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HEALTH IMPACTS OF CLIMATE CHANGE AND MITIGATION POLICIES IN IRELAND

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ECONOMIC & SOCIAL RESEARCH INSTITUTE

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ABBREVIATIONS

CLIMAQ-H	Climate Change Mitigation, Air Quality and Health
COACCH	CO-designing the Assessment of Climate CHange
COP	Conference of Parties
EEA	European Environment Agency
EPA	Environmental Protection Agency
EU	European Union
GHG	Greenhouse Gas
HIPE	Hospital In-Patient Enquiry
HPO	Healthcare Pricing Office
ICHEC	Irish Centre for High-End Computing
IPCC	Intergovernmental Panel on Climate Change
NDC	Nationally Determined Contribution
RCM	Regional Climate Model
RCP	Representative Concentration Pathway
UNFCCC	United Nations Framework Convention on Climate Change
WHO	World Health Organization

EXECUTIVE SUMMARY

0.1 INTRODUCTION

Recognition of the need to limit climate change has led countries to sign up to concerted efforts to decrease greenhouse gas (GHG) emissions. These efforts culminated in the ratification of the Paris Agreement by Ireland and 196 other countries in 2015. This agreement, and the subsequent Climate Action and Low Carbon Development Act of 2021, commit Ireland to a GHG emissions reduction goal of at least 55 per cent compared to 1990 levels by 2030 and net-zero emissions by 2050.

These commitments to reduce GHG emissions through various Climate Action Plans will have considerable economic and societal ramifications, including on population health. For EU countries, the health implications of climate change are estimated to be extensive, while climate change may impede the sustainability of healthcare service provision. The changing climate, predicted to intensify, can exacerbate health impacts, especially in vulnerable demographic groups such as children, older people, and individuals with chronic diseases. However, in addition to the direct benefits for health from emission reductions (e.g., from fewer extreme weather events), emission reduction policies may also have co-benefits for health, e.g., the shift to more bicycle-based commuting through increased cycle lanes or the switch to lower meat consumption can help reduce emissions and improve health outcomes. Despite the growing evidence on the link between increasing temperatures, and likely emission reduction target policies, on health, little evidence exists on the health effects of climate change and associated mitigation actions in an Irish context.

The aim of this report is to contribute to the understanding of the link between climate change and health by examining the impact of temperature changes on health and healthcare utilisation in Ireland. While there are multiple dimensions of climate change that may affect health (e.g., increasing temperature, increased precipitation, wildfires, etc.), temperature change is considered one of the principal health threats facing Ireland with respect to climate change. First the report undertakes an in-depth review of the literature on the link between temperature change and health, focusing on evidence from other regions with moderate climates that are similar to Ireland. It also provides an overview of the literature that has assessed the health benefits and co-benefits of climate change mitigation action. Second, the report utilises Met Éireann temperature data to develop Irish climate projections based on simulations performed by the Irish Centre for High-End Computing (ICHEC). Next, the research examines the impact of increases in temperature on use of emergency in-patient hospital care in Ireland. Finally, the report also outlines some of the potential health benefits and co-benefits of climate change mitigation actions, in Ireland.

0.2 METHODS

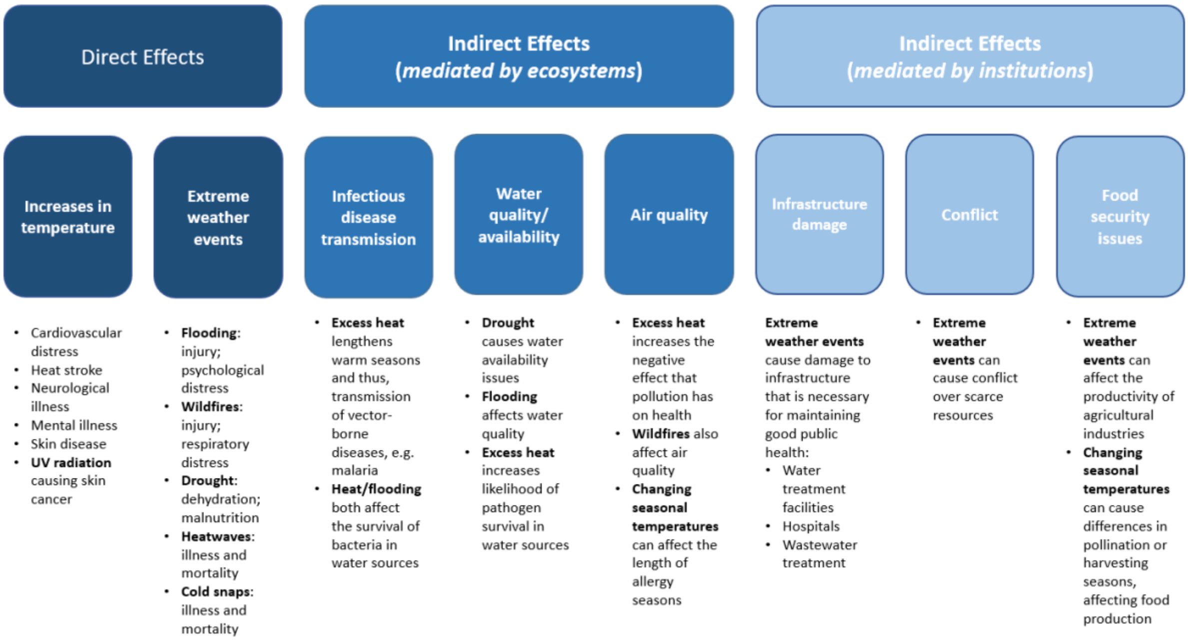
0.2.1 Climate change modelling

Regional climate models (RCMs) have been developed to provide an understanding of climate change and to simulate and project future climate conditions at a country or regional level. In this report, an Irish climate projections model is developed based on simulations performed by the Irish Centre for High-End Computing (ICHEC). Climate researchers at the ICHEC provide high spatial resolution (with grids of $4km^2$) climate information for the evaluation of the local effects of climate change, using two RCMs: the Consortium for Small-scale Modelling-Climate Limited-area Modelling (COSMO-CLM) and Weather Research and Forecasting (WRF). Simulations were run for the base period 1981–2000 and the future period 2041–2060. The difference between the two periods gives a measure of climate change, with uncertainty in future emissions also simulated. Findings from the simulations are also used to inform the analysis of potential health effects of temperature increases in the future.

0.2.2 Health impacts

The report develops a framework to conceptualise the ways in which climate change, and temperature change in particular, affects health. This framework is informed by international studies that highlight complex pathways through which climate change affects health both directly and indirectly. Figure 0.1 presents the conceptual framework underpinning the analysis. It identifies multiple outcomes that can occur from a single climate change event (e.g., increases in temperature can cause cardiovascular and respiratory distress, while also contributing to longer warm seasons, aiding the transmission of insect-borne and water-borne diseases). These outcomes are likely to be worse among certain vulnerable groups.

FIGURE 0.1 INFOGRAPHIC OF EFFECTS OF CLIMATE CHANGE ON HEALTH



Source: *Infographic devised by authors based on literature.*

Informed by the conceptual model above, the first part of the report examines the impact of temperature change on morbidity in Ireland over the period 2015-2019, by matching high-frequency data on emergency in-patient hospitalisations from the Hospital In-Patient Enquiry (HIPE) system with meteorological data from Met Éireann (the Irish Meteorological Service). The HIPE data includes detailed diagnostic information for patients as well as socio-demographic information, including county of residence and date of admission. This analysis provides an indication of the effect that higher temperatures might have on the healthcare system if hotter temperatures occur more frequently.

0.2.3 Health benefits and co-benefits

The report also provides an analysis of the health benefits and co-benefits of climate change mitigation actions, with a particular focus on Ireland. These analyses are based in part on outputs from the CO-designing the Assessment of Climate CHange costs (COACCH) project, an EU project analysing the costs of climate change across different economic and social dimensions in Europe. The co-benefits of reductions in air pollution are also assessed using a new model developed by the World Health Organization (WHO), CLIMAQ-H. Analyses using the HIPE data is also combined with the climate projections data to analyse the potential impact of future scenarios of temperature change on emergency in-patient hospitalisations in Ireland.

0.3 KEY FINDINGS

0.3.1 Climate change modelling

According to the ICHEC simulation analysis, Ireland will be exposed to higher mean temperatures in the future. The mean annual temperature is projected to increase by 1–1.6^{o}C by the middle of the century (i.e., 2041–2060) compared to the reference period 1981–2000, under the RCP4.5 climate scenario (the most likely scenario). With this warming will come hotter days and nights. In comparison to the baseline period, the warmest 5 per cent of daily maximum temperatures are projected to increase by 1–2.2^{o}C while the coldest 5 per cent of daily minimum temperatures are projected to rise by 1–2.4^{o}C. However, these projections show variations in temperature across the country that are expected to be marked by increased temperatures in eastern regions.

0.3.2 Health effects of temperature change

The analysis finds that higher temperatures increase the number of emergency in-patient hospital admissions. Compared to a reference temperature of 10–13^{o}C, linear increases in hospital admissions are observed between temperatures of 16–25^{o}C. These results show that at temperatures between 22–25^{o}C there was an increase in emergency hospital admissions of 4.71 per 100,000 population compared to when temperatures were in the reference category (10–13^{o}C). This represents an 8.5 per cent increase in emergency hospitalisations.

The analysis also compared the effects of rising temperature across diseases and age groups. At warmer temperatures, certain health conditions tend to be exacerbated such as circulatory, respiratory and infectious diseases as well as injuries. The largest relative impacts across age are seen for children (0–14 years). At temperatures 22–25^{o}C there was a 12.2 per cent higher rate of emergency hospitalisations for children compared to when temperatures were in the reference category (10–13^{o}C.) For the working age group (15–64), the effects are smaller in magnitude. Hospital admissions for the older (65+) age group exhibit a similar pattern to the results in the main analysis, although are not statistically significant. This latter result may indicate adaptive behaviour on the part of older people to higher temperatures in Ireland, an effect that may kick in at lower temperatures than for other population groups.

Overall, these analyses highlight that even in Ireland, a country with a moderate climate, a positive relationship between higher temperature and emergency in-patient hospital utilisation is observed.

0.3.3 Health benefits and co-benefits of climate change mitigation measures

The review of the literature identifies a range of benefits and co-benefits of climate change mitigation measures, such as improved air quality (which reduces cardiovascular and respiratory disease in particular), and reductions in disease and mortality from more sustainable diets and more active travel. Evidence from the COACCH project finds that towards the end of the 21st century, annual excess mortality under the most pessimistic climate scenario in terms of climate action (RCP8.5) is around 1,400 additional deaths per annum in Ireland. This compares to 216 under the most optimistic scenario (RCP2.6). This highlights that the health benefits of mitigation measures to reduce the impacts of climate change could be substantial when expressed in mortality terms. Evidence from the WHO CLIMAQ-H project suggests that there are health and economic benefits associated with improved air quality in particular (e.g., a reduction in restricted activity days of nearly 80,000 by 2030).

Focusing on morbidity, a case study of the effect that different scenarios for increased temperatures would have on emergency in-patient hospitalisations in the future also shows large variation across climate change scenarios. The analysis finds that an additional day in summer months above the 90th temperature percentile increases the rate of emergency in-patient hospitalisations by 2.85 per 100,000 population. Applying this estimate to the various climate change scenarios, the analysis shows that there would be a 9.4 per cent annual increase in emergency in-patient hospitalisations for health conditions linked with temperature increases for the period 2021–2040 under the most realistic scenario (RCP4.5 scenario), and a 12.2 per cent increase in the period 2041–2060. A plateau would occur thereafter. After 2060, and particularly 2080, the implications of not acting to limit climate change become much starker, as the increase in annual emergency in-patient hospitalisations under the most pessimistic RCP8.5 (“no mitigation”) scenario continues to increase.

0.4 DISCUSSION

This report examines the potential consequences of rising temperatures, a significant aspect of climate change, on health and healthcare in Ireland. The report also provides new evidence on the link between higher temperatures and increased emergency hospital admissions. Furthermore, the report identifies two major policy response categories to climate change: mitigation and adaptation. The analysis largely focuses on mitigation strategies and their potential health benefits and co-benefits, though it underlines the importance of also considering the unintended consequences of these measures.

The findings of increased hospitalisations from higher temperatures underscore the broad impacts of climate change on the health sector. While such impacts are higher in countries with less moderate climates, as outlined by the European Environment Agency (EEA), adapting healthcare facilities to temperature change is important even in more moderate climates. The amplified risk of extreme weather events (e.g., flooding and heatwaves) also poses significant challenges to healthcare infrastructure. Preparing for these events, through measures like improving physical infrastructure, planning for backup power sources, and devising emergency response plans, has become a common practice in regions like the

United States' Gulf Coast.

Finally, the report underlines the importance of appropriate data collection and availability in climate change research. Global Burden of Disease studies are only now starting to include temperature change as a risk factor for global disease and mortality, and are underpinned by numerous assumptions, many of which will not be transferable to an Irish (or moderate climate) context. The research in this report adopted a more direct approach, quantifying temperature change impacts on health (i.e., morbidity) via hospital admissions from the HIPE dataset. This approach allowed for the control of additional factors influencing hospital admissions and emphasises the value of making administrative health data like HIPE accessible to researchers and policymakers, and the linking of such data with other datasets (e.g., weather data), to fully harness its richness for evidence-based policy formulation.

CHAPTER 1

Background

1.1 INTRODUCTION

Recognition of the need to limit climate change has driven global negotiations concerning combined efforts to decrease greenhouse gas (GHG) emissions over the past decades within the United Nations Framework Convention on Climate Change (UNFCCC). In 2015, the Paris Agreement was adopted and to date has been ratified by 197 states and the European Union (EU); the global commitment to this agreement was reinforced in the Conference of Parties (COP) held in November 2021 and the resulting Glasgow Climate Pact. Under the Paris Agreement, the EU has submitted its EU-wide emissions targets (through Nationally Determined Contributions (NDCs)), which commit to a GHG emissions reduction goal of at least 55 per cent compared to 1990 levels by 2030 and net-zero emissions by 2050. These targets have been legislated through the EU Climate Law, making them legally binding.

Ireland has shown its commitment to reducing emissions, where the Programme for Government 2020 included an annual emissions reduction target of 7 per cent, resulting in a 51 per cent reduction of emissions by 2030 (Government of Ireland, 2020). This target was made legally binding by the Climate Action and Low Carbon Development (Amendment) Act of 2021, and further commits to net-zero emissions by 2050. The government has also made significant strides over the past years to introduce and formulate policies needed to ensure these targets are met. The Climate Action Plans 2019 and 2021 provide a detailed plan of measures needed for this transition, with the third national update, the Climate Action Plan 2023, setting out the additional measures required to align with economy-wide carbon budgets and sectoral emission ceilings (Government of Ireland, 2021, 2022). However, the Environmental Protection Agency (EPA) has noted that Ireland is only on target to achieve a reduction of 29 per cent in GHG emissions by 2030 compared to a target of 51 per cent (EPA, 2023).

When analysing the effects of climate change, the focus is often on the economic costs to society. For example, the European Environment Agency (EEA) estimated that the economic losses from weather- and climate-related extremes in Europe reached approximately half a trillion euro over the last 40 years (European Environment Agency, 2021), and €48bn in 2021 alone (van Daalen et al., 2022). For Germany, Karlsson and Ziebarth (2018) estimate that one additional hot day with temperatures above 30°C would create monetised health losses of between €750,000 to €5 million per 10 million population. In France, Adélaïde et al. (2022) estimate that the economic impact of health effects from heatwaves over the period 2015–2019 amounts to approximately €25.5 billion including mortality, minor restricted activity days and morbidity. Hensher (2023) highlights the fact that climate change can also affect the sustainability of the healthcare sector. He notes that it will be necessary to prepare the healthcare system for emerging health needs as well as the physical, economic and social impacts of continued climate change.

Health impacts of climate change are important and remain relatively unexplored for Ireland. As climate change is predicted to worsen over time, climate change-related health impacts are likely to become more pronounced even in temperate climates (Gibney et al., 2022). In addition, the health risks associated with climate change are more pronounced for vulnerable population groups, such as the older population and children, and those with pre-existing chronic diseases (Crimmins et al., 2016; EASAC, 2019; Flood et al., 2020; Romanello et al., 2022). More socio-economically disadvantaged populations are also more vulnerable to the effects of climate change (Kaźmierczak et al., 2022).

There is also little discussion of the avoided climate impacts in Ireland as a result of climate change mitigation measures. Mitigation measures limit the extent of climate change and hence limit the climate-related health impacts in Ireland. Certain mitigation measures also have concomitant health co-benefits, e.g., the shift to more bicycle-based commuting through increased cycle lanes or the switch to lower meat consumption can help reduce emissions and improve health outcomes. The research detailed in this report, carried out as part of a research programme funded by the Irish Heart Foundation and Irish Cancer Society on behalf of the Climate and Health Alliance, aims to help fill this gap. It focuses on the health impacts of climate change (and specifically temperature change) and how global and national commitments to limiting temperature change may reduce these impacts in Ireland. Therefore, it also aims to better understand some of the health benefits and co-benefits of climate change mitigation efforts.

The following section (Section 1.2) sets out a conceptual framework that describes the various ways in which climate change may affect health. It provides a framework that underpins the analysis of the health effects of climate change in the Irish context (carried out in Chapter 3). Focusing on the health impacts of temperature change, Section 1.3 then discusses the national and international literature on the health effects of temperature change. Section 1.4 introduces the conceptual framework that underpins the analysis of health benefits and co-benefits of climate change mitigation actions (carried out in Chapter 4), while Section 1.5 discusses the national and international literature on the health benefits and co-benefits of climate mitigation actions. Section 1.6 provides a brief overview of the structure of the remainder of the report.

1.2 CONCEPTUAL FRAMEWORK (CLIMATE CHANGE AND HEALTH)

When examining the effects of climate change on health, it is helpful to provide a framework in which to conceptualise the ways in which climate change affects health. International studies have shown that the pathways through which climate change affects health are complex (Crimmins et al., 2016; Romanello et al., 2022).

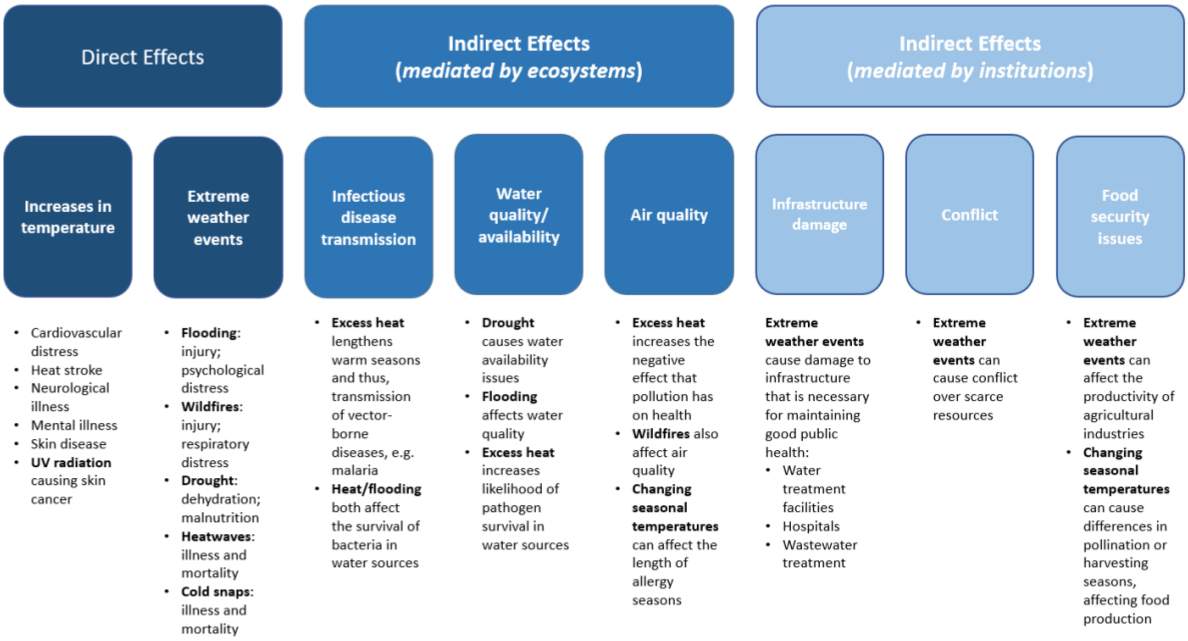
There are three reasons underpinning this complexity:

- the various events that could occur (e.g., increasing temperatures, heatwaves, flooding);
- whether pathways are direct or indirect (i.e., mediated via other factors);
- the various health outcomes that can be measured (e.g., specific diseases, mortality).

The latest Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) sets out the most up-to-date scientific information in relation to global climate change. Physical changes attributed to climate change include increases in hot extreme temperatures, upper ocean acidification, global sea level rise, glacier retreat, increase in heavy precipitation, increase in flooding, increase in fire weather and increase in agricultural and ecological drought (Cisse and McLeman, 2023). For Europe, extreme weather events (e.g., heatwaves), northward movement of diseases (e.g., malaria), drought, forest fires and soil moisture deficits have been highlighted as particular concerns (European Environment Agency, 2021).

In terms of pathways, the literature that aids in the conceptualisation of climate change effects on health illustrates the effect pathways in the following way (Smith, 1999; Department of Health, 2019; EASAC, 2019; Romanello et al., 2022). The pathways are separated into two distinct channels: direct and indirect. Indirect pathways are further separated into effects mediated by (1) ecosystem/environment, and (2) institutions/infrastructure. Direct effects are not mediated by other factors and capture, for example, the effect that increasing temperatures or extreme weather events have on health outcomes. This could include flooding directly causing injury, but also heat exacerbating cardiovascular and respiratory diseases, especially among frailer individuals. Indirect pathways, by contrast, are mediated by other factors. Hotter temperatures can give rise to bacterial conditions in water that can lead to water-borne disease outbreaks, or wildfires that can be linked with respiratory and circulatory disease complications (Navarro et al. 2019). These pathways are summarised in the following infographic devised by the authors of this report.

FIGURE 1.1 INFOGRAPHIC OF EFFECTS OF CLIMATE CHANGE ON HEALTH

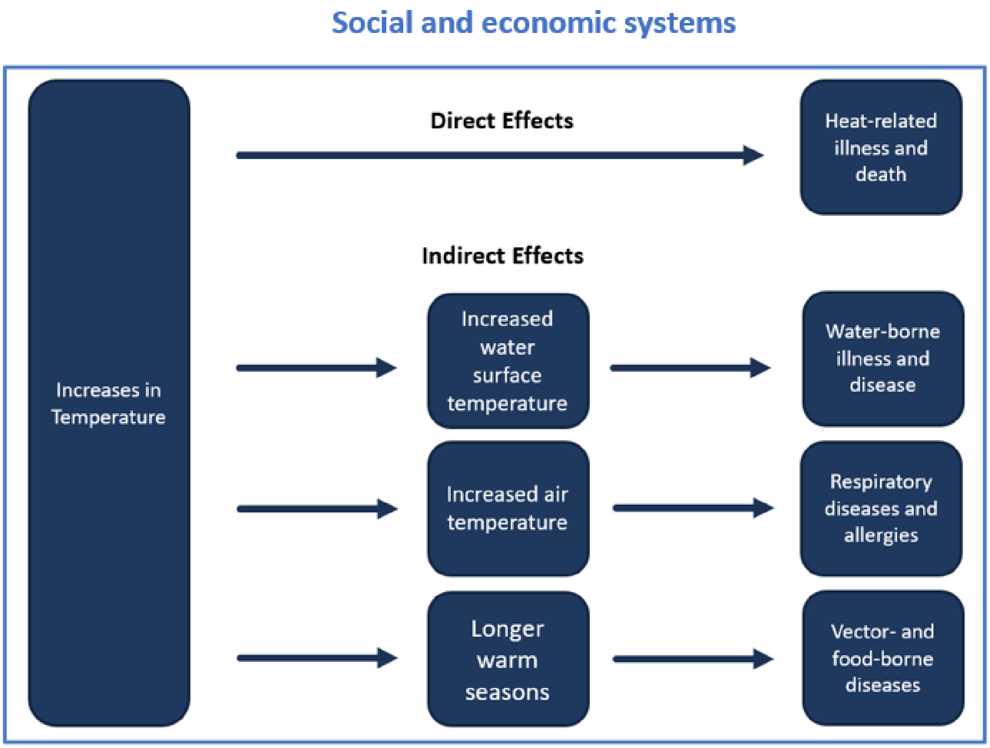


Source: *Infographic devised by authors based on literature.*

Figure 1.1 shows that there are multiple health outcomes from even just one climate change event. For example, increases in temperature can cause cardiovascular and respiratory distress, while also contributing to longer warm seasons, aiding the transmission of insect-borne and water-borne diseases. According to research carried out as part of the 2019 Global Burden of Disease (GBD) study, the high temperature-related disability-adjusted life year (DALY) and death rates were the highest for lower respiratory infections, followed by stroke and diabetes mellitus (Song et al., 2021).

The direct and indirect effects of climate change occur within a social and economic context. This context is important to consider because certain vulnerable groups in the population are more at risk. Literature has shown that these groups include, but are not limited to, those who are aged over 65 or under 5, those with chronic illnesses or disabilities and those who are socio-economically disadvantaged (Crimmins et al., 2016; EASAC, 2019; Romanello et al., 2022). For example, those in more disadvantaged social positions may be more likely to live in areas that are exposed to climate change (European Environment Agency, 2018). Vulnerable population groups may also be more vulnerable to the health-damaging effects of climate change such as air pollution, due to other characteristics such as poor housing conditions, chronic disease, etc. Certain occupational groups, such as outdoor workers, paramedics, firefighters and transport workers, as well as workers in hot indoor work environments, will be especially vulnerable to extreme heat (Flood et al., 2020). These complex interactions are illustrated for increasing temperatures in the following infographic devised by the authors based on reports from the IPCC (Smith et al., 2014; Cisse and McLeman, 2023), Department of Health (2019) and EASAC (2019). It would be possible to conceptualise other climate change events (e.g., flooding) in a similar framework.

FIGURE 1.2 INFOGRAPHIC OF EFFECTS OF INCREASING TEMPERATURES ON HEALTH



Source: *Infographic devised by authors based on literature.*

This framework underpins the approach taken to structure the analysis in the first part of the report. The analysis will primarily examine the effects of increasing temperatures on health, which is identified by the EEA to be one of the key climate-health threats facing Europe (Kaźmierczak et al., 2022). The EEA also notes that despite high average living standards, Europe's ageing society and prevalence of chronic diseases make its population particularly vulnerable to heat (Kaźmierczak et al., 2022). While climate-health threats are likely to differ between northern and southern Europe, the Department of Health (2019) and Desmond et al. (2017) have identified increasing temperatures as one of the principal health threats facing Ireland with regard to climate change. In Ireland, mean air temperatures have increased by 0.8°C in the 1900–2011 period, with projections out to the mid-century estimating an increase of 1.1–1.6°C (Desmond et al., 2017). Desmond et al. (2017) also highlight the risk from increased precipitation or flooding which can increase the risk of water-borne diseases such as campylobacteriosis and cryptosporidiosis. Future research (discussed in Chapter 5) could examine the health impacts of these and other likely climate change events in Ireland, as well as the impacts on other outcomes such as worker productivity. In the following section, we provide a more detailed overview of the national and international literature that has examined the effect of temperature change on health, before moving on to discuss the conceptual framework and literature on the health benefits and co-benefits of climate change mitigation.

1.3 LITERATURE REVIEW (TEMPERATURE CHANGE AND HEALTH)

The available literature on the effects of temperature change on health covers a wide range of countries, time periods and modelling approaches. The climate in which temperature-health studies are conducted is important as countries or cities that are more acclimatised to heat may have already developed adaption measures to deal with hotter temperatures. Acclimatisation can occur through physical adaptation, housing characteristics, or behavioural patterns (e.g., staying indoors, changing work patterns) (Anderson and Bell, 2009).[1] Indeed Barreca et al. (2016) found that the diffusion of air conditioning explained nearly all of the decline in heat-related mortality observed in the US since 1960. This means that any identified effects of temperature on health from these studies may be muted or only exist for extreme temperatures, and may not therefore be generalisable to more temperate climates. Baccini et al. (2008) deal with this in their study of multiple cities by allowing the threshold temperature value to vary across different cities: they show that the threshold temperature for London is 23.9°C compared to Rome, which had a threshold value of 30.3°C.

How temperature is characterised, and the resulting modelling approach, can also differ considerably across studies. For example, Karlsson and Ziebarth (2018) contrast the differing approaches implemented across epidemiological and economic studies. In some cases, temperature is characterised as a continuous variable, in others temperature is categorised into 'temperature bins' to allow for more flexible functional forms (Deschênes and Greenstone, 2011; White, 2017; Gibney et al., 2022; Liao et al., 2023), while in others threshold or percentile values are constructed (Hajat et al., 2006; Baccini et al., 2008; Breitner et al., 2014). Many studies also take account of the potential for lagged effects in the response of health outcomes (e.g., mortality) to changes in temperature (Goodman et al., 2004; Baccini et al., 2008; Anderson and Bell, 2009; Zeka et al., 2014; Liao et al., 2023).

Furthermore, previous research uses a variety of health outcome measures to assess the health impacts of temperature change. Indeed, a recent overview of systematic reviews of the literature on the effects of climate change on health categorised health impacts into ten broad groups (Rocque et al., 2021). These groups covered outcomes such as hospitalisations, mortality, infectious diseases and respiratory, cardiovascular and neurological disease, and mental health and wellbeing (Rocque et al., 2021). Mortality is generally measured by using the number of deaths (all-cause and in some cases, cause-specific) or the age-standardised mortality rate. Mortality is the most common outcome examined in existing studies of the effects of temperature on health (Hajat et al., 2006; Baccini et al., 2008; Deschênes and Greenstone, 2011; Breitner et al., 2014; Gasparrini et al., 2022; Liao et al., 2023). However, while mortality measures deaths in a population, morbidity is also a key outcome. Morbidity focuses on the prevalence

[1] It has been suggested the same is true for cold weather. Deschênes and Greenstone (2011), however, find very weak evidence in support of this hypothesis for cold weather.

and impact of diseases and health conditions, including non-fatal conditions. Morbidity allows for the broader impact of disease, or the causes of disease (e.g., temperature increases), on quality of life and healthcare systems to be examined. Morbidity is commonly proxied by calculating healthcare utilisation, such as in-patient hospital admission rates or the rate of attendances to emergency departments (EDs). In Section 3.2 in Chapter 3, we describe the data and methods we use in this analysis to model the impact of temperature change on health in Ireland. In the following sections (Sections 1.3.1 and 1.3.2), we survey the relevant national and international literature on temperature change and health.

1.3.1 International literature on temperature change and health

The 2019 GBD study provides a comprehensive picture of mortality and disability across countries, time, age, and sex. It quantifies health loss from hundreds of diseases, injuries and risk factors. As a result of multiple requests to begin capturing important dimensions of climate change into the GBD study, the direct relationship between high and low non-optimal temperatures on all GBD disease and injury outcomes was modelled in the 2019 study (Murray et al., 2020).[2] Globally, low temperature or cold was the 12th-leading level 3[3] risk factor for deaths in 2019, contributing to 2.9 per cent of all deaths, or 1.65 million deaths. Globally, 308,000 deaths in 2019 were attributable to exposure to high temperatures, concentrated mainly in south Asia, north Africa, the Middle East and Sub-Saharan Africa. A related study for the 2019 GBD focused specifically on high temperature, and evaluated the disease burden attributable to high temperature. The results show that in 2019, 589 deaths (or a rate of 0.06 per 100,000 population) in Western Europe were attributed to high ambient temperature. The analysis also showed that the disease burden attributable to high temperature varied spatially, with the heaviest burden in regions with low socio-demographic index (SDI) and the lightest burden in regions with high SDI (Song et al., 2021).

There are two key pan-European studies that examined heat effects on mortality in cities. While Baccini et al. (2008) examined the effects of temperature, Hajat et al. (2006) analysed whether there is an added heatwave effect on mortality. Overall, positive associations between temperature and mortality were identified. Baccini et al. (2008) estimated the observed mortality effect past a city-specific threshold at about 3.1 per cent for Mediterranean cities and 1.8 per cent for northern Europe for each 1°C increase above the threshold. Hajat et al. (2006) found that for London, mortality increased by 5.1 per cent for every 1°C increase above the identified threshold. The studies found that overall summertime mortality burden is more important to examine than the acute effects of

[2] However, other climate-related relationships, such as between precipitation or humidity and health outcomes, have not yet been evaluated.

[3] The GBD methodology has a risk factor hierarchy. Level 1 risk factors are behavioural, environmental and occupational, and metabolic; Level 2 risk factors include 20 risks or clusters of risks (e.g., non-optimal temperature); Level 3 includes 52 risk factors or clusters of risks (e.g., high temperature) (Murray et al., 2020).

heatwaves. Their findings also showed greater associations for respiratory deaths, even when air quality was controlled for.

Other studies have examined the temperature-heat relationship within one country. Breitner et al. (2014) conducted a study on three German cities, using time-series analysis to investigate the association between daily air temperature and cause-specific mortality. They found that an increase from the 90th to the 99th percentile of 2-day mean temperature led to an increase in non-accidental mortality by 11.4 per cent. Alternatively, a decrease from the 10th to the 1st percentile in a 15-day mean temperature led to an increase in mortality by 6.2 per cent. They found that the population aged over 85 were the most susceptible to excess heat. Adélaïde et al. (2022) analysed the health effect of heatwaves in France using ED visits and out-patient clinic visits. They found a significant effect of temperature on ED visits for heat-related symptoms. Liao et al. (2023) examined the relationship between extreme heat and mortality using county-level data for China over the period 2000–2015. They found that an additional day with a maximum temperature of 38°C or above was associated with a 1.7 per cent net increase in the monthly mortality rate (relative to if that day's maximum had been in the 16–21°C range).

The use of ED data to estimate temperature-related health effects is also applied in a study for the UK (Gibney et al., 2022). This study draws on a similar methodology as White (2017), who investigated the relationship between temperature and ED attendances in California. There are similar findings from the two studies, but the analysis in the UK study is more relevant to the analysis in this report. Gibney et al. (2022) found an immediate temperature effect on heat-related morbidity, as measured by ED visits. In contrast, cold-related morbidity has a lagged response of up to three weeks after the temperature shock, with a greater cumulative effect.

Other health outcomes have also been examined; for example, Graff Zivin et al. (2018) exploited variation in survey interview dates with young people from the US National Longitudinal Survey of Youth to examine the effect of temperature on cognitive performance. They find that maths performance declines linearly above 21°C, with the effect statistically significant beyond 26°C (the effects of temperature fluctuations on assessments of reading recognition and comprehension were non-significant). Mullins and White (2019) analysed the effect of temperature fluctuations on a variety of mental health outcomes (including ED visits for mental health conditions, and suicides) in the US, and found that cold temperatures reduce mental health symptoms while hot temperatures increase them. A recent systematic review found evidence of associations between heat and preterm birth (Bekkar et al., 2020). Yu et al. (2023) note that climate change will widen inequities in cancer incidence and treatment through its complex connections with modifiable risk factors, such as ambient and household air pollution. While the evidence base for associations between high temperatures and cancer is still developing, increasing ultraviolet radiation (UV) exposure is associated with increased risks of melanoma and other skin cancers (e.g., squamous cell skin cancer). Recent research from the US has also found that firefighters who deal with wildfires have increased risks of lung cancer and cardiovascular disease mortality (Navarro et al. 2019).

A few studies examining temperature effects on health look at distributional impacts and cause-specific impacts. Rizmie et al. (2022) used a similar methodology to both White (2017) and Gibney et al. (2022) for UK ED attendance data, but subsequently stratified the analysis by age and socio-economic deprivation. They also stratified by type of diagnosis. They found that older and deprived populations were the most at risk of adverse health effects from temperature-related illness, and in particular for admissions due to metabolic disease and injuries. Gasparrini et al. (2022) also examined the distribution of vulnerability to health risks from temperature for England using small-area data. While cold-related excess mortality over the period 2000–2019 was substantially higher than heat-related excess mortality, they found that there was increased risk of heat-related mortality in more socio-economically deprived and urban areas. They found an increased risk of cold-related mortality in northern regions of England. Using data from New York City, Lin et al. (2009) found that extreme high temperatures increase hospital admissions for cardiovascular and respiratory disorders, with older and Hispanic residents particularly vulnerable to the temperature effects on respiratory illnesses.

1.3.2 Irish literature on temperature change and health

Irish studies examining the link between temperature change and health[4] are similar in methodology to the European studies mentioned in the previous section, although all of the Irish studies summarised in this section use mortality as the outcome of interest. The Irish literature shows that a broader analysis of both hot and cold weather is necessary, as both are shown to have significant associations with mortality.

There are two pan-European studies in which data from Ireland is included. Healy, 2003 used a multi-country analysis using 14 European countries to examine the effect of cold weather on mortality. Baccini et al. (2008) used a similar approach but with multiple European cities and examined the effect of heat on mortality. Healy (2003) found that Ireland had the third highest rates of excess winter mortality after Portugal and Spain for the period 1988 to 1997. Baccini et al. (2008) found that there was no significant association between heat and mortality for Dublin between 1990 and 2000. Another study, Pascal et al. (2013), examined the mortality effects of five heatwaves in Ireland from 1981 to 2006. Overall, they found that 294 excess deaths were attributed across all of the heatwaves. The authors highlight the urban-rural divide showing that during the summer months,

[4] While not examined in this report, an emerging literature is examining the link between other aspects of climate change and health in Ireland (see for example, Musacchio et al. (2021) who quantify the capacity of private well users in Ireland to cope with flood-triggered contamination risks).

average temperatures were higher in urban areas with mean temperatures of 15.3°C compared to 14.6°C in rural areas. The authors concluded that (over the period they examined) heat was a moderate but real risk in Ireland, particularly for older adults and those in urban areas. Ščasný et al. (2019) assessed the mortality impacts of temperature change for regions in Europe, including estimates for Ireland. They found that temperature increases increase mortality. These results will be presented and discussed in more detail in Chapter 4.

Two studies examine the association between cold and mortality in Ireland. Goodman et al. (2004) examined the association between temperature and mortality (controlling for air pollution) for Dublin over 17 years. They found that increases in temperature of 1°C were associated with increases in mortality of 0.4 per cent, while decreases in temperature of 1°C were associated with a 2.6 per cent increase in mortality over 40 days after the initial decrease in temperature. Cardiovascular mortality was shown to have the largest effect and effects were observed almost immediately, while respiratory mortality showed greater lags. Zeka et al. (2014) examined daily fluctuations in the cold months for both the Republic of Ireland and Northern Ireland between 1984 and 2007. They found that the impact of cold weather on mortality persisted for up to 35 days, resulting in a cumulative mortality increase for all-causes of 6.4 per cent for every 1°C decrease in temperature. Similar estimates were found for cardiovascular disease and stroke, but estimates were twice as high for respiratory causes.

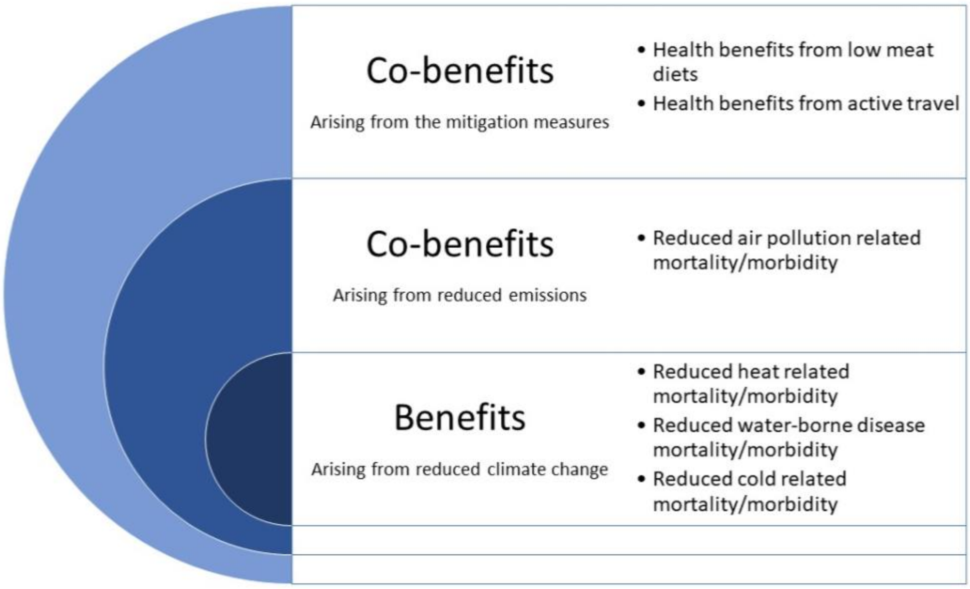
1.4 CONCEPTUAL FRAMEWORK (HEALTH BENEFITS AND CO-BENEFITS OF CLIMATE CHANGE MITIGATION)

The EEA highlights that dealing with climate change requires two interlinked actions working together:

- Climate change mitigation, i.e., reducing the emission of greenhouse gases into the atmosphere to slow down climate change;
- Climate change adaptation, i.e., actions to adapt to the impacts of climate change, like preventing flooding, preparing for heatwaves and reducing other climate risks.

In addition to the direct benefits for health from emissions reductions (e.g., from lower temperatures), emission reduction policies may also have co-benefits for health, e.g., the shift to more bicycle-based commuting through increased cycle lanes or the switch to lower meat consumption can help reduce emissions and improve health outcomes. Figure 1.3 provides an infographic of the health benefits and co-benefits of mitigation action. The primary benefit of mitigation action is the resulting reduced climate change, which reduces health impacts resulting from climate change. These benefits arise from global climate mitigation efforts. Co-benefits are defined as additional benefits related to the reduction of GHG emissions that are not directly related to climate change, which generally arise from national mitigation measures. The health co-benefits associated with climate change mitigation efforts can arise through several pathways, including through reduced air pollution, increased physical activity, and dietary change (Haines, 2017).

FIGURE 1.3 INFOGRAPHIC OF HEALTH BENEFITS AND CO-BENEFITS OF MITIGATION ACTIONS



Source: Infographic devised by authors based on literature.

1.4.1 Air pollution

Air pollution is well recognised as a major risk factor for disease and premature mortality worldwide (Murray et al., 2020; Vos et al., 2020; European Environment Agency, 2022). The global burden of disease attributable to air pollution is now estimated to be comparable with other major health risks such as unhealthy diet and tobacco smoking, and was in the top five out of 87 risk factors for male and female deaths in 2019 (Murray et al., 2020). As a result, air pollution is now recognised as the single largest environmental threat to public health (WHO, 2021).

The greatest health damage from ambient air pollution is caused by chronic exposure to particulate matter, in particular to $PM_{2.5}$ which increases the risk of heart diseases, stroke, lung cancer and many respiratory diseases including asthma, bronchitis, chronic obstructive pulmonary disease (COPD) and respiratory infections (Brook et al., 2010; OECD, 2016, 2020; Cohen et al., 2017). Air pollution exposure may also increase the incidence of, and mortality from, a larger number of diseases and conditions than those currently considered, such as cognitive impairment and dementia (Weuve et al., 2012; Ailshire and Crimmins, 2014; Peters et al., 2019; Wood et al., 2022), lung cancer (Pimpin et al., 2018), type 2 diabetes and neonatal mortality (Murray et al., 2020). There is also a growing evidence base linking air pollution (particularly $PM_{2.5}$) with poorer mental health and wellbeing, including depression and anxiety (Power et al., 2015; Braithwaite et al., 2019), suicide (Gładka et al., 2021), bipolar disorder (Hao et al., 2022) and life satisfaction (Orru et al., 2016). Aguilar-Gomez et al. (2022) survey the growing literature within economics that has begun to investigate the causal effects of air pollution on numerous 'non-health' outcomes, such as worker productivity, school performance, decision-making, and even crime.

A number of assessments of the mortality and morbidity burden associated with air pollution in Ireland are available. Using data for 2019, Goodman et al. (2023) estimate that approximately 1,700 premature deaths (680 from cardiovascular disease) per annum in Ireland can be attributed to exposure to $PM_{2.5}$. These premature mortality estimates for $PM_{2.5}$ are higher[5] than those published by the EEA or the GBD study which ranged from 535 to 1,300 (European Environment Agency, 2019, 2022; Murray et al., 2020). Clancy et al. (2002) and Dockery et al. (2013) examined the impact of the so-called 'smoky coal bans' on mortality and hospitalisations during the 1990s. A more recent quasi-experimental analysis of the extension of smoky coal bans to small towns in Ireland over the period 2010–2018 found that the bans reduced the incidence of chronic lung disease among the older population, but non-significant effects on all-cause mortality were found (Lyons et al., 2023).

1.4.2 Sustainable transport and diet

The Climate Action Plan 2023 notes that diets that shift away from meat consumption can not only reduce our carbon footprint, but also reduce the risk of some health conditions like heart disease, while embracing active travel (walking and cycling) can have improved physical and mental health benefits (Government of Ireland, 2022). According to the 2019 GBD study, diet quality (comprised of 15 indicators such as red meat intake, sodium intake, insufficient fruit and vegetable intake, etc.) is the fifth leading level 2 risk factor[6] for attributable DALYs. Globally, a diet high in red meat was responsible for 23.9 million DALYs and 896,000 deaths in 2019. The top diseases associated with red meat consumption were cardiovascular disease, diabetes and kidney disease, and cancer (Murray et al., 2020). Focusing on physical inactivity, low physical activity was ranked 18th in attributable DALYs among level 2 risk factors in 2019, accounting for 198.4 age-standardised DALYs per 100,000 population and 11.1 age-standardised deaths per 100,000, globally. Once again, cardiovascular disease, diabetes and kidney disease, and cancer were the primary diseases caused by low physical activity (Murray et al., 2020). The study notes that increased body mass index (BMI) can be traced to the combination of physical inactivity, excess caloric intake, and diet quality, and that globally, we are failing to change some behaviours, particularly those related to diet quality, caloric intake, and physical activity. They also note that tackling this

[5] This reflects the authors' use of updated dose response functions.

[6] Level 2 risk factor.

diet quality and excess energy intake will not only be important for human health but has important ramifications for environmental sustainability (Murray et al., 2020). These behaviours also have economic consequences; it was estimated that the cost of overweight and obesity in Ireland was €1.16 billion in 2009 (Dee et al., 2015).

1.5 LITERATURE REVIEW (HEALTH BENEFITS AND CO-BENEFITS OF CLIMATE CHANGE MITIGATION)

Previous analyses of climate change mitigation health benefits and co-benefits have either assessed the potential health effects of climate mitigation actions in aggregate by examining the possible benefits of different scenarios of emissions reduction (e.g., Markandya et al. (2018)), or by focusing on specific actions (e.g., plant-based diets, carbon taxes). In Section 1.5.1, we summarise previous research that uses the former approach, while Section 1.5.2 summarises previous studies that have followed the latter approach.

1.5.1 Scenario-based analyses

Gao et al. (2018) carried out a systematic review of 36 studies examining the health co-benefits associated with GHG emission mitigation in the energy generation, transportation, agriculture and food, household, and industry sectors at global, national and regional levels. The results indicate mostly positive associations between GHG emission reductions and health co-benefits. They also note that due to variations in study design, mitigation scenarios, exposure-response functions, model assumptions and selection of methods, it is often difficult to compare health co-benefit assessments even if the study area and target time scales are identical.

Focusing on quantifying the health effects associated with varying emission scenarios, Markandya et al. (2018) used the Global Change Assessment Model to quantify the GHG pathways and the related mitigation costs for six scenarios representing different combinations of climate target and mitigation strategy (where each scenario has its own GHG emission pathway). They then translated the resulting emission levels into pollutant concentrations, exposure, and premature deaths, and then monetised these effects. They found that at the global level, the value of the health co-benefits was greater than the cost of achieving the mitigation target for all the scenarios. The ratio of health co-benefit to mitigation cost ranged between 1.4 and 2.45. A similar exercise by Sampedro et al. (2020) found that the ratio of health co-benefit to mitigation cost for various energy supply scenarios ranged between 1.45 and 2.19. Hamilton et al. (2021) examined the GHG and population health effects resulting from current NDC targets within the energy, food and agriculture, and transport sectors, and the potential effects of more ambitious interventions consistent with the Paris Agreement for nine countries (Brazil, China, Germany, India, Indonesia, Nigeria, South Africa, the UK, and the USA). They found that mitigation actions that reduce emissions could lead to substantial improvements in health. For example, compared with the current pathways scenario, the sustainable pathways scenario (i.e., achievement of the Paris Agreement targets) resulted in an annual reduction of 1.18 million air pollution-related deaths, 5.86 million diet-related deaths, and 1.15 million deaths due to physical inactivity, across the nine countries, by 2040. The longer governments wait to implement mitigation actions, the greater the delay in the number of deaths avoided.

Focusing on Great Britain, Williams et al. (2018) modelled the impact of three possible emission reduction scenarios on future life expectancy; they found that over the period 2011 to 2154, the projected decline in NO_2 concentrations would lead to 4,892,000 life-years saved for the nuclear power scenario and 7,178,000 life-years saved for the low-GHG scenario. However, they noted that substitution towards other sources of fuel (e.g., biomass), and an increase in non-exhaust emissions could mean that the reductions in total $PM_{2.5}$ and PM_{10} concentrations in the nuclear power and low-GHG scenarios may not be as large as they might have been without the biomass increase. West et al. (2013) simulated the co-benefits of global GHG reductions on air quality and human health using a global atmospheric model and consistent future scenarios. They estimated global health co-benefits from reduced GHG emissions for 2030 (0.5 million fewer deaths), 2050 (1.3 million) and 2100 (2.2 million) relative to the baseline scenario in their model. Reductions in premature deaths related to respiratory diseases such as chronic obstructive pulmonary disorders (COPD) and lung cancer.

At the EU level, the PESETA IV project[7] evaluates the benefits (avoided negative impacts) of reducing GHG emissions and the potential of adaptation measures at EU sectoral level. For the scenario without climate policy actions, impacts are assessed at global warming of 3°C and no adaptation. The mitigation benefits of achieving the Paris warming targets are evaluated by estimating impacts with 1.5°C and 2°C global warming. It assesses the consequences of climate change for 11 climate impact categories: human mortality from heat and cold waves, windstorms, water resources, droughts, river flooding, coastal flooding, wildfires, habitat loss, forest ecosystems, agriculture and energy supply.[8] Focusing on the results for human mortality from heatwaves, the analysis indicates that with 1.5°C around 100 million Europeans would be exposed each year to an intense heatwave (corresponding to a present 50-year or more extreme heatwave event), or tenfold compared to now. This would further grow to 170 million per year with 2°C and nearly 300 million per year, or more than half of the EU and UK population, with 3°C global warming. Assuming present vulnerability (i.e., not accounting for the fact that the European population is ageing) and no additional adaptation, annual fatalities from extreme heat could rise from 2,700 deaths per year at present to approximately 30,000 and 50,000 by 2050 with 1.5°C and 2°C global warming,

[7] See https://joint-research-centre.ec.europa.eu/peseta-projects/jrc-peseta-iv_en.

[8] The authors note that is not comprehensive in terms of the broad range of potential consequences of climate change. Key impacts not studied include those related to aquatic and marine ecosystems, water- and vector-borne diseases, air quality, displacement of people, conflicts and security, the irreversible damage to nature and species losses, and the potential consequences of passing climate tipping points.

respectively. With 3°C in 2100, each year 90,000 Europeans could die from extreme heat. The rise in fatalities from extreme heat would be more acute in southern European countries, such as France, Italy and Spain (Feyen et al., 2020).

1.5.2 Analyses of co-benefits of specific mitigation actions

Specific mitigation actions can also result in co-benefits to health. Within the Irish context, the Climate Action Plan 2023 (CAP23) sets forth an action to support and promote a modal shift towards healthy active and sustainable mobility (CP/23/11), which would have positive impacts on health. Although these benefits are hard to quantify, the below literature review can create a better understanding of the potential level of health co-benefits for Irish mitigation actions. Haines et al. (2009) summarise a series of studies that assessed the health co-benefits of a broad range of mitigation strategies across four realms: (1) household energy; (2) transport; (3) food and agriculture; and (4) electricity generation. The results show that actions to reduce greenhouse gas emissions often, although not always, entail net benefits for health. For example, more active travel in London, UK, is estimated to lead to a substantial reduction in disease burden (approximately 7,400 DALYs per million population). They note that the greatest health gains in high-income countries are likely to come from changes towards active transport, and from diets that are low in animal source foods.

Haines et al. (2009) also point out that there are important caveats to consider with these mitigation strategies and that there are potential negative side effects of certain interventions. For example, greater energy efficiency in homes in the UK might reduce ventilation and increase radon concentrations, mould and indoor air pollution in the home; greater active travel may increase road injuries. Moreover, costs of mitigation strategies vary depending upon which types of policies are enacted: taxes, subsidies or investment in infrastructure. Estimates of the effectiveness of mitigation strategies is also dependent upon modelling assumptions and available data and as such, estimates of health co-benefits must be approached critically in the literature.

Focusing on actions to reduce air pollution, van Daalen et al. (2022) note that stringent air pollution emission controls (e.g., for electricity generation, industrial emissions, and agricultural practices) have resulted in reduced $PM_{2.5}$-related mortality in Europe since 2005. Approximately 117,000 deaths (about 2% of all deaths) were attributed to combustion of fossil fuels in 2020 in Europe, a decrease of 11,700 (60%) from 29,300 deaths attributable to combustion of fossil fuels in 2005. As a result of coal phase-down, the annual deaths attributable to $PM_{2.5}$ from coal-fired power plants decreased from 103,000 deaths annually in 2005, to 23,000 deaths in 2020.

In terms of diet, Springmann et al. (2016) used a region-specific global health model to link the health and environmental consequences of changing diets. They analysed the environmental and health impacts of four dietary scenarios in the year 2050, and found that moving to diets with fewer animal-sourced foods would have major health benefits. Compared with the reference scenario, they project that adoption of global dietary guidelines would result in 5.1 million avoided deaths per year and 79 million years of life saved. The equivalent figures for the vegetarian diet are 7.3 million avoided deaths and 114 million life years saved, and for the vegan diet 8.1 million avoided deaths and 129 million life years saved. Milner et al. (2015) estimate that if the average UK dietary intake were optimised to comply with the WHO recommendations[9], there could be an incidental reduction of 17 per cent in GHG emissions. Adherence to such a diet could save almost 7 million years of life lost prematurely in the UK over a 30-year period and increase average life expectancy by over 8 months.

Focusing on carbon taxation, Vandenberghe and Albrecht (2018) simulate three carbon tax scenarios in the energy and food sector in Belgium and assess the resulting health-related co-benefits (i.e., reduction in PM air pollution, and consumption of animal products). They find that the carbon tax could prevent 42,300–78,800 DALYs in Belgium, or save 0.6–1.1 per cent of total healthcare expenditure and an additional 0.06–0.12 per cent of Belgian GDP.

Many of the above studies rely on data and estimates from the epidemiological literature that examine the impact of behaviours that are consistent with climate change mitigation actions, such as increased active travel and more plant-based diets, on health outcomes (for summaries, see Saunders et al., 2013; Godfray et al., 2018). These estimates are then used to simulate the impact of specific climate change mitigation actions on health (for example, see Shaw et al., (2011) for active travel and Farchi et al. (2017) for diet). However, establishing causality in the underlying relationships is difficult (e.g., does active travel lead to better health outcomes, or are those in better health more likely to use active travel?) (Kroesen and De Vos, 2020). These estimates tend not to take into account the environmental and health consequences (both positive and negative) of broader behavioural changes (e.g., a switch from meat- to plant-based diets is likely to lead to increases in the consumption of other food groups such as nuts and seeds) (Springmann et al., 2016). In addition, the timing of health co-benefits is likely to differ, making quantification of co-benefits into the future difficult. For example, benefits from climate change mitigation actions include likely immediate reductions in acute respiratory infections in children from decreases in air pollution (particularly in low-income countries), short-term and medium-term reductions in cardiovascular disease incidence and mortality that might occur over a period of years, and reductions in cancer incidence and mortality related to obesity that might take place over decades (Haines et al., 2009).

[9] In order to conform to the WHO nutritional recommendations, the UK diet would need to contain less red meat, dairy products, eggs and sweet and savoury snacks, but more cereals, fruit and vegetables.

1.6 REPORT STRUCTURE

The remainder of the report is structured as follows: in Chapter 2, we provide an overview of climate modelling and the climate change projection process and scenarios used throughout this report; in Chapter 3 we outline the results of our analysis of the effects of temperature changes over the period 2015–2019 on emergency in-patient hospital admissions; in Chapter 4 we examine the health benefits and co-benefits of climate change mitigation measures on mortality, morbidity and selected economic outcomes. We also illustrate the potential effects on morbidity using a simulation that predicts the impacts on emergency in-patient hospital admissions of different temperature paths for Ireland out to 2100. Chapter 5 summarises and discusses the results.

CHAPTER 2

Climate change modelling

2.1 INTRODUCTION

The Earth's climate system is highly complex and involves a multitude of interaction mechanisms. To understand the Earth's climate system, climate models have been developed and improved significantly over the past decades. Climate models also give insights into the evolution of the climate and enable the prediction of future changes to the climate. The Earth's climate system consists of the atmosphere (i.e., the layers of gases that envelop the Earth), the hydrosphere (i.e., water), the cryosphere (i.e., ice and snow), the land surface (i.e., soil and rocks), and the biosphere (i.e., animals and plants), all influenced by various external forcing mechanisms such as solar and orbital variations (IPCC, 2013). Climate change modelling is an essential tool for understanding the Earth's climate system and hence how it will impact society. This chapter provides an overview of climate change modelling, including global and regional climate models, greenhouse gas emissions (GHG) scenarios, and Irish climate projections based on simulations performed by the Irish Centre for High-End Computing (ICHEC).

2.2 GLOBAL AND REGIONAL CLIMATE MODELS

Global Climate Models (GCMs) are used to understand past climate variations, reproduce historical climate patterns, and predict the characteristics of the future climate. They are complex mathematical representations of the components of the Earth's climate system (atmosphere, cryosphere, hydrosphere, land surface, and biosphere) and their interactions. By representing the Earth's climate system as a set of mathematical equations that are numerically solved using established mathematical techniques, GCMs capture the interactions between the various components and their behaviour over time, enabling climate scientists to study the long-term impacts on the climate (IPCC, 2013; Auffhammer, 2018).

GCMs require a large amount of computational power to solve the complex equations that control the climate system. Using supercomputers, they divide the Earth into a three-dimensional grid and calculate interactions between grid cells at different latitudes and locations. These calculations are performed over short periods of time, or "time steps", allowing the model to mimic weather phenomena or climatic events on timescales ranging from hours to hundreds of years (IPCC, 2013).

While GCMs have greatly improved our understanding of the Earth's climate system and its response to external influences such as solar variations and GHG emissions, they are not without flaws. Model parameters are prone to uncertainty, small-scale processes cannot be fully resolved, and it is challenging to precisely represent feedback mechanisms, cloud formation, and regional climate dynamics.

Climate scientists continue to refine and validate these models using observational data. Also, multiple models or ensemble simulations are used to account for uncertainties and present a range of potential future climate scenarios. The Coupled Model Intercomparison Project (CMIP) is paramount in this regard, as it brings together climate modelling groups from around the world to compare and analyse climate model simulation results.

Like GCMs, regional climate models (RCMs) are used to simulate and project future climate conditions. However, RCMs provide more detailed information on the climate in a particular region, such as a country, a town, or a river basin. They can capture regional features, topography, and local climate drivers that may not be adequately resolved in GCMs. In other words, the primary distinction between RCMs and GCMs lies in their spatial resolution and the scope of the areas they cover.

RCMs often use the outputs from larger-scale GCMs as initial and boundary conditions. That is, they take the coarse-scale information provided by GCMs and refine it to provide more localised climate projections. This downscaling makes it possible to provide climate data at scales that are important for regional planning, impact assessments, and decision-making. It is important to note that RCMs have the same limitations and uncertainties as GCMs, including parametrisation and model biases. Moreover, the quality of RCM projections is influenced by how accurately GCMs supply the boundary conditions (IPCC, 2013).

2.3 GREENHOUSE GAS EMISSIONS SCENARIOS

Human behaviour continues to increase the level of GHG emissions. GHG accumulates in the atmosphere, reflecting the outgoing radiation from the sun back to the Earth, essentially trapping the sun's heat. As GHG emissions are the main driver of observed changes in our climate, understanding the future path of GHG emissions is essential to estimate future climate change. Given the uncertainty of what future GHG emissions will be, different scenarios have been developed by the international community of climate researchers. These scenarios of GHG emissions are an integral part of climate change modelling and are useful for several purposes, including understanding and predicting future climate change. They help in establishing a connection between atmospheric GHG concentrations and changes in global temperature and other climate variables. By simulating various emissions scenarios in climate models, climate scientists can assess the climate system's sensitivity to various amounts of greenhouse gases.

To ensure consistency across research applying future climate change scenarios, the IPCC developed a Special Report on Emissions (SRE) with concomitant scenarios (SRES) in 2000. These scenarios were replaced by the Representative Concentration Pathway (RCP) scenarios for the IPCC fifth Assessment Report (AR5) in 2014. RCPs represent the different future trajectories of GHG concentrations in the atmosphere based on a wide range of assumptions regarding population growth, economic development, technological innovation and attitudes to social and environmental sustainability (IPCC, 2014). For instance, all RCPs include the assumption that air pollution control becomes more stringent over time as a result of rising income levels (van Vuuren et al., 2011). There are four main RCPs with numerical values 2.6, 4.5, 6.0, and 8.5. These numbers represent the radiative forcing (i.e., the difference between the incoming and outgoing energy from the sun) values in the year 2100. The four RCPs comprise a mitigation scenario (RCP2.6) that results in a very low forcing level, two stabilisation scenarios (RCP4.5 and RCP6.0), and a scenario (RCP8.5) that has extremely high GHG emissions. In other words, RCP2.6 represents a pathway where GHG emissions are significantly reduced, leading to an estimated 1.6°C increase in global average temperature by 2100 relative to the pre-industrial period (1850–1900). In what follows, we will refer to this as the “Paris Agreement” Scenario. This is an ambitious interpretation of the Paris Agreement, reflecting the goals of the agreement, and does not refer to the current pledges under the Paris Agreement which would result in significantly higher concentrations. RCP8.5 is a pathway where GHG emissions continue to grow unmitigated, resulting in a best estimate global average temperature rise of 4.3°C by 2100. We will refer to this pathway as the “no mitigation” pathway, acknowledging that this is an extreme interpretation of no climate action and refers to a worst case scenario. RCP4.5 and RCP6.0 are two medium stabilisation pathways, with varying levels of mitigation (Met Office, 2018). RCP4.5 is referred to as the “most likely” scenario in the context of this report. The increase in global mean temperature predicted by the RCP pathways for the late 21st century is shown in Table 2.1.

RCPs and Shared Socio-economic Pathways (SSPs) are conceptually related, which is crucial to highlight. SSPs are a set of scenarios aimed at providing a consistent framework for examining the interaction between socio-economic development and climate change. There are five SSPs, and they represent the range of possible futures based on different assumptions of future societal trends. See below for a summary of SSP narratives (Riahi et al., 2017).

SSP1 (Sustainability – taking the green road)

This represents a future characterised by gradual but pervasive shifts towards a more sustainable path, emphasising more inclusive development that respects perceived environmental boundaries. This implies a world with a balanced use of resources and a transition to renewable energy sources.

SSP2 (Middle of the road)

This represents a future that does not differ significantly from historical trends in the areas of social, economic, and technological development. This means a world where societal and environmental policies evolve slowly, with some improvements but also persistent challenges.

SSP3 (Regional rivalry – a rocky road)

This represents a future marked by resurgent nationalism, concerns about competitiveness and security, and regional conflicts that push countries to increasingly focus on domestic or, at most, regional issues. This means a world with growing inequalities, regional conflicts, and uneven access to resources.

SSP4 (Inequality – a divided road)

This represents a future characterised by highly unequal investments in human capital, combined with increasing disparities in economic opportunity and power with the resultant consequences being increasing inequalities and stratification both across and within countries. This means a world with significant social disparities, resource depletion, and environmental degradation.

SSP5 (Fossil-fuelled development – taking the highway)

This represents a future where the push for economic and social development is coupled with the exploitation of abundant fossil fuel resources and the adoption of resource- and energy-intensive lifestyles. This means a world heavily reliant on fossil fuels, with high GHG emissions and limited climate change mitigation efforts.

The previous IPCC SRES scenarios were developed in a sequential fashion where the socio-economic assumptions were translated into resulting radiative forcing and temperature change. In the new process, the RCPs and SSPs were developed separately and later linked. This has led to a lack of a clear connection between the SSPs and RCPs, were an SSP could be linked to different RCPs. Table 2.1 displays the SSPs linked to the four main RCP scenarios and the resulting estimated temperature change.

TABLE 2.1 THE INCREASE IN GLOBAL MEAN TEMPERATURE COMPARED TO PREINDUSTRIAL LEVEL

SSP Scenario	RCP Scenario	Change in temperature (°C) by 2081–2100
SSP 1	RCP2.6 “Paris Agreement”	1.6 (0.9 to 2.3)
SSP 2	RCP4.5 “most likely”	2.4 (1.7 to 3.2)
	RCP6.0	2.8 (2.0 to 3.7)
SSP 5	RCP8.5 “no mitigation”	4.3 (3.2 to 5.4)

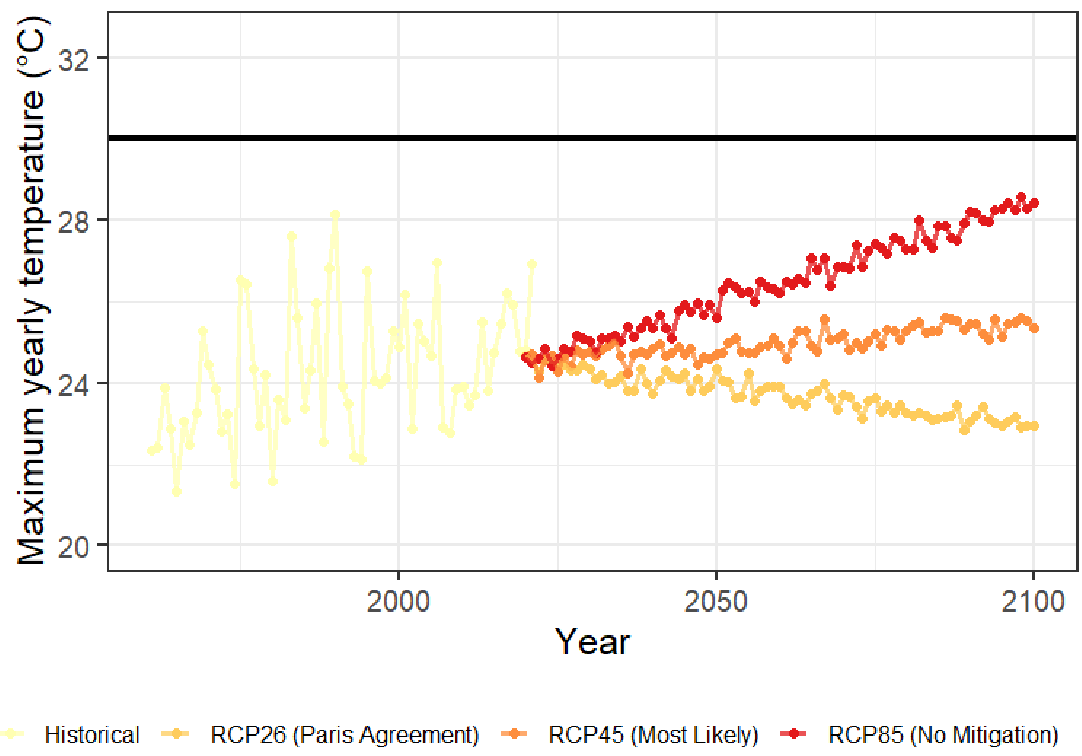
Source: *Met Office (2018), based on Table 12.3 of IPCC AR5 Working Group One.*
Notes: *Numbers in parentheses indicate the likely range.*

2.4 FUTURE CLIMATE PROJECTIONS FOR IRELAND

The approach of regional climate modelling was employed by climate researchers at the ICHEC to accurately model the Irish climate, capture its distinctive features, and provide high spatial resolution (with grids of $4km^2$) climate information for the evaluation of the local effects of climate change. Two RCMs, the Consortium for Small-scale Modelling-Climate Limited-area Modelling (COSMO-CLM) and the Weather Research and Forecasting (WRF), were used to downscale five CMIP–Project 5 (CMIP5) GCM datasets: CNRM-CM5, EC-EARTH (four ensemble members), HadGEM2-ES, MIROC5, and MPI-ESM-LR. The simulations were run for the base period 1981–2000 and the future period 2041–2060. The difference between the two periods provides a measure of climate change. To account for the uncertainty in future GHG emissions, the future climate was simulated under both the RCP4.5 ("most likely") and RCP8.5 ("no mitigation") scenarios (Nolan and Flanagan, 2020).

According to their simulation analysis, Ireland will be exposed to higher mean temperatures in the future. The mean annual temperature is projected to increase by 1–1.6°C by the middle of the century (i.e., 2041–2060) compared to the reference period 1981–2000, under the RCP4.5 ("most likely") climate scenario. With this warming will come hotter days and nights. In comparison to the baseline period, the warmest 5 per cent of daily maximum temperatures are projected to increase by 1–2.2°C while the coldest 5 per cent of daily minimum temperatures are projected to rise by 1–2.4°C. However, these projections show variations in temperature across the country that are expected to be marked by increased temperatures in eastern regions. For instance, Figure 1 demonstrates that the annual maximum temperature in Dublin County has been rising between 1961 and 2021. The ICHEC simulations show that such an upward trend is more likely to persist, especially in the high-risk scenario implied by the RCP8.5 ("no mitigation") emission trajectory. Note that the yellow line has a considerable degree of variability because it represents the yearly maximum temperature that was observed in Dublin County.

FIGURE 2.1 DUBLIN COUNTY HISTORICAL AND FUTURE ANNUAL MAXIMUM TEMPERATURE

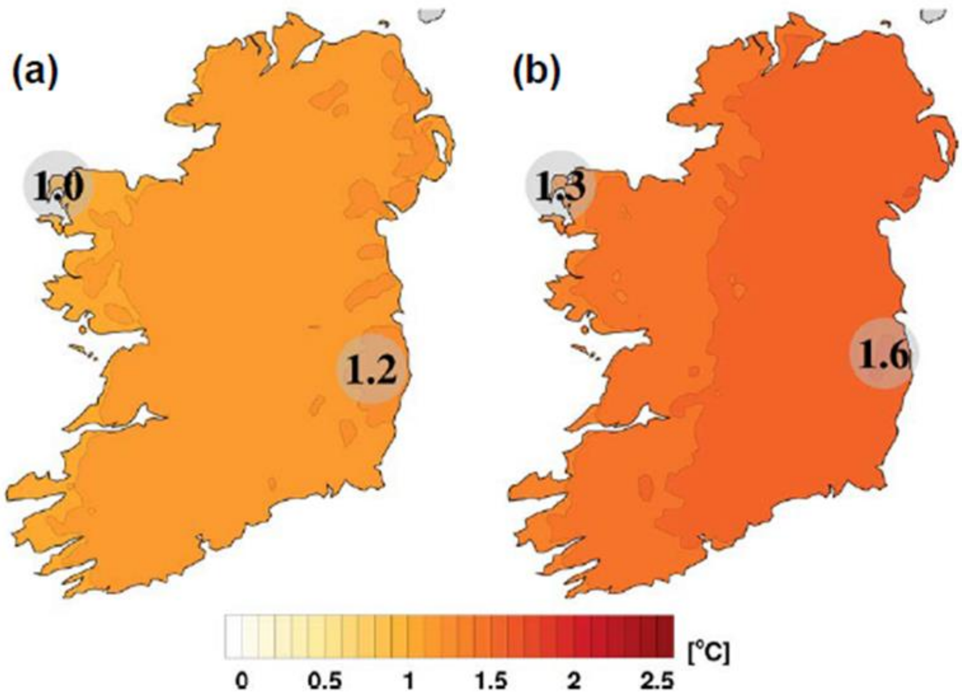


Source: *Met Éireann gridded weather dataset for historical observations (1961–2021), ICHEC simulations for future projections (Nolan and Flanagan, 2020). Authors' calculation for aggregation at the Dublin County level.*

Notes: *Yellow line represents the observed annual maximum temperature in Dublin County. The orange and red lines give the projections for the annual maximum temperature in Dublin County for RCP4.5 (orange) and RCP8.5 (red), averaged over a 10-year rolling window among the five GCMs considered in ICHEC simulations.*

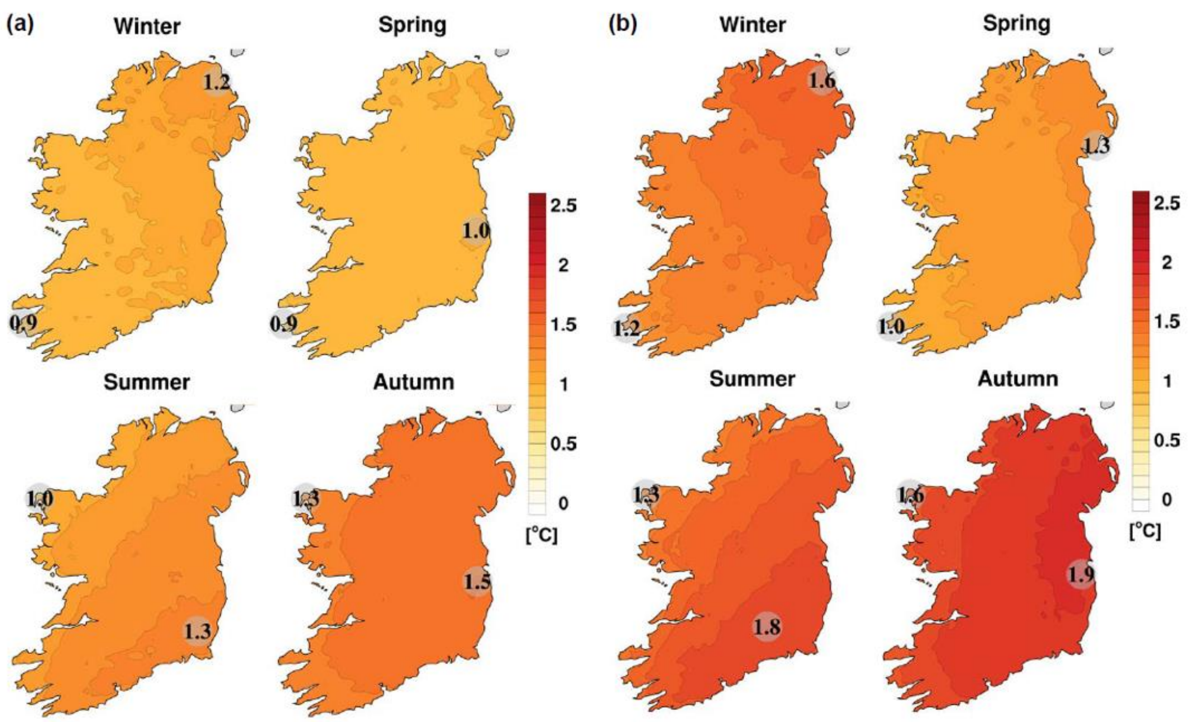
The projected annual and seasonal temperatures for Ireland are shown in Figures 2.2 and 2.3, respectively. It should be noted that in each figure and scenario, the future period, 2041–2060, is compared with the 1981–2000 period. Also, the numbers included in each plot are the minimum and maximum projected changes, displayed at their locations.

FIGURE 2.2 PROJECTIONS OF TEMPERATURE CHANGE FOR RCP4.5 "MOST LIKELY" (A) AND RCP8.5 "NO MITIGATION" (B) SCENARIOS



Source: *Nolan and Flanagan (2020)*

FIGURE 2.3 MID-CENTURY SEASONAL PROJECTIONS OF TEMPERATURE CHANGE FOR RCP4.5 "MOST LIKELY" (A) AND RCP8.5 "NO MITIGATION" (B) SCENARIOS



Source: *Nolan and Flanagan (2020)*

Heatwaves are also predicted to become more frequent by the middle of the century, with the southeast experiencing the biggest increases. Table 2.2 presents the projected increases over the 20-year period 2041–2060 for the "mostly likely" and "no mitigation" scenarios.

TABLE 2.2 PROJECTED INCREASE IN THE NUMBER OF HEATWAVE EVENTS OVER THE PERIOD 2041–2060

Scenario	Projected increase
RCP4.5 ("most likely")	1 to 8
RCP8.5 ("no mitigation")	3 to 15

Source: *Nolan and Flanagan (2020)*

In the RCP4.5 ("most likely") and RCP8.5 ("no mitigation") scenarios, the number of "frost days", or days with a minimum temperature below 0^{o}C, is expected to decline by 45 per cent and 58 per cent, respectively. Additionally, under the RCP4.5 ("most likely") and RCP8.5 ("no mitigation") scenarios, respectively, it is predicted that the proportion of ice days (days with a maximum temperature colder than 0^{o}C) will decline by 68 per cent and 78 per cent. For precipitation, a substantial decrease is projected for the summer months, although non-summer months are projected to record marginal changes. Overall, it is projected that precipitation will display more variability by the middle of this century as a result of an increasing frequency of droughts and heavy rainfall events. More so, the projected increase in heatwaves will directly impact public health and mortality, but this may be offset by the projected decrease in frost and ice days (Nolan and Flanagan, 2020).

2.5 SUMMARY

This chapter gave an overview of the climate modelling behind the climate projections used in this report. Projecting future climate change and social and economic developments remains a complex task with high levels of uncertainty. Applying an Irish-specific climate model that regionalises global projections is the most robust way to approach projections of the future climate for Ireland. In the following analysis, we focus on three RCP scenarios, namely the RCP8.5 (“no mitigation”), RCP4.5 (“most likely”), and the RCP2.6 (“Paris Agreement”).

CHAPTER 3

Health effects of temperature change

3.1 INTRODUCTION

Using the conceptual framework outlined in Section 1.2, and building on the literature described in Section 1.3, this chapter examines the impact of temperature change on health in Ireland by examining morbidity (as proxied by emergency in-patient hospital admissions). All of the Irish-based empirical studies reviewed in Chapter 3 have used mortality as the outcome of interest. The analyses so far have looked only at heatwave effects or specifically at cold-weather effects and we extend this further by looking at a broader range of temperatures in a similar methodology to both White (2017) and Gibney et al. (2022). Finally, the literature that does exist for Ireland has examined periods before 2010 and more recent years have seen the greatest increases in summer temperatures. It is important to update the literature to reflect these climate changes and their subsequent impacts on health.

Specifically, this chapter describes our analysis of the impact of temperature change on health in Ireland over the period 2015–2019. In order to investigate the impact of temperature change on health, it is necessary to obtain high-frequency data on health outcomes that can be linked to meteorological conditions. As outlined in Chapter 1, most analyses of the effects of temperature on health in Ireland have focused on mortality. In this report, for data availability reasons, we focus on morbidity, using data on emergency in-patient hospital admissions in acute public hospitals. Ideally, emergency department (ED) presentations would be used as they are less susceptible to hospital supply-side constraints such as constraints on bed capacity or workforce than in-patient activity data. However, in Ireland, data on ED presentations contain only very limited demographic information, and no diagnostic information on patients. We therefore use hospital admissions data in our analysis because the data have detailed diagnostic information for patients as well as socio-demographic information. For this analysis, we match data on emergency in-patient hospitalisations from the Hospital In-Patient Enquiry (HIPE) system with meteorological data from Met Éireann. This analysis provides an indication of the effect that higher temperatures might have on the healthcare system if hotter temperatures occur more frequently. The chapter is structured as follows: the data are introduced and described in section 3.2, the methodology is explained in section 3.3 and results are presented in section 3.4. A discussion of the results and their implications concludes the chapter in section 3.5.

3.2 DATA

3.2.1 Hospital In-Patient Enquiry (HIPE)

For this analysis, the authors obtained HIPE data from the Healthcare Pricing Office (HPO). The data covered the period 2015–2019 inclusive (i.e., before the COVID-19 pandemic, when hospital activity data were affected by the various public health restrictions in place from early 2020).

The HIPE is a health information system designed to collect clinical and administrative data on admissions into, and deaths in, acute public hospitals in Ireland. The full dataset covers day and in-patient (elective, emergency and maternity) admissions for 53 acute public hospitals in Ireland.[10] A HIPE record contains administrative, demographic and clinical information for a discrete episode of care (see Table A.1 in the Appendix for a full list of variables contained on the HIPE data file provided to the research team). An episode of care begins at admission to hospital, as a day or in-patient, and ends at discharge from (or death in) that hospital. Due to the absence of a unique patient identifier in the Irish healthcare system, it is not possible to follow activity at the patient level (that is, attribute multiple hospitalisations to the same patient) across hospitals (Keegan et al., 2020).

Importantly, the data includes information on the home residence of each patient, aggregated to the county council level. To allow for this information to be merged with our meteorological data (described in Section 3.2.2), we aggregated city councils (such as Waterford) with the corresponding county that they are in (Waterford County, for example). Tipperary North and Tipperary South were also aggregated into one category. We retained North Dublin and South Dublin as separate residence categories. All observations with "no fixed abode" or "unknown" values were excluded as these cannot be matched to meteorological data. This provided us with 27 counties. In our analysis, we use county of residence as opposed to using the hospital or health region as the geographic unit as is chosen in previous literature (Gibney et al., 2022). Using county of residence allows us to capture more accurately the exposure of an individual to temperature. It would be difficult to accurately capture people's exposure to temperature according to the hospital they presented at under the Irish healthcare system because the hospital to which they are admitted may be outside their county of residence.

As this analysis focuses on the effect of temperature change on hospitalisations, we restrict the sample to emergency in-patient hospitalisations only (i.e., those admitted for elective care as a day patient, or for maternity care, are excluded). Furthermore, not all patient groups are likely to be affected by temperature changes. In the analysis, we concentrate on those diagnosis groups that have been

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[10] Private hospital activity is not captured in HIPE. The Irish healthcare system is a mixture of public and private delivery and financing.

shown in previous literature to be most affected by temperature changes. Therefore, we only include hospital admissions data related to the following disease categories based on previous literature (Lin et al., 2009; White, 2017; Rizmie et al., 2022; Romanello et al., 2022):

- Circulatory diseases
- Respiratory diseases
- Metabolic diseases[11]
- Infectious diseases
- Injuries

Finally, we exclude hospital stays with a length of stay of over 180 days.

3.2.2 Population data

For some specifications of the statistical models (see Section 3.3), hospital admissions are expressed as a rate per 100,000 population (in each county). Population data by single year of age (SYOA) for each county is sourced from the 2011, 2016, and 2022 Censuses of Population. For the years 2015–2019 included in our analyses, we estimate county populations using linear interpolations across censuses for each intercensal year. Similarly, for calculating the dependent variable in the models for different age groups, we estimate county populations for each age group once more using linear interpolations across censuses for each intercensal year.

3.2.3 Meteorological data

The meteorological data used in this analysis is derived from the historical 1km x 1km grid data from Met Éireann. The data is aggregated to county level (except for Dublin) for each day for the period 2014–2019.[12] Data on daily maximum daily rainfall (measured in millimetres) are also provided. We use rainfall data to account for humidity (Barreca and Shimshack, 2012). Importantly, the temperature data accounts for the spatial distribution of population in each county and more accurately reflects the weather experienced by the population in the county. For example, in Wicklow there is an unpopulated mountainous area around the Wicklow Mountains that would be incorrectly weighted and produce inaccurate weather results, potentially biasing the temperature downwards. This adjustment provides a better picture of the exposure variable (temperature) and how this affects population health.

Meteorological data are aggregated to the weekly level using the mean for each

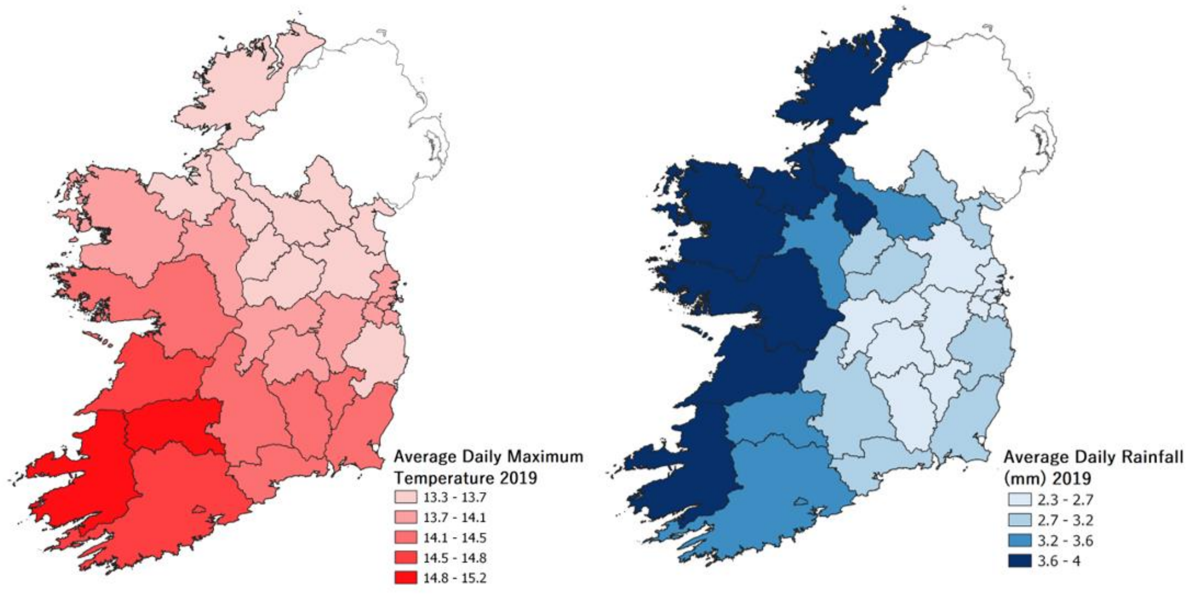
[11] Metabolic diseases include hereditary and acquired diseases such as diabetes and obesity. Rizmie et al., (2022) include these diseases in their study because they are underlying health conditions that are particularly vulnerable to temperature shocks.

[12] As described in Section 3.3, lags of temperature are also included in certain specifications of the models. Therefore, temperature data for 2014 are also required.

week. Weeks are constructed based on the HIPE definition of weeks numbered from 0–52 with each week beginning on a Sunday. A week-start variable was constructed based on this information and used to calculate weekly mean temperature. Lagged values for three weeks were also calculated for each county for each week in our period of analysis. This accounts for the delayed effect that temperature in a previous week might have on emergency hospital admissions (for example, temperature in week 1 might have residual effects on emergency hospital admissions in week 3).

Figure 3.1 shows the average daily maximum temperature for the year 2019. The daily maximum temperature values for each county were averaged over the year 2019 and are presented in the figure. This figure shows that there are slightly higher temperatures in the southern counties of Ireland. However, it is worth noting that the range in temperature is between 13.3–15.2°C. The second panel in this figure shows the daily rainfall averaged over the whole year (2019) for each county. As illustrated, the west and southern counties have the highest levels of rainfall, on average, in the country.

FIGURE 3.1 AVERAGE DAILY MAXIMUM TEMPERATURE (°C) AND RAINFALL (MM) BY COUNTY IN 2019



Source: *Met Éireann*

3.2.4 Analytical sample

A merged dataset, with the county-week-year as the unit of analysis is constructed by matching each county-week-year observation in the HIPE dataset with the corresponding meteorological data for that county, week and year. The fully merged dataset consists of 7,154 observations, comprising five years, 53 weeks and 27 county categories. It is important to note that the number of observations used in the analyses differs depending on the model specification, as detailed in Section 3.3.

3.3 METHODOLOGY

Following other studies in the literature, we estimate panel fixed effects models with the county-week as the unit of analysis (White, 2017; Gibney et al., 2022).

3.3.1 Outcome variables

We estimate two different model specifications using slightly different outcome variables in the statistical analyses. These models focus on two different, but inter-related questions and patient samples. Our first specification examines the relationship between temperature changes and hospitalisation changes across the full temperature distribution (cold, moderate and warm days) for all months of the year. This analysis uses temperature bins to characterise our temperature variable; this is similar to studies from Gibney et al. (2022), White (2017) and Rizmie et al. (2022). In this case, the dependent variable used is an admissions rate per 100,000 population per county. The model provides an insight into how the wide distribution of temperature can impact hospitalisations for these patient groups.

The second specification focuses on the warmer months (quarters 2 and 3) to allow us to explicitly examine the impact hot days have on hospitalisations, an important focus of this study. The findings from this model are also used to help inform the projection analyses undertaken in Chapter 4. This analysis uses a 'mean deviation' model. This model exploits the deviations from the mean at the hospital-week level for both the dependent variable (hospital admissions) and temperature. In this specification, the underlying population is accounted for by the differencing in the hospital admissions variable. How these variables are constructed is explained in greater detail below. Additional analyses focus on hospitalisations for particular age groups (age 0–14, 15–64 and 65+), and diagnostic groups (circulatory disease, respiratory disease, metabolic disease, infectious disease, and injuries). We discuss in more detail the specifications of these models below.

Identification strategy

The identification strategy in this analysis exploits the fact that temperature is an exogenous shock in line with previous analyses (Rizmie et al., 2022). The analysis exploits the exogenous variation in weekly temperature across hospital catchments and time. Moreover, there is no mechanism in which changes in hospital admissions affects changes in temperature and so, we can interpret our coefficients as causal estimates. This analysis uses emergency hospital admissions as opposed to ED presentations and as such, our estimates may be biased downwards due to hospital supply-side constraints. For example, the existence of supply side constraints may reduce the number of people who can be admitted to hospital from the ED, thus potentially underestimating the effect.

3.3.2 Model specification 1: Temperature bins

This model specification uses temperature bins to characterise the relationship between temperature and emergency hospital admissions. The temperature bins used are shown in Table 3.1. This model allows for flexibility in capturing the potential non-linear relationship between temperature and emergency hospital admissions. The dependent variable in this model is an admissions rate per 100,000 county population. The admissions rate variable is calculated as follows:

$$admissions\ rate_{c,w,y} = \left(\frac{hospital\ admissions_{c,w,y}}{population_c}\right) * 100{,}000$$

As noted, the population data used for each county (c) are from the 2016 Census (interpolated for intercensal years). Dublin is not separated into North and South as there was no population data available by Dublin postcode.

Table 3.2 illustrates that we partition our Met Éireann temperature variable into 10 temperature bins. As Ireland is a moderate climate country, as expected, the majority of days lie within the 7°–19°C range. In our statistical analyses, we include the most common temperature bin, 10°–13°C, as our reference category.

TABLE 3.1 TEMPERATURE BINS USED IN THE ANALYSIS

Temperature Bin	*Parameters*	*% Weekly Maximum Temperature*
1°–4°C	*=1 if [1.0°C, 3.0°C]*	*0.35*
4°–7°C	*=1 if [4.0°C, 6.9°C]*	*3.65*
7°–10°C	*=1 if [7.0°C, 9.0°C]*	*19.69*
10°–13°C	*=1 if [10.0°C, 12.9°C]*	*22.88*
13°–16°C	*=1 if [13.0°C, 15.0°C]*	*17.48*
16°–19°C	*=1 if [16.0°C, 18.9°C]*	*20.49*
19°–22°C	*=1 if [19.0°C, 21.0°C]*	*12.84*
22°–25°C	*=1 if [22.0°C, 24.9°C]*	*2.21*
25°–28°C	*=1 if [25.0°C, 27.0°C]*	*0.28*
28°C+	*=1 if [28°C+]*	*0.13*

Source: *Authors' analysis of Met Éireann data.*

The main sample in this specification model analysis includes all emergency in-patient hospitalisations in our data across the full period (January 2015 to December 2019). We also undertake separate analysis for three age cohorts: child (0–14), working age (15–64) and older (65+). We also undertake analysis on each diagnosis group separately, to examine whether some diagnosis groups are more sensitive to temperature changes than others. The general specification is outlined in equation 3.1:

$$Y_{c,w,y} = \alpha + \sum_{j=1}^{9} \beta_j temp_{c,w,y} + \sum_{j=1}^{9}\sum_{k=1}^{1} \phi_{j,k} temp_{c,w-k,y} + \sum_{j=1}^{9}\sum_{l=1}^{2} \delta_{j,l} temp_{c,w-l,y} + \boldsymbol{X}_{c,w,y} + CI_{c,w,y} + \eta_{c,w,y} + \tau + \varphi + m + \varepsilon_{c,w,y} \qquad (3.1)$$

where *c* represents the county of residence, *w* represents the week, and *y* the year.

The dependent variable, $Y_{c,w,y}$, represents the emergency in-patient admission rate per 100,000 population in a particular county, week and year. The temperature variable, $temp$, is characterised in a number of different ways in order to test various specifications for the relationship between temperature and emergency hospital admissions (described in greater detail below). Lagged temperature variable is also included in the specification because there can be residual effects on hospital admissions from temperature in previous weeks.[13] Specifically, $temp_{c,w,y}$ represents the indicator variable for temperatures in bin *j* for the current week. Similarly, $temp_{c,w-k,y}$ represents the indicator variable for temperatures in bin *j* for the *k*-th lagged week (or the previous week), and $temp_{c,w-l,y}$ represents the indicator variable for temperatures in bin *j* for the *l*-th lagged week (or the two previous weeks). The coefficients associated with these variables are represented by β_j, $\phi_{j,k}$, and $\delta_{j,l}$ respectively. In addition, the diagnosis categories are represented by $\eta_{c,w,y}$, year trend by τ, county fixed effect by φ, and month fixed effect by m. The year trend and month fixed effects are included to control for annual and seasonal factors respectively. Rainfall is used to account for the effects of humidity along with its lagged values, as is done in previous studies (White, 2017). However, for brevity, it has been excluded from equation (4.1) but was controlled for during the estimation process. We include a number of control variables to account for the casemix of patients, socio-economic status, and case severity which may differ across hospital, years, and weeks within a given year. The vector, $\boldsymbol{X}_{c,w,y}$, denotes the socio-demographic variables that we control for in our regression analysis. These controls variables capture the mean composition of admitted patients by age and sex for each county, week and year, as well as the mean marital status composition, mean proportion of patients that are admitted as private patients, and the mean proportion of patients with a medical card. Additionally, the variable, $CI_{c,w,y}$, is the mean Charlson co-morbidity index taken for each county, week and year. The Charlson co-morbidity index is a score based on all of a patient's diagnoses (using ICD codes) and serves as a predictor of mortality risk within a year following hospitalisation (Charlson et al., 1987).

3.3.3 Model specification 2: Mean deviation model

The previous temperature bins specification examines all months and explores the impact of both colder and hotter weather on emergency in-patient hospitalisations for our patient groups. However, a key question in this study is the implications of increases in hotter days on hospitalisations, as hotter days are likely to become more prevalent due to climate change in the future. Therefore, in this analysis, we focus only on quarter 2 (April, May, June) and quarter 3 (July, August, September), the periods where hot weather in Ireland occurs.

[13] This is common practice in similar literature and the standard number of lags is 30 days or three weeks (Hajat et al., 2006; Baccini et al., 2008; Breitner et al., 2014; White, 2017; Gibney et al., 2022).

In this specification, we construct the dependent and temperature variable of interest using a methodology that estimates deviations from a multi-year (2015–2019) mean. For each county, week, and year (denoted as c, w, y), the number of admissions ($adm_{c,w,y}$) and the temperature ($temp_{c,w,y}$) are compared against the respective five-year averages ($\overline{adm}_{c,w}$ for admissions and $\overline{temp}_{c,w}$ for temperature):

$$diff(adm)_{c,w,y} = \frac{adm_{c,w,y} - \overline{adm}_{c,w}}{\overline{adm}_{c,w}},$$

where $adm_{c,w,y}$ is the number of emergency in-patient hospital admissions by county, week and year. $\overline{adm}_{c,w,y}$ represents the average number of admissions per county and week over the five-year span from 2015 to 2019. This approach allows us to measure the admissions for a specific county, week, and year as a proportion of its five-year average.

A similar approach is applied to the temperature variable of interest:

$$diff(temp)_{c,w,y} = \frac{temp_{c,w,y} - \overline{temp}_{c,w}}{\overline{temp}_{c,w}},$$

where $temp_{c,w,y}$ represents the average temperature for a county, week, year (in °C) and $\overline{temp}_{c,w}$ represents the average temperature per county and week over the five-year span from 2015 to 2019.

Table 3.2 provides a numerical illustration of this process, using week 27 in North Dublin as an example. A mean level of admissions is calculated for each week across the five years (column 3), indicated above by the $\overline{adm}_{c,w}$ variable. A difference is taken between the actual level of admissions ($adm_{c,w,y}$) for that week and the five-year mean (column 4). This difference is then calculated as a percentage (column 5). This is done for each county, week, and year observation for both hospital admissions and maximum temperature.

TABLE 3.2 ILLUSTRATION OF MEAN DEVIATION ADMISSIONS VARIABLE

Year	*Total Admissions*	*Mean Admissions, 2015–2019*	*Difference*	*% Difference*
2015	*252*	*274.46*	*-22.46*	*-8.18*
2016	*265*	*274.46*	*-9.46*	*-3.45*
2017	*258*	*274.46*	*-16.46*	*-6.00*
2018	*283*	*274.46*	*8.54*	*3.11*
2019	*307*	*274.46*	*32.54*	*11.86*

Source: Authors' analysis.

The specification is as follows:

$$diff(adm)_{c,w,y} = \alpha + \beta_j diff(temp)_{c,w,y} + \phi_j diff(temp)^2{}_{c,w,y} + \boldsymbol{X}_{c,w,y} + CI_{c,w,y} + \eta_{c,w,y} + \tau + \varphi + m + \varepsilon_{c,w,y} \qquad (3.2)$$

where *c* represents the county of residence, *w* represents the week, and *y* the year. The dependent variable, $adm_{c,w,y}$, represents the number of admissions compared against the respective five-year average ($\overline{adm}_{c,w}$). $temp_{c,w,y}$ represents the number of admissions compared against the respective five-year average ($\overline{temp}_{c,w}$). Once more, the vector, $\boldsymbol{X}_{c,w,y}$ denotes the socio-demographic and casemix variables that we control for in our regression analysis, and $CI_{c,w,y}$ is the mean Charlson co-morbidity index taken for each county, week and year. Diagnosis categories are represented by $\eta_{c,w,y}$, year trend by τ, county fixed effect by φ, and month fixed effect by m. The year trend and month fixed effects are included to control for annual and seasonal factors respectively. Rainfall is used to account for the effects of humidity along with its lagged values.

3.4 RESULTS

Before presenting the results for the main model specifications (temperature bins and mean deviation), in Table 3.3 we show how emergency in-patient hospital admissions (per 100,000 population) varied over the period 2015–2019. This table shows the average weekly emergency hospital admissions rate across counties for each year-quarter.

TABLE 3.3 EMERGENCY IN-PATIENT HOSPITAL ADMISSIONS (PER 100,000 POPULATION) 2015–2019

	2015	2016	2017	2018	2019
Quarter 1	57.8	58.6	58.5	64.9	64.9
Quarter 2	53.3	56.3	58.3	59.2	59.8
Quarter 3	48.3	52.3	53.6	55.0	55.4
Quarter 4	53.3	61.0	61.4	62.1	59.9

Source: Authors' analysis.

Figure A.1 in Appendix A shows how emergency hospital in-patient admissions (per 100,000 population) vary by county of residence (using 2019 as an example). The data show that admissions are highest in the west and midlands. This could be due to an ageing population in those areas.

3.4.1 Temperature bin analysis

Table 3.4 shows the results from the temperature bin analysis. The reference category used is the temperature bin 10–13°C. This temperature bin has the greatest proportion of week-county observations. All other coefficients are interpreted with respect to this temperature bin. These coefficients are also plotted in Figure 3.2.

The results show that for temperatures greater than 16°C, there are greater rates of emergency hospital admissions. There is a statistically significant relationship between temperatures of 16–25°C and emergency hospital admissions. The coefficient plot illustrates how the coefficient gets larger at higher temperatures. The two highest temperature bins show no statistically significant relationship, which is likely due to two reasons: there are much fewer observations in these temperature bins (see also Table 3.1), and at higher temperatures, individuals are more likely to take precautionary measures that protect them from high temperatures (e.g., staying indoors during the hottest period of the day).

The coefficients in Table 3.4 can be interpreted as changes per 100,000 admissions. For example, at temperatures between 22°C and 25°C, there was an increase in emergency hospital admissions of 4.71 per 100,000 population compared to when temperatures are in the reference category (10–13°C). These coefficients can also be interpreted as percentage changes if they are interpreted with respect to the mean admissions rate (55.61 per 100,000 population). In this case, there is an increase in emergency admissions of 8.5 per cent[14] when the temperature is between 22°C and 25°C compared to 10–13°C.

Full model results can be found in Appendix B.

[14] Calculated as a proportion of the weekly mean admissions rate: ((4.71/55.61)*100).

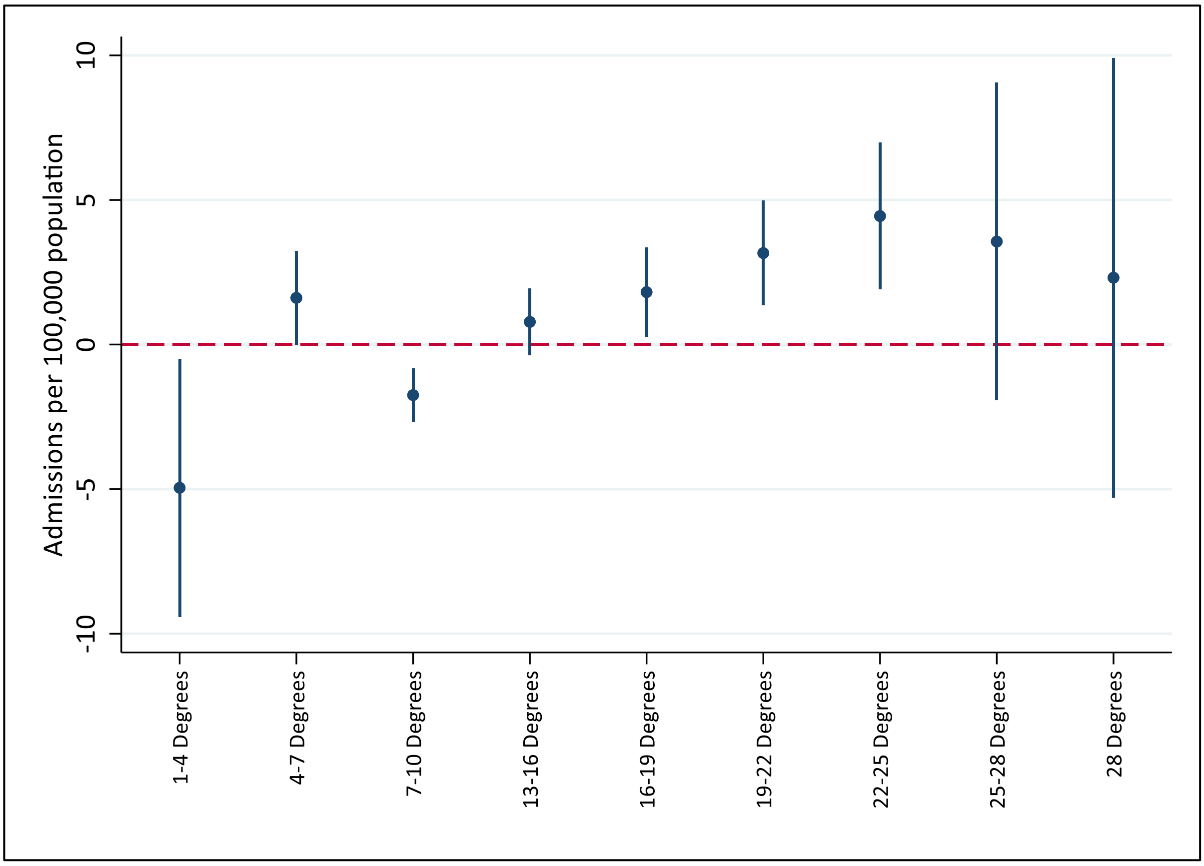
TABLE 3.4 TEMPERATURE BIN ANALYSIS

	Admissions Rate
Temperature Bin: 1–4°C	-5.17** (2.28)
Temperature Bin: 4–7°C	1.73** (0.83)
Temperature Bin: 7–10°C	-1.93*** (0.47)
Temperature Bin: 10–13°C	Ref. -
Temperature Bin: 13–16°C	0.91 (0.58)
Temperature Bin: 16–19°C	1.97** (0.78)
Temperature Bin: 19–22°C	3.29*** (0.91)
Temperature Bin: 22–25°C	4.71*** (1.30)
Temperature Bin: 25–28°C	3.94 (2.75)
Temperature Bin: 28°C+	2.78 (3.76)
County Fixed Effects	Yes
Year Trend	Yes
Month Fixed Effects	Yes
Lagged Temperature Bins	Yes
Socio-Demographic Controls	Yes
Mean dependent variable	55.61
N	6,889[15]
R^2	0.56

Source: *Authors' analysis.*
Notes: *Standard errors in parentheses.*
** p<0.05, ** p<0.01, *** p<0.001*

[15] In order to calculate an admissions rate, North Dublin and South Dublin were aggregated – therefore, the final sample size is 6,889 (5 years x 53 weeks x 26 counties – 1 week Carlow 2017).

FIGURE 3.2 COEFFICIENT PLOT OF TEMPERATURE BINS



Source: Authors' analysis.

The analysis was also carried out separately for each age group; the results are presented in Table 3.5. Results show that the effect of temperature has a larger impact on hospitalisation for children (0–14) compared to other age groups. A statistically significant effect of temperature emerges above 16°C, similar to the main analysis. At temperatures 22–25ºC there was an increase in emergency hospital admissions of 7.02 per 100,000 population compared to when temperatures are in the reference category. This equates to an increase in emergency admissions of 12.2[16] per cent among children.

For the working age group (15–64), the effects are smaller in magnitude, and similarly significant only between 16 and 25 degrees. At temperatures 22–25ºC there was a 7.8[17] per cent increase in emergency hospital admissions compared to when temperatures are in the reference category (10–13°C). Hospital admissions for the older (65+) age group exhibit a similar pattern to the results in Table 3.4 although none of the effects (with the exception of temperatures between 4–7ºC) are statistically significant. While the results may indicate no effect of temperature change on emergency in-patient hospitalisations for the older population over the period, these results could also indicate adaptive behaviour on the part of older

[16] (7.02/57.64)*100
[17] (2.14/24.45)*100

people to higher temperatures in Ireland, an effect that may kick in at lower temperatures than for other population groups.

TABLE 3.5 TEMPERATURE BIN ANALYSIS – AGE GROUP ANALYSIS

	Children (0–14)	Working Age Group (15–64)	Older Adults (65+)
Temperature Bin: 1–4°C	-6.79 (4.27)	-1.80 (1.63))	-13.20 (9.32)
Temperature Bin: 4–7°C	1.03 (1.55)	-0.05 (0.59)	17.58*** (3.27)
Temperature Bin: 7–10°C	-2.15** (0.89)	-1.16*** (0.34)	-0.26 (1.82)
Temperature Bin: 10–13°C	Ref. -	Ref. -	Ref. -
Temperature Bin: 13–16°C	1.75 (1.10)	0.24 (0.42)	1.73 (2.32)
Temperature Bin: 16–19°C	3.41** (1.46)	1.15** (0.56)	-3.19 (3.03)
Temperature Bin: 19–22°C	6.26*** (1.72)	1.52** (0.66)	-1.93 (3.52)
Temperature Bin: 22–25°C	7.02*** (2.43)	2.14** (0.93)	3.25 (4.88)
Temperature Bin: 25–28°C	0.26 (5.25)	0.60 (2.01)	11.47 (10.57)7)
Temperature Bin: 28°C+	-5.29 (7.26)	2.71 (2.78)	-1.52 (15.37)
County Fixed Effects	Yes	Yes	Yes
Year Trend	Yes	Yes	Yes
Month Fixed Effects	Yes	Yes	Yes
Lagged Temperature Bins	Yes	Yes	Yes
Socio-Demographic Controls	Yes	Yes	Yes
Mean Dependent Variable	57.64	27.45	179.45
N[1]	6,853	6,886	6,884
R^2	0.41	0.34	0.51

Source: *Authors' analysis.*
Notes: *Standard errors in parentheses.*
[1] The sample sizes differ across specifications because some county-week-year units will have no HIPE observations for that age group.
** p<0.05, ** p<0.01, *** p<0.001*

This analysis is also carried out for each of the five diagnosis groups and Table 3.6 shows these results. The results for the diagnosis analysis show very similar patterns for the whole temperature bin analysis, except that there are also statistically significant results for the coefficients at lower temperatures (apart from metabolic diseases, which are significant only at lower temperatures). At temperatures between 1–4°C, it can be seen that there is a decrease in the emergency hospital admissions rate across all diagnostic groups. As pointed out by previous literature, this is likely a behavioural effect where the very cold weather prevents people from seeking medical care (Gibney et al., 2022).

For all of the chapters on diseases (except metabolic diseases), we can see that there are statistically significant effects of both cold and warm temperatures on emergency hospital admissions. At lower temperatures, there is a decrease in emergency hospital admissions. This is consistent with the literature in this field which posits that at cold temperatures, there is an avoidant health-seeking behaviour as people do not want to venture out in unsafe conditions (Gibney et al., 2022). At warmer temperatures, certain health conditions tend to be exacerbated such as circulatory, respiratory and infectious diseases as well as injuries. Our analysis shows that emergency admissions due to metabolic diseases are not statistically significantly responsive to cold temperatures. However, they are statistically significantly responsive to warmer temperatures. Some of the international literature also posits that the effect of rising temperatures on infectious diseases (including E.coli VTEC) may be due to contaminated water sources, where the warm weather allows bacteria to live longer and enter drinking water streams (Romanello et al., 2022).

TABLE 3.6 TEMPERATURE BIN ANALYSIS – DIAGNOSTIC GROUP ANALYSIS

	(1) Circulatory Disease	(2) Respiratory Disease	(3) Metabolic Diseases	(4) Infectious Diseases	(5) Injuries
Temperature Bin: 1–4°C	-5.34** (2.25)	-5.22** (2.29)	-4.15* (2.21)	-5.38** (2.23)	-5.07** (2.25)
Temperature Bin: 4–7°C	1.91** (0.82)	1.76** (0.83)	1.03 (0.83)	2.01** (0.80)	1.46* (0.82)
Temperature Bin: 7–10°C	-1.65*** (0.46)	-1.87*** (0.47)	-0.91** (0.45)	-1.28*** (0.45)	-1.65*** (0.46)
Temperature Bin: 10–13°C	Ref. -	Ref. -	Ref. -	Ref. -	Ref. -
Temperature Bin: 13–16°C	0.87 (0.58)	0.79 (0.59)	0.89 (0.56)	0.76 (0.57)	0.82 (0.58)
Temperature Bin: 16–19°C	1.81** (0.77)	1.67** (0.78)	1.86** (0.76)	1.74** (0.76)	1.79** (0.77)
Temperature Bin: 19–22°C	3.05*** (0.90)	2.86*** (0.92)	2.72*** (0.88)	2.96*** (0.89)	3.23*** (0.91)
Temperature Bin: 22–25°C	4.44*** (1.27)	4.36*** (1.30)	4.42*** (1.25)	4.42*** (1.25)	4.64*** (1.27)
Temperature Bin: 25–28°C	3.89 (2.71)	3.89 (2.76)	6.22** (2.73)	4.71* (2.71)	3.72 (2.72)
Temperature Bin: 28°C+	1.69 (3.71)	1.88 (3.76)	2.44 (3.61)	1.66 (3.61)	1.69 (3.71)
County Fixed Effects	Yes	Yes	Yes	Yes	Yes
Year Trend	Yes	Yes	Yes	Yes	Yes
Month Fixed Effects	Yes	Yes	Yes	Yes	Yes
Lagged Temperature Bins	Yes	Yes	Yes	Yes	Yes
Socio-demographic controls	Yes	Yes	Yes	Yes	Yes
Mean dependent variable	56.30	56.22	57.63	56.54	56.28
N[1]	6,869	6,887	5,969	6,743	6,874
R^2	0.57	0.56	0.61	0.58	0.57

Source: *Authors' analysis.*
Notes: *Standard errors in parentheses.*
[1] The sample size differs by diagnosis group because for some county-week-year units there were no HIPE observations for certain diagnosis groups.
** p<0.05, ** p<0.01, *** p<0.001*

3.4.2 Mean deviation model

Table 3.7 presents the results from the mean deviation model, which is estimated for the months April–September (quarters 2 and 3) only. The effect size of the differences model is 0.18, which means that a 1 percentage point deviation in maximum weekly temperature from the mean induces a 0.18 percentage point deviation in weekly hospital admissions from the mean.

TABLE 3.7 MEAN DEVIATION MODEL, QUARTERS 2 AND 3

	%Δ In-Patient Hospital Admissions
% Difference in Maximum Temperature	0.18*** (0.03)
% Difference in Maximum Temperature²	-0.64*** (0.18)
Temperature Lag 1	-0.04 (0.03)
Temperature Lag 2	-0.01 (0.03)
County Fixed Effects	Yes
Year Trend	Yes
Month Fixed Effects	Yes
Diagnosis Fixed Effects	Yes
Socio-demographic Controls	Yes
N	3,518
R^2	0.11

Source: *Authors' analysis.*
Notes: *Standard errors in parentheses.*
** p<0.05, ** p<0.01, *** p<0.001*

Table 3.7 clearly shows that temperature increases are related to higher rates of hospitalisation. To provide a more intuitive illustration of findings to highlight the size of this effect, Table 3.8 applies the results from Table 3.7 to the first week of July in North Dublin as a linear predictor. In this county-week observation, the mean temperature across the five-year period is 19.3°C and the mean number of weekly admissions is 278. We estimate the predicted change in emergency in-patient hospitalisations for 1°C, 5°C, and 10°C increase in temperature. It is clear that for very large changes, a number of additional admissions (23, or 8.3% per admissions) results.

TABLE 3.8 NUMERICAL ILLUSTRATION

	Change in Max Temperature	*Additional Admissions*
0.5°C increase (≈ 3pp ↑)	*19.8°C*	*1*
1.0°C increase (≈ 5pp ↑)	*20.3°C*	*2*
5.0°C increase (≈ 25pp ↑)	*24.3°C*	*11*
10.0° increase (≈ 50pp ↑)	*29.3°*	*23*

*Note: Results in Appendix D show that the child cohort had the largest effect (0.30***), followed by the working age cohort (0.14***). However, no statistically significant effect was found for older people.*

3.5 DISCUSSION

The analysis in this chapter highlights that even in Ireland, a country with a moderate climate, a positive relationship between warm temperature and hospital utilisation is found. According to the results of the main model specification using temperature bins, significantly higher emergency in-patient hospitalisations are observed when temperatures increase above 16°C. The greatest effects are observed for temperatures between 22°C and 25°C; temperatures in the range between 22°C and 25°C are associated with an 8.5 per cent increase in emergency in-patient hospitalisations, compared to when temperatures are in the range between 10°C and 13°C. Further specifications of the model show that these results hold for all diagnostic categories but are particularly pronounced for younger age groups.

Previous research has shown that the countries with less moderate climates may acclimatise to heat, and therefore the impact of temperature on healthcare utilisation occurs at higher temperature. Indeed, Baccini et al. (2008) show that the threshold temperature for temperature and hospital use is 30.3°C in Rome, but only 23.9°C in London. The study finds that emergency in-patient hospital admissions tend to increase from a relatively low temperature (16°C). Therefore, while Ireland shares a relatively similar moderate climate with the UK, we find that hospitalisations tend to increase at a lower temperature than observed in London.

This analysis shows that there appears to be a diminishing effect of temperature on hospitalisation rates at higher temperatures. We find that above 22–25°C, the effect remains stable, or reduces slightly. This may reflect those who are potentially impacted by high temperatures altering their behaviours and taking preventative measures such as staying at home during the hottest hours. It could also be the case that our analysis lacks the statistical power to detect a statistically significant effect at temperatures above 25°C, which are relatively rare in Ireland (as illustrated in Table 3.1).

As noted in Chapter 1, in addition to higher average temperatures, Ireland may also be expected to be exposed to more extreme temperatures in the future. The results from the mean deviation model specification provide insights into how such outlier temperatures may affect emergency in-patient hospital admissions. For example, a 5-degree Celsius average deviation in temperature would be associated with approximately 11 extra emergency hospital admissions in a typical week and county per annum.

A limitation of this study is the challenge in identifying those most vulnerable to higher temperatures using the data available, i.e., attributing hospitalisation to temperature change. To mitigate this limitation, we identified those diagnoses that have been shown to be at greater vulnerability to requiring healthcare as a consequence of high temperatures. The lack of a unique patient identifier in Ireland prevents us from following patients across hospital episodes. Therefore, it was not possible to examine the impact of varying temperature at a patient level. Moreover, because our data is based on hospital admissions at the discharge level, we are unable to account for healthcare capacity and supply-side constraints that could be limiting the response in hospital admissions to temperature variation. While we have controlled for year trends, and county and seasonal patterns that may affect emergency in-patient hospitalisations over time, it is still possible that there are omitted variables that may be correlated with temperature. For example, previous analyses Goodman et al. (2004) for Dublin and Breitner et al. (2014) for Germany discuss the issue of whether results are robust to the potential modifying effects of air pollution. Finally, the data minimisation principle applied to sensitive data for the purposes of research was necessarily applied to the HIPE data. This means it was not possible to examine all emergency in-patient hospitalisations, including hospitalisation for malignant neoplasms (i.e., cancer). However, previous research that have examined the impact of temperature increases on hospitalisation for neoplasms found little to no effect (Rizmie et al., 2022).

CHAPTER 4

Health benefits and co-benefits of climate change mitigation measures

4.1 INTRODUCTION

With the European Climate Law, the EU made climate neutrality by 2050 a legally binding goal, set an interim target of a net 55 per cent emission reduction by 2030 and is working on setting the 2040 target. In Ireland, legally binding targets for emissions reductions by 2030 and 2050 are contained in the Climate Action and Low Carbon Development (Amendment) Act of 2021, and the Climate Action Plans 2019 and 2021 provide a detailed plan of measures needed for this transition, with the third national update, the Climate Action Plan (CAP) 2023, setting out the additional measures required to achieve alignment with economy-wide carbon budgets and sectoral emission ceilings (Government of Ireland, 2021, 2022). The CAP 2023 contains multiple mitigation and adaptation actions covering 19 themes, including agriculture, transport, carbon pricing, etc.

In this chapter, we focus on the health benefits and co-benefits of climate change mitigation actions, with a particular focus on Ireland. Chapter 1 provided an overview of the relevant literature that has attempted to quantify the health benefits and co-benefits of climate change mitigation actions, using a variety of different data sources and methodologies. Figure 1.3 in Chapter 1 provided an infographic of the health benefits and co-benefits of mitigation action. In this chapter, we first present results from two models that have assessed the health benefits and co-benefits of climate change mitigation for Ireland (Section 4.2). In Section 4.3, we illustrate the potential health benefits and co-benefits of climate change mitigation in Ireland by applying HIPE model estimates to the temperature path scenarios described in Chapter 2. This approach provides an initial assessment of the projected healthcare impacts of climate change mitigation in Ireland under various temperature path scenarios. Section 4.4 summarises the main findings, and highlights avenues for further research in the Irish context.

4.2 ANALYSES OF HEALTH BENEFITS AND CO-BENEFITS FOR IRELAND

Global climate change mitigation measures, which aim at limiting greenhouse gas (GHG) concentrations in the atmosphere and their influence on the Earth's climate system as well as enhancing carbon sinks, can result in different temperature paths. Reduced climate change will reduce health impacts resulting from climate change.

As discussed in Chapter 2, RCPs represent the range of climate change mitigation and adaptation policies for the 21st century by defining paths for GHG concentrations and, in effect, the amount of warming that might take place by the end of the century. For instance, keeping the global temperature rise below the

Paris Agreement's 2°C target essentially equates to nations adopting an RCP2.6 emissions pathway. That is, a world where people adopt active lifestyles like cycling and walking and there is a greater usage of renewable energy sources and carbon capture technologies. Whereas RCP8.5 represents a world with no climate action and a temperature increase of 4°C. The RCP4.5 scenario represents the most likely future.

The COACCH (CO-designing the Assessment of Climate CHange costs) project[18] is funded by the European Union's Horizon 2020 research and innovation programme and carried out by a consortium of 13 European organisations. The objective of COACCH is to produce an improved downscaled assessment of the risks and costs of climate change in Europe. This project assessed the impacts of global climate change mitigation efforts on Irish public health. The focus was on the burden of heat stress on mortality under various RCP scenarios and over the period: 2030–2039, 2050–2059, 2070–2079, and 2080–2099 (Ščasný et al., 2019). The estimation process was divided into two steps. First, based on historical time series data, mortality per 100,000 people was estimated using a pooled epidemiological association that links heat exposure (temperature) to health effects (death). In particular, the UN World Population Prospects' projection of the future Irish population was combined with the exposure-response function of Gasparrini et al. (2017), which had been modified to reflect various levels of urbanisation (strictly urban, suburban, and predominantly rural surroundings) using modifiers presented in Sera et al. (2019). Gasparrini et al. (2017) estimated the excess mortality or heat-attributable fraction (AF) of all-cause deaths in Europe considering three potential climate change scenarios: RCP2.6 ("Paris Agreement"), RCP4.5 ("most likely"), and RCP8.5 ("no mitigation"). The study by Sera et al. (2019) examined the effects of several ecological and socio-economic variables on the attributable fraction of deaths due to heat exposure using data from the "Multi-City Multi-Country" network (MCC) and indicators of the "OECD regional and metropolitan database".

Second, the estimated coefficients of the temperature-mortality relationship were combined with future daily mean temperature series under three climate change scenarios (i.e., RCP2.6, RCP4.5, and RCP8.5) to project excess mortality, assuming no adaptation and population changes. Figure 4.2 displays the estimated additional deaths in Ireland by RCP scenarios over time. According to Figure 4.2, towards the end of the century, annual mortality under the RCP8.5 ("no mitigation") scenario is around 1,400 additional deaths caused by non-optimal temperature, including excess heat. The mortality rate is about one-half as large under RCP4.5 ("most likely") with 483 deaths and about one-fifth for RCP2.6 ("Paris Agreement") with 216 deaths. The finding suggests that measures to reduce GHG emissions at the global level can have local benefits such as lowering the incidence of heat-related illnesses including heat exhaustion, heatstroke, and dehydration.

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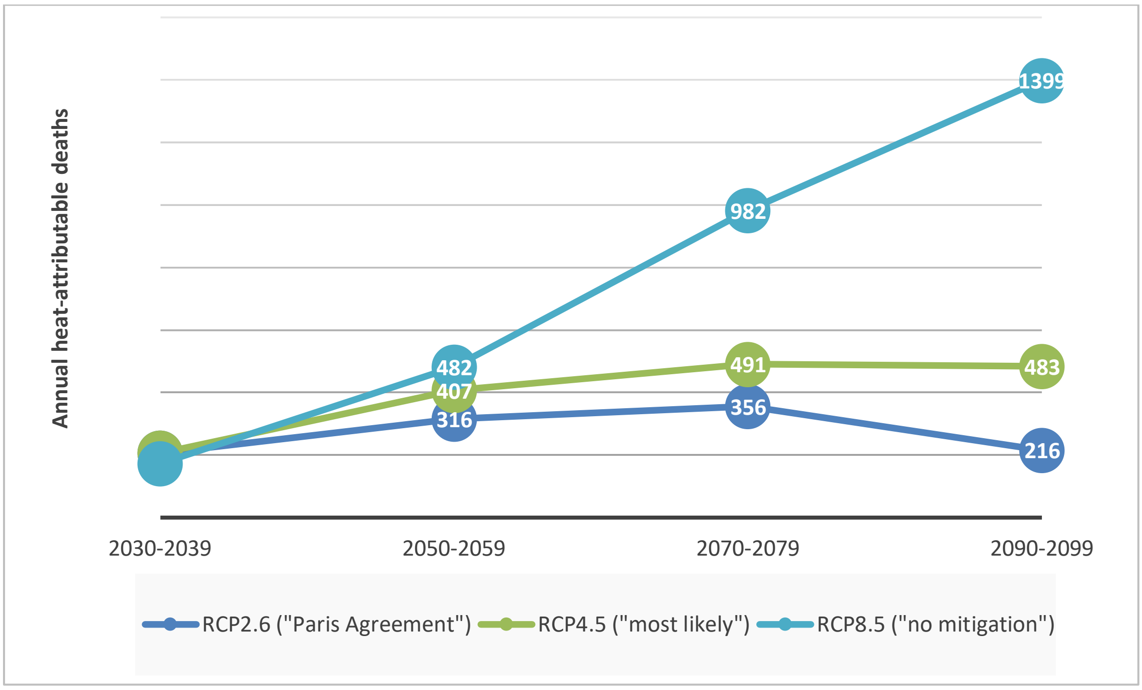
[18] See www.coacch.eu.

FIGURE 4.2 TREND IN HEAT-ATTRIBUTABLE DEATHS



Source: COACCH project

Table 4.1 provides the estimated additional deaths for the different RCPs. RCP2.6 approximates the global mitigation ambitions of the Paris Agreement whereas RCP8.5 represents a world of no mitigation efforts. By comparing the additional deaths across these two scenarios, we can approximate the health benefits of global mitigation action. This is presented in the last row of Table 4.1. The impact is large, whereby the end of the century mitigation (consistent with the Paris Agreement) could reduce the additional deaths by more than 1,000 per annum.

TABLE 4.1 HEAT-ATTRIBUTABLE MORTALITY IN IRELAND (ADDITIONAL DEATHS)

	2030–2039	2050–2059	2070–2079	2090–2099
RCP2.6 (Paris Agreement)	206	316	356	216
RCP4.5 (most likely)	206	407	491	483
RCP8.5 (no mitigation)	173	482	982	1399
Lives saved due to mitigation (Paris Agreement compared to no mitigation)	-33	166	626	1183

Source: COACCH project

In July 2023, WHO Europe released Climate Mitigation, Air Quality and Health (CLIMAQ-H), a software tool that analyses the effects of climate change mitigation policy actions. Specifically, CLIMAQ-H estimates the health and related economic gains achievable by WHO European Region Member States by improving national air quality through domestic climate policies to mitigate carbon dioxide (CO_2) and other greenhouse gases, as proposed in the nationally determined contributions (NDCs). The tool uses evidence from epidemiological studies to calculate the annual benefit of averted long-term mortality and morbidity from exposure to ambient air pollution by primary emissions of $PM_{2.5}$ and changes in secondary PM aerosols due to reduced emissions of SO_2, NO_2 and NH_3. Health benefits include fewer episodes of illnesses (morbidity) and averted premature mortality, especially among children, older people and people with medical conditions aggravated by exposure to ambient air pollution. Health benefits are calculated from concentration-response functions, which relate a change in the health outcome of concern (e.g. a decrease in the number of asthma attacks in children) to a change in the ambient air concentration of a specific pollutant (e.g. decreased $PM_{2.5}$ concentration due to implementation of NDC targets in 2030) (WHO, 2023).

The results of the CLIMAQ-H model, applied to Ireland, are presented in Table 4.2. The results show that, by 2030, 66 deaths (95% CI 53 -77) could be averted per annum if air pollution concentrations were to fall to levels set out in the NDC, relative to the 'business as usual' baseline. Other health 'endpoints' are also projected, as well as impacts on broader productivity, including restricted activity days. Potential benefits can also be expressed in terms of life years gained (659 life years gained; 95% CI 498–739) and total economic benefits out to 2030 (expressed in $US) ($214,173,681; 95% CI 98,834,955–336,129,634).

TABLE 4.2 HEALTH AND ECONOMIC BENEFITS OF AIR POLLUTION REDUCTIONS (PER ANNUM)

	Central Estimate	Lower Bound	Upper Bound
Death averted from all (natural) causes in adults (≥ 30 years)	66	50	73
Cardiovascular hospital admissions (all ages)	12	2	21
Respiratory hospital admissions (all ages)	26	0	54
Restricted activity days (all ages)	77,883	72,754	83,012
Lost workdays in the employed population (18–65 years)	17,470	14,863	20,059
Life years gained	659	498	739
Total economic benefit ($)[1]	214,173,681	98,834,955	336,129,634

Source: *CLIMAQ-H (WHO, 2023)*
Note: *[1] Assesses the total economic benefit in $US 2020 prices assuming a 5% discount rate.*

4.3 HEALTH EFFECTS OF ACTIONS TO MITIGATE TEMPERATURE CHANGE IN IRELAND: CASE STUDY

Chapter 3 highlighted a relationship between temperature fluctuations and emergency in-patient hospital utilisation in Ireland, which can be interpreted as a proxy for morbidity. This raises concerns about how continued climate change will affect population health, the Irish healthcare system and infrastructure in the future, and how different temperature paths (and associated mitigation effort) may lead to greater or lesser impacts on emergency hospitalisation utilisation. In this section, we conduct an illustrative projection analysis to estimate the effect that different scenarios for increased temperatures would have on emergency in-patient hospitalisation in the future. We follow the broad approach outlined above by using various scenarios of future temperature change to simulate the projected impact on emergency in-patient hospitalisations, using parameter estimates from models estimated on the HIPE data used in Chapter 3.

Data

The data applied in this analysis concerns average daily maximum temperatures, temperature thresholds and projected number of days above these thresholds over the period 2020–2100 for three RCP scenarios. The RCP scenarios have been described in detail in Chapter 2. We apply the RCP4.5 (“most likely”) scenario in this analysis.[19]

[19] RCP4.5 – intermediate emissions. CO2 emissions increase only slightly before decline commences around 2040 (consistent with full implementation of all current policies).

We apply two key variables within this projection analysis:

1. The average daily maximum temperature per quarter per 20-year projection period up to 2100;
2. The proportion of days per quarter per 20-year period above the 75th, 90th and 95th temperature percentiles.

Each of these variables has values for each RCP, each 20-year period, each quarter and each county. This is illustrated in Table 4.3 for the RCP4.5 ("most likely") scenario.

TABLE 4.3 ILLUSTRATION OF TEMPERATURE SCENARIO DATA

RCP Scenario	Baseline: 1980–2000	Q1 – 4	Counties + Dublin PCs[1]
RCP4.5	Baseline: 1980–2000	Q1 – 4	Counties + Dublin PCs
	2021–2040	Q1 – 4	Counties + Dublin PCs
	2041–2060	Q1 – 4	Counties + Dublin PCs
	2061–2080	Q1 – 4	Counties + Dublin PCs
	2081–2100	Q1 – 4	Counties + Dublin PCs

Note: [1] *PC is an acronym for post code.*

It is difficult to explicitly project extreme weather events, and for example the number of very hot days in a given period in the future. In the projection analyses, we include three threshold values that are equivalent to the 75th percentile temperature, the 90th percentile temperature and the 95th percentile temperature. These threshold values are based on the baseline data for the period 1980–2000. These thresholds are used to proxy for very high temperature days in which the temperature exceeded each different threshold in the baseline periods. The data from the RCP scenarios also contain projections of the number of days per quarter per 20-year period above each of these thresholds. Given the proportion of days projected to be above a certain threshold in a quarter, we multiplied this proportion by the number of days in that quarter.

The projections of the number of days per quarter per 20-year period above each of these thresholds differ across RCP scenarios. Table 4.4 presents the number of days above the 90th percentile threshold for each quarter and 20-year projection period for the RCP4.5 ("most likely") scenario. This scenario projects that in quarter 3 in the 2020–2040 and 2040–2060 periods, there will be approximately 22–25 days in which the temperature exceeds the 90th percentile temperature from the 1980–2000 baseline period. This decreases in subsequent periods as climate change mitigation measures are adopted.

TABLE 4.4 NUMBER OF DAYS PER QUARTER ABOVE THE 90TH THRESHOLD FOR THE RCP4.5 ("MOST LIKELY") SCENARIO

	2020–2040	2040–2060	2060–2080	2080–2100
Quarter 1	11.3	10.8	24.3	19.6
Quarter 2	11.9	19.4	18.7	17.1
Quarter 3	22.2	24.9	15.3	21.6
Quarter 4	25.9	16.1	22.9	32.8

Methodology

In order to align the climate projections data with the HIPE data used in Chapter 3, the HIPE model was estimated at the county, quarter and year level. Using the temperature data for 2015–2019, it was possible to calculate whether a day was above the 75th, 90th or 95th temperature thresholds. The number of days were aggregated up to the quarter level for each county and year. Table 4.5 provides an illustration of the average temperature threshold for each quarter based on the historical 1980–2000 data.

TABLE 4.5 AVERAGE QUARTERLY THRESHOLD VALUES FOR THE 75TH, 90TH AND 95TH THRESHOLDS

Mean temperature thresholds by quarter for Ireland			
	75th Threshold	**90th Threshold**	**95th Threshold**
Quarter 1	10.80	11.97	12.64
Quarter 2	16.48	18.53	19.94
Quarter 3	19.95	21.85	23.03
Quarter 4	12.56	13.88	14.57

This data was then used to estimate a model (one for each temperature threshold) that regressed the number of days per county per quarter per year above the respective threshold on the rate of emergency in-patient hospital admissions per county per quarter per year. As before, year and county fixed effects were included. The coefficient estimates from this model indicate the effect that one extra day above the threshold in a quarter has on emergency hospital admissions. The model is estimated only for quarter 2 and quarter 3 and is applied only to quarter 2 and quarter 3 projections in this analysis. We do not apply the model estimates to all quarters, as higher than average temperatures in winter months (quarter 4 and quarter 1) would possibly result in fewer emergency hospitalisations.[20] Therefore, our number of observations in the estimated model is 260 (26 counties, 2 quarters and 5 years of data).

[20] When the model was estimated for quarter 1 and quarter 4 only, the coefficient (for the number of days per quarter above the relevant threshold) was negative (and not statistically significant). When the model was estimated for quarter 2 and quarter 3 only, the coefficient was positive and statistically significant.

Next, we apply these coefficient estimates to the projected quarterly estimates of the number of days above the respective thresholds (see Table 4.4 for these data for each 20-year projection period for the RCP4.5 (“most likely”) scenario for the 90th percentile). For each temperature threshold, RCP scenario and 20-year projection window, this gives us a projection of the average number of extra hospital admissions in a quarter that we would expect. Finally, we aggregate the quarterly projections to derive an annual estimate of emergency in-patient hospitalisations. This procedure results in 36 possible projections (3 RCP scenarios x 3 temperature thresholds x 4 20-year projection windows). In the discussion that follows, we mainly focus on the results using the 90th percentile threshold, but full results for the RCP4.5 (“most likely”) scenario are available in Appendix E.

Results

Table 4.6 presents the coefficient estimate results for the analysis; each column is for a different temperature threshold. The dependent variable is the emergency hospital admissions rate (per 100,000 population). The coefficient estimates the effect that one extra day in a quarter above the threshold has on the emergency hospital admissions rate. The model is estimated for quarter 2 and quarter 3 only.

TABLE 4.6 EMERGENCY IN-PATIENT MODEL RESULTS, HIPE 2015–2019

	75th Percentile Threshold	90th Percentile Threshold	95th Percentile Threshold
Coefficient estimate	1.79** (0.52)	2.85*** (0.71)	3.22*** (0.90)
Observations	260	260	260
R^2	0.91	0.92	0.91
Mean dependent variable[a]	1,036	1,036	1,036

Note: [a] relates to emergency in-patient hospitalisations per 100,000 population. Controls include socio-demographic characteristics, medical casemix, county fixed effects, year fixed effects.
**p<0.05, **p<0.01, ***p<0.001*

Our results above suggest that an additional day in quarter 2 or quarter 3 above the 90th temperature percentile increases the rate of emergency hospital admissions by 2.85 per 100,000 population. We apply the estimate above for the 90th threshold to the number of projected days above the 90th percentile in both quarter 2 and quarter 3. These estimates are also totalled to give an annual estimate.

Table 4.7 shows the estimated number of additional emergency hospitalisations per quarter, averaged over the 20-year period. These results give us an indication of what the average quarterly increase in hospital admissions would be under the RCP4.5 (“most likely”) scenario for each projected 20-year period. Our results suggest that there would be an increase of 97.2 per 100,000 each year in the period

2021–2040. This figure increases to 126 per 100,000 in the period 2041–2060. As a proportion of the mean level of admissions, this is indicative of a 9.4 per cent[21] increase in emergency hospital admissions annually in the period 2021–2040. This increases to 12.2 per cent annually for the period 2041–2060.

TABLE 4.7 PROJECTED INCREASE IN EMERGENCY IN-PATIENT HOSPITALISATIONS BY 20-YEAR PERIOD (RCP4.5, 90TH PERCENTILE)

	2021–2040	2041–2060	2061–2080	2081–2100
Quarter 2	34.0	55.2	53.4	48.8
Quarter 3	63.2	71.1	43.5	61.6
Total	**97.2**	**126.3**	**97.0**	**110.4**

Climate change adaption scenario

It is unlikely that there will be no adaption to a warmer climate undertaken by both individuals and the healthcare system. As such, we use the 95th percentile threshold as an estimate of the lower bound in this projection analysis. It will provide a preliminary indication of what the burden on the healthcare system might be if the population and healthcare system adapt to higher temperatures. If this occurs, then a higher temperature threshold would be more indicative of the effect of climate change on emergency hospitalisations in the future. Using the coefficient estimate in the final column of Table 4.6, we obtain the following results that we can use as our lower bound.

TABLE 4.8 LOWER BOUND ESTIMATES (RCP4.5, 95TH PERCENTILE)

	2021–2040	2041–2060	2061–2080	2081–2100
Quarter 2	22.0	39.3	37.3	34.5
Quarter 3	53.4	57.0	26.9	46.0
Total	**75.5**	**96.3**	**64.2**	**80.5**

In this case, the annual increase in emergency hospital admissions for the 2021–2040 period is 75.5 per 100,000 population. This is equivalent to a 7.3 per cent annual increase. For the period 2041–2060, this annual increase becomes 9.3 per cent.

Although these are lower bound estimates, they still indicate a relatively large increase in annual emergency hospital admissions. This is particularly true for a healthcare system that is currently functioning at full capacity. These estimates suggest the need for climate change adaption in the healthcare system to prevent future capacity problems from arising. Table 4.9 compares the projection analysis and lower bounds under the RCP2.6, RCP4.5 and RCP8.5 scenarios.

[21] We take the annual estimate (97.2) as a proportion of the mean dependent variable (1,036).

TABLE 4.9 COMPARISON OF ANNUAL INCREASES ACROSS RCP SCENARIOS

	RCP2.6 – Paris Agreement		RCP4.5 – most likely		RCP8.5 – no mitigation	
	90th percentile	95th percentile	90th percentile	95th percentile	90th percentile	95th percentile
2021–2040	10.7%	9.1%	9.4%	7.3%	10.2%	7.9%
2041–2060	14.1%	10.4%	12.2%	9.3%	13.0%	10.0%
2061–2080	7.3%	5.0%	9.4%	6.2%	13.5%	9.5%
2081–2100	9.1%	7.2%	10.7%	7.8%	18.3%	14.1%

These findings predict a significant increase in the number of high temperature days in Ireland under all RCP scenarios. Even under the most optimistic RCP scenario, the projected rise in emergency in-patient hospitalisations during the 2021–2040 and 2041–2060 periods is stark. However, the more optimistic RCP scenarios do project a lesser effect on hospital demand in later periods.

When considered alongside international evidence, these results emphasise the potential need for policymakers to implement adaptive measures and increase capacity to accommodate the higher hospital demand from higher temperatures. The outcomes in this section should be interpreted as average annual increases within each projected period. However, the surges in hospital demand due to high temperatures are likely to be concentrated around specific years, dates, and locations. The increased demand for hospital care due to higher temperatures is expected to be most acute in the summer months, with quarter 3 recording the highest number of days exceeding each threshold. Furthermore, geographical variations in high-temperature days may also influence the hospitals that might experience the highest demand for care. Therefore, the health system's adaptability to handle higher temperatures at particular times and in specific regions will be crucial in adjusting to the elevated temperatures in the coming years.

4.4 SUMMARY

In this chapter, we first provided an overview of the health benefits and co-benefits of climate change mitigation in Ireland, using approaches that simulate the effects of various temperature path scenarios on health, thereby deriving an assessment of the potential health benefits and co-benefits of different scenarios. The COACCH project results show that mitigation in line with the Paris Agreement (consistent with RCP2.6) would still result in approximately 200 heat-attributed deaths in the last decade of the 21st century. A future consistent with the RCP8.5 ("no mitigation") scenario would result in more than 1,000 additional deaths in the same decade compared to RCP2.6 ("Paris Agreement"). Focusing specifically on air pollution mitigation measures, the results of the WHO CLIMAQ-H model for

Ireland suggest that 66 deaths per annum could be averted, with considerable additional social and economic benefits (e.g., in terms of worker productivity).

In the second part of the chapter, we applied climate projections to the HIPE data used in Chapter 3. This analysis shows that, under the most benign climate change scenario (RCP2.6, Paris Agreement), emergency in-patient admissions in quarter 2 and quarter 3 could increase by an average of 10 per cent per annum over the period 2020–2040. If climate change mitigation actions were implemented fully in accordance with the Paris Agreement (RCP2.6), the impact on emergency in-patient hospitalisations could be lower in the latter half of this century. However, if no policy changes are implemented to reduce emissions (i.e., a future consistent with the RCP8.5 scenario), there could be a steep increase in annual emergency in-patient admissions across quarter 2 and quarter 3, of up to 18.3 per cent in the period 2080–2100 (depending on the temperature threshold used).

Simulation exercises such as these are subject to numerous assumptions that are necessary in order to simplify the analysis but which may induce error in projections. In particular, in this application, the model estimated for HIPE data over the period 2015–2019 assumes that the relationship between the average number of days per quarter above the various temperature thresholds and emergency in-patient hospitalisations holds over the entire projection period, i.e., up to 2100. As discussed in Chapter 1, previous literature has suggested that individuals may adopt adaptive strategies to cope with hotter temperatures; therefore, the behaviours we are assuming for 2015–2019 may represent an upper bound on the simulated effects over time.

CHAPTER 5

Summary, discussion and policy implications

5.1 SUMMARY OF MAIN FINDINGS

Recognition of the need to limit climate change has driven global negotiations concerning combined efforts to decrease greenhouse gas (GHG) emissions. In Ireland, the Climate Action and Low Carbon Development (Amendment) Act of 2021 commits to the achievement of an annual emissions reduction target of 7 per cent, resulting in a 51 per cent reduction of emissions by 2030, and further commits to net-zero emissions by 2050. The Climate Action Plans provide a detailed plan of measures needed for this transition.

When analysing the effects of climate change, the focus is often on the economic costs to society. Population health impacts of climate change are also important and remain relatively unexplored for Ireland. In addition, there is also little discussion of the potential benefits and co-benefits of emission reduction policies for population health. The research detailed in this report, carried out as part of a research programme funded by the Irish Heart Foundation and Irish Cancer Society on behalf of the Climate and Health Alliance, aimed to help fill this gap. It focuses on the health impacts of climate change (and specifically temperature change) and how global and national commitments to limiting temperature change may reduce these impacts in Ireland. Therefore, it also aims to better understand the health benefits and co-benefits of climate change mitigation efforts.

According to the climate simulation analysis, Ireland will be exposed to higher mean temperatures in the future. The mean annual temperature is projected to increase by 1–1.6°C by the middle of the century (i.e., 2041–2060) compared to the reference period 1981–2000, under the RCP4.5 climate scenario (the most likely scenario). With this warming will come hotter days and nights. The implications of higher temperatures on morbidity were then assessed by combining detailed meteorological data with data on acute public hospital emergency in-patient hospitalisations from the Hospital In-Patient Enquiry (HIPE) system over the period 2015–2019. The results showed that temperatures between 22°C and 25°C are associated with an 8.5 per cent increase in emergency in-patient hospitalisations, with children particularly affected.

In terms of health benefits and co-benefits, the research highlighted findings from the COACCH project which estimate that annual mortality under the most pessimistic scenario (RCP8.5) could be around 1,400 additional deaths by the end of the 21st century, in contrast to 216 under the most optimistic scenario (RCP2.6). Focusing specifically on air pollution mitigation measures, the results of the WHO CLIMAQ-H model for Ireland suggest that 66 deaths per annum could be averted, with considerable additional social and economic benefits (e.g., in terms of worker productivity). In terms of morbidity, an analysis of the HIPE data showed that an additional day in summer months above the 90th temperature percentile in the period 2081–2100 could be associated with a 10.7 percentage increase in annual emergency in-patient hospitalisations under the RCP4.5 scenario ("most likely"), and as high as 18.3 percentage increase under the most pessimistic ("no mitigation") RCP8.5 scenario.

5.2 DISCUSSION AND POLICY IMPLICATIONS

The analysis in this report has highlighted a number of key findings for Ireland in relation to climate change in health, in terms of future temperature paths, impacts on morbidity and projections of future health impacts of selected temperature paths. The analysis is necessarily limited in scope, and does not consider a number of other important issues that would need to be considered to assess a) the full health effects of climate change in Ireland and b) the full health benefits and co-benefits of climate change mitigation actions. In particular, as illustrated in Figure 1.1, the impact of climate change on health is complex, covering multiple pathways that link a variety of climate change features (e.g., rising temperatures, rising sea levels, more extreme events, etc.) with a myriad of health outcomes (e.g., mortality, chronic disease incidence, mental health, etc.).

In this report, we focused on the impact of the feature of climate change (i.e., increasing temperature) that is considered one of the most likely and harmful climate change features for Ireland (Desmond et al., 2017). Future work in Ireland could consider the impact of other climate change events on health in Ireland, a broader set of health outcomes, and the potential for health benefits and co-benefits on other dimensions of health in addition to mortality and emergency hospital admissions. In addition, while the analysis in this report has focused on the potential health co-benefits of mitigation action in terms of various projected future temperature paths (consistent with different mitigation scenarios), future work could assess the health benefits and co-benefits of selected mitigation actions (e.g., more sustainable transport).[22]

A number of implications for policy arise from the analysis in this report. Policy responses to climate change fall broadly into two categories: mitigation (preventing or reducing the scale of future harm), and adaptation, implementing a wide range of adaptation solutions, including effective heat health action plans, urban greening, appropriate building design and construction, and adjusting working times (Hensher, 2023; Kaźmierczak et al., 2022). The analysis in this report has focused primarily on mitigation, and the potential health benefits and co-benefits of limiting future temperature rises and impacts. An important conclusion for policy is that there are considerable health benefits and co-benefits from mitigation that should be considered in policymaking. The broader literature

[22] This type of analysis was outside of the scope of the current report due to the data and methodological requirements. For example, in assessing the health benefits/co-benefits of increased cycling, an assessment is needed of a) how much extra cycling, b) how cycling is linked to health and c) what aspect of health is affected, and how is that quantified?

highlights the importance of careful consideration of mitigation and adaptation measures, including an assessment of the potential for unintended consequences. For example, past decades of efforts to reduce CO_2 emissions in Europe without adequate consideration of health include promoting diesel over gasoline-powered vehicles, and the promotion of biomass for residential heating, both of which resulted in considerable emissions of health-damaging air pollutants (van Daalen et al., 2022). Similar concerns can be raised over adaptation technologies; for example, Deschenes (2022) notes that more attention needs to be devoted to increasing opportunities and finding solutions to protect human health from extreme heat while at the same time minimising the damages from the local and global externalities caused by the electricity generation necessary for meeting the increased cooling demand that climate change will bring.

Nonetheless, the findings highlight the continued importance of policy measures to achieve the targets set out in the Climate Action Plans. In terms of air quality, for example, the recent Clean Air Strategy commits to achieving the final WHO ACQ values by 2040 (Government of Ireland, 2023), and at EU level, the proposed revision to the Ambient Air Quality Directive will set interim 2030 EU air quality standards, aligned more closely with WHO guidelines, and set Europe on a trajectory to achieve zero pollution for air by 2050. Policy measures to mitigate the impacts of climate change, such as decarbonising home heating, promoting active travel and transitioning to electric vehicles, will be an important component of the policy response, and will also have concomitant benefits for population health (van Daalen et al., 2022).

The findings in relation to temperature effects on emergency hospital admissions highlight the importance of considering the broader impacts of climate change on the health sector. The EEA note that improving the resilience of healthcare facilities across Europe is necessary not only due to the pressure on their capacity to deliver patient care during heatwaves or diagnostics during outbreaks of climate-sensitive infectious diseases, but also due to the fact that they tend to be located in urban areas that are more prone to the ‘urban heat island’ effect (Kaźmierczak et al., 2022). Many healthcare systems have also introduced plans to adapt to climate change. In October 2020, the English National Health Service (NHS) became the world’s first national health system to commit to becoming ‘net zero’, pledging to reduce its carbon emissions to net zero by 2040, including in its facilities and buildings.[23] The HSE has now followed suit. In June 2023, the HSE launched its Climate Action Strategy 2023–2050.[24] This is a health service-wide strategy that aims to reduce the impacts of climate change on the health service and deliver healthcare in a more environmental and socially sustainable manner. A key goal is to achieve net-zero emissions for the HSE by 2050.

[23] NHS Net Zero Building Standard www.england.nhs.uk/estates/nhs-net-zero-building-standard/#:~:text=The%20NHS%20Net%20Zero%20Building,now%20and%20in%20the%20future.
[24] www.hse.ie/eng/about/who/healthbusinessservices/national-health-sustainability-office/climate-change-and-health/hse-climate-action-strategy-2023-50.pdf.

Policy changes that are required to help mitigate the impact of climate change on health are also part of the most recent "Climate Change Adaptation Plan for the health sector – 2019–2024"[25] which was developed under the 2018 National Adaptation Framework and the Climate Action and Low Carbon Development Act 2015. This plan outlines some key policies, including:

- Develop a better understanding of the health impacts of climate change in Ireland by undertaking analysis and research to obtain baseline information on the impacts of severe weather, flooding and drought on public health (AD/23/15).
- Develop a new public health heatwave plan and seek to ensure more uniform system-wide planning for heatwaves (AD/23/16).
- Build the knowledge base required to improve health infrastructure resilience to severe weather events: severe wind, heatwaves, flooding, and extreme cold snaps (AD/23/17).
- Develop a better understanding of the health impacts of climate change in Ireland by undertaking analysis and research to obtain baseline information on the impacts of severe weather, flooding, and drought on public health. Analysis of impacts of air quality on health to identify potential increase/decrease in air quality risks. Build and refine Irish-specific climate change epidemiology relating to air pollution and identify risk groups (AD/23/15).

As acknowledged in the Climate Change Adaptation Plan for the health sector, climate change increases the likelihood of extreme weather events impacting healthcare infrastructure in Ireland and elsewhere. Recent examples have occurred of public hospitals in Ireland being flooded due to extensive rainfall during summer months.[26] These occurrences have had impacts on an already overstretched healthcare system. Ireland is currently undertaking development of a number of large healthcare facilities. Such hospitals and health centres will need to be built or retrofitted to withstand events linked with climate change, including flooding, heatwaves, and potential wildfires. This might include improving the physical infrastructure of buildings, planning for back-up power sources, ensuring adequate water supplies, and creating evacuation or emergency response plans. Such measures have become common in regions that experience weather events such as hurricanes. In the Gulf Coast region of the United States, which is disproportionately affected by hurricanes, hospitals have begun to construct infrastructure such as back-up generators and fuel supplies and on-site sewage treatment facilities to protect them against the effects of storm surges, and also continued sea level rises (Tarabochia-Gast et al., 2022). Results in Section 4.3 indicate that even in the most optimistic scenarios, the number of days with high temperatures is projected to increase significantly this century. Based upon evidence in this study, these temperature increases could increase emergency

[25] www.gov.ie/en/campaigns/708481-climate-change-adaptation-plan-for-the-health-sector-2019-2024.
[26] e.g., Letterkenny General Hospital in August 2014 and University Hospital Kerry in July 2023.

in-patient hospital care demand by over 9 per cent during the warmer months. This increased demand is likely to disproportionately occur in certain higher temperature locations. Sufficient planning by policymakers to meet this increased demand will be required.

Continuity of patient care during weather events is also of paramount concern to healthcare providers. Natural weather disasters have been shown to affect continuity of care over the longer term (Baum et al., 2019). This means adaption measures need to go beyond infrastructure. For example, flooding can hinder staff, patients, and supplies from reaching healthcare facilities. Therefore, stockpiling of supplies and removal of obstacles such as limited storage capacity can help. While other factors such as insurance coverage and access to patient medical records can still pose significant hurdles in the delivery and accessibility of care (Adalja et al., 2014). In some countries, some hospitals have also been closed temporarily due to wildfires in their vicinity.[27] Policymakers and health providers should begin to prioritise stress tests for climate and health. These can be developed to enhance the ability of health systems and associated sectors to handle potential disruptions caused by climate-related shocks and stresses (Ebi et al., 2018).

This research, and AD/23/15 above highlights the importance of the collection and availability of appropriate data. While research by international organisations has assessed the global burden of disease attributed to climate change (see for example, Song et al., 2021), these types of analyses must by necessity make a myriad of assumptions that may or may not be generalisable to particular country settings. In this report, we took a more direct approach, estimating the impacts of temperature changes on morbidity, as proxied by hospital admissions data from HIPE. This allowed us to link hospital admissions to temperature very precisely, while also controlling for other factors that may influence hospital admissions, such as season, county of residence, age, sex and clinical characteristics. The analysis highlights the value of making administrative health data such as HIPE available to researchers and policymakers to exploit the full richness of the data for policy and evidence.

[27] www.cbc.ca/news/canada/sudbury/forest-fires-hospital-surgeries-cancelled-1.6871588.

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APPENDIX A – DATA, VARIABLES AND SUMMARY STATISTICS

Table A.1 provides a summary of the variables used in our analysis from the HIPE dataset.

TABLE A.1 SUMMARY OF VARIABLES USED FROM HIPE

Variable	Notes
County	All counties in the Republic of Ireland; incl.:
	North Dublin; South Dublin
	Tipperary North; Tipperary South
	Waterford County; Waterford City
	Cork County; Cork City
	Limerick County; Limerick City
	Galway County; Galway City
	Not Ireland
	No fixed abode
Age (5yr Brackets)	From 0–4 to 100+
Sex	Male/Female
Public or Private Status	Public/Private
Medical Card Status	No Medical Card
	Medical Card
	Unknown
Marital Status	Single
	Married
	Widowed
	Other (incl. separated)
	Unknown
	Divorced
	Civil Partner
	Former Civil Partner
	Surviving Civil Partner
Length of Stay	Measured in days, minimum value is 0.5
Diagnosis Codes	From primary diagnosis to 30th diagnosis code
	Uses ICD-10-AM
Mode of Emergency Admission	Emergency Department
	AMAU-In-patient
	Other
	Unknown
	AMAU Only
	Local Injury Unit
	ASAU-In-patient
	ASAU Only

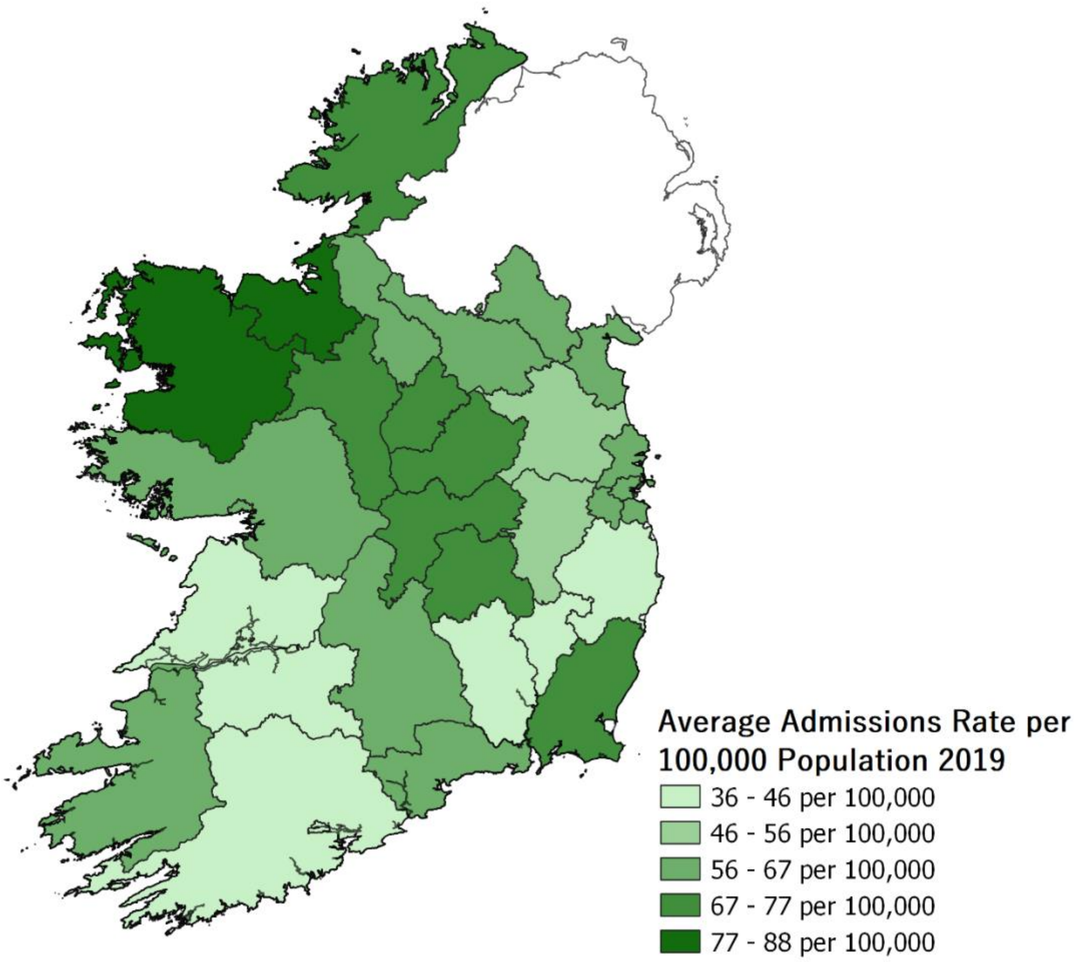
Elective/Emergency/Maternity	Indicates whether an admission is elective, emergency or maternity
Admission Month	January–December
Admission Week	Weeks 0–52 Weeks start on the first Sunday of each year. 2017 has weeks numbered 1–53 because it starts on a Sunday

TABLE A.2 ICD-10-AM CODES FOR DIAGNOSIS VARIABLES

Diagnosis	ICD-10-AM Codes
Circulatory Diseases	I00 – I99
Respiratory Diseases	J00 – J99
Metabolic Diseases	E00 – E99
Infectious Diseases	A00 – A99 & B00 – B99
Injuries	T00.1 – T00.9; T01.0 – T01.4;

Figure A.1 shows the emergency in-patient hospital admissions rate (per 100,000 population) by county for 2019. The admissions rate is calculated for every week of the year and these weekly admission rates are averaged across the whole year (for 2019). The figure below shows the variation in emergency hospital admissions rates across county of residence. There are higher rates of emergency hospital admissions among people who live in the west of Ireland and in the midlands.

FIGURE A.1 EMERGENCY IN-PATIENT HOSPITAL ADMISSIONS RATE BY COUNTY (2019)



APPENDIX B – LAGGED EFFECTS OF TEMPERATURE BIN MODEL

Table B.1 shows the coefficient estimates for the control variables of the temperature bin analysis.

TABLE B.1 COEFFICIENT ESTIMATES FOR TEMPERATURE BIN ANALYSIS

	Hospital Admissions Rate
Mean of Charlson Co-Morbidity Index	0.59 (0.71)
Mean Number of Medical Card	7.02*** (1.90)
Mean Public/Private Status	6.12*** (2.39)
Mean Married or Cohabiting	-1.52 (1.06)
Male – Age 0–9	-5.91 (7.88)
Male – Age 10–19	-16.88* (8.74)
Male – Age 20–29	-12.74** (9.27)
Male – Age 30–49	-24.01*** (8.19)
Male – Age 50–69	-13.85* (7.75)
Male – Age 70–79	-17.51** (7.82)
Male – Age 80–89	-11.10 (8.01)
Male – Age 90+	Ref -
Female – Age 0–9	-18.42** (8.01)
Female – Age 10–19	-4.69 (9.29)
Female – Age 20–29	-24.11** (10.60)
Female – Age 30–49	-18.72** (8.55)
Female – Age 50–69	-12.55 (7.90)
Female – Age 70–79	-13.47* (7.96)
Female – Age 80–89	-8.78 (8.02)
Female – Age 90+	-14.19 (9.12)

APPENDIX C – MEAN DEVIATION MODEL: GROUP/DIAGNOSIS ANALYSIS AND FULL MODEL RESULTS

Table C.1 shows the results of the mean deviation model when it estimated by age group. The age groups are those that are used in the temperature bin analysis and are grouped accordingly: (1) children (ages 0–14); (2) working (ages 15–64); and (3) older (ages 65+). The analysis shows that there are significant effects of maximum temperature on emergency in-patient hospitalisations for the children's age group and the working age group for the differences model. This is likely to be a reflection of how the model is constructed mathematically using a deviation from the mean level of hospital admissions by age group. The older age group would have a relatively high average number of hospital admissions, so any deviations from this mean would be quite small in proportion.

TABLE C.1 MEAN DEVIATION MODEL BY AGE GROUP

	(1) Child	(2) Working	(3) Retired
% Difference in Maximum Temperature	0.30*** (0.07)	0.14*** (0.05)	0.07 (0.05)
% Difference in Maximum Temperature²	-0.92** (0.39)	-0.58* (0.30)	-0.38 (0.29)
Temperature Lags	Yes	Yes	Yes
County Fixed Effects	Yes	Yes	Yes
Year Trend	Yes	Yes	Yes
Month Fixed Effects	Yes	Yes	Yes
Socio-demographic Controls	Yes	Yes	Yes
N	3,521	3,532	3,522
R^2	0.05	0.04	0.19

Note: *Analysis includes precipitation controls, including lagged precipitation for three weeks.*
Standard errors in parentheses.
** p<0.05, ** p<0.01, *** p<0.001*

Table C.2 illustrates the results of the model when it is estimated for each diagnosis group. The analysis shows that for injuries, the relationship between temperature and admissions is statistically significant. Previous literature supports the fact that risky and aggressive behaviour becomes more common during hot spells of weather – this could also be due to the fact that people are more likely to consume alcohol during hotter weather, increasing the likelihood of accidents (Hagström, Widman and Seth, 2019). We also find that emergency in-patient admissions for infectious and metabolic diseases are also statistically significant and positively related to temperature. International literature exploring the effects of climate change on health have noted the fact that longer periods of hot weather can increase the incidence of water-borne and vector-borne diseases (Kaźmierczak et al., 2022; Romanello et al., 2022). Our results show tentative support for this.

TABLE C.2 DIFFERENCES MODEL BY DIAGNOSIS GROUP

	(1) Circulatory Disease	(2) Respiratory Disease	(3) Metabolic Diseases	(4) Infectious Diseases	(5) Injuries
% Difference in Maximum Temperature	-0.06 (0.05)	0.10** (0.05)	0.11 (0.12)	0.26*** (0.07)	0.29*** (0.05)
% Difference in Maximum Temperature²	0.07 (0.32)	-0.65 (0.30)	0.15 (0.50)	-0.50 (0.41)	-0.42 (0.30)
Temperature Lags	Yes	Yes	Yes	Yes	Yes
County Fixed Effects	Yes	Yes	Yes	Yes	Yes
Year Trend	Yes	Yes	Yes	Yes	Yes
Month Fixed Effects	Yes	Yes	Yes	Yes	Yes
Socio-demographic Controls	Yes	Yes	Yes	Yes	Yes
N	3,527	3,533	3,101	3,477	3,537
R^2	0.07	0.09	0.07	0.05	0.07

Notes: *Standard errors in parentheses.*
** p<0.05, ** p<0.01, *** p<0.001*

Table C.3 shows the coefficient estimates for the control variables from the mean deviation model.

TABLE C.3 COEFFICIENT ESTIMATES FROM THE MEAN DEVIATION MODEL

	%Δ In-Patient Hospital Admissions
Mean of Charlson Co-Morbidity Index	-0.03* (0.01)
Mean Number of Medical Card	0.04 (0.03)
Mean Public/Private Status	-0.01 (0.04)
Mean Married or Cohabiting	0.00 (0.02)
Male – Age 0–9	0.04 (0.12)
Male – Age 10–19	-0.17 (0.13)
Male – Age 20–29	0.13 (0.13)
Male – Age 30–49	-0.08 (0.13)
Male – Age 50–69	-0.07 (0.11)
Male – Age 70–79	-0.19 (0.11)
Male – Age 80–89	-0.20 (0.12)
Male – Age 90+	-0.13 (0.17)
Female – Age 0–9	-0.05 (0.12)
Female – Age 10–19	0.21 (0.14)
Female – Age 20–29	0.02 (0.16)
Female – Age 30–49	-0.05 (0.13)
Female – Age 50–69	-0.04 (0.11)
Female – Age 70–79	-0.12 (0.11)
Female – Age 80–89	-0.08 (0.11)
Female – Age 90+	Ref. -

APPENDIX D – PROJECTION ANALYSIS

SCENARIO RCP4.5 – MOST LIKELY

TABLE D.1 NUMBER OF DAYS PER QUARTER ABOVE THE 75TH THRESHOLD (RCP4.5)

	2020–2040	2040–2060	2060–2080	2080–2100
Quarter 1	24.8	23.6	41.9	35.6
Quarter 2	25.9	36.9	36.9	32.5
Quarter 3	37.4	42.6	33.4	39.8
Quarter 4	38.5	31.1	38.5	44.6

TABLE D.2 PROJECTED INCREASE IN EMERGENCY HOSPITALISATIONS (75TH THRESHOLD AND RCP4.5)

	2021–2040	2041–2060	2061–2080	2081–2100
Quarter 2	46.4	66.1	66.1	58.2
Quarter 3	66.9	76.2	59.8	71.3
Total	**113.3**	**142.4**	**125.9**	**129.5**

TABLE D.3 NUMBER OF DAYS PER QUARTER ABOVE THE 95TH THRESHOLD (RCP4.5)

	2020–2040	2040–2060	2060–2080	2080–2100
Quarter 1	6.5	6.1	16.2	13.1
Quarter 2	6.8	12.2	11.6	10.7
Quarter 3	16.6	17.7	8.3	14.3
Quarter 4	20.7	9.9	15.9	27.6

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