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Temperature-related mortality in Scotland’s changing climate: Science and policy landscape

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August 2023
Declaration

I declare that this thesis has been composed solely by myself and that it has not been submitted, either in whole or in part, in any previous application for a degree. Except where states otherwise by reference or acknowledgement, the work presented is entirely my own.

Parts of this thesis have been published in journal articles and conference proceeding.

Chapter 2.3.1–2.3.3 and Chapter 3 were partly published in a journal article “Heat-health governance in a cool nation: A case study of Scotland” in Environmental Science and Policy by Kai Wan and her supervisors Dr Matt Lane and Dr Zhiqiang Feng. Kai Wan was the leading author and responsible for the conceptualisation, methodology, formal analysis, investigation, data curation and writing of the manuscript. Dr Lane and Dr Feng supervised the study and were involved in the conceptualization, methodology and review of the paper.


Chapter 4 was partly published in a journal article “Temperature-related mortality and associated vulnerabilities: evidence from Scotland using extended time-series datasets” in Environmental Health by Kai Wan and her supervisors Dr Zhiqiang Feng, Prof Shakoor Hajat and Prof Ruth Doherty. Kai Wan was the leading author and responsible for the conceptualisation, methodology, formal analysis, investigation, data curation and writing of the manuscript. Dr Feng, Prof Hajat and Prof Doherty supervised the study and were involved in the data acquisition, conceptualization, methodology and review of the paper.


Chapter 5 was partly published in a journal article “Integrating Shared Socioeconomic Pathway-informed adaptation into temperature-related mortality projections under climate change” in Environmental Research by Kai Wan and her supervisors Prof Shakoor Hajat, Dr Zhiqiang Feng and Prof Ruth Doherty. Kai Wan was the leading author and responsible for the conceptualisation, methodology, formal analysis, investigation, data curation and writing of the manuscript. Prof Shakoor Hajat, Dr Zhiqiang Feng and Prof Ruth Doherty supervised the study and were involved in the data acquisition, conceptualization, methodology and review of the paper.


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Abstract

Non-optimal temperatures have negative health effects on human beings. Under climate change, most parts of the world are warming with increasing frequencies and intensities of heatwaves. There is growing recognition of the dangers heat stress poses to public health, even in locations that have a historically cool summer such as Scotland. People in these places may be uniquely vulnerable to heat-related health impacts because of lacking experience in responding and adapting to heat-health risks due to their infrequent historical exposures to high temperatures. The extent to which populations will successfully adapt to continued warming temperatures will be a crucial factor in determining future health burdens. Therefore, there is a need in exploring the challenges and opportunities of heat-health governance in cool locations, taking into account both qualitative evidence of stakeholder perspectives, epidemiological evidence on the health impacts of extreme temperatures as well as population adaptation.

Scotland is chosen as the research location because it has a cool climate but like most world regions is facing higher temperatures under climate change. The majority of research on the impacts of extreme temperature on health to date for the UK has been predominantly conducted in England. While the UK Health Security Agency offers an Adverse Weather and Health Plan for England which includes strategies for both heat and cold, there is currently no corresponding plan available for Scotland.

The impacts of ambient temperature, particularly heat on health outcomes and the associated vulnerabilities in Scottish populations remain largely unknown. The Scottish population has been experiencing poorer health compared to the rest of the UK and western European countries since 1950s, and hence may face increased vulnerability to the impact of extreme temperatures. Therefore, studies on the health impacts of extreme temperatures in Scotland and governance needs are desirable to protect the public health of Scottish residents from adverse health impacts associated with ambient temperatures.
The objective of the PhD thesis is to investigate the combined science and the policy landscape for temperature-related health impacts in Scotland. Firstly, the challenges and opportunities of heat-health governance in Scotland are explored through stakeholder interviews. Secondly, the association between daily ambient temperature and mortality in Scotland are studied using time series analysis with extensive historical data between 1974-2018. The associated demographic and socioeconomic vulnerabilities are also assessed. Lastly, the historical variations in temperature-related mortality risks are investigated, which is assumed to reflect changes in adaptive capacity to ambient temperatures. Based on this assumption, future mortality burdens associated with extreme temperatures in Scotland are estimated under projections of consistent climate change, population and adaptive capacity for a number of future pathways.

This thesis found challenges in managing heat-health risks in Scotland including a perceived lack of heat risks in Scotland and priorities for heat-related policies. Meanwhile, opportunities were also identified for governing cold and heat risks holistically within existing institutional systems, reducing inequality and improving the indoor thermal comfort of both cold and heat. The epidemiological analysis found increased mortality risk under both low and high temperatures. Aggregate all-cause mortality risk in Scotland was estimated to increase by 4% (95% confidence interval CI: 3%, 5%) under extreme heat (i.e. the mortality risk at the 99th percentile of annual temperature distribution compared to the 90th percentile) and 10% (CI: 8%, 11%) under extreme cold (i.e. the 1st compared to the 10th percentile of temperature distribution). The elderly, the younger population (less than 75 years old) in deprived communities, and those with underlying respiratory and cardiovascular diseases had higher mortality risks from extreme temperatures compared to their counterparts.

The cold risk decreased sharply in the recent two decades, whereas there has been little change in the heat risk over time. The increases in heat-related mortalities are estimated to outweigh cold reductions in the future under all
Greenhouse Gas (GHG) emission scenarios. In the future, the combined heat- and cold-related mortality is lowest under the scenario of low GHG emission with a sustainable development pathway and highest under the scenario of high emission, fossil-fueled socioeconomic development pathway. This reflects the substantial health benefits of climate change mitigation and adaptation actions.

This thesis reveals that heat will become an important health determinant in Scotland under the climate change and socio-economic scenarios investigated, underscoring the need for heat-health governance and more ambitious climate adaptation and mitigation measures.
Lay Summary

It has become evident that non-optimal temperatures can have detrimental effects on human health. Under climate change, the temperature is escalating in many parts of the world, extending the health risks of heat even to regions traditionally characterised by cooler climates such as Scotland. People in these regions might be especially at risk from health problems related to high temperatures. This is because they haven't had much experience dealing with heat-related risks due to their infrequent exposure to very hot weather in the past.

Scotland is chosen as the research location of this thesis due to its historically cool climate and increasing temperatures under climate change. The health effects of ambient temperature in England and Wales have been studied with some existing work from Ireland, but very little from Scotland to date. The UK Health Security Agency provides an Adverse Weather and Health Plan for England, which includes strategies for both heat and cold, whereas there is currently no equivalent plan in Scotland. To protect the Scottish people from adverse health risks associated with increasing temperatures, it is crucial to understand these impacts and devise effective governance strategies, which are investigated in this thesis.

Through engagement with stakeholders via interviews, this thesis has revealed a spectrum of challenges and potential opportunities in the governance of health risks stemming from high temperatures in Scotland. A prevalent challenge lies in the perception of Scotland as possessing minimal heat risks stemming from heat. Concurrently, the research identifies opportunities for a holistic integration of policies addressing both heat and cold risks, whilst enhancing indoor thermal comfort and reducing socio-economic inequalities.

The research explored the relationship between daily temperatures and mortality in Scotland from 1974 to 2018. The investigation provides evidence of heightened mortality risk associated with both low and high temperatures in Scotland. Vulnerable groups, such as the elderly, disadvantaged younger
individuals, and those with existing respiratory or cardiovascular conditions, faced higher risks during temperature extremes.

In the last twenty years, the mortality risk associated with cold has gone down substantially, but the heat-health risk has not changed much. Looking ahead, the health risks associated with heat and cold will be lower if there are fewer greenhouse gas emissions and our society adopts a sustainable development approach. On the other hand, if greenhouse gas emissions are high and continue with fossil-fuel-based development, the health risk due to temperature-related issues could be over 800 deaths/year higher by 2080 compared to the low emission scenario.

In summary, this PhD thesis reveals the health risks associated with heat and cold under the changing climate in Scotland. It highlights the need for effective heat-health management strategies, especially in places like Scotland where people are less accustomed to high temperatures. The research emphasises the significance of considering both climate adaptation and mitigation measures to protect public health. 
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# List of Abbreviations

Abe: Aberdeen  
AC: Air Conditioning  
ARI: acute respiratory illness  
ARR: adaptive risk reduction  
ASMR: age-standardised mortality rate  
BAT: brown adipose fat  
BP: blood pressure  
CCAP: Climate Change Adaptation Programme  
CCC: UK Committee on Climate Change  
CCRA: Climate Change Risk Assessment  
CI: confidence interval  
CoD: cause of death  
COPD: chronic obstructive pulmonary disease  
CS: cubic spline  
CVD: cardiovascular diseases  
DAG: directed acyclic graph  
DLNM: distributed lag non-linear models  
dow: day-of-week  
Dundee: Dun  
DVT: deep venous thrombosis  
Edi: Edinburgh  
ERF: exposure–response function
HR: heart rate
UKHSA: UK Health Security Agency
GCM: general circulation model
GDP: gross domestic product
GHG: Greenhouse Gases
Gla: Glasgow
GP: general practitioner
h: hour
HHAP: Heat-Health Action Plan
ICD: International Classification of Diseases
IHD: ischemic heart diseases
ILI: influenza-like illness
IPCC: Intergovernmental Panel on Climate Change
JJA: June, July and August
M: male
MA: married
marstat: marital status
max: maximum
MMT: minimum mortality temperature
min: minimum
MST: mean summer temperatures
MtS: May to September
NS: natural cubic spline
OtA: October to April (next year)

PET: Physiologically Equivalent Temperature

PM$_{10}$: particulate matter with an aerodynamic diameter smaller than 10 µm

PPE: perturbed-physics ensemble

RCP: Representative Concentration Pathway

RESP: respiratory diseases

RH: relative humidity

RR: relative risk

SEPA: Scottish Environmental Protection Agency

SES: socioeconomic status

SSP: Shared Socioeconomic Pathway

Sco: Scotland

SMT: summer average temperature

temp: temperature

TM association: temperature-mortality association

UHI: Urban Heat Island effect

UM: unmarried

UTCI: Universal Thermal Climate Index

WBGT: Wet Bulb Globe Temperature

WHO: World Health Organization

YLL: years of life lost
Chapter 1. Introduction

This section presents an overview of the thesis and outlines objectives and structure.

1.1. Overview

Excess mortality is associated with high and low ambient temperatures. This has been shown by epidemiological studies and supported by plausible physiological mechanisms. High and low temperatures have been added as risk factors to human health in the latest Global Burden of Diseases, Injuries, and Risk Factors Study in 2019 (Murray et al, 2020). Globally, approximately 5 million deaths annually are attributed to ambient temperatures, comprising 9.43% of total fatalities with 8.52% being cold-related deaths and 0.91% heat-related deaths (Zhao et al, 2021). Although the global cold burden is larger than heat in the past, the adverse impact of increasing temperatures is one of the most significant climate change risks.

In 2011-2020, the global land surface has warmed by 1.59 °C compared to 1850-1900 (IPCC, 2021; p5). The temperature is expected to increase in most land areas until at least the middle of the century regardless of the Greenhouse Gas (GHG) emission scenarios considered, and the global surface temperature is projected to increase by 3.3-5.7°C under high GHG emissions scenarios (IPCC, 2021; p14). Heatwaves have also increased since the 1950s across most land regions including the intensity, duration and frequency, which are projected to continue increasing under climate change (IPCC, 2021; p8 & 15).

Global warming exacerbates heat risks everywhere including locations that have a historically temperate or cool climate. During the summer of 2022, an unprecedented heatwave occurred in Europe including the UK. A new UK temperature record was established on 19th August 2022, reaching 40.3°C in Coningsby, Lincolnshire, England. This heatwave extended north to Scotland, where it reached a record-breaking Scottish temperature of 35.1°C at Floors Castle, Borders (Kendon, 2022). Scotland, known for its cool climate with an average annual temperature of 6.9°C in 1961-1990, has experienced a
warming of 0.9°C in 2011-2020 compared to 1961-1990, which may also face an escalating heat-health risk under climate change (Murphy et al, 2019).

However, there is a lack of research focusing on the heat-health risk and the management of it in cool places such as Scotland. The majority of studies about temperature-related health risks in the UK has been conducted for England and Wales, particularly for London, with little research for Scotland (Keatinge et al, 2000; Hajat et al, 2005; Baccini et al, 2008; D'Ippoliti et al, 2010).

Following the 2003 European heatwave, heatwave plans have been implemented in many European countries in 2004 including England. The Heatwave Plan for England aims to reduce the health impacts due to high temperatures through long-term planning and a summer heat-health watch alert system (Public Health England, 2018). More recently, bringing together the Heatwave Plan and Cold Weather Plan, a new Adverse Weather and Health Plan was established in England in 2023 to protect the public health from the impact of adverse weather including both heat and cold (UK Health Security Agency, 2023).

Despite a heatwave plan having been active in England for two decades, there is currently a lack of a dedicated national heat-health action plan in Scotland. People in Scotland may be less acclimatised to heat due to a lack of historical exposure. Their behaviours, along with the infrastructures, buildings and policies may not be readily adapted to the higher projected temperatures under global warming. The Scottish population has been experiencing poorer health than other UK and western European since the 1950s due to multifaceted factors including poor quality housing, overcrowding and job loss. Scotland’s older population is also growing faster than the rest of the UK. These factors may further contribute to the vulnerability of Scottish people to the adverse impacts of climate change, calling for a country-specific climate change risk assessment on heat-health impacts.

Contrary to the little attention on heat-health risks, these cool places may have rich experience in managing cold risks. Reducing fuel poverty and improving
energy efficiency in cold weather have been key priorities for the Scottish Government (Scottish Parliament, 2019). These policies have co-benefits of both improving the health in cold weather and reducing GHG emissions to mitigate climate change. The Government provides numerous support to help people pay fuel bills and keeping homes warm, such as improving insulation and implementing renewable energy (Scottish Government, 2018). This extensive experience in reducing cold risks may bring both opportunities and challenges in addressing heat-health risks, which are investigated in the thesis.

Most previous studies assessing future temperature-related health burdens have largely focused on the effect of climate change. In addition, the extent to which populations will successfully acclimatise or adapt to continued warming temperatures will be a crucial factor in determining future health burdens. The concept of adaptation in relation to future cold and heat risks can be considered from several aspects. The first one is physiological changes in the body to attenuate the detrimental effects of extreme temperatures, maintain fitness and improve performance, which will be referred to as acclimatisation hereafter in this thesis (Brown et al., 2022). The second is behavioural changes that reduce the exposure to and/or the impacts of ambient temperature, such as adjusting clothes and activity patterns. The third is socioeconomic conditions that affect the adaptive capacities to extreme temperatures, which is referred to as socioeconomic adaptation. Socioeconomic adaptation is typically affected by economic factors (e.g. income), social factors (e.g. social network and cohesion), and the natural and built environments.

Existing literature on temperature-related health impacts in Scotland presents multiple research gaps. Firstly, there is a lack of literature characterising the demographic and socioeconomic groups that are susceptible to the impacts of ambient temperatures. This research is important for providing evidence supporting targeted interventions and services to vulnerable populations. Secondly, no studies have explored the historical trend in temperature-related mortality risks, which will be valuable to reflect changes in population vulnerability and adaptation to ambient temperatures. Thirdly, considering the
increasing temperatures, there is a need for health impact assessment under climate change while integrating potential effects of adaptation. Furthermore, research on the policy needs in reducing the health risks from high temperatures in Scotland, specifically taking into account the challenges and opportunities brought by the extensive experience in managing cold risks would be valuable in informing effective policy actions.

1.2. Research objectives

The overall aim of the PhD thesis is to investigate the health risks of ambient temperature in Scotland in terms of the epidemiological evidence and the governance needs to manage the risks. This is examined through three research objectives.

1) Understand the challenges and opportunities of heat-health governance in Scotland.

Climate change brings increasing heat-health risks to many parts of the world, including locations with historically cool summers such as Scotland. Scotland has extensive experience in managing cold risks but lack acclimatisation and adaptation to heat. A Heatwave Plan (now merged into the Adverse Weather and Health Plan) has been active in England for two decades, whereas there is currently a lack of similar dedicated heat-health plan in Scotland. Therefore, the first research objective is to understand the challenges and opportunities of heat-health governance in Scotland for effective policy design and implementation.

2) Investigate the epidemiological association between ambient temperature and mortality.

Previous studies on the epidemiological association between ambient temperature and mortality in the UK has been primarily conducted for England and Wales, particularly London. This research aims to investigate the mortality risk associated with both cold and heat in Scotland. In addition, stratified analyses by demographic and socioeconomic groups are performed to identify
the populations that are most susceptible to the impacts of ambient temperatures.

3) Explore future mortality burden associated with cold and heat

Research assessing the future change in temperature-related mortality burden is valuable to quantify the impacts of climate change on health. Importantly, the mortality burden is also determined by people’s ability to adapt to climate change. However, there is currently no study estimating the future mortality burden associated with cold and heat under climate change or adaptation scenarios in Scotland. Therefore, this research aims to explore the future cold-and heat-related mortality burdens in Scotland under various scenarios of climate change, adaptive capacity as well as the size and age structure of the population.

1.3. Thesis structure

The structure of this thesis is illustrated in Figure 1-1. In Chapter 1, an overall introduction is given for the thesis including the research aim and objectives.
Chapter 2 provides a detailed background to the thesis, which is separated into three sections. In the first section (Chapter 2.1), physiological responses of human bodies to cold and heat (Chapter 2.1.1), human thermal indices combining multiple meteorological variables (Chapter 2.1.2) and the socioeconomic factors contributing to people’s vulnerability to ambient temperatures (Chapter 2.1.3) are reviewed.

In the second section of Chapter 2, the review focuses on study design and key methods for this thesis, including epidemiological methods to study the health effects of ambient temperature (Chapter 2.2.1), and methods to integrate adaptation scenarios into future projections on temperature-related mortalities/morbidities under climate change are conducted (Chapter 2.2.2).

In the third section of Chapter 2, a review is performed for the research location Scotland specifically, focusing on its climate (Chapter 2.3.1), demography (Chapter 2.3.2), and existing policies relevant to heat and cold-health risk prevention (Chapter 2.3.3). In the last section of the review, a scoping review is
performed on existing literature investigating the association between temperature and mortality/morbidity in Scotland (Chapter 2.3.4).

This thesis includes three empirical research in Chapter 3 to 5 for the three objectives described in Chapter 1.2 respectively. The methods of the individual empirical studies are detailed within the relevant research chapters.

In the concluding section of the thesis (Chapter 6), the findings from the empirical research are summarised (Chapter 6.1) and the collective findings are synthesised (Chapter 6.2) and discussed in terms of the contributions to the field and policy implications (Chapter 6.3). Finally, the limitations of this thesis (Chapter 6.4) and potential future research are explored (Chapter 6.5). This chapter concludes with final remarks for the thesis (Chapter 6.6).
Chapter 2. Background

This Chapter provides a review of the background of this thesis. The structure of the review is detailed in Chapter 1.3 and illustrated in Figure 1-1. The chapter identifies current gaps in the literature that form the basis for the objectives behind this thesis (Chapter 1.2) and shapes the understanding, implementation and interpretation of this thesis.

2.1. Human thermal impacts and socioeconomic vulnerabilities

This section is separated into three sections, including the physiological responses to heat and cold (Chapter 2.1.1), the effects of other meteorological variables as well as the integration of these meteorological variables in human thermal indices (Chapter 2.1.2) and socioeconomic factors contributing to people’s vulnerabilities to ambient temperatures (Chapter 2.1.3).

2.1.1. Physiological response to ambient temperature

Human beings require a specific range of temperature for proper metabolic processes and physiological functions, which typically falls within 35–40°C with an optimal body temperature of 37±0.5°C at rest (Margolis, 2014). This near-constant body core temperature can be maintained in a wide range of ambient conditions and activity levels through a series of physiological processes, as well as contextual and behavioural adjustments (Margolis, 2014; Charkoudian & Morrison, 2023).

To maintain a constant body temperature, continuous heat exchanges occur between the body and the surroundings following thermodynamics, which can be simplified by the heat balance equation shown below (Hanna & Brown, 1983; Margolis, 2014).

\[ M \pm S = E \pm K \pm C \pm R \]  

Equation (1)

Where \( M \) = metabolic heat production, \( S \) = heat storage, \( E \) = evaporation, \( K \) = conduction, \( C \) = convection, \( R \) = radiation. The left side of Equation (1) represents processes of internal heat gain and storage. Metabolic heat production leads to internal heat gain, which arises from basal metabolic
processes (chemical processes inside the body to produce energy for normal function of life at rest and neutral environment), physical activities and even shivering. The human body also has a capacity to store heat providing a buffer of heat exchange, e.g. the heat storage may be increased under heat exposure to reduce strain on the need of heat loss. The right side of Equation (1) shows the main mechanisms of heat exchange with the environment. Conduction, convection and radiation are involved in both heat gain and loss. Heat also transfers within the body through conduction between connected tissues and convection via blood flow. Evaporation through sweating is the most important source of heat dissipation in warm environments, which is affected by humidity and will be reviewed in Chapter 2.1.2.

![Diagram](image)

*Figure 2-1. Physiological responses to thermal stress in humans (Charkoudian & Morrison, 2023).*

In warm and cold environments, key physiologic processes triggered to aid heat loss or gain are illustrated in Figure 2-1 (Charkoudian & Morrison, 2023). In addition, the flow and composition of blood change along with the thermoregulatory process. Under heat exposure, there is an increased blood flow to transfer internal body heat to the body surface, which is then transferred into the environment mainly through evaporative cooling through sweating accompanied by cutaneous vasodilation to enhance heat convection. This process is facilitated by increased heart rate, cardiac output and minute ventilation rate (volume of gas inhaled/exhaled from a person’s lung per minute), and hence result in potential strain on the cardiovascular, respiratory

The inhalation of hot air can cause direct stress in the respiratory system which exacerbates respiratory infections, asthma and COPD (Hayes et al, 2012; Anderson et al, 2013). In addition, dehydration often occurs due to excessive sweating without effective rehydration, which can impair normal physiological functions, e.g. reduced skin blood flow which attenuates heat loss and tolerance (Coon & Low, 2023). Renal diseases such as acute kidney injury and kidney stones can occur under heat stress due to a combination of dehydration and redistribution of the blood from the internal organs to the skin (Borg et al, 2017; Nerbass et al, 2017).

The strain caused by the thermoregulatory processes, accompanied by dehydration and electrolyte imbalance (blood salts and minerals are depleted due to sweating) may lead to heat cramps (i.e. muscle spasm or jerk involuntarily) and heat exhaustion (tiredness, dizziness, headache, feeling sick). At the very extreme, hyperthermia occurs which is the situation that thermoregulatory functions fail and the core body temperature rises to over 40°C, leading to life-threatening heatstroke and multiple organ dysfunction (Bouchama & Knochel, 2002; Iba et al, 2022). Previous studies have found that heatstroke can progress rapidly to fatality, often within a few hours of the onset of symptoms (Kilbourne, 1997).

Prolonged cold exposure can lead to hypothermia which is a potentially fatal condition in which thermoregulatory functions are impaired and the body temperature drops below the normal range (typically 35°C) (Turk, 2010; Osilla et al, 2022). Before severe hypothermia occurs, the initial response to cold exposures involves two main thermoregulatory processes—cutaneous vasoconstriction to reduce heat loss and increase in heat production mainly in skeletal muscle (e.g. shivering) and in brown adipose fat (BAT) (Figure 2-1). A series of changes in the property of blood is associated with the thermoregulatory processes, including increases in red blood cell, platelet count, plasma viscosity and blood pressure, all associated with increased risks
of hypertension, coronary and cerebral thrombosis and stroke (Keatinge et al, 1984; Goodwin, 2000).

Increases in respiratory infections and diseases have also been widely observed in cold weather. Breathing cold air can directly trigger nasal congestion, bronchoconstriction, coughing and exacerbating asthma and Chronic Obstructive Pulmonary Disease (Koskela, 2007). The resulting cooled and dried airways have reduced self-cleaning ability, which encourages the residing and spreading of virus within the respiratory tract (Lowen et al, 2007). Additionally, the transmission of virus among people may increase in cold weather due to gathering indoors and reduced window opening and ventilation (Arbuthnott et al, 2018). In terms of the virus particle, some virus, such as the influenza virus has been found to be more stable in cold and dry environments, contributing to the spread among hosts including humans (Lowen et al, 2007; Mäkinen et al, 2009). Furthermore, cardiovascular and respiratory diseases may also be triggered or exacerbated indirectly due to declined immune functions and behavioural changes in cold weather such as lacking exercise (Arbuthnott et al, 2018). These indirect impacts of cold on health may develop slowly and hence mortality can occur at a long lag upon cold exposure (Arbuthnott et al, 2018).

2.1.2. Human thermal indices
Apart from air temperature, other meteorological variables such as humidity, wind speed and radiation can also affect the heat exchange between the body and the surrounding environment (Sherwood & Huber, 2010; Department of Health and Human Services, 2016; Mora et al, 2017). Solar radiation is a main source of heat gain. Evaporative cooling through sweating is diminished if the surrounding humidity is high, therefore hot and humid conditions pose higher heat stress than the same temperature with lower humidity (Mora et al, 2017; Wehner et al, 2017; Sherwood, 2018). When the surrounding air is cooler, winds carry heat away from the human body faster through enhancing localised convection and evaporation of moisture from the skin, which may reduce heat stress in summer but increase cold stress in winter (Turk, 2010). However,
when the temperature is high, wind may enhance heat gain by blowing hot air to the human body and accelerate dehydration, and hence the use of fans is generally discouraged when the air temperature exceeds the skin temperature, typical at 35°C (WHO, 2018). Nevertheless, there has been discussion that the WHO recommendation is over restrictive. Lab experiments have shown that fans are effective in cooling when the temperature is 42°C with a RH of 50%, and 36°C when the RH is 80% among healthy males (Ravanelli et al, 2015).

Making use of human energy balance model, fans have been found to be beneficial in 93 out of 115 most populous cities considering the most extreme heat events in 1990-2014 (Tartarini et al, 2022).

Because of the impacts of these other meteorological variables on thermal dynamics and regulation of human bodies, over 160 human thermal indices combining temperature and one or multiple of these meteorological variables have been constructed to indicate thermal comfort, physical well-being or environmental risk (De Freitas & Grigorieva, 2015). These thermal indices have differences in multiple aspects, such as the meteorological variables considered, the theory based on (e.g. body–atmosphere energy balance, physiological strain, perceived comfort level), the applicable thermal conditions (e.g. temperature range, season), physical activity designed for (e.g. at rest, sports and military training), body-related inputs (e.g. clothing, metabolic rate) (De Freitas & Grigorieva, 2015).

For example, some thermal indices are designed to indicate the air temperature equivalent perceived by humans, which is also referred to as felt or apparent temperature, such as Humidex which combines temperature and humidity to indicate the felt temperature in warm weather (Wehner et al, 2017), and wind chill indices combining temperature and wind speed for cold weather (Kunst et al, 1994). Some thermal indices are constructed integrating all four key meteorological variables (air temperature, humidity, wind speed and solar radiation) relevant to heat exchange between human bodies and the environment, such as Wet Bulb Globe Temperature (WBGT), Physiological Equivalent Temperature (PET) and Universal Thermal Climate Index (UTCI).
These indices are further differed in term of their rationale and designated application. WBGT is developed empirically and has been widely utilised to determine the safety of the weather for sports events or military training. However, it has been criticised that it underestimates heat stress when evaporative cooling is restrictive and solar radiation is strong (Thorsson et al, 2021). PET and UTCI are constructed based on human energy balance, whereas they have been found to deviate self-reported thermal sensation due to various factors such as thermal perception, expectation, adaptation and duration of exposure (Pantavou et al, 2018).

In addition, some research utilised the synoptic approach which studies the impact of weather on human health by identifying synoptic or large-scale weather patterns and/or regimes such as anticyclonic conditions over a region associated with adverse health outcomes (Kalkstein, 1991; Gosling et al, 2009b; Huang et al, 2020). This approach takes into account the synergetic effect of large-scale meteorology on local-scale meteorological variables and their health impacts rather than individually (Kalkstein & Smoyer, 1993). Another benefit of this approach is the increased persistency and predictability of some large-scale weather patterns compared to local meteorological variables. Therefore, the synoptic approach has been used as the basis for heat health alerts in some places (e.g. Toronto, Canada) (Hajat et al, 2010).

There is no consensus on a superior measure of temperature or thermal index that outperforms others in predicting temperature-related mortality and morbidity risks (Barnett et al, 2010; Armstrong et al, 2019). For example, mean temperature gave a better fit to the association between daily temperature and mortality than the apparent temperature in London, Budapest, and Milan (Hajat et al, 2006; Armstrong et al, 2011). The wind chill index was found to be a better predictor of daily mortality in the Netherlands than air temperature alone (Gill et al, 1988; Kunst et al, 1994); however, no evident difference in the results using these two measures was found for Scotland (Carder et al, 2005). One study compared the association of temperature and mortality in 107 US cities using 8 measures (mean, minimum and maximum temperature with and without
humidity, and apparent temperature) (Barnett et al, 2010). The results of the study suggested that the measure that provides a better model fit varies by city and no single measure provided a consistently better fit than the others, and hence practical issues such as data availability may be the primary concern in the selection of temperature measurements.

The subsequent section will explore how people of different socioeconomic and environmental conditions encounter varying levels of cold and heat exposures and the associated adverse health risks.

2.1.3. Vulnerability and adaptive capacity
People experience varying degrees of exposure and susceptibility to adverse effects of low and high temperatures. Factors that contribute to increased exposure or susceptibility are vulnerabilities or vulnerable factors, and individuals who experience these vulnerabilities are referred to as vulnerable populations in this thesis. Some people may have attenuated physiological capabilities leading to a higher susceptibility to heat and/or cold stresses, which is referred to as physiological or demographic vulnerability. Common contributory factors to the ability to tolerate heat or cold exposure include age (the very young and old), underlying health conditions and body composition (e.g. body fat) (Kingma et al, 2012; Castellani & Young, 2016). In addition to physiological susceptibility, behavioural factors such as clothing, rehydration, intake of alcohol, drug and certain medications and physical activity patterns play a role in mediating the exposure to and health impacts of ambient temperature (Margolis, 2014; Castellani & Young, 2016). Furthermore, the ability of individuals to prepare for, respond to, and recover from non-optimal temperatures is influenced by socioeconomic, institutional factors as well as the built and natural environments (hereafter referred to as “socioeconomic adaptive capacity”) (Ellena et al, 2020; Lindley et al, 2011). The mechanisms of key factors that affect the socioeconomic adaptive capacity to ambient temperatures are reviewed in this section.
2.1.3.1. Socioeconomic conditions

Being in low income, socioeconomic status (SES) or deprivation affects multiple aspects of people’s lives and their ability to prepare for, respond to and recover from non-optimal temperatures. People with a low income or who live in deprived areas are more likely to rent homes from private and social landlords (Scottish Government, 2022b), and hence have less ability or are less willing to modify their living environments to prepare for non-optimal temperatures, e.g. installing shutters (Lindley et al, 2011). In addition, the increased mental stress, housing overcrowding, underlying health conditions and poorer neighbourhood environments (e.g. green space) of those in low income or deprivation may contribute to the vulnerability as well.

Fuel poverty is a major issue in the UK and especially in Scotland, which describes the situation in which a household cannot afford to keep the home warm enough (Scottish Government, 2021b). Low income is also a main cause of fuel poverty, under which households struggle to pay for energy bills to make their homes warm enough and hence affect the adaptive capacity to cold (Scottish Government, 2016).

However, a direct association between heat/cold-related health risks and socioeconomic conditions remains elusive. Some studies have studied the effect of SES on heat-related mortality risks. In the US, heat-related mortality risk was found to be mediated by SES (Curriero et al, 2002). However, studies in the UK often did not find significant effects of SES or deprivation (Aylin et al, 2001; Maheswaran et al, 2004). This may be due to the incapability of a single SES indicator or current deprivation indices to fully capture the temporal varying socioeconomic vulnerability to cold and heat exposures (Lindley et al, 2011; Schofield et al, 2016).

Additionally, air conditioning (AC) was found to be a strong protective factor of the impact of heat (Naughton et al, 2002; O’Neill, 2005). The prevalence of AC increased rapidly in the second half of the 20th century in the US and the ownership of it varies by SES, which may contribute to the variation of the heat-related mortality risk by SES in the US (O’Neill, 2005; Petkova et al, 2017). With
the generally cooler, maritime climate in the UK, AC prevalence remains very low regardless of the SES in the UK with only around 1–3% of homes in the UK having air conditioning (McLachlan et al, 2016).

2.1.3.2. Societal inequality
In addition to individual SES and deprivation status, temperature-related health risks can also be affected by social inequality and cohesion. Inequality can cause crime, drug use and violence (Pratt & Cullen, 2005). During heatwaves, opening windows, especially at night when the outdoor temperature is lower than the indoor temperature, is an efficient way of cooling and restoring from the heat stress. However, worries about noise and security may prevent people from opening windows and hence they experience sustained heat stress at night (Morgan et al, 2017; Murage et al, 2017). Socioeconomic inequality is also detrimental to social cohesion, affecting the availability and support from social networks, which will be discussed in the next section (Berkman et al, 2000; Nicholson, 2012; Scambler, 2012).

2.1.3.2. Social capital and network
Social capital refers to the networks and social relations of people, such as families, communities, and voluntary organizations that enable individuals to benefit from working together than in isolation. Social isolation has been found to be an important risk factor of heat-health risks in previous studies. For example, living alone was identified as a significant risk factor for elevated mortality during the 1999 heatwave in Chicago, US (Naughton et al, 2002). A study that interviewed 19 elderly Swedes on their experience of a heatwave in 2018 found that social isolation was the strongest driver of heat vulnerability (Malmquist et al, 2022). This may be because social support could provide information support on cold/heat warnings and coping measures, and instrumental support such as obtaining medical help when getting a heat stroke or help with getting medicines and groceries when the temperature is too extreme for those who are vulnerable to go out (Berkman et al, 2000). Emotional support through social networks is also important for mental health, especially when people are confined indoors or having difficulties going out alone due to extreme ambient temperature (Malmquist et al, 2022).
The unmarried population have been found to experience increased heat-health risk than married, e.g. in France (Fouillet et al, 2006), Italy (Ellena et al, 2020; Stafoggia et al, 2006) and the US (Gronlund et al, 2015). This may partially be due to social isolation and living alone of those who are unmarried. In addition, the differential risk among the married and unmarried population may also because of social selection (i.e. those who are healthier and less vulnerable are more likely to get married) or social causation (people become more vulnerable because of being unmarried) (Molloy et al, 2009).

2.1.3.3. Urban environments and land use/cover

Urban environments affect the adaptive capacity to heat due to a generally higher temperature in urban than in surrounding rural areas, i.e. the Urban Heat Island effect (UHI) (Hamilton et al, 2014). For example, during the August 2003 heatwave in West Midlands, UK, urban areas are around 3 °C warmer than rural areas, and the UHI effect contributed to around half of the excess mortality that occurred during this heatwave (Heaviside et al, 2016).

The UHI can be mitigated through strategies such as modifying the albedo of urban surfaces including using special materials for roofs and pavements (i.e. cool roof/pavement), increasing green space, decreasing anthropogenic heat and using natural heat sinks such as ground cooling (Santamouris, 2015). A modelling study in West Midlands, UK shows that the cooling potential of cool roofs is around 3 °C in summer, which is much larger than the cooling effect of 0.5°C in winter (Macintyre et al, 2021a). Increasing green space is highly effective in providing shade from solar radiation and cooling the environment, which can extend beyond the border of the green space (Hamilton et al, 2014; Santamouris, 2015). Temperatures were found to be lower in neighbourhoods with higher levels of vegetation in London, which was associated with a strong protective effect on heat-related mortality (Murage et al, 2020).

2.1.3.4. Housing

People spend a long period of time indoors and hence the adaptive capacity to non-optimal outdoor temperatures is mediated by building thermal performance. Increasing energy efficiency is a key focus of the UK government, both in terms
of reaching Net Zero Greenhouse Gas emissions by 2050 as well as tackling fuel poverty (Committee on Climate Change, 2020; UK Government, 2022). Benefits such as the Winter Fuel Payment, Cold Weather Payments and Warm Home Discount Scheme are also available for those who need help need in keeping their homes warm (Scottish Government, 2019a; Warmworks, n.d.).

Improving housing insulation has been one of the actions for increasing energy efficiency and reducing fuel poverty. However, insulation and airtightness may have mixed effects on indoor overheating and health (Milner et al, 2023). On one hand, insulation may reduce the peak indoor temperature by preventing the heat from penetrating into the buildings (Mavrogianni et al, 2017). However, insulation and airtightness along with a lack of ventilation may trap heat, moisture and air pollution from indoor generated sources inside, leading to indoor overheating, mould and worsened air quality (Crump et al, 2009; Peacock et al, 2010; Gupta & Kapsali, 2016; Gupta & Gregg, 2018; Symonds et al, 2019).

2.1.3.5. Individual behaviours and empowerment
The effect of socioeconomic, institutional and environmental factors on vulnerability is mediated by individuals’ adaptive behaviours. Adaptive behaviours can affect heat and cold health risks ranging from the choice of clothes to the control of windows, shutters, fans, heating and water intake and diet (Fabi et al, 2012). For example, a survey in Europe found people in colder regions (e.g. south Finland) took better protective measures against cold such as having higher living-room temperatures and wearing hats and gloves when being outdoors than people in warmer regions (e.g. Athens), which may have contributed to the lower susceptibility to cold in cooler than warmer locations (Keatinge et al, 1997).

There is a difference between the availability of a measure to reduce the impacts of non-optimal temperatures and the effective use of it, which may be due to various reasons such as the worries of noise, insects and security, the cost of the utility bill, cultural customs and lack of knowledge (Abrahamson et
al, 2008; Gupta et al, 2012). This is also linked to socioeconomic conditions (Chapter 2.1.3.1) and inequality (Chapter 2.1.3.2) as reviewed above.

There are further concerns for the most vulnerable populations such as those living in care homes. A lack of the power of control, such as window-opening and adjusting the temperature of thermostats particularly in care settings or nursing homes also affects the adaptive capacity of the residents, who are often very vulnerable to extreme temperatures (Gupta et al, 2017a; Malmquist et al, 2022). Therefore, it is vital to engage and empower vulnerable populations, their care providers, close contacts and communities in taking action plans to prevent and mitigate the impacts of extreme temperatures.

This section reviews key factors contributing to the vulnerability to the health impacts of ambient temperature, including individual socioeconomic conditions, societal inequality, land use and urban environment, housing as well as individual behaviours. They are interconnected and have overlapping effects on people’s vulnerabilities to ambient temperature.
2.2. Review on key methods

This section reviews the key methods relevant to the thesis, including epidemiological methods for the investigation of health effects of ambient temperatures (Chapter 2.2.1) and methods for the modelling of adaptation in the estimation of temperature-related mortalities/morbidities in the future under climate change (Chapter 2.2.2).

2.2.1. Epidemiological methods to study the health effects of ambient temperatures

Epidemiology studies the distribution and determinants of health outcomes in specified populations, and the means to improve health (Bailey et al, 2005). This section provides a review of epidemiological methods to study the impact of ambient temperature on health, including the measure of excess deaths during extreme heat/cold episodes (Chapter 2.2.1.1), a review on potential confounders of the temperature-mortality association (Chapter 2.2.1.2), as well as statistical modelling methods that enable the investigation of the association between short-term exposure of ambient temperature and health outcomes (Chapter 2.2.1.3).

2.2.1.1. Measure of excess death

The influence of extreme temperature episodes on mortality can be explored by comparing the difference in mortality over a short period of time wherein extreme temperatures are experienced against a reference period. This reference period could be the same time period but for different years, a period of neighbouring days without extreme temperatures, or a long-term period (e.g. a 30-year representing average climatology).

Excess deaths during heatwave episodes have been estimated annually in England and Wales by the Office for National Statistics since 2016 (commonly referred to as heat episode analysis), but not in Scotland. The estimation of excess mortality depends on the duration of the analysis period (e.g. start and end of the summer period) and the definition of heatwave, including the threshold or percentile for temperature, the location and duration of exceeding the threshold.
In summer 2022, the UK experienced record-breaking heatwaves, surpassing the historical maximum temperatures in England, Wales, and Scotland (Kendon, 2022). A total of 2803 heatwave-related excess deaths among those of age 65 and above were estimated in England in 2022, with a highest daily excess deaths of 253 during the peak of the heatwave (Figure 2-2) (Office for National Statistics, 2022a).

Figure 2-2. Excess mortality for aged 65 years and over in 2022 compared to +/- two-week baseline deaths for each heat-period, England. COVID-19 deaths are excluded and registration delays are adjusted. Estimated by the UK Health Security Agency and reported in collaboration with the Office for National Statistics (2022a). Heat episode analysis only indicates the health impacts during heatwaves. However, excess deaths start to occur on moderately hot days when the temperature is usually lower than the heatwave threshold, for example, the mortality risk was found to start increasing at the daily maximum temperature of above 24°C in London, which is lower than the heatwave threshold of 32°C (Williams et al, 2019). Between 1997-2012 (excluding 2003 due to the unusual heatwave), deaths during heatwave days account for less than 10% of the total heat-related deaths (Williams et al, 2019). This is due to
the high prevalence of moderately hot days and hence a large number of excess deaths occur on days below the heatwave thresholds. Therefore, other epidemiological methods are needed to investigate the health effects of ambient temperatures, including both moderately and extremely high and low temperatures.

Although the heat episode analysis is relatively easy to perform, it has limitations in providing credible information on the elevated mortality risk under both moderate and extreme temperatures and controlling the effect of confounders, which will be introduced in the next section.

2.2.1.2. Confounders
One key consideration in studying the association between temperature and mortality is the control of confounders. Confounders are variables that influence both the exposure and the outcome so failing to adjust for them may lead to biased results (O’Neill et al, 2005; Petrie, 2013). The association between the day-to-day association between temperature and mortality may be confounded by variables that influence both the exposure and the outcome, which are referred to as confounders (O’Neill et al, 2005; Petrie, 2013). Failing to adjust for them may lead to biased results.

A list of potential confounders for the short-term association between temperature and mortality identified in the literature includes trends and periodicities in time, day-of-week and holidays, air pollution, influenza epidemics, other meteorological variables, as well as demographic and socioeconomic factors (O’Neill et al, 2005; Baccini et al, 2008; Basu, 2009; Barnett et al, 2010).

The causal relationships between these factors and the confounders are explored using directed acyclic graphs (DAG) in this review. DAG is a simple visualisation of assumptions about the relationships between variables which can aid causal relationship deductions of observational studies. Although the quality of the causal inference depends on the accuracy of a DAG in describing the real relationships, the practice of presenting DAGs increases transparency of the hypotheses and assumptions. In DAGs, the variables and their
measurements are depicted as nodes and connected by unidirectional arrows representing the hypothesised relationships between the variables with the direction denoting causality (Tennant et al, 2019). Variables that may confound the TM association identified in existing literature are included in the DAG as nodes. Probable relationships between any two variables are linked by arrows. A relation between two variables should generally be assumed to exist because omitting an arrow implies absolutely no causal effect, which is a stronger assumption than permitting a causal effect which can be of any sign or magnitude (Tennant et al, 2019). A DAG can help identify causal pathways as well as the variables required to be adjusted to sufficiently minimise confounding bias. This is performed using the DAGitty online platform (Textor et al, 2017) in this review and the result is shown in Figure 2-3.

Variables considered in the DAG include other meteorological factors, the natural environment (e.g. green and blue space, air pollution), the built
environment (housing, infrastructure), socioeconomic factors, widespread diseases such as influenza and water, food and vector borne diseases, day of week and holidays as well as trend and periodicities in time. The effect of specific meteorological factors, environmental and socioeconomic factors have been discussed in Section 2.1.2 and 2.1.3. Air pollution and widespread diseases may modify the effect of temperature on health. People’s activities and the health service vary across the week and during holidays, and hence they are included in this DAG. However, whether they should be treated as confounders will be discussed below.

Observed time series almost always has trends and periodicities (which is often due to seasonality for mortality and temperature data, and hence periodicity and seasonality are used interchangeably in this thesis). The long-term trend and periodicity can confound the short-term TM association if they are not controlled. For example, if there is a downward trend of daily mortality and an increasing trend of temperature over time, the conclusion of a negative TM association will be drawn if the long-term trend is not controlled. However, the negative TM association may be an artefact of the decreasing mortality rate due to improved health services and increasing temperatures driven by global warming. The trends and periodicities arise from known and unknown slowly changing factors such as population size, demographic structure and underlying health conditions. Therefore, long-term trends and periodicities in time should be adjusted as confounders in the analysis. Controlling for trends and periodicities in time simultaneously controls for all of these known and unknown factors and hence there is no need to control for these factors individually (Bhaskaran et al, 2013).

Apart from trends and seasonality, whether the other environmental, demographic, socioeconomic and disease pattern factors should be treated as confounders depends on their position in the causal relationship between temperature and health. There are five potential causal pathways of the impact of temperature on mortality, illustrated in green arrows in Figure 2-3. One main mechanism of the impact of regional temperature on mortality risk is through
the direct impact of the thermal environment on human health, as reviewed in Chapter 2.1. Additionally, temperature may impact air pollution, influenza epidemics, food, water and vector-borne diseases as well as cause other impacts such as infrastructural damage, and then influence mortality risk indirectly. The total causal effect is the combined effect transmitted through all causal paths between temperature and mortality risk (Tennant et al, 2019). Therefore, air pollution, influenza epidemics, food, water and vector-borne diseases should not be controlled, and doing so blocks causal paths that operate through these variables (Buckley et al, 2014). For example, the adverse effect of ozone on mortality was found to be higher under hot days in summer than on other days in London (Pattenden et al, 2010). It indicates that some of the adverse health effects of temperature operate through ozone. Some previous studies adjusted air pollution or influenza epidemic when analysing the TM association, which blocks the causal paths operating through them. Nevertheless, it may be useful when the objective is estimating the thermal effect of temperature on mortality.

When the analysis is conducted at population-level, a proxy exposure is taken as the representative exposure for all populations in a location. The exposure may be represented by the temperature measurement from a nearby weather station or a city/regional average value estimated using multiple station observations or gridded climate datasets (Spangler et al, 2019; De Schrijver et al, 2021). Although the above mentioned environmental and socioeconomic may affect health, they are unlikely to affect regional temperature, and hence are not identified as confounders. However, if the TM association is investigated on an individual level, the individually experienced temperature would be the exposure rather than the regional temperature. Under this situation, in addition to trend and seasonality in time, any factors that may affect both experienced temperature and the underlying mortality rate should also be treated as confounders, including the day of week and holiday, the built and natural environments and socioeconomic factors.
2.2.1.3. Statistical modelling

The short-term association between temperature and mortality can be studied using statistical models with mortality as the response variable and temperature as the predictor variable. There are two main study designs for this objective: case-crossover design and time series design (Basu et al, 2005; Lu & Zeger, 2007).

In case-crossover study design, trends and periodicities are controlled by creating data strata, which are stratifications of the data using terms of time (e.g. year, season, week). A day with an outcome occurring is treated as a case day, and other days in the same stratum are control days. Other variables such as demographic and socioeconomic factors introduced in Chapter 2.2.1.2 can also be controlled by creating case-control sets within each stratum. After the inclusion of relevant confounders, the case days can then be compared to other days in the case-control set. This study design has the capability to operate on the individual level and take into account individual exposures. However, the analysis can be computationally intensive because the data is expanded with unique rows for each case and all its control days sets (Armstrong et al, 2014).

Another widely used method for temperature-mortality association is the time series study design. A time series is a collection of observations sampled at equally spaced and ordered time points. Therefore, the unit of statistical modelling is the mortality count at regular time intervals (i.e. typically on the scale of days, but can also be week or month) rather than individuals (Bhaskaran et al, 2013). Generalised linear models are often used for the analysis, and a general representation of the statistical model for time series design is specified in Equation (2) (Gasparrini, 2011).

\[
g[E(Y_t)] = f(x_t; \theta) + \sum_{j=1}^{J} s_j(t; \gamma_j) + \sum_{p=1}^{P} h_p(z_{pt}; \eta_p) + \alpha \quad \text{Equation (2)}
\]

Where \( g \) is a link function for the generalised linear model, \( Y_t \) is the daily mortality count on day \( t \), and \( E(Y_t) \) is the expected daily mortality. The function \( f \) specifies the relationship between the exposure \( x_t \) and the linear predictor utilised in the model is defined by coefficients \( \theta \). Functions \( s_j \) specifies the...
relationships between time $t$ and the linear predictor to control for trends and periodicities in time, specified by coefficients $\gamma_j$. The functions $h_p$ specifies the relationship between covariates, such as the confounders identified in Chapter 2.2.1.2 and the linear predictor, defined by coefficients $\eta_p$. $\alpha$ are model residuals.

Various functions can be used to control trends and periodicities. Long-term trends can be modelled using quadratic and linear functions of time. Dummy variables for months and periodic functions (e.g. Fourier terms) can be used to model periodicities. In addition, time series design allows for the use of spline functions to model trends and periodicities flexibly. A spline function splits the whole range of the data into multiple continuous pieces at knots (i.e. the location of the splits) and performs piece-wise polynomial functions for each piece while ensuring the regression line is smooth around the knots (Perperoglou et al, 2019). The type of spline is determined by the degree of the polynomial function (e.g. quadratic, cubic) and the constraints of the function at the boundaries of the data. For example, a cubic spline performs a cubic polynomial function between neighbouring knots. Spurious results may arise at the boundaries where there is less data. Therefore, natural cubic spline is sometimes utilised which imposes an additional constraint requiring the regression line to be linear at the boundary knots.

The relationship between temperature and mortality is non-linear with increased mortality risk under both low and high temperatures. A simplified method to modelling the non-linear association is using a linear threshold function for $f$, where the TM association is assumed to be linear below or above a threshold of exposure. Like the model of trends and periodicities, spline functions for $f$ can be utilised to model the non-linear temperature-mortality association too.

The effect of exposure on the outcome may last over a period of time after the same day’s exposure, which is called the lagged effect. The lagged effect can be seen from a forward or backward perspective (Figure 2-4). For example, exposure to temperature on a given day is not only associated with elevated mortality risk on the same day but also over a period of time in the future.
(forward perspective). In other words, the mortality risk of a certain day is associated with the exposure on the same day, and also the exposures multiple days before (backward perspective).

![Conceptual model for the interpretation of exposure-lag-response associations: forward (left panel) and backward (right panel) perspectives (Gasparrini & Leone, 2014).](image)

This exposure–lag–response association can be studied using the framework of distributed lag non-linear models (DLNM) (Gasparrini, 2014). In the DLNM framework, the function $f(x_t; \theta)$ in Equation (2) is extended to $f(x_t, l; \theta)$ where $l$ are the lagged days (Gasparrini & Leone, 2014). In addition to defining a function to model the exposure–response association (the same as $f(x_t)$), another function is also defined to model the association between exposure at lagged days and outcome. These two functions are then combined together to model the exposure–lag–response association, which can be achieved in R using the package dlnm (Gasparrini, 2011). The result of the exposure–lag–response association can be illustrated using a 3-dimensional graph as shown in Figure 2-5 a, or be reduced to 2-dimensional focusing on the cumulative effect over the maximum lag length (Figure 2-5 b), temperature-specific effect across different lags or lag-specific effect over the exposure range.

The main output of the statistical analysis is an exposure–response function (ERF) that describes the mortality risks associated with a risk factor. Mortality risk is defined in this thesis as the expected number of deaths over a period of time within a population due to certain risk factors (i.e. ambient temperature exposure in this thesis). Therefore, the mortality risk distinguishes from the mortality rate with the former being related to a risk factor, and the latter is a
descriptive statistic of death events of a population. Mortality risk is usually used in a comparative manner, for example, to compare the mortality risk between different levels of exposures, populations, or temporal periods by taking the ratio of the mortality risks, which is expressed as relative risk (RR).

Sensitivity analyses should be conducted for the specifications of the functions and terms in Equation (2) to explore the robustness of the results in relation to model settings (e.g. choice of splines and placement of knots). In addition, model checking should be conducted in order to reveal any problems with the model specification. This includes plotting the model residuals against the predictor and response variables to detect any outliers and remaining variations that are not explained by the predictors. The original daily mortality time series data often shows features of autocorrelation. This is where the data is correlated with the lagged version of itself. When the statistical model is adequately specified, this time pattern in the mortality data should be largely explained by the predictor variables with little residual autocorrelation left.

Because the outcome variable is daily mortality counts which follow Poisson distribution, the link function of the Poisson regression model is often employed for $g$ in Equation (2) (Petrie, 2013). In Poisson regression, the variation of the residual is assumed to be the same as the mean. However, this assumption may be violated if the variance is larger than the mean, which is the phenomenon of overdispersion. Ignoring overdispersion may result in an
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underestimation of the standard error and an overestimation of the precision of the estimation (Petrie, 2013). When residual overdispersion is detected, it can be adjusted using the quasi-Poisson model in time series analysis which incorporates a scaling term of data variance (Ver Hoef & Boveng, 2007). Nevertheless, large residual overdispersion may indicate a deficiency in the control of trend and periodicities or missing important explanatory variables, and hence considerations should be made to improve the model terms and specifications (Bhaskaran et al, 2013).

When the exposure is common to all the population under investigation, the time series design with indicator variables for time is equivalent to the case-crossover design (Lu & Zeger, 2007). For example, a case-crossover design where monthly strata are taken to match one case day with 30 control days is equivalent to a time series design with indicators of months. Previous empirical studies compared using the case-crossover design and time series analysis method for the TM association resulted in consistent and comparable results (Basu et al, 2005; Tong et al, 2012).

However, compared to the case-crossover study design, time series design has the advantages of taking into account overdispersion and hence improving the model precision, the ability to use spline functions to model trends and periodicities in time flexibly and being more computationally efficient (Armstrong et al, 2014). Therefore, the time series design is utilised in the thesis to study the association between temperature and mortality in Chapter 4 and 5.
2.2.2. Methods to model adaptation in the estimation of future temperature-related mortalities/morbidities under climate change

Future heat risks are expected to increase in many parts of the world due to climate change. In addition to climate change, the health impacts of temperatures are also influenced by the ability of the population to acclimatise and adapt to the change. Adjustments in the physiological processes may be induced after chronic or repeated non-lethal cold and heat exposure to improve thermoregulatory capacity and reduce the morbidity and mortality risks from future exposures, which is referred as acclimatisation (Margolis, 2014; Hanna & Tait, 2015; Castellani & Young, 2016). In addition, people’s behaviours can also adjust to changes in climate, such as through clothing, staying in shades or indoors, which is seen as behavioural adaptation. Some previous studies have found that the heat-health risk is higher in the early months of the warm season than the later months, e.g. in Sweden (Rocklov et al, 2011), the US (Barnett et al, 2012) and France (Alari et al, 2023), which is likely due to a lack of physiological acclimatisation and/or behavioural adjustments in the early months (Sheridan & Lin, 2014). Furthermore, socioeconomic changes (e.g. building, infrastructure, health service) can also affect the impact of climate on human health, which is referred to as socioeconomic adaptation. This can be investigated by comparing the variation in the temperature-health risks among population across different socioeconomic groups. However, it is very challenging to disentangle physiological, behavioural and socioeconomic adaptation because they often occur simultaneously. For example, some studies found that there is a higher heat-health risk associated with the same temperature in cooler than warmer locations, and similarly a higher cold-health risk in warmer regions than cooler locations (Keatinge et al, 1997; Curriero et al, 2002; Anderson & Bell, 2009). This may be due to a combination of all of the acclimatisation and adaptation mechanisms introduced above. Therefore, the term adaptation is used in this thesis to indicate all mechanisms that lower the adverse health effects of low and high temperatures.
It is important to integrate potential future changes in adaptation in the estimation of temperature-related mortality to reflect the risk in real-world situations. Multiple approaches have been used in previous studies to model adaptation in the estimation of deaths associated with cold and heat (which is also referred to as mortality burden), such as shifting the threshold temperature beyond which the mortality risk starts to increase (referred to as threshold temperature below), adjusting the slope of the temperature-mortality (TM) association, and applying the TM association identified in analogue locations. There is currently no consensus on the best method of modelling adaptation.

This section provides a scoping review of the methods to integrate adaptation into estimating deaths or other health outcomes (e.g. years of life lost, YLL) attributable to heat and/or cold under climate change in the existing literature. Research into estimating the mortality burden associated with extreme temperatures in Scotland under climate change and adaptation scenarios is then performed in Chapter 5.

Relevant literature was searched in the Web of Science Core Collection on 17th Oct 2022 using the searching terms below:

(mortality OR death OR “health impact” OR “health burden”) AND (heat OR cold OR temperature) AND (“climate change” OR “global warming”) AND (adaptation OR vulnerability) AND (project* OR scenario)

Figure 2-6 shows the study selection flow chart and exclusion criteria, which resulted in 55 articles included in this review.
Figure 2-6. Study selection flow chart of the scoping review on future health burdens associated with heat and cold under climate change and adaptation scenarios.

The methods to model adaptation along with the study location and main findings of individual studies are extracted and summarised in Supplementary S1. No study has been found for Scotland. The focus of this review is exploring the methods that have been used in previous studies to model the effect of adaptation on future temperature-related health burdens, and hence there is no restriction on the location of the study region. The results of these studies are not reviewed or synthesised in this thesis because the main focus is the method and their advantages and limitations, and the results are largely not comparable due to different study regions and methods.

This review identified and categorised the method to integrate acclimatisation and/or adaptation into the research on temperature-related health burdens into the following types. Some papers utilised multiple approaches to model adaptation, and hence the sum of the number of papers under each category is larger than the total number of papers reviewed.

Type 1. Modification of the risk function:
(1) Shifting the threshold temperature by an absolute value (n=12) or using a relative threshold (n=17)

(2) Adjusting the TM association slope by a certain percentage (n=14).

(3) Extrapolating historical trends in the slope (n=4) or the threshold temperature (n=1) to the future

(4) Using the risk function in analogue locations (n=4) or in analogue time (n=6).

(5) Building the TM association incorporating climatic (n=6) or socioeconomic (n=8) covariates that are assumed to represent acclimatisation/adaptation. Constructing future TM associations based on the assumed or projected values of the covariates in the future. Six of the papers made use of projected values of the socioeconomic covariates under the Share-Socioeconomic Pathways (SSP).

Type 2. In addition to modifying the risk function, changes in land use and buildings have also been investigated as the adaptation mechanism and the effect on temperature-related mortality burden is estimated based on the changes in the exposure to temperature (n=4).

These different methods are discussed in the following sections.

2.2.2.1. Shifting the threshold temperature
The most commonly used method to integrate adaptation to the projection of temperature-related health burdens is by shifting the threshold temperature. The MMT is sometimes used as the threshold, where the heat and cold thresholds are identical. Some of the studies assumed an increase in the heat threshold by a fixed value. However, there is a lack of evidence and consensus regarding the amount of temperature shift in the threshold and this threshold will vary regionally and demographically. For example, an increase of 1 °C in the heat threshold every 3 decades was assumed by Dessai (2003) and (Watkiss & Hunt, 2012), a 0.25 °C increase in threshold every 2 decades was used in Wang et al (2022) and an increase of 1-4°C was used for future periods
Another method of modelling acclimatisation and adaptation in a warming climate is a shift of the threshold temperature proportional to the projected change in annual average temperature (Ballester et al., 2011; Huynen & Martens, 2015; Huang et al., 2018). This method is based on previous findings of a positive correlation between the MMT and annual average temperature. For example, a global study investigated the MMT of 658 communities in 43 countries, which found an increase in the MMT by 0.8 °C for each degree rise in local annual mean temperature (Tobías et al., 2021). Another study in Spain found a similar result in which the MMT increased by 0.84 °C per 1 °C rise in mean summer temperature across Spanish cities (Huber et al., 2022). This study also found that the MMT of a city increased by 0.73 °C per 1 °C rise in mean summer temperature over time (Huber et al., 2022). The larger change in the MMT against mean summer temperature across cities than in the same city over time may reflect location-specific adaptation and acclimatisation conditions.

Some papers used a “relative” threshold approach and assumed the percentile to which the heat/cold threshold corresponds remains constant over time. In several studies, a future threshold temperature accounting for adaptation was estimated by applying the threshold percentile to the projected climate, which is also seen as a “full-pace” adaptation scenario (Guo et al., 2018; Diaz et al., 2019a; Diaz et al., 2019b; Diniz et al., 2020; Shindell et al., 2020; Liu et al., 2023). The mean of the historical threshold temperature (no adaptation) and the future threshold under the full-pace adaptation was used as the future threshold temperature to represent lagged adaptation (Hales et al., 2014; Honda et al., 2014; Zacharias et al., 2015; Anderson et al., 2018; Zhang et al., 2018; Abadie & Polanco-Martinez, 2022).

Shifting the threshold temperature by annual average temperature change focuses on adaptation to the long-term change in the average climate while the relative threshold approach takes into account the change in climate variability.
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(Shindell et al, 2020). However, it is unknown to what extent the threshold will shift in according to the average temperature under climate change. A key consideration is that there may be an upper limit in the threshold temperature and the increase in the heat threshold may slow down over time because of a potential limitation in heat acclimatisation.

2.2.2.2. Adjusting the slope of the temperature-mortality association
Another widely used approach to model adaptation is adjusting the slope of the TM association or RRs, to represent a change in the susceptibility to ambient temperatures due to adaptation. Due to the lack of empirical evidence on probable changes in the susceptibility in the future, a range of up to a 50% reduction in the heat slope has been applied in previous studies (Martens, 1998; Huynen & Martens, 2015; Li et al, 2016; Li et al, 2018a; Li et al, 2018b; Aboubakri et al, 2020). Instead of predetermining the adjustment of the sensitivity, some studies estimated the need for the reduction in the heat susceptibility under climate change so that the future heat burden would remain at approximately the same level as the present (Chen et al, 2021).

2.2.2.3. Extrapolating historical trends
Some studies shifted the threshold temperature or TM association slope by extrapolating the historical trend of them. Muthers et al (2010) explored the historical trend in heat susceptibility in Vienna, Austria between 1970 and 2007 and when a significant historical trend was observed, the trend was extrapolated linearly into the future. If there was no significant historical trend, the susceptibility at the end of the historical period was applied to the future. Petkova et al (2017) found a decreasing trend in the temperature-specific RRs in New York in the 1900s-2000s, which was extrapolated to the end of the 21st century while assuming a further 20% and 80% reduction in the RRs in 2100 compared to the 2000s to represent three adaptation scenarios. Similarly, Lee et al (2019) estimated temperature-specific RRs in 1991–2000 and 2006–2015, and the trend therein was extrapolated into the future up to 2100 using a sigmoid function assuming an 80%, 50% and 20% reduction in temperature-specific RRs in 2100 compared to 1991-2015 to represent three adaptation
scenarios. Another study applied the historical trend found in other locations, including the historical trend of heat susceptibility in Shanghai, China and New York, US, as well as the historical trend in the MMT in France, to the study location Guangzhou, China as adaptation scenarios (Liu et al, 2019). However, it is unknown to what extent the historical findings are applicable to the future change in heat sensitivity due to changes in rates of global warming and socioeconomic development. In addition, the validity of applying the historical trend found in one location to other locations remains questionable, which is similar to the analogue location approach to incorporate the effect of adaptation that will be discussed in Chapter 2.2.2.4.

Eight studies also explored the effect of adaptation on temperature-related health burdens by shifting the threshold and adjusting the TM association slope at the same time, although with little empirical evidence supporting the assumptions (Ballester et al, 2011; Huynen & Martens, 2015; Huang et al, 2018; Li et al, 2018a; Li et al, 2018b; Lee et al, 2019; Kouis et al, 2021; Wang et al, 2022).

2.2.2.4. Analogue location and time
The “analogue location” method applies the TM association in locations whose present climate approximates the projected climate of the location under investigation (Kalkstein & Greene, 1997). This method is based on the findings that populations in warmer places tend to be less sensitive to high temperatures and similar to cold which is likely due to acclimatisation and adaptation (Keatinge et al, 1997; Curriero et al, 2002; Anderson & Bell, 2009). Therefore, this method assumes that people in the target location will acclimatise and adapt to temperatures as the analogue locations have achieved at present. For example, Knowlton et al (2007) applied the association between high temperature and mortality risk derived from two US cities, Washington, DC and Atlanta, Ga to New York as the adaptation scenario because the present climate of Washington and Atlanta are within 1°F of the projected climate in New York region in the 2050s under climate change scenario SRES A2. Mills et al (2015) calculated the 1st and 99th percentile of temperature distributions in 33
US cities as the cold and heat thresholds respectively, and modelled adaptation by applying the highest threshold temperature for both the cold and heat among the 33 cities for all cities in 2100. The increase in the cold threshold assumed a loss in cold adaptation in a warming world, which is discussed in Chapter 2.2.2.7. As stated in Chapter 2.2.2.3, a major limitation of any assumption about one location representing another in a future period is that different cities have varying demographic and socioeconomic profiles and hence the ERFs may not be comparable (Gosling et al, 2017).

Instead of using the ERF in analogue cities, another approach to model adaptation is to use the ERF in the same location but in an “analogue time”. This method assumes that people will most likely respond to heat under climate change conditions as they do today during some special periods when acclimatisation and adaptation may have occurred. Three studies in this review found a lower heat susceptibility in hot summers compared to other summers which was likely due to short-term acclimatisation, and therefore the TM association in hot summers was applied to the future under global warming representing an acclimatised scenario (Kalkstein & Smoyer, 1993; Hayhoe et al, 2004; Cheng et al, 2008). One study assessed the TM association in three historical periods and found a decrease in the heat susceptibility in 40 US cities over time, and hence applied the ERF in the first period to the future as no adaptation scenario, and the ERF in the latest period as adaptation scenario (Greene et al, 2011). Similarly, another study fitted risk functions separately in four historical time periods in the US and used the risk function from the first and last historical period as an approximation of a low and high adaptation scenario respectively (Lay et al., 2021).

One extension of this method is to extrapolate the historical trend to the future as outlined in Chapter 2.2.2.3. Finally, In another study, acclimatisation was modelled by estimating excess deaths during heatwaves but neglecting all heat-related mortality that occurred in the first 3 days of a given heat episode (Sheridan et al, 2012). However, the lower mortality risk in the following period after the first 3 days of a heat episode may not only be due to acclimatisation
but could be a combination of short-term acclimatisation and mortality displacement, which is the phenomenon that death events of those with severe underlying illnesses are brought forward by days or weeks (Hajat et al, 2005).

2.2.2.5. Integrating climatic or socioeconomic covariates into the model of temperature-mortality association

Another method of modelling acclimatisation that has been used in recent years is using a covariate of a climatic variable (e.g. summer/annual mean temperature) or using this variable as an interaction term with daily temperature as a predictor of mortality. The effect of adaptation in reducing future heat-related mortality was estimated by the difference in the predicted temperature-related mortality burden using models with and without the climatic covariate (Wang et al, 2018; Shindell et al, 2020; Bressler et al, 2021; Carleton et al, 2022; Huber et al, 2022).

Socioeconomic conditions are important for adaptive capacity and in modifying the TM association (Chapter 2.1.2). Thus, Socioeconomic variables have also been used as a covariate in the TM association to model and predict the effect of socioeconomic adaptation. Population ageing, the prevalence of using air conditioning (AC), social isolation, ethnicity and poverty were identified as strong predictors of summer mortality in Greater Houston, US (Rohat et al, 2019b). GDP and income per capita were most widely used as an indicator of socioeconomic adaptive capacity to ambient temperatures (Wang et al, 2019; Bressler et al, 2021; Carleton et al, 2022). AC prevalence was also used as a predictor in the heat risk function or the MMT (Ostro et al, 2011; Kouis et al, 2021). However, this method is not applicable to all locations. For example, Lay et al (2021) assessed the predictive effect of seasonal mean temperature, AC prevalence and population ageing of heat susceptibility in 208 US cities of 9 climatic clusters and did not find stable predicting effects of these variables on heat-related mortality risk. The authors indicate that it may be because of the small number of cities included in individual climatic clusters, the low variation in some of the predictors within clusters, and the high correlation among some predictor variables.
To construct future TM associations using the risk functions with climatic and/or socioeconomic covariates, assumptions were made on the future value of these covariates, which were applied to the risk function to build the future TM association. Recently, the SSP framework has been utilised to explore plausible future values of such socioeconomic variables (Rohat et al., 2019b; Bressler et al., 2021; Kouis et al., 2021; Carleton et al., 2022; Rai et al., 2022). The SSPs include five potential futures of how society, demographics and economics might change over the next century, designed to reflect varying levels of challenges to climate change mitigation and adaptation (O’Neill et al., 2017). They have been widely used by the climate and social science communities for climate change projections and impact assessments, including the latest Intergovernmental Panel on Climate Change (IPCC) assessment reports (IPCC, 2021; 2022).

2.2.2.6. Reducing the exposure to cold and heat by land cover and housing

All of the methods above modified the risk function to model adaptation. A different approach considering the land cover/use and buildings on modifying the temperature that people are exposed to. Hence the associated change in health burdens has also been modelled by some studies as the difference in health burden with and without the modification. Stone et al. (2014) estimated changes in the number of heat-related deaths in the US in 2050 under 7 scenarios of modifications to vegetative cover and surface albedo. A more detailed study quantified the effect of greenspace, AC and building stock upgrade on heat susceptibility in the UK and constructed 12 adaptation pathways with varying combinations of the change in the three measures (Kingsborough et al., 2017). Haddad et al. (2020) also constructed a considerable number of adaptation scenarios (11 in total) including combinations of an increase of greenery, application of cool materials, water spray system, shading and green roof, and estimated the impact of these strategies on the change in the microclimate and future temperature-related heat burdens. This approach has the advantage of estimating the change in temperature-related mortalities based on empirical evidence of the effect of land cover/use and housing on temperature exposure. However, it does not
take into account potential changes in the risk function which is also affected by adaptation.

2.2.2.7. Assumptions on gain and loss in adaptation
A common limitation of previous research is that they predominantly assumed an increase in heat acclimatisation and adaptation in the future (Sanderson, 2011; Rai et al, 2022). However, the impact of a reduction in heat adaptation on the heat-related health burden has seldom been investigated. For example, there is expected to be increasing nationalism and growing international tensions accompanied by a decrease in social support, education, health and public infrastructures in the future under SSP3—the regional rivalry scenario (O’Neill et al, 2017). Under SSP4, higher inequality is assumed, with deteriorating social cohesion and health services for most of the public (O’Neill et al, 2017). These scenarios, therefore, suggest future adaptation could be more challenging than for present-day. Therefore, it is imperative to conduct research that takes into account the projected heat-related health burdens in the face of climate change, considering both an enhancement and decline in the adaptive capacity to heat.

Contrary to the assumption of an increase in heat acclimatisation in previous studies, a loss in cold adaptation has been assumed by many studies. These studies assume the threshold temperature for both cold and heat shifts according to the average temperature under climate change, and hence the population’s current cold acclimatisation and adaptation ability deteriorate as the temperature increases. Modelling adaptation using this method results in an increase in the cold threshold and the associated cold burden (Ballester et al, 2011; Huynen & Martens, 2015; Huang et al, 2018; Li et al, 2018a; Li et al, 2018b; Zhang et al, 2018; Diaz et al, 2019a; Huang et al, 2019; Wang et al, 2022). An increase in the slope of the cold risk function as well as a combination of an increase in the cold threshold and an increase in the slope have also been utilised to model decreases in cold adaptation (Huynen & Martens, 2015).
Some other studies instead assume an increase in both heat and cold adaptation in the future, assuming a positive scenario where the adaptive capacity to heat and cold both improves. Watkiss & Hunt (2012) assumed an increase in cold adaptation at the same rate as heat adaptation, modelled through lowering the cold threshold and elevating the heat threshold by 1°C every three decades. An increase in heat and cold adaptation has also been modelled by reducing the slopes of their risk functions (Aboubakri et al, 2020; Wang et al, 2022). Two studies integrated an increase in the cold threshold and a decrease in the cold slope (Lee et al, 2019; Wang et al, 2022). However, there is no consistent evidence of either a loss or gain in cold adaptation over time in different locations, and it is uncertain how adaptive capacity to cold may develop in the future. The SSP is a useful framework to construct adaptation scenarios which contain situations with both an increase and decrease in the adaptive capacity and is used in this thesis in Chapter 5.
2.3. Scottish-specific background

This section provides a background to the targeted location of this thesis—Scotland, including its climate (Chapter 2.3.1), demography (Chapter 2.3.2) and policy context (Chapter 2.3.3). A scoping review of existing literature investigating the health effects of ambient temperatures in Scotland is performed in Chapter 2.3.4.

2.3.1. Climate

The Scottish climate is generally temperate with cool summers and mild yet windy winters. The annual average daily mean temperature in Scotland is 7°C between 1961-1990 (Figure 2-7 a). Spatial variations in temperature arise from the combined effects of latitude, maritime influence, coast proximity, topography and urban development (Met Office, 2016a). The western part of Scotland is overall milder, wetter and cloudier than the eastern side due to the stronger influence of the prevailing westerlies.

Scotland is the most mountainous nation in the UK. It has been traditionally separated into the mountainous 'Highlands' to the north and west, and the 'Lowlands' to the south and east (Figure 2-7 b). The Lowlands can be further divided into the central belt, where the majority of the Scottish population resides, and the Southern Uplands comprising a range of hills. The northern and western mountainous areas generally experience cooler temperatures compared to the southern and eastern low-lying areas due to the influence of altitude.

2.3.1.1. Historical climate

The mean annual temperatures over the low latitude areas vary from around 10 °C in western Scotland and 9 °C in eastern Scotland (Met Office, 2016a; c). Scotland has a cool summer with July or August being the warmest month. The mean daily maximum temperature in the warmest month approaches 20 °C in low-lying areas (Met Office, 2016a). The highest daily maximum temperature recorded in Scotland is 34.8 °C in July 2022 (Met Office, n.d.-b). The previous record was 32.9 °C in August 2003 (Met Office, 2016a).
The winter in Scotland is relatively mild with January or February being the coldest month. The mean daily minimum temperature in the coldest month ranges from around 2 °C in coastal areas to less than -1 °C over the higher grounds (Met Office, 2016a; b; c). The lowest temperature record in Scotland is -27.2 °C occurred in January 1982, February 1895 and December 1995, which is also the UK record (Met Office, n.d.-b).

The climate has been warming in Scotland in the last decades (CCC, 2022). An increase of 0.9°C in annual mean temperature has been observed in Scotland in 2011-2020 compared to 1961–1990 (Kendon et al, 2021).

### 2.3.1.2. Climate projections

How climate may change in the future is uncertain, whereas models that represent/simulate the Earth's climate system can be used to estimate future climates with the inputs of pathways of future human influences such as Greenhouse Gas emissions, which is referred to as climate projections. In the past, several sets of scenarios have been utilised, such as the Representative Concentrative Pathways (RCP), which is a scenario set containing future concentrations of greenhouse gases and air pollutants and land-use change, the main variables driving anthropogenic climate change (Van Vuuren et al,
Four RCPs were initially developed, which are named by the radiative forcing levels (the size of the energy imbalance in the atmosphere) reached by the end of the century: 8.5, 6.0, 4.5 and 2.6 W/m², with a larger radiative forcing indicating higher global warming level. This RCP was adopted as the scenario used for the fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) in 2014. In the latest IPCC Assessment Report (AR6), a newer generation of scenario—the Shared Socioeconomic Pathways (SSPs) is adopted. As introduced in Chapter 2.2.2, the SSPs are scenarios of projected socioeconomic global changes up to 2100, serving as the foundation for developing diverse greenhouse gas emissions scenarios aligned with various climate policies.

The UK Climate Projections 2018 (UKCP18) project the future climate in the UK under various RCPs, which provides data for the UK on fine spatial resolutions (up to on 1km-by-1km grid). Therefore, the UKCP18 projections are used in the thesis in Chapter 5. The RCP scenarios can be mapped onto the SSPs for probable future socioeconomic conditions and GHG emissions, which is introduced in Chapter 5.

The annual mean temperature in Scotland is estimated to increase by 1.1°C under RCP 2.6, and 2°C under RCP 6.0 by the 2080s relative to 1981-2000 (Sniffer, 2021). The warming is larger in the summer than winter, and also larger for summer maximum temperature than mean temperatures, particularly in southern and middle Scotland (Figure 2-8). Daily temperature series in Scotland using the UKCP18 projection is provided in Chapter 5.
2.3.2. Demography

There are 5.48 million people in Scotland as of in 2021, 27% of whom reside in the four largest cities—Glasgow, Edinburgh, Aberdeen and Dundee (NRS, 2022a). The Scottish population has been ageing, with a 6% decrease in the number of children (aged 0 to 15) and a 33% increase in those who were 65 years old and above in the two decades since 2000 (NRS, 2022a). The ageing population is expected to continue increasing, and those of age 75 and above are expected to increase by 67% between 2020-2045 (NRS, 2022b), which is higher than the UK-average increase of 59% (Office for National Statistics, 2022d). Population ageing will contribute to increased population vulnerability and challenges in health and social care services.

Although declining over the UK (including Scotland) since the 1950s, the mortality rate in Scotland, especially in Glasgow, has been higher than in the rest of the UK and among the highest in Western Europe (McCartney et al, 2012b; Schofield et al, 2016; NRS, 2021b). As reviewed in Chapter 2.1.2.2,
inequality is an important contributing factor to people’s vulnerability to ambient temperatures. Health inequality has also been striking within Scotland. Individuals residing in the most deprived areas of Scotland experienced a healthy life expectancy that was 24 years shorter compared to those in the most affluent areas in 2018-2020 (National Records of Scotland, 2021), which is higher than the difference of 18 years in England (Office for National Statistics, 2022b). However, the poorer health in Scotland compared to the rest of the UK persists after the control of deprivation (Walsh et al, 2010; Schofield et al, 2016). Hypotheses of the principal factors leading to the poorer health of the Scottish population include lagged adverse effects of overcrowding, poor housing conditions, negative effects of deindustrialisation, job loss, skilled labour loss, population relocation and city “redevelopment” policies since the 1950s (Collins & Levitt, 2016; Walsh et al, 2017). These resulted in weakened and deprived communities and negative health behaviours (e.g. smoking, drinking alcohol and illicit drug taking).

The long-term decreasing trend in the mortality rate stalled from 2012 in Scotland, and an increase in the mortality rate was seen for the most deprived young people (age 0-64) for both females and males (Figure 2-9). This is likely due to the austerity policies by the UK Government from 2010 including reduced public spending on services such as local government and healthcare and a reduction in social security payments, both of which particularly affected the most deprived population (McCartney et al, 2022). The ageing population, historically poorer health in Scotland and widening health inequality in the last decade may contribute to the vulnerability of the Scottish population to the impacts of ambient temperatures.
Figure 2-9. Age-standardised mortality rates of females (a) and males (b), aged 0-64 in Scotland (blue line) and for those lived in the most deprived quintile (Q1, orange line) and least deprived quintiles (Q5, green line). Three-year rolling averages between 1981 and 2021 (Walsh & McCartney, 2023).

2.3.3. Policy context

This section reviews existing climate change adaptation policies relevant to the reduction of heat-health risks for Scotland. Policies relevant to the management of cold risks are reviewed too, which may be transferable to heat risks and bring opportunities and challenges to heat-health governance.

As a devolved nation of the UK, Scotland is in charge of creating its own policies on the environment, health and social care matters—those that are linked to heat-health strategies under climate change (Scottish Parliament, n.b.). Climate change mitigation and adaptation are enforced by law through the UK Climate Change Act 2008 and the Climate Change (Scotland) Act 2009, which were amended in 2019 to include a target of reaching net zero
Greenhouse Gas emissions by 2050 in the UK and 2045 in Scotland. The laws require the publication of a climate change risk assessment (CCRA) by the Committee on Climate Change (CCC) and the implementation of a national climate change adaptation programme (CCAP) by the government every five years. Climate change adaptation objectives and policies are included in CCAPs, the progress of which is required to be reported annually. Until now, three CCRAs (DEFEA, 2012; UK Government, 2017; CCC, 2021) have been published, each with a national summary for Scotland (DEFRA, 2012; CCC, 2017; Sniffer, 2021). The heat-health risk in Scotland was identified as a research priority by the 2\textsuperscript{nd} CCRA (Committee on Climate Change, 2016), and one of the most urgent risks that need more action by the 3\textsuperscript{rd} CCRA (Sniffer, 2021).

Another policy target of the Scottish Government is improving home energy efficiency, which would not only reduce GHG emissions but also contribute to reducing fuel poverty. Fuel poverty refers to the challenge of a home being warm long enough, as defined by the Fuel Poverty (Targets, Definition and Strategy) (Scotland) Act 2019, which also sets statutory targets for eradicating fuel poverty in Scotland by 2040. The Scottish Government funds multiple schemes to help people who have difficulties paying fuel bills or keeping homes warm, such as by improving insulation and implementing renewable energy.

There is a National Severe Weather Warning service provided by the UK Met Office, which is extended to include warnings for extreme heat for the UK including Scotland in June 2021 (Met Office, 2021). It is to be issued based on the impact of extreme heat on infrastructure, transport, energy, business as well as health, which has two levels of alert based on medium and high levels of impact (corresponding to amber and red warning respectively) (Met Office, n.d.-d).

An amber warning of extreme heat was issued in a large part of Scotland in July 2022, which activated the operation of the Scottish Government Resilience Division (Scottish Government, 2022a). The Resilience Division is responsible for leading emergency planning, response and recovery for the Scottish
Government that involves a large variety of organisations such as local authorities, police, fire, health boards and ambulance (Ready Scotland, 2016). Hot weather is one of the severe weathers of which preventative information is provided at Ready Scotland (n.d.), the website maintained by the Resilience Division. Existing evidence on the health effects of ambient temperature in Scotland will be reviewed in the next section.

2.3.4. Temperature-related mortalities and morbidities in Scotland
Epidemiological studies investigating the relationship between ambient temperature and mortality and morbidity have been performed in many locations globally (Gasparrini et al, 2015; Zhao et al, 2021), including North and South America (Curriero et al, 2002; Anderson & Bell, 2009; Barnett et al, 2010; Bobb et al, 2014; Wen et al, 2021), Asia (Ma et al, 2014; Chen et al, 2018; Fu et al, 2018; Lee et al, 2018; Aboubakri et al, 2019), Australia (Guo et al, 2011; Vardoulakis et al, 2014; Lu et al, 2020), Europe (Keatinge et al, 1997; Keatinge et al, 2000; Baccini et al, 2008; Leone et al, 2013; Masselot et al, 2023) and to a less extent in Africa (Azongo et al, 2012; Egondi et al, 2012). Previous studies have mostly found increased mortality risks at both low and high temperatures, whereas the effect size varies by location due to various demographic and socioeconomic factors associated with the region and the cohort studies. Further caution is needed in comparing the results from different studies due to differences in temperature metrics used, the threshold temperature used to estimate RRs, length of the lag, control of confounders, study period, statistical modelling method including the number and location of knots if splines are used to model non-linearity.

A scoping review was conducted for existing literature that investigated the health impacts of ambient temperature in Scotland. This aim is to understand the current state of research and the latest findings in Scotland, as well as identify research gaps.

2.3.4.1. Literature search
The Web of Science Core Database was searched on 7th November 2019 using the key terms “temperature” and “mortality” and “Scotland”. To include
publications on health outcomes other than mortality and to find newly published articles, an updated search was conducted on 3rd August 2023 using the search terms below:

- (mortalit* OR morbidit* OR death* OR "health impact" OR "health burden" OR “health outcome*” OR “hospital admission*” OR hospitalisation) AND
- (heat OR hot OR cold OR temperature*) AND
- (Scotland OR Glasgow OR Edinburgh OR Aberdeen OR Dundee)

The asterisk mark * is used to represent any number of letters in a word, which can be useful for finding variations of spellings. For example, mortalit* will find both mortality and mortalities.

The returned publications were firstly refined by excluding irrelevant categories based on the journals that they were published in, such as marine freshwater, fisheries and veterinary sciences. Title, abstract screening was conducted to remove irrelevant papers. The full-text screening was performed when necessary. The exclusion criteria are:

- non-human studies;
- studies not for Scotland;
- studies about exertional heat stroke;
- studies that do not investigate the impacts of ambient temperature;
- studies only investigated the seasonal variation in mortality/morbidity;
- studies about therapeutic hypothermia, e.g. in preventing brain injury;
- studies that only assessed the effect of housing interventions on health;
- studies that only investigated the mechanisms, characteristics, outcomes or treatment of hypothermia/hyperthermia;
- studies that use temperature as a control or modifier when studying the health impacts of air pollution
- studies that were only published as conference abstracts without the main text

Five and four articles were identified from the initial and updated search respectively. One article is a publication from this PhD research, which is included in Chapter 4 of this thesis. Therefore, eight identified publications are
reviewed in this section. The detailed search strategy is described in the Supplementary S2.

2.3.4.2. Literature review
The identified publications are summarised in Table 2-1, including the study period, location, population (e.g. age, sex), temporal unit of data (e.g. daily, weekly, monthly), temperature metric, health outcome, statistical analysis method, result and notes. The results are summarised and discussed below and compared with previous findings in Europe including the UK.

Among the eight articles, five studies investigated the change in mortality risks associated with cold and heat (Gemmell et al, 2000; Carder et al, 2005; Aubiniere-Robb et al., 2013; Ramsay et al. 2018; Dimitriadou et al., 2022). An increase in the mortality risk at both low and high temperatures was found in Scotland. A minimum mortality temperature (MMT) of 10-14 °C was found by Gemmell et al (2000) and Carder et al (2005). Dimitriadou et al (2022) examined the association between daily mean temperature and mortality from cardiovascular and respiratory diseases in 1982-2018, and identified the lower and upper threshold temperatures beyond which the mortality risk increases due to cold and heat respectively. This study reported low/high thresholds of 10.17/14.39°C, 1.67/15.20°C, 0.53 /11.29°C and 0.82/13.80°C in Aberdeen, Dundee, Edinburgh and Glasgow respectively. The MMT in Scotland is lower than in London, which was found to be 21-25 °C in various studies (Armstrong, 2006; Hajat et al, 2006; Baccini et al, 2008; Gasparrini et al, 2015). The lower MMT in Scotland compared to London is likely due to a general adaptation and acclimatisation to the cooler climate in Scotland.

For the cold effect, Gemmell et al (2000) found that each 1°C decrease in weekly mean temperature below 2°C and 10°C was associated with an increase in all-cause mortality risk by 1.06% and 0.8% respectively in 1981-1993. Carder et al (2005) investigated the cold effect on different causes of death, and found that each 1°C decrease below a daytime mean temperature of 11°C was associated with an accumulative increase in mortality by 2.9% (all-cause), 3.4% (cardiovascular diseases), and 4.8% (respiratory diseases) over a
lag of 30 days in 1981-2001. The cold-related mortality risk due to respiratory
diseases was found to have a longer lag than cardiovascular diseases in
Scotland (Gemmell et al, 2000; Carder et al, 2005). The strongest
cardiovascular and respiratory diseases mortality risk occurred at a lag of 1-6
and 13-18 days respectively upon cold exposure, which diminished at longer
lags but persisted for up to a month (Carder et al, 2005).

The cold effect found in Scotland is comparable to the findings in Great Britain.
The mortality risk was found to increase by 1.5% for each 1°C fall from the 10-
year average winter temperature in Great Britain in 1986-1996 (Aylin et al,
2001) and by 2% for every 1°C decrease below the 60th percentile of all-year
temperature distribution (i.e. 19.6°C) in England and Wales in 1993-2006 (Hajat
et al, 2014). The longer lag of cold-related mortality risk from respiratory
diseases compared with cardiovascular diseases was also found in Europe
including London (Keatinge et al, 1997; Analitis et al, 2008).

Regarding the heat effect, Gemmell et al (2000) found an increase in weekly
all-cause deaths by 1% with each 1°C increase in weekly mean temperature
higher than 14°C. For cause-specific mortality, Carder et al (2005) observed an
increase in all-cause, cardiovascular and respiratory mortality risks by 0.3%,
0.2% and 0.9% respectively for every 1°C increase above the daytime mean
temperature of 11°C on the same day of the heat exposure. The heat effect in
Scotland is comparable to that in North East and North West England but lower
than in London, where each degree increase in temperature above the 93rd
percentile of location-specific annual temperature distribution is associated with
0.8%, 1.3% and 3.8% increase in all-cause mortality respectively (Armstrong et
al, 2011).

The effect of high temperatures on mortality has a shorter lag than low
temperatures with most studies demonstrating a lag of 0-3 days for heat-related
mortality risk (Gosling et al, 2009b). At a lag of more than 1 day after the heat
exposure, Carder et al (2005) found a decrease in mortality risk under high
temperatures, apart from a weak increase in RESP mortality risk at lag 1-6.
This decrease in mortality risk at lagged heat exposure is likely due to mortality
displacement. This was also found in London where the mortality risk elevated for 2 days after heat exposure, followed by mortality deficits leading to no accumulated effect by day 11 (Hajat et al, 2005). Despite mortality displacement, the acute increase in mortality risk is important for public health since short-term additional health services may be required.

Apart from temperature-related mortality risk, four studies investigated the effect of temperatures on hospital admission in Scotland (Dawson et al, 2007; Brown et al, 2009; Aubiniere-Robb et al, 2013; Ramsay et al, 2018). All-cause emergency hospitalisation was found to increase at weekly temperatures lower than 10 °C, and hospital admission due to COPD and trauma was found to increase at temperatures above 10 °C (Ramsay et al, 2018). Low temperatures were found to be associated with deep venous thrombosis incidence in the following 3-12 days in Scotland (Brown et al, 2009). High temperatures were found to be associated with an increase in hospital admissions for ischaemic stroke in Glasgow (Dawson et al, 2008). In addition, Lawlor et al (2005) investigated the effect of ambient temperature on the birthweight of newborn babies and found a differentiated effect of temperature at different stages of pregnancy. A 1°C increase in mean ambient outdoor temperature in the first trimester of pregnancy was associated with a 5.4 g decrease in birthweight, whereas a 1°C increase in the temperature in the third trimester was associated with a 1.3 g increase in birthweight (Lawlor et al, 2005).

This review identified three important research gaps:

1) No literature that assessed the difference in the temperature-related mortality risks across populations of different demographic and socioeconomic groups apart from age in Scotland.

2) No study explored the temporal trend or variation in temperature-related mortality risks in Scotland.

3) No study projected future health burdens associated with ambient temperatures considering climate change and adaptation in Scotland.
These are crucial research gaps that this thesis aims to fill. Such research is crucial for identifying the vulnerable people who would benefit most from targeted actions to reduce cold- and heat-related health impacts, which is studied in Chapter 4 of this thesis. In addition, historical changes in population vulnerability and adaptation as well as future health burdens under climate change can provide valuable evidence and support for making preventative plans, which is investigated in Chapter 5.
### Table 2-1. Summary of eight studies on temperature-related mortality in Scotland.

<table>
<thead>
<tr>
<th>Author (year) title</th>
<th>Place</th>
<th>Study period</th>
<th>Temporal unit</th>
<th>Temp metric</th>
<th>Health outcome</th>
<th>Population</th>
<th>Statistical analysis method</th>
<th>Main result on temperature-related mortality risk</th>
<th>Notes and comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gemmell et al (2000) Seasonal variation in mortality in Scotland</td>
<td>Abe, Edi &amp; Gla</td>
<td>1981-1993</td>
<td>weekly</td>
<td>Mean temp</td>
<td>Mortality (all-cause, CVD, IHD, RESP)</td>
<td>All</td>
<td>Time series Poisson regression of weekly temp and deaths with adjustment for long-term and seasonal trends, serial autocorrelation and influenza epidemics.</td>
<td>Increase in deaths by 1.06% and 0.8% associated with a 1°C decrease in weekly mean temp when it is below 2°C and 2-10°C respectively. Negligible change in deaths at 10-14°C. Increase in deaths by 1% associated with a 1°C increase in temp above 14°C.</td>
<td>There is 30% (around 350 deaths/week) excess mortality rates in summer compared to winter in 1981-1993, which decreased from 38% in 1981-1983 to 26% in 1991-1993. No significant variation in the result across cities.</td>
</tr>
<tr>
<td>Carder et al (2005) The lagged effect of cold temperature and wind chill on cardiorespiratory mortality in Scotland.</td>
<td>Abe, Edi &amp; Gla</td>
<td>1981-2001</td>
<td>Daily</td>
<td>Daytime mean temp, wind chill (temp, dew point and wind speed)</td>
<td>Mortality (all non-accidental, CVD, RESP and non-accidental other causes)</td>
<td>All, age 0-64 and 65+</td>
<td>Time series Poisson regression of daily temp and mortality with lag up to 30 days controlling long-term and seasonal trends, dow and smoke.</td>
<td>When temp is below 11°C, a 1°C decrease in daytime mean temp is associated with an accumulative increase in mortality by 2.9% (all-cause), 3.4% (cardiovascular), and 4.8% (respiratory) over a lag of 30 days. At temp above 11°C, an increase in the same day temperature of 1°C is associated with an increase in mortality by 1% and 1.3% over a lag of 30 days.</td>
<td>&quot;Wind chill&quot; temp was not found to be a better mortality prediction compared to (dry bulb) temp. No significant variation in the result across cities.</td>
</tr>
</tbody>
</table>
### Chapter 2

<table>
<thead>
<tr>
<th>Study</th>
<th>Location</th>
<th>Time Period</th>
<th>Exposure</th>
<th>Outcome</th>
<th>Methodology</th>
<th>Results</th>
<th>Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lawlor et al (2005)</td>
<td>Aberdeen</td>
<td>1950-1956</td>
<td>10-day mean temp</td>
<td>Birthweight</td>
<td>Linear regression of mean temperature in the middle 10-day period of each trimester of pregnancy and birthweight</td>
<td>1°C increase in mean ambient outdoor temperature in the first trimester was associated with a 5.4 g (95% CI 2.9, 7.9 g) decrease in birthweight, whereas a 1°C increase in the third trimester was associated with a 1.3 g (95% CI 0.50, 2.1 g) increase in birthweight.</td>
<td>The effect of temperature was found to differ by pregnancy stage in this study, with a larger effect of the temperature during the first trimester than other trimesters. The effect of temperature on birthweight is consistent in different seasons.</td>
</tr>
</tbody>
</table>
| Dawson et al (2007) | Glasgow | 1990-2005 | Daily max, min and mean temp, daily change in mean temp over preceding 24h | Stroke hospitalisations | Negative binomial regression of daily met variables and stroke hospitalisations while controlling for long-term and seasonal trends and doy. Poisson regression was used for rare stroke events, where the negative binomial regression was preferred. | Only change in mean temp over the preceding 24h was found to be associated with stroke admission significantly (P<0.05) among all temp metrics, with a 2.1% increase in IS stroke admissions for every 1°C increase in mean temp during the preceding 24h. | The association between other met variables and stroke admission was also analysed, including sea level pressure, boundary layer depth (reflecting air quality), and pressure change over the preceding 24h and 48h. Among these met variables, only a
| Brown et al (2009) The influence of meteorologic al variables on the development of deep venous thrombosis | Sco | 1981-2001 | Daily | Max and min temp | Deep venous thrombosis (DVT) hospital admission | All | To assess the short-term effects of weather, daily meteorological statistics (including max and min temp, atmospheric pressure, snow and sunshine) and numbers of DVTs were analysed using Poisson regression models, adjusted for trend and seasonality. | This study found an increase in DVT incidence between 3 and 12 days after the exposure to low temperatures, with the largest increase of 0.67% per 1°C decrease in daily minimum temp at lag 7, although did not reach statistical significance. | Meteorological variables that have been found to be significantly associated with the short-term increase in the incidence of DVT are snow on the same day, and low atmospheric pressure, high wind speed, and high rainfall around 10 days earlier. Meteorological variables are inter-related, and hence their results on DVT incidence should not be considered additive. The association between meteorological |
variables and DVT may be non-linear, which is not investigated in this study.

This study compared the mortality rate between those whose BP were sensitive and non-sensitive to temp change. It does not model the effect of temp on mortality directly.

There is an increase in mortality and morbidity when the weekly temperature is lower than 10°C. An increase in weekly temperatures of above 10°C is associated with increased all-cause mortality in those aged 75-84 and COPD and ARI consultation explains a larger proportion of the health outcomes than temperature.


<table>
<thead>
<tr>
<th>Study</th>
<th>Time Period</th>
<th>Measurement</th>
<th>Outcome</th>
<th>Methodology</th>
<th>Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimitriadou et al (2022)</td>
<td>1982-2018</td>
<td>Daily Mean Temp</td>
<td>Mortality (CVD, RESP)</td>
<td>All</td>
<td>Threshold regression of daily temp and mortality resulting in two threshold temperatures (lower and upper), which are the temperatures below (or above) which the coefficient of mortality changes. For CVD and RESP mortality combined, the lower/higher thresholds are 10.17/14.39°C, 1.67/15.20°C, 0.53/11.29°C and 0.82/13.80°C in Abe, Dun, Edi &amp; Gla respectively.</td>
</tr>
<tr>
<td>Abe, Dun, Edi &amp; Gla</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Confounders such as long-term trends and seasonality are not controlled.</td>
</tr>
</tbody>
</table>
Chapter 3. Heat-health governance in a cool nation: a case study of Scotland

3.1. Introduction
A recording-breaking heatwave occurred across Europe in summer 2022, which extended north to Scotland with a record-high maximum temperature of 35°C (Kendon, 2022). Scotland has a cool climate with an annual average temperature of 7°C between 1961-1990 (Chapter 2.3.1). Whilst being historically cool, there is an increasing heat risk in Scotland under climate change (Undorf et al, 2020).

Considerable evidence shows that high temperatures are associated with adverse health effects, including increased hospitalisation and mortality (Arbuthnott & Hajat, 2017). For example, the record-breaking warm summer in the UK in 2022 resulted in over 3000 excess deaths in England and Wales (Office for National Statistics, 2022a). Another exceptional heatwave occurred in Europe in the summer of 2003, which led to around 70,000 excess deaths (Robine et al, 2007; García-Herrera et al, 2010). A global review study of 11 papers with a total of 64 locations in six continents found that mortality generally increased by 1%-3% with each degree increase in high temperatures (Hajat & Kosatky, 2010).

Without effective intervention and adaptation, the risk of adverse health effects due to heat could increase substantially through the combined effects of global warming, population ageing and urbanisation (WHO Europe, 2021). Heat-health warning systems (HHWS) with forecasts on high temperatures are useful to alert policy-makers, stakeholders and the public and take preventative actions to avoid adverse health impacts, with the first operational HHWS in Europe established in Lisbon, Portugal in 1999 (Leite et al, 2020). The World Health Organization Regional Office for Europe (WHO Europe, 2008; 2021) published
Chapter 3

guidance on Heat-Health Action Plans (HHAPs) aiming to support countries and regions in designing, improving and implementing heat-health strategies to prevent adverse heat-health impacts. By 2019, around 20 European countries have implemented national, regional or local HHAPs and/or heat-health warning systems (European Climate and Health Observatory, n.d.).

Although heat-health impacts have been mostly regarded as a risk in hot areas, it may also be a risk, often an invisible one, in areas that have a historically cool or temperate climate, which may be exacerbated under climate change (Brimicombe et al, 2021). Research has found an increase in mortality under high temperatures in cold places such as Scotland (Wan et al, 2022a), Sweden (Baccini et al, 2008; Rocklov et al, 2011; Gasparrini et al, 2015), Estonia (Oudin Åström et al, 2016), Finland (Donaldson et al, 2003; Baccini et al, 2008) and Russia (Revich & Shaposhnikov, 2008). For example, it is estimated that there were 601-750 excess deaths during the exceptionally hot summer in Sweden in 2018 (Astrom et al, 2019).

The threshold temperature above which mortality risk begins to rise has been found to be generally higher in warmer areas, indicating population adaptation (Hajat & Kosatky, 2010; Guo et al, 2014). Therefore, people in cold areas may be more vulnerable and less able to adapt to high temperatures compared to those living in warm areas. This may be due to various factors such as physiological acclimatisation, preventative and protective behaviours, heat-health governance and cooling strategies in housing and planning (Ekamper et al, 2009; Christidis et al, 2010).

With a high focus on cold risks, there is a need to explore the particular need for heat-health strategies in cold countries. For example, while those living in cold and temperate climates may be more vulnerable to extreme heat events, experience in governing and managing cold-health risks may offer transferable knowledge, beneficial to managing heat-health risks. Equally, however, embedded practices focused on cold-weather events may pose barriers to the development of effective heat-health strategies.
This research explores heat-health adaptation and governance using Scotland as a case study. Scotland is an optimal case study to investigate heat-health governance in a historically cool place, which has been introduced in Chapter 2.3.

To do this, the research focuses on two key questions: i) what are the key considerations in preventing and managing heat-health risks by policy-makers and stakeholders in the health, climate change, environment, and planning sectors; and ii) what are the associated challenges and opportunities.

3.2. Methods

A stakeholder mapping was conducted to identify organisations and individuals who have the potential to influence, either directly or indirectly, policy decisions and the delivery of HHAPs (Chevalier & Buckles, 2019). A snowball approach was adopted in the stakeholder mapping with additional stakeholders recommended by identified stakeholders. The mapping initially focused on Scottish stakeholders, with stakeholders in England added for their close relevancy to this research as suggested by identified stakeholders. For instance, this included stakeholders who had a work or research background in Scotland, or who had collaborations with the Scottish stakeholders. The list of identified stakeholders is included in Supplementary S3 in (the interviewees are excluded for confidentiality).

This research has undergone research ethics assessment, which was reviewed and approved by the School of GeoSciences, University of Edinburgh. An information sheet was provided to each interviewee giving the study information, their rights and data protection measures. Oral consent was obtained prior to the interviews.

A total of fifty-nine interview invitations were sent out to identified stakeholders in Scotland and England between October 2020 and February 2021. Among the fifty-nine invited stakeholders, nineteen refused the interview and reported a lack of focus or expertise in this topic. Nine stated no capacity, and sixteen did not reply. In the end, fifteen semi-structured interviews were conducted with stakeholders in the health, climate change, environment, and planning sectors.
in Scotland and England. Two additional written responses were also obtained. The low response rate and high rate of reported lacking expertise among the invited stakeholders partly reflect the situation of a gap in heat-health research and governance in Scotland.

The interviews focused on five themes: 1) socio-cultural barriers to intervention; 2) vulnerable population and communication; 3) heat-health strategy at different temporal and geographical levels; 4) key sectors and leading and collaborative agencies; and 5) governance approach. The first theme was selected to investigate the particular social and policy context in Scotland contributing to its status of heat-health governance. The following themes were informed by the core elements of a comprehensive HHAP identified by the WHO Europe (2008). The semi-structured questions and the corresponding themes are as below. Because of the nature of semi-structured interviews and the overlapping of the themes, answers to one question may be mapped to multiple themes. The interviewers were given the information that the context of the interview is Scotland. The questions were primarily designed for the context of Scotland. When interviewing individuals located in England, their experience and perspectives in the Scottish context were specifically asked.

1) Why is there currently no heat wave plan in Scotland? (Theme 1)
2) Do you think there is a need for a targeted heat wave plan in Scotland? Or do you think it could be incorporated into other plans? (Theme 5)
3) How important do you think the Heatwave Plan and the Heat-Health Watch Service are in minimising the health impacts of high temperatures? (Theme 5)
4) How do you see the importance of long-term plan and preparation versus reactive action upon alerts? (Theme 3)
5) Who do you think should take the main responsibility for minimising the health impacts of extreme temperatures in Scotland? (Theme 4)
6) What responsibilities do you think the national-level government and organisations should take, and city-level government and organisations should take? (Theme 3)
7) How do you think people from different sectors will collaborate in developing and providing related policies and services? What challenges may there be? (Theme 4)

8) How do you expect scientists and policy-makers to interact with each other? (Theme 4)

9) How do you see the balance at the moment in terms of heat-related and cold-related health impacts in Scotland? (Theme 1)

10) What factors do you think will affect temperature-related health risks of a certain population or place? (Theme 3,4,5)

11) What indicators do you think may be useful in indicating the vulnerability to the impacts of extreme temperature? What considerations you may have in using composite indices versus single indicators, and commonly used deprivation indices versus dedicated heat social vulnerability indices? (Theme 2)

12) How much difference in the heat-related health impacts do you think there will be with and without future adaptation policy? For example, comparing the difference in the impacts under scenarios—one with a targeted heat-health plan and services developed in the near future in Scotland and another scenario without such policy or services. (Theme 2,3,5)

13) What other information do you think is needed to minimise temperature-related health impacts under climate change? What other challenges do you think there may be? (Theme 1,2,3,4,5)

The interviews were audio-recorded upon oral consent from the interviewees and then transcribed for analysis. The interview transcriptions were analysed by thematic analysis (Gray, 2014). The transcriptions were read by one researcher to find themes with patterns and common topics. The questions and themes are not one-to-one corresponded with the answers to one question may be mapped to multiple themes. This was because a) the themes are not mutually exclusive; b) interview questions were informed by the literature and asked to interviewees based on their background from the stakeholder analysis, to ensure they were relevant; and c) interviewees were afforded sufficient time to provide their
opinions on topics in which they possessed greater knowledge and experience. This approach is beneficial in gaining in-depth information, but has the drawback of potentially straying from the original question and limiting time for other questions. Nevertheless, this approach was adopted because it yielded detailed and useful additional information.

The interviewees were anonymised with abbreviations of their agency or main expertise. Please see the abbreviation and a brief description of their background and expertise in Table 3-1. Each transcription document was line-numbered. Quotes were indexed with the abbreviation of the interviewee who expressed them, followed by a dash and the starting line number of the quote, placed in square brackets, e.g. [PHE-376]. Sometimes, one or multiple quote indices are given for an argument instead of presenting individual original quotes. It should be noted that the number of quote indices provided should not be extracted to calculate the proportion of the interviewees who support or oppose an argument from the total interviewees or the strength of the argument because not all interviewees were asked the same questions.

Table 3-1. List of interviewee abbreviations with descriptions of their position, the type of organisation they are working in and their current location (Scotland or England).

<table>
<thead>
<tr>
<th>Interviewee</th>
<th>Description</th>
<th>Organisation</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCAR</td>
<td>Climate change adaptation researcher with expertise in adaptation practice and policy</td>
<td>Academic</td>
<td>Scotland</td>
</tr>
<tr>
<td>CCHE</td>
<td>Climate change and health epidemiologist and a lead scientist for the UK Climate Change Risk Assessment</td>
<td>Academic</td>
<td>England</td>
</tr>
<tr>
<td>CCPM</td>
<td>Climate change programme manager leading projects on behalf of the Scottish Government and local authorities</td>
<td>Third sector</td>
<td>Scotland</td>
</tr>
<tr>
<td>Code</td>
<td>Name</td>
<td>Role</td>
<td>Sector</td>
</tr>
<tr>
<td>-------</td>
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<td>----------------------------------------------------------------------</td>
<td>-------------</td>
</tr>
<tr>
<td>CCRA</td>
<td>Climate change risk and adaptation</td>
<td>researcher with expertise in disaster risk reduction and risk assessment methods and tools</td>
<td>Academic and third sector</td>
</tr>
<tr>
<td>EHO</td>
<td>Environment and health official with work experience in both health service and environmental agency</td>
<td>Public sector</td>
<td>Scotland</td>
</tr>
<tr>
<td>EHR1</td>
<td>Environment and health researcher with a focus on the health effects of climate change</td>
<td>Public sector</td>
<td>England</td>
</tr>
<tr>
<td>EHR2</td>
<td>Environment and health researcher with experience in working in the public health sector in Scotland</td>
<td>Public sector</td>
<td>England</td>
</tr>
<tr>
<td>ESS</td>
<td>Environmental social scientist focusing the relationship among people and the natural and built environments, especially adaptation to climate change</td>
<td>Academic</td>
<td>Scotland</td>
</tr>
<tr>
<td>HG</td>
<td>Human geographer on urban environment, human-environment interactions and vulnerability mapping</td>
<td>Academic</td>
<td>Scotland</td>
</tr>
<tr>
<td>NHSF</td>
<td>Manager at the Facilities Directorate of an NHS board providing support services to buildings with a focus on housing and health</td>
<td>Public sector</td>
<td>Scotland</td>
</tr>
<tr>
<td>PHS</td>
<td>Honorary professor of public health and previous director of the public health department of an NHS board.</td>
<td>Public sector</td>
<td>Scotland</td>
</tr>
</tbody>
</table>
There are some limitations of this research. The interviews were conducted in winter 2020/2021 when the COVID19 pandemic was the major social, policy and medical focus. We only received one written response from a medical general practitioner, and we did not interview health and social care practitioners who have close contact with patients and the vulnerable population. However, we did interview professionals from Public Health Scotland, Public Health England, NHS health board, and environmental epidemiologists. In addition, the interviews were conducted in winter, and the temperatures at which the interviews were conducted may affect the perception of the interviewees. For example, the result of the perceived heat-health risk might be slightly different if the interviews were undertaken during a heatwave. Nevertheless, valuable insights could still be obtained from the results and the opportunities and challenges in heat-health governance.

3.3. Results
In this section, the interviewees’ viewpoints and responses are organised and presented in the five themes introduced above.

3.3.1. Socio-cultural context to intervention
Interviewees indicated that the heat-health risks had been perceived to be low and remain low in Scotland at least in the near future because of the cool
climate and rare frequency of heatwaves [CCPM-28, ESS-71, PHS-49, PHE-309, SCB-188, EHO-76]. This can be reflected by the culture that Scottish people do not usually take hot summers seriously, as an interviewee indicated “There’s a kind of psychology that if it’s a warm and sunny day, you have to be outside. If you are not outside in the sunlight, you are wasting all of the sunny days. [ESS-91]”

There was also a perception that increased temperatures may bring about some benefits to Scotland because of the potential for a reduction in cold-related deaths [ESS-73] and increased outdoor activity and time in green space [SG-32].

There was also a lack of evidence on the heat-health in Scotland. An interviewee indicated that the heat-health risk was not flagged as a particularly high risk at the 2nd Climate Change Risk Assessment [CCPM-32], although the urgency level had been elevated in the 3rd CCRA. There was anecdotal evidence of the impact of heat in Scotland, such as the melting of the roof of the Glasgow Science Centre, but in general, there was a lack of scientific evidence that heat is a risk to health in Scotland [CCHE-86, CCPM-32, ESS-110].

Preventing heat-health risks under climate change was less of a priority that the government focused on, compared to cold and other meteorological hazards such as flooding [NHS-24, SP-230]. In addition, managing the increasing heat-health risks under climate change was one part of climate change adaptation, which had, however, been overlooked generally compared to mitigation [SP-248, SCB-232, CCPM-58]. For example, a spatial planner shared that “we’re very much about to let’s go and prevent the problem from happening in the first place [SP-248].”

A climate change and health scientist indicated that compared to other policy areas, public health was responsive and quick. They added “When you decide you need a heatwave plan, you can move things very quickly. So public health is extremely effective. If Scotland wanted to do a heatwave plan, they could set one up in 12 months. [CCHE-97]” Many other European countries developed their heatwave plans in response to the 2003 heatwave.
Therefore, a lack of historical heat exposure, risk and the evidence around it led to a low policy priority and hence a lack of HHAP in Scotland.

3.3.2. Vulnerable population groups
As discussed in Section 1, some people may be more susceptible to adverse effects from high temperatures making them more vulnerable to heat-related health risks. An official at the PHE (now UKHSA) expressed that there are different types of vulnerabilities, including physiological vulnerability affected by age and underlying comorbidities, contextual vulnerabilities due to place and space such as urban and rural, floor level and building elevation, social vulnerabilities such as from social isolation, and economic vulnerabilities such as poverty and deprivation [PHE-90].

A spatial planner suggested that the definition and selection of vulnerability indicators or indices should depend on the objectives of actions [SP-154]. When communicating the key health risks, the PHE generally pulled out individual factors that increase vulnerability [PHE-101]. This could inform individual sectors and the public in targeting those who may be more vulnerable and hence provide targeted services.

Some stakeholders expressed that poverty is a significant factor underlying vulnerability regardless of the type of risk, and hence should be a primary focus of intervention [NHSF-262, EHO-294]. An environmental health official stated, "from what I understand, I think that if you looked at the determinants of ill-health and health vulnerability, we knew enough about how they relate to poverty...Can we address the causes of poverty? Which, in turn, will reduce the vulnerability through these things. [EHO-294]"

In terms of planning, the spatial planner suggested that all these vulnerabilities should be assessed together for a composite picture because “everything within a place is such an interrelated set of equations [SP-156]”. They expressed that it was unlikely to have an impact focusing on one aspect in isolation. This also links to the preference for a holistic approach to be discussed in Section 4.5.
When attempting to identify and monitor the vulnerable population, a climate change risk and adaptation scientist explained that there was a tension between developing a customised heat-health vulnerability index and maintaining efficiency by using a more general index or dataset that is easier to manage and maintain over time [CCRA-271]. They added that the decision was largely based on practicability – “it was always a trade-off between what we needed to deliver and getting the most available data. It wasn't always the best quality data. It was kind of what we even have [CCRA-271].”

The method on effective information dissemination and service provision to the vulnerable groups requires careful design. The interviewees recommended that it is crucial that those who are in close contact with the vulnerable population, such as nurses and professionals at care homes and hospitals are engaged in the plan, receive early warnings, are able to interpret the alerts and deliver services to reduce the heat-health risk of the vulnerable populations [HG-363, EHR2-254]. Local knowledge and connection were also suggested to be valuable. For example, an interviewee shared that they discovered that the person who held the most trust among the local population was a priest rather than the government or scientists during a flood risk research in Aberdeenshire [ESS-383]. Therefore, it is both a challenge and an opportunity to identify and provide targeted information and services to vulnerable populations.

3.3.3. Temporal and geographical levels
Strategies to prevent and reduce heat-health risks are needed to be more prepared for the increasing temperatures under climate change, at least some point in the future, agreed by many interviewees [HG-300, CCHE-93, EHO-95]. Scottish people may be more vulnerable to heat because buildings, public transport, and people’s behaviours are not adapted to heat. For example, an environmental social scientist said, “If you look at the tropics, places like Taiwan and the south of Japan … coping with heat is not new. People have got strategies for not going out in the middle of the day. And in Japan, they sprinkle water on the pavements and people use strategic greenery and things like that.
We don’t have that at all in Scotland... our buildings and public transport are not designed for hot weather. [ESS-164]"

It is important to have a long-term plan in addition to only relying on short-term responses to alerts [EHR2-144, PHE-376]. A climate change and health epidemiologist indicated, “If you just focus on weather-based alerts, you’re missing 1/3 of the picture [CCHE-37].” Long-term awareness raising is also needed because “you have a few years without heatwaves, it doesn't mean it's not coming at its some later time [EHR1-396]”. Therefore, other long-term planning and strategies such as behaviour change, modification of the built environment and building regulations are crucial to mitigate heat risks [CCHE-36].

Only having a national plan is insufficient in protecting the public from heat impacts, the implementation and delivery of preventative information and actions on regional and local levels, particularly to the vulnerable population is vital for the plan to be effective. Plans and actions on national, city and community levels are all required [NHS-177]. When introducing a new national plan, the National Planning Framework is carefully referred to [IS-293]. On the regional level, Joint Boards between the health service and local authorities are formed, the main focus of which is on health and social care, but it can stray into housing and neighbourhood planning [NHSF-199]. It is the responsibility of local authority officials to translate and establish national and regional plans into something useful and practical for the city or local scale [CCRA-66].

Empowering communities instead of just imposing the plans on them is crucial to making effective plans [SCB-121]. As an interviewee indicated, “If something just comes from the SG, and people think it's alien, then they will fight against it [PHS-177].” Community and neighbourhood support is also crucial in promoting the health of local people. An interviewee gave an example by relating to the situation during the lockdown due to the COVID19 pandemic, “the local authority and the NHS were just so pushed or not able to actually check that people were OK, so people just got on and took care of themselves [SCB-408]”. For example, local communities and neighbourhoods took action to help each
other such as checking on the elderly and delivering groceries. A similar situation may happen during prolonged heatwaves and hence it is important to make use of community knowledge and empower local communities [SCB-408].

3.3.4. Key sectors, leading agencies and collaborations

Designing and delivering a heat-health strategy involves a wide range of organisations and professionals in different sectors, e.g. meteorological and climate services, health and social care, and the built and natural environment [CCPM-183]. Therefore, collaboration and joint working across the sectors are essential in taking integrated preparedness and response actions to heatwaves.

The Met Office provides weather forecasts and the health service sector was perceived by multiple stakeholders to be the leading agency in heat-health strategy [EHO-143, EHR2-251, CCPM-181]. As a climate change project manager expressed, “it should be Public Health Scotland that takes a lead on it. I think that would be the equivalent body has taken the lead in England, so it seems a natural fit [CCPM-181]”. Perceived key roles of the health service sector include determining the trigger points of a heat-health alert, translating weather forecasts and alerts into health risks and targeting specific vulnerable populations and regions [EHO-159, CCPM-170].

Scottish Environmental Protection Agency (SEPA) is Scotland’s national flood forecasting, warning and strategic risk management authority. Therefore, a stakeholder expressed that SEPA could contribute to a heat-health strategy with the existing framework, collaboration and experience in flood risk management [EHO-142]. Environmental consultancies such as Sniffer could play an advisory role in the development of the plan and promote partnerships among different sectors [CCPM-199].

Due to a lack of regulation on preventing indoor overheating, some of the newly built buildings such as hospitals and schools face indoor overheating conditions and are unfit for extreme temperatures in the future [EHR1-259]. In addition to indoor overheating, an interviewee indicated concerns that highly insulated and airtight buildings may lack air circulation and fresh air exchange from the
outside, leading to the building up of dampness and mould and negative health impacts [EHR1-243]. In order to avoid indoor overheating and imbed the cooling needs of buildings, an update of the building regulation was needed [EHR1-264].

Land use and the built and natural environments are also crucial sectors, with green and blue spaces providing natural shading and cooling during high temperatures and multiple co-benefits such as promoting physical and mental health, increasing runoff absorption and mitigating flooding [SCB-116]. Green space should be carefully designed so that people feel safe there, have a sense of ownership and are willing to spend time and make use of it [SP-202, ESS-289].

3.3.5. Governance approach

A preference for taking the climate change risks and resilience of a place or organisation holistically was expressed by many interviewees [SP-71, CBM-207, CCPM-8, CCRA-439, SCB-207]. A heat-health strategy can be integrated into existing policy priorities and plans, such as fuel poverty and health inequality [SG-4, CCRA-185, ESS-189, SP-192&303]. Some interviewees recommended looking at a community or a place in its full sense and considering what its challenges and opportunities are, including physical (e.g. overheating, abandoned buildings and traffic) and social aspects (e.g. drug problems and social cohesion) [CCPM-84, SG-17].

One advantage of this approach is increasing awareness of heat-health risks using the traction of existing focus and priorities. A climate change resilience researcher gave an example, “If you combine the two [heat and cold plans], then you’re also preparing people for heat, even if they’re more interested in the cold [CCRA-189].” Another crucial importance of taking a holistic view is to minimise the risk of maladaptation, e.g. by considering both keeping homes warm through insulation as well as avoiding indoor overheating and air pollution [PHE-266].

When designing, delivering and evaluating plans and services, in addition to quantitative data and statistics, it is also crucial that people’s lived experience is
taken into account, especially those who are already disadvantaged—“How are they being affected by overheating risk and how is that being really fed into evidence base? [CCPM-216]”, suggested by a climate change programme manager. An environmental social scientist also emphasised the value of qualitative evidence, e.g. people's narratives and stories, but the government and the public health departments preferred “medical, quantitative, usually economic data because they need to justify the decisions that they're making [ESS-413]”.

A spatial planner confirmed that the planning performance framework, the assessment and evaluation in planning done by Scottish councils, is mostly quantitative, e.g. “how many planning applications have you processed? How up-to-date is your local development plan? [SP-121]” They said that “the qualitative aspect about what is the quality of the place you’re shaping and what impact is it having on health is not being asked at the moment [SP-126]” because it is difficult to present and compare as quantitative information. However, they expressed that there is a desire to include more qualitative measures in the planning performance assessments to ensure the decisions are the best for the health and wellbeing of the communities.

3.4. Discussion and conclusions

The interview results provide insights into the challenges and opportunities of heat-health governance in a nation with a cool or temperate climate, which will be the focus of the discussion in this section. The challenges and opportunities are not static; instead, they can be transformed into each other, which will be discussed in more detail below.

The results of Theme 1 found that due to being historically relatively cool in Scotland, there has been a favour of warm sunny days and a lack of perceived heat-health risks. Similar findings of feeling positive about warm or even hot weather were also found in England, although it was generally agreed that temperatures above 26°C were “too hot” among the study participants of Williams et al (2019). This may bring challenges in managing heat-health risks and taking planned preventive measures as people also do not usually perceive
themselves as being vulnerable or at risk of heat effects (Wolf et al, 2010a; Williams et al, 2019). For example, the elderly have been identified as being vulnerable to heat-health risks, however, previous studies found the elderly in the UK tend not to consider themselves either old or at risk of heat effects (Abrahamson et al, 2008; Wolf et al, 2010b; Ratwatte et al, 2022).

This links to Theme 2 of this study on engaging the vulnerable population. The phenomenon that people tend to perceive themselves as not being affected by heat links to the Third Person Effect in media studies. It describes the situation where an individual perceives themselves as less influenced by persuasive information than others (Davison, 1983). Therefore, one strategy to communicate heat warnings and preventative actions can be framing the advice as helping their vulnerable relatives and neighbours (Roberts, 2022). This is in line with previous research results that social support from peers, e.g. friends and community members is a valuable mechanism for facilitating the elderly during heatwaves (Sampson et al, 2013).

However, the effect of social networks on reducing the vulnerability to heatwaves of the elderly is also complex and affected by their social contacts’ perception of heat risks, knowledge on coping and preventive measures as well as perceptions of personal independence and resilience (Wolf et al, 2010b). This highlights the importance of a whole system approach involving the government, health and social care sector and communities at multiple geographical levels, as presented in Theme 3.

The results in Theme 4 show that there are concerns about indoor overheating, especially in new buildings in Scotland. The buildings in Scotland have been primarily designed to reduce heat loss by enhancing airtightness and increasing insulation, which may increase the risk of insufficient ventilation and overheating (Gupta & Kapsali, 2016; Tink et al, 2018). A study found that overheating occurred in 20 out of 26 newly built low-energy homes monitored in Scotland, some of which experienced overheating in all seasons (Morgan et al, 2015). The health risk of overheating has widely been found to be higher for flats in high-rise residential buildings due to reduced conductive heat loss and
ventilation opening, lack of shading, additional solar gain for top-floor flats and limited garden access to escape from indoor heat (Lomas & Kane, 2013; Baborska-Narożny et al, 2017).

Building designs are crucial for preventing overheating. The effect of insulation on overheating is mixed, which is by other factors such as insulation type, room orientation and occupant behaviour (Porritt et al, 2012). External wall insulation and roof insulation can mitigate overheating by reducing solar gain (Mavrogianni et al, 2017). On the contrary, internal insulation may contribute to overheating by prohibiting heat dissipation when the external temperature is lower than the internal, or trapping the heat generated internally (Fosas et al, 2018). Nevertheless, studies have demonstrated that this can be mitigated through closing blinds during the day and opening windows at night and therefore improved energy efficiency and thermal comfort can be achieved in both winter and summer with proper building design, operation and occupant behaviour (Crump et al, 2009; Tink et al, 2018).

In addition to building design, the practicality of mitigation measures and occupant behaviours are crucial in influencing external and internal heat gain as well as ventilation (Jenkins et al, 2009; Baborska-Narożny et al, 2017). Occupants may be reluctant to open windows due to concerns about security, noise or air pollution (Crump et al, 2009; Morgan et al, 2015). Various factors can affect the effectiveness of mechanical ventilation and cooling, such as occupants’ insufficient understanding of the system, worry about energy expenses and noise, particularly using a boost mode at night during heatwaves (Dengel & Swainson, 2012; Gupta & Kapsali, 2016). These practical issues should be considered in building design (Scottish Government, 2023). For example, secure noise-attenuating vents could be considered when security and noise are concerns (Tink et al, 2018).

Overheating in care settings, hospitals, communal establishments and schools is of particular concern because the occupants often have reduced mobility or control over adjustments to maintain thermal comfort, which also links to Theme 2. Mitigating overheating in these settings requires more than good building
design, but also a high level of awareness, knowledge, care, and management among those responsible for the well-being of occupants, including care providers, teachers, and managers (Gupta et al, 2017a; Sinclair, 2018; Ibbetson et al, 2021).

The use of air-conditioning induces extra costs and energy use, which is contradictory to climate change mitigation and may lead to the worsening of fuel poverty, whereas caused by the need for indoor cooling rather than heating (Peacock et al, 2010; Thomson et al, 2019). Currently, only around 1%-3% of homes in the UK have air conditioning (McLachlan et al, 2016). Therefore, passive measures for mitigating overheating should be prioritised, with active measures like air-conditioning only considered when passive measures are not sufficient, as suggested by the latest Scottish Building Standards (Scottish Government, 2023).

Compared to the predominant focus on keeping the indoor environment warm in cold weather, outdoor environments play a crucial role in modifying heat-health impacts (Theme 4). Greenspace is highly effective in providing shade from solar radiation and ambient cooling, which can extend beyond the area of the greenspace by modifying the local climate and hence alleviating the Urban Heat Island effect (Santamouris, 2015; Vaz Monteiro et al, 2016). One of the pieces of advice for staying safe in hot weather provided by Public Health England (2022) is to walk in the shade. There may be some concern about the increased cold stress and energy demand for heating due to the cooling effect of greenspace in winter (Mavrogianni et al, 2009). This trade-off depends on various factors such as the land cover type, the type, location and coverage of vegetation as well as global warming levels; whereas with careful design, the benefits of greenspace on reduced heat stress are likely to outweigh the effect on cold stress (Macintyre et al, 2021b; Rahman et al, 2022). There is also the need to highlight the value of greenspace to good health by promoting mental health and healthy behaviours (Mavrogianni et al, 2009; Murage et al, 2020). In addition to the quantity of greenspace, the quality such as tranquillity,
greenness and perceived safety is also influential in its health benefits (Baka & Mabon, 2020).

As presented in Theme 5, a holistic approach to an HHAP that targets and deals with key risk factors of a place together, such as weather- and environment-related hazards including cold, heat and flood and other social challenges such as fuel poverty and health inequality is generally preferred by the stakeholders. Integrating heat-health governance with other existing policies may create opportunities in increasing the focus on heat using the traction of the current public and policy focus (Theme 5), as well as making use of existing institutional frameworks and collaborations (Theme 4).

One opportunity for holistic governance is to extend the concept of fuel poverty to both cold and heat (Theme 5). As energy prices soar, communal warm spaces have been developed to keep people warm, particularly for those who cannot afford heating bills. For example, Bristol City Council is planning “welcoming places” which provide warmth as well as food, benefits advice and educational support (Roig, 2022). Similarly, public cool places are desirable too, as Public Health England (2022) suggested the public considers visiting cool public buildings such as places of worship, local libraries or supermarkets as a way to cool in hot weather.

Holistic governance of cold and heat risks is in line with the practice in Scotland where hot weather is dealt with as one of the adverse weathers by the Scottish Government Resilience Division, along with cold, snow and ice, storms and winds, and rain and flooding. It also resonates with the movement by the UK Health Security Agency to merge the current separate Cold Weather Plan and Heatwave Plan for England into a single Adverse Weather and Health Plan integrating guidance on cold and hot weather, drought and flooding (Oliver & Ford, 2022).

In conclusion, this study found that the cool climate in Scotland poses both challenges and opportunities in managing heat-health risks. Challenges include a lack of policy priority due to a perceived lack of heat-health risk and evidence,
the difficulties in reaching the vulnerable population and the potential conflict between keeping homes warm by improving insulation and indoor overheating.

Nonetheless, challenges can also be transformed into opportunities, as demonstrated by the preference of stakeholders for a holistic governance approach that combines heat-health governance with other policy priorities such as cold, fuel poverty, and health inequality. This approach enables heat-health actions to gain traction and make use of the existing institutional support. Additionally, common information dissemination and service provision methods can be utilised to mitigate both cold and heat risks.

There is an opportunity to enhance the thermal comfort of homes in relation to both cold and heat through effective building design and occupant behaviour, reflected in the latest Scottish Building Standards. Greenspace also plays a crucial role in mitigating heat risks, which requires careful design to promote its health benefits.

Indeed, and in a more conceptual sense, it is perhaps productive to move away from a hot-cold binary and instead think about ‘unstable temperature’ governance, which covers both hot and cold at the same time. As the climate continues warming, rather than focusing on the external, and thus uncontrollable factor (the temperature), it is also crucial to focus on adaptation and the underlying vulnerabilities which would offer a more tangible framework for structuring the governance of temperature-related health concerns in populations.
Chapter 4. Temperature-related mortality and associated vulnerabilities in Scotland, 1974-2018

4.1. Introduction

In line with the UK hosting the 26th United Nations Climate Change Conference of the Parties (COP26) in Glasgow, Scotland in 2021, there is growing recognition of the dangers heat stress poses to public health, even in higher latitude settings. Climate change is unmistakeably evident in Scotland, with average temperatures between 2011-2020 being 0.9°C warmer than the 1961-1990 average (Kendon et al, 2021). The mean temperature in Scotland is projected to continue rising with heatwaves projected to become more frequent (Murphy et al, 2019; Undorf et al, 2020), yet little is known about the impacts of high temperatures on human health in Scotland, especially for the vulnerable populations (see Chapter 2.3.4). Even though England has had a Heatwave Plan and Heat-Health Warning System in operation for almost 20 years now (Public Health England, 2018), there are still no such measures in the devolved countries of the UK, including Scotland (Chapter 2.3.3). This may be based on the assumption that heat is not a public health risk factor in Scotland, which has been explored in Chapter 3.

Previous research found spatial heterogeneity in cold and heat effects between populations resulting from regional acclimatisation and varying distributions of vulnerability factors such as socioeconomic status (Keatinge et al, 1997; Curriero et al, 2002; Howieson & Hogan, 2005; Hajat & Kosatky, 2010). Evidence on temperature-mortality relationships in one city or region is therefore not readily applicable to other settings and hence is ill-equipped to support policies and interventions in other places (Anderson & Bell, 2009). The
mortality rate in Scotland, especially in Glasgow, has been higher than in the rest of Britain and other western European countries since the 1950s with multiple contributory factors such as inequality, negative health behaviours, and lagged effects of high historical level of deprivation, overcrowding and poor economic, urban development and planning policies (Chapter 2.3.2). Therefore, Scotland may also be more vulnerable to ambient high and low temperatures compared to many countries despite its relatively moderate climate, and hence there is a need to characterise the temperature-health risk present in Scottish populations.

An effective heatwave plan or heat-health warning system needs to be able to identify and support the most vulnerable population groups during extreme weather, and so characterising risk based on demographic (e.g. age, gender), socioeconomic factors (e.g. deprivation) and other risk factors are essential (Stafoggia et al, 2006; Analitis et al, 2008; Baccini et al, 2008; Son et al, 2019). Among social factors, being unmarried and living alone have been found to increase the impact of extreme temperatures on mortality in some studies, but it was not clear whether this was independent of the effects of age (Naughton et al, 2002; Fouillet et al, 2006). The most vulnerable members of society may be at higher risk of extreme temperatures, which can be further exacerbated by future climate change and contribute to climate injustice (Oliver & Mossialos, 2004; Asaria et al, 2016).

In this chapter, the current gaps in knowledge of how low and high ambient temperatures affect mortality risk in Scotland and associated vulnerable subgroups are addressed using extended time series datasets based on daily mortality records for the past 45 years for Scotland, including the four largest cities (Aberdeen, Dundee, Edinburgh and Glasgow) and northern, western and eastern Scotland. This chapter aims to investigate the relationship between ambient daily temperature and mortality risk and assess the variation of cold/heat-related mortality risk by demographic and socio-economic features including age-group, sex, marital status, area-level deprivation and cause of death.
4.2. Methods

4.2.1. Data

Daily mortality counts in Scotland between 1974-2018 were obtained from the National Records of Scotland. The daily mortality counts were aggregated into the four Scottish cities (i.e. Aberdeen, Dundee, Edinburgh and Glasgow) and three regions (East, West and North excluding the four cities). The location of the cities and regions are shown in Figure 4-1, and the local authorities included in each region are listed in Supplementary S4. The three regions were identified in accordance with the regions for which climate summaries are provided by the UK Met Office (Met Office, 2016b; a; c).

![Figure 4-1. City and region of study locations: the four cities (as marked) and three regions (North—yellow, west—green and east—blue) in Scotland.](image)

Attributes of the mortality data refer to the features of the deceased, including age group (0-64, 65-74, 75-84, 85 and over), sex, marital status (married, unmarried), underlying cause of death and socio-economic deprivation. Those who were unmarried include never married, divorced and widowed, and so can include both younger and older populations. Previous studies found that...
mortality from multiple diseases increased under ambient cold and heat, particularly cardiovascular and respiratory diseases (Hajat et al, 2007; Arbuthnott & Hajat, 2017; Arbuthnott et al, 2018). Therefore, as well as all-cause mortality, separate assessments of these two main causes of death are also made. Supplementary S5 lists the International Classification of Diseases (ICD) codes for underlying causes of death in different time periods.

Socioeconomic deprivation is represented by the Carstairs Index, which is originally constructed using Scottish Census outputs in 1981 on postcode sectors as a measure of material deprivation and has been widely used to study health inequality in Scotland (Levin & Leyland, 2006; Carder et al, 2010; Brown et al, 2014). Although the Scottish Index of Multiple Deprivation, developed by the Scottish Government, is a more up-to-date deprivation index, it is only available since 2004 and so cannot cover the whole study period (National Statistics, 2020). The original Carstairs Index is composed of four indicators: overcrowding, unemployment among men, low social class and not having a car (Carstairs & Morris, 1989). In this study, the Carstairs Index was modified by replacing the male unemployment component with total unemployment to reflect the increase in female participation in the labour market (e.g. the employment rate of Scottish females increased by 10% between 1992 and 2018) (Office for National Statistics, 2022c). This is expected to have little effect on the Carstairs score because a pre-analysis showed high correlations between the percentage of male and total unemployment (0.96, 0.95, 0.92 and 0.91 in 1981, 1991, 2001 and 2011 respectively) (Supplementary S6.2). However, the decreasing correlation also indicates that male unemployment becomes less representative of the total unemployment situation in society over time.

To calculate the modified Carstairs scores, the neighbourhood-level data for each component were extracted from the Scottish census outputs in 1981 (on enumeration area level), 1991, 2001 and 2011 (on census output area level). The census variables used for the calculation of the modified Carstairs Index are listed in Supplementary S6.1. The modified Carstairs score for each small
area was an unweighted combination of the four components that were standardised to have a mean of zero and a variance of one. The spatial distribution of the deprivation quintiles is shown in Supplementary S6.3. Population-weighted quintiles of modified Carstairs scores were derived and linked to daily mortality counts in the same small area for stratified analysis by deprivation level.

Daily maximum and minimum ambient temperatures were obtained from HadUK-Grid Gridded Climate Observation (v1.0.0.0) (Hollis et al, 2019) on a 1km-by-1km grid and downloaded from the Centre for Environmental Data Analysis (Hollis et al, 2018). The data in each of the four cities and three regions were cropped with the digital boundaries of the local authorities obtained from EDINA Digimap Service (the data in the four cities were excluded from the three regions) and area-level mean daily maximum and minimum temperatures were calculated. The daily mean temperature of each locality was taken as the average of the area-level mean daily maximum and minimum temperature.

Other meteorological variables and air pollution may confound the relationship between temperature and mortality (Chapter 2.2.1.2). Due to data limitations, only data on relative humidity, particulate matter with an aerodynamic diameter smaller than 10 µm (PM$_{10}$), and ozone for Edinburgh during 2004-2018 were available for sensitivity analysis. The relative humidity data were monitored at Edinburgh Royal Botanical Garden and downloaded from MIDAS Open: UK hourly weather observation data. The air pollution data were monitored at Edinburgh St Leonards and downloaded from the Scottish Environmental Protection Agency.

Missing data of less than 20 consecutive days were imputed using a combination of seasonal decomposition and linear interpolation. Missing data with larger gaps were imputed with the mean relative humidity value at the Edinburgh Royal Botanical Garden and the mean PM$_{10}$ and ozone concentration at Edinburgh St Leonards during 2004-2018 without the missing data. This was conducted using R package ImputeTS.
4.2.2. Statistical analysis

Firstly, city- and region-specific time series quasi-Poisson regression analyses with distributed lag models were performed (Chapter 2.2.1.3). The outcome was daily mortality count and the predictor was daily mean temperature.

The effect of low and high temperatures on increased mortality risk (cold and heat effect thereafter) may last over a period of time (i.e. lagged effect), with a longer lag for the cold effect (e.g. 14-28 days) and a short lag for the heat effect (0-3 days) found by previous studies (Chapter 2.2.1.3). In this study, distributed lag models were used to take into account lagged effects (Gasparrini, 2014). The modelled result is the accumulated relative risk (RR) under the same day and lagged exposures on previous days. The analysis was done in R/RStudio using package dlnm (Gasparrini, 2011).

A maximum lag of 14 days and 1 day were considered for the cold and heat effects respectively in this study. The analysis of cold and heat effects was conducted separately by using data in October through to April next year (OtA for short) and June, July and August (JJA) respectively. The transitional months of May and September were excluded from the analysis for either cold or heat effects initially in this Chapter with the aim of reducing noise in the exposure. Because of the relatively cool climate in Scotland, a longer period within a year was used for the analysis of the cold effect. Some previous studies also separated the analysis by season or restricted the analysis of the heat effect to summer months and the cold effect to winter months (Barnett, 2007; Lee et al, 2018).

Previous studies found that when using a long lag (e.g. 4 weeks) for the heat effect, the all-cause mortality risk due to temperature increase is lower than using shorter lags in London. In addition, a simulation shows that when the lag of an exposure-response relationship is relatively short (e.g. 3 days), using a distributed lag structure of 7 days to model the relationship resulted in a larger root mean square error than using dummy variables for individual lag days over lag 0-3 (Gasparrini, 2016). Therefore, using separate models with appropriate
lag times allows for capturing the maximum cumulative effect within the lagged period as well as reducing imprecision due to the inclusion of longer lags.

In OtA, the relationship between the lag days and daily mortality is modelled using a natural cubic spline (NS) with two internal knots equally spaced on the log scale. In JJA, dummy variables at lag 0 and lag 1 were used to model the lag-response relationship.

The relationships between daily mean temperature and mortality in OtA/JJA were first explored using distributed lag non-linear models using a NS for temperature with internal knots at the 30th and 70th percentile of the daily mean temperature in OtA/JJA averaged for the four cities and three regions. Placing the knots at the same absolute temperature in all cities and regions allows for aggregating the relationships through meta-analysis easily. It is expected to have little effect on the result compared to using different knots in different cities/regions as the temperature difference across the cities and regions is generally small and the result is relatively robust to the placement of knots (see the sensitivity analysis in Section 2.3 and the result in Supplementary S7).

Long-term trends and medium-term variations over time may confound the relationship between daily temperature and mortality. For example, there is an overall long-term decrease in the number of deaths and mortality rate in Scotland since 1951, whereas the trend changed in 2012 with an increasing number of deaths and a stable mortality rate, particularly in the most deprived areas (Scottish Government, 2010; NRS, 2019). This is likely affected by various factors, with austerity policies as the most likely causal factor including reduced public spending on services such as local government and healthcare, decreased incomes of the poorest (due to increased conditionality and real-term value of social security payments) resulting in widening inequality (Schofield et al, 2016; Fenton et al, 2019; McCartney et al, 2022). This long-term change and short-term variation in mortality count were controlled using an interaction term between indicators of year and a natural cubic spline of day-of-OtA with 5df for cold effects, and similarly an interaction term between year
and a natural cubic spline of day-of-year with 3df for heat effects. Day-of-week and public holidays were also controlled using dummy variables.

Previous studies show that the heat effect usually starts to appear at a more extreme temperature than cold, with the temperature corresponding to the lowest mortality risk at roughly the 90th percentile of the daily temperature distribution in London (Hajat et al, 2006; Gasparrini et al, 2015). The mechanisms under moderate and extreme cold may differ with direct cold effects more likely to occur under extreme cold (Arbuthnott et al, 2018). In this study, we aim to study the impacts of extreme temperatures. Therefore, the RR is calculated by taking the ratio of the mortality risk under a temperature in relation to the mortality risk at the 10th and 90th percentile of annual temperature distribution averaged across the four cities and three regions for OtA and JJA respectively (corresponding to 2.3°C and 14.5°C).

The city- and region-specific results were then combined through multivariate meta-analysis using R package mixmeta (Gasparrini et al, 2012). In addition, a meta-regression of the results with indicators of urban and rural regions as a meta-predictor was also conducted.

We also performed subgroup analysis by demographic factors (age, gender and marital status), cause of death and small area-level deprivation indicated by the Carstairs Index by refitting the above-described DLNM stratified by the subgroups. The results in individual cities and regions were combined using meta-regression with indicators of subgroups while allowing for random effects across study regions for a national result. Age may confound the effect of gender, marital status and deprivation on the heat and cold effect. For example, a higher mortality risk among females may be confounded by age because a higher proportion of the older population is females due to their longer life expectancy (NRS, 2021b). Therefore, we performed further analysis by stratifying the mortality data by subgroups crossing age and sex, marital status and deprivation. To increase the number of observations in each subgroup, the age groups were reduced into two categories: age 0-74 and 75 and above representing the younger and older populations. For example, there were four
subgroups resulting from our age and sex categorisation: young females, young males, old females and old males. The city- and region-specific subgroup results were also combined using meta-regression with indicators of subgroups and random effects across study regions to represent a national result.

The increase in mortality risk under extreme temperatures was summarised with the RR at the 1st and 99th percentile of the annual temperature distribution averaged across the four cities and three regions (corresponding to -1.7°C and 17.9°C) and the associated 95% confidence intervals (CI) for the cold and heat effects respectively.

4.2.3. Model checking and sensitivity analysis
Diagnostic plots of deviance residuals of the models in individual cities and regions were produced in order to reveal any problems with the model assumptions, anomalies in the data and potential residual temporal pattern and autocorrelation (as introduced in Chapter 2.2.1.3). The diagnostic plots include residual partial autocorrelation, as well as plotting model residuals against the predictor (daily mean temperature), fitted values (daily mortality count) and time.

Multiple analyses were undertaken to explore the sensitivity of the main model to certain methodological choices. We conducted sensitivity analyses with varying lengths of the lag period, different number and placements of the knots of the temperature NS and different methods for controlling the long-term trend and variation in time. Relative humidity (RH) and air pollution including ozone and PM_{10} in Edinburgh between 2004-2018 were also included in the model as a sensitivity analysis. Table 4-1 lists the sensitivity analyses carried out and the difference in the model settings with the main model.
Table 4-1. Model settings for sensitive analysis. Only the settings that are different from the main model are listed here.

<table>
<thead>
<tr>
<th>Description</th>
<th>OtA model</th>
<th>JJA model</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1: Daily mean temperature</td>
<td>NS with 1 internal knot at the 50&lt;sup&gt;th&lt;/sup&gt; percentile, 2 internal knots at the 50&lt;sup&gt;th&lt;/sup&gt; and 90&lt;sup&gt;th&lt;/sup&gt; percentile and 3 internal knots at the 25&lt;sup&gt;th&lt;/sup&gt;, 50&lt;sup&gt;th&lt;/sup&gt; and 75&lt;sup&gt;th&lt;/sup&gt; percentile of OtA temperature distribution.</td>
<td>NS with 1 internal knot at the 50&lt;sup&gt;th&lt;/sup&gt; percentile, 2 internal knots at the 50&lt;sup&gt;th&lt;/sup&gt; and 90&lt;sup&gt;th&lt;/sup&gt; percentile and 3 internal knots at the 25&lt;sup&gt;th&lt;/sup&gt;, 50&lt;sup&gt;th&lt;/sup&gt; and 75&lt;sup&gt;th&lt;/sup&gt; percentile of JJA temperature distribution.</td>
<td>Four cities and three regions, 1974-2018</td>
</tr>
<tr>
<td>S2: Maximum length of lag</td>
<td>1 (dummy variables), 7 and 21 days (NS with 1 and 3 internal knots at equally-spaced log-values of lag length).</td>
<td>3 days (dummy variables), 7 and 14 (NS with 1 and 2 internal knots at equally-spaced log-values).</td>
<td>Four cities and three regions, 1974-2018</td>
</tr>
<tr>
<td>S3: Long-term trend and medium-term variation in time</td>
<td>1) Quadratic and linear terms of date for long-term trend. NS of day-of-OtA with 5df for medium-term variation. 2) NS with 5*45 df for the entire JJA dataset.</td>
<td>1) Quadratic and linear terms of date for long-term trend. NS of day-of-year with 3df for medium-term variation. 2) NS with 3*45 df for the entire JJA dataset.</td>
<td>Four cities and three regions, 1974-2018</td>
</tr>
<tr>
<td>S4: Daily PM&lt;sub&gt;10&lt;/sub&gt; and ozone</td>
<td>NS of 2-day average value with 4df</td>
<td></td>
<td>Edinburgh, 2004-2018</td>
</tr>
<tr>
<td>S5: RH</td>
<td>NS of 2-day average value with 4df</td>
<td></td>
<td>Edinburgh, 2004-2018</td>
</tr>
</tbody>
</table>
4.3. Results

The daily mean temperature and median daily mortality count in each city and region are summarised in Table 4-2. The average daily mean temperature across the four cities and three regions is 5.4°C in OtA and 13.6°C in JJA. Daily mean temperatures are higher in the four cities than in the three regions (Table 4-2). The daily median mortality count in the whole year ranges from 5 in Dundee and 6 in Aberdeen to 45 and 58 in eastern and western Scotland respectively (Table 4-2). The median mortality count is generally larger in OtA than in JJA. See daily mortality count and temperature in individual months in Supplementary S7.1.

Table 4-2. Daily mean temperature and median mortality in each city and region in the whole year, October to April (next year) (OtA) and June, July and August (JJA) between 1974-2018.

<table>
<thead>
<tr>
<th>Region</th>
<th>Daily mean temperature (standard deviation)</th>
<th>Daily median mortality (interquartile range)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Whole year</td>
<td>OtA</td>
</tr>
<tr>
<td>Abe</td>
<td>8.3 (4.6)</td>
<td>5.4 (3.3)</td>
</tr>
<tr>
<td>Dun</td>
<td>8.8 (4.9)</td>
<td>5.7 (3.4)</td>
</tr>
<tr>
<td>Edi</td>
<td>8.7 (4.9)</td>
<td>5.6 (3.5)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gla</td>
<td>9.2 (4.9)</td>
<td>6 (3.5)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>North</td>
<td>7.8 (4)</td>
<td>5.3 (2.8)</td>
</tr>
<tr>
<td>West</td>
<td>8.2 (4.7)</td>
<td>5.1 (3.3)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>East</td>
<td>7.8 (4.9)</td>
<td>4.7 (3.4)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Comparing the mortality count among subgroups (Supplementary S7.2), there is a higher proportion of mortality count among those who are 75-84 years old than other age groups, slightly more females than males except in the North, and more unmarried than married. A large proportion of mortality is due to cardiovascular diseases and other causes, with less due to respiratory diseases. In Dundee, Edinburgh, Glasgow and Western Scotland, there is more mortality in the most deprived quintile than the least deprived quintile; while it is reversed in Aberdeen, North and East.

The mortality counts of the population at the intersection of two attributes are shown in Supplementary S7.3. Among the mortality at younger ages (age 0-64 and 65-74), there are more males than females, and more married than unmarried; whereas it is reversed among the older age groups (75-84 and 85 and above). More deceased females are unmarried than married, whereas more males are married. Among the five quintiles of deprivation, there is a higher proportion of mortalities in the youngest age group (0-64 years old), males and unmarried who are from the most deprived neighbourhood compared to their counterparts.

The city- and region-specific and meta-analysis results of the relationships between RR and daily mean temperature in OtA and JJA are shown in Figure 4-2 (see values in Supplementary S8.1). The meta-estimation of RR in all cities and regions at the 1st percentile compared to the 10th percentile of the annual temperature distribution is 1.10 (CI: 1.08, 1.11) for the cold effect, and the meta-estimation of RR at the 99th percentile compared to the 90th percentile of daily temperature distribution is 1.04 for the heat effect (CI: 1.03, 1.05).

For the cold effect in OtA, as the temperature decreases, the RR increases non-linearly in all cities and regions (Figure 4-2). The meta-analysis results show that as the temperature decreases in OtA, the RR increases rapidly when the temperature is below 3°C or between 9°C and 15°C, and there is a levelling-off period in-between.
In JJA, there is a heat effect in all cities and regions (Figure 4-2). The meta-analysis results show an evident increase in mortality risk as the temperature increases when the temperature is above 14.5°C.

The meta-estimation results of the RR of subgroups at the 1st and 99th percentiles for the cold and heat effect are shown in Figure 4-3 (also see values in Supplementary S8.2). There is an increase in the mortality risk among all age groups under extreme cold, and the risk is higher for the older age groups (Figure 4-3 a). For the heat effect, the relative risk is the highest in the oldest age group (Figure 4-3 b). The result also shows that males have a slightly higher cold-related mortality risk than females, while females have a slightly higher heat-related mortality risk than males (Figure 4-3 a).

Extreme cold increases the mortality risk of both those who are married or unmarried, and for the heat effect, those who are unmarried experience a higher risk than those married (Figure 4-3). Those in the most and least deprived area experience slightly higher cold effects compared to other deprivation quintiles (Figure 4-3 a).
During exposure to cold and heat, there is an increase in mortality risk from all causes under investigation, with the highest increase in risks for respiratory deaths (Figure 4-3).

**Figure 4-3.** Meta-estimation of relative risk of subgroups at (a) 1st daily temperature distribution for cold effects and (b) 99th daily temperature distribution for heat effects. The full terms for the abbreviations are: marstat: marital status, dep: deprivation, dep1-5: quantile 1-5 of deprivation (from the least deprived to the most deprived), CoD: cause of death, CIRC: cardiovascular diseases, RESP: respiratory diseases, OTHR: causes of death other than CIRC and RESP.

The cold and heat effects by sex, marital status, deprivation and cause of death when controlling for age are shown in Figure 4-4 (also see values in Supplementary S8.2). This shows that, after controlling for age, the higher cold-related mortality risk of males than females and the slightly higher heat-related mortality risk of females are more evident among the older age group. The married population experience a slightly higher cold-related mortality risk than the unmarried population, whereas those who are unmarried experience a slightly higher heat-related mortality risk regardless of age. Among the younger age group, those in the most deprived areas have higher cold and heat effects. The mortality risk from cardiovascular diseases is higher among the older
population than the younger population under both extreme cold and heat, whereas the mortality risk from respiratory diseases is higher among the younger than the older population.
Figure 4-4. Meta-estimation of relative risk of subgroups by age (a) at the 1st percentile of temperature distribution compared to the 10th percentile for cold effects, and (b) at the 99th percentile of temperature distribution compared to the 90th percentile for heat effects. The full terms for the abbreviations are: female (F), male (M), married (MA), unmarried (UM) (See the full term of other abbreviations in the caption of Figure 4-3). The underline joins two attributes, e.g. age0-74_F represents those who are at the age of 0-74 and also being female.
The model diagnostic plots in Glasgow are shown in Figure 4-5 (diagnostic plots in other cities and regions are in Supplementary S9, which show similar patterns to the plots in Glasgow). No abnormal variance was observed in the deviance result against the predictor and response. No evident temporal trend or pattern was shown in the residuals, and the autocorrelation was low. The overall pattern of the temperature-mortality relationships from the sensitive analyses does not change compared to the main model (Figure 4-6).

Figure 4-5. Model diagnostics of deviance residual in Glasgow. JJA: (a)-(d). OtA: (e)-(h).
Figure 4-6. Sensitivity analysis results of alternative model settings. Sensitivity analysis 1: knot locations of the natural cubic spline of daily mean temperature in JJA (a) and OtA (b). Sensitivity analysis 2: maximum length of lag in JJA (c) and OtA (d). Sensitivity analysis 3: control of long-term trend and
4.4. Discussion and conclusions

This study found increased mortality risk under both low and high temperatures in Scotland. There was a continuous but non-linear increase in the mortality risk as the temperature decreased in OtA. In JJA, mortality risk started increasing as the temperatures increase above around 14.5°C in Scotland. This is comparable to the temperature thresholds corresponding to the lowest mortality risk (heat threshold thereafter) in Scotland found in another study (Dimitriadou et al., 2022) but lower than previous studies in other places (Baccini et al, 2008; Gasparrini et al, 2015; Gasparrini et al, 2022). This indicates that the heat-health impacts can also be observed at relatively low temperatures in places with a cool climate. It may partly be because of the acclimatisation and adaptation effect where people and society are adapted to their local climate as previous studies found higher heat thresholds in warmer places than cooler places of Europe, e.g. around 30°C in Athens and Rome and around 20°C in Helsinki and Stockholm (Baccini et al, 2008; Gasparrini et al, 2015; Gasparrini et al, 2022).

Due to a historically cool climate, the cultural, behavioural and policy focus in Scotland has been the reduction of cold impacts with heat largely remaining an invisible risk, which is further discussed below. People may experience enhanced heat exposure indoors as the focus of building design and energy efficiency has been to keep buildings warm (Peacock et al, 2010; Gupta et al, 2017b), which may contribute to the low heat threshold in Scotland as well. It raises research and policy needs in considering city/region/country-specific conditions for the estimation of cold/heat-health burdens and the design of cold/heat-health warnings and strategies. Although some of the mortalities under heat may have been brought forward by those in advanced forms of illness, a significantly elevated heat risk was observed in all age groups in our study. Our results are useful in indicating the acute increase in mortality risk for health services to be more prepared for increased needs in health and emergency services during hot weather.
The RR at the 1st percentile compared to the 10th percentile of daily temperature distributions (i.e. 1.7°C and 2.3°C) was 1.10 (CI: 1.08, 1.11) to represent the cold effect, and the RR at the 99th percentile compared to the 90th percentile of temperature distribution (i.e. 17.9°C and 14.5°C) was 1.04 (CI: 1.03, 1.05) for the heat effect. In line with previous studies, the heat effect in cities was found to be higher than in rural regions (Hajat et al, 2007).

The cold effect in Scotland was comparable to England where a 3.44% (CI: 3.01, 3.87) increase in all-cause mortality for each degree decrease at low temperatures was found (Hajat et al, 2016). However, caution is needed in making direct comparisons because of differences in thresholds, lag structures, and other model specifications (Arbuthnott et al, 2018). The heat effect in Scotland was smaller than in England and Wales as a whole, where a mean increase of 3% (CI: 2%-3%) in mortality risk for each degree increase under high temperature was found (Hajat et al, 2007). The heat effect in Scotland was more comparable to that found in North East England and Wales, where there was an increase of 1.7%-2.0% for each degree increase in high temperature (Hajat et al, 2007).

The oldest age group was found to experience the highest cold and heat effects, which is in line with most other studies (Collins, 2000; Gouveia et al, 2003; Analitis et al, 2008; Romero-Lankao et al, 2012; Hajat et al, 2016; Son et al, 2019). The older population had a higher RR in cardiovascular mortality than the younger group, which has also been found in previous studies (Goodwin, 2000; Keatinge & Donaldson, 2000; Carder et al, 2005); in contrast, the younger group had a higher cold-related mortality risk in respiratory diseases than the older group. Although less common, a higher cold-related respiratory mortality risk among the younger population was also found in Chicago, USA (O’Neill, 2003) and Spain (Achebak et al, 2020). This may be related to the higher prevalence and incidence of asthma among children, young and middle-aged adults (British Lung Foundation, n.d.), and a higher proportion of smokers among the younger population (ASH, 2021), or the elderly tend to stay indoors.
when the outdoor temperature is low and hence avoid the exposure to cold and infectious diseases (Achebak et al, 2020).

Males were found to experience higher cold-related mortality risk, which remained after controlling for age. This may be associated with physiological, lifestyle and behavioural factors, e.g. less likely to seek help from doctors (Wang et al, 2013) and to wear appropriate clothing and hats and gloves in cold outdoors (Keatinge et al, 1997), and also more likely to smoke (Scottish Government, 2019b; ASH, 2021). A higher cold-related respiratory mortality risk among males than females was found in Spain (Achebak et al, 2019), but in a study in eight regions in Europe, females showed higher risks than males (Keatinge et al, 1997). Therefore, more research is needed to investigate whether vulnerabilities by gender are region-specific.

Females experienced slightly higher heat-related mortality risk, which may partly be confounded by age due to their longer life expectancies. However, females may still be more vulnerable to heat as shown by the higher heat-related mortality risk among older females than older males in this study. Some possible explanations include physiological features such as a lower sweating ability (Mehnert et al, 2002), and menopausal effects such as elevated body temperature and sweating (Archer et al, 2011). There are more older females living alone than older males, and females have been experiencing lower socioeconomic status than males in the past, e.g. having lower employment rate, lower payment and less representation in senior positions, which may contribute to their vulnerabilities (Breitenbach & Wassoff, 2007; NRS, 2021a; n.d.).

Marital status as a risk factor is rarely investigated in previous research compared to age and gender. In this study, those who were unmarried had higher RR under extreme heat, which is still evident after controlling for age. The high vulnerability among the unmarried was also found in some previous studies, e.g. in France (Fouillet et al, 2006), Italy (Stafoggia et al, 2006; Ellena et al, 2020) and the US (Gronlund et al, 2015). All of the various unmarried states (being single, never married, being separated/divorced and being
widowed) were found to be associated with elevated mortality risks, particularly relating to cardiovascular diseases in a cohort study with around 14,000 Scottish men and women (Molloy et al, 2009). Experiencing existing health conditions, physiological stresses and being more likely to be living alone and socially isolated may contribute to the vulnerability of the unmarried population under heat exposure (Cramer, 1993; Fouillet et al, 2006; Molloy et al, 2009). Although living alone cannot fully explain the worse health status among the unmarried population, it has been identified as a significant risk factor for elevated mortality during a 1999 heatwave in Chicago, US (Naughton et al, 2002).

Deprivation is usually considered to contribute to health inequalities due to a lack of material and social resources (Morris & Carstairs, 1991; Howieson & Hogan, 2005). Deprivation is differentiated from poverty in that deprivation can reflect multiple disadvantages, such as clothing, housing, household facilities, education, environmental, working and social conditions (Townsend, 1987). Those who are deprived may have fewer resources to prepare, respond and adapt to cold and heat (Lindley et al, 2011). This study found higher cold- and heat-related mortality risks among younger people who lived in the most deprived areas compared to younger people in less deprived areas, whereas no evident pattern was observed in the older population. Affluent old people may be more likely to live in big and old houses with lower energy efficiency, and are more likely to experience cooler indoor temperatures and a higher cold-health risk. This could be supported by the generally positive relationship between energy efficiency and deprivation in Scotland (Supplementary S10). Further research on the modification effects of deprivation, particularly with the interaction of age on the cold and heat effects is needed.

Some previous studies found an increase in cold- and heat-related mortality risks among people in more deprived areas in England and Wales (Murage et al, 2020; Gasparrini et al, 2022). Higher excess winter mortality was also found in regions with higher deprivation in Scotland (Howieson & Hogan, 2005). However, evidence of the effect of deprivation on cold-/heat-related mortality is
mixed and little effect of deprivation was found in two studies in the UK (Aylin et al, 2001; Maheswaran et al, 2004) and most studies of the 2003 heatwave in Europe (Kovats & Hajat, 2008). This may be because current deprivation indices cannot fully reflect socio-economic vulnerability to cold and heat exposures (Lindley et al, 2011). In addition, deprivation includes diverse dimensions which also vary over time and hence it is unlikely that any indicator could capture it fully (Schofield et al, 2016). For example, the difference in the age and gender-standardised all-cause mortality rate after the adjustment of deprivation using the Carstairs Index between Scotland and England increased from 4% to 10% between 1981 and 2011 (Schofield et al, 2016). The decreased relevance of the Carstairs Index to health is, at least partially, due to changes in peoples’ lived experience and the relative importance of different aspects of deprivation (Schofield et al, 2016). Deprivation is often studied at small area levels, whereas caution is also needed when drawing inferences at an individual level (Openshaw, 1984; Flowerdew et al, 2008).

This study provides new evidence of the impacts of short-term exposure to extreme cold and heat on mortality in Scotland and associated vulnerable subgroups. It uses particularly long time series of daily temperature and mortality for the four most populated Scottish cities and three regions in the past 45 years, which enables enough statistical power in the estimation of the mortality risk under extreme cold and heat. This study is novel in that, in addition to the investigation of the widely studied individual modifying factors such as age and sex, it also investigated the effect of marital status and socio-economic deprivation on cold- and heat-related mortality risk whilst controlling for age.

There are potential limitations in this study. Although seasonal variation in mortality has been controlled for, this study did not explicitly control for influenza epidemics which may leave residual confounding. However, whether a factor is a confounder depends on its position on the causal pathway between temperature and mortality (Buckley et al, 2014), which is also discussed in Chapter 2.2.1.2. As the temperature has a direct influence on influenza
transmission, it is debatable whether influenza epidemics should be controlled as a confounder (Arbuthnott et al, 2018). Due to the use of extreme thresholds, the number of observations beyond the thresholds is small, yielding limited statistical power in the stratified analysis. Therefore, formal tests of interaction effects were not assessed, and hence this research focuses more on effect sizes rather than statistical significance. An averaged temperature series over a city or region is used in the study which may not reflect temperatures that individuals are exposed to at any time since individuals spend a large proportion of time indoors with different heating and ventilating situations. As a final limitation, marital status was only separated into married and unmarried, whereas the effect of cohabitation status and different subcategories of being unmarried, e.g. single, divorced, widowed could not be investigated.

This is the first research exploring the temperature-mortality association for the whole population of Scotland and found increased mortality risk associated with both cold and heat exposure. The results reveal heat is a risk factor to health in Scotland. This is particularly evident in some vulnerable groups, including the elderly, females, unmarried and people who have pre-existing conditions, particularly respiratory and cardiovascular diseases. Further research should be conducted to identify modifiable factors that heighten heat-health risk in these groups and also to estimate probable future health burdens under climate change scenarios. Such results could support heat-health policies and actions to prevent excess mortality during high temperatures in Scotland.
Chapter 5. Integrating Shared Socioeconomic Pathway-informed adaptation into temperature-related mortality projections under climate change

5.1. Introduction

The adverse health impact of ambient temperatures is one of the most prominent climate change risks (Romanello et al., 2021). Previous studies often estimate future heat burdens focusing on the temperature under climate change while assuming other factors remain static at historical levels (Sanderson et al., 2017). Such methods are useful in exploring the contribution of climate change, whereas they will not reflect realities where socioeconomic conditions strongly influence future health burdens, thus limiting their usefulness for policymakers.

There is a gap in projecting future temperature-related mortality burdens not only because of uncertainty in regional temperature change but importantly because of uncertainty in how people will adapt to future temperatures. While some research has shown that vulnerability and adaptation contribute substantially to the mortality burdens associated with ambient temperatures, adaptation is frequently disregarded. Among the limited body of literature that explored the effect of vulnerability and adaptation in future temperature-related health burdens, assumptions lacking credible empirical evidence are usually employed, which has been reviewed in Chapter 2.2.2.

The methods used in previous studies to model adaptation in the quantitative projection of future temperature-related mortality burdens include shifting the threshold temperature from which mortality risk starts to increase, adjusting the slope of the temperature–mortality (TM) association and using the TM
association in analogue cities (Chapter 2.2.2). However, these techniques often make simplistic assumptions which lack empirical evidence. Historical trends in the TM association or the threshold temperature can inform estimates of current and future adaptation through extrapolation, to aid the holistic projection of future temperature-related mortality burdens. However, the historical trend in the TM association may not be directly applicable to the future due to different rates of climate change and pathways of societal development.

Previous studies predominantly assume a decrease in the vulnerability to heat under climate change because of heat acclimatisation (Chapter 2.2.2). One common method to model acclimatisation is shifting the temperature at which the mortality risk is the lowest (minimum mortality temperature, MMT) according to the rate of temperature increase under climate change. Some studies adjust the susceptibility to extreme temperatures, represented by the slope of the TM association or the relative risk (RR) of mortality under a certain temperature against an MMT or threshold temperature. However, vulnerability is influenced by a myriad of socioeconomic conditions that affect the adaptive capacity to extreme temperatures (Chapter 2.1.3), which are not taken into account by these methods. In addition to increased acclimatisation and adaptation to heat, decreased adaptive capacities to heat is a possible situation where the vulnerabilities are intensified, yet the future heat burden under this scenario has been rarely explored (Chapter 2.2.2.7). Health has been found to deteriorate during recessions because of losses of important services and increased levels of poverty, stress and mental illness (Walsh et al, 2016).

The Shared Socioeconomic Pathway (SSP) is a widely used set of scenarios describing five alternative futures of how society, demographics and economics globally might change over the 21st century (Riahi et al, 2017). National SSPs have been developed in some places such as the UK which include location-specific details consistent with the global SSPs (UK Climate Resilience Programme, n.d.). These SSPs provide a useful framework to explore the health burden considering both future adaptive capacities to extreme temperatures and to demographic change. Key socioeconomic changes
relevant to the adaptive capacity to low and high temperatures under individual UK SSPs are summarised in Figure 5-1.

Figure 5-1. UK-SSP narratives related to the adaptive capacities to heat and cold (UK Climate Resilience Programme, n.d.). Some recent studies assume a positive association between Gross Domestic Product (GDP) and the adaptive capacity to extreme temperatures, and estimate future temperature-related mortality burdens based on adjusted TM associations according to projected GDP under the SSPs (Wang et al, 2019; Rai et al, 2022). However, GDP is not the only factor affecting the adaptation to extreme temperatures (Lindley et al, 2011). For example, global GDP is projected to increase rapidly under SSP5—a fossil fuel-dominated pathway, whereas the natural environment may deteriorate under this pathway, counteracting the benefits of high GDP (UK Climate Resilience Programme, n.d.). Therefore, there is a need to assess the effect of the composite socioeconomic adaptive capacity level on the projection of mortality burden attributable to extreme temperatures considering climate change and socioeconomic scenarios.

In addition, the adaptive capacity may increase or decrease in the future depending on the socioeconomic conditions. The SSP is a useful framework
which contains scenarios of improvement and deterioration in the adaptive capacity. For example, there is expected to be increasing nationalism and growing international tensions accompanied by a decrease in social support, education, health and public infrastructures in the future under SSP3—the regional rivalry scenario (O’Neill et al, 2017). Under SSP4, higher inequality is assumed, with deteriorating social cohesion and health services for most of the public (O’Neill et al, 2017). These scenarios, therefore, suggest future adaptation could be more challenging than for present-day.

This research investigates future mortality burdens associated with low and high temperatures in Scotland integrating changes in climate, adaptive capacity and demography. An innovative evidence-based method is utilised to take into account the changes in the susceptibility to extreme temperatures under scenarios of changing adaptive capacities. It fills the research gap in assessing the effect of adaptation on temperature-related mortality burdens under scenarios of increased and decreased adaptive capacities supported by empirical evidence and informed by the SSPs. Scotland was chosen as the research location because it has been experiencing poorer health compared to other western European countries since the 1950s due to socioeconomic vulnerabilities (Walsh et al, 2016). In addition, Scotland has a relatively cool climate and few actions have been taken to reduce heat risks, so there may be a low adaptive capacity to heat-health risks under climate change as discussed in Chapter 3. Therefore, there is a need to investigate future temperature-related mortality burdens in Scotland, particularly incorporating uncertainties associated with adaptation.

5.2. Methods

5.2.1. Data

The National Records of Scotland provided daily all-cause mortality counts in the whole of Scotland between 1974-2018, which is separated into the four biggest cities (Aberdeen, Dundee, Edinburgh and Glasgow) and three regions (East, West and North excluding the four cities). The mortality count was
provided for two age groups (0-74 and 75 and above years old) to investigate the different risks among the younger and older age groups.

Historical populations in 1981, 1991, 2001 and 2011 were obtained for the two age groups from the PopChange dataset (Lloyd et al, 2017). Population projection data under each SSP was attained from the UK-SSP project for each decade from 2020 to 2080 (UK Climate Resilience Programme, n.d.). Both the historical and projected population data are on a 1km-by-1km grid.

The socioeconomic adaptive capacity levels were determined by the composite change in key socioeconomic factors (Rohat et al, 2019a; Wan et al, 2022b), including income, income inequality, social cohesion, health care, public awareness, urban population, green space and energy efficiency, as introduced in Chapter 2.1.3. The projection of these factors was obtained from the UK-SSP project (UK Climate Resilience Programme, n.d.). Three scenarios of adaptive capacity were adopted: high under SSP1 (Sustainable Pathway), no change under SSP2 (Middle of the Road Pathway) and SSP5 (Fossil-Fueled Development), and low under SSP3 (Regional Rivalry Pathway) and SSP4 (Inequality Pathway) (Wan et al, 2022b).

The high adaptive capacity under SSP1 is driven by a huge increase in social cohesion, public awareness and health care availability and a decrease in income inequality (UK Climate Resilience Programme, 2021a). Under SSP2, the adaptive capacity remains largely unchanged because of the small changes in individual indicators and mixed effects of the improvement and decline of different indicators. Income, social cohesion, public awareness and protected area are assumed to increase slightly, whereas health care availability decreases slightly in the near future and income inequality increases slightly under this pathway (UK Climate Resilience Programme, 2021b). Energy efficiency increases, which drives an increase in the cold adaptive capacity. Urban population strongly increases, which may counteract the positive effects of the improvement in other indicators and lead to an overall unchanged adaptive capacity.
Similarly, the adaptive capacity is assumed to remain unchanged under SSP5 due to counteracting effects of different factors. Income and health care availability are projected to increase strongly, inequality decreases slightly due to economic growth (UK Climate Resilience Programme, 2021e). However, other factors are assumed to decline including social cohesion and green space, counteracting the benefits of economic developments (UK Climate Resilience Programme, 2021e). The adaptive capacities are assumed to decrease strongly under SSP3 and SSP4 driven by the worsening of almost all factors affecting the adaptive capacity under these two pathways (UK Climate Resilience Programme, 2021d; c).

The HadUK-Grid Gridded Climate Observation dataset was used for daily maximum and minimum temperatures on a 1km-by-1km grid in Scotland between 1974-2018 (Hollis et al, 2019) from which daily mean temperature ($T_{daily}$) was calculated. Population-weighted average temperatures were calculated for the four cities and three regions by weighing the temperature in each 1km grid-cell with the proportion of the population in that grid-cell against the total population in individual cities/regions. This temperature series, combined with daily mortality counts between 1974-2018, was used to investigate the exposure–response function (ERF) between temperature and mortality in Scotland.

$T_{daily}$ in Scotland between 1980-2080 were obtained from the CHESS-SCAPE dataset (Robinson et al, 2022), which is bias-corrected and downscaled to a 1km-by-1km grid using climate model outputs of the UK Climate Projections 2018 (UKCP18) under Representative Concentration Pathway (RCP) 8.5. This dataset was selected because of its extended outputs under RCP 2.6 and 4.5 (Robinson et al, 2022). The dataset contains climate projections from four perturbed-physics ensembles (PPE) to sample the uncertainties arising from General Circulation Model (GCM) parameters (Robinson et al, 2022), providing four temperature series for each RCP. The historical simulation period is for 1980-2010, which was merged with RCP4.5 for 2010-2020 to obtain two 20-year historical periods (1980-2000 and 2000-2020). Population-weighted
temperatures were used to estimate temperature-related mortality burdens in both historical and future periods for consistency.

5.2.2. Epidemiological analysis
The association between temperature and all-cause mortality in Scotland was modelled using a two-stage approach. In the first stage, time series quasi-Poisson regression with distributed lag non-linear models (DLNM) was utilised for individual age groups and cities/regions. This was performed for every annual rolling 20-year period between 1974-2018, i.e. 1974-1993, 1975-1994,…,1999-2018 (26 overlapping periods in total). This approach was utilised to capture the continuous change in the ERF over time while ensuring a sufficient sample size. Separate analyses were conducted for May to September (MtS) and October to April (OtA) to capture the different lengths of lagged effects of heat and cold respectively (Chapter 4.2.3). Maximum lags of 1 and 14 days were used to model the lagged effects of heat and cold respectively, which was found to capture the maximum cumulative effects (Chapter 4.2.3). The data in MtS was used to obtain the heat risk function in this research rather than in June to August as in Chapter 4. This was because September appears to have some high temperature days particularly under climate change scenarios. Although May has a relatively lower temperature than June-September, it is included in the research because heat risk may be larger in the early time of the warm season than later time in summer due to the lack of acclimatisation and adaptation as discussed in the Background (Section 2.2.2). This disparity in the months used for the analyses will be discussed in more detail in Chapter 6.4.2.2.

The lag-response association was modelled with indicators of lag 0 and 1 in MtS and a natural cubic spline (NS) with two knots on the log scale of 14 in OtA. NS with two inner knots at the 30th and 70th percentiles of the temperature series were used to model the TM association (Chapter 4.2.3). Long-term trend and medium-term variation in the mortality series were controlled using an interaction term of year indicators and the day of MtS/OtA. Day-of-week and public holidays were controlled.
In the second stage, the ERFs in individual age groups, periods and locations from the first stage analysis were aggregated using multivariate meta-regression to generate a mean estimate for Scotland. Age and period were predictors and location was a random-effects predictor of the meta-regression. The 26 periods are overlapping, so an NS with 3 degrees of freedom was used to model the effect of the temporal period on the ERF.

The 10th and 90th percentiles of population-weighted $T_{daily}$ in Scotland in 1974-2018 (i.e. 2.6 and 15.0 °C) were used as the temperature thresholds for cold and heat extremes respectively. These thresholds were selected to calculate the RRs and estimate the mortality burden attributable to extreme temperatures in this research rather than the MMT. This is because the point estimate of the MMT can vary considerably across a region (Tobías et al, 2017), suggesting treating the optimal temperature as a range is more appropriate. A previous study found an average MMT range of 2.6 to 14.5°C in Scotland (Dimitriadou et al, 2022), which is similar to the cold and heat thresholds respectively used in this research. The threshold temperatures were kept constant in each period, which allowed the comparison of the RR under the same temperature exposures.

The analyses were conducted in R/RStudio using packages dlnm (Gasparrini, 2011) and mixmeta (Sera et al, 2019).

5.2.3. Modification of the risk function under adaptation scenarios
A prior exploration of the variation in the susceptibilities to extreme temperatures found a steady decrease in the cold susceptibility, whereas a slight increase in the heat susceptibility in the last two decades (Wan et al, 2022a). The decline in cold susceptibility is likely a result of increased adaptive capacities to cold due to existing interventions such as increased insulation and energy efficiency and decreasing fuel poverty. On the contrary, fewer heat-related interventions have been undertaken in Scotland (Chapter 2.3.3).

Therefore, we assume the variation in the ERF found in the 26 historical periods reflects changes in the adaptive capacities to both cold and heat. Three adaptation scenarios informed by the UK-SSPs were constructed in this
research utilising the ERF in analogue periods. The ERFs with the lowest and highest susceptibilities for the historical periods were applied to estimate the mortality burdens under the scenarios of increased and decreased adaptive capacities respectively. The ERF found in 1981-2000 was used as the baseline ERF corresponding to the baseline climate period of 1980-2000, which was applied as the ERF under a third “no adaptation” scenario.

5.2.4. Mortality burden estimation

Daily temperature-related mortality ($M_{temperature}$) was calculated for the two age groups using the functions below (Hajat et al, 2014).

\[
M_{temperature} = BMR \times P \times (RR - 1)
\]

\[
BMR = \frac{DMR}{RR}
\]

$M_{temperature}$ is the multiplication of the baseline daily all-cause mortality rate (BMR), the population across Scotland ($P$) and the temperature-specific RR. The RR were predicted using the ERFs adopted for each adaptation scenario with historical and projected temperature data. The BMR was calculated from the daily mortality rate (DMR) for the two age groups excluding deaths attributed to cold or heat. Daily $M_{temperature}$ was summed for each year in two historical and two future periods under each scenario.

Three components determining the mortality burdens attributable to extreme temperatures: temperature, ERF and population are compared. The average DMR between 2010-2018 was applied to the estimation of mortality burdens in all periods to enable the attribution of the estimated mortality burden to the three individual components. The time and scenario of the data for the three components used for estimating $M_{temperature}$ is shown in Table 5-1.

<table>
<thead>
<tr>
<th>Period of Temperature Exposure–Response Function (ERF)</th>
<th>Population</th>
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<tbody>
<tr>
<td>Table 5-1. The time of the data for the three components in estimating the mortality burden attributable to extreme temperatures in four periods.</td>
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mortality burden

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<td>1980-2000</td>
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<td>2000-2020</td>
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Three adaptation scenarios

<table>
<thead>
<tr>
<th></th>
<th>No change (SSP2&amp;5)</th>
<th>Low adaptation (SSP3&amp;4)</th>
<th>High adaptation (SSP1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dec 2040- Nov 2060 (RCP2.6, 4.5 &amp; 8.5)</td>
<td>The ERF in the 20-year historical period</td>
<td>The ERF in the 20-year historical period (SSP1-5)</td>
<td></td>
</tr>
<tr>
<td>2060</td>
<td>Baseline period</td>
<td></td>
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<tr>
<td>2060</td>
<td>1981-2000 to extreme susceptibility temperatures</td>
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<tr>
<td>2080</td>
<td>(RCP2.6, 4.5 &amp; 8.5)</td>
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Future $M_{temperature}$ were estimated under five SSP-RCP scenarios: SSP1-RCP2.6, SSP2-RCP4.5, SSP4-4.5, SSP3-RCP8.5, and SSP5-RCP8.5. These scenarios were selected as being the most typical and important scenarios (O’Neill et al, 2016; Riahi et al, 2017). Although RCP8.5 could not be achieved under SSP3 from some integrated assessment models, it can be elicited under additional assumptions such as higher economic growth (Riahi et al, 2017),
which makes SSP3-RCP8.5, a combination of both high emission and vulnerability, a useful scenario for climate change impacts, adaptation and vulnerability research relating to extremes. The five scenarios and their corresponding combination of changes in temperature, adaptive capacity, population size and ageing are illustrated in Figure 5-2. The changes in the mean annual burden from 1980-2000 to 2000-2020 and 2060-2080 were decomposed into the three components using the Das Gupta method (Das Gupta, 1993).

![Figure 5-2. Five SSP-RCP scenarios utilised in this research and qualitative representations of the level of temperature increase, adaptive capacity and population size and ageing under each scenario. The darker the colour orange of the squares the higher the global temperature under climate change. The darker blue colour of the squares reflects higher challenge to adaptation (equivalent to lower adaptive capacity). The size of the circle reflects the total population size with a larger circle indicating a larger population. The colour of the circle represents the level of population ageing: blue—low ageing and orange—high ageing.

5.2.5. Sensitivity analysis

Natural cubic splines (NS) were widely used to model the non-linear TM association (Vardoulakis et al, 2014), which were also used in this research. However, it may lead to an underestimation of the risks at the temperature extremes and CS was found to alleviate this issue (Rocklöv & Ebi, 2012). Therefore, we conducted sensitivity analyses by conducting the epidemiological analysis using CS for the TM association.
5.3. Results
There were 4.9 and 0.3 million people for those below and above 75 years old respectively in Scotland in 2011, with an average of 20.8 and 34.9 thousand annual deaths respectively in 2010-2018. The older population is projected to increase under all SSPs with a lower increase under SSP3 (increase by 165%), a medium increase under SSP2 (265%) and SSP4 (263%) and the largest increase under SSP1 (355%) and SSP5 (357%) between 1991 and 2070 (Figure 5-3a). In the same period, the younger population is projected to decrease SSP3 (21%) and SSP4 (10%), and increase under SSP1 (5%), SSP2 (7%) and SSP5 (35%).

The annual average population-weighted \( T_{dail} \) increases from 8.4°C to 9.1°C between 1980-2000 and 2000-2020 in Scotland, and is projected to increase by 1.5°C, 2.2°C and 3.3°C on average for Scotland under RCP2.6, RCP4.5 and RCP8.5 respectively in 2060-2080 compared to 1980-2000 (Figure 5-3b). Under climate change, the increase in the number of hot days is double to triple the decrease in the cold days (Figure 5-3c).
Figure 5-3. (a) Population in Scotland under the five UK-SSPs. (b) Population-weighted daily mean temperatures under four RCPs. (c) Change in the percentage of hot and cold days in two future periods under three RCPs compared to 1974-2018 during which there were 10% days below and above the cold
and heat thresholds respectively. The dashed line in (b): individual perturbed-physics ensembles (PPEs); solid line: PPE mean.

The TM association in Scotland in the 26 20-year historical periods between 1974-2018 is shown in Figure 5-4 a. The susceptibilities to cold and heat were higher among the older than the younger age group. The cold susceptibility increased slightly between 1974-2003 and 1982-2001, with an abrupt increase in 1983-2002 and remained largely unchanged until 1987-2008 and a steady decrease thereafter. The variation in the heat susceptibility is smaller than cold. The cold and heat susceptibilities were found to be the highest in 1985-2004 and 1974-1993 respectively, and the lowest cold and heat susceptibility was observed in 1999-2018 and 1983-2002 respectively. The ERF under each adaptation scenario is illustrated in Figure 5-4 b.

The annual mortality burdens attributed to cold and heat estimated for 1980-2000, 2000-2020 and 2060-2080 are shown in Figure 5-5 a (and for 2040-2060 in Supplementary S11.1). There were 278 and 23 deaths/year attributable to
extreme cold and heat respectively between 1980-2000. In 2000-2020, the cold burden decreased by 90% and the heat burden increased by 291% compared to 1980-2000. The heat burden is projected to be larger than cold in the future under all scenarios. In 2060-2080, the cold burden was projected to be the highest under RCP4.5-SSP4 (158 deaths/year), and the lowest under RCP8.5-SSP3 (48 deaths/year) followed by RCP2.6-SSP1 (54 deaths/year). In the same period, the heat burden was projected to be the highest under RCP8.5-SSP5 (1196 deaths/year), and the lowest under RCP2.6-SSP1 (323 deaths/year).

The mortality rate per 1 million total population is presented in Figure 5-5 b. The mortality rate decreased from 55 to 5 attributable to cold and increased from 5 to 17 for heat from 1980-2000 to 2000-2020. The heat- and cold-related mortality rate is projected to be the highest under RCP8.5-SSP3 and RCP4.5-SSP4 respectively. In 2060-2080, RCP2.6-SSP1 observed the lowest mortality rate attributable to both cold and heat, with 8 and 50 deaths per million population respectively.

The contribution of the three components: temperature, ERF and population to the change in the mortality burden in 2000-2020 and 2060-2080 (under five scenarios) compared to 1980-2000 is shown in Figure 5-5 c (see values in Supplementary S11.2). The ERF contributed to most of the change in the cold burden in 2000-2020 and 2060-2080 under RCP2.6-SSP1. The temperature increase drove a decrease in the cold burden among the younger population; however, this effect was largely counteracted by the increase in population among the older population.

The temperature increase also drove the largest proportion of the elevated heat burden in 2000-2020 and in 2060-2080 under all scenarios except RCP2.6-SSP1, during which the contribution of increase in the older population is comparable to temperature increase. Adaptive capacity made the lowest contribution to the change in the heat burden among the three components. The most notable effect of adaptive capacity was observed under RCP8.5-
SSP3 and RCP4.5-SSP4, under which the lower adaptive capacity contributed to 17% of the increase in heat burden.

Figure 5-5. (a) Annual mortality burden for two age groups and (b) annual mortality burden per 1 million population attributed to cold and heat in Scotland in two historical periods (1980-2000 and 2000-2020) and 2060-2080 under five RCP-SSP scenarios. (c) The change in mean annual mortality burden in 2000-2020 and 2060-2080 under five scenarios compared to 1980-2000 and the decomposition of the change into three components.

The mortality burdens estimated using temperature outputs from individual PPEs are shown in Figure 5-6 to isolate the year-to-year variation from model uncertainty. The year-to-year variability in temperature contributed to a larger variation of the annual burdens than uncertainties from the PPEs. Compared to using an NS for the TM association, the CS resulted in a more non-linear TM association with higher RRs under temperature extremes (Supplementary S12). However, because of the low prevalence of the most extreme temperatures,
using a CS and NS resulted in comparable results with similar magnitude (the Supplementary S12).

Figure 5-6. Annual mortality burden attributed to cold and heat in Scotland for two historical periods (1980-2000 and 2000-2020) and in a future period (2060-2080) using temperature outputs from four PPEs of UK Climate Projections 2018 (UKCP18).

5.4. Discussion and conclusions
This research utilised 45 years of historical evidence from the TM association in Scotland to project the future mortality burden until 2060-2080. It takes into account changes in temperature, adaptive capacities, and population under a consistent RCP-SSP framework. The rise in hot days exceeds the decline in cold days under all RCPs in Scotland. Future scenarios of an increase and decrease in adaptive capacities to extreme temperatures were constructed informed by the SSPs and historical variations in the susceptibilities to extreme temperatures. A larger variation in the cold susceptibility than heat in the historical period was found in this research. The cold burden decreased by 90%
between 1980-2000 and 2000-2020, mainly due to the sharp decrease in the susceptibility to cold. The projected cold burden is the highest under RCP4.5-SSP4, which is around two times higher than RCP2.6-SSP1 in 2060-2080, even though the latter has a cooler climate and a larger population. In comparison, the annual mortality burden attributable to heat increased by 70% between 1980-2000 and 2000-2020, and was projected to increase further by 2.6 and 12.3 times in 2060-2080 under RCP2.6-SSP1 and RCP8.5-SSP5 respectively.

The contribution of fuel poverty as affected by energy price, income and housing performance may have contributed to the variation in the cold susceptibility (Scottish Government, 2017b). There was an increase in the UK energy price between 2002-2010, a reverse of the previous decreasing trend between the 1970s-1990s (Fouquet, 2014), which may have contributed to the increase in the cold susceptibility during this period. Between 2011 and 2017, there is a general improvement in energy efficiency and fuel poverty (Scottish Government, 2017b), corresponding to a steady decrease in cold susceptibility.

In addition, the recent decrease in the cold susceptibility may also be a consequence of fuel poverty policies and actions to mitigate the impacts of cold weather on vulnerable populations (Scottish Government, 2017a). These policies include the Cold Weather Payments launched in 1988 (Scottish Government, 2019a), the Winter Fuel Payment scheme that was introduced in 1997 and the substitute Winter Heating Assistance since 2016, and the Warmer Homes Scotland scheme which provides support for insulation, efficient heating and renewable technologies since 2015 (Warmworks, n.d.). These actions provide support to those who are most vulnerable to cold effects, e.g. pensioners (i.e. the elderly) and benefits recipients (e.g. low income, unemployment, disability). Some policies like the Winter Fuel Payment and Cold Weather Payments were introduced UK-wide, and may explain a decrease in the cold susceptibility in England and Wales also during 1976-2005, although a few years had typically high cold effects, e.g. in 1976, 1986, 1989, 1997 and 1999 (Christidis et al, 2010).
A smaller variation whereas with a general opposite trend was observed in the heat susceptibility compared to cold. This may be associated with elevated indoor overheating risk due to measures of increasing energy efficiency such as internal wall insulation, and an increase in airtightness and reduction in ventilation (Fosas et al, 2018). A similar trend has also been observed in Czeck Republic (Janoš et al, 2023).

The annual cold-related deaths in 1980-2000 and 2000-2020 in Scotland found in this research are smaller than cold-related mortalities estimated in other parts of the UK (Vardoulakis et al, 2014). In addition to the difference in the risk function in different locations, one reason is that a milder temperature was adopted for the cold threshold in these studies (Hajat et al, 2014; Vardoulakis et al, 2014). Previous research has revealed that the cold burden is highly sensitive to the cold threshold, and a substantial portion of cold-related mortalities is attributed to days with moderate cold temperatures, which are more prevalent compared to extremely cold days (Arbuthnott et al, 2018). However, the excess mortality under extreme cold is more likely to be directly caused by low temperatures compared to moderate temperatures (Arbuthnott et al, 2018).

One limitation of this research is that the historical variations in the cold and heat susceptibilities were assumed to reflect changes in adaptive capacity. The effect of adaptive capacity on the heat burden estimated in this research may be conservative under any climate change and adaptation scenarios due to the small variation in the heat susceptibility observed in the historical period. On the contrary, this research may overestimate the projected cold burden under the scenario with low adaptive capacity because the effect of existing interventions in reducing cold risks, such as building insulation and increasing energy efficiency have long-lasting effects and hence the likelihood that the cold susceptibility deteriorates to the highest historical level may be small.

Nonetheless, this research used a novel approach with the adaptation assumptions informed by both the SSPs and observed susceptibilities historically, and hence the cold/heat burdens projected under five future RCP-
SSPs reflect a wide range of probable future risks. This method is applicable to the estimation of climate change health risks in any locations that have historical risk functions or historical data from which these can be derived and similar SSP frameworks.

In conclusion, the increase in the hot days and associated mortality burden surpasses the decrease in cold days under all scenarios of climate change, indicating heat is a significant health concern even in a cool place like Scotland and the net increase in health risks related to extreme temperatures due to climate change. More than half of the increase in the heat burden between 1980-2000 and 2060-2080 could be prevented if there were no global warming, corresponding to 180-758 deaths/year under different scenarios. The cold and heat mortality rate and the combined mortality burden are both the lowest under RCP2.6-SSP1, which is a low future emissions pathway with high adaptive capacity, emphasising the health benefits of adaptation and climate change mitigation.
Chapter 6. Conclusions

This chapter summarises the three empirical chapters (Chapter 3-5) individually and synthesises the findings along with contributions to the research field and policy implications. It also identifies the limitations of the thesis and makes recommendations for future areas of research.

6.1. Summary of empirical research

Each empirical chapter is summarised briefly in this section focusing on the background, method and findings. The context of each chapter in relation to previous studies is discussed in individual chapters and hence is not repeated here.


Under climate change, many parts of the world are warming with increasing frequencies and intensities of heatwaves, bringing heat-health risks to places including those that have a historically temperate or cool climate. These places may have extensive experience in managing cold-health risks, while experience is lacking in dealing with heat-health risks due to their lack of historical exposure to high temperatures.

This research identified that the cool climate in Scotland poses both challenges and opportunities in managing heat-health risks. Challenges include a perceived lack of heat-health risks by stakeholders and the public, a deficiency in scientific evidence around heat-health risks, and low priority for policy design and implementation. The building stock in Scotland has been primarily designed to reduce heat loss, raising concerns about indoor overheating.

Some people are more susceptible to the adverse impacts of heat, such as the elderly, people who have underlying health conditions. In addition, income, housing design and retrofit, green space and behaviours have been suggested by the stakeholders as important factors affecting the adaptation and susceptibility to ambient temperatures.
This research also highlights multiple opportunities, including a holistic governance approach that combines heat-health governance with other policy priorities such as cold, fuel poverty, and health inequality. This approach improves the efficiency of policy design and implementation by making use of the existing institutional framework and collaboration.

More crucially, adopting a holistic perspective reduces the likelihood of maladaptation (where addressing one issue leads to adverse effects in other domains). For instance, this involves contemplating actions such as insulating homes for warmth and energy efficiency while also considering preventing indoor overheating and air pollution.

6.1.2. Chapter 4: “Temperature-related mortality and associated vulnerabilities: evidence from Scotland using extended time-series datasets”

Adverse health impacts have been found under extreme temperatures in many parts of the world whereas the impacts of ambient temperature on health outcomes in Scottish populations and the vulnerable subgroups remain largely unknown.

This research found adverse cold and heat effects in all cities (Aberdeen, Dundee, Edinburgh and Glasgow) and three other regions in Scotland. The mortality risk is the lowest when the daily mean temperature is 14.5 °C. A higher mortality risk was found for extreme cold than heat, with an increase in all-cause mortality risk by 10% (CI: 8%, 11%) and 4% (CI: 3%, 5%) under extreme cold (the 1st percentile of annual temperature distribution) and extreme heat (the 99th percentile of annual temperature distribution) respectively.

The stratified analysis by demographic and socioeconomic factors identified those who are more susceptible to ambient temperature. The increase in the mortality risk under extreme temperatures was the highest for deaths from respiratory diseases, followed by cardiovascular diseases. This indicates those who have underlying respiratory and cardiovascular diseases are more vulnerable to extreme temperatures. Older age was associated with higher mortality risks from all-cause and cardiovascular diseases under extreme
temperatures. Interestingly, the temperature-related mortality risk from respiratory diseases was higher among the younger (below 75 years old) than the older population. Additionally, the younger population living in the most deprived areas had higher temperature-related all-cause mortality risks than those in less deprived areas.

This research also found differences in the vulnerability to cold and heat. Females experience greater heat effects than males, whereas the reverse is true for the effects of cold, particularly among the elderly. In addition, those who were unmarried have a higher mortality risk than those married under extreme heat, and the effect remains after controlling for age, which was not observed for the cold effect.

It is the first research exploring the temperature-mortality association for the whole population of Scotland and found increased mortality risk associated with both cold and heat exposure. This is particularly evident in some vulnerable groups, including the elderly, deprived young population and people who have pre-existing conditions especially cardiovascular and respiratory diseases.

6.1.3. Chapter 5: “Integrating Shared Socioeconomic Pathway-informed adaptation into temperature-related mortality projections under climate change”

The extent to which populations will successfully adapt to warming temperatures is a crucial factor in determining future health burdens. Previous assessments of temperature-related mortality burdens mostly disregard adaptation or make simplistic assumptions. In addition, the future heat-related mortality burden under a decrease in adaptive capacity, which is a probable scenario where socioeconomic conditions deteriorate, has rarely been explored.

This research utilises a novel method to model adaptation based on historical variation in the susceptibility to cold and heat. These results were used to construct three scenarios of future adaption consistent with the SSPs: increase in adaptation under SSP1, decrease under SSP3 and 4, and no change under SSP2 and 5. These adaptation projections were combined with climate and
population projections to estimate heat- and cold-related mortality up to 2080 under five RCP-SSP scenarios.

Mortality burdens attributable to heat and cold were estimated to be highest under RCP8.5-SSP5 (1196 deaths/year) and RCP4.5-SSP4 (158 deaths/year) respectively by 2080. The increase in the heat burden outweighs the reduction in the cold burden under all scenarios in all future periods by 2080. The total temperature-related mortality burden is lowest under RCP2.6-SSP1 and highest under RCP8.5-SSP5 by 2080. The improvement in adaptation is the largest contributor in reducing the cold burden under RCP2.6-SSP1 whilst the temperature increase determines the high heat burden under RCP8.5-SSP5.

This research indicates that ambient heat will become a more important health determinant than cold in Scotland under all climate change and socio-economic scenarios, underscoring the need for ambitious climate adaptation and mitigation measures.
6.2. Synthesis of research findings and contributions to research

This thesis investigates the important research and policy area of the health risks associated with heat and cold in Scotland under climate change through three interconnected empirical pieces of research encompassing the governance needs (Chapter 3), historical risks (Chapter 4) and future burdens (Chapter 5), as outlined in section 5.1. The thesis as a whole fills the important research gap on this topic in Scotland, and contributes to the evidence needed for the successful development and improvement of policy actions to mitigate the adverse health impacts of heat and cold.

The policy context and governance need on heat and cold-health risks under climate change are explored through stakeholder interviews in Chapter 3. Stakeholder engagement supports multiple objectives of the thesis. Firstly, it highlights a lack of perceived heat-health risks and scientific evidence on heat-health risks in Scotland. This finding provides evidence on the opportunities and challenges of heat-health governance in Scotland, which supports the development of effective heat-health policies and services. It also emphasises the need for understanding the health impacts of high temperatures in Scotland, which is investigated in Chapter 4. Secondly, the findings from the stakeholder engagement informed the design of the empirical studies as well as the interpretation and application of the results. Because of the substantial impacts of low temperatures in Scotland expressed by stakeholders in Chapter 3, the epidemiological study (Chapter 4) and projection of future burden (Chapter 5) are conducted for both high and low temperatures. Engaging the vulnerable population has been identified as a crucial approach to lower heat-health risks in Chapter 3, and hence stratified epidemiology analyses by demographic and socioeconomic factors have been conducted in Chapter 4. The qualitative findings from the stakeholder engagement and the quantitative epidemiological findings are complimentary for the overall objective of the thesis on the science and policy landscape of heat-health impact and governance in Scotland.

As Scotland faces continuing temperature rise under climate change, it becomes imperative to delve into the potential future temperature-related
mortality burdens to be adequately prepared for forthcoming risks. As illustrated in Chapter 3 and 4, temperature-related mortality risks are affected by vulnerability and changes across time due to physiological acclimatisation and socioeconomic adaptation. The change in the susceptibility to cold and heat should be taken into account when estimating future temperature-related mortality burdens to reflect realities where socioeconomic conditions strongly influence future health burdens, which is investigated in Chapter 5.

Under climate change, the rise in hot days and the resulting mortality burden outweighs the decline in cold days regardless of the emission scenario, underscoring the significant health implications of heat, even in regions like Scotland known for cooler climates. Nevertheless, the cold burden should not be neglected too.

Over half of the heat burden increase observed between 1980-2000 and 2060-2080 could be reduced under a counterfactual scenario with no global warming, potentially preventing 180-758 deaths per year across various scenarios. The future temperature-related mortality burdens are also hugely influenced by the increase in population size and especially in the elderly population. Demographic changes counteract a considerable portion of the decrease in the cold burden resulting from temperature increases and contribute substantially to the rise in the heat burden.

The heat- and cold-related mortality rate is projected to be the highest under RCP4.5-SSP4 and RCP8.5-SSP3 respectively. In 2060-2080, RCP2.6-SSP1 observed the lowest mortality rate attributable to both heat and cold, with 50 and 8 deaths per million population respectively, illustrating the health benefits of a low emission scenario with sustainable socioeconomic development pathways.

This thesis uses Scotland as a case study to investigate the temperature-related mortality in a cool nation across three pivotal research fields: policy, epidemiology and climate change health impact assessment. The research collectively addresses the research gap on vulnerability and adaptation to cold and heat in Scotland. Thus, stakeholders’ perceptions of vulnerability and
preferences for different types of vulnerability measures are first discussed qualitatively. This informs empirical epidemiological research through stratified analyses to quantitatively assess the difference in the population’s susceptibility to heat and cold. Assuming that socioeconomic adaptive capacity explains the temporal variation in the heat/cold susceptibility in the historical 45 years, future risk functions with adaptation scenarios were combined with temperature and population projections from consistent scenarios to estimate temperature-related mortality burdens by 2080.

6.3. Policy implications

The health and wellbeing impacts of high temperatures are one of the most urgent climate change risks in Scotland identified by the UK Climate Change Risks Assessment (Sniffer, 2021). This thesis could support the development of policies by providing evidence in terms of both epidemiological findings on the health impacts of ambient temperature and stakeholder perspectives on heat-health governance in Scotland. An essential strength of these studies is the early involvement of stakeholders during the PhD research, where their valuable perspectives are integrated into the study design of the epidemiological and health impact investigations. This approach enhances the policy relevancy and practical applicability of the results, ultimately benefiting the research's overall outcome.

This thesis found a decrease in the cold-related mortality risk in 2000-2020 compared to 1980-2000 in Scotland. This decrease in cold risk may reflect the effect of policy actions on reducing fuel poverty and improving energy efficiency (Scottish Parliament, 2019; Scottish Government, 2021a). These policies are also driven by the Scottish Government’s target of reaching net zero greenhouse gas emissions by 2045 as required by the Climate Change (Emissions Reduction Targets) (Scotland) Act 2019.

On the contrary, there has been a lack of policy on reducing heat-health risks in Scotland. As expressed by stakeholders, a lack of scientific evidence on heat-health risk in Scotland contributes to its low policy priority. This thesis helps fills this gap by conducting epidemiological analyses for the association between
mortality risk and temperature which reveals that the mortality risk starts to increase when the daily mean temperature is above 14.5°C in Scotland. Additionally, the mortality burden due to extreme heat is estimated to exceed the cold burden in the future under climate change scenarios. In addition, the temperature-related mortality burden is lowest under the low-emission scenario RCP2.6-SSP1 and highest under the high-emission RCP8.5-SSP5 by 2080. These findings demonstrate that ambient heat will become an important health determinant in Scotland, underscoring the need for climate adaptation and mitigation measures as well as actions to reduce heat-health risks.

It is crucial to identify the vulnerable populations who experience higher health impacts from ambient temperature, which could help develop strategies to provide targeted interventions and reduce health inequality. This thesis identified the elderly, younger populations living in deprived communities, and people who have pre-existing conditions, particularly respiratory and cardiovascular diseases are more susceptible to the adverse health impacts of ambient temperatures compared to their counterparts.

There are several challenges in engaging the vulnerable population. There is generally low awareness of the heat-health impacts among the public of Scotland. In addition, some vulnerable populations such as elderly people may not perceive themselves to be at risk of health impacts of heat (Wolf et al, 2010a; Ratwatte et al, 2022). This may prevent them from taking preventative actions and hence face severe health risks that progress fast before receiving medical treatment, reflected by the higher heat-related mortality than hospitalisation risks found in previous studies (Liu et al, 2022).

One strategy to communicate heat warnings and encourage preventative actions can be framing the advice as helping their vulnerable relatives and neighbours as people tend to not perceive themselves as being vulnerable but may be keen to help people around them (Sampson et al, 2013; Roberts, 2022). In addition, heatwaves may be named as the way that winter storms are given names in the UK to raise public awareness (Portsmouth, 2022; Met Office, n.d.-c). This approach has not been widely adopted because heatwaves
are usually characterised based on local climate with no universal definition as the impact of the same high temperature may cause different impacts in different places (Xu et al, 2016; Page, 2022). Nevertheless, Seville, Spain named the heatwave hitting Seville at the end of July 2022 as “Zoe”, which is the first city in the world to start naming heatwaves (Arsht-Rock Resilience Center, 2021; Osborne, 2022).

A holistic governance approach integrating the governance of cold and heat-health risks has been preferred by stakeholders. This is in line with the recent publication of a single Adverse Weather and Health Plan in England by merging the previous Heatwave Plan and Cold Weather Plan (UK Health Security Agency, 2023). One benefit of holistic governance is to achieve synergetic effects and co-benefits on multiple issues, such as heat and cold risks, fuel poverty, health inequality and climate change management. These issues may have common underlying contributors such as poverty and deprivation, and hence addressing these common vulnerabilities is beneficial to the improvement of all issues. In addition, measures on heat-health risks can be integrated into current measures to make use of existing infrastructure and networks. For example, Bristol City Council provides “welcome spaces”, which are communal spaces where the public can keep warm as well as access food, benefits advice and educational support (Roig, 2022). Considering the increasing temperature under climate change, it is desirable to provide communal cool spaces in hot weather as well.

Taking a holistic approach could also minimise the negative impact of an isolated action on another issue. For example, indoor overheating risk should be considered in building design and renovation along with keeping homes warm, improving energy efficiency and indoor air quality. In addition, air conditioning is a measure of reducing indoor overheating, whereas reducing indoor overheating by passive cooling and building design may be preferred considering energy consumption and climate change mitigation.

6.4. Limitations
Some main limitations of this thesis are discussed in this section.
6.4.1. Stakeholder interview
The interviewee sample size (n=15) for the heat-health governance study is relatively small, and hence the findings may not be a conclusive picture of stakeholder perspectives. However, an extensive stakeholder mapping was conducted to identify organisations and individuals who have the potential to influence, either directly or indirectly, policy decisions and the delivery of heat-health action plans. Stakeholders in Scotland and England who have a work or research background in Scotland, or who have collaborations with the Scottish stakeholders are identified. A total of 59 interview invitations were sent out to identified stakeholders. Among them, 19 refused the interview and reported a lack of focus or expertise in this topic, 9 stated no capacity, and 16 did not reply.

The low response rate and high rate of reported lacking expertise among the invited stakeholders partly reflect the situation of a gap in heat-health research and governance in Scotland. It was found that a small number of stakeholders who have expertise or interest in this topic were not interviewed because they have no capacity to take the interview. The interviews were conducted in the winter of 2020/2021 when the COVID-19 pandemic was the major social, policy and medical focus. We only received one written response from a medical general practitioner. This brings a limitation of this thesis which lacks perceptions of health and social care practitioners who have close contact with patients and the vulnerable population. However, we interviewed professionals from Public Health Scotland, Public Health England, NHS health boards, and environmental epidemiologists.

In addition, the interviews were conducted in winter, and the temperatures at which the interviews were conducted may affect the perception of the interviewees. This may introduce recall bias, e.g. the result of the perceived heat-health risk might be slightly different if the interviews were undertaken during a heatwave, which is an interesting future research topic.
6.4.2. Heat effect modelling in Chapter 4 and 5

Both Chapter 4 and 5 performed epidemiological analyses of the temperature-mortality association. The focus of Chapter 4 is investigating the mortality risk associated with ambient temperature for the Scottish population as well as demographic and socioeconomic subgroups in 1974-2018. The temporal trend in the slope of the temperature-mortality association is analysed in Chapter 5, with the objective of informing future adaptation scenarios. There are several differences in the data used for the epidemiological analysis in Chapter 4 and 5.

6.4.2.1. Population-weighted and unweighted temperature

In Chapter 4, population unweighted city/regional average daily mean temperatures are used as the exposure variable, but population-weighted temperatures are used for Chapter 5. The latter variable was chosen in Chapter 5 to reduce the exposure measure error. As the outcome variable is the mortality count on population level over a city or region in Scotland in this thesis, one proxy daily temperature exposure was used as the representative exposure for the whole population or area of interest to match the spatial resolution of the exposure and outcome data.

This may bring exposure measurement error when the temperature of a region is not homogenous, e.g. the urban areas are hotter than the surrounding areas due to the Urban Heat Island effect (Tomlinson et al, 2011; Ma et al, 2015), and/or the population a region is not evenly distributed (Lee et al, 2016; Spangler et al, 2019). This exposure measurement error may reduce the precision of the epidemiological analysis results on the relative risk of mortality under cold and heat. One solution to reduce this exposure measurement error is to use population-weighted city/regional average temperatures as the exposure, which takes into account the temperature and population distribution over an area. The population-weighted average temperature in Scotland is higher than the unweighted temperature, with the heat threshold (the 90th percentile of temperature distribution in 1974-2018) being 14.5 and 15.0°C respectively. Sensitivity analyses comparing the mortality risk associated with
high and low temperatures by using population-weighted and unweighted temperatures as the exposure measurement is an interesting future study.

6.4.2.2. Months used for the heat effect analysis
The heat effect was analysed using data in June, July and August (JJA) in Chapter 4, and data in May-Sep (MtS) was used for Chapter 5. Initially, JJA was used in Chapter 4 because these are the typical summer months which have higher monthly temperatures than other months. May and September are excluded in the analysis for either the cold or the heat effect in Chapter 4 because these two months contain both moderately low and high temperatures and hence including them in the cold or heat analyses may introduce noise in the exposure.

As the PhD research progressed, the heat effect analysis was extended to MtS in Chapter 5. This is because May and September contain days in which the temperature is beyond minimum mortality temperature. In addition, the adverse health effects of heat have been found to be higher in the early part of the warm season in previous studies such as the US, France and Sweden (Rocklov et al, 2011; Barnett et al, 2012; Alari et al, 2023). This may be the effect of the absence of short-term acclimatisation and preparedness in the early warm season (Sheridan & Lin, 2014). Therefore, May and September are included in the analysis of the heat effect in Chapter 5, which also provides the basis for the health impact assessment under climate change in order to capture total mortality burdens.

An interesting future research is to study the potential monthly variation of the mortality and morbidity risk associated with daily temperatures, especially for different age groups, cause of deaths and the pattern of mortality displacement. This research could indicate the potential difference in the vulnerability in different months and have implications on designing effective interventions. For example, the temperature threshold trigger a heat warning of the Heat Health Warning System in Germany is adjusted by the meteorological conditions in the 30 previous days to take into account short-term acclimatisation (Matzarakis et al, 2020).
6.4.3. The effect of other meteorological variables on health

As reviewed in Chapter 2, other meteorological variables such as humidity, wind and solar radiation can affect thermal comfort and stress. A sensitivity analysis is conducted for the modifying effect of relative humidity (RH) on the temperature-mortality association using data from Edinburgh between 2004-2018 (Chapter 4), which finds no difference in the temperature-mortality association with and without the control of RH. However, relative humidity may not be the most relevant humidity variable. A recent review by Baldwin et al (2023) suggests water vapour mass-based measure of humidity (see below) is a more suitable variable to be included in health assessments for thermal impacts rather than relative humidity.

The air humidity influences thermal comfort mainly by affecting the evaporation rate of sweat. Evaporation from a moist surface (i.e. the skin in the context of sweating) is affected by multiple factors, especially the concentration of water vapour in the air (Baldwin et al, 2023). Water vapour concentration can be reported using multiple measures such as specific humidity (the ratio of water vapour mass to air mass), dew point temperature (the temperature to which air would have to be cooled with no change in air pressure or moisture content for saturation to occur) and vapour pressure (the ratio of water vapour pressure to total pressure) (Ahrens, 2013). These measures of water vapour concentration are unaffected by the air temperature.

In contrast, RH is the ratio of the air’s actual water vapour content to its capacity, with the capacity being affected by the air’s temperature (Ahrens, 2013). Therefore, RH accounts for fluctuations in both air temperature and water content. Using a humidity measure that is affected by temperature, or a composite thermal index such as apparent temperature integrating multiple meteorological variables including temperature and humidity makes it difficult to disentangle the contribution of temperature and humidity to the health impacts (Baldwin et al, 2023). Therefore, humidity measures that are unaffected by temperature rather than RH are recommended by Baldwin et al (2023) for the epidemiological study on the TM association.
However, as reviewed in Chapter 2.1.2, previous epidemiological studies do not reach a consensus that integrating humidity in the modelling of the association between temperature and mortality leads to a better model fit (Carder et al, 2005; Barnett et al, 2010). Several hypotheses have been postulated to explain the different findings of the importance of humidity in thermal stress in physiological and epidemiological studies (Baldwin et al, 2023), such as

- The temperature and humidity conditions resulting in sweating deficiency have rarely been reached in the study locations of existing studies such as Scotland, and hence humidity has less effect on evaporative cooling.
- Difference in the specification of humidity as discussed above.
- Humidity may be less accurately forecasted than temperature.
- Sweating is an important mechanism of heat dissipation, and the efficiency is lower when the surrounding humidity, which is a major reason that heat stress indices often integrate air humidity. However, sweating may be attenuated in the vulnerable population due to ageing, taking certain medication or dehydration, and hence the surrounding humidity has a limited effect on heat dissipation in epidemiological studies.
- Some temperature-related hospitalisation and mortality may be an effect of temperature and unrelated to humidity or other meteorological variables.

Along with humidity, cloud cover (affecting radiate temperature) and wind were not controlled in this thesis. Although they may influence thermal comfort, they are often disregarded in epidemiological studies on the TM association because they are less frequently and reliably measured than air temperature (Oertel et al, 2015; Simpson et al, 2023). In addition, a previous study in Glasgow performed outdoor surveys of thermal sensation and found air temperature has a similar prediction of thermal sensation to the composite thermal index Physiologically Equivalent Temperature which integrates air temperature, relative humidity, wind velocity and radiant temperature (Oertel et al, 2015). However, the effect of different meteorological variables on thermal comfort and
temperature-related mortality and morbidity impacts require more research, which may vary depending on population and region.

6.4.4. Vulnerability and adaptive capacity

In Chapter 4, the variation in the heat- and cold-related mortality risk across different demographic and socioeconomic subgroups are assessed to identify the vulnerable subgroup. In order to protect the personal information of the deceased, the mortality data can only be obtained as a daily count aggregated over a city or region and for some demographic and socioeconomic factors. Due to data availability and practicability issues, this thesis selected age, sex, marital status, areal deprivation and cause of death as the key factors. For deprivation at the small-area level, the Carstairs Index score was used. The Carstairs Index is composed of four indicators—overcrowding, unemployment, low social class and not having a car (Carstairs & Morris, 1989). These measures together reflect material deprivation and the Carstairs Index has been widely used to study health inequality in Scotland (Brown et al, 2014).

There are multiple limitations arising from using the Carstairs Index. Firstly, it may not fully reflect socio-economic vulnerability to cold and heat exposures because the Carstairs Index was initially designed to reflect material deprivation (Lindley et al, 2011). In addition, the factors affecting deprivation are different in different locations and have been changing over time, and hence it is unlikely that any indicator could capture deprivation and its spatial-temporal distribution fully. Previous studies found the Carstairs Index has a decreased ability in explaining the health inequality between Scotland and England between 1981-2011 (Schofield et al, 2016). The decreased ability is, at least partially, due to changes in peoples' lived experiences and the relative importance of different aspects of deprivation such as car access (Schofield et al, 2016). Furthermore, the Carstairs Index is calculated at small area levels, which may not reflect the deprivation situation that individuals experience due to ecological fallacy (Openshaw, 1984; Flowerdew et al, 2008). Therefore, using the Carstairs Index may underestimate the effect of deprivation on temperature-related mortality risks.
The Carstairs Index was used in Chapter 4, rather than more up-to-date deprivation indices such as the Scottish Index of Multiple Deprivation (SIMD) which includes a more comprehensive list of factors affecting material and social deprivation such as education, crime and geographical access to services. This is because the Carstairs Index can be calculated for as early as 1981 using Census data whereas the SIMD is only available since 2004 and so cannot cover the whole time period of the data used in this thesis (National Statistics, 2020).

Other factors may modify the vulnerability to heat and/or cold, such as green space and housing conditions as found in Chapter 3. This thesis found the historical variation in the cold effect largely coincides with the historical energy price (Chapter 5). The effect of these factors on the vulnerability to heat and cold is not assessed in this thesis. In addition, the historical variations in the heat and cold effect are assumed to reflect changes in adaptive capacities in Chapter 5, whereas the specific mechanisms for adaptation are not explored. These are noteworthy future research areas and will be discussed in more detail in Section 5.4.2.

6.5. Future research

Continuing studies in multiple areas can be conducted in the future, including further epidemiological studies to explore the health impacts of ambient temperature. Some future areas of research have been mentioned in Chapter 6.4. For example, comparing the mortality risks associated with daily temperatures using population-weighted and unweighted temperatures, and investigating potential differences in the mortality risk associated with daily temperatures in different months (Chapter 6.4.2). Additionally, examining the potential effect of seasonal temperatures on how the general public and policymakers perceive health risks associated with cold and heat as well as the influence on long-term planning and immediate health protection behaviours is a compelling area of exploration (Chapter 6.4.1).

Two potential future research topics are explored in more detail in this section, one on the temperature-related health risks from respiratory diseases of
different age groups (Chapter 6.5.1), and another one on the relationship between energy price and cold-related mortality risk (Chapter 6.5.2).

6.5.1. Temperature, age and health impacts on the respiratory system

The older population has generally been found to be more susceptible to cold and heat than the younger population. A higher mortality risk from all-cause and cardiovascular diseases among the elderly than the younger population is found for the Scottish population in Chapter 5.1. However, this thesis finds those who are 0-74 year’s old have a higher cold and heat-related mortality risk from respiratory diseases (RESP) than those 75 years old and above. The increase in temperature-related mortality risk from RESP among the younger population may indicate premature ageing and mortality for individuals who could have had a longer life expectancy if not exposed to cold or heat. This is in contrast to mortality displacement where deaths are brought forward shortly (typically within days or weeks) by cold/heat exposure in individuals who are already in an advanced stage of illnesses (Hajat et al., 2005).

Future research could utilise lagged exposure to cold/heat to estimate premature mortality and mortality displacement. An increase in the mortality risk shortly after cold/heat exposure followed by a decrease in the mortality risk (i.e. deficit) at long lags typically implies mortality displacement (Hajat et al., 2005). A previous study finds the increase in all-cause mortality risk persisted for 2 days after heat exposure, followed by deficits in the following days, leading to a negligible cumulative risk by day 11 in London, indicating mortality displacement (Figure 6-1; Hajat et al. 2005). A similar pattern is shown for CVD mortality under heat exposure in this research. However, the mortality risk from RESP sustains over a lag of 4 weeks, suggesting an increase in heat-related premature mortality from RESP (Figure 6-1). Therefore, temperature-related mortality risks from different causes of death have different lengths of lag and mortality displacement patterns.
Importantly, the mechanisms contributing to the difference in temperature-related mortality risk from RESP among different age groups have rarely been investigated in previous studies. Several hypotheses of the higher risk among the younger than the older population include the higher prevalence and incidence of asthma among children, young and middle-aged adults in the UK (British Lung Foundation, n.d.), and a higher proportion of smokers among the younger population (ASH, 2021). In addition, the elderly tend to stay indoors when the outdoor temperature is low and hence might have reduced their exposure to low temperatures (Achebak et al, 2020).

A higher RESP mortality risk due to cold exposure among the younger than the older population has also been found in previous studies in Scotland (Carder et al, 2005), some locations in Europe including Hungry, Spain and Sweden (Analitis et al, 2008; Achebak et al, 2020) and Chicago, the US (O’Neill, 2003). However, it should be noted that the age grouping of 0-75 year’s old is relatively broad, and temperature-related mortality may still be dominated by the older population within this age group. Therefore, finer age groupings would be useful.
in future research to explore the vulnerability of temperature-related mortality from respiratory diseases.

In contrast to the findings for Scotland, many other European locations, including London, show that the older population have a higher cold-related RESP mortality risk compared to the younger population (Analitis et al, 2008). Therefore, there is a need for further research to explore temperature-related mortality and hospitalisation due to RESP diseases among more detailed age groups as well as different RESP diseases such as asthma, chronic obstructive pulmonary disease, lung cancer and bronchitis. In addition, the effect of socioeconomic, environmental and behavioural factors such as deprivation, green space, housing conditions, air pollution and smoking should also be preferably assessed to help interpret the results and to identify the vulnerable population. The Scottish Longitudinal Study may be useful data for this purpose, which contains a wide range of variables describing cultural, demographic, economic, health, education, ecological, housing and social data for a five per cent sample of the population of Scotland since 1991 (Boyle et al, 2008).

6.5.2. Energy price and cold-related mortality risk

The findings of Chapter 5 reveal a sudden increase in the cold effect from 1982-2001 to 1983-2002. The cold effect remains high until 1987-2008 and then decreases steadily until 1997-2018. Due to the large overlap between the two periods 1982-2001 and 1983-2002, the sudden increase in the cold effect is likely due to

1) new risk factors or an increase in the severity of risk factors in 2002; and/or

2) the presence of protective factors contributing to cold acclimatisation/adaptation before 1982

In addition, the risk or protective factor should only have an effect on cold-related mortality because there is no abrupt change in the heat effect between 1982-2001 to 1983-2002 (Chapter 5.3). One hypothesis for the factor contributing to the cold acclimatisation in 1982 is that there is a severe cold
Chapter 6

spell and the lowest daily mean temperature in 1982 within the period 1974-2018 (Figure 6-2). People may have gained short-term acclimatisation from the cold spell and hence have reduced cold susceptibility. This hypothesis can be tested by conducting the epidemiological analysis in Chapter 5 while excluding the year 1982.

Another more likely hypothesis of the temporal variation in the cold effect and the abrupt increase of it between 1982-2001 to 1983-2002 is the change in energy price and fuel poverty. The availability and cost of energy may affect indoor thermal comfort and hence cold-health risks.

There is an increase in domestic energy bills for gas from 2002 and for electricity in 2004 in the UK, a reverse of the previous decreasing trend (Figure 6-3 a). In addition, there is an increase in fuel poverty between 2003 and 2010 despite the increase in energy efficiency in Scotland, which then decreases between 2011 and 2016 (Figure 6-3 b).
Figure 6-3. (a) Average domestic fuel bill for a typical consumer back to 1996 in the UK (2010 prices) (Rutherford, 2018). (b) Average UK household fuel prices (p/kWh, 2012 prices) (Department of Energy & Climate Change, 2013). (c) Trends in energy price, energy efficiency (EE) and median income in Scotland between 2003-2016 (Scottish Government, 2017b).

The annual cold effect in Scotland suggests a connection between historical energy costs and fuel poverty. Future research can be conducted to investigate the association between energy price, fuel poverty and cold-related mortality risk. This will have crucial policy implications considering the sharp rise in energy prices in the UK in 2022. The huge increase in energy price may lead to increased adverse health impacts and in turn further economic costs (e.g. from excess deaths and hospitalisation), which requires further research to inform intervention measures and policies. This is currently being investigated.
for England by the Health Protection Research Unit in Environmental Change and Health at the London School of Hygiene and Tropical Medicine.

6.6. Concluding remarks
This PhD study delves into the health implications of extreme temperatures in Scotland, presenting a need for heat-health governance and ambitious climate adaptation and mitigation measures. As historical climate conditions in Scotland have been relatively cooler, Scotland has been actively implementing measures to mitigate the impacts of cold weather, while the population lacks the experience to cope with escalating heat-health risks under climate change. Addressing these issues requires comprehensive and well-coordinated governance, considering both qualitative evidence from stakeholders and epidemiological evidence on health impacts and burdens, which has been explored in this thesis.

In conclusion, this thesis sheds light on the multifaceted health impacts of extreme temperatures in Scotland. The findings demonstrate that heat is poised to become a significant determinant of public health in Scotland under climate change. As temperatures continue to rise, the health risks associated with extreme heat demand urgent attention to safeguard vulnerable populations, such as the elderly and young people in deprivation. The research emphasises the importance of proactive heat-health governance and climate adaptation and mitigation measures to combat the escalating risks associated with rising temperatures.
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**Supplementary materials**

### S1. Summary table of the scoping review in Chapter 2.2.2.

Summary of the 55 studies projecting future temperature-related health burden integrating adaptation scenarios. The method used to model adaptation has been categorised into: analogue location (AL), analogue time (AT), adjusting the susceptibility to ambient temperatures (AS), constructing the TM association while incorporating other climatic (CV-C) or socioeconomic (CV-S) covariates, extrapolating historical trend in the susceptibility (HT-S) or MMT (HT-M), land-use and building changes (LB), adaptation projected under Shared Socioeconomic Pathways (SSP), shift in the threshold temperature—absolute (TS-A) or relative (TS-R).

<table>
<thead>
<tr>
<th>Category</th>
<th>Paper</th>
<th>Location</th>
<th>Method of modelling adaptation</th>
<th>Result</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>AL</td>
<td>An evaluation of climate/mortality relationships in large U.S. cities and the possible impacts of climate change (Kalkstein &amp; Greene, 1997)</td>
<td>44 US cities</td>
<td>Analogue cities were established for each evaluated city. These analogues represent cities whose present climate approximates the estimated climate of a target city as expressed by the GCMs.</td>
<td>Excess winter and summer mortalities were projected for 2020 and 2050 using three GCMs assuming acclimatisation, but not projected assuming no acclimatisation.</td>
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<tr>
<td>AL</td>
<td>Projecting heat-related mortality impacts under a changing climate in the New York City</td>
<td>New York City region, USA</td>
<td>Adaptation was modelled by applying the heat exposure-mortality response function derived from two US cities, Washington, DC and Atlanta, Ga, whose present climates are within 1°F of the projected climate in the New</td>
<td>Adaptation reduced additional heat-related mortality due to climate change by around 25%.</td>
<td></td>
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### Supplementary materials

<table>
<thead>
<tr>
<th>Study</th>
<th>Region</th>
<th>Climate Change Impacts</th>
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</thead>
<tbody>
<tr>
<td>AL</td>
<td>York region in the 2050s under SRES A2.</td>
<td>The cold and heat thresholds (1&lt;sup&gt;st&lt;/sup&gt; and 99&lt;sup&gt;th&lt;/sup&gt; percentile of temperature distribution in May-Sep and Nov-Mar respectively) were calculated for 33 US cities under investigation. Adaptation was modelled by applying the highest threshold temperature for both the cold and heat thresholds among the 33 cities for all cities in 2100.</td>
<td>Adaptation reduced heat-related mortality by 30%-60% under different scenarios by 2100.</td>
<td>This study assumed a gain in heat adaptation (reflected by using a high heat threshold) and a loss in cold adaptation (using a high cold threshold) in the future.</td>
<td></td>
</tr>
<tr>
<td>AL</td>
<td>33 US cities</td>
<td>Applying the ERF in analogue cities for the location under investigation to take into account adaptation.</td>
<td>Adaptation decreased heat-related mortality by 11% and 36% in the 2050s and the 2070s respectively (RCP8.5).</td>
<td>It's unknown which city was selected as the analogue city.</td>
<td></td>
</tr>
<tr>
<td>AT</td>
<td>55 Chinese cities</td>
<td>Applying the ERF in analogue cities for the location under investigation to take into account adaptation.</td>
<td>Adaptation decreased heat-related mortality by 11% and 36% in the 2050s and the 2070s respectively (RCP8.5).</td>
<td>It's unknown which city was selected as the analogue city.</td>
<td></td>
</tr>
</tbody>
</table>

### Study Details

**AL**
- **Climate change impacts on extreme temperature mortality in select metropolitan areas in the United States (Mills et al, 2015)**
- **55 Chinese cities**
  - Applying the ERF in analogue cities for the location under investigation to take into account adaptation.
  - Adaptation decreased heat-related mortality by 11% and 36% in the 2050s and the 2070s respectively (RCP8.5).
  - It's unknown which city was selected as the analogue city.

**AT**
- **The impact of climate change on human health: Some international implications**
- **15 cities in the USA, 10 cities in Canada, 2 in China and 1 in Egypt**
  - This study assumed the difference in the relationship of summer temperature and mortality between hot and cool summers was attributable to acclimatisation. The regression line slope during hot summers is used for acclimatisation.
  - Acclimatisation was found in most US and Canadian cities studied. No acclimatisation was found for China and Egypt. In some cities negative acclimatisation was observed.
### Supplementary materials

<table>
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<th>Study</th>
<th>Location</th>
<th>Methodology</th>
<th>Result</th>
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<tr>
<td>(Kalkstein &amp; Smoyer, 1993)</td>
<td></td>
<td>future projections representing the acclimatised scenario.</td>
<td>(higher mortality under acclimatised than unacclimatised scenarios). Under acclimatisation scenario, the mortality was reduced by up to around 50% compared to the unacclimatised scenario.</td>
</tr>
<tr>
<td>AT</td>
<td>Emissions pathways, climate change, and impacts on California (Hayhoe et al, 2004)</td>
<td>Los Angeles, USA To account for potential acclimatisation, the study applied the TM association in the 5 hottest summers in 24 years in Los Angeles to the future, which had a lower heat susceptibility than other summer.</td>
<td>Adaptation reduced heat-related mortality by 20-25% by the 2090s (SRES B1 and A1fi).</td>
</tr>
<tr>
<td>AT</td>
<td>Differential and combined impacts of extreme temperatures and air pollution on human mortality in south-central Canada. Part II: future estimates (Cheng et al, 2008)</td>
<td>4 cities in south-central Canada This study assumed the difference in daily mean deaths within five hot and five cool summers was attributable to acclimatisation. The difference was applied to discount projected heat-related deaths to take into account acclimatisation.</td>
<td>40% heat-related mortality was reduced due to acclimatisation</td>
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<th>AT</th>
<th>An Examination of Climate Change on Extreme Heat Events and Climate–Mortality Relationships in Large U.S. Cities (Greene et al, 2011)</th>
<th>40 US cities</th>
<th>Future extreme heat event attributable deaths were projected using the TM associations in 1975-1995, 1996-2004 and 1975-2004. The projected heat-related mortality based on the TM association in 1975-1995 is the baseline burden, and the projection based on the TM association in 1975-2004 (to gain estimation precision from a larger sample size, this longer period was used instead of 1996-2004) was applied to the future to take into account of existing adaptation.</th>
<th>Excess mortality reduced by around 20% under adaptation scenario (using the ERF from 1975-2004) compared to no adaptation scenario (1975-1995).</th>
<th>There was an increase in heatwave alert, response and public awareness following the 1995 heatwave in Chicago, and hence the study assumed the difference between the shape of the ERFs with and without post-1995 periods represents the effect of adaptation. The adaptation scenario assumed the ERF in the future is the same with the period 1975-2004, where future adaptation was not modelled.</th>
</tr>
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<tbody>
<tr>
<td>CV-C</td>
<td>Accounting for adaptation and intensity in projecting heat wave-related</td>
<td>209 US cities</td>
<td>An interaction term of the occurrence of heatwave and mean summer temperature (MST) was used in the risk function of heatwave and mortality (1962–2006) to account for adaptation. The effect of adaptation in reducing The heat susceptibility decreased with higher MST, suggesting that adaptation occurred. The association between heatwave mortality and MST is nonlinear—higher MST</td>
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<th>AT</th>
<th>Future heat vulnerability in California, Part II: projecting future heat-related mortality (Sheridan et al, 2012)</th>
<th>California, US</th>
<th>Acclimatisation was modelled by neglecting all heat-related mortality that occurs in the first 3 days of a given string of oppressive weather type days.</th>
<th>Acclimatisation may reduce heat-related mortality by 37%-56 % in the 2090s under various climate change scenarios. The projected heat-related mortality under acclimatisation assumption is still 4-11 times the historical mortality values (1975–2004)</th>
<th>Little empirical evidence supporting the adaptation assumption.</th>
</tr>
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<tr>
<td>CV-C</td>
<td>City-level vulnerability to 208 US cities</td>
<td>Adaptation was explored in 2 ways: 1) seasonal mean temperature, AC</td>
<td>Adaptation reduced the heat-related mortality by 97% and</td>
<td>This study did not find stable predictors of heat</td>
<td></td>
</tr>
<tr>
<td>CV-S</td>
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Future heatwave mortality was estimated by the difference in the projection results using models with and without the interaction term with MST. Resulted in lower effect of heatwave when the MST was below 30 °C, and the adaptation effect lessened when the MST was between 20-30°C; the adaptation ceased when the MST was above 30 °C. Future adaptation was expected to play a larger role in northern US where there is a lower AC prevalence at present and hence a larger adaptation potential than southern US.

AT: Analysis of results for the entire dataset. CV-C: City-level vulnerability to 208 US cities. CV-S: Seasonal mean temperature, AC.
### Supplementary materials

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<th>AT</th>
<th>temperature-related mortality in the USA and future projections: a geographically clustered meta-regression (Lay et al, 2021)</th>
<th>prevalence, total population and population ageing were assessed as predictors of heat susceptibility in each climatic cluster (9 in total). 2) The ERFs were fitted separately in four time periods (1973–82, 1983–92, 1993–2002, and 2003–13) to quantify the historical trend. The study used the result from the first and last historical period as an approximation of a low and high adaptation scenario respectively.</th>
<th>84% in a 2°C and 6°C increase in mean temperature scenarios respectively.</th>
<th>susceptibility because of the small number of cities included in each individual cluster, the low variation in some of the predictors within clusters, and tight correlations among some predictor variables resulted.</th>
</tr>
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<tbody>
<tr>
<td>CV-C</td>
<td>Evidence of rapid adaptation integrated into projections of temperature-related excess mortality (Huber et al, 2022)</td>
<td>This study assessed the association between the MMT and mean summer temperatures (MSTs) across time (1978–2017). Under the adaptation scenario, the future MMT was predicted from the association between MMT and MST using the projected climate.</td>
<td>The MMT increased by 0.73 °C per 1 °C rise in MST over time. Adaptation reduced heat-related mortality by 63.5%, increased cold-related excess mortality by 63.7%, and reduced net temperature-related mortality by 11.2% in the 2090s under ssp3-7.0.</td>
<td>The study also found the MMT increased by 0.84 °C per 1 °C rise in MST across cities. The increasing rate in the MMT may decline over time because there may be a limitation in heat acclimatisation, which was not taken into account in the study. When shifting the MMT,</td>
</tr>
</tbody>
</table>
**TS-A**  
Heat stress and mortality in Lisbon Part II. An assessment of the potential impacts of climate change (Dessai, 2003)  
Lisbon, Portugal  
This study assumed that an increase of 1 °C in the heat threshold is reached after 3 decades (compared to the 1990s).  
Adaptation reduced the heat-related mortality rate by around 60% in the 2050s.  
The author expressed that “the assumption that people will acclimatise to 1 °C per 30 years is simply illustrative.”

**TS-A**  
Projection of economic impacts of climate change in sectors of Europe based on bottom up analysis: human health (Watkiss & Hunt, 2012)  
European Union member states  
A 1 °C increase in the heat threshold and a 1°C decrease in the cold threshold every 3 decades to model heat and cold adaptation.  
Acclimatisation can reduce up to 100% of additional heat-related mortality and reduction in cold-related mortality from climate change by 2100 under SRES B2 compared to 1961–1990.  
Under SRES A2, acclimatisation can reduce 55%-84% of additional heat-related mortality and 75%-100% of the reduction  
This authors stated that the scenario with a decline in the cold sensitivity should be treated cautiously due to little evidence on this assumption. The reduction in cold burden was projected to outweigh the increase in heat burden in 2010-
### Supplementary materials

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<tr>
<th>TS-A</th>
<th>Climate change and heat-related mortality in six cities Part 2: climate model evaluation and projected impacts from changes in the mean and variability of temperature with climate change (Gosling et al, 2009a)</th>
<th>Boston and Dallas US; Budapest, Hungary; Lisbon, Portugal; London, UK; Sydney, Australia</th>
<th>This study assumed two adaptation scenarios where the heat thresholds increase by 2°C and 4°C in 2070–2099 compared to 1961–1990.</th>
<th>Acclimatisation of 2°C reduced heat-related mortality rate by 30–50%, and acclimatisation of 4°C further reduced the heat-related mortality rate by 20-60% in the 6 cities worldwide.</th>
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<td>TS-A</td>
<td>Climate change and temperature rise in the Greater Beirut Area: implications on heat-related premature mortality</td>
<td>Greater Beirut Area, Lebanon</td>
<td>A 1 °C in the heat threshold in 2095 compared to the identified threshold temperature in 1997-1999.</td>
<td>Adaptation reduced the additional heat-mortality due to climate change in 2095 compared to 1961–1990 by 46% under SRES A1FI, 68% under SRES A2 and 159% under B1.</td>
</tr>
<tr>
<td>Study</td>
<td>Description</td>
<td>Area</td>
<td>Impact</td>
<td>Adaptation</td>
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<tr>
<td>(El-Fadel &amp; Ghanimeh, 2013)</td>
<td>Probabilistic spatial risk assessment of heat impacts and adaptations for London (Jenkins et al, 2014)</td>
<td>Greater London and the surrounding region, UK</td>
<td>An increase in the heat threshold by 1 °C or 2 °C in both the 2030s and 2050s.</td>
<td>Adaptation reduced annual heat-related mortality by 32–69% across the scenarios tested.</td>
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<tr>
<td>TS-A</td>
<td>Updated projections of UK heat-related mortality using policy-relevant global warming levels and socio-</td>
<td>Whole UK</td>
<td>Absolute threshold shift: Shift the heat threshold by 1 °C or 2 °C in any future periods. Relative threshold shift: Full on-pace acclimatisation to global warming (using the same threshold temperature percentile for the historical and future</td>
<td>In low global warming worlds of 1°C and 2°C, adaptation is able to maintain heat-related deaths at a similar or lower level to the near past. However, heat-related deaths increases in 3°C and 4°C global warming worlds</td>
</tr>
</tbody>
</table>
Supplementary materials

| TS-R | Quantitative risk assessment of the effects of climate change on selected Global | Defining the threshold using fixed percentile of the temperature distribution. | 100% and 63% additional heat-mortality due to climate change are reduced due to 100% and 50% adaptation respectively in |}

- economic scenarios (Jenkins et al, 2022)

  periods and estimate the temperature based on the corresponding temperature distribution.

  under all adaptation assumptions made.

  Shifting the threshold temperature is more effective in reducing heat-related deaths than on-pace acclimatisation in 1°C and 2°C global warming worlds, which reduces heat-related deaths by 60-70% compared to no adaptation (Figure 2).

  On-pace acclimatisation results in a higher reduction in heat-related deaths than absolute threshold shifts by 1°C or 2°C under 3°C and 4°C global warming world, which reduces annual heat-related deaths by 70%-85% compared to no adaptation.
<table>
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<tr>
<th>Causes of death, 2030s and 2050s (Hales et al, 2014).</th>
<th>No adaptation: the threshold temperature in the future is the same as the current climate. Relative threshold-100% adaptation: The future threshold temperature is determined by applying the same threshold percentile to the projected climate. Relative threshold-50% adaptation: the arithmetic mean of the threshold temperature of the same threshold percentile from the present and projected climate.</th>
<th>2050 compared to 1961–1990 under SRES A1b globally. Adaptation may reduce all excess heat-mortality due to climate change (ARES A1b)</th>
</tr>
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<td>TS-R</td>
<td>Heat-related mortality risk model for climate change impact projection (Honda et al, 2014).</td>
<td>Global</td>
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<td>TS-R</td>
<td>Climate Change Effects on Heat Waves and Future Heat Wave-</td>
<td>Germany</td>
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<tr>
<td>TS-R</td>
<td>Quantifying excess deaths related to heatwaves under climate change scenarios: A multicountry time series modelling study (Guo et al, 2018)</td>
<td>Adaptation reduced excess heat-mortality due to climate change in 2031-2080 compared to 1971-2020 in the UK by 45% (RCP2.6) and 68% (RCP8.5).</td>
</tr>
<tr>
<td>TS-R</td>
<td>Projection of temperature-related mortality due to cardiovascular disease in Beijing under different climate change, Beijing, China</td>
<td>A net increase in temperature-related mortality considering adaptation compared to no adaptation because the gain in cold burden due to the loss in cold adaptation outweigh the reduction in heat adaptation</td>
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<td></td>
<td>No adaptation, relative threshold-50% adaptation and relative threshold-100% adaptation using the MMT as the threshold</td>
<td>This study investigated the scenario with a gain in heat adaptation and a loss in cold adaptation, and found a net loss of health due to this adaptation assumption.</td>
</tr>
<tr>
<td></td>
<td>412 communities in 20 countries / regions</td>
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<td>TS-R</td>
<td>Mortality attributable to high temperatures over the 2021-2050 and 2051-2100 time horizons in Spain: Adaptation and economic estimate (Diaz et al, 2019b)</td>
<td>Spain</td>
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<tr>
<td>TS-R</td>
<td>Heat Wave and Elderly Mortality: Historical Analysis and Future Projection for Metropolitan Region of Sao Paulo, Brazil (Diniz et al, 2020)</td>
<td>Sao Paulo, Brazil</td>
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<tr>
<td>TS-R</td>
<td>Sensitivities of heat-wave mortality projections: Moving towards stochastic model assumptions (Abadie &amp; Polanco-Martinez, 2022)</td>
<td>Madrid, Spain</td>
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<tr>
<td>TS-R</td>
<td>Projecting the excess mortality due to heatwave and its characteristics under climate change, population and adaptation scenarios (Liu et al, 2023)</td>
<td>Guangzhou, China</td>
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<tr>
<td>TS-R</td>
<td>Projected trends in high-mortality heatwaves under different scenarios</td>
<td>82 US communities</td>
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<th>TS-R</th>
<th>Will there be cold-related mortality in Spain over the 2021-2050 and 2051-2100 time horizons despite the increase in temperatures as a consequence of climate change? (Diaz et al, 2019a)</th>
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<tr>
<td>Spain</td>
<td>Cold-related mortality is projected under two adaptation (to hotter climate) scenarios: No adaptation: the threshold temperature calculated using the historical climate was applied to the projection to estimate the occurrence of cold waves. Adaptation: the percentile to which this threshold corresponds remains constant over time—threshold temperature is calculated using the projected future climate.</td>
</tr>
<tr>
<td></td>
<td>Without adaptation processes, if the cold-wave threshold definition temperature in Spain is assumed to be constant, then cold waves will disappear in 2021–2050 and 2051–2100 under both RCP4.5 and RCP8.5, as a consequence of global warming. When considering adaptation, the occurrence of cold waves is constant, but the difference between daily temperature and the threshold becomes smaller, leading to a decrease in cold wave mortality over time (a</td>
</tr>
<tr>
<td></td>
<td>In this study, “adaptation” indicates loss in cold adaptation under global warming.</td>
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</tbody>
</table>

of climate, population, and adaptation in 82 US communities (Anderson et al, 2018) used climate in 2023–2042 to calculate relative metrics for heatwaves in 2061-2080. On-pace adaptation: it assumed communities keep pace with climate change and used the projected climate in the corresponding period to calculate relative heatwave characteristics. projected number of and exposure to high-mortality heatwaves.
### Supplementary materials

| TS-R CV-C | The Effects of Heat Exposure on Human Mortality Throughout the United States (Shindell et al, 2020) | US | The temperature-related RR of mortality was modelled as a function of city-specific summer average temperature (SMT) and daily temperature above the MMT. Two adaptation scenarios are adopted for future projection: Adaptation to SMT: Using the RR estimated using the SMT based on the projected climate. Adaptation to MMT: Using the future climate to calculate the MMT based on a fixed threshold percentile. A scenario with half adaptation is also assumed. | This study estimated around 12,000 (95% CI 7,400–16,500) annual average premature heat-related deaths in the 2010s. The total number of U.S. deaths, accounting for adaptation, rises by a factor of about 9, 5 and 2 under RCP8.5, 4.5 and 2.6 respectively. The two adaptation scenarios result in similar effects, which reduced around half of the increase compared to no adaptation. | Adaptation to SMT assumes people adapt to higher seasonal average temperatures. Adaptation to MMT assumes that what used to be considered “extreme” is no longer so under global warming. The first assumption focuses on the change in the average climate while the later one takes into account the change in variability. |
| AS | Projection of future temperature extremes, related | Taiwan | This study estimated the need for the reduction in the RRs under climate change so that future heat-related... | In the 2051-2060, all places in Taiwan require 81%-100% reduction in RR to maintain the... |
mortality, and adaptation due to climate and population changes in Taiwan (Chen et al, 2021)

<table>
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<tr>
<th>AS</th>
<th>Climate change, thermal stress and mortality changes (Martens, 1998)</th>
<th>20 cities globally</th>
<th>Three adaptation scenarios apart from no adaptation: shifting the MMT, adjusting the warm slope and adjusting the cold slope.</th>
<th>Various results under different scenarios.</th>
<th>Shifting the MMT was assumed to reflect physiological acclimatisation and adjusting the slopes was assumed to technological/behavioural adaptation by the authors.</th>
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<tbody>
<tr>
<td>TS-R+AS</td>
<td>Long-term projections and acclimatization scenarios of temperature-related mortality in Europe (Ballester et al, 2011)</td>
<td>16 European countries</td>
<td>The study shifted the cold and heat thresholds and transformed the sensitivity to cold and heat in according to the increase in annual mean temperature under climate change by applying a factor from 0 to 1. The study explored scenarios with only an increase in the heat threshold while keeping the cold threshold unchanged,</td>
<td>There is up to around 38% less heat-mortality due to acclimatisation compared to no acclimatisation. When shifting the cold and heat threshold by the same percentage, the increase heat-mortality outweigh the decrease in cold-mortality, leading to a</td>
<td>The authors expect that coefficient R decreases in parallel with temperature rise, as human adaptability is subject to nonlinearities and limits imposed by heat stress.</td>
</tr>
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Supplementary materials

| TS-R AS | Climate Change Effects on Heat- and Cold-Related Mortality in the Netherlands: A Scenario-Based Integrated Environmental Health Impact Assessment (Huynen & Martens, 2015) | The Netherlands | Three adaptation scenarios: 1) a shift of the threshold temperature proportional to the projected change in annual average temperature 2) a 10% decrease in the heat slope and a 10% increase in the cold slope. 3) a combination of 1) and 2). | Assuming no adaptation, the population attributable fractions (PAF) of mortality to cold decreased by 6.56%–7.85% in 2050 under different climate change scenarios compared to 1981–2010, which outweighs the increase in PAF to heat (1.66%–2.52%). Under the different adaptation scenarios, the PAF to heat was 0.94%–2.52% and the PAF to cold was 6.56%–9.85%. | Adaptation scenario 2 assumed a decrease in the heat slope and an increase in the cold slope, which lacks empirical support. |
### Supplementary materials

<table>
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<th>AS</th>
<th>Aging Will Amplify the Heat-related Mortality Risk under a Changing Climate: Projection for the Elderly in Beijing, China (Li et al, 2016)</th>
<th>Beijing, China</th>
<th>A reduction of 0%, 5%, 15%, 30% and 50% of the temperature-specific RRs as 5 adaptation scenarios. The MMT was also shifted simultaneously (how the MMT was shifted was not stated).</th>
<th>Heat-related mortality was approximately halved considering a 30% adaptation. In the 2080s, the increase in heat-related death was estimated to be around 20, 7.4 and 1.3 times larger than in the 1980s under the no adaptation, 30% and 50% adaptation rate respectively (high population growth and RCP8.5)</th>
<th>30% was used as the reference adaptation rate in this study based on the decrease in heat sensitivity reported for New York in the 20th century (Petkova et al, 2014). However, the 30% reduction in heat sensitivity was observed among those who were over 65 years old. The heat susceptibility decreased by 24% among the total population in New York between 2000s and 1900s. It is unknown to what extent the result in New York is applicable to other locations.</th>
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<tr>
<td>TS-R+AS</td>
<td>Projections for temperature-related years of life in Ningbo, China</td>
<td>Ningbo, China</td>
<td>The study transformed the cold and heat thresholds and ERFs in according to the increase in annual mean</td>
<td>To offset the projected heat-related YLL increment related to the temperature increase in the</td>
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Supplementary materials

<p>| TS-A+AS | Projected Temperature-Related Years of Life Lost From Stroke Due To Global Warming in a Temperate Climate City, Asia Disease Burden Caused by Future Climate Change (Li et al, 2018a) | Ts-A+AS | Tianjin, China | Shifting the MMT by 1.0°C and 1.2°C in the 2050s and 2070s respectively in the meanwhile reducing the heat slope by 25%. | 2070s compared to 2008-2015, 39% and above 50% adaptation is required under RCP4.5 and RCP8.5 respectively. | Adaptation could fully offset the additional heat-related adverse effects under RCP2.6, but not RCP4.5 and RCP8.5 by the 2080s. | This study assumes a simultaneous increase in the cold and heat thresholds under climate change. Only the heat slope was modified under the adaptation scenarios while the cold slope was assumed to unchanged. |</p>
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<th><strong>TS-A+AS</strong></th>
<th>Future temperature-related years of life lost projections for cardiovascular disease in Tianjin, China (Li et al, 2018b)</th>
<th>Tianjin, China</th>
<th>Shifting the MMT by 1.0°C and 1.2°C in the 2050s and 2070s respectively in the meanwhile reducing the heat slope by 25%.</th>
<th>Adaptation could fully offset the additional heat-related adverse effects under RCP2.6, but not RCP4.5 and RCP8.5 by the 2080s.</th>
<th>Same as (Li et al, 2018a)</th>
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<tr>
<td><strong>TS-A+AS</strong></td>
<td>Projections of the effects of global warming on the disease burden of ischemic heart disease in the elderly in Tianjin, China (Huang et al, 2019)</td>
<td>Tianjin, China</td>
<td>Shifting the MMT by 1.0°C and 1.2°C in the 2050s and 2070s respectively in the meanwhile reducing the heat slope by 25%.</td>
<td>Adaptation could fully offset the additional heat-related adverse effects under RCP2.6 and RCP4.5, but not RCP8.5 by the 2080s.</td>
<td>Same as (Li et al, 2018a)</td>
</tr>
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</table>
| **AS HT-S HT-M** | Modification Effects of Population Expansion, Ageing, and Adaptation on Heat-Related Mortality Risks | Guangzhou, China | Three adaptation scenarios: 1): a decrease of the heat slope by 8.92%/decade, based on empirical evidence in Shanghai, China (Yang et al, 2015) | Various results under different scenarios and period in figure. Additional heat-related YLLs were be largely counteracted by adaptation scenario 1 and 3 by the 2090s compared to the | It is unknown to what extent the historical findings in other locations are applicable to Guangzhou, China.
### Supplementary materials

<table>
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<th>Scenario</th>
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<td>TS-A</td>
<td>Projection of mortality attributed to heat and cold; the impact of climate change in a dry region of Iran, Kerman (Aboubakri et al, 2020)</td>
<td>Kerman, Iran</td>
<td>No adaptation scenario with an MMT of 11 °C. Shift the MMT: MMT of 16 °C and 22.7°C, which was found in another study for Kerman (Aboubakri et al, 2019). Modification of the cold and heat susceptibility: reduction by 20% and 30%.</td>
<td>There is an increase in the fraction of mortality attributable to heat over time, and none of the adaptation scenarios could offset the increase even under RCP2.6.</td>
</tr>
<tr>
<td>TS-R+AS</td>
<td>Projecting future temperature-related mortality using annual time series data: An example from Hong Kong (Wang et al, 2022)</td>
<td>Hong Kong</td>
<td>Three adaptation scenarios. 1): 0.25 °C increase in threshold every 2 decades (corresponding to 1°C increase at the end of the century) 2): 5% reduction in the cold and heat slope every 2 decades (corresponding to a 20% decrease at the end of the century)</td>
<td>The net temperature-related mortality was estimated to increase by 39%, 65%, and 29% in the 2090s compared to 2014-2018 under the three adaptation scenarios respectively (RCP8.5).</td>
</tr>
</tbody>
</table>

**Under Different Climate Change Scenarios in Guangzhou, China (Liu et al, 2019)**


3): an increase in the MMT by 0.2°C/decade based on findings in France (Todd & Valleron, 2015).

1980s, but less modified under scenario 2

| HT-S | New York City, US | Temperature-specific RRs (compared to 22 °C) were calculated for 1900s-2000s, and the historical trend was extrapolated to the end of the 21st century using a sigmoid function while assuming a further 20% and 80% reduction in the RRs in 2100 compared to the 2000s representing moderate and high adaptation scenarios respectively. | Moderate and high adaptation reduced heat-related mortality by around 18% and 77% respectively in the 2080s under both RCP4.5 and 8.5 (no population change) | The extrapolation of historical trend in RRs required a long time series of historical data and a consistent trend. The authors stated that decrease in RRs observed in this study is very likely attributed to AC uptake, which increased from 39% in 1970 to 84% in 2003. However, this may not be observed in other places such as the UK which has very low usage of household AC. The authors also acknowledge that the 20% and 80% reduction in RRs assumptions were somewhat |
### HT-S

**Supplementary materials**

| HT-S | **Climate Change and Mortality in Vienna-A Human Biometeorological Analysis Based on Regional Climate Modeling (Muthers et al, 2010)** | Vienna, Austria | This study explored the historical trend in the heat effect between 1970-2007 and constructed the adaptation scenarios based on the historical trend. If a significant historical trend in the heat sensitivity was observed, the trend would be extrapolated linearly into the future. If there was no significant historical trend in the heat sensitivity, the sensitivity at the end of the historical period of examination would be used. | Relative mortalities were found to decrease significantly on days with PET between 35-41 °C between 1970-2007. A conservative decrease of RR by 0.77% per decade was found and applied to project heat-related mortality at PET 35-41 °C in the future. There was a huge yet non-significant historical decrease in RR at PET above 41°C, and hence a RR of 1.05 observed at the end of the historical period was applied to the future. Adaptation could not offset the increase in heat-related mortality due to climate change due to physiological acclimatisation limits. |

Following the past trend might be a reasonable assumption if climate change rate and socioeconomic development do not vary much from the past; whereas the future is uncertain. This study used a linear extrapolation method, whereas the trend might not be linear, e.g. due to physiological acclimatisation limits.
### CV-S
**Quantifying the health impacts of future changes in temperature in California (Ostro et al, 2011)**

California, US

Historical association between AC prevalence and heat-related excess mortality risk was assessed. Based on the association, two adaptation scenarios were utilised: an adaptation scenario with a 10% increase in AC ownership by 2025 and a 20% increase in AC ownership equivalent by 2050. 16% and 33% in excess heat-related mortality under climate change was reduced due to 10% increase in AC in 2025 and 20% increase in AC equivalent in 2050 respectively. This adaptation scenario is based on the effect of AC ownership. This study found that a 10% increase in AC prevalence reduced the heat slope by 1.4% per 10 °C change in apparent temperature. However, other environmental and socioeconomic changes may affect heat-related mortality risk too. The assumption of 10% and 20% increase in AC ownership in the future is somewhat arbitrary.

### LB
**Avoided Heat-Related Mortality through Climate Adaptation**

Three US Cities

The study estimated changes in the number of heat-related deaths in 2050 under 7 scenarios of modifications to vegetative cover and surface albedo. Increasing vegetative cover and surface albedo reduces future heat-related mortality increases. In some cities increasing

The authors acknowledged that historical ERF was applied to the future,
### Strategies in Three US Cities (Stone et al., 2014)

| LB | Development and appraisal of long-term adaptation pathways for managing heat-risk in London (Kingsborough et al., 2017) | London, UK | This study quantified the effect of three adaptation methods—greenspace, AC and building stock upgrade on heat-related mortality risk and constructed 12 adaptation pathways with varying combinations of the change in the three adaptation methods. Adaptation strategies focusing solely on urban greening or building adaptation based on current best practices are unlikely to offset the increasing heat risk under climate change. AC may play a growing role in managing heat risk; however, increasing air-conditioning will exacerbate the urban heat island and further increase the risks of overheating. | Vegetative cover is more effective while it is reversed in some other cities. Whereas it may be affected by physiological acclimatisation and other behavioural and socioeconomic changes. Advantage: future projections on heat-related mortality is based on adaptation measure of which mechanisms are quantified with empirical evidence. Feedback on the increase in AC on UHI is included in the estimation, and the effect of the use in AC by the rich and the vulnerable is also considered. Limitation: the effect of greenspace is only quantified in terms of spatial cooling, whereas... |
Supplementary materials

| LB | Holistic approach to assess co-benefits of local climate mitigation in a hot humid region of Australia (Haddad et al, 2020) | Darwin, Australia | This study constructed 11 adaptation scenarios including the increase of greenery, application of cool materials, water spray system, shading, green roof, and combination of the selected strategies. The impact of these strategies on the change in the microclimate and future temperature-related heat effects are projected. | The best-performing mitigation scenario, which combined cool materials, shading, and greenery, reduced the peak ambient temperature by 2.7 °C and saved 9.66 excess deaths per year per 100,000 people. | Similar as above |

| TS-A AS TS-A+AS HT-S | Temperature-Related Summer Mortality Under Multiple Climate, 7 cities in South Korea | Four methods to model adaptation: 1) shift the MMT by 1 °C, 2 °C and 3 °C 2) slope reduction by 10%, 20%, and 30% | The four adaptation scenarios (slope reduction, the absolute threshold shift, the combination, and sigmoidal function) can | The RR in 2006–2015 was approximately 43% smaller than 1991–2000. The authors expressed |
### Supplementary materials

| CV-SLB SSP | Population, and Adaptation Scenarios (Lee et al, 2019) | Characterizing the role of socioeconomic pathways in shaping future urban heat-related challenges (Rohat et al, 2019b) | The heat risk model using daily minimum temp in summer and demographic and socioeconomic factors to predict daily mortality has been constructed in a previous study (Heaton et al, 2014), which identified population ageing, prevalence of AC, social isolation, ethnicity and poverty as strong predictors of summer mortality. These vulnerability variables, along with land use and future climate are projected for each Census tract of Greater Houston, US | Changes in vulnerability and population drive most of the projected increase in summer mortality, with ageing dominating the effect of vulnerability. SSP1 is associated with the most summer mortalities among all SSPs under investigation due to the increase in ageing under this scenario. | Advantage: this study projected heat-related mortality considering changes in climate, population, land use (its effect on UHI) and a series of factors affecting vulnerability under combinations of RCP-SSP scenarios. The association between summer mortality and... |

3) a combination of slope reduction and threshold shift
4) The temperature-specific RR in 1991–2000 and 2006–2015 was extrapolated into the future up to 2100 using a sigmoid function assuming an 80%, 50% and 20% reduction in temperature-specific RRs in 2100 compared to 1991-2015.

reduce the reference MR of 12.9 (median GCM, RCP 8.5, medium population, and no adaptation) by up to 1.4, 2.5, 3.6, and 5.0 times, respectively.

that such rapid reduction in heat susceptibility may be due to the wide introduction of air conditioning, medical advancements, and improvements in housing. This study didn’t find a change in the MMT between 1991-2000 and 2006-2015.
Greater Houston under 7 SSP-RCP scenarios, which was used as the inputs to the existing heat risk model to estimate summer mortality.

Vulnerability variables was based on empirical evidence. Limitation: it assumes the mortality-temperature-vulnerability association found by historical data will apply to the future, whereas these effects may change, e.g. as a result of population acclimatisation. Despite this, it incorporates a comprehensive range of factors that may affect mortality under aligned climate change and socioeconomic scenarios.

| CV-SSP | Tens of thousands additional deaths annually in cities of China between 1.5 | 27 Chinese cities | High GDP/capita was used as an indicator of the adaptive capacity to heat risk. The association between temperature-specific RRs and Heat-related deaths were projected to be the most under SSP5 and 1, and lowest under SSP3, under both the 1.5 and GDP is not the only factor that affects the adaptive capacity to heat. | Vulnerability variables was based on empirical evidence. Limitation: it assumes the mortality-temperature-vulnerability association found by historical data will apply to the future, whereas these effects may change, e.g. as a result of population acclimatisation. Despite this, it incorporates a comprehensive range of factors that may affect mortality under aligned climate change and socioeconomic scenarios. |
Supplementary materials

| CV-C / CV-S SSP | Estimates of country level temperature-related mortality damage functions (Bressler et al, 2021) | 23 countries globally | Temperature-related mortality risk was predicted using projected warming, and an interaction term with average temp in the hottest/coldest month (to account for acclimatisation) and another interaction term with income/capita (to account for socioeconomic adaptation). Income was projected under SSP3 and compared with a scenario of no change in income to take into account the protective effect of income on temperature-related mortality. | GDP/capita improved the model performance for the heat effect but not for cold. Hotter countries are expected to on average experience larger temperature-related mortality burden than currently colder countries. Richer countries can ameliorate some of the damages associated with higher temperatures. | 2°C warming world, with or without adaptation, likely driven by population ageing. Adaptation reduced around 50% heat-related deaths. |
| --- | --- | --- | --- | --- |
| TS+CV-S SSP | Heat-related mortality under climate change and Thessaloniki, Greece | Adaptation was modelled using a gradually increasing temperature threshold shift (2 °C by 2099) | When black carbon was considered as the primary fuel source, the negative effect of air | There is a lack of evidence supporting the assumption of a...
| CV-C | CV-S | SSP | Valuing the Global Mortality Consequences of Climate Change Accounting for Adaptation Costs and Benefits (Carleton et al, 2022) | 40 countries globally | Temperature-related mortality effect was predicted using interaction terms of daily temperature and annual mean temperature and income/capita. Population and income were projected under SSP2,3, and 4. | Both higher income and a warmer long-run climate substantially moderate mortality sensitivity to temperature. Adding other candidate determinants of adaptation in the mortality-temperature function, such as institutional quality, doctors per capita, and educational attainment, did not | The two terms used to model adaptation are based on the assumption that 1) a higher long-run average temperature incentivises investment in heat-related adaptive behaviours (e.g., AC), as the return to any given |
| AS+CV-S SSP | Future temperature-related mortality considering physiological and socioeconomic adaptation: a modelling framework (Rai et al, 2022) | Bavaria, Germany | This study assumes that future heat- and cold-RRs are affected by an additive effect of physiological acclimatisation/sensitivity and socioeconomic adaptation. Physiological acclimatisation: A decrease in the heat-related RR by 5% and 10% assuming medium and high adaptation respectively. An increase in the cold-related RR by 15% and 30% assuming medium and high sensitivity respectively. | This study found a 13% increase in cold-RR and a 1% decrease in heat-RR between 2002-2006 and 1990-1993. A negative association was found between GDP and heat/cold-RR, reflecting the protective effect of high GDP. The increase in GDP resulted in larger potential in reducing heat-related mortality in the future. | There is little evidence supporting the additive effect of the assumptions on the physiological acclimatisation/sensitivity and socioeconomic adaptation. GDP is only one factor affecting socioeconomic adaptation. | alter the TM association, supporting the authors' assumption that climate and income are key determinants of the TM association. adaption is higher the more frequently the population experiences days with life-threatening temperatures. 2) higher incomes relax people’s budget constraints and hence facilitate adaptive behaviour. Temperature-related mortalities under SSP1 and 5 were not explored. |
Socioeconomic adaptation: GDP is used as the indicator and future GDP was projected under SSP1 and 3 and the corresponding RRs were derived from the historical association between GDP and RR. The effects of acclimatisation/sensitivity and GDP on RR were assumed to be additive. than physiological acclimatisation.
S2. Search strategy for the scoping review in Chapter 2.3.4.
Scoping review on temperature-related mortalities and morbidities in Scotland

➢ **Initial search on 7th November 2019**
  - Database: Web of Science Core Database
  - Search terms:
    Topic (TS) = “temperature” AND “mortality” AND “Scotland”

Topic include publication title, abstract and key words.

Initial result: 82 papers

  - Exclusion by category

Excluding papers published by journal category categorised by Web of Science. One journal can be allocated to multiple categories. The number of papers excluded is included in brackets.

marine freshwater biology (n=27), fisheries (n=26), ecology (n=9),
  oceanography (n=7), veterinary sciences (n=5), zoology (n=5), biodiversity conservation (n=2), forestry (n=2), immunology (n=2), infectious diseases (n=2), ornithology (n=2), toxicology (n=2), virology (n=2), agriculture dairy animal science (n=1), air pollution (n=2), anatomy morphology (n=1), biotechnology applied microbiology (n=1), body temperature (n=1), computer science interdisciplinary applications (n=1), geography physical (n=1), international relations (n=1), microbiology (n=1), operations research management science (n=1), surgery (n=1)

  - Title, abstract and full text screening:

Exclusion criteria:

  o Studies that are not about Scotland
  o Studies not about human health
  o Studies not about the impacts of ambient temperature (e.g. studies about air pollution and mortality, and study about blood pressure and room temperature instead of ambient temperature)
  o Studies that only investigated seasonal pattern of mortality without studying the association between temperature and mortality

  - One publication identified from the reference list and one reported recommend by experts were added for the review.
Five relevant publications were identified

**Updated search on 7th November 2019**
- Database: Web of Science Core Database
- Aims

1) Identify new studies that analysed the exposure-response association between ambient temperature and human mortality in Scotland published after the initial search.

2) The initial search only included mortality as the health outcome, and the updated search aims to also identify publications about ambient temperature and morbidity in Scotland.

- Search terms:
  \[
  \text{TS} = (\text{mortalit}^* \text{ OR } \text{morbidit}^* \text{ OR } \text{death}^* \text{ OR } \text{“health impact” OR “health burden” OR “health outcome” OR “hospital admission” OR hospitalisation})
  \]
  \[
  \text{AND TS} = (\text{heat OR hot OR cold OR temperature}^*)
  \]
  \[
  \text{AND TS} = (\text{Scotland OR Glasgow OR Edinburgh OR Aberdeen OR Dundee})
  \]

Note: the asterisk mark * is used to represent any number of letters in a word, which can be useful for finding variations of spellings. For example, mortalit* will find both mortality and mortalities. US and UK Spelling Variations. Web of Science automatically finds spelling variations (such as US. and UK. spelling differences) in Topic and Title search terms. For example, hospitalisation finds both hospitalisation and hospitalization.

Result: 550 articles

- Exclusion by category

  Marine Freshwater Biology (n=34), Fisheries (n=32), Veterinary Sciences (n=15), Anaesthesiology (n=10), Oceanography (n=9), Zoology (n=7), Microbiology (n=5), Chemistry Physical (n=1), Mycology (n=1), Operations Research Management Science (n=1)

Result: 468 articles
Note: One journal can be allocated for multiple categories. Therefore, there is the possibility that one relevant papers fall into two categories with one being irrelevant, and hence excluding the irrelevant category risks missing the relevant publication. Therefore, fewer categories were excluded in the updated search to minimise the risk of missing relevant publications.

- Exclusion by language

Only review articles in English

Result: 457 articles

- Remove duplication

One duplicated article

Result: 456 articles

- Title, abstract and full text screening:

Exclusion criteria: excluding

- non-human studies;
- studies not for Scotland;
- studies about exertional heat stroke;
- studies that do not investigate the impacts of ambient temperature;
- studies only investigated the seasonal variation in mortality/morbidity;
- studies about therapeutic hypothermia, e.g. in preventing brain injury;
- studies that only assessed the effect of housing interventions on health;
- studies that only investigated the mechanisms, characteristics, outcomes or treatment of hypothermia/hyperthermia;
- studies that use temperature as a control or modifier when study the health impacts of air pollution
- studies that only published as conference abstracts without main text

➤ Four additional articles were identified

One of the addition article was a publication of my PhD research and is included in Chapter 4 in detail, and hence is not included in the review.
Supplementary materials
### S3. Stakeholder mapping result

<table>
<thead>
<tr>
<th>Stakeholder</th>
<th>Description</th>
<th>Resources and note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environmental health department of local councils</td>
<td>The local authority’s environmental health department is responsible for enquiry relates to local environmental health problems, for example local environmental hazards.</td>
<td>Invitation was sent to the local councils in Aberdeen, Edinburgh, Dundee and Glasgow. Five other councils were selected randomly.</td>
</tr>
<tr>
<td>The Adaptation Scotland programme</td>
<td>Funded by Scottish Government and delivered by Sniffer to provide advice and support to organisations,</td>
<td>Annual progress report on the on the “Climate Ready Scotland: climate change adaptation programme 2019-2024”.</td>
</tr>
<tr>
<td>Supplementary materials</td>
<td></td>
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<tr>
<td>-------------------------</td>
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</tr>
<tr>
<td><strong>Committee on Climate Change’s Adaptation Sub-Committee (ASC)</strong></td>
<td>Providing regular independent advice to the UK Government and devolved administrations (e.g. environment, health and social services matters at the Scottish Government) on preparing for climate change.</td>
<td>ASC (2016) <em>UK Climate Change Risk Assessment 2017 Evidence Report – Summary for Scotland</em>. Adaptation Sub-Committee of the Committee on Climate Change, London. Key relevant member: Professor Michael Davies, UCL Institute for Environmental Design and Engineering (IEDE). His research interests relate to the built environment and human well-being.</td>
</tr>
<tr>
<td><strong>ClimateXChange</strong></td>
<td>Providing independent advice, research and analysis to support the Scottish Government for developing and implementing policies on climate change adaptation and low carbon transition.</td>
<td></td>
</tr>
</tbody>
</table>
### National Centre for Resilience (NCR)

Supporting the interface between academia, policy-makers, emergency responders, volunteers and communities to inform better practice in dealing with emergencies and providing research capabilities to meet the needs of the resilience community to natural hazards. It is funded by the Scottish Government and hosted by the University of Glasgow.

A report on the associations between Ambient Outdoor Temperature and Patterns of Morbidity and Mortality in Scotland
[http://eprints.gla.ac.uk/165571/](http://eprints.gla.ac.uk/165571/)

### Sustainable Scotland Network (SSN), ECCI

A network for public sector professionals engaged in sustainability and climate action, e.g. including NHS Scotland, Alliance for Sustainability Leadership in Education (EAUC) Scotland and Convention of Scottish Local Authorities (COSLA, an organisation to help councils build better and more equal local communities). The SSN is led by

A collection of climate change reports by local councils, Integration Joint Boards (between council and NHS Boards), educational institutions and other organisations.
[https://sustainablescotlandnetwork.org/reports](https://sustainablescotlandnetwork.org/reports)
## Supplementary materials

<table>
<thead>
<tr>
<th>George Tarvit at Edinburgh Centre for Carbon Innovation.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scottish Communities Climate Action Network (SCCAN)</td>
</tr>
<tr>
<td>Inspiring and promoting, connecting and supporting community-led action on climate change.</td>
</tr>
<tr>
<td>Tools and guides for understanding behaviour change, climate change communication, top tips for community projects to work with local authorities, a Compass of Resilience to assess community resilience.</td>
</tr>
<tr>
<td>Place-based Climate Action (PCAN)</td>
</tr>
<tr>
<td>PCAN is an ESRC-supported network that facilitates two-way engagement between the research community and stakeholders at the local level.</td>
</tr>
<tr>
<td>Met Office</td>
</tr>
<tr>
<td>Providing weather forecast, seasonal climate prediction and climate change projections.</td>
</tr>
<tr>
<td>Heat-Health Watch service for England</td>
</tr>
<tr>
<td>Climate Just</td>
</tr>
<tr>
<td>Climate Just is an information tool designed to help with the delivery of equitable responses to climate change at the local level. Its main focus is to assist the development of socially just</td>
</tr>
<tr>
<td>New map data showing where extreme events like floods and heat waves are likely to have the biggest impacts as a result of the characteristics of people and communities. Most recently new</td>
</tr>
</tbody>
</table>
responses to the impacts of extreme events, such as flooding and heatwaves, as well as supporting wider climate change adaptation. It also includes issues related to fuel poverty and carbon emissions.

<p>| Edinburgh Climate Commission | Edinburgh Climate Commission aims to accelerate action and impact on climate change in the city, and provides independent, expert and authoritative advice to enable and support the best choices being made for Edinburgh. The Commission will feed into the democratic process through City of Edinburgh Council, producing reports and position papers on key issues in the city. |
| Climate Ready Clyde, Sniffer | A cross-sector initiative funded by 14 member organizations and supported by the Scottish Government to create a Climate Vulnerability Map |
|---|---|---|
| Glasgow Centre for Population Health | Focus on understanding the causes of health inequalities and identifying and supporting the implementation of solutions. Their current work programmes are focused on four main themes: action on inequality across the life-course; understanding health, health inequalities and their determinants; sustainable, inclusive | Our way of working | Glasgow Centre for Population Health (gcph.co.uk) |</p>
<table>
<thead>
<tr>
<th><strong>Supplementary materials</strong></th>
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<tbody>
<tr>
<td><strong>places; and innovative approaches to improving outcomes.</strong></td>
</tr>
<tr>
<td><strong>Usher Institute</strong></td>
</tr>
<tr>
<td><strong>Scottish (Managed) Sustainable Health Network (SMASH)</strong></td>
</tr>
<tr>
<td><strong>Health Facilities Scotland (HFS)</strong></td>
</tr>
</tbody>
</table>
Health and Social Care Directorate (SGHSCD) and NHSScotland bodies in relation to all aspects of healthcare facilities to support and improve health and well-being services. The HFS is actively involved in the development of national policy, sharing of best practice, development of technology and innovation as well as delivering effective advice and support.

HFS provides services to NHS Boards to reduce greenhouse gas emissions and adapt their buildings and service delivery to minimise exposure to climate hazards.


NHS guidance for completing annual Public Bodies Climate Change Duties reporting.

The Incident Reporting and Investigation Centre (IRIC) of the HFS provides safety alerts including hazard notice, safety action notice and estates and facilities alerts.

Environmental Public Health team, Public Health Scotland

Providing specialist operational support and advice to stakeholders around environmental hazards.
Providing advice during acute incidents and also for chronic exposures resulting from incidents that extend over a longer period of time. Surveillance and monitoring of hazards and exposures. Fostering a new post-Brexit UK-wide collaborative approach to the surveillance of communicable diseases and health problems associated with environmental hazards, including training and the development of a shared strategy.

<table>
<thead>
<tr>
<th>NHS Boards</th>
<th>NHS Boards have a legal duty to prepare for climate change and complete annual reporting.</th>
<th>Five NHS boards were selected randomly for interview invitation.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Midlothian Community Health and Social Care Partnerships</td>
<td>The partnership brings together parts of Midlothian Council and NHS Lothian. It is governed by the Integrated Joint Board (IJB).</td>
<td></td>
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</tbody>
</table>

253
<table>
<thead>
<tr>
<th>Organisation</th>
<th>Description</th>
<th>Supporting Document</th>
</tr>
</thead>
<tbody>
<tr>
<td>Care Inspectorate</td>
<td>It is a scrutiny body for care services in Scotland that looks at the quality of care, find where improvement is needed and support services (advice, guidance and good practice) to make positive changes.</td>
<td>A dedicated website, the Hub, provides advice for care professionals.</td>
</tr>
<tr>
<td>Scottish Social Services Council (SSSC)</td>
<td>The SSSC is the national regulator for the social service workforce in Scotland that registers social service workers, sets standards for their practice, conducts training and education, leads workforce development and planning for social services in Scotland</td>
<td>SSSC Strategic Plan 2020-2023</td>
</tr>
<tr>
<td>National Records of Scotland</td>
<td>The NRS collect, preserve and produce information about Scotland's people and history and make it available to inform current and future generations.</td>
<td></td>
</tr>
<tr>
<td>Health and Social Care Alliance Scotland</td>
<td>It is a national third sector intermediary for health and social care organisations</td>
<td></td>
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</tbody>
</table>
### Supplementary materials

<table>
<thead>
<tr>
<th><strong>Institution</strong></th>
<th><strong>Description</strong></th>
<th><strong>Website</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Age Scotland</strong></td>
<td>Supporting people over the age of 50 to improve people's lives and promote their rights and interests.</td>
<td><a href="https://www.ageuk.org.uk/information-advice/health-wellbeing/mind-body/staying-cool-in-a-heatwave/">Advice for staying cool in a heatwave</a></td>
</tr>
<tr>
<td><strong>Shelter Scotland</strong></td>
<td>Providing help and advice on housing and homelessness topics.</td>
<td>Winter weather precaution advice</td>
</tr>
<tr>
<td><strong>Voluntary Health Scotland</strong></td>
<td>VHS is the national intermediary and network for voluntary health organisations in Scotland. We work with our members and others to address health inequalities, to improve health related policy, systems and partnership working, and to help people and</td>
<td></td>
</tr>
</tbody>
</table>
Specialist in号楼 256
communities live healthier and fairer lives.

Usher Institute, Edinburgh Medical School
To catalyse the transformation of health in society by working with people, populations and their data.

Building Research Establishment
BRE is a centre of building science to make buildings better for people and for the environment

Guidance Document: Overheating in dwellings by BRE. Assessing the application and limitations of a standardised overheating risk-assessment methodology in a real-world context.
Supplementary materials
### S4. Scottish regions and local authorities

<table>
<thead>
<tr>
<th>City/region</th>
<th>Local authority</th>
</tr>
</thead>
<tbody>
<tr>
<td>Edinburgh</td>
<td>City of Edinburgh</td>
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<tr>
<td>Glasgow</td>
<td>Glasgow City</td>
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<tr>
<td>Aberdeen</td>
<td>Aberdeen City</td>
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<tr>
<td>Dundee</td>
<td>Dundee City</td>
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<tr>
<td>West</td>
<td>Argyll and Bute</td>
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<td></td>
<td>East Dunbartonshire</td>
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<td>East Renfrewshire</td>
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<td>Inverclyde</td>
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<td>Renfrewshire</td>
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<td>West Dunbartonshire</td>
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<td>South Lanarkshire</td>
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<td>East Ayrshire</td>
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<td>North Ayrshire</td>
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<td>South Ayrshire</td>
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<td>Dumfries and Galloway</td>
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<td>Stirling</td>
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<td>East</td>
<td>Aberdeenshire</td>
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<td>Angus</td>
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<td>Perth and Kinross</td>
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<td>Fife</td>
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<td>West Lothian</td>
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<td>Midlothian</td>
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<td>East Lothian</td>
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<td>Scottish Borders</td>
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<td>Clackmannanshire</td>
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<td>Falkirk</td>
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<td>Moray</td>
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<tr>
<td>North</td>
<td>Na h-Eileanan Siar (Western Isles) [Eilean Siar*]</td>
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<tr>
<td></td>
<td>Orkney Islands</td>
</tr>
<tr>
<td></td>
<td>Shetland Islands</td>
</tr>
<tr>
<td></td>
<td>Highland</td>
</tr>
</tbody>
</table>
**S5. International Classification of Diseases (ICD).**

Causes of death under investigation and the associated ICD: ICD-8, ICD-9 and ICD-10 for the 8th, 9th and 10th Revision respectively.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Underlying cause of death ICD-10</td>
<td>ICD-10</td>
<td>ICD-9</td>
<td>ICD-8</td>
</tr>
<tr>
<td>All-cause</td>
<td>A00-Z99</td>
<td>000-799 &amp; E800-</td>
<td>000-799 &amp; E800-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>E999</td>
<td>E999</td>
</tr>
<tr>
<td>Cardiovascular diseases</td>
<td>I00-I99</td>
<td>390-459</td>
<td>390-459</td>
</tr>
<tr>
<td>Respiratory diseases</td>
<td>J00-J99</td>
<td>460-519</td>
<td>460-519</td>
</tr>
</tbody>
</table>
Supplementary materials

S6. Carstairs index
S6.1. Census variables used for the calculation of the modified Carstairs Index.

<table>
<thead>
<tr>
<th>Carstairs components and corresponding census variables</th>
<th>Code of variables used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overcrowding: proportion of all persons living in private households with more than one person per room</td>
<td>81sas100937</td>
</tr>
<tr>
<td>Total residents in all private households with over 1 and up to 1.5 persons per room</td>
<td>81sas100948</td>
</tr>
<tr>
<td>Total residents in all private households with over 1.5 persons per room</td>
<td>81sas100947</td>
</tr>
<tr>
<td>Unemployment: proportion of total economically active persons²</td>
<td>81sas090719</td>
</tr>
</tbody>
</table>

¹ Provided by GROS

2 Total economically active persons
| economically active persons seeking or waiting to start work | 247 (total economically active females) + 
246 (total economically active males) + 
247 (total economically active females) + 
306612 (full-time work males) + 
306622 (full-time work females) + 
306611 (part-time work males) + 
306621 (part-time work females) + 
306613 (self-employed males) + 306623 (self-employed females) 
All excludes full-time students |
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Total unemployed economically active persons</td>
<td>81sas090859</td>
</tr>
<tr>
<td>Low social class: proportion of all persons in private households with an economically active head with head of household in social class IV or V</td>
<td>Total residents in private households with an economically active head</td>
</tr>
<tr>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>81sas525409 (social class I) + 81sas525412 (social class II) + 81sas525415 (social class III-non-manual) + 81sas525418 (social class III-manual) + 81sas525421 (social class IV) + 81sas525424 (social class V) + 81sas525427 (armed forces + inadequately described)</td>
<td>s900002 uv0310001 2084</td>
</tr>
<tr>
<td>Total residents in private households with an economically active head of social class IV (semi-skilled)</td>
<td>81sas525421 s900027 uv0310031 (Lower technical process operator) + uv0310034 (Semi-routine Service) + uv0310310036 (Semi-routine operative)</td>
</tr>
<tr>
<td>Code</td>
<td>Description</td>
</tr>
<tr>
<td>----------</td>
<td>---------------------------------------------------------------</td>
</tr>
<tr>
<td>uv0310037</td>
<td>(Semi-routine agriculture)</td>
</tr>
<tr>
<td>uv0310039</td>
<td>(Semi-routine childcare)</td>
</tr>
<tr>
<td>uv0310041</td>
<td>(Routine sales and service)</td>
</tr>
<tr>
<td>uv0310042</td>
<td>(Routine production)</td>
</tr>
<tr>
<td>uv0310045</td>
<td>(Routine Agricultural)</td>
</tr>
</tbody>
</table>

**Total residents in private households with an economically active head of social class V (unskilled)**

- Total residents in private households: 81sas525424
- uv0310044 (Routine operative): s900032

No car: proportion of all persons in all private households

- Total residents in all private households: 81sas100937
- KS0010008: s210044

2127^4

314217
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| private households which do not own a car | Total residents in all private households with no car | Provided by GROS¹ | 314218 |
| Population weighting | Total residents in all private households | 81sas010044 | s010065 | KS0010008 | 136983 |

Note:
1. General Register for Scotland (GROS) provided data not available online.
2. In 2001 and 2011, economic activity is applicable to those aged between 16 and 74; whereas in 1981, 1991, it refers to those aged 16 and over.
4. In 2011, the NS-SEC is only given in analytic scale. Those who belongs to NS-SEC-7 and 8 are used to approximate SC-IV and SC-V.
S6.2. Male and total unemployment
S7. Descriptive statistics of historical daily mortality and temperature

S7.1. Daily deaths and temperature (population unweighted and weighted) in each month in each city and region, 1974-2018.

<table>
<thead>
<tr>
<th>Region</th>
<th>Median daily mortality count (interquartile range in brackets)</th>
<th>Average daily mean temperature, °C (standard deviation in brackets)</th>
<th>Average daily mean population-weighted temperature, °C (standard deviation in brackets)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Month</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Supplementary materials
### S7.2. The total number of daily mortality count of subgroups in all cities and regions from 1974 to 2018.

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Subgroup</th>
<th>Total mortality in 1974-2018</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Abe</td>
</tr>
<tr>
<td>age</td>
<td>0 to 64</td>
<td>21963</td>
</tr>
<tr>
<td></td>
<td>65 to 74</td>
<td>23839</td>
</tr>
<tr>
<td></td>
<td>75 to 84</td>
<td>33762</td>
</tr>
<tr>
<td></td>
<td>85 and above</td>
<td>25419</td>
</tr>
<tr>
<td>sex</td>
<td>Female</td>
<td>55008</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>49975</td>
</tr>
<tr>
<td>marstat(^1)</td>
<td>Married</td>
<td>40719</td>
</tr>
<tr>
<td>Unmarried</td>
<td>64264</td>
<td>53555</td>
</tr>
<tr>
<td>CVD(^2)</td>
<td>43885</td>
<td>35241</td>
</tr>
<tr>
<td>RESP(^4)</td>
<td>12529</td>
<td>11119</td>
</tr>
<tr>
<td>Other</td>
<td>48569</td>
<td>40240</td>
</tr>
<tr>
<td>CoD(^3)</td>
<td>24192</td>
<td>10407</td>
</tr>
<tr>
<td>Quintile 1(^5)</td>
<td>17791</td>
<td>11624</td>
</tr>
<tr>
<td>Quintile 2</td>
<td>26837</td>
<td>16266</td>
</tr>
<tr>
<td>Quintile 3</td>
<td>22420</td>
<td>22805</td>
</tr>
<tr>
<td>Quintile 4</td>
<td>12871</td>
<td>25388</td>
</tr>
<tr>
<td>Quintile 5(^6)</td>
<td>872</td>
<td>110</td>
</tr>
<tr>
<td>Missing</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: 1. marstat: marital status. 2. CoD: Cause of Death. 3. CVD: Cardiovascular diseases. 4. RESP: Respiratory diseases. 5. Quintiles 1: the least deprived neighbourhood. 5. Quintiles 5: the most deprived neighbourhood.
S7.3. The total number of daily mortality count of subgroup interactions in all cities and regions from 1974 to 2018.

<table>
<thead>
<tr>
<th>Subgroup</th>
<th>age</th>
<th>sex</th>
<th>marital</th>
<th>CoD</th>
<th>deprivation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-64</td>
<td>601980</td>
<td>NA</td>
<td>NA</td>
<td>231592</td>
<td>370388</td>
</tr>
<tr>
<td>65-74</td>
<td>NA</td>
<td>634338</td>
<td>NA</td>
<td>274656</td>
<td>359682</td>
</tr>
<tr>
<td>75-84</td>
<td>NA</td>
<td>NA</td>
<td>847638</td>
<td>455634</td>
<td>391104</td>
</tr>
<tr>
<td>85+</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>609939</td>
<td>423354</td>
</tr>
<tr>
<td>sex</td>
<td>F</td>
<td>231592</td>
<td>456534</td>
<td>1386136</td>
<td>349249</td>
</tr>
<tr>
<td>M</td>
<td>370388</td>
<td>39682</td>
<td>186585</td>
<td>1307759</td>
<td>423354</td>
</tr>
<tr>
<td>marital</td>
<td>MA</td>
<td>330534</td>
<td>298940</td>
<td>1060595</td>
<td>443962</td>
</tr>
<tr>
<td>CoD</td>
<td>CVD</td>
<td>188489</td>
<td>278463</td>
<td>597132</td>
<td>607753</td>
</tr>
<tr>
<td>Other</td>
<td>375135</td>
<td>288638</td>
<td>609939</td>
<td>512680</td>
<td>443962</td>
</tr>
<tr>
<td>dep.</td>
<td>Q1</td>
<td>37330</td>
<td>134387</td>
<td>129595</td>
<td>545693</td>
</tr>
<tr>
<td>Q2</td>
<td>93202</td>
<td>111120</td>
<td>169790</td>
<td>301346</td>
<td>443962</td>
</tr>
<tr>
<td>Q3</td>
<td>117893</td>
<td>140888</td>
<td>194599</td>
<td>396757</td>
<td>545693</td>
</tr>
<tr>
<td>Q4</td>
<td>137575</td>
<td>149235</td>
<td>187245</td>
<td>356116</td>
<td>443962</td>
</tr>
<tr>
<td>Q5</td>
<td>173276</td>
<td>146354</td>
<td>160709</td>
<td>363255</td>
<td>443962</td>
</tr>
</tbody>
</table>

**Attribute**
- age
- sex
- marital
- CoD
- deprivation

**Subgroup**
- 0-64
- 65-74
- 75-84
- 85+

**Sex**
- F
- M

**Marital Status**
- MA
- UM

**Cause of Death**
- CVD
- RESP
- Other

**Depression**
- Q1
- Q2
- Q3
- Q4
- Q5

<table>
<thead>
<tr>
<th>Age Range</th>
<th>Group</th>
<th>Sex</th>
<th>Marital Status</th>
<th>Cause of Death</th>
<th>Depression</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-64</td>
<td>601980</td>
<td>NA</td>
<td>NA</td>
<td>231592</td>
<td>370388</td>
</tr>
<tr>
<td>65-74</td>
<td>NA</td>
<td>634338</td>
<td>NA</td>
<td>274656</td>
<td>359682</td>
</tr>
<tr>
<td>75-84</td>
<td>NA</td>
<td>NA</td>
<td>847638</td>
<td>455634</td>
<td>391104</td>
</tr>
<tr>
<td>85+</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>609939</td>
<td>423354</td>
</tr>
<tr>
<td></td>
<td>F</td>
<td>231592</td>
<td></td>
<td>456534</td>
<td>1386136</td>
</tr>
<tr>
<td></td>
<td>M</td>
<td>370388</td>
<td></td>
<td>39682</td>
<td>186585</td>
</tr>
<tr>
<td></td>
<td>MA</td>
<td>330534</td>
<td></td>
<td>298940</td>
<td>1060595</td>
</tr>
<tr>
<td></td>
<td>CVD</td>
<td>188489</td>
<td></td>
<td>597132</td>
<td>607753</td>
</tr>
<tr>
<td></td>
<td>Other</td>
<td>375135</td>
<td></td>
<td>512680</td>
<td>443962</td>
</tr>
<tr>
<td></td>
<td>Q1</td>
<td>37330</td>
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<td>129595</td>
<td>545693</td>
</tr>
<tr>
<td></td>
<td>Q2</td>
<td>93202</td>
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<td>301346</td>
<td>443962</td>
</tr>
<tr>
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<td>Q3</td>
<td>117893</td>
<td></td>
<td>396757</td>
<td>545693</td>
</tr>
<tr>
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<td>Q4</td>
<td>137575</td>
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<td>173276</td>
<td></td>
<td>363255</td>
<td>443962</td>
</tr>
</tbody>
</table>

**Total**

- 601980
- 634338
- 847638
- 609939
- 231592
- 456534
- 330534
- 188489
- 375135
- 37330
- 93202
- 117893
- 137575
- 173276

**Additional Notes**
- Numbers represent daily mortality counts.
- The table includes data from 1974 to 2018 for various age groups, sex, marital status, cause of death, and depression.
S8. Relative risk of extreme temperatures

Relative risk at the 1st and 99th percentile of daily temperature distribution compared to the 10th and 90th percentile for the cold and heat susceptibility respectively (95% confidence interval in brackets).

S8.1. Relative risk of extreme temperatures of total population in each city and region and pooled results

<table>
<thead>
<tr>
<th>Region</th>
<th>Relative risk</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cold</td>
<td>Heat</td>
<td></td>
</tr>
<tr>
<td>Aberdeen</td>
<td>1.12 (1.04,1.20)</td>
<td>1.04 (0.99,1.11)</td>
<td></td>
</tr>
<tr>
<td>Dundee</td>
<td>1.05 (0.96,1.14)</td>
<td>1.04 (0.99,1.09)</td>
<td></td>
</tr>
<tr>
<td>Edinburgh</td>
<td>1.13 (1.08,1.18)</td>
<td>1.06 (1.03,1.09)</td>
<td></td>
</tr>
<tr>
<td>Glasgow</td>
<td>1.11 (1.07,1.15)</td>
<td>1.04 (1.03,1.06)</td>
<td></td>
</tr>
<tr>
<td>North</td>
<td>1.10 (1.00,1.21)</td>
<td>1.00 (0.90,1.12)</td>
<td></td>
</tr>
<tr>
<td>West</td>
<td>1.10 (1.07,1.12)</td>
<td>1.03 (1.02,1.05)</td>
<td></td>
</tr>
<tr>
<td>East</td>
<td>1.08 (1.06,1.11)</td>
<td>1.06 (1.04,1.08)</td>
<td></td>
</tr>
<tr>
<td>Meta-estimation in cities</td>
<td>1.11 (1.07,1.16)</td>
<td>1.04 (1.00,1.10)</td>
<td></td>
</tr>
<tr>
<td>Meta-estimation in regions</td>
<td>1.09 (1.05,1.13)</td>
<td>1.04 (1.00,1.09)</td>
<td></td>
</tr>
<tr>
<td>Meta-estimation in all cities and regions</td>
<td>1.10 (1.08,1.11)</td>
<td>1.04 (1.03,1.05)</td>
<td></td>
</tr>
</tbody>
</table>

S8.2. Meta-estimation of RR among subgroups

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Subgroup</th>
<th>Meta-estimation of relative risk</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>OtA</td>
</tr>
<tr>
<td>age</td>
<td>0 to 64</td>
<td>1.05 (1.02,1.08)</td>
</tr>
<tr>
<td></td>
<td>65 to 74</td>
<td>1.10 (1.07,1.13)</td>
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<td>75 to 84</td>
<td>1.10 (1.07,1.12)</td>
</tr>
<tr>
<td></td>
<td>85 +</td>
<td>1.12 (1.09,1.16)</td>
</tr>
<tr>
<td>sex</td>
<td>Female</td>
<td>1.09 (1.07,1.11)</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>1.10 (1.08,1.12)</td>
</tr>
</tbody>
</table>
### Supplementary materials

<table>
<thead>
<tr>
<th>marstat</th>
<th>Married</th>
<th>1.10 (1.07,1.12)</th>
<th>1.03 (1.01,1.04)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Unmarried</td>
<td>1.09 (1.07,1.11)</td>
<td>1.05 (1.04,1.06)</td>
</tr>
<tr>
<td>CoD</td>
<td>CVD</td>
<td>1.12 (1.09,1.14)</td>
<td>1.04 (1.03,1.06)</td>
</tr>
<tr>
<td></td>
<td>RESP</td>
<td>1.17 (1.13,1.21)</td>
<td>1.09 (1.06,1.12)</td>
</tr>
<tr>
<td></td>
<td>Other</td>
<td>1.04 (1.02,1.06)</td>
<td>1.03 (1.02,1.05)</td>
</tr>
<tr>
<td>dep</td>
<td>Quintile 1</td>
<td>1.09 (1.06,1.13)</td>
<td>1.04 (1.01,1.07)</td>
</tr>
<tr>
<td></td>
<td>Quintile 2</td>
<td>1.09 (1.06,1.12)</td>
<td>1.04 (1.02,1.06)</td>
</tr>
<tr>
<td></td>
<td>Quintile 3</td>
<td>1.06 (1.03,1.09)</td>
<td>1.04 (1.02,1.06)</td>
</tr>
<tr>
<td></td>
<td>Quintile 4</td>
<td>1.10 (1.07,1.13)</td>
<td>1.04 (1.02,1.06)</td>
</tr>
<tr>
<td></td>
<td>Quintile 5</td>
<td>1.12 (1.09,1.15)</td>
<td>1.05 (1.03,1.06)</td>
</tr>
<tr>
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<td>age0-74_F</td>
<td>1.07 (1.04,1.10)</td>
<td>1.04 (1.01,1.06)</td>
</tr>
<tr>
<td></td>
<td>age0-74</td>
<td>1.07 (1.05,1.10)</td>
<td>1.04 (1.01,1.06)</td>
</tr>
<tr>
<td></td>
<td>age75+</td>
<td>1.10 (1.07,1.12)</td>
<td>1.05 (1.03,1.08)</td>
</tr>
<tr>
<td></td>
<td>age75+</td>
<td>1.12 (1.09,1.15)</td>
<td>1.03 (1.01,1.06)</td>
</tr>
<tr>
<td>Age*marstat</td>
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<td>1.03 (1.01,1.06)</td>
</tr>
<tr>
<td></td>
<td>age0-74</td>
<td>1.06 (1.03,1.10)</td>
<td>1.04 (1.02,1.07)</td>
</tr>
<tr>
<td></td>
<td>age75+</td>
<td>1.12 (1.08,1.16)</td>
<td>1.03 (1.00,1.05)</td>
</tr>
<tr>
<td></td>
<td>age75+</td>
<td>1.10 (1.08,1.12)</td>
<td>1.05 (1.03,1.08)</td>
</tr>
<tr>
<td>Age*dep</td>
<td>age0-74_Q1</td>
<td>1.06 (1.01,1.12)</td>
<td>1.02 (0.98,1.05)</td>
</tr>
<tr>
<td></td>
<td>age0-74_Q2-4</td>
<td>1.06 (1.03,1.08)</td>
<td>1.03 (1.01,1.06)</td>
</tr>
<tr>
<td></td>
<td>age0-74_Q5</td>
<td>1.12 (1.07,1.16)</td>
<td>1.05 (1.02,1.08)</td>
</tr>
<tr>
<td></td>
<td>age75+_Q1</td>
<td>1.11 (1.07,1.16)</td>
<td>1.05 (1.01,1.08)</td>
</tr>
<tr>
<td></td>
<td>age75+_Q2-4</td>
<td>1.10 (1.08,1.12)</td>
<td>1.04 (1.01,1.07)</td>
</tr>
<tr>
<td></td>
<td>age75+_Q5</td>
<td>1.12 (1.07,1.17)</td>
<td>1.05 (1.02,1.08)</td>
</tr>
<tr>
<td>Age* CoD</td>
<td>age0-74_CIRC</td>
<td>1.10 (1.07,1.13)</td>
<td>1.03 (1.00,1.05)</td>
</tr>
<tr>
<td></td>
<td>age0-74_RESP</td>
<td>1.20 (1.13,1.27)</td>
<td>1.11 (1.06,1.16)</td>
</tr>
<tr>
<td></td>
<td>age0-74_OTHR</td>
<td>1.02 (0.99,1.05)</td>
<td>1.03 (1.02,1.05)</td>
</tr>
<tr>
<td></td>
<td>age75+_CIRC</td>
<td>1.12 (1.10,1.15)</td>
<td>1.05 (1.03,1.07)</td>
</tr>
<tr>
<td></td>
<td>age75+_RESP</td>
<td>1.15 (1.10,1.20)</td>
<td>1.08 (1.04,1.12)</td>
</tr>
<tr>
<td></td>
<td>age75+_OTHR</td>
<td>1.05 (1.02,1.09)</td>
<td>1.03 (1.01,1.05)</td>
</tr>
</tbody>
</table>
S9. Model checking—diagnostic plots of deviance residual
Supplementary materials

JJA: Residuals vs. fitted values

Aberdeen

Dundee

Edinburgh

Glasgow

North

West

East
Supplementary materials

JJA: Residuals over time

Aberdeen

Dundee

Edinburgh

Glasgow

North

West

East
Supplementary materials

JJA: Residual Partial Autocorrelation

Aberdeen

Dundee

Edinburgh

Glasgow

North

West

East
Supplementary materials

OtA: Residuals vs. fitted values

Aberdeen

Dundee

Edinburgh

Glasgow

North

West

East
Supplementary materials

OTA: Residuals over time

Aberdeen

Dundee

Edinburgh

Glasgow

North

West

East
Supplementary materials

CTA: Residual partial autocorrelation

Aberdeen

Dundee

Edinburgh

Glasgow

North

West

East
S10. Energy performance and deprivation

The energy efficiency of domestic houses is indicated by the Energy Performance Certificate (EPC) score, which was downloaded from the Scottish Government from [https://statistics.gov.scot/data/domestic-energy-performance-certificates](https://statistics.gov.scot/data/domestic-energy-performance-certificates). An EPC is produced when a new building has been constructed and when a new building is to be sold or rented to a new tenant. The EPC data provided by the Scottish Government is quarterly data from 2012 to 2021, and EPC scores are provided on postcode level. Therefore, there can be multiple EPC scores for each postcode. In the analysis, an average of the EPC scores between 2012 and 2021 was taken for each postcode. It was further averaged on census output levels for the comparison of EPC scores and Carstairs scores (in 2011).

A scatter plot of EPC scores and Carstair scores for each census output areas are shown in figure below. A higher EPC score indicates better energy efficiency, and a higher Carstairs score indicates higher deprivation (Pearson correlation coefficient: 0.29). Therefore, the result shows that people living in more deprived areas tend to have a higher home energy efficiency.

Carstairs score and average EPC score in 2012-2021 in Scotland for census outputs areas
S11. Estimated and projected annual mortality burden in Scotland

S11.1. Annual deaths attributable to cold and heat in Scotland for two historical and two future periods

The median annual deaths attributable to cold and heat in Scotland for two historical and two future periods using a natural cubic or cubic spline for the temperature-mortality association (interquartile range in brackets).

<table>
<thead>
<tr>
<th>Period</th>
<th>Scenario</th>
<th>Natural cubic spline</th>
<th>Cubic spline</th>
<th>Age 0 to 74</th>
<th>Age 75 and above</th>
<th>Age 0 to 74</th>
<th>Age 75 and above</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Cold</td>
<td>Heat</td>
<td>Cold</td>
<td>Heat</td>
</tr>
<tr>
<td>1980-2000</td>
<td>NA</td>
<td>104 (70,148)</td>
<td>7 (3,11)</td>
<td>175 (120,251)</td>
<td>16 (8,24)</td>
<td>90 (60,129)</td>
<td>5 (2,8)</td>
</tr>
<tr>
<td></td>
<td>2000-2020</td>
<td>0 (0,0)</td>
<td>27 (16,45)</td>
<td>27 (17,48)</td>
<td>63 (37,101)</td>
<td>2 (2,2)</td>
<td>26 (15,44)</td>
</tr>
<tr>
<td>2040-2060</td>
<td>RCP26-SSP1</td>
<td>0 (0,0)</td>
<td>36 (26,49)</td>
<td>45 (24,87)</td>
<td>240 (185,327)</td>
<td>0 (0,0)</td>
<td>29 (21,41)</td>
</tr>
<tr>
<td></td>
<td>RCP45-SSP2</td>
<td>28 (14,56)</td>
<td>45 (32,58)</td>
<td>130 (65,260)</td>
<td>249 (181,322)</td>
<td>23 (12,47)</td>
<td>36 (25,51)</td>
</tr>
<tr>
<td></td>
<td>RCP45-SSP4</td>
<td>31 (16,63)</td>
<td>81 (59,105)</td>
<td>158 (78,318)</td>
<td>412 (300,529)</td>
<td>27 (13,54)</td>
<td>70 (51,94)</td>
</tr>
<tr>
<td></td>
<td>RCP85-SSP3</td>
<td>15 (7,32)</td>
<td>108 (71,159)</td>
<td>68 (30,144)</td>
<td>481 (325,713)</td>
<td>12 (5,27)</td>
<td>96 (62,144)</td>
</tr>
<tr>
<td></td>
<td>RCP85-SSP5</td>
<td>17 (7,35)</td>
<td>74 (47,112)</td>
<td>77 (34,162)</td>
<td>406 (269,600)</td>
<td>14 (6,29)</td>
<td>66 (39,99)</td>
</tr>
<tr>
<td>2060-2080</td>
<td>RCP26-SSP1</td>
<td>0 (0,0)</td>
<td>31 (25,45)</td>
<td>54 (23,119)</td>
<td>293 (227,394)</td>
<td>0 (0,0)</td>
<td>24 (19,38)</td>
</tr>
<tr>
<td></td>
<td>RCP45-SSP2</td>
<td>20 (7,33)</td>
<td>63 (48,87)</td>
<td>113 (42,187)</td>
<td>423 (331,586)</td>
<td>16 (6,27)</td>
<td>52 (39,79)</td>
</tr>
<tr>
<td></td>
<td>RCP45-SSP4</td>
<td>20 (8,33)</td>
<td>102 (80,142)</td>
<td>138 (51,227)</td>
<td>691 (547,956)</td>
<td>17 (6,28)</td>
<td>90 (69,128)</td>
</tr>
<tr>
<td></td>
<td>RCP85-SSP3</td>
<td>7 (2,16)</td>
<td>177 (136,241)</td>
<td>41 (10,87)</td>
<td>967 (752,1313)</td>
<td>6 (1,13)</td>
<td>170 (125,238)</td>
</tr>
<tr>
<td></td>
<td>RCP85-SSP5</td>
<td>10 (3,23)</td>
<td>162 (121,225)</td>
<td>58 (14,124)</td>
<td>1034 (795,1413)</td>
<td>8 (2,18)</td>
<td>158 (106,234)</td>
</tr>
</tbody>
</table>
S11.2. Decomposition of the projected changes in mean annual deaths

Decomposition of the changes in mean annual deaths attributable to cold and heat to temperature, the sensitivity to extreme temperature and in population from 1980-2000 to 2000-2020, 2040-2060 and 2060-2080.

<table>
<thead>
<tr>
<th>Period</th>
<th>Scenario</th>
<th>Temperature</th>
<th>Sensitivity</th>
<th>Population</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Age 0 to 74</td>
<td>Age 75 and above</td>
<td>Age 0 to 74</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cold</td>
<td>Heat</td>
<td>Cold</td>
</tr>
<tr>
<td>2000-2020</td>
<td>NA</td>
<td>-21.9</td>
<td>15.8</td>
<td>-52.1</td>
</tr>
<tr>
<td></td>
<td>RCP26-SSP1</td>
<td>-37.7</td>
<td>30.8</td>
<td>-158.9</td>
</tr>
<tr>
<td></td>
<td>RCP45-SSP2</td>
<td>-81.9</td>
<td>35.8</td>
<td>-264.3</td>
</tr>
<tr>
<td></td>
<td>RCP45-SSP4</td>
<td>-87.5</td>
<td>49.9</td>
<td>-298.2</td>
</tr>
<tr>
<td></td>
<td>RCP85-SSP3</td>
<td>-99.4</td>
<td>81.4</td>
<td>-306.6</td>
</tr>
<tr>
<td></td>
<td>RCP85-SSP5</td>
<td>-103.5</td>
<td>65.7</td>
<td>-345.4</td>
</tr>
<tr>
<td>2040-2060</td>
<td>RCP26-SSP1</td>
<td>-39.3</td>
<td>28.2</td>
<td>-206.7</td>
</tr>
<tr>
<td></td>
<td>RCP45-SSP2</td>
<td>-95.3</td>
<td>55.6</td>
<td>-363.3</td>
</tr>
<tr>
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<td>RCP45-SSP4</td>
<td>-97.1</td>
<td>73.4</td>
<td>-410.2</td>
</tr>
<tr>
<td></td>
<td>RCP85-SSP3</td>
<td>-104.7</td>
<td>149.8</td>
<td>-367.7</td>
</tr>
<tr>
<td></td>
<td>RCP85-SSP5</td>
<td>-123.9</td>
<td>140.5</td>
<td>-497.3</td>
</tr>
</tbody>
</table>
S12. Sensitivity analysis for Chapter 5

Using a cubic spline for the temperature-mortality association. (A) The RR at -1.5°C and 18.3°C (i.e. the 1st and 99th percentile of population-weighted daily mean temperature between 1974-2018) in Scotland in 26 20-year historical periods indicated by the central year of each period, e.g. 1983 for 1974-1993. (B) The assumed TM association under each SSPs.

Results of using a cubic spline for the temperature-mortality association. (A) Annual mortality burden for two age groups and (B) annual mortality burden per 1 million population attributed to cold and heat in Scotland in two historical periods (1980-2000 and 2000-2020) and 2060-2080 under five RCP-SSP scenarios. (C) The change in mean annual mortality burden in 2000-2020 and
2060-2080 under five scenarios compared to 1980-2000 and decomposition of the change into the three relevant driving components.