UNIVERSITY of TASMANIA

Understanding the human health impacts of extreme events in a changing climate using an environmental health translational research approach

by

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Acknowledgement of Country

The author wishes to acknowledge the traditional and original owners of the country on which this thesis was composed: the muwinina people of nipaluna/Hobart, and the Gubbi Gubbi people of the area now known as the Sunshine Coast, Queensland. The author pays her deep respects to Elders past and present, acknowledging those who have walked on and cared for this land for thousands of years, and the descendants who maintain their connection and traditions with this land.

Declaration of originality

This thesis contains no material which has been accepted for a degree or diploma by the University or any other institution, except by way of background information and duly acknowledged in the thesis, and to the best of my knowledge and belief no material previously published or written by another person except where due acknowledgement is made in the text of the thesis, nor does the thesis contain any material that infringes copyright.

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The research associated with this thesis has been approved by the University of Tasmania's Health and Medical Human Research Ethics Committee under ethics approval H0016638.

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Campbell, SL, Jones, PJ, Williamson, GJ, Wheeler, AJ, Lucani, C, Bowman, DMJS, Johnston, FH, 2020, 'Can digital technology help reduce smoke exposure and protect health in extreme air quality events?', World Public Health Congress, Virtual online, October 2020. (Also published as **Campbell, SL**, Jones, PJ, Wheeler, AJ, Lucani, C, Williamson, GJ, Bowman, DMJS & Johnston, FH 2020, 'Can digital technology help reduce smoke exposure and protect health in extreme air quality events?', *European Journal of Public Health*, vol. 30, no. Supplement_5, DOI:10.1093/eurpub/ckaa165.701).

Campbell, SL, Remenyi, TA, Williamson, GJ, Rollins, D, White, CJ, Johnston, FH, 2021, 'Ambulance dispatches and heatwaves in Tasmania: A case-crossover analysis', Australian Public Health Conference, Virtual online, 23-24 September 2021. **Finalist: Best research presentation in conference**

Poster presentations

Campbell, SL, Fox-Hughes, PD, Jones, PJ, Remenyi, TA, Chappell, K, White, CJ, Johnston, FH 2019, 'Epidemic Thunderstorm Asthma in Tasmania: Yes or no?', Thunderstorm asthma conference, Bureau of Meteorology, Melbourne, March 2018.

Campbell, SL, Remenyi, TA, Williamson, GJ, White, CJ, Johnston, FH, 'Applying local research: How do heatwaves impact the health system in Tasmania?, Australian Public Health Conference, Adelaide, September 2019. **Awarded: Best poster in conference**

Campbell, SL, Remenyi, TA, Williamson, GJ, White, CJ, Johnston, FH, 'Applying local research: How do heatwaves impact the health system in Tasmania?, Australasian College of Emergency Medicine Conference, Hobart, November 2019.

Additional papers co-authored during PhD candidature

Johnston, FH, Wheeler, AJ, Williamson, GJ, **Campbell, SL**, Jones, PJ, Koolhof, IS, Lucani, C, Cooling, NB and Bowman, DMJS, 2018, 'Using smartphone technology to reduce health impacts from atmospheric environmental hazards', *Environmental Research Letters*, vol. 13, no. 4, pp. 1-11.

Marfori, MT, **Campbell, SL**, Garvey, K, McKeown, S, Veitch, M, Wheeler, AJ, Borchers-Arriagada, N and Johnston, FH, 2020, 'Public health messaging during extreme smoke events: are we hitting the mark?', *Frontiers in Public Health*, 8 Article 465.

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Workman, A, Jones, PJ, Wheeler, AW, **Campbell, SL**, Williamson, GJ, Lucani, C, Bowman, DMJS, Cooling, N, Johnston, FH, 2021, 'Environmental hazards and behaviour change: User perspectives on the usability and effectiveness of the AirRater smartphone app', *International Journal of Environmental Research and Public Health*, vol. 18, no. 7.

Jones, PJ, Koolhof, IS, Wheeler, AJ, Williamson, GJ, Lucani, C, **Campbell, SL**, Bowman, DMJS, Cooling, N, Gasparrini, A, Johnston, FH, 2021, 'Non-linear associations between pollen and respiratory symptoms in Tasmania, Australia: a novel case time series approach using the AirRater smartphone app', *Environmental Health Perspectives*, vol. 200, no. 111484.

Weeramanthri, TS, Quilty, S, **Campbell, SL**, 2021, 'Climate, extreme heat and human health: risks and lessons for Australia', *Medical Journal of Australia,* vol. 2015, no. 9, pp. 393-395.

Awards during candidature

Best poster in conference

Campbell, SL, Remenyi, TA, Williamson, GJ, White, CJ, Johnston, FH, 'Applying local research: How do heatwaves impact the health system in Tasmania?, Australian Public Health Conference, Adelaide, September 2019.

University of Tasmania Research Impact Award

AirRater team, 2017.

University of Tasmania Vice-Chancellor Award

Award for Outstanding Contributions in Response to COVID-19 as a member of the College of Health and Medicine Pandemic Response Team, December 2020.

Additional related projects undertaken during PhD candidature

Tasmanian Climate Change and Health Roundtable, Hobart, April 2019

With funding from the Tasmanian Climate Change Office, I conceived, initiated and managed the first Tasmanian Climate Change and Health Roundtable, held in Hobart, Tasmania on 3 April 2019. Researchers in climate change and health from around Australia met with local Tasmanian clinicians, policymakers and researchers, with the aim of identifying and prioritising climate change and health polices and programs specific for Tasmania into the future. A final report for the event can be found at www.health.tas.gov.au/publichealth/climate_change

Contribution to the 'Curious Climate' initiative, July 2019

As part of the Curious Climate initiative, I participated in a radio interview on ABC Hobart, discussing the human health impacts of climate change: www.abc.net.au/radio/hobart/programs/mornings/curious-climate:-health-impacts/11338738

'Living with Fire' unit, Diploma of Sustainability, University of Tasmania

I developed the written material for two of the modules contained in this unit:

- Module 3, Chapter Four: What do we do after fire: Supporting community recovery
- Module 4, Chapter Five: Bushfire resilient communities – what are the ingredients?

This unit was launched in Semester 1, 2021.

Attendance at 'Diversity in Disaster' conference, April 2018, Melbourne, Victoria

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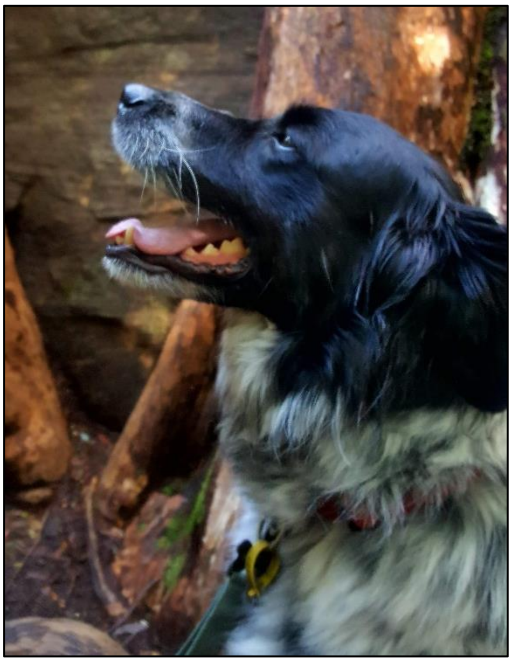

Abstract

Anthropogenic climate change is influencing healthcare outcomes, policy and service delivery around the world, from the direct impact of extreme events, to the consequences of water and food insecurity and the management of poor mental health arising from trauma and displacement associated with these events. Understanding how extreme events impact health outcomes allows the healthcare system to prepare for, manage and support an appropriate emergency response and recovery effort when these events occur.

This thesis uses an existing environmental health translational research framework (Kaufman & Curl 2019) to contextualise a series of studies related to climate change and health. The five stages of this framework: i) discovery; ii) health implications; iii) policy implications; iv) policy and practice implementation and v) outcome evaluation, are applied to the studies. Each study relates to climate-related extreme events, such as heatwaves, severe storms, and bushfires across international, national and local settings, all with direct relevance to the state of Tasmania, Australia. This thesis uses a mix of methods, including a literature review, a descriptive survey, and quantitative epidemiological analyses of health services utilisation data using case-crossover and case-control study designs. Datasets from a number of existing sources were integrated, including meteorological (temperature, wind and lightning strike), air quality (particulate matter and pollen), and health outcomes (hospital emergency department presentations and ambulance dispatches), as well as online data collection and surveys to generate and analyse unique datasets.

Through a literature review (Chapter 2), I found that research on heatwaves and human health is not evenly distributed across the globe, but concentrated on those regions with the greatest capacity to respond to and recover from these types of events. I found that regions at greatest risk of adverse human health outcomes, due to the likelihood of non-survivable temperatures in the near future and/or high rates of poverty and disadvantage, are substantially underrepresented in the research. This process enabled the identification of research gaps, thereby supporting the

progression of research in subsequent chapters, and fitting to Stage 1 (the discovery stage) of the identified research translation framework.

In Chapters 3 and 4, I used a case-crossover study design to evaluate the association between heatwaves and hospital emergency department presentations (Chapter 3) and heatwaves and ambulance dispatches (Chapter 4) in the temperate island state of Tasmania, Australia. I found that severe and extreme heatwave events were associated with a 5% increase in emergency department presentations (OR 1.05, 95% CI 1.01-1.09) across the whole population, with a 13% increase for children 15 years and under (OR 1.13, 95% CI 1.03-1.24), and a 19% increase for children 5 years and under (OR 1.19, 95% CI 1.04-1.36). My results for ambulance dispatch data were similar. I found that severe heatwaves were associated with a 10% increase in ambulance dispatches overall (OR 1.10, 95% CI 1.05-1.15), and extreme heatwaves were associated with an increase of 34% (OR 1.34, 95% CI 1.18-1.52). In both studies I found an increased magnitude of association between heatwaves and health service use in younger and older age groups, and for ambulance dispatches, an increase in utilisation for areas of greater socio-economic disadvantage. These findings critically inform public health responses and health promotion efforts. Both chapters are placed in Stages 2 and 3 of the framework, where the health implications and policy and practice implications are identified.

In Chapter 5, I analysed 14.5 years of meteorological and asthma emergency department data and found no documented instance of an epidemic of asthma coinciding with thunderstorm activity, despite recurrent serious and life-threatening epidemic thunderstorm asthma events repeatedly experienced in mainland Australia over a similar time period. I concluded that that the risk of epidemic thunderstorm asthma events in Tasmania is minimal, due to its island biogeography and climate leading to different seasonal patterns of thunderstorms unlikely to coincide with peak pollen seasons. This risk assessment informs the policy and practice implementation of asthma management in Tasmania, thereby providing a robust example of Stage 4 of the Kaufman and Curl framework.

In Chapter 6, I distributed an online survey to users of the AirRater smartphone app and asked about their experience of the Australian 2019-20 bushfire season.

Respondents documented a wide range of self-reported symptoms attributed to smoke exposure with one-third of respondents visiting a medical professional for assistance with health issues associated with smoke exposure. Furthermore, the responses informed how digital technology is used in extreme and prolonged smoke events. These findings helped to inform policy and practice in a third climate-related extreme event, thereby supplying a second example of Stage 4 in the research translation framework.

These findings have broad policy implications, with a clear research to policy translation pathway. Within Tasmania, these findings can be used to target public health campaigns to reduce heat illness during periods of extreme heat, while also enabling emergency responders such as paramedics and emergency physicians to understand and manage surge capacity during these events. Public health policymakers in Tasmania can also use this research to realistically manage the threat of a local thunderstorm asthma event. More broadly, public health policymakers seeking to understand the impact of adverse air quality on human health have been provided with an insight into the needs and concerns of those experiencing prolonged and extreme poor air quality events. The inclusion of a research translational framework, and placing these studies into the framework, describes the range of outcomes translational research can provide.

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Abbreviations

ACE CRC	Antarctic Climate and Ecosystems Cooperative Research Centre
ACEM	Australasian College for Emergency Medicine
ACT	Australian Capital Territory
AMA	Australian Medical Association
AQICN	Air Quality Index Collaborative Network
AWS	Automatic weather station
BARRA	Bureau of Meteorology Atmospheric high-resolution Regional Reanalysis for Australia
BLANkET	Base Line Air Network of EPA Tasmania
BoM	Bureau of Meteorology
CI	Confidence interval
CINAHL	Cumulative Index to Nursing and Allied Health Literature
COPD	Chronic obstructive pulmonary disease
CSIRO	Commonwealth Scientific and Industrial Research Organisation
ED	Emergency department
EHF	Excess heat factor
EMS	Emergency medical services
EPA	Environmental Protection Authority
ETA	Epidemic thunderstorm asthma
GP	General practitioner
GPATS	Global Position and Tracking System
HEPA	High-efficiency particulate air
ICD	International Classification of Disease
IPCC	Intergovernmental Panel on Climate Change
IQR	Interquartile range
LGH	Launceston General Hospital
MCH	Mersey Community Hospital
NERAG	National Emergency Risk Assessment Guidelines
NHMRC	National Health and Medical Research Council

NSW	New South Wales
NWRH	North West Regional Hospital
OR	Odds ratio
$PM_{2.5}$	Particulate matter with a diameter <2.5μm
QLD	Queensland
RHH	Royal Hobart Hospital
SA2	Statistical Area 2 (Australian Bureau of Statistics)
SD	Standard deviation
SEIFA	Socio-Economic Index for Areas
THS	Tasmanian Health Service
TSNDRA	Tasmanian State Natural Disaster Risk Assessment
UHI	Urban heat island
UTC	Coordinated Universal Time
UV	Ultra-violet
VIC	Victoria
WHO	World Health Organization

Chapter 1:
Introduction

1.1 Extreme events

Extreme events are natural weather, environmental or geophysical events that have the potential to cause disruption to the normal function of a specific community or the broader society, leading to “widespread adverse human, material, economic, or environmental effects that require immediate emergency response to satisfy critical human needs” (IPCC 2012, p.3). Weather-related extreme events, which include heatwaves, bushfires, severe storms, floods, droughts and cyclones, have severe human health and ecological impacts, and occur worldwide across varied climatic, geographic and socio-economic domains. They are, by definition, rare events, occurring at or close to the limit of the range of historical records. In this thesis, the term ‘extreme events’ is used throughout to refer to the weather-driven events of heatwaves, bushfires and severe storms.

These events and their impacts are examined through the lens of a translational research framework, from scoping the international literature to applied projects directly relevant to public health and health service delivery in Tasmania. This approach is critical as we enter a period of rapid climate change, where extreme events and their population-wide impacts need to be swiftly understood by policy makers, in order to deliver relevant, evidence-based and localised adaptation strategies.

1.2 Climate change

A large body of evidence has demonstrated a rapid rise in the average global air temperature occurring from the 1950s onwards, and this is likely to continue and accelerate into the future (CSIRO and Bureau of Meteorology 2015; IPCC 2013; UK Met Office 2020). The main cause of this rise is the corresponding increase in atmospheric greenhouse gasses, predominantly composed of carbon dioxide, with lesser concentrations of methane, nitrous oxide, ozone and fluorinated gases such as hydrofluorocarbons (Department of Agriculture Water and the Environment 2020; US Environmental Protection Agency 2020). Human activities are the major source of these emissions, primarily through the burning of fossil fuels, land clearing and industrial and agricultural outputs (Department of Agriculture Water and the

Environment 2020). This warming trend is generally known as 'climate change', 'global warming' or 'global heating', and has impacts on vast and multiple aspects of the earth's ecological and biological systems and processes. In this thesis, the term 'climate change' is used throughout, with a concentration on how these changing climate patterns determine and create the types of extreme weather events described above.

While there are regional patterns of difference in the projection of these events, they are broadly expected to increase in frequency, severity and intensity in a changing climate, with consequential adverse pressures on human and ecosystem health. Specifically, Australia is expected to see a rise in the number and length of heatwaves, bushfires and severe storms (CSIRO 2020; IPCC 2013), as experienced in the catastrophic and extended bushfire and extreme heat events over the 2019-20 summer season across much of southeast Australia.

1.3 The link between climate change and human health

In 2009, *The Lancet* described climate change as "the biggest global health threat of the 21st Century", putting the "lives of billions of people at increased risk" (Costello et al. 2009, p. 1693) – highlighting the overwhelmingly negative human health outcomes of a warming climate. Furthermore, climate change acts as a threat multiplier by exacerbating existing health and social issues, with the burden of illness borne by those with the most disadvantage. These are populations with the poorest health infrastructure and the least ability to adapt, prepare and respond, with this gradient operating both across and within countries and communities (World Health Organization 2017).

Framing climate change as a health issue (rather than an environmental or ecological issue) allows greater understanding and engagement with climate change action, by increasing personal investment and relevance. This potentially moves individuals across the spectrum from climate denial to climate activism (Maibach et al. 2010). A number of prominent health bodies both in Australia and internationally, including the Australian Medical Association (AMA) and the Australasian College for Emergency

Medicine (ACEM) have recognised the importance of this framing, declaring climate change a 'health emergency' (ACEM 2019; AMA 2019).

Multiple areas of human health impacts from climate change have been identified (see Figure 1.1). These include both the direct and indirect effects from extreme events (Watts et al. 2015; World Health Organization 2012).

Direct effects include:

- death as result of exposure to heatwaves, bushfires, cyclones, floods and severe storms
- illness or injury arising from exposure to these events (including, but not limited to, heat stroke, burns, fractures and lacerations).

Indirect effects include:

- emerging environmental challenges (for example, increased pollen, increased air pollution, increased ozone and ultra-violet (UV) radiation) leading to various chronic medical conditions (for example, cardiovascular, respiratory and diabetic conditions)
- rising rates of infections (for example, malaria, diarrhoea, meningitis and dengue fever) due to the increased spread of vectors such as ticks and mosquitoes
- challenges to mental health as a result of displacement, trauma and migration
- water and food insecurity due to the impact of extreme events and ocean acidification, resulting in reduced aquacultural and agricultural productivity
- changes to the price and quality of fresh food as a result of extreme events, leading to poor nutrition, especially for those living with the greatest disadvantage
- loss of biodiversity, leading to increases in pests and potential ecosystem collapse
- other social factors, including decreased work capacity and increased levels of migration, violent conflict and homelessness.

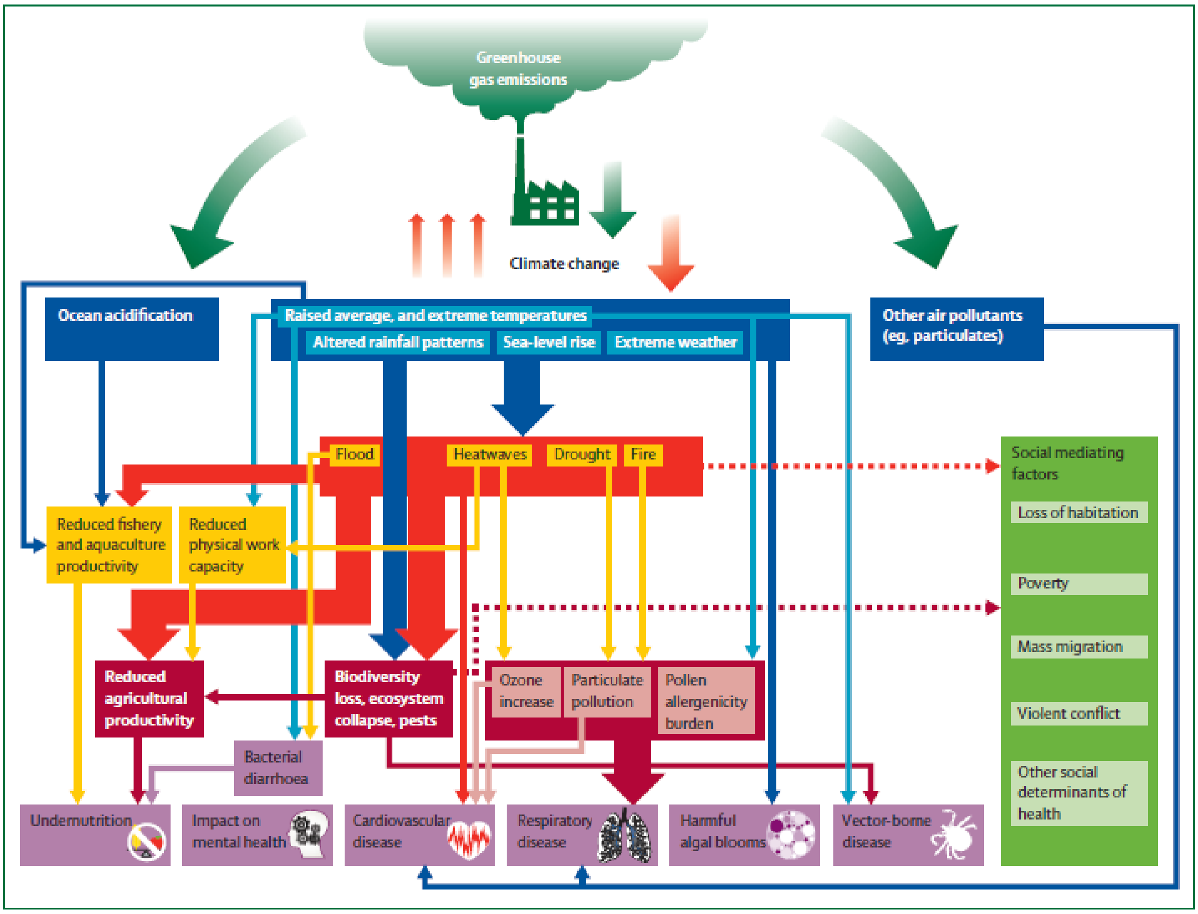


Figure 1.1: An overview of the links between greenhouse gas emissions, climate change and health (Watts et al. 2015)

1.4 Contextualising the research problem

There is a large and growing body of research already underway exploring the myriad of interconnected direct and indirect effects of climate change and their impact on human health. This complex field has multiple and diverse research areas, highly relevant both now and into the future. For example, research to investigate and analyse the mental health impacts of a changing climate; to develop effective adaptation models; to appreciate community perception of risk and to improve vulnerability mapping at local levels are all valid and appropriate. Recent and more severe or intense extreme events (for example, the south-east Australian Black Summer bushfires of 2019-20) also give rise to novel avenues of research, which ideally, are investigated as soon as practical during or after the event.

Central to all research efforts in this space is the ability to translate findings into health system policy, in order to pursue adaptative actions both across governments and for individuals or communities. Research translation, defined as "the process whereby research findings are translated into practice, policy, or further research to drive real-world change and outcomes" (Papageorgiou A, McLaren T & Schoep T 2021, p. vi) is fundamental to improving health outcomes (Woolf 2008).

In this context, this thesis contains a series of translational research examples, where the central theme across the various studies is applied research outputs – providing evidence to inform policy decisions which ultimately result in improved care models, targeted health promotion campaigns, and a reduction in preventable heath care episodes. Specific issues in climate change and health have been selected based on both recognised knowledge gaps, and as a rapid response to understanding recent extreme events which have significant policy implications. Importantly, using a translational research lens prioritises rapid responsiveness to emerging threats, gaining new and timely information for action and adaptation, thereby generating a 'sooner rather than later' ethos of producing research results (Maienschein et al. 2008).

1.5 Presenting an environmental health translational research framework

To assist in contextualising the broad field of translational health research into the more specific boundaries of environmental health research, an environmental health translational research framework was used (Kaufman & Curl 2019). This framework was developed to assist environmental health researchers to structure research questions into a translational research paradigm.

The framework developed by Kaufman & Curl has five distinct stages, as shown in Figure 1.2.

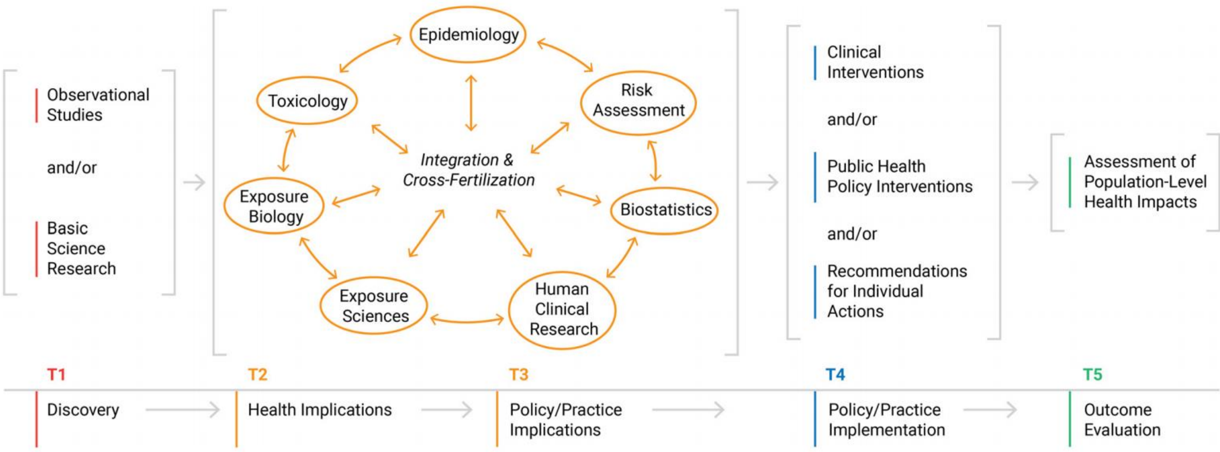


Figure 1.2: A proposed framework for translational research in the context of environmental health sciences (Kaufman & Curl 2019)

Stage 1 (T1), which the authors define as 'Discovery', refers to the fundamental epidemiological or clinical observation studies undertaken when a problem is first uncovered or suspected. This basic science level is common across all translational research paradigms, including clinical health. These types of studies assist in defining the scope problem, and assist in determining research gaps. In a clinical setting, these studies may include fields such as molecular biology, for example, establishing the biological plausibility of the chain of events between smoking and lung cancer.

For environmental health, the discovery stage may involve studies determining the cause of population-wide illness (or indeed cases of population-wide wellness) when compared to other populations. Broad examples may include the role of fluoride in preventing dental caries, the link between asbestos and respiratory disease, or behavioural differences in children exposed to lead (Merewether ERA & Price CW 1930; National Institute of Dental and Craniofacial Research 2018; Needleman & Landrigan 1981). This stage may also involve bringing multiple or collaborative research streams together to highlight and define a new problem.

Stages 2 and 3 (T2 and T3) are defined by Kaufman and Curl as 'Health and Policy Implications'. These stages focus on establishing the practical implications for improving health outcomes and defining health policy based on research from Stage 1. Here, a multi-disciplinary and collaborative approach is emphasised as a key ingredient (labelled as 'integration and cross-fertilisation' in Figure 1.2), with each discipline informing the other leading to a motivation and advancement across the spectrum. From an environmental health angle, this stage could, for example, define an exposure-response relationship, and what this means for public health promotion or health protection policy in establishing reasonable and evidence-based interventions. Narrowing to the example of asbestos exposure mentioned above, ongoing studies established there is no safe level of asbestos exposure (World Health Organization 2014), which then informed prudent policy implementation (Stage 4).

Stage 4 (T4) is defined by Kaufman and Curl as moving beyond understanding and establishing the policy implications as defined in Stage 3, to implementing these into public health practice. As per Figure 1.2, this could potentially involve interventions within a population, or providing recommendations for individual actions. This stage also necessitates a collaborative and multi-disciplinary focus as the scope of stakeholder actions and understanding continues to widen, for example, community engagement or co-design of actions may be a feature. This stage is likely to involve communication and dissemination of messages.

As a further example dealing with asbestos, the establishment of the risks associated with low levels of asbestos toxicity after exposure, as described above, has led to a series of strong policy responses. These include a national ban on asbestos mining since 2003 and a highly regulated asbestos waste disposal industry (examples of population-wide interventions), and a number of public health awareness campaigns aimed at reducing public exposure to asbestos already in the environment (an example of recommendations for individual actions) (Commonwealth of Australia n.d.).

Finally, Stage 5 (T5) is described by Kaufman and Curl as the evaluation of population-level health impacts, or 'accountability research'. This is effectively evaluating the results of policy implementation efforts (or interventions) expended in Stage 4, with the potential to reconsider or refine those interventions. A specific challenge of this stage for public and/or environmental health policy is that the measures implemented are often preventive in nature, or at least have a preventive focus (for example, establishing an asbestos mining ban). In a suite of multiple implementation actions, it is also potentially difficult to attribute changes in health outcomes to a specific implementation action. Kaufman and Curl describe a potential solution to this challenge in comparing the current situation to a proposed possible situation without the intervention, again requiring a multi-disciplinary approach to research.

1.6 Using an environmental health research translation framework in practice

This thesis examines the human health impacts of climate-related extreme events, providing examples of direct translation to public health policy that support the protection of those most vulnerable to poor health outcomes. With reference to the framework outlined in Section 1.5 and Figure 1.2, each chapter presented in this thesis can be contextualised into the framework. By identifying a new problem through synthesis of existing knowledge (Chapter 2), analysing datasets to establish the magnitude and type of health impacts (Chapters 3 and 4), and identifying subsequent policy implications and performing a risk assessment (Chapters 5 and 6), this body of work demonstrates a translational research framework in practice.

Chapter 2 provides a greater understanding of the scope and application of heatwave and human health impact research, highlighting gaps in understanding and providing evidence for why this type of research is needed in targeted regions. This chapter acts as an example of Stage 1 (Discovery), where an analysis of the existing literature has clearly highlighted a new phenomenon: the disparity of research on heatwaves and human health in settings of social disadvantage, location and risk. As part of the Discovery stage as described in Kaufman and Curl, this analysis leads to insights that drive further research, such as that undertaken in Chapters 3 and 4.

Chapters 3 and 4 are presented as examples of Stages 2 and 3, where identifying health implications act to shape policy implications. Specifically, this research has direct relevance for the understanding of heatwaves in the Tasmanian setting, for both hospital emergency departments (Chapter 3) and ambulance services (Chapter 4). For example, this research shows that extreme heat events increase ambulance dispatches in Tasmania by 34% above normal, thereby providing clear metrics for ambulance services to implement surge capacity planning in these types of events. Furthermore, identification of specific higher-risk population groups, such as the elderly and young children, provide public health planners with well-defined target groups for harm prevention and health promotion communication and messaging.

Chapter 5 is presented as an example of Stage 4. This research has defined the risk of epidemic thunderstorm asthma (ETA) events in Tasmania (a necessary step in an evidenced-based response to the ETA event in nearby Melbourne in 2016) and therefore provided Tasmanian public health decision makers with the required evidence to implement an appropriate public health action. This is a good example of translational research that provided a timely response to an emerging threat, as discussed in Section 1.4. Prior to this research, the understanding of ETA events in Tasmania was very poor and limited to the understanding available in other jurisdictions where local meteorological factors influencing this hazard were vastly different.

Finally, Chapter 6 provides a further example of Stage 4, where policy and practice implementations are explored alongside recommendations for individual actions. Furthermore, in the capacity of understanding the impact of and responses to the emerging threat of prolonged and extreme smoke exposure, national health policymakers in the field of air quality now have a greater evidence base from which to understand the needs and expectations of those exposed, helping to inform ongoing programs and projects in this area and assess the role of digital technology during these events. For example this research can directly inform the response to Recommendation 14.1 of the Royal Commission into National Natural Disaster Arrangements, which recommends “nationally consistent air quality information, health advice and interventions” (Commonwealth of Australia 2020). Again, this research was conducted as a rapid response to a particular event occurring during candidature, which had direct relevance to public health in Tasmania, while aligning with the broad thesis aims. Taking ‘advantage’ of the research opportunity presented by this event has resulted in outcomes that informed a broad range of health policy makers nationally, as well as directly informing local Tasmanian policy.

Research of this nature has direct impact, relevance and significance for the community, by providing an evidence base for clear thresholds in emergency operations and response, and by allowing public health policymakers to develop realistic, localised and pragmatic plans concerning environmental hazards and health demand.

1.7 Aims of this thesis

This thesis was originally intended as a research portfolio examining heatwaves in Tasmania, with the aim to support public health policy in protecting those most vulnerable to poor health outcomes. However, significant extreme events (notably the epidemic thunderstorm asthma event in Melbourne in 2016, and the southeast Australian bushfires in summer 2019-20) occurring just prior to and during candidature, created an increased research focus and priority in these areas. Research into these events was therefore included to give a broader scale view of the health impacts of a changing climate, over and above extreme heat, and to inform policy and practice aligned with current events in a timely manner. Therefore, the context of highly responsive and translational research outcomes, supporting the preparedness and response of public health policy makers and decision makers, has substantially shaped the aims of this body of work. Incorporating a translational research framework across the body of research work has highlighted and contextualised the placement of each individual study.

The aims of this thesis are to:

- review the distribution of global literature on heatwaves and human health (Chapter 2)
- investigate the association between heatwaves and emergency hospital presentations in Tasmania, Australia, informing evidence-based planning, preparedness and response to these events in local hospital emergency departments (Chapter 3)
- investigate the association between heatwaves and ambulance dispatches in Tasmania, Australia, informing evidence-based planning, preparedness and response to these events in local ambulance services (Chapter 4)

- investigate the historic coincidence of thunderstorms, pollen and asthma in Tasmania, Australia, to better understand the local risk of ETA events in the region (Chapter 5)
- assess the usefulness of digital technology during periods of prolonged and extreme poor air quality as a result of bushfires (Chapter 6).

Chapter 2:
Heatwave and health impact research: A global review

2.1 Preface

This chapter provides a systematic literature review of the depth and breadth of international research on the human health impacts of heatwaves. The chapter presents information on the location of research, how this research has changed over time, how research location matches with the vulnerability of the affected population (by latitude, population wealth and population density), and the type of health outcome on which the research is focussed (mortality or morbidity).

The findings show that heatwave and human health research is limited in cooler climates, and in areas with greater socio-economic disadvantage (as measured by wealth). Furthermore, research in morbidity impacts is limited. Therefore, the findings contained in this chapter assist with placing the study location of subsequent chapters, specifically Chapters 3 and 4, into context. These findings also inform the health outcome type under analysis in Chapters 3 and 4 (hospital emergency presentations and ambulance dispatches).

This chapter acts as an example of Stage 1 of the Kaufman and Curl environmental health translational research framework (see Figure 2.1). This chapter contextualises the issue of heatwave and human health impact leading toward more local and in-depth research contained in future chapters. This study uses a literature review to make a series of 'discoveries' about the scope and depth of global heatwave and human health research, especially to identify gaps in research.

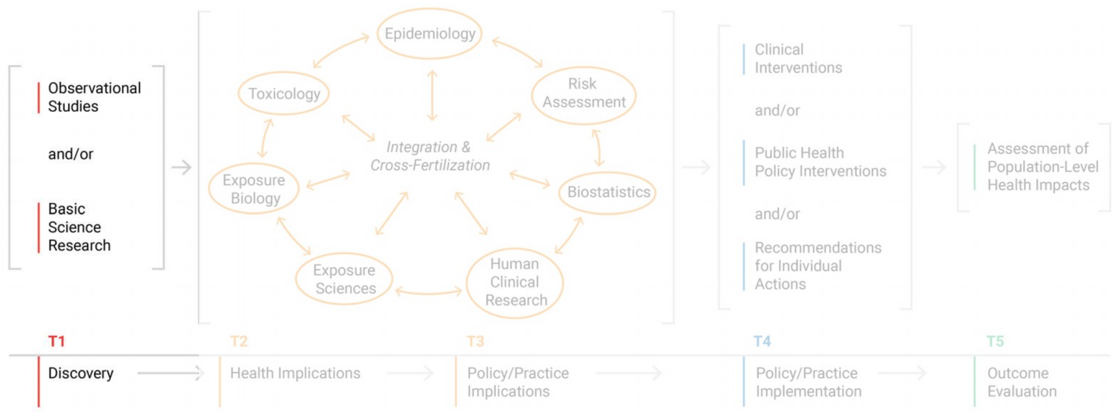


Figure 2.1: Kaufman and Curl (2019) environmental health translational research framework, Stage 1

This chapter has been reproduced as published in Campbell, S, Remenyi, TA, White, CJ, Johnston, FH 2018, 'Heatwave and health impact research: A global review', *Health and Place*, vol. 53, pp. 210-218.

2.2 Abstract

Observed increases in the frequency and intensity of heatwave events, together with the projected acceleration of these events worldwide, has led to a rapid expansion in research on the health impacts of extreme heat. To examine how research on heatwaves and their health-related impact is distributed globally, a systematic review was undertaken. Four online databases were searched for articles examining links between specific historical heatwave events and their impact on mortality or morbidity. The locations of these events were mapped at a global scale, and compared to other known characteristics that influence heat-related illness and death. When examining the location of heatwave and health impact research worldwide, studies were concentrated on mid-latitude, high-income countries of low- to medium-population density. Regions projected to experience the most extreme heatwaves in the future were not represented. Furthermore, the majority of studies examined mortality as a key indicator of population-wide impact, rather than the more sensitive indicator of morbidity. While global heatwave and health impact research is prolific in some regions, the global population most at risk of death and illness from extreme heat is under-represented. Heatwave and health impact research is needed in regions where this impact is expected to be most severe.

2.3 Introduction

Climate change has been described as "the biggest global health threat of the 21st Century", putting the "lives and wellbeing of billions of people at increased risk" (Costello et al. 2009, p. 1693). Furthermore, the projected effects of climate change have been described as representing "an unacceptably high and potentially catastrophic risk to human health" (Watts et al. 2015, p.1861). The World Health Organization (WHO) recognises the overall health impacts of a changing climate as overwhelmingly negative, with regions exhibiting the poorest health infrastructure being the least able to adapt, prepare and respond to the variety of increased health risks likely in a changing climate (World Health Organization 2017).

As a result of human-induced changes in climate, global mean surface air temperature shows a rising trend over the last 100 years (IPCC 2013). This has led to a worldwide increase in frequency, intensity and duration of extreme heat events or heatwaves (Perkins, Alexander & Nairn 2012) (noting these terms are used interchangeably in this paper). The Intergovernmental Panel on Climate Change 5th Assessment Report indicates an increase in frequency, length and intensity of heatwaves will be "very likely over most land areas" well into the future (IPCC 2013, p. 135).

It is widely accepted that increased exposure to heat has a detrimental effect on human health, resulting in increased mortality (death) and morbidity (illness) across a variety of geographical locations (Anderson & Bell 2011; Haines et al. 2006; Loughnan, Nicholls & Tapper 2010; Martiello & Giacchi 2010; Zeng et al. 2016). This effect has been demonstrated by a number of extreme heat events worldwide, including in Chicago, USA in 1995 (Whitman et al. 1997), the European-wide heatwave in 2003 (Kosatsky 2005) and in southeast Australia in 2009 (Nitschke et al. 2011b). Furthermore, a relationship between increasing temperature and increasing mortality and morbidity has been found across several global locations (Michelozzi et al. 2009; Stafoggia et al. 2006; Sugg, Konrad & Fuhrmann 2016; Sung et al. 2013), demonstrating that heat illness and death can occur irrespective of absolute temperature and outside a designated extreme event.

While all sectors of the population are at risk of illness and death when exposed to increased heat, and especially extreme heat, particular sub-groups are more vulnerable than others. However, relationships between temperature and health impacts are neither uniform nor predictable, influenced by a number of complex and interacting factors including biological, environmental, medical, social and geographical factors (Klinenberg 2002; Uejio et al. 2011; Yihan et al. 2013).

While the elderly appear more likely than other age groups to experience illness and death as a result of extreme heat events—as demonstrated in a number of locations around the world including Europe, Australia and China (Bai et al. 2014; Cerutti et al.

2006; Fouillet et al. 2006; Johnson et al. 2005; Schaffer et al. 2012a)—a small number of studies show no direct relationship between heat-related deaths or illness and age (Bustinza et al. 2013; Dalip et al. 2015), suggesting social factors may be of influence at a local level. Heat-related mortality also appears to be associated with a range of pre-existing chronic health conditions, including cardiovascular, cerebrovascular, respiratory, endocrine, genitourinary, nervous system conditions and mental health disorders (Fouillet et al. 2006; Haines et al. 2006), and at different rates in different global locations (Astrom et al. 2015; Yin & Wang 2017). Other identified sub-groups with increased vulnerability to heat-related illness include those working outdoors or in non-cooled environments (Hanna et al. 2011; Yin & Wang 2017) and those using particular medications (Beggs 2000). Furthermore, populations living in regions already experiencing hot weather may experience temperatures rated as non-survivable for humans in the future (Im, Pal & Eltahir 2017; Pal & Eltahir 2016), making their existing vulnerabilities more urgent to address.

Social determinants contribute substantially to an increased risk of heat-related mortality and morbidity. Those living in isolation, in low socio-economic situations, those who are homeless or living in unsafe communities, and those living in regions with low access to urban green space are also more vulnerable to the effects of heat (Bambrick et al. 2011; Klinenberg 2002; Loughnan et al. 2013). The urban heat island (UHI) effect—where temperatures increase in urban areas as a result of man-made structures and activities—may also increase the risk of illness and death for vulnerable residents in major cities (Tomlinson et al. 2011). The UHI effect has been shown to be associated with an increasing impact of heatwaves on populations, in both Europe (Laaidi et al. 2012; Ward et al. 2016) and China (Tan et al. 2010), and appears to be more likely in cities with a growing population, rather than cities with a stable population (Yee Yong et al. 2017). This poses a major risk to rapidly urbanising regions, especially for populations in developing countries experiencing multiple vulnerabilities.

The nature of systematic reviews examining the impact of heatwaves on mortality and morbidity varies considerably. Some reviews examine the impact of heatwaves on mortality (for example, Xu et al. (2016) and Hajat and Kosatky (2010)) or on morbidity (for example Li et al. (2015)) exclusively. A number of reviews examine the breadth and depth of heatwave and health research across specific populations (for example, Astrom et al. (2011) and Benmarhnia et al. (2015)); for specific medical conditions (for example, Bhaskaran et al. (2009), Phung et al. (2016) and Turner et al. (2012)); and for specific climates (for example, Burkart et al. (2014)).

A small number of studies examining extreme heat and human health impact consider geographical factors in the methodology. For example, Bao et al. (2016) examine cities in China across differing latitudes; Medina-Ramon & Schwartz (2007) examine how mortality differs in response to temperature across multiple US cities with different climates; and Na et al. (2013) examine the relationship between heat-related illness and temperature across cities in Korea differing in regionality and latitude. However, there are no studies examining heatwave and health impact research at a global scale, and how research concentration and spread differs when examined through a vulnerability lens. This review seeks to address this gap.

The aim of this study is to describe heatwave and health impact research at a global scale, using information gathered from previously published studies on this topic. This study does not include research characterising the broad relationship between air temperature and population health outcomes.

The objectives of this study are: (1) to examine the distribution of heatwave and health impact research globally, (2) to examine changes in the regional origin of heatwave and health impact publications over time, (3) to examine these publications in relation to different health outcomes (the use of mortality and/or morbidity outcomes), and (4) to determine if this body of research is meeting the needs of the global population at risk of poor health outcomes due to extreme heat, as defined by socio-economic status, population density, acclimatisation capability and physical vulnerability to heatwaves.

2.4 Methods

Four online databases (PubMed, Scopus, Web of Science and CINAHL) were searched for heatwave and health impact peer-reviewed English language articles published to May 2017. No start date was used in order to capture all historical publications. The following search terms were used in examining keywords, titles and abstracts: (‘extreme heat’ OR ‘heat wave*’ OR ‘heatwave*’) AND (‘mortality’ OR ‘morbidity’ OR ‘hospital*’ OR ‘ambulanc*’ OR ‘emergenc*’ OR ‘death’).

Articles were included which examined human mortality and/or morbidity rates (including ambulance dispatches and/or hospital admissions) with respect to specific heatwave events, and where the main objective of the study was to determine if a change in these indicators had occurred during the period of the heatwave. Studies examining both cold waves and heatwaves were included. Both whole population level studies and partial population level studies (for example, the elderly) were included. Furthermore, mortality and morbidity studies examining all-cause and cause-specific cases (for example, cardiovascular disease) were included. Some studies examined the effectiveness of different methodologies, for example, Kalkstein (1991), and while assessing the impact of heatwaves on a population was not the intent of the study, the aim of the study necessitated this. These types of studies were included in this review.

As stated earlier, studies examining ambient temperature (i.e. the influence of temperature gradients on health) were not included. Studies which examined other impacts on health were extremely rare, and included the impact of extreme heat on pre-term birth (Kent et al. 2014) and years of life lost (Huang et al. 2012). These were not included in this review. Studies evaluating interventions aimed at reducing the public health impact of heatwaves were not included.

For each of these included articles, the location or locations of the study were determined by examining the title, abstract or full text, and then recorded in a spreadsheet. Where multiple locations were studied in one article, all study locations were recorded. For two articles (Bobb et al. 2014; Wang et al. 2016), study locations were not specified, and therefore not included or recorded. For one article (Ma et al. 2015) only a partial list of locations were supplied, and these locations were included.

If the studied locations were regions (for example, counties, states or provinces), the largest two cities in those regions were recorded. Where research involved whole countries, the largest three cities in those countries were recorded as representative of the country. This approach enabled populations to be highlighted as the focus of the research, rather than geographical regions which may be large or dispersed.

Data on global wealth was sourced from Shorrocks et al. (2016), and data on global population density was sourced from the Center for International Earth Science Information Network (2016).

The articles included in the systematic review were examined in three ways. Firstly, the global distribution of study locations was mapped and tabled, including a publication date. Secondly, articles were scanned to assess which health outcome indicator was used. Finally, research locations were examined in relation to the needs of populations at risk of poor health outcomes from extreme heat events.

2.5 Results and discussion

2.5.1 Search criteria

Of 1752 papers initially retrieved, 188 were eligible for inclusion, after removal of duplicates and review of content against the inclusion criteria (see Figure 2.2).

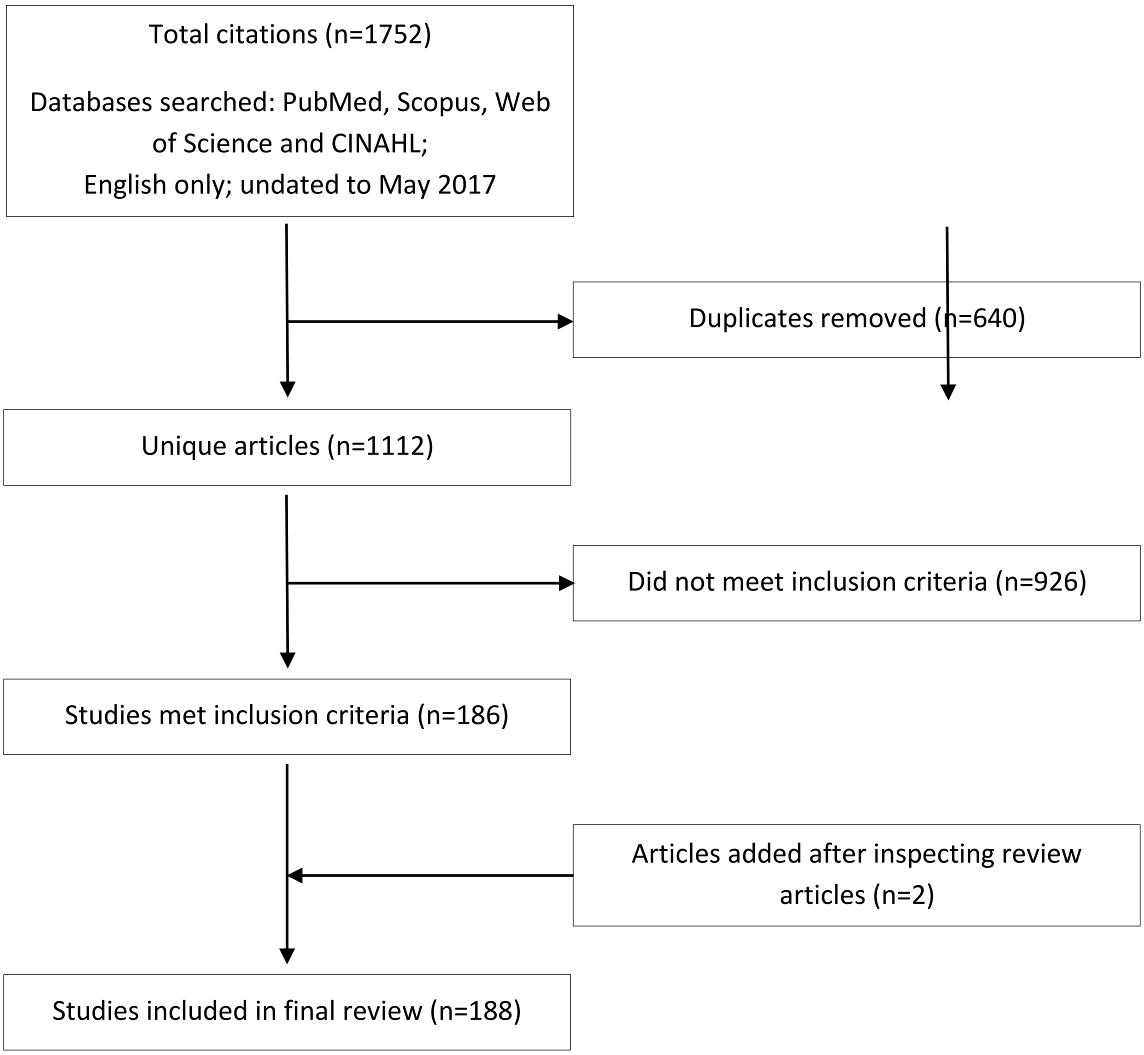


Figure 2.2: Flow diagram showing search strategy and results

2.5.2 Global distribution of study locations

From the 188 articles included in the review, 854 locations were identified where the health impact of heatwaves had been researched. This reduced to 292 unique values. (For a full list of included articles and their study locations, see Table A.1 in Appendix A: Supplementary data for Chapter 2.) These locations were then categorised into continents (see Table 2.1) and plotted on a world map (see Figure 2.3).

Table 2.1: Study locations by continent

Continent	No. of study sites	No. of unique locations
Africa	0	0
South America	1	1
Australia	34	5
Asia	91	53
Europe	144	64
North America	584	167
TOTAL	854	292

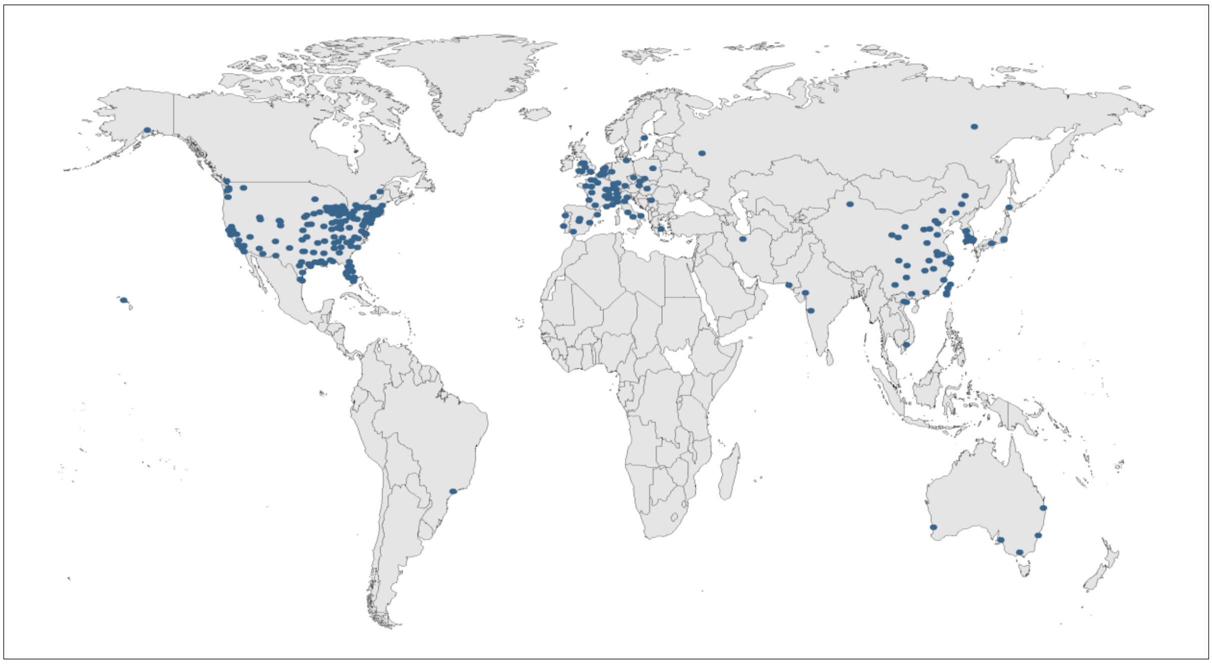


Figure 2.3: Locations of heatwave and health impact research, 1964-2017

A concentration of research effort was evident in the mid-latitude temperate zones of North America and southern Europe, followed by eastern China and southern Australia. Very few studies were found elsewhere, including tropical and high-altitude zones. Almost no studies covered South and Central America, northern Australia, central and south-east Asia, eastern and far northern Europe, Africa and the Middle East.

Studies varied widely in style and methodological approach, making broad comparisons between studies difficult and not included in the scope or objectives of this review. Despite heterogeneity between study locations and health outcome measured, studies found that heatwave events had a significant impact on ambulance and hospital load in varying geographical regions. For example, Turner et al. (2013) found a 18.8% increase in total ambulance calls during defined heatwave events in Brisbane, Australia, while Phung et al. (2017) found a 2.5% increase in all-cause admissions in Vietnam hospitals during heatwaves. Ghumman and Horney (2016) showed that residents of Karachi, Pakistan were 17 times more likely to die of a heat-related illness during a defined heatwave period when compared with a non-heatwave reference period, while Isaksen et al. (2016) found a 10% increase in the risk of death on a heatwave day versus a non-heatwave day, for all causes and ages in the Seattle region, USA. Some studies identified social risk factors impacted health outcomes during heatwave events. For example, Madrigano et al. (2015) demonstrated that heat-related deaths were more likely among poor black populations, especially those living in areas with relatively less green space. Vanhems, Gambotti & Fabry (2003) found those living in socially isolated conditions with limited access to health care and health information were most likely to be affected. Other studies highlighted the importance of this type of research in influencing government policy and procedures in the management of and response to heatwave events, for example, Wang et al. (2015) and Bustinza et al. (2013).

While it is evident that heatwave research is lacking in several regions across the world (for example, Africa and South America), this may be attributable in some part to the lack of research funding in these areas, a dearth of active researchers located within the study areas, and issues with data availability. For example, a lack of resources and infrastructure needed for adequate and robust data collection methods, enabling data of good quality to be available to researchers, may not be paramount in locations where general health infrastructure is poor. To address the paucity of research in areas of high heatwave and health impact risk, emphasis must be placed on developing access to reliable datasets.

While out of the scope of this paper, heatwave and health impact research may potentially constitute one case study of several highlighting research funding inequities between richer and poorer regions.

2.5.3 Publication date

The publication year of each article, along with the continent of study location, was recorded and charted. For this analysis only, studies from 2017 were eliminated to allow for complete years of analysis, leaving 177 publications (see Figure 2.4).

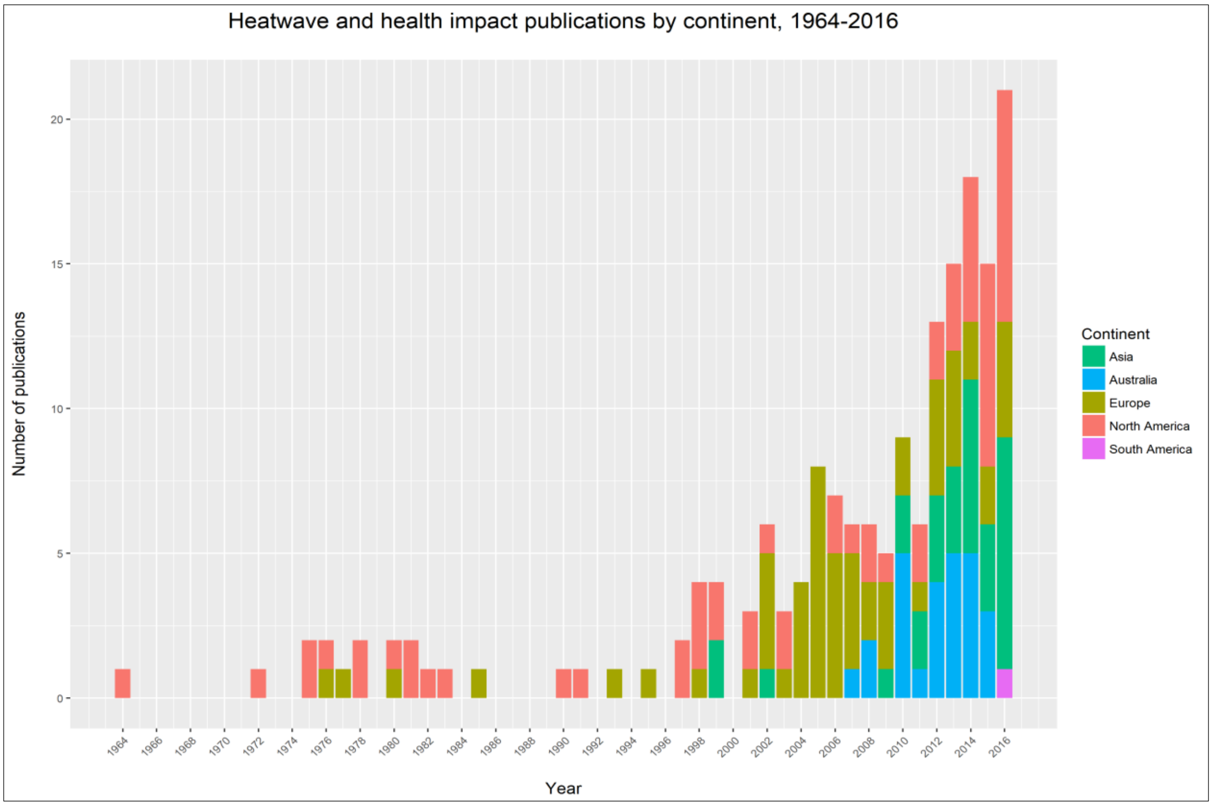


Figure 2.4: Number of published heatwave and health impact research articles per year, by continent (1964-2016)

The number of published studies per year demonstrates an overall increase from around 2002. Although relatively consistent from 2002 to 2011, there was a marked increase from 2012. The total number of studies published in the five years between 2012 and 2016 was 84, compared to 93 studies published in the previous 48 years combined.

Examining research publications by both date and region of origin uncovers two noteworthy points. Firstly, the marked increase in publications in 2005-2006 (when compared to previous years) was accounted for by studies examining the severe European heatwave in 2003. Similarly, the severe heatwave in southeast Australia in 2009 preceded a number of Australian studies published in 2010, accounting for a publication spike in this year. While small in number, these two examples may suggest that specific severe heatwave events increase the number of published studies in subsequent years. Examination of this trend in the future would be worthwhile, especially as the frequency and severity of heatwave events worldwide continues to rise (IPCC 2013).

Secondly, prior to 2002 studies concentrating on locations in North America (primarily the United States) were almost three times more common than those covering locations in Europe, and over ten times more common than those covering locations in Asia. In the period 2002 to 2011, the balance shifted to a greater proportion of studies located in Europe, now three times more likely than studies located in North America. Australian studies were first represented in this period also. Studies in Asia (primarily in China) became prominent after 2010, and by 2016 represented almost 40% of the worldwide studies for that year. The rapidly changing nature of heatwave and health impact research region of origin indicates that investigator capacity is growing and changing in response to a growing identified risk in more vulnerable regions. Taken together with the rise in research output after a specific heatwave event, these trends may suggest that researchers are strongly responsive to the demands and interests of policymakers and society in this particular field.

2.5.4 Evaluated health outcomes

Included articles represented both mortality and morbidity studies (hospital admissions and ambulance/emergency medical services (EMS) call outs), including those with a mix of these outcomes. Of the 188 articles, mortality studies were most highly represented at 61% (n=114), followed by hospital admission studies at 21% (n=40), mixed studies at 13% (n=24), and ambulance/EMS call out studies at 5% (n=10) (see Figure 2.5).

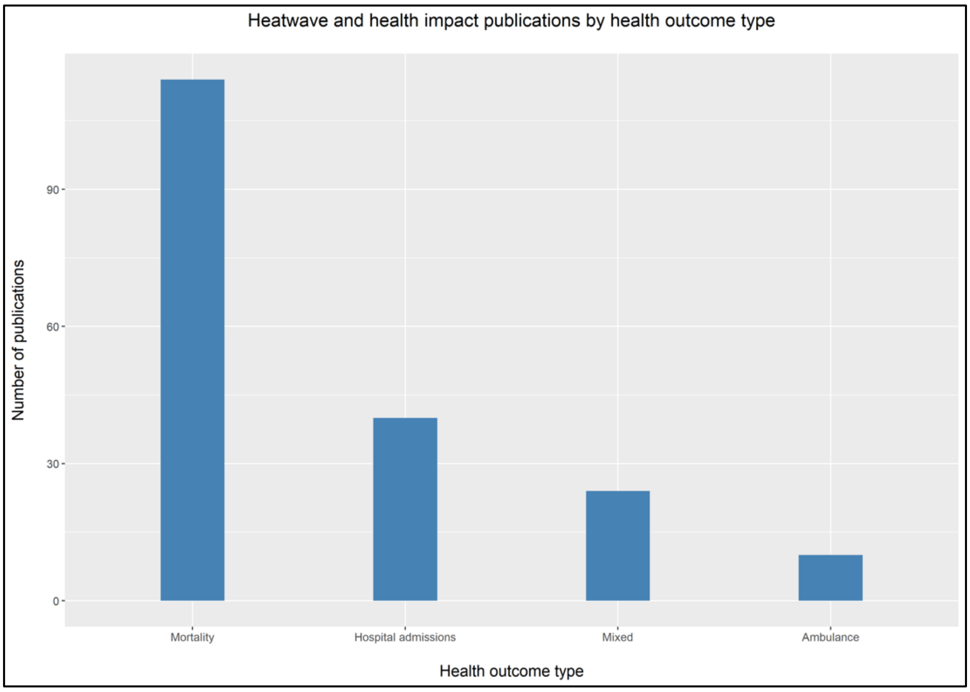


Figure 2.5: Heatwave and health impact publications by health outcome type

Mortality was assessed as the main outcome measure more than all other types combined. This may potentially be a practicality of the studies in question, as mortality data are usually available for large-scale population level studies. However, as an early sign of heatwave impact on a population, mortality is a blunt measure of population-wide heat impact (Chan et al. 2001), with morbidity a more subtle measure (Bi et al. 2011). A focus on mortality rather than morbidity as an indicator of heatwave impact tends to overshadow impacts that are less extreme than death, yet also significant to the narrative that explains extreme heat and health-related impact on a population. For example, research on how extreme heat impacts productivity or output for outdoor workers remains relatively unexplored, but has the potential to impact the economy (Hanna et al. 2011). These more nuanced but important measures of extreme heat impact remain a critical part of research, discussion and public policy concerning heatwaves.

The global distribution of research by health outcome type was generally consistent with the overall distribution, with no one region displaying a predominance of any particular health outcome study type.

2.5.5 Vulnerable populations

The distribution of heatwave and health impact research leads to a comparison with other types of global distribution mapping approaches, such as wealth distribution and population density. Comparisons can also be made across the spread of latitudes represented by heatwaves and health impact research.

By examining global wealth distribution alongside global heatwave and health impact research distribution, an understanding of how social constructs may influence research delivery is gained. Low-income regions, or regions experiencing high poverty, are less likely to have comprehensive data collection systems, inhibiting detection and evaluation of extreme events, and less capacity to adapt and respond to these threats when they do occur (Olsson et al. 2014). Poorer countries are less likely to have active researchers located within the country, and have less access to research funds. Furthermore, extreme climatic events, including heatwaves, tend to exacerbate existing poverty due to impacts on water resources, agriculture and livelihood (Olsson et al. 2014).

While still impacted by heatwaves as a result of geography and meteorological conditions, high-income countries tend to have access to resources and strategies to reduce this impact. These may include (but not be limited to) the implementation of alert and warning systems (Lowe, Ebi & Forsberg 2011), access to community-wide prevention strategies, for example, the provision of public cool spaces (Eisenman et al. 2016), and adequate medical care for those experiencing heat-related illness.

In mapping wealth distribution alongside the location of heatwave and health impact research across the globe, it can be seen that this research tends to be concentrated in high- to very high-income countries. With the exception of China, relatively few or no studies examine the impact of heatwaves in middle- to low-income regions (see Figure 2.6). This effect is consistent with expected social influences on research, and is not isolated to extreme heat research. A similar distribution noted by Schmitt, Graham & White (2016) in a review of the economic evaluations of health impacts in other weather-related extreme events.

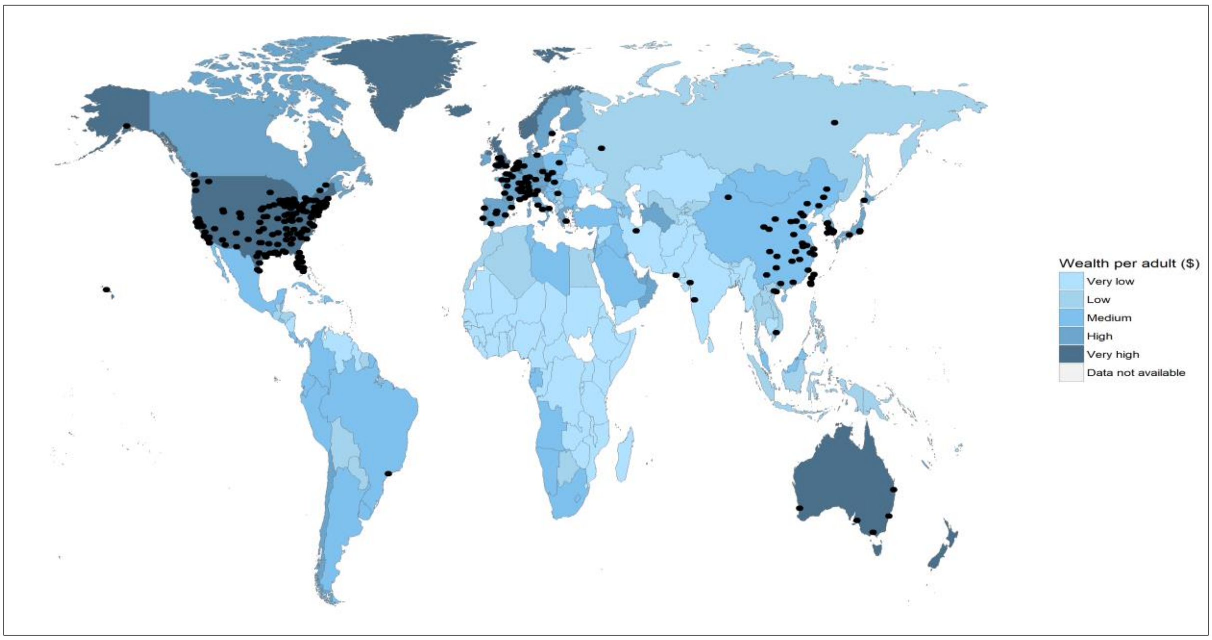


Figure 2.6: Global average wealth per adult 2016, adapted from Shorrocks et al. (2016), with locations of heatwaves and health impact research

China's research response to extreme heat events is notable as the only low- to middle-income country with a major research effort on heatwaves. Given the high number of people affected, overall climate change impacts in China are recognised as the greatest in absolute population terms, with significant social and health impacts as a result of melting glaciers, rising sea levels and an increase in natural disasters (Lai 2009). China's top-down approach to policy-making in the climate change sector (known as 'authoritarian environmentalism') has resulted in public mandates associated with energy efficiency and transport, with research to develop and direct these policy mandates considered key to the process (Gilley 2012).

Mapping population density alongside global heatwave and health impact research distribution allows further insight into how social influences shape research outcomes. While there is some concentration of heatwave and health impact research in areas of medium to high population density (for example, United States, southern Europe and eastern China), there is a paucity of research covering other highly population-dense regions. These include Central America, central Africa, eastern Europe, the Middle East, India, Bangladesh, Pakistan and south-east Asia, especially Indonesia (see Figure 2.7).

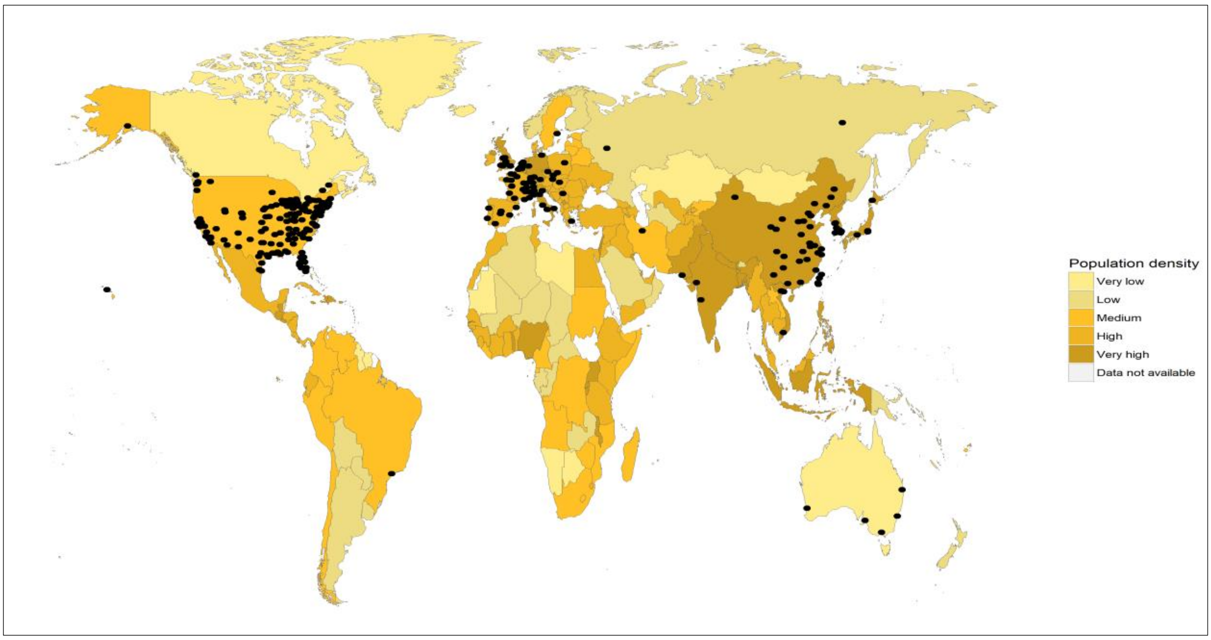


Figure 2.7: Global population density 2016, adapted from the Center for International Earth Science Information Network (2016), with locations of heatwaves and health impact research

Heatwaves have been shown to have an increased mortality effect on communities with higher relative population densities (Medina-Ramon & Schwartz 2007). Furthermore, the population density of urban areas is closely linked to the UHI effect (Elsayed 2012), where increased urban infrastructure and development create significantly warmer ground temperatures than experienced in less developed areas.

While strength of association between global wealth, population density and research distribution is out of scope for this study, this area is worthy of further research to extend these initial findings.

Heatwave and health impact research was concentrated in regions in the mid-latitudes (approximately between 25° and 55° either side of the equator), with a lack of research apparent in the tropics (within 25° either side of the equator) and at higher latitudes (over 55° either side of the equator) (see Figure 2.8). The bulk of high-income countries are situated in the mid-latitudes, with locations in the European and North American continents representing approximately 80% of all heatwave and health-related research (see Table 2.1).

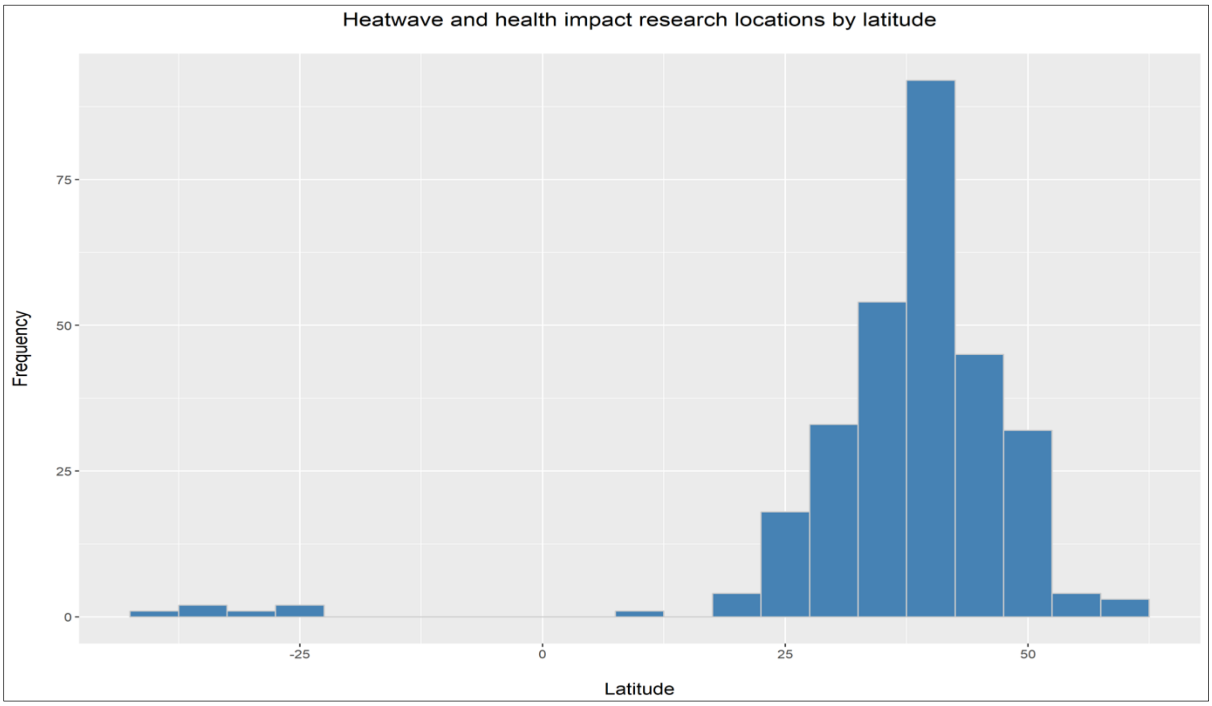


Figure 2.8: Heatwave and health impact research locations by latitude

Tropical climates are notably under-represented in heatwave and health impact research. The small number of studies located in tropical regions evaluated in this review found links between heatwaves and all-cause hospitalisation in Vietnam (10°-23°N) (Phung et al. 2017), heatwaves and all-cause mortality in Ahmedabad, India (23°N) (Azhar et al. 2014) and Guangzhou, China (23°N) (Yang et al. 2013) and heatwaves and mortality from non-infectious diseases in Vadu, India (18°N) (Ingole et al. 2015). The few studies that covered tropical regions, while examining specific causes, specific populations or high ambient temperatures, found elevated rates of cardiovascular hospital admissions during high temperatures in Vietnam (10°-23°N) (Phung, Guo, et al. 2016); elevated mortality for stroke and cardiovascular disease during high temperatures in Puerto Rico (18°N) (Mendez-Lazaro et al. 2016); and higher mortality rates during the hottest season in Burkina Faso (10°-15°N) (Kynast-Wolf et al. 2010). The combined results of these studies tend to suggest that tropical regions are prone to extreme heat health-related impacts, but better characterising of the risks is needed.

While regions at higher latitudes tend to have relatively cooler maximum summer temperatures and experience heatwaves less often when compared to regions in mid and lower latitudes, a number of studies indicate that populations at higher latitudes still experience significant heat-related health risks. Multi-city or nationwide studies demonstrated this effect in the United States (Curriero et al. 2002), South Korea (Na et al. 2013), Vietnam (Phung et al. 2017) and Europe (Ward et al. 2016), while studies in the United States demonstrate larger heatwave impacts in cities with milder summers (Medina-Ramon & Schwartz 2007). A similar pattern was noted in a multi-city study from Europe, the United States and Australia, where cities with lower mean summer temperatures had a significantly lower threshold at which heat-related mortality began to occur (Gosling, McGregor & Paldy 2007).

This may plausibly be explained through a lack of acclimatisation to hotter weather from individuals residing in cooler regions, and therefore a heightened impact to extreme heat events when they do occur. Exceedance of an absolute temperature for a specified time (for example, a daily mean exceeding 28°C for three or more days) does not necessarily define an extreme heat event, as the population at that location will be adapted to the 'normal' temperatures for that region. This acclimatisation phenomenon is taken into account by Nairn and Fawcett (2015b) when calculating the Australian Bureau of Meteorology's National Heatwave Service using the Excess Heat Factor (EHF) methodology. EHF has been shown to be a better measure of health service utilisation and demand following an extreme heat event than other definitions of heatwaves that do not account for acclimatisation (Scalley et al. 2015).

2.5.6 Risks associated with projected future impact

Climate change projections of heatwave frequency and severity show that specific regions around the world are at greater future risk than others. Research by Mora et al. (2017a) shows that when compared to other regions, Central and South America, Africa, India, south-east Asia and northern Australia are more likely to experience a greater number of days per year when weather conditions are above a survivable human threshold. These conditions remain valid using any of three future greenhouse gas concentration scenarios or Representative Concentration Pathways (further described by Intergovernmental Panel on Climate Change (2013)). Similarly, Im et al. (2017) demonstrate high risk to populations from exceedances in survivable wet bulb temperatures (temperature readings which take humidity into account) in the Middle

East, Pakistan, India, Bangladesh, eastern China and northern Australia, while Pal and Eltahir (2016) show regions in the Middle East are likely to exceed critical survivable threshold temperatures in the future.

The majority of these regions are significantly under-represented in current heatwave and health impact research, while regions most heavily researched were not identified in the regions most at risk in future scenarios. The one exception to this observation is eastern China.

2.5.7 Study strengths and limitations

Strengths of this study include the wide range of health outcomes examined over a relatively long time period. Cross-checking studies identified for inclusion with similar review studies ensured as many studies as possible were captured in the process.

Limitations included restriction to articles in English, which may partly explain fewer studies in non-English speaking regions such as South America, South-East Asia and Africa. However, a similar examination of heatwave and health-related research by Mora et al. (2017a) yielded comparable results, while also including studies in Spanish, French, Japanese and Chinese.

This study was restricted to mortality and morbidity data, using health outcomes from three sources (death data, hospital data and ambulance data). While acknowledging that health impact from heat exposure is a continuum from mild to severe and therefore may not always be captured in these datasets, this study sought to aggregate a sufficient number of publications to enable comment on global research distribution. The health outcomes chosen were considered most likely to enable this depth of investigation.

This review would benefit from ongoing updates as further heatwave and health impact research is developed, particularly in regions more vulnerable to the impact of heat-related illness (such as regions with low wealth, greater population density and in tropical regions projected to experience non-survival temperatures in the near future). Further research examining more novel heat-related health outcomes (for example, GP presentations, workplace illness and injury) would enhance the understanding of this issue.

2.6 Conclusion

In this review of studies of health impacts of heatwaves, a mismatch was identified between research effort (as measured by the number and location of studies) and need (as suggested by several indicators of population level vulnerability).

The global distribution of research into heatwaves and their impact on human health is not uniform, and tends to cluster in regions with high levels of resources and income. Furthermore, as a risk associated with heatwave mortality and morbidity, global population density does not match the location of current heatwave and human health studies.

Our analysis shows significant gaps in tropical and high-latitude regions, with additional gaps across South America, Africa, Eastern Europe, northern Australia and the Middle East. Countries in parts of Asia are also under-represented. These regions contain significant heat-vulnerable populations, and inhabitants at high risk from other climate-related impacts. The regions most covered by heatwave and health impact research are not necessarily matched by those regions most at risk in future climate scenarios. Furthermore, this type of research appears skewed towards mortality rather than morbidity outcomes, which may give a better picture of heatwave impact in a population.

As the likelihood of extreme heat events increases into the future, heatwave and health impact research is urgently needed across regions where the impact of these events will be felt more acutely.

Chapter 3:
The value of local heatwave impact assessment: A case-crossover analysis of hospital emergency department presentations in Tasmania, Australia

3.1 Preface

Chapter 2 identified numerous gaps in research on heatwave and human health impact, including for regions of higher latitude (and therefore cooler climate), regions of relative greater social disadvantage, and in the limited use of morbidity datasets such as ambulance dispatches and hospital presentations to determine impact on those services. These findings lay the groundwork for Chapters 3 and 4, where the human health impacts of heatwaves are analysed in Tasmania, Australia, for both emergency hospital presentations (Chapter 3) and ambulance dispatches (Chapter 4).

Tasmania has a cooler climate relative to the rest of mainland Australia and exhibits relatively greater social disadvantage when compared to other Australian jurisdictions. Tasmania's population has minimal experience living with heatwaves, although a warming climate will increase this risk in the future. Creating a baseline for these settings is important to inform future work, and to inform current surge capacity planning and health promotion efforts to prevent heat illness in Tasmania.

Chapters 3 and 4 act as examples of Stages 2 and 3 in the Kaufman and Carl research translation framework (see Figure 3.1). Stage 2 describes the use of a variety of methods (for example, epidemiology, exposure science and statistics, which are appliable to the research in Chapters 3 and 4) to identify the health implications of an event under consideration. Stage 3 identifies the policy and practice implications of these implications. Both the health implications and the policy and practice implications of the association between heatwaves and health outcomes are clearly detailed in these chapters.

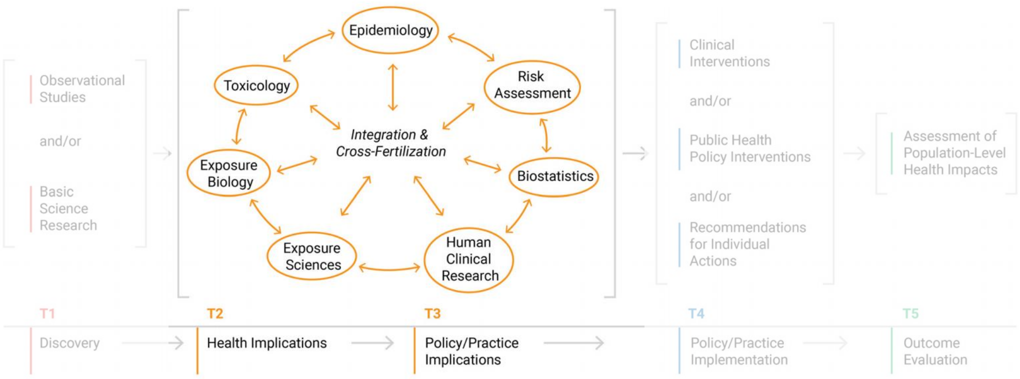


Figure 3.1: Kaufman and Curl (2019) environmental health translational research framework, Stages 2/3

This chapter was originally published as Campbell, SL, Remenyi, TA, Williamson, GJ, White, CJ, Johnston, FH 2019, ‘The Value of Local Heatwave Impact Assessment: A case-crossover analysis of hospital emergency department presentations in Tasmania, Australia’, *International Journal of Environmental Research and Public Health*, vol. 16, 3715. The original publication can be found in Appendix B. The contents of this chapter contain minor modifications to correct a coding error detected after publication. An erratum has been sent to the journal to correct this error.

3.2 Abstract

Heatwaves have been identified as a threat to human health, with this impact projected to rise in a warming climate. Gaps in local knowledge can potentially undermine appropriate policy and preparedness actions. Using a case-crossover methodology, we examined the impact of heatwave events on hospital emergency department (ED) presentations in the two most populous regions of Tasmania, Australia, from 2008-2016. Using conditional logistic regression, we analysed the relationship between ED presentations and severe/extreme heatwaves for the whole population, specific demographics including age, gender and socio-economic advantage, and diagnostic conditions that are known to be impacted in high temperatures. ED presentations increased by 5% (OR 1.05, 95% CI 1.01-1.09) across the whole population, by 13% (OR 1.13, 95% CI 1.03-1.24) for children 15 years and under, and by 19% (OR 1.19, 95% CI 1.04-1.36) for children 5 years and under. A less precise association in the same direction was found for those over 65 years. For diagnostic subgroups, significant associations with heatwaves were found for conditions relating to exposure to heat and light (OR 9.62, 95% CI 3.13-29.51) and with presentations for psychoses (OR 1.84, 95% CI 1.14-2.97). Non-significant increases in ED presentations were observed for asthma, diabetes, hypertension, and atrial fibrillation. These findings may assist ED surge capacity planning and public health preparedness and response activities for heatwave events in Tasmania, highlighting the importance of using local research to inform local practice.

3.3 Introduction

Anthropogenic climate change represents "an unacceptably high and potentially catastrophic risk to human health" (Watts et al. 2015, p.1861). While climate change may not necessarily impact health through the introduction of new diseases or disorders, it is likely to expand and amplify existing health issues (Blashki et al. 2011), presenting to the global population as a broad spectrum of health risks (World Health Organization 2012). The Intergovernmental Panel on Climate Change describes global mean surface air temperature as rising over the last 100 years (IPCC 2013), which has led directly to an increase in frequency, intensity, and duration of extreme heat events since 1950 (Perkins, Alexander & Nairn 2012). It is widely accepted that extreme heat, and specifically extreme heat events, have a detrimental effect on human health. In Australia, extreme heat is responsible for over 55% of total fatalities caused by natural events since 1900; more deaths than all other natural hazards combined (Coates et al. 2014).

Heatwaves have been studied across many parts of the world, although significant geographic gaps exist (Campbell et al. 2018). Heat-related illness and death does not present equally across populations, with some groups appearing more vulnerable than others (Bi et al. 2011). Meta-analyses show that the greatest impacts appear likely for the elderly, children, and those with existing medical conditions, including cardiovascular diseases and mental illnesses (Benmarhnia et al. 2015; Li et al. 2015).

Several methods exist to assess the extent to which extreme heat events impact human health; these include analysing mortality data for the period of the event and shortly after (Fouillet et al. 2006); analysing morbidity indicators, such as ambulance dispatches, emergency hospital presentations, and hospital admissions (Kue & Dyer 2013a); or a combination of mortality and morbidity data (Nitschke, Tucker & Bi 2007; Williams et al. 2012b). Studies investigating the economic impact and work output have also emerged (Orlov et al. 2019). Studies of outcomes relating to heatwave-associated morbidity are, however, far less common than studies of mortality (Bi et al. 2011; Campbell et al. 2018). This is an important discrepancy, as mortality represents the extremes of health impacts, while understanding the association with other health outcomes is equally important for quantifying the greater impacts on the healthcare system and the society.

In Australia, several studies have examined the link between extreme heat and health outcomes (Khalaj et al. 2010; Lindstrom, Nagalingam & Newnham 2013; Nitschke et al. 2011b; Toloo et al. 2014; Tong et al. 2014; Turner, Connell & Tong 2013; Williams et al. 2012b), including for specific cohorts (Dalip et al. 2015; Hansen et al. 2008). Across these studies, a positive association has been established between extreme heat events and increases in ambulance dispatches, hospital emergency department (ED) presentations, and deaths. These studies have principally concentrated on urban settings in the larger capital cities of Melbourne, Perth, Adelaide, Sydney, and Brisbane, which are all located in warmer climate regions. To date, no studies have been conducted specifically in the cooler climate regions of Australia, where health outcomes associated with heatwaves are unknown.

3.3.1 Study setting

Tasmania is an island state in Australia, located to the south of mainland Australia (40°S-43°S). The majority of the Tasmanian population reside in a regional or remote classified area (Australian Bureau of Statistics 2011). The state's total population in 2016 was 510,000, with most of the population residing in one of three major centres—Hobart, the capital, located in the southeast (population 204,000), Launceston in the north (population 84,000) or Burnie-Devonport in the northwest (population 70,000) (Australian Bureau of Statistics 2018b). There are slightly more females than males in Tasmania (98 males to 100 females), and the median age is 42.3 years, the highest of any Australian state or territory (Australian Bureau of Statistics 2018b).

Tasmania has four major public hospitals, each with an emergency department, located in the most densely populated regions—one located in Hobart (Royal Hobart Hospital); one in Launceston (Launceston General Hospital); and two in the Burnie-Devonport region (the Mersey Community Hospital and the North West Regional Hospital).

Severe heatwaves are not a common feature of the Tasmanian summer experience, with average maximum summer temperatures of approximately 20°C, some of the lowest found in Australia. However, Tasmania still experiences occasional extreme heat events. In late January 2009, for example, Tasmania experienced its hottest maximum temperature on record, reaching 42.2°C at Scamander in the state's northeast region. Several other towns in the north and northeast experienced similar maximum temperatures over the following days (Bureau of Meteorology 2010). In 2013, Hobart experienced its hottest maximum temperature ever recorded (41.8°C on 4 January) and several other highest summer temperature records were broken in the surrounding regions on that day (Bureau of Meteorology 2013). This period in the southeast was also marked by severe wildfires (Tasmanian Government 2013).

When compared to other Australian jurisdictions, Tasmania has a greater proportion of people in higher risk groups identified as vulnerable to heat events. With 19.3% of the population over 65 years of age, Tasmania has the highest proportion of elderly residents (Australian Bureau of Statistics 2018c), and the highest proportion of cardiovascular disease (7.7%), and long-term mental or behavioural problems (21%) (Department of Health 2018). Tasmania also has a higher proportion of people living in greatest disadvantage (33%) than any other Australian state and territory (Department of Health 2018), with less than half of Tasmanian households having access to air-conditioning for cooling (Department of Health and Human Services 2016). These factors potentially make the Tasmanian population more vulnerable to heatwaves when they do occur.

As a compounding factor, typical Tasmanian weather patterns do not involve uniform increases and decreases in temperature throughout the spring-summer-autumn period. Due to its location within the westerly wind belt, and the consequent regular passage of cold frontal systems, Tasmanian meteorology is characterised by highly variable conditions and rapid shifts in temperature. For example, a month before the warmest day on record in Hobart (41.8°C on 4 January 2013), the nearby community of Maydena in Tasmania's southeast experienced the coldest summer day on record (9.4°C on 4 December 2012) (Bureau of Meteorology 2013). This variability impedes the ability of the Tasmanian population to adequately acclimatise to heat events over the summer period, potentially increasing vulnerability to heat events when they do occur (Braga, Zanobetti & Schwartz 2001).

While Tasmania has had a state heatwave plan in place since 2013, a paucity of research on heatwaves in Tasmania and their impact on local health systems has hampered efforts by public health policymakers to develop targeted policies and programs to reduce the public health impact of heatwaves. To date, policy and planning has relied on research conducted in other geographic settings, which does not take Tasmania's unique vulnerabilities or climate into account.

3.3.2 Research aim

The aim of this research was to investigate the impact of heatwaves on ED presentations in Tasmania, highlighting similarities and differences with other jurisdictions. Associations with all-cause, age-specific, location-specific, and condition-specific presentations were analysed.

3.4 Materials and methods

3.4.1 Exposure data

Temperature data from the Bureau of Meteorology Atmospheric high-resolution Regional Reanalysis for Australia (BARRA) dataset (Su et al. 2019) were obtained from the Bureau of Meteorology (BoM). BARRA data were used because they provide better spatial and temporal resolution than station data. Averaged maximum and minimum temperatures across a 24-hour period (from midnight-to-midnight Australian Eastern Standard Time, adjusted from UTC) were used to identify extreme heat events. Heatwaves were identified using the Excess Heat Factor (EHF) index which was described elsewhere (Nairn & Fawcett 2015b). The index is a relative measure of temperature compared with historical data for each location, and does not rely on meeting an absolute temperature threshold. Using this index, a heatwave is classified as a low-intensity, severe or extreme event, where an extreme event is classified as three times the threshold for a severe heatwave event (Nairn & Fawcett 2015b). This method is used by the Australian Bureau of Meteorology for the Heatwave Service for Australia (Bureau of Meteorology 2019b) and has been found to be an effective predictor of health service demand during heatwave events (Scalley et al. 2015; Urban et al. 2019). Given their impact on health, only severe and extreme events were considered in this analysis. As only a very small number of extreme events were identified, these were combined with severe events for analysis.

The BARRA data were matched with the Australian Bureau of Statistics Statistical Area 2 (SA2) regions that displayed a population density >50 persons per km^2 (see Figure 3.2). Population density data were sourced from the Australian Bureau of Statistics (Australian Bureau of Statistics 2018b).

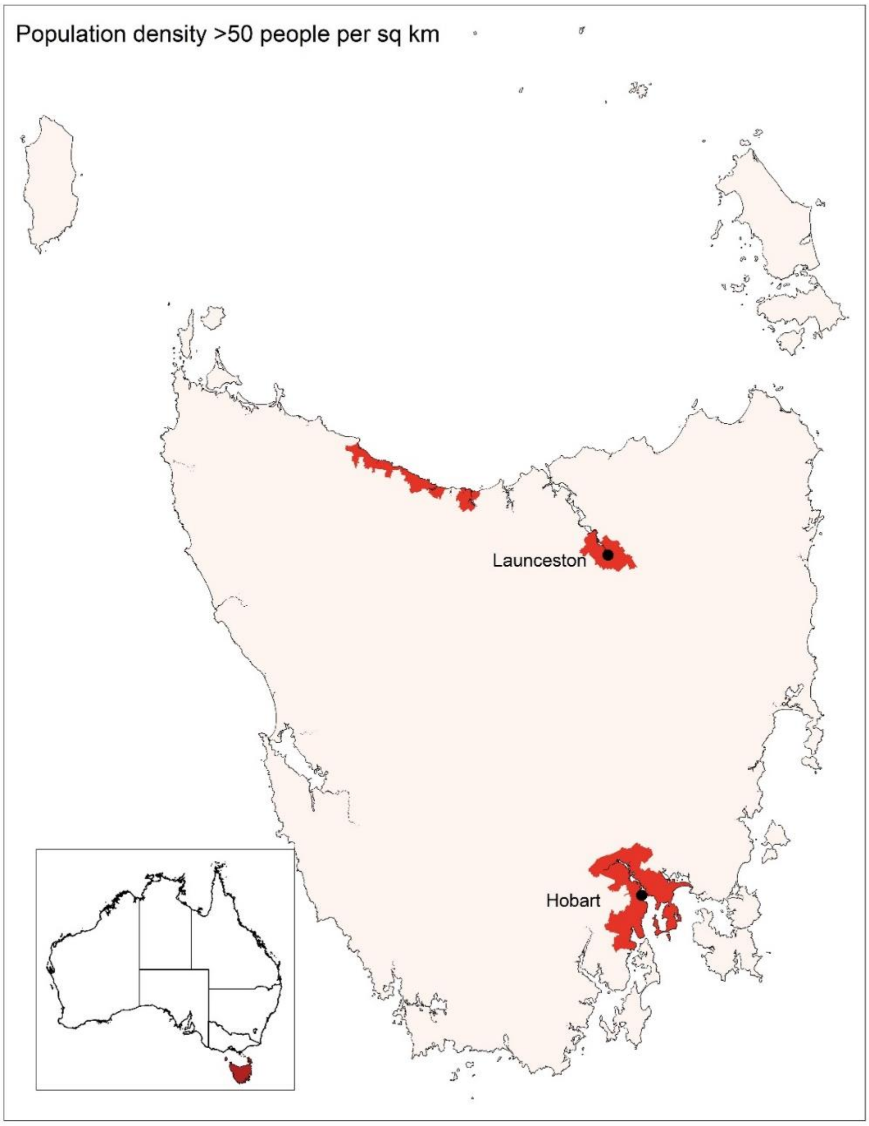


Figure 3.2: Locations in Tasmania where population density >50 persons per km^2, inset showing location of Tasmania within Australia

Air pollution data were obtained from the Environment Protection Authority (EPA) of Tasmania's air quality monitoring network, known as Base Line Air Network of EPA Tasmania (BLANkET). New Town station data were used to represent Hobart, and Ti Tree Bend station data were used to represent Launceston. Ambient 24-hour (midnight to midnight) average concentrations of particulate matter with a diameter less than 2.5µm ($PM_{2.5}$) readings were used. Where data-points for a 24-48 hour period were missing, the average of a 7-day period, on either side of the missing data-points were interpolated. Where data-points were missing for longer than 48 hours, data were linearly interpolated using the na.approx() function from the 'zoo' package in R (Zeileis et al. 2019).

State-wide public holidays for Tasmania were obtained using the Python 'holidays' package (Montel 2019). Locally specific holidays were identified and incorporated.

3.4.2 Outcome data

ED presentation data were obtained from the Tasmanian Health Service for public hospitals in Tasmania. Only data for Hobart (Royal Hobart Hospital) and Launceston (Launceston General Hospital) were used. This was due to the relatively small number of patient episodes in the much less populated northwest area of the state.

3.4.3 Study design

This study used a time-stratified case-crossover design. This methodology is commonly used in environmental epidemiology and is suited to a situation where the study population is exposed to a short-term event (for example, a heatwave), and experiences a health outcome (for example, an emergency department presentation) (Jaakkola 2003; Maclure 1991). Individual presentations, rather than days, are the unit of observation, with each person acting as their own control. Environmental data on the date of the health event were compared with that on control days of the same day of the week and within the same calendar month and year.

This methodology has been used previously for similar studies in other locations (Basagana et al. 2011; Wang et al. 2012) and has been compared to a time-series analysis with analogous results (Basu, Dominici & Samet 2005; Tong, Wang & Guo 2012).

Threats to validity of this method, as described by Maclure (1991) are discussed in Appendix C: Threats to validity of the case-crossover method.

The study period was from 1 January 2008 to 31 December 2016.

3.4.4 Analyses

A conditional multivariate logistic regression was performed using the clogit() function from the 'survival' package in R (Therneau & Lumley 2020). The odds ratio, a measure of the association between an exposure and an outcome (Szumilas 2010), and the 95% confidence intervals were calculated for presentations to ED during identified severe/extreme heatwaves. This was performed for the whole population for all conditions combined, and for the following sub-categories:

- age group (0-5, 0-15 and over 65)
- gender
- Socio-Economic Index for Areas (SEIFA) category (by suburb of patient address), using the Index of Relative Socio-Economic Disadvantage
- diagnostic group.

SEIFA categories were amalgamated by condensing scores 1-3 as 'low advantage', scores 4-7 as 'middle advantage', and scores 8-10 as 'high advantage'.

The presenting conditions were classified into diagnostic groups using the International Classification of Disease (ICD-10) codes for the primary diagnosis (World Health Organization 2011). Table 3.1 shows the diagnostic groups and sub-groups analysed.

The regression model controlled for both observed public holidays and $PM_{2.5}$ for the nearest EPA station.

Table 3.1: International Classification of Disease (ICD-10) codes for analysed diagnostic conditions

Diagnostic Condition	**ICD-10 Code**
All respiratory	J00–J99
Asthma	J45–J46
Chronic obstructive pulmonary disease (COPD)	J40-J44, J47, J67
Diabetes	E10-E11, E13-E14
All cardiovascular	I00-I99, G45-G46
Hypertensive	I10-I13
Ischemic heart disease	I20-I25
Atrial fibrillation	I48
Cardiac failure	I50
All mental disorders	F00-F99
Dementia	F00-F03
Psychoses	F20-F29
Mood disorders (including depression)	F30-F39
Neurotic and stress disorders (including anxiety)	F40-F49
All renal disorders	N00-N39
Acute renal failure	N17
Renal calculus	N20-N21
Heat and light disorders (including sunburn, heat stroke)	T67, X30

3.5 Results

In the nine-year period from 1 January 2008 to 31 December 2016, 841,965 people presented to the ED of the Royal Hobart Hospital and the Launceston General Hospital. Characteristics of these presentations are shown in Table 3.2.

During this period, there were multiple days identified as heatwaves of varying intensities, affecting both regions under study (see Table 3.3). All identified heatwave days occurred in summer (December to February), where hot days were characterised as arising from hot northerly winds and days of low humidity gave rise to dry heat conditions.

Significant associations between ED presentations and identified severe/extreme heatwave days were found (see Figure 3.3).

ED presentations increased across the whole population (OR 1.05, 95% CI 1.01-1.09), for children aged 15 years and under (OR 1.13, 95% CI 1.03-1.24), and for children aged 5 years and under (OR 1.19, 95% CI 1.04-1.36), while a less precise association in the same direction was found for those aged over 65 years (OR 1.06, 95% CI 0.97-

1.16). Results for males and females were similar, although the point estimate was slightly higher in females and attained statistical significance (female OR 1.06; male OR 1.05). There was no clear trend associated with socio-economic disadvantage.

A significant association was found for conditions relating to exposure to heat and light (OR 9.62, 95% CI 3.13-29.51) and psychoses (OR 1.84, 95% CI 1.14-2.97). No associations were observed with any other diagnostic subgroups. Results were much less precise due to the smaller number of cases in these subgroups although non-significant elevations in the ORs were observed for asthma (OR 1.40, 95% CI 0.94-2.09), diabetes (OR 1.57, 95% CI 0.82-3.01), hypertension (OR 1.40, 95% CI 0.58-3.38), and atrial fibrillation (OR 1.03, 95% CI 0.63-1.60). Insufficient data were available to perform a conditional logistic regression for dementia and renal calculus, and these conditions were not presented in the results.

There were no meaningful differences between the crude and adjusted associations (for full results, see Table D.1 in Appendix D: Crude and adjusted associations between ED presentations and heatwaves in Tasmania, Australia).

Table 3.2: Characteristics of ED presentations to the Royal Hobart Hospital and Launceston General Hospital for specific population characteristics and diagnostic groups (2008-2016)

Population characteristic/ Diagnostic group	**Number (% of total)**	**Mean daily presentations (SD)***	**Median (IQR)^**	**Range**
Whole population	841 965 (100%)	256.1 (31.4)	256 (43)	153-358
Age				
≤5	85 450 (10.1%)	26.0 (7.2)	26 (10)	5-56
≤15	160 315 (19.0%)	48.8 (10.9)	48 (15)	18-108
16–65	521 072 (61.9%)	158.5 (20.3)	158 (27)	90-232
>65	160 500 (19.1%)	48.8 (10.3)	48 (15)	21-85
Gender				
Male	434 660 (51.6%)	132.2 (18.3)	132 (25)	80-201
Female	407 032 (48.3%)	123.8 (17.6)	124 (25)	67-181
SEIFA				
Low	437 577 (52.0%)	133.1 (17.6)	133 (24)	75-194
Middle	252 039 (29.9%)	76.7 (11.7)	77 (17)	36-118
High	135 392 (16.1%)	41.2 (8.7)	41 (12)	15-78
All respiratory	67 439 (8.0%)	20.5 (7.6)	20 (10)	3-63
Asthma	8546 (1.0%)	2.6 (1.7)	2 (3)	0-10
COPD	10 365 (1.2%)	3.2 (2.0)	3 (2)	0-14
All cardiovascular	49 436 (5.9%)	15.0 (4.3)	15 (6)	3-31
Cardiac failure	5199 (0.6%)	1.6 (1.3)	1 (1)	0-9
Hypertensive	1312 (0.2%)	0.4 (0.6)	0 (1)	0-5
Atrial fibrillation	6102 (0.7%)	1.9 (1.4)	2 (2)	0-8

Ischemic heart disease	13 964 (1.7%)	4.2 (2.1)	4 (3)	0-15
Diabetes	1994 (0.2%)	0.6 (0.8)	0 (1)	0-5
All mental conditions	34 509 (4.1%)	10.5 (3.7)	10 (5)	1-27
Dementia	655 (0.1%)	0.2 (0.5)	0 (0)	0-4
Psychoses	5501 (0.7%)	1.7 (1.3)	1 (1)	0-8
Depression	8381 (1.0%)	2.5 (1.7)	2 (3)	0-11
Anxiety	6459 (0.8%)	2 (1.5)	2 (2)	0-9
All renal	20 914 (2.5%)	6.4 (2.7)	6 (4)	0-19
Acute renal failure	1416 (0.2%)	0.4 (0.7)	0 (1)	0-5
Renal calculus	160 (0.02%)	0.05 (0.23)	0 (0)	0-2
Exposure to light and heat	199 (0.02%)	0.06 (0.4)	0 (0)	0-12

* Standard deviation

^ Interquartile range

Table 3.3: Number of days identified as heatwave days for each region, at each heatwave intensity (Tasmania, Australia, 2008-2016)

Region	Low-intensity days	Severe days	Extreme days
South (Hobart)	82	7	0
North (Launceston)	139	14	5

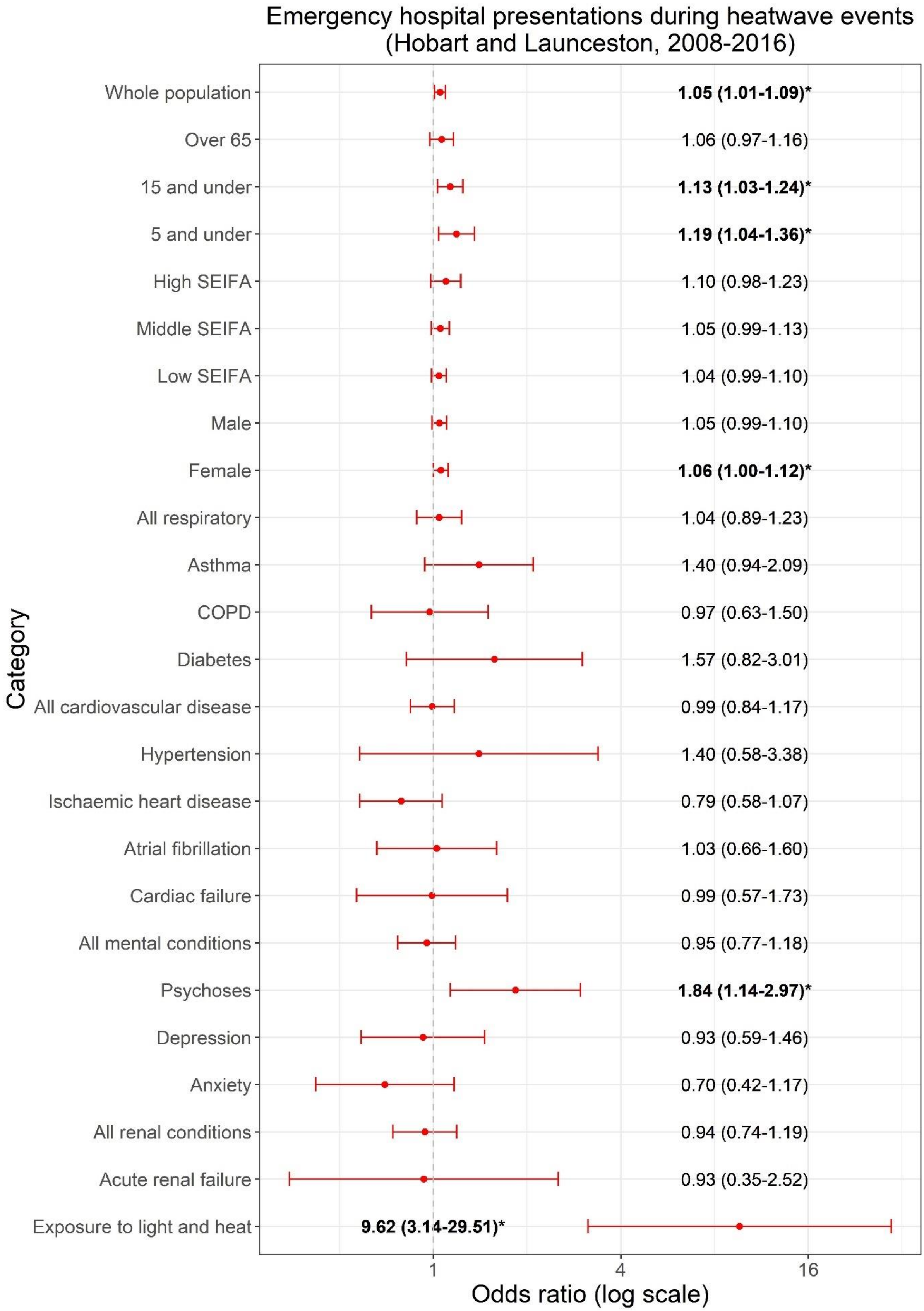


Figure 3.3: Odds ratios and 95% confidence intervals for the association between ED presentations for specific population characteristics, diagnostic groups, and heatwaves in Hobart and Launceston, Tasmania (2008-2016), adjusted for public holidays and $PM_{2.5}$ (* and bold indicates $p < 0.05$)

3.6 Discussion

In this study, we found that hospital emergency departments in Tasmania's major population centres experienced a significant increase in presentations (5%) during severe and extreme heatwaves, disproportionately affecting younger age groups. ED presentations increased by 13% for children aged 15 years and under and 19% for children aged 5 years and under. Significant increases in presentations were also found for conditions related to exposure to light and heat (for example, sunburn and heatstroke) and psychoses. A less precise increase in risk was found for older people, although this group exhibited a similar magnitude to the overall population risk.

Our findings were largely consistent with similar studies in other locations around Australia, showing an association between heatwave events and increases in emergency department presentations (Lindstrom, Nagalingam & Newnham 2013; Schaffer et al. 2012a). Other international studies have demonstrated similar trends in associations between ED presentations and heatwave events (Fuhrmann et al. 2016; Sun et al. 2014; Zhang, Chen & Begley 2015).

Our findings for increased risk to children in the magnitude observed (2.6x for children aged 15 years and under, and 3.6x for children aged 5 years and under, over the general population) appeared to be unique in the literature. While some studies have demonstrated an elevated morbidity risk to children in heatwaves (Knowlton et al. 2009; Leonardi et al. 2006), an overwhelming number of studies have consistently highlighted the elderly to be most at risk. This finding warrants further research in the Tasmanian context and has clear policy implications for public health preparedness and communication during heatwave events.

In our study, the difference between ED presentations for males and females during heatwaves was small, showing a slightly higher risk for females. Similar studies, both in Australia and overseas, have demonstrated mixed results for the risk between genders (Li et al. 2015; Michelozzi et al. 2005; Xiao et al. 2017), while some report differences in gender with specific diagnostic conditions (Li et al. 2015). Due to the small number of cases in this study, specific diagnostic conditions were not further analysed by gender.

Other similar studies have demonstrated that poorer health outcomes appear to be more likely in areas with a greater disadvantage, both in Australia (Loughnan, Nicholls & Tapper 2010; Xiao et al. 2017) and overseas (Kim & Kim 2017; Michelozzi et al. 2005). Contrary to expectations, our results did not show a trend in the risk associated with socio-economic disadvantage, however, our ability to identify associations was limited by the lower statistical power in the subgroup analyses. This result also deserves further investigation.

Results of the sub-analyses by diagnostic groups were generally less precise due to the smaller numbers of cases evaluated, resulting in wide confidence intervals and no clear associations. Based on similar studies elsewhere, increased risk in cardiovascular, mental, respiratory and renal disease were expected. Recent meta-analyses of cardiovascular and respiratory conditions suggest that mortality is greater than morbidity for these diagnostic groups during heatwaves (Cheng et al. 2019), which might partially contribute to the results found in this study, and deserves further study in the local context.

The exception to this general trend was the identification of an association between psychoses and heatwave days, despite the small number of cases involved and no association with the broader category of mental health disorders. This finding is partially consistent with a systematic review by Thompson et al. (2018), which found a positive and significant association with a number of mental health conditions, notably schizophrenia and bipolar disorder. This effect may be due to altered brain function in extreme heat, compromised ability to perform adaptive behaviours in some individuals, sleep disruptions and use of psychotropic medication which increases heat vulnerability (Lõhmus 2018). These results also deserve further study.

This study benefitted from analysing data across a nine-year time frame, indicating ED presentation changes over a number of heatwave events, rather than the analyses of a specific or singular event. Our study also controlled for co-incident air pollution ($PM_{2.5}$) on health outcomes, a well-documented association (Edwards et al. 2018; Johnston et al. 2013; Johnston et al. 2014; Johnston et al. 2019), and for public holidays, which influence the patterns of healthcare utilisation.

The results of this study are confined to the relatively small population of Tasmania, making additional sub-categorisation analyses difficult to achieve, for example, analysing the impact of heatwave events on children with asthma (Xu et al. 2013). While other similar studies have controlled for ozone (Wang et al. 2012), these data were not available for the studied population centres and could not be included in this analysis.

While limitations are known to exist with reanalysis data for meteorological variables (Parker 2016), including the possibility of underestimating extremes (Raghavendra et al. 2019), our study used reanalysis data given the improvement in spatial and temporal resolution offered over observed station data in the study region. Further studies examining the difference between reanalysis and observed data for this region may be warranted but were outside of the scope of our study.

Our findings can assist policy and planning directives in two key areas of health. Detailed planning in Tasmanian hospital emergency departments for heatwave events is now possible, especially as these types of events can be forecast with accuracy in the days prior (Parkyn, Yeo & Bannister 2010). This allows for long lead times to accurately adjust rostering and implement surge capacity procedures, potentially minimising the impact. Secondly, targeted and specific public health preparedness campaigns aimed at the carers of young children, such as parents, child care centres and schools can be incorporated into the existing heatwave campaigns and health promotion campaigns already targeting this group, with the aim of reducing the incidence of ED presentations during these events. Neither of these interventions currently exist due to a lack of local evidence.

These findings also allow the issue of self-care in heatwaves to be explored through the media, giving evidence towards heatwaves being a health risk that can be managed. Current media coverage of hot weather tends to focus on recreation opportunities that can be best enjoyed in hot weather (The Mercury 2017), rather than emphasising the potential health issues and mitigation actions.

Further research that analyses the associations between heatwave events and other healthcare outcomes (for example, mortality, hospital admissions, ambulance dispatches, and GP visits) would assist in strengthening preparedness and response activities, including policy measures associated with extreme heat events in Tasmania.

3.7 Conclusion

This research shows an association between heatwave events and hospital emergency department presentations in the most populated regions of Tasmania, Australia. These associations were apparent across the whole population under study, predominantly for children aged 0-15 and 0-5. These findings may assist in surge-capacity planning for hospital emergency departments during forecast heatwave events, and can help tailor public health preparedness policies for heatwaves. This example of research-to-policy translation highlights the importance of developing well-informed health policy and planning initiatives at a local level, based on local research, demonstrating that while general associations could be made using research from other regions with large-scale studies, specific and targeted responses serve to better inform local practice.

Chapter 4:
Ambulance dispatches and heatwaves in Tasmania, Australia: A case-crossover analysis

4.1 Preface

This chapter complements Chapter 3 by providing an analysis of the association between heatwaves and ambulance dispatches in Tasmania, Australia.

As discussed in Section 3.1, this chapter and the previous chapter were informed by the findings in Chapter 2, where research gaps were identified in the association between heatwaves and human health outcomes for regions of higher latitude (cooler climate) and regions of relative greater social disadvantage. Furthermore, a paucity of research on the associations between heatwaves and ambulance dispatches was identified in Chapter 2.

The impact on ambulance dispatches, as distinct from hospital presentations, is important to recognise. Heat illness can occur on a spectrum from mild to life-threatening, thereby potentially affecting a broad range of health services. Associations identified for one health service are not necessarily generalisable to a different health service. Furthermore, as ambulance services work on a flexible rostering system prepared in advance, research that can assess the impact on that system during a forecastable event is highly useful in surge capacity planning.

Similar to Chapter 3, Chapter 4 stands as an example of Stages 2 and 3 in the Kaufman and Carl research framework (see Figure 4.1). Again, this research clearly identifies the health implications of heatwave events, leading to the identification of policy and practice implications for ambulance services in Tasmania.

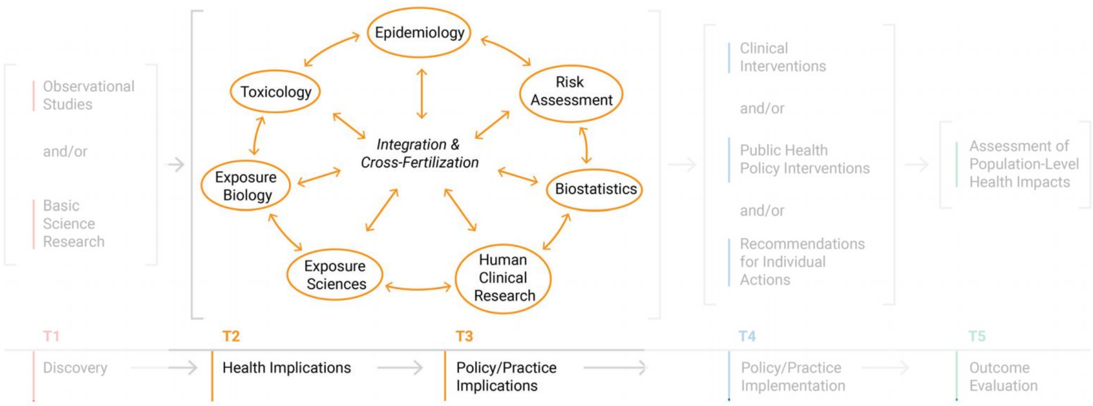


Figure 4.1: Kaufman and Curl (2019) environmental health translational research framework, Stages 2/3

This chapter has been reproduced as published (with minor changes) in Campbell, SL, Remenyi, TA, Williamson, GJ, Rollins, D, White, CJ, Johnston, FH 2021, 'Ambulance dispatches and heatwaves in Tasmania, Australia: A case-crossover analysis', *Environmental Research*, vol. 202, no. 111655.

4.2 Abstract

Climate change is causing an increase in the frequency and severity of heatwave events, with a corresponding negative impact on human health. Health service utilisation during a heatwave is increased, with a greater risk of poor health outcomes identified for specific population groups. In this study, we examined the impact of heatwave events on ambulance dispatches in Tasmania, Australia from 2008 to 2019 to explore health service utilisation and identify the most vulnerable populations at a local level. We used a time-stratified case-crossover analysis with conditional logistic regression to examine the association between ambulance dispatches and three levels of heatwave events (extreme, severe, and low-intensity). We examined the relationship for the whole study population, and by age, gender, socio-economic advantage and clinical diagnostic group. We found that ambulance dispatches increase by 34% (OR 1.34, 95% CI 1.18-1.52) during extreme heatwaves, by 10% (OR 1.10, 95% CI 1.05-1.15) during severe heatwaves and by 4% (OR 1.04, 95% CI 1.02-1.06) during low-intensity heatwaves. We found significant associations for the elderly (over 65), the young (5 and under) and for regions with the greatest socio-economic disadvantage. All levels of heatwaves were associated with increased demands on ambulance services, especially among the elderly, the young and those in disadvantaged regions.

4.3 Introduction

Anthropogenic climate change is causing a global increase in the frequency, severity and duration of heatwaves (Perkins, Alexander & Nairn 2012), with a growing body of evidence linking heatwave events to an increase in human mortality and morbidity (Han et al. 2017). Furthermore, climate modelling suggests that increased temperatures in the future will likely result in non-survivable conditions for many densely populated regions around the world (Mora, Dousset, et al. 2017b). The negative health outcomes associated with heatwaves are the result of a range of interrelated physiological pathways (Mora, Counsell, et al. 2017) and are measured using mortality and morbidity data including the number of deaths, hospital presentations, hospital admissions or ambulance dispatches during and after a specific heatwave event or across a series of heatwave events.

Numerous studies have demonstrated the disproportionate health impact of heatwaves, with the elderly (Dalip et al. 2015), children (Campbell et al. 2019), those with existing medical conditions (Yin & Wang 2017) and those from more disadvantaged socio-economic regions (Xiao et al. 2017) most at risk when exposed to prolonged and extreme temperatures. This type of research has been conducted over multiple years and across multiple settings (Campbell et al. 2018), showing a strong pattern of human health impact with local variations. In Australia, several studies have examined extreme heat events using mortality and morbidity data, generally focusing on large metropolitan centres (Nitschke et al. 2011a; Wang et al. 2015; Williams et al. 2012a). Specifically, the impact of heatwaves on ambulance dispatches has been studied in Sydney (Schaffer et al. 2012b), Brisbane (Turner, Connell & Tong 2013) and Adelaide (Nitschke et al. 2011a), cities with large populations and temperate climates.

Ambulance dispatch data offers an opportunity to examine the health impact of short-term environmental hazards such as heatwaves, given the real-time nature of paramedic attendances. Specifically, paramedic assessments offer a clinically robust and informative dataset, as standardised diagnostic protocols are used to evaluate patients (Johnston et al. 2019). Previous studies of ambulance dispatch data during and after heatwave events have shown an overall increase in the volume of calls (Kue & Dyer 2013b; Onozuka & Hagihara 2016), as well as increases in cases from specific high-risk patient groups related to age and pre-existing cardiovascular and respiratory conditions (Turner, Connell & Tong 2013). These studies are important for surge capacity planning during heatwave events, especially as these events are largely forecastable a few days in advance.

In Tasmania, an island state of Australia, heatwaves have been identified as a natural disaster risk through the Tasmanian State Natural Disaster Risk Assessment (White et al. 2016), however, evidence on the impact of heatwaves on local health service structure is limited to hospital emergency presentations (Campbell et al. 2019; Watson, Gardiner & Singleton 2020). This study aimed to redress this gap by examining the impact of heatwave events on ambulance dispatches in Tasmania, analysing all-cause cases, demographic-specific breakdowns of age, gender and socio-economic status, and condition-specific cases. Covariates of air pollution and public holidays were incorporated into the analysis.

4.3.1 Study location

Tasmania lies approximately 300 km south of mainland Australia. The majority of the Tasmanian population reside in an area classified as regional or remote (Australian Bureau of Statistics 2011). The state's total estimated population in 2019 was 534 500, with the majority of the population residing in one of three major centres: Hobart in the south (population 216 700), Launceston in the north (population 88 200), the north-west coastal centres of Burnie, Wynyard, Devonport and Ulverstone (population 72 500), and smaller but economically important regional centres on the east coast at St Helens (population 1449), and the west coast at Queenstown (population 1755) (Australian Bureau of Statistics 2016a). The remaining 153 800 residents are scattered across small towns and settlements (Figure 4.2). The population gender distribution is slightly uneven, with 1.02 females for every male (Australian Bureau of Statistics 2020).

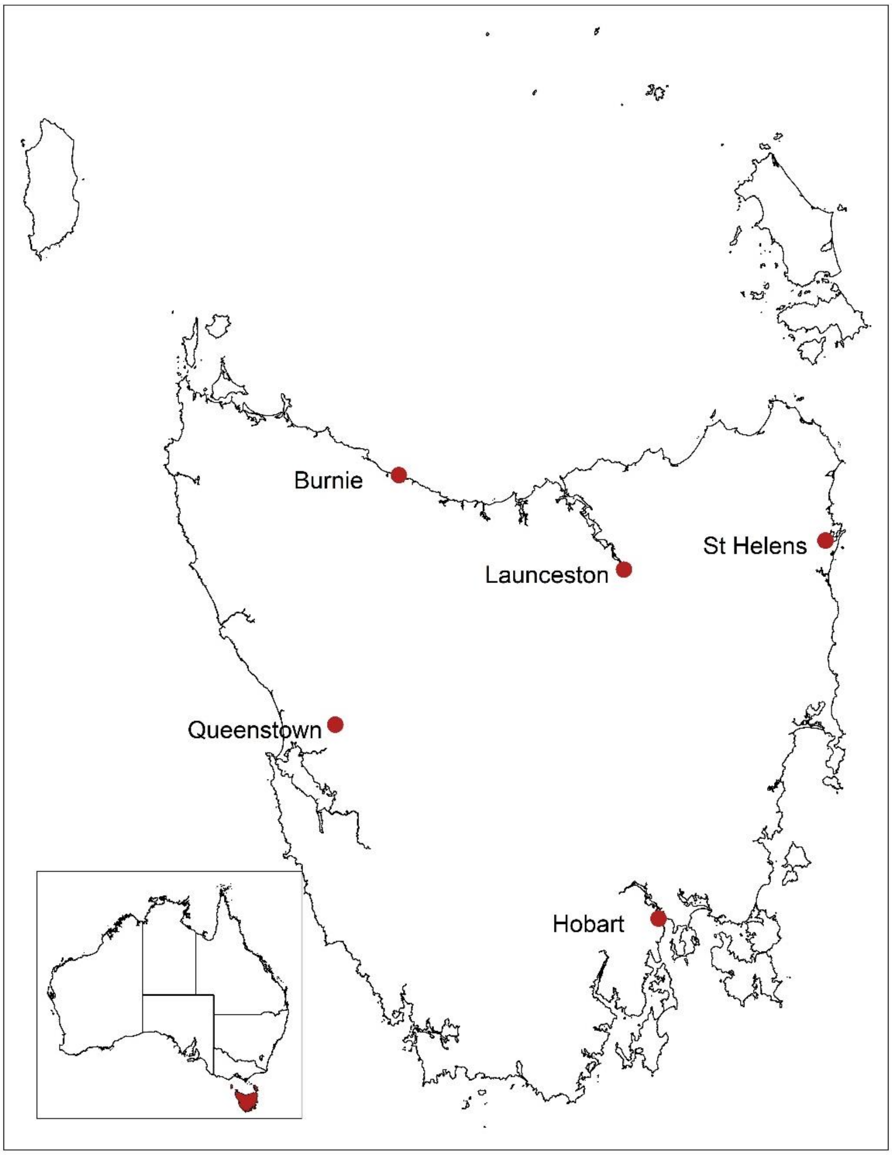


Figure 4.2: Map of Tasmania, Australia

Although heatwaves are relatively rare (Campbell et al. 2019), Tasmania has a greater proportion of elderly people, a greater proportion of those living with a chronic condition, and the highest proportion of those living in disadvantaged regions when compared to other Australian jurisdictions (Australian Bureau of Statistics 2018a; Department of Health 2018), making it a potentially more vulnerable population to heat-related illness when heatwaves occur.

4.4 Methods

4.4.1 Outcome data

Paramedic assessment data covering 1 January 2008 to 28 February 2019 were obtained from Ambulance Tasmania for all regions of Tasmania. These data are clinical records completed by the attending paramedic at the time of, or immediately following, the incident prompting the ambulance dispatch. Records containing 'Standby' and 'Transfer' dispatches were excluded as they do not reflect acute clinical cases, as were records with no date, no suburb or those recorded as outside Tasmania.

Each case was classified by:

- age group (0-5, 0-15, 16-65, over 65)
- sex
- diagnostic condition by paramedic assessment, including cardiovascular, respiratory, renal, diabetic, psychological, direct heat-related and other heat-related conditions (see Table E.1 in Appendix E: Supplementary data for Chapter 4 for conditions associated with each diagnostic group).

In addition, each case was classified by the Socio-Economic Index for Areas (SEIFA) category by suburb of incident, using the Index of Relative Socio-Economic Disadvantage (Australian Bureau of Statistics 2018a). SEIFA categories were amalgamated by condensing scores 1-3 as 'low advantage', scores 4-7 as 'middle advantage', and scores 8-10 as 'high advantage'.

4.4.2 Exposure data

Temperature data were obtained from the Bureau of Meteorology Atmospheric high-resolution Regional Reanalysis for Australia (BARRA) dataset (Su et al. 2019), with average temperatures across a 24-hour period (midnight to midnight Australian Eastern Standard time, adjusted from UTC) used to identify heatwave events. Hourly data at 1.5 km gridded intervals were obtained for the period from 1 January 2000 to 28 February 2019. Boundary polygons for each Tasmanian suburb were obtained from the Australian Statistical Geography Standard (Australian Bureau of Statistics 2016c) and transformed onto the same projection as the gridded temperature dataset. The daily mean temperatures for each suburb were determined by first calculating the daily mean temperature for each grid cell, then taking the spatial mean across all grid cells that were wholly or partially within the suburb boundary.

We used the heatwave definition and categorisation of the Australian Bureau of Meteorology which is based on daily calculation of the Excess Heat Factor (EHF) index for each suburb. The EHF is based on the deviation of the 3-day forecast average temperature from the short- and long-term temperature observations at a given location, and has been described in detail elsewhere (Nairn & Fawcett 2015a). The Australian Bureau of Meteorology uses the EHF to define three levels of heatwave intensity: extreme, severe, and low-intensity (Bureau of Meteorology 2019a).

4.4.3 Covariate data

Health outcomes associated with heatwaves may be confounded with those associated with elevated air pollution. This is because landscape fires producing elevated air pollution (which are often concurrent with heatwave events) have also been associated with ambulance callouts (Edwards et al. 2018; Johnston et al. 2019). We therefore included fine particulate matter with a diameter less than 2.5µm ($PM_{2.5}$) as a covariate. Relevant air pollution data were obtained through the Environmental Protection Agency (EPA) Tasmania's air quality monitoring network, the Base Line Air Network of EPA Tasmania (BLANkET). Ambient 24-hour (midnight to midnight) average concentrations of $PM_{2.5}$ were used, with missing data linearly interpolated using the na.approx() function from the 'zoo' package in R (Zeileis et al. 2019). Suburbs from the ambulance dataset were matched with BLANkET air monitoring station locations around Tasmania, and mapped to the closest monitor within a 50 km radius. This produced a daily average 24-hour measurement of $PM_{2.5}$ for each suburb for each day, where available.

Public holidays were also included as a covariate, with state-wide public holidays for Tasmania obtained using the Python 'holidays' package (Montel 2019). Holiday periods influence both exposure behaviours and health service availability, potentially influencing demand for ambulance services.

4.4.4 Study design

We used a time-stratified case-crossover study design, where individual dispatches, rather than days, are the unit of control and each person acts as their own control (Maclure 1991). This method is commonly used in environmental epidemiology for examining the health impact of short-term exposure events (Jaakkola 2003), and has been used for similar studies analysing the health impact of heatwave events (Campbell et al. 2019; Wang et al. 2012). Threats to validity of this method, as outlined in Maclure (1991) are further described in Appendix C: Threats to validity of the case-crossover method.

4.4.5 Statistical analyses

For the statistical analysis, we used conditional multivariate logistic regression using the clogit() function from the 'survival' package in R (Therneau & Lumley 2020). We calculated the odds ratio (OR) and the 95% confidence intervals (CI), for the association between extreme, severe and low-intensity heatwave events and ambulance dispatches.

We tested for associations with heatwaves for the entire study population and by the following subgroups:

- age group (0-5, 0-15, 16-65, over 65)
- sex
- diagnostic condition by paramedic assessment (see Table E.1 in Appendix E: Supplementary data for Chapter 4 for conditions associated with each diagnostic group)
- Socio-Economic Index for Areas (SEIFA) category (by suburb of incident).

While potential confounders such as state-wide public holidays and $PM_{2.5}$ by suburb of incident were included as covariates in the analyses, other potential confounders such as day of week, season, smoking status and age were controlled by the time-stratified, case-crossover study design.

4.5 Results

From 1 January 2008 to 28 February 2019, 593,117 urgent and emergency ambulance dispatches were documented in Tasmania. Table 4.1 shows the number and distribution of these dispatches across various population characteristics and diagnostic groups.

Table 4.1: Characteristics of ambulance dispatches in Tasmania, Australia (Jan 2008-Feb 2019)

Population characteristic/ diagnostic group	Number (% of total)	Mean daily presentations (SD)*	Median (IQR)^	Range
Whole study population	593 117 (100%)	145.5 (33.2)	150 (37)	25-227
Age				
≤5	26 304 (4.4%)	6.5 (3.1)	6 (4)	0-19
≤15	50 106 (8.4%)	12.3 (4.7)	12 (6)	0-31
16-65	296 230 (49.9%)	72.7 (17.5)	75 (20)	9-133
>65	242 673 (40.9%)	59.5 (15.9)	60 (20)	11-109
Gender				
Male	284 174 (47.9%)	69.7 (17.1)	71 (20)	12-123
Female	307 756 (51.9%)	75.5 (18.4)	78 (21)	11-124
SEIFA of suburb of dispatch				
Low	375 701 (63.3%)	92.2 (22.1)	95 (25)	16-153
Middle	144 111 (24.3%)	35.3 (9.6)	36 (12)	1-66
High	70 978 (12.0%)	17.4 (5.7)	18 (7)	0-40
All cardiovascular	67 023 (11.3%)	16.4 (5.2)	16 (7)	0-36
All respiratory	43 858 (7.4%)	10.8 (5.0)	10 (7)	0-40
All renal	2 743 (0.5%)	0.7 (0.9)	0 (1)	0-6
All diabetic	6 892 (1.2%)	1.7 (1.3)	2 (1)	0-8
All psychological	30 935 (5.2%)	7.6 (3.5)	7 (5)	0-25
Other heat-related	41 267 (7.0%)	10.1 (4.2)	10 (6)	0-30
Direct exposure to heat	573 (0.1%)	0.1 (0.4)	0 (0)	0-10

* SD: Standard deviation
^ IQR: Interquartile range

Extreme, severe, and low-intensity heatwaves were identified across Tasmania on multiple occasions and across all regions. Heatwave counts are illustrated in Figure 4.3, using data from the major population centres of Burnie (north-west), Hobart (south), Launceston (north), Queenstown (west), and St Helens (east). Heatwaves were most prevalent in the north of the state, as shown by Launceston and Burnie. Hobart, the most populated centre, experienced no extreme heatwave days and fewer severe and low-intensity days than other representative suburbs during the study period.

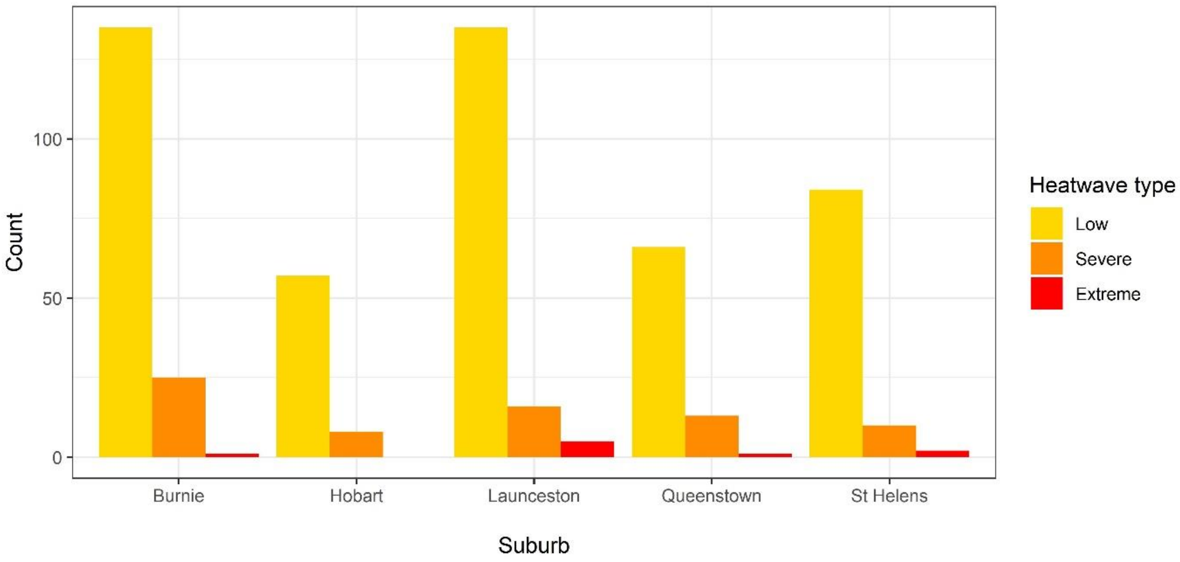


Figure 4.3: Number of heatwaves by major population centre, Tasmania, Australia (2008-2019)

Overall, we found that ambulance dispatches increased during heatwaves, with the magnitude of the association broadly associated with increasing heatwave intensity. Ambulance dispatches in the study population increased by 34% (OR 1.34, 95% CI 1.18-1.52) for extreme heatwave events; 10% (OR 1.10, 95% CI 1.05-1.15) for severe heatwaves; and 4% (OR 1.04, 95% CI 1.02-1.06) for low-intensity heatwaves (Table 4.2, Figure 4.4). When all heatwave events were combined across all heatwave types, ambulance dispatches increased by 6% (OR 1.06, 95% CI 1.04-1.08).

Associations between low-intensity heatwaves and ambulance dispatches were similar for males and females. While greater point estimates were observed in females during severe heatwaves and in males during extreme heatwaves, confidence intervals were widely overlapping in these less frequent heatwave types (Table 4.2, Figure 4.4).

When evaluating the pattern of association among different age groups, we observed greater associations in children up to 15 years and adults over the age of 65, and smaller increases in the 16-64 year age group. Results for children were less precise than for other age groups due to the smaller number of cases in this group. For children aged 5 years and under, ambulance dispatches increased approximately 36% in severe heatwaves (OR 1.36, 95% CI 1.10-1.68), and by nearly double this (64%) for extreme heatwaves but with much wider confidence intervals that included the null (OR 1.62, 95% CI 0.93-2.82). For children aged 0-15 years there were imprecise increases in the odds of ambulance dispatches of similar magnitude to that of the overall population (Table 4.2, Figure 4.4).

For adults older than 65 years, the magnitude of the association was similar to that observed for the entire population during low-intensity and severe heatwaves but disproportionately higher during extreme heatwaves, with an increase of 47% (OR 1.47, 95% CI 1.21-1.78) compared with 24% (OR 1.24, 95% CI 1.03-1.49) in adults 16-64 years, and 34% (OR 1.34, 95% CI 1.18-1.52) across the whole study population (Table 4.2, Figure 4.4).

There were also notable differences by socio-economic status, with regions of greatest disadvantage experiencing higher odds of ambulance dispatches in all types of heatwaves than the overall population (Table 4.2, Figure 4.4).

Less than half of all callouts were able to be allocated to a particular diagnostic group based on paramedic assessment. The number of cases in some diagnostic groups are therefore very small and results generally have lower precision. Despite this, direct heat-related conditions were strongly associated with all levels of heatwave intensity with very high odds of a dispatch during extreme heatwaves (OR 48.00, 95% CI 6.24-369.18). 'Other' heat-related conditions were associated with low-intensity (OR 1.09, 95% CI 1.02-1.17) and severe heatwaves (OR 1.43, 95% CI 1.20-1.70).

There were imprecise positive associations for cardiovascular conditions during low-intensity (OR 1.05, 95% CI 0.99-1.11) and extreme events (OR 1.42, 95% CI 0.98-2.06), with less precise elevations for respiratory (OR 1.05, 95% CI 0.97-1.13) and psychological conditions (OR 1.03, 95% CI 0.95-1.11) in low-intensity events. However, all results included the null.

Results were not meaningfully influenced by $PM_{2.5}$ at suburb of residence, nor by coincident public holidays (see Table E.2 in Appendix E: Supplementary data for Chapter 4 for presentation of crude and adjusted results).

Table 4.2: Associations between ambulance dispatches and heatwave events, Tasmania, Australia, 2008-2019 (adjusted for $PM_{2.5}$ and public holidays)

	Heatwave type OR (95% CI)		
	Low-intensity	**Severe**	**Extreme**
Whole study population	1.04 (1.02-1.06)***	1.10 (1.05-1.15)***	1.34 (1.18-1.52)***
Age			
≤5	1.06 (0.97-1.16)	1.36 (1.10-1.68)**	1.62 (0.93-2.82)
≤15	1.05 (0.98-1.12)	1.14 (0.97-1.33)	1.33 (0.85-2.08)
16-65	1.04 (1.01-1.07)**	1.07 (1.00-1.14)*	1.24 (1.03-1.49)*
>65	1.04 (1.01-1.07)**	1.13 (1.05-1.22)***	1.47 (1.21-1.78)***
Gender			
Male	1.05 (1.02-1.07)**	1.16 (1.09-1.24)***	1.26 (1.05-1.52)*
Female	1.04 (1.01-1.07)**	1.05 (0.98-1.12)	1.41 (1.19-1.68)***
Socio-economic status			
Low SEIFA	1.05 (1.03-1.08)***	1.10 (1.04-1.17)***	1.40 (1.18-1.65)***
Middle SEIFA	1.04 (1.00-1.08)*	1.09 (0.99-1.20)	1.30 (1.05-1.61)*
High SEIFA	0.99 (0.93-1.06)	1.12 (0.94-1.32)	1.11 (0.67-1.82)
Conditions			
Cardiovascular	1.05 (0.99-1.11)	0.99 (0.85-1.15)	1.42 (0.98-2.06)
Respiratory	1.05 (0.97-1.13)	1.07 (0.87-1.30)	0.84 (0.46-1.53)
Renal	1.08 (0.83-1.40)	0.63 (0.26-1.51)	1.20 (0.12-11.57)
Diabetic	1.09 (0.92-1.29)	1.26 (0.85-1.85)	2.18 (0.73-6.52)
Psychological	1.03 (0.95-1.11)	0.95 (0.77-1.17)	0.55 (0.26-1.16)
Other heat-related	1.09 (1.02-1.17)*	1.43 (1.20-1.70)***	0.98 (0.60-1.58)
Direct heat	3.19 (2.06-4.95)***	5.33 (2.73-10.41)***	48.00 (6.24-369.18)***

* p<0.05; ** p<0.01; *** p<0.001

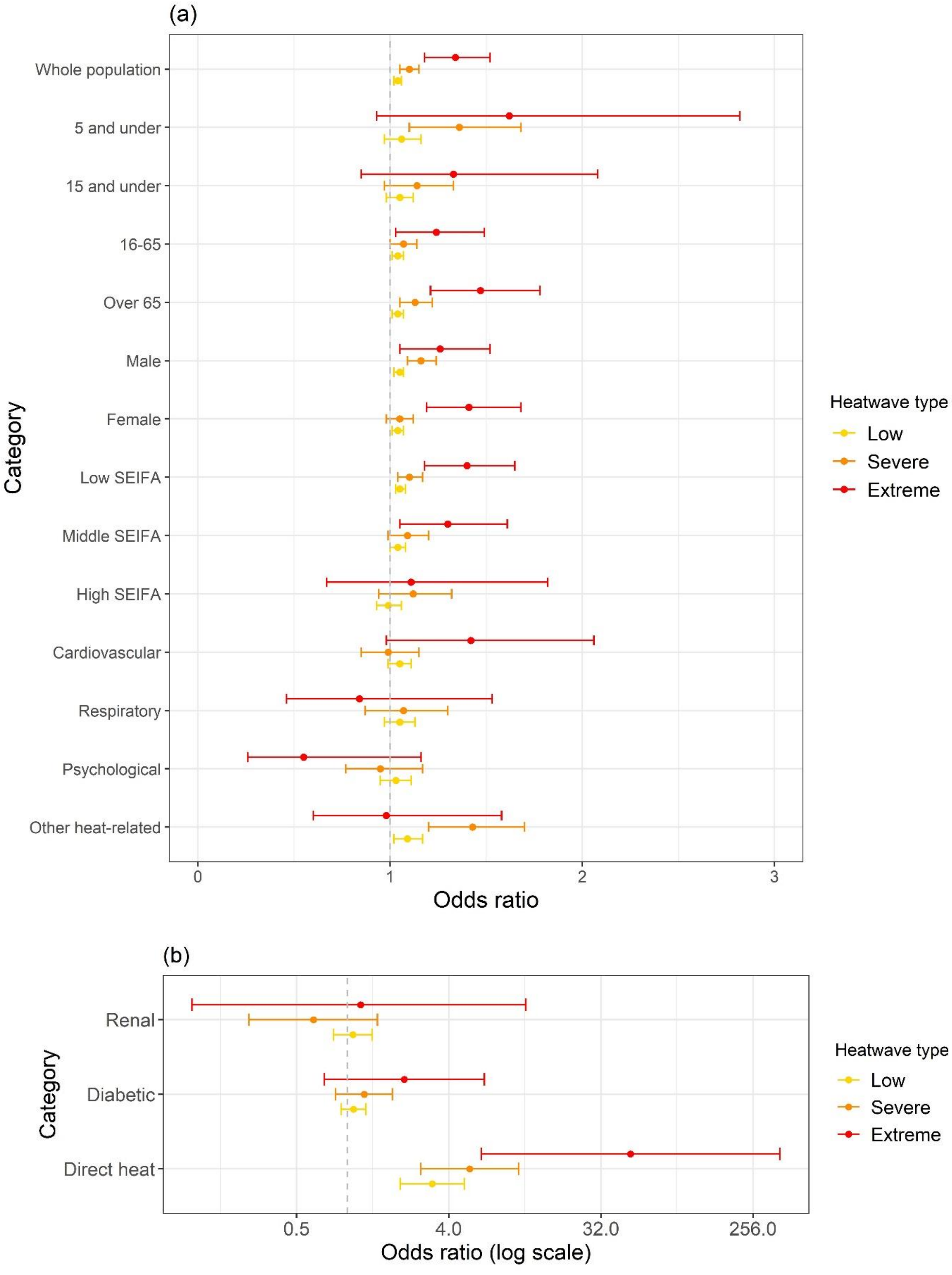


Figure 4.4: (a) Ambulance dispatches during heatwave events, Tasmania, Australia (2008-2019) using a numeric scale; and (b) Ambulance dispatches during heatwave events, Tasmania, Australia (2008-2019) for callouts relating to renal, diabetic and direct heat problems shown using a log scale to display the wide confidence intervals

4.6 Discussion

Our study found a statistically significant increase in ambulance dispatches in Tasmania, for all levels of heatwaves across the whole study population, and with greater effect sizes observed in people over 65 years, children up to 5 years of age, and in dispatches from areas with greatest socio-economic disadvantage. Large increases in dispatches were observed for conditions related to direct exposure to heat and other heat-related conditions. Less precise increases were observed for dispatches associated with cardiovascular conditions.

Strengths of our study include the relatively long timeframe used (11 years, 2 months), enabling the inclusion of multiple heatwaves rather than a small number of individual heatwave events. The use of paramedic assessment data rather than ambulance call centre data provides greater clinical accuracy, as these assessments are based on personal history and clinical examination following standard diagnostic protocols. The use of reanalysis temperature data by suburb across Tasmania, rather than observational temperature data from the nearest weather station, provides a more accurate heatwave calculation for all areas of Tasmania, including those remote from automatic weather stations. The relatively dense network of air quality monitoring stations enable adjustment for $PM_{2.5}$ which is known to influence ambulance utilisation in Tasmania (Edwards et al. 2018).

Limitations include the relatively small population of Tasmania, and the proportion of cases where it was possible to assign a clinical diagnostic group. This limited the statistical power and scope for more detailed analyses of sub-groups (for example, those who are both elderly and living with respiratory or cardiovascular conditions), which may provide further benefits to targeting health interventions. Outcome misclassification is another limitation in ambulance datasets, as facilities for detailed diagnoses (such as x-rays or blood tests) are limited. However, such misclassification is unlikely to be associated with the exposure, and would therefor bias results towards the null.

In this study, the indicator of socio-economic disadvantage was based on suburb of incident, rather than individual patient data. This has two limitations. The area level classification might not reflect that of an individual, and ambulance dispatches may not reflect the suburb of residence of the individual. Furthermore, older, remote and socially disadvantaged groups are more likely to use ambulance transport to hospital rather than other means of transport (Svenson 2000), therefore making this study less generalisable to the whole population who may use other means of transport to hospital or seek alternative forms of health care for similar conditions (for example, primary healthcare).

Our study results are broadly consistent with similar studies conducted in Australia, especially Turner et al. (2013), who found increases in ambulance dispatches in Brisbane during heatwaves for the whole study population, for those over 65, and for those with cardiovascular and respiratory conditions. Other studies examining the association between ambulance dispatches and heatwaves conducted in Adelaide (Nitschke et al. 2011a) and Sydney (Schaffer et al. 2012b) show similar patterns to this study with increases in all-cause ambulance attendances during heatwave events of 16% and 14% respectively for specific heatwave events in those regions.

Within Tasmania, this study is consistent with previous work showing a positive association between heatwaves and emergency department presentations (Campbell et al. 2019; Watson, Gardiner & Singleton 2020) and a positive association between maximum temperature and symptom reporting rates of asthma and hay fever (Jones et al. 2020), therefore adding further evidence regarding the local impact of extreme heat events while demonstrating the range of health impacts from extreme temperatures.

More widely, international studies examining the association between ambulance dispatches and heatwaves demonstrate a general trend towards increased dispatches during heatwave events, with local variations concerning demographics and conditions. For example, Kue and Dyer (2013b) found a significant overall increase in dispatches during heatwave-days in Boston, USA, however no change in the types of calls, except for direct heat-related conditions. Onozuka and Hagihara (2016) found a significant overall increase in all-cause attendances and respiratory disease, and a non-significant increase for cardiovascular disease in Japan. In China, Bai et al. (2014)

found a greater impact for males, the elderly and children during selected heatwave events, although all age groups showed elevated risk. These variations in outcomes could reflect differences in population, health care accessibility or differences in study design.

With respect to other healthcare outcomes such as deaths and hospital admissions, our study follows a similar worldwide trend showing an association between heatwaves and poor health outcomes, especially for the young, the elderly and those with co-morbidities (Xiaofang et al. 2012; Xu et al. 2016). Consistency among these studies, which use different analysis methods and were conducted in different climates, demonstrate some coherence in the limited body of evidence concerning ambulance services, and increases the overall confidence in our findings.

Locally targeted research such as this study strongly supports policy decisions regarding surge capacity planning for ambulance services in the immediate region. Heatwave events are forecast from three days prior to the event, allowing for achievable lead times for rostering and capacity changes. Furthermore, identification of high-risk groups allows for a targeted approach to health promotion messages around heat safety, with the aim of reducing incidences of heat illness and therefore ambulance attendances in heatwave events.

Future research in this area could include an analysis of associations between GP attendances and heatwaves, and between heatwaves and mortality, giving a more complete understanding of how heatwaves impact health outcomes and health care systems in Tasmania. Furthermore, an economic analysis of this impact would be useful to understand the burden of extreme heat events on the health system in Tasmania.

4.7 Conclusion

Heatwaves create increased health service utilisation and pose a health risk to the Tasmanian population, with the elderly, the young and those most disadvantaged at greatest risk. With a warming climate, and heatwaves projected to be greater in frequency and intensity into the future, this burden is also likely to increase. This information is useful for ambulance services to prepare for surge capacity in future heatwaves events.

Chapter 5:
Evaluating the risk of epidemic thunderstorm asthma: Lessons from Tasmania, Australia

5.1 Preface

This chapter describes a second type of climate-related extreme event with overwhelmingly poor health outcomes: epidemic thunderstorm asthma (ETA). These events are relatively rare and therefore poorly understood. This chapter examined if any undetected events had occurred in Tasmania in the past, and the likelihood of these events occurring in the future. This research was undertaken in direct response to an ETA event occurring in Melbourne in November 2016, and subsequent interest by Tasmanian public health policymakers regarding the risk of a local ETA event.

While distinct from extreme heat events and their impact on the health care system, this research topic has a well-considered place within the Kaufman and Carl framework, demonstrating the depth of application that a research translation framework can provide. As these research findings inform and enable health policy implementation, this chapter acts as an example of Stage 4 (see Figure 5.1). This stage describes a number of interventions which apply to public health policy, from systems change, to interventions in a community or social setting, to recommendations for individual action.

The risk assessment undertaken in this chapter provides the groundwork for recommendations on the extent and type of interventions needed to match the evaluated risk, both at a local level and in response to a nearby catastrophic event. Without this research, it is uncertain as to the scope and coverage that public health policy should traverse, for example, should a highly-resourced warning system be established, as has been implemented in Victoria? Or is community education of ETA episodes a more effective intervention? Assessing the population risk, as outlined in this chapter, make this policy response clear.

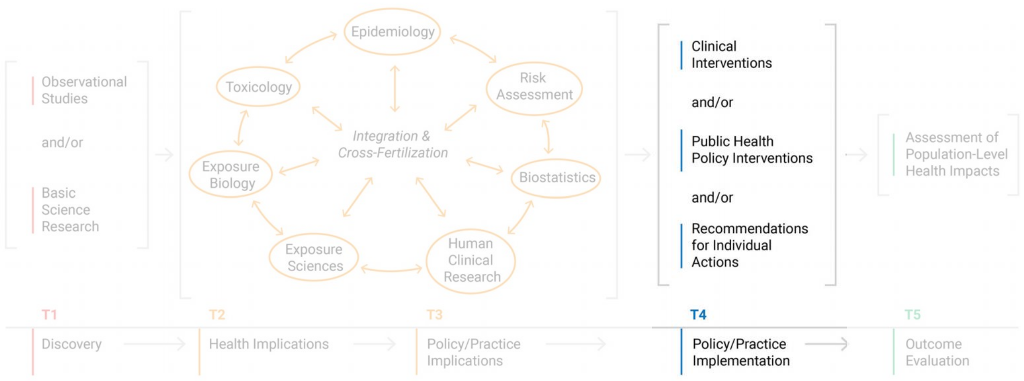


Figure 5.1: Kaufman and Curl (2019) environmental health translational research framework, Stage 4

This chapter has been reproduced as published (with minor additions) in Campbell, SL, Fox-Hughes, PD, Jones, PJ, Remenyi, TA, Chappell, K, White, CJ, Johnston, FH 2019, ‘Evaluating the Risk of Epidemic Thunderstorm Asthma: Lessons from Australia’, *International Journal of Environmental Research and Public Health*, vol. 16, 837.

5.2 Abstract

Epidemic thunderstorm asthma is an emerging public health threat in Australia, highlighted by the 2016 event in Melbourne, Victoria, that overwhelmed health services and caused loss of life. However, there is limited understanding of the regional variations in risk. We evaluated the public health risk of ETA in the nearby state of Tasmania, by quantifying the frequency of potential ETA episodes and applying a standardised natural disaster risk assessment framework. Using a case-control approach, we analysed emergency presentations in Tasmania’s public hospitals from 2002 to 2017. Cases were defined as days when asthma presentations exceeded four standard deviations from the mean, and controls as days when asthma presentations were less than one standard deviation from the mean. Four controls were randomly selected for each case. Independently, a meteorologist identified the dates of potential high-risk thunderstorm events. No case days coincided with thunderstorms during the study period. ETA was assessed as a very low risk to the Tasmanian population, with these findings informing risk prioritisation and resource allocation. This approach may be scaled and applied in other settings to determine local ETA risk. Furthermore, the identification of hazards using this method allows for critical analysis of existing public health systems.

5.3 Introduction

Epidemic thunderstorm asthma (ETA) is seen as an emerging public health threat in Australia and other parts of the world, creating the need to develop a sustained level of community resilience and preparedness in affected regions (Victorian Government 2017b).

The mechanism of ETA, described in detail elsewhere (Marks & Bush 2007; Marks et al. 2001; Taylor & Jonsson 2004), involves the concurrent presence of (a) aeroallergens (for example, pollen, ruptured pollen or fungal spores), (b) specific weather conditions (thunderstorms and strong wind gusts) and (c) a susceptible population group who are sensitised to the aeroallergen and have a history of allergic rhinitis or asthma (Davies et al. 2017) (see Figure 5.2, adapted from Davies et al. (2017)).

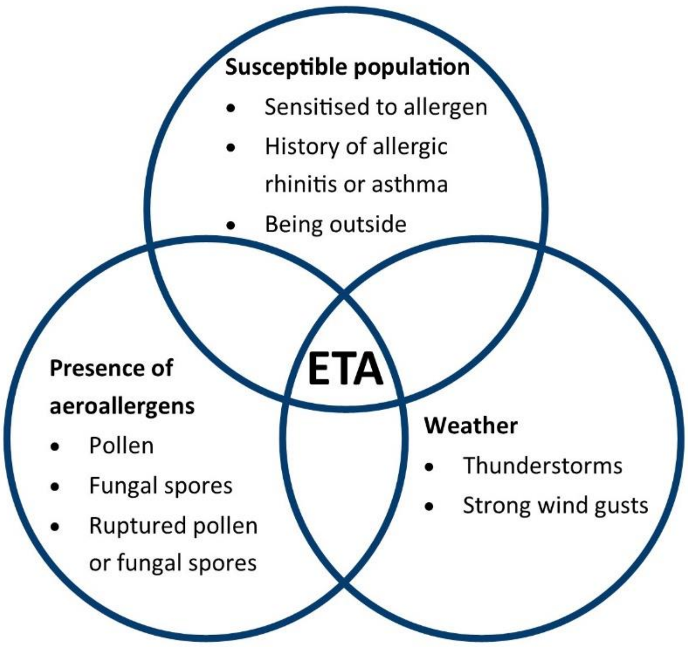


Figure 5.2: Intersection between aeroallergens, specific weather conditions and a susceptible population, giving rise to a potential ETA event

Due to the requirement for the concurrent presence of these three components, ETA events are very rare, having been recorded on only ten occasions in south-eastern Australia: seven times in Melbourne (Victoria), and once in Canberra (Australian Capital Territory), Newcastle (New South Wales) and Wagga Wagga (New South

Wales) respectively (Davies et al. 2017). Twelve notable events have been recorded in other areas of the world (Davies et al. 2017), with a number of additional studies also showing a positive association between asthma presentations and thunderstorm events (Dabrera et al. 2013). These may potentially indicate further previously undetected ETA events.

Each of the Australian events has caused an increase in emergency department presentations and/or admissions (Davies et al. 2017). The most striking of these events occurred in Melbourne, Victoria, on 21 November 2016, which caused an exceptional level of demand on ambulance and hospital services and a number of deaths (Thien et al. 2018; Victorian Government 2017b). This event was widely publicised, with considerable media commentary provided about the community impact, emergency response and steps needed to reduce the impact of this event in the future (Davey 2016; Marks 2016; Wood 2017). In response, a substantial research investment in forecasting and predicting these events was provided by the Victorian Government (Victorian Government 2017a). In addition to research assessing the public health impact, this rare event was examined in detail from a meteorological perspective (Grundstein, Shepherd & Miller 2017).

The thunderstorm complex associated with the 2016 Melbourne event moved south and crossed Bass Strait, passing over northern Tasmania (including the population centres of Burnie and Launceston). Investigations at the time showed no increase in ambulance or emergency department activity in those Tasmanian regions, in contrast to the severe health outcomes in Melbourne. However, the severity of the Melbourne event—and its proximity to Tasmania—prompted significant local concern about the potential for an ETA event to occur in the state. This was highlighted by the extensive traditional and social media response to a subsequent thunderstorm asthma warning issued by the Tasmanian Department of Health and Human Services one year later (Billings 2017; Department of Premier and Cabinet 2017; Monery 2017). In this context, public health policymakers identified a gap in understanding how and where these events occur in Tasmania, and to what degree they pose a risk. This study seeks to redress this gap and create an assessment methodology that can be applied across other at-risk regions.

5.3.1 Study location

Tasmania is the only island state of Australia. Melbourne, Victoria, lies approximately 300 km north of the state's north coast, separated by Bass Strait. The majority of the Tasmanian population resides in a regional or remote classified area (Australian Bureau of Statistics 2011). The state's total population in 2016 was 510 000, with the majority of the population residing in one of three major centres: Hobart (population 204 000), Launceston (population 84 150) or Burnie-Devonport (population 70 000) (Australian Bureau of Statistics 2017).

Tasmania has four major public hospitals located in the most densely populated regions of the state—one located in Hobart (Royal Hobart Hospital); one in Launceston (Launceston General Hospital); and two in the Burnie-Devonport region (the Mersey Community Hospital and the North West Regional Hospital). Each of these hospitals has an emergency department.

5.3.2 Thunderstorms in Tasmania

In contrast to continental south-eastern Australia, Tasmania has a more maritime and temperate climate, with less frequent thunderstorms overall (Kuleshov et al. 2002). In particular, Tasmania experiences fewer 'dry microburst' thunderstorms that can potentially generate strong wind gusts (Allen & Karoly 2014). Furthermore, the Tasmanian topography and predominantly westerly-flowing air mass influence the occurrence and location of thunderstorms across the state. More storms are reported in the west and north of the state as air is forced to ascend when these air masses encounter the Tasmanian landmass, and this ascent is conducive to the development of thunderstorms under some conditions. In contrast, these same westerly winds descend along the contour of the landscape into south-eastern Tasmania, rendering thunderstorms less common in this region (Jones 1990; Kuleshov et al. 2002).

5.3.3 Pollen in Tasmania

With respect to pollen abundance, there are both similarities and differences between Tasmania and mainland south-eastern Australia that are relevant for understanding ETA risk. Grass pollen—and in particular, rye grass pollen—is the major aeroallergen implicated in previous Australian thunderstorm asthma events (Bellomo et al. 1992; Davies et al. 2017; Marks et al. 2001). Although levels are typically lower than in mainland south-eastern Australia (Haberle et al. 2014), grass pollen is prevalent across Tasmania during the peak season of November to January (Johnston et al. 2018; Tng et al. 2010) (see Figure 5.3, Panel B). As rye grass is an important pasture grass species (Lane et al. 2015), a significant proportion of this is highly likely to be rye grass-derived. Beyond grass pollen, Tasmania also experiences seasonally high loads of several other aeroallergens, including *Betula* (birch), Cupressaceae (cypress) and *Plantago* (plantain) (Johnston et al. 2018; Tng et al. 2010). These have peak seasons that are different from peak grass pollen season. Overall, this means Tasmania experiences generally high pollen conditions—though not necessarily high grass pollen concentrations—from approximately July through to January (Johnston et al. 2018) (see Figure 5.4).

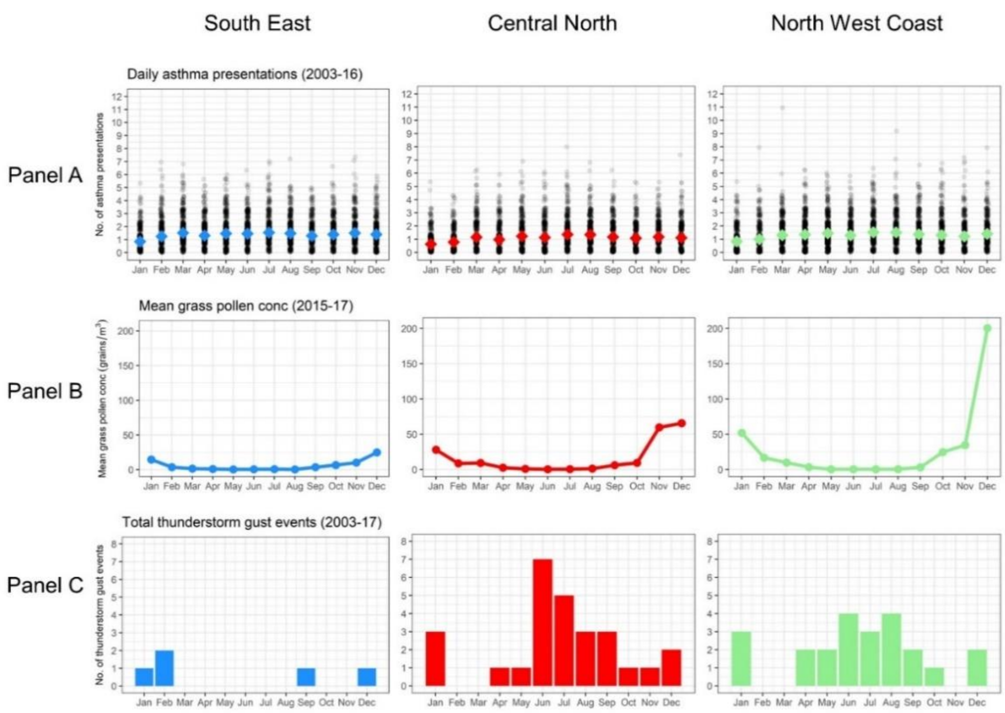


Figure 5.3: Daily asthma presentations (Panel A) (Source: Tasmanian Health Service), mean grass pollen concentrations (Panel B) (Source: unpublished AirRater data) and total thunderstorm asthma gust events (Panel C) (Source: Bureau of Meteorology) for each of the relevant Tasmania forecast districts (South East, Central North and North West Coast)

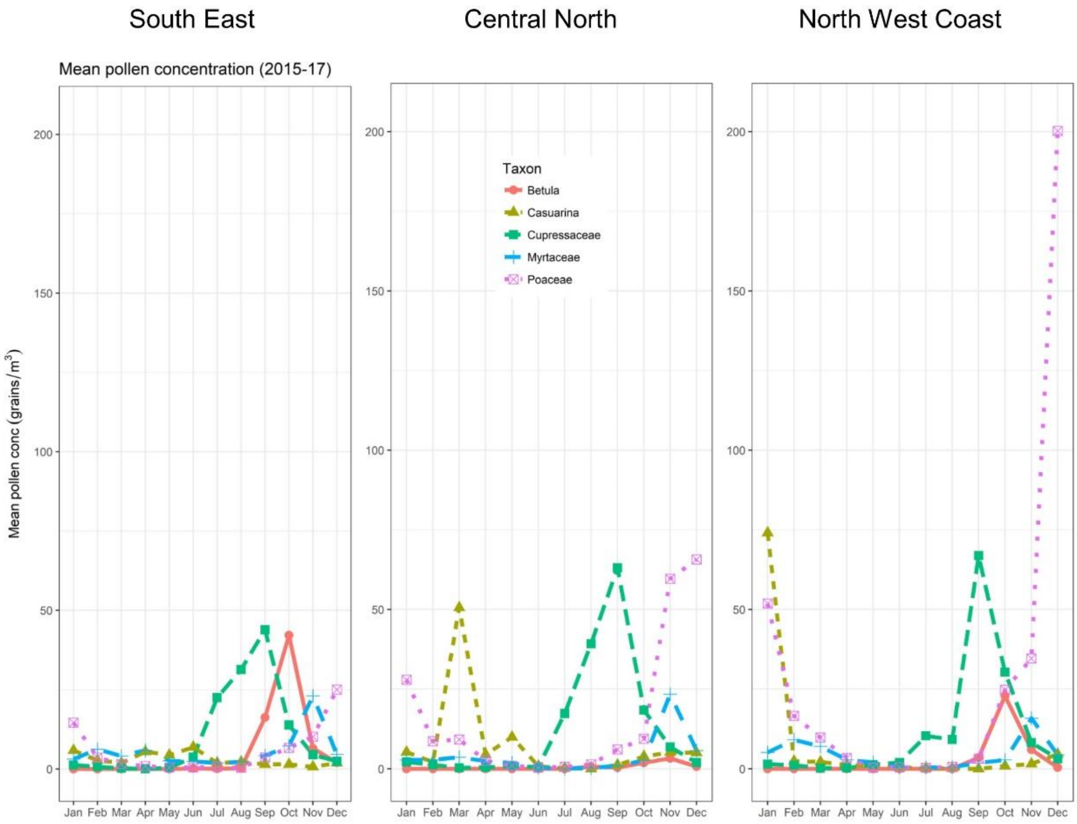


Figure 5.4: Pollen counts for each relevant Tasmanian forecast district showing the five major taxa (Source: unpublished AirRater data)

5.3.4 Natural disaster risk assessment in the Tasmanian context

Tasmania's natural disaster risk is assessed using the Tasmanian State Natural Disaster Risk Assessment (TSNDRA) framework that aims to "produce a state-wide priority natural hazard risk assessment, in accordance with the relevant International and Australian standards" (White et al. 2016). This framework is consistent with the 2015 National Emergency Risk Assessment Guidelines (NERAG), the Australian standard for natural disaster risk assessment (Commonwealth of Australia 2015), and complies with a number of relevant risk management standards (White et al. 2016). Similar frameworks exist globally (Federal Office for Civil Protection 2015; Organisation for Economic Cooperation and Development 2018).

The TSNDRA framework was most recently updated in 2016, assessing state-wide natural disaster risks for the following hazards: bushfire, flood, severe storm, landslide, tsunami, earthquake, heatwave, coastal inundation and pandemic influenza (White et al. 2016).

TSNDRA uses five ‘impact sectors’ to determine the overall risk for each hazard. These sectors cover a range of consequences across a broad spectrum of outcomes, including ‘People’, ‘Economic’, ‘Environmental’, ‘Public administration’ and ‘Social setting’. For more information on these sectors and how they translate to the Tasmanian context, see Appendix F: Natural disaster risk assessment in Tasmania.

To assess a hazard’s overall risk level, the likelihood and consequences of the risk are ascertained for each sector and plotted on a risk matrix. The confidence of each of these plots is then assessed based on available evidence. Finally, a priority level is set, based on the risk level and confidence associated with that risk.

5.3.5 Research aim

The aims of this study were to (a) understand the history of ETA events in Tasmania (and determine if any undetected ETA events had occurred in the study period), and (b) apply these results to the TSNDRA framework and determine the risk of these events, specifically the public health risk, in the Tasmanian context. This will determine the effectiveness of applying this methodology to other regions at risk of ETA events.

5.4 Materials and methods

5.4.1 Study design

In order to understand the history of thunderstorm asthma events in Tasmania, we adapted the case-control design used by Marks et al. (2001), in which the unit of analysis is a day rather than an individual person. Using this approach, Marks et al. discovered a number of previously undetected ETA events in central New South Wales, in cities with similar-sized populations to Tasmania’s major centres. This demonstrates the capacity of this approach to detect ETA events in analogous demographic contexts. Here, we employed a similar study design, modified to accommodate the different climatic and geographical setting of Tasmania. We use the results of this study to assess risk in the Tasmanian context using the TSNDRA framework.

5.4.2 Health outcomes

We obtained emergency department (ED) presentation data for public hospitals in Tasmania from the Tasmanian Health Service (THS) for the Royal Hobart Hospital, Launceston General Hospital, Mersey Community Hospital and the North West Regional Hospital. Due to the small size and close proximity of the two hospitals in the north-west region, we combined data from the Mersey Community Hospital and North West Regional Hospital to represent the entire north-west. Data were extracted for the period from 20 December 2002 to 30 June 2017.

Ambulance data (call centre data and paramedic assessment data), and hospital admission data were also examined as potential sources of health outcome data. ED presentation data was chosen as the best candidate, with both good clinical robustness and a large enough dataset to detect case days.

Presentations were identified where International Classification of Disease (ICD) codes for asthma were given as the primary diagnosis (J45, J45.0, J45.1, J45.8, J45.9 and J46). We estimated expected daily attendances for each region using a log linear model. Modelling included accounting for linear, quadratic and cubic time trends (including overall time trends), seasonal factors and day of the week effects. Case days were identified when the daily presentations for asthma exceeded four standard deviations (SD) from the expected value. Control days were randomly selected from all dates where the number of ICD-coded asthma presentations were less than one standard deviation from the expected value. A sensitivity analysis also examined case days where daily presentations for asthma exceeded five standard deviations. For each case day, four times the number of control days were generated. To account for potential differences in coding and to provide a more sensitive analysis, we also separately analysed ICD-coded presentations for wheezing (R06.2) and dyspnoea (R06.0). Specifics of each case (for example gender, age, type of asthma) were not considered in this analysis, as the total number of cases was the variable of interest.

5.4.3 Meteorological data

Weather observation data were obtained from the Global Position and Tracking System (GPATS) and Bureau of Meteorology (BoM) automatic weather stations (AWS).

We combined lightning data from GPATS and wind data from AWS to identify likely thunderstorm gust events close to populated regions of Tasmania. Sixteen AWS were identified in the three BoM forecasts districts (South East, Central North and North West Coast) that most closely matched the major population centres feeding the four public hospitals (see Figure 5.5).

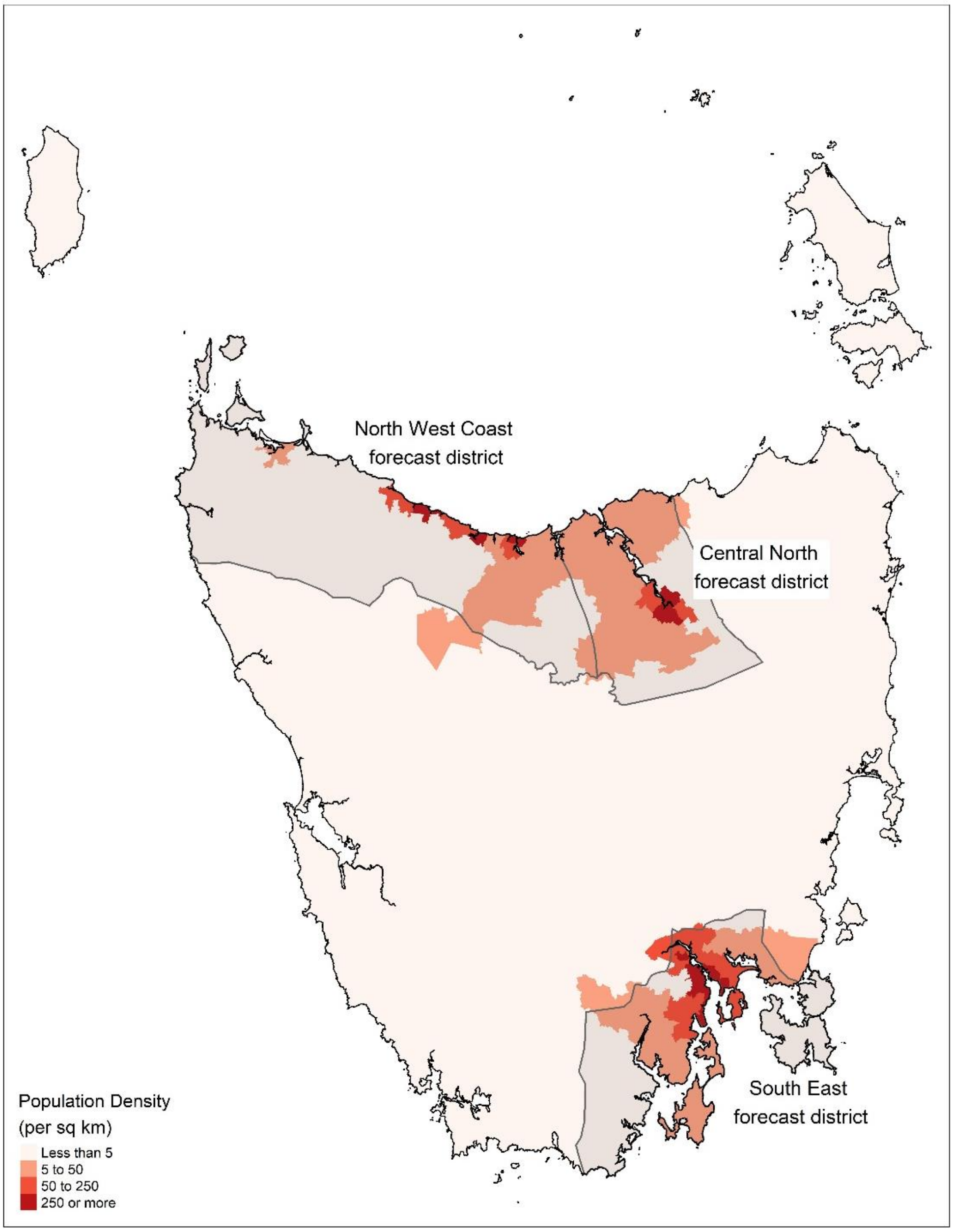


Figure 5.5: Population density in Tasmania and BoM forecast districts used in this study

The topography of Tasmania is vastly different to that of inland New South Wales, with Tasmania mostly displaying a rugged landscape of hills and valleys compared to the relatively flat plains of central New South Wales. To reflect this difference, the radius of influence of a thunderstorm gust event on a population centre used in Marks et al. (2001) (80 km) was reduced. Here, we identified a thunderstorm gust event if (1) a lightning strike occurred within a 0.1 degree rectangle (approximately 10 km) of an AWS location, and (2) a wind gust in excess of 60 km/h was recorded by the AWS within 10 minutes of this lightning strike. We also employed a sensitivity test to increase the strike range to within a 0.2 degree rectangle (approximately 20 km) and increase the time differential to 20 minutes, while keeping the gust strength at 60 km/h.

The list of combined asthma case and control days was given to the meteorologist, who was blinded to which days were case or control. The meteorologist then compared these days to the identified thunderstorm gust days to determine any overlap.

5.4.4 Risk assessment

Using the TSNDRA framework (White et al. 2016), we analysed likelihood and consequence for each sector to determine the combined overall risk. For consequence levels, results of the Tasmania case-control ETA event study informed the 'People' sector. Learnings from the Melbourne 2016 ETA event (Thien et al. 2018; Victorian Government 2017b) and other post-disaster research (Commonwealth of Australia 2011; Noji 2000; Thornley et al. 2015) informed the remaining sectors. For more information, see Appendix F: Natural disaster risk assessment in Tasmania.

5.5 Results

5.5.1 Health outcomes and meteorological data

Daily emergency department presentations for asthma for the three major population centres, as well as for the state as a whole, were analysed (see Figure 5.3, Panel A). For this analysis only, dates in 2002 and 2017 were eliminated to allow for complete years of analysis (i.e. 1 January 2003 to 31 December 2016). A similar analysis was performed on ambulance data (call centre and paramedic data) and hospital admission data, with only ED presentation data reported here.

In Tasmania, asthma presentations remained relatively steady throughout the year and across regions, with the coldest months of July and August demonstrating the highest rate of presentations. The lowest rates for all regions occurred in January, which is the warmest month. This is generally consistent with the global pattern of seasonality in asthma (Chen, Xirasagar & Lin 2006; Lincoln et al. 2006; Silver et al. 2018; Silverman, Stevenson & Hastings 2003).

A total of 5307 days and 2 107 594 presentations were analysed for the whole study period. We found 19 979 asthma presentations across all regions and identified asthma case days in all regions. The total number of presentations, mean number of daily presentations, maximum number of daily presentations, and the number of case and control days for each hospital is presented in Table 5.1.

Table 5.1: ICD-coded asthma total presentations, daily presentation mean, maximum and number of case and control days for each hospital

Hospital	Total presentations	Daily mean[1]	Daily maximum	No. of case days	No. of control days
Royal Hobart	7268	1.37	7	10	40
Launceston General	5807	1.09	8	16	64
MCH/NWRH[2] combined	6904	1.30	11	11	44

[1]unadjusted daily mean
[2]Mersey Community Hospital/North West Regional Hospital

We also found ICD-coded presentations for wheezing and dyspnoea in all regions. However only 462 cases of wheezing and 2562 cases of dyspnoea were observed across the whole study period. Given the low number of these cases, wheezing and dyspnoea presentations were not analysed further.

Figure 5.3, Panel C shows the total number of days per month during the study period where thunderstorm gust events were identified for each BoM forecast district. Thunderstorm gust events were rare in the South East forecast district all year round. Events were more common in the Central North and North West Coast forecast districts, with the majority occurring in the winter period.

There was no overlap between days where daily asthma presentations exceeded four SDs (case days) and thunderstorm gust events. Only one control day was identified in the South East district that overlapped with an identified thunderstorm gust event, and none in the other two districts. On this basis, no ETA events were identified in Tasmania during the study period.

5.5.2 Risk assessment

Table F.1 (see Appendix F) shows the consequence categories for each sector using the TSNDRA framework, mapped against the likely outcomes of an ETA event in Tasmania and the evidence for these outcomes. We assigned a consequence rating of 'Insignificant' across all sectors.

Based on the Tasmanian case-control ETA event study, we determined the likelihood of an event occurring in Tasmania was rare (occurring once every 100-1000 years) to very rare (occurring once every 1000-10 000 years) (White et al. 2016).

Using the TSNDRA framework and combining the consequence and likelihood outcomes, we determined ETA events have an overall risk rating of 'very low'. Confidence in this result is high. This hazard is the lowest-ranked risk across all nine hazards examined in the TSNDRA framework (White et al. 2016) (see Figure 5.6).

For each of the hazards in Figure 5.6 described in the 2016 TSDNRA (i.e. all except ETA), the results range was derived from a comprehensive series of workshops and a stakeholder consultation process. As an equivalent process was not available for this specific hazard, we have not included the results range for ETA in Figure 5.6.

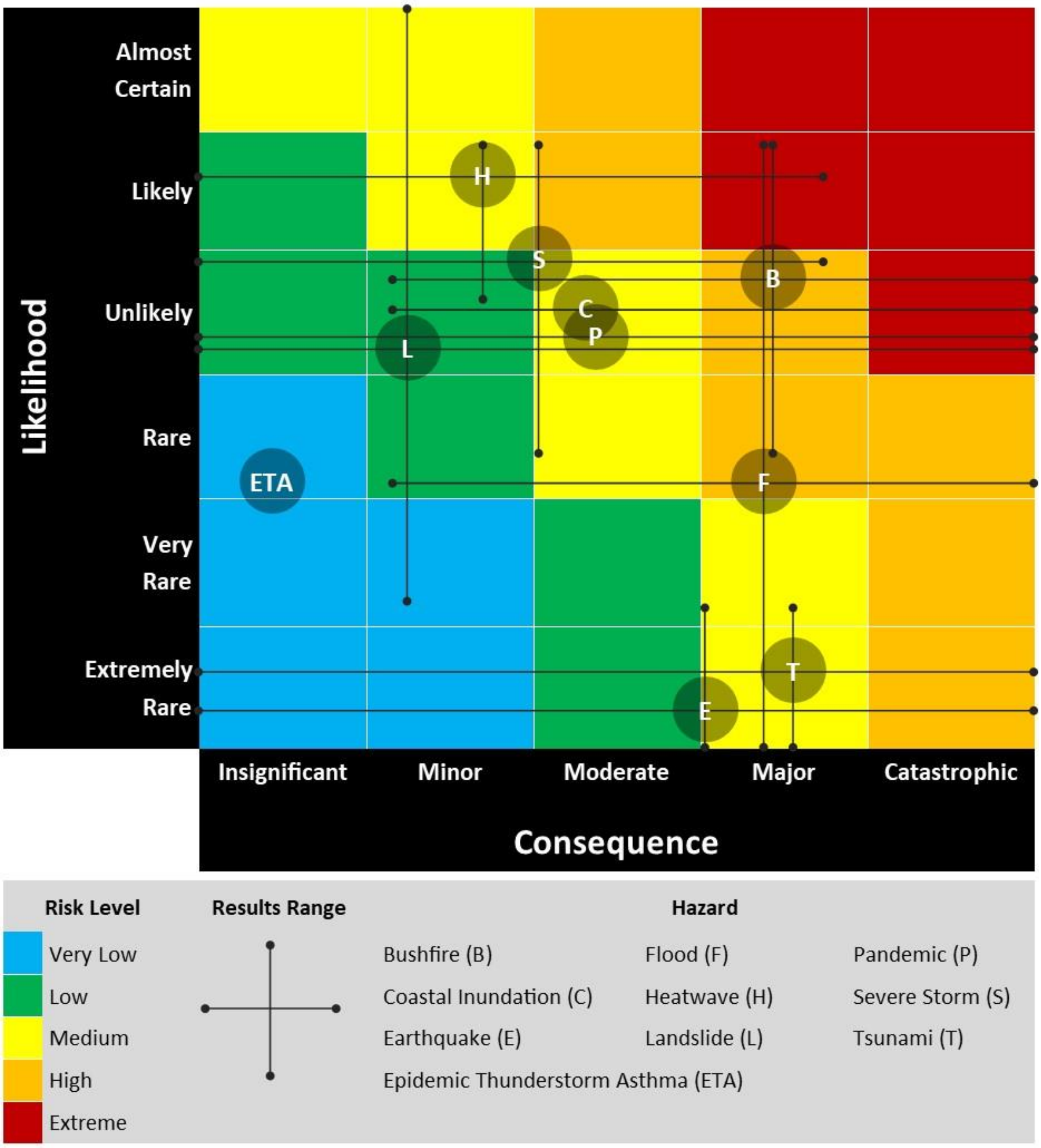


Figure 5.6: Summary of the risk level posed by each hazard as assessed in the 2016 Tasmania State Natural Disaster Risk Assessment (TSNDRA), adapted from White et al. (2016) to include ETA risk as determined by this study

In specifically examining the public health risk of ETA events, we determined a risk level of 'very low' for both the 'People' and 'Social setting' sectors, and 'insignificant' for the other three sectors (Economic, Environment and Public Administration). Across all sectors, ETA events ranked in the lowest level of risk when compared to all natural hazards examined within TSNDRA 2016 (White et al. 2016).

5.6 Discussion

The results show that there were no ETA events in Tasmania during the 14.5-year study period. Using the TSNDRA framework, ETA events were categorised as a very low public health risk and a very low risk overall. Furthermore, we found that thunderstorm gust events are uncommon in the more densely populated south-eastern region of Tasmania compared to the less densely populated north and north-west regions of the state, therefore reducing the likelihood of these events happening over a population centre. In addition, the north of Tasmania experiences thunderstorm gust events most commonly in winter, outside the high grass pollen season.

This study uses a previously published methodology (Marks et al. 2001), adapted for Tasmania's geography and topography. Blinding of the meteorologist to epidemic case days ensured unbiased interpretation of results. Application of a standardised risk assessment framework for natural disasters, as exists in other locations (Federal Office for Civil Protection 2015; Norwegian Directorate for Civil Protection 2014; Organisation for Economic Cooperation and Development 2018), makes this a robust and globally transferable model against which to measure this risk. Furthermore, this method can be easily scaled to allow investigation across variety of spatial locations, making it applicable for both smaller and larger regions.

The results of this study rely on the somewhat limited understanding of the underlying science of ETA events. While coincident high grass pollen and thunderstorm gust events are incorporated in the working theory for these event triggers, the actual mechanism for ETA events has not been conclusively proven (Davies et al. 2017). It is possible that another, as yet undiscovered mechanism has a contribution to ETA events, and this factor (or combination of factors) is not currently incorporated into the methodology.

Pollen data were not examined in detail for this study. As the aim of this study was to determine if any undetected ETA events had occurred in the study period, analysis of pollen data was not required. While pollen data exists for some areas of Tasmania (Johnston et al. 2018; Tng et al. 2010), the available data does not cover the complete

14.5-year period of this study, nor for all regions of the state examined in this research. If ETA events had been detected in this study, it may have been of value to examine any available pollen data related to these events. Given a focus on the identification of epidemic thunderstorm asthma, this study does not examine the interaction between the prevalence of asthma cases and other air quality variables, such as particulate matter, wind speed, temperature or humidity. Similarly, the impact of thunderstorms on other forms of illness or injury was not examined.

The study covers a period notably longer than other similar case-control studies examining thunderstorm events and health outcomes (Higham et al. 1997; Ilias 1998; Marks et al. 2001). This allows for a more thorough examination of the temporal influences and trends impacting the result. Examining thunderstorm gust event data over this extended period has allowed for observations on frequency and timing of these events across the regions, which has further contributed to understanding risk levels.

By understanding the public health and overall state-wide risk of ETA events, policymakers are now able to determine the most appropriate local policy response to this threat, especially in a setting of finite resources and multiple and competing risk priorities. With a risk rating of 'very low', placing a low priority on addressing the risk of ETA events in Tasmania may be seen as a valid course of action. However, analysis of such events allows policymakers to examine the robustness of existing public health and emergency response systems when exposed to similar threats, from both known and unknown sources.

In Tasmania, asthma is a serious and common health condition, with over 12% of the population currently affected (Australian Bureau of Statistics 2015), and over 25% reporting they have been diagnosed with asthma at some point in their lives (Department of Health and Human Services 2017). Nineteen people died from asthma in Tasmania in 2016 (Australian Bureau of Statistics 2016b), compared to nine people in the Melbourne ETA event (Victorian Government 2017b). Upskilling the community in asthma management more generally is likely to have a sustainable and long-term impact and reduce the burden of this disease both within the context of an ETA event and more broadly across the community.

The contribution of environmental factors to higher than average daily asthma presentations is not fully understood and further research is needed in the Tasmanian context. Potential contributors may include air pollution, weather extremes (including wind, rainfall or temperature), high aeroallergen levels, or circulation of respiratory viruses such as colds or influenza in the community, influencing winter peaks.

The impact of climate change on the risk of ETA events is yet to be fully assessed and understood. While it is likely that pollen seasons will increase in length due to a warming climate (Anenberg et al. 2017; Lake et al. 2017), potential changes to the frequency and/or severity of thunderstorms are more difficult to ascertain (Walsh et al. 2016). While thunderstorms and other similar weather patterns are likely to increase in severity and frequency as a result of a warming climate (Hoogewind, Baldwin & Trapp 2017; Romps et al. 2014), increased atmospheric stability may result in a slight decline in conditions favourable for lightning strike in Tasmania (Press 2016). Further research in this area is required.

5.7 Conclusion

In conclusion, no ETA events were identified during the 14.5 study period, and an examination of weather and pollen data against a standardised risk assessment framework suggests the coincidence of thunderstorm gust events with a high rye grass pollen season, occurring close to a susceptible population, is very low in Tasmania. Using a similar methodology and appropriate risk assessment framework, this study could be repeated in other locations, both nationally and internationally, to assess ETA risk in a consistent way. This study demonstrates how research can inform appropriate priority and resource allocation, especially in the public health sector.

Chapter 6:
Using digital technology to protect health in prolonged poor air quality episodes: A case study of the AirRater app during the Australian 2019-20 fires

6.1 Preface

This chapter takes a third type of climate-related extreme event—bushfires and consequential smoke exposure—and examines both the human health impacts of prolonged and severe bushfire smoke and the potential of smartphone app technology to reduce individual smoke exposure during these events, using the 2019-20 Australian bushfires and the AirRater app as a case study.

This research was developed in direct response to the unprecedented extreme bushfire and smoke events over the Australian summer of 2019-20. With a large uptake in the number of AirRater app users over this time, this was identified as a unique opportunity to gather knowledge about how people were using app technology in a time of severe and prolonged smoke exposure, with the prospect of informing recommendations for usage of the app across all regions of Australia.

By providing a suitable and evidence-based public health response in the face of these types of events, this chapter is directly applicable to the Tasmanian context, where bushfire and prolonged smoke events are not uncommon. For example, just prior to the 2019-20 south east Australian event, Tasmania experienced significant bushfires and widespread smoke exposure to major population centres (Marfori et al. 2020). This also occurred to a lesser extent in the summers of 2016 and 2013.

In the context of providing a response to a different emerging environmental threat, this chapter further demonstrates the applicability and flexibility of an environmental research translation framework, such as Kaufman and Carl. This chapter acts as a second example of Stage 4 (policy and practice implementation) (see Figure 6.1). The research findings in this chapter directly inform the implementation of a suite of responses to prolonged and extreme smoke events, concentrating on recommendations for individual actions. To a lesser extent, this chapter informs public health policymakers as to the applicability of digital apps in disasters of this nature, potentially generating community interventions and systems changes.

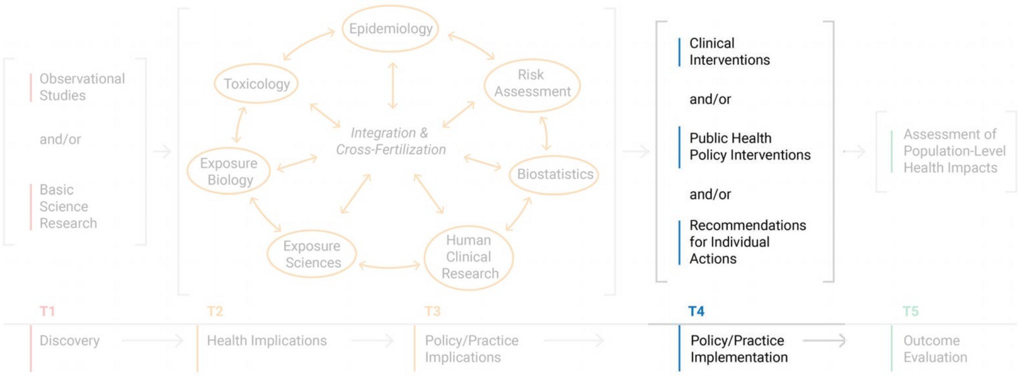


Figure 6.1: Kaufman and Curl (2019) environmental health translational research framework, Stage 4

This chapter has been published in Campbell, SL, Jones, PJ, Williamson, GJ, Wheeler, AJ, Lucani, C, Bowman, DMJS, Johnston, FH, 2020, 'Using digital technology to protect health in prolonged poor air quality episodes: A case study of the AirRater app during the Australian 2019-20 fires', *Fire*, vol. 3, 40.

6.2 Abstract

In the southern hemisphere summer of 2019-20, Australia experienced its most severe bushfire season on record. Smoke from fires affected 80% of the population, with large and prolonged exceedances of the Australian National Air Quality Standard for fine particulate matter ($PM_{2.5}$) recorded in all major population centres. We examined if AirRater, a free smartphone app that reports air quality and tracks user symptoms in near real-time, assisted those populations to reduce their smoke exposure and protect their health. We distributed an online survey to over 13 000 AirRater users to assess how they used this information during the 2019-20 bushfire season, and why it was helpful to aid decision-making in reducing personal smoke exposure. We received responses from 1732 users (13.3%). Respondents reported the app was highly useful, supporting informed decision-making regarding daily activities during the smoke-affected period. Commonly reported activities supported by information provided through the app were staying inside (76%), rescheduling or planning outdoor activities (64%), changing locations to less affected areas (29%) and informing decisions on medication use (15%). Innovative and easy-to-use smartphone apps such as AirRater, that provide individual-level and location-specific data, can enable users to reduce their exposure to environmental hazards and therefore protect their health.

6.3 Introduction

Globally, landscape fires cause major environmental, economic, social and health impacts, both through the direct effects of fire and from consequential negative impacts on air quality (Bowman et al. 2017; Johnston et al. 2012). Climate projections indicate a substantially greater fire risk in the future, with a warming climate driving conditions that precipitate landscape fires. These include more severe and prolonged droughts, resulting in increased fuel loads and increased efficiency of ignition sources such as dry lightning (Dowdy & Mills 2009; Nolan et al. 2020). As a result, future fires are likely to be more frequent, larger, longer and more often, with prolonged and severe episodes of poor air quality more likely in many regions (Clarke & Evans 2019; IPCC 2019).

These conditions have major implications for human health, as landscape fire smoke has a well-established association with poor health outcomes—Johnston et al. (2012) estimated 339,000 deaths annually are attributable to landscape fire smoke exposure worldwide. Although landscape fire smoke is complex in character and contains many chemicals harmful to health, the major component affecting health is particulate matter less than 2.5 microns in diameter, or $PM_{2.5}$ (Johnston et al. 2012). Effects on health are especially pronounced for specific population groups, such as the elderly, the young, and for those with existing medical conditions, including cardiovascular and respiratory conditions (Borchers Arriagada et al. 2019; Cascio 2018; Hystad et al. 2020; Leibel et al. 2020; Morgan et al. 2010; Pope et al. 2011). For example, a study of landscape fire events in the state of Washington (USA) from 2006-2017 found a 35% increase in the odds of same-day respiratory mortality for those aged 45-64 years when exposed to smoke from landscape fires (Doubleday et al. 2020), while research from the 2010 fires in Moscow showed excess deaths of almost 11,000 during this period when compared to other periods without fires, and mostly from older age groups and for those with existing cardiovascular and respiratory conditions (Shaposhnikov et al. 2014). There is also some evidence for health impacts on pregnant women and their developing foetus (Holstius et al. 2012; Melody et al. 2020).

Considering the interconnections between bushfire activity, climate change and health (see Sections 1.1-1.4), there is an urgent and increasing global need to develop and adopt public health communication tools, both at the individual and the government/agency level, to assist vulnerable people to reduce their smoke exposure and to manage their health during landscape fire events (Marfori et al. 2020). The use of digital technology is one possible adaptation solution, with smartphone apps playing a key and growing role in information dissemination and communication during disasters (Tan et al. 2017).

In recent times, a plethora of digital services have become available allowing consumers to track air quality. These include websites, and more commonly smartphone apps, that display air quality data from around the world (for example, IQAir, AirMatters, BreezoMeter and PurpleAir) or for specific locations (for example, Smoke Sense in the United States and CanberraAir in Canberra, Australia). These technologies gather data from a mix of regulatory government air quality monitoring networks and/or low-cost air quality monitors, although difficulties ensuring the reliability and applicability of low-cost air quality monitors remain (Karagulian et al. 2019). Smartphone apps specifically have the potential to support health during prolonged or extreme poor air quality events by providing vulnerable individuals with easily accessible information to inform health-protecting behaviours (for example, staying indoors to reduce exposure or taking preventative medications).

However, despite this proliferation, to date there has been a paucity of research on the efficacy of smartphone apps to help individuals reduce their smoke exposure and manage their health during extreme or prolonged smoke events, including analysing factors that might be important in determining usability.

6.3.1 AirRater app

AirRater is a free smartphone app developed by the University of Tasmania, launched in Tasmania, Australia in October 2015 (see www.airrater.org). The app was designed to assist people vulnerable to poor air quality to better manage their health. The app provides users with easily understood, near real-time air quality information, including $PM_{2.5}$ and temperature (gathered from official government sources) and pollen (gathered from local pollen monitors where available). Users can enter their respiratory symptoms (such as sneeze, wheeze or cough) into the app, which also records their location. Over time, AirRater helps the user determine potential environmental triggers of their symptoms, and can send a notification when these are recorded at high levels in the user's current location, enabling the user to take actions to protect their health. AirRater's functionality, and capacity to identify local drivers of respiratory disease, are explained in detail elsewhere (Johnston et al. 2018; Jones et al. 2020).

6.3.2 Research aim

Using a case study approach, this study aims to investigate if digital technology (such as the AirRater smartphone app, which provides user-friendly, real-time and location-specific air quality information) is useful in helping individuals to reduce their smoke exposure and therefore protect their health during a period of prolonged poor air quality (as experienced in the Australian 2019-20 summer season). We specifically investigate if AirRater was successful in reaching individuals vulnerable to poor health outcomes during prolonged exposure to smoke; the types of impacts experienced by respondents; if information obtained through AirRater caused health protective behaviour change; and the features of AirRater that most enabled ease of use.

6.4 Materials and methods

6.4.1 Study setting

While fires are a common and well-established feature of the Australian forest landscape (Bradstock, Gill & Williams 2012), the complex of megafires which occurred across Australia's eastern seaboard from September 2019 to February 2020 was exceptional in terms of geographic scale, duration, severity and the size of the population affected (Boer, Resco de Dios & Bradstock 2020). Several other large-scale fires also occurred during this period, including on Kangaroo Island in South Australia, and numerous fires through Western Australia (see Figure 6.2). Combined, these events burned approximately 97,000km^2 (Ward et al. 2020) and caused significant smoke exposure for the most densely populated regions of Australia, with large exceedances of the Australian National Air Quality Standard for particulate air pollution (Australian Government 2005) occurring from days to months and affecting 80% of the Australian population (Johnston et al. 2020).

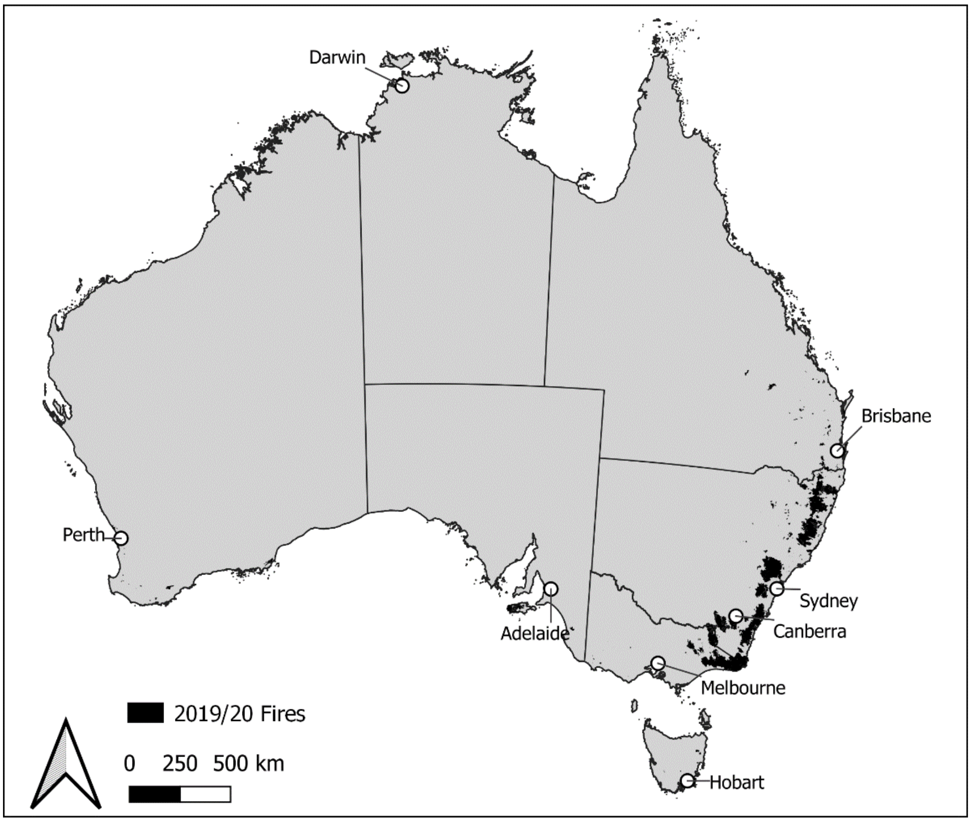
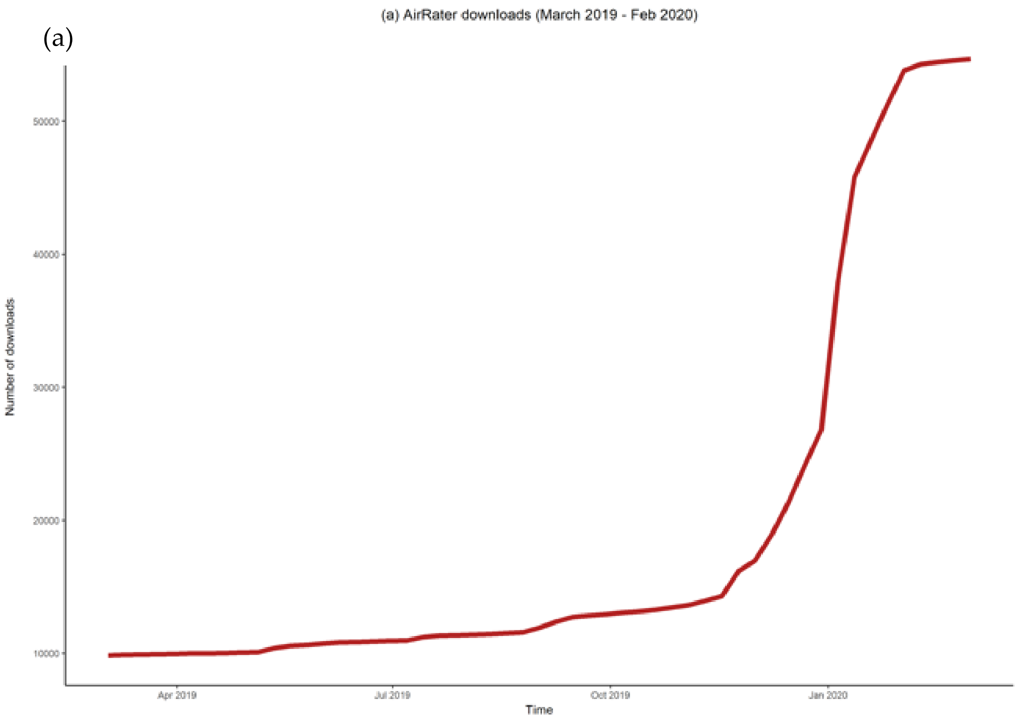


Figure 6.2: Fire boundaries for the Australian 2019-20 fire season, within areas classified as temperate forests and woodlands (Australian Government Department of Agriculture Water and the Environment 2020; United States Geological Survey 2020)

Early research using statistical modelling estimates that smoke from this event was responsible for over 400 excess deaths, over 2000 hospitalisations for respiratory conditions and over 1000 hospitalisations for cardiovascular conditions (Borchers Arriagada et al. 2020). This is compared to 35 deaths directly attributed to the bushfires (Coates 2020).

During the 2019-20 bushfire season, downloads of AirRater increased over five-fold from pre-season levels (see Figure 6.3a), with substantial user downloads occurring outside the three jurisdictions where AirRater is currently funded to operate (Tasmania, the Australian Capital Territory and the Northern Territory) (see Figure 6.3b). This reflected the growing number and location of people affected by fires and smoke throughout the season, especially in densely populated regions around Brisbane, Sydney and Melbourne.

(a)



(b)

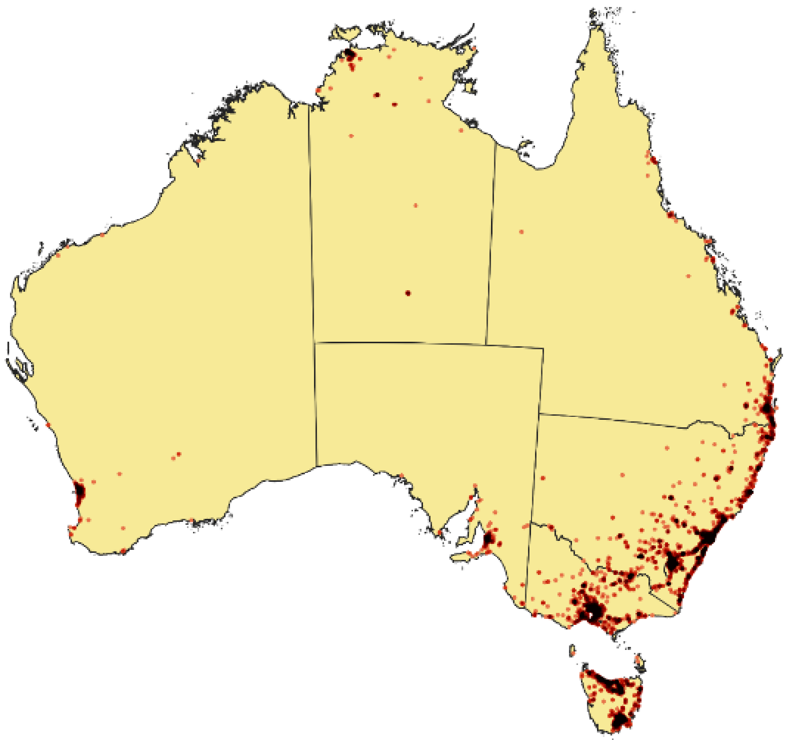


Figure 6.3: (a) Number of AirRater downloads from March 2019 to Feb 2020. (b) Map of Australia showing AirRater downloads (as of 6 March 2020), where darker areas indicate a greater concentration of downloads.

6.4.2 Study methodology

During February 2020, an online survey request was emailed to 13 162 AirRater users who had given permission for follow-up when registering for the app, across six Australian jurisdictions highly affected by the 2019-20 summer bushfire season: New South Wales (1849 users), Queensland (204 users), Victoria (1133 users), South Australia (82 users), West Australia (177 users) and the Australian Capital Territory (9717 users). Differences in user numbers across jurisdictions reflect the time the app had been available in that region, and the relative populations of each region that were smoke affected. The survey was open for two weeks and reached 13 021 users, with a reminder sent at day 10.

Survey questions centred on three themes: the health of the respondent during the prolonged smoke events of summer 2019-20; high-efficiency particulate air (HEPA) room cleaner purchase and use; and how the respondent used the information provided by AirRater. This paper focuses on two of these themes: the health of respondents and AirRater use. A mix of qualitative and quantitative questions were used. A full list of survey questions and response options can be found in Appendix G: AirRater survey questions and response options. Survey responses were downloaded in CSV format. R v3.5.3 (R Core Team 2020) was used to analyse quantitative data, while qualitative data was analysed using thematic analysis.

6.5 Results

A total of 1732 survey responses were received, giving a response rate of 13.3%. The vast majority (94.1%; n=1630) replied to the survey questions for themselves, with a minority (4.3%; n=75) replying on behalf of someone they cared for (for example, a child). The remainder responded on behalf of a group, for example, as an educator in a day care facility, as sports club executive or as a work safety delegate for a work site, public amenity or at a public event.

6.5.1 Health-related outcomes

The majority of respondents (61.4%) identified one or more risk factors that could result in them being more vulnerable to poor health as a result of prolonged smoke exposure. Most noteworthy was having a pre-existing lung condition (35.9%), followed by being over 65 years (21.2%), noting that respondents could nominate more than one type of risk factor (see Figure 6.4).

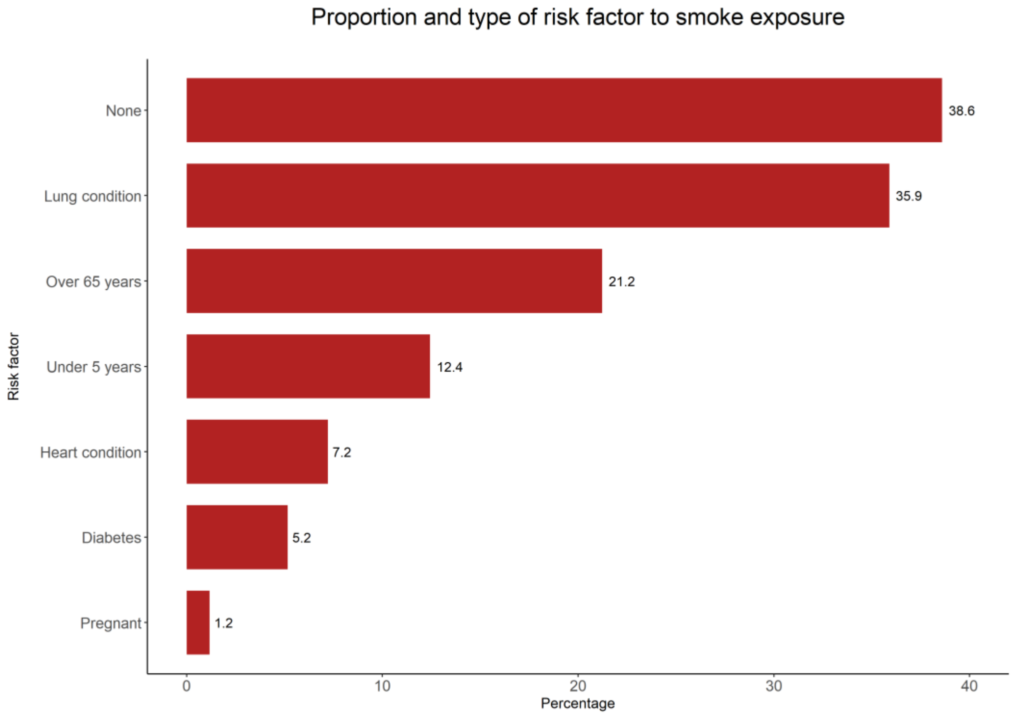


Figure 6.4: Proportion of respondents reporting a risk factor to smoke exposure

When asked about symptoms related to smoke exposure, the majority of respondents (79.8%; n=1382) reported that smoke from the bushfires had affected their health or the health of the person they cared for, citing a wide variety of symptoms. These included minor physical symptoms such as irritated or dry throat (61.4%), irritated or watery eyes (60.8%) and sneezing (30.2%), through to potentially more severe physical symptoms such as shortness of breath (37.7%) and chest tightness (31.5%). Mental or mood-based symptoms were also reported by respondents, with almost half (46.6%) reporting feeling anxious, stressed or worried; 22.4% reporting feeling irritable, angry or short-tempered; and 21.3% reporting feeling depressed (see Figure 6.5, noting respondents could report more than one symptom).

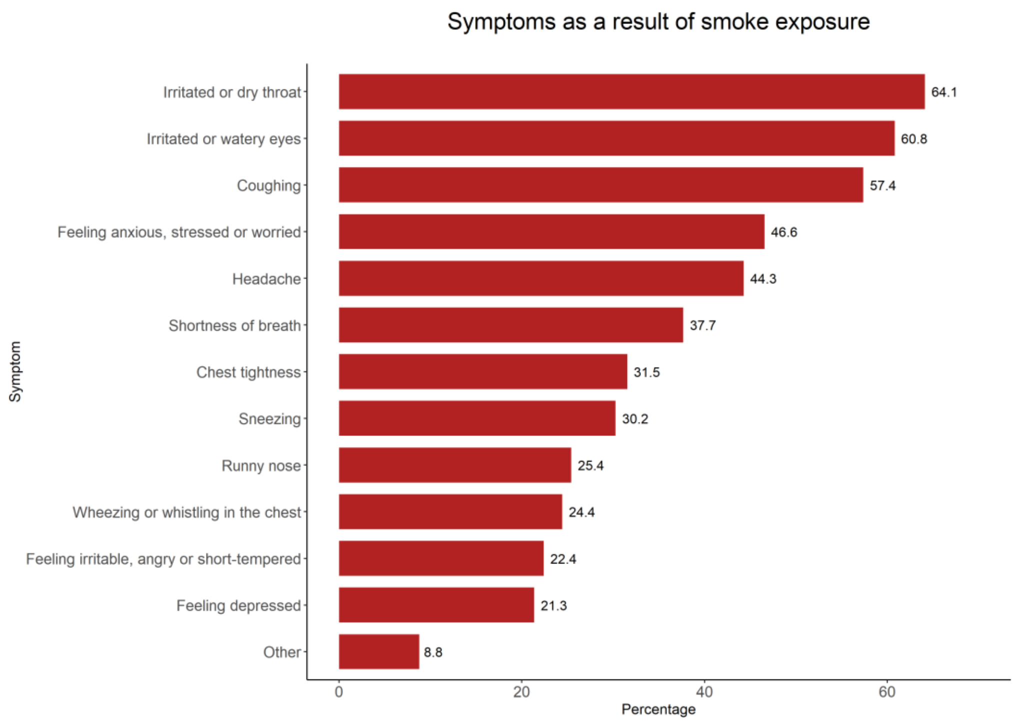


Figure 6.5: Symptoms reported as a result of smoke exposure

Other symptoms reported (n=143) included nose bleeds, nausea, flare-ups of asthma symptoms, chest pain, inability to sleep, tiredness and lethargy. Several respondents noted decreased mental health related to an inability to exercise safely, solastalgia, and stress related to previous bushfire events.

Approximately one third of respondents (32.6%) reported missing school or work as a result of smoke and/or fires, with 7.2% reporting this occurred five times or more. For 6.5% of respondents, this was due to school or work being closed.

Approximately one third of respondents sought medical advice about their symptoms, with visiting a general practitioner (GP) (22.6%) and talking to a pharmacist (12%) the most prominent activities (see Figure 6.6, noting this reports only the types of medical advice when advice was sought). Several respondents sought online advice, searching information on minimising smoke in the house; reading government advice and directives; using 'Dr Google'; and researching international advice. Some respondents left their place of residence to avoid smoke, for example, to an air-conditioned motel for an extended time, and other respondents reported seeking advice from complementary medicine practitioners. Two-thirds of respondents did not seek medical advice.

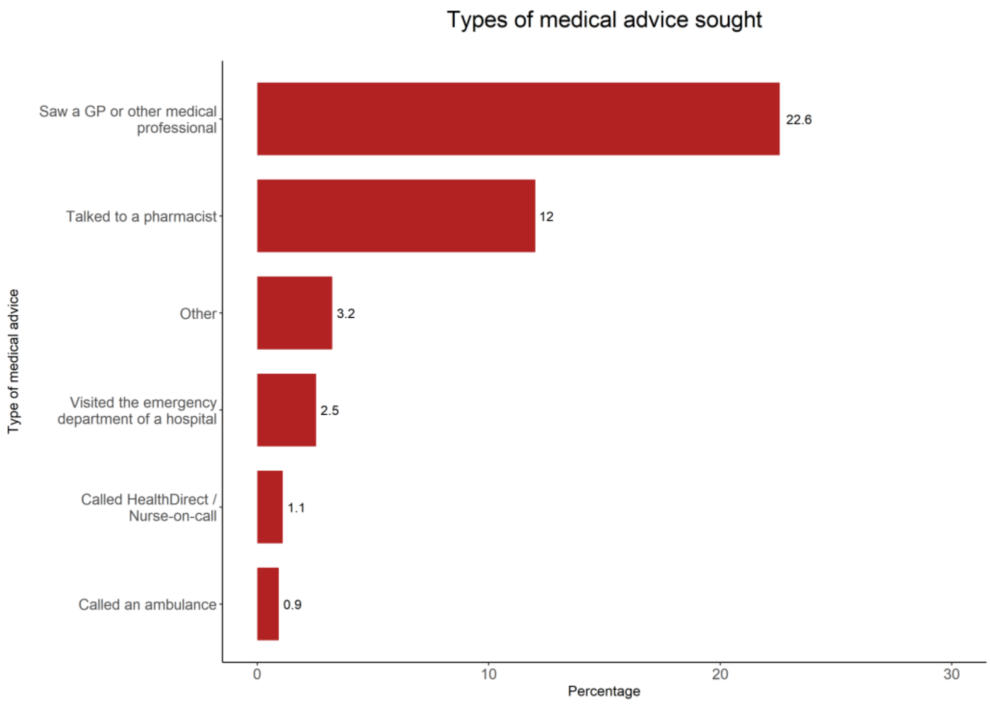


Figure 6.6: Types of medical advice sought for health conditions associated with smoke exposure

6.5.2 AirRater use

Almost 60% of respondents found AirRater ‘extremely useful’ or ‘very useful’ in helping to manage symptoms associated with smoke, with a further 20.2% rating it as ‘quite useful’. The features respondents liked most about AirRater included the map showing air quality information nearby (74.7%), the ability to save multiple locations (for example, both home and work) (43.7%) and automated notifications when smoke levels were elevated (37.8%) (see Figure 6.7, noting respondents could choose multiple features).

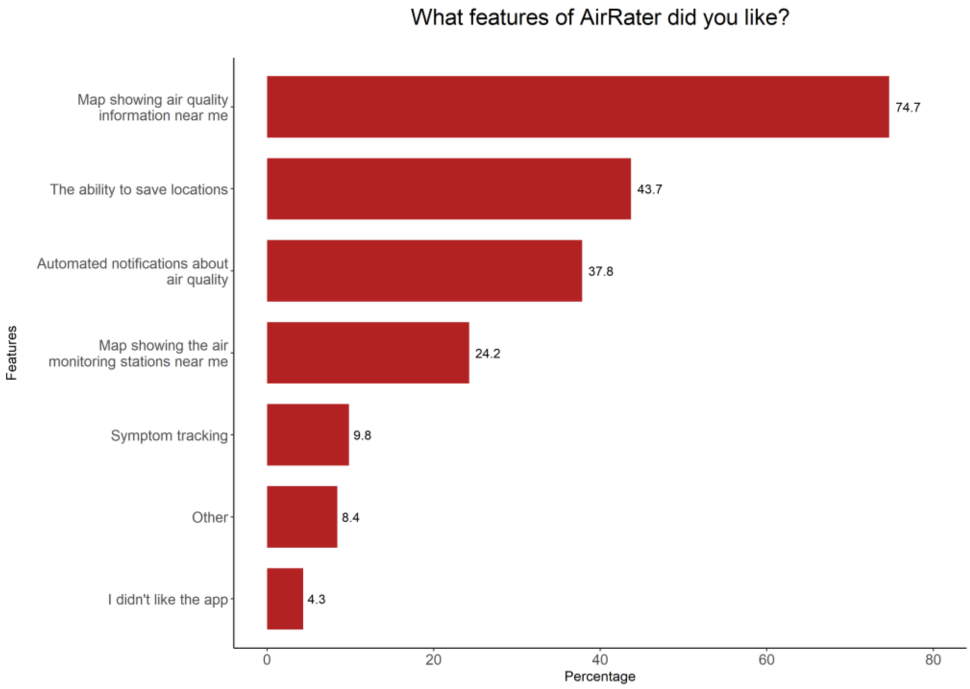


Figure 6.7: Features of AirRater most liked by respondents

Other AirRater features liked by respondents included having access to near real-time updates (1-hour average updates as opposed to 24-hour rolling averages typically reported by regulatory agencies); the ability to easily see air quality information in multiple locations; and seeing air quality trends. Respondent statements supporting these preferences can be found in Appendix H: Supporting text statements from AirRater survey respondents.

A small percentage of respondents (4.3%) did not like the app, citing technical reasons. Respondents who liked some features of the app also commented on technical difficulties experienced at times. Some respondents commented on the reliability of the air quality data in their region as a limitation of the app.

When asked how information from AirRater was used, almost 95% of respondents reported they changed one or more behaviours to reduce their smoke exposure. Over three-quarters (75.9%) of respondents stayed indoors, and around two-thirds (66.2%) of respondents used AirRater to determine when it was best to close or open their windows and doors. Just under two-thirds (64.1%) used AirRater information to reschedule or plan their outdoor activities, while just over one-fifth (20.7%) were more aware of the link between air quality and their own health (see Figure 6.8, noting respondents could choose multiple options).

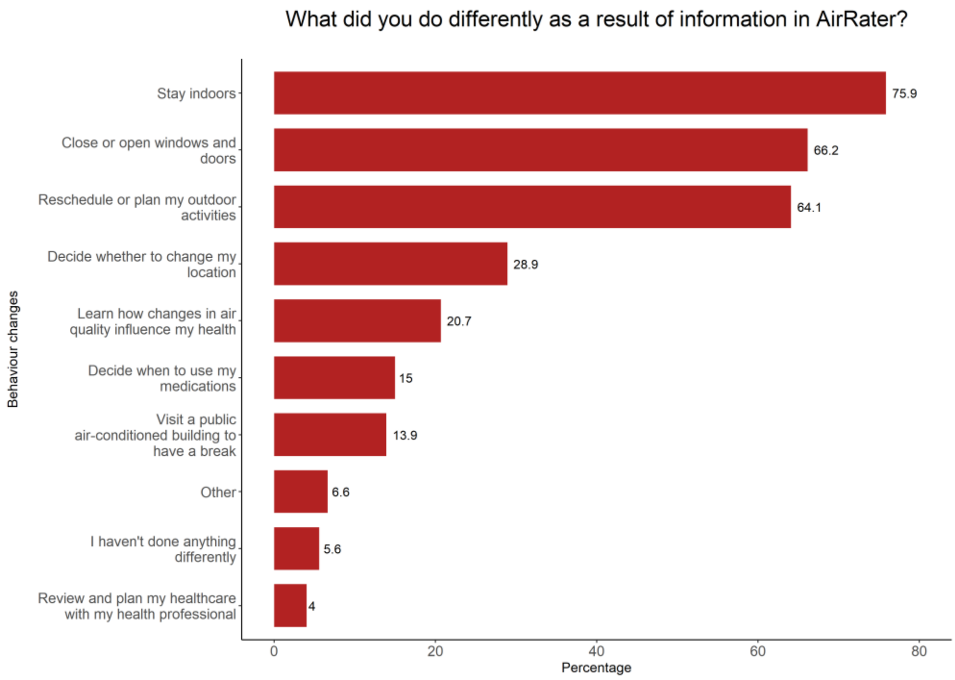


Figure 6.8: Behaviour change as a result of local information provided by AirRater

Other behaviour changes informed by the app aimed at reducing smoke exposure included deciding on exercise plans; deciding on work patterns; deciding when to wear a face mask; and helping to explain or inform others of the situation. Respondent statements supporting these behaviour changes can be found in Appendix H: Supporting text statements from AirRater survey respondents.

Over two-thirds (69.5%) of respondents also sought air quality information from alternate sources. These included various state government air quality and health websites (for example, ACT Health, Victoria Environment Protection Authority and NSW Department of Planning, Industry and Environment), other apps and websites (for example, AirVisual, CanberraAir, AQICN, PurpleAir, AirMatters) and traditional news sources such as radio, TV and online. Checking visibility of nearby landmarks and viewing and smelling the air were also used in conjunction with formal government sources.

When asked about the features of the app or website users found most useful, ease of use and navigation (45.7%), ease of understanding information (43.6%) and access to near real-time data (40.9%) were cited as the top three features (see Figure 6.9, noting respondents could choose more than one response). Trustworthiness of information (31.8%) and access to local information (30.8%) were also important.

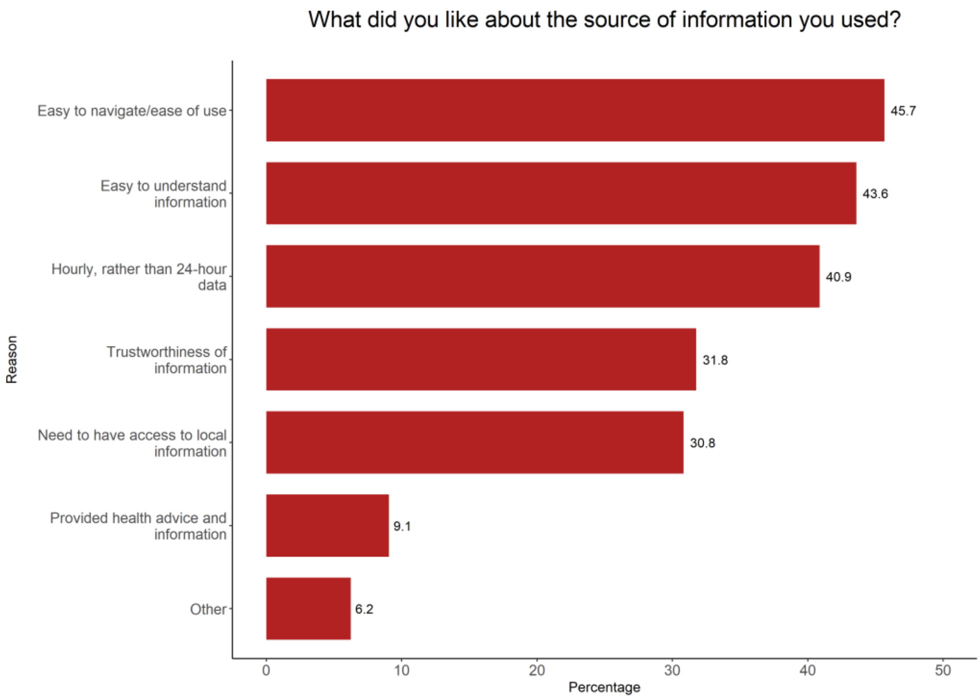


Figure 6.9: Features of information source most liked by respondents

6.6 Discussion

Our study shows that prolonged and severe smoke events, such as those occurring in Australia over the 2019-20 summer season, have substantial and potentially serious health and social impacts mainly for vulnerable individuals. Our results further demonstrate the AirRater smartphone app supported these individuals to make decisions to reduce their smoke exposure. This suggests that digital technologies such as AirRater, that provide easily interpreted, reliable, real-time and location-specific air quality information, are useful in helping vulnerable individuals to make decisions about reducing their smoke exposure and protecting their health during these types of events.

Behaviours such as staying indoors, limiting exercise on days of poor air quality, and reducing the movement of air from outdoors to indoors (i.e. closing doors and windows) have previously been identified by Laumbach et al. (2015) as measures that successfully reduce smoke exposure. In addition, health protection measures such as using preventive medications, visiting air-conditioned buildings and wearing face masks have similarly been identified by Vardoulakis et al. (2020) as behaviours supporting reduced smoke exposure. These measures are strongly recommended by public health authorities (for example, NSW Department of Health (2019) and the Centre for Air Pollution, Energy and Health Research (2019)). Survey respondents report these types of behaviour changes based on air quality information supplied by AirRater, demonstrating that when individuals have access to relevant and accurate information, they are able to act on the recommended advice to protect their health.

Furthermore, the most-liked features of air quality information sources highlighted by survey respondents demonstrate that easy to understand, timely, localised and trusted information is critical to decision-making. These information characteristics are strongly recommended by Vardoulakis et al. (2020) to manage health risks due to smoke exposure, and are highlighted as key features of smartphone apps for asthma management (Kenner 2016).

Our key finding—that apps with features such as AirRater can reduce smoke exposure and support health management during poor air quality events—is potentially generalisable across regions where landscape fire smoke poses a potential health risk. For example, this has been demonstrated by the Smoke Sense app in the United States (Rappold et al. 2019). However, these regions must have robust, supported and widely distributed air quality monitoring networks and a reliable population-wide internet connection. As we found in our study, there are limits to usability when lack of reliable air quality data leads to unreliable information. A further caveat is that our findings likely reflect utility amongst a subset of the population, as AirRater's overall user base is more likely to be drawn from those with a concern about air quality and health impacts. Furthermore, the AirRater user base (or the user base for any air quality information app) is more likely to include those with adequate digital, health and language literacy to facilitate downloading an app and understanding the information, and sufficient economic and social means to act or change behaviours based on that information (Johnston et al. 2018).

While our study specifically examined the use of AirRater during an extreme event, the findings are broadly consistent with previous evaluations of the app that focused on app use during periods with no major air quality exceedances, or in more predictable periods of poor air quality, such as increased seasonal pollen loads, increased smoke as a result of planned burns, and urban air pollution caused by winter wood heater use. These evaluations found that users had still applied app information to support health-promoting decisions about their home environment, activities and medication use (Johnston et al. 2018). Our findings on the prevalence and nature of the health impacts experienced during the 2019-20 summer are also consistent with the FluTracking survey (Howard et al. 2020) and the Asthma Australia survey (Asthma Australia 2020), which investigated the extent to which respondents experienced health symptoms as a result of smoke exposure over the course of summer 2019-20.

Strengths of our study include the timing of survey, which was distributed, responded to and closed before COVID-19 became a widespread public health emergency in Australia. The responses therefore reflect participant views in the few weeks between the bushfire and smoke crisis and the COVID-19 pandemic, with subsequent surveys on the fire season unlikely to yield similar results.

Our study has two limitations of note. Firstly, it is limited by self-reporting bias, as it is likely to be completed by those with a strong interest in health and air quality, and more likely to be completed by those with higher levels of literacy (as discussed earlier). Secondly, the relatively low response rate (13.3%) reduces confidence in making a conclusive recommendation on the broader policy or practice implications of these findings, without further research to understand the specifics of the reach and uptake of the app across a larger population. These findings help inform how the app may be useful for some people, however the applicability of the app across the wider population is still unknown. These two limitations reduce the generalisability of the findings.

While accurate air quality information is clearly helpful for individual decision making, delivery of this information via digital technology is heavily reliant on a reliable internet connection and a level of literacy and numeracy that enables decision-making to be effective. Where this is not the case, consistent public health advice, distributed through multiple networks that do not rely on reliable internet connections and high levels of literacy, is paramount (Marfori et al. 2020). Solutions to these issues deserve further attention by researchers and policymakers.

Our findings also highlight the ongoing role that access to reliable and accurate public health information plays in a natural disaster. While Finch et al. (2016) show that social media potentially has several beneficial roles in these circumstances, the specific use of smartphone apps in natural disaster and emergency response situations deserves greater research and policy consideration. For example, further investigation is needed of the health economic benefits of providing timely and accurate air quality information and public health advice, which allows health protective behaviours to occur, as opposed to an increased load on emergency services in response to smoke exposure. Further research on the uptake and use of smartphone apps by socio-demographic factors (for example, age, gender, literacy level or economic disadvantage) would also be useful to improve understanding of how these types of apps are used in emergencies, and if our findings are generalisable to the wider community.

6.7 Conclusion

In summary, digital technology such as the AirRater smartphone app appears to be highly useful to inform individual decision-making aimed at protecting health during periods of prolonged and severe poor air quality, such as those experienced in the 2019-20 Australian bushfires. With increasing likelihood of these types of events globally due to a warming climate, the expansion of technologies such as AirRater, coupled with investment in robust air quality monitoring networks, is likely to bring greater benefits to vulnerable individuals in affected communities around the world.

Chapter 7:
Discussion

7.1 Aims and summary

This thesis aimed to provide a suite of timely, targeted and translatable evidence regarding the risks to human health associated with extreme events, providing evidence-based metrics for planning, preparing and responding to these events. While the majority of the studies (Chapters 3, 4 and 5) focussed on Tasmania, Australia, with specific relevance for public health policy and practice in Tasmania, other studies complemented this approach. For example, Chapter 2 provided an international context to heatwave research (and identified research gaps that were responded to in Chapters 3 and 4), and Chapter 6 provided a national perspective on an emerging issue highly relevant and applicable for Tasmania, given similar events in the recent past.

Each of these research projects were drawn together under an environmental health translational research framework (Kaufman & Curl 2019), with each chapter aligned under a specific section of the framework.

Chapter 2 provided the first systematic review of the distribution of heatwave and human health studies from around the globe, showing that this type of research is focussed on wealthier regions more likely to have health systems and healthcare capacity to prepare for and respond to heatwave events. The findings show that cooler climate regions, regions more susceptible to extreme heat and regions that have proportionally lower income levels are not well-represented in global heatwave and human health research. This research highlights the critical gap in climate change impact research between wealthier and more vulnerable regions, where those most at-risk are more likely to experience adverse health outcomes. This study also demonstrated that heatwave and human health impact research to date is dominated by mortality studies, leaving a gap in understanding regarding the influence of heatwaves on health service utilisation, such as hospital presentations and ambulance dispatches.

This chapter provided an international context and position for the fundamental driver of this thesis—the value of translating research into policy and practice. As such, this chapter offered an example of Stage 1 of the Kaufman and Curl environmental health research translation framework, by identifying specific research gaps in cooler climates, regions of greater disadvantage and morbidity outcomes. This identification enabled a pathway for the next two chapters, examining the association between heatwaves, emergency presentations and ambulance dispatches in Tasmania, which experiences a cooler climate and greater social disadvantage relative to other Australian jurisdictions. Chapter 3 examined the association between heatwave events and hospital ED presentations in Tasmania using a case-crossover methodology. I found that ED presentations rose during severe and extreme events. Notably, this study found that the subgroups of children under five and children under 15 had a stronger association than the general population, and a stronger association than the elderly who had a similar association to the general population. This finding is not generally consistent with other similar studies in Australia, which commonly find the elderly are more likely to attend a hospital emergency department during heatwaves (Mayner, Arbon & Usher 2010; Schaffer et al. 2012a; Toloo et al. 2014). Analysis of the under 5 cohort is rare, however, although some studies find an increased risk for children with specific conditions (Wang et al. 2014) or those aged under 15 years (Johnston et al. 2012). Contrary to the study hypothesis, there appeared no clear pattern of association with gender, level of social advantage or with particular diagnostic groups other than psychoses, with wide confidence intervals for diagnostic groupings a result of small numbers of presentations within these groups. This analysis concentrated on severe and extreme heatwave events only, and may have benefitted from including an analysis of low-intensity events, potentially providing a greater number of events and more precise results.

By providing health impact metrics for these events, this research assists with surge capacity planning for hospital emergency departments prior to forecast heatwaves, and for targeting health promotion for preventing heat illness to those population groups identified as most at-risk. Therefore, Chapter 3 provided a robust example of Stage 2 (identifying health implications) and Stage 3 (identifying policy and practice implications) within the Kaufman and Curl framework.

Complementing and extending Chapter 3, Chapter 4 examined the association between heatwave events and ambulance dispatches in Tasmania, Australia, also using a case-crossover study design. This study documented statistically significant increases in ambulance dispatches across all levels of heatwave intensity and for all age groups. In contrast to the study of ED attendances (Chapter 3), this study found stronger associations in both the elderly and the younger age groups than for the general population. Other similar ambulance studies in Australia have found an increased association with the elderly, although children were not specifically analysed (Schaffer et al. 2012a; Turner, Connell & Tong 2013). This study also found a significant risk for those living in areas of low socio-economic advantage compared to areas of greater advantage. Limited numbers of other Australian ambulance studies have included social disadvantage as an indicator, and found that areas of middle disadvantage had a stronger association than the general population (Patel et al. 2019) or lower disadvantage had a stronger association (Xiao et al. 2017).

Similar to Chapter 3, this chapter provided a strong example of Stages 2 and 3 within the Kaufman and Curl framework. This chapter provides pivotal planning and health promotion information for a different morbidity-related health outcome, supplementing and expanding on the information provided in Chapter 3.

In comparing the results of studies contained in Chapters 3 and 4, Chapter 4 has a greater number of associations with subgroups and more consistent results with the wider literature on heatwaves and health outcomes. This is potentially a result of the method used of attributing heatwave events by suburb, thereby giving a greater number of heatwave events overall and more precise exposure categorisation. This attribution method could not be used for analysis in Chapter 3, as the patient suburb data were not available due to de-identification. Notably, both studies found strong associations between heatwaves and health outcomes in children. This was an important finding for local public health practice where interventions for heatwave preparedness and response had predominantly been focussed on older age groups.

Chapter 5 examined the related but different environmental health risk of epidemic thunderstorm asthma. This study was undertaken to assess the risk of this emerging and little understood public health threat within Tasmania with the intention of supporting and informing public health decision making with regard to response, especially after the large and fatal ETA event in Melbourne in 2016. Using a case-control approach, this study found no evidence of thunderstorm activity in any region of Tasmania on days when there were historic epidemics of asthma. This method of historical analysis to identify previously unrecognised events had proved useful in central NSW (Marks et al. 2001). Furthermore, the likelihood of future events was assessed to be very low given particular weather patterns shaped by Tasmania's island setting, however, a changing climate resulting in an increased length of pollen season and changing climate patterns may see this risk revised into the future. This resulted in an evidence-based management approach to ETA events in Tasmania, while recognising risk factors for asthma are still largely prevalent and can be mitigated by the promotion of individual health-promoting behaviours.

As such, this chapter provided a robust example of Stage 4 of the Kaufman and Curl translational research framework, where systems-wide policy and practice implementations were recommended alongside recommendations for individual health-promoting or health-protecting actions.

While Chapter 5 informed a response to the public health risk of an extreme event in Tasmania, Chapter 6 examined the utility of an intervention for a common and serious public health hazard both in Tasmania and throughout Australia, that of poor air quality originating from severe and prolonged bushfire smoke. Specifically, I examined the perceived impact of smoke and the utility of the AirRater smartphone app in supporting health protective behaviours among those affected by poor air quality during the south-east Australian bushfires in 2019-20. As the AirRater app was developed and first released in Tasmania, there is a large local base of engaged and health-aware AirRater users (Johnston et al. 2018; Jones et al. 2020), making these findings directly relevant to the local context, and especially in light of similar and recent prolonged smoke events in Tasmania.

Users of the AirRater smartphone app were surveyed to find out how the smoke affected their health and how they used the app during this time. The study found a high proportion of users experienced cardiovascular and respiratory symptoms, including chest pain and difficulty breathing, which can be associated with serious health impacts. These results were consistent with other surveys conducted by Asthma Australia (Asthma Australia 2020) and Howard et al. (2020). Furthermore, the study examined the use of digital technology during a prolonged and severe smoke event affecting a large population, and found that this technology could be of benefit in promoting behaviour change towards actions that reduce smoke exposure and therefore protect health. Respondents found benefit in having accurate and up-to-date information in order to make decisions.

While the study examined a case study across a geographically large part of Australia, bushfire and consequential smoke exposure remains one of the greatest natural disaster risks for Tasmania (White et al. 2016). As such, the findings of this study are relevant for the Tasmanian response to prolonged and severe smoke events.

This chapter provided a further comprehensive example of Stage 4 in the Kaufman and Carl translational research framework, by providing an assessment of and recommendations for broader health policy actions, alongside an overview of the way individual health-promoting behaviours are adopted. This approach covered the spectrum of system-wide actions through to individual actions, as described in Stage 4 of the framework.

7.2 Limitations and caveats

The findings contained in this thesis must be considered within the context of their settings and methods, which have limitations broadly discussed in the individual chapters. Studies conducted wholly in Tasmania (Chapters 3, 4 and 5), for example, with a relatively small population, need to be interpreted with some caution. Where there were relatively few events and small numbers of people affected in specific diagnostic subgroups, the study was not sufficiently powered, the results were imprecise and effect estimates unstable. This was illustrated by the wide confidence intervals associated with the evaluation of diagnostic subgroups in Chapters 3 and 4, and particularly evident for the ED study (Chapter 3).

To some extent, this limitation can be overcome by triangulating datasets, such as how ED attendances and ambulance callouts were analysed in Chapters 3 and 4. Where there is coherence in results from multiple studies in different settings using different methodologies, then confidence in the results is much greater than for a single small observational study. This can also be achieved by drawing on the availability of a variety of datasets, as has been performed in the ETA analysis (Chapter 5), where two types of ambulance data and both ED presentation and admitted data were examined for evidence of asthma epidemics. Finding a research question and study design appropriate for the available data is especially important in research on small populations (National Academies of Sciences Engineering and Medicine 2018), and as such, further related research questions have been suggested in Section 7.5.

For the studies in Chapters 3, 4 and 5, there are necessary assumptions regarding pre-collected data that need to be considered. This is particularly relevant to health outcome data (hospital ED presentations and paramedic assessment), which are designed for purposes unrelated to epidemiological studies. Such data have several recognised limitations, such as missing data, coding errors and diagnostic misclassification (Althubaiti 2016), all of which are largely independent of outdoor environmental conditions. In environmental epidemiological studies, these factors are likely to bias results towards the null.

Self-reported survey data, such as those collected and analysed in Chapter 6, also have many limitations. These include the representativeness of self-selected respondents compared with all people invited to join the study. For example, in an online survey, self-selected respondents are likely to be more engaged in the topic and have higher digital literacy levels. Furthermore, these studies can be affected by several types of bias including recall bias (for example, over or under emphasising symptoms related to smoke exposure) and confirmation bias (for example, respondents over emphasising the impact of smoke, knowing this is a survey on smoke exposure) (Althubaiti 2016). However, given the primary research question for Chapter 6 was regarding perceptions of app use, a questionnaire to app users remains the most appropriate method. Smoke exposure and health impact research (a secondary question) can be more rigorously tested using other methods, for example, validated epidemiological study designs such as the case-crossover analyses used in Chapters 3 and 4 with objective health outcome measurements. These were out of scope for this particular study.

Potential gaps in this series of studies include ‘book-ending’ the story of heatwaves in Tasmania, with an examination of the association between heatwaves and both primary health care outcomes (such as GP visits at the common but less serious end of the spectrum of health impacts) and mortality data (as the least common but most serious health outcome). With the identification of heatwaves events across Tasmania now undertaken, these studies could be conducted in the future with access to relevant health outcome data. Additionally, the influence of other extreme events on health outcomes at the local setting could be examined, for example, temperature variability, extreme cold or severe storm activity. Furthermore, while heatwave policy implementation is relatively new in Tasmania, an evaluation of the effectiveness of health-protecting interventions enacted as a result of this policy could potentially be conducted.

7.3 Significance and impact of results

This research was undertaken primarily to inform public health policy in Tasmania, recognising that local evidence on extreme events informs and motivates local solutions. Several findings from this thesis are prominent for their influence on public health policy in Tasmania: the importance of focussing on children in extreme heat health promotion campaigns; an evidence-based policy approach to the management of ETA events; and an increased awareness of the role of apps in prolonged natural disasters.

The consistent finding of clear associations between extreme heat events and children, both for hospital ED presentations and ambulance dispatches, has led to a shift in health promotion activity. Previous to these findings, the impact of extreme heat on Tasmanian children was poorly recognised, leading to under-representation in health promotion efforts. As a direct result of this research, emphasis on child health during days of hot weather has been captured in the Department of Health 'Healthy Kids' website (Department of Health Tasmania 2020c) and the Department of Health 'Extreme heat' webpage (Department of Health Tasmania 2020b), while social media posts on hot days have a greater emphasis on child health.

The second finding is the improved understanding of epidemic thunderstorm asthma events in Tasmania. The finding that no epidemic thunderstorm asthma events had occurred in the period under study, combined with various topographical and consequential meteorological factors making this event highly unlikely, have informed a policy direction equal to the perceived risk. An emphasis on community-wide active management of asthma and hay fever while providing education about the risks of these conditions (Department of Health Tasmania 2020e), has the aim of reducing the impacts and burden of these conditions throughout the year, including in the unlikely event of a local ETA episode. In contrast, the extensive Victorian approach following the fatal 2016 Melbourne ETA event, including the establishment of state-wide pollen monitors, a forecasting and warning system and extensive public and clinical education campaigns (Bannister et al. 2020) is proportionate to the higher risk in that jurisdiction.

Thirdly, Tasmania is at the forefront of understanding the role of apps in natural disasters, having developed the AirRater smartphone app with an extensive local user base, combined with the insights gained from this and other research (Johnston et al. 2018; Jones et al. 2020). Public health campaigns and health information sources reference and recommend the AirRater app for use in poor air quality (Department of Health Tasmania 2020a). Findings from this research increase the confidence of this approach, and will serve to inform future recommendations, especially in emergency bushfire situations.

Together, these three findings have supported public health policy in Tasmania being evidence-based and locally relevant for improved health in vulnerable populations during extreme events.

More broadly, research in this thesis has also been widely cited internationally. Chapter 2, as published in the journal *Health and Place*, has attracted 70 citations to date across a range of journals. This includes reference in the most recent landmark paper on climate change and health, as published in *The Lancet* (Watts et al. 2021). As at March 2021, papers published as Chapters 3 and 5 have attracted four citations each within 18 months of publication, and the most recently published Chapter 6 has attracted two citations within six months of publication.

This thesis was completed through a period of significant extreme events with profound public health impacts, affecting the local and national settings under study.

Heatwaves and bushfires affected Southern Tasmania through January and February 2019, while heatwaves and bushfires affected south-east Australia throughout the 2019-20 summer season. The coronavirus pandemic, while not an extreme event, has profoundly affected global the public health landscape since January 2020.

Against the backdrop of these events, the influence of science and research on policy has been discussed more widely and broadly than ever before, with observations contrasting the willingness of policymakers to embrace and enact strategies that are supported by evidence, depending on the issue (Balmford et al. 2020; Davies 2020). In this context, the importance of ongoing research in this area cannot be underestimated, with the likelihood that climate change and health impact research and its translation to policy will continue to remain under scrutiny, supported by discipline-specific research translation frameworks.

7.4 Wider implications of this work

Research with a policy translation focus, as undertaken in this thesis, aims to have a direct impact in the real world. As such, the implications of these studies can be explicitly linked to the priorities, focus and application of decision-making processes undertaken in the Tasmanian public health context, with the aim of limiting poor health outcomes of the most vulnerable members of the population during these types of extreme events.

Related to the direct implications of these results is the heightened awareness of the issue in Tasmania, more broadly than within the processes of public health policymaking. An example of this is the Tasmanian Climate Change and Health Roundtable event held in Hobart in April 2019, which I conceived and managed. This event connected clinicians, policymakers and researchers from Tasmania with researchers and policymakers around Australia, aiming to identify and prioritise Tasmanian health needs in a changing climate. The outputs of this event are a list of programs and policies directly applicable to the Tasmanian setting (Department of Health Tasmania 2020d). These are to be prioritised and tested further, with an aim of leading sustainable policy implementation across a broad range of sectors outside healthcare, including transportation, agriculture, research and procurement. While the priority of COVID-19 has consumed significant public health resources in 2020, it is envisaged this work will resume in 2021.

A further benefit of this work has been the establishment and support of strong linkages between agencies, made possible by the multidisciplinary nature of the research being undertaken. These linkages have proved pivotal in the success of public health management of emergency situations, such as state-wide heatwaves in January 2018, involving significant input from the local Bureau of Meteorology office, and the large-scale southern Tasmania bushfires in January-February 2019, which saw high levels of involvement from the Tasmanian Bureau of Meteorology and the Environment Protection Authority agencies. Future events of this nature with a public health emergency management component will include regular input from these sources.

7.5 Future directions

This thesis focusses on a specific detail of the complex and broadscale topic of climate change and health: the impact of extreme events on the healthcare system. However, this research does not attempt to address the myriad of consequential health burdens associated with these events including, but not limited to, the mental health impacts associated with trauma from loss of community or repeated lived experience of extreme events; price increases in fruits and vegetables due to crop failures and transportation difficulties, leading to food insecurity and poor nutrition; and the mental and physical impacts of violence, homelessness and resettlement associated with migration due to local extreme events or food and water shortages. These topics also deserve research attention through the lens of those most vulnerable – the elderly, the young, those living with disabilities, and those from a culturally diverse background. These research topics form a vital and important part of the climate change and human health narrative. I will have the opportunity to investigate some of these topics in upcoming post-graduate research projects throughout 2021.

As suggested in Section 7.2, further refinement of research questions raised in Chapters 3 and 4 are recommended, with methodologies appropriate to the local setting. For example, an examination of medical records for children presenting in ED during extreme heat events could reveal trends in preventable conditions, further informing public health and health promotion advice during heatwaves. Discussions regarding this research direction are ongoing with clinicians at the Royal Hobart Hospital.

Research into the impact and consequences of extreme events on specific vulnerable population cohorts is warranted, especially groups that already experience poor health outcomes. These groups include those with diverse language, cultural and ethnic backgrounds, Aboriginal Australians, those living with disabilities and special needs, the homeless and the gender diverse.

A main driver of future climate change and health research to be undertaken in Australia is the findings and recommendations from the Royal Commission into National Natural Disaster Arrangements (Commonwealth of Australia 2020). Specifically, Chapter 14 (Air quality) and Chapter 15 (Health) provide recommendations focussing on the provision of nationally consistent air quality information and advice; smoke forecasting capability; the inclusion of primary care in disaster management; mental health support and mental health research. This thesis touches on each of these areas. Furthermore, Chapter 10 (Community education) makes recommendations regarding the development and delivery of disaster education and resilience programs, in which I have been involved in during candidature and will continue to be involved in as part of post-doctoral research.

Finally, the National Health and Medical Research Council's Special Initiative in Human Health and Environmental Change, a new $10,000,000 AUD research investment over five years, aims to "strengthen the Australian health system's resilience, preparedness and responsiveness to changing environmental conditions and extreme weather events" (National Health and Medical Research Council 2020). The successful collaboration will have the expertise, funding and momentum to increase research into future health impacts and needs, providing a coordinated national approach to the issue. This will be a major driver of climate change and health research in Australia into the future.

Future research in climate change and health needs to draw from a multidisciplinary framework, where research findings are translated to policy and action across multiple streams of society. To limit climate change and health research to the health sector alone would miss an important opportunity for engagement with the broader issues. Future climate change and health research linked to agricultural and aquacultural food production, animal health, transport, justice and land use and town planning, all with an intention towards robust policy translation outcomes and integration of policymaker needs, will serve to bring climate change to the forefront of research priorities into the future.

7.6 Conclusion

The interaction between extreme events and human health is diverse, complex and fast-changing, given the increased frequency and intensity of these events into the future due to a changing climate. Researching the impact of extreme events on human health is a wide-ranging and growing field, with extensive and multifaceted interactions and associations. This thesis addressed specific and targeted questions within that field, placing a strong emphasis on policy translation with a direct relevance to public health decision makers.

Using the metrics of service demand, our findings show that extreme events, such as bushfires and heatwaves, are already placing an increased burden on health service delivery. Future research will extend this lens to climate change projections and economics, driven by an increasing severity, intensity and impact of extreme events on populations across the world.

Relative to the complex, urgent and global need for adaptation research and policy implementation, this research has made a small but meaningful contribution to Tasmania, and much of this research can be—and is being—adapted for use and uptake in other parts of Australia and the globe. As extreme events become more frequent and severe, this type of research will become fundamental to the development of both public health and clinical health policy around the world.

Appendices

Appendix A: Supplementary data for Chapter 2

Table A.1: Articles and study locations included in literature review for Chapter 2

Article	Study location(s)
Ahmadnezhad, E., K. H. Naieni, A. Ardalan, M. Mahmoudi, M. Yunesian, K. Naddafi, and A. R. Mesdaghinia. 2013. 'Excess mortality during heat waves, Tehran Iran: An ecological timeseries study', *Journal of Research and Health Science*, 13: 24-31.	Tehran, Iran
Allen, M. J., and S. C. Sheridan. 2015. 'Mortality risks during extreme temperature events (ETEs) using a distributed lag non-linear model', *International Journal of Biometeorology*	United States: Atlanta, GA; Austin, TX; Baltimore, MD; Birmingham, AL; Boston, MA; Buffalo, NY; Charlotte, NC; Chicago, IL; Cincinnati, OH; Cleveland, OH; Columbus, OH; Dallas, TX; Denver, CO; Detroit, MI; Hartford, CT; Houston, TX; Indianapolis, IN; Jacksonville, FL; Kansas City, KS; Las Vegas, CA; Los Angeles, CA; Louisville, KY; Memphis, TN; Miami, FL; Milwaukee, WI; Minneapolis-St Paul, MN; Nashville, TN; New Orleans, LA; New York, NY; Oklahoma City, OK; Orlando, FL; Philadelphia, PA; Phoenix, AZ; Pittsburgh, PA; Portland, OR; Providence, RI; Raleigh, NC; Richmond, VA; Riverside, CA; Rochester, NY; Sacramento, CA; Salt Lake City, UT; San Antonio, TX; San Diego, CA; San Francisco, CA; Seattle, WA; St. Louis, MO; Tampa, FL; Virginia Beach, VA; Washington, DC
Allexenberg, R. S. 1981. 'Combatting the heat wave of 1980: lessons for the future', *Urban Health*, 10: 26-30.	St. Louis, MO, USA

Article	Study location(s)
Anderson, G. Brooke, and Michelle L. Bell. 2011. 'Heat Waves in the United States: Mortality Risk during Heat Waves and Effect Modification by Heat Wave Characteristics in 43 U.S. Communities', *Environmental Health Perspectives*, 119: 210-18.	United States: Atlanta, GA; Bakersfield, CA; Baltimore, MD; Birmingham, AL; Boston, MA; Charlotte, NC; Chicago, IL; Cincinnati, OH; Cleveland, OH; Columbus, GA; Dallas, TX; Dayton, OH; Detroit, MI; El Paso, TX; Fresno, CA; Houston, TX; Indianapolis, IN; Jacksonville, FL; Kansas City, KS; Louisville, KY; Memphis, TN; Miami, FL; Milwaukee, WI; Minneapolis-St Paul, MN; Nashville, TN; New York, NY; Newark, NJ; Oklahoma City, OK; Orlando, FL; Philadelphia, PA; Phoenix, AZ; Pittsburgh, PA; Providence, RI; Raleigh, NC; Salt Lake City, UT; San Antonio, TX; San Bernardino, CA; St Petersburg, FL; Stockton, CA; Tampa, FL; Tucson, AZ; Tulsa, OK; Washington, DC
Applegate, W. B., J. W. Runyan, L. Brasfield, M. L. Williams, C. Konigsberg, and C. Fouche. 1981. 'Analysis of the 1980 Heat Wave in Memphis', *Journal of the American Geriatric Society*, 29: 337-42.	Memphis, TN, USA
Astrom, D. O., P. Schifano, F. Asta, A. Lallo, P. Michelozzi, J. Rocklov, and B. Forsberg. 2015. 'The effect of heat waves on mortality in susceptible groups: a cohort study of a mediterranean and a northern European City', *Environmental Health*, 14.	Rome, Italy; Stockholm, Sweden
Azhar, G. S., D. Mavalankar, A. Nori-Sarma, A. Rajiva, P. Dutta, A. Jaiswal, P. Sheffield, K. Knowlton, and J. J. Hess. 2014. 'Heat-related mortality in India: excess all-cause mortality associated with the 2010 Ahmedabad heat wave', *PLoS One*, 9: e91831.	Ahmedabad, India

Article	Study location(s)
Bai, L., G. Ding, S. Gu, P. Bi, B. Su, D. Qin, G. Xu, and Q. Liu. 2014. 'The effects of summer temperature and heat waves on heat-related illness in a coastal city of China, 2011-2013', *Environmental Research*, 132: 212-9.	Ningbo, China
Bark, N. 1998. 'Deaths of psychiatric patients during heat waves', *Psychiatric Services*, 49: 1088-90.	New York City, USA
Basagaña, X., C. Sartini, J. Barrera-Gómez, P. Dadvand, J. Cunillera, B. Ostro, J. Sunyer, and M. Medina-Ramón. 2011. 'Heat waves and cause-specific mortality at all ages', *Epidemiology*, 22: 765-72.	Catalonia, Spain
Bishop-Williams, Katherine E., Olaf Berke, David L. Pearl, and David F. Kelton. 2015. 'A spatial analysis of heat stress related emergency room visits in rural Southern Ontario during heat waves', *BMC Emergency Medicine*, 15: 17-17.	Southern Ontario, Canada
Bittner, M. I., M. Nubling, and U. Stossel. 2013. 'Heat-related mortality in Freiburg and Rostock in 2003 and 2005 - methodology and results', *Gesundheitswesen*, 75: e126-30.	Freiburg, Germany; Rostock, Germany
Bobb, J. F., Z. Obermeyer, Y. Wang, and F. Dominici. 2014. 'Cause-specific risk of hospital admission related to extreme heat in older adults', *Journal of the American Medical Association*, 312: 2659-67.	Not available
Bogdanović, D. Ĉ, Z. G. Milošević, K. K. Lazarević, Z. Ć Dolićanin, D. M. Randelović, and S. D. Bogdanović. 2013. 'The impact of the July 2007 heat wave on daily mortality in Belgrade, Serbia', *Central European Journal of Public Health*, 21: 140-45.	Belgrade, Serbia
Bridger, C. A., F. P. Ellis, and H. L. Taylor. 1976. 'Mortality in St. Louis, Missouri, during heat	St. Louis, MO, USA

Article	Study location(s)
waves in 1936, 1953, 1954, 1955, and 1966', *Environmental Research*, 12: 38-48.	
Brunetti, N. D., D. Amoruso, L. De Gennaro, G. Dellegrottaglie, G. Di Giuseppe, G. Antonelli, and M. Di Biase. 2014. 'Hot spot: impact of July 2011 heat wave in southern Italy (Apulia) on cardiovascular disease assessed by emergency medical service and telemedicine support', *Telemedicine Journal and E-Health*, 20: 272-81.	Apulia, Italy
Bulbena, A., L. Sperry, C. Garcia Rivera, A. Merino, G. Mateu, M. Torrens, J. San Gil, and J. Cunillera. 2009. 'Impact of the summer 2003 heat wave on the activity of two psychiatric emergency departments ', *Actas Esp Psiquiatr*, 37: 158-65.	Barcelona, Spain
Bustinza, R., G. Lebel, P. Gosselin, D. Belanger, and F. Chebana. 2013. 'Health impacts of the July 2010 heat wave in Quebec, Canada', *BMC Public Health*, 13: 56.	Quebec, Canada
Calkins, M. M., T. B. Isaksen, B. A. Stubbs, M. G. Yost, and R. A. Fenske. 2016. 'Impacts of extreme heat on emergency medical service calls in King County, Washington, 2007-2012: relative risk and time series analyses of basic and advanced life support', *Environmental Health*, 15.	King County, WA, USA
Cerutti, B., C. Tereanu, G. Domenighetti, E. Cantoni, M. Gaia, I. Bolgiani, M. Lazzaro, and I. Cassis. 2006. 'Temperature related mortality and ambulance service interventions during the heat waves of 2003 in Ticino (Switzerland)', S*ozial-Und Praventivmedizin*, 51: 185-93.	Ticino, Switzerland
Chen, R., T. Li, J. Cai, M. Yan, Z. Zhao, and H. Kan. 2014. 'Extreme temperatures and out-of-	China: Harbin; Beijing; Tianjin; Nanjing; Shanghai;

Article	Study location(s)
hospital coronary deaths in six large Chinese cities', *Journal of Epidemiology and Community Health*, 68: 1119-24.	Guangzhou
Cheng, J., Z. Xu, D. Zhao, M. Xie, H. Zhang, S. Wang, and H. Su. 2016. 'The burden of extreme heat and heatwave on emergency ambulance dispatches: A time-series study in Huainan, China', *Science of the Total Environment*, 571: 27-33.	Huainan, China
Chien, L. C., Y. Guo, and K. Zhang. 2016. 'Spatiotemporal analysis of heat and heat wave effects on elderly mortality in Texas, 2006-2011', *Science of the Total Environment*, 562: 845-51.	Texas, USA
Conti, S., M. Masocco, P. Meli, G. Minelli, E. Palummeri, R. Solimini, V. Toccaceli, and M. Vichi. 2007. 'General and specific mortality among the elderly during the 2003 heat wave in Genoa (Italy)', *Environmental Research*, 103: 267-74.	Genoa, Italy
Conti, S., P. Meli, G. Minelli, R. Solimini, V. Toccaceli, M. Vichi, C. Beltrano, and L. Perini. 2005. 'Epidemiologic study of mortality during the Summer 2003 heat wave in Italy', *Environmental Research*, 98: 390-99.	Italy
Culqui, D. R., C. Linares, C. Ortiz, R. Carmona, and J. Diaz. 2017. 'Association between environmental factors and emergency hospital admissions due to Alzheimer's disease in Madrid', *Science of the Total Environment*, 592: 451-57	Madrid, Spain
Dalip, J., G. A. Phillips, G. A. Jelinek, and T. J. Weiland. 2015. 'Can the elderly handle the heat? a retrospective case-control study of the impact of heat waves on older patients attending an inner city Australian emergency department', *Asia Pacific Journal of Public*	Melbourne, Australia

Article	**Study location(s)**
Health, 27: NP1837-NP46.	
Dessai, S. 2002. 'Heat stress and mortality in Lisbon part I. model construction and validation', *International Journal of Biometeorology*, 47: 6-12.	Lisbon, Portugal
Diaz, J., A. Jordan, R. Garcia, C. Lopez, J. C. Alberdi, E. Hernandez, and A. Otero. 2002. 'Heat waves in Madrid 1986-1997: effects on the health of the elderly', *International Archives of Occupational and Environmental Health*, 75: 163-70.	Madrid, Spain
Diaz, J., R. Garcia, F. V. de Castro, E. Hernandez, C. Lopez, and A. Otero. 2002. 'Effects of extremely hot days on people older than 65 years in Seville (Spain) from 1986 to 1997', *International Journal of Biometeorology*, 46: 145-49.	Seville, Spain
D'Ippoliti, D., P. Michelozzi, C. Marino, F. de'Donato, B. Menne, K. Katsouyanni, U. Kirchmayer, A. Analitis, M. Medina-Ramon, A. Paldy, R. Atkinson, S. Kovats, L. Bisanti, A. Schneider, A. Lefranc, C. Iniguez, and C. A. Perucci. 2010. 'The impact of heat waves on mortality in 9 European cities: results from the EuroHEAT project', *Environmental Health*, 9.	Athens, Greece; Barcelona, Spain; Budapest, Hungary; London, England; Milan, Italy; Munich, Germany; Paris, France; Rome, Italy; Valencia, Spain
Dolney, T. J., and S. C. Sheridan. 2006. 'The relationship between extreme heat and ambulance response calls for the city of Toronto, Ontario, Canada', *Environmental Research*, 101: 94-103.	Toronto, Canada
Dong, W. T., Q. Zeng, Y. Ma, G. X. Li, and X. C. Pan. 2016. 'Impact of Heat Wave Definitions on the Added Effect of Heat Waves on Cardiovascular Mortality in Beijing, China', *International Journal of Environmental Research and Public Health*, 13.	Beijing, China
Ellis, F. P., and F. Nelson. 1978. 'Mortality in the elderly in a heat wave in New York City,	New York City, USA

Article	Study location(s)
August 1975', *Environmental Research*, 15: 504-12.	
Ellis, F. P., F. Nelson, and L. Pincus. 1975. 'Mortality during heat waves in New York City July, 1972 and August and September, 1973', *Environment Research*, 10: 1-13.	New York City, USA
Ellis, F. P., H. P. Prince, G. Lovatt, and R. M. Whittington. 1980. 'Mortality and morbidity in Birmingham during the 1976 heatwave', *Quarterly Journal of Medicine*, 49: 1-8.	Birminghan, UK
Fish, P. D., G. C. Bennett, and P. H. Millard. 1985. 'Heatwave morbidity and mortality in old age', *Age and Ageing*, 14: 243-5.	Balham, UK
Fisher, J. A., C. Jiang, S. I. Soneja, C. Mitchell, R. C. Puett, and A. Sapkota. 2017. 'Summertime extreme heat events and increased risk of acute myocardial infarction hospitalizations', *Journal of Exposure Science and Environmental Epidemiology*, 27: 276-80.	United States: Baltimore, MD; Columbia, MD
Fouillet, A., G. Rey, F. Laurent, G. Pavillon, S. Bellec, C. Guihenneuc-Jouyaux, J. Clavel, E. Jougla, and D. Hemon. 2006. 'Excess mortality related to the August 2003 heat wave in France', *International Archives of Occupational and Environmental Health*, 80: 16-24.	France
Fowler, D. R., C. S. Mitchell, A. Brown, T. Pollock, L. A. Bratka, J. Paulson, A. C. Noller, R. Mauskapf, K. Oscanyan, A. Vaidyanathan, A. Wolkin, E. V. Taylor, and R. Radcliffe. 2013. No No author, 'Heat-Related Deaths After an Extreme Heat Event - Four States, 2012, and United States, 1999-2009', *MMWR-Morbidity and Mortality Weekly Report*, 62: 433-36.	United States: Maryland; Ohio; Virginia; West Virginia;
Fuhrmann, C. M., M. M. Sugg, C. E. Konrad, and A. Waller. 2016. 'Impact of Extreme Heat Events on Emergency Department Visits in North Carolina (2007-2011)', *Journal of Community Health*, 41: 146-56.	North Carolina, USA

Article	Study location(s)
Gao, J., Y. Sun, Q. Liu, M. Zhou, Y. Lu, and L. Li. 2015. 'Impact of extreme high temperature on mortality and regional level definition of heat wave: a multi-city study in China', *Science of the Total Environment*, 505: 535-44.	China: Beijing; Tianjin; Nanjing; Shanghai; Changsha
Garssen J, Harmsen C, and De Beer J. 2005. 'The effect of the summer 2003 heat wave on mortality in the Netherlands', *Euro Surveillance*, 10(7): 557.	The Netherlands
Gasparrini, A., and B. Armstrong. 2011. 'The impact of heat waves on mortality', *Epidemiology*, 22: 68-73.	United States: Akron, OH; Albuquerque, NM; Anchorage, AK; Arlington, VA; Atlanta, GA; Austin, TX; Bakersfield, CA; Baltimore, MD; Baton Rouge, LA; Biddeford, ME; Birmingham, AL; Boston, MA; Buffalo, NY; Cayce, SC; Cedar Rapids, IA; Charlotte, NC; Chicago, IL; Cincinnati, OH; Cleveland, OH; Colorado Springs, CO; Columbus, GA; Columbus, OH; Corpus Christi, TX; Coventry, RI; Dallas, TX; Dayton, OH; Denver, CO; Des Moines, IA; Detroit, MI; El Paso, TX; Evansville, IN; Fort Wayne, IN; Fresno, CA; Grand Rapids, MI; Greensboro, NC; Honolulu, HI; Houston, TX; Huntsville, IL; Indianapolis, IN; Jackson, MS; Jacksonville, FL; Jersey City, NJ; Johnstown, PA; Kansas City, KS; Kansas City, MO; Kingston, NY; Knoxville, TN; Lafayette, LA; Lake Charles, LA; Las Vegas, NV; Lexington, KY; Lincoln, NE; Little Rock, AR; Los Angeles, CA; Louisville, KY; Lubbock, TX; Madison, WI; Memphis, TN; Miami, FL; Milwaukee, WI; Minneapolis-St Paul, MN; Mobile, AL; Modesto, CA; Muskegon, MI; Nashville, TN; New Orleans, LA; New York, NY; Newark, NJ; Newport

Article	Study location(s)
	News, VA; Norfolk, VA; Oakland, CA; Oklahoma City, OK; Olympia, WA; Omaha, NE; Orlando, FL; Philadelphia, PA; Phoenix, AZ; Pittsburgh, PA; Portland, OR; Providence, RI; Raleigh, NC; Richmond, VA; Riverside, CA; Rochester, NY; Sacramento, CA; Salt Lake City, UT; San Antonio, TX; San Bernardino, CA; San Diego, CA; San Francisco, CA; San Jose, CA; Santa Ana/Anaheim, CA; Seattle, WA; Shreveport, LA; Spokane, WA; St. Louis, MO; St. Petersburg, FL; Stockton, CA; Syracuse, NY; Tacoma, WA; Tampa, FL; Toledo, OH; Topeka; Tucson, AZ; Tulsa, OK; Washington, DC; Wichita, KS; Worcester, MA
Ghumman, Usman, and Jennifer Horney. 2016. 'Characterizing the Impact of Extreme Heat on Mortality, Karachi, Pakistan, June 2015', *Prehospital and Disaster Medicine*, 31: 263-66.	Karachi, Pakistan
Golden, J. S., D. Hartz, A. Brazel, G. Luber, and P. Phelan. 2008. 'A biometeorology study of climate and heat-related morbidity in Phoenix from 2001 to 2006', *International Journal of Biometeorology*, 52: 471-80.	Phoenix, USA
Greenberg, J. H., J. Bromberg, C. M. Reed, T. L. Gustafson, and R. A. Beauchamp. 1983. 'The epidemiology of heat-related deaths, Texas--1950, 1970-79, and 1980', *American Journal of Public Health*, 73: 805-7.	Texas, USA
Grize, L., A. Huss, O. Thommen, C. Schindler, and C. Braun-Fahrlander. 2005. 'Heat wave 2003 and mortality in Switzerland', *Swiss Medical Weekly*, 135: 200-5.	Switzerland
Gronlund, C. J., A. Zanobetti, G. A. Wellenius, J. D. Schwartz, and M. S. O'Neill. 2016.	United States: Akron, OH; Albuquerque, NM; Allentown

Article	Study location(s)
'Vulnerability to Renal, Heat and Respiratory Hospitalizations During Extreme Heat Among U.S. Elderly', *Climate Change*, 136: 631-45.	PA; Atlanta, GA; Atlantic City, NJ; Austin, TX; Bakersfield, CA; Baltimore, MD; Baton Rouge, LA; Passaic, NJ; Birmingham, AL; Boston, MA; Buffalo, NY; Canton, OH; Charlotte, NC; Chattanooga, TN; Chicago, IL; Cincinnati, OH; Cleveland, OH; Columbia, SC; Columbus, OH; Dallas, TX; Daytona Beach, FL; Denver, CO; Des Moines, IA; Detroit, MI; El Paso, TX; Erie, PA; Flint, MI; Fort Myers, FL; Fort Worth, TX; Fresno, CA; Ft. Lauderdale, FL; Gary, IN; Grand Rapids, MI; Greensboro, NC; Greenville, SC; Hartford, CT; Houston, TX; Indianapolis, IN; Jacksonville, FL; Jersey City, NJ; Kansas City, MO; Knoxville, TN; Lakeland, FL; Lancaster, PA; Lansing, MI; Las Vegas, NV; Little Rock, AR; Los Angeles, CA; Madison, WI; McAllen, TX; Melbourne, FL; Memphis, TN; Miami, FL; Middlesex, NJ; Milwaukee, WI; Minneapolis-St. Paul, MN; Mobile, AL; Monmouth, NJ; Nashville, TN; Nassau, NY; New Haven, CT; New York, NY; Newark, NJ; Oakland, CA; Oklahoma City, OK; Omaha, NE; Orlando, FL; Pensacola, FL; Philadelphia, PA; Phoenix, AZ; Pittsburgh, PA; Portland, OR; Providence, RI; Raleigh, NC; Riverside, CA; Rochester, NY; Rockford, IL; Sacramento, CA; Salinas, CA; Salt Lake City, UT; San Antonio, TX; San Diego, CA; San Francisco, CA; San Jose, CA; Sarasota, FL; Scranton, PA; Seattle, WA; Shreveport, LA; Spokane, WA; Springfield, MA; St. Louis, MO; Stamford, CT; Stockton, CA; Syracuse, NY; Tacoma,

Article	Study location(s)
	WA; Tampa, FL; Toledo, OH; Trenton, NJ; Tucson, AZ; Tulsa, OK; Utica, NY; Virginia Beach, VA; Washington, DC; West Palm Beach, FL; Wichita, KS; Worcester, MA; Youngstown, OH
Gronlund, C. J., A. Zanobetti, J. D. Schwartz, G. A. Wellenius, and M. S. O'Neill. 2014. 'Heat, Heat Waves, and Hospital Admissions among the Elderly in the United States, 1992-2006', *Environmental Health Perspectives*, 122: 1187-92.	United States: Akron, OH; Albuquerque, NM; Allentown, PA; Atlanta, GA; Atlantic City, NJ; Austin, TX; Bakersfield, CA; Baltimore, MD; Passaic, NJ; Birmingham, AL; Boston, MA; Baton Rouge, LA; Brownsville, TX; Buffalo, NY; Canton, OH; Charleston, WV; Charlotte, NC; Chattanooga, TN; Chicago, IL; Cleveland, OH; Columbia, SC; Columbus, OH; Dallas, TX; Daytona Beach, FL; Dayton, OH; Denver, CO; Des Moines, IA; Detroit, MI; Poughkeepsie, NY; El Paso, TX; Erie, PA; Flint, MI; Fresno, CA; Galveston, TX; Gary, IN; Grand Rapids, MI; Greensboro, NC; Greenville, SC; Hartford, CT; Houston, TX; Indianapolis, IN; Jacksonville, FL; Jersey City, NJ; Kansas City, MO; Knoxville, TN; Lakeland, FL; Lansing, MI; Las Vegas, NV; Los Angeles, CA; Louisville, KY; Lubbock, TX; Madison, WI; Memphis, TN; Miami, FL; Middlesex, NJ; Milwaukee, WI; Minneapolis-St. Paul, MN; Mobile, AL; Monmouth, NJ; Myrtle Beach, SC; Nashua, NH; Nashville, TN; Newark, NJ; Newburgh, NY; New Haven, CT; New London, CT; New York, NY; Oakland, CA; Ocala, FL; Oklahoma City, OK; Omaha, NE; Newport Beach, CA; Orlando, FL;

Article	Study location(s)
	Philadelphia, PA; Phoenix, AZ; Pittsburgh, PA; Portland, ME; Portland, OR; Providence, RI; Raleigh, NC; Scranton, PA; St. Louis, MO; Ventura, CA; Reading, PA; Stockton, CA; Virginia Beach, VA; San Diego, CA; Rochester, NY; Syracuse, NY; Washington, DC; Seattle, WA; Rockford, IL; Tacoma, WA; Wichita, KS; San Francisco, CA; Sacramento, CA; Tampa, FL; Wilmington, DE; Shreveport, LA; Saginaw, MI; Worcester, MA; San Jose, CA; Toledo, OH; Salt Lake City, UT; West Palm Beach, FL; Spokane, WA; Trenton, NJ; San Antonio, TX; Springfield, MA; Tucson, AZ; Youngstown, OH; Sarasota, FL; Stamford, CT; Tulsa, OK
Gronlund, C. J., V. J. Berrocal, J. L. White-Newsome, K. C. Conlon, and M. S. O'Neill. 2015. 'Vulnerability to extreme heat by socio-demographic characteristics and area green space among the elderly in Michigan, 1990-2007', *Environmental Research*, 136: 449-61.	United States, MI: Detroit; Grand Rapids; Ann Arbor; Flint; Holland; Kalamazoo; Lansing; Saginaw
Ha, S., E. O. Talbott, H. D. Kan, C. A. Prins, and X. H. Xu. 2014. 'The effects of heat stress and its effect modifiers on stroke hospitalizations in Allegheny County, Pennsylvania', *International Archives of Occupational and Environmental Health*, 87: 557-65.	Allegheny county, PA, USA
Hajat, S., R. S. Kovats, R. W. Atkinson, and A. Haines. 2002. 'Impact of hot temperatures on death in London: A time series approach', *Journal of Epidemiology and Community Health*, 56: 367-72.	London, UK
Han, J., S. Liu, J. Zhang, L. Zhou, Q. Fang, J. Zhang, and Y. Zhang. 2017. 'The impact of temperature extremes on mortality: a time-series study in Jinan, China', *BMJ Open*, 7:	Jinan, China

Article	Study location(s)
e014741.	
Hansen, A. L., P. Bi, P. Ryan, M. Nitschke, D. Pisaniello, and G. Tucker. 2008. 'The effect of heat waves on hospital admissions for renal disease in a temperate city of Australia', *International Journal of Epidemiology*, 37: 1359-65.	Adelaide, Australia
Hansen, A., P. Bi, M. Nitschke, P. Ryan, D. Pisaniello, and G. Tucker. 2008. 'The effect of heat waves on mental health in a temperate Australian city', *Environmental Health Perspectives*, 116: 1369-75.	Adelaide, Australia
Hartz, D. A., J. S. Golden, C. Sister, W. C. Chuang, and A. J. Brazel. 2012. 'Climate and heat-related emergencies in Chicago, Illinois (2003-2006)', *International Journal of Biometeorology*, 56: 71-83.	Chicago, USA
Hertel, S., A. Le Tertre, K. H. Jockel, and B. Hoffmann. 2009. 'Quantification of the heat wave effect on cause-specific mortality in Essen, Germany', *European Journal of Epidemiology*, 24: 407-14.	Essen, Germany
Hoffmann, B., S. Hertel, T. Boes, D. Weiland, and K. H. Jockel. 2008. 'Increased cause-specific mortality associated with 2003 heat wave in Essen, Germany', *Journal of Toxicology and Environmental Health-Part a-Current Issues*, 71: 759-65.	Essen, Germany
Holstein, J., F. Canoui-Poitrine, A. Neumann, E. Lepage, and A. Spira. 2005. 'Were less disabled patients the most affected by 2003 heat wave in nursing homes in Paris, France?', *Journal of Public Health*, 27: 359-65.	Paris, France
Huang, W., H. Kan, and S. Kovats. 2010. 'The impact of the 2003 heat wave on mortality in	Shanghai, China

Article	**Study location(s)**
Shanghai, China', *Science of the Total Environment*, 408: 2418-20.	
Hutter, H. P., H. Moshammer, P. Wallner, B. Leitner, and M. Kundi. 2007. 'Heatwaves in Vienna: Effects on mortality', *Wien Klin Wochenschr*, 119: 223-27.	Vienna, Austria
Huynen, Mmte, P. Martens, D. Schram, M. P. Weijenberg, and A. E. Kunst. 2001. 'The impact of heat waves and cold spells on mortality rates in the Dutch population', *Environmental Health Perspectives*, 109: 463-70.	The Netherlands
Ingole, V., J. Rocklov, S. Juvekar, and B. Schumann. 2015. 'Impact of Heat and Cold on Total and Cause-Specific Mortality in Vadu HDSS-A Rural Setting in Western India', *International Journal of Environ Research in Public Health*, 12: 15298-308.	Vadu HDSS, India
Isaksen, T. B., R. A. Fenske, E. K. Hom, Y. Ren, H. Lyons, and M. G. Yost. 2016. 'Increased mortality associated with extreme-heat exposure in King County, Washington, 1980-2010', *International Journal of Biometeorology*, 60: 85-98.	King county, WA, USA
Isaksen, Tania Busch, Michael G. Yost, Elizabeth K. Hom, You Ren, Hilary Lyons, and Richard A. Fenske. 2015. 'Increased hospital admissions associated with extreme-heat exposure in King County, Washington, 1990-2010', *Reviews on Environmental Health*, 30: 51-64.	King County, WA, USA
Jegasothy, E., R. McGuire, J. Nairn, R. Fawcett, and B. Scalley. 2017. 'Extreme climatic conditions and health service utilisation across rural and metropolitan New South Wales', *International Journal of Biometeorology*.	New South Wales, Australia
Joe, L., S. Hoshiko, D. Dobraca, R. Jackson, S. Smorodinsky, D. Smith, and M. Harnly. 2016. 'Mortality during a Large-Scale Heat Wave by Place, Demographic Group, Internal and	California, USA

Article	Study location(s)
External Causes of Death, and Building Climate Zone', *International Journal of Environmental Research and Public Health*, 13.	
Johnson, H., R. S. Kovats, G. McGregor, J. Stedman, M. Gibbs, and H. Walton. 2005. 'The impact of the 2003 heat wave on daily mortality in England and Wales and the use of rapid weekly mortality estimates', *Euro Surveillance*, 10: 168-71.	England and Wales
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Jones, T. S., A. P. Liang, E. M. Kilbourne, M. R. Griffin, P. A. Patriarca, S. G. Wassilak, R. J. Mullan, R. F. Herrick, H. D. Donnell Jr, K. Choi, and S. B. Thacker. 1982. 'Morbidity and mortality associated with the July 1980 heat wave in St Louis and Kansas City, MO', *Journal of the American Medical Association*, 247: 3327-31.	United States: St. Louis, MO; Kansas City, MO
Josseran, L., N. Caillere, D. Brun-Ney, J. Rottner, L. Filleul, G. Brucker, and P. Astagneau. 2009. 'Syndromic surveillance and heat wave morbidity: a pilot study based on emergency departments in France', *BMC Medical Informatics and Decision Making*, 9: 14.	France
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Katsouyanni, K., A. Pantazopoulou, G. Touloumi, I. Tselepidaki, K. Moustris, D. Asimakopoulos, G. Poulopoulou, and D. Trichopoulos. 1993. 'Evidence for interaction between air pollution and high temperature in the causation of excess mortality', *Archives of Environmental Health*, 48: 235-42.	Athens, Greece
Khalaj, B., G. Lloyd, V. Sheppeard, and K. Dear. 2010. 'The health impacts of heat waves in five regions of New South Wales, Australia: A case-only analysis', *International Archives of Occupational and Environmental Health*, 83: 833-42.	Greater Sydney, NSW, Australia
Kim, E. J., and H. Kim. 2017. 'Effect modification of individual- and regional-scale characteristics on heat wave-related mortality rates between 2009 and 2012 in Seoul, South Korea', *Science of the Total Environment*, 595: 141-48.	Seoul, South Korea
Klenk, J., C. Becker, and K. Rapp. 2010. 'Heat-related mortality in residents of nursing homes', *Age and Ageing*, 39: 245-52.	South West Germany
Knobeloch, L., H. Anderson, J. Morgan, and R. Nashold. 1997. 'Heat-related illness and death, Wisconsin, 1995', *Wisconsin Medical Journal*, 96: 33-38.	Wisconsin, USA
Knowlton, K., M. Rotkin-Ellman, G. King, H. G. Margolis, D. Smith, G. Solomon, R. Trent, and P. English. 2009. 'The 2006 California Heat Wave: Impacts on Hospitalizations and Emergency Department Visits', *Environmental Health Perspectives*, 117: 61-67.	California, USA
Kosatsky, T., S. B. Henderson, and S. L. Pollock. 2012. 'Shifts in Mortality During a Hot Weather Event in Vancouver, British Columbia: Rapid Assessment With Case-Only Analysis', *American Journal of Public Health*, 102: 2367-71.	Vancouver, Canada

Article	Study location(s)
Kovats, R. S., S. Hajat, and P. Wilkinson. 2004. 'Contrasting patterns of mortality and hospital admissions during hot weather and heat waves in Greater London, UK', *Occupational and Environmental Medicine*, 61: 893-98.	London, UK
Kue, Ricky C., and K. Sophia Dyer. 2013. 'The impact of heat waves on transport volumes in an urban emergency medical services system: a retrospective review', *Prehospital and Disaster Medicine*, 28: 610-15.	Boston, USA
Kysely, J. 2004. 'Mortality and displaced mortality during heat waves in the Czech Republic', *International Journal of Biometeorology*, 49: 91-7.	Czech Republic
Kysely, J., and J. Kim. 2009. 'Mortality during heat waves in South Korea, 1991 to 2005: How exceptional was the 1994 heat wave?', *Climate Research*, 38: 105-16.	South Korea
Lan, L., G. Cui, C. Yang, J. Wang, C. Sui, G. Xu, D. Zhou, Y. Cheng, Y. Guo, and T. Li. 2012. 'Increased mortality during the 2010 heat wave in Harbin, China', *Ecohealth*, 9: 310-4.	Harbin, China
Le Tertre, A., A. Lefranc, D. Eilstein, C. Declercq, S. Medina, M. Blanchard, B. Chardon, P. Fabre, L. Filleul, J. F. Jusot, L. Pascal, H. Prouvost, S. Cassadou, and M. Ledrans. 2006. 'Impact of the 2003 heatwave on all-cause mortality in 9 French cities', *Epidemiology*, 17: 75-79.	France: Bordeaux; Le Havre; Lille; Lyon; Marseilles; Paris; Rouen; Strasbourg; Toulouse
Lee, W. K., H. A. Lee, Y. H. Lim, and H. Park. 2016. 'Added effect of heat wave on mortality in Seoul, Korea', *International Journal of Biometeorology*, 60: 719-26.	Seoul, South Korea
Levy, M., M. Broccoli, G. Cole, J. L. Jenkins, and E. Y. Klein. 2015. 'An analysis of the relationship between the heat index and arrivals in the emergency department', *PLoS Currents*, 7.	Balitmore, USA

Article	Study location(s)
Lin, Y. K., T. J. Ho, and Y. C. Wang. 2011. 'Mortality risk associated with temperature and prolonged temperature extremes in elderly populations in Taiwan', *Environmental Research*, 111: 1156-63.	Taiwan: Taipei; Taichung; Tainan; Kaohsiung
Linares, C., P. Martinez-Martin, C. Rodriguez-Blazquez, M. J. Forjaz, R. Carmona, and J. Diaz. 2016. 'Effect of heat waves on morbidity and mortality due to Parkinson's disease in Madrid: A time-series analysis', *Environment International*, 89-90: 1-6.	Madrid, Spain
Lindstrom, S. J., V. Nagalingam, and H. H. Newnham. 2013. 'Impact of the 2009 Melbourne heatwave on a major public hospital', *Internal Medicine Journal*, 43: 1246-50.	Melbourne, Australia
Liss, A., R. Wu, K. K. Chui, and E. N. Naumova. 2017. 'Heat-Related Hospitalizations in Older Adults: An Amplified Effect of the First Seasonal Heatwave', *Science Reports*, 7: 39581.	Boston, USA
Loughnan, M. E., N. Nicholls, and N. J. Tapper. 2010. 'The effects of summer temperature, age and socioeconomic circumstance on Acute Myocardial Infarction admissions in Melbourne, Australia', *International Journal of Health Geography*, 9.	Melbourne, Australia
Lye, M., and A. Kamal. 1977. 'Effects of a heatwave on mortality-rates in elderly inpatients', *The Lancet*, 1: 529-31.	Manchester, UK
Ma, W., W. Zeng, M. Zhou, L. Wang, S. Rutherford, H. Lin, T. Liu, Y. Zhang, J. Xiao, Y. Zhang, X. Wang, X. Gu, and C. Chu. 2015. 'The short-term effect of heat waves on mortality and its modifiers in China: an analysis from 66 communities', *Environment International*, 75: 103-9.	China: Nanjing; Hangzhou; Hefei; Shanghai; Nanning; Wuhan; Changsha; Nanchang; Fuzhou; Guangzhou; Taiyuan; Lanzhou; Yinchuan; Urumqi; Xining; Chengdu; Guiyang; Kunming; Chongqing; Harbin; Shenyang; Changchun; Beijing; Tianjin; Shijiazhuang; Taiyuan;

Article	Study location(s)
	Chifeng; Zhengzhou
Ma, W., X. Xu, L. Peng, and H. Kan. 2011. 'Impact of extreme temperature on hospital admission in Shanghai, China', *Science of the Total Environment*, 409: 3634-7.	Shanghai, China
Macfarlane, A., and R. E. Waller. 1976. 'Short term increases in mortality during heatwaves', *Nature*, 264: 434-6.	London, UK
Madrigano, J., K. Ito, S. Johnson, P. L. Kinney, and T. Matte. 2015. 'A Case-Only Study of Vulnerability to Heat Wave-Related Mortality in New York City (2000-2011)', *Environmental Health Perspectives*, 123: 672-78.	New York City, USA
Marmor, M. 1975. 'Heat wave mortality in New York City, 1949 to 1970', *Archives of Environmental Health*, 30: 130-6.	New York City, USA
Marmor, M. 1978. 'Heat wave mortality in nursing homes', *Environmental Research*, 17: 102-15.	New York City, USA
Mastrangelo, G., U. Fedeli, C. Visentin, G. Milan, E. Fadda, and P. Spolaore. 2007. 'Pattern and determinants of hospitalization during heat waves: An ecologic study', *BMC Public Health*, 7.	Veneto region, Italy
Matte, T. D., K. Lane, and K. Ito. 2016. 'EXCESS MORTALITY ATTRIBUTABLE TO EXTREME HEAT IN NEW YORK CITY, 1997-2013', *Health Security*, 14: 64-70.	New York City, USA
Mayner, L., P. Arbon, and K. Usher. 2010. 'Emergency department patient presentations during the 2009 heatwaves in Adelaide', *Collegian*, 17: 175-82.	Adelaide, Australia

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Medina-Ramón, M., A. Zanobetti, D. P. Cavanagh, and J. Schwartz. 2006. 'Extreme temperatures and mortality: assessing effect modification by personal characteristics and specific cause of death in a multi-city case-only analysis', *Environmental Health Perspectives*, 114: 1331-36.	United States: Albuquerque, NM; Atlanta, GA; Austin, TX; Baltimore, MD; Birmingham, AL; Boston, MA; Boulder, CO; Canton, OH; Charlotte, NC; Chicago, IL; Cincinnati, OH; Cleveland, OH; Colorado Springs, CO; Columbus, GA; Dallas, TX; Denver, CO; Detroit, MI; Fort Lauderdale, FL; Greensboro, NC; Honolulu, HI; Houston, TX; Jersey City, NJ; Kansas City, KS; Los Angeles, CA; Miami, FL; Milwaukee, WI; Minneapolis-St Paul, MN; Nashville, TN; New Haven, CT; New Orleans, LA; New York, NY; Oklahoma City, OK; Orlando, FL; Philadelphia, PA; Phoenix, AZ; Pittsburgh, PA; Portland, OR; Provo, UT; Sacramento, CA; Salt Lake City, UT; San Diego, CA; San Francisco, CA; Seattle, WA; Spokane, WA; St Louis, MO; Tampa, FL; Terra Haute, IN; Tulsa, OK; Washington, DC; Youngtown, OH
Michelozzi, P., F. de Donato, L. Bisanti, A. Russo, E. Cadum, M. DeMaria, M. D'Ovidio, G. Costa, and C. A. Perucci. 2005. 'The impact of the summer 2003 heat waves on mortality in four Italian cities', *Euro Surveillance*, 10: 161-5.	Italy: Bologna; Milan; Rome; Turin
Miron, I. J., C. Linares, J. C. Montero, J. J. Criado-Alvarez, and J. Diaz. 2015. 'Changes in cause-specific mortality during heat waves in central Spain, 1975-2008', *International Journal of Biometeorology*, 59: 1213-22.	Castile-La Mancha, Spain
Monteiro, A., V. Carvalho, T. Oliveira, and C. Sousa. 2013. 'Excess mortality and morbidity during the July 2006 heat wave in Porto, Portugal', *International Journal of Biometeorology*,	Porto, Portugal

Article	**Study location(s)**
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Montero, J. C., I. J. Miron, J. J. Criado-Alvarez, C. Linares, and J. Diaz. 2012. 'Influence of local factors in the relationship between mortality and heat waves: Castile-La Mancha (1975-2003)', *Science of the Total Environment*, 414: 73-80.	Castile-La Mancha, Spain
Nakai, S., T. Itoh, and T. Morimoto. 1999. 'Deaths from heat-stroke in Japan: 1968-1994', *International Journal of Biometeorology*, 43: 124-7.	Japan
Nitschke, M., G. R. Tucker, A. L. Hansen, S. Williams, Y. Zhang, and P. Bi. 2011. 'Impact of two recent extreme heat episodes on morbidity and mortality in Adelaide, South Australia: a case-series analysis', *Environmental Health*, 10.	Adelaide, Australia
Nitschke, M., G. R. Tucker, and P. Bi. 2007. 'Morbidity and mortality during heatwaves in metropolitan Adelaide', *Medical Journal of Australia*, 187: 662-65.	Adelaide, Australia
No author, 1980. 'Heat wave related mortality--United States', *Journal of the Medical Association of Georgia*, 69: 749-50.	United States: Dallas, TX; Little Rock, AR; St. Louis, MO
No author, 2003. 'Heat-related deaths--Chicago, Illinois, 1996-2001, and United States, 1979-1999', *MMWR Morbidity and Mortality Weekly Report*, 52: 610-3.	Chicago, USA
No author, 2006. 'Estimated daily mortality during July 2006 in England and Wales', *Health Stat Quarterly*: 107-11.	England and Wales
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Article	Study location(s)
Ogbomo, A. S., C. J. Gronlund, M. S. O'Neill, T. Konen, L. Cameron, and R. Wahl. 2017. 'Vulnerability to extreme-heat-associated hospitalization in three counties in Michigan, USA, 2000-2009', *International Journal of Biometeorology*, 61: 833-43.	Michigan, USA
Onozuka, D., and A. Hagihara. 2016. 'Spatial and temporal variation in emergency transport during periods of extreme heat in Japan: A nationwide study', *Science of the Total Environment*, 544: 220-9.	Japan
Pascal, M., A. Le Tertre, and A. Saoudi. 2012. 'Quantification of the heat wave effect on mortality in nine French cities during summer 2006', *PLoS Currents*.	France: Bordeaux; Le Havre; Lille; Lyon; Marseilles; Paris; Rouen; Strasbourg; Toulouse
Phung, D., C. Chu, S. Rutherford, H. L. Nguyen, C. M. Do, and C. Huang. 2017. 'Heatwave and risk of hospitalization: A multi-province study in Vietnam', *Environmental Pollution*, 220: 597-607.	Vietnam
Phung, D., Y. Guo, P. Thai, S. Rutherford, X. Wang, M. Nguyen, C. M. Do, N. H. Nguyen, N. Alam, and C. Chu. 2016. 'The effects of high temperature on cardiovascular admissions in the most populous tropical city in Vietnam', *Environmental Pollution*, 208: 33-9.	Ho Chi Minh City, Vietnam
Ponjoan, A., J. Blanch, L. Alves-Cabratosa, R. Marti-Lluch, M. Comas-Cufi, D. Parramon, M. D. Garcia-Gil, R. Ramos, and I. Petersen. 2017. 'Effects of extreme temperatures on cardiovascular emergency hospitalizations in a Mediterranean region: a self-controlled case series study', *Environmental Health*, 16.	Catalonia, Spain
Qiu, D., T. Tanihata, H. Aoyama, T. Fujita, Y. Inaba, and M. Minowa. 2002. 'Relationship between a high mortality rate and extreme heat during the summer of 1999 in Hokkaido	Hokkaido, Japan

Article	**Study location(s)**
Prefecture, Japan', *Journal of Epidemiology*, 12: 254-7.	
Rabczenko, D., B. Wojtyniak, M. Kuchcik, W. Szymalski, W. Seroka, and E. Zmudzka. 2016. 'Association between high temperature and mortality of Warsaw inhabitants, 2008-2013', *Przegl Epidemiology*, 70: 629-40.	Warsaw, Poland
Ramlow, J. M., and L. H. Kuller. 1990. 'Effects of the summer heat wave of 1988 on daily mortality in Allegheny County, PA', *Public Health Reports*, 105: 283-9.	Allegheny county, PA, USA
Revich, B. A., and D. A. Shaposhnikov. 2010. 'Extreme temperature episodes and mortality in Yakutsk, East Siberia', *Rural Remote Health*, 10.	Yakutsk, East Siberia
Revich, B., and D. Shaposhnikov. 2008. 'Excess mortality during heat waves and cold spells in Moscow, Russia', *Occupational and Environmental Medicine*, 65: 691-96.	Moscow, Russia
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Appendix B: Published version of Chapter 3

B.1 Abstract

Heatwaves have been identified as a threat to human health, with this impact projected to rise in a warming climate. Gaps in local knowledge can potentially undermine appropriate policy and preparedness actions. Using a case-crossover methodology, we examined the impact of heatwave events on hospital emergency department (ED) presentations in the two most populous regions of Tasmania, Australia, from 2008-2016. Using conditional logistic regression, we analysed the relationship between ED presentations and severe/extreme heatwaves for the whole population, specific demographics including age, gender and socio-economic advantage, and diagnostic conditions that are known to be impacted in high temperatures. ED presentations increased by 5% (OR 1.05, 95% CI 1.01-1.09) across the whole population, by 13% (OR 1.13, 95% CI 1.03-1.24) for children 15 years and under, and by 19% (OR 1.19, 95% CI 1.04-1.36) for children 5 years and under. A less precise association in the same direction was found for those over 65 years. For diagnostic subgroups, non-significant increases in ED presentations were observed for asthma, diabetes, hypertension, and atrial fibrillation. These findings may assist ED surge capacity planning and public health preparedness and response activities for heatwave events in Tasmania, highlighting the importance of using local research to inform local practice.

B.2 Introduction

Anthropogenic climate change represents “an unacceptably high and potentially catastrophic risk to human health” (Watts et al. 2015, p.1861). While climate change may not necessarily impact health through the introduction of new diseases or disorders, it is likely to expand and amplify existing health issues (Blashki et al. 2011), presenting to the global population as a broad spectrum of health risks (World Health Organization 2012). The Intergovernmental Panel on Climate Change describes global mean surface air temperature as rising over the last 100 years (IPCC 2013), which has led directly to an increase in frequency, intensity, and duration of extreme heat events since 1950 (Perkins, Alexander & Nairn 2012). It is widely accepted that extreme heat, and specifically extreme heat events, have a detrimental effect on human health. In Australia, extreme heat is responsible for over 55% of total fatalities caused by natural events since 1900; more deaths than all other natural hazards combined (Coates et al. 2014).

Heatwaves have been studied across many parts of the world, although significant geographic gaps exist (Campbell et al. 2018). Heat-related illness and death does not present equally across populations, with some groups appearing more vulnerable than others (Bi et al. 2011). Meta-analyses show that the greatest impacts appear likely for the elderly, children, and those with existing medical conditions, including cardiovascular diseases and mental illnesses (Benmarhnia et al. 2015; Li et al. 2015).

Several methods exist to assess the extent to which extreme heat events impact human health; these include analysing mortality data for the period of the event and shortly after (Fouillet et al. 2006); analysing morbidity indicators, such as ambulance dispatches, emergency hospital presentations, and hospital admissions (Kue & Dyer 2013a); or a combination of mortality and morbidity data (Nitschke, Tucker & Bi 2007; Williams et al. 2012b). Studies investigating the economic impact and work output have also emerged (Orlov et al. 2019). Studies of outcomes relating to heatwave-associated morbidity are, however, far less common than studies of mortality (Bi et al. 2011; Campbell et al. 2018). This is an important discrepancy, as mortality represents the extremes of health impacts, while understanding the association with other health outcomes is equally important for quantifying the greater impacts on the healthcare system and the society.

In Australia, several studies have examined the link between extreme heat and health outcomes (Khalaj et al. 2010; Lindstrom, Nagalingam & Newnham 2013; Nitschke et al. 2011b; Toloo et al. 2014; Tong et al. 2014; Turner, Connell & Tong 2013; Williams et al. 2012b), including for specific cohorts (Dalip et al. 2015; Hansen et al. 2008). Across these studies, a positive association has been established between extreme heat events and increases in ambulance dispatches, hospital emergency department (ED) presentations, and deaths. These studies have principally concentrated on urban settings in the larger capital cities of Melbourne, Perth, Adelaide, Sydney, and Brisbane, which are all located in warmer climate regions. To date, no studies have been conducted specifically in the cooler climate regions of Australia, where health outcomes associated with heatwaves are unknown.

B.2.1 Study setting

Tasmania is an island state in Australia, located to the south of mainland Australia (40°S-43°S). The majority of the Tasmanian population reside in a regional or remote classified area (Australian Bureau of Statistics 2011). The state's total population in 2016 was 510,000, with most of the population residing in one of three major centres—Hobart, the capital, located in the southeast (population 204,000), Launceston in the north (population 84,000) or Burnie-Devonport in the northwest (population 70,000) (Australian Bureau of Statistics 2018b). There are slightly more females than males in Tasmania (98 males to 100 females), and the median age is 42.3 years, the highest of any Australian state or territory (Australian Bureau of Statistics 2018b).

Tasmania has four major public hospitals, each with an emergency department, located in the most densely populated regions—one located in Hobart (Royal Hobart Hospital); one in Launceston (Launceston General Hospital); and two in the Burnie-Devonport region (the Mersey Community Hospital and the North West Regional Hospital).

Severe heatwaves are not a common feature of the Tasmanian summer experience, with average maximum summer temperatures of approximately 20°C, some of the lowest found in Australia. However, Tasmania still experiences occasional extreme heat events. In late January 2009, for example, Tasmania experienced its hottest maximum temperature on record, reaching 42.2°C at Scamander in the state's northeast region. Several other towns in the north and northeast experienced similar maximum temperatures over the following days (Bureau of Meteorology 2010). In 2013, Hobart experienced its hottest maximum temperature ever recorded (41.8°C on 4 January) and several other highest summer temperature records were broken in the surrounding regions on that day (Bureau of Meteorology 2013). This period in the southeast was also marked by severe wildfires (Tasmanian Government 2013).

When compared to other Australian jurisdictions, Tasmania has a greater proportion of people in higher risk groups identified as vulnerable to heat events. With 19.3% of the population over 65 years of age, Tasmania has the highest proportion of elderly residents (Australian Bureau of Statistics 2018c), and the highest proportion of cardiovascular disease (7.7%), and long-term mental or behavioural problems (21%) (Department of Health 2018). Tasmania also has a higher proportion of people living in greatest disadvantage (33%) than any other Australian state and territory (Department of Health 2018), with less than half of Tasmanian households having access to air-conditioning for cooling (Department of Health and Human Services 2016). These factors potentially make the Tasmanian population more vulnerable to heatwaves when they do occur.

As a compounding factor, typical Tasmanian weather patterns do not involve uniform increases and decreases in temperature throughout the spring-summer-autumn period. Due to its location within the westerly wind belt, and the consequent regular passage of cold frontal systems, Tasmanian meteorology is characterised by highly variable conditions and rapid shifts in temperature. For example, a month before the warmest day on record in Hobart (41.8°C on 4 January 2013), the nearby community of Maydena in Tasmania’s southeast experienced the coldest summer day on record (9.4°C on 4 December 2012) (Bureau of Meteorology 2013). This variability impedes the ability of the Tasmanian population to adequately acclimatise to heat events over the summer period, potentially increasing vulnerability to heat events when they do occur (Braga, Zanobetti & Schwartz 2001).

While Tasmania has had a state heatwave plan in place since 2013, a paucity of research on heatwaves in Tasmania and their impact on local health systems has hampered efforts by public health policymakers to develop targeted policies and programs to reduce the public health impact of heatwaves. To date, policy and planning has relied on research conducted in other geographic settings, which does not take Tasmania’s unique vulnerabilities or climate into account.

B.2.2 Research aim

The aim of this research was to investigate the impact of heatwaves on ED presentations in Tasmania, highlighting similarities and differences with other jurisdictions. Associations with all-cause, age-specific, location-specific, and condition-specific presentations were analysed.

B.3 Materials and methods

B.3.1 Exposure data

Temperature data from the Bureau of Meteorology Atmospheric high-resolution Regional Reanalysis for Australia (BARRA) dataset (Su et al. 2019) were obtained from the Bureau of Meteorology (BoM). BARRA data were used because they provide better spatial and temporal resolution than station data. Averaged maximum and minimum temperatures across a 24-hour period (from midnight to midnight Australian Eastern Standard Time, adjusted from UTC) were used to identify extreme heat events. Heatwaves were identified using the Excess Heat Factor (EHF) index which was described elsewhere (Nairn & Fawcett 2015b). The index is a relative measure of temperature compared with historical data for each location, and does not rely on meeting an absolute temperature threshold. Using this index, a heatwave is classified as a low intensity, severe or extreme event, where an extreme event is classified as three times the threshold for a severe heatwave event (Nairn & Fawcett 2015b). This method is used by the Australian Bureau of Meteorology for the Heatwave Service for Australia (Bureau of Meteorology 2019b) and has been found to be an effective predictor of health service demand during heatwave events (Scalley et al. 2015; Urban et al. 2019). Given their impact on health, only severe and extreme events were considered in this analysis. As only a very small number of extreme events were identified, these were combined with severe events for analysis.

The BARRA data were matched with the Australian Bureau of Statistics Statistical Area 2 (SA2) regions that displayed a population density >50 persons per km^2 (see Figure B.1). Population density data were sourced from the Australian Bureau of Statistics (Australian Bureau of Statistics 2018b).

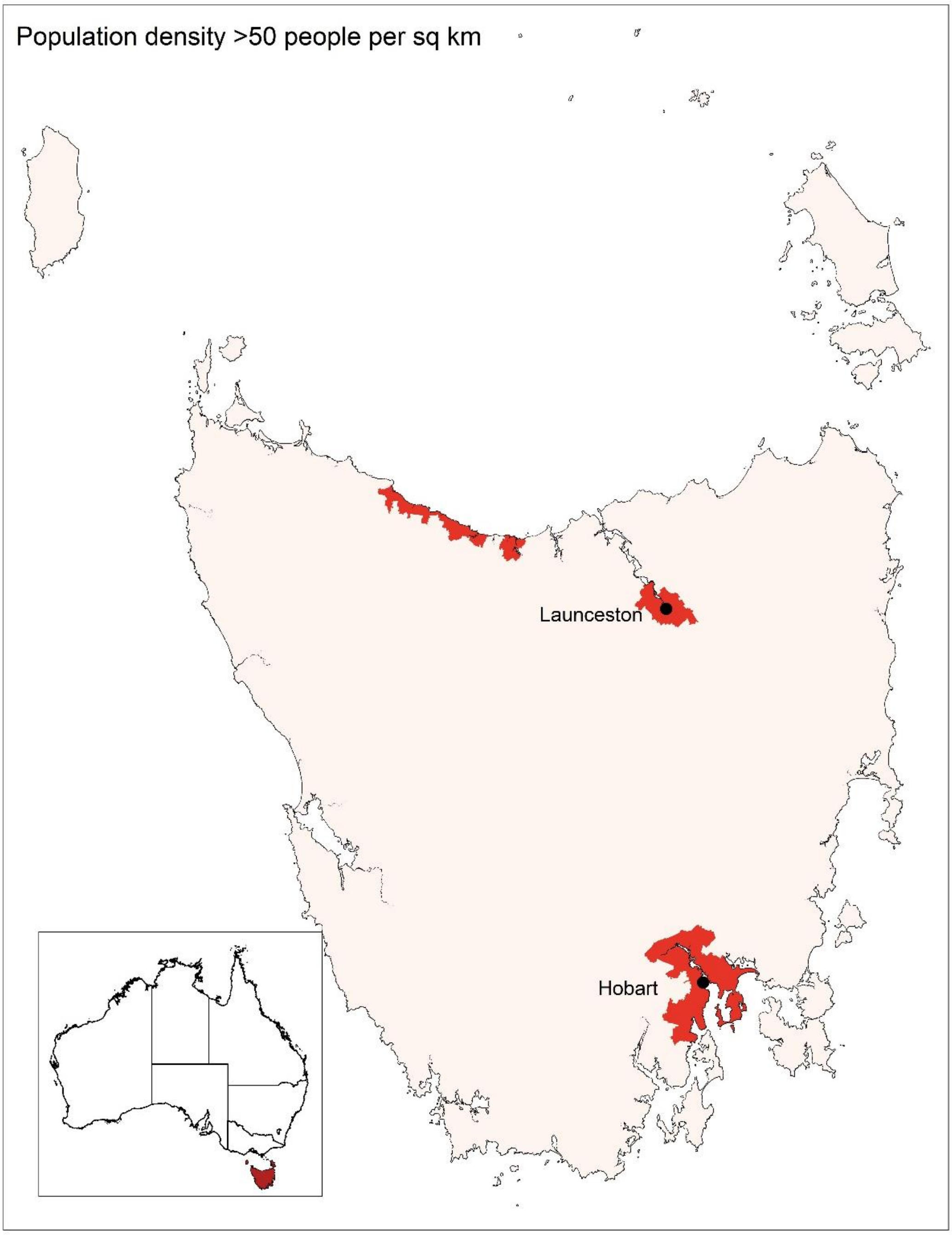

Figure B.1: Locations in Tasmania where population density >50 persons per km^2, inset showing location of Tasmania within Australia

Air pollution data were obtained from the Environment Protection Authority (EPA) of Tasmania's air quality monitoring network, known as Base Line Air Network of EPA Tasmania (BLANkET). New Town station data were used to represent Hobart, and Ti Tree Bend station data were used to represent Launceston. Ambient 24-hour (midnight to midnight) average concentrations of particulate matter with a diameter less than 2.5µm ($PM_{2.5}$) readings were used. Where data-points for a 24-48 hour period were missing, the average of a 7-day period, on either side of the missing data-points were interpolated. Where data-points were missing for longer than 48 hours, data were linearly interpolated using the na.approx() function from the 'zoo' package in R (Zeileis et al. 2019).

State-wide public holidays for Tasmania were obtained using the Python 'holidays' package (Montel 2019). Locally specific holidays were identified and incorporated.

B.3.2 Outcome data

ED presentation data were obtained from the Tasmanian Health Service for public hospitals in Tasmania. Only data for Hobart (Royal Hobart Hospital) and Launceston (Launceston General Hospital) were used. This was due to the lack of heatwave events exclusively in the northwest region, compounded with the relatively small number of patient episodes in this much less populated area of the state.

B.3.3 Study design

This study used a time-stratified case-crossover design. This methodology is commonly used in environmental epidemiology and is suited to a situation where the study population is exposed to a short-term event (e.g. a heatwave), and experiences a health outcome (e.g. an emergency department presentation) (Jaakkola 2003; Maclure 1991). Individual presentations, rather than days, are the unit of observation, with each presentation acting as its own control. Environmental data on the date of the health event were compared with that on control days of the same day of the week and within the same calendar month and year.

This methodology has been used previously for similar studies in other locations (Basagana et al. 2011; Wang et al. 2012) and has been compared to a time-series analysis with analogous results (Basu, Dominici & Samet 2005; Tong, Wang & Guo 2012).

The study period was from 1 January 2008 to 31 December 2016.

B.3.4 Analyses

A conditional multivariate logistic regression was performed using the clogit() function from the 'survival' package in R (Therneau & Lumley 2020). The odds ratio, a measure of the association between an exposure and an outcome (Szumilas 2010), and the 95% confidence intervals were calculated for presentations to ED during identified severe/extreme heatwaves. This was performed for the whole population for all conditions combined, and for the following sub-categories:

- age group (0-5, 0-15 and over 65)
- gender
- Socio-Economic Index for Areas (SEIFA) category (by suburb of patient address), using the Index of Relative Socio-Economic Disadvantage
- diagnostic group.

SEIFA categories were amalgamated by condensing scores 1-3 as 'low advantage', scores 4-7 as 'middle advantage', and scores 8-10 as 'high advantage'.

The presenting conditions were classified into diagnostic groups using the International Classification of Disease (ICD-10) codes for the primary diagnosis (World Health Organization 2011). Table B.1 shows the diagnostic groups and sub-groups analysed.

The regression model controlled for both observed public holidays and $PM_{2.5}$ for the nearest EPA station.

Table B.1: International Classification of Disease (ICD-10) codes for analysed diagnostic conditions.

Diagnostic Condition	**ICD-10 Code**
All respiratory	J00–J99
Asthma	J45–J46
Chronic obstructive pulmonary disease (COPD)	J40-J44, J47, J67
Diabetes	E10-E11, E13-E14
All cardiovascular	I00-I99, G45-G46
Hypertensive	I10-I13
Ischemic heart disease	I20-I25
Atrial fibrillation	I48
Cardiac failure	I50
All mental disorders	F00-F99
Dementia	F00-F03
Neuroses	F40-F48
Psychoses	F80-F89
Organic mental disorders (including depression, anxiety)	F00-F09
All renal disorders	N00-N39
Acute renal failure	N17

Renal calculus	N20-N21
Heat and light disorders (including sunburn, heat stroke)	T67, X30

B.4 Results

In the nine-year period from 1 January 2008 to 31 December 2016, 841,965 people presented to the ED of the Royal Hobart Hospital and the Launceston General Hospital. Characteristics of these presentations are shown in Table B.2.

During this period, there were multiple days identified as heatwaves of varying intensities, affecting both regions under study (see Table B.3). All identified heatwave days occurred in summer (December to February), where hot days were characterised as arising from hot northerly winds and days of low humidity gave rise to dry heat conditions.

Significant associations between ED presentations and identified severe/extreme heatwave days were found (see Figure B.2).

ED presentations increased across the whole population (OR 1.05, 95% CI 1.01-1.09), for children aged 15 years and under (OR 1.13, 95% CI 1.03-1.24), and for children aged 5 years and under (OR 1.19, 95% CI 1.04-1.36), while a less precise association in the same direction was found for those aged over 65 years (OR 1.06, 95% CI 0.97-1.16). Results for males and females were similar, although the point estimate was slightly higher in females and attained statistical significance (female OR 1.06; male OR 1.05). There was no clear trend associated with socio-economic disadvantage.

A significant association was found for conditions relating to exposure to heat and light (OR 9.62, 95% CI 3.13-29.51). No associations were observed with any other diagnostic subgroups. Results were much less precise due to the smaller number of cases in these subgroups although non-significant elevations in the ORs were observed for asthma (OR 1.40, 95% CI 0.94-2.09), diabetes (OR 1.57, 95% CI 0.82-3.01), hypertension (OR 1.40, 95% CI 0.58-3.38), and atrial fibrillation (OR 1.03, 95% CI 0.63-1.60). Insufficient data were available to perform a conditional logistic regression for psychoses, dementia, and renal calculus, and these conditions were not presented in the results.

There were no meaningful differences between the crude and adjusted associations (for full results, see Appendix D: Crude and adjusted associations between ED presentations and heatwaves in Tasmania, Australia).

Table B.2: Characteristics of ED presentations to the Royal Hobart Hospital and Launceston General Hospital for specific population characteristics and diagnostic groups (2008-2016)

Population Characteristic/ Diagnostic Group	Total Number (% of Total)	Mean Daily Presentations	Standard Deviation	Minimum/Maximum Presentations
Whole population	841,965 (100%)	256.1	31.4	153/358
Age				
≤5	85,450 (10.1%)	26.0	7.2	5/56
≤15	160,315 (19.0%)	48.8	10.9	18/108
16–65	521,072 (61.9%)	158.5	20.3	90/232
>65	160,500 (19.1%)	48.8	10.3	21/85
Gender				
Male	434,660 (51.6%)	132.2	18.3	80/201
Female	407,032 (48.3%)	123.8	17.6	67/181
SEIFA				
Low	437,577 (52.0%)	133.1	17.6	75/194
Middle	252,039 (30.0%)	76.7	11.7	36/118
High	135,392 (16.0%)	41.2	8.7	15/78
All respiratory	67,439 (8.0%)	20.5	7.6	3/63
Asthma	8546 (1.0%)	2.7	1.6	1/10
COPD	10,365 (1.2%)	3.4	1.9	1/14
All cardiovascular	49,436 (5.9%)	15.0	4.3	3/31
Cardiac failure	5199 (0.6%)	2.0	1.1	1/9
Hypertensive	1312 (0.2%)	1.2	0.5	1/5
Atrial fibrillation	2724 (0.3%)	2.2	1.2	1/8
Ischemic heart disease	13,964 (1.7%)	4.3	2.1	1/15
Diabetes	1994 (0.2%)	1.3	0.6	1/5
All mental disorders	34,509 (4.1%)	10.5	3.7	1/27
Dementia	655 (0.1%)	1.3	0.4	1/4
Neuroses	6459 (0.8%)	2.3	1.3	1/9
Organic mental	2639 (0.3%)	1.5	0.8	1/7
Psychoses	21 (0.002%)	1.0	0	1/1
All renal	20,914 (2.5%)	6.4	2.6	1/19
Acute renal failure	1416 (0.2%)	1.3	0.5	1/5
Renal calculus	120 (0.01%)	1.1	0.3	1/2
Exposure to light and heat	199 (0.02%)	1.3	1.1	1/12

Table B.3: Number of days identified as heatwave days for each region, at each heatwave intensity

Region	Low Intensity Days	Severe Days	Extreme Days
South (Hobart)	85	9	1
North (Launceston)	153	18	5

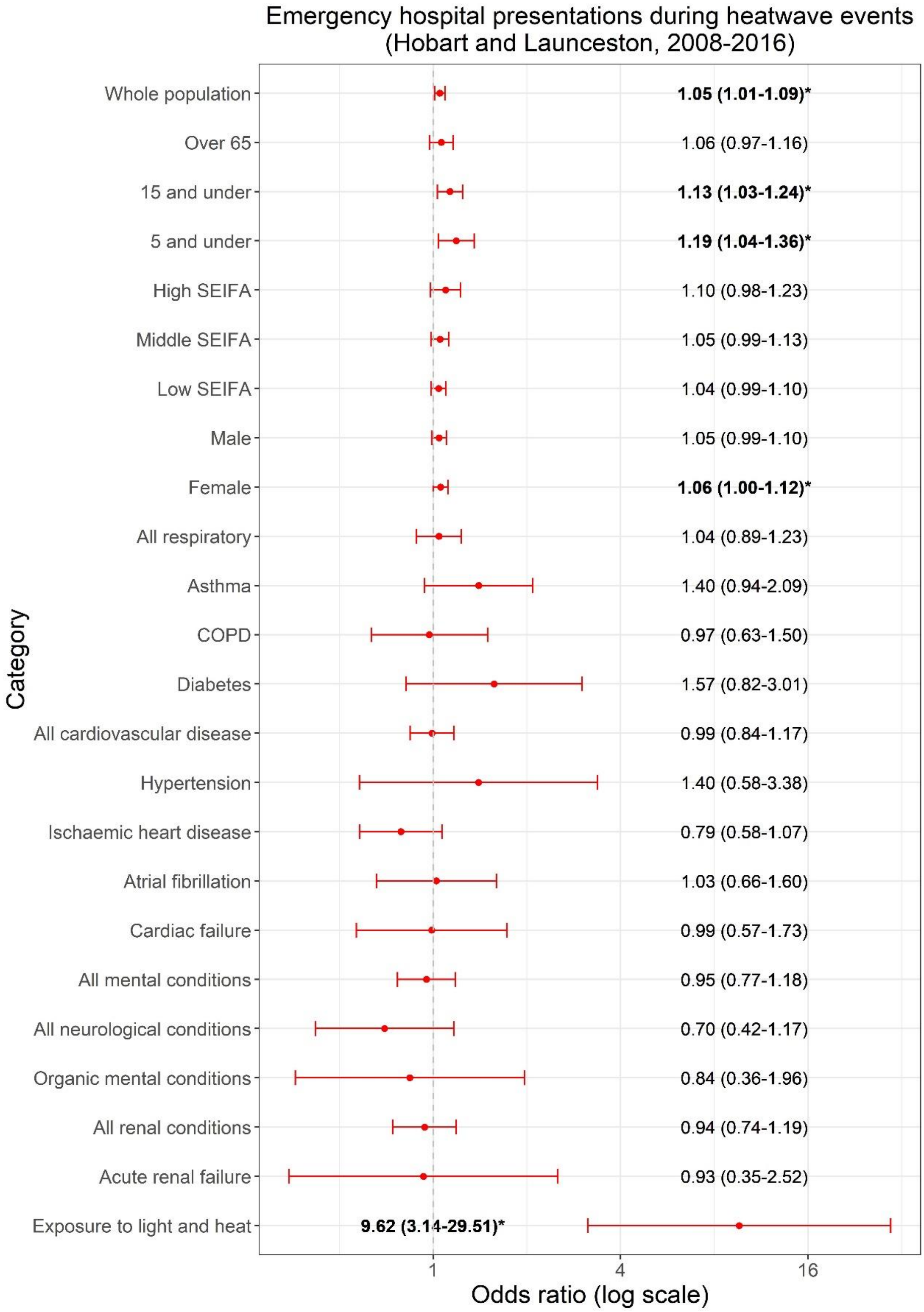

Figure B.2: Odds ratios and 95% confidence intervals for the association between ED presentations for specific population characteristics, diagnostic groups, and heatwaves in Hobart and Launceston, Tasmania (2008-2016), adjusted for public holidays and $PM_{2.5}$ (* and bold indicates $p < 0.05$)

B.5 Discussion

In this study, we found that hospital emergency departments in Tasmania's major population centres experienced a significant increase in presentations (5%) during severe and extreme heatwaves, disproportionately affecting younger age groups. ED presentations increased by 13% for children aged 15 years and under and 19% for children aged 5 years and under. Significant increases in presentations were also found for conditions related to exposure to light and heat (for example, sunburn and heatstroke). A less precise increase in risk was found for older people, although this group exhibited a similar magnitude to the overall population risk.

Our findings were largely consistent with similar studies in other locations around Australia, showing an association between heatwave events and increases in emergency department presentations (Lindstrom, Nagalingam & Newnham 2013; Schaffer et al. 2012a). Other international studies have demonstrated similar trends in associations between ED presentations and heatwave events (Fuhrmann et al. 2016; Sun et al. 2014; Zhang, Chen & Begley 2015).

Our findings for increased risk to children in the magnitude observed (2.6x for children aged 15 years and under, and 3.6x for children aged 5 years and under, over the general population) appeared to be unique in the literature. While some studies have demonstrated an elevated morbidity risk to children in heatwaves (Knowlton et al. 2009; Leonardi et al. 2006), an overwhelming number of studies have consistently highlighted the elderly to be most at risk. This finding warrants further research in the Tasmanian context and has clear policy implications for public health preparedness and communication during heatwave events.

In our study, the difference between ED presentations for males and females during heatwaves was small, showing a slightly higher risk for females. Similar studies, both in Australia and overseas, have demonstrated mixed results for the risk between genders (Li et al. 2015; Michelozzi et al. 2005; Xiao et al. 2017), while some report differences in gender with specific diagnostic conditions (Li et al. 2015). Due to the small number of cases in this study, specific diagnostic conditions were not further analysed by gender.

Other similar studies have demonstrated that poorer health outcomes appear to be more likely in areas with a greater disadvantage, both in Australia (Loughnan, Nicholls & Tapper 2010; Xiao et al. 2017) and overseas (Kim & Kim 2017; Michelozzi et al. 2005). Contrary to expectations, our results did not show a trend in the risk associated with socio-economic disadvantage, however, our ability to identify associations was limited by the lower statistical power in the subgroup analyses. This result also deserved further investigation.

Results of the sub-analyses by diagnostic groups were generally less precise due to the smaller numbers of cases evaluated, resulting in wide confidence intervals and no clear associations. Based on similar studies elsewhere, increased risk in cardiovascular, respiratory, renal disease, and mental disease were expected. Recent meta-analyses of cardiovascular and respiratory conditions suggest that mortality is greater than morbidity for these diagnostic groups during heatwaves (Cheng et al. 2019), which might partially contribute to the results found in this study, and deserves further study in the local context.

This study benefitted from analysing data across a nine-year time frame, indicating ED presentation changes over a number of heatwave events, rather than the analyses of a specific or singular event. Our study also controlled for co-incident air pollution ($PM_{2.5}$) on health outcomes, a well-documented association (Edwards et al. 2018; Johnston et al. 2013; Johnston et al. 2014; Johnston et al. 2019), and for public holidays, which influence the patterns of healthcare utilisation.

The results of this study are confined to the relatively small population of Tasmania, making additional sub-categorisation analyses difficult to achieve, for example, analysing the impact of heatwave events on children with asthma (Xu et al. 2013). While other similar studies have controlled for ozone (Wang et al. 2012), these data were not available for the studied population centres and could not be included in this analysis.

While limitations are known to exist with reanalysis data (Parker 2016), including the possibility of underestimating extremes (Raghavendra et al. 2019), our study used reanalysis data given the improvement in spatial and temporal resolution offered over observed station data in the study region. Further studies examining the difference between reanalysis and observed data for this region may be warranted but were outside of the scope of our study.

Our findings can assist policy and planning directives in two key areas of health. Detailed planning in Tasmanian hospital emergency departments for heatwave events is now possible, especially as these types of events can be forecast with accuracy in the days prior (Parkyn, Yeo & Bannister 2010). This allows for long lead times to accurately adjust rostering and implement surge capacity procedures, potentially minimising the impact. Secondly, targeted and specific public health preparedness campaigns aimed at the carers of young children, such as parents, child care centres, and schools, can be incorporated into the existing heatwave campaigns and health promotion campaigns already targeting this group, with the aim of reducing the incidence of ED presentations during these events. Neither of these interventions currently exist due to a lack of local evidence.

These findings also allow the issue of self-care in heatwaves to be explored through the media, giving evidence towards heatwaves being a health risk that can be managed. Current media coverage of hot weather tends to focus on recreation opportunities that can be best enjoyed in hot weather (The Mercury 2017), rather than emphasising the potential health issues and mitigation actions.

Further research that analyses the associations between heatwave events and other healthcare outcomes (for example, mortality, hospital admissions, ambulance dispatches, and GP visits) would assist in strengthening preparedness and response activities, including policy measures associated with extreme heat events in Tasmania.

B.6 Conclusion

This research shows an association between heatwave events and hospital emergency department presentations in the most populated regions of Tasmania, Australia. These associations were apparent across the whole population under study, predominantly for children aged 0-15 and 0-5. These findings may assist in surge-capacity planning for hospital emergency departments during forecast heatwave events, and can help tailor public health preparedness policies for heatwaves. This example of research-to-policy translation highlights the importance of developing well-informed health policy and planning initiatives at a local level, based on local research, demonstrating that while general associations could be made using research from other regions with large-scale studies, specific and targeted responses serve to better inform the local practice.

Appendix C: Threats to validity of the case-crossover method

Chapters 3 and 4 utilise a case-crossover methodology, described in detail in Maclure (1991) and Jaakkola (2003), and in the Methods section of Chapters 3 (3.4.3) and 4 (4.4.4).

Maclure (1991) describes the 'threats to validity' of case crossover studies as:

1. Carry over and period effects
2. Treatment sequencing and patient assignment
3. Crossover rules and timing
4. Dropouts and faulty or outlying data
5. Inappropriate statistical analyses for repeated outcomes

With reference to the studies covered in Chapters 3 and 4, each of these threats to validity are discussed below.

Carry over and period effects: Maclure defines this threat as "uncertainty about the duration of the effect-period" (Maclure 1991, p.149), where the effect-period is defined as "the period of altered risk in a population" (Maclure 1991, p.146). In using the Excess Heat Factor index, the heatwave 'effect-period' for the two studies in Chapters 3 and 4 is well-defined, and uses a consistent and well-documented methodology. This leads to a low threat to validity.

Treatment sequencing and patient assignment: Maclure defines this threat as related to "within-individual confounding, because the timing and frequency of crossover are not under the investigator's control" (Maclure 1991, p.149). As the event in question is an external and relatively rare event (therefore reducing the frequency of crossover), and the cases are controlled to a limited period of the same calendar month by using the time-stratified crossover methodology, the threat is reduced. This time-stratification methodology has been employed in Chapters 3 and 4.

Crossover rules and timing: Maclure (1991) defines this threat as similarly related to the timing and frequency of crossover, as above. Again, using a time-stratified methodology (controlling case crossover to within a calendar month, on the same day of the week) reduces and controls this risk.

Dropouts and faulty or outlying data: According to Maclure (1991), this type of threat is a result of selection or information bias. As the health outcome data used in these chapters (ED presentations and ambulance dispatches) is not subject to selection bias (as all cases are recorded) or information bias (the same information is collected for all cases), then this threat does not apply to these studies.

Inappropriate statistical analyses for repeated outcomes: Maclure does not recognise this threat to outcomes that are 'rare' (using the example of myocardial infarction). As ED presentations and ambulance dispatches are rare events for the majority of the population, this threat does not apply in this context.

The methods, exposures and outcomes used in Chapters 3 and 4 cause minimal threats to validity of the studies, making case-crossover design an appropriate choice.

Appendix D: Crude and adjusted associations between ED presentations and heatwaves in Tasmania, Australia

Table D.1: Crude and adjusted associations between ED presentations and heatwaves in Tasmania, Australia

Category	Heatwave	Heatwave + $PM_{2.5}$	Heatwave + Public Holiday	Heatwave + $PM_{2.5}$ + Public Holiday
Whole population	1.052 (1.012-1.093)	1.047 (1.007-1.088)	1.056 (1.016-1.097)	1.051 (1.011-1.093)
Over 65	1.075 (0.985-1.174)	1.064 (0.975-1.162)	1.074 (0.984-1.172)	1.063 (0.974-1.160)
15 and under	1.131 (1.031-1.242)	1.127 (1.026-1.237)	1.137 (1.036-1.248)	1.133 (1.032-1.244)
5 and under	1.188 (1.042-1.356)	1.176 (1.030-1.342)	1.199 (1.051-1.368)	1.187 (1.040-1.355)
High SEIFA	1.080 (0.968-1.206)	1.079 (0.966-1.205)	1.098 (0.984-1.226)	1.097 (0.982-1.225)
Middle SEIFA	1.057 (0.989-1.129)	1.050 (0.982-1.121)	1.059 (0.992-1.132)	1.052 (0.985-1.125)
Low SEIFA	1.044 (0.989-1.102)	1.040 (0.985-1.098)	1.046 (0.991-1.104)	1.042 (0.987-1.100)
Male	1.047 (0.992-1.105)	1.040 (0.985-1.098)	1.051 (0.996-1.110)	1.045 (0.990-1.103)
Female	1.057 (1.000-1.117)	1.054 (0.997-1.114)	1.060 (1.003-1.121)	1.057 (1.000-1.118)
All respiratory	1.035 (0.878-1.220)	1.038 (0.880-1.224)	1.041 (0.883-1.227)	1.044 (0.885-1.231)
Asthma	1.419 (0.952-2.113)	1.386 (0.929-2.066)	1.434 (0.962-2.137)	1.401 (0.939-2.090)
COPD	0.972 (0.632-1.494)	0.974 (0.633-1.499)	0.971 (0.632-1.493)	0.973 (0.633-1.498)
Diabetes	1.711 (0.896-3.267)	1.613 (0.843-3.089)	1.667 (0.873-3.184)	1.570 (0.820-3.008)
All cardiovascular disease	1.004 (0.854-1.180)	0.997 (0.848-1.173)	0.999 (0.850-1.174)	0.992 (0.844-1.166)
Hypertension	1.288 (0.537-3.090)	1.390 (0.577-3.351)	1.297 (0.540-3.112)	1.400 (0.580-3.377)
Ischaemic heart disease	0.799 (0.590-1.082)	0.793 (0.585-1.075)	0.794 (0.586-1.075)	0.788 (0.581-1.068)
Atrial fibrillation	1.042 (0.670-1.619)	1.028 (0.660-1.600)	1.040 (0.670-1.616)	1.026 (0.659-1.598)
Cardiac failure	0.965 (0.553-1.683)	0.993 (0.569-1.735)	0.962 (0.551-1.678)	0.990 (0.567-1.729)
All mental conditions	0.963 (0.778-1.191)	0.954 (0.770-1.181)	0.961 (0.776-1.189)	0.952 (0.769-1.179)
Psychoses	1.820 (1.128-2.937)	1.845 (1.141-2.984)	1.811 (1.23-2.923)	1.836 (1.135-2.970)
Depression	0.968 (0.613-1.529)	0.941 (0.595-1.488)	0.954 (0.604-1.506)	0.926 (0.586-1.464)
Anxiety	0.718 (0.431-1.197)	0.699 (0.419-1.165)	0.718 (0.413-1.197)	0.699 (0.419-1.165)

All renal conditions	0.929 (0.735-1.175)	0.939 (0.742-1.188)	0.929 (0.735-1.175)	0.939 (0.742-1.188)
Acute renal failure	0.927 (0.344-2.502)	0.930 (0.344-2.511)	0.930 (0.345-2.509)	0.932 (0.345-2.517)
Exposure to light and heat	15.122 (5.080-45.016)	9.496 (3.102-29.070)	15.243 (5.111-45.459)	9.621 (3.137-29.507)

Appendix E: Supplementary data for Chapter 4

Table E.1: Classification of paramedic assessments for diagnostic groups

Diagnostic group	**Paramedic assessments**
Cardiovascular	Acute coronary syndrome; acute myocardial infarction; acute pulmonary oedema; angina; aortic dissection; arrythmia; cardiac arrest; cardiac failure; hypertension; hypotension; intracranial haemorrhage; palpitations; stroke; transient ischemic attack
Respiratory	Asthma; bronchiolitis; bronchitis; chest infection; chronic obstructive pulmonary disease; croup; pneumonia; pulmonary embolism; respiratory arrest; respiratory failure; respiratory tract infection; short of breath
Renal	Renal calculi/colic; renal failure
Diabetic	Hyperglycaemia; hypoglycaemia
Psychological	Anxiety; depression; emotional distress; overdose; panic attack; psychiatric episode; self-harm ideation; suicide ideation
Other heat-related	Dehydration; dizzy; faint; febrile; headaches; migraine; nausea; point loss of consciousness; vomiting
Direct heat	Cramps; heat stress; heat stroke; sunburn

Table D.2: Crude and adjusted associations between ED presentations across three different types of heatwaves in Tasmania, Australia (2008-2019)

Category	**Extreme heatwave**	**Extreme heatwave + $PM_{2.5}$**	**Extreme heatwave + public holiday**	**Extreme heatwave + $PM_{2.5}$ + public holiday**
Whole population	1.34 (1.18-1.52)	1.34 (1.18-1.52)	1.34 (1.18-1.52)	1.34 (1.18-1.52)
5 and under	1.62 (0.93-2.82)	1.62 (0.93-2.82)	1.62 (0.93-2.82)	1.62 (0.93-2.82)
15 and under	1.33 (0.85-2.08)	1.33 (0.85-2.08)	1.33 (0.85-2.08)	1.33 (0.85-2.08)
16-65	1.24 (1.03-1.49)	1.24 (1.03-1.49)	1.24 (1.03-1.49)	1.24 (1.03-1.49)
Over 65	1.47 (1.21-1.78)	1.47 (1.21-1.78)	1.47 (1.21-1.78)	1.47 (1.21-1.78)
Male	1.27 (1.05-1.53)	1.26 (1.05-1.52)	1.27 (1.05-1.53)	1.26 (1.05-1.52)
Female	1.41 (1.19-1.68)	1.41 (1.19-1.68)	1.41 (1.19-1.68)	1.41 (1.19-1.68)
Low SEIFA	1.40 (1.18-1.65)	1.40 (1.18-1.65)	1.40 (1.18-1.65)	1.40 (1.18-1.65)
Middle SEIFA	1.30 (1.05-1.62)	1.30 (1.05-1.61)	1.30 (1.05-1.62)	1.30 (1.05-1.61)
High SEIFA	1.12 (0.68-1.84)	1.12 (0.67-1.82)	1.12 (0.68-1.84)	1.11 (0.67-1.82)
Cardiovascular	1.42 (0.98-2.06)	1.42 (0.98-2.06)	1.42 (0.98-2.06)	1.42 (0.98-2.06)
Respiratory	0.84 (0.46-1.54)	0.84 (0.46-1.53)	0.84 (0.46-1.54)	0.84 (0.46-1.53)
Renal	1.24 (0.13-11.92)	1.20 (0.12-11.57)	1.24 (0.13-11.92)	1.20 (0.12-11.57)
Diabetic	2.19 (0.73-6.53)	2.18 (0.73-6.52)	2.19 (0.73-6.53)	2.18 (0.73-6.52)
Psychological	0.55 (0.26-1.16)	0.55 (0.26-1.16)	0.55 (0.26-1.16)	0.55 (0.26-1.16)
Other heat-related	0.98 (0.60-1.58)	0.98 (0.60-1.58)	0.98 (0.60-1.58)	0.98 (0.60-1.58)
Direct exposure to heat	48.00 (6.24-369.15)	48.00 (6.24-369.15)	48.00 (6.24-369.15)	48.00 (6.24-369.18)

Category	Severe heatwave	Severe heatwave + $PM_{2.5}$	Severe heatwave + public holiday	Severe heatwave + $PM_{2.5}$ + public holiday
Whole population	1.10 (1.05-1.16)	1.10 (1.05-1.15)	1.10 (1.05-1.16)	1.10 (1.05-1.15)
5 and under	1.36 (1.10-1.68)	1.36 (1.10-1.68)	1.36 (1.10-1.69)	1.36 (1.10-1.68)
15 and under	1.14 (0.97-1.33)	1.14 (0.97-1.33)	1.14 (0.97-1.33)	1.14 (0.97-1.33)
16-65	1.07 (1.00-1.14)	1.07 (1.00-1.14)	1.07 (1.00-1.14)	1.07 (1.00-1.14)
Over 65	1.14 (1.06-1.23)	1.13 (1.05-1.22)	1.14 (1.06-1.23)	1.13 (1.05-1.22)
Male	1.17 (1.09-1.25)	1.16 (1.09-1.24)	1.17 (1.09-1.25)	1.16 (1.09-1.24)
Female	1.05 (0.98-1.12)	1.05 (0.98-1.12)	1.05 (0.98-1.12)	1.05 (0.98-1.12)
Low SEIFA	1.10 (1.04-1.17)	1.10 (1.04-1.17)	1.10 (1.04-1.17)	1.10 (1.04-1.17)
Middle SEIFA	1.09 (1.00-1.20)	1.09 (0.99-1.20)	1.09 (1.00-1.20)	1.09 (0.99-1.20)
High SEIFA	1.12 (0.95-1.33)	1.12 (0.94-1.32)	1.12 (0.95-1.33)	1.12 (0.94-1.32)
Cardiovascular	0.99 (0.85-1.15)	0.99 (0.85-1.15)	0.99 (0.86-1.15)	0.99 (0.85-1.15)
Respiratory	1.07 (0.88-1.31)	1.07 (0.88-1.30)	1.07 (0.88-1.31)	1.07 (0.87-1.30)
Renal	0.65 (0.27-1.55)	0.63 (0.26-1.51)	0.64 (0.27-1.54)	0.63 (0.26-1.51)
Diabetic	1.26 (0.86-1.85)	1.26 (0.85-1.85)	1.26 (0.86-1.85)	1.26 (0.85-1.85)
Psychological	0.95 (0.77-1.18)	0.95 (0.77-1.17)	0.95 (0.77-1.18)	0.95 (0.77-1.17)
Other heat-related	1.43 (1.20-1.69)	1.43 (1.20-1.70)	1.43 (1.20-1.69)	1.43 (1.20-1.70)
Direct exposure to heat	5.50 (2.82-10.71)	5.31 (2.72-10.37)	5.52 (2.83-10.76)	5.33 (2.73-10.41)

Category	Low-intensity heatwave	Low-intensity heatwave + $PM_{2.5}$	Low-intensity heatwave + public holiday	Low-intensity heatwave + $PM_{2.5}$ + public holiday
Whole population	1.04 (1.02-1.06)	1.04 (1.02-1.06)	1.04 (1.02-1.06)	1.04 (1.02-1.06)
5 and under	1.06 (0.97-1.16)	1.06 (0.97-1.16)	1.06 (0.97-1.16)	1.06 (0.97-1.16)
15 and under	1.05 (0.99-1.12)	1.05 (0.98-1.12)	1.05 (0.99-1.12)	1.05 (0.98-1.12)
16-65	1.04 (1.02-1.07)	1.04 (1.02-1.07)	1.04 (1.01-1.07)	1.04 (1.01-1.07)
Over 65	1.04 (1.01-1.08)	1.04 (1.01-1.07)	1.05 (1.02-1.08)	1.04 (1.01-1.07)
Male	1.05 (1.02-1.08)	1.05 (1.02-1.08)	1.05 (1.02-1.08)	1.05 (1.02-1.07)
Female	1.04 (1.02-1.07)	1.04 (1.01-1.07)	1.04 (1.02-1.07)	1.04 (1.01-1.07)
Low SEIFA	1.05 (1.03-1.08)	1.05 (1.03-1.08)	1.05 (1.03-1.08)	1.05 (1.03-1.08)
Middle SEIFA	1.04 (1.01-1.08)	1.04 (1.00-1.08)	1.04 (1.01-1.08)	1.04 (1.00-1.08)
High SEIFA	1.00 (0.93-1.06)	0.99 (0.93-1.06)	1.00 (0.93-1.06)	0.99 (0.93-1.06)
Cardiovascular	1.05 (0.99-1.11)	1.05 (0.99-1.11)	1.05 (0.99-1.11)	1.05 (0.99-1.11)
Respiratory	1.06 (0.98-1.14)	1.05 (0.97-1.14)	1.05 (0.97-1.14)	1.05 (0.97-1.13)
Renal	1.10 (0.85-1.43)	1.08 (0.83-1.40)	1.10 (0.84-1.42)	1.08 (0.83-1.40)
Diabetic	1.09 (0.92-1.29)	1.08 (0.91-1.29)	1.09 (0.92-1.29)	1.09 (0.92-1.29)
Psychological	1.03 (0.95-1.12)	1.03 (0.95-1.11)	1.03 (0.95-1.12)	1.03 (0.95-1.11)
Other heat-related	1.09 (1.01-1.17)	1.09 (1.02-1.17)	1.09 (1.01-1.17)	1.09 (1.02-1.17)
Direct exposure to heat	3.27 (2.11-5.06)	3.20 (2.06-4.96)	3.27 (2.12-5.06)	3.19 (2.06-4.95)

Appendix F: Natural disaster risk assessment in Tasmania

The 2016 Tasmanian State Natural Disaster Risk Assessment (TSNDRA) uses five 'impact sectors' to determine the overall risk for each hazard. These sectors cover a range of consequences across a broad spectrum of outcomes, including:

- People: deaths or injuries as a direct consequence of the identified hazard
- Economic: the loss in economic activity or the economic impact on specific industries as a direct result of the identified hazard
- Environmental: the loss of ecosystems, species or environmental values as a direct result of the identified hazard
- Public administration: the decreased capacity of government and utilities to deliver core functions as a direct result of the identified hazard
- Social setting: the decreased capacity of the community to function as normal, or the loss of culturally significant objects or events as a direct result of the identified hazard (Commonwealth of Australia 2015; White et al. 2016).

For each sector, consequence categories determine the level of impact, rated from 'Catastrophic' to 'Insignificant' in the National Emergency Risk Assessment Guidelines (NERAG). For example, the 'People' sector defines a risk as 'Catastrophic' if more than 1 in 10 000 people are killed as a direct result of the event in a national context. For the Tasmanian context used in TSNDRA 2016, this equates to greater than 50 people.

As a specific type of risk, public health risk is largely determined by impact on the 'People' sector. Depending on the type of disaster, the public health risks can vary from fatalities as a direct result of the event, through to disruption of clean water supplies, disease outbreaks and exacerbation of existing illnesses such as cardiovascular and respiratory illnesses (Noji 2000). However, the 'Social setting' sector, particularly an impact on the capacity of the community to function as normal, can have wide-ranging impacts on the health of community members, especially following a natural disaster or emergency (Commonwealth of Australia 2011).

Table E.1: TSNDRA sectors and consequence categories assigned to ETA events in Tasmania

Sector	Consequence category	Description of consequence category[1]	Evidence
People			
Death	Insignificant	Deaths directly from emergency > 1 in 100 000 000 people (>0.005 people)	No ETA event occurred in Tasmania in the study period, therefore no deaths observed
Injury or Illness	Insignificant	Critical injuries with long-term or permanent incapacitation > 1 in 100 000 people (>0.005 people) – OR – serious injuries > 1 in 10 000 people (>0.5 people)	No ETA event occurred in Tasmania in the study period, therefore no injuries observed
Economic			
Activity/value	Insignificant	Economic decline and/or loss of asset value greater than 4% GSP (~$100k)	No evidence to suggest economic loss due to an ETA event
Impact on an important industry	Insignificant	Inconsequential business sector disruption due to emergency event	No evidence to suggest specific business or industry impact due to an ETA event
Environment			
Loss of species or landscape	Insignificant	Minor damage to an ecosystem or species recognised at the local or regional scale	No evidence to suggest landscape or species impact due to an ETA event
Loss of value	Insignificant	Inconsequential impact on environmental values of interest	No evidence to suggest impact on environmental values due to an ETA event
Public Administration	Insignificant	Governing bodies' delivery of core functions is unaffected or within normal	While the Melbourne ETA event placed heavy demand on emergency services,

		parameters	(Thien et al. 2018; Victorian Government 2017b) core government functions were not affected
Social Setting			
Loss of community wellbeing	Insignificant	The community of interest's social connectedness is disrupted such that the re-prioritisation of existing resources is required, no dispersal	No evidence to suggest impact on social connectedness due to an ETA event. Some evidence of social connectedness increasing as a result of a natural disaster (Thornley et al. 2015)
Loss of cultural significance	Insignificant	Minor damage to culturally significant objects – OR – minor delay of a major culturally important activity or event	No evidence to suggest impact on cultural objects or events due to an ETA event

[1]Descriptions adapted from White et al. (2016)

Appendix G: AirRater survey questions and response options

Introduction page

Thank you for taking the time to complete this survey. We appreciate your feedback. This survey will take approximately 10 minutes.

We would like to understand how you used AirRater during recent months, when large parts of Australia were affected by bushfires and smoke. Smoke affected different places at different times; for example in Port Macquarie, NSW, there were peat fires in late winter, while in other parts of parts of NSW and Queensland bushfires and smoke began in spring. In the ACT and Victoria, the most severe fires and smoke were in summer.

When answering this survey, we would like you to think about **all time periods when smoke was in your area during the 2019-20 fire season.**

For more information, please contact us at air.rater@utas.edu.au or call 1800 322 102.

Information about you or someone you care for

Firstly, we would like to ask some questions about how smoke in the air affected your health, or the health of someone you care for. You will need to answer all the questions in this section about this one person.

1. **Please let us know if you will be answering the following questions about yourself or someone you care for.**

   ☐ Myself
   ☐ Someone I care for
   ☐ Other (please specify) [*free text*]

   1a. [Answered 'Myself' to Q1] Do any of the following statements describe you? Please tick all that apply.

   ☐ I have a lung condition (asthma, chronic bronchitis, COPD or other)
   ☐ I have a heart condition (heart disease, history of stroke or related problems)
   ☐ I have diabetes (either type 1 or type 2)
   ☐ I am over 65 years old
   ☐ I have a child under 5 years old
   ☐ I am pregnant
   ☐ None of these statements describe me

1b. [Answered 'Someone I care for' or 'Other' to Q1] Do any of the following statements describe the person you care for? Please tick all that apply.

☐ They have a lung condition (asthma, chronic bronchitis, COPD or other)
☐ They have a heart condition (heart disease, history of stroke or related problems)
☐ They have diabetes (either type 1 or type 2)
☐ They are over 65 years old
☐ They are under 5 years old
☐ They are pregnant
☐ None of these statements describe the person I care for

2. **Do you feel that periods of increased smoke in your region throughout this fire season have affected your health, or the health of the person you care for?**

Yes / No

If yes, what did you/they experience? Please tick all that apply.

☐ Irritated or watery eyes
☐ Irritated or dry throat
☐ Sneezing
☐ Runny nose
☐ Coughing
☐ Headache
☐ Feeling anxious, stressed or worried
☐ Feeling depressed
☐ Feeling irritable, angry or short-tempered
☐ Shortness of breath
☐ Chest tightness
☐ Wheezing or whistling in the chest
☐ Other? Please specify [*free text*]

3. **Throughout this fire season, did you (or the person you care for) miss study, paid work or unpaid work due to smoke-related health symptoms?**

☐ No, never
☐ Once
☐ Two to four times
☐ Five times or more
☐ The school or workplace closed due to fire or smoke risk, but I was/they were not prevented from attending because of health issues

4. **Throughout this fire season, did you (or the person you care for) seek medical advice due to smoke-related symptoms?**

☐ No
☐ Called Health Direct / Nurse-on-call

- ☐ Talked to a pharmacist
- ☐ Saw a GP or other medical professional
- ☐ Visited emergency department of a hospital
- ☐ Called an ambulance
- ☐ Other (please specify) [*free text*]

Information about air filters

Now we would like to ask you some questions about portable air cleaners (also called air purifiers). This is in relation to your home.

5. Did you purchase a portable air cleaner or air purifier for your home during this fire season?

Yes/No/I already had one

5a. If yes or you already had one, please provide the date, or your best estimate of the date, you started using the air cleaner. If you purchased more than one, please list information about the first one you purchased.

Date field

5b. How confident are you about the date you started using it?

- ☐ I am confident of this date
- ☐ I estimated this date

5c. Did the air cleaner have a high efficiency particulate air (HEPA) filter for reducing indoor particles?

(Note: Most portable air cleaners filter out particles, however simple humidifiers, odour absorbers and negative ion generators do not. If the air cleaner removes particles it will use a HEPA filter and the ability to remove particles is made clear on the product information.)

Yes/No

Information about AirRater

Next, we would like to ask you about your experience using AirRater.

6. Please provide the postcode where you most often used AirRater over this fire season when it was smoky.

Numeric 4-digit response field

7. **On a scale of 1 to 5 (where 1=no use and 5=extremely useful), please rate how useful you found AirRater in helping you to manage symptoms over the time you have used it.**

   [*scale bar = no use; a little useful; quite useful; very useful; extremely useful*]

8. **What were the features you liked most about AirRater? Please tick all that apply.**

   ☐ Map showing air quality information near me
   ☐ Map showing the air monitoring stations near me
   ☐ Automated notifications about air quality
   ☐ Symptom tracking
   ☐ The ability to save locations
   ☐ I didn't like the app
   ☐ Other (please specify) [*free text*]

9. **Have you done anything differently as a result of information from AirRater? Please tick all that apply.**

   I used information in the app to:

   ☐ help me decide whether to stay indoors
   ☐ help me reschedule or plan my outdoor activities
   ☐ help me decide when to close or open windows and doors at my location (for example, at home or work)
   ☐ help me decide to visit a public library or other public air-conditioned building to have a break from poor air quality
   ☐ help me decide when to use my medications (for example, the reliever and/or the preventer) to better manage my asthma
   ☐ help me decide whether to change my location (for example, I avoided going to locations with poor air quality or went to places with better air quality)
   ☐ learn how changes in air quality influence my health
   ☐ help review and plan my healthcare with my health professional
   ☐ I haven't done anything differently
   ☐ Other (please specify) [*free text*]

10. **How did you find out about AirRater? Please tick all that apply.**

   ☐ Social media (for example, Facebook or Twitter)
   ☐ Community or other health newsletter
   ☐ Newspaper or radio
   ☐ Word of mouth/recommendation from a friend
   ☐ My health provider or pharmacy
   ☐ Asthma Australia
   ☐ My workplace, union or professional society
   ☐ I don't remember

11. Other (please specify) [*free text*] **Many different agencies and services (for example, government organisations and private websites and apps) provide air quality data. Did you also seek air quality information from other sources?**

Yes/No

12a. If yes, please rank in order of usefulness for all that you used.

- ☐ AirRater
- ☐ ACT Health website
- ☐ Victoria EPA website
- ☐ NSW DPIE website
- ☐ Queensland DES website
- ☐ Canberra Air website
- ☐ AirVisual website or app
- ☐ AQICN website
- ☐ Other (please specify) [*free text*]

12b. Why did you like the information source that you ranked first? Please tick all that apply.

- ☐ Easy to navigate/ease of use
- ☐ Easy to understand information
- ☐ Trustworthiness of information
- ☐ Need to have access to local information
- ☐ It provided hourly, rather than 24-hour data
- ☐ It provided health advice and information
- ☐ Other (please specify) [*free text*]

12. Is there anything else you would like to tell us, particularly in relation to the smoky conditions during this fire season, that can help us understand the information you have provided?

[*free text*]

You're done!

Thank you for your time in completing the survey. Your answers will only be available to the research team. If you have any questions about this survey, please contact us on air.rater@utas.edu.au

If you would like to go into the draw to win one of five $30 grocery vouchers, please email us at air.rater@utas.edu.au with the subject "Survey draw".

Appendix H: Supporting text statements from AirRater survey respondents

Statements supporting 'other' features liked by survey respondents (Figure 6.7)

- having access to near real-time updates (1-hour average updates as opposed to 24-hour rolling averages typically reported by regulatory agencies)

  "*Has more rapid updates than other services*"

  "Accurate hourly readings unlike NSW govt website"

  "Provided current not averaged $PM_{2.5}$ data"

  "The fact that the readings are current, not averages"

- the ability to easily see air quality information in multiple locations

  "I also monitored air quality in areas where my family were located"

  "Ability to check areas we were heading to"

  "Being able to look at other areas assisted me with decision-making about travel"

  "Comparison of air quality with other locations"

- seeing air quality trends

  "Being able to track the history of the air quality over time"

  "24 hour graph so you could see that the smoke was getting worse"

  "Graph of air quality over 24 hours so I could see if it was trending up or down"

  "Just wanted to check air quality and compare to other days"

Statements supporting behaviour change as a result of information in AirRater (Figure 6.8)

- deciding on exercise plans both for themselves and for groups they were responsible for

  "I lead and participate in long 60-90km bike rides. App helped me to decide when to go and when not"

"My lung specialist wanted me to walk 1.5k per day. AirRater showed me when to walk the 1.5k in the supermarket rather than outside which my specialist said was excellent idea!"

"help me decide whether to cancel sporting events"

- deciding on work patterns

  "Assisted with decisions on workforce and heavy activities"

  "Help me decide what actions to take at my workplace, as I work with children in care and education settings (childcare & school holiday programs)"

  "Helped me decide when to work from home"

- helping to decide when to wear a face mask

  "Help me decide whether to wear a mask at work as I work outdoors"

  "Help me decide to bring a P2 respirator with me"

  "I used app for info on when to use p2 filter mask when cycling to gym, shops etc"

- helping to explain or inform others of the situation

  "helped me to dissuade an interstate visitor with asthma from coming to visit until the air quality improved"

  "helped me explain the situation to children"

  "I used it to warn my son in Melbourne to stay inside and also buy a mask when the air quality was persistently very bad"

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