Understanding the healthcare costs of temperature-related morbidity under the changing climate

Berhanu Wondmagegn

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School of Public Health

Faculty of Health and Medical Sciences

The University of Adelaide

Australia

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Thesis Abstract

Background

Exposure to non-optimum temperature may contribute to a substantial morbidity and mortality burden to our society. A growing number of studies have investigated the risks of increasing temperatures on morbidity and health service use. Estimating the economic burden of treating temperature-attributable emergency department (ED) presentations and hospital admissions is paramount to better understand the resource implications of temperature to the healthcare system. As the climate is shifting towards a warmer temperature, government and public health agencies demand evidence of future climate-related morbidity burden and economic cost to design practical guidelines, adaptive strategies, and tailored public health interventions.

Aims

The overall aim of this thesis was to provide scientific evidence for policymaking and practical guideline development to reduce the public health impacts and economic burden associated with extreme temperature and heatwaves. This thesis encompasses four studies, with specific aims to i) establish the temperature-morbidity and temperature-cost relationships; ii) quantify the total ED presentations and costs attributed to heatwave intensity and heatwave severity; iii) estimate the current net-, cold-, and heat-attributable ED presentations, hospital admissions, length of hospital stay (LoS), and associated healthcare costs; and v) estimate future health and cost burden attributed to projected temperatures under different climate and population growth scenarios.

Methods

Based on the exposure and response variables, the study can be broadly divided into three parts, namely: ED presentations and ED costs with mean temperatures; hospital admission, LoS, and associated costs with mean temperatures; and ED presentations and costs with heatwaves. All the studies in this thesis were conducted using daily aggregated patients' data from all public hospitals in Adelaide metropolitan area, South Australia (SA). Based on the 2016 census, the total population of the city was nearly 1.3 million. International classifications of diseases 10th version (ICD-10) was used to identify specific diagnosis groups including respiratory, renal, mental health disorders, heat-related illnesses (HRI), ischaemic heart diseases (IHD), and diabetes. These diseases were merged to increase the statistical power and termed as temperature related diseases (TRDs). A time-series analysis combined with a distributed lag nonlinear model (DLNM) was used to estimate the exposure-response relationships and delayed effects simultaneously. Using the current relationships, future morbidity and cost burdens of mean temperatures were projected under three representative concentration pathways (RCPs) (RCP2.6, RCP4.5, and RCP8.5) and medium population growth scenarios. All costs were calculated in Australian dollars (AU$).

Results

In study 1: The study used ED presentations data of all public hospitals in the Adelaide metropolitan area from 2014-2017. Both extreme cold and hot temperatures increased the risks of TRD-ED presentations and costs with much more risks associated with heat exposures. The baseline heat-attributable ED presentations and costs were estimated to be 3,633 (95% empirical confidence interval (eCI): 695, 6,498) and AU$4.7 million (95% eCI: 1.8, 7.5) costs,

respectively. Under RCP8.5 and with a constant population, heat-attributable ED presentations and healthcare costs are projected to increase by 1.5% (95% eCI: 0.8, 2.2) and 2.0% (95% eCI: 1.1, 2.8) during 2054-57, respectively. When population change is considered, heat-attributable ED presentations and costs would increase by 1.9% (95% eCI: 0.8, 3.0) and 2.5% (95% eCI: 1.3, 3.7) during 2034-2037 and by 3.7% (95% eCI: 1.7, 5.6) and 5.0% (95% eCI: 2.6, 7.1) during 2054-2057, respectively. There may be no change in cold-attributable ED presentations and costs.

In study 2: Using hospital admission data from 2010-2015, a comprehensive impact assessment of non-optimum temperature on TRD hospitalisations, LoS, and healthcare costs showed significant risks associated with heat exposure. During the baseline period, the net temperature-attributable hospital admissions, LoS, and associated costs were estimated to be 3,915 cases (95% empirical confidence interval (eCI): 235, 7,295), 99,766 days (95% eCI: 14,484, 168,457), and AU$159.1 million (95% eCI: 18.8, 269.0), respectively. Hot ambient temperature will have a substantial impact during 2040s and 2060s. Under RCP8.5 and demographic change, heat-attributable hospital admissions, LoS, and costs were projected to increase by 1.1%, 4.7%, and 4.2% during 2040s and further increased by 2.2%, 8.4%, and 7.7% in 2060s, respectively.

In study 3: In Adelaide, the risks of ED presentations and cost increase as heatwave intensity and severity increase for all-cause, most diagnosis groups and age categories. During the four warm seasons of 2014-2017, heatwave-attributable all-cause ED presentations were estimated to be 1,161 (95% eCI: 342, 1,944) with an associated cost of AU$1,020.3 (95% eCI: 224.9, 1,804.7), costs are in thousands. The HRI was the disease category contributing most to ED presentations and costs.

Age groups ≤ 14 and ≥ 65 years were most susceptible to heat. For the elderly population, heatwave attributed to 554 (95% eCI: 228, 834) ED presentations and AU$530.1 (95% eCI: 160.2, 890.4) costs during the study period.

Conclusions

Heat-related risks and attributable ED presentations, hospital admission, LoS, and associated healthcare costs were dominant during the baseline periods. Young and old populations were the most vulnerable populations to heatwaves contributing a higher cost burden to the healthcare system. The projected estimates indicated that hot ambient temperatures are likely to increase future morbidity and healthcare costs substantially under all climate change scenarios. The broad implication of this thesis is to inform relevant stakeholders and provide evidence for policymaking about the morbidity and economic burden of observed and projected temperature. The results help to track the future burden of climate change and to develop a range of climate change mitigation and public health adaptation responses. Moreover, the results suggest targeted intervention actions such as protecting the vulnerable population and the need to build the capacity of the health system.

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Keywords

Climate change

Emergency department

Emergency department presentations

Excess heat factor

Forecasting

Healthcare cost

Heat-attributable

Heatwave

Heatwave severity and intensity

Hospital admissions

Hospitalization cost

Morbidity

Temperature

List of Abbreviations

ABS	Australian Bureau of Statistics
AU$	Australian dollar
BOM	Bureau of Meteorology
CMIP5	Coupled Model Intercomparison Project Phase 5
CVD	Cardiovascular disease
DLNM	Distributed Lag Non-linear Model
eCI	Empirical confidence interval
ED	Emergency Department
EHF	Excess heat factor
GHG	Greenhouse gas
HRI	Heat-related illness
IHD	Ischaemic heart disease
IHPA	Independent Hospital Pricing Authority
IPCC	Intergovernmental Panel on Climate Change
LoS	Length of hospital stays
O_3	Ozone
OR	Odds ratio
OT	Optimum temperature
PM_{10}	Particulate matter
RCP	Representative Concentration Pathway
RR	Relative risk
SA	South Australia
TRD/s	Temperature related disease/s
USA	United States of America

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Dear God, thank you for granted me the opportunity and strength throughout this journey!

Dedication

I am dedicating this thesis to Yazew Wondmagegn Mulatu who raised me, loved me, and send me to school. Without him, this would not be possible. He is no longer in this world but forever in my heart. May God rest his soul in peace!

Publications

Publications contributing to this thesis

1. **Wondmagegn BY**, Xiang J, Williams S, Pisaniello S, and Bi P. What do we know about the healthcare costs of extreme heat exposure? A comprehensive literature review. *Science of the Total Environment* (Impact factor: 7.963). 2019, 608–618.
2. **Wondmagegn BY**, Xiang J, Dear K, Williams S, Hansen A, et al. Increasing impacts of temperature on hospital admissions, length of stay, and related healthcare costs in the context of climate change in Adelaide, South Australia. *Science of the Total Environment* (Impact factor: 7.963). 2021, 145656.
3. **Wondmagegn BY**, Xiang J, Dear K, Williams S, Hansen A, et al. Impact of heatwave intensity using Excess Heat Factor on emergency department presentations and related healthcare costs in Adelaide, South Australia.*Science of the Total Environment* (Impact factor: 7.963). 2021, 146815
4. **Wondmagegn BY**, Xiang J, Dear K, Williams S, Hansen A, et al. Understanding current and projected costs of emergency department presentations in a changing climate. Currently under-review. *Occupational and Environmental Medicine*, (Impact factor: 4.402).

Other relevant publications to this thesis

5. Tong MX, **Wondmagegn BY**, Xiang J, Dear K, Williams S, et al. Emergency department visits and associated healthcare costs attributable to increasing temperature in the context of climate change in Perth, Western Australia, 2012-2019. *Environmental Research Letters* (Impact factor: 6.192). 16 (2021) 065011.
6. Tong MX, **Wondmagegn BY,** Xiang J, Williams S, Hansen A, et al. Hospital healthcare costs attributable to heat and future estimations in the context of climate change in Perth, Western Australia. *Advances in Climate Change Research* (Impact factor: 4.130). S1674-9278(21)00107-6.
7. Tong MX, **Wondmagegn BY,** Xiang J, Williams S, Hansen A, et al. Heat-attributable hospitalization costs in Sydney: current estimations and future projections in the context of climate change. . Currently under-review. *Science of the Total Environment* (Impact factor: 7.963).
8. Williams S, Nitschke M, **Wondmagegn BY,** Tong MX, Xiang J, et al. Evaluating cost benefits from a heat health warning system in Adelaide, South Australia. Currently under-review. Australian & New Zealand Journal of Public Health. (Impact factor: 2.939).
9. Tong MX, **Wondmagegn BY,** Williams S, Hansen A, Dear K, et al. Hospitalization costs of respiratory diseases attributable to temperature in the context of climate change in Australia (Manuscript in draft).

Conference presentations arising from this thesis

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1. **Wondmagegn BY**, Xiang J, Williams S, Pisaniello S and Bi P. Healthcare costs of extreme heat exposure: Evidence from a comprehensive review (*Poster presentation*). The Florey Postgraduate Research Conference, the University of Adelaide, Australia, 2018.
2. **Wondmagegn BY**, Xiang J, Dear K, Williams S, Hansen A, et al. Current and projected healthcare costs for emergency department presentations under the changing climate (*Poster presentation*). The 32nd Annual Conference of the International Society for Environmental Epidemiology (ISEE), Virtual Conference, 2021.
3. **Wondmagegn BY**, Xiang J, Dear K, Williams S, Hansen A, et al. Degrees to dollars: current and projected healthcare costs associated with non-optimum temperatures in a changing climate (*Oral presentation*). The 2020 Population Health Association of Australia (PHAA) SA State Population Health Conference.
4. **Wondmagegn BY**, Xiang J, Dear K, Williams S, Hansen A, et al. How much does emergency department visits costs during heatwaves in Adelaide? (*Oral presentation*). The 2020 Population Health Association of Australia (PHAA) SA State Population Health Conference.
5. **Wondmagegn BY**, Xiang J, Dear K, Williams S, Hansen A, et al. The burden of heatwaves on emergency department presentations and associated healthcare costs (*Poster presentation*). The 33nd Annual Conference of the International Society for Environmental Epidemiology (ISEE), Virtual Conference, 2021.
6. **Wondmagegn BY**, Xiang J, Dear K, Williams S, Hansen A, et al. Understanding the Impacts of Temperature on Hospital Admissions, Length of Stay, and Related Healthcare Costs under the Changing Climate (*Poster*

presentation). The 33nd Annual Conference of the International Society for Environmental Epidemiology (ISEE), Virtual Conference, 2021.

Chapter 1: Introduction

1.1. Preface

Climate change can directly or indirectly affect human health through increased intensity and frequency of non-optimum ambient temperatures. Extreme temperatures have been reported to increase the risk of morbidity and mortality in Australia and around the world (1). Currently, there have been many studies focusing on exposure-response associations between temperature and various health outcomes, however, little is known about the total burden of emergency department (ED) presentations and hospital admissions attributable to cold and hot temperatures. More importantly, the temperature-cost relationship and economic burden to the healthcare system is poorly understood (2). Furthermore, little attention has been paid to the potential future health and economic impacts of the warming climate. Hence, this thesis aimed to examine the temperature-health and temperature-cost relationship; and estimate the current and future morbidity and cost burden of the warming climate with a major focus on heat effect.

This Chapter presents general background information about the rationale that underpins this study. A brief description of the research methodology is presented in Section 1.3 followed by the aims and scope of the research project in Section 1.4 and 1.5, respectively. The final Section of this Chapter outlines the structure of the thesis (Section 1.6).

1.2. The background rationale and motivation

Globally, spending on health continues to rise above gross domestic product growth (3) and this is not an exception to Australia. After adjusting for inflation and population change, the health spending in Australia increased from $91 billion in 2000-2001 to $185 billion in 2017-2018, an annual 2.7% increase per person (4). A large body of literature has documented that exposure to temperature is associated with higher risks of morbidity and mortality (5-7) that may increase healthcare spending. However, the fraction of costs attributable to temperature is largely unknown and the temperature-cost relationships were not yet examined. This research established the dose-response relationship between temperature and healthcare costs and then estimated the net-, cold-, and heat-attributable economic impact to the health system.

The rises in the global and regional temperature capture public interest and several studies have been conducted to examine the temperature-health relationship (5, 6, 8, 9). However, the great majority of the studies focused on the health impacts of extreme weather events such as cold and heatwave episodes that could occur a few days a year, and the impacts of mild but non-optimum temperatures received little attention. Moreover, the effects of temperature on morbidity were widely presented using risk ratios such as relative risk (RR), odds ratio (OR), or percentage change that might not be easily understandable by policy makers and donors (10, 11). Hence, research that quantifies the fractional morbidity and costs burden attributable by year-round non-optimum temperature is timely to assist public health intervention actions.

Despite heatwaves being one of the most common environmental hazards to public health around the world, there is no consistent definition making the comparison of results difficult (12). The excess heat factor (EHF) is a new heat metric developed by Nairn et al. in 2009 has several advantages over other heat indices, as it takes acclimatization and length of heatwave into account (13). In Australia, EHF has been reported to be a valid predictor of heat-related health outcomes (14) and health service demand (15). To our knowledge, however, it has not been used in the estimation of heat-attributable healthcare costs. Moreover, it has been increasingly used to estimate heatwave attributable health outcomes globally (16-18). However, it has not been used in the estimation of heat-attributable healthcare costs. The study in this thesis used the continuous EHF metric as the exposure variable to examine comprehensively the economic burden of heat-attributable health outcomes to the healthcare system. Furthermore, in Australia, the Bureau of Meteorology (BOM) used EHF categories (low and severe heatwaves) to forecast heatwave conditions (19). Evidence on the fraction of heatwave attributable burden by population's age categories and disease diagnosis groups may help to improve the heartwarming system and to target intervention actions.

The extent to which future temperatures pose health and economic impact has been absent from the scientific literature. A recent literature review indicated that the economic impact on the healthcare system is significant and future costs of extreme heat are likely to increase substantially in more heat prone areas (20). This research work estimated future temperature-attributable ED presentations, hospital admissions, and associated healthcare costs under different greenhouse gas emission scenarios and demographic change that could contribute to shaping climate mitigation and public health adaptations strategies.

1.3. A brief introduction of research design and methodology

This research work is conducted in Adelaide, the capital city of South Australia. Morbidity, healthcare costs, meteorology, and population data spaning from 2010 to 2017 were obtained from different departments/bureau representing the Adelaide metropolitan area. A time-series ecological study design was employed and the exposure-response relationships were examined using generalized linear models combined with distributed lag non-liner model (DLNM). The current net-cold-, and heat-attributable morbidity and healthcare costs were quantified for the current period and projected under different climate and medium population growth scenarios.

1.4. Thesis aim

This PhD thesis aims to comprehend the health burden and associated economic costs of temperature to the healthcare system in Adelaide, South Australia. It establishes the temperature-cost associations (Chapter 4-6) and provides new insight into the healthcare cost attributed to temperatures. The thesis also aimed to further increase our understanding of the association between health and temperature using an advanced statistical approach. The study investigated further the potential morbidity and cost burden of the changing climate under different greenhouse gas emissions scenarios and demographic change (Chapters 4 and 5). The thesis makes a summary of evidence-based recommendations for public health interventions and highlights the directions for future research. The finding from this thesis may also inform policymakers and relevant stakeholders in planning and communicating the health risks and economic costs of extreme temperatures posed by climate change.

1.5. Scope of the thesis

A range of weather conditions may affect the health of the population. However, our study only focused on the impacts of non-optimum temperatures including cold, heat, and heatwaves on ED presentations, hospital admissions, and associated health service costs in Adelaide, South Australia. The association between temperature, ED presentation, hospital admissions, and medical costs may be influenced by multiple environmental factors such as air pollutions (21) (particulate matter, carbon monoxide, ozone, sulphur dioxide, and nitrogen oxides) and humidity. This thesis did not account for these confounding factors although O_3 and PM_{10} have little influence in Australia (22) and Adelaide (23).

This study has investigated the direct medical costs of treating temperature-attributable ED presentations and hospital admissions to the Australian health system.

1.6. Thesis outline

This PhD Thesis is presented as a thesis by publication style which contains eight chapters. In Chapter 1, general background information drivers of climate change; historical and projected climate change; and temperature rise were presented. An overview of epidemiological studies looking at disease burden at the hospital emergency department and inpatient units caused by non-optimum temperatures. Moreover, it outlines the aim and scope of the thesis.

Chapter 2 presents a comprehensive literature review (published) focusing on the cost impacts of hot ambient temperatures on the healthcare system. The chapter is supplemented with an additional updated review of relevant literature published since our last review. Chapter 3 outlines the aims and objectives of the studies in this thesis. It provides a summary of the methodological framework and analytical technique followed to address research questions presented in section 1.4. Chapters 4, 5 and 6 represents the original papers of this thesis. Chapter 4 and Chapter 5 focused on the health and cost impacts of temperature at the ED and inpatient units, respectively. Both studies explored the temperature-health and temperature-cost relationship and calculated current and projected temperature (net)-, cold-, and heat-attributable morbidity and associated costs in Adelaide. Chapter 6 examined the relationship and burden of heatwaves on ED presentations and costs. Chapter 7 brings major results from chapters 3, 4, and 5 and provides a comprehensive discussion. Moreover, the chapter also presents the significance, limitations and strengths of the study by proposing areas of future research. Finally, chapter 8 presents the conclusion and draw recommendations based on the research findings.

Chapter 2: Literature review

2.1. Introduction

This Chapter presents general background information about global and regional climate change and review of literature about the morbidity and costs impacts of temperature. The public health impacts of climate change are introduced in Section 2.3, and the general overview of epidemiological studies on the association of temperature with ED presentations and hospital admissions are highlighted in Section 2.3.1.1 through to 2.3.1.4. Section 2.4 briefly introduces the concepts of healthcare costs related to temperature and a more detailed published review on economic costs associated with temperature is presented in section 2.5.1. The review in this chapter is mainly focused on the healthcare costs associated with exposure to hot ambient temperatures and highlighted the health impacts mainly morbidity. It is a published review entitled "*What do we know about the healthcare costs of extreme heat exposure? A comprehensive literature review. Science of the Total Environment 657 (2019) 608–618*". The review covers available peer-reviewed including grey literature from inception to December 2017 with a major focus on healthcare costs of hot ambient temperature. The final section of this Chapter updates the literature on healthcare costs of temperature published after December 2017.

2.2. Background information about climate change and temperature

Climate change is one of the biggest challenges threatening the ecological, social, and economic systems in the 21st century with compelling evidence that anthropogenic activities are contributing to this change (24). It is a long-term shift in precipitation, humidity, temperature, wind and other types of weather elements (25, 26) driven by both internal and external influences (24, 27, 28). The flow of energy in the earth's climate system (Figure 1.1) is the fundamental causes of climate change which can be influenced by many factors (29) like greenhouse gas (GHG) emissions.

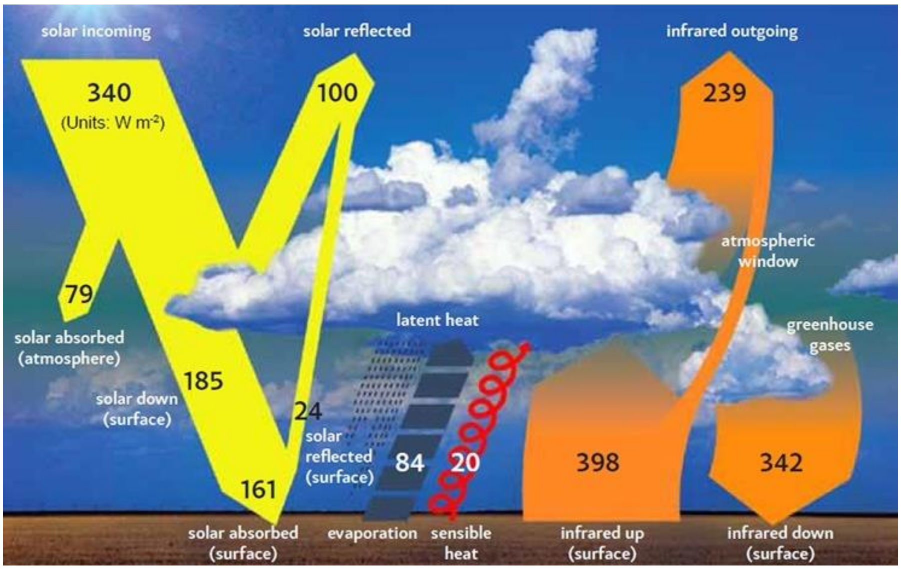


Figure 1. Global mean energy budget under current climate conditions. The arrows show global average energy transfer rates in units of Watts per square metre.

(Source: Intergovernmental Panel on Climate Change (IPCC) 2013)

Greenhouse gases are important to maintain the earth planet warm enough to sustain life, without them the average global temperature would be about 30°C cooler than it is now (24, 30). Since the industrial revolution, most atmospheric GHGs such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and ozone (O_3) (31) are increasing in their concentration over time and absorb more radiation energy causing global warming (24, 32). For example, the concentration of CO_2, CH_4, and N_2O increased by 43, 150, and 20 percent from the pre-industrial level (33), and most GHGs have the potential to remain in the atmosphere for long period, ranging from decades to centuries (34). Human actions such as the burning of fossil fuels contribute significantly to the observed growth in atmospheric GHGs concentration (24) (Figure 1.2).

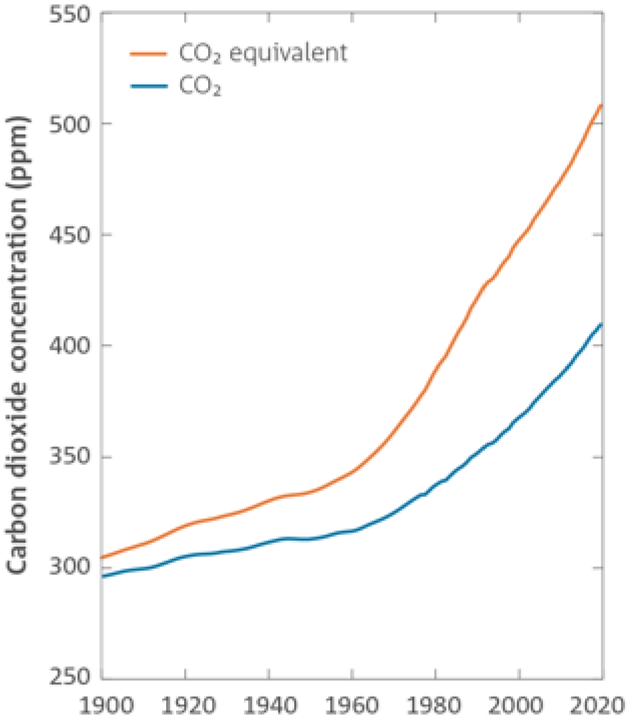


Figure 2. Atmospheric concentrations of carbon dioxide (CO2) and CO2 equivalent (CO2-e) of all greenhouse gases.
(Source: CSIRO).

Observed and projected global climate change

Our climate has been measurably changing (35), and on timescales, the rate of change at the global and regional levels is rapid (36). According to the fifth assessment report of the IPCC, the warming of the planet is unequivocal (37). The average global temperature increased by 0.85°C (0.65 to 1.06) from 1850 to 2012 (38). Scientists are confident that the observed global and regional temperature rise is attributed to the increase of GHGs (32). Overall, the world is becoming warmer with increasing surface temperature (Figure 1.3). Snow-covered areas including mountains and sea ice have been shrinking and melting. On the global scale, the number of warm days and nights has increased and the number of cold days and nights has decreased since 1950 (37). It is conceivable that the increase in the impacts of heatwave conditions is one of the most widely felt impacts in many parts of the world including the USA, Europe, Asia, and Australia (26, 37).

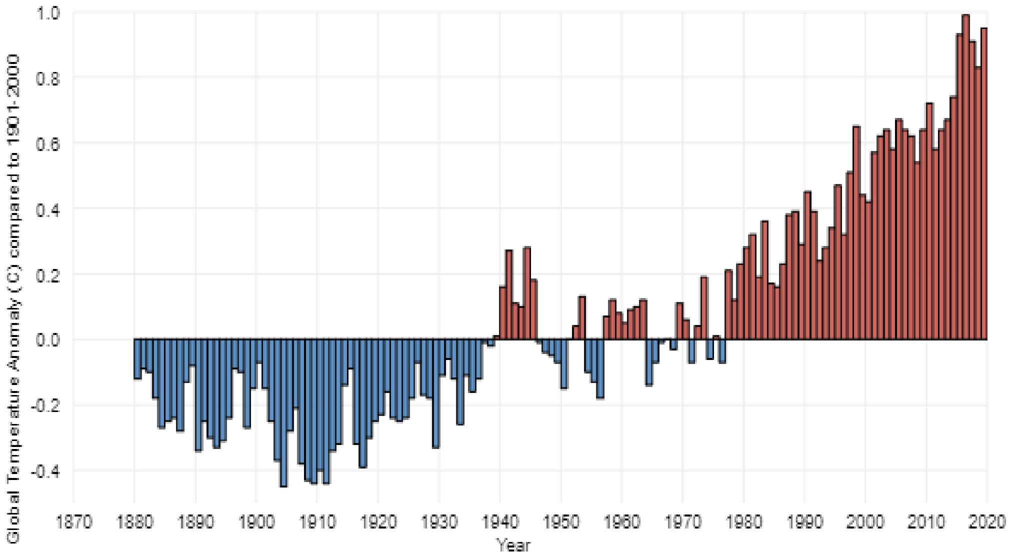


Figure 3. The graph shows the average annual global temperatures since 1880 compared to the long-term average (1901-2000) (Source: Climate Change- Global Temperature).

The central aim of the 2015 Paris Agreement is to reinforce the global response to the threat of climate change by limiting the increase in global average temperature to 1.5°C to 2°C above the pre-industrial average (39). However, the already increase in average temperature by 2°C in some regions, including Australia is associated with a substantial increase in extreme weather conditions and related factors (40, 41). The observed shift in climate pattern is predicted to continue into the foreseeable future with greater intensity (26) (Figure 1.4). By the end of the 21st century, global mean surface temperature will likely exceed 2°C relative to 1850 to 1900 for all RCP except RCP2.6 (42). The occurrence of extreme weather conditions such as heatwaves will be more frequent, longer, and more intense (43). Global surface temperature is likely to reach 1.5°C between 2030 and 2052 above the pre-industrial period (44). For the period 2081 to 2100, the Coupled Model Intercomparison Project Phase 5 (CMIP5) model simulation indicated a global mean surface temperature increase in the ranges from 0.3°C to 1.7°C (RCP2.6), 1.1°C to 2.6°C (RCP4.5), 1.4°C to 3.1°C (RCP6.0), 2.6°C to 4.8°C (RCP8.5) relative to 1986-2005 (37). This temperature increase is of paramount concern for future population health and only a few studies have attempted to quantify the potential health and economic impacts of projected temperatures. The expected change and attributable burden can vary by region (1, 45) and in some heat prone areas like Australia, the impact of climate change can be more pronounced with the aging population.

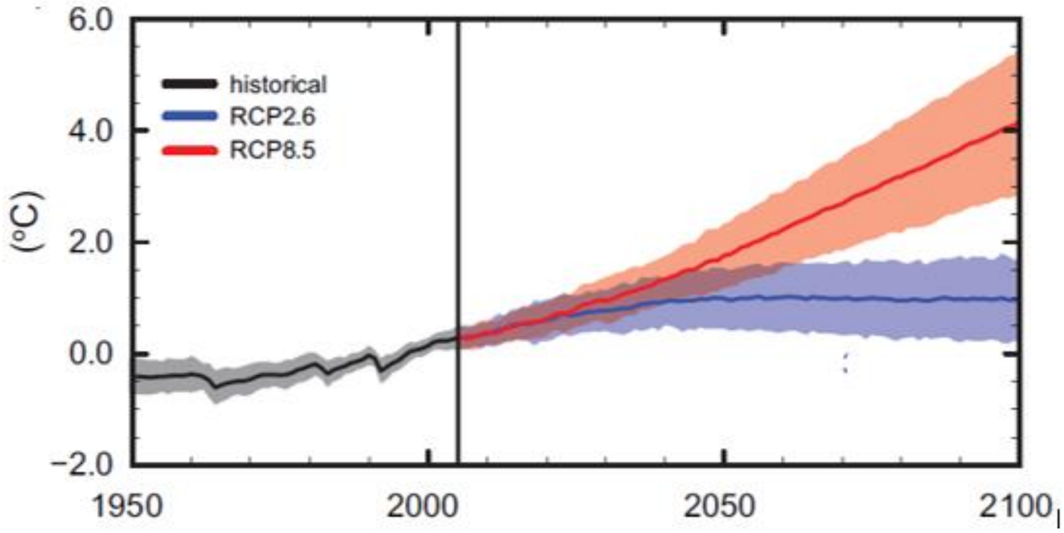


Figure 4. Global average surface temperature change: CMIP5 multi-model simulated time series from 1950 to 2100 for change in global annual mean surface temperature relative to 1986-2005.
(Source: IPCC 2013).

Current and projected climate change in Australia

In Australia, elevated ambient temperature and recurrent heatwaves are growing public health concerns (46). The country's climate has changed and an increase in average surface air temperature of around 1.44°C was observed since the national records began in 1910 (Figure 1.5) (47). From the 1960s, some states of Australia experienced an increase of temperature up to 2ºC (24), and the frequency, intensity, and duration of extreme heat events increased in many states and territories (48) (Figure 1.6). The number of days and nights with higher maximum temperature increased by 9% during 2001-2015 compared to 1951-1980 (48). The number of extreme heat events registered outnumbered the extreme cold records by 3 to 1 during daytime and 5 to 1 for the night since 2001 (49).

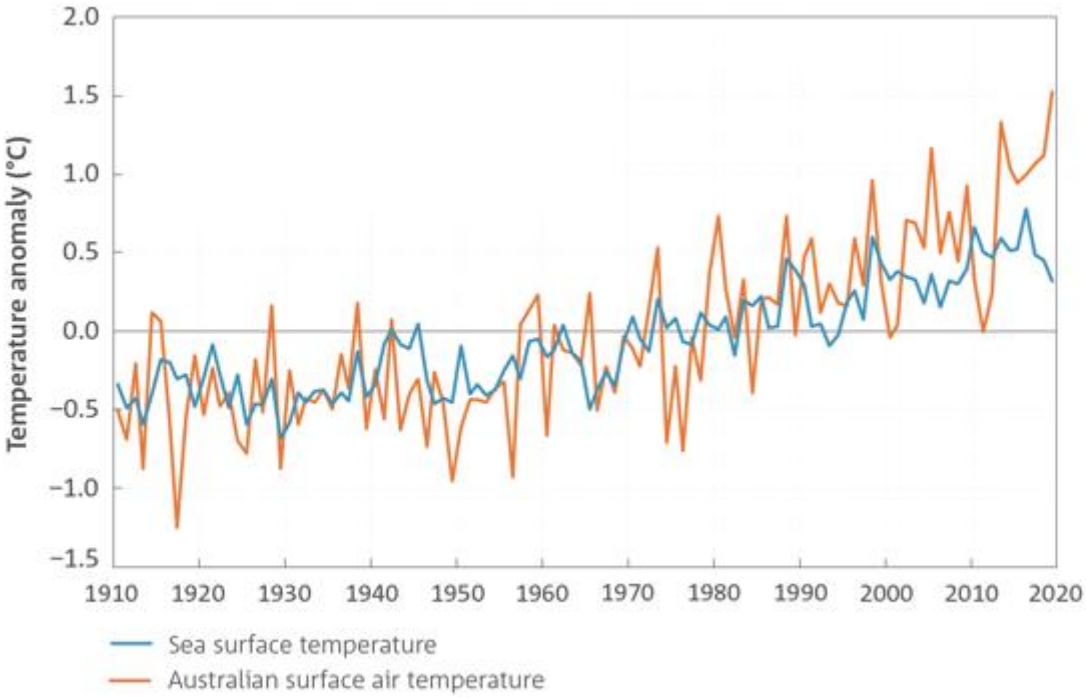


Figure 5. Annual mean temperature anomaly in Australia from 1910-2020

(Source: BOM)

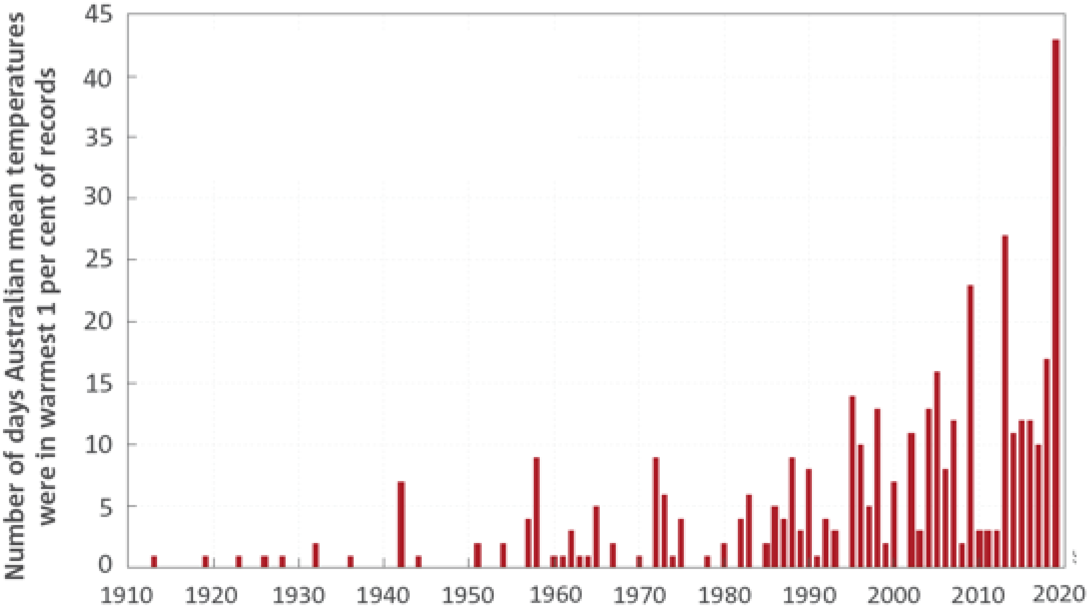


Figure 6. The number of extreme days above the 99th percentile of each month for the years 1910-2019
(Source: BOM).

The observed temperature rise in Australia is projected to continue in the future. Based on climate projections, the average temperature is predicted to increase by 1°C in 2030 above the 1990 temperatures. By 2050, a temperature increase of between 0.8 to 1.8ºC is predicted using low greenhouse gas emission scenarios and 1.5 to 2.8ºC based on high greenhouse gas emission scenarios. Near the end of the century, a high-temperature increase is expected. Accordingly, a temperature increase of 2.2ºC and 5ºC was projected in 2070 based on low and high emission scenarios, respectively (24). Drier winters are likely to be observed in the southern area of Australia.

In Adelaide, the capital of South Australia, for example, the number of days with a temperature of over 35°C will be doubled by 2070 compared to 1971-2000 (24). The average temperature will continue to increase (Figure 1.7) in all scenarios with very high confidence of more hot days and warm spells (50). In Adelaide, the average annual number of days below 2°C (frost risk) is predicted to decrease from 1.1% during 1981-2010 to 0.5 (0.8 to 0.4) during 2030 (50). Regardless of the decrease in cold temperature exposure, it seems that cold temperature can be a public health concern at least until mid-century with much greater concern from the warming climate. Hence, the estimation of future health and economic impact attributed to cold and heat exposures based on the baseline exposure-response relationship will provide needed evidence to policymakers.

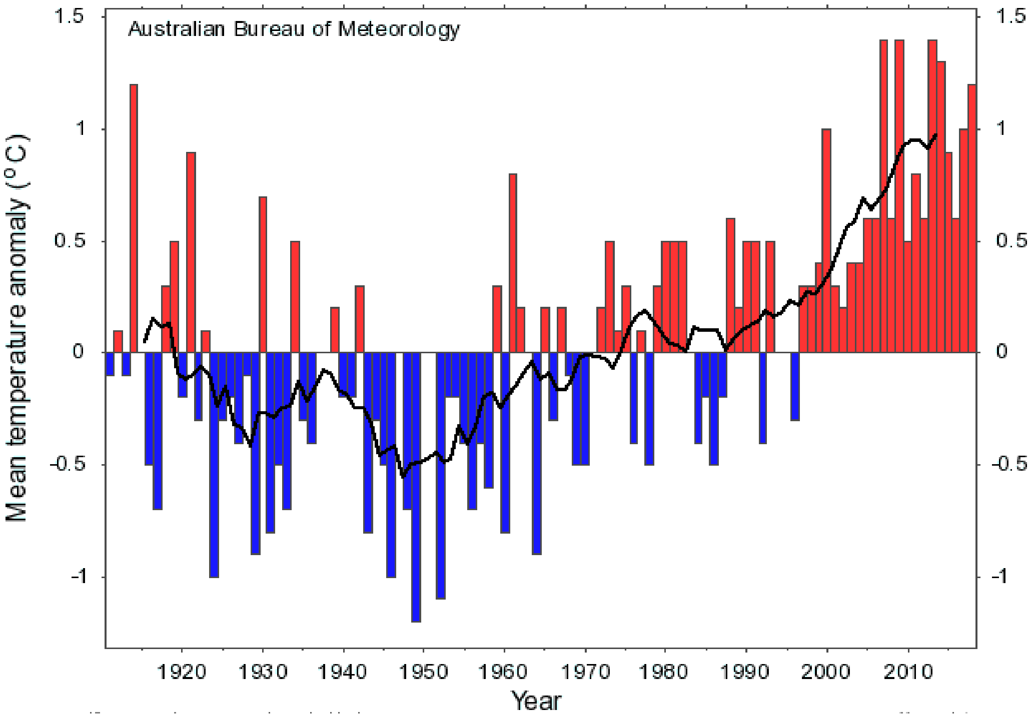


Figure 7. Annual mean temperature anomaly (with 10 years of running average) of Adelaide, South Australia (at site 023090) for 1911-2018
(Source: BOM)

2.3. Health impacts of ambient temperature

Although extreme weather has been recognized to affect human health since the time of Hippocrates, understanding the linkage under different climatic and socio-economic environments is an increasing scientific interest (51-53). A review of relevant epidemiological studies indicated that ambient temperature is associated with elevated risks of morbidity and mortality to the population (5-7). In recent years, the global surface air temperature is increasing; and future extreme weather events such as heatwaves are expected to be more frequent events (54, 55). In the absence of adaptive measures, the temperature-related health burden is likely to increase substantially (56, 57). The health impacts of temperature can be further amplified due to the global and regional ageing population and the increasing prevalence of chronic health conditions (58). The majority of previous studies have focused on the exposure-response relationship, and there is a need to understand and quantify the health burden and economic costs of temperature-attributable morbidities to the healthcare system.

Characteristics of the temperature-health relationship

Descriptive, case-crossover, time-series, and spatial models (59-61) have been used to assess the impacts of temperature on various health outcomes. Time-series analysis has been the most commonly used method to examine the short-term effects of temperature on human health (morbidity and mortality) (21, 62). Daily measures of exposure and outcome variables have been widely used in previous time-series studies, while weekly, monthly, seasonal or annual data were also used in some studies (21). Data of longer time intervals have shortcomings in detecting acute effects of temperature exposure (63, 64) unless it is related to infectious diseases which normally require several weeks of the incubation period to cause diseases. The time-series and case-crossover designs allow controlling of time-varying potential confounding factors such as season, day of the week, and holiday (65).

Many epidemiological studies have provided abundant evidence of the association between ambient temperature and morbidity including all-cause and cause-specific

ED presentations, and hospital admission (6, 7). It is widely reported that the relationship exhibited a non-linear U-, or J-, or V-shaped functions (7, 21) with increasing health risks below or above an optimum temperature range at which the risk is the lowest.

Lag effect

Exposure to extreme ambient temperatures can result in acute health outcomes during the time of the event. However, there are possibilities that the morbidity and mortality effects of temperature can be extended after the time of exposure (66); this portion of temperature impact is referred to as a “lag” effect. Understanding the lag effect of temperature on morbidity and health service use could help in the planning of public health interventions and mobilize available healthcare resources. Depending on the types of temperature exposure, the lag time for the health outcome may vary, ranging from the current day (lag 0) to four weeks (10, 11, 67, 68). Despite the differences in methodological consideration, several studies have reported that heat exposure has a shorter lag effect while the effects of cold temperature can last several weeks, up to one month (11, 21).

Temperature threshold

Temperature threshold can be defined as a value at which risks of health outcomes of interest change (1). Several studies have attempted to identify threshold temperatures for different weather-related morbidities and mortalities (7). It should be noted that temperature thresholds may vary by population, climate zone, and geographical location. For example, people living in warmer regions may have a higher heat threshold because of population adaptation to hot conditions (21, 69).

The threshold temperature can be identified in different ways. Some identified based on model fit that on the temperature-morbidity smoothed curve, the points that correspond to the lowest morbidity risk on the plot were chosen as a temperature threshold (70-72) while others assigned median (73) or a certain temperature percentiles (eg. 5th, 25th, 50th, 75th, 95th) of temperature during the study period (74, 75). Furthermore, the threshold temperature for heatwaves varies by exposure indicators and durations (76, 77) which is further complicated by a diverse definition of heatwaves across different regions. The EHF is a heatwave severity and intensity metric that can help to simplify this variation. It is a globally comparable exposure index of human health across different locations that can be implemented within the international heatwave early warning system (19, 78). The value of EHF > 0 is the threshold for heatwave intensity and severity (13) (see Chapter 6 for details information about EHF).

Confounding variables of temperature-health association

The effects of temperature on ED presentations and hospital admissions can be confounded by different environmental and socioeconomic factors (21). The aim of time-series analysis in environmental epidemiology is to address whether daily environmental exposure of interest explains the daily variation in health outcomes (62). However, the outcome variables can differ across the time scale. For example, the number of patients appearing in a healthcare system can be different during the weekend, on public holidays, between cold and warm seasons, and from year to year. Hence, it is customary to control seasonality and long-term trends (62). Socio-economic factors such as the introduction and adoption of technologies that can create variation in time on the population level, and environmental exposures such as air pollutions and humidity, are important confounders to be controlled (79).

2.3.1. The impacts of temperature on ED presentations and hospital admission

Extreme temperatures appear to increase pressure on the EDs and hospital systems (2). Sections 1.6.1 and 1.6.2 highlight evidence of the association between temperature and ED presentations and hospital admissions for potential temperature sensitive diseases including respiratory, renal, mental health disorder, IHD, heat-related illnesses (HRI) that includes dehydration, heat cramps, heat exhaustion, and heat stroke, and diabetes. Presenting some of the findings from such studies could help us to shape our understanding of the exposure-response relationship historically. However, in Study 1 (Chapter 4) and Study 2 (Chapter 5) of this thesis, the analyses were performed by clustering together these diagnosis categories (termed as TRDs) to achieve more statistical power.

2.3.1.1. Overview of epidemiological studies on the relationship between ambient temperature and ED presentations

Currently, medical emergency department services are overburdened due to the additional increasing temperature-related disease episodes in some cities (2, 80). A large number of existing studies in the broad literature have examined the association between ambient temperature and ED presentations (5, 6, 8, 9). Despite compelling evidence of a positive association between ambient temperature and risks of ED presentations, there are differences in study results, types of temperature metrics used, geographic locations/scales, interests of disease conditions, and statistical approaches. This section highlights evidence of the association between temperature and ED presentations and hospital admissions for potential temperature sensitive diseases including respiratory, renal, mental health disorder, IHD, diabetes and other heat-related illnesses.

A study of heat and emergency room admissions in the Netherlands from 2002-2007 reported a positive relationship above a temperature threshold of 21°C for the disease category ‘potential heat-related diseases’. The greatest effects (RR) were observed at lag 0 (81). This result is similar to the study from Verona, Italy, that heat exposure is positively associated with ED presentations, and the effects were also found to be immediate (82). The study reported a 3.75% (90% CI: 3.01-4.49) increase in all-cause ED visits for each 1°C increase in mean apparent temperature above the threshold at lag 0-3 days (82). Cheng et al. reported that heat and cold exposures increased the risks of ED visits in both Australian and Chinese cities (83). However, results are divergent between countries that the heat was associated with a lower risk of ED visits in China, 1.009 (95% CI: 1.007, 1.011) compared to Australia, 1.014 (95% CI: 1.010-1.018). The relative risks of cold temperature were similar in both countries (83). A study by Nitschke et al. in Adelaide reported incidence rate ratios (IRR) of 1.02 (95% CI: 1.01-1.04) for total ED presentations during 2009 heatwaves compared to non-heatwave days. However, the 2014 heatwaves showed a protective effect, 0.97 (95% CI: 0.95-0.98), possibly due to the heat and health early warning system implemented since early 2010 (84).

Exposure to heat may cause a range of preventable direct HRI including dehydration, heat cramps, heat exhaustion, and heat stroke. Some of these health conditions could be such as heat stroke could be life-threatening (85). Studies in the USA indicated that heat exhaustion and dehydration were the most common forms of HRI at the ED (86, 87), and a total of 23,981 and 2539 HRI ED presentations were reported during warm seasons in Florida from 2005-2012 and North Carolina from 2007-2008, respectively (85, 88). Similarly, a large number of HRI presentations were evidenced at the ED during days of high maximum temperature in England between 2007-2012. However, the number of presentations decreased when the maximum temperature exceeded 38°C (89) suggesting the presence of some prevention actions. In 2009, an IRR of 12.03 (95% CI: 9.23-15.68) HRI was observed at the ED among all age groups in Adelaide, Australia (84)

Exposure to extreme temperature can exacerbate pre-existing medical conditions such as cardiovascular disease (CVD), respiratory, renal, mental health disorders, and diabetes (6, 8, 90). Many studies have examined the relationship between outdoor temperature and the risks of ED presentations from CVDs (91-93). During extreme heat events, an increased number of CVDs presentations were reported at the ED in Italy (91), North Carolina (86), California (94), Toronto (92), and China (95). On the other hand, a negative correlation was reported from Croatia and Taiwan (96, 97). This contradiction could be due to the difference in population, socioeconomic and climatic conditions. Moreover, patients with CVD may directly be admitted to the inpatient unit without arriving at the ED and perhaps some may die before they reach the healthcare facilities.

Several studies identified a positive association of low (98-100) and high (86, 98, 100, 101) temperatures with respiratory diseases. A time-series study between 2007 and 2017 in Greater London identified a significant overall increase in respiratory ED presentations for a 1°C temperature rise (101). Some studies in China reported the effects of both cold and hot temperatures. For example, a risk of 1.06 (95% CI: 0.70-1.60) and 0.92 (95% CI: 0.56-1.53) respiratory ED presentations were associated with low and high temperatures at a lag of 21 days, respectively (98). Another study in China substantiated this result that cold spills and heatwaves reported having a significant effect on above or below the minimum-mortality temperature threshold of 21.5°C (100). Similarly, a sharp increase in the risks of respiratory ED presentations at extremely low temperatures was reported with a greater effect on lag 3 with a declining effect until lag 27 days (99). Moreover, ED visits of respiratory diseases were reported to increase by 0.94% (95% CI: 0.34-1.55%) for each 1℃ increase in diurnal temperature (102). In North Carolina, extreme heat increased ED visits by 5-7% (86). The rate of emergency department visits of three heatwave periods (heatwaves between 1993 and 2008, 2008, and 2009) was compared with the non-heatwave period in Adelaide. Respiratory ED presentations were not affected during the 2008 heatwaves showing a reduction during other heatwave periods (103). The disparity of the results could be due to the low number of cases which could result in low predictive power or variation in precautions during heatwave days.

The epidemiology of kidney diseases can be exacerbated by ambient temperature and several studies reported the association between heat exposure and ED presentations of renal diseases (104, 105). For example, high temperature is associated with increased ED presentations for renal colic in the USA, Japan, Italy, Spain, and Canada (68, 106-109). Some scholars also studied the impacts of heat on renal diseases in Australia (22, 23, 110-112). In Perth, renal-related ED presentations were reported to increase by 10.2% (IRR 1.102; 95%CI: 1.071-1.135) per 10°C increase in maximum temperature (22). A strong link between a heatwave and urinary diseases were reported in Adelaide using EHF as heatwave intensity/severity metric. A lag of 10-days was found and the maximum effect was observed at lag 3 and then gradually decreased with significant effect until eight lag days (112). The authors used minimum temperature as exposure variable and found IRR of 1.009 (95% CI: 1.006-1.011) for total renal disease, 1.030 (95% CI: 1.022-1.039) for renal failure, and 1.017 (95% CI: 1.001-1.033) for chronic kidney diseases per 1°C increase. The strongest effects were observed after 1-3 days of heat exposure (113). However, a study by Williams et al. in Adelaide from 2003-2009 did not found a significant association with elevated and extreme daily maximum and minimum temperatures and renal diseases (23), possibly due to a lower number of cases. Most studies evidenced that males are at greater risks of renal diseases than female populations (68, 108, 109, 112, 114). The possible reason could be that males are more engaged in outdoor activities and exposed to extreme ambient temperatures.

Mental health disorder is another set of conditions that can be influenced by ambient temperature. Studies from multiple countries (115-118) reported an increasing mental health presentation at the ED with the increase in temperature. For example, in California (115) and Korea (116), ED presentations for mental health diseases increased by 4.8% (95% CI: 3.6-6.0%) and 1.4% (95% CI: 1.0-1.7%) for every 5.6°C and 1°C increase of temperature, respectively. Similarly, daily maximum and mean temperature was positively associated with ED presentations for mental illnesses in Tel-Aviv (117) and Canada (118), respectively. A different study in California, USA, reported that cold temperature seemingly reduces the negative mental health outcomes while hot temperature increases risks of ED presentation for mental illness, suicides, and self-reported days of poor mental health (119).

Given that the global prevalence of diabetes is increasing, the danger posed by extreme temperatures to diabetic patients is rarely studied (120). Diabetes patients have impaired thermoregulatory and sweating abnormalities because of autonomic neuropathy (121) and available studies found its positive association with high ambient temperatures (92, 122-125). A study in England indicated an increase in General Practitioner (GP) consultations during the period of both high and low temperatures among diabetes patients. A 9.7% increase in the odds of type-2 diabetes GP consultations per 1°C in the high temperature with much of the effect occurred with 2-day lags while the cold risk was significantly higher on lags 0 and 6 days (120). A time-stratified case-crossover study in California, USA, from 2005-2008 reported an excess risk of 4.3 (95% CI: 2.8-5.9) per 10^0F (5.6°C) increase in temperature for combined 16 climate zones (122).

2.3.1.2. The burden of temperature-attributable ED presentations

In the past decades, non-optimum temperatures such as heat, cold, heatwaves, and cold spells caused a remarkable increase in the total burden of morbidity and mortality both in high and middle-income countries (11) with little evidence from low-income countries. Most available temperature-health related studies used RR, OR, or percentage change to calculate the dose-response relationship (11, 126). These effect measurements provide a clear understanding of how health risks can change when daily temperature exposure varies. However, given that the temperature-health relationship is reported to be predominantly non-linear (11) and the health effect can also vary by length of exposure, these effect estimates have major limitations in informing the magnitude of the public health burdens of the whole temperature range. Few studies estimated the burden of ED presentations attributed to ambient temperature (82, 83, 127-129). The majority of these studies used daily mean temperature as exposure index (82, 83, 127) with most come from developed countries (82, 83, 127-129). Some studies considered cold and heat exposure (83, 127) while others studied contemplate only the heat effect (82, 128, 129).

In most cases, making a direct comparison of results for different settings is difficult due to variations in study design and statistical models. Cheng et al. used similar analytical protocols to study the impacts of heat and cold temperature on ED visits in Australian and Chinese cities (83). The authors reported that both heat and cold exposures increased ED visits in both study settings. The relative risks of cold temperature were similar in both countries; however, the cold-attributable fraction was much higher in China (9.6%) compared to Australia (1.5%). This contradiction could be because the burden of diseases attributable to non-optimum temperature is determined by multiple factors mainly by frequency of exposure, risk trigger temperature, and slop of risks. Nevertheless, both countries had a similar proportion of heat-attributable ED presentations (83).

A study of the heat effect in Verona, Italy found that apparent temperature attributed to 1,177 high-priority all-age ED visits during the warm seasons of 2011-2012 above the temperature threshold. Heat effect by age category showed an attributable burden of 155, 695, and 326 ED visits for people aged 0-14, 15-64, and 65$^+$ years, respectively (82). The result indicated that the effect of heat for the middle age group was much greater compared to other age groups and the possible reason could be due to occupational exposure, as this group belongs to the working class.

A study in Southern New England presented the burden of ED presentations associated with cold and heat temperatures using ED data from 2005-2014 for Rhode Island and Boston. The fraction of ED visits attributable to deviations from minimum morbidity temperature accounted for 2.0% (95% eCI: 0.8-3.3) which is corresponding to an annual 8,981 (95% eCI: 3,382-14,557) temperature-related number of ED visits in Rhode Island (127). In Boston, extreme heat contributed to 1,408 (95% eCI: 419, 2369) attributable ED presentations accounting 0.2% (95% eCI: 0.1-0.4) fractions. Generally, lower ED visits were observed during extreme temperature compared to moderate cold and heat which might be due to peoples precaution and planned interventions as studies indicated that the heat warning system implemented in some areas such as Adelaide and Philadelphia reduced the incidence of health outcomes (84) and cost savings (130). Another study in New England reported an annual average of 784 (95% CI: 658-908) excess ED visits over the temperature threshold of 95°F (128).

The future burden of emergency health episodes would likely to increase with the warming climate. Weinberger et al. projected effects of climate change for the 2090s using CMIP5 climate models and under two greenhouse gas emission scenarios. The mean daily temperature projected for the 2090s under RCP4.5 and RCP8.5 were 2.2 °C (range: 0.6, 3.3) and 4.7 °C (range: 2.7, 6.5), respectively. Under the assumption of constant population, future temperature exposure under RCP8.5 would result in 5,976 (95% eCI: 1,630-11,379) more ED visits (127).

Gronlund et al. and her colleagues projected extreme heat-attributable heat ED presentations for Michigan, USA. The study found an annual count of 7,800 ED visits were attributed to excess heat during 2040-2070. Heat-attributable ED visits were projected to increase from 52,7% during the baseline period to 62.6% during the projection periods for 65+ years. The study projected an annual 21.8 days with a temperature >32.2°C using the A2 scenario from the six general circulation models (129).

2.3.1.3. Overview of epidemiological studies on the relationship between ambient temperature and hospital admissions

Exposure to low and high ambient temperatures may result in moderate or severe health outcomes which may end up in hospitalization. All segments of the population could be at risk with the very young and the very old are more likely to be hospitalized due to extreme heat exposure. For example, a study in Hanoi, Vietnam, reported a strong association between low temperature and children hospitalizations; however, the high temperature was found to be negatively associated (131) possibly because of less engagement of children's in outdoor activities. On the other hand, the association of paediatric emergency hospital admissions and high ambient temperature were observed in the United Kingdom (132). As demographic projections show an ageing population particularly in developed countries, the vulnerability in older age groups is an increasing concern (132).

Exposure to extreme weather may increase the risk of direct TRDs. Prolonged exposure to heat can cause HRI such as heat exhaustion, heat cramps, and heat stroke (133). When the heat increase over 35℃, mortality and morbidity will significantly escalate based on the duration and level of temperature (134). Most HRIs can be treated at the ED, however, some HRIs can be severe and resulted in hospitalizations. For example, an increase in hospital admission due to HRI were observed between 2001 and 2010 in the USA compared to non-HRI hospitalizations. It is reported that nearly 73% of emergency hospital admissions were due to HRI (135). A study from 2005 to 2012 in Florida, USA, identified 4,814 hospital admissions of non-work-related HRIs (136). Despite a study in North Carolina, USA showed low rates of HRI of younger and the elderly age groups at the ED during higher temperatures (89), these population groups experience more severe HRI and subsequent hospitalization (137).

Evidence has shown that exposure to extreme temperature could result in hospitalizations from a range of comorbidities such as respiratory illnesses, mental health disorders, renal diseases, and CVDs (8, 10, 132, 138-140). A growing body of literature has evaluated the association between extreme temperature and CVD hospitalization (10, 141-144) and reported a positive association. Both cold and hot temperatures were reported to have a significant effect (10). A systematic review and meta-analysis study separately reported the effects of cold-, heat-, and heatwave-exposures. The risk of cardiovascular hospitalizations was increased by 2.8% (RR, 1.028 (95% CI: 1.021-1.035) for cold exposure and by 2.2% (RR, 1.022 (95% CI: 1.006-1.039) for heatwave exposure (10). Likewise, the heatwave was reported to be a risk factor for CVD hospital admission with RR of 1.01 (95% CI: 1-1.02) (94) in California, 1.23 (95% CI: 1.07-1.38) (145) in Chicago and 1.08 (95% CI: 1.05-1.11) (146) in China. However, the pooled heat effect from the review showed a non-significant result, 0.997 (95% CI: 0.994-0.999) (10). In Sydney, Australia, the odds of admission for CVD increased by 1.01 (95% CI: 1.00-1.02) at extremely hot temperatures (95th percentile) (147). A study of five hospitals in the Northern Territory, Australia also reported a 23% increase in IHD hospital admission during hot days (148).

A systematic review and meta-analysis of cardiorespiratory morbidity by Turner et al. indicated that heat has a potential effect on respiratory hospital admissions (67). Several studies identified a linear association of temperature and respiratory hospitalizations above or below a certain temperature threshold. For example, a study in 12 European cities indicated that a 1°C increase above 90th percentile of city-specific maximum temperature was associated with an increase of respiratory admissions by 4.5% in the Mediterranean cities and 3.1% in North-Continental cities for people aged ≥75 years (149). Similarly, a 1°C increase of apparent temperature above a threshold temperature of 37.4°C was linearly associated with an increased risk of respiratory hospitalizations for people aged 85 years in Washington DC (150). In Greater London, the UK, a linear increase in respiratory hospital admissions was observed above a daily mean temperature of 23°C (151). Two decades of time-series data in Hong Kong, China, indicated that both low and high temperatures were associated with increased respiratory hospital admissions (152). In some regions, cold temperature is found to be an important predictor of respiratory hospitalizations (60, 153).

Associations of heatwaves and respiratory hospital admissions were examined in different cities of Australia. For example, a study of health impacts of extreme heat events in five regions of the New South Wales reported a significant risk of respiratory hospital admissions at lag 1 (OR= 1.09; 95% CI: 1.04-1.14) and lag 2 (OR=1.02; 95% CI: 0.97-1.06) (154). Another study in Sydney reported a risk of 1.02 (95% CI: 1.01-1.04) after adjusting for relative humidity, O_3 and PM_{10} (147).

Socioeconomic status was reported to be a predisposing factor for temperature-related respiratory hospital admissions. For example, a study in Northern Territory, Australia indicated that both cold and heat exposures were associated with higher rates of hospitalisations for indigenous compared to non-indigenous communities (155). Demographic factors such as age, sex, and race were also found to be risk factors for temperature-related respiratory admissions (155-157).

Heat exposure can affect fluid balance and impact the urinary and kidney systems (158) which may subsequently lead to hospitalizations. Exposure to hot weather was found to increase hospital admission of patients with kidney diseases (123, 150, 151, 158, 159). Similarly, renal diseases are major heat-related admissions in many states of Australia. For example, the risk of hospital admission for acute renal failure increased by 1.25 (95% CI: 1.02-1.54) at a temperature of 99th percentile in Sydney (147) and the odds of renal admission increased by 41% during heatwaves in Brisbane (160). In Adelaide, Hansen et al. (2008) found an overall 10% increase in renal admission during the heatwave period (161). Another study in Adelaide by Williams et al. (23) reported a significant increase in an incidence rate ratio of renal hospital admission by 1.006 (95% CI: 1.032-1.101) for daily maximum temperature and 1.108 (95% CI: 1.017-1.208) for daily minimum temperature above the threshold temperature of 26°C and 16°C, respectively. However, the effect of extreme temperature became insignificant after adjusting for air pollution such as O_3 and PM_{10} (23).

Some studies have examined the impacts of temperature on mental, behavioural, and cognitive disorders and reported that it can exacerbate health conditions (138, 162-164). The physical, mental, and pathological impairment together with psychiatric medications affect the ability of mental health patients to cope and adapt to change in ambient temperature (165) and put them at higher risk of morbidity and mortality (165-167). A systematic review of the association between temperature and mental health outcomes indicated a significant increase in the risks of hospital admissions during heatwave periods (138). The elderly, outdoor workers, singles, and urban residents were reported to be at higher risk of mental health admission during the time of high-temperature Jinan, China (168). In Adelaide, a 7.3% increase in mental health admissions were observed during heatwave periods of 1993 to 2006 above a temperature of 26.7°C (163).

The global incidence of diabetes mellitus is increasing substantially (169) and type 2 diabetes is associated with ambient temperature (124). Few studies in recent years pointed out that diabetes patients are increasingly susceptible to both hot and cold temperatures (170). A study conducted in the 50 states of the USA revealed that a 1°C increase in temperature, age-adjusted diabetes incidence increased by 0.314 per 1000 population (95% CI: 0.194-0.434). The number of hospitalizations due to diabetes increased by 3.1% (95% CI: 0.4-5.9) for each 10^0F (5.6°C) increase of mean apparent temperature in nine California counties (123). In Sydney, a total of 97,418 diabetes hospital admissions were observed between 1991 and 2009 and an OR of 1.06 (95% CI: 1.02-1.10) was reported during extremely hot days (147). However, the study in Brisbane found insignificant hospital emergency admission during heatwave time (160).

Few projection studies reported future impacts of the changing climate. Based on the climate model of intermediate severity warming, Special Report on Emission Scenarios (SRESa1b), nephrolithiasis would grow from 40% in 2000 to 56% and 70% by 2050 and 2095 in the USA respectively (171). Future climate patterns may considerably affect global variations in the prevalence of diabetes (125).

2.3.1.4. The burden of temperature-attributable hospital admissions

Weather variability and climate change put profound pressure on hospital services around the world. Some studies in America, Europe, Australia, and Asia quantified the burden of temperature on hospital admissions (172-180). These studies investigated the burden for all-cause admissions and specific diseases diagnosis categories such as different types of CVDs, diabetes, and mental health disorders. The majority of these studies accounted for the effects of both cold and heat effects (172, 173, 175, 178, 179) and others focused on heat (174, 176).

A study of heart disease and stroke in Ontario, Canada from 1996-2013 reported a 9 and 11 percent increase of daily hospitalization for coronary heart disease and Acute myocardial infarction (AMI) associated with 1st percentile of cold temperature relative to days with optimum temperature, respectively (172). High temperature (99th percentile) also caused a 6% increase in hospital admission for CHD (172). Attributable fraction and numbers of hospital admissions for cold-attributable CHD were reported to be 2.49% (95%CI: 1.03-3.67) and 34,456 (95%CI: 14,244-50,758), respectively. Heat attributable fractions for CHD and stroke were reported to be 1.20% (95%CI: 0.22-2.14) and 1.82% (95%CI: 0.06-3.21) with a corresponding attributable number of 16,628 (95%CI: 3,040-29,559) and 6,469 (95%CI: 223-11,378) hospital admissions, respectively (172). A study of stroke hospital admission in China by Guo et al. indicated that only cold temperature contributed to a significant burden of hospital admission for different stroke subtypes (175) with an attributable fraction of 9.06% (95% CI: 1.84-15.00) for covert brain infarcts and 15.09% (95% CI: 5.86-21.96) for intracerebral haemorrhage; older peoples were much vulnerable than young. Similarly, a study from China by Luo et al. reported an overall cold-attributable fraction of 1.57%

(95% CI: 0.06-2.88) for ischemic stroke at lag 0-7 and 1.90% (95% CI: 0.40-3.41) for hemorrhagic stroke at lag 0-3 (178).

Research evidence from Hong Kong, China, found that the fraction of hospital admissions attributed to moderate cold temperature was 6.33% which is estimated to be 33,030 cases while the extreme cold temperature was responsible for less fraction (0.82%), around 4257 hospital admission for total circulatory diseases (179). Heart failure, IHD and acute myocardial infarction were the major subgroups of circulatory diseases with the highest fraction and number of hospital admissions attributable to extreme and moderate cold temperature. Overall, cold temperature attributed to 7.15% of circulatory hospitalizations in Hong Kong (179). A population-based study in Canada by Bai et al. investigated the effects of both low and high temperature on hospitalization from hypertensive diseases, diabetes, and arrhythmia from 1996-2013. Cold temperature contributed to 9.99% (5,058 admissions) of hospitalizations for hypertension and heat contributed to 11.16% (36,045 admissions) hospitalizations for diabetes. However, both low and high temperatures have no effects on arrhythmia (173).

Pre-existing mental health disorder is one of the disease conditions which can be highly influenced by exposure to ambient temperature. Studies by Culqui et al. in Spain and by Lee et al. in South Korea estimated the impacts of heat on mental illnesses (174, 176). The percentage fraction of hospital admissions for Alzheimer's disease attributed to heatwave above a temperature threshold of 34°C were 23.1% (95% CI: 10.7-34.2) in Madrid, Spain (174). In six South Korean cities, of the total 166,579 hospital admissions for mental health problems from 2003-2013, 1663.4 (1002.6, 2324.2) were heatwaves attributable (14.6%). From all emergency admissions for mental diseases attributed to extreme temperatures, anxiety and dementia accounted for 31.6% and 20.5%, respectively (176). An annual of 100 excess hospital admission and 616 days of hospital admission were estimated for respiratory diseases in New York State during 1991-2004 (177).

Limited studies projected the disease burden of the warming climate to the population. For example, a study by Aström et al. indicated that the contribution of respiratory hospital admissions attributable to heat was projected to increase from 0.13% to 0.27% for Northern Europe in the period 2021-2050, 26,000 hospital admissions annually compared to 11,000 in the reference period (181). For England and Wales, the number of inpatient hospital stays was projected to increase to 285,000 per year by 2050 under a medium greenhouse gas emissions scenario compared to the baseline 81,000 days per year in 1995 and 1996 (132). A study in Michigan, USA reported that there will be an annual 185 heat-attributable hospital admission from 2040-2070 (129). Similarly, Lin et al. estimated an annual excess hospital admission of 206-607 and excess days of hospitalizations from 1,299-3,744 during 2080-2099 in New York State (177).

2.4. Cost impacts of temperature on the healthcare system

Over the past decades, several studies have examined the health impacts of cold and heat exposures around the world (6, 7, 182). The number of temperatures related to ED presentations and hospital admissions increased and the cost burden to the healthcare system is expected to be high. Few studies estimated the healthcare costs of cold and/or heat attributable to morbidities. Evidence of available peer-reviewed and grey literature were reviewed and presented in Chapter 2. The Chapter highlights the economic impacts of temperature with special reference to the cost impacts of heat on the healthcare system. It covers the costs of heat on the ambulance call-out, emergency department, and hospital admissions. The review was published as “**Berhanu Y. Wondmagegn**, Jianjun Xiang, Susan Williams, Dino Pisaniello and Peng Bi. What do we know about the healthcare costs of extreme heat exposure? A comprehensive literature review. *Science of the Total Environment* (2019) 608–618”. Moreover, the chapter also presented an updated review of the literature published after the publication of our comprehensive review.

2.5. Health care costs of extreme heat exposure

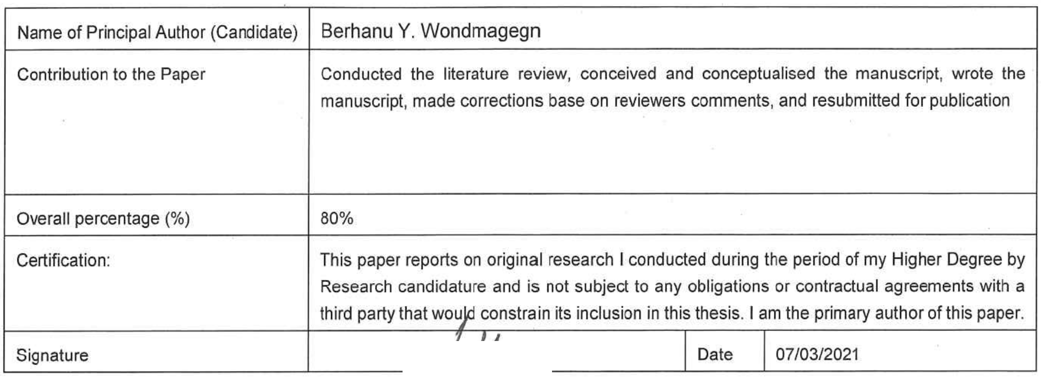
2.5.1. Publication

Wondmagegn BY, Xiang J, Williams S, Pisaniello S, and Bi P. What do we know about the healthcare costs of extreme heat exposure? A comprehensive literature review. *Science of the Total Environment* (Impact factor: 7.963). (2019), 608–618. DOI: 10.1016/j.scitotenv.2018.11.479

2.5.2. Statement of authorship

Title of Paper	What do we know about the healthcare costs of extreme heat exposure? A comprehensive literature review
Publication Status	☑ Published ☐ Accepted for Publication ☐ Submitted for Publication ☐ Unpublished and Unsubmitted work written in manuscript style
Publication Details	**Wondmagegn BY**, Xiang J, Williams S, Pisaniello S, and Bi P. What do we know about the healthcare costs of extreme heat exposure? A comprehensive literature review. Science of the Total Environment (2019) 608–618. DOI: 10.1016/j.scitotenv.2018.11.479

Principal Author



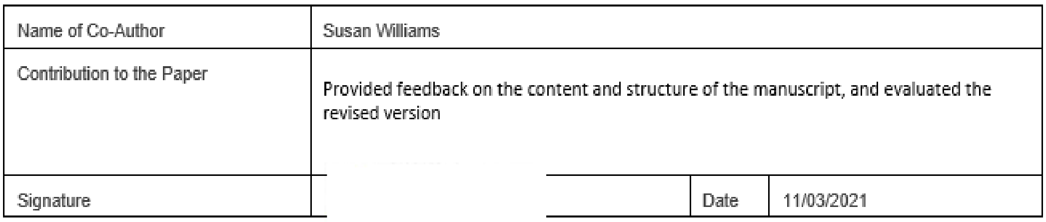
Name of Principal Author (Candidate)	Berhanu Y. Wondmagegn		
Contribution to the Paper	Conducted the literature review, conceived and conceptualised the manuscript, wrote the manuscript, made corrections base on reviewers comments, and resubmitted for publication		
Overall percentage (%)	80%		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
Signature		Date	07/03/2021

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate’s stated contribution to the publication is accurate (as detailed above);
ii. permission is granted for the candidate in include the publication in the thesis; and
iii. the sum of all co-author contributions is equal to 100% less the candidate’s stated contribution.

Name of Co-Author	Jianjun Xiang		
Contribution to the Paper	Supervise the development of the work, provided feedback on the content and structure of the manuscript, and evaluated the revised version		
Signature		Date	9-March-2021



Name of Co-Author	Susan Williams		
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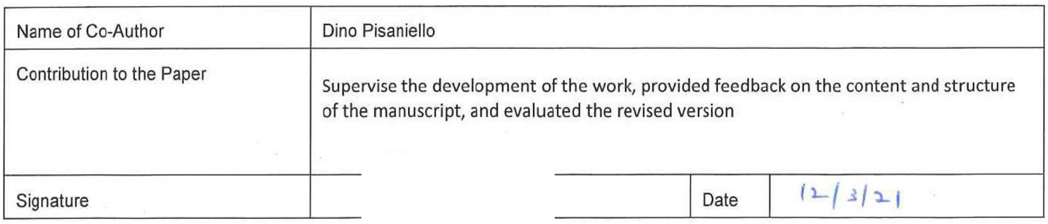

Name of Co-Author	Dino Pisaniello		
Contribution to the Paper	Supervise the development of the work, provided feedback on the content and structure of the manuscript, and evaluated the revised version		
Signature		Date	12/3/21

Name of Co-Author	Peng Bi		
Contribution to the Paper	Supervise the development of the work, provided feedback on the content and structure of the manuscript, and evaluated the revised version		
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Review

What do we know about the healthcare costs of extreme heat exposure? A comprehensive literature review

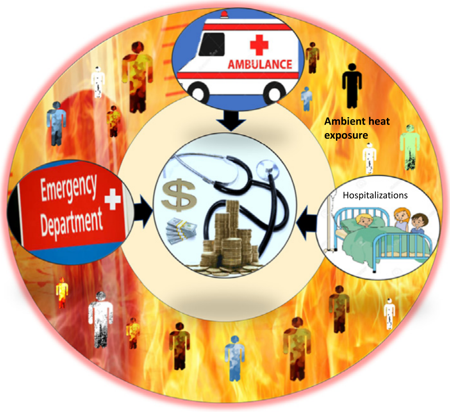
Berhanu Y. Wondmagegn [a,b], Jianjun Xiang [a], Susan Williams [a], Dino Pisaniello [a], Peng Bi [a,*]

[a] School of Public Health, The University of Adelaide, 57 North Terrace, Adelaide, South Australia 5000, Australia
[b] College of Health and Medical Sciences, Haramaya University, Ethiopia, P.O. Box 138, Dire Dawa, Ethiopia

HIGHLIGHTS

- Heat exposure was causing a substantial economic burden on healthcare systems.
- Heat attributable healthcare costs are likely to increase in a changing climate.
- Females, the elderly, and low income groups had the highest heat healthcare costs.
- More evidence is needed for the evaluation of heat attributable healthcare costs.

GRAPHICAL ABSTRACT



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ABSTRACT

Exposure to extreme heat can lead to a range of heat-related illnesses, exacerbate pre-existing health conditions and cause increased demand on the healthcare system. A projected increase in temperature may lead to greater healthcare expenditure, however, at present the costs of heat-related healthcare utilization is under-researched. This study aims to review the literature on heat-related costs for the healthcare system with a focus on ED visits, hospitalization, and ambulance call-outs. PubMed, Scopus, and Embase were used to search relevant literature from database inception to December 2017 and limited to human studies and English language. After screening, a total of ten papers were identified for final inclusion. In general, the healthcare costs of heat extremes have been poorly investigated in developed countries and not reported in developing countries where the largest heat-vulnerable populations reside. Studies showed that exposure to extreme heat was causing a substantial economic burden on healthcare systems. Females, the elderly, low-income families, and ethnic minorities had the highest healthcare costs on a range of health services utilization. Although a few studies have estimated heat healthcare costs, none of them quantified the temperature-healthcare cost relationship. There is a need to systematically examine heat-attributable costs for the healthcare system in the context of climate change to better inform heat-related policy making, target interventions and resource allocation.

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* Corresponding author at: School of Public Health, The University of Adelaide, Adelaide, South Australia 5005, Australia.
E-mail addresses: berhanu.wondmagegn@adelaide.edu.au (B.Y. Wondmagegn), jianjun.xiang@adelaide.edu.au (J. Xiang), susan.williams@adelaide.edu.au (S. Williams), dino.pisaniello@adelaide.edu.au (D. Pisaniello), peng.bi@adelaide.edu.au (P. Bi).

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Contents

1. Introduction

The global burden of disease treatment is a growing economic cost (Yach et al., 2004; Bell et al., 2014). Decision makers at all levels of the healthcare system are increasingly facing the challenges of reconciling the ever increasing demand for healthcare services with limited resources (Palmer and Torgerson, 1999; Goeree and Diaby, 2013). While many health promotion and disease prevention measures can improve health outcomes at relatively low cost, only a small fraction of health spending goes on prevention activities (Gmeinder et al., 2017). Environmental factors are among the major determinants of health, and can include such factors as climate and weather (Smith et al., 1999). Interventions to mitigate the effects of these factors could provide sustainable health benefits with low opportunity costs. However, the health costs associated with climatic factors, and the potential health and economic benefits of relevant interventions have not been explored (Severens and Milne, 2004).

At present, extreme heat has been identified as a major environmental hazard for population health (Houghton et al., 2017). Many epidemiological studies have shown that extreme heat is associated with excess morbidity and mortality, resulting in increased ambulance call-outs (Ordon et al., 2016; Turner et al., 2013; Nitschke et al., 2011; Zuo et al., 2015), emergency department (ED) visits (Zuo et al., 2015; Chen et al., 2017; Fuhrmann et al., 2016; Ghirardi et al., 2015; Zheng et al., 2016), and hospitalizations (Zuo et al., 2015; Phung et al., 2017; Isaksen et al., 2015; Liss et al., 2017; Williams et al., 2012). Nonetheless, costs associated with heat driven healthcare service utilization is under researched. The predicted increase in the frequency, intensity, and duration of hot days under climate change scenarios are likely to cause more adverse health outcomes (Pachauri et al., 2014), which may subsequently burden the already overloaded and budget-constrained healthcare system (Saniotis and Bi, 2009; Schieppati and Remuzzi, 2005), especially for some middle- and low-income countries.

Heat-related health effects have economic consequences through incurred medical treatment and healthcare costs, and loss of work productivity (Schmitt et al., 2016). Heat attributable sicknesses and complications may demand advanced medical technologies, services, and extended hospitalizations which may lead to huge medical expenses. Heat driven health cost can be described as direct (health interventions) and indirect (productivity) costs (Fig. 2). The direct costs can be further classified into healthcare cost (cost to the healthcare provider) and non-healthcare costs (costs to patients and their family). The cost to the healthcare providers is associated with their staffs, trainings, medical devices, pharmaceuticals, diagnostic procedures (e.g. laboratory tests etc.), procedures (e.g. surgical interventions), outpatient services (GP visits, ED, etc.), inpatient services (hospital admissions), capital costs (e.g. building or space needed to deliver the intervention), overhead costs (such as light, heat or cleaning costs) and related services (community and ambulance services). The costs to patients and/or families are the narrower perspective which include costs to transport, over-the-counter drugs, and co-payments (McIntosh and Luengo-Fernandez, 2006; Nagata et al., 2018).

Indirect cost represents a significant amount of economic losses due to morbidity and mortality associated with 1) Work absenteeism which represent the lost productivity due to sick-leave and 2) Presenteeism, a reduced productivity and work performance while at work (Nagata et al., 2018). Such cost implications includes: reduced outdoor work activities, reduced economic activities, disruption to public services (including transport), losses to agricultural and horticultural enterprises, and costs to power outages (Zuo et al., 2015). Heat can also cause intangible costs (e.g. pain, anxiety) which can be measured in natural units such as quality adjusted life year (Pandit, 2016). However, this review will focuses on the direct healthcare costs of extreme heat exposure particularly to the healthcare resource utilizations such as medications, diagnosis tests, consumable medical equipment, follow-up, and ambulance services.

Heat-attributable healthcare costs represent spending for ambulance services, ED visits, and hospitalizations to save lives and restore the health of peoples affected by hot ambient temperature. Estimation of such healthcare costs due to extreme heat provides an economic perspective to the burden of heat attributable health impacts, which has been assessed mainly in terms of incidence of cases and deaths, disability-adjusted life years, and years of life lost (Huang et al., 2013; Yoon et al., 2014; Xu et al., 2014; Nitschke et al., 2007). Studies on healthcare costs of extreme heat are currently very limited. This review aims to synthesize the published evidence on healthcare costs associated with health service usage from heat extremes. The specific research question addressed in this review is: What is the current evidence for the direct healthcare costs of extreme heat exposure, considering hospital (ED and admissions), pre-hospital (ambulance), and other primary healthcare costs? The outcomes of this review will help to inform policy-making, develop extreme heat management guidelines, and support organizational decision making on resource allocation and capacity building.

2. Methods

2.1. Search strategy

Major databases commonly used in reviews (Levi et al., 2018; Aboubakri et al., 2018) such as PubMed, Embase, and Scopus were searched to identify peer-reviewed scientific journals from a wide range of disciplines. Search term protocols included three categories of keywords: heat exposure, heat-health effects, and heat-attributable healthcare costs. Keywords and MeSH terms for heat exposure include: extreme heat, climate change, temperature, weather, hot days, heat, hot, and season; for heat-health effects, they include hospitalization, emergency, ambulance, admission, visit, triage, emergency department (ED), room, morbidity, disease, mortality, death; and for heat-attributable costs, they include costs, cost analysis, economic, health cost, hospital cost, health care cost as shown in Appendix A. The Boolean connector (Wee and Banister, 2016) "OR" was used to combine terms within each keyword and "AND" to connect each keywords to do the final literature search. Moreover, we scanned all references listed by candidate papers and searched relevant grey literature using Google Scholar.

2.2. Inclusion/exclusion criteria

Studies were selected based on the following criteria and procedures.

(1) To the authors' best knowledge, there is no previous literature review related studies around healthcare costs and extreme heat exposure, literature in English from database inception to December 2017 were included.
(2) Limited to studies of human population anywhere in the world
(3) Investigated ambulance call-out and/or, ED visit and/or, hospitalization and/or mortality in combination with ambient heat exposure and healthcare cost.
(4) Studies on cold temperature were excluded. However, literature which considered both hot and cold temperature together, only the results corresponding to the hot ambient temperature were included.
(5) Relevant literature encompassing peer-reviewed articles and grey literature were included.

The search yield was loaded into an EndNote library and selected through a four-step process, as shown in Fig. 1. First, duplicates were removed using the EndNote function of 'find duplicates'. Second, titles relevancy was reviewed. Third, the abstracts were reviewed. Finally, selected articles were fully retrieved for full-text review and evaluation. Examples of literature excluded at this stage include healthcare cost and economic evaluation based on the value of statistical life (VSL) (Ebi et al., 2004; Liao et al., 2010). Data extracted from included articles comprises first author's last name, year of publication, country, study period, heat indices, data type and sources, study design, statistical methods, main findings, and projection years (Xu et al., 2014; Li et al., 2015). For comparison purpose (Bahadori et al., 2009), all monetary costs were converted to United States Dollar (USD) based on the exchange

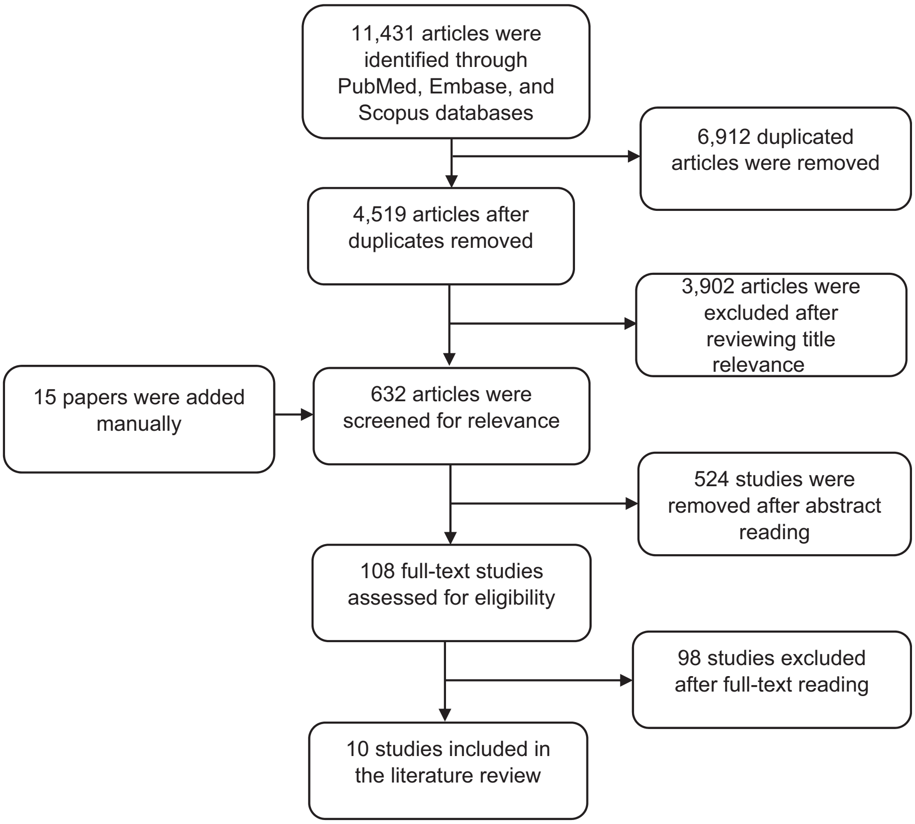

Fig. 1. Selection procedures of literature for inclusion in the review.

rate on 04 May 2018 (1 USD is equivalent to 1.3266 AUD and 0.8355 Euro, respectively).

3. Results

The focus of this review is the economic costs to the health services attributable by extreme heat. The results section proceeds as follows. Under Section 3.1 we describe current evidence related to heat-related healthcare costs. In Section 3.2 we describe future heat-healthcare cost burdens of predicted climate change. In these sections, results are summarized by category of healthcare services, including pre-hospital acute care (ambulance call-outs and ED visits) and admission (inpatient) hospital services.

A total of 10 (8 peer-reviewed and 2 grey) articles were included in the final review (summarized in Table 1). All studies were from high income countries: six (60%) from the USA (Ebi et al., 2004; Jagai et al., 2017; Lin et al., 2012a; Merrill et al., 2008; Noe et al., 2012; Schmeltz et al., 2016), two from Australia (Toloo et al., 2015; AECOM, 2012), and one each from Germany (Hübler et al., 2008) and Spain (Roldan et al., 2015). Middle and low income countries who are more vulnerable to extreme heat and have relatively low heat resilience capacity were not represented in this literature. All studies used historical health surveillance data to estimate the heat attributable healthcare costs. The study time-span ranged from 1 to 27 years. The type of data used includes hospitalizations, ED visits, ambulance call-outs, causes of death registry, and weather records. Four studies projected future heat attributable healthcare costs in a changing climate (Lin et al., 2012a; Toloo et al., 2015; AECOM, 2012; Knowlton et al., 2011).

Variations between studies were observed. In terms of study design, six were ecological studies, three were descriptive studies, and one was a case study. Moreover, differences in terms of health outcome measures, characteristics of study population, data source, types of heat metrics, statistical measures, and assumption of change in climate, population, and future healthcare cost were observed. However, all research used cost description method to estimate the economic impacts of extreme heat to the healthcare system.

3.1. Current heat-attributable healthcare costs

3.1.1. Costs of heat-attributable hospitalizations

The six studies from the USA calculated heat attributable economic costs of hospitalizations (Jagai et al., 2017; S. Lin et al., 2012; Merrill et al., 2008; Noe et al., 2012; Schmeltz et al., 2016; Knowlton et al., 2011). Among these studies, three were descriptive (Merrill et al., 2008; Noe et al., 2012; Schmeltz et al., 2016), two were ecological (Jagai et al., 2017; S. Lin et al., 2012), and one was a case study (Knowlton et al., 2011). Four studies analyzed hospital admission records associated with heat-related illnesses (Jagai et al., 2017; Merrill et al., 2008; Noe et al., 2012; Schmeltz et al., 2016). Knowlton et al. and Lin et al. specifically investigated heat attributable excess hospitalizations for all-cause and respiratory diseases, respectively (S. Lin et al., 2012; Knowlton et al., 2011). Daily mean apparent temperature (AT) (S. Lin et al., 2012), average monthly maximum temperature (Tmax) (Jagai et al., 2017), and heatwave (Knowlton et al., 2011) were used as temperature exposure metrics, while three studies (Merrill et al., 2008; Noe et al., 2012; Schmeltz et al., 2016) did not clearly indicate the use of meteorological temperature measurements. Great variations were observed on the scope/type of healthcare cost estimations. Two studies estimated excess cost (S. Lin et al., 2012; Knowlton et al., 2011), two studies calculated total/overall cost for the entire study period (Jagai et al., 2017; Noe et al., 2012), while others calculated costs per hospital stay (Merrill et al., 2008), or mean cost per hospitalizations (Schmeltz et al., 2016). Most of these studies stratified the result into population subgroups such as by age, gender (S. Lin et al., 2012; Merrill et al., 2008; Noe et al., 2012; Schmeltz et al., 2016), income (Lin et al., 2012a; Merrill et al., 2008; Schmeltz et al., 2016), race (Noe et al., 2012; Schmeltz et al., 2016), insurance conditions (Lin et al., 2012a; Noe et al., 2012; Schmeltz et al., 2016), and geographic region (Jagai et al., 2017; Merrill et al., 2008; Noe et al., 2012).

Lin et al. estimated the annual excess heat attributable hospital costs from respiratory disease in New York State. The study encompasses >95% of all respiratory related acute care admissions in the state. The average excess annual respiratory hospitalization cost between 1991 and 2004 was estimated to be $644,069, nearly $6500 per admission (Lin et al., 2012a). Schmeltz et al. studied the costs of hospitalizations due to heat-related illness (HRI) using a National Inpatient Sample (NIS) data from 2001 to 2010 and found a nationally adjusted mean cost of $5359 (95% CI: $5327–$5390) per hospitalization (Schmeltz et al., 2016). The overall healthcare cost due to HRI for the study period (10 years) was nearly $392.2 million.

Knowlton et al. studied healthcare costs due to major categories of climate-related events in the United States from 2000 to 2009 and the 2006 California heatwave was presented as a case study (Knowlton et al., 2011). The study used the number of excess hospitalizations attributed by the 2006 heatwave reported in their previous study (Knowlton et al., 2009) to calculate healthcare costs. They also used cost data from the Healthcare Cost and Utilization Project (HCUP). According to the findings, the overall economic cost of hospitalizations associated with the 2006 heatwave in 2008 US dollar value was nearly $28 million. The cost per admission was about $18,000. This cost is nearly 3 times higher than the result ($6200) reported by Merrill et al. using the 2005 NIS data (Merrill et al., 2008). A study which covers 97% of hospitals in Illinois, USA revealed that the total heat-stress illness hospitalization charge between 1987 and 2014 was 168 million, approximately $6 million per year during the 28 years of study period. The mean per person hospitalization charge was $20,500 (in 2014 US dollar value) (Jagai et al., 2017). Another US study by Noe et al. used fee-for-health service claims submitted to Medicare for hyperthermia-related visits. The study found an overall heat related healthcare cost of $36 million during 2004–2005 (Noe et al., 2012). Comparison of hyperthermia associated medical care costs of these two consecutive years demonstrated an increase by more than double, from $11 million in 2004 to $25 million in 2005.

An interdisciplinary study which combined knowledge from medical, meteorological, geographical, and economic field was conducted in Germany to estimate the national health damage costs of the rising temperature in the changing climate. Due to lack of suitable data on costs of heat related treatment and medication in practice, the study used federal state general hospitalization costs per case. The study presented a total annual cost of $98 million between 1971 and 2000 (Hübler et al., 2008).

Demographic factors associated with heat attributable hospitalizations depend on population sensitivity and adaptive capacity (Cui et al., 2005; Bi et al., 2011). The majority of published literature suggested a lower risk of heat exposure among females (Jagai et al., 2017; Merrill et al., 2008; Noe et al., 2012; Schmeltz et al., 2016) while the cost of treatment for heat-related illnesses was found to be higher for females than males (S. Lin et al., 2012; Schmeltz et al., 2016). For example, Schmeltz et al. in the USA reported that the average cost per HRI hospitalization for females from 2001 to 2010 was $5922 (95% CI: $5858–$5985), higher than males by nearly $800 (Schmeltz et al., 2016). In New York, Lin et al. found that females contributed 86% of the overall excess costs of heat associated respiratory hospitalizations per year during 1991–2004 (S. Lin et al., 2012). At an individual patient level, costs of heat attributable respiratory hospitalization were greater in females by approximately $500 than males. This disparity may be due to the biological susceptibility of females such as pregnancy conditions.

In terms of age, people over 75 years were estimated to cost an extra $1586 (95% CI: $1466–$1707) per heat-related hospitalization in the USA, compared to younger age groups (Schmeltz et al., 2016). Results of Lin's study in New York State showed that 16–64 and ≥ 75 age groups had similar excess costs per year (about $240,000) for heat associated

Table 1

Summary of studies on health and economic costs of high temperature associated with ambulance call-out, ED visits, and hospitalizations; ordered according to the county of origin.

Author and year	Country	Study period	Heat indices	Data type and sources	Study design	Statistical methods	Health outcome measures	Scope/types of cost	Main findings	Projection for future costs
Jagai et al. (2017)	USA, Illinois	1987–2014	Average monthly maximum temperature (Tmax)	Monthly hospitalization rate from all public and private hospitals using the Illinois Department of Public Health (IDPH) Hospital Discharge Database	Ecological study	Multi-level linear regression models	Heat-stress illness	Total and mean per person hospital charge	A 1 °C increase in monthly Tmax was associated with 0.34 and 0.02 increase in rural and urban heat-stress illness (HSI) hospitalization per 100,000 population respectively. The total hospital charge for HSI cases was $167.7 million with a mean charge of $ 20,500 per person per year.	No
Knowlton et al. (2011)	USA, California	2000–2009	Heatwave (extreme heat >2 consecutive days)	Total hospitalizations, ED, and outpatient visits obtained from literature and public health agencies and cost data from healthcare cost and utilization project (HCUP)	Case study	Extrapolation of cases, derivation of costs, and climate model	All-cause morbidity	Excess cost	An estimated total healthcare visits of 169,881 were observed. The cost of excess hospitalization, ED visit, and outpatient visit in 2006 heatwave was estimated to be $28,435,000, $14,110,000, and $136,380,000 respectively.	No
S. Lin et al. (2012)	USA, New York State	1991–2004	Daily mean apparent temperature (AT)	Daily respiratory hospitalizations of public and private hospitals from the New York State Department of Health State-wide Planning and Research Cooperative System database	Ecological study	Two-stage Bayesian model	Respirator disease	Excess cost	An estimate of 100 excess annual hospital admissions during the baseline year with associated costs of $0.64 million. Projected heat attributable hospitalization costs for the period 2046–2065 and 2080–2099 ranges from $5.5 to $7.5 million and from $26 to $76 million respectively.	2046–2065 2080–2099
Merrill et al. (2008)	USA, Nationwide	2005	Not used	Hyperthermia admission from HCUP (2005) Nationwide Inpatient Sample (NIS) database	Descriptive study	Descriptive statistics	Heat-related illness	Per heat-related hospital stay	A total of about 6200 heat-related hospitalizations with a cost of $6200 per hospitalization were observed in 2005. The poor and people in rural areas were the most vulnerable groups.	No
Noe et al. (2012)	USA, Nationwide	2004–2005	Not used	All hyperthermia inpatient and outpatient data obtained from nationwide Centers for Medicare and Medicaid Services	Descriptive study	Crude incidence rate and Mantel-Haenszel rate ratios (IRR)	heat-related illness	Total cost	The number of hyperthermia healthcare visits were 10,007 with a mortality rate of 0.06 per 100,000. The median hospital stay was 2 days and the overall total estimated cost was $36 million.	No
Schmeltz et al. (2016)	USA, Nationwide	2001–2010	Not used	Total heat-related illness (HRI) Hospitalization data from NIS database	Descriptive study	ANOVA and log-gamma model	Heat-related illnesses	Mean cost per hospitalization	Higher mean cost of hospitalization associated to hot ambient temperature was evident among ethnic minorities: Asian/Pacific Islanders $1208 ($793–$1624) followed by black $319 ($197–$440). Females and older peoples share the highest cost accounting $5922 ($5858–$5985) and $1586 ($1466–$1707) respectively.	No
AECOM (2012)	Australia, Melbourne	2012	Heatwave (3 days of ≥35 °C) and single hot day/maximum temperature/	Ambulance transport with/without spot treatment, and ED presentation (>64 years) data from the literature	Ecological study	Interpolation of health and cost data, climate model	Heat-related illnesses	Total cost	The total undiscounted heat driven (heatwave and single hot day temperature) costs of ambulance service for 2012, 2030 and 2050 were $32,800, $99,300, and $154,400 respectively. ED visit cost for the age group 64+ were $5800, $21,000 and $29,800 for each respective year. The overall discounted cost for ambulance service and ED during 2012–2051 was $2,604,500 and $489,200 respectively.	2030 2050
Toloo et al. (2015)	Australia, Brisbane	2000–2012	Daily Tmax	Daily ED visit was provided by Queensland Health Department	Ecological study	Generalized linear regression with Poisson link	All-cause morbidity	Excess cost	During the baseline year, older people (≥65) have a higher risk of 1.09 (95% CI: 1.06–1.13) of ED visit on hot days (≥35 °C). The number of excess visit was projected to be 98–336 (2030) and 229–2300 (2060) for younger groups and 42–127 (2030) and 145–1188 (2060) for older people. Based on 2012–13 prices, heat attributable extra cost was anticipated to be between $59,232–$195,693 in 2030 and $162,587-1,496,221 in 2060.	2030 2060
Hübler et al. (2008)	Germany, Nationwide	1971–2000	Heatwave	Data from all States meteorology, geography, medical and economic fields	Ecological study	Exponential extrapolation and Regional Climate Model	All-cause morbidity	Total annual cost	The baseline (1971–2000) hospitalization cost was $98 million. The total projected annual cost of hospitalization for the period 2071 to 2100 was estimated to be about $592 million.	2071–2100
Roldan et al. (2015)	Spain, Zaragoza	2002–2006	Daily Tmax	Daily in-hospital mortality data obtained from Public Health Directorate	Ecological study	Autoregressive integrated moving average model of a time series	All-cause mortality	Overall and total annual cost	Risk of mortality increased by 1.28 (95%CI: 1.08–1.57) above a threshold temperature of 38 °C. A total of 107 (95%CI: 42–173) deaths and an associated cost of $509,978 (95% CI: $200,178–$824,544) was observed.	No

respiratory hospitalizations, however the number of excess heat attributable respiratory hospitalizations per year in the 16–64 age group was about 1.5 times (40 vs 27) higher than ≥75 age group. On the contrary, the study reported that higher temperature reduced the number of respiratory hospitalizations and costs in the 0–15 age group (S. Lin et al., 2012).

Taking the White population as a reference group, Schmeltz et al. found that the mean cost difference per hospitalization was $1208 higher (95% CI: $793–$1624) among Asian/Pacific Islanders; followed by Black, $319 (95% CI: $197–$440); and Hispanics, $243 (95% CI: $98–$387) (Schmeltz et al., 2016). The study also analyzed the economic burden associated with HRI hospitalizations among populations of lower income quartiles. The result indicated that the mean cost per hospitalizations for black and Hispanic populations were $432 (95% CI: $245, $620) and $262 (95% CI: $71, $453) higher than white, respectively. Similarly, Merrill et al. in the USA reported higher heat caused hospitalization rate and longer hospital stay among low-income populations compared to groups with higher income. Heat associated hospitalizations were >2 times higher among the poorest than the wealthiest communities across the USA (Merrill et al., 2008).

Length of hospital stay is another indicator used to reflect heat healthcare burden and disease severity. Jagai et al. found that the median and mean length of hospitalization from heat-stress illness in Illinois, USA, from 1987 to 2014 were 3.7 and 2.0 days respectively (Jagai et al., 2017). Similarly, Noe et al. in the USA used Medicare and Medicaid service data and reported an increase of hospital stay from 2 days in 2004 to 3 days in 2005 possibly due to warmer temperatures in 2005 throughout the USA (Noe et al., 2012). This finding is in accordance with the result reported by Merrill which used data from HCUP, USA, confirming 3.2 days of average hospital stay (Merrill et al., 2008). In New York, the total excess days of hospitalization due to heat attributable respiratory diseases were estimated to be 616 days per year (approximately 6 days per admission) during 1991–2004. Moreover, nearly 84% of the heat attributable excess annual hospital stays were from females (533 days) and 36% from those aged ≥75 years (238 days) (S. Lin et al., 2012).

3.1.2. Costs of heat-attributable ED presentations

Three of the reviewed studies calculated heat attributable ED service costs (Toloo et al., 2015; AECOM, 2012; Knowlton et al., 2011). The two studies in Australia (Toloo et al., 2015; AECOM, 2012) aimed to examine the health and economic impacts of extreme temperature using age as demographic risk factor (Toloo et al., 2015; AECOM, 2012). Populations aged 65 and above were included in both studies using maximum temperature, or heatwave, as the heat metric (AECOM, 2012). While Toloo et al. and Knowlton et al. studied all-cause heat attributable morbidity and the associated excess healthcare costs (Toloo et al., 2015; Knowlton et al., 2011), the study in Melbourne specifically focused on heat-related illnesses and its overall/total healthcare costs (AECOM, 2012).

The study by Toloo et al. examined costs of ED visits over the warm seasons of 2000–2012 in Brisbane, Australia, using all-cause excess ED visits. A total of 22 hot days with maximum temperature (Tmax) ≥35 °C occurred and resulted in 135 excess ED visits over this period. The pricing approach "Urgency Disposition Groups (UDG)" was used to estimate the cost of heat associated ED visits. The cost was determined using the National Efficient Price (NEP) of 2012–13 set at $3624 multiplied by price weight (PW) of each triage category (from Most urgent = 1 to Least urgent = 5) and departure status (admitted, discharged) (Toloo et al., 2015). The overall extra ED cost for the base year (2012−13) was reported to be $61,625.The extra economic burden to the ED from all-cause morbidity associated with heat for 0–64 and 65^+ age groups accounted a cost of $46,320 and $15,409 respectively. The study in Melbourne, Australia, estimated costs of ED visit for people aged 65^+ in relation to heat (heatwave and single hot day) to be $5800 in 2012 (AECOM, 2012). In the study by Knowlton et al., for a 2006 heatwave in California, using health outcome estimations from literature and cost data from HCUP, a total cost of $150.5 million was reported due to all-cause excess ED and outpatient visits (Knowlton et al., 2011).

3.1.3. Costs of heat-attributable ambulance call-outs

We identified only one study, from grey literature, that has examined heat and ambulance call-out costs. The study was conducted in Melbourne, Australia, and considered high temperature (single hot day) and heatwave exposure on ambulance services costs (AECOM, 2012). The authors divided ambulance services into two categories: (1) ambulance attendance requiring transport to hospital assuming that all heat-related cases were taken to ED than direct admission to the inpatient department, and (2) ambulance attendance requiring on the spot treatment only. In 2012, the total costs of heat (heatwave and single hot day) driven ambulance dispatches requiring both road transportation and spot treatment was reported to be $32,800. Ambulance road service to patients of heat driven illnesses (heatwave and single hot day) contributed to a substantial proportion of costs compared to spot treatment ($31,000 vs $1800), higher by 17-fold.

3.1.4. Costs due to heat-related deaths

The only available study estimating the healthcare costs of extreme heat on mortality was an ecological study by Roldan et al. in Zaragoza, Spain (Roldan et al., 2015). The study investigated extreme heat attributable additional mortality associated healthcare costs above the temperature threshold of 38 °C. The study used a cost of $4773 per death, derived by averaging costs associated with heat attributable in-hospital deaths, obtained from the Ministry of Health. The total mean extra cost during the entire five years (2002 to 2006) was estimated to be $509,978 (95% CI: $200,178–$824,544) with highest annual mean costs of $271,362 (95% CI: $104,736–$447,509) in 2003 (Roldan et al., 2015).

3.2. Climate change and heat-attributable healthcare burden

Four studies projected future heat attributable healthcare costs by extrapolating the baseline heat-health relationships and cost burden to future climate change (S. Lin et al., 2012; Toloo et al., 2015; AECOM, 2012; Hübler et al., 2008) and population scenarios (Toloo et al., 2015; AECOM, 2012; Hübler et al., 2008). All of these studies suggested a significant increase in heat attributable healthcare burden without efficient interventions.

3.2.1. Hospital admissions

Lin et al. in New York projected the mean summer apparent temperature (AT) for two future periods: 2046–2065 and 2080–2099 (S. Lin et al., 2012). The highest future AT was projected from high greenhouse gas emission scenario (A2) followed by mid emission (A1B) and low emission (B1) (IPCC, 2013). By the middle of the 21st century, heat attributable respiratory hospital admissions were projected to range from 190 to 260 per year in New York under lower to higher emission scenarios, which would be 1.9–2.6 times more than the baseline years (1991–2004) of hospitalizations. The resultant heat attributable additional healthcare costs were estimated to be between $5.5 million and $7.5 million per year. Compared to the reference period, the cost per admission increased by 4–5-fold ($6400 vs $29,000). The annual total days of heat attributable respiratory hospitalizations were projected to be 1202–1630 days in the coming 50 years and this would be raised to 3744 days in 100 years, increased by 6-fold compared to the base years. Using a high emissions scenario, the number and cost of annual excess heat associated respiratory admissions would increase by 2.6 and 11 times by midcentury and 6 and 118 times by the end of the century respectively. The costs were adjusted to healthcare service price inflation and standardized to 2004 USD using an annual discount rate of 3%. However, these projections assumed that the relationship between extreme temperature and health outcomes, demographic profiles, and temperature-health thresholds at the baseline level remain constant (S. Lin et al., 2012).

Additional hot days were estimated for Germany and its surrounding using regional climate model (REMO) which has a better spatial and temporal resolution than the global climate models. The prediction used the Intergovernmental Panel on Climate Change (IPCC) A1B scenario for 2071–2100. The research indicated that the national average healthcare costs of treating heat-attributed diseases in the hospital would be $592 million per year, a 600% increase compared to estimated costs for the baseline years (Hübler et al., 2008). Nearly 54% ($265 million) of future annual healthcare cost change would be due to climate change while 46% ($228 million) would be contributed by the change of demographic profile. The projected number of hot days was 2–5 times more than the reference period (1971–2000) with an associated increase of projected costs by 6-fold. The heat associated hospitalization costs would represent 0.9% of the all-cause hospitalization costs in Germany and 0.3% of the country's health care expenses (Hübler et al., 2008).

3.2.2. ED presentations

Based on the ED data from 11 public hospitals in Brisbane, Australia, the projections by Toloo et al. suggested a considerable increase of excess ED visits on hot days under the highest population growth and climate change scenarios (Toloo et al., 2015). The number of excess annual heat attributable ED visits for the age groups of 0–64 years and >64 years in 2030 was projected to be between 98–336 and 42–127, respectively, compared to 118 and 31 in the baseline years. The corresponding estimated excess annual costs ranged from $38,444–$138,700 for the 0–64 age group and $20,352–$63,319 for the >64 age group. Without interventions, in 2060 the number of heat attributable excess annual ED visits was projected to reach 229–2300 for the 0–64 age group and 145–1188 for the >64 age group, resulting in a cost of between $90,456–$904,568 and $72,365–$592,492, respectively. The study suggested that future heat driven ED costs for the >64 age group would grow twice as much as the 0–64 age group, which would add up to an extra cost of around $58,796–$195,989 in 2030 and $162,068–$1,496,306 in 2060 (Toloo et al., 2015).

A study in Melbourne used predictions of heatwaves and single hot day temperatures for 2030 and 2050 to estimate ED presentation costs for the elderly (64^+ years) (AECOM, 2012). High (A1FI) and low (A1B) greenhouse gas emission scenarios (IPCC, 2013) were used which suggested a 5.5 °C and 2 °C increase of temperature by the end of the 21st century compared to the 1990 level, respectively. The study used historical heat-health relationships and considered population change and forms of urban development into account. The results indicated that overall heat attributable ED visit costs would increase by 3 times in 2030 and by 5 times in 2050, compared to the base year (2012) (undiscounted cost). The overall heat (heatwave and single hot day) attributable ED cost for the population of 65^+ years would be approximately $416,000 from 2012 to 2051 at present value discounted by 3% (AECOM, 2012). However, the study indicated that single hot day temperature would contribute the highest ($292,000) ED cost compared to heatwave ($123,900).

3.2.3. Ambulance call-outs

Only one study from Melbourne projected the increased cost of heat attributable ambulance services due to climate change. The study investigated the cost of heat extremes from 2012 to 2051 considering socio-economic and climate change. It showed that the overall heat (heatwave and single hot day) attributable cost of ambulance services would be $99,300 in 2030 and $154,400 in 2050 (undiscounted cost), showing an increasing heat attributable cost by nearly 3 fold and 5 fold compared to the 2012 costs, respectively (AECOM, 2012). Looking at heatwave alone, the cost of ambulance services, including road transport and spot treatment, would be $70,300 in 2030, three-fold higher than the baseline year, and $111,600 in 2050, five times higher than the baseline cost (undiscounted cost). The overall discounted (at 3% rate) cost of all heat driven ambulance call-outs from 2012 to 2051 was estimated to be over $2.1 million (AECOM, 2012).

4. Discussion

It is likely that future heat exposure will be more severe and increasing in geographic range due to the changing climate (Pachauri et al., 2014). While many studies have examined the likely health impacts, to date there have been only 10 studies that have explicitly addressed the healthcare costs of heat extremes. These studies use different exposure and outcome measures, study population and period, and assessment which largely prevents a direct comparison of estimates. However, all the studies indicate that health costs of heat exposure constitute a substantial economic burden, which will increase markedly in the future. The estimates for current annual costs range from $46,000 to 39 million for hospitalizations, from $5800 to $150 million for ED visits, and approximately $33,000 for ambulance call-outs, depending on the location, health outcomes, and population examined.

Most studies estimated the costs of heat attributable healthcare service utilization based on the underlying heat-health relationships. Therefore, any factors affecting the estimation of heat-health relationships also influence cost estimations. In the following sections, our discussion is focused on factors that might influence cost estimations, directly or indirectly. Sections under 4.1 describe factors which may affect the heat-healthcare cost relationship, including heat metrics used, health outcome measurements, and estimation of baseline heat attributable healthcare costs. In Section 4.2, future climate change and heat-healthcare burdens are presented.

4.1. Heat-healthcare cost relationship

4.1.1. Selection of heat exposure indicators

In the measurement of heat-related healthcare cost impacts, different heat indices have been used, including maximum daily temperatures (Toloo et al., 2015; Roldan et al., 2015), mean AT (S. Lin et al., 2012), average monthly maximum temperature (Jagai et al., 2017), and heatwaves (AECOM, 2012; Knowlton et al., 2011). The selection of temperature indicators, heat thresholds, and different heatwave definitions may influence the estimation of health risks and heat-attributable healthcare costs. There is no consensus in the literature about which heat indicator is the best in predicting heat-induced health outcomes and, accordingly, healthcare costs. Some heat-health outcome studies have reported that different heat indicators had similar predictive ability (Barnett et al., 2010), with no single temperature measure superior to others (Barnett et al., 2010; Yu et al., 2011). Apparent temperature, a combination of air temperature, wind speed and relative humidity, has been reported to be a better temperature measure in some locations (Y.K. Lin et al., 2012; Morabito et al., 2014) and this metric was used by Lin et al. (S. Lin et al., 2012) for the estimation of heat attributable respiratory hospitalization costs in New York.

Due to the nonlinearity of the heat-health outcome association (Song et al., 2017), identification of threshold temperatures is important to quantify heat driven adverse health impacts and associated healthcare costs. Three studies have taken nonlinearity into account when calculating excess heat driven health burden and associated costs (S. Lin et al., 2012; Toloo et al., 2015; Roldan et al., 2015). It is worth noting that the estimation of the burden on health services and costs could vary substantially depending on the estimate of threshold temperatures. However, some studies estimated the overall heat attributable health and economic burden (Merrill et al., 2008; Noe et al., 2012; Schmeltz et al., 2016) other than quantifying the magnitude of excess heat attributable burden. On the other hand, use of aggregated data, for example a study by Jagai et al., can significantly influence the statistical predictive capacity of the model which may affect cost estimation (Jagai et al., 2017).

Several studies estimated health outcomes and costs in relation to heatwave exposure, for a single heatwave event (Knowlton et al., 2011), or for multiple events in a given study period (AECOM, 2012; Hübler et al., 2008). Costs for individual heatwave events are likely to show considerable variation because the health impacts will vary according to the length and severity of the heatwave.

4.1.2. Measurement of heat health outcomes

Appropriate measurement of heat-health outcomes is fundamental to understand the cost burden of heat extremes. However, exposure to heat can cause varieties of illnesses, symptoms, and exacerbate a range of pre-existing medical conditions. Heat-related morbidity and mortality from respiratory, cardiovascular, heat-related illnesses, and renal diseases have been found to escalate during hot seasons (Liao et al., 2010; Jagai et al., 2017; S. Lin et al., 2012; Merrill et al., 2008; Noe et al., 2012; Schmeltz et al., 2016). The broad range of health effects introduces some uncertainty in the diagnosis of heat-related illness, which can (Luber and McGeehin, 2008; Ye et al., 2012) lead to erroneous heat-cost associations.

In the verification of heat-associated illnesses, triangulation of clinical diagnosis results and local weather data are recommended to reach a sound conclusion. In some instances, it is hard to establish the etiologic agents of morbidity and mortality events and oftentimes missed to be classified as heat-related (Luber and McGeehin, 2008). On the other hand, during heatwave periods, it is more likely that patients visiting healthcare facilities to be diagnosed as heat-induced illness, leading to potential over-reporting of heat attributable illnesses. Few studies used medical records solely to verify heat-related morbidity and mortality (Merrill et al., 2008; Noe et al., 2012; Schmeltz et al., 2016). However, these records might be incomplete (Krieger, 1992) and lack accuracy leading to a biased conclusion. Inaccurate estimation of heat-related health impact will likely lead to imprecise cost estimation.

The magnitude of effect estimation of heat exposure on population health and healthcare cost could depend on the type and number of confounding factors considered. The association between extreme heat and health may be confounded by some environmental and socioeconomic factors which may potentially affect cost estimation (Zuo et al., 2015; Ye et al., 2012) directly or indirectly. Studies by Toloo et al. and Lin et al. controlled confounding factors including long-term trend, seasonality, the day of the week, and ozone (O_3) in the examination of heat and health relationship and thereafter to quantify excess heat attributable medical costs (Lin et al., 2012a; Toloo et al., 2015). In addition, Toloo adjusted for the use of air conditioner, particulate matter with an aerodynamic diameter of <10 μm, and nitrogen dioxide (Toloo et al., 2015).

4.1.3. Estimation of heat-healthcare costs

The current literature describes the direct economic cost of heat driven healthcare resource utilization and has not considered the broader societal costs (Gardiner et al., 2017). This review has considered the evidence in relation to hospital (ED visits and admissions) and ambulance costs. Costs are also incurred in primary healthcare settings, for example, community nursing and general practitioners (Huang et al., 2013; Ebi et al., 2004), however, these costs are more difficult to capture at a state or national level and there has been no published research evidence in this area.

As indicated in the conceptual framework (Wee and Banister, 2016) (Fig. 2), the direct cost to the healthcare system can be categorized into fixed costs which includes salary, equipment, and building costs. This fixed cost cannot be saved over a short term whether patients of heat induced health outcome use the service or not. However, the second type of cost to the healthcare system known as variable cost, can vary based on the amount and type of service used (Roberts et al., 1999). These are costs to medications, disposable supplies, and test reagents. Such cost can significantly increase if the demand for health service increased due to ambient heat extremes. However, it is unclear whether the range of this cost refers to government or to customers/patients as there might be different arrangements of healthcare cost payment including direct purchase model (out-of-pocket) and the third party payer model with co-payment system (including out-of-pocket, private insurance, or government).

All these studies examined the cost associated with heat driven illnesses using a cost description method. Even if studies clearly quantified the burden of extreme temperature to the healthcare system in

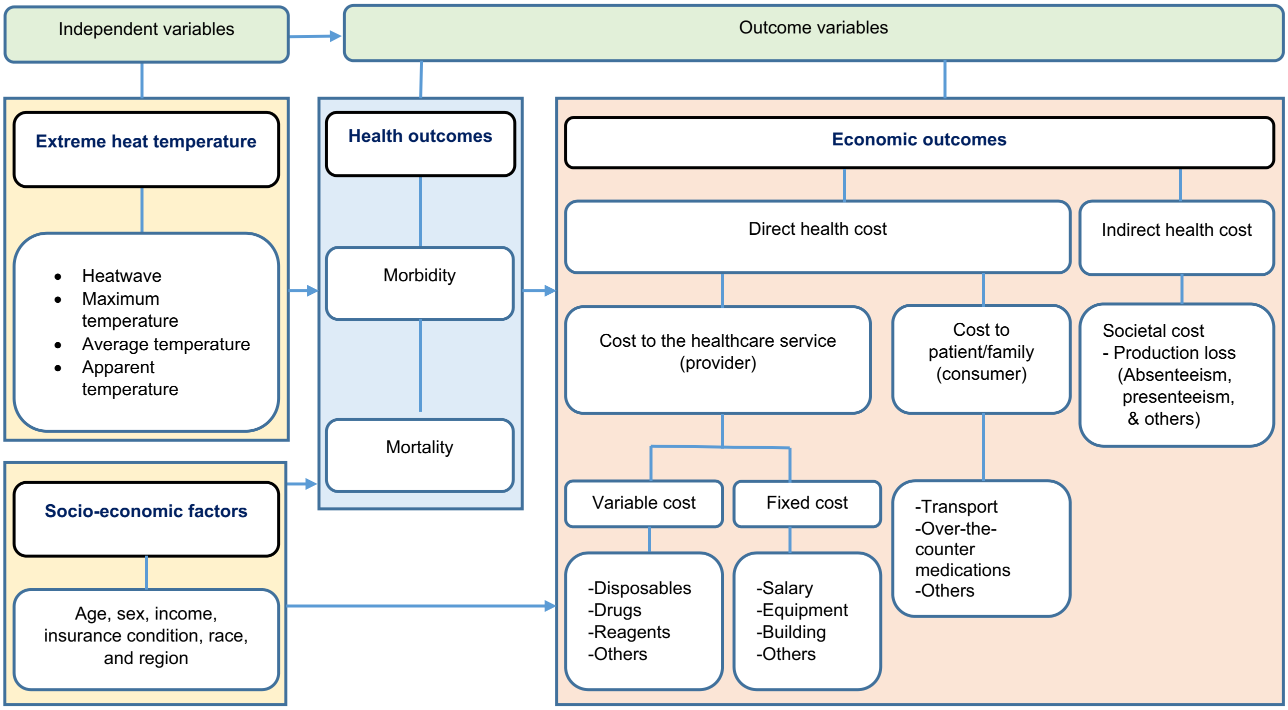

Fig. 2. Representation of factors affecting health and healthcare costs of extreme heat.

monetary terms, the results can be more useful if they are compared with costs of other possible options in addressing health problems associated with extreme temperature including disease prevention and health promotion, heat warning system, climate mitigation, and adaptation activities. Since health economic studies mainly aimed to provide information to decision and policy makers for efficient use of available resources for maximizing health benefits (Dang et al., 2016), allocation of resources based on disease burden studies to the healthcare system alone could not necessarily lead to efficient resource utilization. Therefore, relative costs and benefits of investing healthcare resources on either preventive or curative health interventions, including opportunity cost, needs to be thoroughly evaluated.

Health impact cost studies particularly focusing on the costs of disease treatment in monetary units are very limited in part because of the challenge of getting a comprehensive cost data both from private and public healthcare facilities and lack of consensus on health cost valuation methods (Knowlton et al., 2011). Hence, a couple of studies used statistical extrapolation methods, a judgmental forecasting beyond the range of original observation (Holt, 2004), to estimate the economic damages associated with exposure to heat extremes (Hübler et al., 2008; Knowlton et al., 2011). Because of the absence of actual cost data on heat-related treatment and medication in Germany, statistical estimation of hospitalization cost was made using hospital emergency admission as a proxy indicator, which may underestimate the real costs. Jagai et al. used hospital billed charge to estimate costs of disease treatment (Jagai et al., 2017). However, hospital billed charge does not necessarily reflect the actual cost to the hospital of providing patient care. Compared to cost, hospital billed charge could be inflated and it might not accurately measure the costs of medical service utilization (Jagai et al., 2017). The amount of money reimbursed, and the real cost of service delivery reasonably vary. Some studies calculated adjusted health service utilization cost by using cost-to-charge ratio (CCR) (Lin et al., 2012a; Merrill et al., 2008; Schmeltz et al., 2016) which can provide a better picture of service production cost. Studies suggested that CCR was more recommended to be used in the estimation of costs per diagnosis-related groups than individual patient level (Shwartz et al., 1995).

The research by Toloo et al. in Brisbane, Australia calculated ED cost using the NEP and PW methods (Toloo et al., 2015). This method is primarily developed for funding arrangement in the Australian healthcare system (Bell et al., 2014). Apart from the PW difference, the same value of NEP ($3624) was used to calculate the cost of ED visit for heat attributed cases visiting different triage scales which varies by urgency (from most urgent to least urgent) and admission (admitted or discharged) status. The difference in the complexity of care provided within the same urgency groups could not be adequately captured by either NEP or PW. The cost calculation could be more aggregated and might not be able to accurately measure cost differences between disease severity levels and ultimately leads to underestimation of ED costs. Moreover, it could be hard to capture whether temperature variation caused cost differences or not.

For most studies conducted in the USA, the NIS, which was developed as part of the HCUP was used as the sole source of data (Merrill et al., 2008; Noe et al., 2012; Schmeltz et al., 2016). The database encompasses a large sample of longitudinal hospitalization discharges of the USA population (nearly 8 million). However, apart from sample size, the NIS dataset is limited to the population covered by Medicare, which may vary from the non-Medicare population in terms of heat vulnerability and thereby affect cost estimation (Kinney et al., 2008).

Most mortality studies used the VSL to estimate the health cost in monetary terms (Huang et al., 2013; Ebi et al., 2004). Since the focus of this review is on actual healthcare resource utilization to treat diseases from heat exposure, the mortality study by Roldan and colleagues was the only study identified for healthcare mortality costs. However, this estimate of additional heat induced hospital spending could not rule out the cost variation between deaths from heat and non-heat causes other than frequency differences. The cost estimation would have been more meaningful if it includes medical expenditures to save the life of a person.

4.2. Climate change and heat-healthcare burden

Understanding future climate and its economic impact on our healthcare system can be used to effectively plan preventive actions. Studies used the current/past temperature-health relationship to calculate future health outcomes and estimate the cost of health service utilization (S. Lin et al., 2012; Toloo et al., 2015; AECOM, 2012; Hübler et al., 2008). However, looking at future climate effects embraces key uncertainties in the observation of main drivers at regional and global climate projections. Forecasting future climate resilience is challenging due to the lack of data and uncertainties arising from climate models. Few studies used a global climate model to project regional climate variables that have course spatial scale resolutions compared to regional climate models (S. Lin et al., 2012; Toloo et al., 2015; AECOM, 2012) (Hübler et al., 2008). Nevertheless, the uncertainty of projection increases with the increase of the projection period. Factors such as the interaction of environmental variables and urbanization could affect projections (Toloo et al., 2015). Overall, it is difficult for studies to account for the complex interplay of many variables, including future adaptation, possible changes in medical care, and costs of health services.

For economic assessments, the comparisons of costs and benefits at different point of time require cost adjustment to enable comparison of future and current costs and benefits (Li et al., 2018). In the economic estimation, a considerable uncertainty exists from the methodological framework which is still debatable by health economists and uncertainty surround the data (Briggs and Gray, 1999). For projection of future heat attributable healthcare cost, some studies used an annual discounting rate of 3% (S. Lin et al., 2012; AECOM, 2012). These studies also adjusted for inflation, an increase in the price of healthcare services and goods at the future time, while projection studies by Toloo et al. (Toloo et al., 2015) and Hübler et al. (Hübler et al., 2008) assumed that the cost of future healthcare price remains constant with the baseline years which is unlikely.

Economic studies helps to improve allocative efficiency of healthcare resources which taken into account the production and distribution of health outcomes among the community (Aday et al., 1999). The increasing future temperature will disadvantage certain groups of the populations. Projection studies suggest that the aging populations would be experiencing greater health and economic burdens associated with ever increasing temperature (S. Lin et al., 2012; Toloo et al., 2015). Higher prevalence of chronic diseases, impaired thermoregulatory functions, and use of certain medications could aggravate the effects of heat load on older population. Disease severities could be potentially higher among older population than younger group. A relatively lower ED cost for elderly group (64^+) in Melbourne could be due to the fact that the spot treatment provided by the ambulance service making it the patients endpoint and others with severe heat driven illnesses were admitted directly to the inpatient department (AECOM, 2012). Even though the prediction study by Hübler et al. in Germany did neither account future change in sectoral pattern of the economy nor adaptation to climate change, it suggested that heat-induced cost of hospitalization would increase significantly (Hübler et al., 2008). Unless preventive strategies are designed, heat driven health service demand will increase during hot seasons which will obviously result in higher healthcare costs (AECOM, 2012).

5. Further research needs

Only a small number of studies addressed economic costs of heat extremes, and methodological limitations in creating more advanced economic evaluations were observed. Appraisal of the available research protocol and developing standard and robust methodological foundation could be a research area. Even though 10 studies quantified heat-attributable healthcare cost based on heat-health association, there is a need to explore the causal relationship between temperature exposure and healthcare costs. Apart from descriptive statistics, advanced correlational analysis of healthcare cost could be applied. Healthcare cost estimation should be explicitly defined from societal, government or patients/families perspectives and cost adjustment is needed.

Selection and use of appropriate temperature thresholds can help to determine the magnitude of health and economic impact associated with extreme ambient heat exposure. This can better inform relevant stakeholders to plan, allocate, and mobilize resources efficiently. Moreover, economic evaluation or cost effectiveness studies between costs of disease treatment and other alternatives of managing health impacts of extreme temperature for example: potential savings from heat-health interventions are highly recommended to advice public health intervention strategies.

Use of excess heat factor (EHF), a more universal and new definition of heatwave (Zuo et al., 2015; Langlois et al., 2013; Nairn and Fawcett, 2014), can help to calculate temperature attributable excess costs and enables comparison of research results regardless of climatic variations. The relevance of healthcare cost spending in predicting disease severity can be other benefits researchers need to proof.

It is likely that future heat is more severe and increasing in geographic range due to the changing climate. However, the available studies are unevenly distributed, and some parts of the world particularly those most vulnerable regions with the least resilience were under-represented and further empirical evidence is required to see the global pictures of economic damage to the healthcare system.

Getting underlying detailed costs of health service utilization remains as a challenge. Collection and storage of routine healthcare cost data can strengthen the research endeavour and increase the availability and precision of economic costing studies in the health sector. A comprehensive healthcare cost analysis from both private and public healthcare systems of all levels (from primary to tertiary health care) is required.

6. Conclusion

This literature review indicates that the health costs of high-temperature exposure constitute a substantial economic burden on healthcare systems in the USA, Australia, and Europe. Although the evidence is still developing, studies have suggested that the subgroups incurring greater heat attributable costs include females, the elderly (≥64 years), low-income families, and some ethnic minorities. It is apparent that the future healthcare costs of extreme heat are likely to increase dramatically, globally and most particularly in more heat prone areas without effective heat adaptation measures. Monitoring of health outcomes and healthcare spending in relation to heat exposure may strengthen the research endeavours in the field. It is time for government agencies and policy makers to give more attention to the likely increasing heat attributable healthcare burden in a warming climate.

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Conflict of interest

The authors declare that they have no actual or potential competing financial interests exist.

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2.6. Update: Review of more recent literature

To identify studies on healthcare costs of ambient temperature that have been published since December 2017, a literature search was conducted in February 2021 using strategies described in Chapter 2, Methods section. Only one study was identified and an introduction of this study is presented below.

A time-series analysis using distributed lag non-linear model was used to evaluate the temperature-health outcome relationships in the Minneapolis/St. Paul Twin Cities Metropolitan Area, the USA from 2005-2014 (183). The daily maximum heat index was used as a metric for ambient temperature exposure that integrates air temperature and relative humidity. The study addressed the healthcare costs of both cold and hot temperature exposures for ED presentations and hospital admissions. The study comprehensively addressed both direct medical cost and productivity loss, and costs are adjusted for inflation. However, the cost of ED presentations and hospital admissions were calculated using a constant derived from three factors namely: total billed charges reflected on individual emergency department records, cost-to-charge ratio, and the professional fee ratio (PFR) that was multiplied by the number of and the number of ED presentations and hospital admissions (183).

Liu et al. estimated the RR and calculated attributable fractions (AF) and attributable cases (AC) of ED presentations, hospital admissions, and medical cost associated with temperature exposure by age category (183). Heat contributed to substantial ED presentations and hospital admissions to the younger (0-19 years) age group and no association with the adults (20-64 years) or seniors (65+ years). Moderate and extreme heat exposures caused a comparable morbidity burden to the younger group.

The costs of hospital admission were found to be higher due to the duration of hospital stay compared to ED presentations. The study also reported that due to a higher number of cold attributable cases, the associated medical costs were also much higher than the hot ambient temperature. A significant ED and hospitalisation cost were reported only for the younger age group and no cost was reported for other age groups. The ED cost associated with moderate-extreme heat exposure was $1.40 million (95% eCI: 1.15, 1.65) for the younger group, of this, nearly half, $0.73 million (95% eCI: 0.65, 0.81), of the cost burden was attributed to extreme heat exposure. Similarly, moderate-extreme heat and extreme heat exposure contributed to $1.51 million (95% eCI: 1.11, 1.94) and $0.91million (95% eCI: 0.63, 1.22) cost of hospitalisations, respectively.

In summary, this chapter provided an overview of existing literature on the health and economic impacts of temperature around the world. The results from the literature review in Section 2.3 confirmed that exposure to extreme temperatures increases risks of morbidity including potential temperature sensitive diseases including respiratory, renal, mental health disorders, IHD, diabetes, and other heat related illnesses. Similarly, Section 2.4 has shown that studies on the economic impacts of temperature on the healthcare system are limited and no evidence is available from developing countries. The few descriptively presented economic studies highlighted that the cost of temperature-related ambulance call-out, ED presentations, and hospital admissions is substantial and are likely to grow with the warming climate. The chapter outlined the need to establish the temperature-cost relationship and to quantify the net-, cold-, and heat-attributable morbidity and healthcare costs associated with temperature-sensitive disease conditions. In the following chapter (Chapter 3), an overview of the study design and methods used to address each of the specific research questions is outlined.

Chapter 3: Study design and methodology

3.1. Introduction

This chapter introduces the methodology used to answer the research questions. Section 3.3 briefly describes the study area and period. Section 3.4 through to 3.7 lists the overall research aim, specific objectives, and research questions that this thesis sets out to answer. An overview of the study design and the conceptual framework which maps the whole research work of this thesis is presented in Section 3.8. Section 3.9 covers data type and sources in four sub-sections (3.9.1 to 3.9.4). Finally, the chapter concludes with a description of the data analysis process of each study and research ethics.

3.2. Background of the research project

This thesis addressed a research work in Adelaide which is part of the NHMRC national research project '*Healthcare Costs of Heatwaves and Benefits of a Heat Health Intervention'* in multiple cities of Australia including Perth and Sydney (Figure 3.1). The NHMRC project is led by the University of Adelaide and involves stakeholders from different sectors around Australia including the: States Health Departments (SA and Western Australia), the BOM, and Universities (Adelaide, Queensland University of Technology and Flinders). The mega project aimed to estimate heat-attributable hospital costs; predict future costs under different scenarios of climatic and demographic change, and conduct a cost analysis of a public health heatwave intervention implemented in Adelaide in 2014.

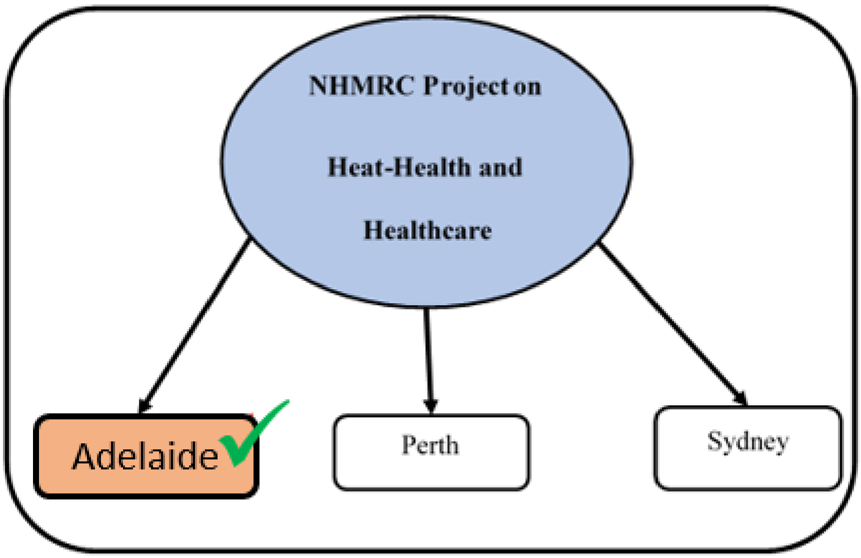

Figure 8. Description of the NHMRC-funded project and the PhD research work

3.3. Study setting and period

Adelaide is the capital city of South Australia (SA) with an urban surface area of 3,258 square kilometres (Figure 3.2). It is the fifth-largest city in Australia with a total population of nearly 1.3 million (184). The population of Adelaide is projected to reach 1.5 million in 2030 and 1.9 million in 2060 under a medium population growth scenario (185). Adelaide is the driest city in Australia with a temperate climate of warm to hot dry summers and mild winters. The average monthly mean temperature ranges from 11.4°C to 23.4°C. It is one of the most heatwave prone city in Australia hitting 46.6ºC, the hottest temperature record in State capital cities in Australia since records start (about 80 years ago). The number of hot days (>35°C) are increasing and it has a low level of relative humidity.

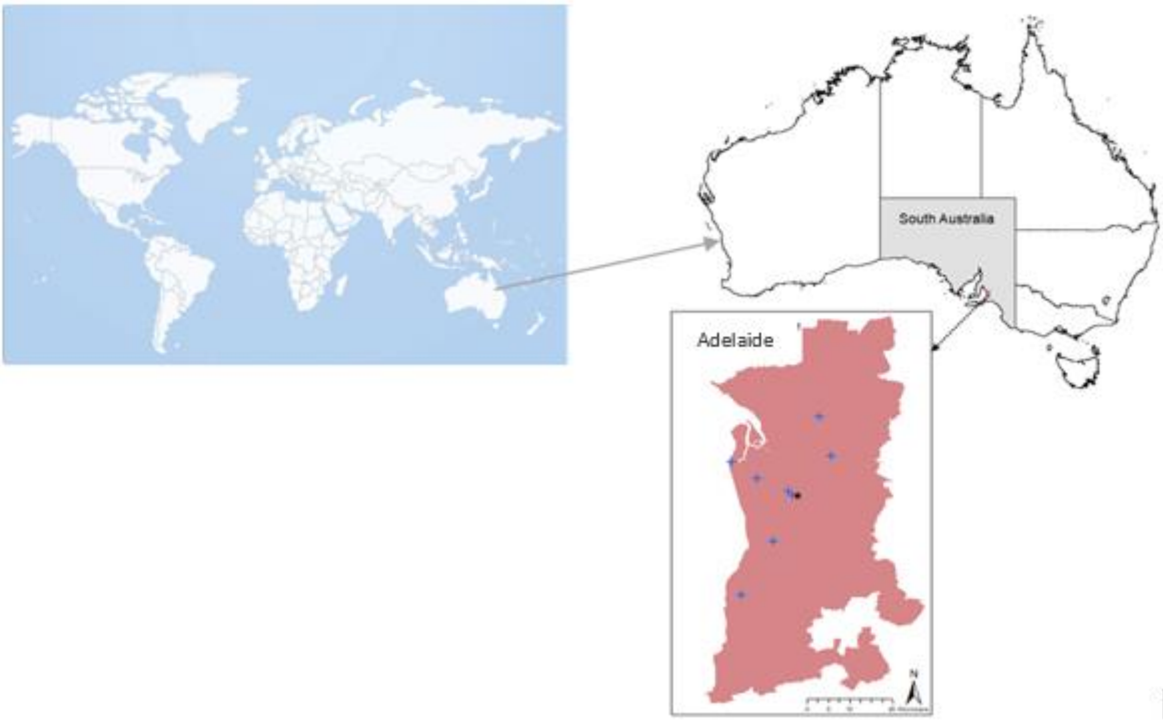

Figure 9. Map of Adelaide metropolitan area showing the location of public hospitals (+) and the central weather station (★).

3.4. Aims and objectives of the thesis

3.4.1. Aims

This research aimed to examine the current and projected morbidity impact (ED presentations and hospital admissions) and cost burden of non-optimum ambient temperature to the healthcare system in Adelaide, South Australia.

3.4.2. Specific objectives

- To examine the relationships of temperature and heatwave with health outcomes and healthcare costs
    - To examine the temperature- ED presentations and temperature-hospital admissions relationships for TRDs
    - To establish the temperature-cost relationship for TRD emergency department and hospital admissions

    - To establish the relationships of heatwaves with TRD-ED presentations and costs by disease diagnostic groups and age categories
- To estimate the morbidity burden attributed to mean temperature and heatwaves
    - To quantify the net-, cold-, and heat-attributable TRD-ED presentations, hospital admissions, and length of hospital stay for the baseline period and estimated future burden under different RCPs and demographic change
    - To calculate the heatwave-attributable ED presentations by disease diagnosis groups and age categories for the baseline period
- To estimate the economic burden of mean temperature and heatwaves to the healthcare system
    - To calculate the net-, cold-, and heat-attributable costs of ED presentations and hospital admissions to the baseline periods and estimated future costs under different RCPs and demographic change
    - To quantify the cost burden of heatwave severity and intensity for different diagnosis groups and age categories for the baseline period

3.5. Research questions

The thesis aims to address the following research questions:

1. How many ED presentations and hospital admissions are attributed to cold, heat, and heatwave exposure in Adelaide?
2. What is the relationship between temperature exposure and healthcare costs in Adelaide?
3. What are the healthcare costs of ED presentations and hospital admissions attributable to cold, heat, and heatwave exposures in Adelaide?

4. How will ED presentations and hospital admissions change in the future due to cold, and heat exposure under different greenhouse gas emissions scenarios and population change in Adelaide?
5. What will be the costs to the healthcare system attributed to projected temperatures under different greenhouse gas emissions and population growth scenarios in Adelaide?

3.6. Study design

This study used a time-series ecological study design to assess the temperature-morbidity and temperature-healthcare cost relationships for hospital ED presentations and hospital admissions in Adelaide. The study estimated the health and economic burden of cold and hot temperatures historically and in future.

The ecological study is an observational study that uses group/population as a unit of analysis to link temperature exposure to health outcomes (186, 187). Many exposure and outcome variables fluctuate in incidence over time. As discussed in Section 1.5 of this thesis, the majority of studies in environmental epidemiology used a time-series analysis to investigate the short-term effects of environmental exposure on health outcomes (62, 188). In this study, daily data of morbidity, healthcare cost, and temperature data were available which makes time-series regression an appropriate approach to answer the above research questions.

Conceptual framework

The conceptual framework (Figure 3.3) maps the overall research framework of this thesis. It describes how variables are linked and the proposed research questions are related to each other and answered. The population exposed to non-optimum ambient temperature that may cause morbidity from a range of disease conditions that can subsequently result in medical costs to the healthcare system. The medical costs associated with temperature-attributable diseases may not be always guided by the number of patients. The level and frequency of exposure may cause different diseases and the severity of the disease will lead to variation in medical costs. Hence, establishing a direct temperature-healthcare cost relationship can help to better understand the temperature-attributable healthcare cost. As awareness about climate change increases, government and public health agencies demand scientific evidence of future climate-related health and economic burden to design practical guidelines, adaptive strategies, and tailored public health interventions. Given that future exposure data can be simulated from climate change models, future morbidity and cost burden can be estimated using the current exposure-response relationship under different RCPs.

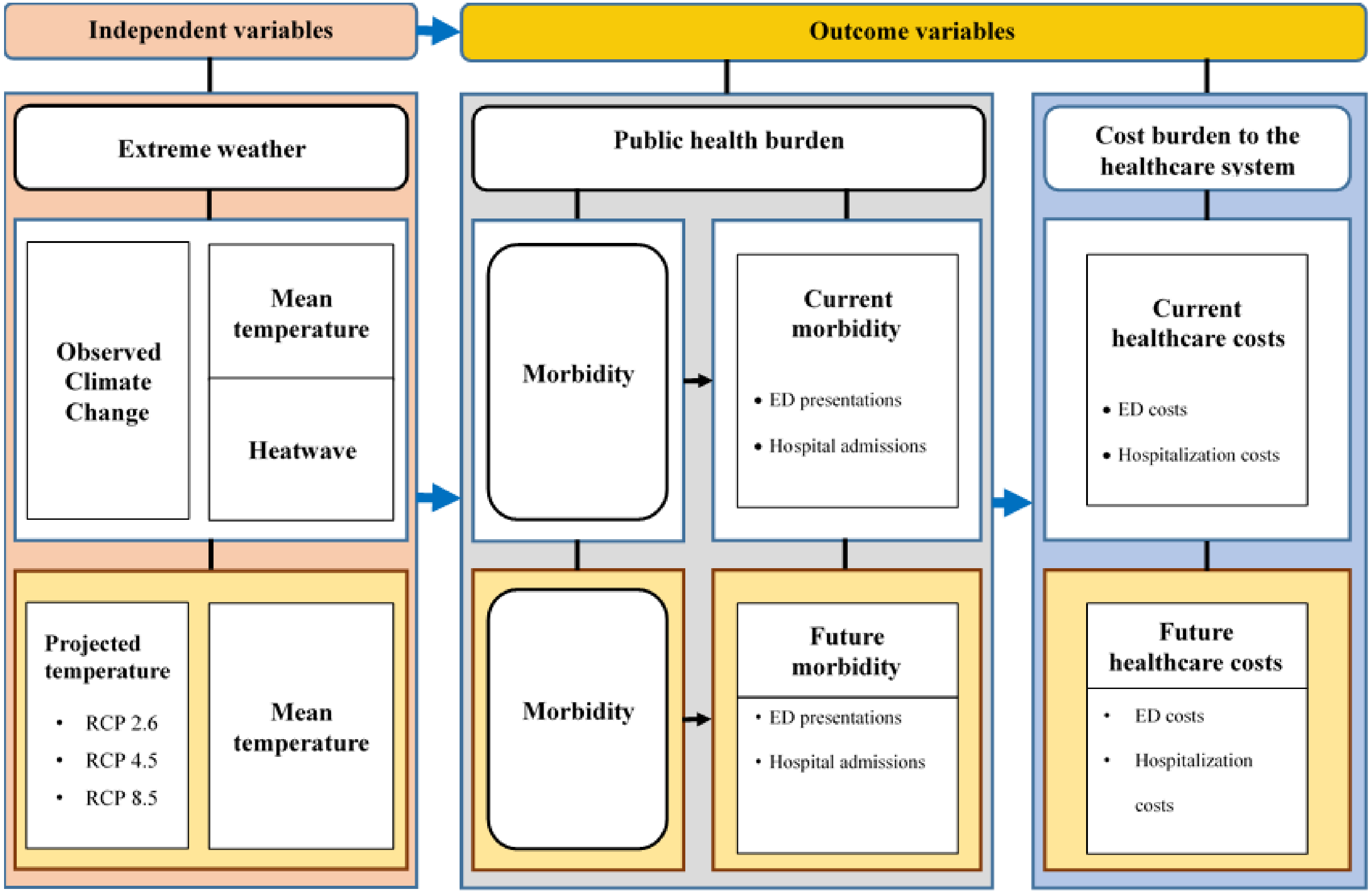

Figure 10. Conceptual framework of the PhD project.

3.7. Data sources and acquisition

For this research, morbidity, healthcare cost, meteorological, Consumer Price Index (CPI), and population data were obtained from different organizations in Australia as described below.

3.7.1. Health and healthcare costs

Aggregated daily ED presentations and related costs from 2014 to 2017 were collected from the South Australian Department of Health and Wellbeing. Aggregated daily hospital admissions, LoS, and costs of hospitalizations from 2010 to 2015 were accessed from the IHPA. The IHPA was established in 2011, which provides independent advice to the Australian government and States about the efficient price of the healthcare services (189). The morbidity and cost data obtained include all public hospitals (7-EDs and 8-inpatient admissions) in the Adelaide metropolitan area. Diagnosis categories including mental health disorders (ICD-10: F00-F99.9), respiratory diseases (ICD-10: J00-J99), renal diseases (ICD-10: N00-N39.9), ischaemic heart diseases (IHD) (ICD-10: I20-I25), diabetes (ICD-10: E10-E14), and heat-related illnesses (HRI) (ICD-10: E86, T67, X30) were identified using International Classification of Diseases, 10th Revision (ICD-10).

Selection of heat-related health outcomes

The specific disease diagnosis groups mentioned in Section 3.9.1 represent the disease conditions that have been proved to be sensitive to temperatures in Adelaide (103, 163, 190, 191) and other locations around Australia (8, 21, 147), and elsewhere (86, 192). Since the daily presentations for each of the individual disease categories mentioned above were small and lack statistical power to predict effect estimates, ED presentations, hospital admission, LoS, and associated costs were merged using the day variable. Thus, the outcome measure used in our analysis represents combined daily potentially all temperature-sensitive ED presentations, hospital admissions, and associated healthcare costs in Adelaide and referred to as TRD.

3.7.2. Meteorological data

In this research, two temperature metrics were used namely: mean temperature and EHF. The mean temperature was chosen to represent all year round temperature exposure variables because it can reasonably represent the level of population exposure throughout the day (193). It is also the most widely used indices for the projection of climate impacts (194). The temperature data are classified as historical (observed data) which includes both mean temperature and heatwaves and projected data which is only available for mean temperature.

Observed mean temperature

The daily mean temperature was obtained from the BOM. The data comprised historical daily mean temperature in degree Celsius (°C) from 2010 to 2017 recorded at the Kent Town (023090), which is the central weather monitoring station for Adelaide and considered to be representative of the metropolitan region (23, 84, 195-197) (Figure 3.2). The mean temperature was chosen to estimate baseline and future temperature burden as it can reasonably represent the level of population heat exposure throughout 24-hours (193). It is also the most widely used temperature index for the projections (194).

Observed heatwave

Daily heatwave severity and intensity measured using the EHF for the period 2014-2017 were obtained from the BOM. The EHF measures heatwave severity and intensity and the calculation comprises of two components: a short-term significance index (EHIsig) and a long-term acclimatization index (EHIaccl) and calculated as follow:

$$EHF_{sig} = (T_i + T_{i+1} + T_{i+2}) / 3 - T_{95} \quad (1)$$

$$EHF_{accl} = (T_i + T_{i+1} + T_{i+2}) / 3 - (T_{i-1} + \ldots + T_{i-30}) / 30 \quad (2)$$

The index in (1) measures significant heat events by comparing the 3-day average temperature with the 95th percentile for historical 30-year temperature data, while equation (2) represents the anomaly between the recent three-day period and the last 30-days which is assumed to be related to human acclimatisation. The EHF is then calculated as follows:

$$EHF = EHF_{sig} \text{ x } \max(1, EHF_{accl}) \; [(°C)^2] \quad (3)$$

Values of $EHF > 0$ indicate the presence of heatwave. Further details on the calculation of EHF is described by Nairn and Fawcett (19).

Projected mean temperature

Future mean temperature changes for 2034 through 2065 were obtained from the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and BOM. The temperature was projected using the CMIP5 relative to the climate reference period (1986-2005) (198) for the Southern and South-Western Flatlands, East region of Australia (198). The CMIP5 models capture the climatological temperature distribution across the continent very well (199). The models simulate future mean temperature using greenhouse gas emission scenarios defined by the IPCC as representative concentration pathways. According to the level of radiative forcing measured as the strength of the greenhouse effect in Wm^{-2}, the scenarios are RCP2.6, RCP4.5, RCP6.5, and RCP8.5. In this study, three scenarios, namely: RCP2.6 (low emission) RCP4.5 (medium emission), and RCP8.5 (upper emission) were selected to capture plausible future increases of mean temperatures. RCP8.5 emission and concentration pathway represents a future of little curving of emission, with a CO_2 concentration continuing to rapidly rise, reaching 940 ppm by the end of 2100. RCP6.0 represents CO_2 concentration slightly below RCP4.5 until mid-century. The RCP4.5 start to peak around 2040 and the CO_2 concentration reaches 540 ppm by 2100. The lowers emission scenario, RCP2.6, is the most ambitious mitigation scenario aiming to limit the increase of global mean temperature to 2°C. In this scenario, emission peaks early in the century (around 2020) then fall due to the active removal of atmospheric CO_2. The CO_2 concentration reaches 440 ppm by 2040 and then slowly declines to 420 ppm by 2100. They often show negative emissions from energy use in the second half of the 21st century (200, 201).

As the daily projected temperature data from the climate model is not available for this study, a daily time series of temperature data for the 2030s, 2040s, 2050s, and 2060s was created using a scaling factor approach (49), a method of adding the projected temperature change on baseline observed daily temperatures. The CSIRO and BOM advised that this is an appropriate method given the similarity in projected temperature change across seasons and at temperature extremes (49). A case study in Brisbane, Australia, also used a closely similar method to simulate future temperature. However, an arbitrary constant temperature value of 1-4ºC was added to the baseline temperature assuming no change in variability (202).

3.7.3. Baseline and future population data

The current and projected population data for Greater Adelaide were obtained from the ABS (203). The population census data conducted once every five years (2006, 2011, and 2016) and annual population projected data by the ABS (from 2017 to

2066) were used to estimate the daily population for the baseline and future periods using linear interpolation (204). The medium population projection scenario was chosen which follows the assumptions of medium fertility, mortality, and migration (overseas and interstate) rates (203). For study 3 (Chapter 6) baseline populations were categorised by age as younger (0-14 years); middle age (15-64 years); and elderly (65 years and over).

3.8. Data analysis

A two-stage data analysis was performed. In stage one, the associations of temperature with ED presentation, ED cost, hospital admissions, LoS, costs of heat-related hospitalizations were established. In stage two, the aggregated daily morbidity (ED presentations and hospital admissions) and cost burden attributed to temperature exposure was estimated for the baseline and future periods.

Step 1. Baseline association between temperature exposure, health outcomes, and healthcare costs

The associations between daily mean temperature and ED presentations, ED costs, hospital admissions, LoS, and costs of hospitalizations were examined using time series regression. A quasi-Poisson distribution for count data (ED presentations and hospital admissions) (205-207) and gamma distribution for cost data (ED costs and cost of hospital admissions) (208).

Regression model assumption is another fundamental element in data analysis. A growing body of literature has reported the non-linear relationship of temperature with morbidity and mortality (209, 210). Risks of morbidity do not increase monotonically across the temperature range, rather it does change at a different rate as temperature varies (either cold, mild, or hot) (209). In this case, the use of the customary linear model (211) perhaps can simplify the interpretability of data but they are unlikely to capture the effect and to provide precise estimates. Hence, the use of non-linear models using flexible spline smoothing could be a better choice.

Another important challenge in the study of temperature-health association is the delayed effect between the time of exposure and health outcomes. The observed health effects on the time scale can be related to the current day's temperature or exposure on previous days (21). In time-series analysis, a DLNM is used to tease out these complexities. The model with the cross-basis function was used to examine the non-linear and delayed effects of exposure-response association (66, 212, 213). The natural cubic spline (ns) with three internal knots were placed at 10th, 75th, and 90th percentile across the main exposure and equally spaced for the lag dimension. To account for delayed effects of mean temperature, particularly cold temperature which can be lagged by several weeks (21), a maximum of 21 lag days were used which is consistent with other similar studies in Australia (214) and elsewhere (1, 63, 175, 179, 205, 215-223). For heatwave, a 7 day lag period was applied in line with the previous studies (16). Seasonal patterns and long-term trends were included in the model using a natural cubic spline function with 7 degrees of freedom (df) per year for ED presentations and costs and 6df per year for hospital admission, LoS, and associated costs. Since the heatwave analysis is restricted to only the warm seasons (October-March), 4df per year was used to control seasonality and long-term trend. A variable for days of the week (dow) was included in the model to control for any confounding by weekly pattern. Public holidays (phol) was also controlled as binary variables (1 for public holiday and 0 otherwise). Akaike's Information Criterion (AIC) was used to identify the optimum model. Current and projected net temperature-, heat-, and cold-attributable morbidity and healthcare costs were calculated with 95% empirical confidence intervals (eCIs) relative to the optimum temperature (OT),temperature values with the lowest effect.

The models were described as follows:
Y_t ~ quasiPoisson (μ_t) for counts (ED presentations/hospital admissions/LoS)
Y_t ~ Gamma (μ_t) for costs
$\text{Log}[E(Y_t)]=\alpha + \beta_{1.}\text{cb}(\text{Tmean}_{t,l}/\text{heatwave}_{t,l}) + \beta_{2.}\text{ns}(\text{time},$
7df/per year * 4 years = ED presentations/costs
6df/per year * 6 years = hospital admissions/LoS/costs
4df/per year * 4 years = heatwaves)
$+ \beta_{3.}\text{dow} + \beta_{4.}\text{phol}$

Where Y_t is ED presentations/hospital admissions/LoS/costs on day t; α is the intercept; cb($\text{Tmean}_{t,l}/\text{heatwave}_{t,l}$) is the cross-basis natural cubic spline function for daily mean temperature or heatwaves with both main response and lag dimension applied from the DLNM. ns(.) is the cubic spline with the corresponding df per year; dow is the day of the week as a 7-level factor. Sunday is the reference day for the day of the week. The phol is a binary variable representing public holidays.

Step 2. Projected temperature-attributable morbidity, LoS, and healthcare costs

The current exposure-response relationships established in Step 1 above between daily temperature and outcome variables was used to estimate aggregated net temperature-, cold-, and heat-attributable ED presentations, ED costs, hospital admissions, LoS, and costs of hospitalizations for the current and projection periods. Conventionally, risk ratios such as OR, RR, and percentage change are used to measure the dose-response relationship (10, 11). These measures are widely used in summarizing the exposure-response associations. However, they provide very limited evidence about the magnitude of disease burden attributed to temperature (216). Recently, the attributable number (AN) and an attributable fraction (AF) were adopted to measure the health burden of exposure to temperature (1, 216). The calculation is the transformation of the dose-response associations through integrating information on both risk ratios and frequency/level of exposure (216). Taking the estimated relative risk from stage one, total attributable ED presentations, hospital admissions, and associated medical costs for the respective study periods were calculated using the simplified formula below (70, 224, 225):

$$\text{AN} = \frac{RR - 1}{RR}$$

Projected temperatures under different greenhouse gas emissions were used to represent future temperature exposure. However, because of the lack of projected heatwave data using EHF metric, the effects of heatwave on ED presentations and costs were performed only for the baseline period. The total net-, cold-, and heat-attributable ED presentations, ED costs, hospital admissions, LoS, and hospitalization costs for RCP2.6, RCP4.5, and RCP8.5 were calculated for each day relative to the OT. All effects due to temperatures lower than OT were defined as a cold-attributable fraction; effects due to temperature values above the OT were heat-attributable, while the net temperature effects were the sum of cold and heat effects. For temperature above the observed values, the Monte Carlo simulation was used to estimate the health and economic effects by taking 1000 samples of coefficients (70, 216). Effects of the changing climate were calculated under the assumption of constant and future population change. Using CPI data obtained from the ABS (226), costs were adjusted for inflation and calculated in 2015 (study 1 and 3) and 2017 (study 2) AU$ value. The risks of exposure were calculated with

95%CI (confidence intervals) and the attributable burdens were calculated with 95% eCI (empirical confidence intervals). All analyses were conducted using R software version 3.4.3.

3.9. Ethics clearance

Before the acquisition of research data, ethical clearances were obtained from the Human Research Council of SA Department of Health and Wellbeing (HREC/18/SAH/34) and The University of Adelaide (ID33179). For confidentiality reasons, the health and cost data were de-identified by data custodians and were aggregated by the date of admission.

Chapter 4 Study 1: Understanding current and projected costs of emergency department presentations in a changing climate

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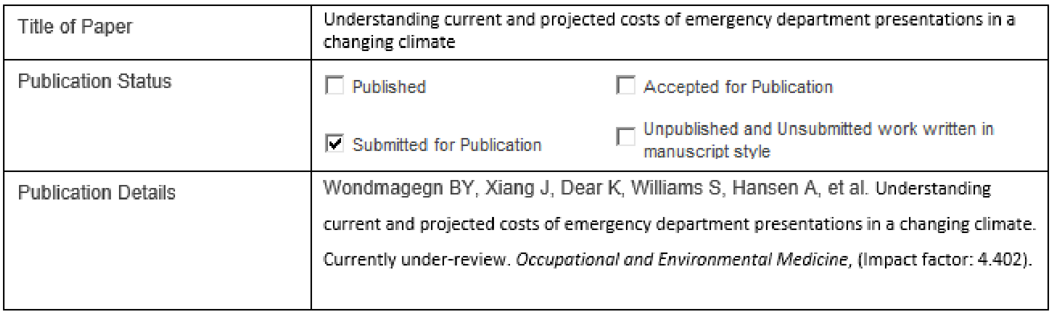
4.1. Introduction

This Chapter presents (Study 1) research findings of the health and economic impacts of temperature under the changing climate. The study particularly addressed the morbidity and cost impacts of non-optimum temperature for current and future periods. The net-, cold-, and heat-attributable ED presentations and costs were calculated for the observed baseline temperature and projected under different greenhouse gas emissions and demographic change scenarios. The Introduction (4.2) described the current knowledge, gaps, and aims of this particular study. Descriptions of the methods including study settings and period, data source and type, and data analysis were presented under Section 4.3. Section 4.4 and 4.5 presents the Result and Discussion, respectively.

4.2. Publication

Wondmagegn BY, Xiang J, Dear K, Williams S, Hansen A, et al. Understanding current and projected costs of emergency department presentations in a changing climate. Currently under-review. *Occupational and Environmental Medicine,* (Impact factor: 4.402).

4.3. Statement of Authorship



Title of Paper	Understanding current and projected costs of emergency department presentations in a changing climate
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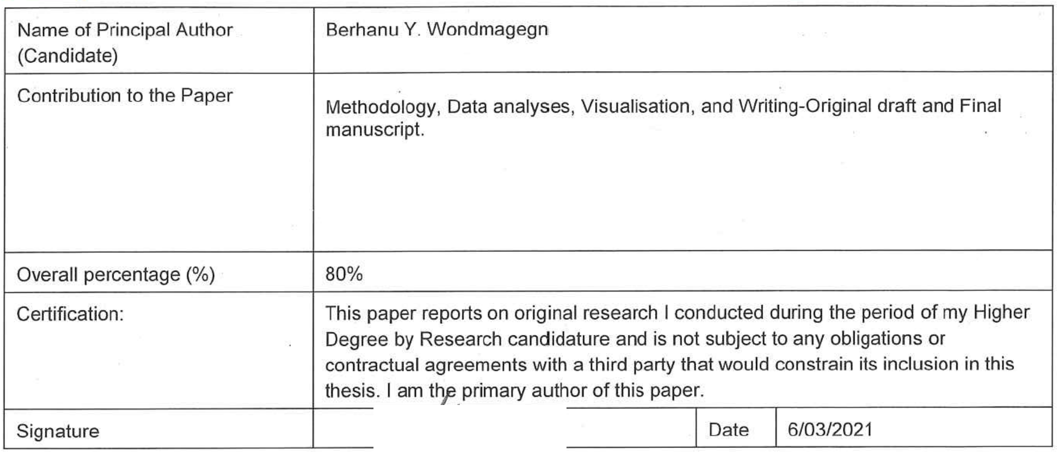
Principal Author



Name of Principal Author (Candidate)	Berhanu Y. Wondmagegn		
Contribution to the Paper	Methodology, Data analyses, Visualisation, and Writing-Original draft and Final manuscript.		
Overall percentage (%)	80%		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
Signature		Date	6/03/2021

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);
ii. permission is granted for the candidate in include the publication in the thesis; and
iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

Name of Co-Author	Jianjun Xiang		
Contribution to the Paper	Methodology, Data analyses, Visualisation, Project management, Supervision, and Writing-Reviewing and editing		
Signature		Date	9-March-2021

Contribution to the Paper	Conceptualisation, Funding acquisition, Methodology, Data analyses, Visualisation, and Writing-Reviewing and editing		
Signature		Date	9 March 2021

Name of Co-Author	Susan Williams		
Contribution to the Paper	Methodology, Data analyses, Visualisation, Project management, and Writing-Reviewing and editing		
Signature		Date	11/03/2021

Name of Co-Author	Alana Hansen		
Contribution to the Paper	Conceptualisation, Funding acquisition, Methodology, and Writing-Reviewing and editing		
Signature		Date	25/3/21

Name of Co-Author	Dino Pisaniello		
Contribution to the Paper	Supervise the development of the work, provided feedback on the content and structure of the manuscript, and evaluated the revised version		
Signature		Date	12/3/21

Name of Co-Author	Monika Nitschke		
Contribution to the Paper	Methodology, Funding acquisition, Data acquisition, and Writing-Reviewing and editing		
Signature		Date	17.03.21

Name of Co-Author	John Nairn		
Contribution to the Paper	Methodology, Funding acquisition, Data acquisition, and Writing-Reviewing and editing		
Signature		Date	12/03/2021

Name of Co-Author	Ben Scalley		
Contribution to the Paper	Methodology, Funding acquisition, Data acquisition, and Writing-Reviewing and editing		
Signature		Date	15.3.21

Name of Co-Author	Jianguo Xiao		
Contribution to the Paper	Methodology, Funding acquisition, Data acquisition, and Writing-Reviewing and editing		
Signature		Date	13/03/2011

Name of Co-Author	Le Jian		
Contribution to the Paper	Methodology, Funding acquisition, Data acquisition, and Writing-Reviewing and editing		
Signature		Date	9/3/2021

Name of Co-Author	Michael Tong		
Contribution to the Paper	Methodology, Data analyses, Visualisation, Project management, And Writing-Reviewing and editing		
Signature		Date	09-March-2021

Name of Co-Author	Hilary Bambrick		
Contribution to the Paper	Conceptualisation, Funding acquisition, Methodology, and Writing-Reviewing and editing		
Signature		Date	10/03/2021

Name of Co-Author	Jonathan Karnon		
Contribution to the Paper	Conceptualisation, Funding acquisition, Methodology, and Writing-Reviewing and editing		
Signature		Date	9/3/2021

Name of Co-Author	Peng Bi		
Contribution to the Paper	Conceptualisation, Funding acquisition, Methodology, Project management, Supervision, and Writing-Reviewing and editing		
Signature		Date	12-03-2021

Abstract

Background:

Exposure to extreme temperatures is associated with increased emergency department presentations (EDs). The resulting burden on health service costs and the potential impact of climate change is largely unknown. This study examines the temperature-EDs/cost relationships in Adelaide, South Australia, and how this may be impacted by increasing temperatures.

Methods: A time series analysis using a distributed lag nonlinear model was used to explore the exposure-response relationships. The cold-attributable, heat-attributable, and net ED presentations for temperature-related diseases and costs were calculated for the baseline (2014-2017) and future periods (2034-2037 and 2054-2057) under three climate representative concentration pathway (RCP) scenarios.

Results: The baseline heat-attributable ED presentations were estimated to be 3,633 (95% empirical confidence interval (eCI): 695, 6,498) with associated cost of AU$4.7 million (95% eCI: 1.8, 7.5). Heat-attributable ED presentations and costs were projected to increase during 2030s and 2050s with no change in the cold-attributable burden. Under RCP8.5 and population growth, the increase in heat-attributable burden would be 1.9% (95% eCI: 0.8, 3.0) for ED presentations and 2.5% (95% eCI: 1.3, 3.7) for ED costs during 2030s. Under the same conditions, the heat effect is expected to increase by 3.7% (95% eCI: 1.7, 5.6) for ED presentations and 5.0% (95% eCI: 2.6, 7.1) for ED costs during 2050s.

Conclusions: Projected climate change is likely to increase heat-attributable emergency presentations and the associated costs, without a significant reduction

in the cold-attributable burden. Planning health service resources to meet these changes will be necessary as part of broader adaptation strategies and public health prevention actions.

Keywords: Healthcare costs, Emergency Department presentations, temperature, climate change, heat-attributable

4.4. Introduction

Numerous studies have demonstrated the strong link between exposure to high ambient temperature and adverse health outcomes in different climatic and socioeconomic settings (6, 7). As global temperatures rise, this will further challenge health services (227), including emergency departments (ED), and could lead to an increasing economic burden to healthcare systems around the world.

In Australia, the climate has warmed by 1.44°C since 1910 (47) and the health impacts of heat are considerable (228). Previous Australian studies have reported increased risks of ED presentations at high temperatures (23) and during heatwaves (15, 103), particularly for heat-related, renal, and mental health conditions (22, 84, 103).

A recent review of temperature-related healthcare costs indicated that, from the limited available studies, the economic impact on the healthcare system is significant and future costs of extreme heat are likely to increase substantially in more heat prone areas (20). However, to understand the likely overall impacts of climate change, it is important to consider the temperature attributable burden across the range of temperatures, including for both extremes of cold and heat, and how these may change in future under different climate change scenarios. This study explores (i) the relationship between temperature and ED presentations and associated costs, and (ii) the potential increase in ED presentations and costs due to the changing climate, in Adelaide, South Australia (SA). Evidence of this nature can contribute to shaping health policies to reduce avoidable temperature-attributable health effects and healthcare costs.

4.5. Methods

4.5.1. Data type and sources

4.5.1.1. Health and healthcare costs data

The study was conducted in Adelaide, the capital city of South Australia. The city has a temperate climate of warm to hot dry summers and mild winters. Based on the 2016 census, the total population of Adelaide reached nearly 1.3 million (184). Data in daily ED presentations and associated healthcare costs were collected from the South Australian Department of Health and Wellbeing for the period 2014-2017. Diagnosis categories for ED visits were identified using International Classification of Disease (ICD-10) codes. In this study, daily ED presentations and associated medical costs of mental health disorders (ICD-10: F00-F99.9), respiratory diseases (J00-J99), renal diseases (N00-N39.9), ischaemic heart diseases (I20-I25), diabetes (E10-E14), and heat-related illnesses (E86, T67, X30) were included. These represent the disease categories that have been shown to increase in relation to temperature in Adelaide (190) and other locations (86, 192). Since the daily presentation counts for each of the individual disease categories were relatively small, the data for all aforementioned disease categories were summed for statistical analysis and referred as “temperature-related disease (TRD)”. The healthcare costs represent the direct expenditure associated with health interventions including diagnosis, treatment, and procedures for TRD-ED presentations.

4.5.1.2. Historical and projected temperature data

Daily temperature data were obtained from the SA Bureau of Meteorology (BOM). The data comprised historical daily mean temperature (°C) from 2014-2017 recorded at the Kent Town weather stations (023090), which is the best representative monitoring station for Adelaide metropolitan area (84, 197). Mean temperature was chosen to represent the exposure variables because it was highly correlated with minimum and maximum temperatures and is the most widely used indices for the projection (194). We also obtained projected future mean temperature change from Commonwealth Scientific and Industrial Research Organisation for 2034-2037, hereafter termed as 2030s, and 2054-2057, hereafter termed as 2050s, projected under three representative concentration pathways (RCPs)- the lower (RCP2.6), medium (RCP4.5), and upper (RCP8.5) emission scenarios relative to the climate reference period (1986-2005) (198).

4.5.1.3. Baseline and future population data

The baseline and projected population data for Greater Adelaide were obtained from the Australian Bureau of Statistics (185). For future population estimations, a medium population projection scenario was used which follows the assumptions of medium fertility, mortality, and migration rates (185).

4.5.2. Data analysis

A two-stage data analysis was performed incorporating firstly the estimation of baseline exposure-response relationships followed by the estimation of future projection as per the method of Vicedo-Cabrera et al. (70).

4.5.2.1. Baseline exposure-response relationship

Time series quasi-Poisson distribution for ED presentations (206, 207) and gamma distribution for ED costs (208) combined with a distributed lag non-linear model (DLNM) were used to estimate the relationship with and delayed effects of mean ambient temperature (212). We used a natural cubic spline with three internal knots placed at the 10th, 75th, and 90th percentile of the daily mean temperature in the exposure-response dimension. To account for delayed effects of temperature, particularly cold temperature which could last several weeks (21), a maximum of 21 lag days were used. Seasonality and long-term trends were included in the model using a natural cubic spline function with 7 degrees of freedom per year. Day of the week and public holidays were controlled as categorical variables. Akaike's Information Criterion (AIC) was used to identify the optimum model (Supplementary Table S1). The model used for ED presentations was:

$Y_t \sim$ quasipoisson (μ_t):

$$\log(\mu_t) = \alpha + \beta_1 T_{t,l} + \beta_2 . \mathrm{ns}(\mathrm{time}, 7\mathrm{df/year}) + \beta_3 . \mathrm{dow} + \beta_4 . \mathrm{phol} \qquad (1)$$

and the model for ED costs was:

$Y_t \sim$ Gamma (μ_t):

$$\log(\mu_t) = \alpha + \beta_1 T_{t,l} + \beta_2 . \mathrm{ns}(\mathrm{time}, 7\mathrm{df/year}) + \beta_3 . \mathrm{dow} + \beta_4 . \mathrm{phol} \qquad (2)$$

where Y_t is ED presentations/costs on day t; α is the intercept; $T_{t,l}$ is the matrix obtained from the DLNM; ns(.) is a natural cubic spline with 7 degrees of freedom per year; dow is the day of the week as a 7-level factor, and phol is a binary variable representing public holidays.

4.5.2.2. ED presentation and healthcare cost burden

Using the exposure-response associations estimated at stage one together with observed baseline temperature, and projected mean temperatures under RCP2.6, RCP4.5, and RCP8.5; total/net-, cold-, and heat-attributable ED presentations and related costs were estimated for 2010s, 2030s and 2050s. The aggregated sum of all ED presentations and costs below and above the optimum temperature (OT), i.e. the temperature at which the number of TRD-ED presentations and costs were lowest was regarded as cold and heat attributable, respectively. The overall (cold plus heat) effects equated to the temperature/net effects. For projected temperatures above the observed values, Monte Carlo simulation was used to estimate the health and economic effects by taking 1000 samples of coefficients (70, 216) Using consumer price index (CPI) data (226), costs were adjusted for inflation and calculated in 2017 Australian dollars (AU$) value. Several sensitivity analyses were conducted to test the robustness of the models for ED presentations and ED costs using different numbers of lag days, df, and knots.

4.6. Results

4.6.1. Descriptive statistics

During the baseline study period of 2014-2017, there were 1,460 observation days, with the minimum, maximum, and mean observed temperatures in Adelaide of 6.5°C, 37.7°C, and 17.4°C, respectively. There were 267,651 total TRD-ED presentations over the study period and total costs of nearly AU$252 million. Daily counts of TRD-ED presentations ranged from 115 to 281 with a mean of 183.2 presentations per day. The daily minimum, maximum, and mean costs across the study period were estimated to be AU$94,665, AU$330,518 and AU$172,476, respectively.

4.6.2. Baseline exposure-response association

The cumulative exposure-response curve appeared to have an approximately J-shaped relationship for both ED presentations (Fig. 11a) and ED costs (Fig. 12a). Effects of cold temperature were lagged up to 18 days for ED presentations and costs; while heat effects were observed over shorter lag periods, i.e. 9- and 2-days for ED presentations and costs, respectively (Figures S1 and S2). The greatest heat effects were observed on day 0 for both outcomes (Figures 11b and 12b).

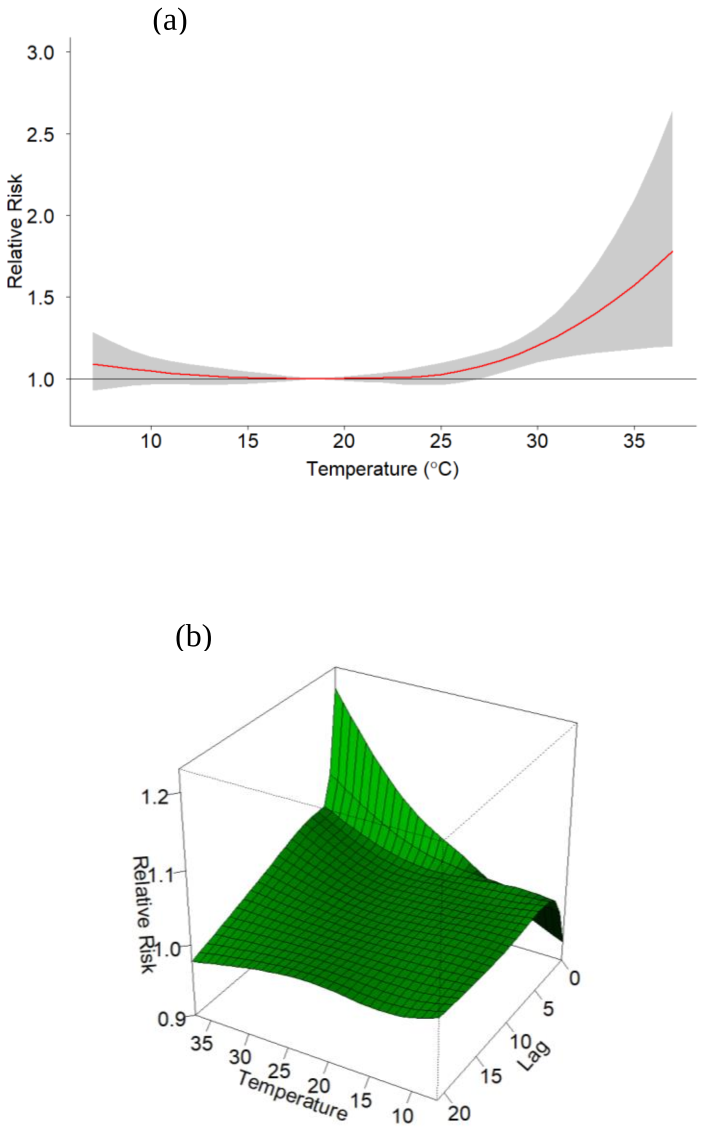
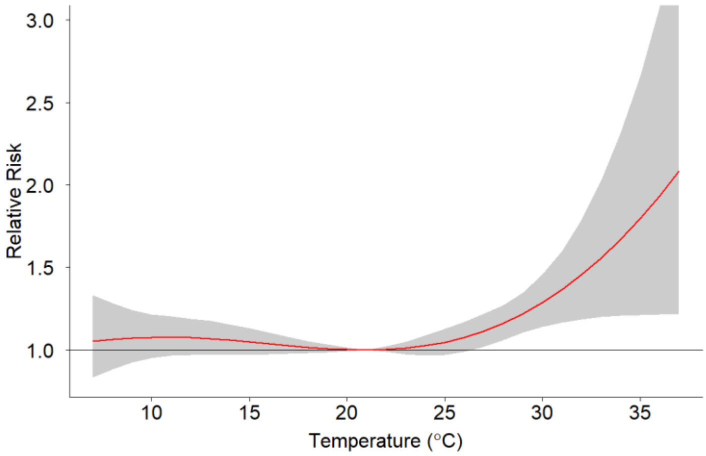


Figure 11. Overall cumulative exposure-response curve (a) and exposure-lag-response relationship (b) between daily mean temperature and ED presentations from 2014-2017 in Adelaide, South Australia. The red line in Fig. 11a represents the overall effect estimate and the grey area is the 95% CI. Figure 11b shows the exposure-lag-response association at 0-21 lag days for ED presentations. The relative risk of ED presentations by daily mean temperature was estimated relative to OT (18.5°C).

(a)



(b)

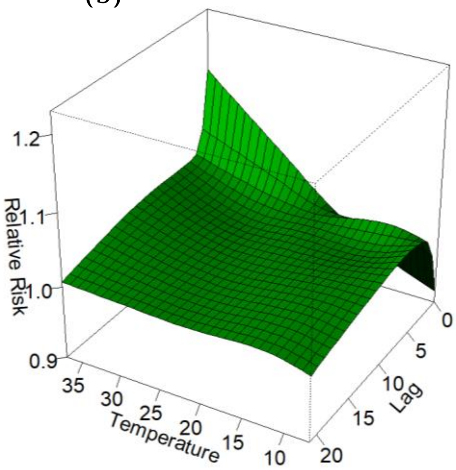


Figure12. Overall cumulative exposure-response curve (a) and exposure-lag-response relationship (b) between daily mean temperature and ED costs from 2014-2017 in Adelaide, South Australia. The red line in Fig. 12a represents the overall effect estimate and the grey area is the 95% CI. Figure 12b shows the exposure-lag-response association at 0-21 lag days for ED costs. The relative risk of ED costs by daily mean temperature was estimated relative to OT (21°C).

4.6.3. Baseline temperature-attributable burden of TRD-ED presentations and costs

Table 1 shows the estimated temperature-attributable ED presentations and costs for the 4-year baseline period. Heat exposure contributed to more TRD-ED presentations compared to cold during the baseline period. An estimated 3,633 (95% eCI: 695, 6,498) ED presentations and AU$4.7 million (95% eCI: 1.8, 7.5) ED costs were estimated as heat-attributable. The estimate of cold-attributable ED costs was AU$7.9 million (95% eCI: -4.1, 19.9), not significantly different from zero.

Table 1. Baseline (2014-2017) net-, cold-, and heat-attributable ED presentations and ED costs at 95% eCI in Adelaide, South Australia.

Temperature exposure	Attributable burden	
	ED presentations (N)	ED costs (million AU$)
Net	6,662 (-1,434, 14,222)	12.6 (-0.3, 24.1)
Cold	3,028 (-3,895, 9,840)	7.9 (-4.0, 18.9)
Heat	**3,633 (695, 6,498)**	**4.7 (1.8, 7.5)**

Bold font indicates statistically significant changes based on the 95% empirical confidence interval.

4.6.4. Estimate of future temperature-attributable burden of TRD-ED presentations and costs

The total number of temperature-attributable ED presentations and associated costs were estimated for different emissions scenarios (RCP2.6, 4.5, 8.5), using the baseline Adelaide population profile and when coupled with medium projected population growth. A substantial estimated increase in ED presentations and costs was observed when projected climate change was coupled with projected population growth (Table 2). Under RCP2.6, the excess heat-attributable ED presentations in 2030s would be 3,707 (95% eCI: 1,311, 6,073) and expected to rise to 5,223 (95% eCI: 1,856, 8,540) in 2050s (Table S4). Estimated heat-attributable ED costs also showed a large increase. Under RCP8.5, the excess costs due to heat would be AU$6.4 million (95% eCI: 3.3, 9.4) in 2030s and further increased to AU$12.5 million (95% eCI: 6.6, 17.8) in 2050s, nearly three-times the overall heat-attributable cost during the baseline period (Table S4).

The results estimated using the baseline population profile, shown in Table S2, generally exhibited a decrease in cold-attributable ED presentations and costs, but a greater increase in heat-attributable effects, leading to a net overall increase in temperature-related ED presentations and costs. Table S3 presents the additional burden attributable to the changing climate under all RCPs and constant population.

Table 2. Projected net-, cold-, and heat-attributable TRD-ED presentations (in thousands) and costs (million AU$) and 95% eCI in Adelaide, South Australia under three RCP emissions and with medium population change scenarios.

Scenarios	Temperature	2034-2037		2054-2057	
		ED Presentations (thousands)	ED costs (million AU$)	ED Presentations (thousands)	ED costs (million AU$)
RCP2.6	Net	10.6 (-0.7, 20.8)	**20.0 (1.5, 36.7)**	12.3 (-0.4, 23.8)	**23.1 (2.3, 41.9)**
	Cold	3.3 (-6.0, 12.2)	10.5 (-6.2, 25.5)	3.5 (-6.8, 13.2)	11.6 (-6.7, 28.1)
	Heat	**7.3 (2.0, 1.5)**	**9.5 (4.1, 14.6)**	**8.9 (2.6, 15.0)**	**11.4 (5.1, 17.5)**
RCP4.5	Net	10.8 (-0.4, 20.8)	**20.2 (2.0, 36.7)**	**13.5 (1.7, 24.3)**	**24.2 (4.6, 42.0)**
	Cold	3.0 (-6.0, 11.3)	10.2 (-5.9, 24.6)	2.5 (-6.1, 11.1)	10.1 (-6.3, 24.9)
	Heat	**7.8 (2.3, 13.1)**	**10.0 (4.5, 15.3)**	**11.0 (3.9, 18.0)**	**14.1 (6.7, 21.0)**
RCP8.5	Net	**11.2 (0.6, 21.0)**	**20.7 (2.9, 36.7)**	**15.2 (3.8, 25.6)**	**25.8 (7.3, 42.8)**
	Cold	2.6 (-5.6, 10.6)	9.5 (-5.6, 23.2)	1.8 (-5.4, 8.9)	8.6 (-5.7, 21.7)
	Heat	**8.6 (2.8, 14.4)**	**11.1 (5.1, 16.9)**	**13.5 (5.5, 21.3)**	**17.2 (8.8, 25.2)**

Bold font indicates statistically significant changes based on the 95% empirical confidence interval.

Under climate and population change scenarios, the increase in heat-attributable ED presentations and costs will not be fully compensated for by the decrease in cold attributable burden. For example, in the 2030s under RCP8.5, heat-attributable ED presentations are estimated to increase by 1.9% while cold-attributable presentations will fall by only 0.2% (Table 3). In 2050s, heat-related ED presentations and costs were expected to increase by 3.7% (95% eCI: 1.7, 5.6) and 5.0% (95% eCI: 2.6, 7.1) contributing to the net increase in temperature-related burden by 3.2% (95% eCI: 1.0, 5.2) and 5.2% (95% eCI: 1.9, 8.2), respectively (Table 3). Despite climatic warming, the cold-attributable effect will increase due to demographic change that further surge the net temperature effect.

Sensitivity analyses were performed by varying the maximum lag days, df for time trend, and the number of knots for temperature splines. The overall temperature-ED presentation (Figure S3 a-d) and temperature-ED cost (Figure S4 a-d) graphs of the alternative models demonstrated that the results were consistent. Furthermore, the model with 21 lag days shows better performance in terms of capturing the morbidity and cost effects of cold and hot temperature exposures (Table S6).

Table3. Projected percentage change of net-, cold-, and heat-attributable TRD-ED presentations and costs in Adelaide, South Australia, with 95% eCI, under three RCP emissions and medium population change scenarios

Scenarios	Temperature	2034-2037		2054-2057	
		ED Presentations	ED costs	ED Presentations	ED costs
RCP2.6	Net	**1.5 (0.1, 2.7)**	**3.0 (0.6, 5.2)**	**2.1 (0.2, 3.9)**	**4.2 (0.8, 7.2)**
	Cold	0.1 (-0.9, 1.0)	1.1 (-0.8, 2.8)	0.2 (-1.2, 1.5)	1.5 (-1.2, 3.9)
	Heat	**1.4 (0.5, 2.3)**	**1.9 (0.9, 2.8)**	**2.0 (0.7, 3.2)**	**2.7 (1.3, 4.0)**
RCP4.5	Net	**1.5 (0.2, 2.8)**	**3.0 (0.6, 5.2)**	**2.6 (0.6, 4.4)**	**4.6 (1.4, 7.6)**
	Cold	0.01 (-0.9, 0.9)	0.9 (-0.8, 2.6)	-0.2 (-1.3, 0.9)	0.9 (-1.3, 2.9)
	Heat	**1.5 (0.6, 2.5)**	**2.1 (1.1, 3.1)**	**2.7 (1.2, 4.3)**	**3.7 (1.9, 5.4)**
RCP8.5	Net	**1.7 (0.3, 3.0)**	**3.2 (0.9, 5.4)**	**3.2 (1.0, 5.2)**	**5.2 (1.9, 8.2)**
	Cold	-0.2 (-1.0, 0.7)	0.7 (-1.0, 2.2)	-0.5 (-1.5, 0.6)	0.3 (-1.6, 2.1)
	Heat	**1.9 (0.8, 3.0)**	**2.5 (1.3, 3.7)**	**3.7 (1.7, 5.6)**	**5.0 (2.6, 7.1)**

Bold font indicates statistically significant changes based on the 95% empirical confidence interval.

4.7. Discussion

In this study, we explored the temperature-ED presentation and temperature-ED cost relationships and estimated baseline and future net temperature-, cold-, and heat-attributable outcomes in Adelaide, under different future greenhouse gas emissions and population change scenarios. We find that temperature contributes to substantial health and economic burden to the healthcare system. Climate change is likely to increase the heat-attributable health and economic burden for TRD diagnosis groups which will not be compensated for by a decline in the cold-attributable burden. Future health and economic impacts of climate change on emergency departments will be amplified by population growth. To our best knowledge, this is the first study to examine the direct association between temperature and ED costs.

4.7.1. Baseline health and economic burden

Our results are consistent with the broader literature showing that temperature-health relationships are non-linear, with heat effects seen at shorter lag periods than cold effects (21). Heat leads to a shorter lagged effect for ED costs than ED presentations. The reason may be the greater variability in the cost data which can easily mask a small cost increase over the lag period. Nevertheless, it should be noted that the lag effect for costs remains positive, although non-significant, after two lagged days. In the calculation of attributable burden, the risk estimates and the OT are the key determinants. We chose to use a model with a 21-day lag because this effectively captured all heat and cold effects and enabled us to estimate net temperature-attributable effects from the one model.

Heat contributed to an estimated 3,633 (95% eCI: 695, 6,498) ED presentations, and AU$4.7 million (95% eCI: 1.8, 7.5) in ED costs, in Adelaide during the 2014-2017 study period. On average, 900 ED presentations and AU$1.2 million ED costs were observed annually with a cost of AU$1,300 per heat-related ED presentation during the baseline period. In Brisbane, Australia, Toloo et al. estimated a total of all-cause heat-related excess ED costs of AU$81,752 for the period 2012-2013 (229). Another study in Melbourne, Australia, reported undiscounted total costs of $5,800 for heat-related illnesses among elderly people in 2012 (230). This wide range of estimates from different Australian cities may be due to the different cost calculation methods, exposure variables, and different population characteristics. The cost estimation in both studies (229, 230) was based on the average treatment cost per heat-related episode, rather than the actual costs. In addition, while these previous studies focused on risks associated with extreme hot temperatures, our study used year-round temperatures. This is an important distinction because studies have indicated that moderate temperatures can contribute to significant health effects (179, 231). Although not statistically significant, the estimated cold-attributable ED costs were greater than heat-attributable for the baseline period. This result is in accordance with findings reported by Noe et al. in the USA that cold temperature resulted in severe health outcomes and higher medical costs than hot temperature (232).

4.7.2. Projected health and economic burden

The Intergovernmental Panel on Climate Change forecast an increase in the global mean surface temperature of up to 4.8°C by 2081-2100 relative to 1986-2005 (54). The mean temperature change projected around mid-century for Adelaide under

RCP2.6, RCP4.5, and RCP8.5 ranges from 0.8-1.9°C (233). Our results largely demonstrate an increase in heat-attributable ED presentations and costs burden under all RCPs. A substantial difference in heat-attributable burden was observed between scenarios during the 2050s compared to 2030s. This shows a strong signal of upcoming heat impact on the healthcare system and the burden is likely to be large as the climate is projected to change significantly by the end of the century. Our findings highlight the importance of climate mitigation policies to minimize the increasing ambient temperature and curb its associated health and economic damages. For example, the RCP2.6 scenario would lead to lower economic cost to the healthcare system by the mid-century compared to RCP8.5 (234). However, the current global emissions are tracking toward the RCP8.5 level (235).

Climate change and human population dynamics could synergistically increase future health and economic impacts. Australian Bureau of Statistics projections shows for the Adelaide metropolitan area that there will be an increase in the aged population over time, from 16.8% in 2010s to 21.2% in 2050s (185). This is in line with other urban populations of developed countries which are characterized by increases in the aged population (236). Under various climate and population change scenarios, our results indicate that the health and economic impacts of hot temperatures will increase substantially. Overall, our findings agree with the findings reported by Toloo et al. that heat-related ED costs in 2030 and 2060 will be higher than the baseline period using different climate and population change scenarios (229).

The study has some particular strengths. We have established the temperature-cost relationship using an advanced statistical approach and evaluated the present and future ED cost using year-round (cold and heat) temperature data. The study used plausible climate scenarios and projected population change. It provides a unique insight into the role that temperature plays in healthcare resource utilization in the present and into future periods. Our work provides combined quantitative evidence of both the health and economic effects of climate change on the healthcare system.

The study has several limitations. First, we assumed the baseline temperature-ED presentations and temperature-ED costs relationships will remain unchanged. Second, the study did not consider population adaptation to future temperature. It is difficult to predict the rate and extent of climate adaptations and there are no applied adaptation scenarios available (237). Third, the projection of future ED presentations and ED costs were performed based on exposure-response relationships using only four years of baseline data. Fourth, the price of future healthcare service was assumed unchanged from the baseline price.

4.7.3. Conclusion

This study has established the relationships between temperature and ED presentations/costs and used this relationship to estimate future health and economic burdens using different climate and population change scenarios. Increased TRD-ED presentations and costs were observed during the baseline period and projected temperatures are likely to cause greater impacts. It is unlikely that the increase in heat-attributable ED burden will be offset by the decrease in cold effects. Our results emphasize the importance of municipal and regional climate policies to stabilize greenhouse gas emission to lower levels and the need to formulate comprehensive urban climate adaptation strategies to reduce the impacts of rising temperatures.

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Disclosure of ethical statements

Ethical clearance was obtained from the Human Research Council of SA Department of Health and Wellbeing (HREC/18/SAH/34) and The University of Adelaide (ID33179).

Competing interests

The authors declare that they have no conflict of interest.

Chapter 5 Study 2: Increasing impacts of temperature on hospital admissions, length of stay, and related healthcare costs in the context of climate change in Adelaide, South Australia

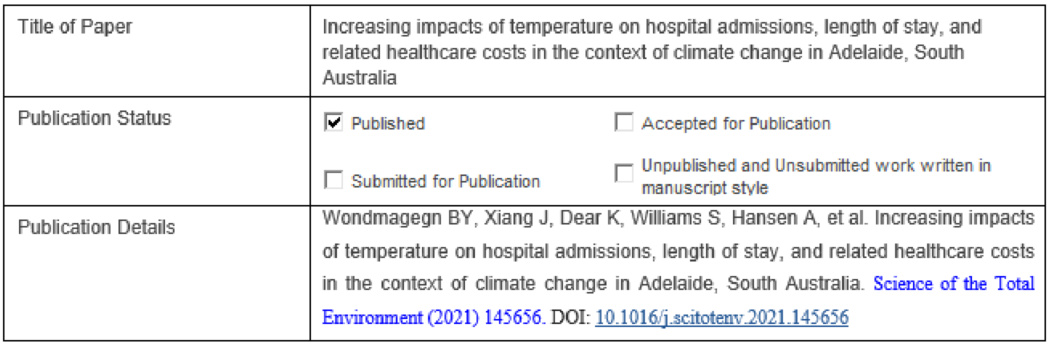
5.1. Introduction

This chapter presents study 3 which is a comprehensive study of the relationship between temperature with hospital admissions, length of hospital stay (LoS), and associated healthcare costs in Adelaide, South Australia from 2010-2015. The study further estimated the burden of ambient temperature on morbidity and healthcare costs for the baseline and two projection periods (2040-2045 and 2060-2065). The study is the first to establish the temperature-LoS and temperature-cost relationship.

5.2. Publication

Wondmagegn BY, Xiang J, Dear K, Williams S, Hansen A, et al. Increasing impacts of temperature on hospital admissions, length of stay, and related healthcare costs in the context of climate change in Adelaide, South Australia. *Science of the Total Environment* (Impact factor: 7.963). 2021, 145656. DOI: 10.1016/j.scitotenv.2021.145656.

5.3. Statement of Authorship



Title of Paper	Increasing impacts of temperature on hospital admissions, length of stay, and related healthcare costs in the context of climate change in Adelaide, South Australia
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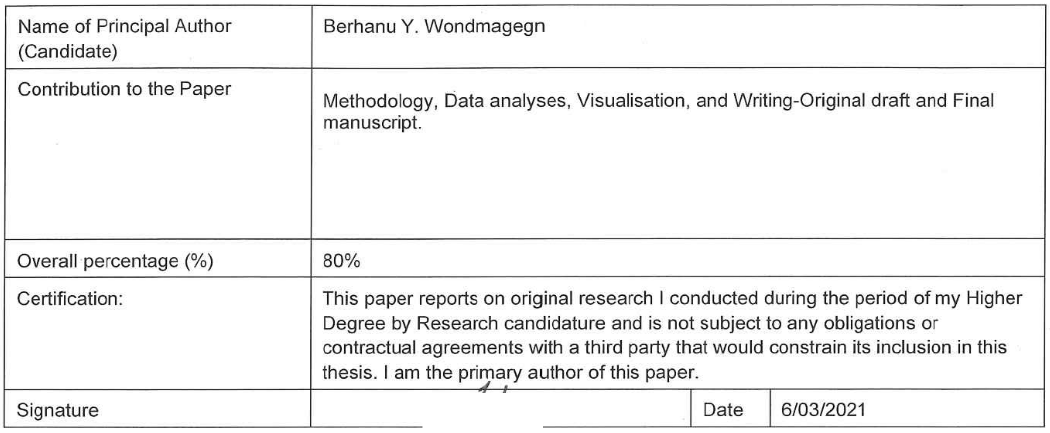
Principal Author



Name of Principal Author (Candidate)	Berhanu Y. Wondmagegn		
Contribution to the Paper	Methodology, Data analyses, Visualisation, and Writing-Original draft and Final manuscript.		
Overall percentage (%)	80%		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
Signature		Date	6/03/2021

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

iv. the candidate’s stated contribution to the publication is accurate (as detailed above);

v. permission is granted for the candidate in include the publication in the thesis; and

vi. the sum of all co-author contributions is equal to 100% less the candidate’s stated contribution.

Name of Co-Author	Jianjun Xiang		
Contribution to the Paper	Methodology, Data analyses, Visualisation, Project management, Supervision, and Writing-Reviewing and editing		
Signature		Date	9-March-2021

Name of Co-Author	Keith Dear		
Contribution to the Paper	Conceptualisation, Funding acquisition, Methodology, Data analyses, Visualisation, and Writing-Reviewing and editing		
Signature		Date	9 March 2021

Name of Co-Author	Susan Williams		
Contribution to the Paper	Methodology, Data analyses, Visualisation, Project management, and Writing-Reviewing and editing		
Signature		Date	11/03/2021

Name of Co-Author	Alana Hansen		
Contribution to the Paper	Conceptualisation, Funding acquisition, Methodology, and Writing-Reviewing and editing		
Signature		Date	25/3/21

Name of Co-Author	Dino Pisaniello		
Contribution to the Paper	Methodology, Supervision, and Writing-Reviewing and editing		
Signature		Date	12/3/21

Name of Co-Author	Monika Nitschke		
Contribution to the Paper	Methodology, Funding acquisition, Data acquisition, and Writing-Reviewing and editing		
Signature		Date	17.03.21

Name of Co-Author	John Nairn		
Contribution to the Paper	Methodology, Funding acquisition, Data acquisition, and Writing-Reviewing and editing		
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Name of Co-Author	Ben Scalley		
Contribution to the Paper	Methodology, Funding acquisition, Data acquisition, and Writing-Reviewing and editing		
Signature		Date	15.3.21

Name of Co-Author	Jianguo Xiao		
Contribution to the Paper	Methodology, Funding acquisition, Data acquisition, and Writing-Reviewing and editing		
Signature		Date	13/03/2011

Name of Co-Author	Le Jian		
Contribution to the Paper	Methodology, Funding acquisition, Data acquisition, and Writing-Reviewing and editing		
Signature		Date	9/3/2021

Name of Co-Author	Michael Tong		
Contribution to the Paper	Methodology, Data analyses, Visualisation, Project management, And Writing-Reviewing and editing		
Signature		Date	09-March-2021

Name of Co-Author	Hilary Bambrick		
Contribution to the Paper	Conceptualisation, Funding acquisition, Methodology, and Writing-Reviewing and editing		
Signature		Date	10/03/2021

Name of Co-Author	Jonathan Karnon		
Contribution to the Paper	Conceptualisation, Funding acquisition, Methodology, and Writing-Reviewing and editing		
Signature		Date	9/3/21

Name of Co-Author	Peng Bi		
Contribution to the Paper	Conceptualisation, Funding acquisition, Methodology, Project management, Supervision, and Writing-Reviewing and editing		
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Increasing impacts of temperature on hospital admissions, length of stay, and related healthcare costs in the context of climate change in Adelaide, South Australia

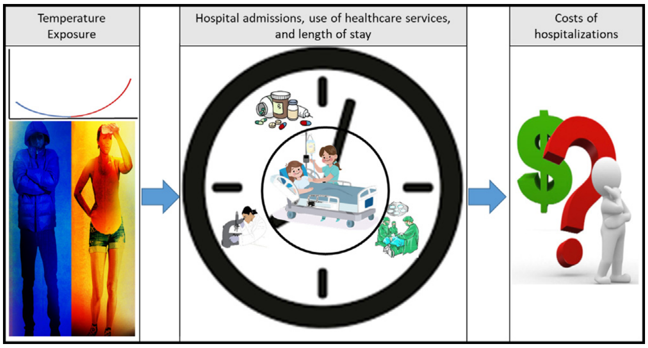
Berhanu Y. Wondmagegn [a,b], Jianjun Xiang [a], Keith Dear [a], Susan Williams [a], Alana Hansen [a], Dino Pisaniello [a], Monika Nitschke [c], John Nairn [d], Ben Scalley [e], Alex Xiao [f], Le Jian [f], Michael Tong [a], Hilary Bambrick [g], Jonathan Karnon [h], Peng Bi [a,*]

[a] *School of Public Health, The University of Adelaide, North Terrace, Adelaide, South Australia, Australia*
[b] *College of Health and Medical Sciences, Haramaya University, Dire Dawa, Ethiopia*
[c] *South Australian Department of Health and Wellbeing, Adelaide, South Australia, Australia*
[d] *Australian Bureau of Meteorology, South Australia, Australia*
[e] *Metropolitan Communicable Disease Control, Department of Health WA, Perth, Western Australia, Australia*
[f] *Epidemiology Branch, Department of Health WA, Perth, Western Australia, Australia*
[g] *School of Public Health and Social Work, Queensland University of Technology, Brisbane, Queensland, Australia*
[h] *College of Medicine and Public Health, Flinders University, Bedford Park, South Australia, Australia*

HIGHLIGHTS

- The risk of hospital admissions, LoS, and costs increases as temperature increases.
- This study provides evidence of climate impact taking account of population change.
- The healthcare costs of projected heat-attributable admissions are expected to be high.
- Strict emission control is needed to challenge the impacts of projected temperature.

GRAPHICAL ABSTRACT



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Background: A growing number of studies have investigated the effect of increasing temperatures on morbidity and health service use. However, there is a lack of studies investigating the temperature-attributable cost burden.
Objectives: This study examines the relationship of daily mean temperature with hospital admissions, length of hospital stay (LoS), and costs; and estimates the baseline temperature-attributable hospital admissions, and costs and in relation to warmer climate scenarios in Adelaide, South Australia.
Method: A daily time series analysis using distributed lag non-linear models (DLNM) was used to explore exposure-response relationships and to estimate the aggregated burden of hospital admissions for conditions associated with temperatures (i.e. renal diseases, mental health, diabetes, ischaemic heart diseases and heat-related illnesses) as well as the associated LoS and costs, for the baseline period (2010–2015) and different future climate scenarios in Adelaide, South Australia.

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* Corresponding author at: School of Public Health, The University of Adelaide, North Terrace, Adelaide, South Australia 5005, Australia.
E-mail addresses: berhanu.wondmagegn@adelaide.edu.au (B.Y. Wondmagegn), jianjun.xiang@adelaide.edu.au (J. Xiang), susan.williams@adelaide.edu.au (S. Williams), alana.hansen@adelaide.edu.au (A. Hansen), dino.pisaniello@adelaide.edu.au (D. Pisaniello), monika.nitschke@sa.gov.au (M. Nitschke), john.nairn@bom.gov.au (J. Nairn), benjamin.scalley@health.wa.gov.au (B. Scalley), jianguo.xiao@health.wa.gov.au (A. Xiao), le.jian@health.wa.gov.au (L. Jian), michael.tong@adelaide.edu.au (M. Tong), h.bambrick@qut.edu.au (H. Bambrick), jonathan.karnon@adelaide.edu.au (J. Karnon), peng.bi@adelaide.edu.au (P. Bi).

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Hospital admissions
Healthcare cost
Heat-attributable

Results: During the six-year baseline period, the overall temperature-attributable hospital admissions, LoS, and associated costs were estimated to be 3915 cases (95% empirical confidence interval (eCI): 235, 7295), 99,766 days (95% eCI: 14,484, 168,457), and AU$159 million (95% eCI: 18.8, 269.0), respectively. A climate scenario consistent with RCP8.5 emissions, and including projected demographic change, is estimated to lead to increases in heat-attributable hospital admissions, LoS, and costs of 2.2% (95% eCI: 0.5, 3.9), 8.4% (95% eCI: 1.1, 14.3), and 7.7% (95% eCI: 0.3, 13.3), respectively by mid-century.

Conclusions: There is already a substantial temperature-attributable impact on hospital admissions, LoS, and costs which are estimated to increase due to climate change and an increasing aged population. Unless effective climate and public health interventions are put into action, the costs of treating temperature-related admissions will be high.

1. Introduction

Extreme temperatures are often associated with substantial public health and economic burdens (Uejio et al., 2011; Huang et al., 2013; Wondmagegn et al., 2019; Schmitt et al., 2016). which are likely to increase with the warming climate (Massad et al., 2011). Estimating the health burden of climate change is of public health interest to assist in prevention strategies and health service planning, and several studies have examined the relationship between temperature and hospitalisations for different cold- and heat-sensitive illnesses (Ye et al., 2012; Turner et al., 2012; Song et al., 2017; McGeehin and Mirabelli, 2001; Gronlund et al., 2018). Hot ambient temperature has been reported to elevate morbidity and mortality from diverse groups of disease conditions such as cardiovascular (Phung et al., 2016), renal (Remigio et al., 2019; Borg et al., 2017), mental health disorders (Min et al., 2019; Peng et al., 2017; Shiue et al., 2016; Hansen et al., 2008a), diabetes (Xu et al., 2019), and heat-related illnesses (HRI) (Bai et al., 2014; Adam-Poupart et al., 2014; Boeckmann and Rohn, 2014). The observed increase in temperature globally and in Australia over recent decades is expected to continue with longer, more severe, and more frequent heat events (Hoegh-Guldberg et al., 2018), which are associated with an increased health service burden, including more hospital admissions (M. Li et al., 2015). There is also the potential for severe heat illnesses, such as heat stroke, that can cause prolonged hospitalisations (Argaud et al., 2007; Lawton et al., 2019). The broad impact associated with temperature-related illness typically encompasses healthcare resource use, patient suffering, and possibly life-shortening (Schmitt et al., 2016). Cost of illness analysis measures all these direct, indirect, and intangible costs in monetary terms related to the health condition.

Some USA studies have attempted to quantify the heat-attributable healthcare expenditure based on counts of hospital admissions (Schmeltz et al., 2016; Noe et al., 2012; Jagai et al., 2017; Knowlton et al., 2011). For example, Lin et al. calculated the annual excess days of hospitalisations and costs in 14 geographic regions of New York State for temperatures above a certain threshold (Lin et al., 2012), while studies by Merrill et al. and Noe et al. described both heat and cold-related hospitalisations and associated costs (Noe et al., 2012; Merrill et al., 2008). In Illinois, USA, mean and median length of hospital stay related to heat-stress illness was reported to be 3.7 and 2 days during 1987–2014, respectively (Jagai et al., 2017). A recent review of the evidence about direct medical costs of temperature from a range of medical conditions indicated that heat is causing a substantial economic burden and appears to have a disparity in vulnerability between population groups. For example, females, the elderly and low-income subgroups had the highest heat-related healthcare costs (Wondmagegn et al., 2019).

The health effects of extreme heat have been well characterised in many parts of the world, including Australian cities (M. Li et al., 2015), however, the cost implications of temperature-attributable hospital admissions to the healthcare system are not well documented and very few studies have projected the health-cost burden associated with the rising temperatures (Lin et al., 2012; Hübler et al., 2008). Given that Adelaide, the hottest state capital in Australia (Li et al., 2017; Palmer et al., 2017) with evidence of increasing healthcare demand during extreme temperatures (M. Li et al., 2015; Williams et al., 2018), there is a particular need for research on the cost burden of temperature-attributable hospital admissions to the healthcare system. Evidence for the potential future burdens of rising temperatures can inform decisions about health services needs and public health funding. Extreme heat events will be more frequent, prolonged and intense in the future (Mach et al., 2016; Mastrandrea et al., 2011), which may lead to a larger health burden and economic cost to the healthcare system. Therefore, this study aimed to (i) examine the relationships between daily mean temperature and hospital admissions for temperature-related diseases, length of hospital stay (LoS), and associated costs; (ii) estimate the baseline temperature-attributable burden of hospital admissions, LoS, and healthcare costs; and (iii) examine how this may be affected by future warming scenarios in Adelaide, South Australia.

2. Methods

2.1. Study area

This study was conducted in Adelaide, the capital city of South Australia, located at 34.9° S latitude and 138.5° E longitude and 42.7 m above sea level (Soebarto, 2008). Based on the 2016 census, the city has a total population close to 1.3 million (Australian Bureau of Statistics (ABS), 2017). It has a Mediterranean climate with relatively mild winters and very warm to hot dry summers.

2.2. Data

2.2.1. Hospital admissions, length of stay, and hospital cost data

Data relating to daily hospital admissions, length of hospital stay, and costs of hospitalisations aggregated by date of admission from January 2010 to December 2015, were obtained from the national Independent Hospital Pricing Authority (IHPA) for all eight public hospitals in the Adelaide metropolitan area. The IHPA was established in 2011 to provide independent advice about the funding of public hospitals by determining the national efficient price and cost in Australia (Independent Hospital Pricing Authority (IHPA), 2018). The International Classification of Diseases, 10th Revision (ICD-10) was used to identify hospitalisations for renal diseases (ICD-10: N00-N39.9), mental health disorders (F00-F99.9), ischaemic heart diseases (IHD) (I20-I25), diabetes (E10-E14), and heat-related illnesses (E86, T67, X30). Previous evidence (Hansen et al., 2008a; Nitschke et al., 2007, 2011; Williams et al., 2012a; Zhang et al., 2013) suggests that these disease categories represent the most sensitive illnesses to high-temperature exposure in Adelaide. Admissions due to these causes were summed according to date of hospital admission and are referred to as “temperature-related disease (TRD)”. The daily LoS represents the aggregated number of days spent in hospital by all patients admitted on the same day. Therefore, daily LoS reflects both the number of daily admissions and the duration of stay associated with those admissions. In this way, this outcome is partly a proxy measure for severity of illness and provides more information about the burden on the healthcare service. The cost refers to the direct use of medical services and goods associated with TRD hospital admissions.

2.2.2. Meteorological data

2.2.2.1. Observed temperature. Data for daily mean temperature were obtained from the Australian Bureau of Meteorology (BOM) for the period 2010–2015. The temperature data were collected from Kent Town (Station ID: 023090), a central weather station which is considered to be representative of the Adelaide urban area (Williams et al., 2012a). We chose mean temperature over other temperature metrics because it can best represent population exposure level throughout the day and night.

2.2.2.2. Climate scenarios. We used a scaling factor approach (CSIRO and Bureau of Meteorology, 2015) recommended by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and BOM to develop daily mean temperature series for future climate scenarios. The baseline daily mean temperature was adjusted by adding the average projected temperature change for three greenhouse gas emission scenarios, namely RCP2.6 (low), RCP4.5 (medium), and RCP8.5 (high) in 2040–2045 ('2040s') and 2060–2065 ('2060s') for the Southern and South-Western Flatlands, East region of Australia, relative to the climate reference period (1986–2005) (CSIRO and Bureau of Meteorology, 2019). The CSIRO/BOM advise that this is an appropriate method given the similarity in projections across seasons and at temperature extremes (CSIRO and Bureau of Meteorology, 2015). Temperature increases of 0.6 to 1.6 °C for the 2040s scenario, and from 0.6 °C to 2.5 °C for 2060s, were derived from CSIRO/BOM projections, which are based on the mean value of 20 models from the international Coupled Model Intercomparison Project Phase 5 (CMIP5) (CSIRO and Bureau of Meteorology, 2019).

2.2.3. Population data

Population census data from 2006, 2011, and 2016 and projected annual population data from 2017 to 2066 were obtained from the Australian Bureau of Statistics (ABS) (2017). For future population estimates, the medium population growth scenario with the assumption of moderate fertility, mortality, and overseas and interstate migration was used in this study, and daily population for the baseline study period and the two future scenarios (2040s, and 2060s) was estimated using a linear interpolation method (Newbury, 1981).

2.3. Statistical analysis

We used the analysis method developed by Vicedo-Cabrera et al. (2019) which consists of two steps:

Step 1. Estimation of the baseline exposure-response relationships

The associations between daily mean temperature and TRD hospital admissions, LoS, and hospitalisation costs were examined using time series regression with distributed lag non-linear models (DLNM). We used the cross-basis function in The R package 'dlnm' to establish a two-dimensional matrix of temperature and lag time (Gasparrini et al., 2010). We used a natural cubic spline with 3 internal knots placed at the 10th, 75th, and 90th percentiles of temperature, and three equally spaced knots along the lag dimension. A maximum of 21 lag days was applied to explore the potential associations of lag effect with temperature. To control for seasonality and long-term trend, we introduced a natural cubic spline with 6 degrees of freedom per year. A categorical variable for days of the week (dow) was included in the model to control for any confounding by weekly pattern. An indicator of public holidays was also included in the model as a binary variable. To ensure that costs are comparable across the different years, the daily aggregated costs of admissions were adjusted for inflation and standardised to 2015 Australian dollars. All effects were calculated in reference to the optimum temperature (OT), the lowest estimate in the cumulative exposure-response curve for each outcome variable. Models with the lowest Akaike's Information Criterion (AIC) values were chosen as the best fit.

Step 2. Estimation of baseline and future temperature-attributable TRD hospital admissions, LoS, and costs

We used the baseline exposure-response relationships (step 1) - between mean daily temperature and outcome variables (TRD hospital admissions, LoS, and costs) to estimate aggregated temperature (net)-, cold-, and heat-attributable outcomes for the baseline period and future temperature scenarios, using the 2040s and 2060s temperature series described in Section 2.2.2. Effects of mean temperature on TRD hospital admissions, LoS, and costs were calculated for each day and summed (aggregated) by study periods (for the baseline and two future scenarios - the 2040s and 2060s) for three temperature categories (net, cold, and heat), and three future temperature scenarios (RCP2.6, RCP4.5, and RCP8.5). The temperature categories were defined as: the sum of cold-and heat-attributable effects (net or temperature-attributable), and the separate effects due to temperatures lower than OT (cold-attributable fraction), and due to temperature values above the OT (heat-attributable). Effects of estimated temperature values above the baseline observed range were estimated using Monte Carlo simulation by generating 1000 samples of coefficients and assuming a multivariate normal distribution for the estimated spline model coefficients (Vicedo-Cabrera et al., 2019; Gasparrini and Leone, 2014). Results are presented as point estimates and 95% empirical confidence intervals (95% eCI).

3. Results

3.1. Descriptive statistics

Table 1 presents descriptive summary statistics of the daily TRD hospital admissions, LoS, and daily hospitalisation costs, and temperature data in Adelaide from January 2010 to December 2015 (2010s). The daily mean temperature recorded over the study period ranged from 6.7 to 37.7 °C. A total of 121,750 TRD hospital admissions were reported during the study period with daily mean admission of 56 cases. The total daily LoS, aggregated for all Temperature-Related Disease patients admitted on the same day, ranged from 11 to 1130 days, equating to approximately 1 to 12 days per admission. The total direct medical costs associated with the use of medical goods and services for all TRD hospitalisations during the study period was nearly AU$1.4 billion, with total daily costs varying from AU$0.2–2.0 million.

3.2. The relationships between mean temperature and TRD hospital admissions, LoS, and costs

Plots of the overall cumulative exposure-response association between the daily mean temperature and the three outcome variables appeared to be approximately U-shaped (Fig. 1a, c, and e). The three-

Table 1
Descriptive statistics of total daily TRD hospital admissions, LoS, hospitalisation costs, and temperature data in Adelaide, South Australia, from 2010 to 2015.[a]

	Min	Max	Mean	SD
Total daily hospitalisations	11	95	56	12
LoS (days)	11	1130	369	154
Costs (AU$)	15,959	1,969,210	635,708	254,512
Temperature (°C)	6.7	37.7	17.42	5.6

[a] Admissions, LoS, and costs for combined renal, mental health, IHD, diabetes, and heat-related diagnoses, aggregated by date of admission.

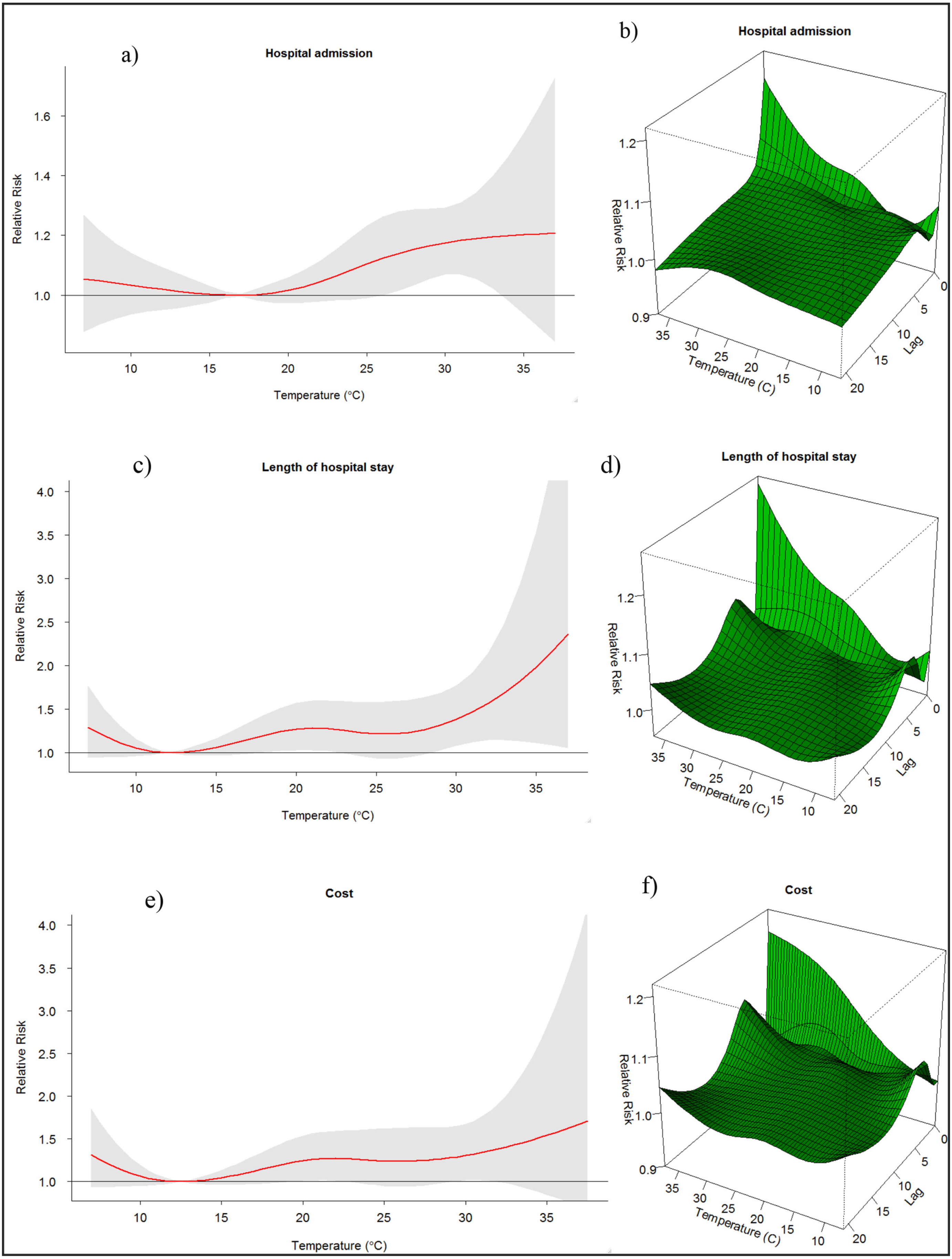
a)
Hospital admission
Relative Risk
1.0
1.2
1.4
1.6
10
15
20
25
30
35
Temperature (°C)
b)
Hospital admission
Relative Risk
0.9
1.0
1.1
1.2
35
30
25
20
15
10
Temperature (C)
0
5
10
15
20
Lag
c)
Length of hospital stay
Relative Risk
1.0
1.5
2.0
2.5
3.0
3.5
4.0
10
15
20
25
30
35
Temperature (°C)
d)
Length of hospital stay
Relative Risk
1.0
1.1
1.2
35
30
25
20
15
10
Temperature (C)
0
5
10
15
20
Lag
e)
Cost
Relative Risk
1.0
1.5
2.0
2.5
3.0
3.5
4.0
10
15
20
25
30
35
Temperature (°C)
f)
Cost
Relative Risk
0.9
1.0
1.1
1.2
35
30
25
20
15
10
Temperature (C)
0
5
10
15
20
Lag

Table 2
The baseline net temperature-, cold-, and heat-attributable TRD hospital admissions, LoS, and costs of hospitalisations with 95% eCI in Adelaide, South Australia from 2010 to 2015.[a]

Outcomes	Net	Cold	Heat
	(95% eCI)	(95% eCI)	(95% eCI)
Hospital admissions (in thousands = N)	**3.9 (0.2, 7.3)**	0.9 (−2.4, 4.1)	**3.0 (0.3, 5.7)**
LoS (in thousand days)	**99.8 (14.5, 168.5)**	5.7 (−4.1, 14.8)	**94.1 (7.2, 163.7)**
Costs (Million AU$)	**159.1 (18.8, 269.0)**	12.2 (−8.5, 32.9)	**147.0 (1.2, 265.1)**

Bold font indicates statistically significant results based on the 95% empirical confidence interval.

[a] Admissions, LoS, and costs for combined renal, mental health, IHD, diabetes, and heat-related diagnoses, aggregated by date of admission.

dimensional graphs show the relative risk (RR) of hospital admissions, LoS, and costs for TRD by main exposure and lag effect (Fig. 1b, d, and f). The highest heat effects were observed on day 0 for the three outcomes. Elevated effects of heat and cold temperature were also observed at the lag of 4–6 days for LoS and costs (Fig. 1d and f). Although most of the TRD hospital admissions included in our analysis are more prone to heat, an overall increase at both low and high extremes of temperature was observed. Optimal temperatures (OT) of 15.1 °C, 12.0 °C and, 12.5 °C were identified for the daily TRD hospital admissions, LoS, and healthcare costs, respectively.

3.3. Baseline temperature-attributable burdens of TRD hospital admissions, LoS and costs

Table 2 shows the baseline (2010s) net temperature-, cold-, and heat-attributable TRD hospitalisations, LoS, and costs. Temperature contributed to a substantial number of hospital admissions, LoS, and costs. A total of 3915 (95% eCI: 235, 7295) admissions were temperature-attributable. Over the study period, temperature contributed to 99,766 days (95% eCI: 14,484, 168,457) days of hospitalisations and AU$159.1 million (95% eCI: 18.8, 269.0) costs to the healthcare system. The impacts of hot ambient temperatures were observed to be higher compared to cold exposures. Heat led to 3010 (95% eCI: 270, 5707) hospital admissions, 94,056 (95% eCI: 7234, 163,725) days of hospitalisations, and AU$147.0 million (95% eCI: 1.2, 265.1) economic cost to the healthcare system (Table 2).

3.4. Estimates of future temperature-attributable TRD hospital admissions, LoS, and costs

Assuming a constant population, the excess burden and fractional percentage change of net temperature-, cold-, and heat-attributable effects were estimated for the 2060s climate scenarios (Table 3). Under the higher temperature scenario, it is estimated there will be 939 (95% eCI: 279, 1549) additional heat-attributable TRD hospital admissions, a 0.8% (95% eCI: 0.2, 1.3) increase relative to the overall baseline admissions. The excess heat-attributable hospitalisation costs will be AU $11.7 million (95% eCI: 0.9, 19.6) in 2040s (Table S3), and AU$27.8 million (95% eCI: 1.9, 46.5) in 2060s. The increase in heat-attributable hospital admissions, LoS, and healthcare costs cannot be fully compensated by the decrease in cold-attributable effects in the 2040s (Table S3) and 2060s (Table 3). A summary of aggregated future net temperature-, cold-, and heat-attributable hospital admissions, LoS, and costs under three different climate change scenarios and constant population are presented in Table S2 for the 2040s and 2060s scenarios.

When the climate scenarios were coupled with predicted population growth, we found a moderate increase in hospital admissions and a greater increase of LoS and hospitalisation costs relative to the overall baseline period. Using the 2060s higher temperature scenario, heat-attributable TRD hospital admissions and LoS were estimated to be 5732 (95% eCI: 838, 10,478) and 162,356 days (95% eCI: 15,026, 279,467). The costs of hospitalisations associated with heat-attributable TRD were expected to be AU$221.6 million (95% eCI: 2.36, 398.9), AU$231.62 million (95% eCI: 2.8, 415.4), and AU$253.6 million (95% eCI: 3.6, 448.8) under RCP2.6, RCP4.5, and RCP8.5, respectively (Fig. 2). For the 2040s scenarios, heat is estimated to contribute costs ranging from AU$195.7 million (95% eCI: 2.0, 352.6) to AU$206.0 million (95% eCI: 2.5, 369.6) for the different temperature scenarios (Table S4).

Table 4 presents estimates for the future additional burden and the fractional percentage change of net temperature-, cold-, and heat-attributable TRD hospital admissions, LoS, and hospitalisation costs under population growth and three different climate scenarios for 2060s. The increases in the number of excess heat-attributable hospital admissions is estimated to range from 1628 (95% eCI: 195, 3022) to 2721 (95% eCI: 556, 4805) (Table 4). Similarly, the additional cost burden was estimated to be in the range AU$74.7 million (95% eCI: 1.1, 133.4) to AU$106.7 million (95% eCI: 3.6, 185.7) (Table 4). The percentage change in net temperature-, cold-, and heat-attributable fraction of hospital admissions, LoS, and costs of hospitalisations are presented in Table S5 for the 2040s and Table 4 for 2060s for the three temperature scenarios. While estimates for heat-related healthcare costs increase significantly, the change in healthcare costs due to cold temperature is not significant. For example, for the higher temperature 2060s scenario, hot ambient temperature will increase TRD hospital admissions by 2.2% (95% eCI: 0.5, 3.9), LoS by 8.4% (95% eCI: 1.1, 14.3), and costs by 7.7% (95% eCI: 0.3, 13.3) with no significant change in the cold-related outcomes (Table 4).

4. Discussion

Global warming and its health impacts are likely to cause considerable economic pressure on the healthcare system. The majority of research internationally (Song et al., 2017; Gronlund et al., 2018; Bunker et al., 2016) and in Australia (Williams et al., 2012a, 2018; Watson et al., 2019; Williams et al., 2012b; Hansen et al., 2008b) has suggested that climate change is likely to increase the burden of heat-related hospital admissions, yet the economic impact to the healthcare system due to increased temperature-attributable hospital admissions and total days of hospital stay has not been thoroughly explored. To shape public health policies and maximize the use of available resources, baseline temperature-attributable, cold-attributable and heat-attributable hospital admissions, LoS, and hospitalisation costs were quantified here, and possible future effects were also estimated under multiple climate and population change scenarios. A combined group of medical conditions termed as TRD, which encompasses renal diseases, mental health disorders, IHD, diabetes, and HRI was used in our analysis. These disease

Fig. 1. Overall cumulative exposure-response curves (panels a, c, and e) and exposure-lag-response (panels b, d, and f) relationships between daily mean temperature and TRD hospitalisations, LoS, and costs at 0–21 lag days in Adelaide, South Australia from 2010 to 2015. The red line in panels a, c, and e represents overall effect estimate and the grey area is the 95% CI. Relative risk (RR) of hospital admissions, LoS, and costs by daily mean temperature was estimated relative to the respective optimum temperature (OT) for each outcome.

Table 3

Estimated excess and percentage change of net temperature-, cold-, and heat-attributable TRD hospital admissions, LoS, and costs of hospitalisations at 95% eCI for 2060s climate scenarios with constant population in Adelaide, South Australia.[a]

Temperature scenarios[b]	Exposure	Excess burden			Percentage change		
		Admissions (N = thousands)	LoS (in thousand days)	Costs (in million AU$)	Admissions	LoS	Costs
Lower	Net	0.1 (−0.2, 0.4)	2.5 (−1.3, 5.6)	3.3 (−3.7, 9.0)	0.08 (−0.17, 0.32)	0.3 (−0.2, 0.7)	0.2 (−0.3, 0.6)
	Cold	−0.09 (−0.3, 0.2)	−1.2 (−2.9, 0.7)	−2.5 (−6.0, 1.2)	−0.07 (−0.28, 0.14)	−0.2 (−0.4, 0.1)	−0.2 (−0.4, 0.2)
	Heat	**0.2 (0.04, 0.3)**	**3.7 (0.7, 6.0)**	**5.8 (0.5, 9.7)**	**0.15 (0.04, 0.26)**	**0.5 (0.1, 0.7)**	**0.44 (0.03, 0.70)**
Mid	Net	0.2 (−0.4, 0.8)	5.7 (−2.3, 12.2)	7.8 (−7.0, 19.9)	0.2 (−0.4, 0.7)	0.7 (−0.3, 1.5)	0.6 (−0.5, 1.4)
	Cold	−0.2 (−0.7, 0.4)	−2.4 (−5.7, 1.3)	−4.9 (−12.0, 2.5)	−0.6 (−0.6, 0.3)	−0.3 (−0.7, 0.2)	−0.4 (−0.9, 0.2)
	Heat	**0.4 (0.1, 0.7)**	**8.1 (1.6, 13.1)**	**12.6 (1.0, 21.3)**	**0.3 (0.1, 0.6)**	**1 (0.2, 1.6)**	**0.9 (0.1, 1.5)**
Higher	Net	0.6 (−0.8, 1.8)	13.7 (−2.8, 27.0)	19.3 (−11.3, 44.6)	0.5 (−0.6, 1.5)	1.7 (−0.3, 3.3)	1.4 (−0.8, 3.2)
	Cold	−0.4 (−1.4, 0.8)	−4.1 (−10.1, 2.5)	−8.5 (−21.4, 5.0)	−0.3 (−1.2, 0.6)	−0.5 (−1.3, 0.3)	−0.6 (−1.5, 0.4)
	Heat	**0.9 (0.3, 1.5)**	**17.8 (3.5, 28.7)**	**27.8 (1.9, 46.5)**	**0.8 (0.2, 1.3)**	**2.2 (0.4, 3.6)**	**2.0 (0.1, 3.3)**

Bold font indicates statistically significant results based on the 95% empirical confidence interval.

[a] Admissions, LoS, and costs for combined renal, mental health, IHD, diabetes, and heat-related diagnoses, aggregated by date of admission.

[b] Temperature scenarios are based on different emissions scenarios, as described. Lower (RCP2.6), Mid (RCP4.5) and Higher (RCP8.5).

conditions were selected because of their public health importance in Australia, particularly in relation to heat exposure in Adelaide (Hansen et al., 2008a; Nitschke et al., 2007, 2011; Williams et al., 2012a; Zhang et al., 2013; Hansen et al., 2008b). Our results suggest that heat contributes to a substantial burden of hospital admissions, total days in hospital, and healthcare costs for the Adelaide population, and future climate change is likely to bring an additional load to the healthcare system.

The cumulative exposure-response plots show significant relationships between mean daily temperature and TRD hospital admissions, LoS, and costs relative to OT. At the highest temperatures, the number of hospital admissions is observed to be steady. The reason could be related to population behaviour change and the heat warning system implemented in Adelaide since 2010 (Nitschke et al., 2016). After the implementation of the program, reductions in the number of hospital admissions were reported (Nitschke et al., 2016). The observed increase in LoS might be due to more severe health conditions associated with exposure to high temperatures. Despite a considerable increase in the LoS, the cost showed only a slightly increasing trend. This could be due to the greater variability of cost data that might lead to weaker statistical power to detect a cost increase.

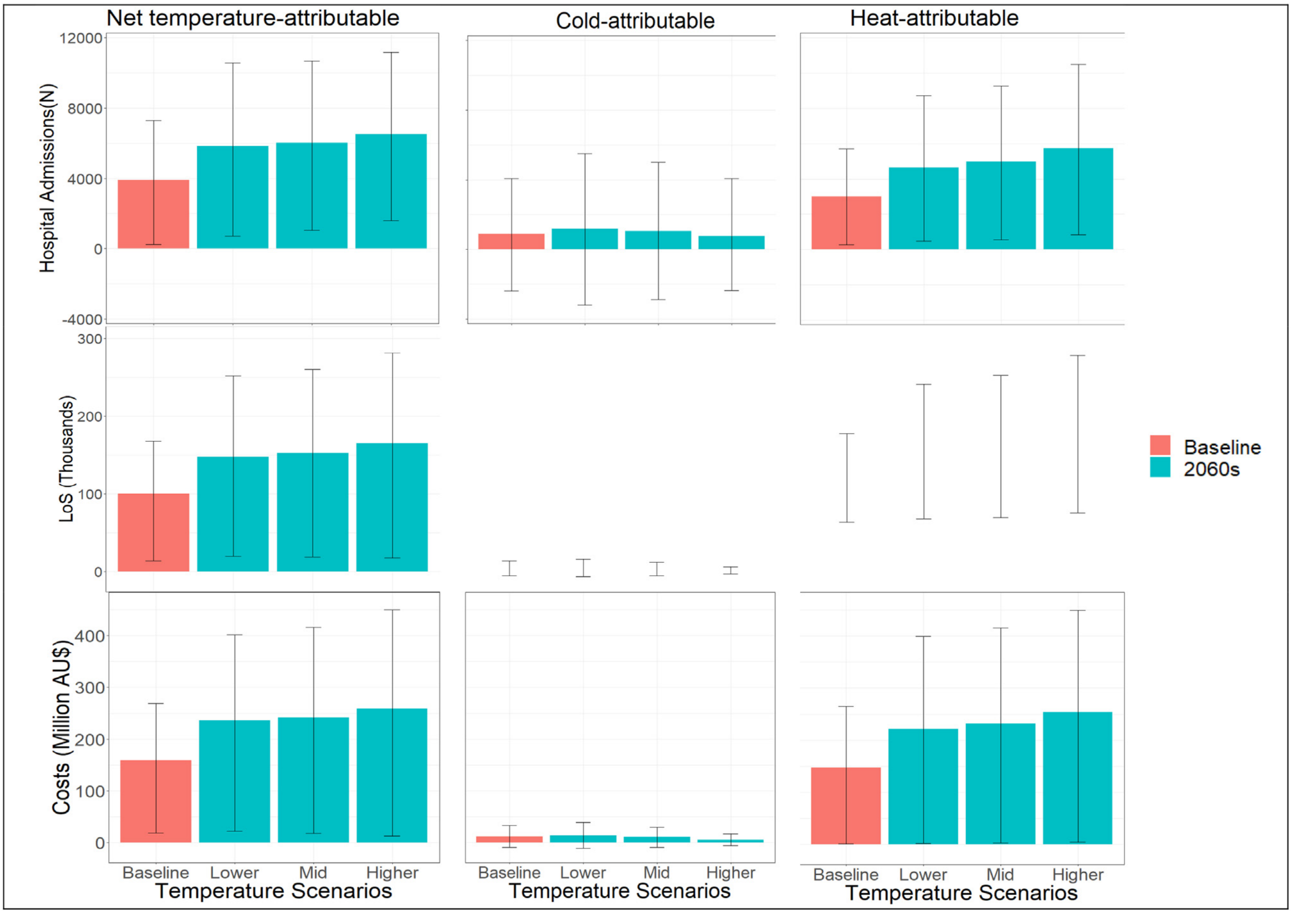

Fig. 2. Estimated net temperature-, cold-, and heat-attributable TRD hospital admissions, LoS, and costs of hospitalisations under three climate and population change scenarios with 95% eCI in Adelaide for 2060s.

Table 4
Estimated excess and percentage change of net/temperature-, cold-, and heat-attributable TRD hospital admissions, LoS, and costs of hospitalisations at 95% eCI under climate and population change scenarios in Adelaide, South Australia for the 2060s.[a]

Temperature scenarios[b]	Exposure	Excess burden			Percentage change		
		Admissions (in thousands = N)	LoS (in thousand days)	Costs (in million AU$)	Admissions	LoS	Costs
Lower	Net	**1.9 (0.4, 3.3)**	**48.6 (5.3, 82.8)**	**76.6 (4.7, 133.3)**	**1.6 (0.3, 2.7)**	**6.0 (0.7, 10.2)**	**5.5 (0.3, 9.6)**
	Cold	0.3 (−0.8, 1.4)	0.8 (−0.9, 2.4)	1.9 (−2.2, 6.0)	0.2 (−0.7, 1.2)	0.1 (−0.1, 0.3)	0.1 (−0.2, 0.4)
	Heat	**1.6 (0.2, 3.0)**	**47.8 (4.4, 82.7)**	**74.7 (1.1, 133.4)**	**1.3 (0.2, 2.5)**	**5.9 (0.5, 10.2)**	**6.0 (0.01, 10.6)**
Mid	Net	**2.1 (0.6, 3.6)**	**53.3 (4.8, 91.8)**	**83.1 (0.1, 147.2)**	**1.7 (0.5, 2.9)**	**6.6 (0.6, 11.4)**	**6.0 (0.01, 10.6)**
	Cold	0.1 (−0.7, 0.9)	−0.9 (−1.7, 0.1)	−1.6 (−2.8, 0.03)	0.1 (−0.5, 0.8)	−0.1 (−0.2, 0.02)	−0.1 (−0.2, 0.002)
	Heat	**2.0 (0.3, 3.6)**	**54.2 (5.8, 93.0)**	**84.7 (1.7, 149.4)**	**1.6 (0.3, 2.9)**	**6.7 (0.7, 11.3)**	**6.1 (0.1, 10.7)**
Higher	Net	**2.6 (0.4, 4.5)**	**64.9 (4.8, 113.5)**	99.8 (−4.8, 181.5)	**2.1 (0.4, 3.7)**	**8.0 (0.6, 14.0)**	7.2 (−0.3, 13.0)
	Cold	−0.1 (−0.7, 0.4)	−3.4 (−8.0, 1.8)	−6.8 (−16.1, 3.1)	−0.1 (−0.6, 0.3)	−0.4 (−1.0, 0.2)	−0.5 (−1.2, 0.2)
	Heat	**2.7 (0.6, 4.8)**	**68.3 (9.1, 115.8)**	**106.7 (3.6, 185.7)**	**2.2 (0.5, 3.9)**	**8.4 (1.1, 14.3)**	**7.7 (0.3, 13.3)**

Bold font indicates statistically significant results based on the 95% empirical confidence interval.

[a] Admissions, LoS, and costs for combined renal, mental health, IHD, diabetes, and heat-related diagnoses, aggregated by date of admission.

[b] Temperature scenarios are based on different emissions scenarios, as described. Lower (RCP2.6), Mid (RCP4.5) and Higher (RCP8.5).

Our results show that hot ambient temperatures are the major contributor to hospital admissions, LoS, and costs, which is unsurprising considering the heat-sensitive disease groups used in our analysis. The cost of hospitalisation due to heat-related admissions was AU$147.0 million (95% eCI: 1.2, 265.1), during 2010–2015, which accounts for about 92% of the overall temperature-attributable healthcare costs. Inclusion of some diagnosis groups such as respiratory illnesses, which is not included in our analysis, would be expected to show greater effects at the cold extremes. This is evident from other studies, for example, in the USA during 2005, the overall admissions of heat- and cold-related hospital admissions were almost equal, with 6200 hospital admissions attributed to cold temperatures and 6500 hospital admissions attributed to hot temperatures (Merrill et al., 2008).

The LoS can be associated with the severity of medical conditions (Zhao et al., 2013) and can be translated into an economic cost to the health care system. Reducing the length of in-hospital stays can significantly save healthcare costs (Taheri et al., 2000). We found that exposure to higher temperature leads to increasing total days of hospitalisation, which can be due to the increase in the number of hospital admissions and/or increasing disease severity. However, we have not examined the average LoS per admission which could be a useful indicator of clinical severity in relation to heat exposure, although this could warrant future research. Some previous studies have examined hospital LoS in relation to ambient temperature. For example, a study of heat stroke hospitalised patients in the USA indicated that the length of hospital stay could be higher, up to 21 days when acute myocardial infarction occurred (Bathini et al., 2020). This would significantly increase the LoS for patients. Similarly, a study of heat-stress illness in the USA indicated an increasing trend in the number of days of hospital stay over time (Wondmagegn et al., 2019; Noe et al., 2012). Our study showed an overall baseline temperature-attributable cost of AU$159.1 million (95% eCI: 18.8, 269.0), with a substantial contribution from the hot ambient temperature. Similar studies in the USA reported a combined cold- and heat-related cost of USD120 million during 2005 (Merrill et al., 2008) and USD134 million during 2004 and 2005 (Noe et al., 2012). Schmeltz et al. reported a total of USD656.1 million hospitalisation costs due to heat-related illness during the period 2001–2010; approximately USD65.6 million per year (Schmeltz et al., 2016). Apart from trend comparison, it is difficult to compare our results to other studies conducted elsewhere, due to substantial differences in population size, national health costs, climatic conditions and disease diagnosis groups considered. Most of the diagnosis groups included in our study are more sensitive to heat than cold temperatures. Adelaide has relatively mild winters and hot summers, and the public health impacts of heat and cold are likely to differ from cities in colder climates.

Climate scenarios have been used for planning and formulating policies in the context of an uncertain climatological future (T. Li et al., 2015). In this study, we used plausible mid-century climate scenarios, based on different greenhouse gas emission scenarios (RCP2.6, RCP4.5 and RCP8.5), to estimate future impacts of temperatures on TRD hospital admissions, LoS and healthcare costs in Adelaide. As global emissions are currently tracking close to the RCP8.5 trajectory (Hawkins et al., 2017), the estimates consistent with this scenario may be the most relevant. In the CSIRO/BOM projections of regional climate change, three uncertainty sources were accounted namely: scenario uncertainty, response uncertainty, and natural variability uncertainty (CSIRO and Bureau of Meteorology, 2015). However, the uncertainty associated with greenhouse gas concentrations is small as the various RCPs differ only marginally for near-term projections (CSIRO and Bureau of Meteorology, 2015). Our results show that higher temperature scenarios will lead to a considerable cost burden due to increased hospital admissions by mid-century in Adelaide. For example, high-temperature scenarios resulted in net temperature-attributable costs of AU$166.3 million (95% eCI: 12.8, 285.4) in the 2040s and AU$178.4 million (95% eCI: 9.1, 310.2) in 2060s. The number of heat-attributable excess hospital admissions and costs in the 2060s scenario would be nearly double that of the 2040s scenario, which suggests the potential impacts of the warming climate.

The estimated burden of climate change needs to take future population growth into account. Compared to the baseline period, the apparent increase in heat-related hospital admissions and costs estimated for the 2060s scenario (i.e. 2060–2065) would be amplified by a combination of climate and population change. Previous studies also concluded that the economic cost of climate change to the healthcare system will increase substantially with the population increase. For example, in Germany, the national annual heat-related hospitalisation cost is estimated to be €495 million by the end of the century (2071 and 2100), an increase of 6 times relative to the 1971 to 2000 period. Of this cost, demographic change accounted for nearly 39% (€191 million) (Hübler et al., 2008). Similarly, our study estimated that in 2060s, the costs of heat-attributable hospitalisations for TRD due to climate change alone would be nearly AU$174.7 million under higher temperature scenario and when coupled with population change, the cost would increase to AU$253.6 million, of which population increase accounted for 32% (AU $78.9 million).

The cost of providing healthcare has been growing at unsustainable rates in many countries, e.g. in the USA (Branning and Vater, 2016; Borgonovi and Compagni, 2013), the European countries (Borgonovi and Compagni, 2013), and Australia (Calder et al., 2019) and the key issue will be how to maximize benefits of available resources in the healthcare system in the context of climate change (Higgins and Harris, 2012). To this end, projection studies may facilitate the development of effective and efficient climate adaptation and mitigation actions (Hamin and Gurran, 2009). Moreover, tackling climate change tends to have health and other co-benefits such as clean air and sustainable economic development (Cheng and Berry, 2013). It is unclear how populations will adapt to the warming climate in the coming decades. Hence, healthcare policies will play a vital role in tackling the impacts of climate change on population health.

It is apparent that healthcare spending is rising continuously and many contributing factors including disease prevalence/incidence (Thorpe et al., 2005), service price (Dunn et al., 2016), population growth and ageing (Dieleman et al., 2017) have been hypothesised as the main drivers. We estimated direct medical costs of future temperature to the healthcare system assuming that the price is constant to the baseline value. Under different climate and population change scenarios, our results indisputably indicate that the cost of heat-related hospitalisations will increase in the future regardless of currency inflation. Therefore, relevant stakeholders including decision-makers, industries, and healthcare professionals should be at the forefront of the battle against the impacts of climate change.

This study has three key strengths. Firstly, we have used multiple and relevant outcomes including hospital admissions, days in the hospital, and associated hospital costs to provide a comprehensive and more detailed assessment of the temperature-attributable burden to the healthcare system. Secondly, our study provides estimates of the possible future burden of climate change using plausible climate scenarios (based on RCP2.6, RCP4.5, and RCP8.5 emissions trajectories) to capture likely impacts. Thirdly, the validity of our estimates is enhanced by combining future population change into account.

This study has some limitations. Firstly, since there is no conventional method of predicting future exposure-response relationships, our estimates for different climate scenarios assume that the observed baseline relationship would be unchanged temporally. Secondly, the six-year baseline data used to establish the exposure-response relationship and to estimate future hospital admissions, LoS, and costs might not be robust which is likely to be affected by anomalous temperature. Thirdly, a more precise estimate of future temperature effects would be possible if the potential for climate adaptation and mitigation actions were considered (Gasparrini and Leone, 2014). Our results highlight the need for adaptation; however, it is difficult to predict the rate and extent of future possible behavioural, physiological, and technological adaptations (Bunker et al., 2016). Therefore, these findings provide a counterfactual scenario that can be used for policy advocacy or targeted interventions. Fourth, even though our study incorporates the effects of population growth in the scenarios, the temperature burden on the ageing population is not addressed. Fifth, our scenarios were based on plausible mid-century regional temperature projections, for RCP2.6 (low), RCP4.5 (medium), and RCP8.5 (high) emissions scenarios, and derived from the CMIP5 models of most relevance to the Australian context. However, the scenarios may not adequately account for increased climate variability and the potential for unprecedented heat and cold extremes. Last, we assumed the price of healthcare services will be the same in the future as the baseline cost.

5. Conclusion

In this contribution, we examined the relationship of temperature with TRD hospital admissions, LoS, and healthcare costs and then quantified the baseline and future temperature-attributable burden for the population of Adelaide, South Australia. Temperature contributed to a substantial number of hospital admissions and costs during the baseline period and is likely to pose greater effects in the future if the temperature increases as projected. The growing heat attributable burden is not likely to be compensated by the decline in the cold attributable burden. The results of this study highlight the likely health and economic consequences of increasing temperatures to the healthcare system. Understanding the link between climate change with health and medical costs can help governments build the capacity of the health system and to guide the formulation of local public health policies, and allocation of healthcare resources. Further studies may be necessary to determine the extent of adaptation needed and to suggest plausible measures to protect and promote population health in a warming climate.

CRediT authorship contribution statement

Berhanu Y. Wondmagegn: Methodology, Data analyses, Visualisation, and Writing-Original draft and Final manuscript. **Jianjun Xiang**: Methodology, Data analyses, Visualisation, Project management, Supervision, and Writing-Reviewing and editing. **Susan Williams** and **Michael Tong**: Methodology, Data analyses, Visualisation, Project management, and Writing-Reviewing and editing. **Keith Dear**: Conceptualisation, Funding acquisition, Methodology, Data analyses, Visualisation, and Writing-Reviewing and editing. **Dino Pisaniello**: Methodology, Supervision, and Writing-Reviewing and editing. **Monika Nitschke**, **John Nairn**, **Ben Scalley**, **Alex Xiao**, and **Le Jian**: Methodology, Funding acquisition, Data acquisition, and Writing-Reviewing and editing. **Alana Hansen**, **Hilary Bambrick**, and **Jonathan Karnon**: Conceptualisation, Funding acquisition, Methodology, and Writing-Reviewing and editing. **Peng Bi**: Conceptualisation, Funding acquisition, Methodology, Project management, Supervision, and Writing-Reviewing and editing.

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Compliance with ethical standard

The research was approved by the South Australia Department for Health and Wellbeing Human Research Ethics Committee (HREC/18/SAH/34) and The University of Adelaide Human Research Ethics Committee (ID33179). The study used daily aggregated data and cell values less than five were restricted. The researchers declare that the confidentiality of the data was kept.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2021.145656.

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Chapter 6 Study 3: Impact of heatwave intensity using Excess Heat Factor on emergency department presentations and related healthcare costs in Adelaide, South Australia

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6.1. Introduction

Chapter 5 presents the results of study 2 that examined the relationship of heatwave severity and intensity defined by the Excess Heat Factor (EHF) index and ED presentations and costs in Adelaide, South Australia for the warm seasons from 2014-2017. The study is unique in using the continuous (heatwave intensity) and categorical (low and severe heatwave) heatwave severity category to estimate the number of ED presentations and cost to the healthcare system. A subgroup analysis by age and specific disease diagnosis groups were performed the results are summarized.

6.2. Publication

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Principal Author

Name of Principal Author (Candidate)	Berhanu Y. Wondmagegn		
Contribution to the Paper	Methodology, Data analyses, Visualisation, and Writing-Original draft and Final manuscript.		
Overall percentage (%)	80%		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
Signature		Date	6/03/2021

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By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);

ii. permission is granted for the candidate in include the publication in the thesis; and

iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

Name of Co-Author	Jianjun Xiang		
Contribution to the Paper	Methodology, Data analyses, Visualisation, Project management, Supervision, and Writing-Reviewing and editing		
Signature		Date	9-March-2021

Name of Co-Author	Keith Dear		
Contribution to the Paper	Conceptualisation, Funding acquisition, Methodology, Data analyses, Visualisation, and Writing-Reviewing and editing		
Signature		Date	9 March 2021

Name of Co-Author	Susan Williams		
Contribution to the Paper	Methodology, Data analyses, Visualisation, Project management, and Writing-Reviewing and editing		
Signature		Date	11/03/2021

Name of Co-Author	Alana Hansen		
Contribution to the Paper	Conceptualisation, Funding acquisition, Methodology, and Writing-Reviewing and editing		
Signature		Date	25/3/21

Name of Co-Author	Dino Pisaniello		
Contribution to the Paper	Methodology, Supervision, and Writing-Reviewing and editing		
Signature		Date	12/3/21

Name of Co-Author	Monika Nitschke		
Contribution to the Paper	Methodology, Funding acquisition, Data acquisition, and Writing-Reviewing and editing		
Signature		Date	17.01.21

Name of Co-Author	John Nairn		
Contribution to the Paper	Methodology, Funding acquisition, Data acquisition, and Writing-Reviewing and editing		
Signature	[redacted]	Date	12/03/2021

Name of Co-Author	Ben Scalley		
Contribution to the Paper	Methodology, Funding acquisition, Data acquisition, and Writing-Reviewing and editing		
Signature		Date	15.3.21

Name of Co-Author	Blesson M Varghese		
Contribution to the Paper	Methodology, Writing-Reviewing, and editing		
Signature	[redacted]	Date	25|03|2021

Name of Co-Author	Jianguo Xiao		
Contribution to the Paper	Methodology, Funding acquisition, Data acquisition, and Writing-Reviewing and editing		
Signature		Date	13/03/2011

Name of Co-Author	Le Jian		
Contribution to the Paper	Methodology, Funding acquisition, Data acquisition, and Writing-Reviewing and editing		
Signature	[redacted]	Date	9/3/2021

Name of Co-Author	Michael Tong		
Contribution to the Paper	Methodology, Data analyses, Visualisation, Project management, And Writing-Reviewing and editing		
Signature		Date	09-March-2021

Name of Co-Author	Hilary Bambrick		
Contribution to the Paper	Conceptualisation, Funding acquisition, Methodology, and Writing-Reviewing and editing		
Signature		Date	10/03/2021

Name of Co-Author	Jonathan Karnon		
Contribution to the Paper	Conceptualisation, Funding acquisition, Methodology, and Writing-Reviewing and editing		
Signature		Date	9/3/2021

Name of Co-Author	Peng Bi		
Contribution to the Paper	Conceptualisation, Funding acquisition, Methodology, Project management, Supervision, and Writing-Reviewing and editing		
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Impact of heatwave intensity using excess heat factor on emergency department presentations and related healthcare costs in Adelaide, South Australia

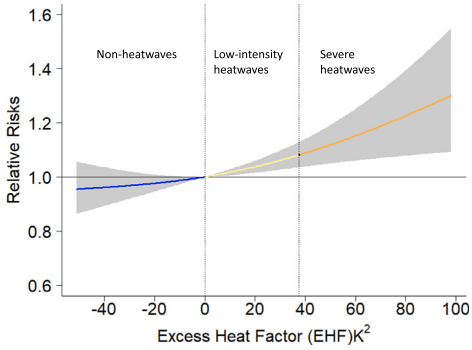
Berhanu Y. Wondmagegn [a,b], Jianjun Xiang [a,c], Keith Dear [a], Susan Williams [a], Alana Hansen [a], Dino Pisaniello [a], Monika Nitschke [d], John Nairn [e], Ben Scalley [f], Blesson M. Varghese [a], Alex Xiao [g], Le Jian [g], Michael Tong [a], Hilary Bambrick [h], Jonathan Karnon [i], Peng Bi [a,*]

[a] School of Public Health, The University of Adelaide, North Terrace, Adelaide, South Australia, Australia
[b] College of Health and Medical Sciences, Haramaya University, Ethiopia, Dire Dawa, Ethiopia
[c] Department of Preventive Medicine, School of Public Health, Fujian Medical University, Fujian Province 350108, China
[d] South Australian Department of Health and Wellbeing, Adelaide, South Australia, Australia,
[e] Australian Bureau of Meteorology, South Australia, Australia
[f] Metropolitan Communicable Disease Control, Department of Health WA, Perth, Western Australia, Australia
[g] Epidemiology Branch, Department of Health WA, Perth, Western Australia, Australia
[h] School of Public Health and Social Work, Queensland University of Technology, Brisbane, Queensland, Australia
[i] College of Medicine and Public Health, Flinders University, Bedford Park, South Australia, Australia

HIGHLIGHTS

- The increase of heatwave intensity increases risks of ED presentations and cost.
- Severe heatwaves were associated with higher rates of ED presentations and costs.
- Heat-related illness contributed most to the ED presentations and ED costs.
- The young and the elderly are particularly vulnerable to the effects of heatwave.

GRAPHICAL ABSTRACT



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ABSTRACT

Background: The health impacts of heatwaves are a growing public health concern with the frequency, intensity, and duration of heatwaves increasing with global climate change. However, little is known about the healthcare costs and the attributable morbidity associated with heatwaves Objective

This study aims to examine the relationship between heatwaves and costs of emergency department (ED) presentations, and to quantify heat-attributable burden during the warm seasons of 2014–2017, in Adelaide, South Australia.

Methods: Daily data on ED presentations and associated costs for the period 2014–2017 were obtained from the South Australian Department of Health and Wellbeing. Heatwave intensity was determined using the excess heat

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* Corresponding author at: School of Public Health, The University of Adelaide, North Terrace, Adelaide, South Australia 5005, Australia.
E-mail addresses: berhanu.wondmagegn@adelaide.edu.au (B.Y. Wondmagegn), jianjun.xiang@adelaide.edu.au (J. Xiang), keith.dear@adelaide.edu.au (K. Dear), susan.williams@adelaide.edu.au (S. Williams), alana.hansen@adelaide.edu.au (A. Hansen), dino.pisaniello@adelaide.edu.au (D. Pisaniello), monika.nitschke@sa.gov.au (M. Nitschke), john.nairn@bom.gov.au (J. Nairn), benjamin.scalley@health.wa.gov.au (B. Scalley), blesson.varghese@adelaide.edu.au (B.M. Varghese), jianguo.xiao@health.wa.gov.au (A. Xiao), le.jian@health.wa.gov.au (L. Jian), michael.tong@adelaide.edu.au (M. Tong), h.bambrick@qut.edu.au (H. Bambrick), jonathan.karnon@adelaide.edu.au (J. Karnon), peng.bi@adelaide.edu.au (P. Bi).

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factor (EHF) index, obtained from the Australian Bureau of Meteorology. A distributed lag non-linear model (DLNM) was used to quantify the cumulative risk of heatwave-intensity over a lag of 0–7 days on ED presentations and costs. Effects of heatwaves were estimated relative to no heatwave. The number of ED presentations and costs attributable to heatwaves was calculated separately for two EHF severity categories (low-intensity and severe/extreme heatwaves). Subgroup analyses by disease-diagnosis groups and age categories were performed.

Results: For most disease diagnosis and age categories, low-intensity and severe heatwaves were associated with higher rates of ED presentations and costs. We estimated a total of 1161 (95% empirical confidence interval (eCI): 342, 1944) heatwave-attributable all-cause ED presentations and associated healthcare costs (thousands) of AU $1020.3 (95% eCI: 224.9, 1804.7) during the warm seasons of 2014–2017. The heat-related illness was the disease category contributing most to ED presentations and costs. Age groups 0–14 and ≥ 65 years were most susceptible to heat.

Conclusions: Heatwaves produced a statistically significant case-load and cost burden to the ED. Developing tailored interventions for the most vulnerable populations may help reduce the health impacts of heatwaves and to minimise the cost burden to the healthcare system.

1. Introduction

A heatwave is an extreme weather event characterized by a period of excessively high temperatures (Zhang et al., 2019), which has been widely acknowledged as a significant public health concern worldwide. Several studies from the USA, Canada, Europe, Asia, and Australia (Xu et al., 2016; Kravchenko et al., 2013; Campbell et al., 2018) have consistently reported the adverse morbidity and mortality effects of heatwaves in recent years. Some studies have focused on the effects of heatwaves on high-risk populations such as children (Xu et al., 2014) and the elderly (Bunker et al., 2016) while others have focused on total and/or cause-specific health outcomes (Li et al., 2015). Extreme heat may cause heat-related illnesses (HRI) and worsen existing medical conditions such as renal diseases, mental health disorders, respiratory illnesses, heat-related illnesses (HRI), diabetes, and ischaemic heart diseases (IHD) (Li et al., 2015). According to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), heatwaves are becoming more and more common globally and this trend is very likely to continue throughout this century in the context of a changing climate (IPCC, 2014). Heat-attributable morbidities and associated direct medical expenses are expected to increase. Direct medical cost includes expenses related to heat-related health service use such as costs for staff, medical devices, pharmaceuticals, diagnostic tests, and procedures (Wondmagegn et al., 2019). However, in Australia and elsewhere, there is a lack of studies on the economic burden of the heatwave on the healthcare system.

The frequency of extreme heat episodes in Australia has increased and heatwaves have become longer and more intense (Blunden and Arndt, 2016). In addition, the number of days per year with temperatures over 35°C has increased in most parts of Australia (Blunden and Arndt, 2016). Emergency departments are at the front line responding to heat-related morbidities/injuries. Many studies have demonstrated the adverse effects of heatwaves on emergency department (ED) presentations in most jurisdictions of Australia (Campbell et al., 2018; Li et al., 2015). Health effects during a heatwave period are largely preventable (Nitschke et al., 2016) and public health measures can reduce the burden on hospital services. Investigating the healthcare cost of ED presentations due to extreme heat may help policymakers and relevant stakeholders to understand whether the ED system is hampered by extreme heat economically, to plan preventive actions, and to allocate healthcare resources.

Different heat metrics, such as daily minimum and maximum dry-bulb air temperatures (Williams et al., 2011) and apparent temperature, (Loughnan et al., 2014) have been used to measure heatwave intensity. However, these heat metrics do not capture some key factors such as human acclimatization (Sheridan and Kalkstein, 2010) and the duration of heatwaves, (Sheridan and Lin, 2014) which are likely to affect heat impacts. The excess heat factor (EHF), a new heatwave metric developed by Nairn et al. in 2009 has several advantages over other heat indices, as it takes acclimatization and length of heatwave into account (Nairn et al., 2009). In Australia, EHF has been reported to be a valid predictor of heat-related health outcomes (Williams et al., 2018) and health service demand (Jegasothy et al., 2017). Moreover, it has been increasingly used to estimate heatwave attributable health outcomes globally (Roye et al., 2019; Wang et al., 2018; Urban et al., 2017). To our knowledge, however, it has not been used in the estimation of heat-attributable healthcare costs.

This study aimed to provide a comprehensive assessment of the health and economic burden of heatwaves to the hospital emergency department in South Australia. A time-series regression using DLNM model was employed 1) to examine the (EHF-defined) heatwave-ED presentations and heatwave-ED costs relationship, and 2) to estimate aggregated/overall heatwave-attributed burden to emergency departments in Adelaide, South Australia, from 2014 to 2017.

2. Methods

2.1. Study area

Adelaide, the capital city of South Australia, has a Mediterranean temperate climate characterized by hot, dry summers with mild to cold winters. Adelaide generally experiences repeated heatwave events during the summer months of each year. The city has an urban area of 3258 km^2 with a total population of 1,295,714 in 2016 (Australian Bureau of Statistics (ABS), 2019a).

2.2. Data and sources

2.2.1. Health and cost data

Details of daily aggregated ED presentations and associated ED costs for the warm seasons during the period 2014 to 2017 were obtained from the South Australian Department of Health and Wellbeing. The ED data were from all public hospitals in the Adelaide metropolitan area. All-cause ED presentations and costs during the study period were categorised by age groups (0–14 years, 15–64 years, and ≥ 65 years). Furthermore, ED presentations and the corresponding costs were categorised by specific disease diagnosis using the 10th version of the International Classification of Diseases (ICD-10) as: mental health disorders (F00-F99.9), respiratory diseases (J00-J99), renal diseases (N00-N39.9), ischaemic heart diseases (I20-I25), diabetes (E10-E14), and direct heat-related illnesses (E86, T67, X30). Several studies have shown that these health outcomes significantly increase during hot temperatures in Adelaide (Nitschke et al., 2007; Nitschke et al., 2011; Hansen et al., 2008a; Hansen et al., 2008b; Williams et al., 2012; Zhang et al., 2013) and other locations (Fuhrmann et al., 2016; Winquist et al., 2016; Wilson et al., 2013; Toloo et al., 2014). The daily aggregated costs represented the direct medical ED costs to provide health care to ED patients during the study period.

2.2.2. Excess Heat Factor (EHF) data

The EHF index is used to forecast heatwave conditions for the Australian Bureau of Meteorology's (BOM) national heatwave service.

(Nairn and Fawcett, 2014) We obtained daily EHF data from BOM based on the Kent Town meteorological station (station number: 023090), a site considered to be representative of weather conditions across the Adelaide metropolitan area (Nitschke et al., 2007; Borg et al., 2017; Varghese et al., 2019; Borg et al., 2019). According to the BOM, a heatwave is defined as a combination of three consecutive unusual days with excess heat and heat stress relative to the local climate. EHF is based on a three-day averaged daily mean temperature and consists of two components: a short-term (EHI_{sig}) and long-term (EHIaccl) daily mean temperature anomalies which are calculated as follows:

$$EHF_{sig(i)} = (T_i + T_{i+1} + T_{i+2})/3 – T_{95} \quad (1)$$

$$EHF_{accl(i)} = (T_i + T_{i+1} + T_{i+2})/3 – (T_{i-1} + \ldots + T_{i-30})/30 \quad (2)$$

The index in Eq. (1) measures significant heat events by comparing the 3-day average temperature with the 95th percentile for historical 30-year temperature data, while Eq. (2) represents the anomaly between the three days and the recent past 30-days which is assumed to be related to acclimatization. A forward EHF calculation is chosen because EHF is used for the 7-day heatwave severity forecast service. To account for the forward EHF calculation, we conducted a 7-day lag analysis. The EHF is the products of both (EHI_{sig}) and (EHI_{accl}) as shown below.

$$EHF = EHF_{sig} \times \max(1, EHF_{accl}) \left[(K)^2\right] \quad (3)$$

Both indices have temperature units (°C) and their product, EHF, can be expressed in $°C^2$ or more conveniently in K^2 (Nairn and Fawcett, 2014), and the latter is used in this study. Heatwave days are defined as having values of $EHF > 0$ as described by Nairn and Fawcett (2014).

In this study, we used the continuous EHF metric as (i) a variable for heatwave intensity and (ii) to define two heatwave categories (low-intensity and severe). The BOM uses the ratio of daily EHF to the 85th percentile of all positive EHF values (EHF/EHF_{85}) at a particular location to classify heatwaves into three severity categories. Accordingly, heatwave severity ratios between 0 and < 1 define low-intensity heatwaves, ration of 1 to <3 are severe, and ≥3 are extreme (Nairn et al., 2018). Based on this classification, EHF data for Adelaide were categorised into two heatwave severity groups for this study (as no extreme heatwaves were observed during the study period) with EHF ranging from 0.01 to 37.38 K^2 represented low-intensity heatwaves and 37.39 to 112.16 K^2 represented severe heatwaves.

2.3. Statistical analysis

2.3.1. Modelling heatwave-intensity-ED presentations and ED costs

A standard generalized linear time-series regression combined with a distributed lag non-linear model (DLNM) was used to examine the relationship between heatwave-intensity and ED presentations and related healthcare costs. According to previous research, DLNM is a flexible tool to evaluate the delayed and non-linear effects of environmental exposures on health outcomes (Gasparrini, 2011). To model the impact of heatwaves, a quasi-Poisson distribution was used for the count (ED presentation) data, (Watson et al., 2019; Cui et al., 2019) while a Gamma distribution was used for the continuous (ED cost) data (Polesel et al., 2019). The GLM with gamma distribution is a commonly used modelling approach for non-negative, skewed, continuous outcome variables such as insurance claims (Anderson et al., 2012; Chen et al., 2018).

The model for ED presentations was fitted as follows:

Y_t ~ quasiPoisson (μ_t):

$$\log(\mu_t) = \alpha + cb(\beta_1 ehf_{t,l}) + \beta_2.ns(time, 4df{*}4\ year) + \beta_3.dow + \beta_4.phol$$

and the model for ED costs was:

Y_t ~ Gamma (μ_t):

$$\log(\mu_t) = \alpha + cb\left(\beta_1.ehf_{t,l)}\right) + \beta_2.ns(time, 4df{*}4\ year) + \beta_3.dow + \beta_4.phol$$

where, Y_t is the expected value of the daily ED presentations/costs on day t; α is the intercept of the model; cb is the cross-basis matrix produced by applying DLNM to EHF; l is the lag days; ns(.) is a natural cubic spline with 4 degrees of freedom per year (Roye et al., 2019); dow is the day of the week as a 7-level factor; and phol is a binary variable representing public holidays. If the day is a public holiday the value of 1 otherwise 0. Accounting to the lowest Akaike Information Criterion (AIC), the maximum unconstrained lag of $l = 7$ days (Roye et al., 2019) was used to capture delayed effects of heatwave-intensity. Considering that heatwaves only occur during the warmer months, we restricted the analysis to the warm season in Adelaide (October to March). The calculation of EHF indirectly computed the interaction between humidity and minimum daily temperature. Hence, the confounding effects of humidity in human response to heat have been fairly represented inherently in the EHF metric (Nairn and Fawcett, 2014). Moreover, Adelaide has low humidity during the summer season (Varghese et al., 2019; Milazzo et al., 2016; Zhang et al., 2008). Results are presented as relative risks and 95% CI at different heatwave-intensities relative to $EHF = 0\ K^2$, as this defines the threshold value for a heatwave (Roye et al., 2019; Nairn and Fawcett, 2014).

2.3.2. Calculation of heat-attributable ED presentations and cost burden

The estimation of total heat-attributable ED presentations and costs follows the method developed by Gasparrini and Leone (2014). The general definition of attributable number (AN*x*) for heatwave exposure *x* can be given by:

$AN_x = n(1 - \exp(-x.\beta_x))$where, n is the total number of cases, and β_x is the parameter representing the risk associated with the exposure obtained from the DLNM model. It is the association with heat exposure $EHF = x$ relative to a reference value of $EHF = 0$. The overall heat-attributable burdens were calculated for all heatwave days and two heatwave severity categories (low and severe heatwaves) using a continuous EHF metric. Subgroup analysis of heat-attributable ED presentations and costs by age were performed by accounting for population structure in each group. The 95% empirical Confidence Intervals (eCI) were obtained empirically through Monte Carlo simulations. Using data of consumer price index (CPI) obtained from the Australian Bureau of Statistics (ABS) (Australian Bureau of Statistics (ABS), 2019b), costs were calculated in thousands of Australian dollars (AU$) and adjusted for inflation (in 2017 value). All statistical analyses were performed using R software. A sensitivity analysis was conducted by changing the lag period and the degrees of freedom for time. The project received ethics approval from the University of Adelaide Human Ethics Committee (ID33179) and the South Australia Department of Health and Wellbeing (HREC/18/SAH/34).

Table 1
Daily minimum, maximum, and mean ED presentations by age, and disease diagnostic groups in warm seasons (October–March) in Adelaide, South Australia, 2014–2017.

Categories		Min	Max	Mean ± SD
Diagnosis groups	All-cause	794	1297	1013 (±68.4)
	Renal	13	51	29 (±5.9)
	Mental health	28	98	55 (±8.5)
	Respiratory	29	153	69 (±16.6)
	HRI	1	44	4 (±4.1)
	IHD	1	24	10 (±3.5)
	Diabetes	1	10	3 (±1.6)
Age	0–14 years	127	296	209 (±25.2)
	15–64 years	425	771	566 (±43.8)
	≥ 65 years	168	324	239 (±26.1)

HRI: Heat-related illnesses. IHD: Ischemic heart disease.

Table 2
Daily minimum, maximum, and mean ED costs by age, and disease diagnostic groups in warm seasons (October–March) in Adelaide, South Australia, 2014–2017.

Categories		Min	Max	Mean ± SD
Diagnosis groups	All-cause	514,266	1,035,666	753,286 (±75,667.7)
	Renal	6007	55,269	25,744 (±6817.6)
	Mental health	24,905	139,185	64,870 (±18,130.0)
	Respiratory	22,247	133,422	58,516 (±16,900.6)
	HRI	57.92	46,441	3354 (±3583.1)
	IHD	970.4	32,637	9944 (±4415.4)
	Diabetes	63.78	16,946	2811 (±2029.4)
Age	0–14 years	57,715	165,210	108,113 (±17,551.1)
	15–64 years	257,887	587,242	410,750 (±44,894.1)
	≥ 65 years	156,704	359,929	234,423 (±33,931.1)

HRI: Heat-related illnesses. IHD: Ischaemic heart disease.

3. Results

3.1. Descriptive statistics

A total of 738,822 all-cause ED presentations and nearly AU$549 million ED costs were observed in the three complete and two partial warm seasons (729 days) from January 2014 to December 2017. Descriptive summary statistics of daily aggregated ED presentations (Table 1) and costs (Table 2) by disease diagnosis groups and age categories are presented. During the study period, the mean daily all-cause ED presentations and costs in Adelaide were 1013 and AU$753,286, respectively. By diagnosis groups, the daily number of ED presentations ranged from 1 to 153, and ED costs from AU$58 to AU$139,185. Within age categories, the highest mean daily ED presentations and costs were observed for the age group 15–64 years.

3.2. Heatwave-intensity and ED presentations and cost relationships

Based on the continuous EHF heatwave intensity measure, a total of 65 heatwave days were identified (days with EHF > 0) during the study period. Of these, 55 days were categorised as low-intensity heatwave days and 10 days were classified as severe heatwave days. The risks of ED presentations and costs of the heatwave were generally higher during heatwave days relative to non-heatwave days (EHF = 0) for most disease diagnosis groups and age categories. Fig. 1 shows the cumulative exposure-response curves for ED presentations (a) and ED costs (b) using 7 days of lag period for all-cause ED visits. The relative risk (RR) of daily ED presentations and costs plotted was the function of heatwave and lag effects. The curves show non-linear dose-response relationships. Similarly, we observed non-linear heatwave-ED presentations and heatwave-cost relationships for different age categories (Fig. 2) and specific disease conditions (Fig. S1). By heatwave severity category, there was an increasing trend for risks of ED presentations and associated medical costs during low-intensity heatwaves for most disease diagnosis groups and all age categories and the risks further increased during the severe heatwave days. Exceptionally, ED presentations for renal diseases show a non-significant decreasing trend as heatwave severity increased. Analyses of the lag effect using full ranges of EHF value and specific EHF percentiles (10th, 60th, 85th, 95th, and 99th) show significant effects of heatwaves on all-cause ED presentations (Fig. S2) and costs (Fig. S3) were observed until 5 days of the lag period.

3.3. The attributable burden of heatwaves

Heatwaves resulted in a total of 1161 (95% eCI: 342, 1944) all-cause ED presentations (Table 3) and AU$1020.3 (95% eCI: 224.9, 1804.7) associated ED costs in thousands (Table 4) over the study period (2014–2017). Effects of heatwave by severity category indicated that 573 (95% eCI: 340, 1972) ED presentations and AU$505.8 (95% eCI: 89.2, 940.5) costs were attributable to low-intensity heatwaves; with 590 (95% eCI: 180, 1005) ED presentations and AU$516.9 (95% eCI: 61.1, 924.9) costs attributable to severe heatwaves.

Table 3 shows presentations by disease category (renal, mental health disorders, respiratory illnesses, HRI, IHD, and diabetes). The results show that there were 389 (95% eCI: 342, 427) heatwave-attributable ED presentations for HRI during the study period. By

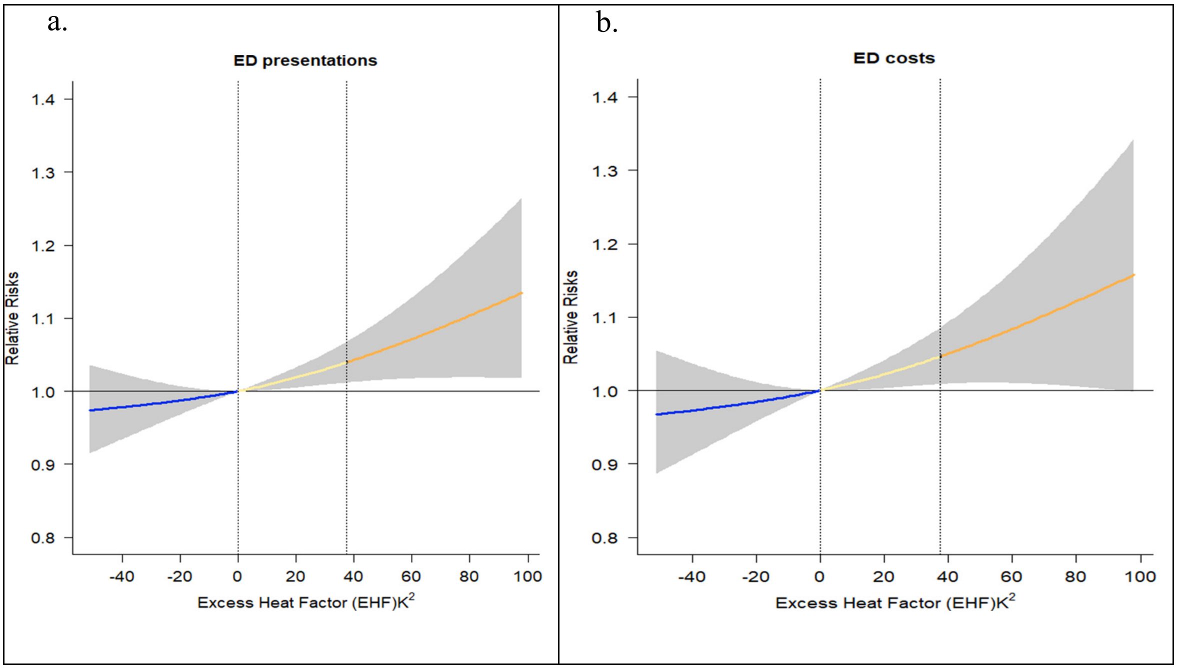

Fig. 1. Cumulative effects of heatwaves on ED presentations (a) and costs (b) for all-cause ED presentations in Adelaide, South Australia from 2014 to 2017. The blue line represents non-heatwave days, the yellow line represents low-intensity heatwave days ($n = 55$), and the orange line represents severe heatwave days ($n = 10$)). Results are expressed as the relative risk (95% CI).

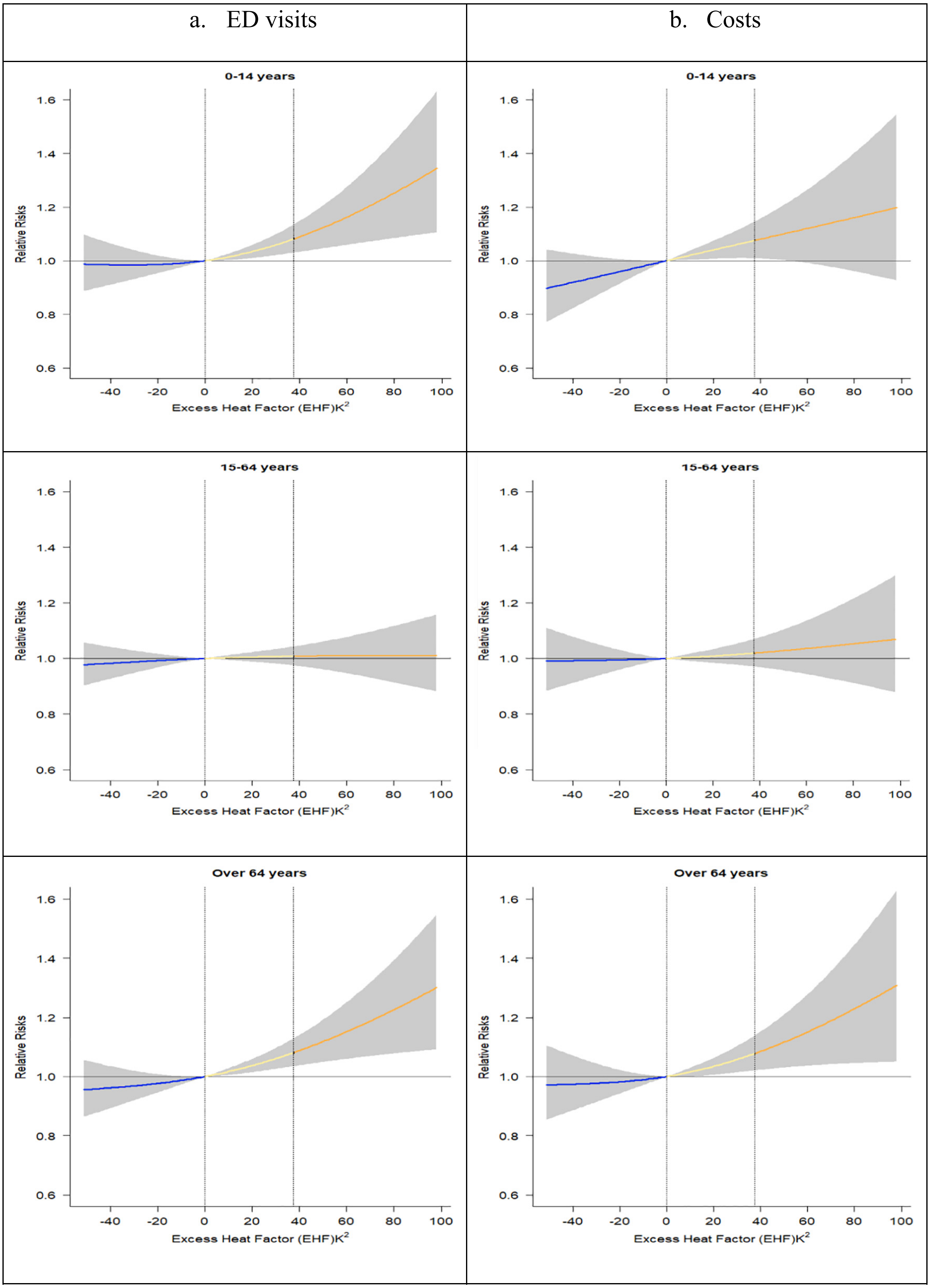

Fig. 2. Cumulative effects of heatwaves on ED presentations (a) and costs (b) by age category in Adelaide, South Australia from 2014 to 2017. The blue line represents non-heatwave days, the yellow line represents low-intensity heatwave days (n = 55), and the orange line represents severe heatwave days (n = 10)). Results are expressed as the relative risk (95% CI).

heatwave severity category, low-intensity heatwaves resulted in an aggregated 198 (95% eCI: 164, 228) HRI ED presentations and AU$126.1 (95% eCI: 93.8, 156.6) costs while severe heatwaves resulted in 220 (95% eCI: 192, 241) ED presentations (Table 3) and AU$188.7 (95% eCI: 152.4, 209.5) costs (Table 4).

By age group, heatwaves were associated with a greater number of ED presentations and medical costs within both the very young and older age groups compared to the intermediate age group. An estimated 449 (95% eCI: 173, 702) ED presentations and AU$222.6 (95% eCI: 48.8, 416.7) healthcare costs in the younger age group were attributable to

Table 3
Aggregated number of ED presentations (N) by diagnosis and age group attributed to heatwaves, low-intensity heatwaves and severe heatwaves (95% eCI) in Adelaide, South Australia, 2014–2017.

Categories		All heatwaves (EHF = 0.01–98.6 K^2)	Heatwave severity categories	
			Low-intensity heatwaves (EHF = 0.01–37.4 K^2)	Severe heatwaves (EHF = 37.5–98.6 K^2)
Diagnosis group (N)	All-cause	**1161 (342, 1944)**	**573 (340, 1972)**	**590 (180, 1005)**
	Renal	44 (−53, 134)	33 (−17, 87)	12 (−50, 60)
	Mental health	100 (−31, 226)	57 (−10, 124)	43 (−29, 104)
	Respiratory	127 (−25, 270)	61 (−24, 143)	67 (−15, 138)
	HRI	**389 (342, 427)**	**198 (164, 228)**	**220 (192, 241)**
	IHD	−3 (−61, 53)	−5 (−37, 26)	2 (−35, 28)
	Diabetes	12 (−15, 34)	7 (−7, 19)	4 (−12, 15)
Age-groups (N)	0–14 years	**449 (173, 702)**	**206 (60, 350)**	**242 (99, 378)**
	15–64 years	160 (−427, 729)	98 (−206, 387)	62 (−273, 352)
	≥ 65 years	**554 (228, 834)**	**271 (114, 430)**	**286 (117, 433)**

Bold cells show significant results at 95% eCI.
HRI: Heat-related illnesses.
IHD: Ischaemic heart disease.

heatwave. Low-intensity heatwaves attributed to 206 (95% eCI: 60, 350) ED presentations and AU$126.4 (95% eCI: 25.1, 223.6) healthcare costs and severe heatwaves contributed to 242 (95% eCI: 99, 378) ED presentations which resulted to an economic cost of AU$94.7 (95% eCI: 3.4, 188.0) to the healthcare system.

This study showed that people aged 65 and over were vulnerable to heatwaves. During the study period, an estimated 554 (95% eCI: 228, 834) ED presentations were attributed to heatwaves. Our analyses by heatwave severity level indicated that an estimated 271 (95% eCI: 114, 430) ED presentations were attributed to low-intensity heatwaves and 286 (95% eCI: 117, 433) presentations attributed to severe heatwaves (Table 3). A cost of AU$530.1 (95% eCI: 160.2, 890.4) was attributed to heatwaves for people aged 65 and over. The healthcare cost attributed to low intensity and severe heatwaves were AU$242.8 (95% eCI: 37.0, 440.0) and AU$289.3 (95% eCI: 101.6, 484.1), respectively (Table 4).

A sensitivity analysis was carried out to assess the robustness of the model by altering the degrees of freedom for time (3 and 6) and the lag period (4 and 10). The results were similar as shown in Fig. S4.

4. Discussion

It is widely acknowledged (IPCC, 2014) that extreme heat is causing increasing adverse health effects leading to an increasing burden on hospital services. In the context of climate change, there is a need to understand the potential economic impacts to the healthcare system of heatwaves and the burden placed on hospital EDs, so that authorities can be aware of any additional needs for resources during heat events. Furthermore, understanding this burden can act as an imperative for developing cost-effective public health prevention strategies to reduce avoidable ED presentations. This study identified the association between heatwaves and ED presentations together with associated costs, and quantified the heat-attributable burden to the ED system in Adelaide, South Australia, using EHF as a measure of heatwave intensity/severity. Differences in the burden of ED presentations and economic costs attributed to heatwaves were observed between specific disease diagnosis groups and age categories. More ED presentations and higher costs were observed for direct heat-related illnesses than other diagnostic categories. People aged 0–14 years and ≥ 65 years were the most vulnerable population groups.

A previous study of heatwave and health outcomes using the EHF metric suggested that the health effects could lag by a period of more than 3 days (Williams et al., 2018). Several other studies identified non-linear associations between health outcomes and extreme temperatures (Ostro et al., 2009; Gao et al., 2015; Gasparrini et al., 2015) even above specific threshold limits (Hondula et al., 2014). In line with the prior study (Roye et al., 2019), we used a DLNM to detect 7-day lag effects of the heatwave and found non-linear, approximately 'J' shaped, heatwave-ED presentations and heatwave-cost relationships. As heatwave severity rises, increased risks of ED presentations and costs were observed for most disease and age categories. To our best knowledge, this is the first such study in the world to use a continuous heatwave intensity metric to establish heatwave-ED presentation and -ED-cost relationships and to quantify attributable burdens. The results from this study indicated that the morbidity and health resource impacts of heatwaves could last up to five days after the heatwave, which has implications for heat-health intervention actions, health service planning, and public health policy.

Table 4
Aggregated costs (in thousands AU$) of ED presentations attributed to heatwave, low-intensity heatwaves, and severe heatwaves (95% eCI) in Adelaide, South Australia, 2014–2017.

Categories		All heatwaves (EHF = 0.01–98.6 K^2)	Heatwaves severity categories	
			Low-intensity heatwaves (EHF = 0.01–37.4 K^2)	Severe heatwaves (37.4–98.6 K^2)
Diagnosis group	All-cause	**1020.3 (224.9, 1804.7)**	**505.8 (89.2, 940.5)**	**516.9 (61.1, 924.9)**
	Renal	77.3 (−45.7, 190.3)	46.6 (−20.0, 107.2)	30.4 (−45.9, 92.7)
	Mental health	−47.9 (−285.7, 167.8)	0.6 (−118.5, 120.8)	−48.9 (−178.0, 55.4)
	Respiratory	137.6 (−6.6, 276.2)	62.6 (−19.0, 138.0)	75.2 (−0.8, 139.5)
	HRI	**295.5 (235.9, 333.8)**	**126.1 (93.8, 156.6)**	**188.7 (152.4, 209.5)**
	IHD	−15.1 (−93.8, 57.4)	−17.2 (−59.0, 23.4)	2.2 (−53.7, 41.9)
	Diabetes	**37.5 (4.6, 61.4)**	**22.1 (6.3, 37.6)**	15.9 (−4.6, 26.8)
Age-groups	0–14 years	**222.6 (48.8, 416.7)**	**126.4 (25.1, 223.6)**	**94.7 (3.4, 187.9)**
	15–64 years	242.8 (−307.7, 858.3)	112.8 (−209.0, 417.6)	130.7 (−189.9, 422.7)
	≥ 65 years	**530.1 (160.2, 890.4)**	**242.8 (37.0, 440.0)**	**289.3 (101.6, 484.1)**

Bold cells show significant results at 95% eCI.
HRI: Heat-related illnesses.
IHD: Ischaemic heart disease.

4.1. Heatwave impacts on all-cause ED presentations and costs

In Australia, heatwaves increase pressure on the ambulance, emergency, and inpatient services and place a substantial health burden on the already overloaded healthcare system (Doctors for the Environment Australia, 2016). During the study period, heatwave contributed to an estimated AU$1020.3 (95% eCI: 224.9, 1804.7) ED costs that can be avoided through integrated heat-health interventions. Few studies have estimated the cost of excess ED presentations associated with heatwave. For example, a study in Brisbane, Australia, reported an excess ED costs of AU $81,752 on hot days (Tmax ≥35 °C) during 2000–2012 (Toloo et al., 2015). In California, USA, the 2006 heatwave resulted in estimated medical costs of $14 million for all-cause excess ED visits (Knowlton et al., 2011). We believe that a more convincing and statistically representative cost estimation can be made using the exposure-response relationship. However, none of the existing studies used the heatwave-cost relationship and EHF as heatwave intensity metric.

We estimated the effects of increasing heatwave severity by using the EHF as a continuous measure, and subsequently by defining two categories of heatwave severity (low-intensity and severe heatwaves). Our results indicated greater risks of ED presentations and costs associated with low-severity heatwaves relative to non-heatwave days, and the risks further increase with increasing heatwave severity. This finding is consistent with the result reported by Williams et al. in South Australia (2018) that the rate of ED presentations increased as heatwave severity increases (Williams et al., 2018). Apart from the substantial difference in the number of low-intensity and severe heatwave days (55 vs 10 days), the estimated cost burden associated with each category was approximately comparable. This suggests that the cost burden to the healthcare system is higher on severe heatwave days, possibly through the increased case-load to the ED (Doctors for the Environment Australia, 2016) and increased disease severity or complications.

Heatwave contributed to nearly 0.2% of total all-cause ED visits and costs during the study period and nearly 1.8% and 2.1% of all ED visits and costs during heatwave days, respectively. Despite the small percentage of the overall ED burden, it still has public health and economic importance, particularly as the numbers of hot days are increasing as projected (Cleugh et al., 2011). On severe heatwave days, an additional 59 ED presentations (8 additional patients per day per EDs in Adelaide). Over a 5-day heatwave, this could increase to almost 300 patients. The additional burden represents potentially avoidable costs and indicates an opportunity for potential cost savings from cost-effective public health prevention strategies.

4.2. Heatwave impacts on specific disease conditions

Heat-related morbidity is reported to be associated with a range of pre-existing medical conditions (Li et al., 2015) including cardiovascular (Phung et al., 2016), renal (Brennan et al., 2019), mental health disorders (Lõhmus, 2018), diabetes (Xu et al., 2019), and HRI (Campbell et al., 2018). Our analysis by specific disease diagnosis indicated that HRI (which encompasses heat rash, heat cramps, heat syncope (fainting), heat exhaustion, and heat stroke) (Spector et al., 2015; Spector et al., 2014) caused the highest number of ED presentations and costs compared to other disease groups. Costs of HRI were estimated to be AU$295.5 (95% eCI: 235.9, 333.8) thousand during the study period (2014–2017) and the warming climate may herald a greater economic burden to the healthcare system. In 2012, a study in Melbourne, Australia estimated an overall cost of $5800 over the year for HRI associated with heatwaves among older people. However, the study used maximum temperature as a heatwave measure (AECOM, 2012) rather than EHF. Understanding the health and economic burden of heat by specific disease diagnosis can help target intervention actions, minimize health impacts, and reduce the use of healthcare resources. For example, during the period of the heatwave, heat-health interventions can particularly target the most susceptible groups with pre-existing disease conditions. In this study, the observed small number of heat-attributable ED visits for some disease conditions such as IHD could be due to mortality before arrival to the ED, as heart diseases can be acutely life-threatening once triggered by extreme temperatures (Lin et al., 2013; Yu et al., 2011). Moreover, low number of cases may limit the statistical power to detect an association between heat and IHD and diabetes.

4.3. Heatwave impacts by age category

Although all segments of the population are at risk of illness when exposed to a heatwave, some sub-groups are more susceptible than others (Song et al., 2017). Individual-level characteristics such as age have been widely documented as potential modifiers of the relationship between high temperature and morbidity (Huang et al., 2015). Information about heat vulnerable groups and cost contributions to the healthcare system by age group could also assist policymakers to deliver intervention actions effectively and efficiently to the targeted population groups to minimise healthcare costs.

Heatwave-attributable ED presentations and economic burden were highest for age groups under 15 years and over 64 years, and this is consistent with previous studies which have reported elevated risks of morbidity from exposure to extreme heat for children (Xu et al., 2014) and the elderly (Kravchenko et al., 2013). In this study, the ED costs attributed to heatwaves were highest in the over 64 years group. The higher cost could be due to heat-vulnerability factors for these age groups. That there were no observed increases in ED presentations and costs to people aged 15–64 years that might be due to low co-morbidities in this group and their better physiological response and overall ability to cope with heat exposures. Moreover, this age group is the working population who might have benefited from occupational heat-intervention actions in the workplace during hot days. The older age group could particularly experience more costly and severe illnesses compared to other age groups due to a relatively high prevalence of underlying illnesses and co-morbidities. A global review of heatwave impact on human health indicated that older adults appear more likely than other age groups to experience illness from extreme heat events, as documented in a number of locations around the world such as the USA, Europe, Australia, and Asia (Campbell et al., 2018). Heat-vulnerability in older people can be due to age-related compromised thermoregulation (Benmarhnia et al., 2015). Our analysis by heatwave severity level indicated that low-intensity and severe heatwaves contributed to an overall cost of AU$242.8 (95% eCI: 37.0, 440.0) and AU$289.3 (95% eCI: 101.6, 484.1) for people aged 65 and over, respectively. The cost burden could be greater in the future as the proportion of the susceptible ageing population is likely to increase (Christensen et al., 2009) as is the intensity and frequency of heatwaves (Perkins et al., 2012).

This study has several strengths. We used the continuous EHF metric as the exposure variable to examine comprehensively the economic burden of heat-attributable health outcomes to the healthcare system. Previous studies reported that the use of a categorical EHF variable could reduce the statistical power of the analysis and lead to loss of information (Williams et al., 2018; Jegasothy et al., 2017). EHF is also acknowledged as a consistent predictor of morbidity (Williams et al., 2018). Although humidity is not directly incorporated in the calculation of EHF, the metric indirectly considers humidity through the use of minimum daily temperature and the climatology of each location. Hence, the compounding effects of humidity in human response to heat are captured inherently in the EHF metric (Nairn and Fawcett, 2014). This is particularly appropriate for Adelaide which has low humidity during the summer season (Varghese et al., 2019; Milazzo et al., 2016; Zhang et al., 2008). This study provides a comprehensive analysis of the health and economic burden to the ED due to heatwaves, enabling policymakers to better understand the burden of climate-related economic impacts on the healthcare system.

There are some limitations to this study. First, even though an ecological study design is appropriate to examine area-based health factors, it does not consider health outcomes at an individual level. Second, the exposure data and population size are specific to the study location and caution should be used in generalizing these findings to other areas. However, the study shows the potential effects of a warming climate on ED visits and associated healthcare costs in a temperate city, and other locations may find similar trends. Third, we do not control for the effect of air pollution as it can potentially confound the relationship and effect of extreme temperature with health outcomes (Williams et al., 2012), although the air quality in Adelaide is generally similar (and excellent) throughout the year. Finally, the cost burden in this study represents the medical costs of ED visits and does not capture the cost of inpatient care and other non-health costs (e.g. productivity costs).

4.4. Conclusion

Exposure to heatwave is associated with potentially avoidable health and economic burden to the ED in Adelaide. HRI caused the highest ED presentations and economic costs to the healthcare system. A subgroup analysis by age indicated that the young and the elderly are groups particularly vulnerable to the effects of extreme heat. Tailored heat-health intervention programs need to be developed to address the most vulnerable population groups. As the frequency and intensity of extreme heat events are predicted to increase, heatwave plans and emergency responses should be strengthened. Moreover, further research is required to explore the future public health impact and economic burden of heatwaves on the healthcare system.

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CRediT authorship contribution statement

Berhanu Y. Wondmagegn: Methodology, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Jianjun Xiang:** Methodology, Formal analysis, Visualization, Project administration, Supervision, Writing – review & editing. **Keith Deare:** Conceptualization, Funding acquisition, Methodology, Formal analysis, Visualization, Writing – review & editing. **Susan Williams:** Methodology, Formal analysis, Visualization, Project administration, Writing – review & editing. **Alana Hansen:** Conceptualization, Funding acquisition, Methodology, Writing – review & editing. **Dino Pisaniello:** Methodology, Supervision, Writing – review & editing. **Monika Nitschke:** Methodology, Funding acquisition, Investigation, Writing – review & editing. **John Nairn:** Methodology, Funding acquisition, Investigation, Writing – review & editing. **Ben Scalley:** Methodology, Funding acquisition, Investigation, Writing – review & editing. **Varghese B. Mathew:** Methodology, Writing – review & editing. **Alex Xiao:** Methodology, Funding acquisition, Investigation, Writing – review & editing. **Le Jian:** Methodology, Funding acquisition, Investigation, Writing – review & editing. **Michael Tong:** Methodology, Formal analysis, Visualization, Project administration, Writing – review & editing. **Hilary Bambrick:** Conceptualization, Funding acquisition, Methodology, Writing – review & editing. **Jonathan Karnon:** Conceptualization, Funding acquisition, Methodology, Writing – review & editing. **Peng Bi:** Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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Chapter 7: Discussion

7.1. Introduction

The main findings from the empirical studies, together with the discussion and conclusions from each study have been provided in Chapters 4-6. In this Chapter, the overall significance of the research, an integration of the findings and general discussion, including strengths and limitations, are presented.

7.2. Preliminary remarks

Populations exposed to ambient temperature variations can develop mild to severe illnesses (238), which may translate to a cost burden on the healthcare system, potentially time-lagged. These costs in a health care facility may be direct or opportunity costs, and includes the use of medical devices, pharmaceuticals, physician consultation time, diagnostics (e.g. laboratory tests), procedures (e.g. surgical), hospital beds, and overhead costs (e.g. light, heat or cleaning costs). Recent studies have utilised data on ambulance dispatches, GP visits, ED presentations, and hospital admissions (239-241). However, little is known about the quantitative relationship between temperature-related morbidity and associated healthcare costs. In principle, the use of morbidity and cost data from multiple sources such as ED presentations and hospital admissions can provide solid scientific evidence about the health impacts arising from contemporaneous weather variability, and potentially, the projected morbidity and costs from climate change models. In this research, ED presentations, hospital admissions, LoS, and associated medical costs of temperature-related diseases (TRDs) namely respiratory, renal, mental health disorder, IHD, diabetes, and heat-related illnesses (HRI) were examined.

Previous studies have mainly focused on the health effects of either extremely cold winter or hot summer temperatures (1). Specifically, heatwave and high temperature are the focus of much research (242) whereas the relatively moderate, but most frequently occurring temperatures, receive comparatively little attention although they may contribute a larger cumulative health effect (1, 94, 179, 231, 243). To fully understand the impacts of temperature on health outcomes, further research is needed to evaluate the exposure-response relationship across a full range of temperature scales. Therefore, year-round temperatures were used in this research to assess the relationships with various morbidity indicators such as ED visits and hospital admissions. The results of this research can provide a comprehensive picture and offer new insights about morbidity and healthcare costs associated with non-optimum temperatures for healthcare providers, healthcare institutions, and other relevant stakeholders.

Broadly, the research in Chapters 4-6 achieved three major objectives: i) established the temperature-morbidity and temperature-healthcare cost (ED presentations and hospital admissions) relationships in Adelaide, a city with Mediterranean climate and significant temperature variability; ii) estimated the current temperature attributable morbidity and associated cost burden; iii) projected future burden in the context of climate and demographic changes. The current relationships between exposure (mean temperature and heatwave) and outcome (ED presentations, hospital admissions, LoS, and associated costs) variables were examined using contemporary statistical modelling, i.e. distributed lag non-linear models. Future morbidity and cost burdens were estimated under different greenhouse gas emissions scenarios (RCP2.6, RCP4.5, and RCP8.5) and demographic change. Using the Australian Consumers Price Index (CPI), costs of ED presentations and hospital admissions were adjusted for possible inflation and standardised to 2015 (for ED costs) and 2017 (for hospitalization costs) Australian dollars, respectively.

7.3. Significance of the research

Australia as a worthwhile target for heat-health-cost research

It has been asserted that climate change is one of the biggest global threats to public health in the 21st century (244). Given that the climate is changing, there is now a compelling need to build evidence about heat-attributable health burden and associated healthcare costs, and how these costs are projected to increase due to climatic and demographic changes in future for Australia. Such effects need to be more thoroughly understood to ensure that intervention actions are designed based on scientific evidence and address public health and economical use of healthcare resources. Although climate change affects every country around the world, some regions such as Australia are particularly prone to climate change and extreme weather events. The research findings in this thesis provide important evidence regarding potential health and resource implications.

Addresses the limited evidence on contemporaneous heat-healthcare costs

Numerous studies have examined the relationships between temperature exposure and human health; however, there is a lack of evidence on the economic impact on the healthcare system and temperature-cost relationships. Moreover, the extent to which future temperatures pose health and economic risk has been absent from the scientific literature. Previous studies have calculated the healthcare cost of temperature-related health outcomes by assigning an average cost value for all presentations or admissions (177, 229, 230, 232, 245-249). The research presented here is the first to establish the temperature-cost relationship for ED presentations and hospital admissions and estimated the cost burden based on the exposure-response curve (Chapters 4-6). Understanding the link between non-optimum temperature and healthcare costs may underpin empirical climate-health studies and offer more precise estimates. This research provides a quantitative estimate of temperature-attributable morbidity burden and associated economic cost to the healthcare system in public hospitals in Adelaide, South Australia. To develop and refine regionally tailored heat-health action plans, research that elucidates local circumstances such as population dynamics and regional climate change is timely.

Addresses the need for evidence on projected heat-healthcare costs within the climate change and population ageing research agendas

As the population is ageing and climate change is happening, future health impacts of climate change are likely to be worse (250). The prevalence of temperature-sensitive diseases (TRDs) such as CVD, mental and behavioural disorders, respiratory illnesses, renal diseases, diabetes, IHD and HRI are increasing among the elderly and can be exacerbated by exposure to heat and cold weathers. Hence, quantifying the overall temperature-attributable disease burden and healthcare costs of TRDs by age and diagnosis group (Chapter 6) is very useful for local health authorities, health service providers such as GPs and councils for their climate change and health plans and action.

There have been few studies projected future disease and cost burdens due to climate change. This research work provides insight into the likely future changes in morbidity and cost burdens associated with future temperatures projected under different greenhouse gas scenarios (Chapters 4 and 5). Moreover, the incorporation of population change into the estimates of future temperature burden is an additional benefit of this study which would provide better estimations. The increasing number of ED presentations and hospital admissions, and associated costs will provide needed evidence for governments and the health systems to find new approaches to address the challenges from climate impact. For example, relevant stakeholders such as public health agencies can take preventive actions proactively by improving resource allocation and infrastructure planning. Medical administrators in hospitals can use the evidence in the negotiation of future resource allocation and to advise the need in the capacity building of the health workforce.

Addresses the limited evidence on heat-healthcare costs over the full range of temperature variability

A considerable body of literature has focused on the health impacts of extreme temperatures (extreme cold or heat). However, few researchers have acknowledged that moderate temperatures can be responsible for a substantial health burden (1, 94, 179, 231, 243). Hence, this research makes available evidence of morbidity and associated cost effects using all-year-round temperatures, which provide a comprehensive picture of temperature-related impacts in Adelaide (Chapters 4 and 5). This has important implication for the planning of public health intervention and for resource allocation to healthcare facilities as moderate temperature occurs in most days of the year.

Addresses heat-healthcare costs using a heatwave metric

To design effective preventive and heat adaptation plans, a better understanding of local heat and population vulnerability is necessary (251). In this thesis, Chapter 6 outlines a unique study that establishes the relationship between heatwaves with health and cost outcomes, using the EHF. It is a newly developed heatwave intensity and severity metric that can be universally adopted and enables comparison of results from different geographic and climatic conditions. This is the first study to use EHF to estimate cost outcomes. Furthermore, the study provides a quantitative estimate of the morbidity burden and cost impacts by heatwave severity category to the ED over the four-year period (2014-2017). The finding has implication for the heat warning system implemented in Adelaide.

Chapter 6 of this study also performed a subgroup analysis by age to determine who is at greater risk and demanding resources associated with exposure to heatwaves. Such studies are useful to target intervention actions thereby reduce health outcomes and economic costs.

7.4. Key findings in context

7.4.1. Exposure-response relationship and burden: Empirical evidence

Measuring the public health burden attributable to a particular environmental risk factor can provide a quantitative estimate of the burden which would not have occurred if the exposure were avoided (252, 253). However, this quantitative epidemiological method is rarely used in temperature-health and healthcare cost studies (238). A comprehensive understanding of morbidity and related healthcare cost impacts can inform intervention policies, as evidence-based allocation of scarce resources is an ongoing challenge in health systems. Establishing exposure-response relationships is a fundamental step in understanding the link between temperature and outcome variables (morbidity and healthcare costs). It also provides the groundwork to accurately estimate (254) how many ED presentations and hospital admissions are attributable to ambient temperature, and the overall costs of health resources required to provide the necessary health care (238). This research has estimated the morbidity risks and costs of illness associated with exposure to temperatures ranging from cold to hot, as well as heatwaves. The health and cost burdens attributable to non-optimum temperature, estimated as attributable number (AN) and an attributable fraction (AF) for the respective baseline and future periods, are also calculated. Under this section (Section 7.4.1), the findings of the research (Chapters 4-6) are discussed into two main broad categories: i) Baseline exposure-response associations and burdens discussed in Section 7.4.1.1 through Section 7.4.1.3, and ii) Estimates of future ED presentations, hospital admissions, LoS, and related medical costs discussed in Section 7.4.2.

7.4.1.1. Associations between mean temperature and ED presentations and costs

Most temperature-health studies using morbidity data have focussed on hospital admissions, whereas fewer have used ED visits, which is a superset of admissions (94). Emergency department presentations can provide valuable data for describing the epidemiology of temperature-related morbidity, especially the acute effects of temperature exposure (113). This is particularly important where extreme heat events become more and more common, a phenomenon acknowledged by Emergency Medicine bodies in Australia (2). Australian EDs are at the forefront of these impacts and the rising temperature poses a risk in the ability of the ED to cope (2).

Exposure-response relationship

The cumulative exposure-response curves for TRD-ED presentations and ED costs show a non-linear relationship (Chapter 4). There were increased risks of all-cause ED presentations and costs at both ends of the temperature scale indicating that non-optimum temperatures were associated with health and economic impacts on the

ED. Nevertheless, the slope for warm temperature was steeper for both ED presentations and costs compared to cold risks, indicating an increased risk of presentations and medical costs. This relationship between mean temperature and ED presentations in Adelaide is similar to previous studies of incidence (240, 255-257).

In the study of a temperature-health relationship, the choice of a lag period between exposure and health outcome is an important methodological issue. A short lag period may result in incorrect estimates particularly if a harvesting effect exists (238) and both cold and hot (all-year-round) temperatures are fitted in the same model. In this study (Chapter 4), a maximum of 21 lag days was chosen to capture the delayed effects of both cold and hot temperatures. Previous temperature-ED presentation studies have also used 21 days or longer lag period to examine the effects of both cold and hot temperatures in one model (92, 98, 240, 256, 258). However, the full range of morbidity associated with temperature exposure might not be captured (for example hip fractures) and its associated impacts may delay several days, weeks, even months following the exposure. For example, a study by Zhao et al. in China on non-accidental ED visits used a lag period of more than 4 weeks (32 days) (256). For the development of an effective response plan, understanding the lag pattern of cold and hot effects is important for the development and implementation of early health warning systems (258). In this study, greater effects of heat were observed at lag 0 for both ED presentations and costs, indicating the acute health impacts from extreme heat. While effects of cold temperature were lagged up to 18 days for ED presentations and associated costs; the heat effects last over shorter lag periods, i.e. up to 9 days for ED presentations and up to 2 days for ED costs. The potential reason for the variation of the lag effect between the cold and heat effect could be due to the difference in physiological responses among different vulnerable populations (259). Overall, these findings are consistent with previous literature that asserts the acute morbidity effects of heat and the more delayed effects of cold exposures (21). For example, Zhao et al. reported that the cold temperature effect appeared on day 2 and persisted until day 30 while the effect of hot temperature appeared immediately that lasted until 3 days (256). Likewise, a study of cardiovascular and respiratory ED visits in Toronto reported that the health effects of hot temperature were more acute than cold temperature (92). However, Bai et al., found delayed and longer-lasting heat effects (up to 27 days) on total emergency room visits in Lhasa, Tibet (240).

Empirical analyses for temperatures and ED presentations and cost burden

This research addressed the knowledge gap on healthcare costs of temperature attributable morbidity burdens. The study quantified the cost of ED presentations using exposure-response relationship. Net temperature-, cold-, and heat-attributable TRD-ED presentations and associated medical costs were estimated for 4-years of the baseline study period. Temperature contributed to a non-significant net 6,662 (-1,434, 14,222) ED presentations and AU$12.6 million (-0.3, 24.1) costs. Heat contributed to a substantial number of TRD-ED presentations, i.e. 3,633 ED visits (95% eCI: 695, 6,498), and AU$4.7 million (95% eCI: 1.8, 7.5) in ED costs over the 4-years study period. This accounted for approximately 1.5% and 2% of all TRD-ED presentations and costs between 2014 and 2017, respectively (Chapter 4). On average, heat contributed a healthcare cost of about AU$1.2 million per year and AU$1,300 per ED presentation during the baseline period in Adelaide. A study of ED cost burden attributed to moderate-extreme heat by Liu et al. in the Minneapolis/St. Paul Twin Cities Metropolitan Area, USA, reported an annual $1.40 million (95% eCI: 1.15, 1.65) cost for 0-19 years age group with no significant heat cost for people aged 20-64 years and 65$^+$ years (232). This is relatively higher compared to our study, which could be due to the differences in the scope of the study area, population, and methods of cost estimation.

Even though the ranges of effect size estimates attributed to cold temperature were not significantly different from zero, the point estimate for cost burden was greater compared to the heat effect. This might be due to severe health outcomes associated with cold exposures which could lead to a triage category that involves higher medical cost. The results of the present study are consistent with findings reported in the USA that cold temperature resulted in higher healthcare costs and a greater number of heat-related healthcare visits (183, 232). For example, the study by Liu et al. reported a cost burden of cold temperature 14 times higher than heat for all-cause ED presentations (232). However, it is hard to directly compare the study in the USA with Australia due to different climatic condition and healthcare systems.

7.4.1.2. Associations between mean temperature and hospital admissions and costs

Exposure-response relationship

A comprehensive assessment of the burden of non-optimum temperature on inpatient hospital services was conducted using hospital admission, LoS, and costs data from 2010-2015 in Adelaide. The cumulative exposure-response curve for all outcome variables indicated approximately U-shaped relationships (Chapter 5), with the risks of hospital admissions, LoS, and costs increase at both ends of the temperature scale relative to the respective OT. Same as previous studies (21, 175, 179, 205, 214, 260), a maximum of 21 lag days were used and stronger effects of heat were observed at a lag of 0 days for all outcome variables, indicating acute health effects.

These results are in line with those reported by previous heat-health studies (10, 261, 262). A study in Tasmania, Australia, for example also reported a peak in hospital admissions on the first day of heat exposure (261).

Baseline hospital admissions, Length of Stay, and cost burden

Chapter 5 focused on the impacts of ambient temperature on hospital admissions and costs from 2010-2015. During the baseline period, a total of 121,750 TRD-hospital admissions and about AU$1.4 billion in costs of hospitalisations were observed. The mean daily hospital admissions, LoS, and costs were 56 cases, 369 days (6.6 days per admission), and AU$635,700 ($11,352 per admission), respectively. This is approximately AU$1,600 per day. It should be noted that the health burden associated with temperature may be under-represented as some affected individuals may not be deemed serious enough for hospital admission or died before reaching a hospital (194).

Estimates of net-, cold-, and heat-attributable hospitalisations, LoS, and costs for the baseline periods showed that temperature contributed to a net 3,900 hospital admissions, about 99,800 days of hospitalisation, and nearly AU$160 million in hospitalisation costs over the four-year study period. Of this, the hot ambient temperature was responsible for a greater proportion of the total (net) temperature-attributable hospitalisations, i.e. roughly 77% of hospital admissions, 94% of the LoS, and 92% of the healthcare costs. Heat contributed to an annual AU$24.5 million costs while cold temperature resulted in a non-significant AU$2.0 million during the baseline period (Chapter 5). During 2005-2014, Liu et al. estimated annual medical costs of around $1.5 million attributed to moderate-extreme hot temperature (for people aged 0-19 years and nill cost for other age groups) while the costs of moderate-extreme cold exposure were $77.8 million in Minneapolis/St. Paul Twin

Cities Metropolitan Area, USA (232). The contradiction of the results between the two study areas might be due to the differences in climatic condition, generally, Minneapolis/St. Paul Twin Cities is much colder (average annual temperature: 7.9ºC (263)) than Adelaide (average annual temperature: 17.4ºC (264)). The morbidity results of the current study are in agreement with previous studies that hot temperature contributed to a higher proportion of morbidity than the cold temperature in China, Spain, and the USA (128, 174, 265). It should be noted, however, that these studies vary in different aspect such as in methodology, climatic conditions, population characteristics, temperature metric used, disease of interest, and types of hospital services. In the warm-temperate climate in Adelaide, the burden due to heat exposure would be expected to be greater than those due to cold. The availability and use of health services is another important consideration when comparing studies from different locations with various climatic characteristics.

7.4.1.3. Heatwaves and TRD-ED presentations and costs

In the studies of heatwave impact, a major challenge is a lack of consistent and universal heatwave definition which greatly varies by geographic location and climatic conditions (12) making epidemiological studies of heatwaves difficult to compare. The EHF severity index define heatwaves relative to local historical and recent temperatures (19) and can be applied across different climate zones (14, 15, 112, 196, 266, 267). The incorporation of historical climate and acclimatisation factors within the EHF severity index makes it useful to identify extreme or unusual heat which is likely to be hazardous to health (19). Some studies have reported that EHF is a good heatwave-health predictor of morbidity and mortality (267, 268). Although a comparative study of human heat stress illness on selected hospital admission in Sydney, Australia, by Goldie and co-authors reported that the performance of EHF in predicting morbidity outcomes was not different from other indices (269), the development of EHF provides a universal and consistent method in the calculation of heatwaves regardless of geographic and local climatic conditions.

The magnitude of a heatwave effect can be modified by its characteristics of intensity and duration (12, 270-272). Recent studies have evaluated the impacts of heatwave severity and duration and reported that intensity plays a relatively more important role than duration in determining a population's vulnerability (12, 273). Chapter 6 of this thesis investigated the potential impacts of heatwave intensity and severity on ED presentations and associated economic costs. Furthermore, the Chapter investigated whether the burden of heatwave intensity/severity varied by specific diagnosis diseases and age categories. The Chapter is summarised in the following two sub-sections.

Exposure-response relationship

In this thesis, the continuous EHF metric (intensity) and two categories of heatwave severity (low-intensity and severe heatwave) were used to examine the relationship between ED presentations and ED costs. The DLNM model was fitted with a maximum of 7-lag days to quantify the cumulative risk of a heatwave (measured using both EHF intensity and EHF severity). The choice of the 7-lag period is based on previous heatwave studies on health outcomes (180, 274). Using ED outcomes, the exposure-response curve indicated that the health and economic impacts of heatwaves increase with heatwave (EHF) intensity. Moreover, analyses by heatwave severity category showed higher risks of ED presentations and costs during days of severe heatwaves than those in low-intensity heatwave days. A study of heatwave impact using EHF metric in Spain also used a maximum lag of 7 days and reported that heatwave intensity is an important predictor of health outcomes (14, 267, 275). In Chapter 6, in addition to the morbidity outcomes, both heatwave severity and heatwave intensity are found to be a good predictor of economic outcomes at a lag of 7-days. The result showed an increasing resource use as heatwave severity increases.

The effects of the heatwave (intensity and severity) varied by specific disease diagnosis groups and age categories, with an increase in intensity and severity being associated with higher rates of ED presentations and costs for most subgroup analyses. For HRI, however, there was a much steeper slope for severe heatwaves when comparing to low-intensity heatwaves. For most disease diagnosis groups such as respiratory diseases, renal diseases, mental health disorders, IHD, and diabetes, the point estimates of the risk of ED presentations and costs showed a positive trend with heatwave severity and intensity but did not reach statistical significance (Chapter 6). Furthermore, the analysis by age category indicated that people under 15 years and greater than 64 years were at increasing risk as heatwave (EHF) intensity and severity increase. Such findings suggest that relevant adaptation measurements should be implemented by a thorough review of the effectiveness of the heat response plan in addressing the most vulnerable groups. Institutions providing services particularly to these vulnerable age groups (e.g. schools and age care centres) need to design heatwave response strategies and evaluate the program regularly by the end of each summer seasons.

The heatwave-attributable TRD-ED presentations and cost burden

As mentioned previously, the burden of heatwave severity and intensity for all TRD-ED presentations was analysed by age and diagnosis groups to examine the disparity of heatwave impact. During the 3-heatwave seasons over the study period, a total of 65 heatwave days were identified in Adelaide. Compared to non-heatwave days, heatwave contributed to an estimated total of 1,161 (95% eCI: 342, 1,944) all-cause TRD presentations and AU$1,020.3 (95% eCI: 224.9, 1,804.7) associated healthcare costs (in thousands) (Chapter 6). The estimated attributable burden varied by disease diagnosis group and age category. Significant health and economic burdens were observed in association with the young and the elderly. Among disease diagnosis groups, HRI contributed to higher estimated ED presentations and costs, 389 (95% eCI: 342, 427) and AU$295.5 (95% eCI: 235.9, 333.8), respectively. Previous studies reported that most HRI were reported in the elderly, children, and people with underlying medical conditions (276, 277). Heat-related health effects are often preventable in vulnerable groups, through basic health education campaign such as encouraging community members keeping hydrated, staying out of the sun and remaining indoors(278, 279).

Age is an important factor in relation to the effects of heatwaves. Several studies have reported the heatwave vulnerability of aged people (59) because of diminished thermoregulatory functions (280). Reduced skin blood flow, reduced sweat gland output, physical inactivity, pre-existing medical conditions, and taking medications can make them susceptible to the adverse effects of heat (281, 282). Similarly, people aged <15 years have limited ability to regulate their body temperature (283). The vulnerability and over-representation of children and older people to heat effects identified in this study highlight the need to further strengthen the existing heat-health intervention to reduce the morbidity and cost burden. The heat warning system in Adelaide provides timely public advice, targeted support, and emergency responses to prevent negative health outcomes (284). After the implementation of the heat warning system in Adelaide, a reduction of ambulance call-outs, hospital admissions, and emergency presentations were evidenced during the 2014 heatwaves compared to (pre-intervention) comparable 2009 heatwave periods (84). Air-conditioning is standard in schools and aged care facilities in Adelaide. However, elderly people living in their own homes may not have access to air conditioning or be motivated to use it due to financial constraint (285, 286). The ABS projections show for the Adelaide metropolitan area there will be an increase in the aged population over time, from 16.8% in the 2010s to 21.2% in 2050s (203) which is consistent with population growth of other developed countries (236). The growing proportion of vulnerable older people in Adelaide may lead to higher healthcare costs as observed in a Brisbane study. A study in Brisbane reported that the number of ED visits for older people were estimated to grow twice as much as those of younger people (229). Future morbidity and cost impacts of heatwave might be even greater in Adelaide because of the higher proportion of the elderly population (17.2% vs 12.8%) (287, 288) and more extreme heat events (289-291).

The attributable number of ED presentations and costs are comparable between heatwave severity category (low-intensity and severe heatwaves) for most disease diagnosis and age categories even though the number of heatwave days in these categories differed considerably (i.e. 55 vs 10 days, respectively), indicating the substantial burden of severe heatwaves. The attributable burden may increase substantially if heatwave severity and intensity increase as projected. The Australian Bureau of Meteorology produces a publicly available on-line 7-day heatwave severity map to inform relevant stakeholders of forthcoming heatwaves. This is one of the crucial parts of the heat warning operation in Adelaide. Better strategies can be designed to improve the public utilization of the heat warning services particularly during the time of severe heatwave days. Awareness-raising of the general public and emergency department medical personnel about the heatwave alert mechanism might be helpful (292).

7.4.2. Estimates of future temperature-attributable TRD-ED presentations, hospital admissions, Length of Stay, and costs

The estimation of the future public health burden associated with climate change is important for climate and environmental health research as it can provide needed information and evidence for policy-makers and service providers for their design and implementation of health interventions, planning for resource allocation for relevant healthcare settings. This research answered the research questions about how ED presentations (Chapter 4) and hospital admissions (Chapter 5) and associated medical costs, will change under different greenhouse gas emission scenarios, using Adelaide as a case.

The estimation of the future burden is determined by both epidemiological and climate models. The DLNM model is an advanced statistical method in environmental epidemiology that is capable of capturing immediate and delayed effects of temperature exposures using smooth spline functions (66, 212, 213). On the other hand, climate models inherently have many uncertainties because forecasting future temperatures requires more sophisticated interaction between multiple factors: the land, atmosphere, oceans, plants, and ice cover (54). The CMIP5 is the most widely used climate model and is considered to project Australian climatological temperature distribution under different greenhouse gas scenarios reasonably well (49). For this study, the temperature change projected by the CSIRO and BOM under three RCPs (RCP2.6, RCP4.5, and RCP8.5) were used. However, some critics argue that pathways greater than RCP2.6 entail multi-faceted risks to the functioning of human civilisation, with the potential breakdown, regionally and perhaps globally, of effective governance and thus the delivery of good public health (293-296). Even RCP2.6 might bring a substantial health and economic challenges regionally and globally (297). Intersectoral and national collaboration is a key strategy to curve the public health impacts of climate change. I acknowledge those risks, but believe that a detailed discussion of them is beyond the scope of this thesis. Therefore, the findings discussed here, for the health costs of heat (and cold) - related conditions at different RCPs, are based on the implicit assumption that these models of health costs at different RCPs assume that any RCP will only affect heat (and cold) related conditions, leaving all other relevant aspects of social function essentially unaltered.

The mean temperature is the most widely used index for the projection of climate impacts (194). Goldie and co-workers in a study of current and future health impacts of temperature across five Australian cities, including Adelaide, evaluated the performance of health-relevant temperature indices from CMIP5 and reported that mean temperature is generally simulated well (194). In this study, future temperatures scenarios for Adelaide were developed using projections data of CSIRO and BOM from around 20 CMIP5 models for the Southern and south-western flatlands region of Australia (198). This region provides the most appropriate projections for Adelaide. The projected temperature changes to future periods were relative to the climate reference period (1986-2005).

Under a high emission scenario (RCP8.5), the temperature of Adelaide is projected to increase by 1.0 °C (0.8-1.2) by 2030s, by 1.3 °C (1.0-1.6) in 2045, 1.6°C (1.3-1.9) in 2050s, and 2.1°C (1.7-2.5) in 2065 (235). The results described in Chapter 4

(ED presentations) and Chapter 5 (hospital admissions) showed an increase in heat-attributable morbidity and healthcare costs cannot be compensated by a decrease in cold-attributable burden for all projection periods and temperature scenarios. As global emissions are currently tracking close to the RCP8.5 trajectory (298), the estimations for this scenario may be the most relevant. It was estimated that a substantial burden of ED presentations, hospital admissions, and costs would increase under a high emission scenario.

The estimation of future morbidity and cost burden under different temperature scenarios and constant population growth, indicated a substantial heat burden around the middle of the century for Adelaide, with no change in cold attributable burden. Under RCP8.5, heat-attributable TDR-ED presentations and costs were projected to increase by 1.5% and 2.0% in the 2050s relative to the baseline period, respectively, with an excess of 1,025 ED presentations and about AU$1.3 million per year (Chapter 4). Similarly, under a constant population and high emission scenario, the number of hospital admissions, LoS, and costs were projected to increase by approximately 0.8%, 2.2%, and 2% in the 2060s compared to the baseline period, respectively (Chapter 5). The findings show that by mid-century, compared to hospital admissions, a higher percentage increase in ED presentations is expected, perhaps due to patients with the heat-attributable disease/s often being treated in emergency departments as acute episode. Despite a small increase in hospital admissions, the associated future hospitalisation costs will increase considerably. This might be due to a possible increase in the length of hospital stay that might have a resource implication to the already overloaded health system.

In addition to climate change, future temperature-related health burden will be driven by demographic changes (299). When climate change was coupled with population growth, substantial heat effects were estimated for both ED and hospital admission services. For example, under all temperature scenarios, the increase in heat attributable fraction would range from 2.0% to 3.7% for ED presentations and from 2.7% to 5.0% for ED costs during the 2050s (Chapter 4). The contribution of demographic change to the burden of both ED presentations and costs was estimated to be around 43%. By 2060s, the excess heat-attributable hospital admissions and costs were estimated to be nearly 2,721 (95% eCI: 556, 4,805) and AU$106.7 million (95% eCI: 3.6, 185.7) under the RCP8.5 scenario. The number of hospital admissions, LoS, and costs was also projected to increase by 2.2%, 8.4%, and 7.7% (Chapter 5).

Toloo and co-workers estimated nearly AU$2 million excess costs for all-age all-cause ED presentations in Brisbane during 2060 (229). In the present study, the annual cost of ED presentations for TRD can reach up to AU$4.4 million during the 2050s (2054-2057). The higher cost estimation for the study in Adelaide might be due to the cumulative cost burden of moderate-extreme temperature while the study in Brisbane considered only cost effects of temperature higher than 35ºC. This shows that even if the risks of extreme temperatures are higher, the moderate temperature can also contribute to a substantial commutative cost burden. This is because of the higher number of days with moderately hot temperatures than extremely hot days. Unlike research restricted to warm seasons, this study has an additional advantage of capturing the effects of moderately warm days that might occur even during the winter season.

7.5. Strengths and Limitations

Strengths

This research has several strengths.

It is the first research to establish the temperature-healthcare cost relationship for TRDs and provides a comprehensive analysis of health and economic outcomes associated with exposure to non-optimum ambient temperatures, using both ED presentations and hospitalisations as health outcomes. The study provides the health and healthcare burden of the year-round temperature range in Adelaide, including both cold and hot temperatures.

Unlike previous studies that used average patient cost to estimate the medical costs involved in the treatment of temperature-attributable diseases, this research calculated the healthcare costs based on the temperature-cost relationships using daily aggregated medical costs and temperature variables. The cost estimation based on the exposure-response relationship can provide a more precise estimate that can be helpful for local health authorities for their decision-making.

The research in this thesis provides evidence of the current and future burden of the changing climate under multiple climate change scenarios. To capture the possible future climate effect, three greenhouse gas emissions scenarios were utilised. Moreover, the projection of temperature-related health and the economic burden has more validity when the projections consider the demographic change. The estimations of future morbidity and associated cost burden of TRD using a medium population growth scenario will provide needed evidence for policy-makers and service providers for their long term health adaptation plan to deal with climate change challenges.

In the study of a heatwave, meteorological variables such as minimum, maximum, or average temperatures provide only a measure of heat stress with no account of human differential response (300). However, the EHF is a biometeorological heat index that takes human acclimatization into account (78). It provides a measure of the intensity, length, and load of a heatwave episode (19, 300). This research (Chapter 6) provides evidence of morbidity effect and cost burden using heatwave intensity (categorical: low and severe heatwave) and heatwave intensity (continuous EHF). The quantitative estimate of morbidity and cost burden using the BOM-defined heatwave severity category can be used as input in the evaluation of the heat-health response plan. Moreover, this study offers possibilities of comparison of these findings with other heatwave studies around the world regardless of local climatic conditions that were not possible when other heatwave definitions used.

Recent studies reported that the relationship between temperature-and health outcomes could be predominantly non-linear even above the selected temperature threshold (209, 210). Moreover, the health and economic outcomes can be delayed after the time of exposure. To overcome this statistical issue, a strength of the research is that it used a relatively recently developed modelling framework in environmental epidemiology (i.e. DLNM) that enables the examination of the non-linear and delayed exposure-response relationships simultaneously in a flexible way. The model also provides a platform to control time-varying confounding factors such as seasonal patterns and long-term trends, day of the week, and public holidays.

This research provides an estimate of net temperature-, cold-, and heat-attributable morbidity (TRD -ED presentations and hospital admissions) and associated healthcare costs during the predefined time period. This has advantages over-reporting measures of relative risk because policymakers can more easily understand the temperature burden when presented in aggregated quantitative measures in time scale (fiscal year, or decades).

Limitations

There are some limitations to this research.

Firstly, it is an ecological study. Similar to other ecological study design, the unit of analysis is the Adelaide population assuming each individual has the same exposure. The findings do not provide information about possible variation in the exposure-response effects at the individual level (186, 187). There is potential exposure misclassification because individuals' exposures to temperature may vary across the population, due to factors such as socioeconomic status including housing condition, access to air conditioning, employment or other influencing factors. The calculated optimum temperatures are estimated for the population that may vary at an individual level. As this study was based on data only from Adelaide, the result might not be able to be generalized to other locations due to the difference in population characteristics, socioeconomic status, healthcare system, and climatic characteristics.

Since there is no conventional method of predicting future exposure-response relationships, the estimates for different climate scenarios assume that the observed baseline relationship would be unchanged temporally. It is also assumed the price of healthcare services will be the same in the future as the baseline cost, which is unlikely. The results provide estimates for future costs relative to the current, rather than predicting absolute costs for future periods that might underestimate future burden.

This study used only health and cost data from public hospitals in Adelaide. It has not comprehensively assessed the temperature-health-cost impact as data from private hospitals and GP visits were not included due to their unavailability. Moreover, the study did not address other aspects of temperature-health-cost impact related to work exposures as it is not within the scope of this study. During the time of extreme temperature, particularly heatwave periods, some patients may go to private hospitals or visit a general medical practitioner. This might underestimate the number of healthcare visits (namely, ED presentations and hospital admissions) and associated healthcare costs attributed to temperature. However, this may have a small influence on the effect estimates as nearly 92% of all emergency hospital admissions in Australia were to public hospitals during 2018-2019 (301). All projection studies have inherent uncertainty. There are several assumptions involved in the climate models to simulate future temperature change that are a possible source of uncertainty to the calculated estimates. The scenarios used in this study were based on plausible mid-century regional temperature projections, derived from the CMIP5 models of most relevance to the Australian context. Future daily temperatures were calculated by adding scenario-based projected temperature change to the observed baseline daily mean temperatures. However, the scenarios may not adequately account for increased climate variability and the potential for unprecedented heat and cold extremes. Estimation of future climate burden was based on the exposure-response relationship using only the available 4-6-years of baseline data, and this could be affected by anomalous temperatures.

Finally, the possible adaptation behaviour was not incorporated into the modelling is another limitation in this study. Progressive adaptation of the population to local weather conditions has already been observed in some countries such as the USA, UK, Spain, and Japan (11). Hence, the incorporation of human adaptation into models of the future health and economic effects of climate change could yield more accurate estimates. However, previous studies in Australia have reported that due to several barriers, population adaptation to unstable weather conditions has not been well established in most cities (302). Therefore in this research, future adaptation has not been taken into consideration as it is not possible to predict the rate and extent of future adjustment to extreme weather.

Chapter 8: Conclusions and recommendations

8.1. Conclusions

The results from this work provide evidence that high temperature contributed to a significant morbidity and cost burden during the baseline periods (Chapters 4 and 5). Furthermore, the risks and burden of ED presentations and costs were found to increase as heatwave severity and intensity increase with higher effects observed for severe heatwaves, measured by EHF (Chapter 6). The results highlighted that not only extreme temperature but also moderate temperature should be considered as a public health threat. The existing heat-health intervention plan could reconsider temperature thresholds not only from adverse health outcomes but also from economic perspectives.

The finding presented in Chapters 6 indicated that some population groups are at higher risk and contributed to a greater cost to the healthcare system. For example, the younger and the elderly were the most vulnerable subpopulations suggesting that targeted heat intervention activities are required to minimize the attributable morbidity and cost burden. Findings also showed that the heat cost burden could vary by disease diagnostic groups. The preventable direct HRI contributed to the higher number of ED presentations and medical costs. Significant activities can be undertaken to reduce exposure to heat and reduce health effects and economic consequences.

Projected estimates showed that there will be greater burdens of heat-attributable ED presentations, hospital admissions, length of hospital stays, and costs associated with increasing temperatures under climate change scenarios, and effects may be further magnified by population change (Chapters 4 and 5). Unless effective public health prevention and climate mitigations actions are in place, greater healthcare resources are required to meet future health service demands.

8.2. Policy and service implications from this research

Policy and guidelines

This research provides evidence of the cost impacts of temperature-related diseases on the healthcare system in a temperate city. The result indicated that the warming climate would pose a greater morbidity impact to the population, especially younger and elder populations, and cost burden to the healthcare system relative to the baseline period (Chapters 4 and 5). It is recommended that state government including SA Health, SA SES, SA Department of Community Service could 1) put climate change and its health impact on their long-term strategy to plan for its future challenges; 2) revisit and update if needed, their current policy and guideline for hospitals to deal with such challenge including an additional (seasonal) budget for ED and hospitalisation—not only for extreme heat but also for moderate heat as well; 3) and work closely with relevant associations, such as the Australian Medical Association and relevant colleges such as the Australasian College of Emergency Medicine, Royal Australasian College of Physicians, Royal Australian College of General Practitioners, with regard to policy and guidelines.

Resources and facilities

The rising temperature is likely to cause greater heat-related morbidities in the future and this will require more healthcare resources to meet the health service demand. For example, during the 2060s, the excess heat-attributable hospital admissions and costs could reach up to 4,800 and AU$185.7 million, respectively, with longer hospital stays. The finding from this study can assist state governments in the allocation of resources and budget to the health system, particularly during the warm season such as more beds for inpatient departments so better climate-resilient services and infrastructures could be achieved. Furthermore, the healthcare workforce capacity building is also important. Regular professional development for the workforce is needed. This could be achieved via collaborative efforts with relevant medical Colleges such as the Royal Australian College of General Practitioners (RACGP), Royal Australasian College of Physicians (RACP), and Australasian College for Emergency Medicine (ACEM).

Other service providers such as local councils, GPs and other primary healthcare providers, NGOs such as Red Cross should also revisit their service guidelines.

Community resilience and capacity building

Results from Chapter 6 of this thesis indicated that particular community groups are more vulnerable to heat (0-14 and over 64 years). The result showed that heatwave contributed to nearly avoidable seven and nine ED presentations per day for the younger and elderly people in Adelaide, respectively. To effectively minimise the health risk and economic impact, intervention action should target the most vulnerable group. Heat response guidelines and educational materials can be developed for families living with children and other at-risk groups. A registry of most vulnerable populations such as the elderly, those with chronic diseases, and taking medications should be undertaken earlier of the heat season to better assist and follow-up. The younger age groups need to be watched carefully during hot days.

Further, the synthesis from this research work suggests that moderate temperatures have lower health and economic risk but higher cumulative burden (Chapter 4 and 5). This is because the population is more exposed to the moderate hot ambient temperatures that occur frequently throughout the year. Hence, this has important public health implications and economic consequences. Building the community resilience to heat through integrated environmental (e.g. more green spaces, building design) and technological (e.g. adoption of air conditioner, sustainable and affordable power supply) adaptations strategies are vital.

Coordination of intervention activities

To minimize the projected morbidity and cost burden (Chapters 4 and 5), multi-sectoral and multidisciplinary intervention is required. Climate change solutions require integrated resource mobilization and commitments from individual to government level and need actions from local to global scales. Relevant stakeholders need to set shared priority goals, common action plans, allocate adequate resources, and maximize co-benefits. Coordination of heat-health actions can help to minimize morbidity and maximize economic benefits. Agencies and departments need to review the experience of heat response and recovery actions undertaken and need to evaluate the readiness for the upcoming warm season. Based on meteorological forecasts, a consistent and situational action should be designed at a different level, for different locations, and different population groups.

8.3. Recommendations

Several recommendations can be made from the research presented here.

The analysis of both ED (Chapters 4) and hospital data (Chapters 5) indicated that heat contributed to substantial morbidity and cost burden during the baseline period and is projected to increase substantially under all greenhouse gas emission scenarios and demographic change. It is recommended that:

- **State and federal governments work on climate mitigation activities** such as emission reduction of greenhouse gasses by investing in clean energy sources (e.g. solar, wind).
- **Public health adaptation strategies are designed in collaboration with relevant stakeholders** including the health department, state emergency services, BOM, and research institutes to minimise future burden and current harm that climate change already poses.
- **The health system workforce should be prepared for emerging extreme heat episodes**. Regular professional development courses should integrate teaching about the health impacts of climate change and heat extremes. The content may address heat presentation and patient management, the adverse effects of medications during high temperatures, together with the different risk factors that can increase the population's vulnerability.

The finding from Chapter 6 identified that the younger and the elderly are the most vulnerable population age groups to heatwaves.

- **It is recommended that education policies should encourage the integration of climate change into a school-based curriculum**. Health and physical education staffs need to be trained to promote weather protection practice at all levels, primary to the higher education system. Regular heat awareness campaigns can be conducted in schools before the beginning of every summer season including special training on symptoms and self-diagnosis of heat-related health outcomes.

- **It is recommended that the facilities catering for older persons should have air conditioning and the internal room temperature should preferably be monitored.** Local health authorities need to undertake routine supportive supervision.

A greater number of ED presentations and costs were observed during severe heatwave days compared to low-intensity heatwave days. The burden becomes even more significant over the course of extended heatwave periods. It is recommended that

- **The state government should ensure that the health system has the capacity to cope with service demands during days of extreme temperatures.**
- The BOM and public health authorities consider improving the accessibility and dissemination of the heatwave forecast using different languages as >25% of the population were born overseas.

The results in Chapter 4 (using moderate and extreme heat) and Chapter 6 (using extreme heat) suggested that moderate temperature contributed to a considerable cumulative disease burden and cost to the healthcare system. Hence,

- **It is recommended that public awareness-raising about the health impacts of not only extreme heat but also moderate temperature be instituted.** The community should be aware that heat alert is issued at the level when heat stress conditions might become “sufficiently hazardous” to human health. It should be understood that other days without the heat alert are not safe for everyone as our susceptibility can be determined by multiple factors such as medical conditions, age, and gender. Awareness-raising of local communities about factors that may determine an individual’s vulnerability to heat is crucial through community campaigns, media, and community events.

- **It is recommended that the current heat-health intervention policies should reconsider both the health and economic impacts of moderate and extreme temperatures in issuing a heat alert.**

The analysis of ED data by disease diagnosis group indicated that HRI contributed to a higher number of cases and more medical resources compared to other disease groups.

- **It is recommended that public awareness-raising and campaign at the beginning of each hot season might contribute to reducing direct HRI**. The health information may focus on behavioural adjustments such as increase fluids intake, reduce outdoor activities, wearing light clothes during day and night time, and consuming food with less protein. Meanwhile, the consumption of caffeine, alcohol and sugary drinks should be discouraged.

The lag structure analysis result of the heatwave (Chapter 6) indicated that the morbidity and health resource impacts could last up to five days after the heatwave.

- **It is recommended that the heat response service at all levels of the health system and in other sectors such as Ambulance Service, Red Cross, BOM, and State Emergency Service should continue to operate at least up to 5 days after the last heatwave.**

8.4. Future research

Although several studies have investigated the temperature-health relationship around the world, further research is needed to understand the economic impact of temperature using mortality and morbidity data of all levels of the healthcare system (primary, secondary, and emergency health care). In this section, future research is suggested to be undertaken at a different level and scope with some methodological recommendations.

It is recommended that the healthcare outcomes in future research should be expanded to provide a more comprehensive picture of costs.

While the research in this thesis focused on morbidity and costs of TRD in a changing climate, future studies might consider using other health indicators such as mortality, GP visits, ambulance dispatches, and even medication usages. This can provide more comprehensive cost impacts of non-optimum temperature to the healthcare system under the warming climate.

It is recommended that future studies address other non-health sector economic impacts of ambient temperature

The cost impacts of temperature are not only limited to the healthcare system. An economic evaluation of temperature-related morbidity and mortality at a wider scope such as societal level that includes productivity loss is timely.

It is recommended that future epidemiological studies on climate change and health be better performed using daily simulated future climate data with high spatial resolutions

It is necessary to use climate studies accessible and useful in making public health decisions at local, regional, and national levels. In this research, the future temperature scenarios for Adelaide were based on the mean temperature change projection data for the Southern and South-Western Flatlands, East region of Australia, relative to the climate reference period (1986-2005). The use of daily simulated projected temperature data from multiple climate models at higher special resolution can provide more accurate results.

It is recommended that future studies incorporate data on population adaptation

Over time, a population may develop adaptation to local climatic conditions and projection studies should incorporate adaptation factors into account to avoid overestimation. In this research, it is unknown that how the future population of Adelaide will adapt to the warming climate, and studies on adaptive capacity in communities are warranted.

It is recommended that future studies address the effectiveness of heat-health warning systems and interventions in terms of morbidity, mortality, GP services, and associated costs

Despite the wide adoption of the heat warning system around the world, only a few studies have evaluated its benefits in terms of reducing morbidity and mortality effects, as well as money savings. Future studies can evaluate the frequency of warnings and how the forecasted weather conditions actually occurred or how often the warning was not issued but adverse weather conditions occurred.

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Appendices

Appendix A: Online Supplementary Material for the review paper (Chapter 2)

Wondmagegn BY, Xiang J, Williams S, Pisaniello S, and Bi P. What do we know about the healthcare costs of extreme heat exposure? A comprehensive literature review. *Science of the Total Environment* (Impact factor: 6.551). (2019), 608–618.

DOI: 10.1016/j.scitotenv.2018.11.479

Appendix A. Logic grid showing search terms and operators

Database	**Keywords and terms**		
	Temperature	**AND Health**	**AND Cost**
PubMed (4522)	extreme heat[mh] OR extreme heat[tiab] OR climate change[mh] OR climate change[tiab] OR Temperature[mh] OR Temperature*[tiab] OR weather[mh] OR Hot days[tiab] OR Heat*[tiab] OR Hot*[tiab] OR Season*[tiab]	Hospitalization[mh] OR hospitaliz*[tiab] OR hospitalis*[tiab] OR Emergency Medical Services[mh] OR Emergency[tiab] OR Ambulance*[tiab] OR Admission*[tiab] OR Visit*[tiab] OR Triage[tiab] OR ED[tiab] OR Room[tiab] OR Morbidity[mh] OR Morbidity[tiab] OR Mortality[mh] OR Mortality[tiab] OR Death[mh] OR Death*[tiab] OR Disease*[tiab]	costs and cost analysis[mh] OR costs and cost analysis[tiab] OR economic*[tiab] OR Health cost*[tiab] OR Hospital cost*[tiab] OR Health care cost*[tiab] OR Cost*[tiab]
Embase (18)	temperature/syn OR Temperature*:ti,ab OR Heat/syn OR Heat*:ti,ab OR “extreme heat”:ti,ab OR “climate change”:ti,ab OR Season/syn OR Season:ti,ab OR “Extreme environment”:ti,ab OR Extreme*:ti,ab OR Ambient:ti,ab OR Heatwave, Heat wave:ti,ab	“health service”/syn OR Hospitalization/de OR Hospitalisation/de OR Hospital/syn OR Hospital*:ti,ab OR “Hospital admission”/de OR “Hospital admission”:ti,ab OR Emergency:ti,ab	“health care cost”/syn OR Cost*:ti,ab OR “cost of illness”/de OR “cost of illness”:ti,ab OR “hospitalization cost”:ti,ab

		OR Ambulance/syn OR Ambulance:ti,ab OR "hospital emergency service"/de OR "emergency ward"/de OR "emergency ward":ti,ab OR Morbidity/syn OR Mortality/syn OR Death/syn OR "emergency treatment"/syn OR "heat stress"/de OR Thermoregulation/syn OR "heat injury"/syn	
Scopus (6,883)	Temperature OR heat OR heatwave OR hot OR season OR Climate	hospital OR ambulance OR admission OR emergency OR mortality OR death OR morbidity OR disease	cost OR economic
Google Scholar (21)	Heat, Temperature, Heatwave, mortality	Morbidity, hospitalization, Admission, Emergency Department Visit, Ambulance Call-out, Ambulance dispatch,	Economics, Costing, Projection

Appendix B: Supplementary material for Study 1 (Chapter 4)

Wondmagegn BY, Xiang J, Dear K, Williams S, Hansen A, et al. Understanding current and projected costs of emergency department presentations in a changing climate. Currently under-review. *Medical Journal of Australia*, (Impact factor: 6.112).

Table S1. QAIC and AIC values for models with different degrees of freedom per year for TRD-ED presentation and ED costs using natural cubic spline

Variables	Degree of freedom per year									
	1	2	3	4	5	6	7	8	9	10
ED presentation (QAIC)	12338.67	12259.31	12085.55	12066.79	12032.46	11984.88	11963.41	11975.67	11972.16	11974.08
ED cost (AIC)	33016	32967	32674	32686	32630	32626	32625	32626	32628	32627

QAIC = quasi-Poisson Akaike's Information Criterion (for over-dispersed count data)
AIC = Akaike's Information Criterion

Table S2. Projected net-, cold-, and heat-attributable TRD-ED presentations (N=in thousand) and costs (in million AU$) at 95% eCI under three RCPs and constant population in Adelaide, South Australia

Scenarios	Temperature	2034-2037		2054-2057	
		ED Presentations	ED costs	ED Presentations	ED costs
RCP2.6	Net	6.9 (-4.4, 13.5)	**13.1 (1.0, 23.9)**	7.0 (-0.2, 13.6)	**13.2 (1.3, 24.0)**
	Cold	2.1 (-3.9, 7.9)	6.9 (-4.0, 16.6)	2.0 (-3.9, 7.6)	6.7 (-3.9, 16.1)
	Heat	**4.8 (1.3, 8.2)**	**6.2 (2.7, 9.5)**	**5.1 (1.5, 8.5)**	**6.5 (2.9, 10.0)**
RCP4.5	Net	7.0 (-0.2, 13.6)	**13.2 (1.3, 24.0)**	**7.7 (0.9, 13.9)**	**13.8 (2.6, 24.0)**
	Cold	2.0 (-3.9, 7.6)	6.7 (-3.9, 16.1)	1.4 (-3.5, 6.3)	5.8 (-3.6, 14.2)
	Heat	**5.1 (1.5, 8.5)**	**6.5 (3.0, 10.0)**	**6.3 (2.2, 10.3)**	**8.0 (3.8, 12.0)**
RCP8.5	Net	**7.3 (0.4, 13.7)**	**13.5 (1.9, 24.0)**	**8.7 (2.2, 14.6)**	**14.7 (4.2, 24.4)**
	Cold	1.7 (-3.7, 6.9)	6.2 (-3.6, 15.1)	1.0 (-3.1, 5.1)	4.9 (-3.3, 12.4)
	Heat	**5.6 (1.8, 9.4)**	**7.2 (3.3, 11.0)**	**7.7 (3.1, 12.2)**	**9.8 (5.0, 14.4)**

Bold font indicates statistically significant changes based on the 95% empirical confidence interval.

Table S3. Projected excess net-, cold-, and TRD-ED presentations (N=in thousands) and ED costs (in million AU$) at 95% eCI under three RCPs and constant population in Adelaide, South Australia

Scenarios	Temperature	2034-2037		2054-2057	
		ED Presentations (95% eCI)	ED costs (95% eCI)	ED Presentations (95% eCI)	ED costs (95% eCI)
RCP2.6	Net	0.3 (-1.3, 1.8)	0.5 (-1.5, 2.6)	0.4 (-1.5, 2.3)	0.6 (-1.8, 3.1)
	Cold	-0.9 (-2.4, 0.6)	-1.0 (-3.0, 1.0)	-1.0 (-2.8, 0.8)	-1.2 (-3.5, 1.2)
	Heat	**10.2 (0.8, 1.7)**	**1.5 (0.8, 2.1)**	**1.4 (0.7, 2.1)**	**1.8 (1.0, 2.5)**
RCP4.5	Net	0.4 (-1.5, 2.3)	5.9 (-1.8, 3.1)	1.1 (-1.9, 4.0)	1.2 (-2.5, 5.1)
	Cold	-1.0 (-2.8, 0.8)	-1.2 (-3.5, 1.2)	-1.6 (-4.3, 1.1)	-2.1 (-5.7, 1.6)
	Heat	**1.4 (0.7, 2.1)**	**1.8 (10.0, 2.5)**	**2.6 (1.4, 3.8)**	**3.3 (1.8, 4.6)**
RCP8.5	Net	0.7 (-1.7, 3.1)	0.9 (-2.2, 4.0)	2.0 (-1.8, 6.0)	2.1 (-2.8, 7.2)
	Cold	-1.3 (-3.6, 0.9)	-1.7 (-4.6, 1.5)	-2.0 (-5.6, 1.5)	-3.0 (-7.6, 2.0)
	Heat	**2.0 (1.0, 2.9)**	**2.5 (1.4, 3.6)**	**4.1 (2.2, 5.8)**	**5.1 (2.8, 7.1)**

Bold font indicates statistically significant changes based on the 95% empirical confidence interval.

Table S4. Projected percentage change of net-, cold-, and heat-attributable TRD-ED presentations and costs in Adelaide, South Australia, with 95% eCI, under three RCP emissions and constant population change scenarios

Scenarios	Temperature	2034-2037		2054-2057	
		ED Presentations	ED costs	ED Presentations	ED costs
RCP2.6	Net	0.1 (-0.5, 0.7)	0.18 (-0.61, 1.02)	0.1 (-0.6, 0.8)	0.23 (-0.71, 1.22)
	Cold	-0.3 (-0.9, 0.2)	-0.40 (-1.18, 0.42)	-0.4 (-1.0, 0.3)	-0.48 (-1.40, 0.48)
	Heat	**0.4 (0.2, 0.6)**	**0.58 (0.32, 0.82)**	**0.5 (0.3, 0.8)**	**0.72 (0.39, 1.01)**
RCP4.5	Net	0.1 (-0.6, 0.8)	0.23 (-0.71, 1.22)	0.4 (-0.7, 1.5)	0.49 (-0.99, 2.01)
	Cold	-0.4 (-1.0, 0.3)	-0.48 (-1.40, 0.48)	-0.6 (-1.6, 0.4)	-0.83 (-2.26, 0.64)
	Heat	**0.5 (0.3, 0.8)**	**0.72 (0.39, 1.01)**	**1.0 (0.5, 1.4)**	**1.32 (0.72, 1.84)**
RCP8.5	Net	0.3 (-0.6, 1.2)	0.35 (-0.88, 1.60)	0.8 (-0.7, 2.3)	0.84 (-1.11, 2.86)
	Cold	-0.5 (-1.3, 0.4)	-0.66 (-1.83, 0.58)	-0.8 (-2.1, 0.6)	-1.18 (-3.02, 0.78)
	Heat	**0.7 (0.4, 1.1)**	**1.01 (0.55, 1.41)**	**1.5 (0.8, 2.2)**	**2.02 (1.11, 2.82)**

Bold font indicates statistically significant changes based on the 95% empirical confidence interval.

Table S5. Projected excess net-, cold-, and heat-attributable TRD-ED presentations (N=in thousands) and ED costs (in million AU$) at 95% eCI under the three RCPs and medium population change scenarios in Adelaide, South Australia

Scenarios	Temperature	2034-2037		2054-2057	
		ED Presentations	ED costs	ED Presentations	ED costs
RCP2.6	Net	**4.0 (0.3, 7.3)**	**7.4 (1.4, 13.0)**	**5.7 (0.6, 10.3)**	**10.5 (2.1, 18.2)**
	Cold	0.3 (-2.3, 2.8)	2.7 (-2.0, 7.0)	0.5 (-3.1, 4.0)	3.8 (-2.9, 9.9)
	Heat	**3.7 (1.3, 6.1)**	**4.8 (2.3, 7.1)**	**5.2 (1.9, 8.5)**	**6.7 (3.3, 10.0)**
RCP4.5	Net	**4.1 (0.5, 7.4)**	**7.6 (1.5, 13.1)**	**6.8 (1.7, 11.6)**	**11.6 (3.6, 19.2)**
	Cold	0.0 (-2.4, 2.4)	2.3 (-2.1, 6.5)	-0.5 (-3.4, 2.3)	2.2 (-3.2, 7.4)
	Heat	**4.1 (1.6, 6.7)**	**5.3 (2.6, 7.8)**	**7.3 (3.1, 11.6)**	**9.4 (4.9, 13.6)**
RCP8.5	Net	**4.6 (0.8, 8.1)**	**8.1 (2.1, 13.7)**	**8.6 (2.8, 13.9)**	**13.2 (4.8, 20.8)**
	Cold	-0.4 (-2.7, 1.8)	1.7 (-2.4, 5.6)	-1.3 (-4.0, 1.5)	0.7 (-4.1, 5.4)
	Heat	**5.0 (2.1, 8.0)**	**6.4 (3.3, 9,4)**	**9.8 (4.6, 14.9)**	**12.5 (6.7, 17.7)**

Bold font indicates statistically significant changes based on the 95% empirical confidence interval.

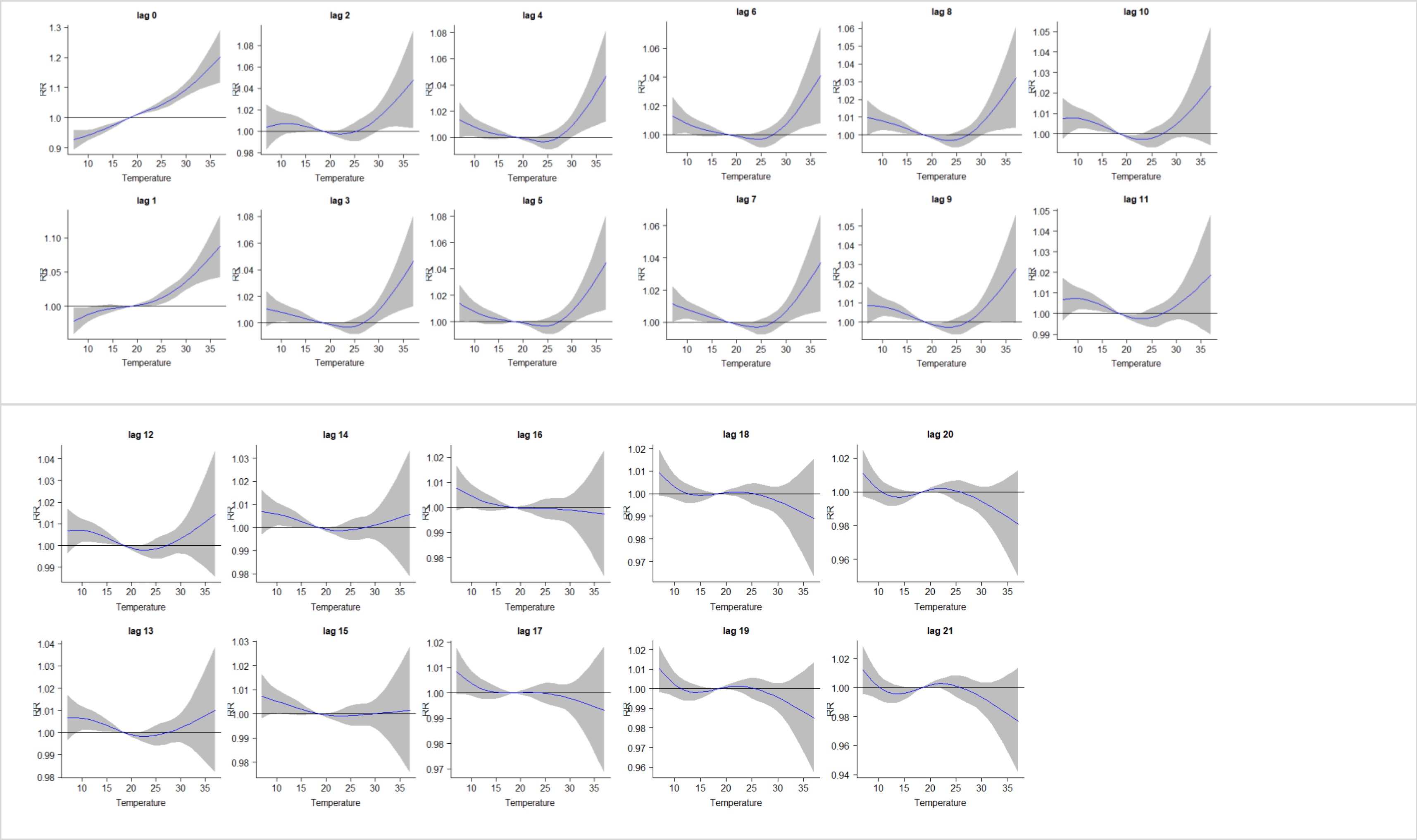


Figure S1. Effects of mean temperature at different lags for TRD-ED presentation from 2014-2017 in Adelaide, Australia. The blue line represents an effect estimate for the indicated lag days for the range of temperature and the grey area is the 95% eCI.

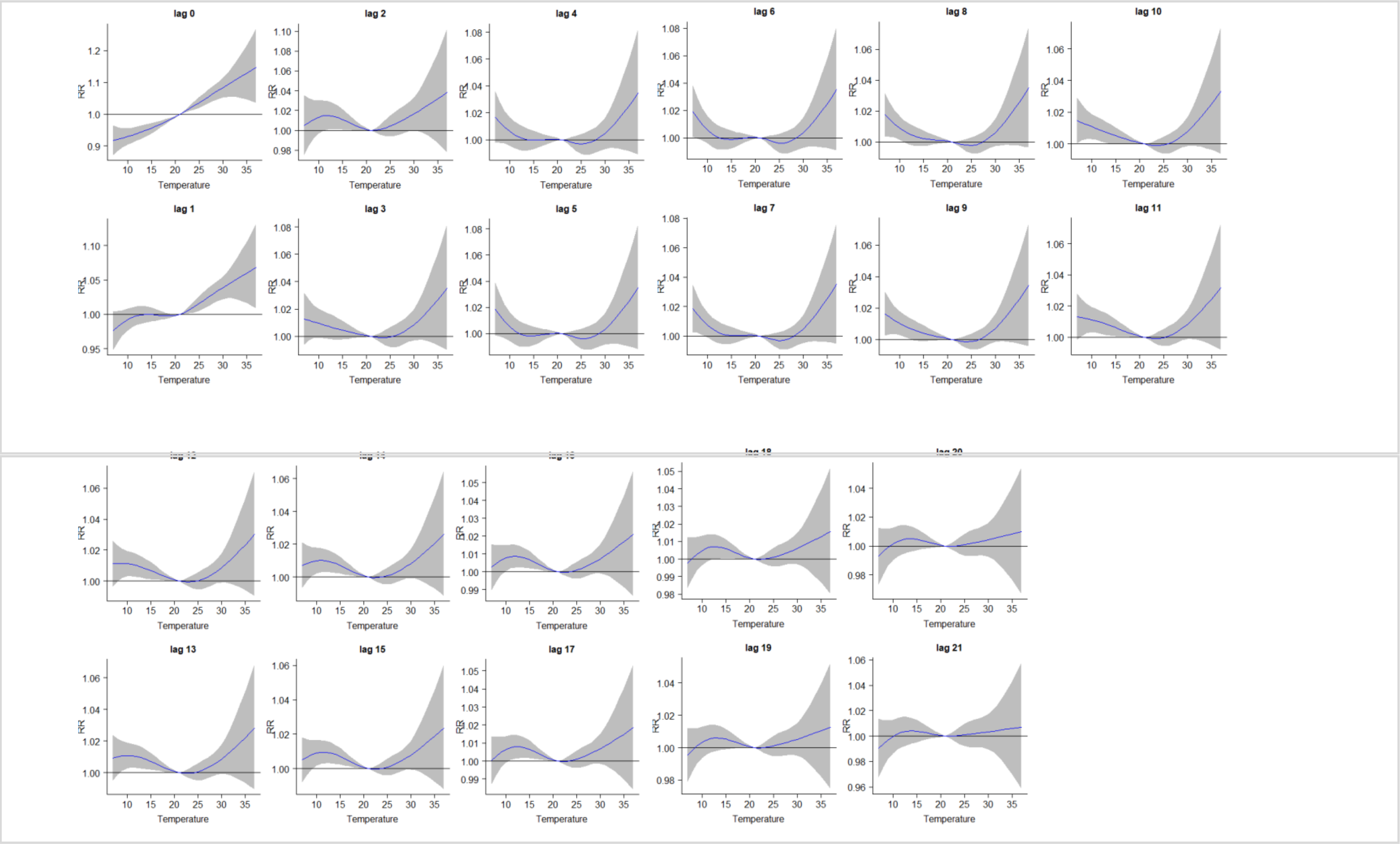
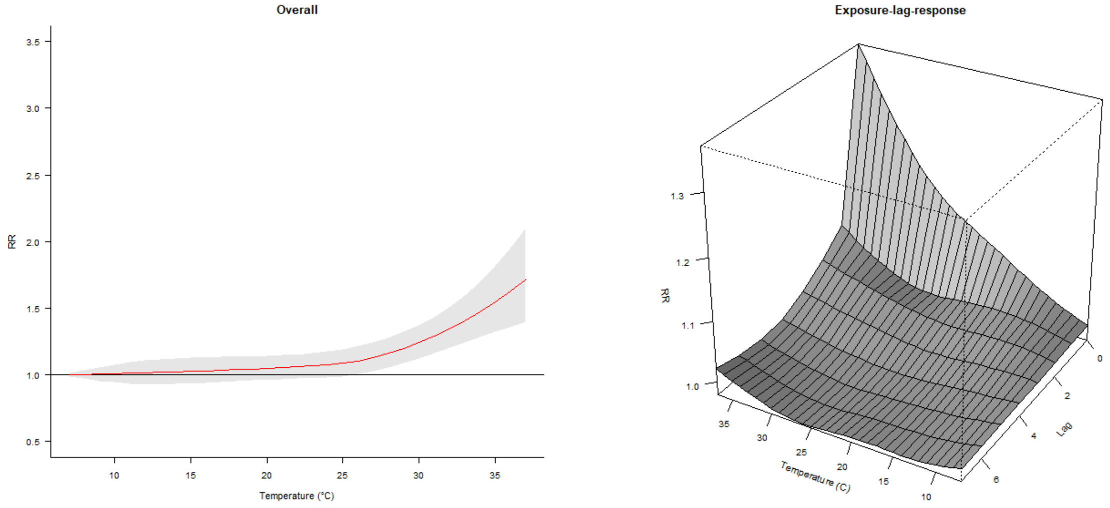
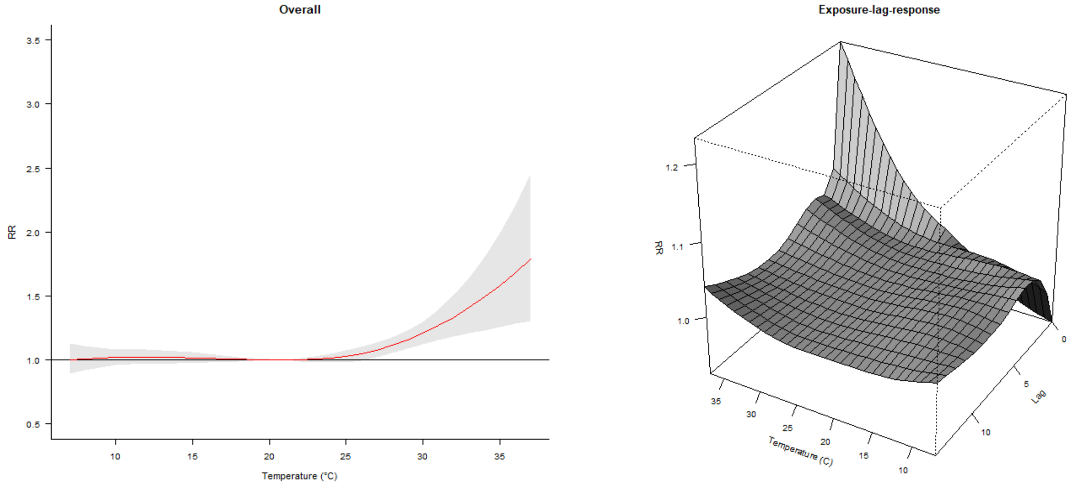


Figure S2. Effects of mean temperature at different lags for TRD-ED costs from 2014-2017 in Adelaide, Australia. The blue line represents an effect estimate for the indicated lag days for the range of temperature and the grey area is the 95% eCI.

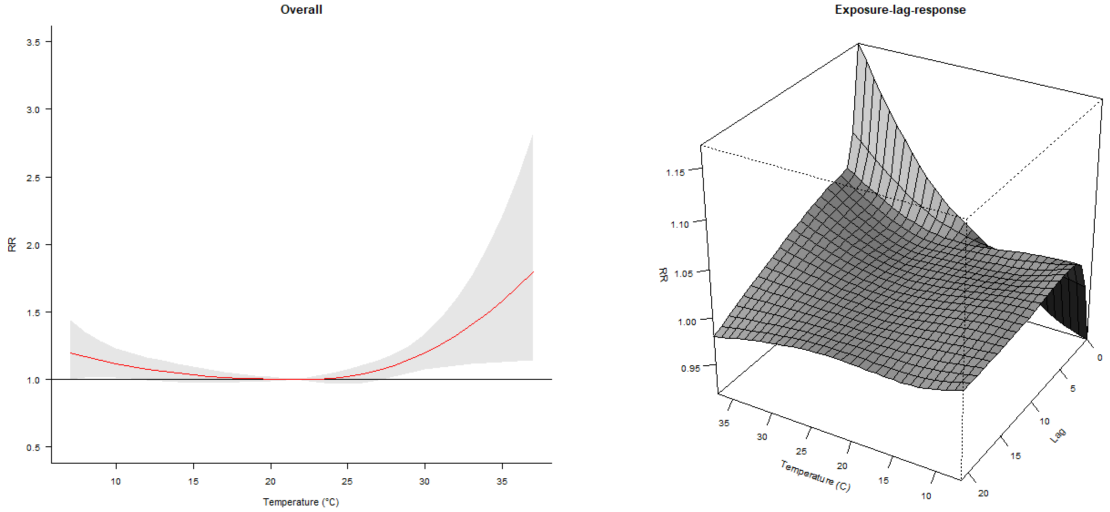
a. Lag 7, df=7, knots=3



b. Lag 14, df=7, knots=3



c. Lag 21, df=9, knots=3



d. Lag 21, df=7, knots=4

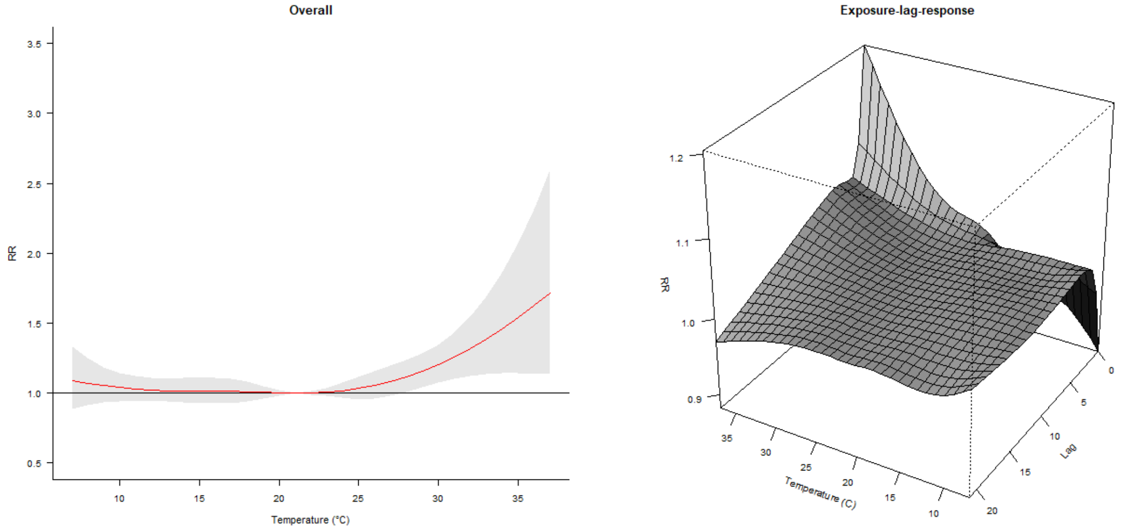
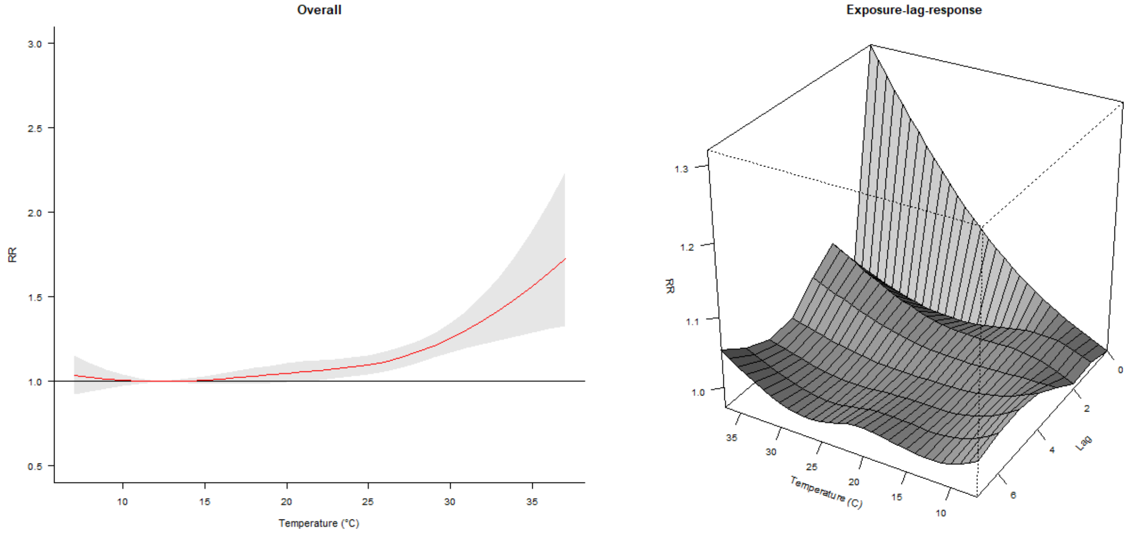
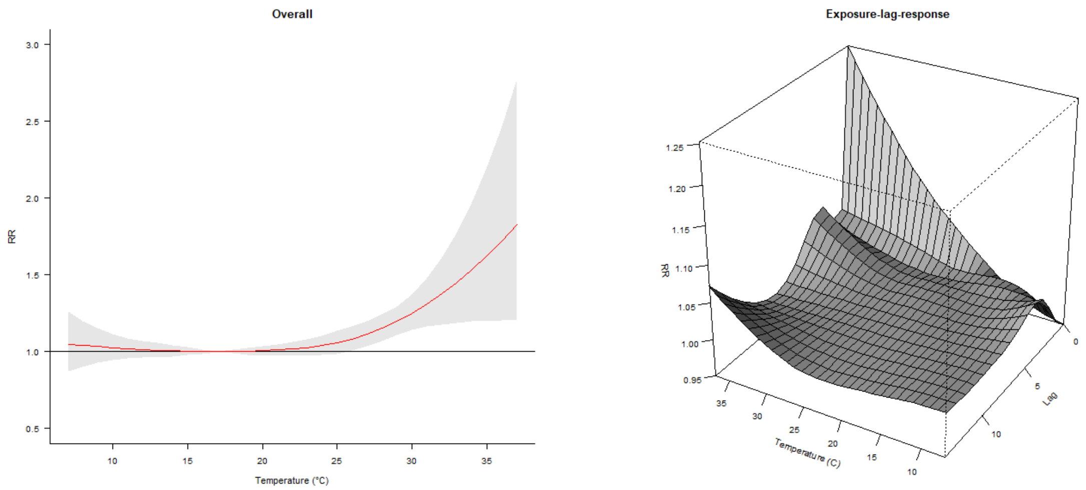


Figure S3. Models sensitivity analyses for TRD-ED presentations with different maximum lag days, df, and knots

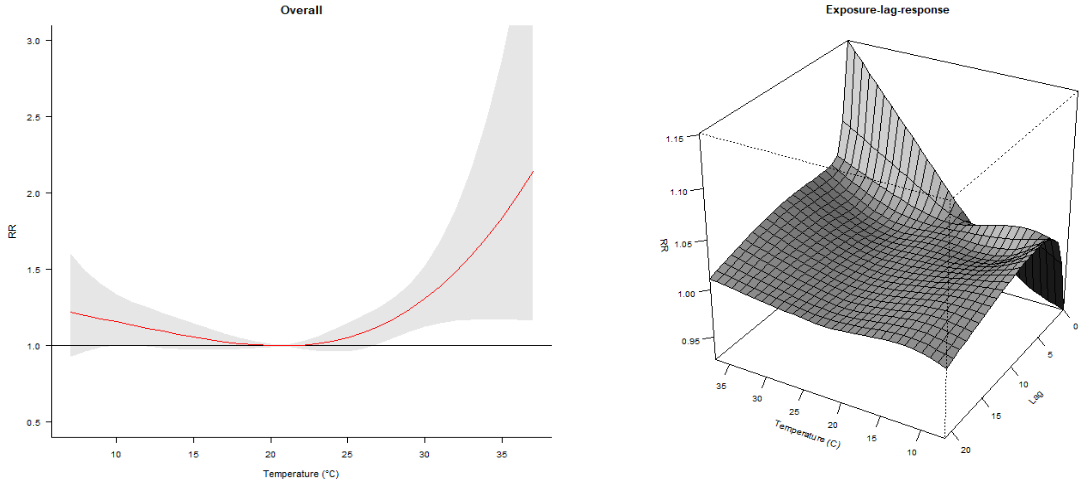
a. Lag 7, df=7, knots=3



b. Lag 14, df=7, knots=3



c. Lag 21, df=9, knots=3



d. Lag 21, df=7, knots=4

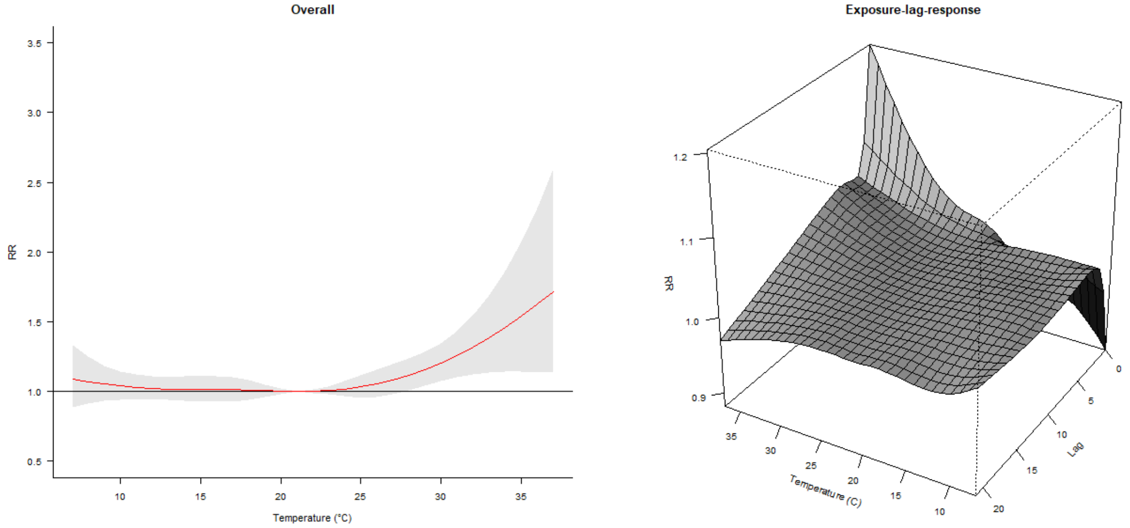


Figure S4. Models sensitivity analyses for TRD-ED costs with different maximum lag days, df, and knots.

Table S6. Relative risks of cold and hot temperatures and optimum temperature at different lag days from 2014-2017 in Adelaide, South Australia

Variables	Lag	Risk				Optimum temperature (OT)	Remarks
		1st (8.4°C)	10th (10.8°C)	90th (25.3°C)	99th (30.9°C)		
ED presentations	7	1.00 (0.97, 1.04)	1.01 (0.94, 1.09)	1.09 (0.99, 1.20)	1.29 (1.16, 1.43)	6.5°C	Only heat effects were observed
	14	1.01 (0.93, 1.10)	1.02 (0.96, 1.08)	1.03 (0.99, 1.08)	1.26 (1.15, 1.38)	20.7°C	Both cold and heat effects were observed
	21	1.07 (0.95, 1.20)	1.04 (0.96, 1.11)	1.03 (0.96, 1.10)	1.28 (1.13, 1.42)	18.5°C	
ED costs	7	1.01 (0.97, 1.04)	1.00 (0.99, 1.02)	1.10 (1.05, 1.16)	1.30 (1.20, 1.41)	12.1°C	
	14	1.03 (0.94, 1.12)	1.02 (0.95, 1.09)	1.06 (0.99, 1.14)	1.12 (1.04, 1.21)	17.1°C	
	21	1.07 (0.95, 1.22)	1.08 (0.96, 1.20)	1.05 (0.97, 1.14)	1.36 (1.16, 1.58)	21.0°C	

Appendix C: Supplementary material for Study 2 (Chapter 5)

Wondmagegn BY, Xiang J, Dear K, Williams S, Hansen A, et al. Increasing impacts of temperature on hospital admissions, length of stay, and related healthcare costs in the context of climate change in Adelaide, South Australia. *Science of the Total Environment* (Impact factor: 6.551). 2021, 145656. DOI: 10.1016/j.scitotenv.2021.145656.

Appendix: Supplementary tables

Table S7. Projected mean temperature change in 2040s and 2060s from the CMIP5 ensemble model for greater Adelaide metropolitan area relative to 1986-2005.

RCPs	Time and projected temperature change			
	2040	2045	2060	2065
RCP2.6	0.8(0.6-1.0) °C	0.8(0.5-1.1) °C	0.9(0.6-1.2) °C	0.9(0.6-1.2) °C
RCP4.5	0.9(0.7-1.1) °C	1(0.8-1.2) °C	1.2(0.9-1.5) °C	1.3(1.0-1.6) °C
RCP8.5	1.1(0.9-1.3) °C	1.3(1.0-1.6) °C	1.9(1.6-2.2) °C	2.1(1.7-2.5) °C

Table S2. Estimated net temperature-, cold- and heat-attributable TRD hospital admissions, LoS, and costs at 95% eCI under three climate change scenarios and a constant population in Adelaide, South Australia for 2040s and 2060s.*

Temperature Scenarios †	Exposure	2040s Admissions (N=in thousand)	2040s LoS (in thousand days)	2040s Costs (in million AU$)	2060s Admissions (N=in thousand)	2060s LoS (in thousand days)	2060s Costs (in million AU$)
Lower	Net	**4.0 (0.4, 7.3)**	**101.4 (13.6, 171.6)**	**161.3 (16.6, 274.4)**	**4.0 (0.5, 7.3)**	**102.2 (13.5, 173.7)**	**162.4 (15.4, 277.0)**
	Cold	0.8 (-2.2, 3.9)	4.9 (-3.6, 12.8)	10.5 (-7.8, 28.7)	0.8 (-2.2, 3.8)	4.5 (-3.3, 11.9)	9.7 (-7.4, 26.8)
	Heat	**3.1 (0.3, 5.9)**	**96.5(7.9, 167.7)**	**150.8 (1.5, 271.6)**	**3.2 (0.3, 6.0)**	**97.7 (8.2, 169.7)**	**152.7 (1.7, 274.8)**
Mid	Net	**4.0 (0.5, 7.3)**	**102.7 (13.3, 174.5)**	**163.1 (15.0, 278.2)**	**4.1 (0.7, 7.4)**	**105.5 (13.1, 179.3)**	**166.9 (12.4, 286.7)**
	Cold	0.8 (-2.1, 3.7)	4.3 (-3.3, 11.5)	9.4 (-7.3, 25.9)	0.7 (-2.0, 3.5)	3.3 (-2.7, 9.1)	7.3 (-6.1, 20.7)
	Heat	**3.2 (0.3, 6.1)**	**98.4 (8.4, 170.8)**	**153.7 (1.7, 276.5)**	**3.4 (0.4, 6.4)**	**102.1 (9.3, 177.0)**	**159.6 (1.9, 286.2)**
Higher	Net	**4.1 (0.7, 7.3)**	**105.0(13.1, 178.4)**	**166.3 (12.8, 285.4)**	**4.5 (1.1, 7.7)**	**113.5 (12.4, 193.4)**	**178.4 (9.1, 310.2)**
	Cold	0.7 (-2.0, 3.5)	3.5 (-2.8, 9.5)	7.7 (-6.3, 21.6)	0.5 (-1.6, 2.8)	1.6 (-1.6, 4.7)	3.7 (-3.9, 11.4)
	Heat	**3.4 (0.5, 6.3)**	**101.5 (9.2, 176.0)**	**158.6 (1.9, 284.6)**	**3.9 (0.6, 7.2)**	**111.9 (10.3, 192.6)**	**174.7 (2.4, 309.2)**

*Admissions, LoS, and costs for combined renal, mental health, IHD, diabetes, and heat-related diagnoses, aggregated by date of admission

Bold font indicates statistically significant results based on the 95% empirical confidence interval.

† Temperature scenarios are based on different emissions scenarios, as described. Lower (RCP2.6), Mid (RCP4.5) and Higher (RCP8.5).

Table S3. Estimated excess and percentage change of net temperature-, cold-, and heat-attributable TRD hospital admissions, LoS, and costs of hospitalisations at 95% eCI under a constant population and different climate change scenarios relative to the current effects in Adelaide, South Australia for the 2040s.*

Temperature Scenarios †	Exposure	Excess			Percentage change		
		Admissions (in thousands = N)	LoS (in thousand days)	Costs (Million AU$)	Admissions (in thousands = N)	LoS (in thousand days)	Costs (Million AU$)
Lower	Net	0.6 (-0.1, 0.3)	1.6 (-0.9, 3.7)	2.1 (-2.5, 59.9)	0.05 (-0.12, 0.22)	0.20 (-0.11, 0.45)	0.15 (-0.18, 0.43)
	Cold	-0.06 (-0.2, 0.1)	-0.8 (-2.0, 0.4)	-1.7 (-4.1, 0.8)	-0.05 (-0.19, 0.10)	-0.11 (-0.25, 0.06)	-0.12 (-0.29, 0.06)
	Heat	**0.1 (0.03, 0.2)**	**2.5 (0.5, 4.0)**	**3.8 (0.3, 6.5)**	**0.10 (0.03, 0.17)**	**0.30 (0.06, 0.49)**	**0.28 (0.02, 0.46)**
Mid	Net	0.1 (-0.2, 0.5)	2.9 (-1.4, 6.5)	3.9 (-4.1, 10.6)	0.10 (-0.20, 0.38)	0.36 (-0.18, 0.80)	0.28 (-0.29, 0.76)
	Cold	-0.1 (-0.4, 0.2)	-1.4 (-3.3, 0.8)	-2.9 (-6.9, 1.4)	-0.08 (-0.33, 0.17)	-0.17 (-0.41, 0.09)	-0.21 (-0.49, 0.10)
	Heat	**0.2 (0.6, 0.4)**	**4.3 (0.8, 7.0)**	**6.8 (0.5, 11.4)**	**0.18 (0.05, 0.30)**	**0.54 (0.10, 0.87)**	**0.49 (0.04, 0.82)**
Higher	Net	0.2 (-0.4, 0.8)	5.2 (-2.1, 11.2)	7.2 (-6.4, 18.3)	0.17 (-0.32, 0.64)	0.65 (-0.26, 1.39)	0.51 (-0.46, 1.32)
	Cold	-0.2 (-0.7, 0.3)	-2.2 (-5.3, 1.2)	-4.6 (-11.1, 2.3)	-0.14 (-0.54, 0.28)	-0.28 (-0.66, 0.15)	-0.33(-0.80, 0.17)
	Heat	**0.4 (0.1, 0.6)**	**7.5 (1.5, 12.1)**	**11.7 (0.9, 19.6)**	**0.31 (0.09, 0.52)**	**0.93 (0.18, 1.50)**	**0.84 (0.07, 1.41)**

*Admissions, LoS, and costs for combined renal, mental health, IHD, diabetes, and heat-related diagnoses, aggregated by date of admission

Bold font indicates statistically significant results based on the 95% empirical confidence interval.

† Temperature scenarios are based on different emissions scenarios, as described. Lower (RCP2.6), Mid (RCP4.5) and Higher (RCP8.5).

Table S4. Estimated net temperature-, cold- and heat-attributable TRD hospital admissions, LoS, and costs at 95% eCI under climate and population change scenarios relative to the current effects in Adelaide, South Australia for the 2040s.*

Temperature Scenarios †	Exposure	Admissions (in thousands = N) (95% eCI)	LoS (in thousand days) (95% eCI)	Costs (in million AU$) (95% eCI)
Lower	Net	**5.2 (0.5, 9.4)**	**131.6 (17.6, 222.8)**	**209.4 (21.5, 356.2)**
	Cold	1.1 (-2.9, 5.0)	6.3 (-4.7, 16.7)	13.6 (-10.1, 37.3)
	Heat	**4.1 (0.4, 7.7)**	**125.3 (10.2, 217.7)**	**195.7 (2.0, 352.6)**
Mid	Net	**5.2 (0.7, 9.5)**	**133.3 (17.3, 226.6)**	**211.7 (19.4, 361.2)**
	Cold	1.0 (-2.8, 4.9)	5.6 (-4.3, 14.9)	12.2 (-9.5, 33.6)
	Heat	**4.2 (0.4, 7.9)**	**127.7 (10.9, 221.7)**	**199.6 (2.2, 359.0)**
Higher	Net	**5.4 (1.0, 9.5)**	**136.4 (17.1, 231.7)**	**215.9 (16.6, 370.5)**
	Cold	1.0 (-2.6, 4.5)	4.5 (-3.6, 12.3)	9.9 (-8.2, 28.0)
	Heat	**4.4 (0.5, 8.2)**	**131.8 (11.9, 228.5)**	**206.0 (2.5, 369.6)**

*Admissions, LoS, and costs for combined renal, mental health, IHD, diabetes, and heat-related diagnoses, aggregated by date of admission

Bold font indicates statistically significant results based on the 95% empirical confidence interval.

† Temperature scenarios are based on different emissions scenarios, as described. Lower (RCP2.6), Mid (RCP4.5) and Higher (RCP8.5).

Table S5. Estimated excess and percentage change of net temperature-, cold- and heat-attributable TRD hospital admissions, LoS, and costs of hospitalisations at 95% eCI under climate and population change scenarios in Adelaide, South Australia for the 2040s.*

Temperature Scenarios †	Exposure	**Excess**			**Percentage change**		
		Admissions (N=thousands)	LoS (in thousand days)	Costs (Million AU$)	Admissions	LoS	Costs
Lower	Net	**1.3 (0.2, 2.2)**	**31.8 (3.5, 54.1)**	**50.2 (3.4, 87.3)**	**1.03 (0.20, 1.81)**	**3.9 (0.4, 6.7)**	**3.6 (0.2, 6.3)**
	Cold	0.2 (-0.5, 1.0)	0.6 (-0.6, 1.8)	1.4 (-1.6, 4.5)	0.2 (-0.5, 0.8)	0.1 (-0.1, 0.2)	0.1 (-0.1, 0.3)
	Heat	**1.1 (0.1, 2.0)**	**31.2 (2.9, 54.1)**	**48.8 (0.6, 87.3)**	**0.9 (0.1, 1.6)**	**3.9 (0.4, 6.7)**	**3.8 (0.1, 6.7)**
Mid	Net	**1.3 (0.3, 2.3)**	**33.6 (3.1, 57.7)**	**52.6 (1.5, 92.8)**	**1.1 (0.3, 1.9)**	**4.15 (0.39, 7.14)**	**3.8 (0.1, 6.7)**
	Cold	0.1 (-0.5, 0.8)	-0.1 (-0.3, 0.1)	-0.07 (-1.0, 1.0)	0.1 (-0.4, 0.6)	-0.02 (-0.04, 0.01)	-0.01 (-0.07, 0.07)
	Heat	**1.2 (0.2, 2.2)**	**33.7 (3.1, 58.0)**	**52.6 (0.9, 93.1)**	**1.0 (0.1, 1.8)**	**4.2 (0.4, 7.2)**	**3.8 (0.1, 6.7)**
Higher	Net	**1.4 (0.4, 2.5)**	**36.6 (2.7, 63.5)**	56.8 (-0.8, 101.3)	**1.2 (0.3, 2.0)**	**4.5 (0.3, 7.9)**	4.1 (-0.1, 7.3)
	Cold	0.5 (-0.4, 0.5)	-1.2 (-2.5, 0.4)	-2.3 (-4.7, 0.5)	0.04 (-0.34, 0.40)	-0.15 (-0.31, 0.05)	-0.2 (-0.3, 0.04)
	Heat	**1.4 (0.2, 2.5)**	**37.8 (4.1, 64.6)**	**59.1 (1.1, 103.9)**	**1.1 (0.2, 2.1)**	**4.7 (0.5, 8.0)**	**4.2 (0.1, 7.5)**

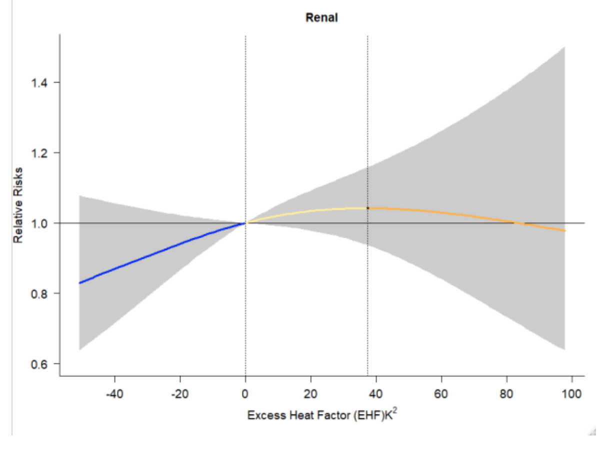
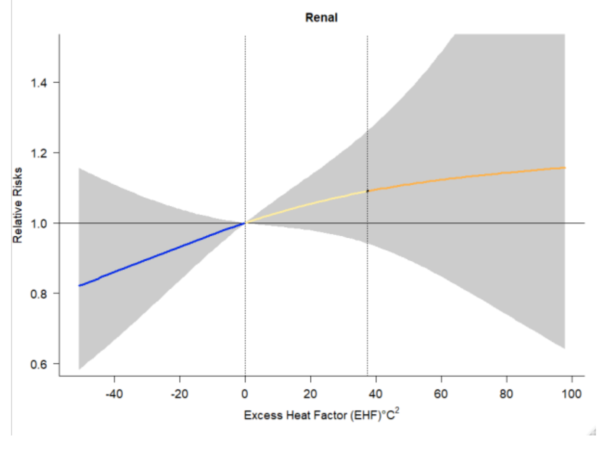
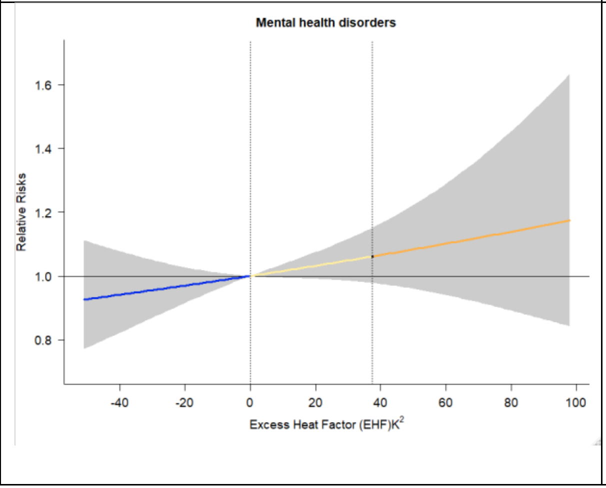
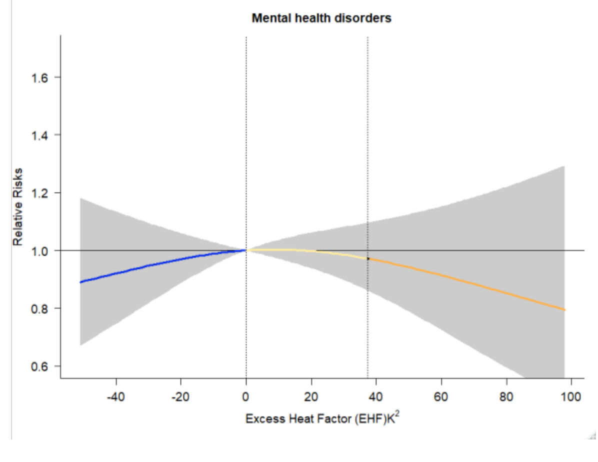
*Admissions, LoS, and costs for combined renal, mental health, IHD, diabetes, and heat-related diagnoses, aggregated by date of admission

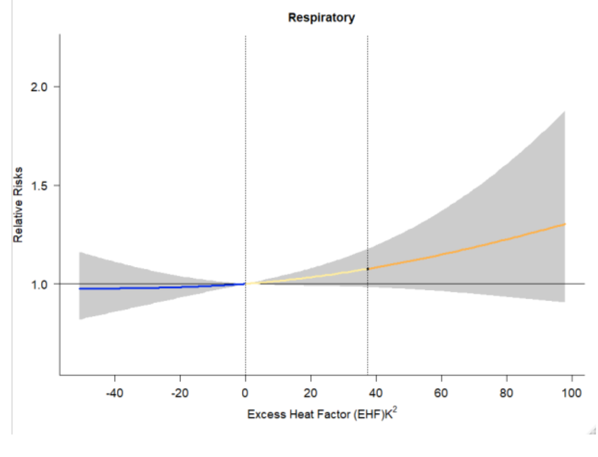
Bold font indicates statistically significant results based on the 95% empirical confidence interval.

† Temperature scenarios are based on different emissions scenarios, as described. Lower (RCP2.6), Mid (RCP4.5) and Higher (RCP8.5).

Appendix D: Supplementary material for Study 3 (Chapter 5)

Wondmagegn BY, Xiang J, Dear K, Williams S, Hansen A, et al. Impact of heatwave intensity using Excess Heat Factor on emergency department presentations and related healthcare costs in Adelaide, South Australia. Accepted on 24 March 2021, *Science of the Total Environment* (Impact factor: 6.551). Ms. Ref. No.: STOTEN-D-20-21768.

a. ED presentations	**b. Costs**
 	
 	


Respiratory
Relative Risks
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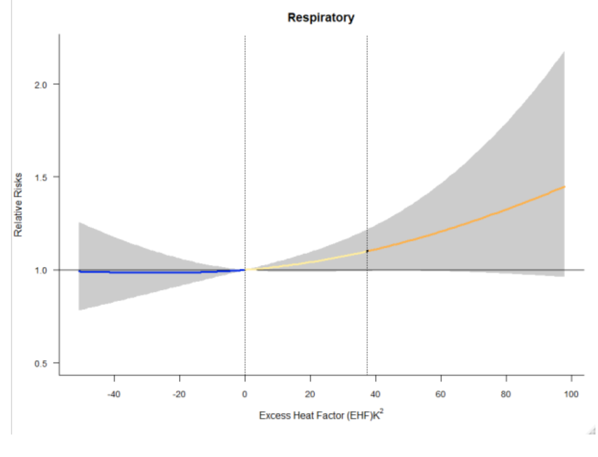
1.5
1.0
-40
-20
0
20
40
60
80
100
Excess Heat Factor (EHF)K^2


Respiratory
Relative Risks
2.0
1.5
1.0
0.5
-40
-20
0
20
40
60
80
100
Excess Heat Factor (EHF)K^2

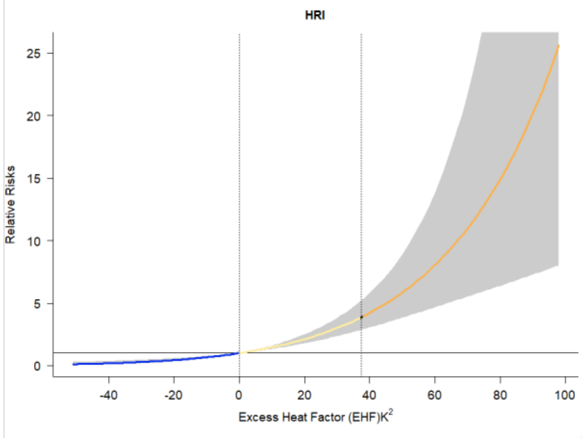
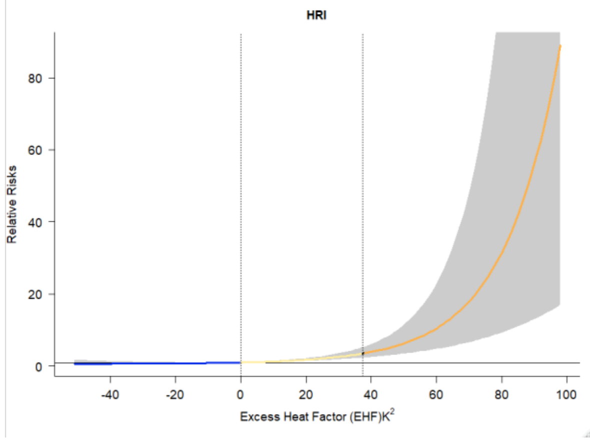
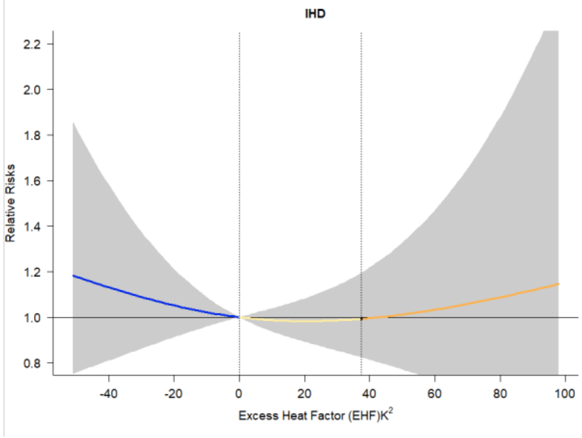
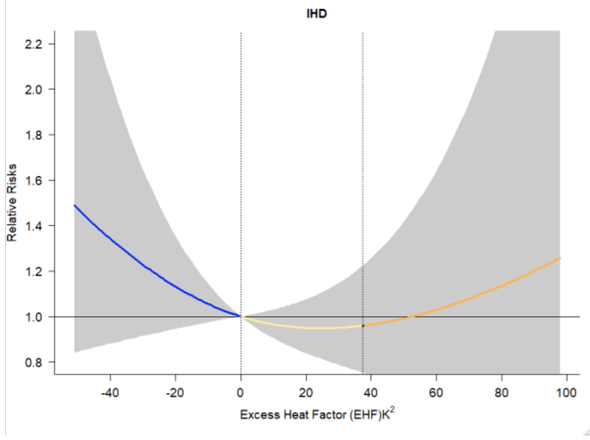
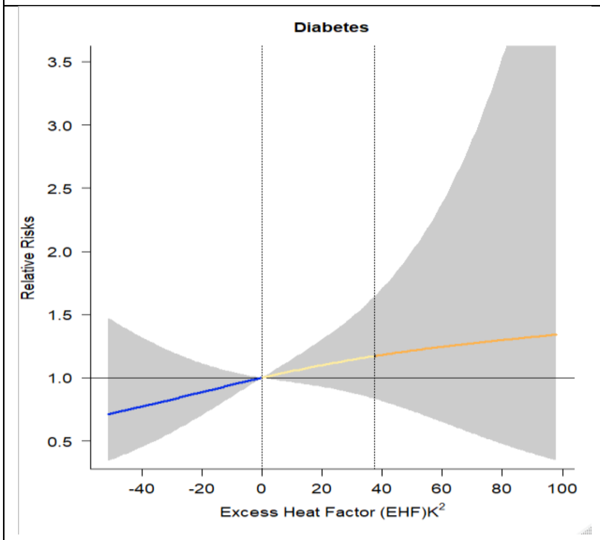
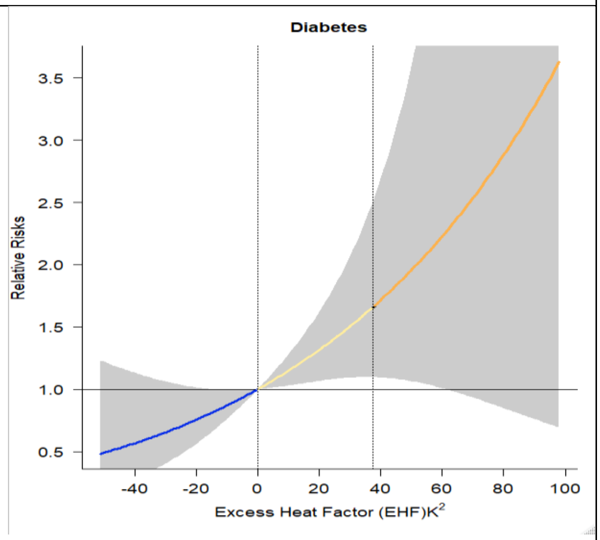
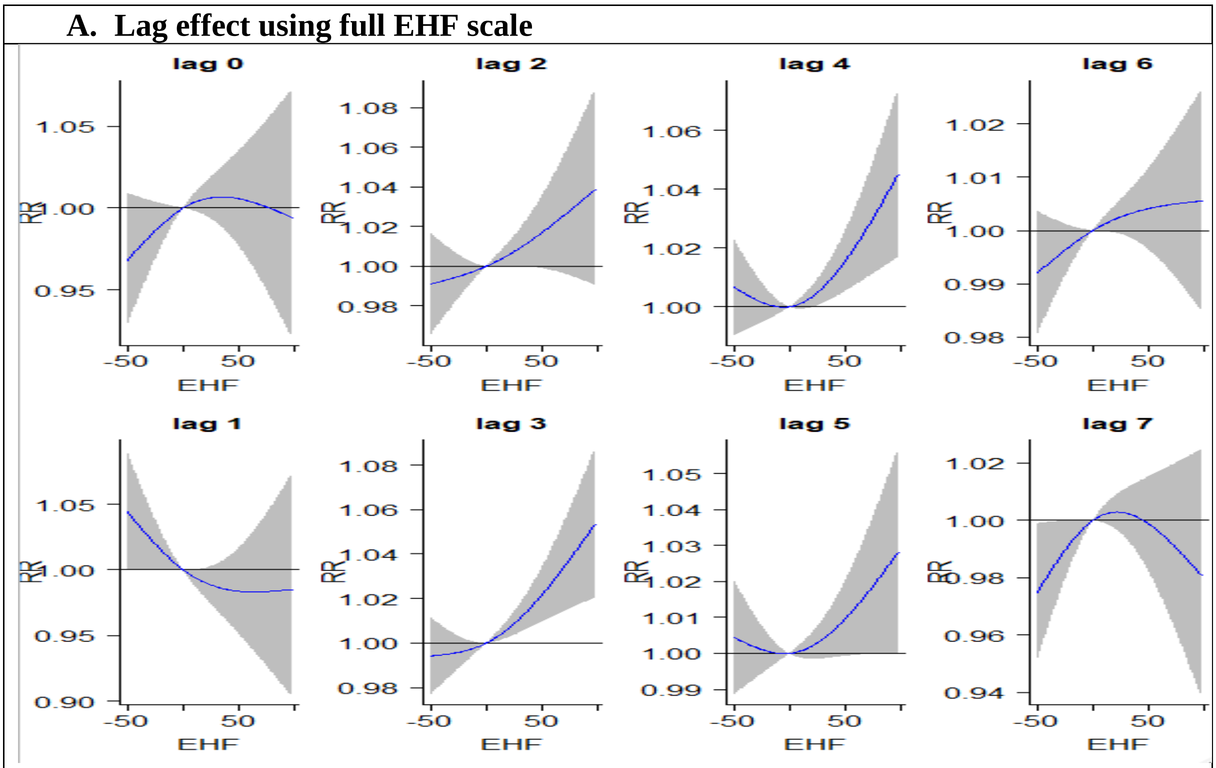
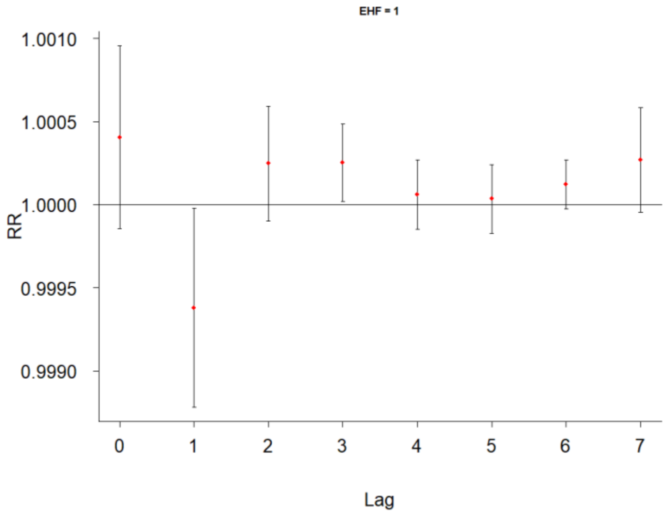
Continue …	
ED presentations	**Costs**
	
	
	

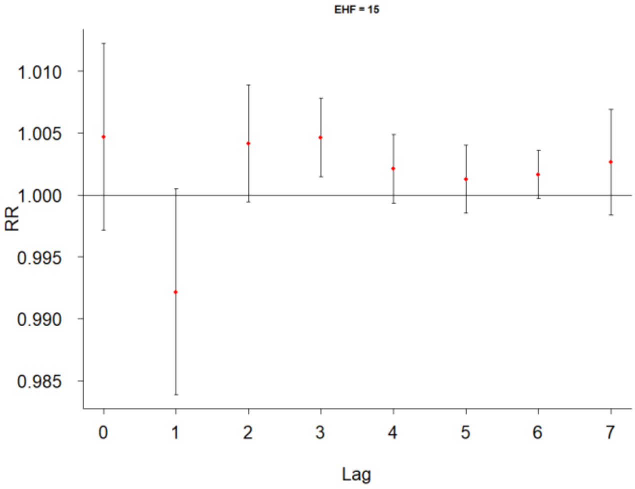
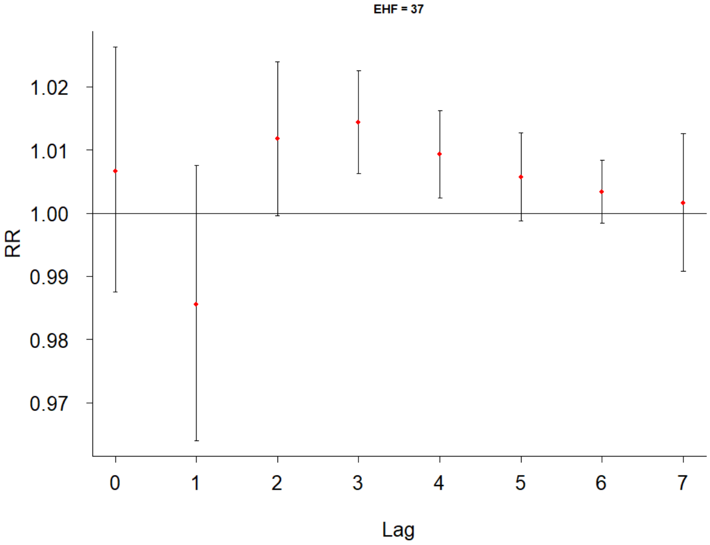
Figure S5. Cumulative effects of heatwaves on ED presentations and costs for specific disease diagnosis in Adelaide, South Australia, 2014-2017. The blue line represents non-heatwave days, the yellow line is low-intensity heatwaves, and the orange line is severe heatwaves).

A. Lag effect using full EHF scale



B. Lag effect at selected EHF percentiles

10th (EHF ≈ 1)	

60th (EHF ≈ 15)	
85th (EHF ≈ 37)	

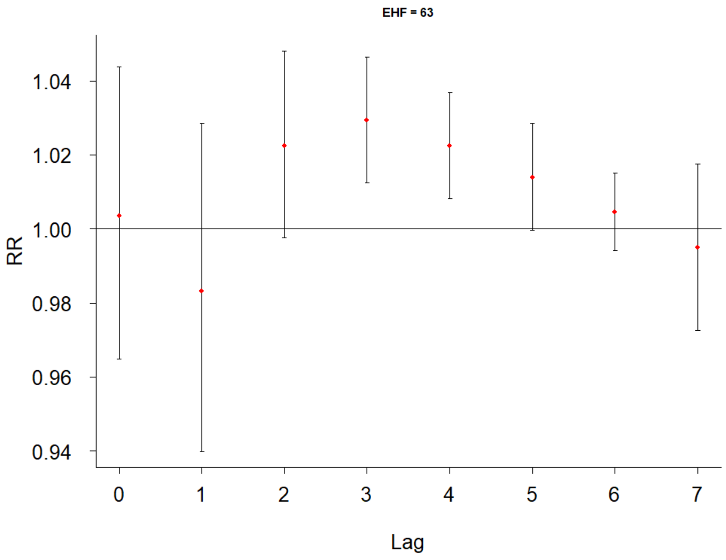
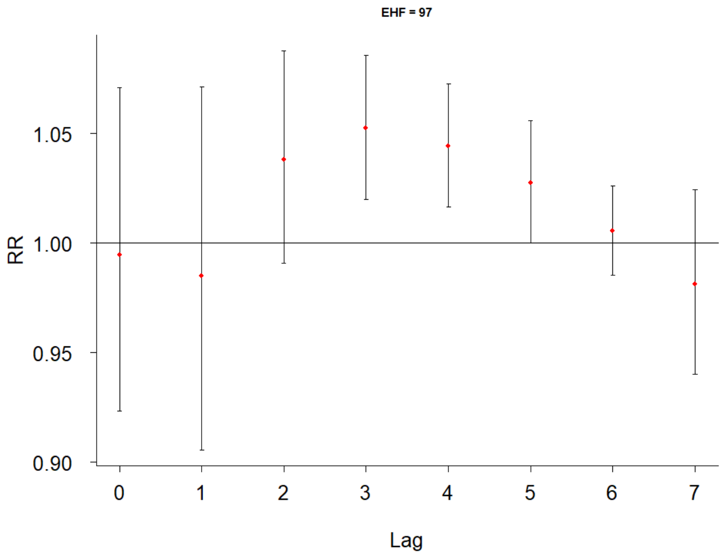
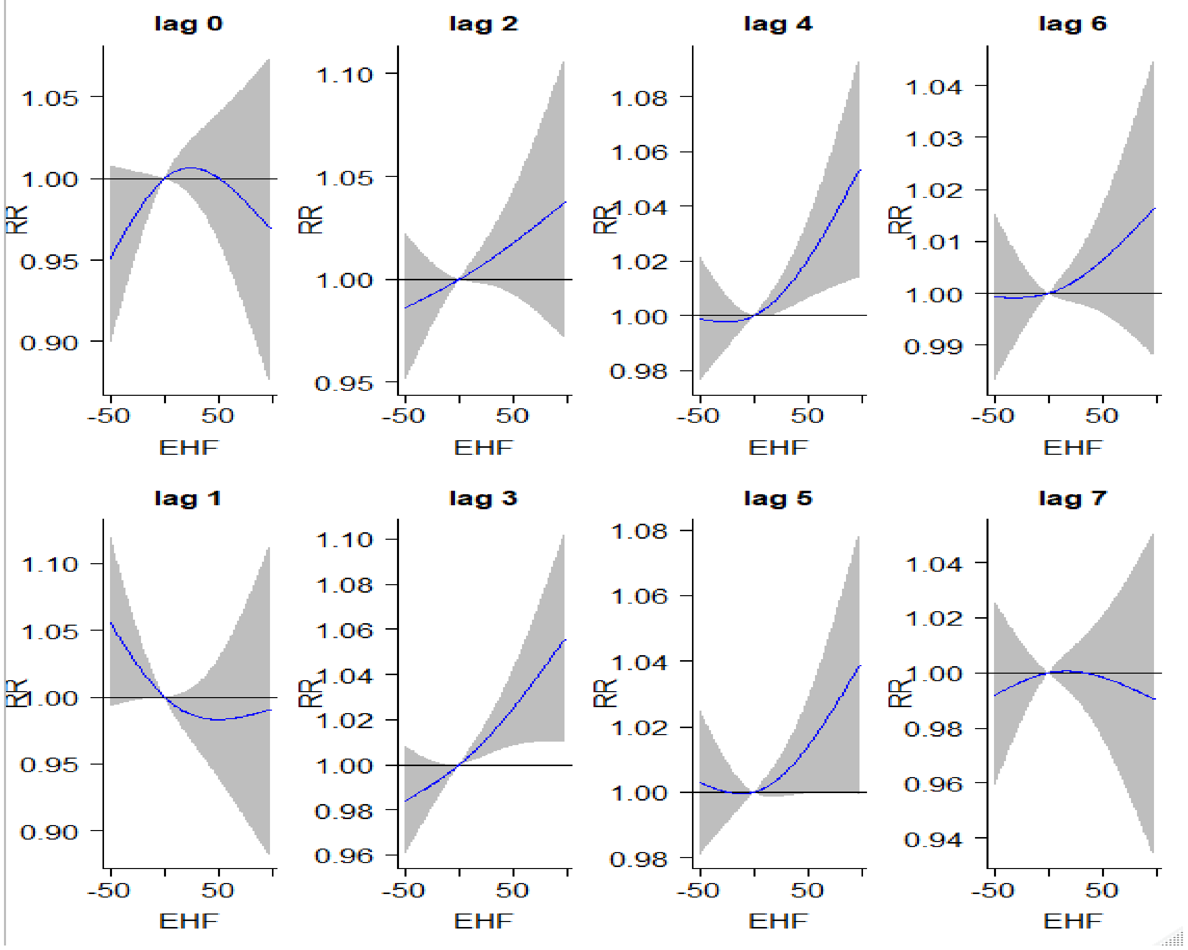
95th (EHF ≈ 63)	
95th (EHF ≈ 97)	

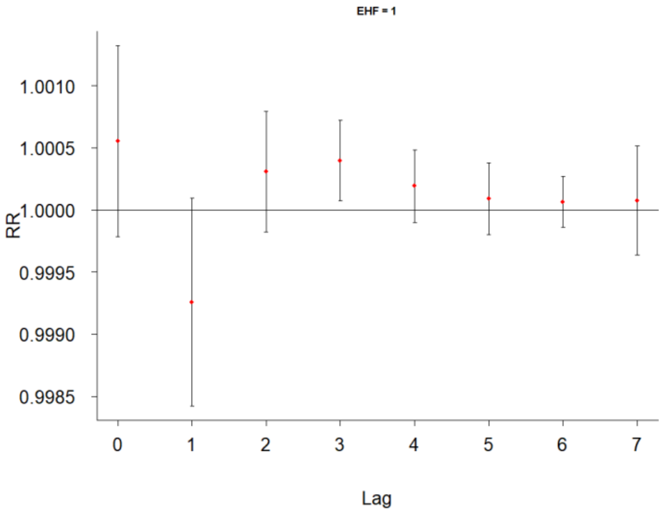
Figure S6. Lag effects of heatwaves exposure to all-cause ED presentations at 7 day lag in Adelaide, South Australia, 2014-17.

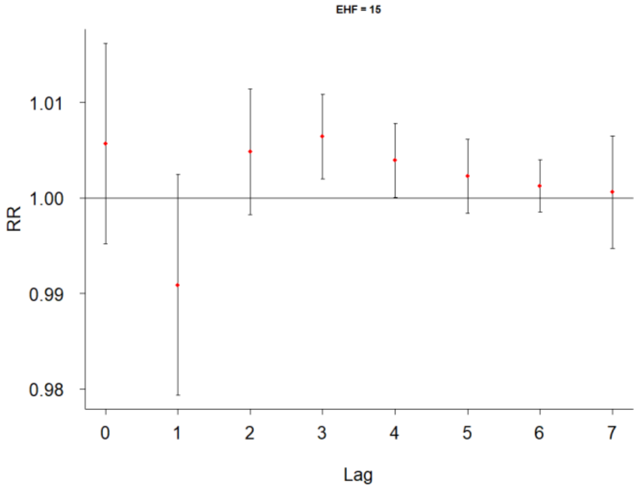
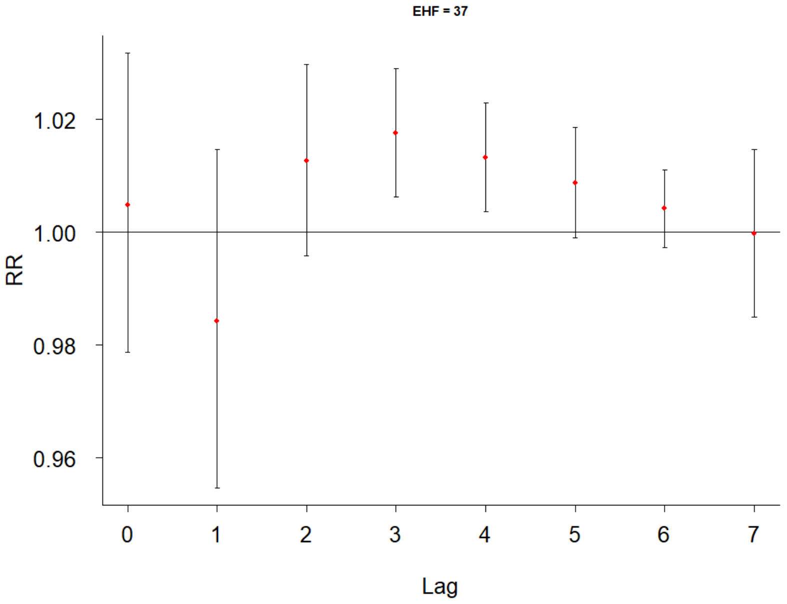
A. Lag effect using full EHF scale



C. Lag effect at selected EHF percentiles

10th (EHF ≈ 1)



60th (EHF ≈ 15)	
85th (EHF ≈ 37)	

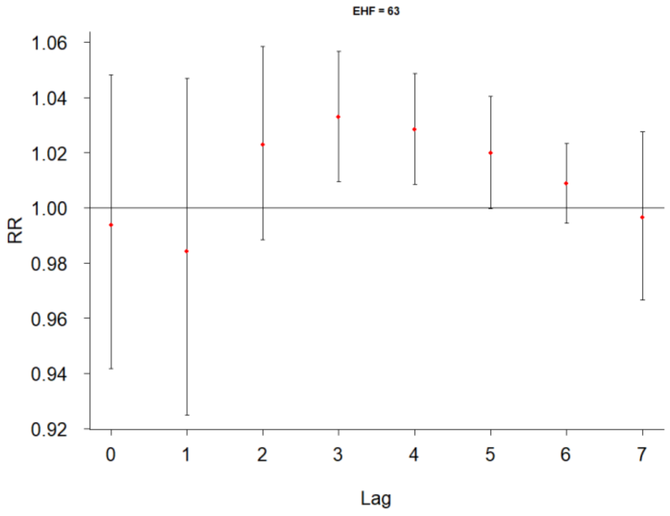
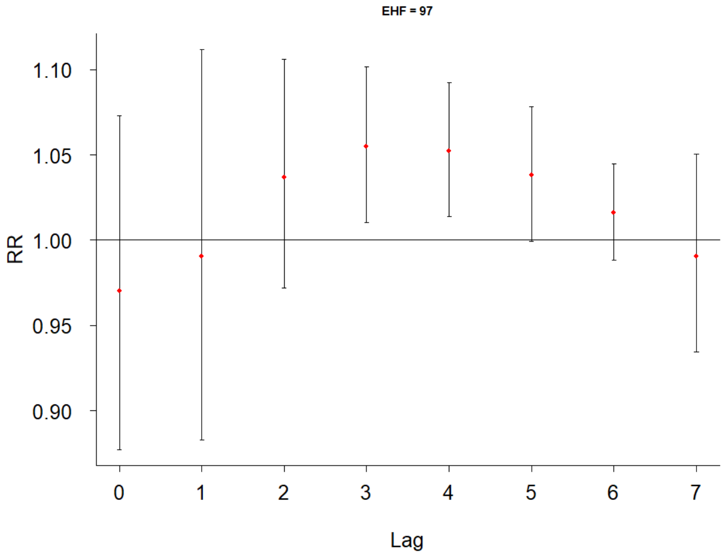
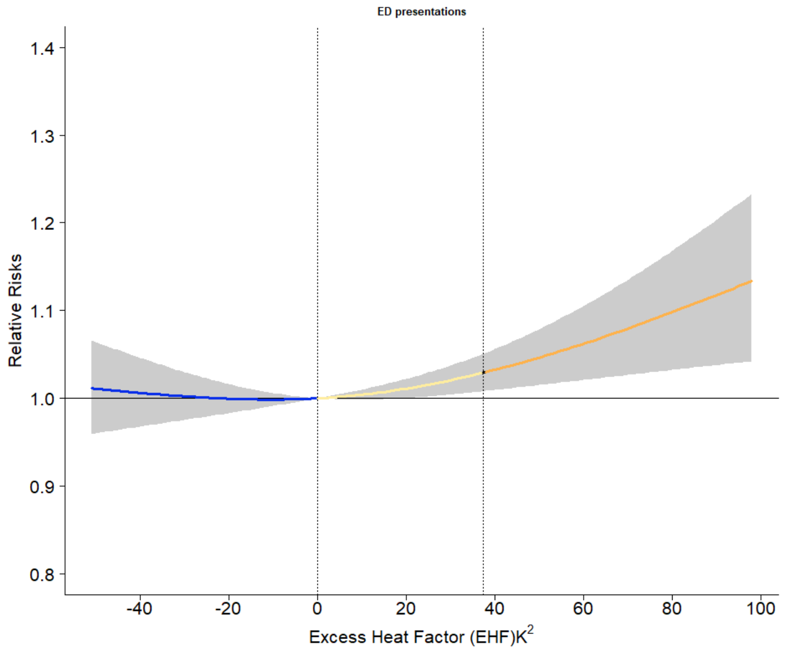
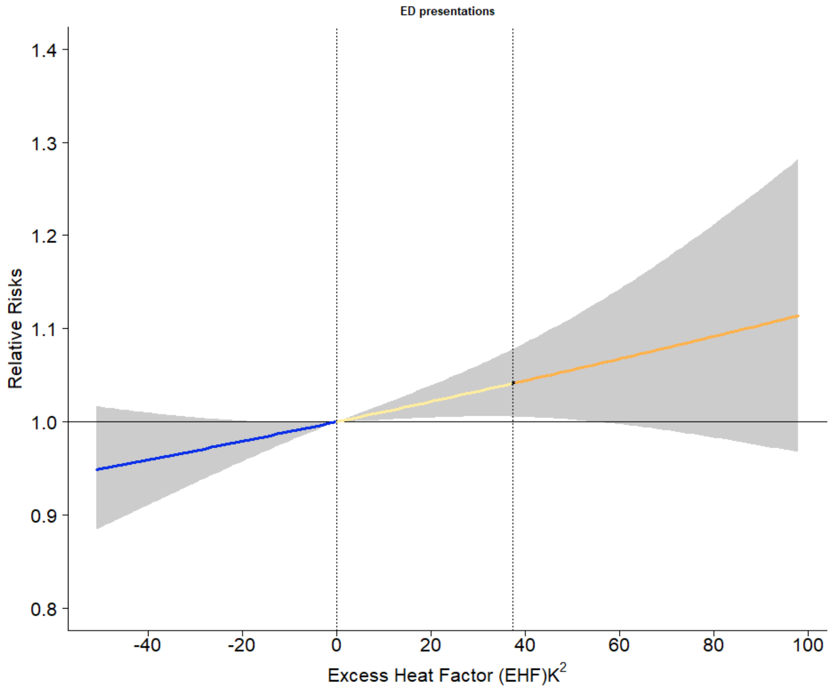
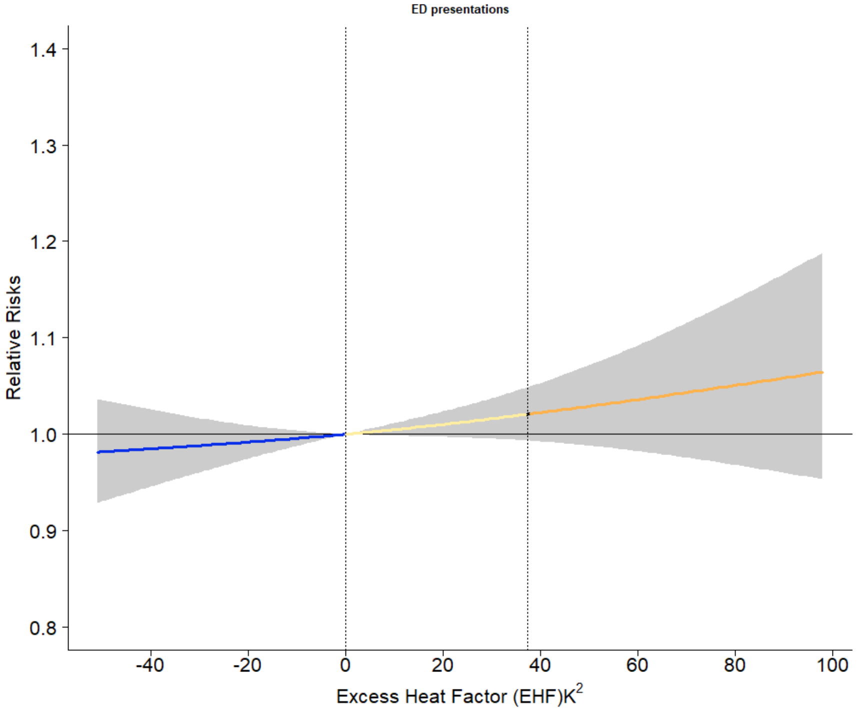
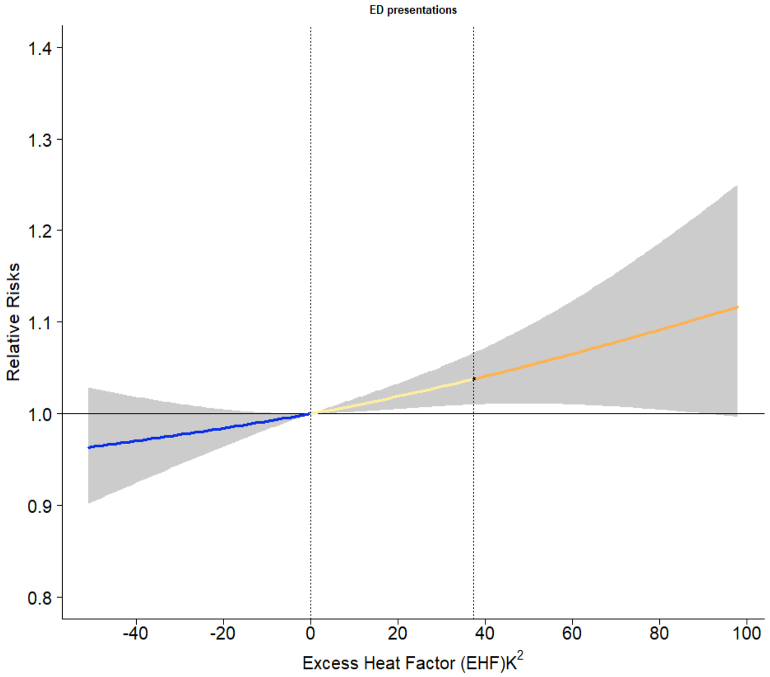
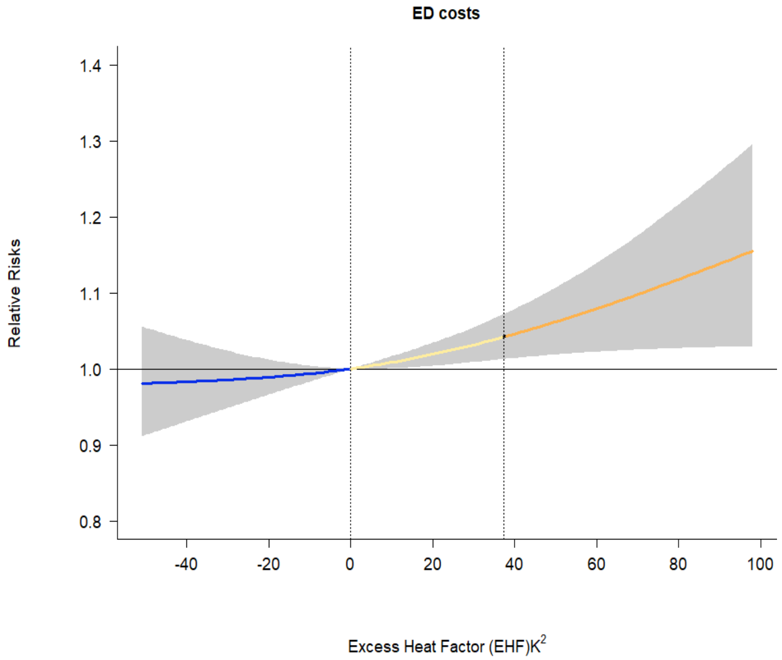
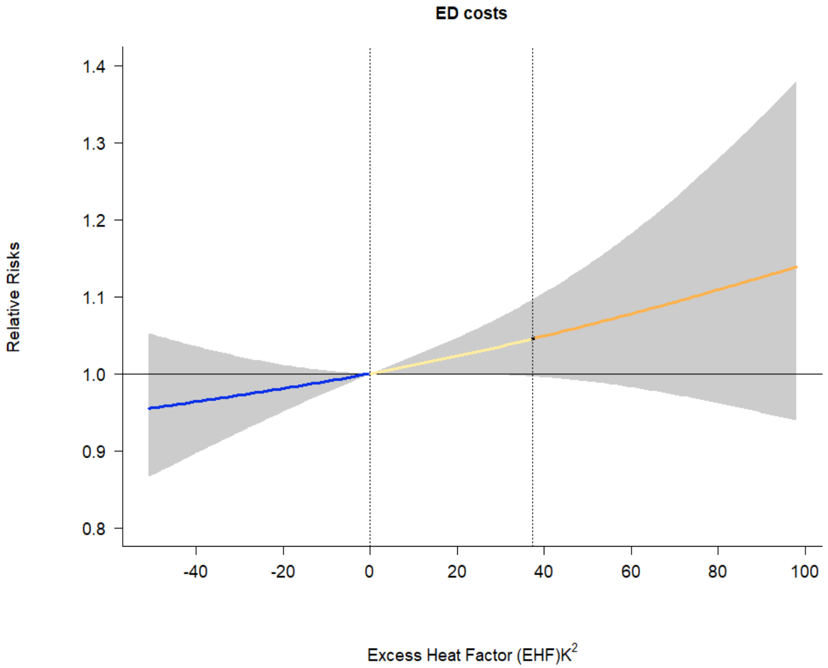
95th (EHF ≈ 63)	
95th (EHF ≈ 97)	

Figure S7. Lag effects of heatwaves exposure to all-cause ED cost at 7 day lag in Adelaide, South Australia, 2014-17.

A. ED Presentation	
lag = 4, long term trend df=4	**lag = 10, long term trend df=4**
	

lag = 7, long term trend df = 3	**lag = 7, long term trend df = 6**
	

B. ED Costs

lag = 4, long term trend df=4	lag = 10, long term trend df=4
	

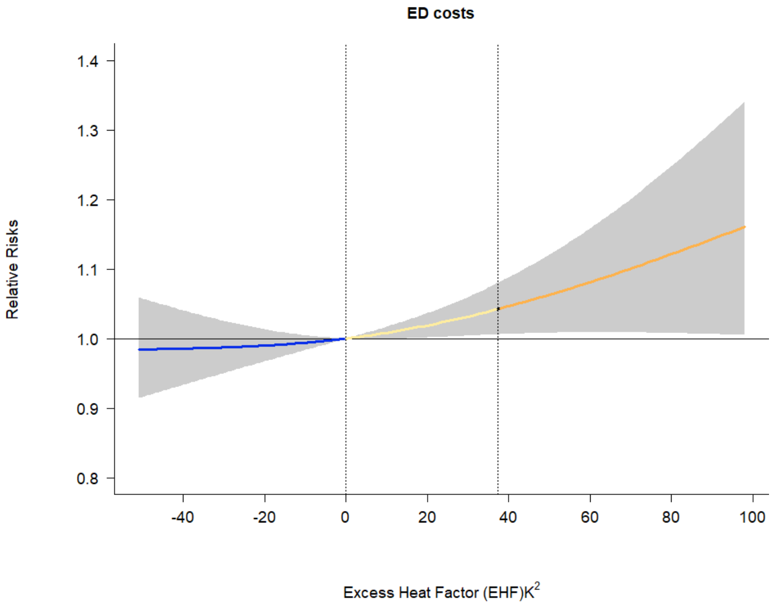
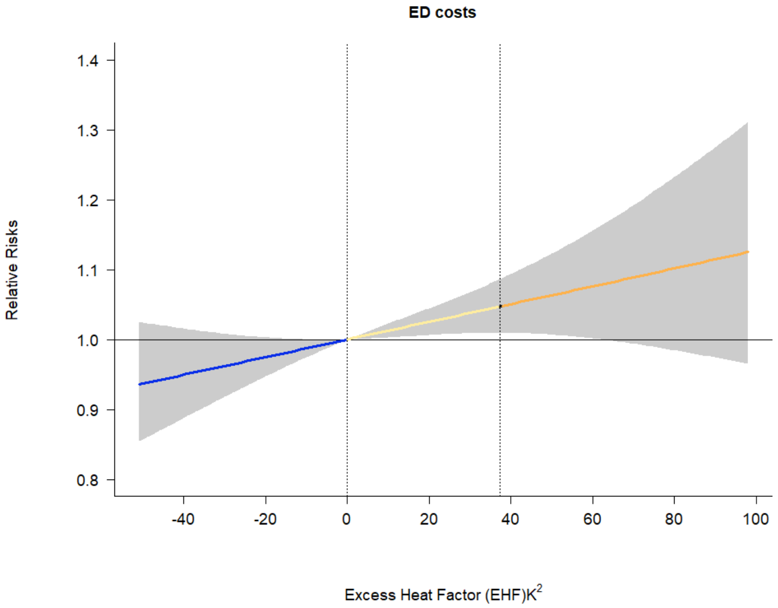
lag = 7, long term trend df = 3	**lag = 7, long term trend df = 6**
	

Figure S8. Lag effects of heatwaves exposure to all-cause ED cost at different lag and df (time) in Adelaide, South Australia, 2014-17.