includes an overall vulnerability index and several sub-themes including Socioeconomic Status and Housing and Transportation. This approach was expanded by adding two additional dimensions relevant for heat-health analysis, Exposure and Adaptive Capacity. This draws upon the vulnerability framework developed by the UN Intergovernmental Panel on Climate Change[69] and used in other studies of heat vulnerability.

The HVI uses the following components and definitions (Table 3):

- Exposure – Factors related to direct heat exposure including microclimate, building performance, or outside work.
- Sensitivity – Factors that influence a community's ability to prepare for, cope with and recover from heatwaves. This component is similar to the CDC SVI approach.
- Adaptive Capacity – Factors that may help promote a community's ability to prepare for, cope with and recover from heatwaves. Adaptive Capacity refers to factors that reduce the overall impact of Exposure and Sensitivity.
- Overall Vulnerability - the combined effects of Exposure and Sensitivity and Adaptive Capacity

The HVIs were constructed using the SVI approach developed by the CDC.[68] Over 50 different indicators of vulnerability were used to determine the heatwave vulnerability for every city neighbourhood (SA2). The construction of the HVI is based on ranking variables at the neighbourhood (SA2) level for each indicator variable, theme, and index. An overall ranking and a combined index were calculated as: HVI = (Exposure + Sensitivity) - Adaptive Capacity. Themes and indices range from 0.0 to 1.0, representing low to high vulnerability. For example, the Socioeconomic Status Theme in Table 3 is a composite of household income, unemployment, and educational attainment. The Themes and Indices describe dimensions of vulnerability that are difficult to describe with single variables. [68] Table 3 describes the indicator variables and themes used construct the HVI indices.

Table 3 - Heat Vulnerability Index framework. Vulnerability Themes are derived from indicator variables and aggregated to form Exposure, Sensitivity, Adaptive and Overall Vulnerability indices

HVI	Indices	Themes	Indicators
Heat Health Vulnerablity	Exposure	Heat Exposure	Land surface temperature, No vegetation, Housing age (Pre-war, Post-war, Late 20th Century, Contemporary), High rise dwellings (Four storeys or more), Outdoor workers
	Sensitivity	Socioeconomic Status	Low equivalised total household income, High unemployment, Education - Year 10 or less
		Household Composition	Aged 65 or older, Aged 0 - 4 years, Disability, Living alone
		Language and Culture	English language profiency, New arrivals/refugees, Indigenous
		Housing Conditions	Flats or apartments, Rental housing, Crowding, No Vehicle, Social housing, No home internet
		Health Status	Arthritis, Asthma, Circulatory System, Chronic Obstructive Pulmonary Disease, Diabetes, High Cholesterol, Hypertension, Mental/Behavioural Problems, Musculoskeletal System, Respiratory
		Health Risk Factors	Alcohol Consumption, Overweight and Obesity, Smokers
	Adaptive Capacity	Access to Health Services	Hospitals, General practitioners, Aged care, Aboriginal and Torres Strait Islander, Community services, Emergency departments, Hospitals, Mental health, Pharmacy, Psychiatry
		Access to Cool Places	Public open space, Cool places, Vegetation, Water bodies
		Social Connectedness	Household stability - moved last year, Household stability - moved last 5 years, Volunteerism, Vehicle at home, Internet at home

An important step in the analysis involved the determination of how well the HVI captures variation in heat-health outcomes.[70-72] In other words: are the HVIs robust indicators of heat-health vulnerability in general? This type of comparison of HVI with relative risk data is not commonly done in Australia. The analysis was conducted in two parts:

- Global analysis – Following the approach outlined above, the HVI components (Exposure, Sensitivity, Adaptive Capacity and Overall Vulnerability) and Themes as effect-modifiers were included in the EHF relative risk models.[70] This allowed examination of neighbourhoods characterised with greater Index and Theme-level vulnerability which have greater mortality/morbidity.[71]

- Local analysis – Spatial analysis of the relationship between HVIs and Themes with relative risk maps of mortality, emergency department presentations, ambulance callouts and primary care attendances. This was undertaken through bivariate mapping and hotspot analysis (See Section 2.4).

2.4 Spatial analysis

The analysis of spatial variation in heat-health outcomes and heat vulnerability was conducted in two parts:

1. Mapping of each heat-health risk across each capital city, and
2. The use of spatial statistics to identify the degree to which heat-health outcomes are clustered or uniformly distributed.

Mapping and spatial analysis was conducted for each Greater Capital City Statistical Area (GCCSA) at the ASGS Statistical Area Level 2 (SA2). SA2's are designed to represent a community that interacts together socially and economically.[73] In urban areas, SA2 areas approximate neighbourhoods in cities and have a population range of 3,000 to 25,000 persons (Figure 3).

Figure 3 - Neighbourhood boundaries based on ASGS Statistical Area Level 2 (SA2) geography

Each heat-health relative risk was mapped along with the HVIs. The univariate mapping is largely descriptive and does not provide a clear indication of statistically significant spatial patterns. To account for this, Anselin's Local Moran's I was applied, also known as local indicators of spatial association (LISA) analysis.[74] This technique identifies statistically significant spatial clusters of features with similar attribute values (hot spots or cold spots). Areas where similar features were not associated with their neighbours were also identified. The Moran's I statistic compares observed patterns to complete spatial randomness (CSR) for significance testing.

Next, the bivariate relationships between heat-health risk and the heat vulnerability indices were examined. This analysis addressed the question: "Are health outcomes related to surrounding neighbourhood vulnerability?" To accomplish this, the bivariate version of Anselin's Local Moran's I analysis was used (or Bivariate LISA).[74] In this analysis, two dimensions with the general form of heat-health risk compared to health vulnerability were specified. In the case of bivariate LISA, of most interest were the two categories with high health risk (HH and HL), or in other words, places where heat risk is the greatest. For each city, bivariate clusters for all health risk variables and heat vulnerability index combinations were identified and mapped. Finally, for each neighbourhood, cluster membership was counted separately for HH and HL clusters and mapped e.g., two HH clusters in a given neighbourhood could mean co-occurring mortality and ED presentation risk.

Results

3.1 Heatwave chronology

Heatwave days as defined by EHF (Table 1) were frequent over the period of analyses in this study (2007-2017). Table 4 shows the number of non-heatwave and heatwaves days by EHF class for each GCCSA. Overall, the ACT had the largest percentage of warm-season days defined as heatwave days. Melbourne had similar numbers but also had the most days rated as Extreme, the greatest number across all cities. The temporal characteristics of heatwaves over the study period varied considerably in terms of duration and severity, so some caution needs to be taken when comparing results across cities given this variation.

3.2 Mortality

During the 2007-2017 study period, there were 739,639 deaths nationally during the warm season (October to March) which were included in the analysis. Cancers and diseases of the circulatory system combined were the principal causes of deaths in 62% of cases. There were increases in mortality in causes associated with heatwave deaths including external causes of morbidity and mortality (injuries; 8%), diabetes (7%), Chronic Obstructive Pulmonary Disorder (COPD; 7%) and heart attack (ischemic heart disease; 7%). The largest increase in all-cause mortality were observed among females (3%), children aged 5-19 years (6%) and working age adults 20-64 years (4%).

Table 4 - Number of heatwave days by varying severity of EHF across Australian capital cities (2007-2017).

City	Non-heatwave	Low intensity	Severe	Extreme
Adelaide	1832	138	32	3
Brisbane	1774	196	33	2
Canberra	1766	193	46	0
Darwin	1862	109	33	1
Hobart	1820	163	19	3
Melbourne	1796	182	20	7
Perth	1821	158	26	0
Sydney	1822	148	33	2

Nationally all-cause mortality increased by two percent during heatwaves. However, relative risk and excess mortality varied geographically and by cause of death. Based on geographic remoteness (Table 5), increased risk of mortality was highest for 'very remote Australia' (7.5% increased risk), ‘outer regional’ (3.4%) and 'major cities' (2.3%). Regional areas Victoria, Tasmania, Queensland, and New South Wales experienced the largest mortality risk (1-11%) and excess deaths (108-245 deaths) during heatwaves.

Table 5 - Percent change in mortality risk during heatwaves by remoteness areas, Australia (2007-2017)

Remoteness Areas	Mortality risk (%)
Major Cities	2.3
Inner Regional	2.0
Outer Regional	3.4
Remote	1.9
Very Remote	7.5

In terms of relative risk and excess mortality, major cities experienced most pronounced effects. Among capital cities, the greatest increase in heatwave related mortality risk and excess deaths was observed in Adelaide (8%; 328 deaths), Hobart (6%; 48 deaths), Melbourne (3%; 355 deaths), Sydney (3%; 341 deaths) and Perth (2%; 94 deaths).

The influence of a range of neighbourhood-level factors on the heatwave-mortality relationship described above was evaluated next. Given the relatively small size of the mortality dataset, the city (GCCSA) data was aggregated for analysis. Table 6 shows the neighbourhood characteristics most associated with increased risk of dying during heatwaves. These include high heat exposure, low socioeconomic status, poor housing and transport, vulnerable household composition, and poor health status.

A similar analysis of the influence of individual level factors on the base heatwave-mortality relationship was conducted. Using linked census and pre-existing conditions data with mortality, it was found that mortality risk was higher during heatwaves among individuals who were culturally and linguistically diverse, and had low socioeconomic status, vulnerable household composition, poor housing and transport, and poor underlying health status (Table 6).

Table 6 - Influence of neighbourhood and individual-level factors on the heatwave-mortality relationship

Index / Theme	Neighbourhood-level	Individual level
Heat exposure	Low vegetation No air conditioning (AC)	
Socioeconomic status	Low equivalised household income	Low equivalised household income
Household composition and disability	Living alone Over 64 years and living alone	Living alone Disability
Language and culture		Insufficient English language proficiency
Housing and transportation	Private rental No vehicle	No vehicle
Health status and risk factor	Diabetes Hypertension Asthma Poor mental health Severe mental illness Self-reported health as 'poor' Overweight Obesity	Diabetes Poor mental health Severe mental illness
Consistent risk factors across levels	Low equivalised household income; Living alone; No vehicle Diabetes and Mental health conditions	

3.3 Morbidity

3.3.1 General practice attendance

General practice is often the first point of contact with the health care system for individuals feeling unwell during heatwaves. Thus, changes in GP attendances during hot weather may be a leading indicator of other more severe illness leading to ambulance response, ED visits, and hospital admissions. A total of 251,772,190 GP attendances occurred in Australia during the warm-seasons (October - March) in the 5-year period 2011-2016. Based on classification of remoteness, 70% of GP attendances were in 'major cities', followed by "inner regional Australia" (19%). Nationally GP attendances only increased during severe/extreme heatwaves by four percent (95%CI: 3-4%) with an estimated 130,915 excess GP attendances, while no increase was found during low-intensity heatwaves.

Among capital cities, the highest impact of heatwave on GP attendances was found in Canberra (16%) and Greater Adelaide (14%), while in regional areas the highest impact areas were Rest of Vic (13%) and SA (10%). No significant increases were observed in Perth, and Rest-of NT, QLD, and WA. Based on the remoteness classification (Table 7), the increases in GP attendances during severe/extreme heatwaves were observed only in “Inner regional Australia” (4.6%), “Major cities” (4.3%), and “Outer regional Australia” (2.4%).

Table 7 - Morbidity risk during severe/extreme heatwaves by remoteness areas, Australia (2011-2016)

Remoteness Areas	GP Attendance risk (%)
Major Cities	4.4
Inner Regional	4.6
Outer Regional	2.4
Remote	nil
Very Remote	nil

Analysis of neighbourhood level factors on heatwave and GP attendances nationally, revealed higher impacts during severe/extreme heatwaves in areas characterised by high percentages of populations with high heat exposure, low socioeconomic status, poor housing and transport, vulnerable household composition, and poor health status (Table 8).

Based on individual level linked census and pre-existing conditions data, the analysis found that GP attendances were higher during severe/extreme heatwaves among individuals in vulnerable household composition, culturally and linguistically diverse, poor housing and transport, and poor underlying health status (Table 8).

It was found that for most cities, the risk of requiring a GP attendance during severe/extreme heatwaves increased across the entire metropolitan area (See Section 3.4.2). However, individual and neighbourhood-level factors increased utilisation of GP services during heatwaves and were related to sensitivity factors such as Household Composition, Language and Culture, Housing Conditions and Health Status.

Table 8 - Influence of neighbourhood individual-level factors on the heatwave-GP visits relationship.

Index / Theme	Neighbourhood-level	Individual level
Heat exposure	No AC	
Socioeconomic status	Low equivalised household income	
Household composition and disability	Over 65 years Living alone Over 65 years and living alone Disability	Over 65 years Living alone Disability
Language and culture	Insufficient English language proficiency	Insufficient English language proficiency
Housing and transportation	Public rental No vehicle No internet	Flats or apartments
Health status and risk factors	Diabetes Arthritis Respiratory diseases Circulatory diseases High cholesterol Poor mental health Severe mental illness	Diabetes Hypertension Congestive heart failure Dementia Psychological Medications: Anti-coagulants, Diuretics Anti-psychotics, Statins
Consistent risk factors across levels	Over 65 years; Living alone; Disability; Insufficient English proficiency Diabetes; Circulatory diseases and medications; Mental health conditions	

3.3.2 Emergency department presentations

Reporting results from the analysis of the national emergency department dataset requires approval from each State and Territory health department before findings can be made public. These approvals were underway at the time of this publication. An update to this report will be released mid-2021. It will describe the analysis undertaken, and how it contributions to understanding heat-health impacts as measured through acute presentations to emergency departments.

Over 23 million all-cause emergency department (ED) admissions were analysed in relation to heatwave severity across the eight capital cities during the warm-seasons (October – March) in the period 2013-2018. As with the mortality and general practice analysis, individual and neighbourhood level variables were included to understand factors contributing overall heat-health. Although the ED dataset has limited individual variables (sex, age), the data does provide an opportunity to assess heat related presentations for specific conditions e.g., direct effects of heat and light, mental health, and cardiovascular health (Table 9). As with the mortality analysis, heat-health relationships were analysed for all the area level factors listed in Table 3. This included the composite vulnerability measures as well.

Table 9 - Heatwave related emergency department presentations considered in this study

Condition group	Specific conditions based on ICD-10-AM and SNOMED-CT
Direct effects	Dehydration Heat exhaustion and stroke Electrolyte imbalance Drugs and alcohol related Foodborne illness
Diabetes	Diabetes complications
Cardiovascular	High blood pressure complications Ischemic heart disease complications Stroke
Renal	Acute kidney failure Kidney stones
Respiratory	COPD Asthma
Mental health	Poor mental health Severe mental illness Dementia

3.4 Spatial analysis

3.4.1 Heat vulnerability mapping

Four heat vulnerability indices (Exposure, Sensitivity, Adaptive Capacity and Overall Vulnerability) were developed based on the definitions and structure described in Table 3. As with the health risk maps presented below, the vulnerability indices were mapped for the capital cities at the neighbourhood (SA2) scale. The maps for Melbourne are presented in this report and a complete set of analysis is available in other publications and by request.

There is clear variation in heat vulnerability across Melbourne (Figure 4). The Overall Vulnerability map is a composite of the other three measures and most closely resembles the Sensitivity map. Exposure and Sensitivity maps have some similarities regarding highly vulnerable suburbs in Melbourne's west and southeast. The Sensitivity map shows some of the most disadvantaged parts of the city as having a lower capacity to cope with extreme heat. Exposure and Sensitivity taken together describe potential heat impacts. Adaptive Capacity describes factors that may mitigate these impacts and is highest in the inner suburbs and CBD. This is due largely to the availability of health services, cool refuges, and high social connectivity. The Overall Vulnerability map combines these factors, and this is evident in places like inner Melbourne which is not considered highly vulnerable due to the offset effect of Adaptive Capacity.

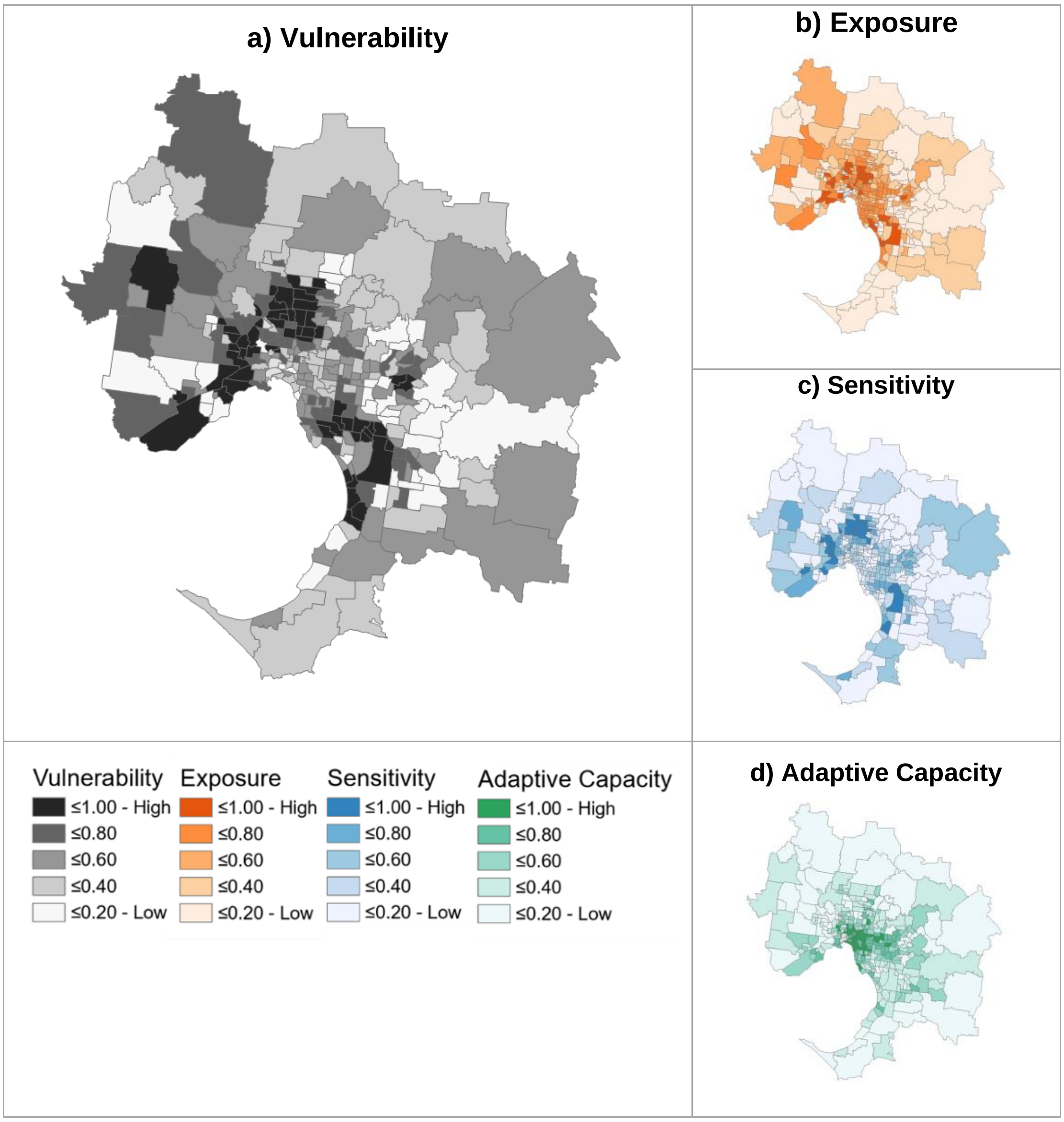

Figure 4 – Heat vulnerability indices for Greater Melbourne

3.4.2 Health outcomes mapping

Analysis of the heatwave-health relationships at the neighbourhood scale allowed for the production of high resolution national and capital city (GCCSA) maps (Figure 5). For brevity, this report focuses on the results for Greater Melbourne. The overall patterns observed for Melbourne are indicative of the types of insights from the analysis and can be generalised to other locations.

There was considerable spatial variation in mortality and morbidity across Melbourne. Note the mortality models underpinning relative risk are based on all EHF heatwave classes. The following sections present spatial analyses that incorporate other variables from the HVI to further explain the heat-health risk geography.

There are some important features in the geography of different heat-health outcomes observed for Melbourne. Changes in mortality risk varies from lower risk (<10%) in outer suburbs to very high risk (> 50%) in several inner-city suburbs. However, within the city and inner suburbs a distinguishing feature is the high degree of heterogeneity from neighbourhood to neighbourhood. In other words, there are pockets of high mortality risk adjacent to areas with lower risk. Note that given the limitations related to sample size and the mortality dataset, relative risk for any heatwave day is reported for this measure.

There is evidence that health impacts increase with heatwaves severity. For example, Figures 5a and 5b demonstrates that GP attendance increases dramatically from low severity to extreme/severe heatwaves. The relative risk of requiring a GP attendance is high only in the far north of Melbourne during low severity events, but risk increased by >20% across the entire city area during extreme and severe events.

3.5 Vulnerability and health outcomes

3.5.1 Global relationships

The relationships between heat-health outcomes and components of the HVI were assessed in two ways. First, a global analysis was conducted following the modelling approach described earlier and using the HVI indices and themes as effect-modifiers in our EHF relative risk models. Figure 7 shows the percent change in risk from the regression analysis, and how the risk of adverse health outcomes (mortality and morbidity) changes with a unit increase in HVI Indices and Themes. At the most aggregate level, overall Vulnerability raises the risk of dying (3.9%) and GP attendance (2.2%). Overall Exposure has a similar influence (mortality 4.4% and GP attendance 2.0%). Sensitivity raises the risk of dying (3.4%), and GP attendance (3.4%). Finally, Adaptive Capacity also has a significant influence on health outcomes. Note that in contrast with the other measures, higher Adaptive Capacity values mean less vulnerability. Higher Adaptive Capacity reduces the risk of dying (1.8%) and GP attendance (4.0%).

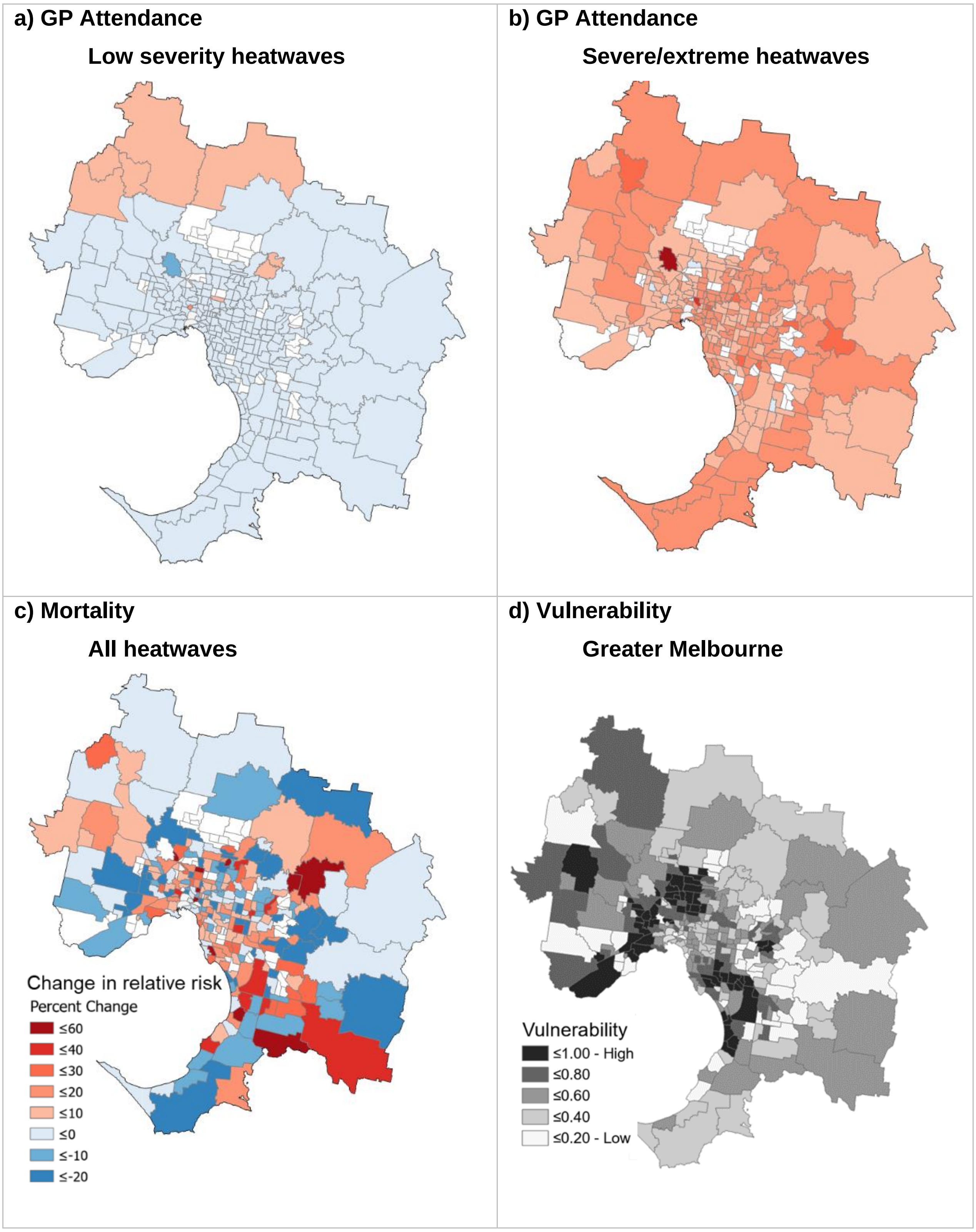

Figure 5 - Change in risk of general practice attendance for low and severe/extreme heatwaves in Melbourne

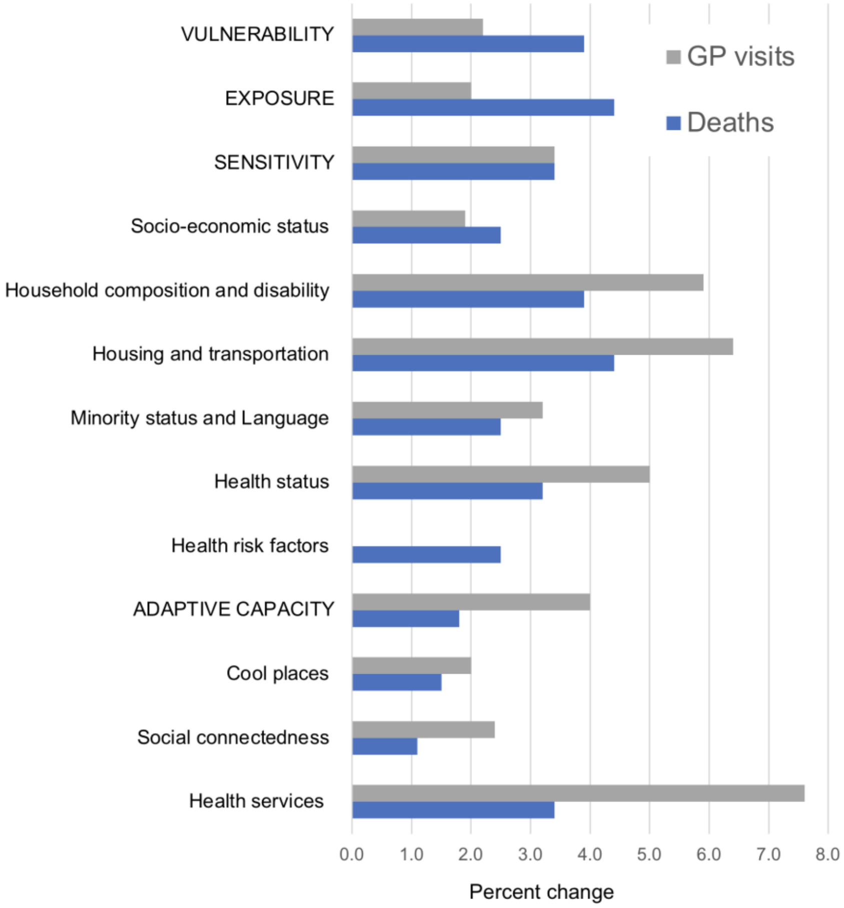

Figure 7: Change in health outcome risk during heatwaves by heat vulnerability index

3.5.2 Local relationships

In addition to assessing the overall (or global) relationships between health outcomes and vulnerability, a bivariate spatial analysis was conducted for each GCCSA using Local Indicators of Spatial Association (LISA).[74] Specifically, the bivariate local Moran's I statistic was used to determine where health outcomes are significantly related to neighbourhood level vulnerability.

The degree to which heat-health outcomes overlap in neighbourhoods across Melbourne was evaluated. However, in this case the role of neighbourhood characteristics based on the heat vulnerably themes and indices was considered. For bivariate LISA, there were two categories; places with High (health) risk AND High vulnerability (HH) and places with High (health) risk AND Low vulnerability (HL), or in other words, places where heat risk is the greatest. For each city, bivariate clusters were identified and mapped for all health risk variables and heat vulnerability index combinations.

There were strong spatial associations found between health risk and the four HVIs. High health risk was significantly associated with high vulnerability in inner suburbs in Melbourne's west and south. The outer suburbs to the west and north also had high heat-health risk but overall vulnerability was low in these areas. This was a recurring pattern where heat related mortality and morbidity was widespread but underlying vulnerabilities were different. The spatial patterns are different depending on which index is being considered. For example, there is a strong relationship between heat exposure and health risk in inner Melbourne, but this is offset by the influence of Adaptive Capacity and thus these areas drop out of the overall vulnerability map.

Discussion

4.1 Australian heatwave characteristics and trends

Heatwaves already present a significant social and environmental burden in nearly all parts of Australia. The frequency, duration and severity of heatwave events is increasing (Table 10), consistent with historical and projected global trends in heatwave severity.[5,8] For example, heatwaves are occurring earlier in the warm season in most capital cities (e.g., 19 and 17 days earlier than is normal for Sydney and Brisbane, respectively), and heatwave intensity has increased as much as 2.5 degrees C for Adelaide.

Table 10: The average number of heatwave days, number of events, length of the longest event, average heatwave intensity, average intensity of the peak heatwave day, and change in the timing of the first summer heatwave for Australia's capital cities (after Perkins and Alexander 2013 in Climate Council 2014).

	Number of heatwave days		Number of heatwaves (events)		Length of longest event		Change in average heatwave intensity (°C)	Change in average intensity of the peak day (°C)	Change in timing of first event (days)
City	1950-1980	1981-2011	1950-1980	1981-2011	1950-1980	1981-2011			
Adelaide	5	9	1 - 2	1 - 2	4	6	2.5	4.3	-2
Brisbane	10	10	2 - 3	2 - 3	6	6	1	1.5	-8
Canberra	6	13	1 - 2	2 - 3	5	7	0	1.5	-3
Darwin	3	7	1	1 - 2	4	5	0	1	-7
Hobart	4	5	1	1 - 2	4	4	-1.5	1.7	-12
Melbourne	5	6	1 - 2	1 - 2	4	4	1.5	2	-17
Perth	6	9	1 - 2	2 - 3	4	5	1.5	1.5	3
Sydney	6	9	1 - 2	2 - 3	4	5	1.5	1.5	-19

These trends are projected to continue with further increases (Table 11) in the number of hot days out to 2030 and 2070 relative to the 2000-2009 reference period based on modelling by the Bureau (2013) and the CSIRO (2007). While similar variability was captured in the study regarding extreme events (Table 4), the use of EHF allowed for the identification of low severity heatwaves. However, our 2007-2017 study period may not have captured the full range of variability in all the areas studied. For example, heatwave conditions for Perth were not necessarily representative of typical longer-term patterns in terms of the most severe events.

4.2 Heatwaves and human health

The severity and duration of heatwaves have significant social, health (physical and mental) and economic impacts on the Australian community [11,16] however, these are largely preventable. More work has been done on heat-related mortality than on heat-related morbidity, and this has probably led to an underestimation of the disease burden caused by heatwaves. Australian and international studies have identified the impacts of heatwaves on different populations including the direct effects of heat (e.g., heat stroke, dehydration across a range of age groups) for those with certain pre-existing health conditions (e.g., diabetes, heart disease). Other factors such as living alone or having a disability also increase risk. [2, 75-77]

Table 11 - The long-term annual average number of hot days (above 35°C) compared to the 2000 – 2009 average and the projected average number for 2030 and 2070 for some Australian capital cities (Source: Webb and Hennessy 2015).

City	Current	2030 RCP4.5	2070 RCP4.5	2070 RCP8.5
ADE	20	26 (24 to 29)	32 (29 to 38)	47 (38 to 57)
BNE	12	18 (15 to 22)	27 (21 to 42)	55 (37 to 80)
CBR	7.1	12 (9.4 to 14)	17 (13 to 23)	29 (22 to 39)
DWN	11	43 (25 to 74)	111 (54 to 211)	265 (180 to 322)
HOB	1.6	2.0 (1.9 to 2.1)	2.6 (2.0 to 3.1)	4.2 (3.2 to 6.3)
MEL	11	13 (12 to 15)	16 (15 to 20)	24 (19 to 32)
PER	28	36 (33 to 39)	43 (37 to 52)	63 (50 to 72)
SYD	3.1	4.3 (4.0 to 5.0)	6.0 (4.9 to 8.2)	11 (8.2 to 15)

Much of the current understanding of heat-health risk relates to the role of heatwaves at the city-scale[14,15, 35], while limited evidence exists for identifying the individual person level (e.g. physical and mental health, age) and local (area or neighbourhood) factors (e.g. urban environment, dwelling type) that place populations most at risk. Heatwave studies are also often limited in their spatial and temporal scope e.g., analysis of a single city during a particular heatwave. In contrast, the RILLH project is one of the few studies that applies a nationally consistent approach using multiple mortality and morbidity measures assessed at different spatial scales.

4.3 Populations and places most at risk

The focus of this project was to evaluate the impact of heatwaves on mortality and morbidity across Australia in order to identify the populations most at risk and where they live. We incorporated individual (person) and neighbourhood level factors that includes demographic, socioeconomic, housing and the built environment, and accessibility to medical facilities and cool places. In some cases, these data have not previously been analysed together. Multiple health measures were used including mortality, ambulance callouts, and attendances at GP.

The results of this study show that mortality/morbidity increases during heatwaves in Australia, but the magnitude of the increase varies both amongst and within places. One of the main drivers of this variation is the difference between individual characteristics and attributes of where they live. For example, mortality risk is high for low-income people who also live in disadvantaged neighbourhoods. Generally, individuals are more susceptible if they have certain underlying health conditions, are from vulnerable groups or live in heat exposed neighbourhoods.

There is considerable spatial variation in heat vulnerability and health outcomes across Australia and especially within larger urban areas. Different factors drive these patterns including the degree to which communities can respond and adapt to heatwaves. In Melbourne there were broad trends in heat-health risk, but at a local scale there was considerable variation from neighbourhood to neighbourhood. Hotspot/cold spot analysis indicates that there are significant clusters of high heat-health risk. The specificity of areas with adverse heat-health outcomes is clearer when outcomes are combined with vulnerability indices (Figure 9). Findings such as these can inform the development of warnings, targeted response plans and other outreach methods that can be customised for specific segments of the population and locations.

4.4 Linked social and environmental data analysis

A broader aim of this study was to assess the utility of linked government data for understanding a significant, complex, and coupled social and environmental problem. More specifically, how individual and neighbourhood characteristics influence health outcomes in relation to heat waves. This project highlighted some of the challenges with environmental exposure and health work, and indeed many of the data linkage challenges were not straightforward.

The project's core datasets were developed using two data linkage approaches, and each had advantages and disadvantages. Person-level linked data extracted from the MADIP data asset[62] by the ABS and analysed in the secure DataLab environment[63] had the advantage of providing high granularity data. This was essential for the modelling of person level influences on the basic heatwave-mortality/morbidity relationships. EHF data were brought into DataLab and linked to the MADIP extract via the SA2 geography.

Statistical Area 2 represents the finest scale available in the dataset and this places limitations on the ability to link environmental datasets. In the case of EHF this was not of concern as it is a synoptic dataset likely to have similar values over relatively large areas. However, the SA2 limitation was also important when other social and environmental data (e.g., vegetation fraction) was included. Thus, these data are characterised as representing the neighbourhoods (area) where people live (person level data). Finally, the SA2 geography meant RR was modelled at the SA2 level. Overall, it was not ideal to have to use data aggregated to an arbitrary analysis scale.

The analysis outside of DataLab, including the RR mapping and HVI, also focused on the neighbourhood (SA2) scale. In this case the SA2s were used as a geography to link over 50 social, health and environmental datasets. This type of area linkage is very common in geospatial analysis and involves aggregation (e.g., gridded land surface temperature, point health service locations) or disaggregation (e.g., from SA3s), depending on the native resolution of the data. As mentioned above, the neighbourhood geography matches the RR maps from the health modelling. Recent research on health and the urban environment demonstrates the importance of highly granular data and spatially matching health outcomes and drivers [Hanigan et al. 2017].

However, a key recommendation from the analysis is that investment in developing coupled social and environmental data assets, akin to MADIP[62], may open up new opportunities for environmental health and warnings related research (e.g., heatwaves, coldwaves, bushfires and smoke**).**

Finally, the somewhat loose coupling of person and neighbourhood level datasets may make it difficult to identify the best scales for potential interventions. That said, the analysis found that many of the individual level risk factors also occur at the neighbourhood scale. Therefore, this suggests the coarser area level results can reflect individual risk. Moreover, the analysis shows that HVI is significantly related to heat-health outcomes and may also be used to develop and target interventions.

4.5 Extending Heat Vulnerability Index with the Location Index

The heat vulnerability indices (HVI) and mapping approaches described above involved the development of composite themes and indices from a set of individual indicators (Table 3) related to heat-health. The datasets and indices were derived for the SA2 level geography, and approximate neighbourhoods in urban areas. This geography was selected to match the scale of data that can be extracted from MADIP and other health datasets as the “safe measure” for health data are SA2s. After testing different approaches (e.g., single variables, Principal Components Analysis), it was decided to focus on the transparent ranking approach used by the

CDC and others. All these approaches have strengths and weaknesses, so there is scope to revisit HVI approaches with new data and techniques (e.g., Digital Twins, Spatial Data Science).

One such approach is the Location Index (Loc-I) framework developed by GA, CSIRO, ABS and DAWE through DIPA support. The Loc-I is a new technology that provides methods for linking data based on location, enabling users to access and query information on the relationships between spatial features without relying on traditional and sometimes complex geography information systems (GIS) operations. The Loc-I team has implemented and tested two methods of data integration: Discrete Global Grid System (DGGS) and Linksets (pre-calculated relationships between dataset objects based on topology rules). Additional information about Loc-I is available online at www.ga.gov.au/locationindex.

A proof-of-concept was developed as part of the RILLH project to assess the utility of the Loc-I framework for extending the HVI component of the project using the datasets described in Section 2.3. The DGGS is the most appropriate Loc-I method of linking socio-economic, environmental, heatwave exposure (EHF) data with the vulnerability indices. Given the scope and short duration of the RILLH project, Linksets were not developed or tested, and this is an area for future work.

Specifically, the DGGS was used to link census, public open space, cool places, EHF, and LST data described above (Table 3). These datasets were DGGS-enabled by assigning unique persistent DGGS cell identifiers to each data record. Next, the data were ready for an automatic linking with other DGGS enabled datasets available through the 'crosswalk tables' developed by GA. As a result, these datasets could be analysed by performing simple dataset querying, and the following scenarios were considered:

- Which Local Government Areas have extreme Excess Heat Factor (EHF) values on a specific heatwave event day?
- What is the percentage of public open space within an SA2 area, as an indicator of the adaptive capacity of neighbourhoods to heatwaves?
- What are the values of the Sensitivity Index for each suburb in a heatwave affected area?
- What are the EHF values in bushfire affected areas by DGGS cells?

Finally, the different approaches to HVI development and analysis were compared, and the following areas identified for improvement using the DGGS approach to address future work:

- Reduce manual data manipulation and GIS processing time for: indicator variables, (including extraction from repositories), data cleaning (error assessment and quality assurance), standardisation and ranking, and incorporation into GIS and statistical software for analysis

- Reduce the time it takes to interrogate relationships between the contributing factors and the higher-level indices
- Potential improvements for updating datasets. Many of the datasets used in HVIs are updated infrequently (e.g., census data), but this may change with greater data availability following recommendations from recent extreme events (e.g. bushfires, heatwaves)
- Interrogate the relationships between the contributing factors and the HVI values directly
- Greater capability for index values to be analysed at different geographic scales. This is an important point as the geographies data that are available may not match the scale of the phenomena. This well-known problem is called the Modifiable Areal Unit Problem (MAUP) or more simply explained as 'aggregation errors'.
- Link and query other environmental information related to the HVI in a timely and efficient manner, e.g., droughts, bushfire scars, flood boundaries.

The RILLH project provided a unique opportunity to compare the Loc-I framework with other, commonly used approaches to heat vulnerability mapping. The approach may be of utility for managing and analysing spatial data applied to heatwave impact forecasting and some aspects of planning heat-health interventions.

4.6 Heatwave warnings and impact forecasting

Heatwave impacts on illness and deaths are largely preventable.[3 4] While heatwave warning systems and interventions addressing the public health risks have been developed by most jurisdictions,[12] there is currently no consistent approach across Australia. States and territories have different portfolio responsibilities for heatwave management and warnings and additionally have their own heatwave metrics, plans, warnings thresholds, terminology, and processes.

From consultation activities throughout this project, it is clear heatwave service users and decision makers want to make more informed decisions about heat-health risk. This requires information on 'where', 'when' and 'who' may be impacted as well as trusted recommended actions. This project's analysis identified who is most at risk for heatwave-related morbidity and mortality, and the contributing community characteristics and built environment. These core insights provide for targeted interventions and heatwave-health warnings for vulnerable groups.

For example, the Bureau of Meteorology has operated a standard forecast (SF) service for heatwaves since 2014 and has recognised the need for a national impact warning service for heatwaves.[78] The SF service needs to be combined with locally relevant action statements in order to create impact heatwave services, consistent with international best practice.[79] There is also recognition that Health and Emergency Services partners (State, territory and

Commonwealth) are key stakeholders in the creation and dissemination of impact warnings, and also in the development of targeted actions for the benefit of better heat-health outcomes.

In 2019, the National Heatwave Warning Framework Working Group (co-chaired by the Bureau and Emergency Management Australia) was established to develop a national framework for consistent heatwave information and warnings. As this progresses, there are opportunities for the RILLH project to inform warning and messaging efforts. As an example, the 2020 COVID-19 outbreak in Melbourne illustrated that certain neighbourhoods were not getting adequate or timely information about the pandemic and what they needed to do to reduce risk to themselves and others. Some of the COVID-19 hotspots are also areas at high risk for health problems during heatwaves, so messaging and outreach during the summer may be required for vulnerable communities, with lessons from the pandemic included in planning and preparation.

There are a range of other intervention strategies that can be informed by this project. For example, registries for vulnerable populations could be expanded. The Australian Red Cross provides the Telecross Redi service in South Australia which reaches out during heatwaves to check the heat-health and wellbeing of vulnerable groups. Opt-in notifications via text messaging or smartphone apps are commonly used by emergency services to warn of fire risk; for example, the University of Melbourne’s pollen and thunderstorm asthma app can provide timely warnings of dangerous conditions. Taking a broader and long-term perspective, this project's analysis of risk and adaptive capacity suggest that targeted social policy and investment in building retrofits, air conditioning and urban greening would have substantial health and long term benefits.

Conclusion

Heatwaves as extreme weather events cause more deaths and hospital admissions than any other hazard in Australia. Heatwaves also cause significant economic impact through disruptions to infrastructure and business. As climate change intensifies, the need to better warn, prepare, and mitigate the impacts of heatwaves becomes more pressing. As heatwave impacts vary between populations and locations, empirical evidence concerning vulnerable places and people at a local level, is critical for targeted and effective policy, planning, and interventions, especially in a warming climate.

The results of this study show that mortality and morbidity increase during heatwaves in Australia, but notably, the magnitude of the increase varies by location and widely within a location as well. The analysis found that some population subgroups and locations were disproportionately affected, highlighting the need for considering the specific context of an area and individual risk factors when designing prevention and adaptation strategies. It also demonstrates the need for place-based interventions and highlights the imperative for targeted and tailored warning messages during events. Importantly, the results from this project provide valuable, data-driven socially and geographically contextual evidence for ways to address heatwave impacts. It also illustrates the issue of heat-heath adaptation disparity for Australian communities and the challenges of identifying vulnerable communities.

By identifying which Australians are most at risk from heatwave and exploring what can be learnt from large datasets about the key vulnerabilities to affect Australians during heatwaves, this project has laid the groundwork for improving warnings, emergency response and health services for heatwaves.

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Appendix

Table A-1: Datasets used in this project

Dataset	Measure	Year	Geography *(converted to)*	Data custodian
	Multi-Agency Data Integration Project - Longitudinal (MADIP)			
Causes of death	**Outcome:** Mortality	2007-2017	SA2 2016	ABS
Census of Housing and Population	**Vulnerability**: Demographic and socio-economic factors	2011	SA2 2016	ABS
Medicare Benefits Schedule	**Outcome:** Morbidity- GP attendances **Vulnerability:** Health factors: pre-existing conditions	2011-2016	SA2 2016	EOH
Pharmaceutical Benefits Scheme	**Vulnerability:** Health factors: prescriptions	2011-2016	SA2 2016	DOH
	External datasets (outside MADIP)			
National Non-admitted Patient Emergency Department Care Database	**Outcome:** Morbidity	2013-2018	SA2 2016	DOH
Health services	**Vulnerability:** Health service locations		Point data (SA2 2016)	NHSD
Ambulance callouts	**Outcome:** Morbidity	2007-2014	POA *(SA2 2016)*	SA Ambulance
NEXIS	**Vulnerability:** Built-infrastructure environment and urban landscape	2018	SA1 2016 *(SA2 2016)*	GA
Digital Earth Australia: Fractional cover and water bodies	**Vulnerability**: Built-infrastructure environment and urban landscape	2016	Raster *(SA2 2016)*	GA
Census of Housing and Population	**Vulnerability**: Demographic and socio-economic factors	2006-2016	CD 2006 *(SA2 2016)* SA2 2011 *(SA2 2016)* SA2 2016	ABS
National Health Survey	**Vulnerability**: Health Factors	2017-2018	SA2 2016	ABS
National Health Survey	**Vulnerability**: Health Factors	2011-2013	SA2 2011 *(SA2 2016)*	PHIDU
Land surface temperature	**Vulnerability**: Built-infrastructure environment and urban landscape	2015-2016	Raster *(SA2 2016)*	CSIRO
Excess Heat Factor (EHF)	**Vulnerability:** Built-infrastructure environment and urban landscape	2007-2018	Raster *(SA2 2016)*	BOM
Bureau of Meteorology Atmospheric high-resolution Regional Reanalysis for Australia (BARRA)	**Vulnerability:** Built-infrastructure environment and urban landscape	2007-2018	Raster *(SA2 2016)*	BOM