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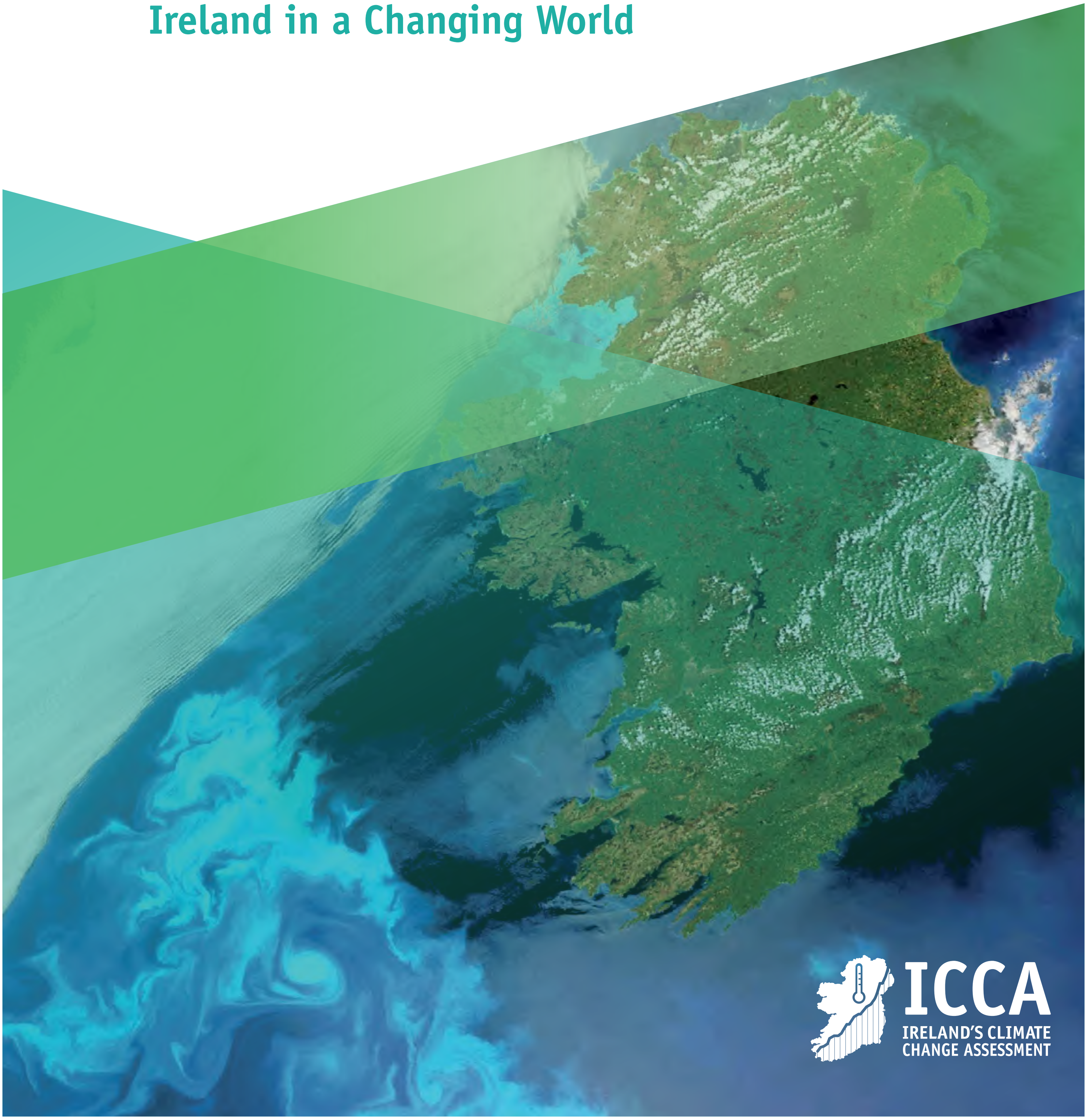
IRELAND'S CLIMATE CHANGE ASSESSMENT

Volume 1: Climate Science – Ireland in a Changing World



ICCA
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Ireland's Climate Change Assessment 2023

Environmental Protection Agency

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Foreword

This is the first Ireland's Climate Change Assessment (ICCA) and is a major contribution to the national dialogue and engagement on climate change. It tells us what is known about climate change and Ireland. It also provides key insights on gaps in our knowledge. The development of ICCA was modelled on the work of the Intergovernmental Panel on Climate Change and the Sixth Assessment Cycle, completed in 2023, with the use of and localisation of its information for Ireland.

ICCA will support the national response to climate change, ensuring that it is informed by the best available science. It also points to how and where that science can be improved through further investments in innovation, in research and in systematic observations. These collectively form the essential backbone of the science and data required to understand how Ireland is being impacted by and responding to the climate change challenge.

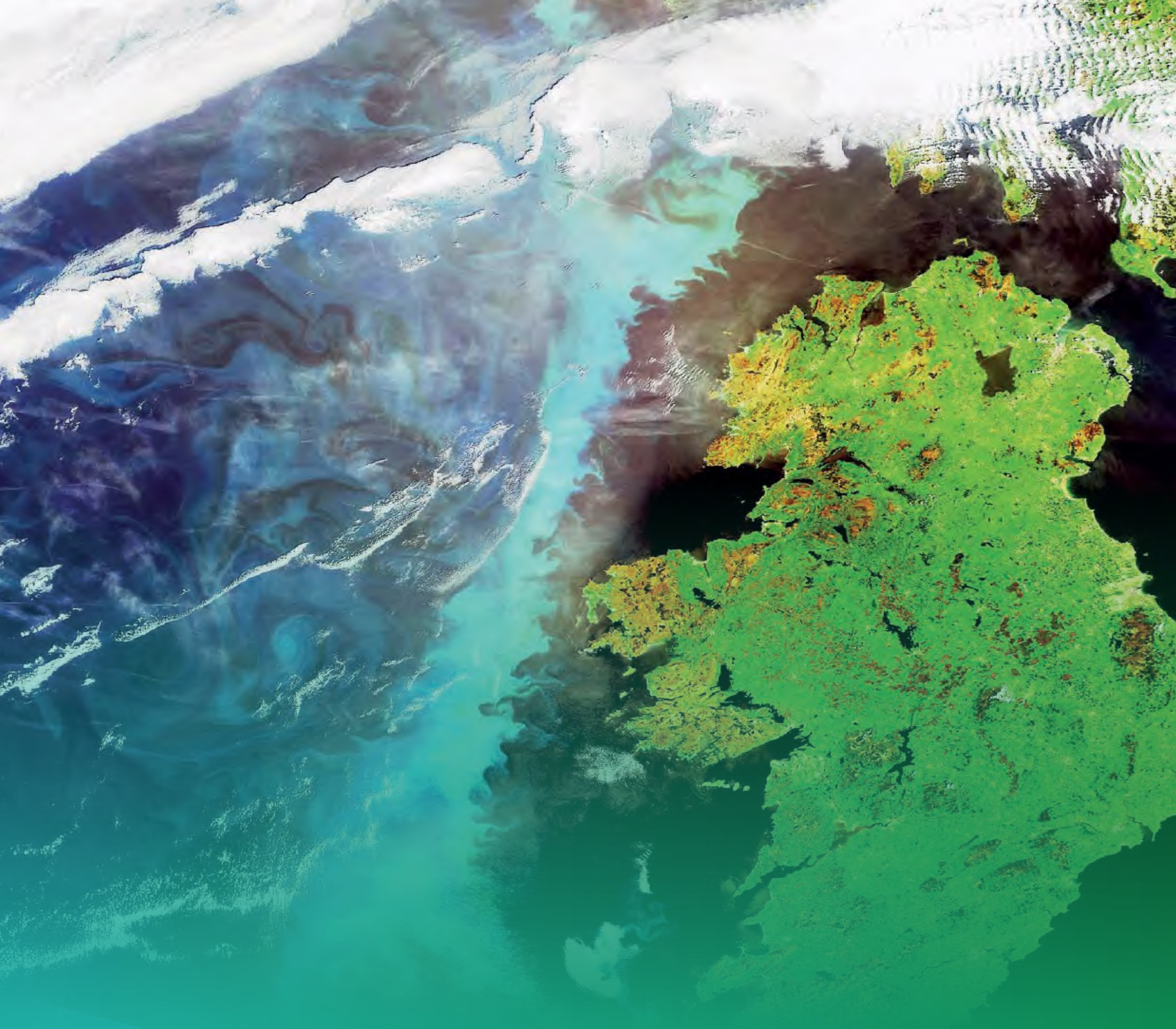
The full Assessment has been developed through a co-creation process between leading academics in Ireland and officials from across state agencies and government departments. Funding was provided by the Environmental Protection Agency, Sustainable Energy Authority of Ireland, Science Foundation Ireland and Department of Transport. The process was collaborative, involving mutual development and agreement of the scope, preparation and review of drafts, wider stakeholder consultation through a series of workshops and meetings, and a detailed sign-off process.

We see the publication of ICCA as a real innovation for Ireland and as a resource for understanding climate change in an Irish context across the underlying science, mitigation and adaptation measures, and opportunities. It is a starting point for further dialogue on the findings and their utility for policymakers, practitioners, researchers, research funders and people. This engagement phase should continue far beyond the publication of this Assessment and support climate action in Ireland.

Dr Eimear Cotter
Director of the Office of Evidence and Assessment, EPA
Chair of the ICCA Steering Committee

"Each degree matters, each year matters, and each decision matters: not acting today is adding to the burden of the next generations .... Limiting global warming to 1.5°C is not impossible but requires strong and immediate policies."

Valérie Masson-Delmotte,
Co-chair of working Group I of the IPCC
(8 October 2018 – French Senate intervention)



Summary for Policymakers

A. Ireland's climate is changing

Aspects of the climate system have been directly observed for the best part of the past two centuries. Today national and international programmes are taking coordinated observations[1] from the depths of the ocean to the very edge of space in unprecedented detail. Numerous scientists nationally and internationally have analysed these observations to create high-quality datasets that provide in-depth understanding of multiple aspects of the changing climate. These directly observed changes can be placed in a much longer-term context of many centuries to in some cases millions of years by indicators of past climates arising from information from proxies such as tree rings, ice cores, pollen samples, lake sediments and ocean sediments. These records have similarly been analysed by many scientists nationally and internationally.

A.1 There has been a rapid rise in atmospheric greenhouse gas concentrations, measured at numerous sites around the world, including Mace Head, since the Industrial Revolution without precedent in millions of years. Concentrations of methane and nitrous oxide are higher now than in over 800,000 years, and for carbon dioxide, for which longer-term reconstructions are possible, concentrations are higher than for millions of years. The increases in greenhouse gas concentrations since 1850 are due to global human activities, principally through fossil fuel combustion and land use change. {Chapters 1, 2}

A.2 Changes in the concentrations of these three major greenhouse gases since 1750 exceed those between successive glacial and interglacial cycles of the past 800,000 years for carbon dioxide and methane. For nitrous oxide the changes in concentration are of comparable magnitude to these successive glacial and interglacial cycles. These past changes in concentrations of all three gases were much slower, occurring over thousands of years. {Chapters 1, 2}

A.3 Globally, widespread and rapid changes in the atmosphere, ocean, land, cryosphere and biosphere have occurred. The scale of recent changes across the climate system as a whole – and the present state of many aspects of the climate system – are unprecedented over many centuries to many thousands of years. {Chapter 1}

A.4 Global surface temperatures have risen by 1.15°C [1.00-1.25°C] between 1850–1900 and the most recent decade, 2013–2022. This most recent decade was likely warmer than any sustained period in at least the past 100,000 years. {Chapter 1}

A.5 In Ireland annual average temperatures are now approximately 1.0°C higher than they were in the early 20th century. Sixteen of the top twenty warmest years since 1900 have occurred since 1990, with 2022 being the warmest year to date. Centennial timescale changes in Ireland are broadly consistent with global changes owing to our geographical situation between Europe (which is warming considerably faster than the global mean) and the North Atlantic (which is warming at a slower rate). {Chapter 3; Figure SPM.1a}

A.6 Globally averaged precipitation over land has likely increased since 1950, with a faster rate of increase since the 1980s. The frequency and intensity of extreme precipitation events has increased almost everywhere, particularly so in already wetter regions in the northern hemisphere, and a greater proportion of total precipitation is falling in extreme precipitation events across most of the globe. {Chapter 1}

A.7 Over Ireland median annual precipitation was 7% higher in the period 1991–2020, compared to the 30-year period 1961–1990. Regions where trends in precipitation since 1950 are significant have generally experienced overall annual increases. Analysis of local observations does not reveal evidence of a clear climate change signal in extreme precipitation indices due to natural variability. Overall, when aggregated, there has been an increase in heavy precipitation extremes across a range of indicators. {Chapter 4; Figure SPM.1b}

[1] Coordination bodies include, but are not limited to, the Global Climate Observing System, the World Meteorological Organization and the Intergovernmental Oceanographic Commission.

A.8 The rate of warming of the global ocean was likely faster in the past century than for any century since the last deglaciation event 11,000 years ago. Global sea level increased by approximately 0.20m between 1901 and 2018, and the rate of global sea level rise is accelerating. Consistent with global open ocean changes, Irish marine waters have experienced long-term acidification due to uptake of anthropogenic atmospheric carbon dioxide. {Chapters 1, 5}

A.9 Recent studies have highlighted higher rates of sea level rise since the late 20th century in Cork and Dublin than the global average. Reasons for this are unclear and currently under investigation. There a range of processes that can lead to local sea level changes diverging to a certain extent from global changes over a broad range of timescales. {Chapter 5; Figure SPM.1c}

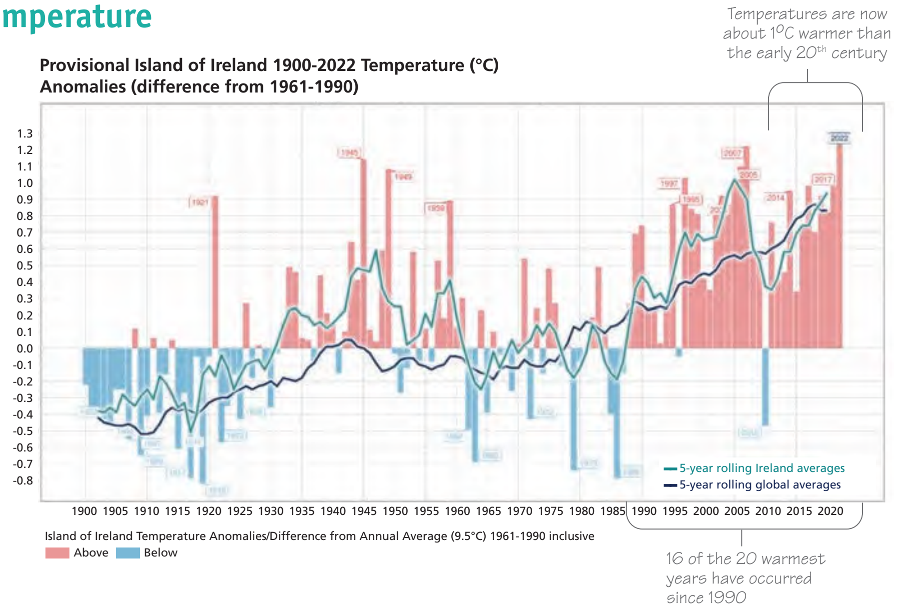
A.10 Globally, over the last century there have been poleward and upslope movements of many terrestrial species in response to climate changes. There have also been changes in the timing of life cycle events, such as birds migrating and plants flowering in all mid-latitude regions. Changes in the marine biosphere are consistent with large-scale warming and changes in ocean geochemistry. The ranges of many marine organisms are shifting towards the poles and towards greater depths, but a minority of organisms are shifting in the opposite directions. {Chapter 1}

A.11 The main impacts of climate change on Irish terrestrial species and habitats observed to date have been changes in species abundance and distribution, lifecycle events, community composition, and habitat structure and ecosystem processes. These changes are in addition to much larger changes arising from other human interventions. In Irish waters, there have been substantial changes in marine ecosystems, including changes in seasonality and abundance of many species, including phytoplankton and zooplankton at the base of the food web. Many of these changes are consistent with a changing climate. {Chapters 5, 7}

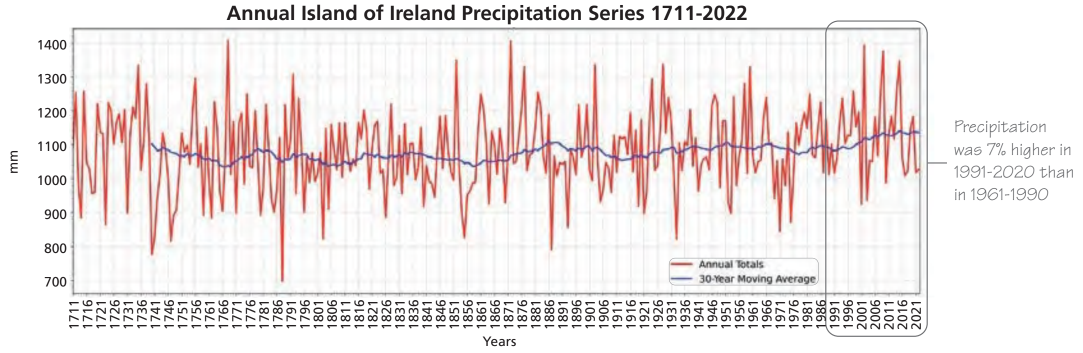
A.12 Global climate changes have been modified over Ireland by proximity to the North Atlantic and by internal climate system variability, mainly, but not exclusively, related to variations driven by the North Atlantic. Most notably, the Atlantic Multi-decadal Variability explains successive multi-decadal periods when Ireland has warmed or cooled relative to global trends (Figure SPM.1a). {Chapters 1, 3, 4, 5}

We are already living in a changed climate

(A) Temperature



(B) Precipitation



(C) Sea level

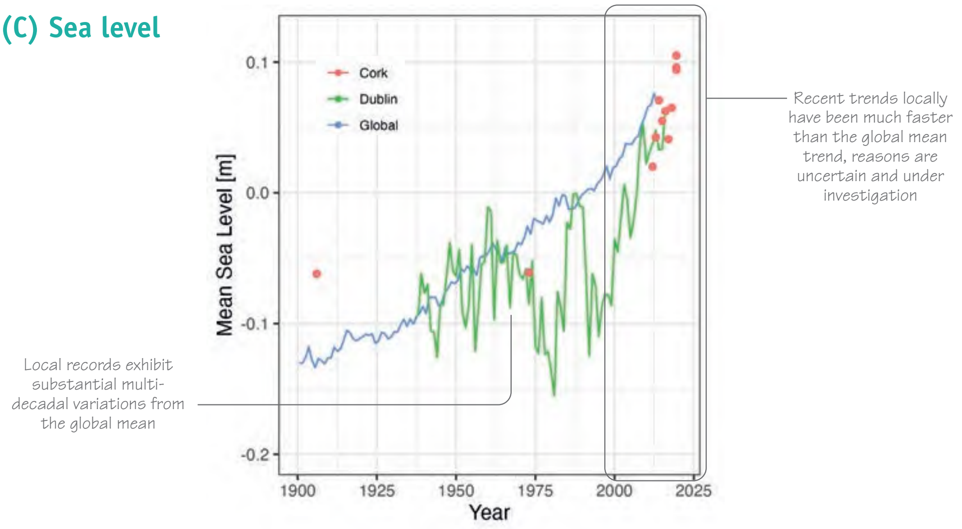


Figure SPM.1 We are already living in a changed climate. (a) Island of Ireland temperature anomalies, 1900–2022 relative to 1961–1990 (Met Éireann). (b) Reconstructed island of Ireland precipitation series showing annual totals (the continuous 305-year (1711–2016) annual rainfall series from Maynooth University with an estimate based upon 12 continuing Met Éireann stations post-2015) and highlighting the presence of substantial decadal to multi-decadal variability. The blue line represents a 30-year moving average. (c) Sea level time series for global, continuous records from Dublin and discontinuous measurements from the Cork region. Source: Figure components sourced from Met Éireann and contributing authors. {Chapter 1, 3, 4, 5}

B. Recent climate changes are due to human activities

Scientific understanding of the physical climate system, along with state-of-the-art statistical analytical approaches comparing climate simulations (Box SPM.1) to observations, provides the basis for detection of global and regional climate change and its attribution to possible causes. This is the scientific detective work of disentangling the causes of the changing climate we are collectively experiencing today.

B.1 It is unequivocal that human activity has warmed the climate system. The best estimate of human-caused global surface temperature increase from 1850–1900 to 2013–2022 is 1.14°C, in close agreement with the best estimate of the observed increase of 1.15°C over the same period. This warming is mainly due to increased atmospheric greenhouse gas concentrations, partly masked by cooling due to increased atmospheric aerosol concentrations (Figure SPM.2). {Chapter 1}

Observed warming from 1850-1900 to 2013-2022 is driven by emissions from human activities

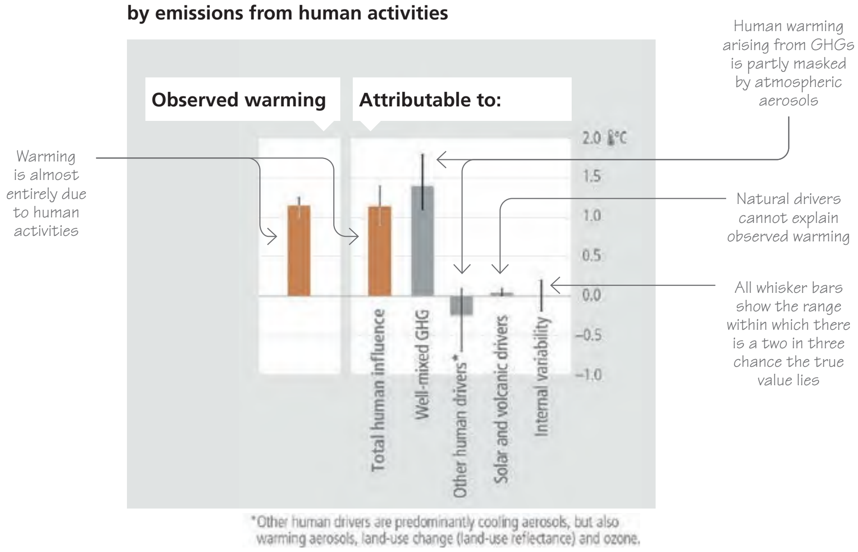


Figure SPM.2 Assessed contributions to observed warming in 2013–2022 relative to 1850–1900. The left hand panel shows observed changes and the right hand panel shows those temperature change components attributable to: total human influence; changes in well-mixed greenhouse gas concentrations; other human drivers due to aerosols, ozone and land use change (land use reflectance); solar and volcanic drivers; and internal climate variability. Whiskers for attributable components show 66% likelihood ranges (a two in three chance the true value lies within the interval). Source: Forster et al. (2023; panel from their figure 8 modified for clarity). Reproduction licensed under the Creative Commons Attribution CC BY 4.0 licence (https://creativecommons.org/licenses/by/4.0/). {Chapter 1}

B.2 Attribution at the global scale shows consistent human signals in observed changes across the atmosphere (surface and upper-air temperatures, humidity, precipitation, circulation), ocean (sea level, ocean heat content, salinity, acidification, deoxygenation) and cryosphere (glaciers, sea ice, ice sheets, seasonal snow cover). The observed changes across the climate system since the mid-20th century cannot be explained without invoking human influences. {Chapter 1}

B.3 Human-induced climate change is already modifying extreme weather events across the globe. Increases in both the frequency and intensity of heatwaves and extreme precipitation have been consistently linked to human activities. Similarly, cold events have been made less likely and severe. In drought-prone regions droughts have tended to be made more severe and frequent. There is limited evidence to date for human influences on many types of extreme storms, including mid-latitude storms. {Chapter 1}

B.4 Many notable recent Irish events have not yet been formally studied in the context of the rapidly emerging science of event attribution using state-of-the-art approaches. However, there is high confidence that recent changes in heat extremes and heavy precipitation events in Ireland can be linked, albeit indirectly, to human-induced climate change. From observations and analysis there is no clear evidence to date for human-induced climate change influencing the frequency or intensity of other types of extreme events in Ireland, such as windstorms. {Chapter 6}

"The observed changes across the climate system since the mid-20th century cannot be explained without invoking human influences"

Box SPM.1 Climate scenarios and climate simulations

Scenarios

How global society will act in future and react to climate change is unknown. Yet, to simulate possible climate futures and inform policymakers and broader society, some illustrative possible futures are required. As such a scenario is a description of how the future may develop based on a set of assumptions about key global drivers, including demography, economic processes, technological innovation, governance and lifestyles, and the relationships among these driving forces. {Cross-volume Box 1}

For this report, we consider 3 broad-families of scenarios:

Early action	Middle action	Late action
Rapid global action towards meeting the Paris Agreement goal of keeping temperature increases well below 2°C and making efforts to limit warming to 1.5°C by 2100. Warming is halted at some point in the second half of this century.	Delayed global action resulting in substantial exceedance of 2°C global warming. Warming generally continues beyond the end of the century in most of these scenarios.	Substantially delayed and uncoordinated global action. Major actions occur only late in the 21st century if at all, with 3°C or more of warming by 2100 and continued warming thereafter.

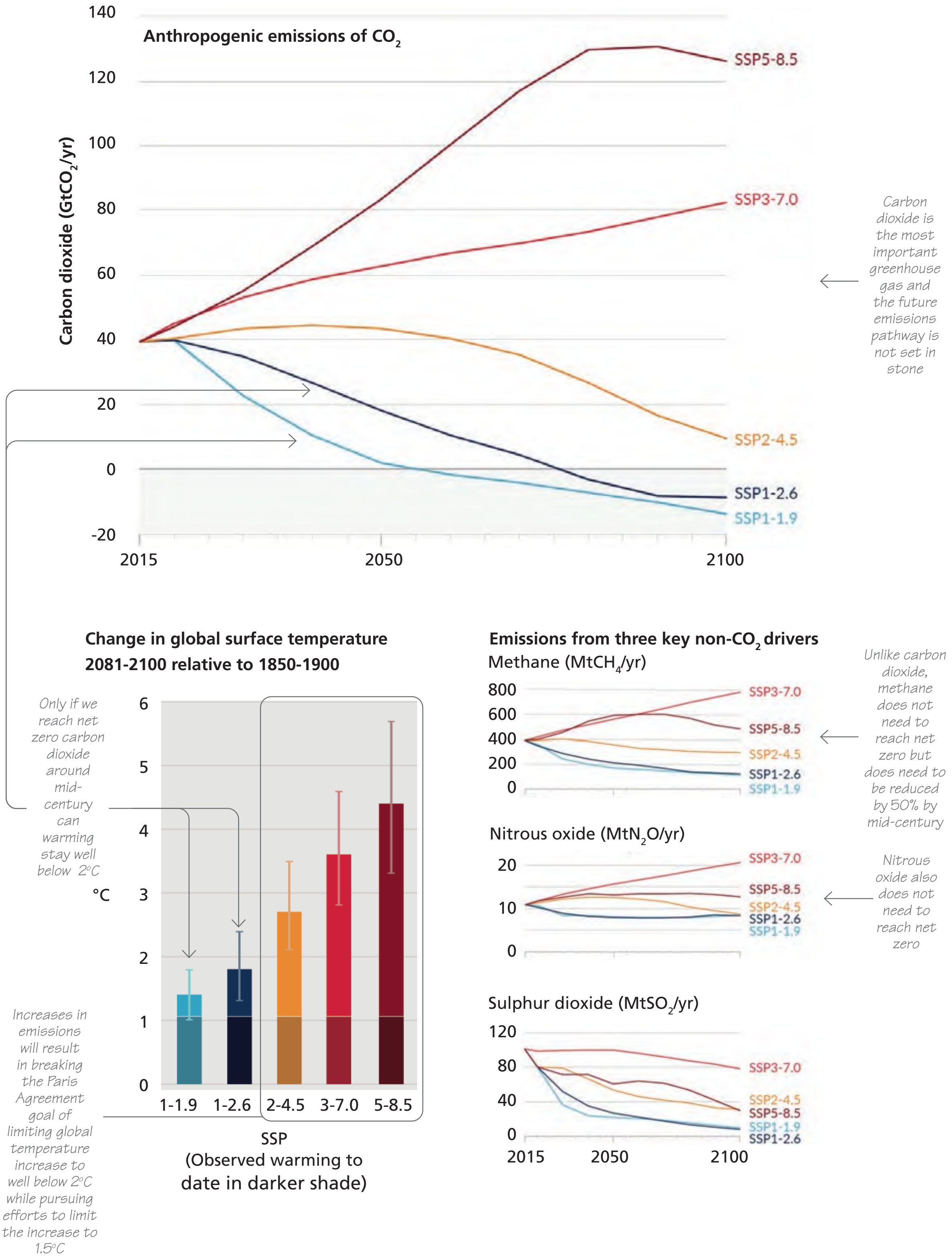
Simulations

Earth System Models (ESMs) are complex numerical simulations of the Earth's climate system, including the atmosphere, ocean, land and ice. They are used to simulate past and current climate, and project possible future climate changes. The Intergovernmental Panel on Climate Change (IPCC) working group I (WGI) sixth assessment report (AR6) features simulations from around 100 climate models produced across 49 different modelling groups (including the Irish Centre for High-End Computing and Met Éireann as partners in the EC-Earth consortium) across the globe (Figure SPM.3a). {Chapter 1}

National climate modelling research also involves simulating the future climate on a regional scale in fine detail. This involves downscaling a subset of global ESMs to provide high-resolution (4km or finer resolution) climate projections for Ireland (Figure SPM.3b). Downscaled simulations for Ireland have recently been standardised as part of the TRANSLATE project and are also available at somewhat coarser resolution, but from a greater range of models, from the European Coordinated Regional Climate Downscaling Experiment (EURO-CORDEX). {Chapters 1, 3, 4}

The future is in our hands

Assessment of future emissions and warming under five scenarios



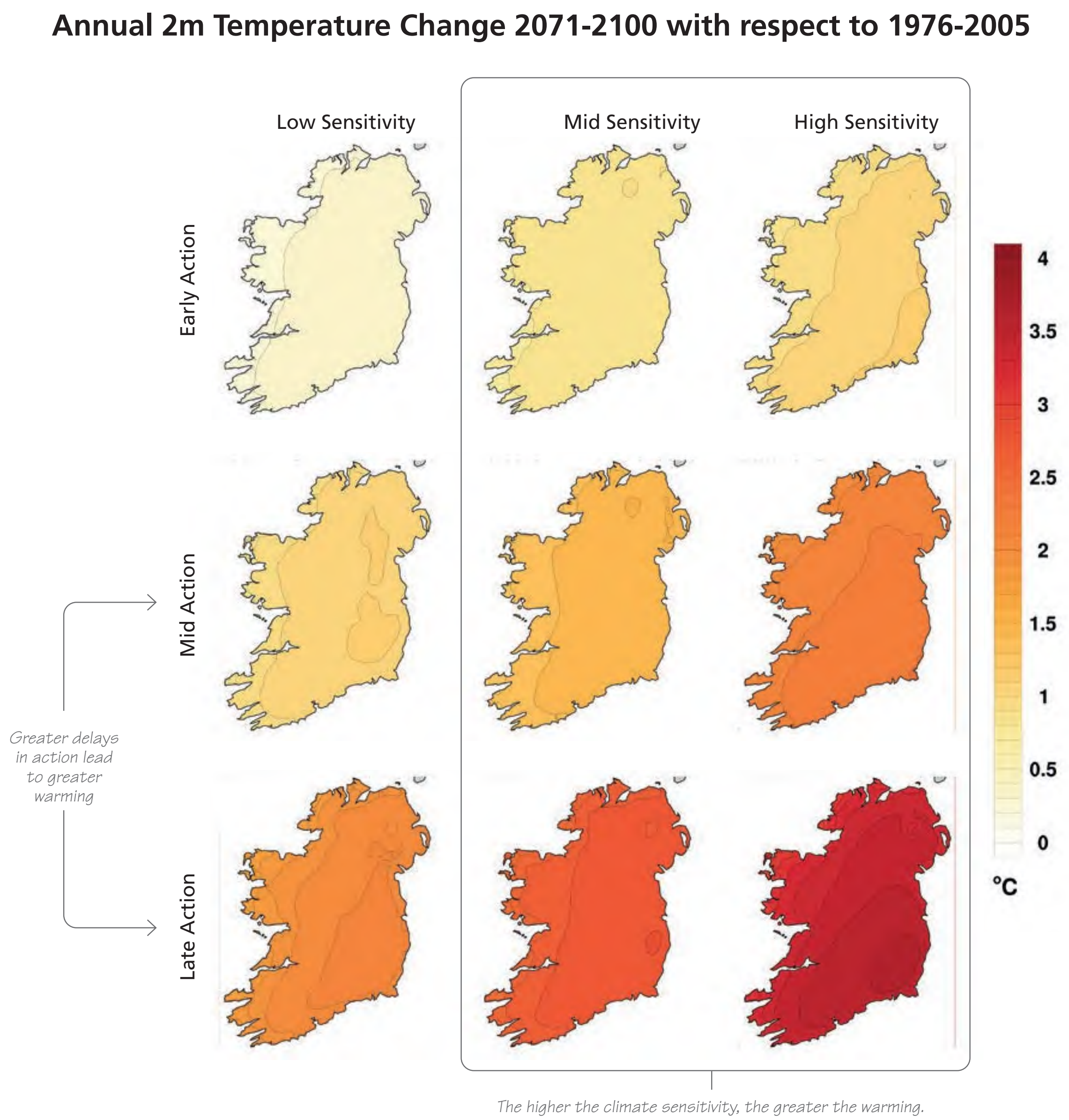


Figure SPM.3 Left panel: illustrative climate scenarios and resulting warming at the end of the century. The five scenarios are SSP1–1.9, SSP1–2.6 (classed here as Early action), SSP2–4.5 (Middle action) and SSP3–7.0 and SSP5–8.5 (Late action). Annual anthropogenic (human-caused) emissions over the 2015–2100 period. Shown are emissions trajectories for CO_2 from all sectors ($GtCO_2yr^{-1}$) (top graph) and for a subset of three key non-CO_2 drivers contributing to anthropogenic aerosols considered in the scenarios: methane, $MtCH_4yr^{-1}$ (top-right graph); nitrous oxide, MtN_2Oyr^{-1} (middle-right graph); and sulphur dioxide, $MtSO_2yr^{-1}$ (bottom-right graph), contributing to anthropogenic aerosols. The bottom-left graph shows resulting warming by scenario in global surface temperature (°C) in 2081–2100 relative to 1850–1900, with indication of the observed warming to date in darker fill. Bars and whiskers represent median values and 5-95% range, respectively. Right panel: TRANSLATE projections for Ireland for Early action (representative concentration pathway (RCP) 2.6), Middle action (RCP4.5) and Late action (RCP8.5) scenarios and for three distinct sets of driving Earth System Models with different transient climate sensitivities over Ireland (see Cross-volume Box 1). Source: IPCC (2021a; their figure SPM.4 (left panel, modified with permission) and authors (right panel). {Chapters 1, 2, 3}

C. Future global emissions will determine our future climate

We have an increasing number of climate simulations from ESMs (Box SPM.1) that can be augmented by downscaling to regional scales by regional models, and allow us to explore what the future climate may be throughout the rest of this century and beyond, both globally and over Ireland. Scientific insights also permit inferences around key policy-relevant questions such as how to stay below a given global temperature threshold.

C.1	To stabilise the global climate requires global carbon dioxide emissions to reach at least net zero. Furthermore, emissions of other greenhouse gases would need to be substantially reduced on a sustained basis. It is still possible to attain the Paris Agreement goal of keeping global temperature increases well below 2°C while making efforts to limit warming to 1.5°C. To limit warming to 1.5°C global carbon dioxide emissions need to be reduced to at least net zero by approximately mid-century and emissions of other greenhouse gases simultaneously substantially reduced. {Chapters 1, 2; Figure SPM.3}
C.2	Many components of the global climate system, such as temperature and precipitation, respond within years to decades to changes in radiative forcing. If we can reach net zero global carbon dioxide emissions around 2050, these components would globally stabilise within the lifetime of many of today's younger citizens. Some other components of the climate system, most notably sea level rise, will take thousands of years to stabilise even once greenhouse gas emissions reach net zero. {Chapters 1, 3, 4, 5, 6, 7; Figure SPM.5}
C.3	Climate change will not unfold uniformly across the globe. There are important regional differences, and these changes are projected to amplify as the level of global warming increases; some regions and populations will experience greater changes than others. For example, the Arctic warms considerably more than other regions, land areas warm more than the ocean, and the northern hemisphere warms more than the southern hemisphere. {Chapter 1}
C.4	Climate change projections under Early, Middle and Late action scenarios (Box SPM.1) show very different potential futures for Ireland beyond the middle of this century. Early and rapid global action on emissions reductions would very likely stabilise many aspects of our climate this century and would likely leave an Irish climate still broadly recognisable as that we experience today. Delayed action on emissions reductions would very likely yield a climate that is increasingly unrecognisable as the century progresses. The global emissions pathway will continue to have impacts beyond the end of the century, most notably on the trajectory of sea level rises that will continue for thousands of years. {Chapters 3, 4 ,5; Figure SPM.3}
C.5	Projections of Irish temperature changes consistently show warming, with the magnitude of this warming increasing with delays in global mitigation action. Under Early action, the temperature increase averaged across the island of Ireland relative to the recent past (1976–2005) would reach 0.91°C [0.44–1.10°C] by mid-century before falling back to 0.80°C [0.34–1.07°C] at the end of the century. Whereas under Late action, by the end of the century it is projected that the temperature increases could be 2.77°C [2.02–3.49°C]. Warming also generally increases with the climate sensitivity of the ESMs used for a given mitigation pathway (see Box SPM.1). Heat extremes will become more frequent and more severe and cold extremes will become less frequent and less severe with further warming. {Chapter 3}
C.6	In Ireland, intense precipitation extremes are projected to become more frequent and extreme with further warming in most locations. Projected changes in precipitation accumulations are more uncertain than those for temperature. While winters tend to get wetter and summers tend to get drier, this signal is not consistently found across all global ESMs. There is also substantial sensitivity to the choice of ESM used to drive the national simulations (Box SPM.1). Changes averaged across the island of Ireland show a slight increase of < 10% in annual mean accumulated precipitation amounts. {Chapter 4}
C.7	Global mean sea level increases will occur under all scenarios and continue for thousands of years after the global temperature is stabilised. By 2100 projected additional rises range from 0.32–0.6m under Early action to 0.63–1.01m under Late action scenarios, with high uncertainty for the latter case whereby 2m rise could occur owing to highly uncertain ice sheet processes. Over the next 2,000 years, global mean sea level will rise by about 2 to 3m if warming is limited to 1.5°C, 2 to 6m if limited to 2°C and 19 to 22m with 5°C of warming. {Chapters 2, 8}

C.8 Global sea level increases will be modified locally around the island of Ireland by ongoing isostatic rebound – the north-east of the island is slowly rising and the south-west slowly sinking (<0.2mm per year in most regions); multi-decadal ocean basin variability (order of several centimetres in a decade); and the relative contributions to sea level change arising from the Greenland and Antarctic Ice Sheets over time. Larger relative contributions from Greenland would result in smaller increases for Ireland and vice versa due to the gravitational effects of the two ice sheets. {Chapter 5}

C.9 Storm surges and extreme waves pose an ever-increasing threat to Ireland as sea levels continue to rise, including for many coastal cities such as Cork, Dublin, Galway and Limerick, and to critical infrastructure. Particularly at risk are soft sediment shorelines. Projections of changes in storminess are highly uncertain and translate into large uncertainties in future frequency and intensity of extreme waves. {Chapter 5}

C.10 Compound events are combinations of multiple climate impact drivers that occur at the same time, in the same area or both. The likelihood of both concurrent heatwave and drought conditions and storm surges with heavy precipitation have been observed to increase to date in Europe and are projected to further increase with additional warming. {Chapter 6}

C.11 Those recent extreme events that have been impacted by human-induced climate change such as heatwaves and extreme rainfall (see Sections B.3 and B.4) are a foretaste of what will likely occur in future with increased frequency and intensity under further warming. The most rare extreme events that impact entire communities and regions are the events that will see the largest relative increases in frequency and intensity. {Chapters 1, 3, 4, 6; Figure SPM.5}

C.12 Ireland will continue to experience seasonal to multi-decadal variability arising from natural internal variations in the climate system. These will serve to modulate aspects such as temperature, precipitation and storminess on seasonal to multi-decadal scales and, in doing so, periodically may reduce or enhance long-term global climate trends arising from human activities. {Chapters 1, 3, 4, 5}

C.13 Current atmospheric carbon dioxide levels are higher than at any time since the Middle Miocene (14 to 16 million years ago), according to the latest consensus atmospheric carbon dioxide record from a global consortium of scientists who study past atmospheric composition using proxies. Paleo-temperature estimates for the North Atlantic Ocean off Ireland indicate sea surface temperatures 10 to 13°C warmer than present-day during the Middle Miocene. Early action would keep global mean surface temperature rise within the bounds of our and our ancestors' (genus *Homo* dates back 3 million years) past experience. {Cross-volume Box 1; Cross-chapter Box 2}

Box SPM.2 Human influences on climate

Human influence on the climate system arises from multiple different forcing agents, such as greenhouse gases and aerosols, which have distinct lifetimes and impacts[2]. Not all of their impacts are therefore equal. Effective Radiative Forcing (ERF) is used to compare their impacts on climate (Figure SPM.4). This describes the net radiative impact of a given agent on the atmosphere. Positive ERF values cause warming of the climate system, and negative ERF values cause cooling of the climate system. Changes in ERF from 1750 to 2022 are dominated by warming by carbon dioxide, methane and nitrous oxide, partly masked by cooling by aerosols, with relatively minor contributions from remaining human sources. {Chapter 2}

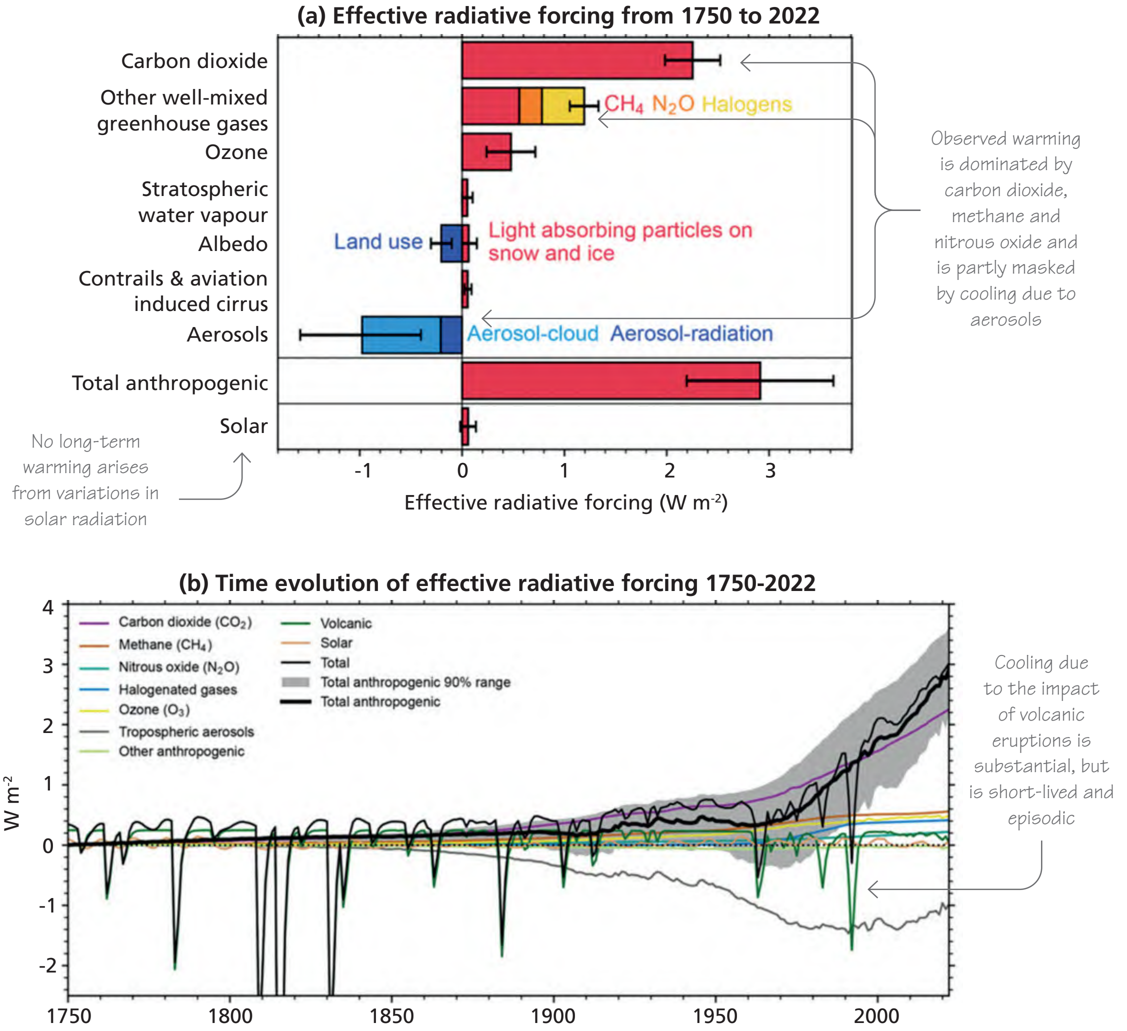


Figure SPM.4 Effective Radiative Forcing (ERF) from 1750 to 2022. (a) 1750–2022 change in ERF, showing best estimates (bars) and 5–95% uncertainty ranges (lines) from major anthropogenic components of ERF, total anthropogenic ERF and solar forcing. (b) Time evolution of ERF from 1750 to 2022. Best estimates from major anthropogenic categories are shown, along with solar and volcanic forcing (thin coloured lines), total (thin black line) and anthropogenic total (thick black line). The 5–95% uncertainty in the total anthropogenic forcing is shown by grey shading. Note that solar forcing in 2022 is a single-year estimate. Source: Forster et al. (2023; their figure 2). Reproduction licensed under the Creative Commons Attribution CC BY 4.0 licence (https://creativecommons.org/licenses/by/4.0/).

[2] Human influences also arise from perturbations to land use and land cover.

These principal human forcing agents arise from a mix of human activities. They differ substantively in terms of their lifetime, how they are removed, their radiative efficiency and, therefore, their impact upon the climate system (Table SPM.1). It is important to recognise this complexity when making mitigation policy decisions, as assessed further in Volume 2. {Chapter 2}

The principle human forcing agents

Forcing agent	Approximate lifetime	Principal human sources	Principal removal mechanisms	Radiative efficiency (W $m^{-2}ppb^{-1}$)	GWP_{100} from IPCC WGI AR6
Carbon dioxide	Centuries to millennia	Fossil fuel combustion, land use, cement production	Ocean and terrestrial uptake (fast), ocean mixing (centuries), geological sequestration (slow)	$1.33 \pm 0.16 \times 10^{-5}$	1
Methane	Around a decade	Fossil fuels, agriculture, landfill	Atmospheric oxidation	$5.7 \pm 1.4 \times 10^{-4}$	30 ± 11 (fossil sources); 27 ± 11 (non-fossil sources)
Nitrous oxide	Around a century	Agriculture, land use, fossil fuels	Stratospheric oxidation	$2.8 \pm 1.1 \times 10^{-3}$	273 ± 130
Aerosols	Days to weeks	Fossil fuel combustion, land use and biomass burning	Wet and dry deposition		

Table SPM.1 Summary of the principal features of the four most important direct human forcing agents as assessed by ERF and accounting for methane's impacts upon tropospheric ozone. Shown are approximate lifetime, principal human sources, principal removal mechanisms and, for the three greenhouse gases, their radiative efficiency and their GWP_{100} value (see C.17). {Chapter 2}

C.14 There exists an almost linear relationship between cumulative carbon dioxide emissions and global surface temperature increases. Based upon this, a global remaining carbon budget can be inferred, conditional upon assumptions of future emissions of a range of additional greenhouse gases, to keep future warming below any given temperature increment threshold. In IPCC AR6 it is assessed that for a two in three chance of limiting warming to 1.5°C globally we can emit only 400 additional gigatonnes (Gt) of carbon dioxide from 2020. This estimate assumes substantial reductions in emissions of remaining greenhouse gases, including a 50% reduction in global methane emissions and a 25% reduction in global nitrous oxide emissions by 2050. If such cuts in non-carbon dioxide greenhouse gases are not fully achieved, the remaining carbon budget would shrink commensurately. In IPCC AR6 this non-carbon dioxide effect is assessed to have an uncertainty of 220Gt carbon equivalent (66% range). Historical human emissions are almost 2,600Gt of carbon dioxide, and, at current global emission rates of c.40Gt of carbon dioxide a year, only a few years remain before exceeding the remaining budget to limit warming to 1.5°C. {Chapter 2}

C.15 Historically, about half of the carbon dioxide that human activities have emitted has been taken up by natural carbon sinks on land and in the ocean. These natural sinks have slowed the build-up of carbon dioxide in the atmosphere and resulting global warming. However, these sinks are already beginning to respond to climate change in a way that weakens their capacity to take up carbon dioxide, and this will likely continue in the future unless global emissions are rapidly reduced. {Chapter 2}

C.16 Policies aimed at addressing climate change may have benefits or trade-offs for air quality. The potential importance of reducing emissions of short-lived climate forcers, such as methane, aerosols and their precursors, is recognised to not only mitigate climate change but also to improve air quality and therefore bring near-term co-benefits in terms of human health, agricultural yields and ecosystem functioning. Measures which negatively impact on air quality such as burning of wood for home heating and gas stoves for cooking as possible mitigation measures should be avoided. {Cross-volume Box 2}

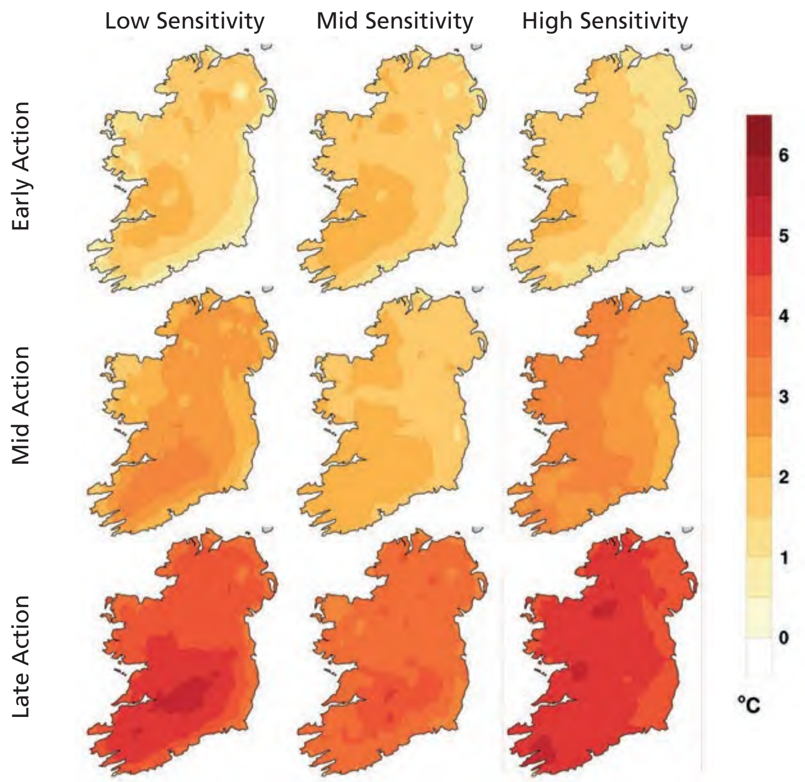
C.17 Common metrics are used to aggregate and compare the effects of different greenhouse gas emissions and policies. Because gases vary substantially in terms of their warming impacts and lifetime in the atmosphere, different metrics provide different perspectives. In international, European and national accounting, GWP_{100}[3], which calculates emissions impacts of each greenhouse gas integrated over a 100-year timescale compared to those of atmospheric carbon dioxide, is used. GWP values are periodically reassessed as the atmospheric composition evolves and new evidence arises. These are compiled and assessed by the IPCC in each assessment cycle. Reaching net zero under GWP_{100} would result in a slow cooling of the climate system. Newer, step-pulse metrics such as GWP* better model the temperature outcomes for a broad range of timescales. Emerging approaches that separately bundle and treat short-lived (less than a decade or so) and long-lived (centennial timescale plus) gases may lead to better policymaking. The IPCC does not recommend a specific emissions metric. Ultimately, the metrics used by policymakers will depend upon the question being posed, and it is therefore not possible to define a preferred metric. {Chapter 2; Volume 2}

[3] In international accounting GWP_{100} values published in IPCC AR5 are currently used.

Future global emissions will determine the future climate

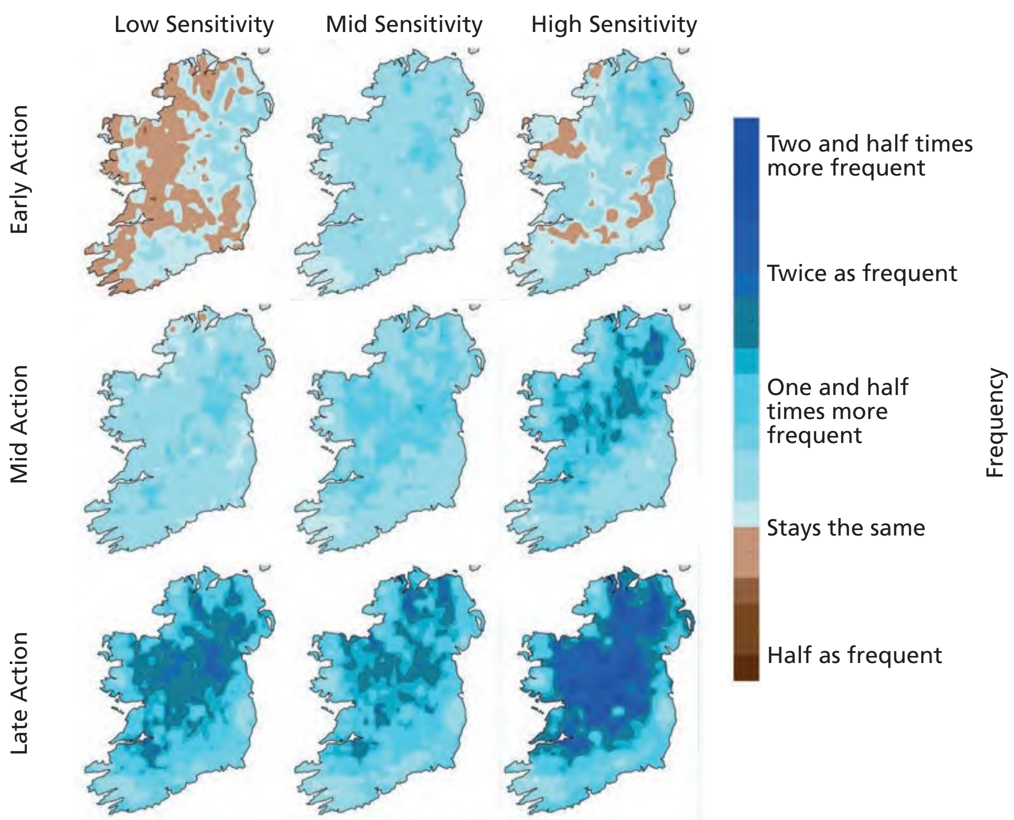
(A) Temperature extremes

Temperature change in warmest day of the year 2071-2100 with respect to 1976-2005



(B) Precipitation extremes

Relative change in annual days with precipitation in excess of 20mm in 2071-2100 with respect to 1976-2005



(C) Change in return times for temperature and precipitation extremes

With early and sustained action, changes in temperature and precipitation can stabilise within the lifetime of today's younger citizens, whereas delayed action will see things continue to get worse

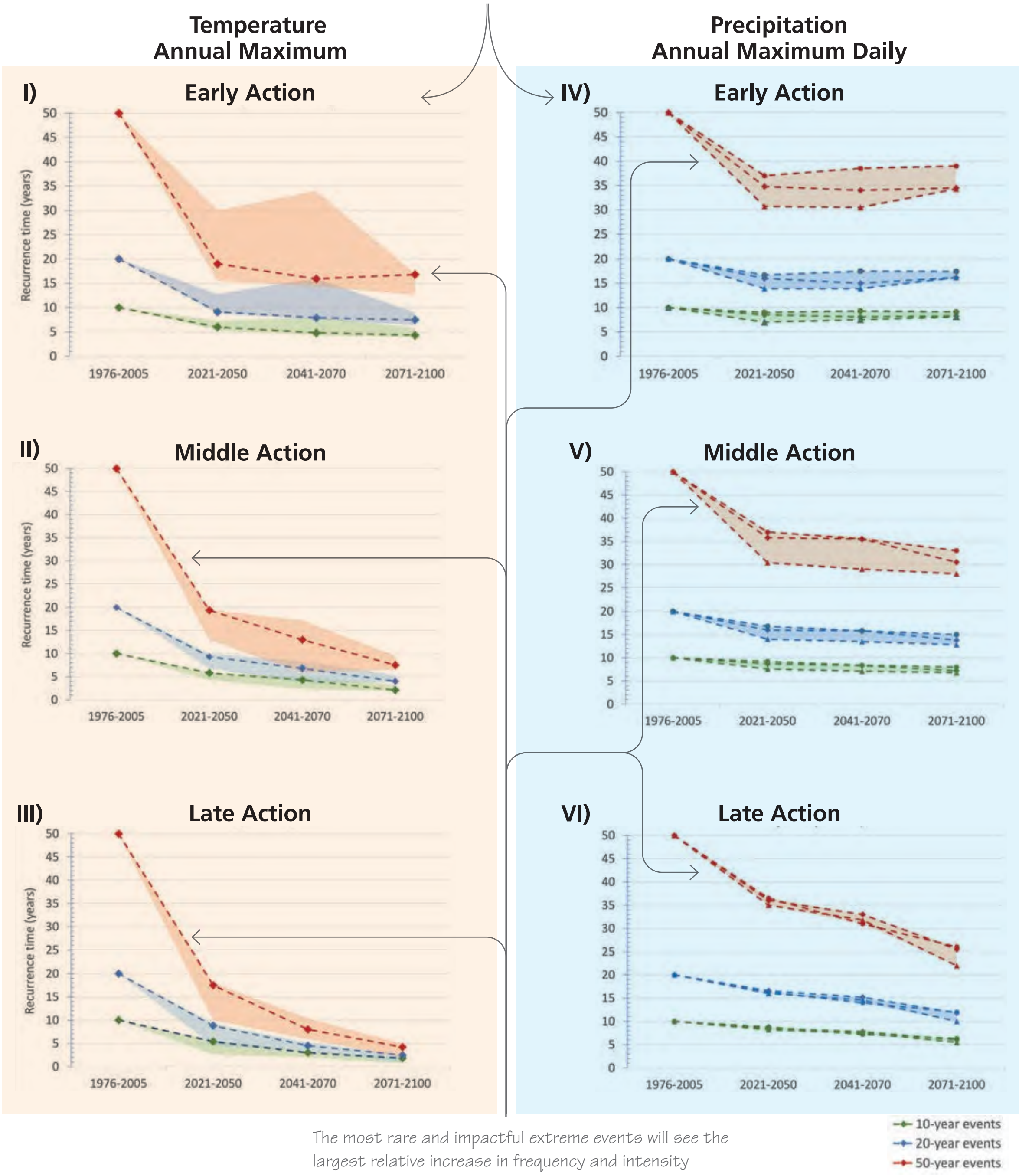


Figure SPM.5 Future global emissions will determine important aspects of the future climate. (A) Projected changes in the annual maximum of daily maximum temperature (TXx), using 30-year means of TXx. (B) Projected changes to the R20mm index, where R20mm is the number of days per year with precipitation >20mm. (C) Projected changes in the recurrence times (or return periods) of Ireland-averaged TXx values (left) and annual maximum daily precipitation (Rx1day) (right) that had recurrence times of 10, 20 and 50 years for different future emissions scenarios (rows). Source: Authors. [Chapters 3, 4]

D. High-impact outcomes, although unlikely, cannot be ruled out

Climate surprises are future possible outcomes, events, circumstances or consequences for Ireland that could stem from global warming which, although unlikely, cannot be ruled out. They include high warming storylines, various possible tipping points in the climate system and possible natural disasters with global climate system implications. Were they to occur these would progress across a range of timescales, with some taking place over years to decades and others over centuries to millennia. Many relate to highly uncertain and/or poorly understood processes.

D.1 In risk assessments it is important that low-likelihood high warming outcomes are taken into account when considering future climate change impacts in Ireland, as there is a high level of risk associated with them[4]. For Ireland a low-likelihood high warming outcome (which is predicted under high climate sensitivity[4]) likely leads to larger warming and commensurately larger changes in precipitation and associated extremes than the equivalent best estimate for any given scenario. {Chapters 2, 8}

D.2 Paleoclimate archives demonstrate periods of much higher land and Atlantic ocean temperatures around Ireland's coastal waters in the geological (e.g. Miocene) and historical past. Archives over the last 10,000 years also show reductions in precipitation of sufficient magnitude to dry peatlands, allowing oak and pine forests to establish on them. {Cross-chapter Box 2; Chapter 8}

D.3 Climate system tipping points represent thresholds beyond which components of the Earth system permanently switch to new states. Tipping points would have considerable impacts, including sea level rise from collapsing ice sheets, dieback of the Amazon rainforest and carbon release from thawing permafrost. Several such tipping points would have implications for Ireland, either through further shifting the global climate or altering the regional climate in the North Atlantic and north-western Europe. {Chapter 8}

D.4 For Ireland, the Atlantic Meridional Overturning Circulation (AMOC) is the most immediately important potential tipping point, given the importance of the North Atlantic in determining our climate[5] and agricultural productivity. The AMOC will almost certainly weaken over the 21st century, and a full collapse cannot be ruled out. If there were to be a collapse in the AMOC, as has occurred repeatedly in the past during rapid climate transitions of past glacial phases, winters would become considerably colder and summers warmer, and there would likely be an increase in storminess and potential implications for sea level. These would have very profound implications for the Irish climate and society. {Cross-chapter Box 2; Chapter 8}

D.5 Future global sea level rise projections over the coming centuries have large uncertainties. Particular concern relates to ice sheets where much of the ice sheet is grounded below present-day sea level, which could reach tipping points, leading to their inevitable collapse over a multi-centennial period. The largest such ice sheet is the West Antarctic Ice Sheet, which alone could contribute several metres of sea level change. Historical global emissions could potentially have already committed to its long-term collapse. Proxies cannot determine the pace of past ice sheet collapse. {Chapter 8}

D.6 Currently, thawing permafrost is losing carbon to the atmosphere. Based on high agreement across model projections, fundamental process understanding and paleoclimate evidence, as the global climate warms permafrost extent and volume will shrink, releasing further greenhouse gases into the atmosphere. Complete thawing of permafrost cannot be ruled out, and this would emit more carbon than humans have emitted to date into the atmosphere, leading to substantial additional warming. {Chapter 8}

[4] If the true equilibrium climate sensitivity lies in the highest end of the plausible range, and beyond the IPCC estimated range, then there would be very substantial warming and impacts across the climate system, even for small additional global greenhouse gas emissions. Because the latest generation of ESMs have a broad range of sensitivities it is possible to draw out individual simulations from models with very high sensitivity to directly inform estimates of such low-likelihood high warming outcomes.

[5] The AMOC is the overturning circulation in the North Atlantic. The surface component advects warm water from the tropics to Ireland via the Gulf Stream and North Atlantic Drift, and this in large part determines our climate.

D.7 Unpredictable and rare natural events not related to human influence on climate may lead to low-likelihood, high-impact outcomes. For example, a sequence of large explosive volcanic eruptions within decades has occurred in the past, causing substantial global and regional climate perturbations over several decades. A future with such a sequence of eruptions over the coming decades would increase the stress on ecosystems and society. Short-term volcanic-induced global cooling will not mitigate long-term human-induced climate changes. Even the most extreme volcanic activity scenario in the 21st century causes little reduction in global surface temperatures at the end of the century. {Chapter 8}

E. Key recommendations for research

In performing this assessment a broad range of priority areas for future research to address gaps have been identified. Specific recommendations are given in the underlying report. Here, thematic groupings are highlighted to illustrate the broad priorities identified to improve the basis for future assessment activities and to enhance information provided for policymaking.

E.1 Sustaining and enhancing Ireland's climate observational capabilities

There is a need to sustain and enhance national observational capabilities of our changing climate system providing a strong evidence base for decision making. This needs to be consistent with a sustained and strong national contribution to the Global Climate Observing System (GCOS), including of our waters within our exclusive economic zone and the broader North Atlantic. Substantial progress has been made, not least through the national GCOS committee. Much remains to be done, including the development of a strategic approach that is aligned with national needs and requirements. This should include enhanced participation in relevant European research infrastructures, including in the European Strategy Forum on Research Infrastructures (ESFRI) process, and related regional and global networks. The work of the national GCOS committee needs to be strengthened and sustained with adequate funding support for relevant agencies and institutions. {Annex 1}

E.2 Enhanced provision and utilisation of past and current climate observations

Enhanced capacity and resources are required to enable better provision and utilisation of past and current observations to better understand Ireland's changing climate and its drivers. As scientists learn more about observations and new techniques and insights emerge, it is critical to periodically reassess understanding of historical and ongoing observations, reanalyse them and produce new and improved products and knowledge. This includes activities such as data rescue of historical holdings of various types not yet available in digitised form and better exploitation of space-based observations. {Annex 1}

E.3 Sustaining and enhancing Ireland's climate modelling capability

There is a need for a sustained and enhanced modelling capability to provide a range of nationally relevant downscaled results, including contributions to the Coupled Model Intercomparison Project (CMIP) and EURO-CORDEX. This includes quantification and provision of uncertainty estimates in a usable manner via portals such as climateireland.ie, which should be maintained to promote and enable exploitation by stakeholders and users. {Annex 1}

E.4 Scaling up support for strategic climate research activities

Substantial scientific uncertainties remain across the ocean, atmosphere and terrestrial domains that still need to be strategically and rigorously addressed. Supports through climate research programmes are needed that transcend short-term projects. This should enable capacity building through the training and retention of the excellent researchers necessary to address these cross- and trans-disciplinary challenges. Particularly important current uncertainties identified in the present volume include, but are not limited to: diurnal temperature changes, precipitation changes, changes in storminess and sea level changes. {Annex 1}

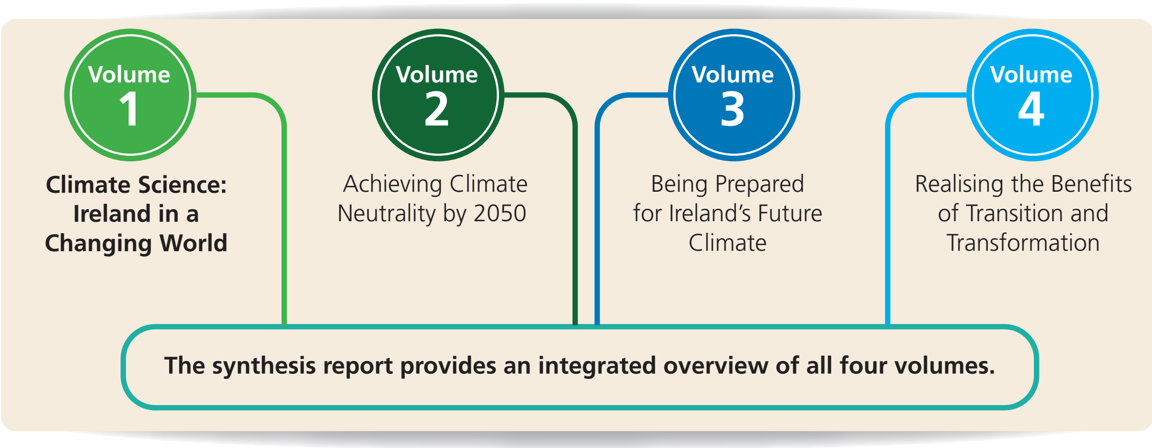
E.5 Increasing Ireland's participation in climate-related European and international scientific activities

There is a need to increase participation in relevant European and international scientific activities to have a stronger contribution to and influence in the development of these activities. These provide expanded access to expertise, opportunities for collaboration, including on internationally funded projects, and learning and sharing of knowledge and best practices, which has important benefits in terms of provision of advice to policymakers. This includes participation in relevant European-level programmes such as the European Space Agency, Horizon Europe and Joint Programming Initiatives, and various research infrastructures. Internationally, participation should be sought in IPCC and Intergovernmental Science–Policy Platform on Biodiversity and Ecosystem Services (IPBES) reports and in relevant international activities such as those undertaken by the World Meteorological Organization and through its (co-sponsored) programmes, including the World Climate Research Programme and GCOS. {Annex 1}

Table of contents

Preamble

The UN Framework Convention on Climate Change (UNFCCC, 1992) has the objective of preventing 'dangerous anthropogenic interference with the climate system', and the Paris Agreement (2015) established the long-term goals of 'holding the increase in global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels' and of achieving 'a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century'. Ireland's Climate Change Assessment (ICCA) delivers a comprehensive, Ireland-focused, state of scientific knowledge report on our understanding of climate change, its impacts on Ireland, the options to respond to the challenges it poses, and the opportunities from transitions and transformations to a climate-neutral, climate-resilient and sustainable economy and society. This serves to complement and localise the global assessments undertaken by the Intergovernmental Panel on Climate Change (IPCC) reports (see www.ipcc.ch). The findings presented build upon these global assessments and add important local and national context.



The present volume, Volume 1: Climate Science: Ireland in a Changing World, builds on the information contained in the IPCC WGI AR6 report and the three IPCC AR6 cycle special reports[6]. In addition, it uses a broad range of peer-reviewed literature and national datasets. It assesses observed and projected changes in climate for Ireland and uses information from a broad range of trusted national resources, such as Climate Ireland, Met Éireann, the Marine Institute and the Environmental Protection Agency. It also utilises information from a range of trusted international sources, such as the World Meteorological Organization, the World Climate Research Programme, UNFCCC COP (Conference of the Parties) Earth Information Days and the Copernicus Climate Change Service. It highlights fundamental research carried out in Ireland that contributes to the analysis of both global and national changes.

Readers of this volume should note that it is the first of four volumes and covers solely the underlying scientific basis and understanding of our changing climate. Similarly, the remaining volumes cover their specific area of charge. Where germane, cross-references have been added between volumes to aid the reader. All volumes highlight gaps where additional research would be beneficial to improve our ability to monitor, understand and predict important aspects of the problem relevant to their charge.

The volume is structured as follows. Part A (Chapters 1 and 2) focuses upon evidence for global climate changes and their causes, as well as key global-scale projections. It then introduces key underpinning concepts necessary to understand our changing climate and to support subsequent volumes. Part B (Chapters 3 to 7) goes on to localise this information to the national context. Consideration is given to key changes in mean climate and extremes, both historically and in projections. It has dedicated chapters on changes in our marine environment and in biodiversity. Finally, Part C (Chapter 8) covers low-likelihood but high-impact climate outcomes that cannot be ruled out and are of relevance to risk-based decision making. This includes low-likelihood high warming storylines, tipping points and the possible implications of intensive volcanism for the 21st century climate.

[6] Note that for reasons of readability (e.g. Adler and Hadorn, 2014) and consistency (e.g. Kause et al., 2022), and because, using the IPCC approach to uncertainty (available from https://www.ipcc.ch/site/assets/uploads/2017/08/AR5_Uncertainty_Guidance_Note.pdf), most national findings that are predicated upon small numbers of datasets/published lines of evidence would necessarily be assessed, erroneously, as low confidence, we do not use IPCC confidence/likelihood constructs throughout this volume. Given the absence of an alternative agreed approach, the assessment 'confidence levels' can be implied by context.

PART A

Our Changing Global Climate

Chapter 1 explores the changes that have been observed in the global climate system, their causes and projected future changes. It covers changes in climate system drivers, natural climate variability, historical observations (including global paleoclimate), attribution studies and future climate projections. Regional information for Ireland is covered in Part B of this report. The information provided in the Intergovernmental Panel on Climate Change (IPCC) working group (WG) I Sixth Assessment Report (AR6) is used as the basis for the assessment. Ireland has historically been under-represented in the IPCC authorship process.

Chapter 2 looks at understanding the key cycles and the biogeochemical cycles of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), as well as Short Lived Climate Forcers (SLCFs). It summarises some key climate system metrics such as Equilibrium Climate Sensitivity (ECS), Global Warming Potential (GWP) metrics and the Remaining Carbon Budget (RCB). Understanding of key processes in the ocean are also covered.

1

The Changes in the Global Climate System

Key messages

Globally, widespread and rapid changes in the atmosphere, ocean, cryosphere and biosphere have occurred. The scale of recent changes across the climate system as a whole – and the present state of many aspects of the climate system – are unprecedented over many centuries to many thousands of years.

There has been a rapid rise in greenhouse gas (GHG) concentrations, measured at numerous sites around the world, including Mace Head, County Galway, since the Industrial Revolution, without precedent in millions of years. Concentrations of methane (CH_4) and nitrous oxide (N_2O) are higher now than in over 800,000 years, and for carbon dioxide (CO_2), for which longer-term reconstructions are possible, concentrations are higher than for millions of years.

Changes in CO_2, CH_4 and N_2O concentrations since 1750 exceed those between successive glacial and interglacial cycles of the past 800,000 years for CO_2 and CH_4. For N_2O, the changes in concentration are of a comparable magnitude to these successive glacial and interglacial cycles. These past changes in concentrations of all gases were much slower, occurring over thousands of years.

Global surface temperatures have risen by 1.15°C [1.00–1.25°C] between 1850–1900 and the most recent decade, 2013–2022. This most recent decade was likely warmer than any sustained period in at least the past 100,000 years.

Globally averaged precipitation over land has likely increased since 1950, with a faster rate of increase since the 1980s. The frequency and intensity of extreme precipitation events has increased almost everywhere, particularly so in already wetter regions in the northern hemisphere, and a greater proportion of total precipitation is falling in extreme precipitation events across most of the globe.

Global sea level increased by approximately 0.20m between 1901 and 2018, and the rate of global sea level rise is accelerating. The rat e of warming of the ocean was likely faster in the past century than for any century since the last deglaciation event 11,000 years ago. Global ocean pH has decreased (ocean acidification) in response to increases in atmospheric CO_2 concentrations.

The rate of global ice sheet loss has increased by a factor of four over the last 30 years and is unprecedented in hundreds of years.

Globally, over the last century, there have been poleward and upslope movements of many terrestrial species in response to climate changes. There have also been changes in phenology (the timing of events such as birds migrating and plants flowering) in all mid-latitude regions. Changes in the marine biosphere are consistent with large-scale warming and changes in ocean geochemistry. The ranges of many marine organisms are shifting towards the poles and towards greater depths, but a minority of organisms are shifting in the opposite directions.

It is unequivocal that human activity is responsible for recent climate warming. This warming is mainly due to increased GHG concentrations, partly masked by cooling due to increased aerosol concentrations. The best estimate of human-caused global surface temperature increases from 1850–1900 to 2013–2022 is 1.14°C, matching almost exactly the best estimate of the observed change of 1.15°C over the same period.

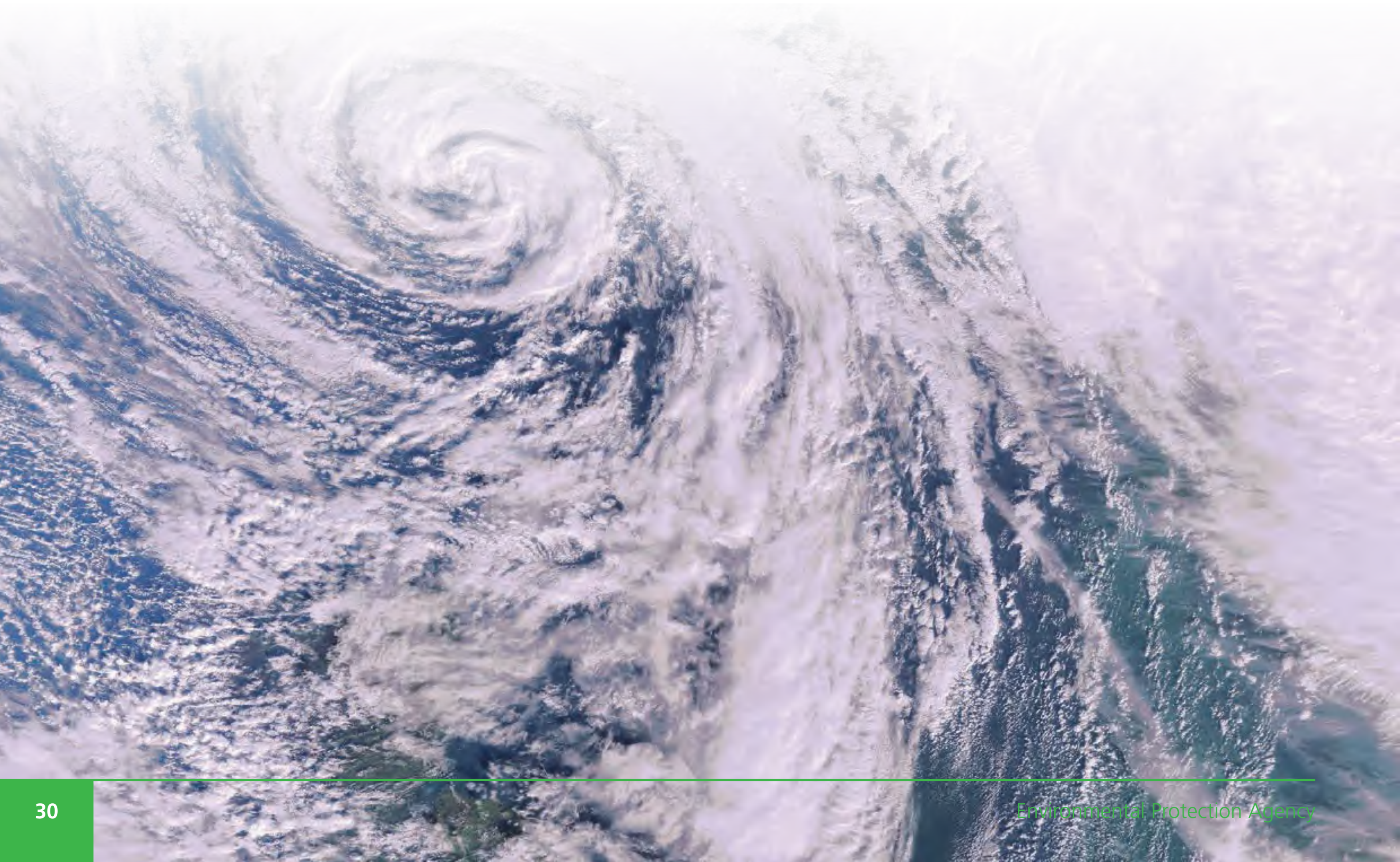
Attribution at the global scale shows consistent human signals in observed changes across the atmosphere (surface and upper-air temperatures, humidity, precipitation, circulation), ocean (sea level, ocean heat content, salinity, acidification, deoxygenation) and cryosphere (glaciers, sea ice, ice sheets, seasonal snow cover). The observed changes across the climate system since the mid-20th century cannot be explained without invoking human influences.

Human-induced climate change is already modifying extreme weather events across the globe. Increases in both the frequency and intensity of heatwaves and extreme precipitation events have been consistently linked to human activities. Similarly, cold events have been made less likely and severe. In drought-prone regions, droughts have tended to be made more severe and frequent. There is limited evidence to date for human influences on many types of extreme storms, including mid-latitude storms.

Many components of the climate system, such as temperature and precipitation, respond within years to decades to changes in radiative forcing. If we can reach net zero global CO_2 emissions around 2050, these components would stabilise globally within the lifetime of many of today's younger citizens. Some other components of the climate system, most notably sea level rise, will take thousands of years to stabilise, even once GHG emissions reach net zero.

Simulations of the future under Early, Middle or Late action scenarios highlight that collective global actions today will decide the climate of the balance of this century and beyond. With early and rapid action on emission reductions, the global temperature rise can be maintained well below 2°C throughout this century, with really concerted early action leading to global surface temperatures returning to below a 1.5°C increase after a temporary and limited overshoot. Late action on emissions reductions, on the other hand, could lead to global temperature increases exceeding 3°C by the century's end.

Climate change will not unfold uniformly across the globe. There are important regional differences, and these changes are projected to amplify as the level of global warming increases; some regions and populations will experience greater changes than others. For example, the Arctic warms considerably more than other regions, land areas warm more than the ocean and the northern hemisphere warms more than the southern hemisphere.



1.1 The global climate system

Earth is often referred to as the 'Goldilocks' planet because its conditions are not too hot and not too cold, but just right to allow life to flourish. These climate conditions are the result of the natural greenhouse effect, which keeps the planet warmer than would otherwise be the case. Human emissions of greenhouse gases (GHGs) have altered this balance in important ways, as this chapter will summarise. The global climate system consists of five major components: the atmosphere (the air), the ocean, the cryosphere (snow and ice), the land surface and the biosphere (living things) – and the interactions between them. The interactions of these components determine not only the weather we experience but also the climate of our planet. Beyond a week or two, individual weather systems are unpredictable. Climate, on the other hand refers to the average weather over a certain time span, usually 20–30 years or longer. As the saying goes: climate is what you expect, weather is what you get. Climate varies from place to place, depending on latitude and other factors, such as elevation and distance to the sea. Climate varies also in time, from season to season, from year to year, or on much longer timescales, such as between glacials (when great ice sheets have covered parts of Eurasia and North America) and interglacials (such as today). Significant variations in the average state of the climate persisting for decades or longer are referred to as climate change.

1.1.2 Scientific pioneers

Scientists have understood the basic workings of Earth's climate for over a hundred years. In 1827, Fourier showed that the Earth was warmer than it should be based on its distance from the sun (Fourier, 1827). In 1856, Eunice Foote, an American scientist and inventor, experimentally showed that sunlight heated CO_2 and water vapour more than air and suggested that changes in gas concentrations might explain evidence of past warm periods (Foote, 1856). In 1859, John Tyndall, a prominent 19th century Irish physicist born in Leighlinbridge, County Carlow, discovered that water vapour, ozone, CO_2 and certain hydrocarbons absorbed longwave (infrared) radiation, the principal mechanism of the greenhouse effect (Tyndall, 1861). Svante Arrhenius (1897) calculated that a doubling of atmospheric CO_2 concentrations would produce a 5–6°C global warming; however, despite important new insights in the interim (Callendar, 1941, 1961), it was only with the publication of the Charney report in 1979 that the implications of these insights became broadly recognised (NAS, 1979).

Roger Revelle and Dave Keeling established CO_2 monitoring stations in Antarctica and Hawaii during the 1957–1958 International Geophysical Year (Keeling, 1960). Today, GHG concentrations are being monitored at several stations around the world, from Mauna Loa in Hawaii to Mace Head on the west coast of Ireland. Long-term measurements of these GHGs and other pollutants allow us to observe how humans have altered the composition of the entire global atmosphere.

1.2 Climate system drivers

The Earth's energy balance is the balance between energy arriving from the sun and energy leaving the Earth (Figure 1.1; Forster et al., 2021). Our planet receives energy from the sun in the form of shortwave radiation, some of which is reflected back to space, particularly so by clouds and by snow and ice, which are highly reflective surfaces. The rest is absorbed by the ocean, land, ice and atmosphere. The planet then emits energy back out to space in the form of longwave radiation. In a world that was not warming or cooling, these energy flows would balance, and global temperatures would remain roughly constant on multi-decadal timescales, as was the case for much of the past several thousand years during which humanity developed from hunter-gatherers to complex modern societies (Gulev et al., 2021). Factors that affect this balance are called climate drivers.

Some changes in climate drivers are natural, while others are caused by humans. They are quantified by the amount of warming or cooling they can produce, which is called (effective) radiative forcing ((E)RF) (section 2.3.1). On centennial and shorter timescales major natural drivers arise from 1) the solar cycle, and 2) volcanic activity (Figure 1.2):

- The strength of solar radiation received at the Earth's surface fluctuates by a small amount over a solar cycle, and these fluctuations can explain global surface temperature variations of up to approximately 0.1°C between the strongest and weakest parts of the cycle. Solar output can also vary over multi-decadal to multi-millennial timescales. Over the last 2,500 years solar radiation has varied relatively little based upon proxy information, with direct observations highlighting an increase in the early 20th century followed by little change (Figure 1.2; Gulev et al., 2021).
- Explosive volcanic events can inject aerosols high enough into the atmosphere that they remain some ten kilometres or more up in the atmosphere for several years. These aerosols act to cool the planet by scattering incoming solar radiation. Reconstructions from ice core samples (and volcanic ash layers in Irish peatland sediments) show that there have been

periods of both quiescent and prolific volcanic activity over the past several thousand years, with the period since 1900 being amongst the quietest of such periods (Figure 1.2; Gulev et al., 2021; see section 8.4 for possible implications of intense volcanic activity this century).

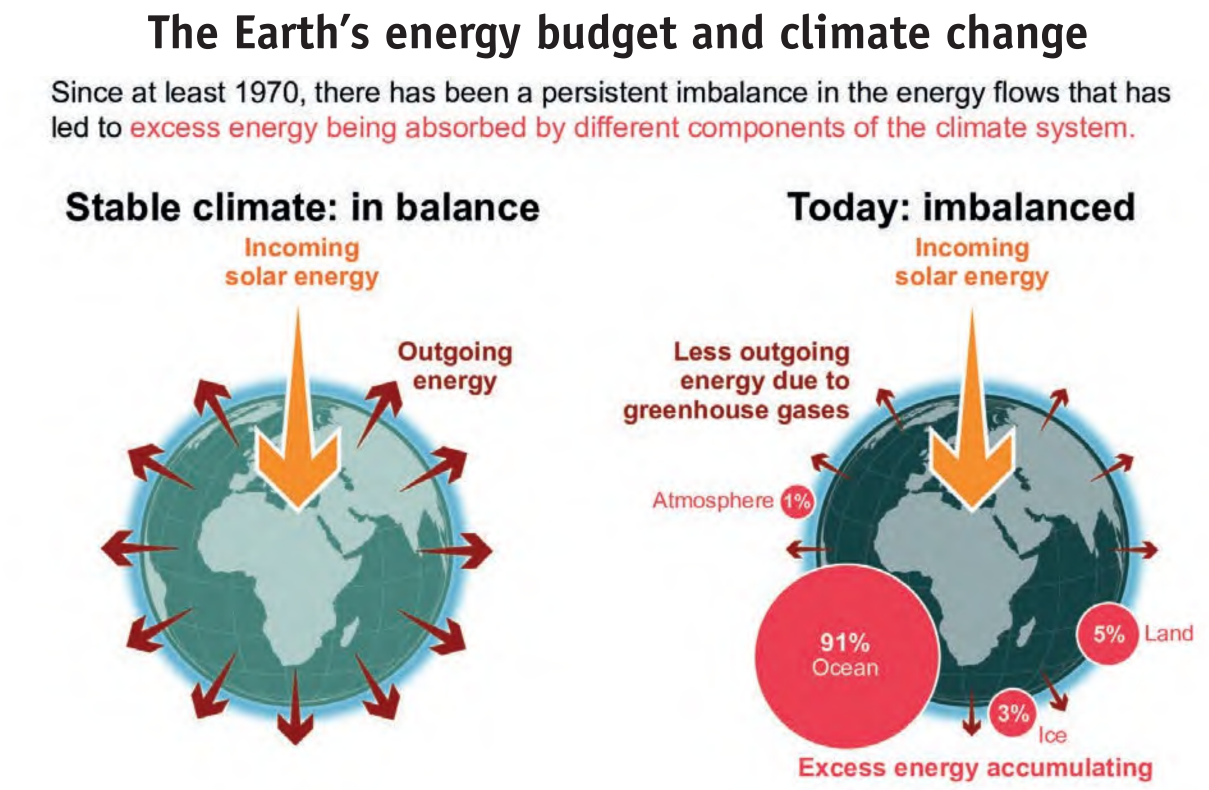


Figure 1.1 Earth's energy budget: the Earth's energy budget compares the flows of incoming and outgoing of energy that are relevant for the climate system. Source: Forster et al. (2021; their FAQ 7.1 figure 1).

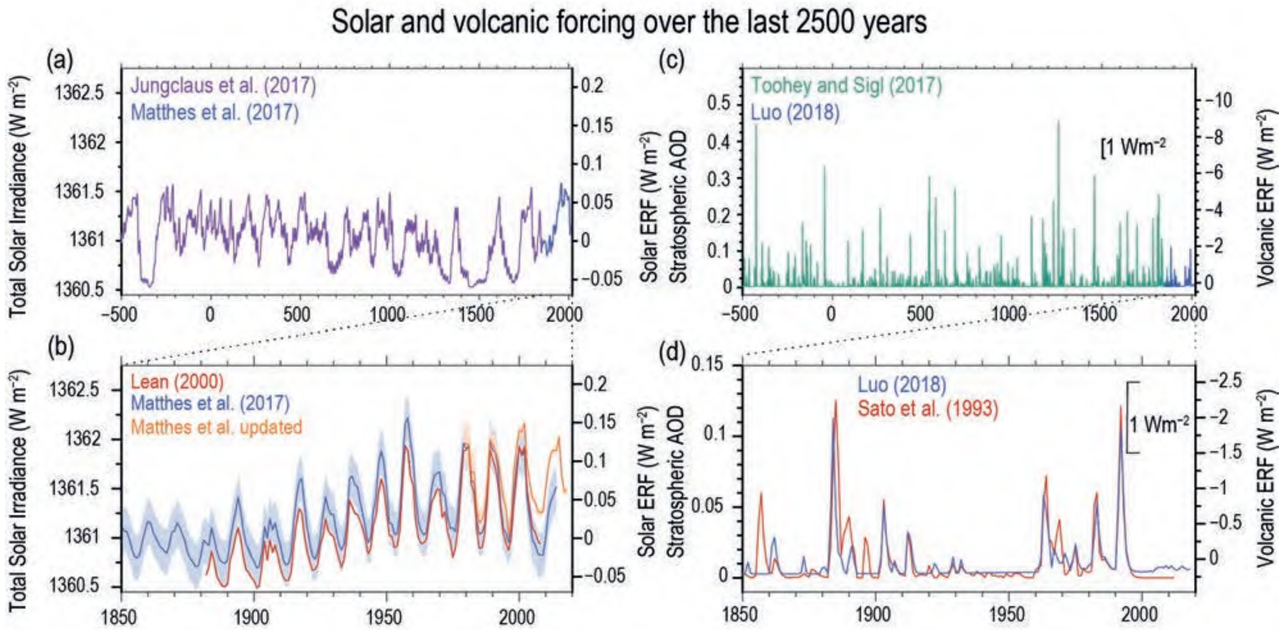


Figure 1.2 Time series of solar and volcanic forcing for the past 2,500 years (a, c) and since 1850 (b, d). (a) Total solar irradiance reconstruction (10-year running averages). (b) Total solar irradiance time series (6-month running averages). (c) Volcanic forcing represented as reconstructed stratospheric aerosol optical depth at 550nm. Estimates covering 500 BCE to 1900 CE (green) and 1850–2015 (blue). (d) Stratospheric aerosol optical depth (AOD) reconstructions from 1850. Note the change in y-axis range between panels (c) and (d). Source: Gulev et al. (2021; their figure 2.2).

Another natural driver on much longer multi-millennial timescales which has led to repeated glacial–interglacial cycles over the past 2 million or so years is the position of Earth in relation to the sun. As Earth travels through space around the sun, cyclical variations in three elements of Earth–sun geometry combine to produce variations in the amount of solar radiation reaching the Earth's surface (insolation) and thus solar forcing; these cycles are known as the Milankovitch cycles (Milankovitch, 1941).

Principal human drivers of climate change include various GHG emissions and atmospheric aerosols. Several GHGs occur naturally, most notably CO_2, CH_4 and N_2O; however, in the last century, humans have been substantially perturbing these natural cycles (section 2.1). Humans have also added a number of synthetic GHGs, such as chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs), to the atmosphere, which have no natural sources and many of which may remain in the atmosphere for thousands of years (Forster et al., 2021). Several of these synthetic gases have a radiative impact per molecule hundreds or thousands of times greater than that of CO_2 (section 2.3.3; Forster et al., 2021).

GHG concentrations in the atmosphere reached annual averages of 415 parts per million (ppm) for CO_2, 1896 parts per billion (ppb) for CH_4 and 335ppb for N_2O in 2021 (Boyer et al., 2022; Figure 1.3). These rises are without precedent in millions of years (Gulev et al., 2021). Since 1750, increases in CO_2 (49%) and CH_4 (160%) concentrations far exceed – and increases in N_2O (24%) are similar to – the natural multi-millennial changes between glacial and interglacial periods over at least the past 800,000 years. Furthermore, CO_2 levels, for which longer-term reconstructions exist, are higher than at any time in at least the last 2 million years (Gulev et al., 2021). Prior changes in concentrations of the three major GHGs between glacials and interglacials occurred much more slowly (over thousands of years) in the past compared to recent changes. Concentrations of CFCs, regulated under the Montreal Protocol, have decreased in recent years, whereas those of HCFCs and HFCs have continued to increase (Figure 1.3).

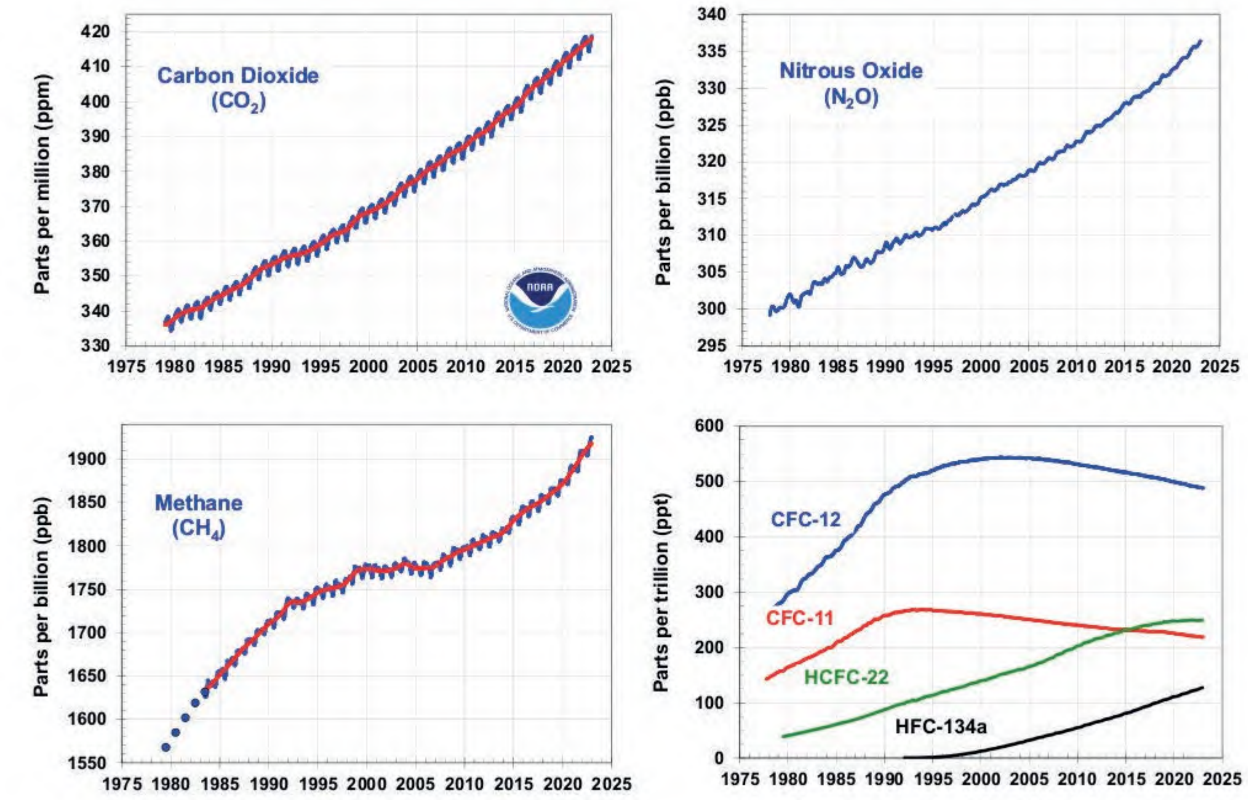
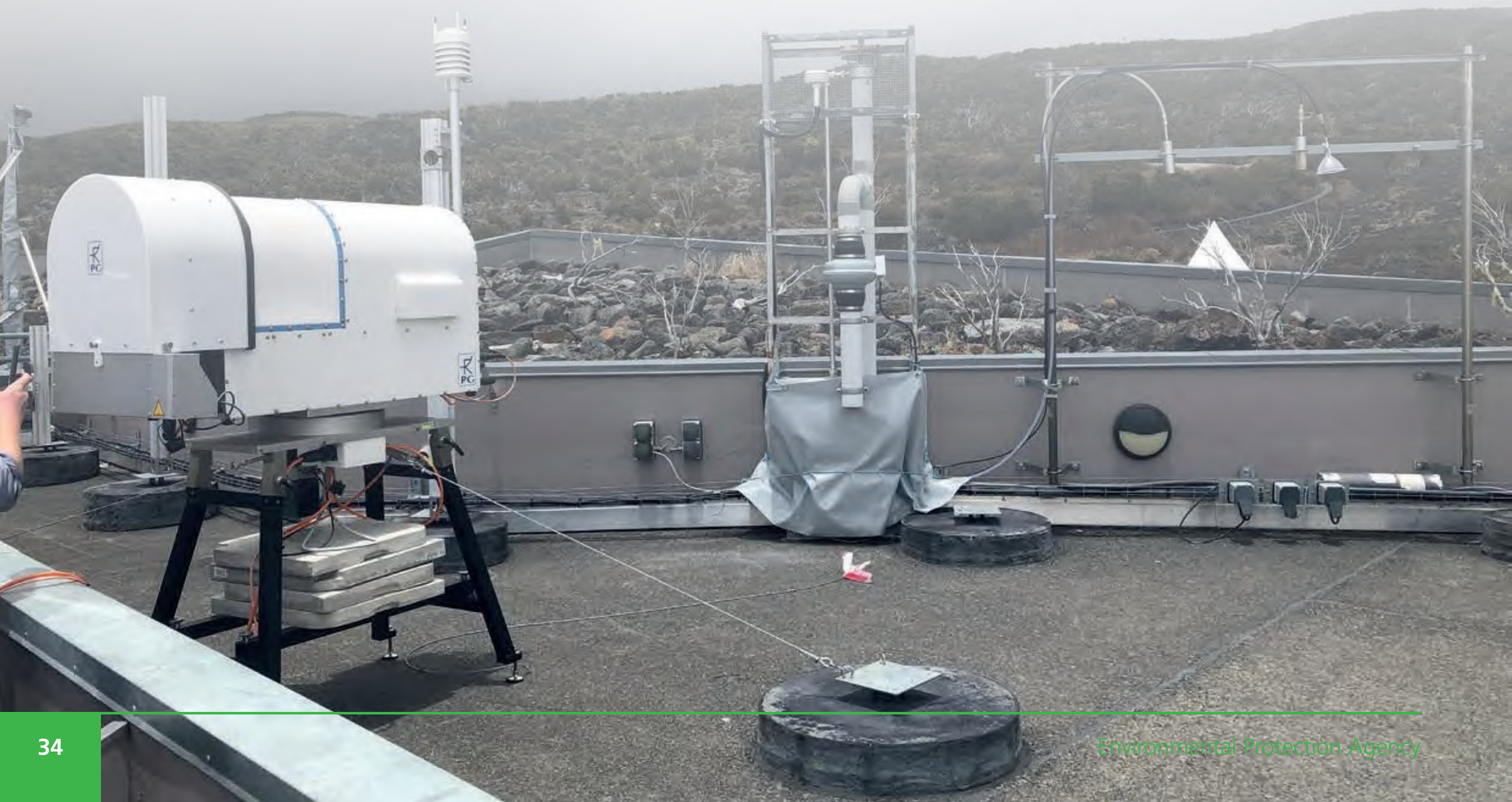


Figure 1.3 Global average abundances of the major, well-mixed, long-lived GHGs – CO_2, CH_4, N_2O, CFC-12 and CFC-11 – from the National Oceanic and Atmospheric Administration (NOAA) global air sampling network since the beginning of 1979. These five gases account for about 96% of the direct radiative forcing by long-lived GHGs since 1750. The remaining 4% is contributed by 15 other halogenated gases, including HCFC-22 and HFC-134a, for which NOAA observations are also shown here. CH_4 data before 1983 are annual averages from Etheridge et al. (1998), adjusted to the NOAA calibration scale (Dlugokencky et al., 2005). Source: https://gml.noaa.gov/aggi/



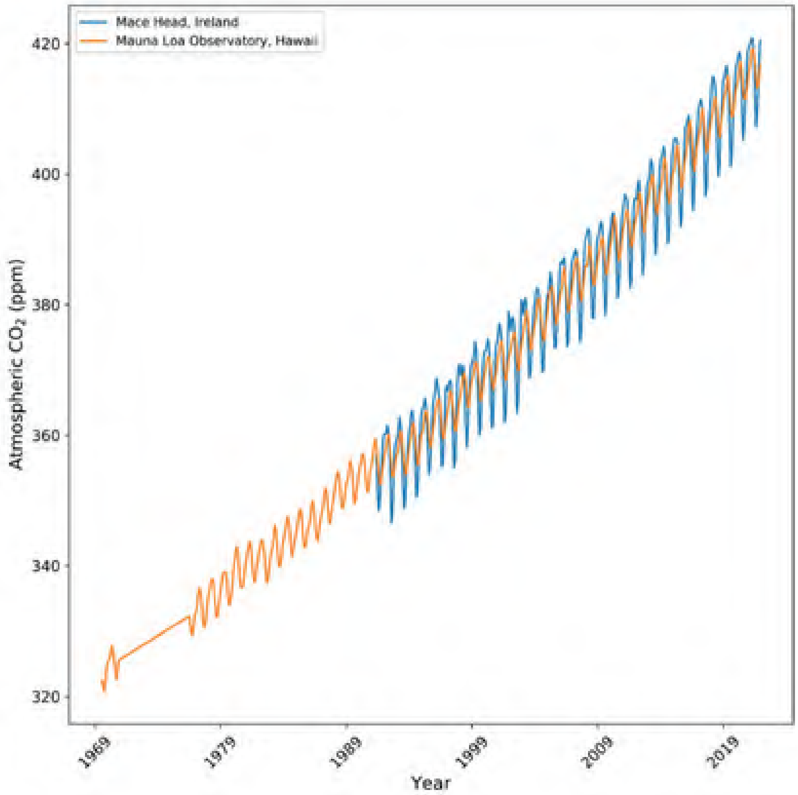
Box 1.1 Mace Head Atmospheric Research Station: Ireland's contribution to GHG monitoring

The Atmospheric Research Station at Mace Head, Carna, County Galway, is unique in Europe, with westerly exposure to the North Atlantic Ocean, offering the opportunity to study atmospheric composition under northern hemispheric background conditions as well as European continental emissions when the winds favour transport from that region. The site (Box 1.1, Figure 1) is owned and operated by the University of Galway and is involved in a number of international projects related to climate monitoring and observations of Essential Climate Variables (ECVs). The Marine Institute has operated a coastal observatory proximate to Mace Head since 2017, where a range of physical, chemical and biological Essential Ocean/Climate Variables are measured in seawater (Cámaro García et al., 2021).

In Ireland, GHG observation systems have been developed through investments by the EPA, the Department of Agriculture, Food and the Marine (DAFM), Teagasc, National Parks & Wildlife Service and Met Éireann, and via European research projects. International investments in GHG measurements at Mace Head mean that it is a leading location in the provision of advanced GHG analysis based on observational data. Mace Head has been part of the preparatory phase of the Integrated Carbon Observation System (ICOS) since 2009 and as part of this work has undertaken high-precision measurements of CO_2 and CH_4 concentrations. On 1 January 2023, Ireland officially joined the European ICOS Research Infrastructure (RI) with 10 sites (five ecosystem sites, four atmospheric sites and one ocean site). The four atmospheric sites consist of Mace Head, Malin Head and Carnsore Point, which are part of the Irish EPA-funded Atmospheric Composition and Climate Change Network, and Valentia Island, run by Met Éireann. Other SLCFs (black carbon and ozone) are monitored at Mace Head as part of the Atmospheric Composition and Climate Change infrastructure and national network.

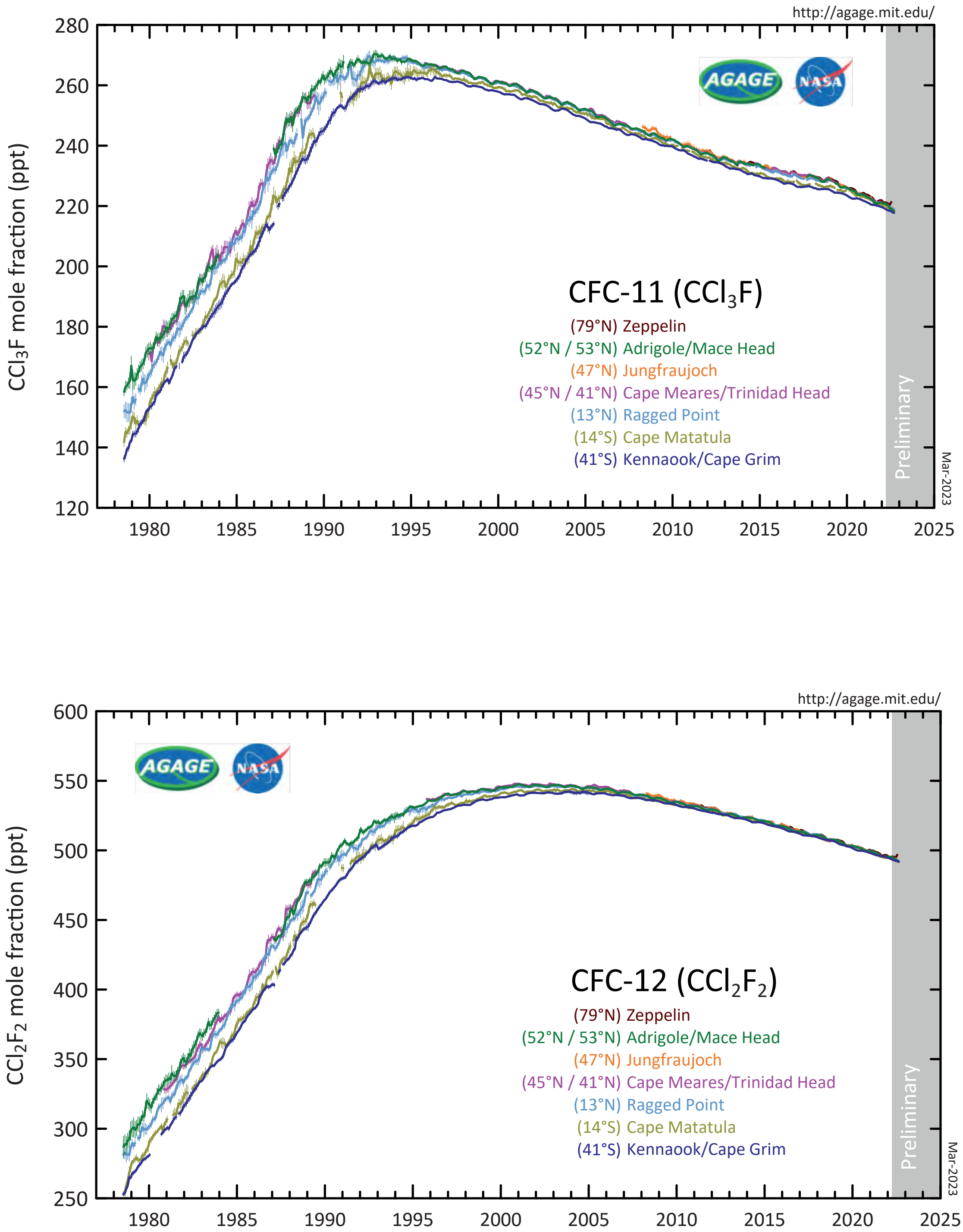
Box 1.1 Figure 1 Mace Head Research Station Ireland. Source: Centre for Climate and Air Pollution Studies, University of Galway.

Mace Head also measures CO_2 concentrations, collected from atmospheric flask measurements as part of the NOAA Global Monitoring Laboratory (GML) Carbon Cycle Cooperative Global Air Sampling Network (Box 1.1, Figure 2).



Box 1.1 Figure 2 Atmospheric CO_2 dry air mole fractions at Mace Head and Mauna Loa. The data record of atmospheric CO_2 dry air mole fractions at Mauna Loa observatory in Hawaii and Mace Head atmospheric research station in Galway, Connemara, are shown. The data are collected from atmospheric flask measurements taken as part of the NOAA GML Carbon Cycle Cooperative Global Air Sampling Network, 1968–2021. Each sample was taken on site using flask containers and sent back to NOAA GML. Source: NOAA GML Carbon Cycle Greenhouse Gases, https://gml.noaa.gov/ccgg/

Mace Head has been measuring GHG concentrations since 1978 under the Advanced Global Atmospheric Gases Experiment (AGAGE). The original AGAGE stations (Mace Head, Trinidad Head, Ragged Point, Cape Matalula and Cape Grim) occupy coastal sites around the world chosen to provide accurate measurements of trace gases whose lifetimes are long compared to global atmospheric circulation times. For example, we have been able to use sites such as Mace Head to effectively monitor interventions such as the 1987 Montreal Protocol (Parson, 2003), which saw the banning of CFCs. In the 1970s and 1980s, scientists established that these synthetic halocarbons, widely used at the time in refrigerants and propellants, were extremely potent GHGs (Ramanathan, 1975) and directly reduced stratospheric ozone (Farman et al., 1985), which protects all life on Earth from harmful ultraviolet radiation from the sun. CFCs kept on rising until the instruments of the protocol came into effect, resulting in their eventual decline. Atmospheric abundances of most CFCs have continued to decline since 2011 (Gulev et al., 2021) and this has been monitored by AGAGE stations, including Mace Head (Box 1.1, Figure 3).



Box 1.1 Figure 3 Measurements of the two principal CFCs – CFC-11 and CFC-12 – taken at AGAGE stations, including Mace Head (Ireland). Source: http://agage.mit.edu/data/agage-data

Atmospheric aerosols, many of which occur due to natural processes, are particles of various types suspended in the atmosphere. Unlike long-lived GHGs, aerosols have a lifetime of days to weeks leading to large regional differences in both mean atmospheric burdens and trends (Gulev et al., 2021). Most aerosols have a cooling effect on the climate system by scattering incoming shortwave radiation, with the notable exception of black carbon, which principally arises from biomass burning and acts to warm the atmosphere (Forster et al., 2021). Atmospheric aerosol emissions arise from a variety of processes associated principally with fossil fuel combustion and land use change. Measurements from sparse in situ sites and proxies from ice cores show increasing atmospheric aerosol burdens through the 20th century, peaking in many places towards the end of the 20th century (Gulev et al., 2021). A combination of in situ and satellite-based observations point to a global reduction in aerosol burdens since 2000, mainly as a result of various clean air legislations, but with large regional differences and continuing increases in South Asia and many parts of Africa (Figure 1.4; Gulev et al., 2021). The regionally shifting nature of the aerosol emissions leads to distinct regional patterns in the resulting radiative forcing. Ireland, like most developed nations, has experienced rapid reductions in aerosol concentrations over the most recent decades after seeing substantial increases throughout the 20th century.

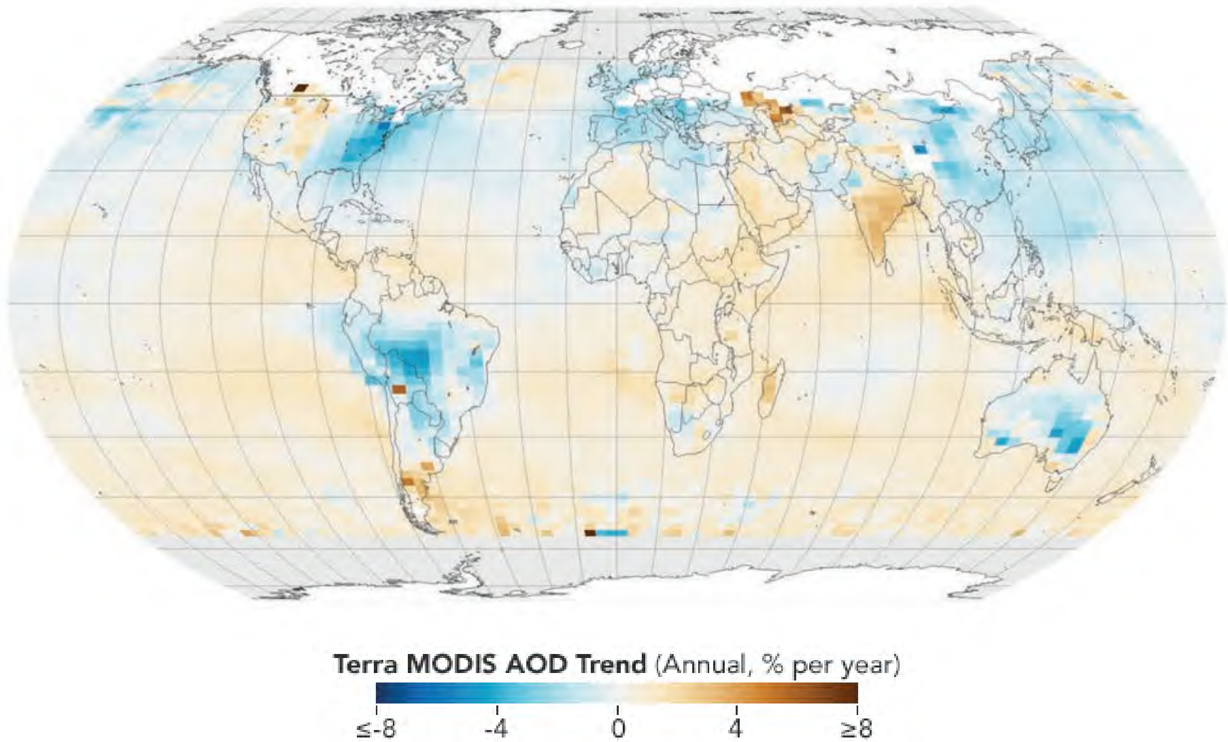


Figure 1.4 Trends in atmospheric aerosols over the lifetime of the NASA Terra MODIS mission in percentage per year of atmospheric optical depth (AOD) at 550nm. Negative values (blues) indicate decreasing aerosol burdens and positive values (browns) indicate increasing burdens. Source: NASA.

1.3 Natural climate variability

Natural variability refers to variations in climate that are caused by processes other than human and natural climate drivers. Features of the climate, such as temperature or precipitation, can change from year to year and from decade to decade owing to natural dynamical variations, termed internal variability.

Modes of variability are broadly recurrent patterns of variability of the climate system with particular spatial patterns, seasonality and timescales. There are several ways to document and describe the modes of climate variability based on statistical techniques and the dynamical nature, interpretation and understanding of the particular mode (Feldstein and Franzke, 2017; Ghil and Lucarini, 2020; IPCC, 2021b). The concept of 'teleconnection' refers to the ability of modes of variability to affect climate in remote regions through associated atmospheric or oceanic pathways (IPCC, 2021b). While there are many modes of variability, only a subset have substantial ramifications for the Irish climate, which we highlight below.

> *Most aerosols have a cooling effect on the climate system by scattering incoming shortwave radiation, with the notable exception of black carbon, which principally arises from biomass burning and acts to warm the atmosphere (Forster et al., 2021).*

1.3.1 North Atlantic Oscillation/Northern Annular Mode

The North Atlantic Oscillation (NAO) is the leading mode of variability in the North Atlantic basin in all seasons (Hurrell and Deser, 2009). The NAO index is based on the surface sea level pressure difference between the Subtropical High (Azores) and the Subpolar Low (Iceland). The Northern Annular Mode (NAM; also known as Arctic Oscillation) is an oscillation of atmospheric mass between the Arctic and northern mid-latitudes. The NAO can be interpreted as the regional expression of the NAM (NAO and NAM are arguably manifestations of the same phenomenon; IPCC, 2021b). Indices measuring the state of the NAO correlate highly with those of the NAM, and teleconnection patterns for both modes are similar (Feldstein and Franzke, 2006).

The phases of the NAO control a significant fraction of the variance in temperature and precipitation over the North Atlantic and surrounding continents, and of the prevailing westerly winds and the related storm tracks (Woollings et al., 2014). In Ireland, during winter, a positive NAO/NAM (below average pressure in Iceland, above average in the Azores) is associated with relatively wet, warm and stormy weather. The negative phase (above average pressure in Iceland, below average in the Azores) is associated with relatively dry, cold and calm anticyclonic conditions. NAO/NAM phases can persist for several weeks to even months, leading to whole seasons that are anomalously stormy or calm.

1.3.2 El Niño–Southern Oscillation

An El Niño condition occurs when surface water in the eastern equatorial Pacific Ocean becomes warmer than average and climatological easterly trade winds blow weaker than normal across the equatorial Pacific (IPCC, 2021b). The El Niño–Southern Oscillation (ENSO) has a broad range of teleconnections, both within and well beyond the Pacific region (IPCC, 2021b). The ENSO influences severe weather, rainfall, river flow and agricultural production over large parts of the world, including north-western Europe and Ireland (McPhaden et al., 2006). The opposite condition is called La Niña and is associated with cool equatorial Pacific waters together with strengthened easterlies in the region. A general reverse association of anomalies to those experienced during an El Niño is found during La Niña events, although there are some asymmetries (Cai et al., 2020). El Niño years tend to be associated with warmer than average global surface temperatures and vice versa.

1.3.3 Atlantic multi-decadal variability

Atlantic Multi-decadal Variability (AMV) refers to a climate mode representing basin-wide multi-decadal fluctuations in surface temperatures in the North Atlantic Ocean (Deser et al., 2010). It has teleconnections that are particularly pronounced over the adjacent continents and the Arctic (IPCC, 2021b). The AMV is usually assessed through departures in sea surface temperature (SST) from long-term averages (anomalies), or changes averaged over the entire North Atlantic basin, but it is associated with many physical processes, including ocean circulation, such as Atlantic Meridional Overturning Circulation (AMOC) fluctuations, gyre adjustments, and salt and heat transport in the entire North Atlantic and subarctic (Zhang, 2017). The AMV has been shown to have modulated regional surface temperatures on multi-decadal timescales before humans started modifying Earth's climate in the 1800s (Knudsen et al., 2011). Results from some of the most advanced climate models provide evidence that human and natural drivers might have modulated AMV over the directly observed period (Booth et al., 2012), although this remains contentious. Owing to the large ocean heat capacity and their long temporal scales, multi-annual to multi-decadal modes of ocean variability, such as AMV, are key drivers of long-term regional climate variations (IPCC, 2021b).

1.4 Paleoclimate evidence can make inferences of climates of the deep past

Paleoclimate is the study of Earth's climates of the past. By understanding how the climate has changed over the past hundreds, thousands and millions of years, and the causes of those changes, we can better predict the pattern and impact of future climate changes (Tierney et al., 2020). Paleoclimate research uses indicators or proxies (Figure 1.5; Cross-chapter Box 2) to reconstruct past climates. Climate proxies, which arise from a variety of geological (e.g. ice cores, sediment on the seabed), biological (e.g. pollen grains, leaf fossils, tree rings, mollusc shells) and chemical (e.g. stable isotopes and element concentrations) sources, provide indirect evidence, often used in combination, to infer past climatic and atmospheric conditions and their consequences (Swindles et al., 2013; Bereiter et al., 2015; Edvardsson et al., 2016; McElwain and Steinthorsdottir, 2017; Hoenisch, 2021; Judd et al., 2022; Ring et al., 2022). Paleoclimate research is the only way of gaining observationally-based insights into previous climate states under high concentrations of CO_2 and associated elevated temperatures (Burke et al., 2018; Tierney et al., 2020).

Examples of paleoclimate proxy measurements (Figure 1.5) include the following. Cores drilled from ice and aquatic sediments provide a timeline of temperature, precipitation and atmospheric data from proxies spanning multiple eras (Bereiter et al., 2015). The density of stomata (pores on a leaf surface allowing for gas exchange) on a fossil leaf surface provides indirect measures of atmospheric CO_2 concentration at the time when the leaf was fossilised (McElwain and Steinthorsdottir, 2017). Fossilised tree rings record temperature, precipitation and wildfires over their lifespan (which can be hundreds of years). In some places, long-term records can be recreated where dead trees have been well preserved, e.g. bog oaks in Ireland (Baillie, 2014; Edvardson et al., 2016).

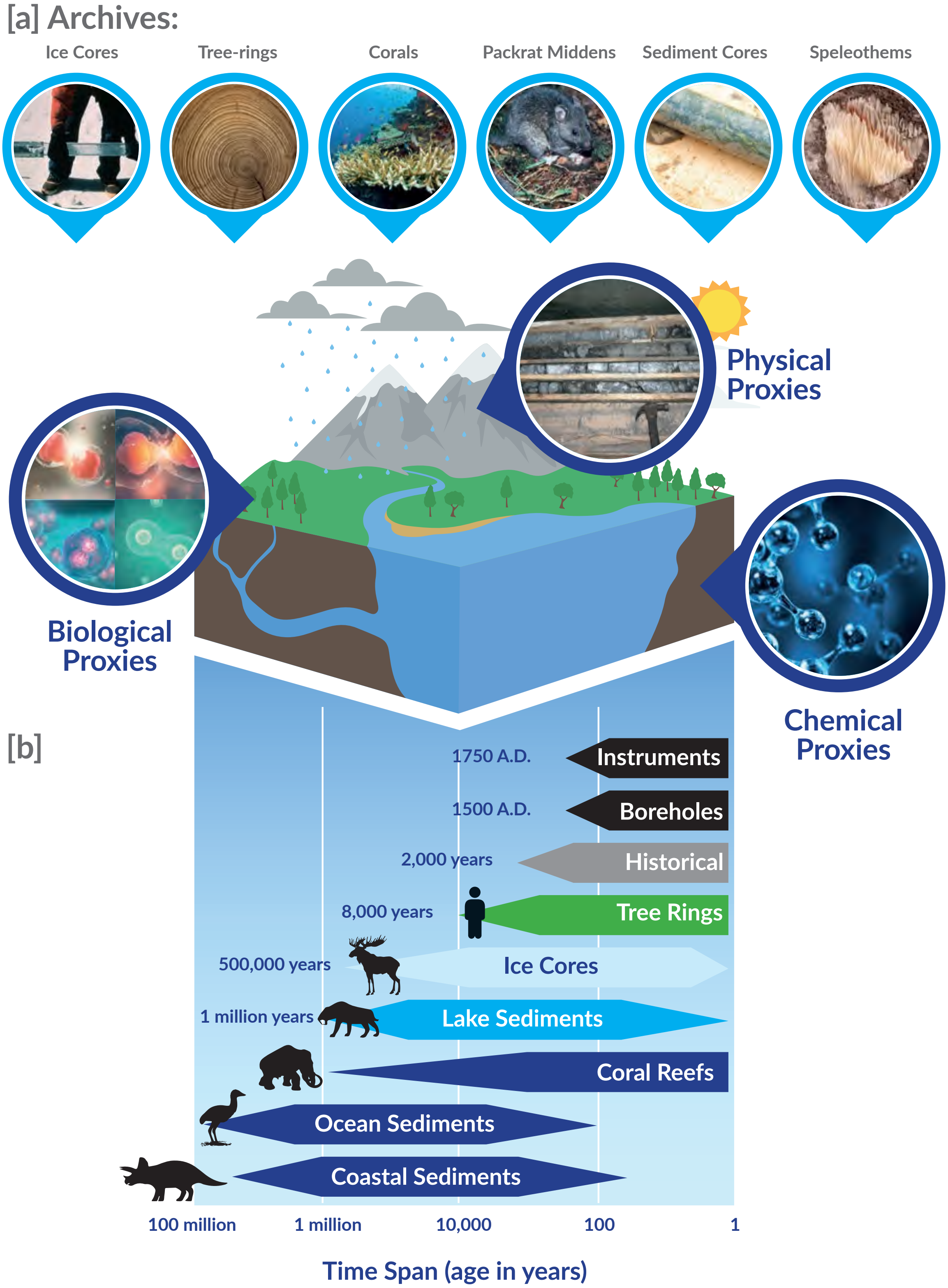


Figure 1.5 Paleoclimate proxy indicators: (a) proxy data sources and (b) how far back the different proxies go.

Box 1.2 What can the past tell us about the future?

In the past, the Earth has experienced prolonged periods of elevated GHG concentrations that have caused global temperatures and sea levels to rise (Cross-chapter Box 2), precipitation patterns to change and ice sheets to appear, grow and disappear (Peters et al., 2015; Miller et al., 2020; Tierney et al., 2020; Gulev et al., 2021). Studying past warm periods from Earth's history and their inception can inform us about the potential consequences of increasing GHG concentrations arising from human emissions today.

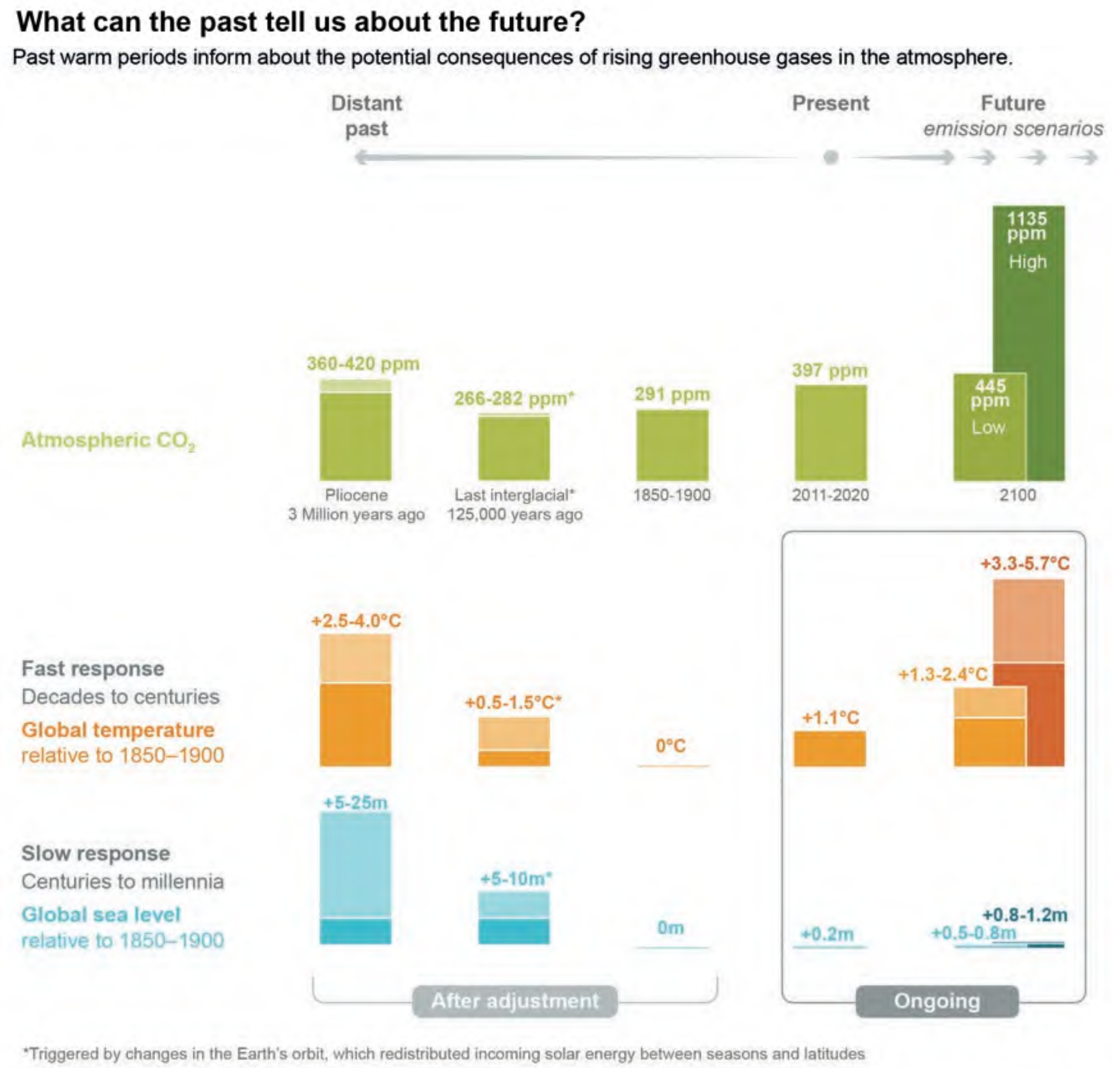
It is important to remember that while fast responses to climate change due to GHGs, such as global temperature increases, can be seen over decades to centuries, slow responses, such as sea level rise will take centuries to millennia to be fully realised (Fox-Kemper et al., 2021).

In Box 1.2, Figure 1, we can see that at the peak of the last interglacial roughly 125,000 years ago global surface temperatures were about 1–2°C warmer than in 1850–1900, and sea levels were between 5 and 10m higher than present (Past Interglacial Working Group of PAGES, 2016). Atmospheric CO_2 concentrations were higher than in the preceding glacial (by +90ppm) but similar to levels for the past several thousand years prior to human interference (Lüthi et al., 2008; Gulev et al., 2021). Modelling studies highlight that increased summer heating of the northern hemisphere due to a combination of higher than glacial CO_2 concentrations and insolation during this time caused widespread melting of snow and ice, reducing the reflectivity of the planet (Köhler et al., 2010). This gave rise to global-scale warming, which led in turn to further ice loss and sea level rise. These self-reinforcing positive feedback cycles (that increase warming and accelerate climate change) are a pervasive feature of Earth's climate system, with clear implications for future climate change under continued GHG emissions (Köhler et al., 2010; Otto-Bliesner et al., 2021).

Roughly 3 million years ago, during the Pliocene Epoch, the Earth underwent a prolonged period of elevated temperatures (2.5–4°C higher than in 1850–1900) and higher sea levels (5–25m higher than in 1850–1900) in combination with atmospheric CO_2 concentrations similar to present-day (Hoenisch et al., 2021; Gulev et al., 2021). During this period orbital configurations were close to present-day conditions, making it a particularly pertinent pointer to our possible long-term climate future (Gulev et al., 2021, their cross-chapter box 2.4).

Going even further back in time, periods of even greater elevated levels of CO_2 (Hoenisch et al., 2021) associated with further elevated global temperatures and sea levels up to 70 m higher than today are apparent in the geological record (Cross-chapter Box 2; Gulev et al., 2021). Paleoclimate records show that the tree line extended well within ice-free polar circles during past episodes of high CO_2 atmospheres and global warmth (McElwain, 2018; West et al., 2020).

Taken together, these past warm climate states present a stark reminder that the long-term adjustment of slow-responding aspects of the climate system, such as sea level to present-day CO_2 concentrations, has only just begun. That adjustment will continue over the coming centuries to millennia (Belcher, 2013).



Box 1.2 Figure 1 Using the past as a window to the future. Comparison of past, present and future. Schematic of atmospheric CO_2 concentrations, global temperature and global sea level during previous warm periods as compared to 1850–1900, present-day (2011–2020) and future (2100) climate change scenarios corresponding to early action scenarios (SSP1–2.6); lighter colour bars) and late action scenarios (SSP5–8.5; darker colour bars) (see Cross-volume Box 1). Source: Chen et al. (2021, their FAQ 1.3, figure 1).

1.5 Observations of our changing climate

Starting in the 1600s, pioneer scientists made observations of surface weather. From the mid-1800s, these became better organised and standardised, and something close to global coverage was attained by the early 20th century (Parker, 1994; Rennie et al., 2014). Weather balloons started taking measurements from the early 20th century, with coverage over most global land regions after the late 1950s (Haimberger et al., 2012). More recently, aircraft-based observations have become available (Peterson, 2016). Over the ocean, ship-based measurements of surface meteorology have been taken since the early 19th century (Freeman et al., 2017). More recently, with the deployment of meteorological buoys, areas not frequented by ships have been better sampled for weather measurements (Freeman et al., 2017). Starting in the early 20th century, samples of ocean profiles have been obtained (Cheng et al., 2016). More latterly, autonomous profilers have greatly improved the sampling quality, quantity and coverage of climate data (Wong et al., 2020). For the cryosphere, direct observations of snow accumulation have been made since the 19th century, with global estimates available from the early 20th century (Brown, 2002). Several glaciers have been measured consistently for decades to centuries, with many others surveyed less frequently (WGMS, 2021). Sea ice occurrence was noted by many early expeditions and whaling ships (Mare, 1997). For the biosphere, many observations exist of changes in phenology – the seasonal cycle of living things (Gulev et al., 2021). There also exist observations of changing species mixes and the latitudinal and elevational distributions of trees (Gulev et al., 2021).

These in situ observations constitute a selected subset of observations being carried out across the Earth system that enable the characterisation of changes. The general picture is one of an increasing ability to monitor long-term changes in all aspects of the climate system through time. Ireland plays its part in this through a mixture of measurements carried out by the EPA, Met Éireann, the Marine Institute, Teagasc, Irish third-level institutions and others, both on our land and in our territorial waters.

Starting in the 1960s, satellite monitoring of the Earth system has become increasingly possible. Sustained observations of essential climate variables (ECVs, such as temperature and precipitation, began in the late 1970s for selected ECVs. Observations are primarily made from geostationary orbits (where the satellite sits over the equator rotating at the same speed as Earth) or from sun-synchronous orbits (moving almost from pole to pole and passing overhead at a consistent local solar time), although a range of other orbital configurations exist. A number of different measurement techniques exist. Passive sensors measure outgoing radiation at specific wavelengths, which correspond to changes in ECVs. For example, in portions of the microwave spectrum, outgoing emissions can be directly related to atmospheric temperatures (Mears and Wentz, 2017). Some active satellite sensors use lasers or other techniques to determine, for example, the height of the surface important for determining changes in sea level (Beckley et al., 2010). Other techniques use time delays of signals between pairs of satellites either near (GRACE (Wahr et al., 1998)) or far (GNSS (Van Malderen et al., 2022)) to determine aspects of the climate system.

The global constellation of satellites measure a broad range of atmospheric, surface ocean, cryospheric and biospheric ECVs and provide (close to) truly global coverage. As records become progressively longer they are becoming increasingly valuable. The European Space Agency (ESA) and the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) contribute vital missions to space-based observational programmes, and both are supported by Ireland.

Finally, using weather and climate forecast models, observational data and methods to incorporate observations with models (data assimilation) to 'reanalyse' archived observations creates global datasets describing the recent history of the atmosphere (Slivinski et al., 2019; Hersbach et al., 2020), land surface (Munoz-Sabater et al., 2021) and ocean (Zuo et al., 2019). A climate reanalysis thus produces 'maps without gaps' of the full global climate system and its evolution over time.

1.5.1 Observed changes in the climate system

Observationally based estimates demonstrate that the mean global surface temperature has been increasing since the Industrial Revolution (Gulev et al., 2021). That the world has warmed is further supported by the fact that many indicators we would expect to increase have increased (e.g. ocean heat content, temperatures in the atmosphere) while other indicators we would expect to decrease have decreased (e.g. sea ice extent, glacial mass balance) over recent decades. It is the combination of these multiple lines of evidence that when taken together demonstrates global warming as an irrefutable fact (Gulev et al., 2021). Evidence across multiple aspects of the climate system observed via multiple techniques and analysed independently by many groups across the world point compellingly to a world that has warmed (Figure 1.6).

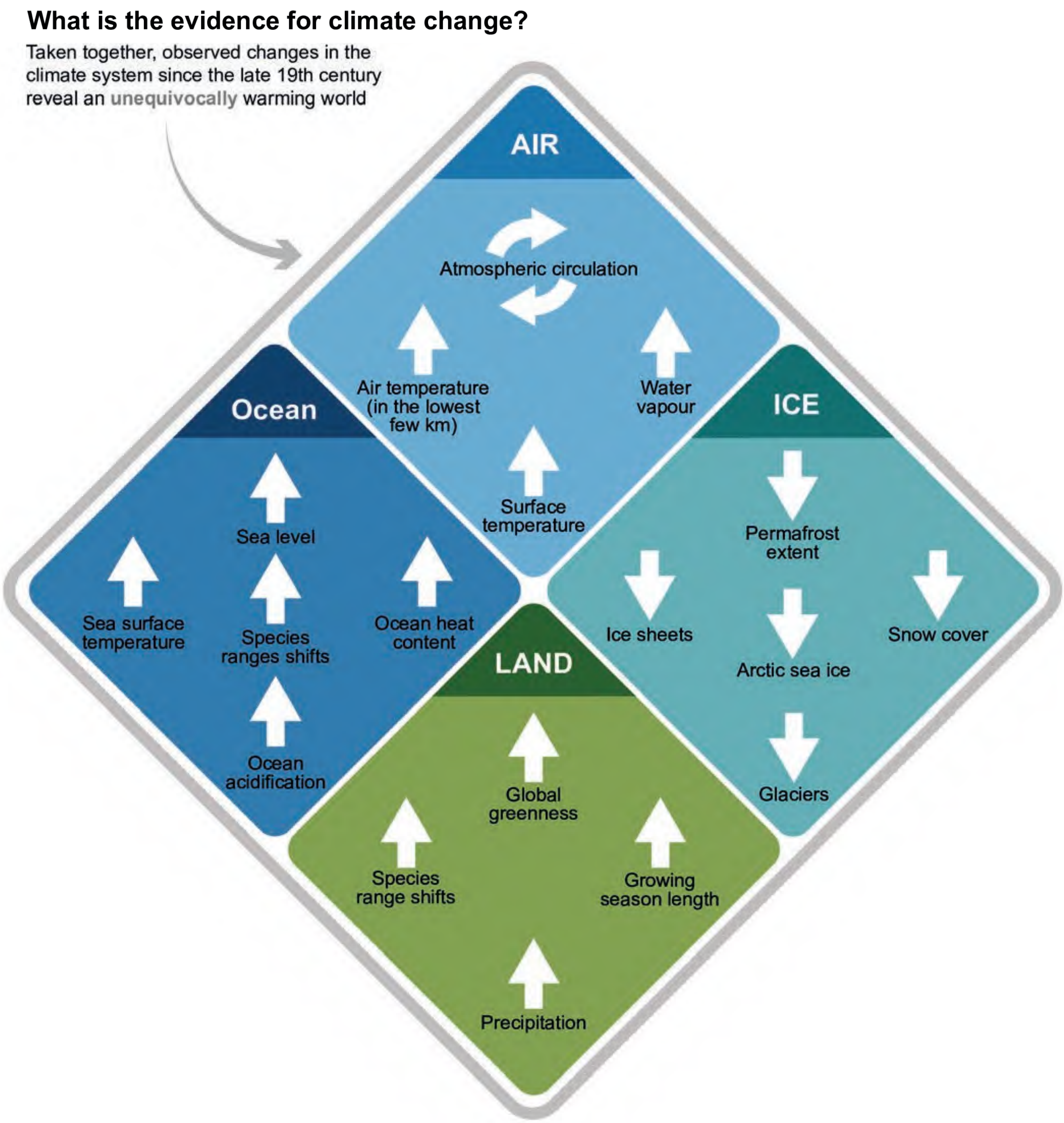


Figure 1.6 Multiple indicators of global change point unequivocally to a world that has warmed. Observed changes in key components of the climate system observed using multiple techniques and analysed by many independent groups paint an unambiguous picture. Source: Gulev et al. (2021; their FAQ 2.2 figure 1).

1.5.1.1 Atmosphere

Since 1950, the global mean surface temperature has increased at a rate unprecedented for any 50-year period in the last 2,000 years (Figure 1.7; Gulev et al., 2021). Temperatures have been rising more quickly over the land than the ocean since 1900, and each of the last four decades has been warmer than any decade preceding it since 1850 (Gulev et al., 2021). Global surface temperatures have risen by about 1.15°C [1.00–1.25°C] between 1850–1900 and the most recent decade, 2013–2022. The most recent decade has probably been warmer than any sustained period in the present interglacial, which would mean that the last time temperatures were as warm as today on a sustained basis was more than 100,000 years ago at the peak of the last interglacial (Gulev et al., 2021) (Cross-chapter Box 2). There has been an increase globally in the frequency and intensity of hot extremes and a decrease in the frequency and intensity of cold extremes (Seneviratne et al., 2021). National temperature changes, including changes in extremes, are assessed in Chapter 3.

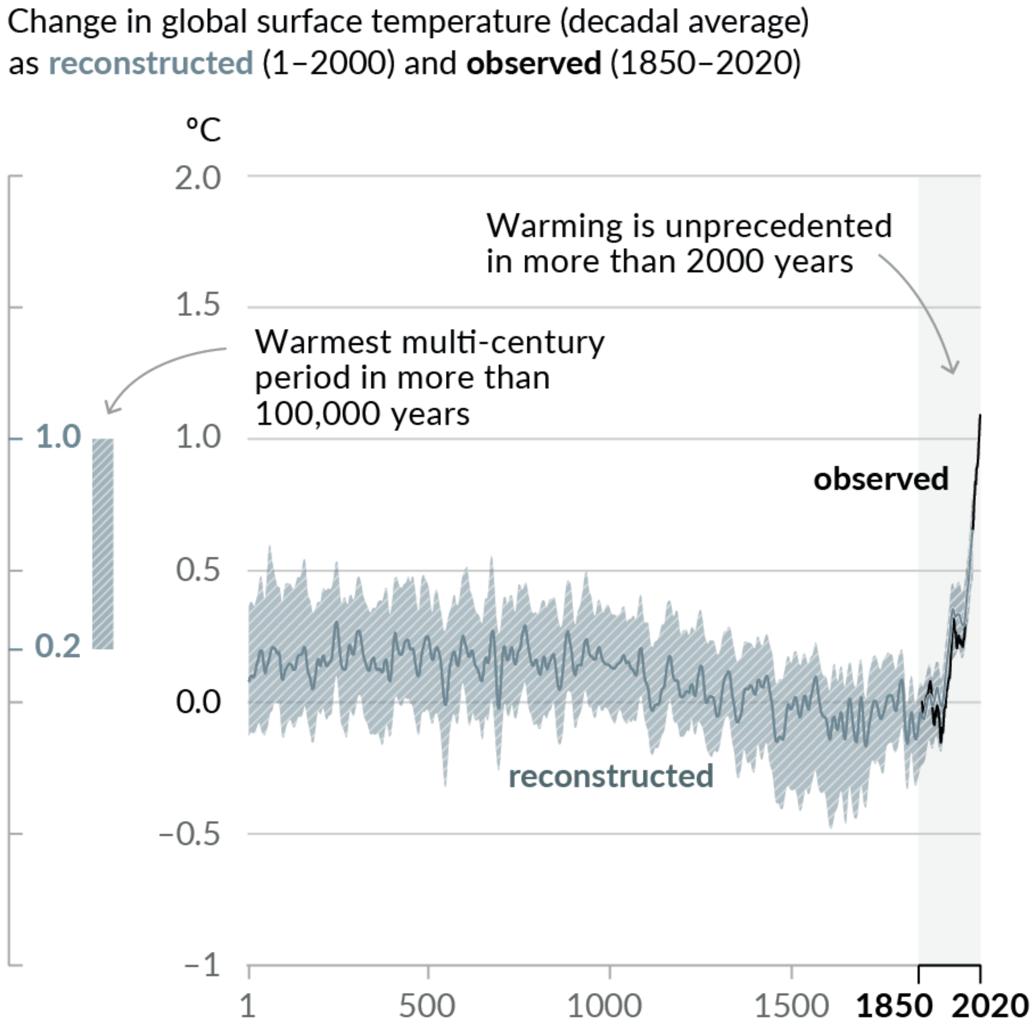


Figure 1.7 Changes in global surface temperature reconstructed from paleoclimate archives (solid grey line, 1–2000) and from direct observations (solid black line, 1850–2020), both relative to 1850–1900 and decadally averaged. The vertical bar on the left shows the estimated temperature (very likely range) during the warmest multi-century period in at least the last 100,000 years, which occurred around 6,500 years ago during the current interglacial period (Holocene) (Cross-chapter Box 2). The last interglacial, around 125,000 years ago, is the next most recent candidate for a period of higher temperature. These past warm periods were caused by slow (multi-millennial) orbital variations. The grey shading with white diagonal lines shows the very likely ranges for the temperature reconstructions. Source: IPCC (2021a; part of their figure SPM.1).

> *"Temperatures have been rising more quickly over the land than the ocean since 1900, and each of the last four decades has been warmer than any decade preceding it since 1850 (Gulev et al., 2021)."*

When globally aggregated, precipitation has increased over the past century, but with large regional signals of both drying and wetting, and substantial decadal to multi-decadal variability (Gulev et al., 2021). Since 1950, when more globally complete monitoring is possible, there has been an overall increase globally, which has been faster since the 1980s (Gulev et al., 2021). The frequency and intensity of extreme precipitation events has increased almost everywhere, particularly so in already wetter regions in the northern hemisphere (Seneviratne et al., 2021). A greater proportion of total precipitation is falling in extreme precipitation events across most of the globe (Seneviratne et al., 2021). In addition to the increase in heavy precipitation events, scientists have also recorded an increase in agricultural and ecological drought, attributable to human-driven climate change through increased evaporation from land surfaces and transpiration (water loss) from plants (Seneviratne et al., 2021). National changes in precipitation and related extremes are assessed in Chapter 4.

There have been changes in the global atmospheric circulation, including a widening and strengthening of the tropical Hadley cell circulation and a strengthening and polar migration of the polar jets (Gulev et al., 2021). Changes in storms of various types are considerably more uncertain, with little evidence of significant changes globally and large sensitivity to choice of observational dataset or reanalysis product, particularly for mid-latitude storms such as those that frequently impact Ireland (Gulev et al., 2021; Seneviratne et al., 2021).

1.5.1.2 Ocean

Approximately 90% of the Earth's excess energy over the last 50 years has been stored in the ocean (Forster et al., 2021). The rate of warming of the ocean is faster in the past century than for any century since the last deglaciation event 11,000 years ago (Gulev et al., 2021). Warmer water expands, contributing to rising sea levels, with remaining contributions arising from the melting of glaciers and ice sheets, and groundwater extraction (Fox-Kemper et al., 2021). Global mean sea level increased by 0.20m [0.15–0.25m] between 1901 and 2018. The average rate of sea level rise was 1.3mmyr^{-1} [0.6–2.1mmyr^{-1}] between 1901 and 1971, increasing to 1.9mmyr^{-1} [0.8–2.9mmyr^{-1}] between 1971 and 2006, and further increasing to 3.7mmyr^{-1} [3.2–4.2mmyr^{-1}] between 2006 and 2018 (IPCC, 2021a). The ocean has also experienced increased acidification (lowering of pH), driven by increased atmospheric CO_2; the mean surface ocean pH in recent decades has been unusually low in the context of the last 2 million years (Gulev et al., 2021). Changes in the shelf seas around Ireland are further assessed in Chapter 5.

1.5.1.3 Cryosphere

Ice sheets in polar regions have fluctuated over millennia through natural ice ages and deglaciation events (Fox-Kemper et al., 2021). The rate of global ice sheet loss has increased by a factor of four over the last 30 years and current rates of ice sheet loss are without precedent in at least hundreds of years (Gulev et al., 2021). Arctic sea ice has declined in recent decades, with the period 2011–2020 showing the lowest annual average since 1850, and the late summer showing the lowest level of sea ice in at least the last 1,000 years (Gulev et al., 2021). Seasonal snow cover is melting earlier in spring in the northern hemisphere (Gulev et al., 2021).

1.5.1.4 Biosphere

The seasonal cycle in atmospheric CO_2 concentration, which is driven by the drawdown of carbon by photosynthesis on land during the summer and release by respiration during the winter, has increased in amplitude since the start of systematic monitoring at global observatories such as Mace Head and Mauna Loa (Gulev et al., 2021). Changes in vegetation productivity and longer growing seasons have been reported as the primary drivers of the increasing amplitude within the seasonal cycle (Park et al., 2016). The northern limit of tree growth (tree line) is now at latitudes unseen in centuries and is progressing poleward (Gulev et al., 2021), as observed in the geological past (see Cross-chapter Box 2). Similarly, many species are moving upslope (Gulev et al., 2021). Changes have been observed in many aspects of phenology (the timing of seasonal events) in mid-latitude regions in response to climate change (Gulev et al., 2021). Changes in the marine biosphere are consistent with large-scale warming and changes in ocean geochemistry. The ranges of many marine organisms are shifting towards the poles and towards greater depths, but a minority of organisms are shifting in the opposite directions (Gulev et al., 2021).

1.6 Earth System Models

Earth System Models (ESMs) are complex simulations of the Earth's climate system, including the atmosphere, ocean, land and ice. They can be used to create estimates of past and current climate or simulate the future climate. Climate modelling started in the 1950s, and the models have become increasingly sophisticated as computing power, observations and our understanding of the climate system have advanced (Chen et al., 2021). Model runs require some of the largest supercomputers in the world to generate their climate projections. These powerful supercomputers allow scientists to probe the connections between various physical and biogeochemical processes, e.g. how the ocean takes up heat and carbon, stores and then redistributes it.

Climate models are constantly being updated, as different modelling groups around the world incorporate higher spatial resolution, new physical processes and biogeochemical cycles. These modelling groups coordinate their updates around the schedule of the IPCC assessment reports, releasing a set of model results (runs) under the auspices of the Coupled Model Intercomparison Project (CMIP). The latest CMIP6 cycle (Eyring et al., 2016) consists of the simulations from around 100 distinct climate models from 49 different modelling groups (Figure 1.8; Chen et al., 2021). The principal benefit of the CMIP framework is that modelling groups all use identical experimental setups and procedures. This means that differences between simulations arise due to choices in the configuration and underlying design of each model. Many groups have additionally increasingly created large ensemble experiments whereby the same set of climate drivers are run repeatedly tens or hundreds of times from slightly distinct initial model states. The resulting large spread of model outcomes enables the effects of internal climate variability – as simulated by that particular model – to be rigorously assessed.

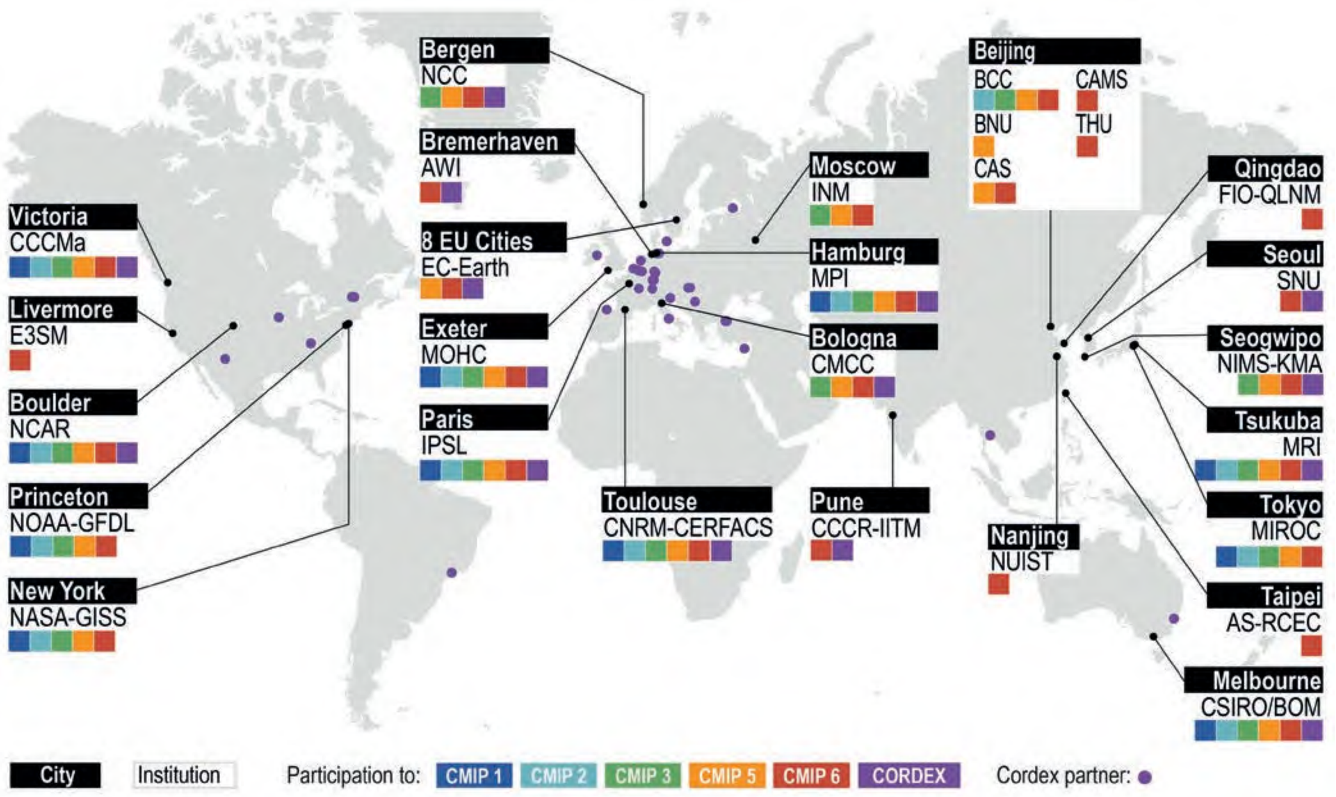


Figure 1.8 A world map showing the increased diversity of modelling centres contributing to CMIP and CORDEX (Coordinated Regional Climate Downscaling Experiment) over successive CMIP experiments. Colour coding denotes inclusion in a given iteration of CMIP/CORDEX. Successively more models have contributed with each iteration of CMIP. Note that CMIP4 was 'skipped' to align CMIP numbering with IPCC report numbering. Source: Chen et al. (2021, their figure 1.20).

Box 1.3 Ireland's contributions to global modelling and the role of regional downscaling

Ireland's participation in CMIP6 comes through the EC-Earth climate modelling consortium (Döscher et al., 2022). EC-Earth is an ESM developed by a European consortium of which the Irish Centre for High-End Computing (ICHEC) and Met Éireann are members. The CMIP6 version of EC-Earth comprises the European Centre for Medium-Range Weather Forecasts (ECMWF) Integrated Forecast System (IFS) atmospheric model (Remy et al., 2022), the Nucleus for European Modelling of the Ocean (NEMO) model (Dupont et al., 2012), the Louvain-la-Neuve sea ice model (LIM), the Tracer Model version 5 (TM5) atmospheric composition model (van Noije et al., 2014), the Lund–Potsdam–Jena General Ecosystem Simulator (LPJ-GUESS) vegetation model (Dantas de Paula et al., 2021) and the Pelagic Interactions Scheme for Carbon and Ecosystem Studies (PISCES) ocean biogeochemistry model (Aumont, et al., 2015). ICHEC is currently working with Met Éireann and European partners to develop and improve the EC-Earth ESM to provide more accurate projections of the North Atlantic and Irish climate. This research will contribute to the development of the next version of EC-Earth in preparation for CMIP7, which in turn will inform the IPCC AR7 reports.

Regional climate projections for Ireland

A second component of national climate modelling research involves simulating the future climate on a regional scale in fine detail. The TRANSLATE project is an initiative of Met Éireann to standardise future climate projections for Ireland. In TRANSLATE, 'raw' climate projections are taken from different modelling sources and are synthesised into a unified projection framework (O'Brien and Nolan, 2023). This research involves downscaling CMIP5 global data to provide high-resolution (4km) climate projections for Ireland, using both standard atmosphere-only (COSMO-CLM (Rockel et al., 2008) and Weather Research and Forecasting (Skamarock et al., 2019) regional climate models (RCMs) for the period 1976–2100. The future climate is simulated under the CMIP5 scenarios (Cross-volume Box 1). The regional climate research is carried out by ICHEC in collaboration with Met Éireann and supported by the EPA, Marine Institute and the Office for Public Works. The regional climate projection datasets form the basis of the standardised national climate projection dataset produced as part of the Met Éireann TRANSLATE project (used in Part B of this volume and elsewhere in other volumes) and is made available via the climateireland.ie portal. Met Éireann is funding TRANSLATE-2, which will build on the results of TRANSLATE, including extending the original analysis to include CMIP6 ESM data and a broader range of regional models.

1.6.1 Evaluating Earth System Model performance

The performance of ESMs can be assessed by comparing historical model simulations to observations under a broad suite of diagnostic tests. This evaluation includes a comparison of large-scale averages of climate variables (e.g. temperature, precipitation and aspects of atmospheric circulation) as well as more detailed regional and seasonal variations. There are two important aspects to consider: (1) how models perform individually and (2) how they perform as a group. CMIP model performance assessment exercises show that many individual models of the new generation perform better than the generations before them (Figure 1.9). This behaviour is repeated across a much broader range of diagnostics than shown in Figure 1.9, including atmosphere, ocean, ice and biosphere components (Eyring et al., 2021).

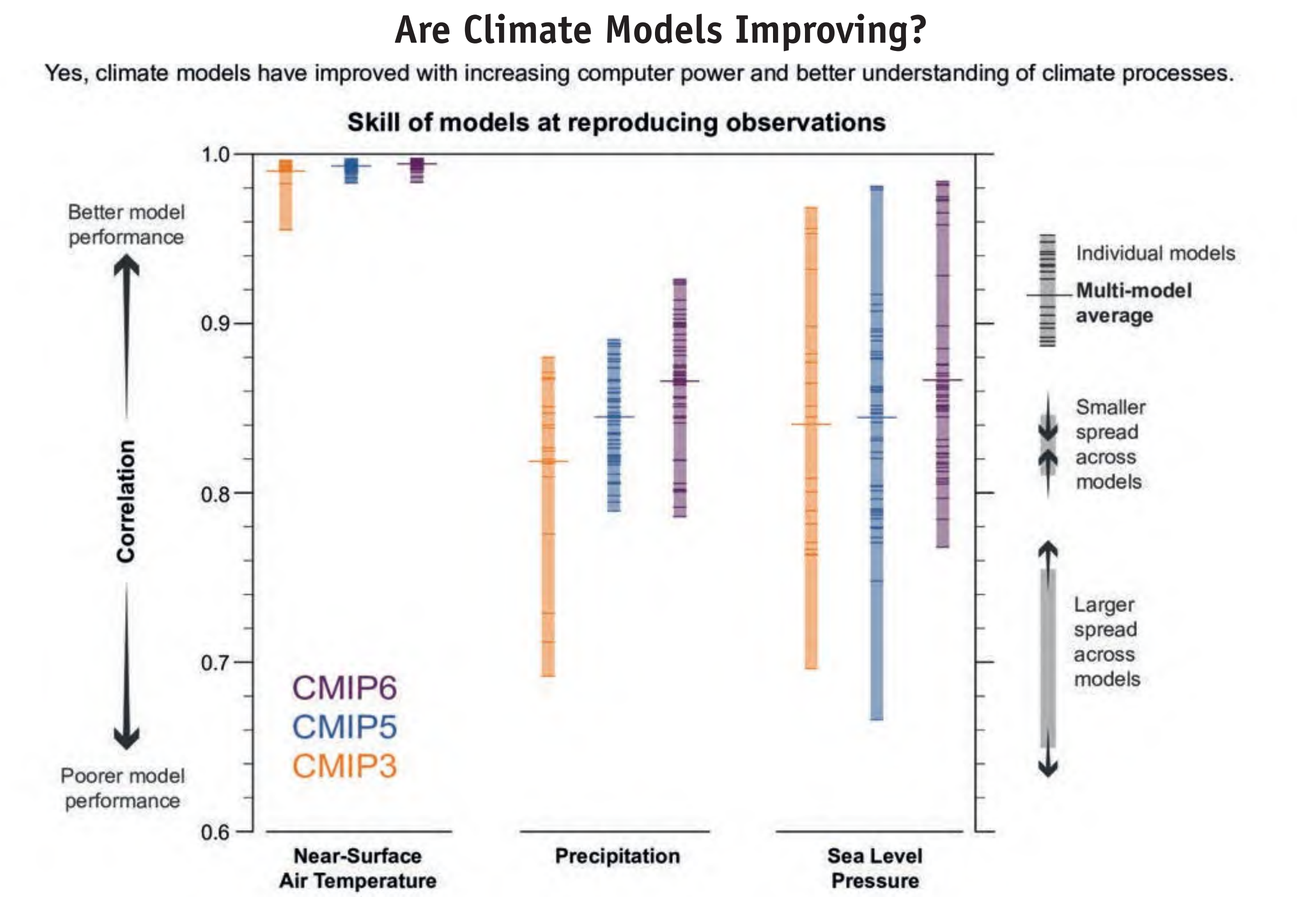


Figure 1.9 A comparison of simulations from the three most recent generations of models (available around 2005, 2012 and present) with observations of three climate variables. This figure shows the agreement between simulated and observed patterns, where a value of 1 represents perfect agreement. Source: Eyring et al. (2021; their FAQ 3.3 figure 1).

1.7 Attribution: how do we know it's us?

The science of attribution examines the role of different climate system drivers in observed long-term climate change. By using ESM simulations to create estimates of what the change would have been due to different combinations of climate system drivers, the probable causes can be uniquely identified. Since 1850–1900, the globe has warmed by an average of about 1.1°C, which can only be explained when human drivers (section 1.2) are invoked (Figure 1.10) (Eyring et al., 2021).

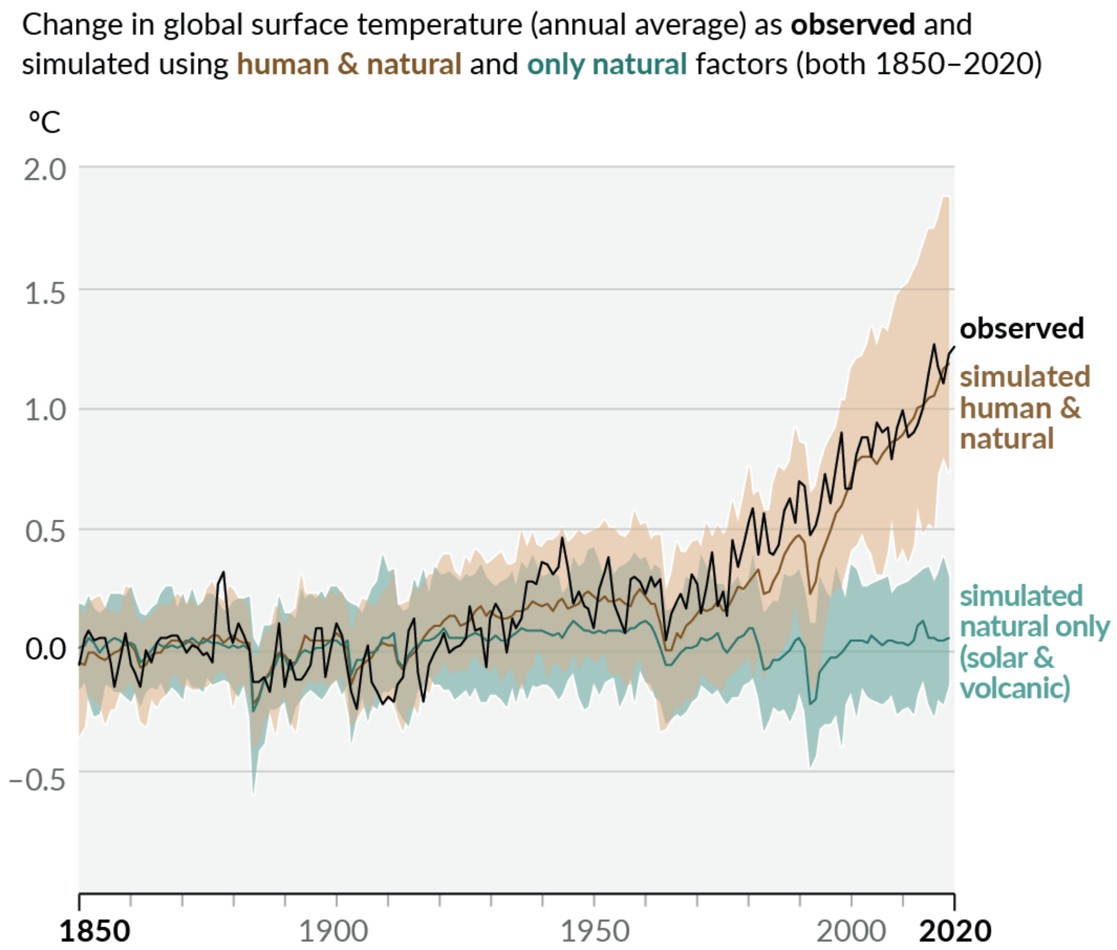


Figure 1.10 Changes in global surface temperature over the past 170 years relative to 1850–1900 and annually averaged, compared to CMIP6 climate model simulations of the temperature response to both human and natural drivers, and to only natural drivers. Source: IPCC (2021a; their figure SPM.1 panel b).

Forster et al. (2023) provide an update to the IPCC AR6, with the assessed likely range (66% confidence level) of total human-caused global surface temperature increase from 1850–1900 to 2013–2022 being 0.9°C to 1.4°C, with the best estimate of 1.14°C matching almost exactly the observed change of 1.15°C over that same period (Figure 1.11). Well-mixed GHGs likely contributed to warming of 1.1°C to 1.8°C, while other human drivers (principally aerosols) likely contributed to an overall cooling of +0.1°C to –0.7°C. Natural drivers likely changed global surface temperature by –0.1°C to 0.1°C, and internal variability likely changed it by –0.2°C to 0.2°C (both these latter estimates have a best estimate of zero contribution).

The time evolution of the various contributors to the warming based upon their ERF (section 2.3.1) shows how impacts of individual large volcanic events can be dominant on timescales of years but that the impacts of GHGs – particularly CO_2 – has been dominant on multi-decadal timescales (Figure 1.12; Forster et al., 2021).

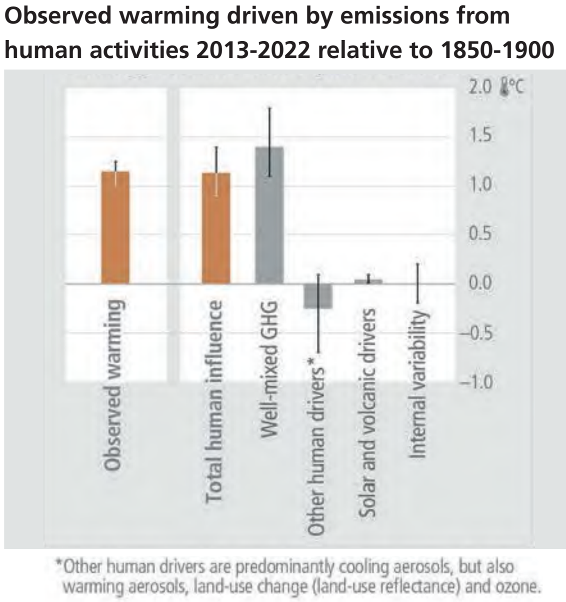


Figure 1.11 Assessed contributions to observed warming in 2013–2022 relative to 1850–1900. The figure shows temperature change attributed to total human influence; changes in well-mixed GHG concentrations; other human drivers due to aerosols, ozone and land use change (land use reflectance); solar and volcanic drivers; and internal climate variability. Whiskers for attributable components show 66% likelihood ranges (a two in three chance that the true value lies within the interval). Source: Forster et al. (2023; panel from their figure 8).

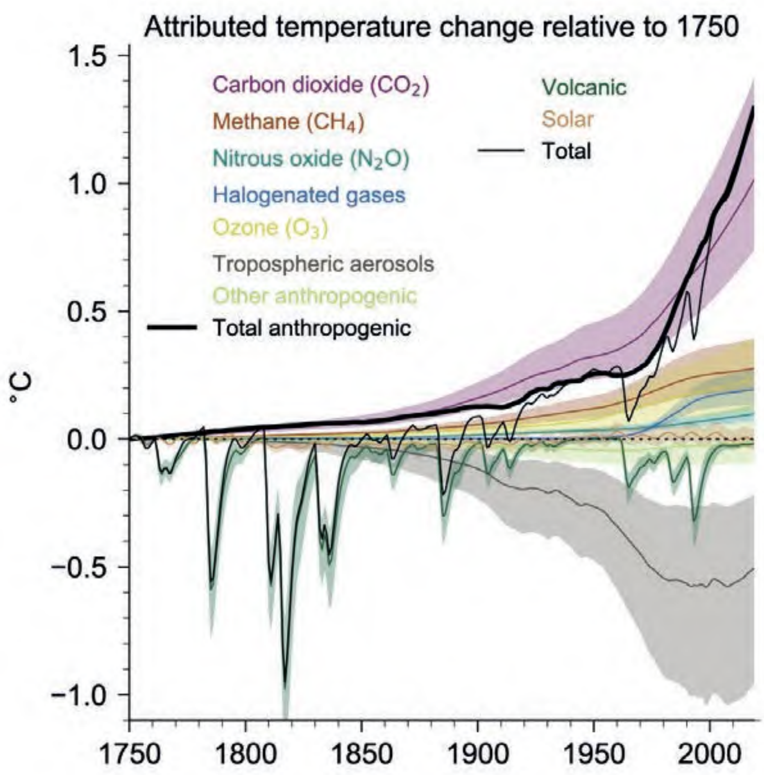


Figure 1.12 Attributed global surface temperature change from 1750 to 2019 produced using the two-layer emulator of Forster et al. (2021), forced with ERF derived therein and climate response constrained to assessed ranges for key climate metrics described in Forster et al. (2021) (see their Cross-chapter Box 7.1). The results shown are the medians from a 2237-member ensemble that encompasses uncertainty in forcing and climate response. Temperature contributions are expressed for CO_2, CH_4, N_2O, other well-mixed GHGs, ozone, aerosols and other anthropogenic forcings, as well as total anthropogenic, solar, volcanic and total forcing. Shaded uncertainty bands show 5–95% ranges. Source: Forster et al. (2021; their figure 7.8).

Attribution at the global scale shows consistent human signals in observed changes across many components of the atmosphere (surface and vertical temperatures, humidity, precipitation, circulation), ocean (sea level, ocean heat content, salinity, acidification, deoxygenation) and cryosphere (glaciers, sea ice, ice sheets, seasonal snow cover) (Eyring et al., 2021). Time and again, scientific investigators find the chief contributors to be human influences and rule out both natural climate drivers and internal variability as plausible explanations (Eyring et al., 2021). It is this confluence of multiple lines of investigative evidence that has finally led every country in the world to agree in the recent IPCC AR6 assessment that human influence on global climate change is an established fact (IPCC, 2021a).

1.7.1 Extreme event attribution

In addition to long-term trends in climate variables, the effect of climate change is increasingly apparent in the occurrence and strength of extreme weather events (Seneviratne et al., 2021). Extreme Event Attribution (EEA) encompasses a set of frameworks (statistical approaches/methodologies) that are developed for discerning the role of human-induced factors in altering the characteristics of climate and weather extremes (Otto et al., 2016; Stott et al., 2016). Using observed records and/or climate model simulations of the factual and counterfactual (without current climate change) worlds (Figure 1.13; for more details, see Philip et al., 2020; Stott et al., 2016), EEA attempts to answer whether an extreme event of interest has been made more or less likely by climate change, or if the event was a manifestation of natural climate variability, by means of a statistical metric called the probability ratio. In simple terms, the probability ratio is defined as the ratio of the probabilities of occurrence of an extreme event in the presence and absence of climate change (Figure 1.13). Such answers are necessary for understanding climate change effects on weather/climate extremes and its impacts in a quantifiable sense (e.g. Harrington et al., 2022; Li and Otto, 2022).

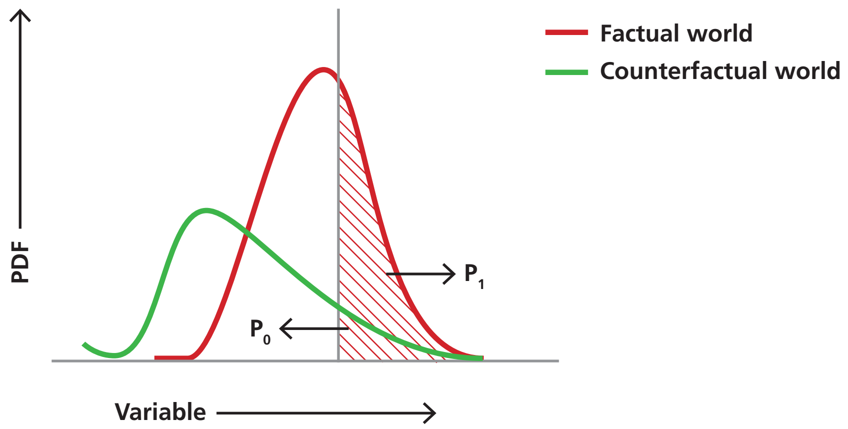


Figure 1.13 Illustration of probability distribution functions (PDFs) of a climate variable in the world we live in (the factual world) and a hypothetical world without the effect of human influence (a counterfactual world) (after Stott et al., 2016). Hatched areas in these plots represent the respective probabilities of exceeding a specific threshold (P1 and P0).

Under the event attribution framework, human-induced climate change has been found to be already causing extreme weather events across many areas of the globe (Seneviratne et al., 2021). Increases in both the frequency and intensity of heatwaves and extreme precipitation have been consistently linked to human activities (Seneviratne et al., 2021). Similarly, cold events have been made less likely and severe (Seneviratne et al., 2021). In drought-prone regions, droughts have tended to be made more severe and frequent (Seneviratne et al., 2021). There is limited evidence to date for human influences on many types of extreme storms, including mid-latitude storms (NAS, 2016). Further details in a national context are given in Chapter 6.

1.8 Scenarios and climate model projections

Future possible climate projections from ESMs are driven by scenarios (Cross-volume box 1). Use of a range of scenarios yields a range of projections of future climate outcomes. In the CMIP framework, modelling groups are required to simulate results for a set of core scenarios and these can then inform assessments of the possible climate futures through the balance of this century and beyond (Lee et al., 2021).

CROSS VOLUME

CROSS-VOLUME BOX 1
USE OF MODELLED SCENARIOS FOR OUR FUTURE

Modelled scenarios for our future

This box explains how scenarios (future potential emissions pathways) are used across Volumes 1, 2 and 3 of this assessment report and how we will simplify this for the reader.

How global society will act in future and react to climate change is unknown. Yet, to simulate possible climate futures and inform policymakers and broader society, some illustrative possible futures are required. As such a scenario is a description of how the future may develop based on a set of assumptions about key global drivers, including demography, economic processes, technological innovation, governance and lifestyles, and the relationships among these driving forces (Rounsevell and Metzger, 2010; Schweizer and O'Neill, 2013; Chen et al., 2021 (their section 1.6.1.1)). In principle, an infinite range of scenarios can be produced. In practice, a large number of scenarios are produced using Integrated Assessment Models (IAMs; Volume 2). Of these IAM-based scenarios, only a handful can be used to drive complex climate simulations by Earth System Models (ESMs) owing to the massive computational costs of ESM simulations. Successive generations of ESMs use revised illustrative future scenarios (Chen et al., 2021). Because climate adaptation studies for the globe and Ireland (Volume 3) are based upon pre-existing ESM model runs, whereas the physical science basis of climate change (this volume) can make use of the latest ESM results (e.g. Coupled Model Intercomparison Project 6 (CMIP6)), there is typically a one generation of simulations, and thus scenarios, lag between the two (shared socioeconomic pathways (SSPs) in this volume, a mix of SSPs and representative concentration pathways (RCPs) in Volume 3).

This heterogeneity of scenarios across volumes could yield substantial user confusion. To address this, we use this box to outline the key issues and the principal scenarios collections (IAMs, SSPs, RCPs) and then propose a pathway for the reader.

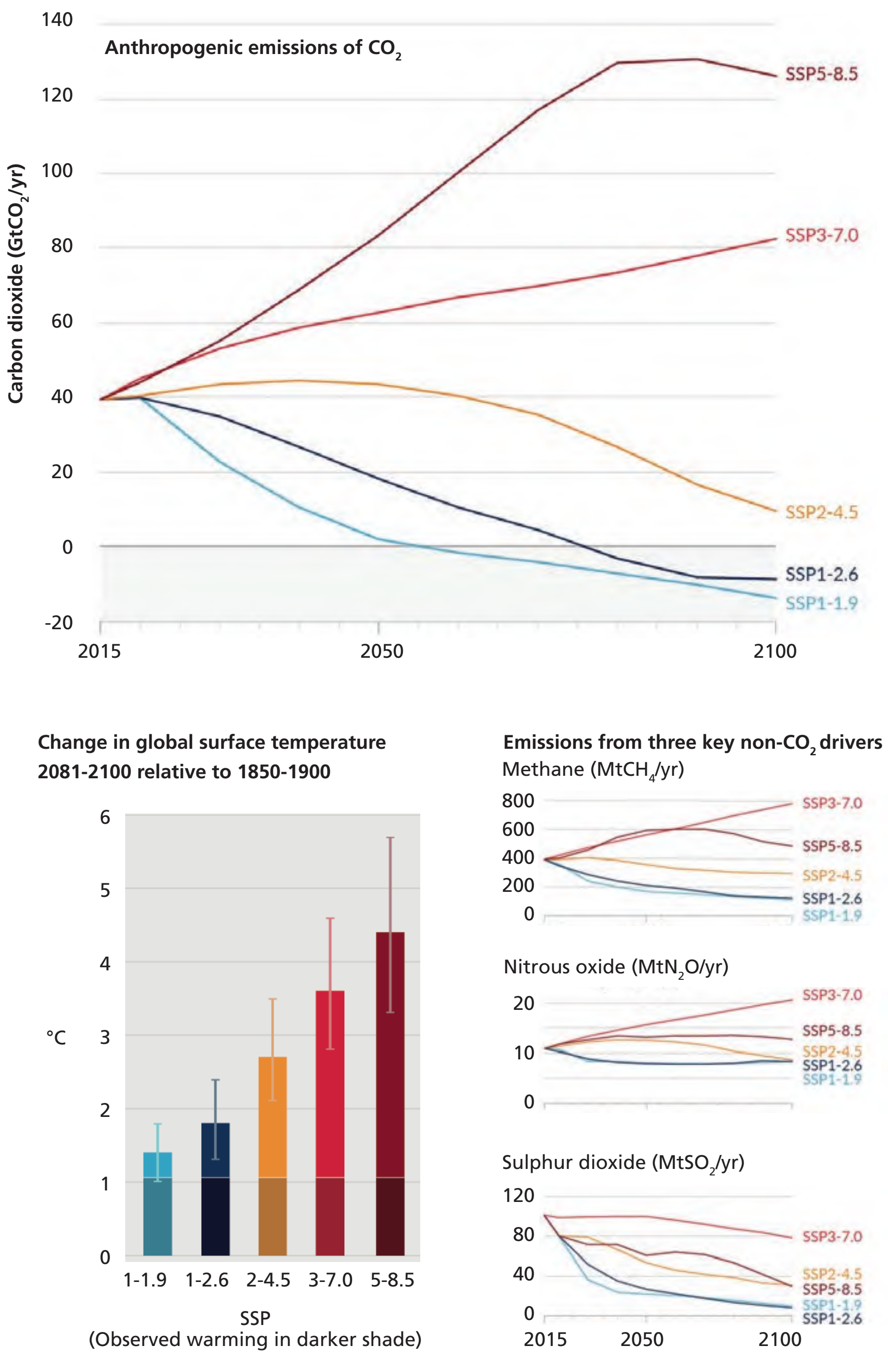
IAMs used in the Working Group (WG) III Sixth Assessment Report (AR6) and Volume 2: IAMs consider broad-ranging socioeconomic, population and technological potential futures and convert these to potential changes in climate system drivers, such as greenhouse gas (GHG) emissions. There are several hundred to several thousand such scenarios produced per cycle of the Intergovernmental Panel on Climate Change (IPCC). In the most recent assessment from the IPCC, seven broad pathways were developed from a collection of 1202 scenarios from a wide range of modelling approaches (IPCC, 2022a). Scenarios tend to be clustered via a variety of techniques, but a common approach is to cluster by the radiative imbalance at the top of the atmosphere at some future time point, such as 2100.

SSP scenarios used in WGI AR6 and Volumes 1 and 3: SSPs are new 'pathways' used in CMIP6. They are being used to explore how societal choices will affect GHG emissions and therefore how the climate goals of the Paris Agreement could be met.

Broadly, the five SSPs represent:

SSP1: Sustainability – Taking the Green Road (low challenges to mitigation and adaptation);
SSP2: Middle of the Road (medium challenges to mitigation and adaptation);
SSP3: Regional Rivalry – A Rocky Road (high challenges to mitigation and adaptation);
SSP4: Inequality – A Road Divided (low challenges to mitigation, high challenges to adaptation);
SSP5: Fossil-fuelled Development – Taking the Highway (high challenges to mitigation, low challenges to adaptation).

Assessment of future emissions and warming under five scenarios



Cross volume Box 1 Figure 1 Illustrative climate scenarios and resulting warming at the end of the century. The five scenarios are SSP1–1.9, SSP1–2.6 (classed here as Early action), SSP2–4.5 (Middle action), SSP3–7.0 and SSP5–8.5 (Late action). Annual anthropogenic (human-caused) emissions over the 2015–2100 period. Shown are emissions trajectories for CO_2 from all sectors ($GtCO_2yr^{-1}$) (top graph) and for a subset of three key non-CO_2 drivers considered in the scenarios: CH_4, $MtCH_4yr^{-1}$, top right graph; N_2O, MtN_2Oyr^{-1}, middle right graph; and sulphur dioxide (SO_2, $MtSO_2yr^{-1}$, bottom right graph, contributing to anthropogenic aerosols. The bottom left graph shows resulting warming by scenario in global surface temperature (°C) in 2081–2100 relative to 1850–1900, with indication of the observed warming to date. Bars and whiskers represent median values and 5–95% range, respectively. The best estimate for observed warming in 2010–2019 relative to 1850–1900 is indicated in the darker column in the 'total' bar. Source: IPCC (2021a; their figure SPM.4, modified herein with permission).

The letters N.N that follow in the SSPM-N.N couplet are the radiative imbalance at the top of the atmosphere in 2100 in Wm^{-2}. A range of different 2100 radiative imbalance values are possible for each SSP. To be able to span the full range of possible outcomes while keeping to a manageable number of outcomes, illustrative scenarios must be run through ESM simulations.

CMIP6 focuses on five scenarios: SSP1–1.9, SSP1–2.6, SSP2–4.5, SSP3–7.0 and SSP5–8.5, the main emissions pathways and assessed temperature implications, which are shown in Cross-volume Box 1, Figure 1.

Representative concentration pathways (RCP) scenarios used principally in: TRANSLATE results in volume 1, WGII AR6 and Volume 3: The RCP scenarios were selected with a similar underlying ethos to the selection of SSP scenarios, but were run on the prior generation of ESMs. The connection between end-of-century forcing and explicit development pathway assumptions is weaker for RCPs. The principal RCPs are RCP2.6, RCP4.5, RCP6.0 and RCP8.5. Three RCPs and SSPs thus have a degree of 'equivalence' (RCP2.6/SSP1–2.6; RCP4.5/SSP2–4.5; and RCP8.5/SSP5–8.5). However, distinctions in the pathway from here to there in terms of the mix of forcings and their variations over time mean that a one-to-one correspondence is not possible. The RCPs have no equivalent to the very high ambition SSP1–1.9. This scenario was added to meet the desire to explicitly look at a climate scenario that could lead to global surface temperatures being stabilised at or below 1.5°C (Meinshausen et al., 2020).

Making sense of these various scenarios: Using various IAMs', SSPs' and RCPs' naming designations within and across Ireland's Climate Change Assessment is not desirable and precludes comparability of assessment results across volumes. For the purpose of this report, we will classify all scenarios across volumes as Early, Middle and Late action.

Cross-volume Box 1 Table 1 Grouping of RCP, SSP and IPCC WGIII families of scenarios into three simple indicative categories to simplify reader interpretation within and across volumes of the EPA Climate Assessment Report. IAM scenarios are classified by 2100 top of atmosphere radiative imbalance, as per the text below

Scenario	Scenario generation		
	CMIP5 (RCP)	CMIP6 (SSP)	IPCC WGIII IAM scenario families
Early action	RCP2.6	SSP1–1.9, SSP1–2.6	C1, C2, C3, (C4)
Middle action	RCP4.5	SSP2–4.5	(C4), C5, C6
Late action	RCP6.0, RCP8.5	SSP3–7.0, SSP5–8.5	C7, C8

Early action: early coordinated and rapid action of the world's nations towards meeting the Paris Agreement's goal of keeping temperature increases well below 2°C and striving to keep them below 1.5°C by 2100. Warming is generally halted at some point in the second half of this century. These scenarios would be likely, but not guaranteed, to result in keeping warming below 2°C. Any scenarios with a radiative imbalance of $3.0Wm^{-2}$ or lower by the year 2100 will be classed as an Early action scenario.

Middle action: delayed action (ambitious targets reached only after the 2020s), resulting in substantial overshoot of the Paris Agreement's goal of keeping warming well below 2°C. Warming generally continues beyond the end of the century in these scenarios. Any scenarios with a 2100 radiative imbalance of $>3.0Wm^{-2}$ to $5.5Wm^{-2}$ will be classed as a Middle action scenario.

Late action: uncoordinated action or major actions only late in the 21st century if at all, with 3°C of warming or greater by 2100 and continued warming thereafter. Any scenarios with a 2100 radiative imbalance in excess of $5.5Wm^{-2}$ will be classed as a Late action scenario.

For full traceability, figures and tables will also explicitly label scenarios where appropriate. However, in the text throughout all four volumes, we shall use these labels to make explicit the link between the effectiveness of global mitigation actions and the resulting climate system response and impacts and thus the adaptation actions that would be needed.

1.8.1 Uncertainties in climate model simulations

When evaluating and analysing simulations, different sources of uncertainty need to be considered (Hawkins and Sutton, 2009; Lehner et al., 2020). These sources are uncertainties in radiative forcings, uncertainty in the climate response to particular radiative forcings, internal and natural variations in the climate system, and interactions among these sources of uncertainty. For ESM projections, it is possible to approximately quantify the relative amplitude of various sources of uncertainty (Hawkins and Sutton, 2009; Lehner et al., 2020). Which sources of uncertainty dominate is inherently a function of the choice of variable, spatial scale, timescale and time horizon (Figure 1.14). Smaller spatial scales and shorter-term projections tend to be dominated by uncertainties associated with internal climate variability, particularly for parameters such as precipitation changes (Lehner et al., 2020). Long-term changes, particularly at the global scale, tend to be dominated by future scenario uncertainty (choice of scenario). Model uncertainties are a substantive contribution across scales, pointing to the importance of understanding and quantifying this source of uncertainty for decision makers and practitioners.

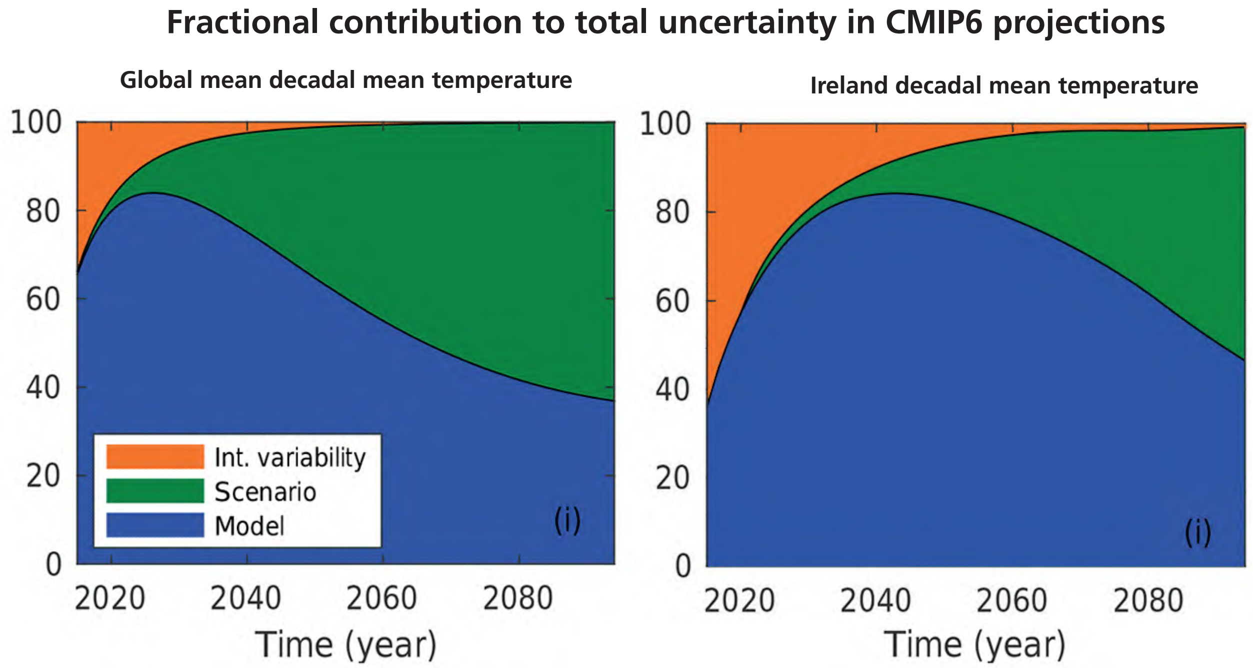


Figure 1.14 The changing total uncertainty and contributions over time to global (left) and Ireland (right) decadal mean temperatures from CMIP6. At smaller spatial scales and shorter periods, internal variability dominates. On a centennial timescale, scenario uncertainty dominates. On multi-decadal timescales, model uncertainty tends to be dominant. Source: Lehner et al. (2020; with Ireland panel provided for this report).

1.8.2 Future projections

The future global emissions pathway will determine the climate trajectory over the coming century and beyond (Figure 1.15). Early action scenarios can maintain the temperature increase below 2°C throughout this century, with aggressive early action returning below 1.5°C global warming after a temporary overshoot (IPCC, 2021a). Late action, on the other hand, could lead to temperature changes relative to 1850–1900, exceeding 3°C global warming by the century's end. Changes will also occur to many other components of the climate system in response to which emissions pathway we follow. Some components, such as temperature and precipitation, respond within years to decades to changes in radiative forcing (Figure 1.15; section 2.3.1), meaning that if net zero GHG emissions were achieved they would stabilise quickly (Lee et al., 2021).

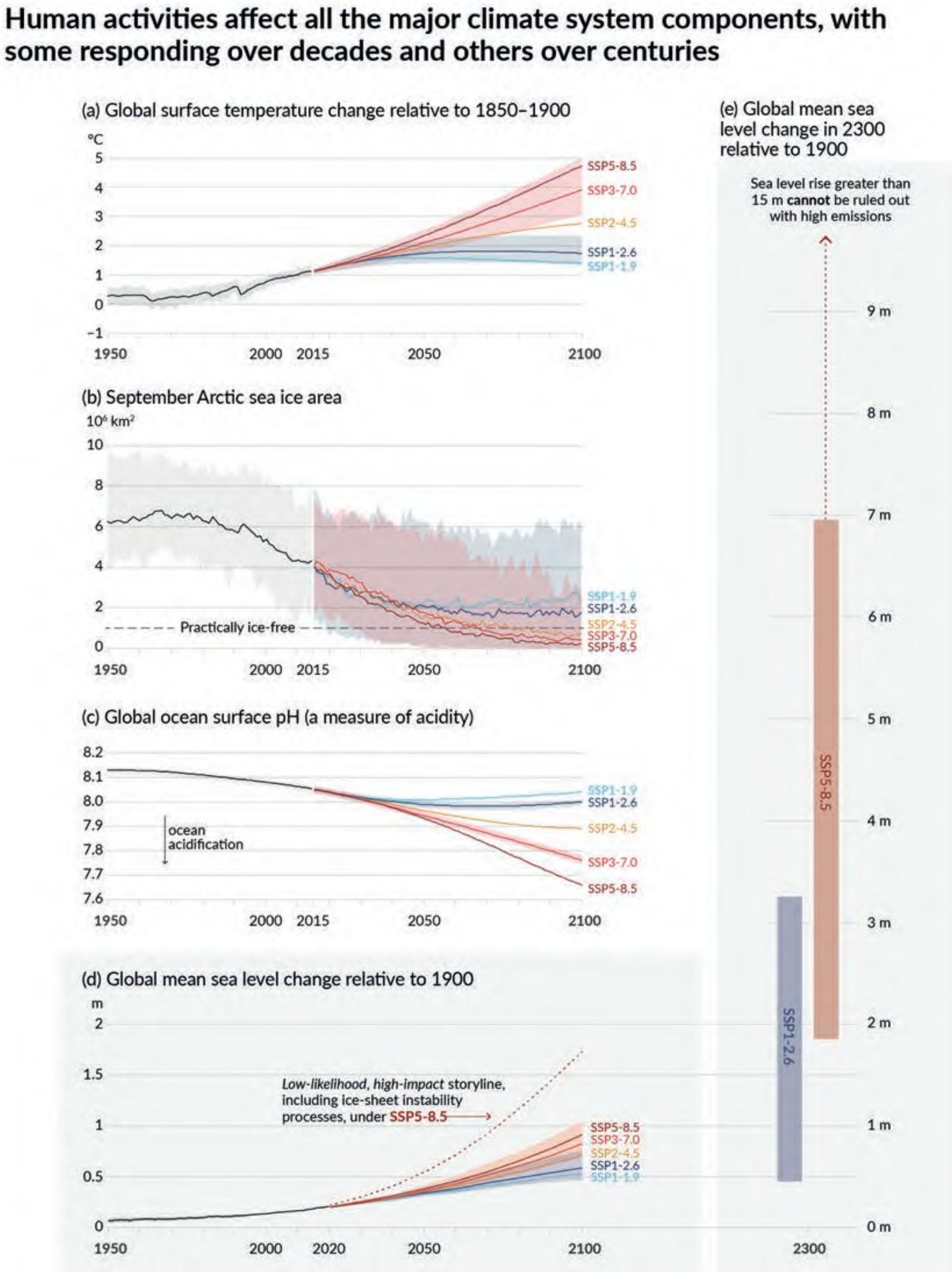


Figure 1.15 Selected indicators of global climate change under the five illustrative scenarios in CMIP6. The projections for each of the five scenarios are shown in colour. Shades represent uncertainty ranges – more detail is provided for each panel below. The black curves represent the historical simulations (panels a, b, c) or the observations (panel d). Historical values are included in all graphs to provide context for the projected future changes. Panel (a) shows global surface temperature (based on CMIP6 model simulations) changes in °C relative to 1850–1900. Panel (b) shows September Arctic sea ice area in 10^6 km^2 (based on CMIP6 model simulations). Very likely ranges are shown for Early (SSP1–2.6) and Late (SSP3–7.0) action in panels (a) and (b). The Arctic is projected to be practically ice free near mid-century under middle and late action scenarios. Panel (c) shows global ocean surface pH, a measure of acidity. Panel (d) shows global mean sea level change in metres relative to 1900. The historical changes are observed (from tide gauges before 1992 and altimeters afterwards), and the future changes are assessed consistently with observational constraints based on emulation of CMIP, ice sheet and glacier models. Likely ranges are shown for Early (SSP1–2.6) and Late (SSP3–7.0) action. Panel (e) shows global mean sea level change for the year 2300 in metres relative to 1900. Only Early (SSP1–2.6) and Late (SSP5-8.5) action are projected at 2300. The 17th–83rd percentile ranges are shaded. The dashed arrow includes low-likelihood, high-impact ice sheet processes that cannot be ruled out under Late action (SSP5–8.5) (see section 8.3.2). Source: IPCC (2021a; their figure SPM.8).

Lee et al. (2021) performed an assessment of when certain temperature thresholds might be exceeded (calculated from rolling 20-year averages) based upon multiple lines of evidence. This included ESM simulations but also the assessment of key processes and the observational and paleoclimate record (Table 1.1). They found that global warming of 1.5°C will likely be reached by the early to mid-2030s in all scenarios, and in all but the earliest action scenario assessed will be exceeded on a sustained basis. Furthermore, global warming of 2°C, relative to 1850–1900, would be exceeded during the 21st century under late action (SSP3–7.0 and SSP–8.5) and would extremely likely be exceeded under Middle action (intermediate scenario SSP2–4.5). Under the Early action scenarios, global warming of 2°C is extremely unlikely to be exceeded (SSP1–1.9) or unlikely to be exceeded (SSP1–2.6). Crossing the 2°C global warming level in the mid-term period (2041–2060) is very likely to occur under the Late action pathway (SSP5–8.5) and more likely than not to occur in the Middle action pathway (SSP2–4.5).

Because of internal variability, single years will exceed a global threshold, such as 1.5°C, in advance of the threshold being reached on a sustained basis. It is important to stress that as we approach a given threshold a single year of exceedance of a value does not mean that the value has been reached in the long-term average and does not mean that it is too late to avoid exceedance on a sustained basis (Lee et al., 2021).

Table 1.1 Summary of temperature projections by time slice and scenario based upon the method of Lee et al. (2021). Very likely ranges correspond to 5–95% expectation that the value will fall within the stated range. SSP1–1.9 and SSP1–2.6 constitute Early action scenarios, SSP2–4.5 Middle action and SSP3–7.0 and SSP5–8.5 Late action

Scenario	Near term, 2021–2040		Mid-term, 2041–2060		Long term, 2081–2100	
	Best estimate (°C)	Very likely range (°C)	Best estimate (°C)	Very likely range (°C)	Best estimate (°C)	Very likely range (°C)
SSP1–1.9 (Early action)	1.5	1.2–1.7	1.6	1.2–2.0	1.4	1.0–1.8
SSP1–2.6 (Early action)	1.5	1.2–1.8	1.7	1.3–2.2	1.8	1.3–2.4
SSP2–4.5 (Middle action)	1.5	1.2–1.8	2.0	1.6–2.5	2.7	2.1–3.5
SSP3–7.0 (Late action)	1.5	1.2–1.8	2.1	1.7–2.6	3.6	3.8–4.6
SSP5–8.5 (Late action)	1.6	1.3 to 1.9	2.4	1.9 to 3.0	4.4	3.3 to 5.7

Source: IPCC (2021a; their table SPM.1).

The future...

The climate we and the young generations will experience depends on future emissions. Reducing emissions rapidly will limit future changes, but continued emissions will trigger larger, faster changes that will increasingly affect all regions. Some changes will persist for hundreds or thousands of years, so today's choices will have long-lasting consequences (Fig 1.16)

Globally, the impacts of many climate extremes scale with global warming (Figure 1.16), and so every bit of warming avoided by effective mitigation (Volume 2) matters. Many of the aspects of the climate that matter to us, such as temperature and rainfall, respond quickly to external climate system drivers such that, if we reach net zero emissions, then we can stabilise these within the lifetimes of today's young adults (Figure 1.15). However, it is important to note that we have set in motion changes in much slower components of the climate system, the ocean and the ice sheets (and sea level rise) that will take centuries to millennia to play out. Actions we take today are the difference between multi-metre rises and tens of metres of rises that future generations will eventually have to cope with (Fox-Kemper et al., 2021).

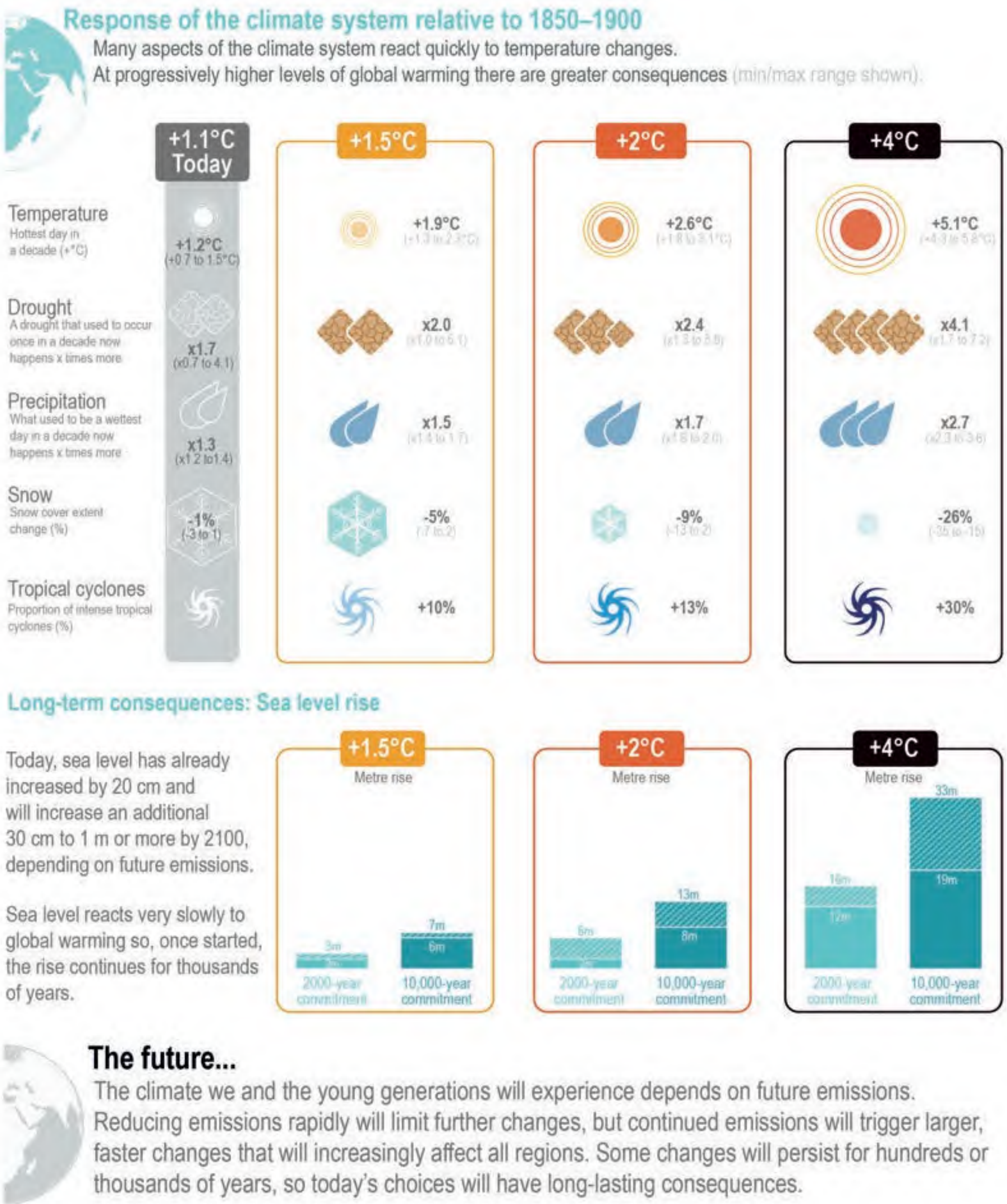


Figure 1.16 Future climate scenarios summary showing how fast and slow reacting components of the climate system would change at different temperature thresholds. Source: Arias et al. (2021; part of their infographic).

Climate change will not unfold uniformly across the globe. There are important regional differences, and some areas are projected to be affected more than others. For example, the Arctic warms considerably more than other regions, land areas warm more than the ocean, and the northern hemisphere warms more than the southern hemisphere (Lee et al., 2021). Precipitation increases over high latitudes, the tropics and large parts of the monsoon regions, but decreases over the subtropics. In other words, wet regions will get wetter and dry regions dryer. These changes are projected to amplify as the level of global warming increases (Figure 1.17). The assessment of national changes is undertaken in Part B of this volume.

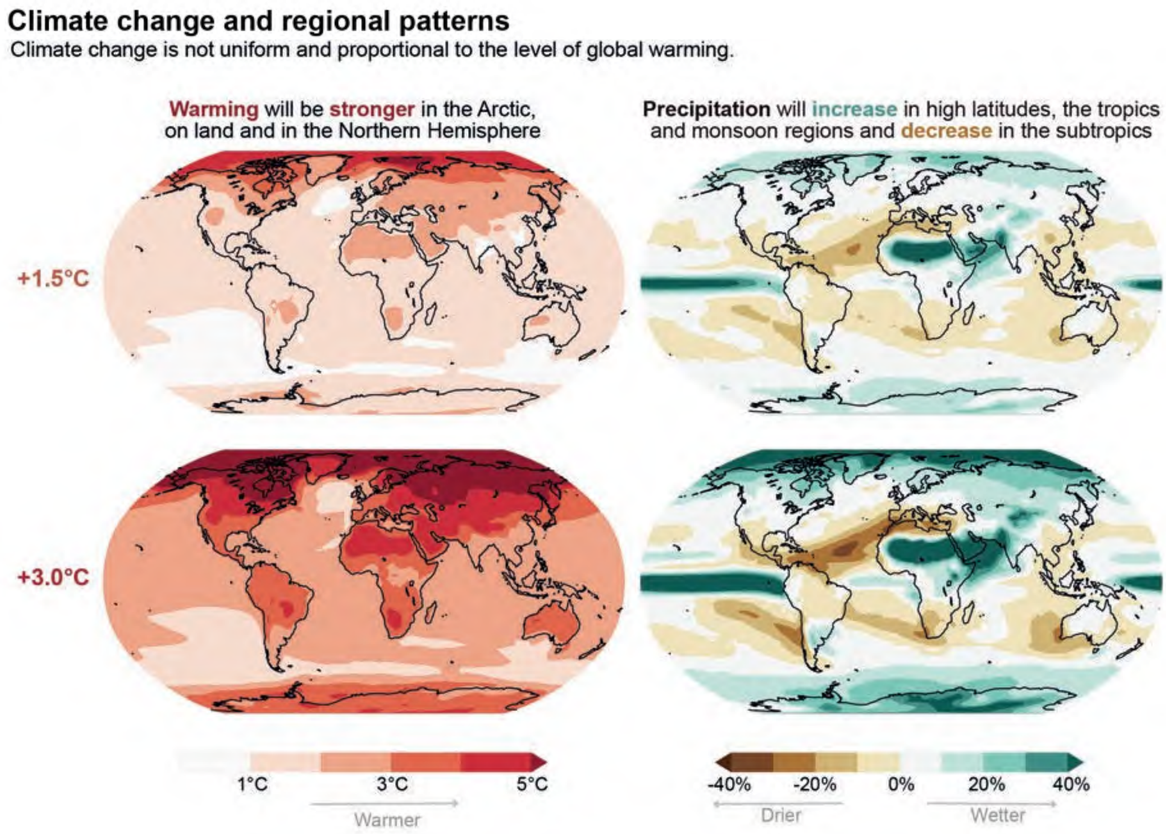


Figure 1.17 Regional patterns in climate change. Regional changes in temperature (left) and precipitation (right) are proportional to the level of global warming, irrespective of the scenario through which the level of global warming is reached. Surface warming and precipitation change are shown relative to the 1850–1900 climate, and for time periods over which the globally averaged surface warming is 1.5°C (top) and 3°C (bottom), respectively. Changes presented here are based on 31 CMIP6 models using the Late action scenario (SSP3–7.0). Source: Lee et al. (2021; their FAQ 4.1 figure 1).

1.9 Recommendations

1.1	Irish participation in IPCC reports should be more actively sought. In several other countries, the government actively tenders for nominations for every Special Report and Working Group report and nominates multiple individuals per report. Strong participation would ensure an Irish voice at the table as well as acting as an opportunity for significant career advancement and building of international research collaboration networks for Irish researchers. Sufficient support for authors needs to be put in place to enable relief from other duties. For those appointed coordinating lead authors, funding should be made available to support a full-time chapter scientist position, as is done by many other countries.
1.2	Much of the Mace Head research is funded through short-term competitive funding. While there is undoubtedly a role for such funding, it is imperative that the long-term monitoring capabilities (including necessary personnel) be given sustained and guaranteed funding support for this critical national contribution to European and global monitoring. This is even more important now that Mace Head is officially part of the Integrated Carbon Observation System Research Infrastructure.
1.3	Sustained and guaranteed support for both national supercomputing capability and modelling research is vital to underpin our national climate research ambitions. Producing ESM and RCM simulations is a continuous and long-term task that requires substantial expertise, high-performance computing and storage resources to run the models, analyse, package up and share the resulting large datasets. It is essential that climate modelling research and the national supercomputing centre (ICHEC) are adequately resourced into the future on a sustained basis in terms of both personnel and hardware.

2

Understanding of the Global Climate System

Key messages

Human activities are changing the natural cycles of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), leading to increases in their concentrations in the atmosphere. These changes arise from the extraction and burning of fossil fuels; changes in land use, land cover and forestry; agriculture; landfill; and cement production.

Historically, about half of the CO_2 that human activities have emitted has been taken up by natural carbon sinks on land and in the ocean. These natural sinks have slowed the build-up of CO_2 in the atmosphere and resulting global warming. However, these sinks are beginning to respond to climate change in a way that weakens their capacity to take up CO_2, and this will likely continue in the future unless global emissions are rapidly reduced.

To stabilise the climate requires CO_2 emissions to reach net zero and emissions of remaining greenhouse gases (GHGs) to be substantially reduced on a sustained basis. It is still possible to attain the Paris Agreement goal of keeping global temperature increases well below 2°C while striving to limit warming to 1.5°C. To limit warming to 1.5°C, global CO_2 emissions need to be reduced to at least net zero by approximately mid-century and emissions of other GHGs simultaneously substantially reduced.

There exists an almost linear relationship between cumulative CO_2 emissions and global temperatures. Based upon this, a global remaining carbon budget can be inferred, conditional upon assumptions of future emissions of a range of additional GHGs, to keep future warming below any given temperature threshold. In the Intergovernmental Panel for Climate Change Sixth Assessment Report (IPCC AR6) it is assessed that for a two in three chance of staying below 1.5°C we can emit only 400 additional Gigatonnes (Gt) of CO_2 from 2020. This estimate assumes substantial reductions in emissions of remaining GHGs, including a 50% reduction in CH_4 emissions and a 25% reduction in N_2O emissions by 2050. If such cuts in non-CO_2 GHG emissions are not fully achieved, the remaining carbon budget would shrink commensurately. In IPCC AR6 this non-CO_2 effect is assessed to have an uncertainty of 220Gt carbon equivalent (66% range). Historical human emissions are almost 2,600Gt of CO_2, and at current global emission rates of c.40Gt of CO_2 a year only a few years remain before exceeding the remaining budget to keep warming below 1.5°C.

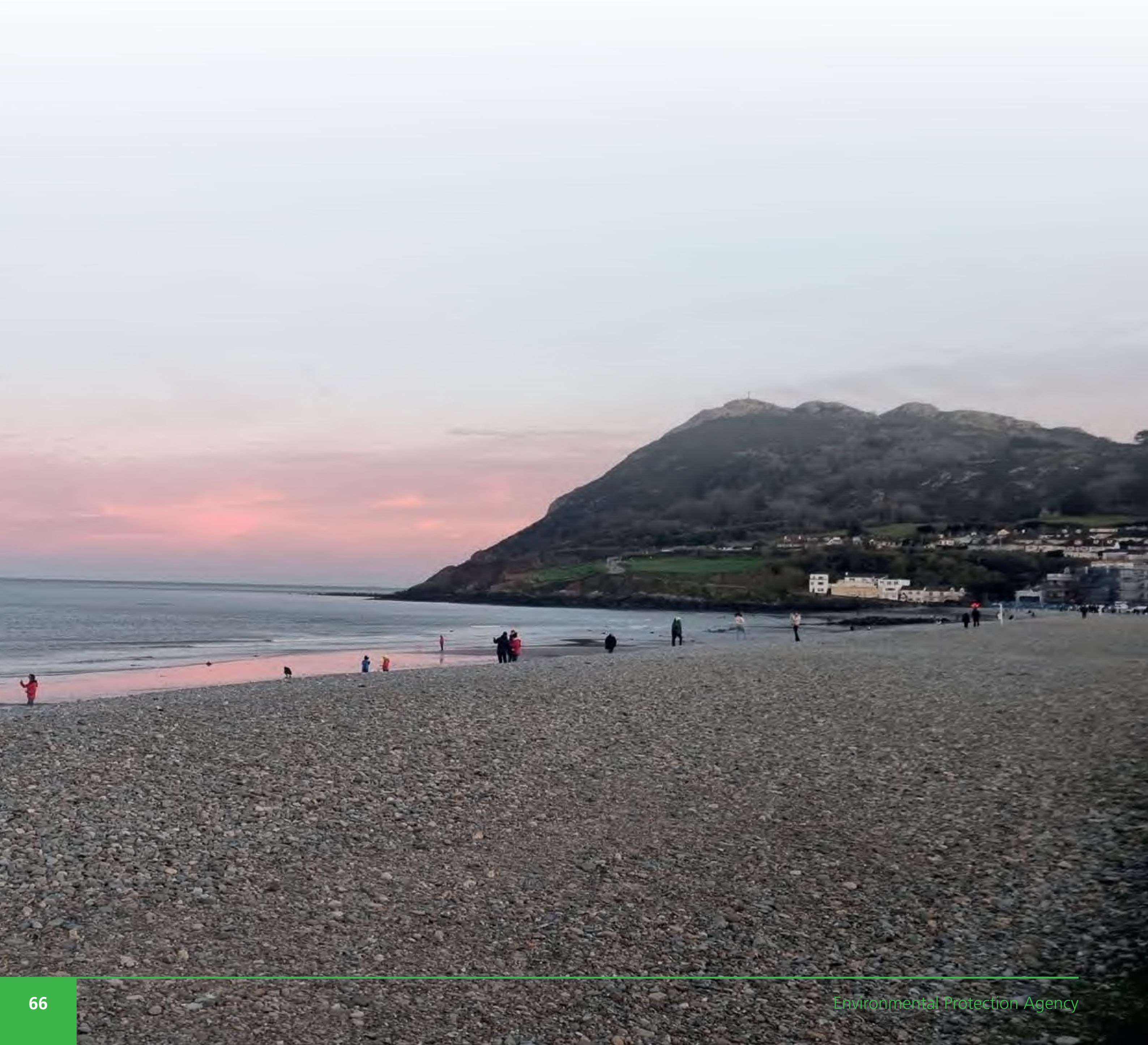
Common metrics are used to aggregate and compare the effects of different GHG emissions and policies. Because gases vary substantially in terms of their warming impacts and lifetime in the atmosphere, different metrics provide different perspectives. In international, European and national accounting, GWP_{100}, which calculates emissions impacts of each GHG integrated over a 100-year timescale compared to those of atmospheric CO_2, is used. GWP values are periodically reassessed as atmospheric composition evolves and new evidence arises. These are compiled and assessed by the IPCC in each assessment cycle. Reaching net zero under GWP_{100} would result in a slow cooling of the climate system. Newer, step-pulse metrics such as GWP* better model the temperature outcomes for a broad range of timescales. Emerging approaches that separately bundle and treat short-lived (less than a decade or so) and long-lived (centennial timescale plus) gases may lead to better policymaking. The IPCC does not recommend a specific metric. Ultimately, the metric used will depend upon the question being posed, and it is therefore not possible to define a preferred metric.

Policies aimed at addressing climate change may have benefits or consequences for air quality. The potential importance of reducing emissions of short-lived climate forcers such as CH_4 is recognised not only to mitigate climate change but also to improve air quality and therefore bring near-term co-benefits in terms of human health, agricultural yields, and ecosystem functioning. Measures which negatively impact on air quality such as burning of wood for home heating and gas stoves for cooking as possible mitigation measures should be avoided.

The North Atlantic Ocean, which has a profound influence on Ireland's climate, will take many centuries to catch up with and respond to the changes we have already set in motion. Changes to the Atlantic Meridional Overturning Circulation (AMOC) may impact Irish climate. The AMOC keeps our winters warm and our summers cool. The AMOC is predicted to decline due to climate change, but observations are not entirely conclusive as to whether this is already occurring.

Global mean sea level increases will occur under all scenarios and continue for thousands of years after stabilising global temperature. By 2100 projected additional rises range from 0.32–0.6m under Early action to 0.63–1.01m under Late action scenarios. Over the next 2,000 years, global mean sea level will rise by about 2 to 3m if warming is limited to 1.5°C, 2 to 6m if limited to 2°C and 19 to 22m with 5°C of warming.

Ocean acidification is a result of ocean chemistry in response to increasing CO_2 concentrations. The average surface pH of the ocean will continue to see an unprecedented rate of change, potentially a doubling of acidity by 2100 under late action scenarios. Ocean acidification and warming will rapidly expose marine ecosystems to conditions they have not experienced over many millions of years, with the potential for catastrophic ecosystem collapse.



2.1 Carbon and nitrogen cycles and their human perturbations

2.1.1 The carbon cycle and CO_2

Carbon cycles naturally through the Earth's biosphere, atmosphere and ocean through a range of processes and timescales (Canadell et al., 2021). The balance of these processes determines the amount of CO_2 in the atmosphere at any given time, ocean pH and a host of other aspects of the Earth system (Canadell et al., 2021). CO_2 is the main atmospheric phase of the global carbon cycle. Processes that affect the amount of CO_2 in the atmosphere are referred to as 'sinks' if they remove carbon and 'sources' if they emit carbon. Annual assessments of changes in sources and sinks are undertaken by the Global Carbon Project and quantify fossil fuel and land use-based sources arising from human activities, changes in atmospheric concentrations, and estimates of changes in terrestrial and ocean processes, which currently act as net sinks (Frieldingstein et al., 2022).

From the middle Holocene 6,000–7,000 years ago until around 1750 the natural carbon cycle was broadly in balance, keeping atmospheric CO_2 relatively stable, varying within c.10ppm in the past two millennia (Canadell et al., 2021; Gulev et al., 2021). However, since 1750, and with increasing rapidity in recent decades, fossil fuel-based emissions, land use and cement production are currently substantially impacting the natural biogeochemical cycle of carbon (Figure 2.1) on land, in the atmosphere and in the ocean. Annual CO_2 concentration averages in the past decade have increased by approximately 2.5ppm per year (Gulev et al., 2021; see Figure 1.3). The ocean pH has also continued to decrease (ocean acidification; Orr et al., 2005; Gulev et al., 2021).

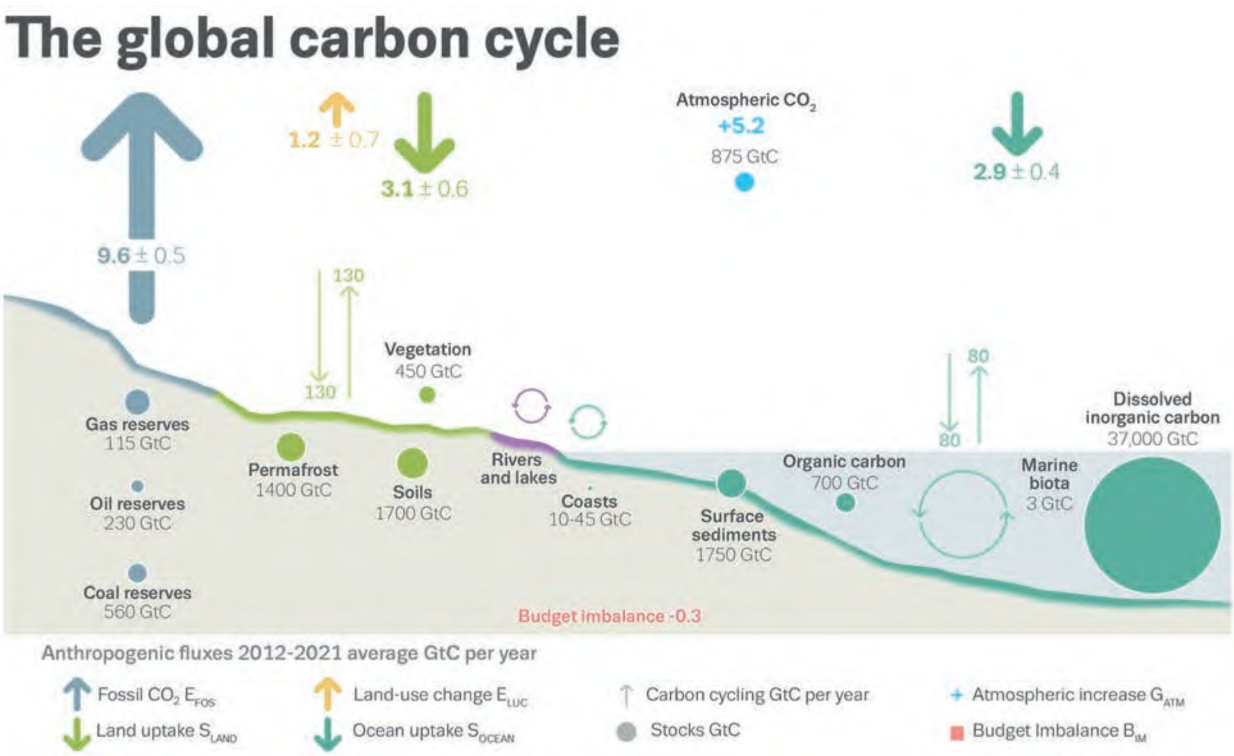


Figure 2.1 Schematic representation of the overall perturbation of the global carbon cycle caused by anthropogenic activities averaged globally for the decade 2012–2021. See legend for the corresponding arrows and units. The uncertainty in the atmospheric CO_2 concentration growth rate is very small ($\pm 0.02 GtCyr^{-1}$) and is not included in the figure. The anthropogenic perturbation occurs on top of an active carbon cycle, with fluxes and stocks represented in the background and taken from Canadell et al. (2021) for all numbers, except for the carbon stocks in coasts, which are from a literature review of coastal marine sediments (Price and Warren, 2016). Source: Friedlingstein et al. (2022; their figure 2). Reproduction licensed under the Creative Commons Attribution CC BY 4.0 licence (https://creativecommons.org/licenses/by/4.0/).

Over the past six decades, about half of the CO_2 that human activities have emitted has been taken up by natural carbon sinks in vegetation, soils and the ocean (Canadell et al., 2021). Quantification of sinks is most uncertain for the terrestrial component across global, regional and national scales (Canadell et al., 2021; CCAC, 2022). These natural sinks buffer human-induced emissions impacts and have slowed the build-up of CO_2 in the atmosphere and resulting global warming. However, observations show that the processes underlying this uptake are beginning to respond to climate change in a way that will weaken nature's capacity to take up CO_2 in the future (Figure 2.2; Canadell et al., 2021). To avoid such a diminished natural sink of CO_2, global emissions must be rapidly reduced.

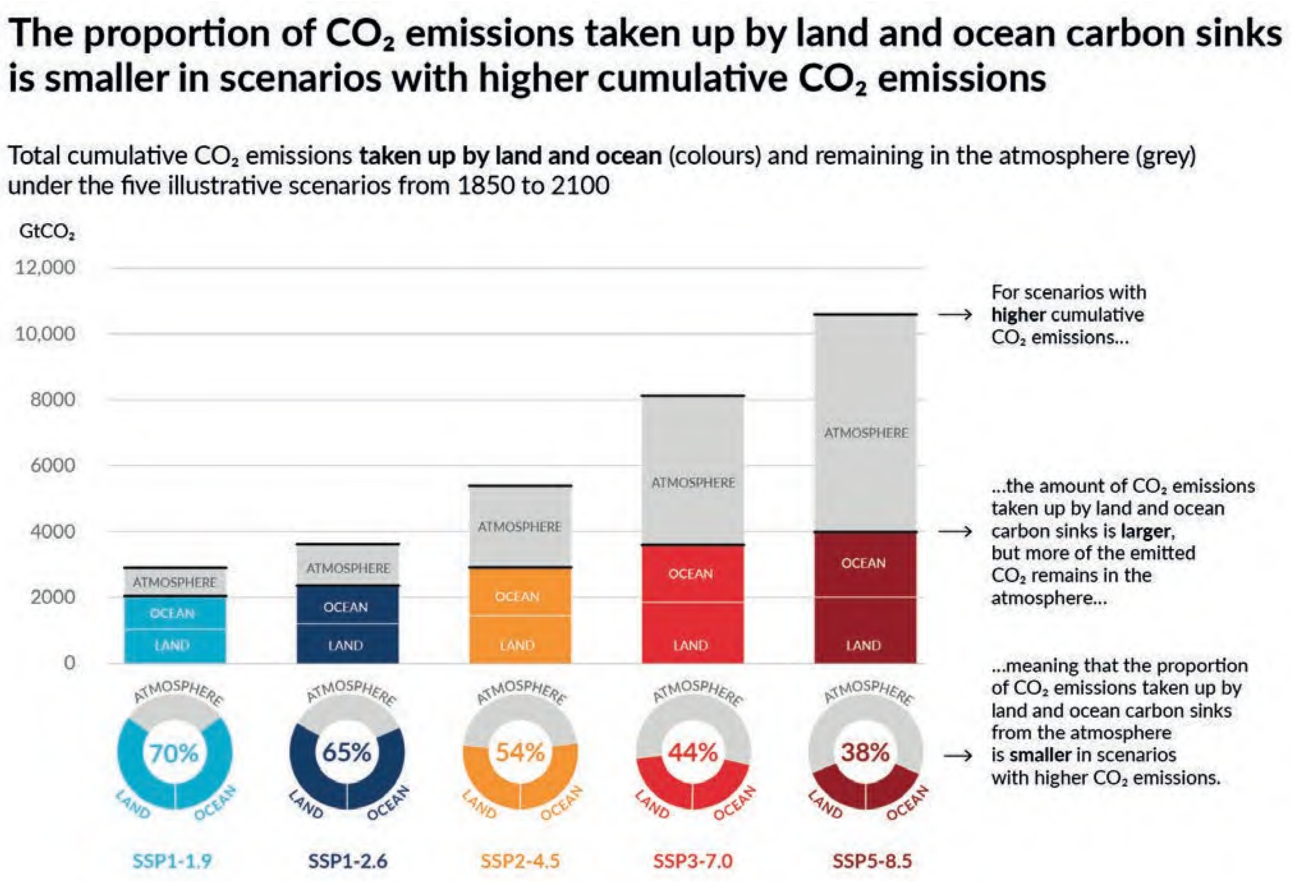


Figure 2.2 The changing efficacy of carbon sinks illustrates the projected amount of cumulative anthropogenic CO_2 emissions ($GtCO_2$) between 1850 and 2100 remaining in the atmosphere (grey part) and taken up by the land and ocean (coloured part) in the year 2100. The doughnut charts illustrate the proportional breakdown. The overall human carbon emissions are calculated by adding the net global land use emissions from the CMIP6 scenario database to the other sectoral emissions calculated from climate model runs with prescribed CO_2 concentrations. Land and ocean CO_2 uptake since 1850 is calculated from the net biome productivity on land, corrected for CO_2 losses due to land use change by adding the land use change emissions and net ocean CO_2 flux. Source: IPCC (2021a; their figure SPM.7).

In the absence of future human interventions to remove and store CO_2 (Volume 2), much of the emissions to date will remain in the atmosphere for millennia, and so would the warming influence (Canadell et al., 2021). The land sink is a fast process, whereas the ocean sink takes the time for the ocean circulation to be well mixed (200–2,000 years). Even once the ocean sink is well mixed it is estimated that 30–35% of the excess CO_2 would remain in the atmosphere (Archer et al., 2009). Eventual removal of this excess carbon will arise from slow processes that sequester carbon into the solid earth via rock weathering, calcium carbonate formation and reactions with igneous (volcanic) rocks, which it is estimated would take thousands of years (Figure 2.3; Archer et al., 2009; Ciais et al., 2013).

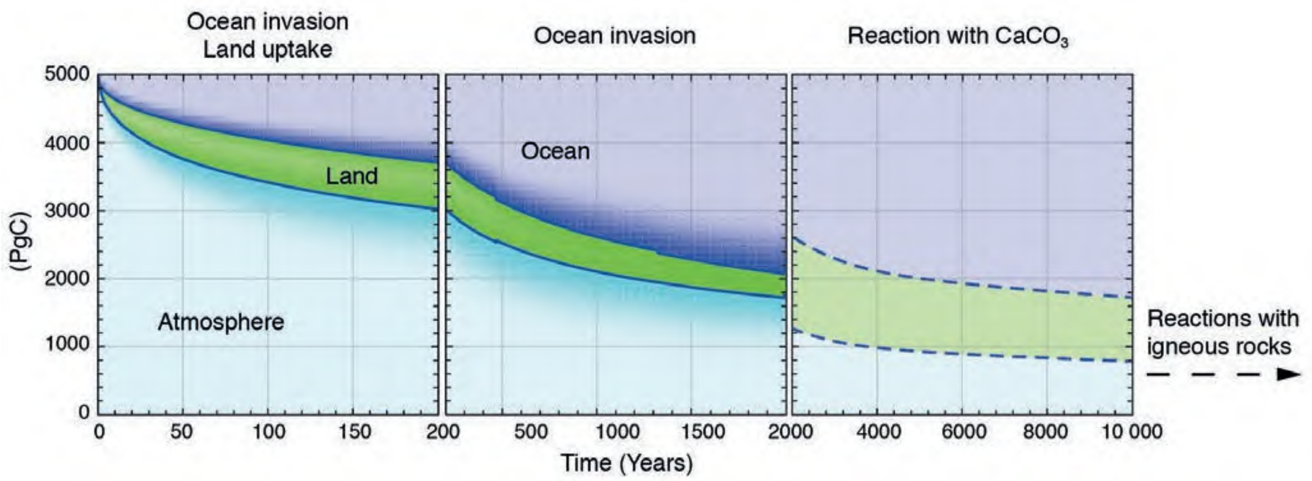


Figure 2.3 Illustration of the relative importance through time of different sinks (removal processes) for a hypothetical pulse emission of 5,000PgC. Note the change in time resolution across the three panels. Source: Ciais et al. (2013; their figure FAQ 6.2 figure 1).

2.1.2 Nitrous oxide

The biogeochemical cycles of nitrogen and carbon are tightly coupled with each other owing to the metabolic needs of organisms for these two elements (Ciais et al., 2013). Changes in the availability of one element will influence not only biological productivity but also availability of and requirements for the other element (Gruber and Galloway, 2008) and, in the longer term, the structure and functioning of ecosystems as well (Shibata et al., 2014; Hideaki et al., 2015). N_2O is principally lost through stratospheric oxidation, which is a slow process. N_2O thus has a lifetime[7] of 116 years and therefore, like CO_2, behaves like a stock forcer (see section 2.3.3) on multi-decadal timescales of relevance to most decision makers and practitioners.

N_2O's natural cycle has been substantially altered by human activities, principally associated with the agricultural sector through the application of chemical nitrogen fertilisers, but with some contributions from fossil fuel combustion (Figure 2.4). Chemical nitrogen fertilisers are key to improvements that have been made in global and national agricultural productivity (Herridge et al., 2008). However, these emissions negatively impact air quality (Aneja et al., 2009) and human health (Davidson, et al., 2011), and have local water pollution issues (Houlton et al., 2019). N_2O also has negative impacts on stratospheric ozone (Tian et al., 2020).

7 Lifetime is defined as the average time an emitted molecule spends in the atmosphere. Because most removal processes involve some form of exponential decay, the lifetime is somewhat longer than the time taken for half the emitted molecules to be removed. Note that due to the complexity of the processes involved CO_2 does not have a quantified lifetime.

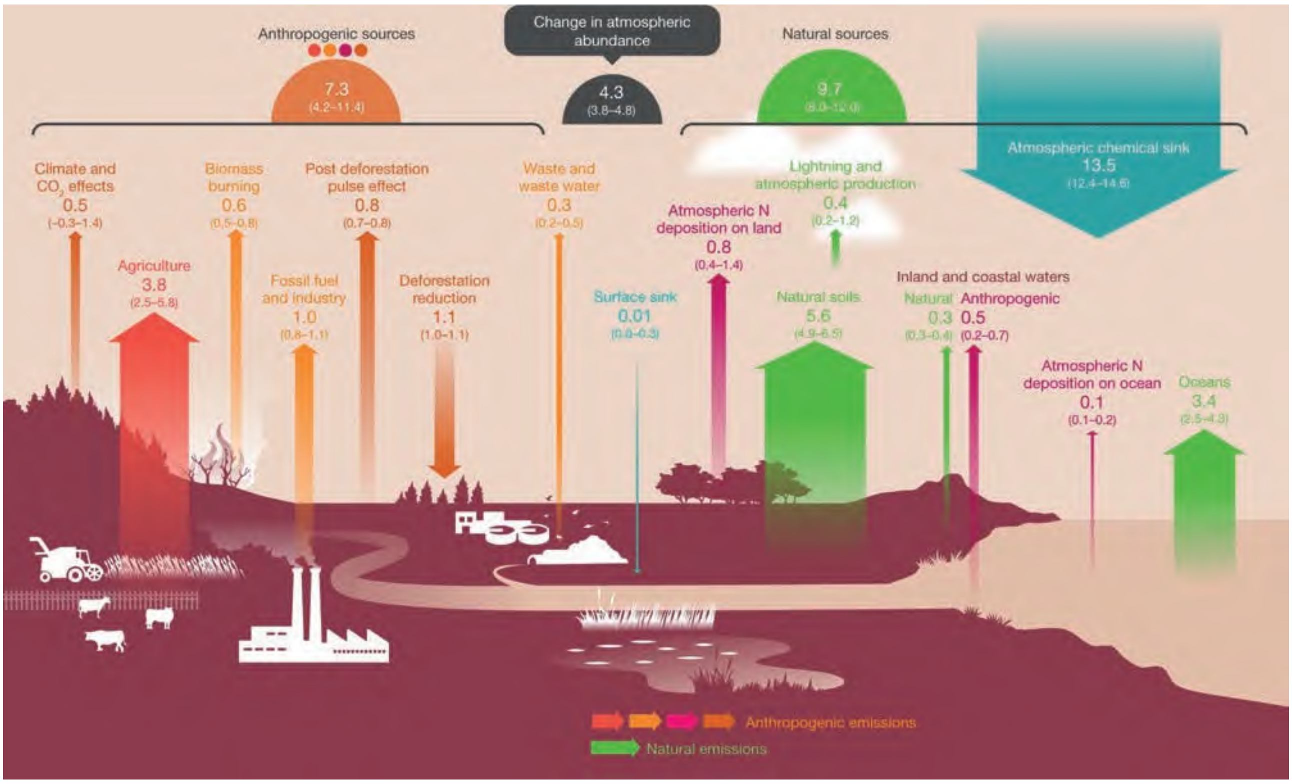


Figure 2.4 The coloured arrows represent N_2O fluxes ($TgNyr^{-1}$) for 2007–2016 as follows: red, direct emissions from nitrogen additions in the agricultural sector (agriculture); orange, emissions from other direct anthropogenic sources; maroon, indirect emissions from anthropogenic nitrogen additions; pink, perturbed fluxes from changes in climate, CO_2 or land cover; green, emissions from natural sources. The anthropogenic and natural N_2O sources are derived from bottom-up estimates. The blue arrows represent the surface sink and the observed atmospheric chemical sink, of which about 1% occurs in the troposphere. The total budget (sources + sinks) does not exactly match the observed atmospheric accumulation, because each of the terms has been derived independently and we do not force top-down agreement by rescaling the terms. This imbalance readily falls within the overall uncertainty in closing the N_2O budget, as reflected in each of the terms. The N_2O sources and sinks are given in $TgNyr^{-1}$. Source: Global Carbon Project.

2.1.3 Methane

CH_4 is one of the most potent GHGs and, per molecule, traps substantially more heat than CO_2 (Forster et al., 2021; section 2.3.3). Through a combination of direct effects and secondary effects on other pollutants, it is assessed to be responsible for 0.5°C (5–95% range 0.3–0.8°C) of the warming since 1850 (Forster et al., 2021; see also Figure 1.11). The CH_4 oxidation process is comparatively quick, with a perturbation lifetime of 11.8 years (Gulev et al., 2021). This means that CH_4 is a flow forcer (section 2.3.3). If emissions of CH_4 were to be reduced, CH_4 concentrations in the atmosphere would fall rapidly, and so would its warming influence. Human-mediated CH_4 emissions principally arise from fossil fuel extraction, landfills and agriculture (principally from ruminants, with a lesser contribution from rice cultivation (Figure 2.5; Saunois et al., 2020)). CH_4 also has non-climate-related effects, as outlined in section 2.2.

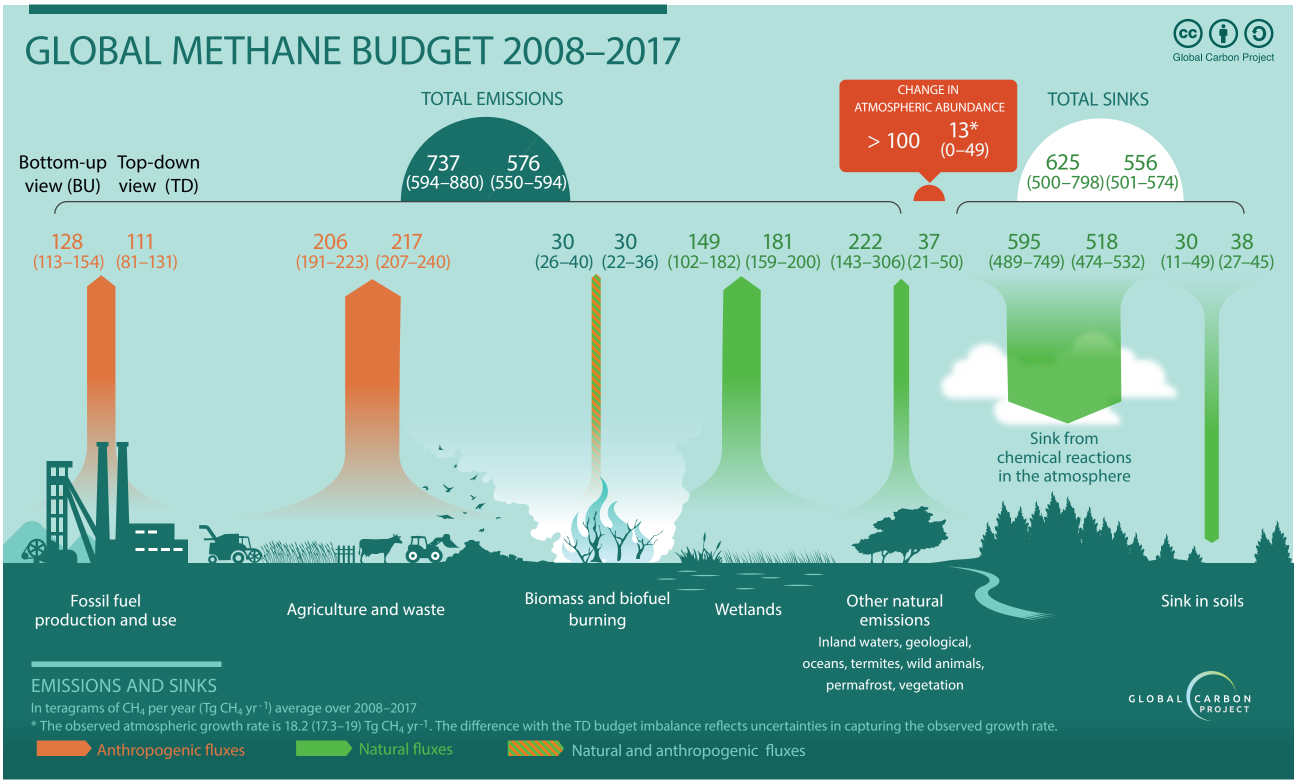


Figure 2.5 Global CH_4 budget for the 2008–2017 decade. Both bottom-up (left) and top-down (right) estimates ($TgCH_4 yr^{-1}$) are provided for each emission and sink category, as well as for total emissions and total sinks. Biomass and biofuel burning emissions are depicted here as both natural and anthropogenic emissions. Source: Saunois et al. (2020; their figure 6). Reproduction licensed under the Creative Commons Attribution CC BY 4.0 licence (https://creativecommons.org/licenses/by/4.0/).

2.2 Short-lived Climate Forcers

Short-lived Climate Forcers (SLCFs)[8] are compounds such as aerosols (suspensions of liquid and solid particles) and gases that warm or cool the Earth's climate over shorter time scales (days to years) than long-lived GHGs such as CO_2 (Szopa et al., 2021). When they absorb radiation they warm the planet, and when they scatter radiation they cool the planet (Figure 2.6). For example, the darkening of snow through the deposition of black carbon and other light-absorbing particles enhances snowmelt in the Arctic, which causes warming (Meredith et al., 2019). They can be classified as direct or indirect, with direct SLCFs exerting climate effects through their radiative forcing and indirect SLCFs being precursors of direct climate forcers. Direct SLCFs include CH_4, ozone (O_3) and some aerosols. Indirect SLCFs include nitrogen oxides (NOx), non-CH_4 volatile organic compounds (NMVOCs), volatile organic compounds (VOCs) and sulphur dioxide (SO_2).

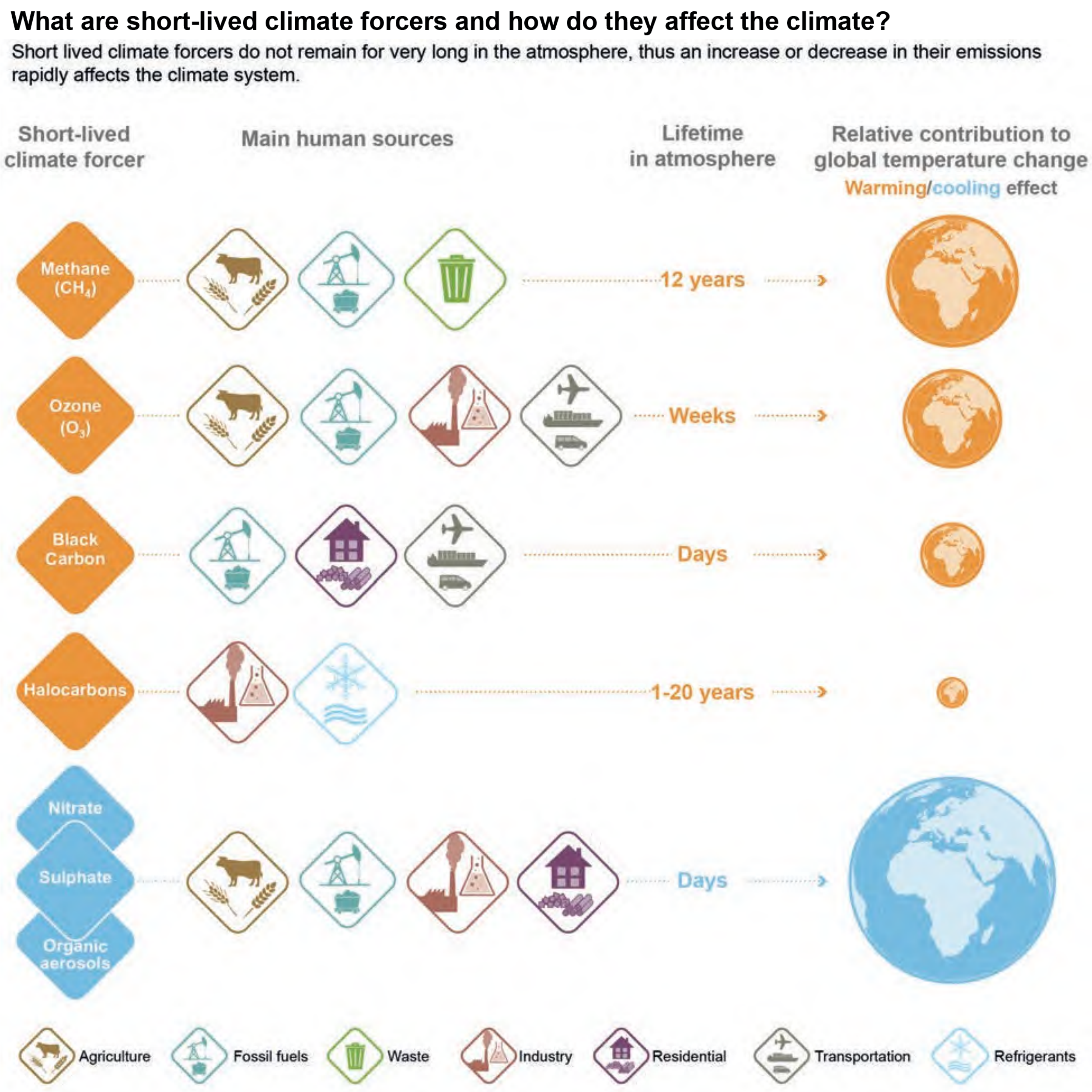


Figure 2.6 Main SLCFs, their sources, how long they exist in the atmosphere, and their relative contribution to global surface temperature changes between 1750 and 2019 (area of the globe). By definition, this contribution depends on the lifetime, the warming/cooling potential (radiative efficiency) and the emissions of each compound in the atmosphere. Blue indicates cooling and orange warming. Note that between 1750 and 2019 the cooling contribution from aerosols (blue diamonds and globe) was approximately half the warming contribution from CO_2. Source: Szopa et al. (2021; their figure FAQ 6.1).

8 Also sometimes referred to as Short-Lived Climate Pollutants (or SCLPs).

Many air pollutants have adverse effects on human health and ecosystems (Szopa et al., 2021). SLCFs also have indoor sources and can play an important role in the health and wellbeing of occupants (Szopa et al., 2021). Sources of indoor pollution include cooking, fireplaces/stoves and household cleaning products. Several indoor air pollutants have been identified as priority pollutants, including particulate matter (PM), radon, nitrogen dioxide, O_3, formaldehyde and carbon monoxide. Studies have highlighted the opportunities for energy retrofits to improve indoor air quality through appropriately designed ventilation (Tieskens et al., 2021; Volume 2). The United Nations Economic Commission for Europe Convention on Long-range Transboundary Air Pollution has been instrumental in lowering the emissions of certain pollutants in Europe, especially SO_2 (Lisowska-Mieszkowska, 2020).

Ozone is a gas that exists in two layers of the atmosphere: the stratosphere (upper atmosphere) and the troposphere (near ground level). The saying goes 'ozone – good up high, bad nearby' (Yang, 2020; Figure 2.7). Here, the 'good' ozone refers to the ozone in the upper atmosphere, the ozone layer, which protects life on Earth from the sun's harmful ultraviolet (UV) rays (Ritchie et al., 2018; see section 1.1.2). The 'bad' ozone is an air pollutant at ground level that is harmful to breathe and damages crops, trees and other vegetation (Saxena et al., 2019).

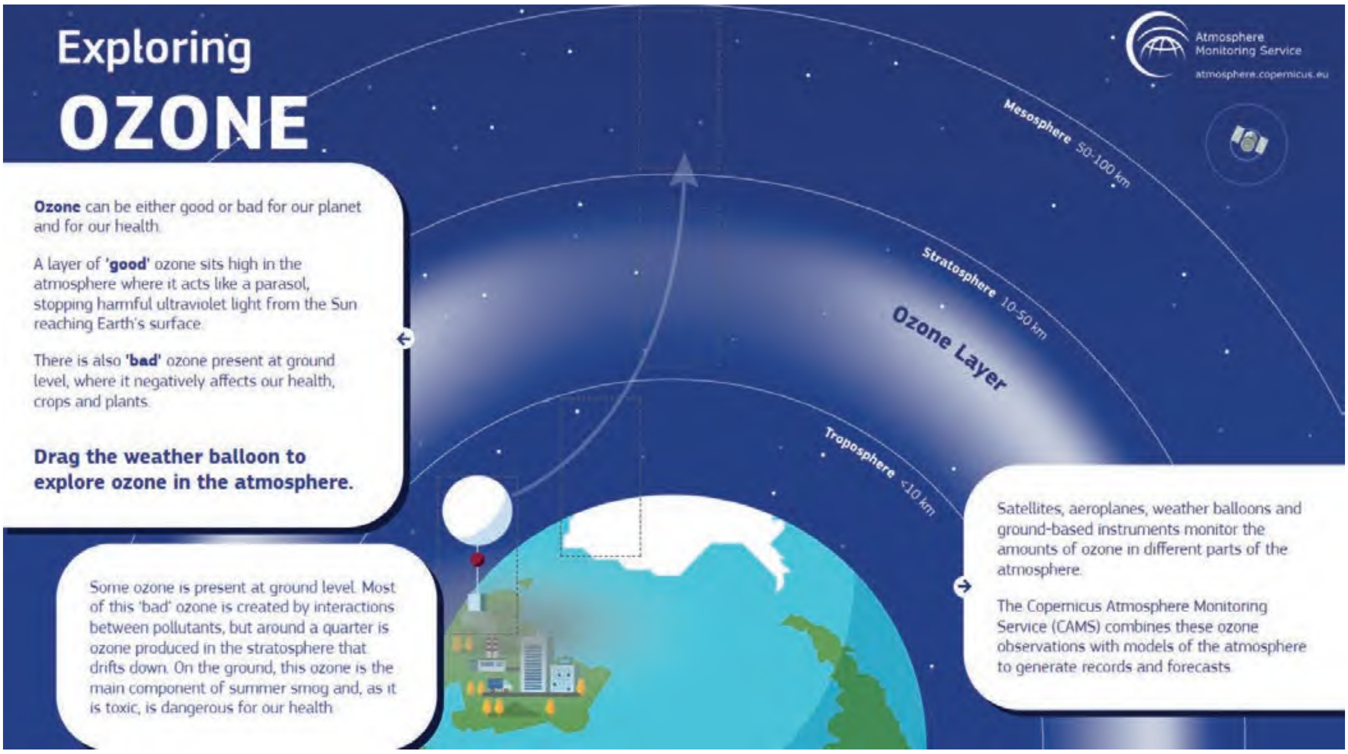


Figure 2.7 Ozone infographic. Source: Copernicus Atmosphere Monitoring Service.

"Air pollution is identified as the single biggest environmental health risk by the World Health Organization (WHO) and the cause of over 7 million premature deaths per year worldwide (Landrigan et al., 2018)."

CROSS VOLUME

CROSS-VOLUME BOX 2 CLIMATE AND AIR POLLUTION

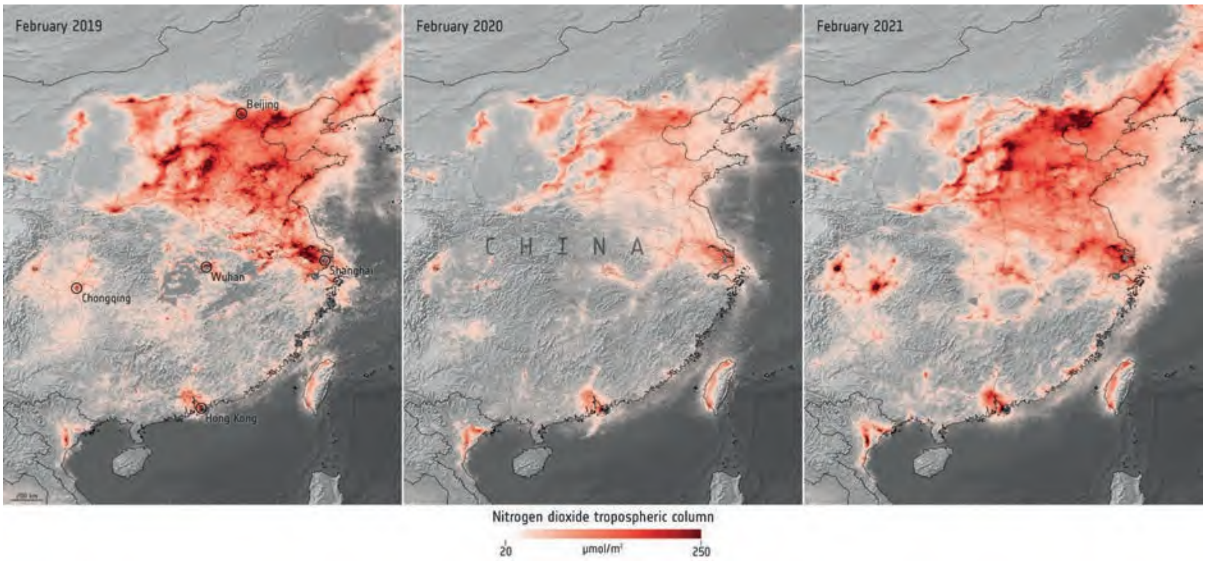
Air pollution is identified as the single biggest environmental health risk by the World Health Organization (WHO) and the cause of over 7 million premature deaths per year worldwide (Landrigan et al., 2018). The potential importance of reducing emissions of short-lived climate forcers (SLCFs) is recognised not only to mitigate climate change but also to improve air quality and therefore bring near-term co-benefits in terms of human health, agricultural yields and ecosystems (UN Environment Programme and World Meteorological Organization, 2011; Climate and Clean Air Coalition, 2018; Rafaj and Amann, 2018; UN Environment Programme, 2018; Volume 3). Air pollutants settle onto vegetation/ecosystems/water surfaces, having a negative impact on their health. Air pollutants also produce adverse health effects; asthma and lung cancer are of major concern due to inhalation exposure of these pollutants (Saxena et al., 2019). Reductions in these pollutants contribute to improved human health and sustainable cities (Lelieveld et al., 2014; Lelieveld and Pöschl, 2017) but also improve access to affordable and clean energy and address climate mitigation, as well as reducing nutrient losses and protecting biodiversity (Amann et al., 2020). Declining SLCF emissions will result in reduced crop losses (Sustainable Development Goal 2; zero hunger) due to the decrease in ozone (O_3) exposure (Emberson et al., 2018).

COVID lockdown

In response to the outbreak of COVID-19, in many countries restrictions were implemented on the movement of people, requiring the majority of the population to stay at home. Owing to the short atmospheric lifetimes of these pollutants, changes in their concentrations were detected within a few days after lockdowns had been implemented (e.g. Bauwens et al., 2020; Gkatzelis et al., 2021); this was termed ‘covid blue’, as people around the globe started posting pictures of blue skies on social media (Cross-volume Box 2, Figure 1).

Cross-volume Box 2 Figure 1 ‘Covid-blue’ skies appearing over New Delhi’s India Gate war memorial during its initial COVID-19 lockdown: 17 October 2019 (left) and 8 April 2020 (right). Photo credits: Anushree Fadnavis and Adnan Abidi/Reuters.

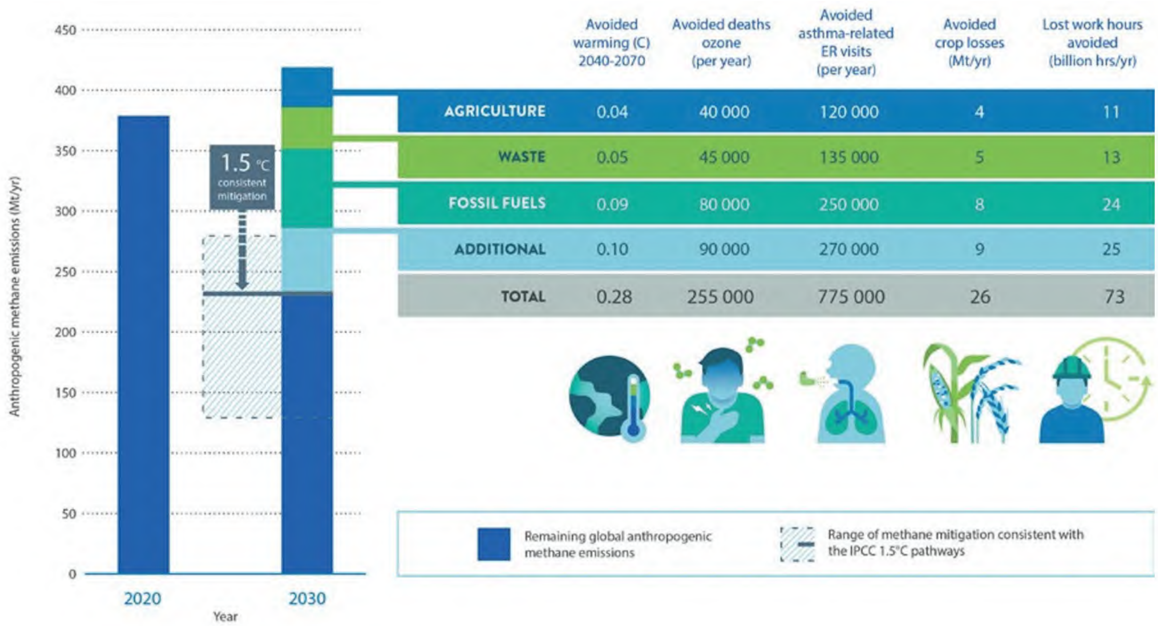
Images captured from the Copernicus Sentinel-5P satellite, provided by the European Space Agency (ESA), showed sharp reductions in nitrogen dioxide (NO_2) concentrations across several cities across the globe (Cross-volume Box 2, Figure 2) due to reduced emissions, principally from transport. However, as restrictions eased, the average level of air pollutants quickly rebounded (Dong et al., 2022). Several studies have examined the effect of COVID-19 containment on air quality, showing that multi-year datasets with proper statistical/modelling analysis are required to distinguish the effect of meteorology from that of emission reductions locally (Dhaka et al., 2020; Zhao et al., 2020). The median observed change in NO_2 was a decrease of between 13% and 48%, and particulate matter decreased by 10–33%, whereas the median O_3 concentration increased by 0–4% (Gkatzelis et al., 2021).



Cross volume Box 2 Figure 2 NO_2 concentrations over China in February 2019, February 2020 and February 2021, from the Copernicus Sentinel-5P satellite. The map shows the fluctuation in levels between the three periods, with dark red indicating high concentrations of NO_2. Source: ESA.

Many sources simultaneously emit carbon dioxide and air pollutants; therefore, policies aimed at addressing climate change may have benefits or side-effects for air quality, and vice versa (Szopa et al., 2021). Short-term 'win–win' policies that improve air quality and limit climate change include the use of clean renewable energy, zero-emission vehicles and using induction stoves for heating and cooking; replacing a gas stove (natural gas or a natural gas mixed with hydrogen or biogas) with an induction stove reduces your carbon footprint and improves air quality.

Methane (CH_4) contributes to the formation of ground-level O_3, a dangerous air pollutant (see section 2.2) and one of the major constituents of smog produced by human pollutants, with the highest levels of O_3 occurring during periods of sunny weather (Manisalidis et al., 2020). Over O_3-producing regions of the world, such as in North America, Europe and East Asia, studies project a general increase in ground-level O_3 in a future warmer climate, particularly during summertime (Fu and Tian, 2019; Nolte et al., 2021; Adame et al., 2022). The Global Methane Assessment integrates the climate and air pollution costs and benefits from CH_4 mitigation (UN Environment Programme and Climate and Clean Air Coalition, 2021). The assessment reports that a 45% reduction in global CH_4 emissions would prevent 260,000 premature deaths, 775,000 asthma-related hospital visits, 73 billion hours of labour lost from the effects of extreme heat, and 25 million tonnes of crop losses annually (Cross-volume Box 2, Figure 3; UN Environment Programme and Climate and Clean Air Coalition, 2021).



Cross volume Box 2 Figure 3: Current and projected anthropogenic CH_4 emissions and the identified sectoral mitigation potential in 2030, along with several benefits associated with CH_4 emissions mitigation. Avoided warming occurs in the 2040s;, other impacts are annual values beginning in 2030 that would continue thereafter. The specific measures include the following:

- Oil, gas and coal: the fossil fuel sector has the greatest potential for targeted mitigation by 2030.
- Waste: existing targeted measures could reduce CH_4 emissions from the waste sector by 29–36Mtyr^{-1} by 2030. The greatest potential is in improved treatment and disposal of solid waste.
- Agriculture: existing targeted measures could reduce CH_4 emissions from the agricultural sector by around 30Mtyr^{-1} by 2030. Three behavioural changes, reducing food waste and loss, improving livestock management and the adoption of healthy diets, could reduce CH_4 emissions by 65–80Mtyr^{-1} over the next few decades.
- Additional measures: measures that reduce CH_4 emissions but do not primarily target CH_4 include decarbonization measures, such as a transition to renewable energy and economy-wide energy efficiency improvements.

Source: UN Environment Programme and Climate and Clean Air Coalition (2021; their figure ES1 and executive summary).

There are, however, also ‘win–lose’ actions. Burning wood, which reduces dependency on fossil fuels, can also result in significant emissions of air pollutants, including carbon monoxide, nitrogen oxides, volatile organic compounds and particulate matter, that locally or regionally affect the climate, human health and ecosystems (Grantz et al., 2003; Von Schneidemesser et al., 2020). Decreasing the amount of sulphate aerosols produced by power and industrial plants and from maritime transport improves air quality but results in a warming influence on the climate, because those sulphate aerosols contribute to cooling the atmosphere by blocking incoming sunlight (thereby temporarily masking some of the long-term warming effect of greenhouse gases) (Forster et al., 2021; Szopa et al., 2021).

2.3 Key climate metrics and concepts

2.3.1 Effective Radiative Forcing

As noted in section 1.2 (Figure 1.1), changes in the climate are the result of changes in the radiative imbalance of the climate system. To compare the climate impacts of different climate system drivers requires the use of a common methodological approach which can enable like-for-like comparisons of their radiative impacts on the climate system. The most commonly used metric today, introduced in the IPCC AR5 assessment (Myhre et al., 2013), is ERF. It quantifies the resulting top of the atmosphere energy imbalance following an imposed perturbation (for instance in concentrations of GHGs or aerosols or solar irradiance) incorporating quasi-instantaneous system feedbacks in both the troposphere (including cloud responses) and stratosphere that are independent of surface temperature changes (Forster et al., 2021).

The change in ERF between 1750 and 2019 as assessed by Forster et al. (2021) is dominated by changes in concentrations of CO_2, other well-mixed GHGs and aerosols (Figure 2.8). Uncertainties in the total change in ERF are dominated by those in aerosol effects which, in turn, are driven by uncertainty in the aerosol–cloud interactions (Forster et al., 2021).

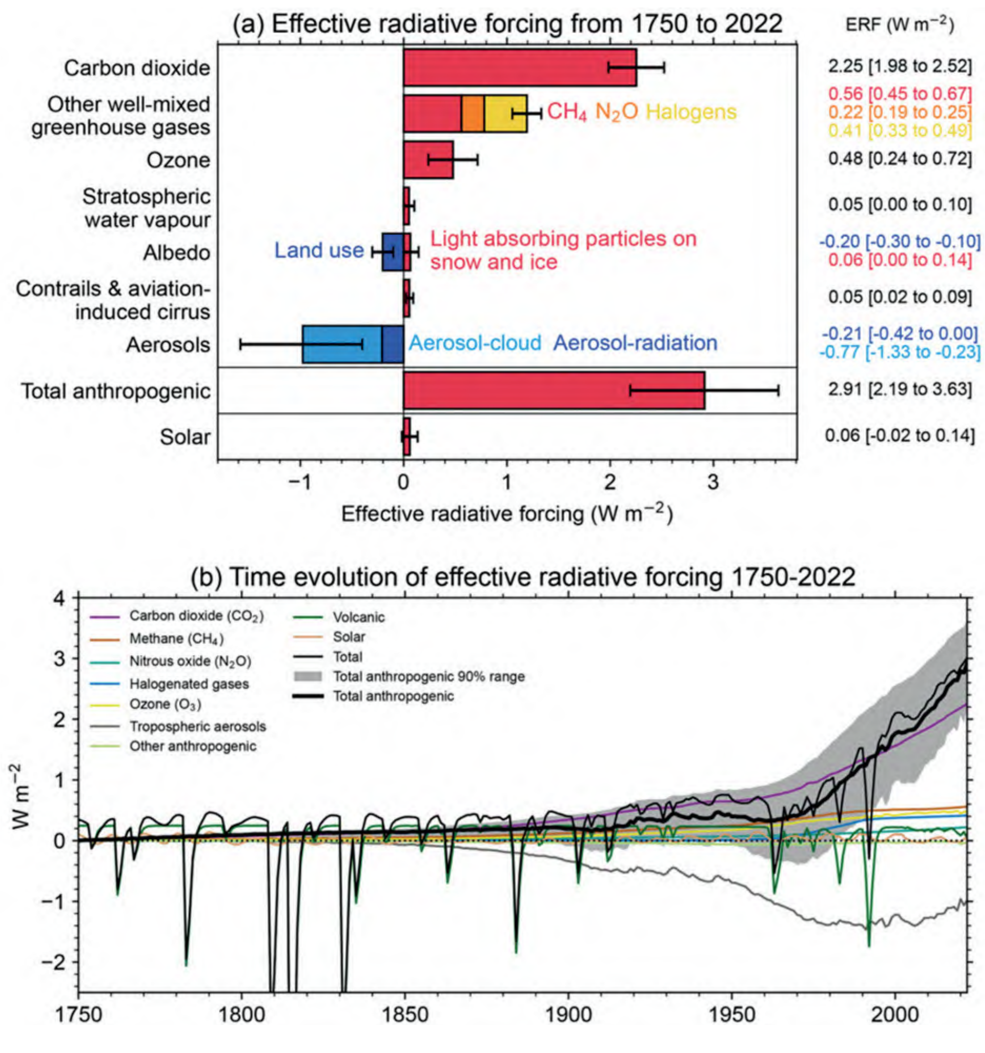


Figure 2.8 ERF from 1750 to 2022. (a) 1750–2022 change in ERF, showing best estimates (bars) and 5–95% uncertainty ranges (lines) from major anthropogenic components to ERF, total anthropogenic ERF and solar forcing. (b) Time evolution of ERF from 1750 to 2022. Best estimates from major anthropogenic categories are shown along with solar and volcanic forcing (thin coloured lines), total (thin black line) and anthropogenic total (thick black line) forcing. The 5–95% uncertainty in the anthropogenic forcing is shown by grey shading. Note that solar forcing in 2022 is a single-year estimate. Source: Forster et al. (2023; their figure 2). Reproduction licensed under the Creative Commons Attribution CC BY 4.0 licence (https://creativecommons.org/licenses/by/4.0/)

2.3.2 Cloud radiative feedback

Clouds cover approximately two-thirds of the globe at any given time, and one of the biggest challenges in climate science has been to predict how clouds will change in a warming world and whether those changes will lead to radiative feedbacks that amplify or partially offset the warming. The problem is far from simple and requires understanding from micro-scale cloud physical processes to global-scale cloud regimes and their climate impacts (Forster et al., 2021). Whether a cloud is optically thin or thick, whether it is low or high in the atmosphere, and whether it is in the tropics, the mid-latitudes or the polar regions can all affect the radiative impact (Forster et al., 2021).

Scientists have made significant progress over the past decade and are now more confident that overall global changes in clouds will amplify, rather than offset, any global warming resulting from additional human emissions of GHGs (Bony et al., 2015; Forster et al., 2021). Figure 2.9 shows the interactions between clouds and the climate today and in a warmer future. Accurately representing clouds in ESMs remains one of the biggest challenges because clouds occur at much finer scales than the resolution of the current generation of ESMs (Forster et al., 2021). To be able to explicitly resolve clouds and cloud physical processes in ESMs would require the ability to undertake simulations of the global climate at <1km resolution (Palmer et al., 2019).

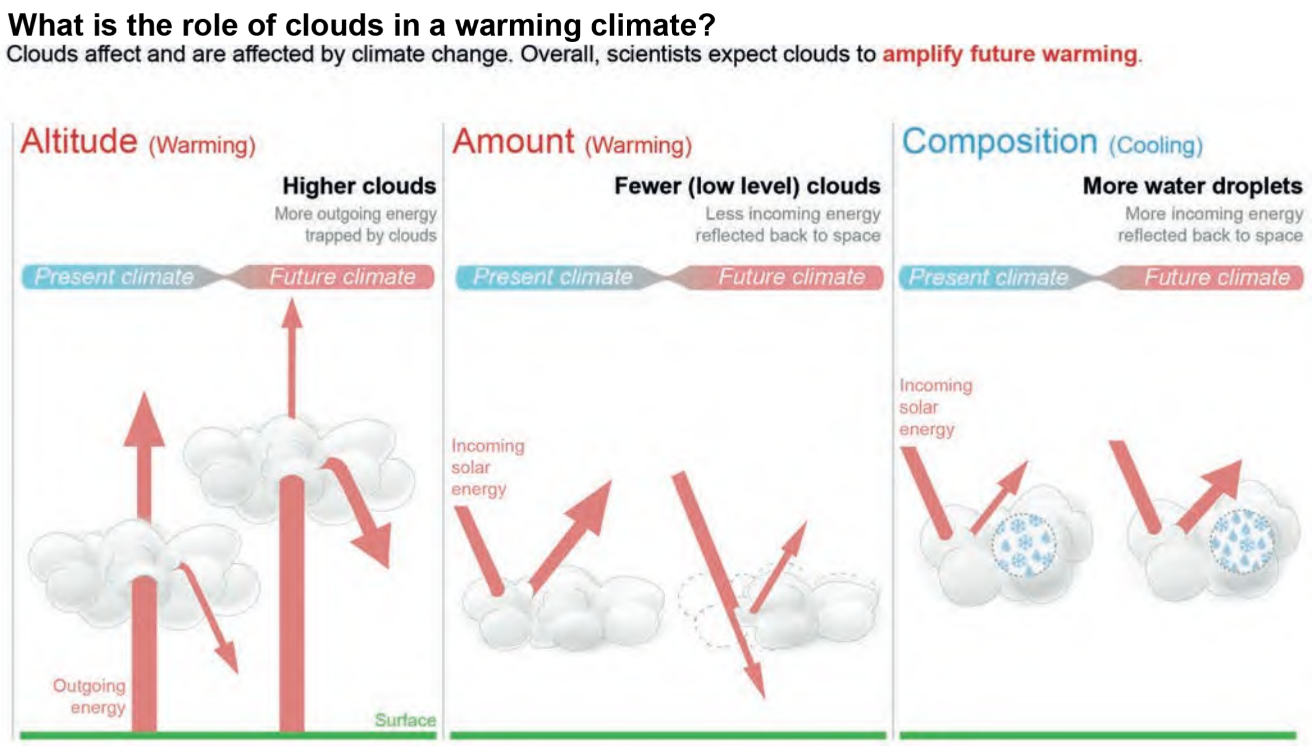


Figure 2.9 Clouds in a warming climate. Global warming is expected to alter the altitude (left) and the amount (centre) of clouds, which will amplify warming. On the other hand, cloud composition will change (right), offsetting some of the warming. Overall, clouds are expected to amplify future warming. Source: Forster et al. (2021; their FAQ 7.2 figure 1).

2.3.3 Equilibrium Climate Sensitivity

It has long been known since the pioneering work of Irish physicist John Tyndall (section 1.1) that under laboratory conditions each doubling of the concentration of CO_2 leads to an incremental warming of about 1.1°C. The climate system, however, contains numerous feedbacks (including cloud feedbacks; section 2.3.2) that serve to either amplify or dampen the response, and the balance of these feedbacks determines the sensitivity of the climate system to such a radiative perturbation (Forster et al., 2021). Scientists have long endeavoured to ascertain what the global response to such a doubling of CO_2 concentration would be, and the most common metric used is ECS (e.g. Arrhenius, 1897; NAS, 1979), which estimates the new state after fast-response components have equilibrated[9].

Forster et al. (2021), largely building upon the comprehensive review by Sherwood et al. (2020), conclude based upon multiple lines of evidence, that there is a 9 in 10 chance that the real-world ECS lies between 2°C and 5°C. This represents a significant reduction in uncertainty compared to the Fifth Assessment Report (Collins et al., 2013), which gave a two in three chance of ECS being between 1.5°C and 4.5°C (Figure 2.10). This reduction in uncertainty has been possible not through a single breakthrough or discovery but instead by combining evidence from many different lines of evidence and better understanding their inherent strengths and weaknesses (Sherwood et al., 2020; Forster et al., 2021).

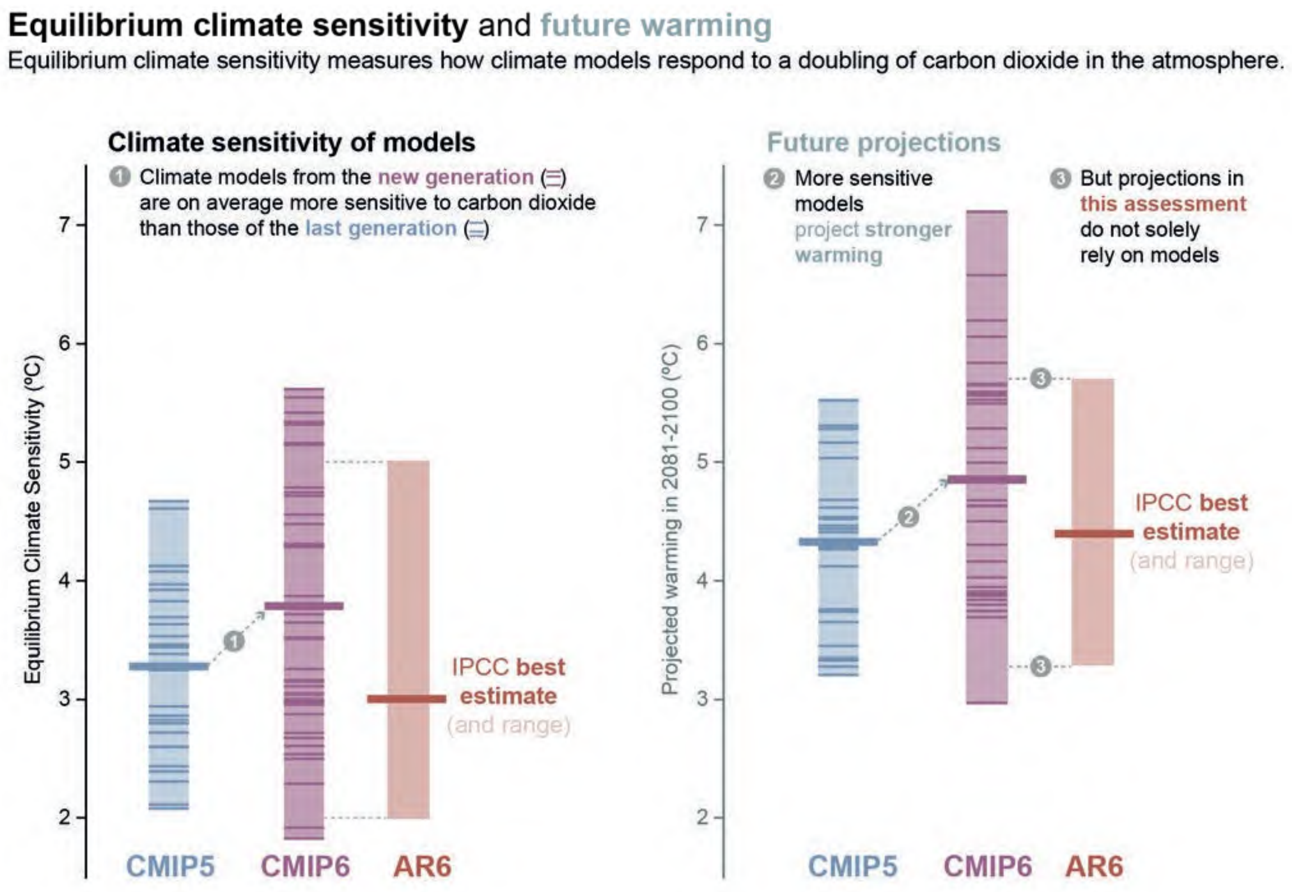


Figure 2.10 ECS and future warming. Left: ECSs for the current generation (CMIP6) climate models and the previous (CMIP5) generation. The assessed range in the report (IPCC AR6) is also shown. Right: climate projections of CMIP5, CMIP6 and AR6 for the Late action scenarios. The thick horizontal lines represent the multi-model average and the thin horizontal lines the results of individual models. The boxes represent the model ranges for CMIP5 and CMIP6 and the range assessed in AR6. Source: Forster et al. (2021; their FAQ 7.3).

[9] ECS is one of a family of linked metrics, including the transient climate response, which quantifies the instantaneous response at the time of doubling, and the Earth system sensitivity, which allows the equilibration of slow-responding components after doubling (for further details, see Forster et al., 2021). We concentrate on ECS in this volume because of its use in selecting low-likelihood, high-warming storylines (Chapter 8). A closely related concept of transient climate sensitivity is similarly used in a regional context in the TRANSLATE results (Chapters 3 and 4).

For a given future scenario, climate models project a range of changes in global mean surface temperature. This range is closely related to the model ECS, which is determined from a set of simulations with abrupt quadrupling of CO_2 concentrations mandated under CMIP protocols to enable its calculation (Eyring et al., 2016). A substantial proportion of newer climate models from CMIP6 exhibit higher ECS than the range in the prior CMIP5 generation (Figure 2.10; sections 8.1 and 8.2), and this leads to end-of-century global warming in some simulations of up to 2–3°C above the current IPCC best estimate (Lee et al., 2021). Although these higher warming levels are not the most likely outcome, high-ECS models are useful for exploring high-impact, low-likelihood futures (section 8.2).

2.3.4 Metrics to aggregate the impacts of greenhouse gas emissions

Emissions metrics can be quantified as the magnitude of the effect a unit mass of emission of a species has on a key measure of climate change, such as radiative forcing or global surface temperature (Forster et al., 2021). These impacts arise from a combination of their atmospheric lifetime and their radiative properties. The atmospheric lifetime of a gas refers to the average time that a molecule of an emitted gas remains in the atmosphere[10]. Lifetimes of GHGs range from seconds to millennia, and radiative properties similarly span several orders of magnitude on a per-molecule basis (Forster et al., 2021). Because of the complex interplay between lifetime and radiative properties, there exist a range of different ways to aggregate and compare (or bundle) the warming effects of GHGs (Forster et al., 2021). Such approaches are necessary to inform policy decision making where policymakers must trade off the impacts of different policy choices relating to different emissions sources of different gases with the resulting climate system effects (assessed further in Volume 2).

Increasingly, there are calls to treat separately short-lived (lifetimes less than a decade or so) and long-lived (lifetimes of a century or longer) gases, noting that there are very few GHGs of note with intermediate lifetimes (Allen et al., 2022). The difference between long-lived gases that act as a 'stock' and shorter-lived gases that act as a 'flow' matters. CO_2 is a long-lived GHG and is often referred to as a 'stock gas'[11]. Once emitted, stock gases will remain and stockpile in the atmosphere for hundreds or thousands of years. On the other hand, CH_4 is a short-lived GHG, or a 'flow gas' with a lifetime of just over a decade. For flow gases, as long as their emissions remain constant, their concentration and warming effect remain roughly constant as well[12] (Allen et al., 2022).

Box 2.1 The carbon bathtub

The difference between stock and flow forcers can be thought of in the context of a bathtub being filled with water. CO_2 and other stock gases with long lifetimes are akin to having the tap on and the plug in. No matter how fast or slow the tap is running, the water level will continue to increase so long as the tap remains on. Whereas CH_4 and other short-lived gases are akin to having the tap running but the plug out. For these, the level of the water in the bath depends upon how fast the tap is running. It follows that to stabilise the climate requires reducing emissions of CO_2 to extremely close to or below zero (IPCC, 2021a; Jenkins et al., 2022), whereas, while it will be necessary to considerably reduce short-lived gas emissions and their warming impacts if we wish to limit warming, these shall not, necessarily, have to go to zero (IPCC, 2021a).

[10] For almost all emitted gases the decay from a pulse emission is some form of exponential decay. The average lifetime is thus beyond the time taken for 50% of the molecules to have been removed because of the long-tail distribution of the removal process, with a small number of molecules remaining for a considerably longer period of time.

[11] Indeed CO_2 is unique amongst all gases in not having a recognised lifetime owing to the complexity of removal processes (see section 2.1.1).

[12] Given that CH_4 removal is via oxidation to CO_2 and water vapour, as well as ocean heating effects, to hold the warming effect absolutely stable would actually require a 3% reduction in CH_4 emissions per decade (Cain et al., 2019).

Although it is possible to calculate absolute metrics, it is more common to create comparative metrics with CO_2 as the reference gas, following the approach adopted in IPCC AR5 (Myhre et al., 2013). This ‘family’ of GWP metrics has been broadly adopted in numerous policy contexts. GWP values are periodically reassessed as new evidence arises. CO_2, by definition, has a GWP of 1 regardless of the GWP metric used, because it is always the gas being used as the reference.

Common GWP metrics include:

- **GWP_{100}**, which compares GHGs with CO_2 on a per molecule basis over a 100-year time span;
- **GWP_{20}**, which is similar but is based on the impact over 20 years;
- **GWP***, which is a metric principally based upon immediate radiative effect considerations and which therefore more directly informs the immediate temperature response to given policy choices (Lynch et al., 2020).

None of these metrics is perfect because there is no perfect way to associate equivalence between emissions of gases which differ by orders of magnitude in both their atmospheric lifetime and their radiative impacts. In addition, different metrics, and even the different ways in which they can be applied, involve different implicit assumptions about aspects such as historical responsibility and global equity (Rogelj et al., 2019; Rogelj and Schlenussner, 2019; Schleussner et al., 2019; Cain et al., 2021). For example, while using a recent baseline to some extent leads to grandfathering of emissions, using GWP* from a very recent baseline effectively grandfathers all historical responsibility and therefore unduly rewards reductions for high emitters while unfairly penalising any increases in emissions from low emitters (Rogelj et al., 2019). Given that historical and current per capita emissions vary by over an order of magnitude globally, these are non-negligible considerations from the viewpoint of international policy and justice (Rajamani et al., 2021). However, used and interpreted appropriately, these and similar metrics can inform mitigation policy choices in a useful manner (Volume 2).

Recognising the imperfect nature of these metrics, the IPCC WGI AR6 report was deliberately agnostic on the choice of metrics (i.e. did not alight on a single metric as preferable), while noting the trade-offs arising from metric choice (Table 2.1; Forster et al., 2021)[13]. For example, using GWP_{100} greatly underestimates the immediate mitigation potential of action on CH_4 and other short-lived forcers while overestimating their effects on longer timescales (Forster et al., 2021). As a result, using GWP_{100} can lead to markedly different temperature outcomes for nominally identical bundles of different gases. For mitigation pathways that limit warming to 2°C with an even chance, the ambiguity arising from using GWP_{100} as sole constraint on emissions of a mix of GHGs (without considering their economic implications or feasibility) could be as much as 0.17°C, which represents about one-fifth of the remaining global warming in those pathways (Denison et al., 2019). Conversely, GWP* and similar metric approaches are well suited to estimate the global surface temperature response from aggregated emissions of a range of gases over time, which can be done by scaling the cumulative CO_2 equivalent emissions calculated with these metrics by the transient climate response to cumulative emissions of CO_2 (Forster et al., 2021).

Regardless of the relative scientific merits of different GWP metrics, in international policy and national law, GWP_{100} is currently the metric most commonly used, being the basis for international accounting under the UNFCCC process, EU reporting and targets, and national carbon budget determinations (see Volume 2). Ultimately, the metric used will depend upon the question being posed, and it is therefore not possible to define a preferred metric. GWP values are periodically reassessed as atmospheric composition evolves and new evidence arises. These are compiled and assessed by the IPCC in each assessment cycle.

[13] “Following AR5, this Report [IPCC AR6 WGI] does not recommend an emissions metric because the appropriateness of the choice depends on the purposes for which gases or forcing agents are being compared.” (Forster et al., 2021).

Table 2.1 Radiative forcing and GWP_{20}, GWP_{100} and GWP_{500} metrics for selected species taken from Forster et al. (2021; their table 7.15). Species have been selected for their importance (CO_2, CH_4, N_2O) or to illustrate the interplay of radiative efficiency and lifetime on the various GWPnnn metrics (remaining species). Details for several hundred species are given in Forster et al. (2021; table SM.6). For CO_2, CH_4 and N_2O the reported values herein include their impacts on atmospheric chemistry, which yields changes in additional GHGs

Greenhouse gas	Lifetime (years)	Radiative efficiency ($Wm^{-2}ppb^{-1}$)	GWP_{20}	GWP_{100}	GWP_{500}
CO_2	Multiple	$1.33 \pm 0.16 \times 10^{-5}$	1	1	1
CH_4 – fossil	11.8 ± 1.8	$5.7 \pm 1.4 \times 10^{-4}$	82.5 ± 25.8	29.8 ± 11	10.0 ± 3.8
CH_4 – non-fossil	11.8 ± 1.8	$5.7 \pm 1.4 \times 10^{-4}$	79.7 ± 25.8	27.0 ± 11	7.2 ± 3.8
N_2O	109 ± 10	$2.8 \pm 1.1 \times 10^{-3}$	273 ± 118	273 ± 130	130 ± 64
HFC-32	5.4 ± 1.1	$1.1 \pm 0.2 \times 10^{-1}$	2,693 ± 842	771 ± 292	220 ± 87
HFC-134a	14.0 ± 2.8	$1.67 \pm 0.32 \times 10^{-1}$	4,144 ± 1,160	1,526 ± 577	436 ± 173
CFC-11	52.0 ± 10.4	$2.91 \pm 0.65 \times 10^{-1}$	8,321 ± 2,419	6,266 ± 2,297	2,093 ± 865
PFC-14	50,000	$9.89 \pm 0.19 \times 10^{-2}$	5,301 ± 1,395	7,380 ± 2,430	10,587 ± 3,692

Box 2.2 The difference in global warming potential metrics for biogenic and fossil fuel CH_4 emissions

CH_4 emissions from both biogenic and fossil fuel sources are radiatively identical; hence, emitted CH_4 molecules have identical climate effects while in the atmosphere. By extension, biogenic and fossil fuel-sourced CH_4 emissions have an identical instantaneous GWP*.

In terms of climate system impacts, the only difference between fossil fuel-based and biogenic emissions is that biogenic CH_4 arises from the exchanges of carbon from within the active carbon cycle, and fossil fuel CH_4 arises from the inactive fossil carbon stores[14]. Because the CO_2 molecule arising from fossil fuel-based CH_4 emissions after oxidation is a new addition to the active carbon cycle and adds to the long-term CO_2 burden and associated forcing, whereas that arising from the biogenic-based emission does not, CH_4 from fossil fuel sources has slightly higher integrated emission GWP_{20} and GWP_{100} metric values (see section 2.3.3; Table 2.1) than those from biogenic sources (Forster et al., 2021).

Regardless of discussions around metrics, it is important to stress that one molecule of biogenic- or fossil fuel-sourced CH_4 released into our atmosphere has the potential to warm the climate by approximately 80 times more than one molecule of CO_2 released into the atmosphere over a 20-year timeframe, which is the one most relevant for many policy decisions.

2.3.5 Net zero CO_2 and greenhouse gas emissions

Limiting human-caused global warming to a specific level requires limiting cumulative CO_2 emissions, reaching net zero or net negative CO_2 emissions, along with strong reductions in other GHG emissions (IPCC, 2023). Future additional warming will depend on future emissions, with total warming dominated by past and future cumulative CO_2 emissions (IPCC, 2021a). Reaching net zero CO_2 emissions is different from reaching net zero GHG emissions (IPCC, 2023). The timing of reaching net zero for a basket of GHGs depends on the emissions metric, such as GWP over a 100-year period, chosen to convert non-CO_2 emissions into CO_2 equivalent. However, for a given emissions pathway, the physical climate response is independent of the metric chosen (IPCC, 2023).

Achieving global net zero GHG emissions requires all remaining CO_2 and metric-weighted non-CO_2 GHG emissions to be counterbalanced by durably stored CO_2 removals. Net zero CO_2 emissions would therefore be reached before net zero GHG emissions. Some non-CO_2 emissions, such as CH_4 and N_2O from agriculture, cannot be fully eliminated using existing and anticipated technical measures and will need to be counterbalanced (IPCC, 2023). As a result, emissions pathways that reach and sustain net zero GHG emissions defined by GWP_{100} imply net negative CO_2 emissions and are projected to result in a gradual decline in surface temperature after an earlier peak (IPCC, 2023).

2.3.6 Remaining global carbon budget quantification

Because CO_2 acts as a stock forcer (section 2.3.3), cumulative emissions can be used as an accounting system or a carbon budget; for the climate system response it matters principally how much was emitted and not when it was emitted. Historical surface temperatures have increased quasi-linearly with historical total cumulative CO_2 emissions (Figure 2.11; Canadell et al., 2021). To date, humans have collectively emitted approximately 2,520Gt of CO_2 (to end 2022; IPCC, 2022b, with assumed annual emissions post 2019 of 40Gt per annum). Within a reasonable range of additional emissions, future global warming is expected to remain roughly linearly proportional to the total net amount of CO_2 emissions (Canadell et al., 2021). The amount of global warming per unit of cumulated CO_2 emissions is called the transient climate response to cumulative CO_2 emissions (TCRE), and can be used to estimate total carbon budgets to avoid reaching or exceeding any given global surface temperature threshold (Allen et al., 2009; Matthews et al., 2009). In Canadell et al. (2021) the TCRE is assessed to be 0.45°C [0.27–0.63°C] per 1,000Gt of CO_2 emissions.

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14 The difference in age of the sources means that ^{13}C content can be used to try to disentangle the causes of spikes or drops in CH_4 emissions because fossil fuel-sourced CH_4 is low in ^{13}C, which arises from galactic cosmic ray collisions.

Subtraction from a total carbon budget of historical emissions results in the ability to quantify an RCB. Such an RCB represents a quantification of additional emissions from a given point in time consistent with avoiding a given temperature threshold (Collins et al., 2013; Rogelj et al., 2019).

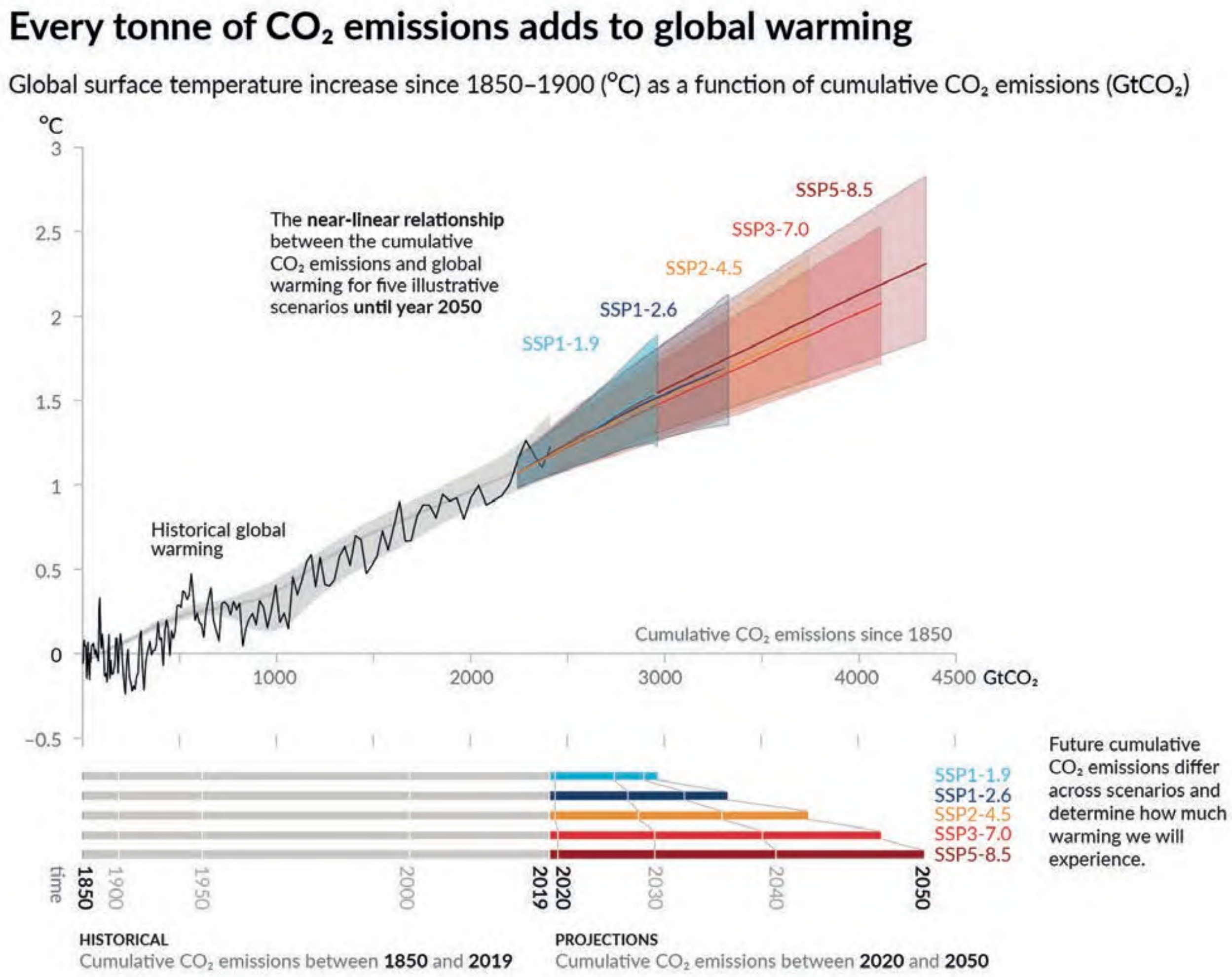


Figure 2.11 Near-linear relationship between cumulative CO_2 emissions and the increase in global surface temperature. Top panel: historical data (thin black line) show observed global surface temperature increase in °C since 1850–1900 as a function of historical cumulative CO_2 emissions in $GtCO_2$ from 1850 to 2019. The grey range with its central line shows a corresponding estimate of the historical human-caused surface warming. Coloured areas show the assessed very likely range of global surface temperature projections, and thick coloured central lines show the median estimate as a function of cumulative CO_2 emissions from 2020 until 2050 for the set of illustrative scenarios (SSP1–1.9, SSP1–2.6, SSP2–4.5, SSP3–7.0 and SSP5–8.5; see figure SPM.4 in IPCC (2021a)). Projections use the cumulative CO_2 emissions of each respective scenario, and the projected global warming includes the contribution from all human drivers. Source: IPCC (2021a; their figure SPM.10).

There are, however, important nuances that require consideration with regards to RCB quantification (Canadell et al., 2021). These include uncertainties in historical estimates of emissions and surface temperature changes, limitations to the TCRE assumptions, the zero-emission commitment and contributions to warming from emissions of other gases. Uncertainties in historical emissions, temperature changes and the TCRE assumptions principally yield increased uncertainties in the quantified budget (Canadell et al., 2021). The zero-emission commitment – the further warming after reaching net zero human emissions of CO_2 – is assessed in Lee et al. (2021) to be zero, albeit with large uncertainties (±0.3°C). Finally, other GHG emissions also affect estimates of RCB by increasing or reducing the amount of warming that could still be permitted to result from CO_2 emissions (Meinshausen et al., 2009; Friedlingstein et al., 2014; Knutti and Rogelj, 2015). For example, the RCB estimates expressed in Table 2.2 assume that the emissions of CH_4 globally are reduced by about 50% by 2050, while those of N_2O are reduced by 25% (Forster et al., 2023). If such non-CO_2 GHGs do not reduce by this amount, then the RCB numbers are commensurately smaller to account for the additional warming resulting from these unmitigated emissions (Canadell et al., 2021). In IPCC AR6 this non-CO_2 effect is assessed to have an uncertainty of 220Gt carbon equivalent (66% range; Canadell et al., 2021). The RCB estimates for progressively higher values also become more uncertain owing to uncertain Earth system feedbacks such as those described in Chapter 8 (Canadell et al., 2021).

The RCB as assessed in Canadell et al. (2021) to restrict the temperature rise to 1.5°C is very small (Table 2.2). To limit global warming to 1.5°C above pre-industrial levels with either a 50% or a 67% chance, the RCBs amount to 500 and 400Gt of CO_2, respectively, from 1 January 2020 (Canadell et al., 2021)[15]. Currently, human activities are emitting around 40Gt of CO_2 into the atmosphere every single year. At this pace of emissions, the RCB, to have a greater than 50% chance of avoiding exceeding 1.5°C, would be used up in about 10 years. It is still possible to attain the Paris Agreement goal of keeping global temperature increases well below 2°C while striving to limit warming to 1.5°C if global CO_2 emissions are reduced to net zero (or below) by approximately mid-century and emissions of other GHGs are simultaneously substantially reduced (IPCC, 2021a; see Cross-volume Box 1, Figure 1).

The physical RCB, which is a global concept, should not be conflated with the national carbon budgets, which are assessed in Volume 2. The physical RCB is applicable to aggregate emissions and resulting changes in global climate drivers. National carbon budgeting, while derived from the same basic principle, includes many judgements around fair share allocations and what other jurisdictions may or may not achieve in terms of emissions reductions (Matthews et al., 2020).

[15] IPCC WGIII, using a different assessment approach to land use emissions and removals and published a year later, came to a somewhat smaller number. The two numbers are consistent within their respective uncertainties and do not alter the fundamental message that time is rapidly running out to meet the Paris Agreement goal to limit warming to 2°C while aiming to avoid warming of 1.5°C. Forster et al. (2023), in an update, estimate the RCB as at 1 January 2023 to be 250 Gt. The central message here is that this number is rapidly diminishing.

Global warming between 1850–1900 and 2010–2019 (°C)				Historical cumulative CO_2 emissions from 1850 to 2019 ($GtCO_2$)			
1.07 (0.8–1.3; likely range)				2,390 (±240; likely range)			
Approximate global warming relative to 1850-1900 until temperature limit (°C)[a]	Additional global warming relative to 2010–2019 until temperature limit (°C)	Estimated remaining carbon budgets from the beginning of 2020 ($GtCO_2$) Likelihood of limiting global warming to temperature limit[b]					Variations in reductions in non-CO_2 emissions[c]
		17%	33%	50%	67%	8%	Higher or lower reductions in accompanying non-CO_2 emissions can increase or decrease the values on the left by 220$GtCO_2$ or more
1.5	0.43	900	650	500	400	300	
1.7	0.63	1,450	1,050	850	700	550	
2.0	0.93	2,300	1,700	1,350	1,150	900	

Table 2.2 Estimates of historical CO_2 emissions and RCBs. Estimated RCBs are calculated from the beginning of 2020 and extend until global net zero CO_2 emissions are reached. They refer to CO_2 emissions while accounting for the global warming effect of non-CO_2 emissions. Global warming in this table refers to human-induced global surface temperature increase, which excludes the impact of natural variability on global temperatures in individual years. TCRE refers to the transient climate response to cumulative CO_2 emissions

[a] Values at each 0.1°C increment of warming are available in tables TS.3 and 5.8 of IPCC WG1 (Arias et al., 2021).

[b] This likelihood is based on the uncertainty in transient climate response to cumulative CO_2 emissions (TCRE) and additional Earth system feedbacks, and provides the probability that global warming will not exceed the temperature levels provided in the two left columns. Uncertainties related to historical warming (±550$GtCO_2$) and non-CO_2 forcing and response (±220$GtCO_2$) are partially addressed by the assessed uncertainty in TCRE, but uncertainties in recent emissions since 2015 (±20$GtCO_2$) and the climate response after net zero CO_2 emissions are reached (±420$GtCO_2$) are separate.

[c] Remaining carbon budget estimates consider the warming from non-CO_2 drivers as implied by the scenarios assessed in SR1.5. The Working Group III contribution to AR6 will assess mitigation of non-CO_2 emissions.

Source: IPCC (2021a; their table SPM.2).

If global emissions of CO_2 were to become net negative following human-mediated CO_2 removal (CDR) via a variety of means (see Volume 2) the question arises whether the global surface temperature would drop commensurately like it had risen (termed return after overshoot; Lee et al., 2021). Amongst the CMIP6 experiments is a very extreme overshoot scenario that enabled a quantification of the effects of overshoot on global surface temperatures and a range of other indicators (Figure 2.12; Lee et al., 2021). Fast-responding components such as global surface temperature, precipitation and Arctic sea ice do revert towards earlier values as CDR leads to decreasing atmospheric CO_2 concentrations, albeit not completely (Lee et al., 2021). However, the thermosteric component of sea level rise arising from ocean heating is not reversed. Overshoot would also have significant impacts upon human and natural systems, many of which would persist beyond the period of overshoot (IPCC, 2022a).

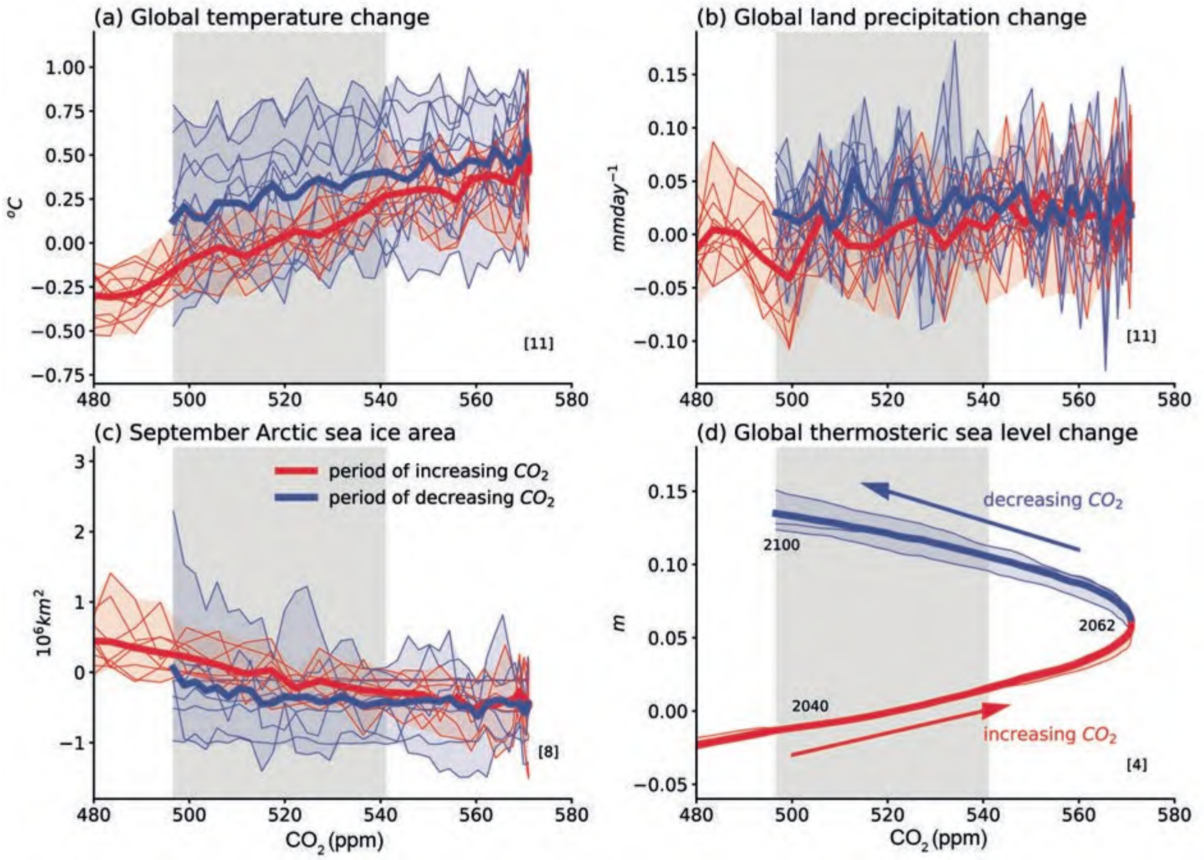


Figure 2.12 Simulated changes in climate indices for SSP5–3.4-OS plotted against atmospheric CO_2 concentration (ppm) from 480ppm up to 571ppm and back to 496ppm by 2100. (a) Global surface air temperature change. (b) Global land precipitation change. (c) September Arctic sea ice area change. (d) Global thermosteric sea level change. Plotted changes are relative to the 2034–2053 mean, which has the same CO_2 concentration as the 2081–2100 mean (shaded grey bar). Red lines denote changes during the period up to 2062 when CO_2 is rising; blue lines denote changes after 2062 when CO_2 is decreasing again. Thick line is multi-model mean; thin lines and shading show individual models and complete model range. Numbers in square brackets indicate number of models used in each panel. Source: Lee et al. (2021; their figure 4.34).

2.4 The ocean in a changing climate

2.4.1 Understanding sea level change

Changes in sea level can be attributed to multiple geological, physical and climatological processes across a range of space and time scales (Fox-Kemper et al., 2021). The sea level budget is said to be closed when the observed sea level change is equal to the sum of scientific understanding of the individual contributions to sea level rise within quantified uncertainties. These contributions arise from ocean expansion/contraction arising from changes in density (temperature and/or salinity) and exchanges with land surface reservoirs (principally ice sheets, glaciers and groundwater) (Fox-Kemper et al., 2021). Improved estimates of both sea level changes and the underlying contributions mean that the sea level budget from 1900 to the present is now closed (Domingues 2008; Frederikse 2020). Historical changes in Irish sea levels are further discussed in Chapter 5.

Future sea level rise will continue for many millennia even after stabilising global temperatures (section 2.3.5) because of the slow response time of the ocean (hundreds of years) and large ice sheets (several millennia) (Fox-Kemper et al., 2021). The final global sea level rise in several millennia is tightly coupled to the level at which global surface temperatures are stabilised. Stabilisation at below 2°C potentially keeps eventual sea level rise to metres, whereas higher stabilisations commits to potentially tens of metres (Fox-Kemper et al., 2021). Over the next 2,000 years, global mean sea level will rise by about 2 to 3m if warming is limited to 1.5°C, 2 to 6m if limited to 2°C and 19 to 22m with 5°C of warming, and would continue to increase thereafter (Arias et al., 2021; Figure 2.13, panel b). These projections are consistent with proxy evidence from prior warm periods (Figure 2.13; Arias et al., 2021). There is a hard upper limit arising from ice sheet contributions of the order 70m if we emit sufficient GHGs to melt in totality the Greenland and Antarctic ice sheets. However, this would require very substantial additional warming, particularly so to entirely melt the largest East Antarctic ice sheet, as has been seen in prior very hothouse Earths many millions of years ago (Gulev et al., 2021).

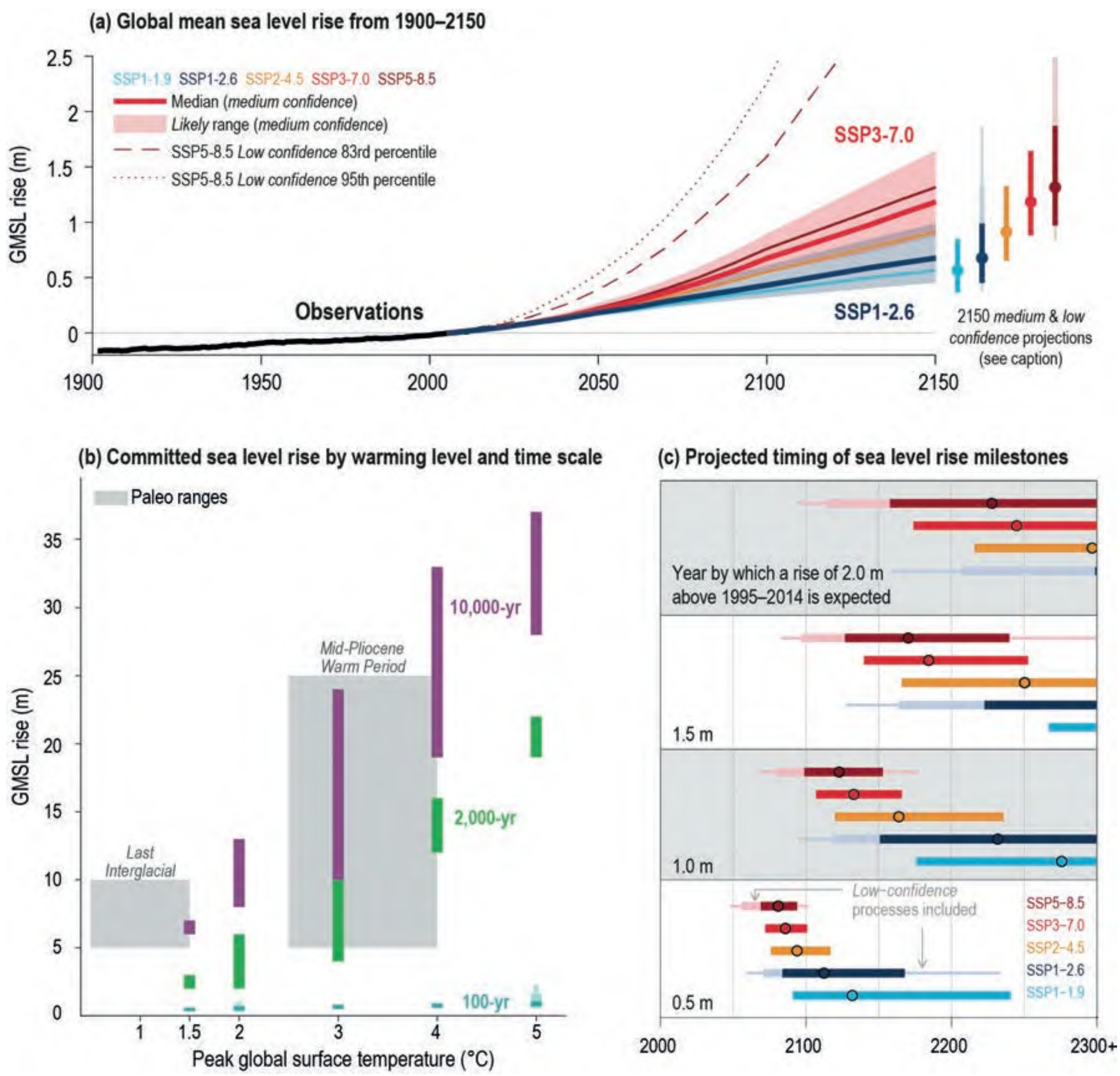


Figure 2.13 Global mean sea level (GMSL) change on different timescales and under different scenarios. (a) GMSL change from 1900 to 2150, observed (1900–2018) and projected under the SSP scenarios (2000–2150), relative to a 1995–2014 baseline. Solid lines show median projections. Shaded regions show likely ranges for Early action (SSP1–2.6) and Late action (SSP3–7.0). Dotted and dashed lines show, respectively, the 83rd and 95th percentile low-confidence projections for late action (SSP5–8.5). Bars on the right show likely ranges for SSP1–1.9, SSP1–2.6 (Early action), SSP2–4.5 (Middle action), SSP3–7.0, and SSP5–8.5 Late action) in 2150. Lightly shaded thick/thin bars show 17th–83rd/5th–95th percentile low-confidence ranges in 2150 for SSP1–2.6 (Early action) and SSP5–8.5 (Late action), based upon projection methods incorporating structured expert judgement and marine ice cliff instability. Low-confidence range for SSP5–8.5 (Late action) in 2150 extends to 4.8/5.4m at the 83rd/95th percentile. (b) GMSL change on 100-year (blue), 2000-year (green) and 10,000-year (magenta) timescales as a function of global surface air temperature, relative to 1850–1900. For 100-year projections, GMSL is projected for the year 2100, relative to a 1995–2014 baseline, and temperature anomalies are average values over 2081–2100. For longer-term commitments, warming is indexed by peak warming above 1850–1900 reached after cessation of emissions. Shaded regions show paleo-constraints on global surface air temperature and GMSL for the last interglacial and mid-Pliocene warm period. Lightly shaded thick/thin blue bars show 17th–83rd/5th–95th percentile low-confidence ranges for SSP1–2.6 (Early action) and SSP5–8.5 (Late action) in 2100, plotted at 2°C and 5°C. (c) Timing of exceedance of GMSL thresholds of 0.5, 1.0, 1.5 and 2.0m, under different SSPs. Lightly shaded thick/thin bars show 17th–83rd/5th–95th percentile low-confidence ranges for SSP1–2.6 (Early action) and SSP5–8.5 (Late action). Source: Arias et al. (2021; their figure TS box 5.1).

2.4.2 The Atlantic Meridional Overturning Circulation

Ocean currents transport heat, salt, fresh water, carbon, ocean nutrients and ocean pollutants from one part of the ocean to another and play a key role in determining climate conditions and weather fluctuations. The AMOC plays a major role in redistributing heat globally and is responsible for up to 90% of the heat transport into the North Atlantic (McCarthy et al., 2015a). This northward transport of surface heat and its release into the atmosphere is responsible for the warmer winter temperatures in northern and western Europe compared to similar maritime climates on the US west coast (McCarthy et al., 2015b; Palter, 2015). The cold winter and extreme storms in 2010/2011 were linked to changes in AMOC (Bryden et al., 2014).

The AMOC is predicted to decline due to climate change, but direct observations are not yet available for long enough to be conclusive as to whether this is already occurring (Gulev et al., 2021). The AMOC has been continuously measured only since 2004 at 26.5°N, and data suggest that it varies a lot throughout the year, primarily driven by variations in surface winds, while interannual and multi-decadal variability are much lower (Srokosz et al., 2012; Buckley and Marshall, 2016). Data prior to 2004 are less complete and so inferring long-term change is difficult. Available proxy evidence (Caesar et al., 2021) implies that the AMOC may be in its weakest state in at least a thousand years. The eastern subpolar North Atlantic, the region of the Atlantic closest to Ireland, has been recently recognised as the key area for AMOC impacts and maintenance (Petit et al., 2020). Continued observation of the changes offshore of Ireland are key to understanding how this key area is changing.

Longer-term evidence from the paleorecord shows that the AMOC has repeatedly fluctuated between weak and strong modes between successive glacials and interglacials over hundreds of thousands of years (Rahmstorf, 2002; Boers et al., 2018). In periods of a strong AMOC, the North Atlantic circulation is like that of today, keeping our winters in Ireland mild and our summers temperate. During weak AMOC events, warm surface water stops being advected to the Arctic and waters off north-west Europe cool substantially, resulting in cooler winters. Between 18,000 and 9,000 years ago, during the transition from the last glacial maximum to our current interglacial climate, the AMOC switched repeatedly between strong and weak phases (Romé et al., 2022). This switching was associated with periodic iceberg and freshwater discharges from the North American and potentially Greenland and Eurasian ice sheets. The resulting pulses of cold and fresh water reduced deep water formation at high latitudes, leading to rapid weakening of the AMOC (see section 8.3.1 for the consequences of this for Ireland).

2.4.3 Ocean acidification, warming and deoxygenation

Absorbing CO_2 from the atmosphere leads to more acidic waters (lower pH), commonly referred to as ocean acidification. Monitoring ocean acidification globally is essential in understanding the risk to marine life (Orr et al., 2005; Bindoff et al., 2019). The average surface pH of the ocean has already decreased by 0.1 units since the beginning of the Industrial Revolution, and a further 0.3- to 0.4-unit decrease is expected by the end of the century (Caldeira and Wickett, 2003). This corresponds to a doubling of acidity by 2100, which is unprecedented in at least hundreds of thousands of years and probably many millions of years. These changes will rapidly expose marine ecosystems to conditions they have not experienced over many millions of years, with the potential, particularly when combined with other stressors, for catastrophic ecosystem collapse (Hoegh-Guldberg et al., 2017). Results from laboratory, field and modelling studies, as well as evidence from the geological record, clearly indicate that marine ecosystems are highly susceptible to increases in oceanic partial pressure of CO_2 (pCO_2) and corresponding decreases in pH (Sunday et al., 2016; Canadell et al., 2021).

The rate of ocean warming has more than doubled since 1993, and between 1982 and 2016 marine heatwaves (defined similarly to meteorological heatwaves as unusually anomalous warmth relative to seasonal expectations) have doubled in frequency and are increasing in intensity (Fox-Kemper et al., 2021). Ocean warming will continue over the 21st century and until 2300 at least, even for Early action scenarios (Fox-Kemper et al., 2021). Ocean warming is irreversible over centuries to millennia, but the magnitude of warming is scenario dependent from the mid-21st century (Fox-Kemper et al., 2021).

Warmer waters also directly decrease the solubility of oxygen in the ocean, leading to deoxygenation, which can be further amplified through other physical and biogeochemical dynamics such as nutrient availability (Oschlies et al., 2018). Climate warming is expected to exacerbate the decrease of oxygen in the global open ocean and have significant negative impacts on ecosystems by reducing ocean column ventilation and extending the seasonal upper ocean stratification period, with implications for nutrient and oxygen availability for marine life (Breitburg et al., 2018). There is ample evidence for the occurrence of oceanic anoxic events in the geological past that lead to marine extinctions and ocean dead zones under high GHG climates (Jenkyns, 2010).

2.5 Recommendations

2.1	It is key that Ireland plays its full part in understanding the changes in the global climate system. This requires investment in research capabilities that take a more global and regional perspective upon our changing climate system. Ireland should play its full part by partaking in relevant global bodies such as the IPCC, the World Climate Research Programme, the Global Climate Observing System (GCOS) and the Global Ocean Observing System, and at the EU level in relevant research infrastructures (such as ICOS, which Ireland recently formally joined) and pan-European projects. Researchers across academia and government agencies need to be encouraged and enabled to participate in such activities.

PART

B

Ireland's Changing Climate

This part of the report focuses on climate changes observed and projected for Ireland. Temperature changes are considered in Chapter 3, including both mean temperatures and selected extremes. Chapter 4 similarly considers changes in precipitation, including changes in mean annual and seasonal accumulations and selected extremes. In Chapters 3 and 4, the projections arise from an ensemble of simulations created by the TRANSLATE project (see Box 1.3). Projections are shown for time slices in the mid- and late century as changes from the recent past. Box 3.2 provides information on how to interpret these projections. Chapter 5 assesses evidence from the changing shelf seas around Ireland. Chapter 6 considers the extent to which memorable climate events can be linked to climate change. Finally, in Chapter 7 the relationships between climate change and biodiversity and Ireland's natural landscape are considered.

Observations and projections of wind and circulation changes are not included in this section of the report. As noted in the recent EPA report *The Status of Ireland's Climate 2020* (Cámaro García et al., 2021), it is currently not possible to determine long-term trends in wind speed for Ireland with confidence due to instrument changes in the 1990s and a lack of homogenisation. Furthermore, the TRANSLATE project results are not processed for winds and circulation changes, and thus any analysis would necessarily be retrospective only, with no information from TRANSLATE on projections of future changes. Inhomogeneities arise when measurement equipment, location, recording methods or aspects of the local environment change, making it difficult to compare records over time.

For many stations the long-term pressure record also needs to be digitised and homogenised despite substantial recent progress with data rescue projects (Compo et al., 2019). There do exist various global reanalysis products such as ERA5 (Hersbach et al., 2020) and 20CRv3 (Slivinski et al., 2019)., and gridded datasets which may provide additional valuable evidence.

In the latest IPCC WGI report, the findings for Europe (the finest granularity of the assessment) point to observed decreases in mean wind speed over recent decades, with evidence of recent, very partial recovery of wind speeds (Ranasinghe et al., 2021). However, more recently discovered processing issues in wind speed observations may call such a partial recovery into question (Dunn et al., 2022). Projections suggest a reduction in mean wind speed but an increase in variability (Ranasinghe et al., 2021). Evidence for historical windstorms is assessed to be highly uncertain, with evidence that peak storm wind speeds have been decreasing (Ranasinghe et al., 2021). It is noted that clustering of storms will increase in many areas of Europe over coming decades. Over northern and western Europe a slight increase in the frequency and amplitude of windstorms is projected, particularly if global surface temperature increases exceed 2°C (Ranasinghe et al., 2021).

CROSS-CHAPTER BOX 1 HOW THE IRELAND YOU GREW UP IN IS DIFFERENT FROM THE IRELAND OF TODAY AND WILL BE DIFFERENT FROM THE IRELAND OF TODAY'S YOUTH WHEN THEY REACH YOUR AGE

Unlike COVID-19 or most other 24-hour news cycle events, climate change and biodiversity loss, even though hugely consequential, can go largely unnoticed and unremarked upon.

To illustrate the changing climate in a way that is more tangible, we highlight here the climates that three hypothetical generations of a family would have experienced during the first 20 years of their lives based upon historical data. It is clear that the most recent generation has already grown up in a climate that has shifted compared with that experienced by their parents and grandparents.

The grandparent (1941–1960): The grandparent grew up in a time when the annual average national temperature was 9.8°C. Annual national rainfall totals were 1,200mm. Carbon dioxide (CO_2) concentration was 317ppm. The winter of 1947 was incredibly cold and snowy, with snow lying on the ground for 3 months (Met Éireann, undated, a). It was the most prolonged cold spell in living memory. Following the end of the Second World War and the disastrous harvest of 1946, it caused severe hardship for many. The last quarter of 1954 was exceptionally wet, leading to widespread flooding in December 1954 (Met Éireann, undated, b).

The parent (1971–1990): The parent grew up in a time when the annual average national temperature was 9.6°C. Annual national rainfall totals were 1,190mm. CO_2 concentration was 340ppm. The prolonged dry period from 1974 culminating in the drought of 1976 (Met Éireann, undated, c) was the driest period for decades and led to significant impacts for agriculture and water supply. Temperatures reached 32.5°C in the summer of 1976. There was heavy snowfall in both January 1982 and January 1987 (Met Éireann, undated, d,e). Several significant storm events were noted by Met Éireann, including the tragic Fastnet yacht race storm in August 1979 (Met Éireann, undated, f).

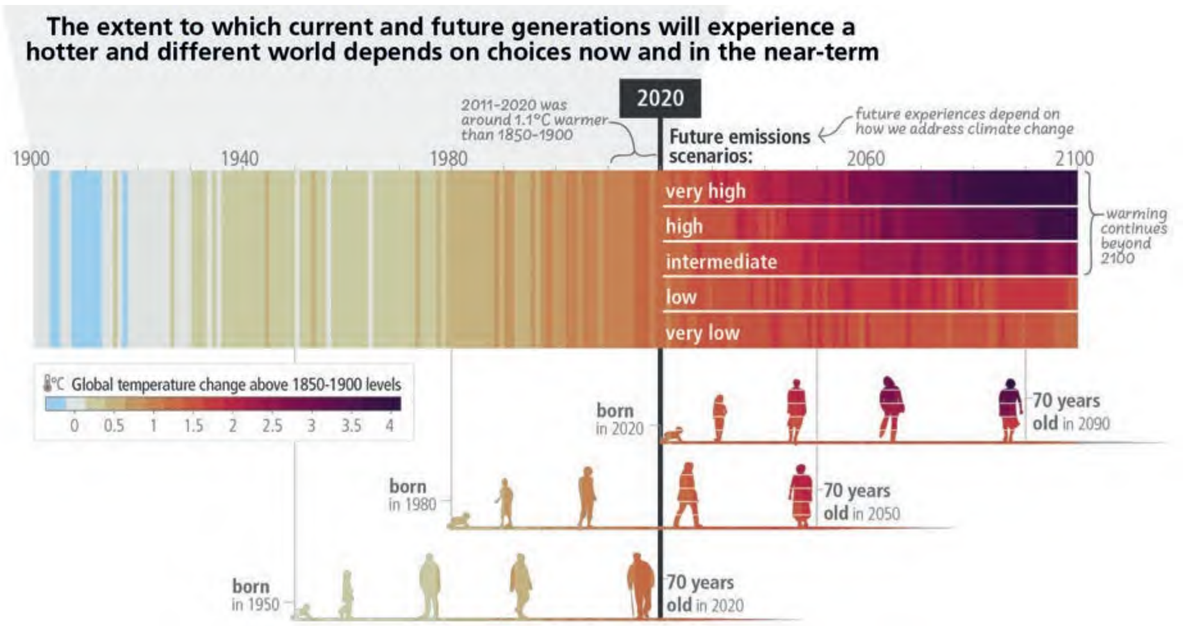
The young adult (2001–2020): The young adult grew up in the most recent two decades when the annual average national temperature was 10.3°C. Annual national rainfall totals were 1,273mm. CO_2 concentration was 392ppm. In the first two decades of their lives they have experienced many extremes (see section 6.1). Notable events included the stormiest winter on record over 2013/14 (Met Éireann, undated, g), the 'Beast from the East' in 2018 (Met Éireann, undated, h), which shut down much of eastern Ireland for days, and the drought and heatwaves of summer 2018 (Met Éireann, undated, i).

Each successive generation has experienced the vagaries of Irish weather, including notable extremes that impacted sectors or all of society in significant ways. The nature and frequency of such extremes has, however, been shifting more recently. More and more heatwaves have been experienced by the most recent generation. Although cold

extremes still occur, they have generally become less frequent for the most recent generation. Changes continue apace. The World Meteorological Organization noted five significant extremes in Ireland in 2021 (RTE, 2022): an unusual drought/dry spell from 29 May lasting up to 30 days; an unusual heatwave from 16 July lasting up to 10 days; an unusual heatwave from 1 September for the following 3 months; an unusual extra-tropical cyclone from 26 November lasting 2 days; and an unusual extra-tropical cyclone from 7 December for 2 days. Meanwhile the summer of 2022 saw 33°C reached at Phoenix Park in Dublin.

The following chapters provide a scientific explanation of why these historical shifts have occurred and what the future holds, depending upon the effectiveness of global mitigation efforts.

The future we give to today's toddlers and future generations is in our collective hands (Cross-chapter Box 1, Figure 1). With early and concerted action to reduce emissions, we can stabilise global surface temperatures within decades, albeit at a level higher than today. Because Ireland's regional climate, on multi-decadal timescales at least, follows the global climate, that means we can stabilise important aspects of Ireland's climate within the lifetimes of today's young adults and children. The Irish climate we would leave them, while being different again from today's, would, in most aspects, still be broadly recognisable if we take action. If we do not take early action, however, the climate will continue to change throughout the lifetime of every Irish citizen alive today and possibly for longer still. The climate that today's younger citizens experience would become increasingly unrecognisable, with ever-increasing impacts (Volume 3).



Cross-chapter Box 1 Figure 1 Observed (1900–2020) and projected (2021–2100) changes in global surface temperature (relative to 1850–1900), which are linked to changes in climate conditions and impacts, illustrate how the climate has already changed and will change along the lifespan of three representative generations (born in 1950, 1980 and 2020). Future projections (2021–2100) of changes in global surface temperature are shown for very low (SSP1–1.9), low (SSP1–2.6) (both classified Early action), intermediate (SSP2–4.5) (Middle action), high (SSP3–7.0) and very high (SSP5–8.5) (both Late action; see Cross-volume Box 1 for scenarios and their definitions). greenhouse gas emissions scenarios. Changes in annual global surface temperatures are presented as 'climate stripes', with future projections showing the human-caused long-term trends and continuing modulation by natural variability (represented here using observed levels of past natural variability). Colours on the generational icons correspond to the global surface temperature stripes for each year, with segments on future icons differentiating possible future experiences. Source: IPCC (2023; their figure SPM.1, panel c).

3

Temperature Changes

Key messages

In Ireland, annual average temperatures are now approximately 1.0°C higher than they were in the early 20th century. Sixteen of the top twenty warmest years on record nationally have occurred since 1990, with 2022 being the warmest year on record. Centennial timescale changes in Ireland are broadly consistent with global changes owing to our geographical situation between Europe (which is warming considerably faster than the global mean) and the North Atlantic (which is warming at a slower rate).

Substantial decadal to multi-decadal variability in temperatures is evident in the historical record and also present in future projections for Ireland under all scenarios. Most notably, the Atlantic Multi-decadal Variability explains successive multi-decadal periods when Ireland has warmed or cooled relative to the global trend. Over coming decades, the evolution of Irish temperatures will likely be determined in part by natural variability. Conversely, where temperatures end up by 2100 is largely determined by future global emissions.

Climate change under Early, Middle and Late action scenarios show very different futures for Ireland. Projections of Irish temperature changes consistently show warming, with the magnitude of this warming increasing with delays in global mitigation action. Under Early action, temperature increases averaged across the island of Ireland relative to the recent past (1976–2005) reach 0.91°C [0.44–1.10°C] by mid-century before falling back to 0.80°C [0.34–1.07°C] at the end of the century. Whereas under Late action, by the end of the century it is projected that temperature increases could be 2.77°C [2.02–3.49°C]. Warming also generally increases with the climate sensitivity of the Earth System Models used for a given mitigation pathway. The projected temperature change shows just a slight increasing change from west to east under all scenarios.

The most serious impacts of climate change for Ireland relate to changes in climate extremes. Extremes of heat in Ireland (heatwaves) are becoming more frequent and more severe in line with global trends, while extremes of cold (cold waves) are becoming less frequent and less severe. Heat extremes will become more frequent and more severe and cold extremes will become less frequent and less severe with further warming. Under Early action scenarios, both average temperatures and extremes would stabilise for Ireland in the latter half of the century. Under late action and high equilibrium climate sensitivity what are currently considered unusually warm days would be typical days and what are currently considered cold days would be incredibly rare by the end of the century.

Truly extreme heat events that are rare in the present climate are projected to become more common under all scenarios. Changes will be larger for the very infrequent, 1-in-50-year events (based upon present climate) than for 1-in-10-year events. The change would be considerably greater under late action than in Early action scenarios. Extreme cold events are conversely projected to become rarer, with greater reductions in the occurrence of what today would constitute 1-in-50-year events than in 1-in-10-year events.

3.1 Observed temperature changes

Temperature directly affects Ireland's agricultural productivity, natural systems, all aspects of our built environment, and the health and wellbeing of all citizens. Temperatures referred to in this chapter are surface air temperatures, typically measured 2m above the ground (Parker, 1994). Originally, the purpose of historical observations was to monitor daily and seasonal climate variability and support weather forecasting. However, today those observations can also support climate change impact studies and climate services. The importance of this historical information is well recognised, and, while several data rescue initiatives have been undertaken, there is still a vast amount of national historical meteorological records that remain undigitised (Mary Curley, Met Éireann, personal communication). Irish academics in conjunction with Met Éireann have led the way in terms of incorporating novel participatory learning techniques in both tertiary and secondary settings (Ryan et al., 2018, 2020; Mateus et al., 2020), which can complement other citizen science-based approaches.

In Ireland temperature is routinely measured at 25 synoptic stations and 78 automatic climate monitoring stations (measuring minute data every half hour, 24 hours a day) maintained by Met Éireann, numerous manual climate stations daily, additional weather stations maintained by a range of entities and individuals, and also at the Irish Marine Data Buoy Observation Network stations maintained by Met Éireann and the Marine Institute (Figure 3.1). Since 2000, the surface air temperature has been measured every hour on the marine data buoys. Records extend back for several land-based stations to the 19th century, allowing long-term changes to be derived after appropriate quality control and consideration of whether the record contains non-climatic data artefacts arising from, for example, station moves or equipment changes (Venema et al., 2012).

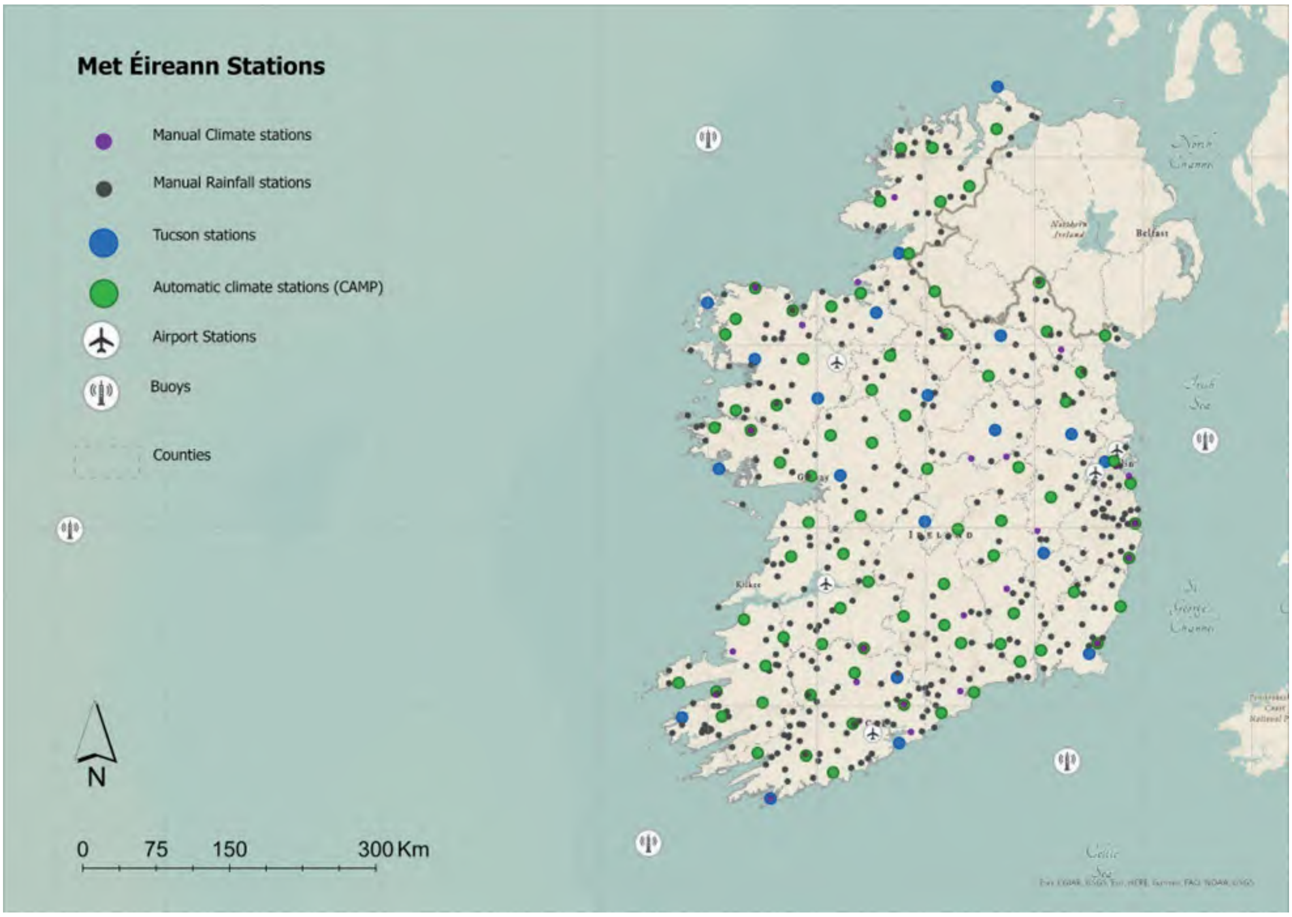


Figure 3.1 Temperature station type. Surface air temperature is measured at the 25 synoptic (blue and airport stations) and numerous climatological (magenta and green) weather stations, and also at the Irish Marine Data Buoy Observation Network stations (buoy symbol). Readings at automated synoptic and climate stations are made every minute (sub-hourly) and, at five staffed stations, located in the main airports, every half hour; at climatological stations readings of maximum and minimum temperature over the previous 24 hours are made once a day at 09:00 Coordinated Universal Time (UTC). Surface air temperature is measured every hour on the marine data buoys, the first of which was deployed in 2000. Source: Met Éireann.

An average national surface air temperature series for Ireland has been derived by Met Éireann using data from five long-term stations at Valentia, Malin Head, Armagh, Birr and Phoenix Park (Figure 3.2). Very similarly to the global mean surface temperature (compare the dark-blue global curve to the light-blue national curve), the mean surface air temperature for Ireland has been trending upwards, and 16 of the top 20 warmest years on record have occurred since 1990. This national temperature series has been increasing at an average rate of 0.09°C per decade since 1900, and the annual average temperature is now approximately 1.0°C higher than it was in the early 1900s. There is substantial decadal to multi-decadal variability in the national temperature record. The departures between global and national temperatures on multi-decadal timescales closely match the phasing of the AMV, with anomalous warmth associated with positive AMV phases and vice versa (section 1.3.3). Centennial timescale changes in Ireland are broadly consistent with global changes owing to our geographical situation between Europe (which is warming considerably faster than the global mean) and the North Atlantic (which is warming at a slower rate).

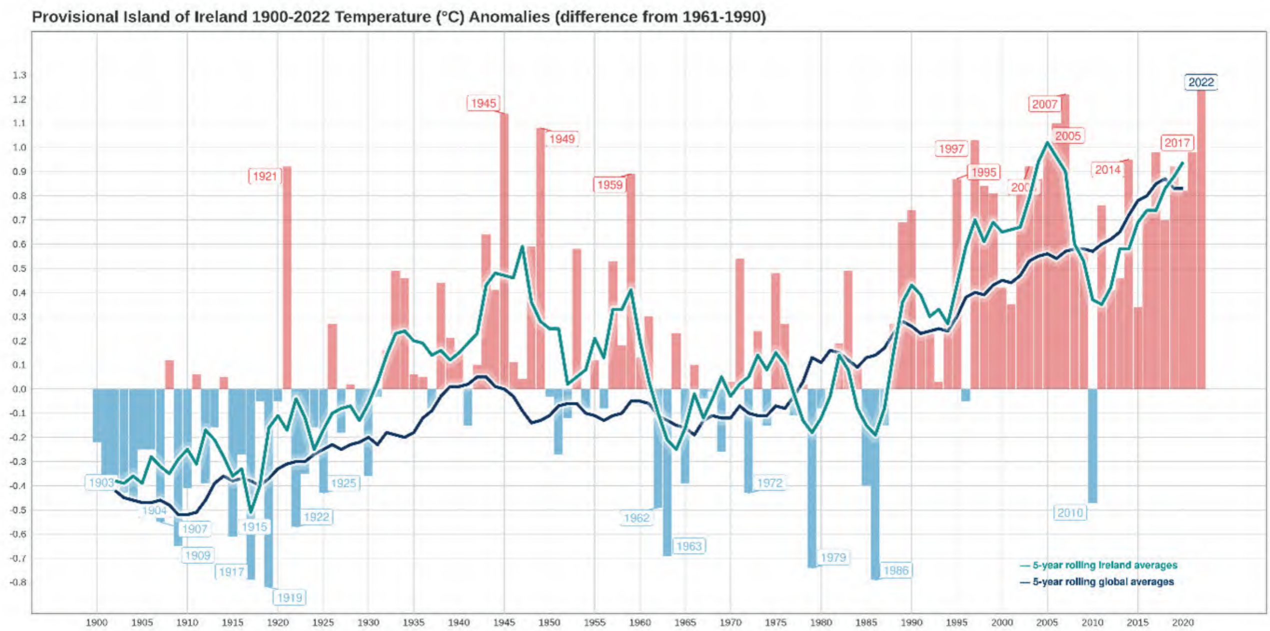


Figure 3.2 Island of Ireland temperature anomalies, 1900–2022 relative to 1961–1990. Source: Met Éireann.

Table 3.1 highlights changes between successive decades in this series. Each of the last three successive decades have been warmer than any preceding decade in the national temperature record. The most recent decade of 2013–2022 was 1.14°C warmer than the first decade in the record (using these consecutive averages), 1903–1912.

Decade	Annual average temperature (°C)	Annual anomaly relative to 30-year base period	
		1961–1990 (average 9.55°C)	1991–2020 (average 10.17°C)
2013–2022	10.37	0.82	0.19
2003–2012	10.25	0.80	0.07
1993–2002	10.09	0.54	–0.08
1983–1992	9.69	0.14	–0.48
1973–1982	9.56	0.01	–0.61
1963–1972	9.46	–0.09	–0.72
1953–1962	9.76	0.21	–0.42
1943–1952	9.91	0.36	–0.27
1933–1942	9.72	0.17	–0.45
1923–1922	9.43	–0.12	–0.74
1913–1922	9.32	–0.23	–0.86
1903–1912	9.23	–0.32	–0.95

Table 3.1 Decadal average temperature changes from 1903–1912 to 2013–2022 relative to two consecutive 30-year base periods (1961–1990 and 1991–2020) Source: Met Éireann.

Spatial trends can be inferred since 1950 from the E-OBS dataset (Cornes et al., 2018), which incorporates data from historical stations across the country in addition to data from the UK and near continent, and performs state-of-the-art interpolation to create 10km resolution reconstructions across Europe. The whole of the island of Ireland has experienced a long-term warming trend that at all locations is statistically significant (Figure 3.3). According to the E-OBS dataset, warming since 1950 has been relatively homogeneous across the island, with local maxima in the south-east and the mid-Atlantic coastal regions and local minima near Cork city and around Leitrim and Armagh. Rates of warming in most locations are between 0.1°C and 0.2°C per decade, which is consistent with the national time series changes over this period (Figure 3.2).

Annual average temperature trends per decade (°C) 1950–2021

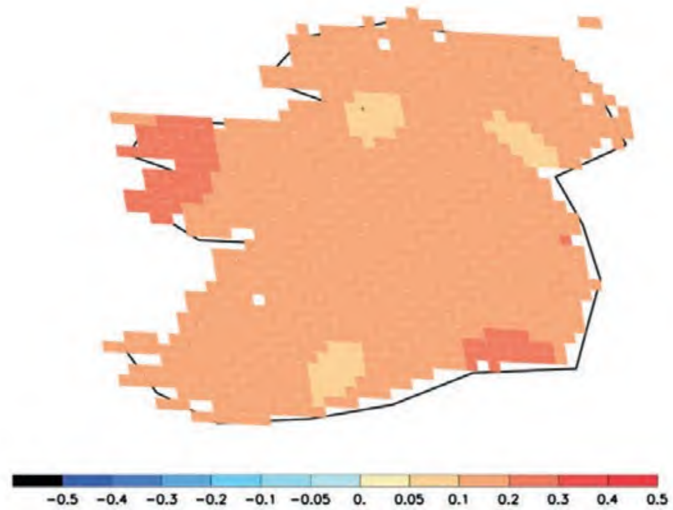


Figure 3.3 Trends in annual average temperatures from the E-OBS dataset. Trends and their significance have been calculated using the method of Santer et al. (2008). Hatched areas (if there were any, which there are not in this case) denote non-significance accounting for autocorrelation effects. We acknowledge the E-OBS dataset and the data providers in the European Climate Assessment & Dataset (ECA&D) project (https://www.ecad.eu; Cornes et al., 2018). Source: Plotted by the authors.

Box 3.1 Interpretation of future climate projections across this volume

There are many ESMs available to science that project how global climate will change in the future under Early, Middle, and Late action scenarios (section 1.5). None of these models, however, has sufficient resolution to make meaningful projections for a land mass as small as the island of Ireland. In order to make meaningful future projections for Ireland, a process called 'downscaling' is required with RCMs that takes into account as many uncertainties as possible during this process.

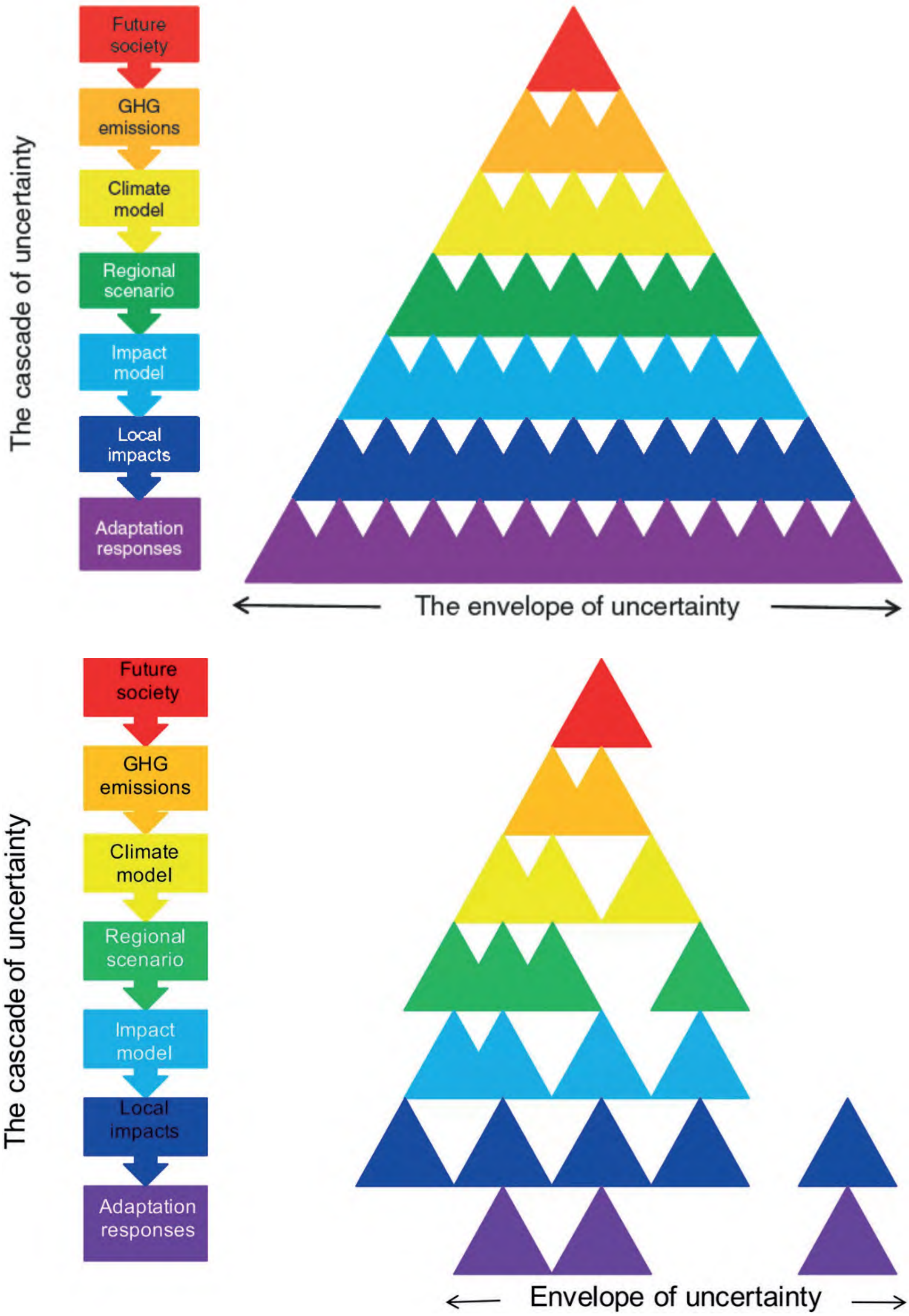
This volume principally relies upon future climate projections produced by the TRANSLATE project (see Box 1.3). The suite of future projections that are produced are called an ensemble. Because of computational limitations, these ensembles are relatively small in size. It is important that the strengths and limitations of the approach taken by the TRANSLATE project be clearly understood to avoid misinterpretation. To do so requires first stepping back and considering the cascade of uncertainty (Box 3.1, Figure 1; Wilby and Desai, 2010; Wilby, 2017). The full uncertainty range in going from scenario construction (Cross-volume Box 1) through ESMs, RCMs and on to actual data applications is substantial but would also require an impossible research task to sample fully. There exists an almost infinite range of plausible scenarios and plausible ESMs and RCMs that would require to be run in an almost endless set of combinations. In reality, therefore, the sampling ends up looking more akin to the lower panel of Box 3.1, Figure 1. Thus, the first key takeaway is that any set of future climate projections, no matter how well designed, will inevitably not sample the full range of possible outcomes, particularly so locally.

There are, of course, ways to design the construction of a model ensemble to capture to the fullest extent possible the true uncertainty for regional projections. Key aspects to consider would be the use of a range of scenarios (Early, Middle and Late action); a range of ESMs screened for realism in key processes; and two or more RCMs to capture regional model downscaling uncertainty.

The TRANSLATE results used in this volume are as documented in O'Brien and Nolan (2023) and are based upon a combination of European Coordinated Regional Climate Downscaling Experiment (EURO-CORDEX) simulations run by agencies across Europe and specific simulations run at ICHEC (Nolan and Flanagan, 2020) on CMIP5 model output[16]. The basis for the ensemble selection is the climate sensitivity over Ireland as described in O'Brien and Nolan (2023), which is based upon the temperature response to selected scenarios over selected windows. While this broadly corresponds to the assessed ECS of the ESMs in IPCC AR5, the mapping is not one to one (O'Brien and Nolan, 2023). The ensemble basis is given in Box 3.1, Table 1, and the associated selection justification is fully documented in O'Brien and Nolan (2023). In each case for each scenario the available simulations are averaged across all available simulations arising within the sensitivity ensemble. The Early action scenario arises from RCP2.6, the delayed action ensemble from RCP4.5 and the late action scenario from RCP8.5.

For TRANSLATE-2 there are also new simulations under development using CMIP6 which will provide updated information once fully complete (Nolan, 2023). In this under-development next generation of simulations the choice of CMIP6 data for downscaling global climate projections to regional projections for Ireland was informed by a careful review carried out in collaboration with EURO-CORDEX partners (COSMO-CLM team, personal communication, 2022). This study identified an initial set of CMIP6 datasets based on many factors, e.g. model level data availability, scenarios considered, whether the spatial resolution of the model would be sufficient for an Irish context, ECS (section 2.3.3), and the skill of the model at reconstructing important components of the climate system that particularly affect Ireland, including extra-tropical storm tracks, ocean circulation and sea surface temperature variations. The choice of CMIP6 data is

[16] CMIP5 models were prepared and submitted in preparation for IPCC AR5 and thus were largely complete by 2012/2013. Newer CMIP6 models were prepared for IPCC AR6 and have been shown to be of somewhat higher overall quality (Eyring et al., 2021). There are inevitable, and unavoidable, delays between ESM production and the production of dynamically downscaled simulations using RCMs.



Box 3.1 Figure 1 Top panel: The cascade of uncertainty from choices made by future society through emissions scenarios and various types of modelling and assessment to decision making. Each step in this process adds uncertainty (Wilby and Desai, 2010). Lower panel: The real-life situation is that only a subset of the uncertainty is sampled, thus leading to under-sampling of the range of plausible outcomes (Wilby, 2017).

further supported by a separate 2021 study carried out by the Finnish Meteorological Institute (Ruosteenoja, 2021). This filtering of CMIP6 models will result in a high-quality, representative and manageable ensemble for downscaling over Ireland. Future work under TRANSLATE-2 will look to further expand and refine the initial ensemble used in this report such that a sufficient sample exists to reissue an improved analysis and users should refer to these updated results as they become available.

Box 3.1 Table 1 Classification of each ESM run for CMIP5-based TRANSLATE results into low-, middle-, and high-sensitivity ensembles, along with the RCMs nested in each. Note that MPI-CSC-REMO2099 ran two instances of the MPI-ESM-LR model (r1i1p1 and r2i1p2). Also, KNMI-RACMO22E ran three instances of the EC-EARTH model (r1i1p1, r3i1p1, r12i1p1). Not all combinations were available for all three RCP scenarios or for all four variables. For example, in practice, for most RCPs and most variables, three EURO-CORDEX members were available from the low-sensitivity ensemble and three from the high-sensitivity ensemble

Sensitivity ensemble	EURO-CORDEX		Nolan and Flanagan (2020)	
	ESM	RCM	ESM	RCM
Low	MPI-ESM-LR	CLMcom-CCLM4 GERICS-REMO2015 KNMI-RACMO22E MPI-CSC-REMO2009 SMHI-RCA4	MPI-ESM-LR	COSMO-CLM5
Middle	CNRM-CM5	CLMcom-CCLM4 CNRM-ALADIN53 KNMI-RACMO22E RMIB-Ugent-ALARO SMHI-RCA4	CNRM-CM5	COSMO-CLM5
	EC-EARTH	CLMcom-CCLM4 DMI-HIRHAM5 KNMI-RACMO22E SMHI-RCA4	EC-EARTH	COSMO-CLM5
	IPSL-CM5A-MR	IPSL-INERIS-WRF331F KNMI-RACMO22E SMHI-RCA4		
	NorESM1-M	DMI-HIRHAM5 GERICS-REMO2015 KNMI-RACMO22E		
			MIROC5	COSMO-CLM5 WRF
High	HadGEM2	CLMcom-CCLM4 GERICS-REMO2015 KNMI-RACMO22E SMHI-RCA4	HadGEM2	COSMO-CLM5

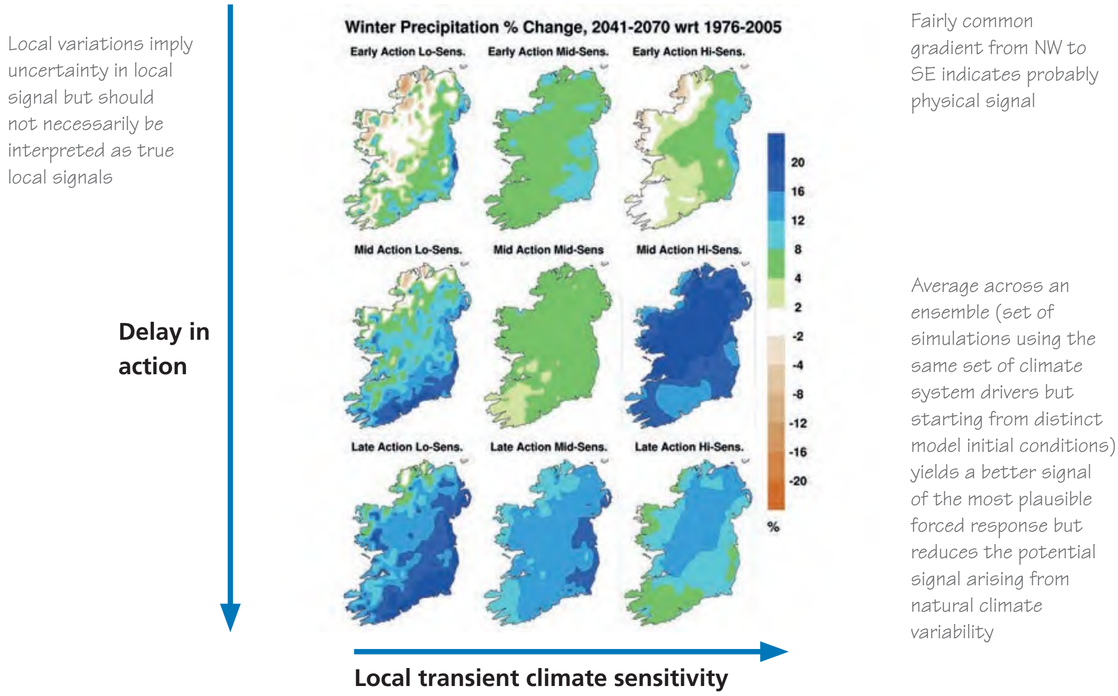
Source: O'Brien and Nolan (2023).

The RCMs nested in the ESMs provide downscaled projections that represent the best that can be achieved by the models. There remains an opportunity for statistics to contribute useful information by adjusting the model projections to correct for systematic biases that can be identified during well-observed historical periods. Without bias correction, raw model projections are usually shown as 'change' fields between a simulated future and a simulated past, in which the biases are assumed to cancel out. Change fields alone may suffice for some purposes, but most practical applications eventually need to match projected changes with recent observations, which amounts to bias correction, however implicit. For example, it is not enough to tell engineers that events with 10-year return periods currently will have 5-year return periods in the future; they also need to know the magnitude of such events, and bias correction is required to more reliably estimate that information.

TRANSLATE (O'Brien and Nolan, 2023) adopted the quantile delta mapping (QDM) method, as described by Cannon et al. (2015), and also show how it is superior to the other quantile mapping variants considered by virtue of explicitly preserving relative changes in (e.g.) precipitation quantiles. By now, QDM has been widely tested and validated, e.g. by Xavier et al. (2022) or Fauzi et al. (2020). The method is applied to each grid point independently, and so is easy to parallelise. However, this suggests a potential weakness of the method, which is that dynamical consistency between fields (e.g. temperature and precipitation) is not enforced and so may be lost, as explored by Rocheta et al. (2014). Indeed, consistency within a single field may also be lost (Maraun, 2013), especially insofar as the method is applied for downscaling purposes. More fundamentally, QDM assumes that biases remain statistically stable from the observed historical period to the end of the future projected period. This is usually a valid assumption, as discussed by Maraun (2012), but nevertheless should not be pushed too far.

There is then the question of how to present and interpret the resulting data, which consist of many Terabytes of numbers, in a meaningful and actionable way. In this report, an ensemble of nine possible futures are shown at different time slices. These nine possible futures for Ireland arise from Early, Middle and Late action scenarios (Cross-volume Box 1) and from three distinct groups of driving ESMs with 'low', 'medium' and 'high' local climate sensitivity[17] (Box 3.1, Figure 2 and Table 1; section 2.3.3). Each map plotted represents an ensemble mean based upon one or more ESMs driving several distinct RCMs for the given scenario. This averaging produces a clearer estimate of the likely climate signal. However, this does risk downplaying the potential role of natural variability. For example, it may average out several model simulations that happen to be in opposite phases of AMV (section 1.3.3) and hence remove an important signal of potential natural variability that could be superposed upon the forced climate response. The averaging approach is insufficient to remove all-natural variability, however, and it is necessary to interpret local structures, unless they can be linked to geophysical reasons such as topography, as likely to be noise. Conversely, large-scale patterns (in the case of Box 3.1, Figure 2, a general north-west to south-east gradient), especially if replicated across panels, should be interpreted as likely to be a geophysical signal.

[17] Note that these do not cover the full range of ECS as assessed in IPCC AR6 and that subsequent model runs, with appropriate experimental design under TRANSLATE-2, could better capture the full spread of ESM ECS consistent with IPCC-assessed ECS, including very high ECS that, although unlikely, cannot be ruled out (see Chapter 8).



Box 3.1 Figure 2 Annotated plot highlighting key aspects for interpretation of the TRANSLATE ensemble predictions, using winter precipitation results for illustrative purposes only. See figures in Chapters 3 and 4 and the main text for analyses. Source: Authors.

Finally, in both this volume and subsequent volumes, other sources of information may be relevant to contextualise the TRANSLATE results and are also used to verify that they reasonably span all possible outcomes. These include the broader EURO-CORDEX simulations, which are available for a much broader range of models but at a somewhat coarser resolution (Jacob et al., 2013; https://euro-cordex.net/index.php.en), and which can be used in conjunction with TRANSLATE results to more fully sample uncertainty (Climate Change Advisory Council, 2022).

3.2 Future average temperature changes

A range of possible future temperature changes over Ireland is shown in Figure 3.4. Several possible changes are shown because these are not forecasts, but rather projections that depend strongly on future GHG emissions scenarios and on uncertainties in the ESMs and regional models used (Box 3.2). All projections are a combination of the forced response and internal variability, and internal variability will have a substantial impact on decadal timescales (see Figure 4.3 and associated discussion in section 4.2).

All projections show higher future temperatures, whether just a fraction of a degree for the low-sensitivity case in response to Early action (top left map in each panel of Figure 3.4), or over 3°C by the end of the 21st century for the high-sensitivity response to Late action (bottom right map in the lower panel of Figure 3.4). While the projected actual temperature fields are quite complex (depending on local geography), the temperature change patterns shown in Figure 3.4 are relatively smooth, with just a slight gradient of increasing change from west to east. There is very little change, in fact a slight cooling, in the Early action scenario between the mid-century window and the late-century window (compare the top row of the upper and lower panels), highlighting that, with immediate and deep mitigation efforts globally (see Volume 2), it is possible to stabilise changes in annual mean surface temperatures on the island of Ireland within the lifetimes of many of our younger citizens. That stabilised climate, while being somewhat different from today's, would still, at least in terms of temperatures, be recognisable. Conversely, failure to undertake early action is projected to lead to future Irish climate states that become increasingly unrecognisable as the century progresses.

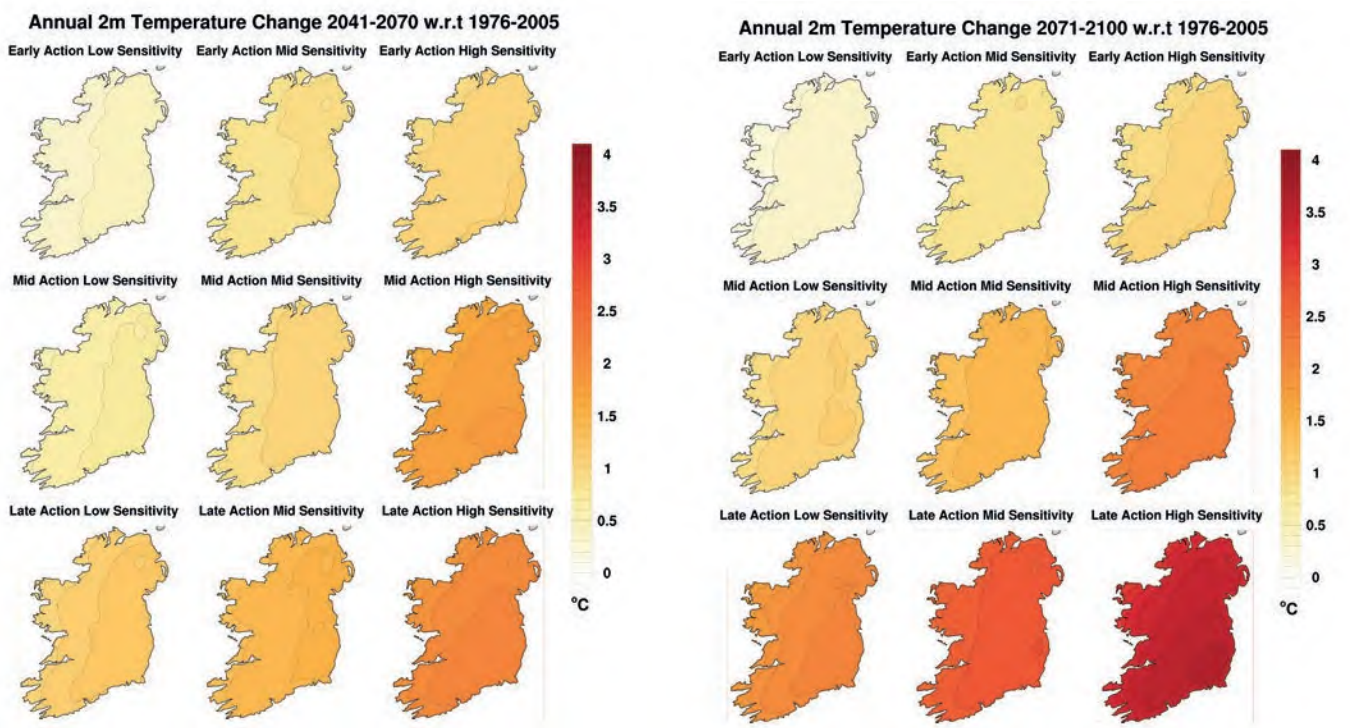


Figure 3.4 Projected range of changes in daily mean temperature (°C) under the Early action (top), Middle action (middle) and Late action (bottom) emission scenarios down each column, and for the low (left), medium (middle) and high (right) local transient climate sensitivity model ensembles across each row. All changes are for ensemble means, computed relative to observations during the reference period 1976–2005. Top array: projections for the mid-century period 2041–2070. Bottom array: same as the top array but for the end-century period 2071–2100. These charts (and others in the same format) are from the TRANSLATE project, and are based on detrended, bias-corrected, downscaled and synthesised output from Nolan and Flanagan (2020) and O'Brien and Nolan (2023). For further details on ensemble design and how to interpret these figures, see Box 3.1. Source: Figures prepared by TRANSLATE contributing authors specifically for this report.

Averaged over the island of Ireland, changes in annual mean temperature (Table 3.2) further highlight that, with Early action, we would broadly stabilise and indeed could begin to reverse temperature rises by the end of the century. Temperature increases relative to the recent past (1976–2005) reach 0.91°C [0.44–1.10°C] by mid-century before falling back to 0.80°C [0.34–1.07°C] at the end of the century. Conversely, both Middle action and particularly Late action see temperature rises continue to the end of this century (and indeed beyond). Under Late action, by the end of the century it is projected by the latest TRANSLATE results that temperature increases could be 2.77°C [2.02–3.49°C]. Warming increases with the sensitivity of the driving ESMs for a given emissions scenario.

Table 3.2 Areally averaged changes in annual mean surface temperatures from the TRANSLATE ensembles across the island of Ireland with a land–sea mask applied. Averages are the ensemble mean in each case and the differences between the 30-year means for end of century and a recent 30-year period, 1976–2005. The use of ensemble means here implies that values may fall above or below the values given arising from natural variability

Scenario	Low sensitivity	Mid-sensitivity	High sensitivity
Mid-century (2041–2070)			
Early action	0.44°C	0.91°C	1.10°C
Middle action	0.66°C	1.02°C	1.77°C
Late action	1.18°C	1.50°C	2.10°C
Late century (2071–2100)			
Early action	0.34°C	0.80°C	1.07°C
Middle action	1.05°C	1.42°C	2.21°C
Late action	2.02°C	2.77°C	3.49°C

Source: Results provided by TRANSLATE contributing authors for this report.

3.3 Observed temperature extremes

The most serious impacts of climate change are often related to changes in climate extremes. In 1998, the World Meteorological Organization (WMO) established the Expert Team on Climate Change Detection and Indices (ETCCDI) to develop a set of climate indices that allows the analysis of extreme events in a uniform way (https://www.climdex.org/). The E-OBS dataset (Cornes et al., 2018), which is derived from daily data arising from 288 stations across the country (plus a number of stations in Northern Ireland and many thousands of stations across Britain and Europe), uses state-of-the-art interpolation techniques to create a high-resolution gridded product for Europe that includes all ETCCDI indicators and is served as a 0.1° (10km) gridded product via the Copernicus Climate Change Service[18]. In the case of temperature, these include the hottest day and coldest night of the year (Figure 3.5). For both of these indicators there have been warming trends over the bulk of Ireland, with most trends being statistically significant. Trends in the warmest day of the year (TXx) have been broadly around +0.2°C to +0.3°C per decade, with the noticeable exceptions of parts of the Midlands and areas around Cork, which show lesser increases or even a slight decrease around Cork city. In these regions, the trends are not significant. Warming trends in the coldest night of the year (TNn) are generally larger than in TXx across the country with many areas warming at >0.3°C per decade, but across swathes of the Midlands, extending to Dublin, Meath and Wicklow, are not significant, and there is even slight cooling in parts of Dublin. Trends in TNn are greatest near the Atlantic coast.

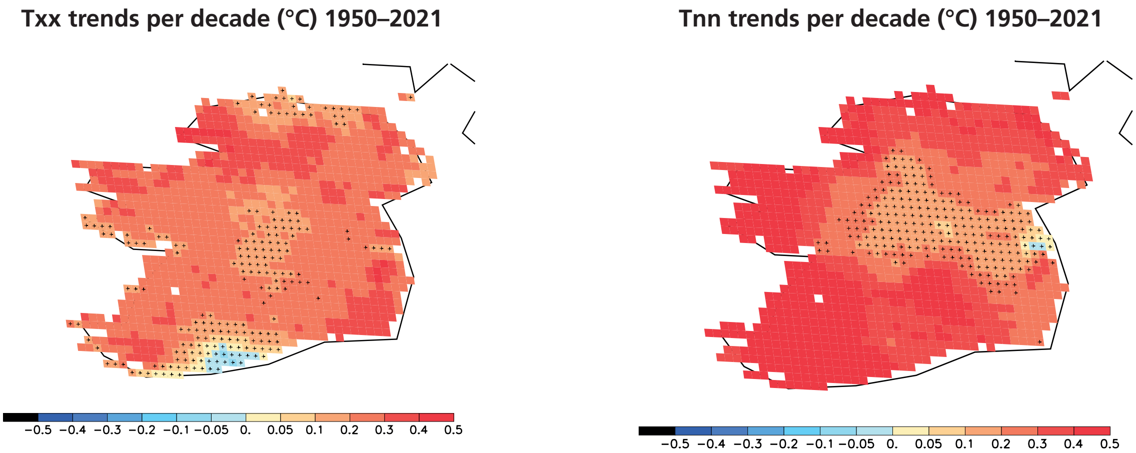


Figure 3.5 Trends in the hottest day of the year (TXx) and the coldest night of the year (TNn) from the E-OBS dataset. Trends and their significance have been calculated using the method of Santer et al. (2008). Hatched areas denote non-significance accounting for autocorrelation effects. We acknowledge the E-OBS dataset and the data providers in the ECA&D project (https://www.ecad.eu; Cornes et al., 2018). Source: Plotted by the authors.

18 Note that in the past year Met Éireann has developed and released station series for these ETCCDI indices and is in the process of deploying a gridded product. Here we need to use a gridded product and thus use the E-OBS product as the only suitable product available at the time of producing this volume.

Trends in unusually warm and cold days and nights are also available. These take the warmest and coldest 10% of days (Tx90p and Tx10p) and nights (Tn90p and Tn10p) over a fixed historical period and then count the changes in the frequency of exceeding these values with time (Figure 3.6). To ease comparison, the colour bar for the Tx10p and Tn10p have been switched in Figure 3.6 so that decreases in frequency of occurrence of exceedance (fewer cold days and nights) are intuitively associated with warm colours. The plots show that unusually cold days and nights have become less frequent, whereas unusually warm days and nights have become more frequent since 1950. These changes have been significant over the vast majority of the island of Ireland. We have been experiencing on average one or two fewer unusually cold days and nights and two or three more unusually warm days and nights per decade across much of the island of Ireland since 1950. This represents a substantial shift – around 7–14 fewer unusually cold days and nights and 14–21 more unusually warm days in a typical year than was the case in the mid-20th century.

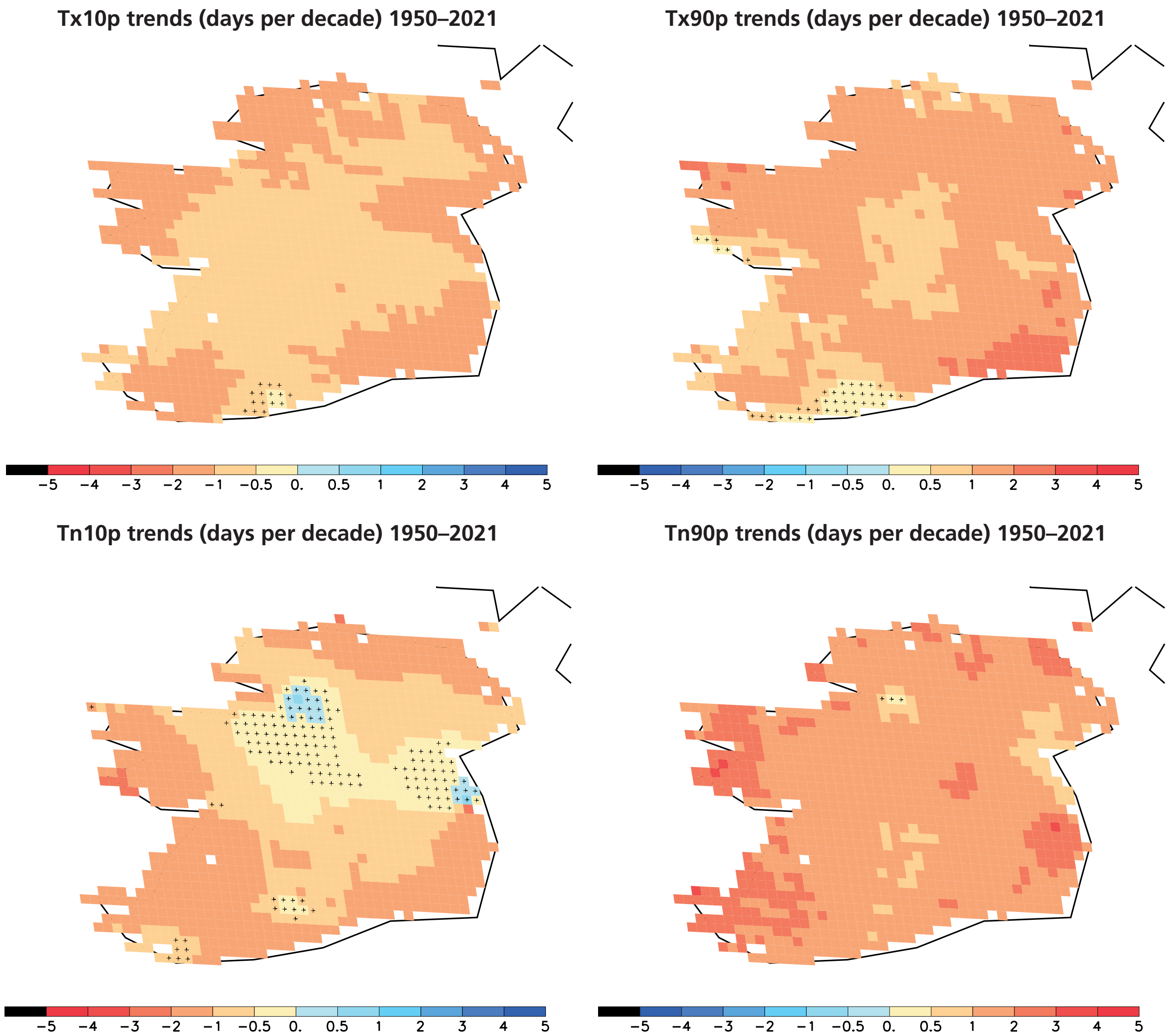


Figure 3.6 Trends in Tx10p, Tx90p, Tn10p and Tn90p from the E-OBS dataset. Trends and their significance have been calculated using the method of Santer et al. (2008). Hatched areas denote non-significance accounting for autocorrelation effects. We acknowledge the E-OBS dataset and the data providers in the ECA&D project (https://www.ecad.eu; Cornes et al., 2018). Note that for intuitive interpretation of the Tn10p and Tx10p parameters the colour bar scale is flipped such that negative values (a decrease in frequency of occurrence of cold extremes) are linked to warmer colours and vice versa. Source: Plotted by the authors.

3.4 Future temperature extremes

The standardised climate ensembles produced by the TRANSLATE project (see Boxes 1.3 and 3.2) can be used to compute any of the 27 standard climate extreme indices defined by the ETCCDI. Figure 3.7 shows the spatial distribution of projected future changes for TXx. Projected changes in temperature extremes tend to be larger than the comparable mean temperature changes (cf. Figure 3.4) in agreement with observed changes to date (section 3.3). In contrast to the changes in mean temperatures, the projected changes to TXx tend to be greatest in the west or south-west of the country. As for mean temperatures, under the Early action scenario changes in the warmest day of the year would broadly stabilise, or even somewhat reduce after peaking, within the lifetimes of today's younger citizens.

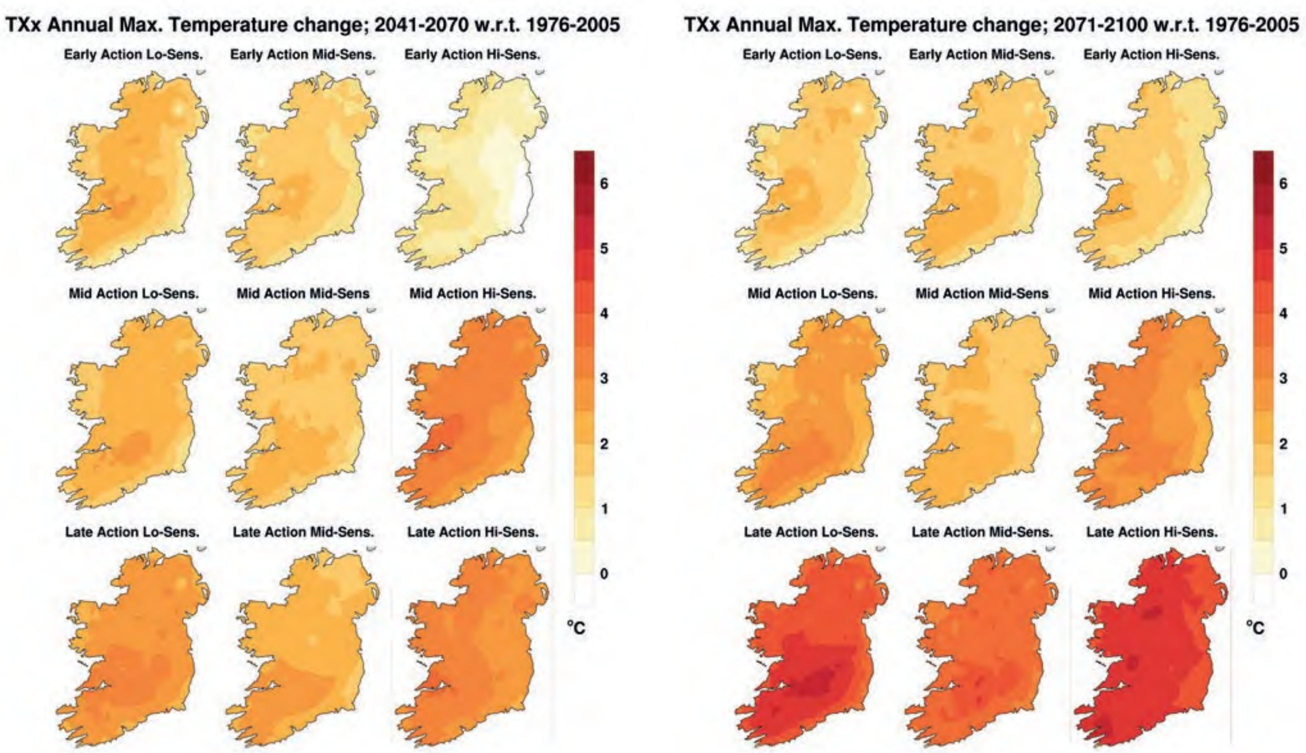


Figure 3.7 Top array: projected changes in the annual maximum of daily maximum temperature (TXx), using 30-year means of TXx for the period 2041–2070 relative to 1976–2005, and the median of all ensemble members. As in Figure 3.4, the columns show output from the Early action (top), Middle action (middle) and Late action (bottom) scenarios, while the rows show output from the ensembles with low (left), medium (middle) and high (right) local transient climate sensitivity. Bottom array: same as top array, but for the end-century period 2071–2100. For further details on ensemble design and how to interpret these figures, see Box 3.1. Source: Figures prepared by TRANSLATE contributing authors specifically for this report.

> *"As for mean temperatures, under the Early action scenario changes in the warmest day of the year would broadly stabilise, or even somewhat reduce after peaking, within the lifetimes of today's younger citizens."*

Projected changes to TNn (Figure 3.8) are broadly similar to the projected TXx changes (Figure 3.7). However, there are subtle differences. Unlike for TXx, changes in TNn tend to be projected to be greatest in the eastern half of the island of Ireland. This is the opposite of observed behaviour since 1950 (see section 3.3). Changes in TNn also tend to be smaller than changes in TXx across the set of projections. Again, this is the opposite of observed changes to date, where TNn changes have, for most of the island of Ireland, exceeded those in TXx (also consistent with observed global trend analyses; Thorne et al., 2016). Whether this highlights a likely change in behaviour moving forwards or limitations in either the observations or the model projections (or some combination of both) is unclear and requires further research.

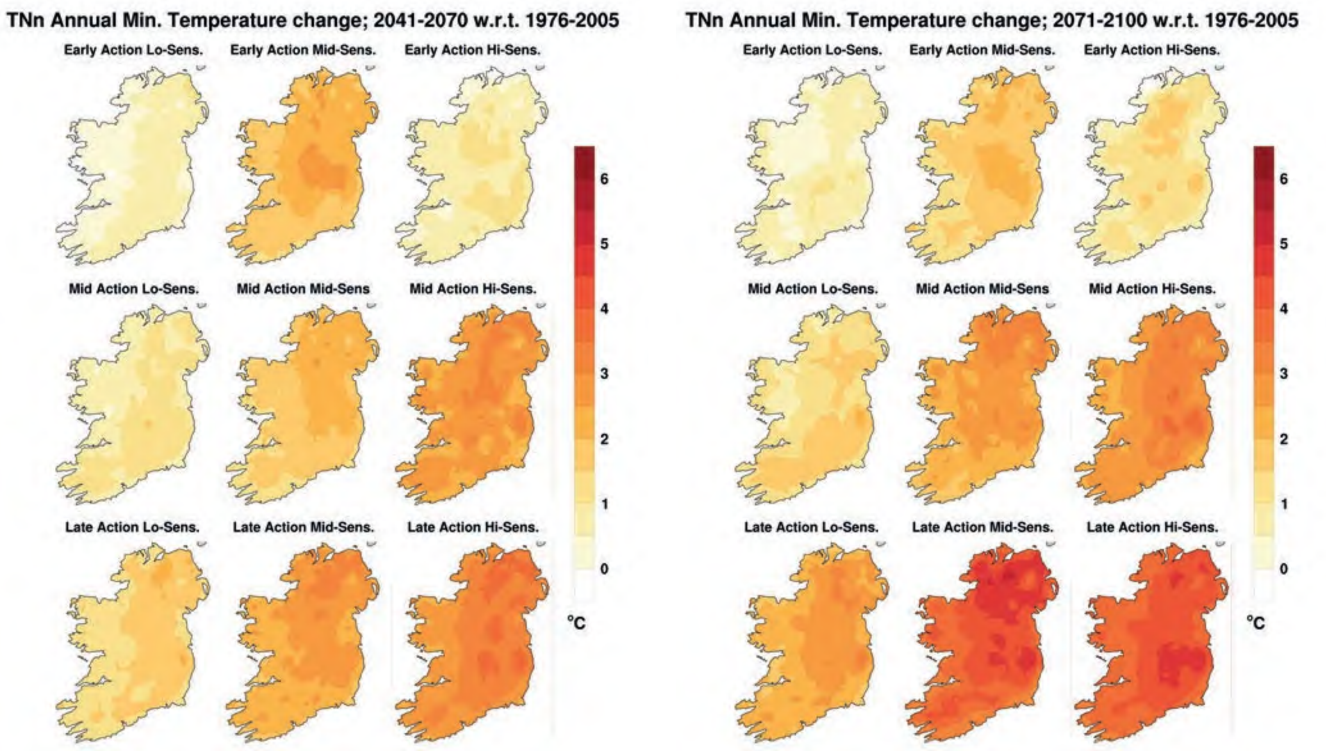


Figure 3.8 Top array: projected changes in the annual minimum of daily minimum temperature (TNn), using 30-year means of TNn for the period 2041–2070 relative to 1976–2005, and the median of all ensemble members. As in Figure 3.4, the columns show output from the Early action (top), Middle action (middle) and Late action (bottom) scenarios, while the rows show output from the ensembles with low (left), medium (middle) and high (right) local transient climate sensitivity. Bottom array: same as top array, but for the end-century period 2071–2100. For further details on ensemble design and how to interpret these figures, see Box 3.1. Source: Figures prepared by TRANSLATE contributing authors specifically for this report.

Projected changes in parameters such as Tx90p, which counts exceedance of the 90th percentile of daily maximum temperatures (30+ occurrences per year in the historical baseline period), will inherently be less subject to noise arising from internal variability than for TXx, which is one value per year (Figure 3.9; cf. Figure 3.7). The changes projected in Tx90p are substantial for all except the Early action scenario, particularly for low climate sensitivity where changes are very small. In all other cases in future, what were considered abnormally warm days historically will become more frequent. By the end of the century, under Late action and high local transient climate sensitivity, it is possible that what we have considered to be abnormal warmth would be the typical daily maxima across much of the southern half of Ireland. Equally, under Early action, again, occurrence of this extreme metric is stabilised after mid-century, and, while there will probably be more abnormally warm days, between one and two-and-a-half times as many depending upon climate sensitivity, the climate would still be largely recognisable.

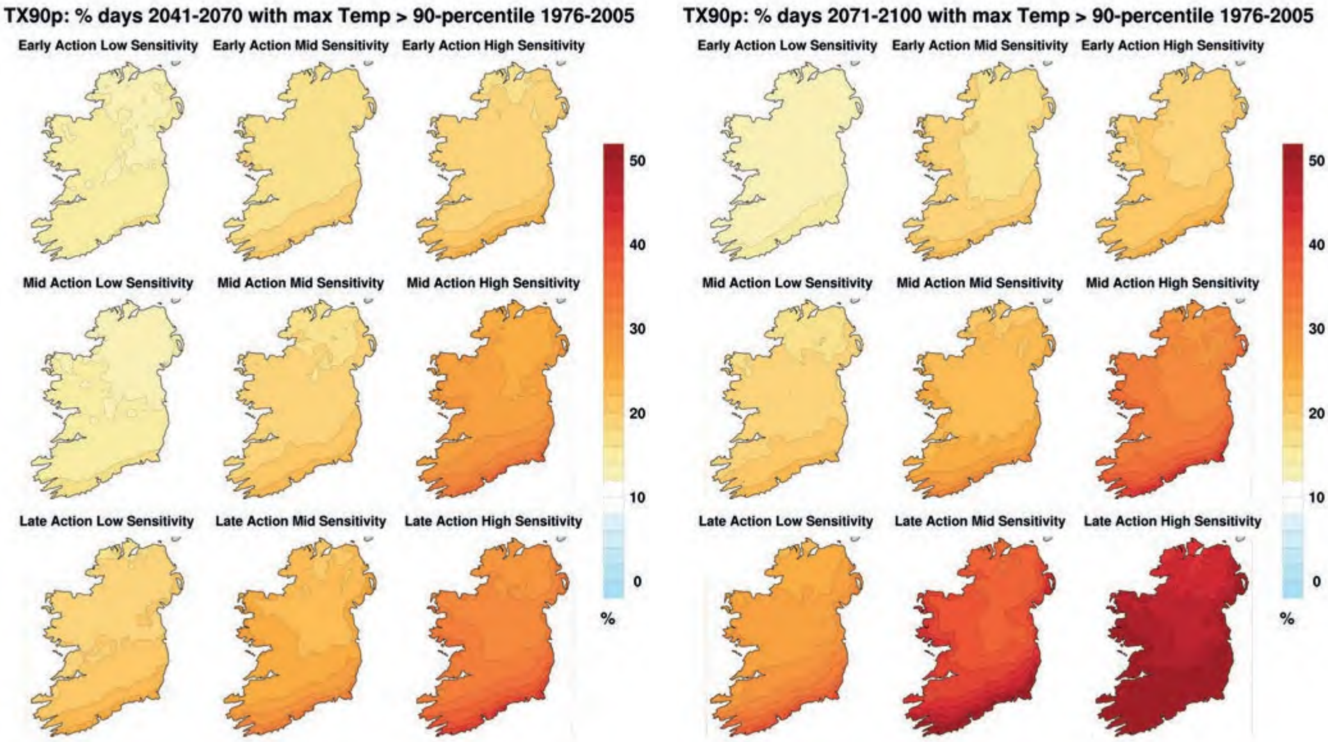


Figure 3.9 Top array: projected changes in TX90p, using 30-year means of TX90p for the period 2041–2070 relative to 1976–2005, and the median of all ensemble members. As in Figure 3.4, the columns show output from the Early action (top), Middle action (middle) and Late action (bottom) scenarios, while the rows show output from the ensembles with low (left), medium (middle) and high (right) local transient climate sensitivity. Bottom array: same as top array, but for the end-century period 2071–2100. In each plot colours denote the percentage of days per year exceeding the 90th percentile (top 10% of days) relative to 1981–2010 which, by construction, would be 10% everywhere in an unchanged climate. For further details on ensemble design and how to interpret these figures, see Box 3.1. Source: Figures prepared by TRANSLATE contributing authors specifically for this report.

Similar consideration can be given to Tx10p, the frequency of occurrence of abnormally cold daytime maximum temperatures (Figure 3.10). Numbers in this metric below 10% indicate a reduction in the frequency of days that are abnormally cold. In both mid-century and at the end of the century, all locations across the island of Ireland are projected to experience a decrease in the frequency of what, historically speaking, we have considered to be unusually cold days. Under the Late action scenario and high climate sensitivity, there are projected to be effectively no occurrences of days as cold as we would currently experience as our top 10% coldest days. Whereas, again, under Early action, it is possible to stabilise the changes after mid-century, and, while in many locations the frequency of occurrences of days as cold as we would consider unusually cold today is projected to roughly halve, such days would still occur.

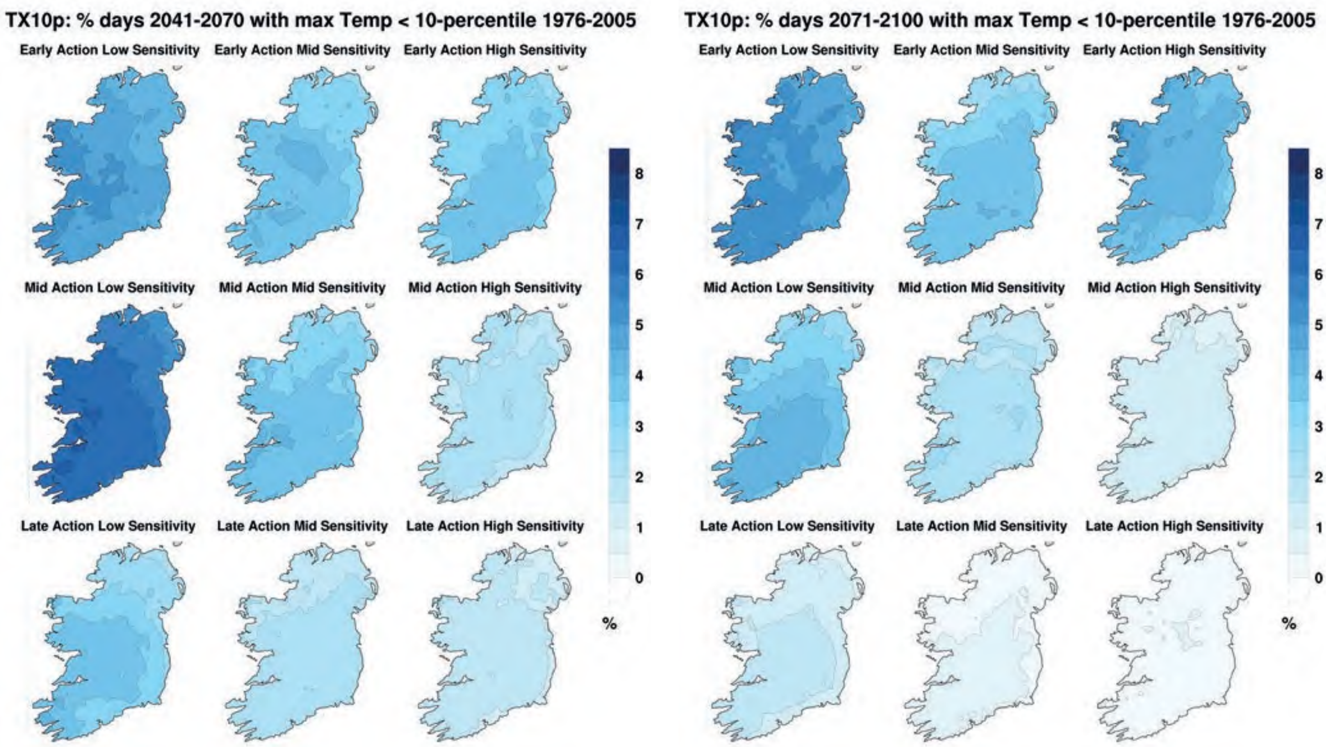


Figure 3.10 Top array: projected changes in TX10p, using 30-year means of TX10p for the period 2041–2070 relative to 1976–2005, and the median of all ensemble members. As in Figure 3.4, the columns show output from the Early action (top), Middle action (middle) and Late action (bottom) scenarios, while the rows show output from the ensembles with low (left), medium (middle) and high (right) local transient climate sensitivity. Bottom array: same as top array, but for the end-century period 2071–2100. For further details on ensemble design and how to interpret these figures, see Box 3.1. Source: Figures prepared by TRANSLATE contributing authors specifically for this report.

In addition to changes in magnitude, the frequency (or return period) of temperature extremes is also expected to change. Extreme hot temperatures are expected to become more frequent (Figure 3.11), while extreme cold temperatures are expected to become less frequent (Figure 3.12).

Extreme TXx recurrence times are projected to become shorter for the next 20 years or so, irrespective of scenario. After that, extreme temperature recurrence times could stabilise or even lengthen again under the Early action scenario, or continue to get shorter under the remaining scenarios. Under the Late action scenario, the annual maximum temperature value with a 10-year return period in 1976–2005 could have an average return period of less than 2 years by 2050, and the annual maximum temperature with a 50-year recurrence time in 1976–2005 could occur every 5 years (or less) by the end of the century. In other words, record-breaking summertime peak temperatures that historically occurred every 50 years will happen every 5 years.

More extreme (and rarer) heat events are projected to have larger proportionate increases in frequency than less extreme events (Figure 3.11), consistent with the global picture assessed in IPCC WGI (Senevaritne et al., 2021). The historical 50-year event more than halves its recurrence time to less than 20 years by 2021–2050 for the medium-sensitivity ensemble (diamond symbols), while the historical 10-year event reduces by less than half. Similarly, more extreme and rarer cold events become much less likely in future, particularly under the Late action scenario, while more common cold extremes, although becoming less likely, change their return periods by a smaller proportion (Figure 3.12).

Overall, the TRANSLATE projections paint a picture of a future in Ireland where extremes of heat are more frequent and intense, and extremes of cold are less frequent and less intense. The extent of the change, particularly by the end of the century, is critically dependent upon the future emissions scenario. If the pathway is Late action and the real-world local transient climate sensitivity is at the high end of the assessed range, then by the end of this century today's children face a climate that in many respects would be unrecognisable to us today. What we consider unusually cold days would be extremely rare, whereas what we consider abnormal warmth would be commonplace. Events of extreme heat that today are extremely rare may occur once a decade or even more frequently. Alternatively, with Early action, the climate could stabilise by mid-century. While that climate would have more frequent abnormally hot days and fewer abnormally cool days, it would not be entirely unrecognisable to the climate we experience today.

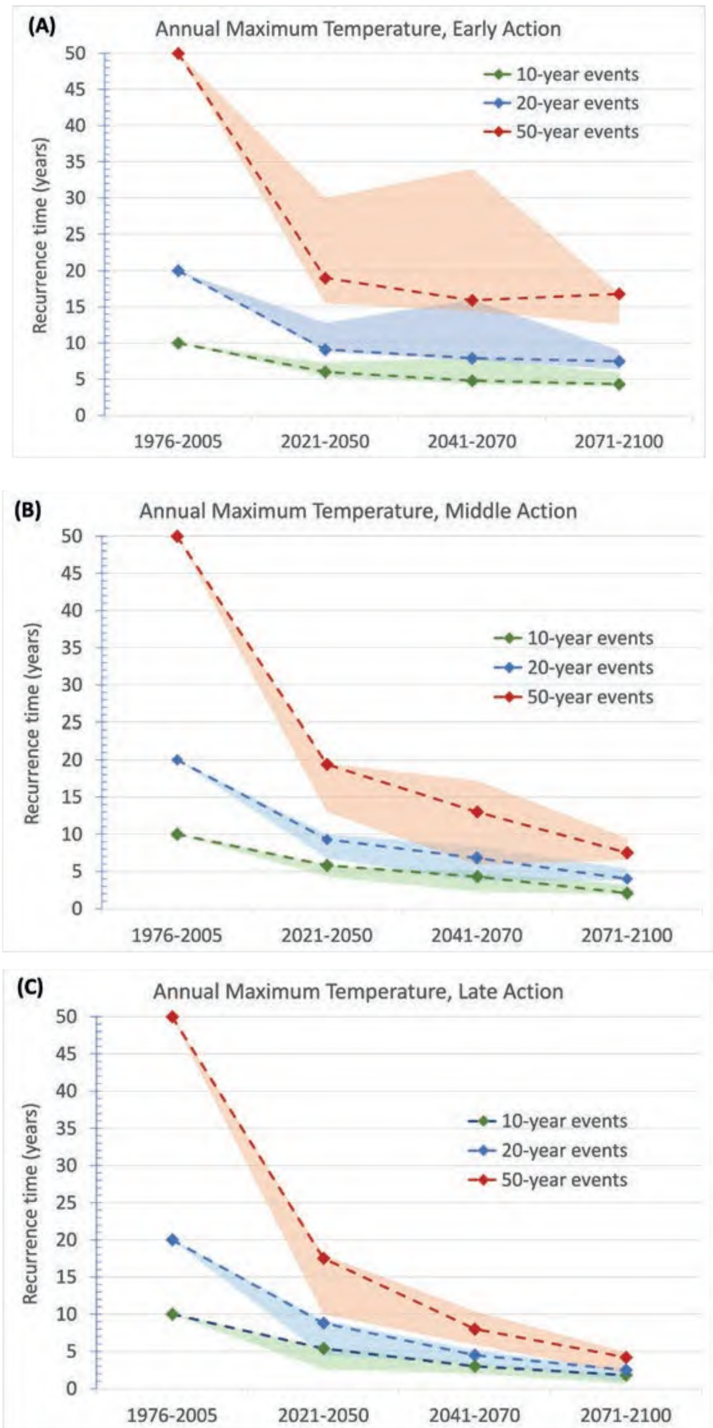


Figure 3.11 Projected changes in the recurrence times (or return periods) of Ireland-averaged TXx values that had recurrence times of 10, 20 and 50 years during the past reference period of 1976–2005 based upon downscaled CMIP5 output. The symbols joined by dashed lines show values from the medium-sensitivity model ensemble, while the shading spans the range between the low- and high-sensitivity ensembles. Panel (a) presents the Early action scenario, (b) the Middle action scenario and (c) the Late action scenario. Source: Figures prepared by TRANSLATE contributing authors specifically for this report.

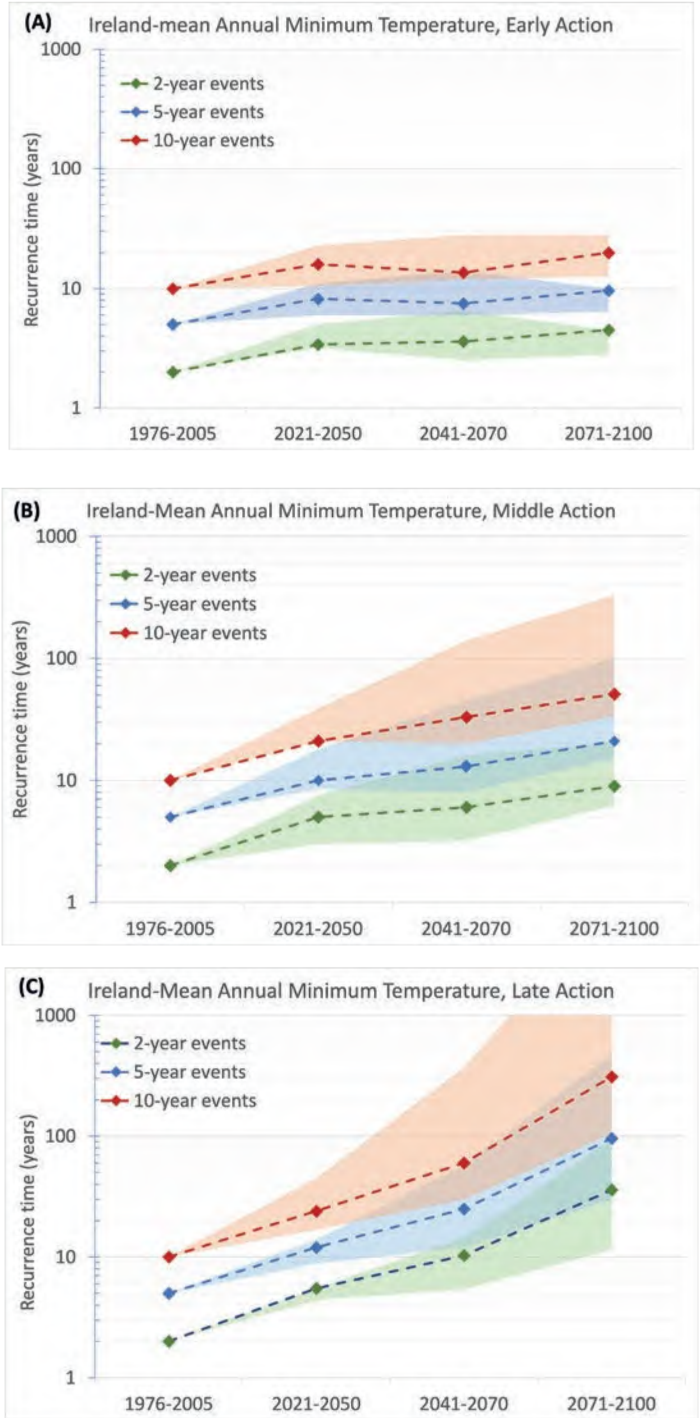
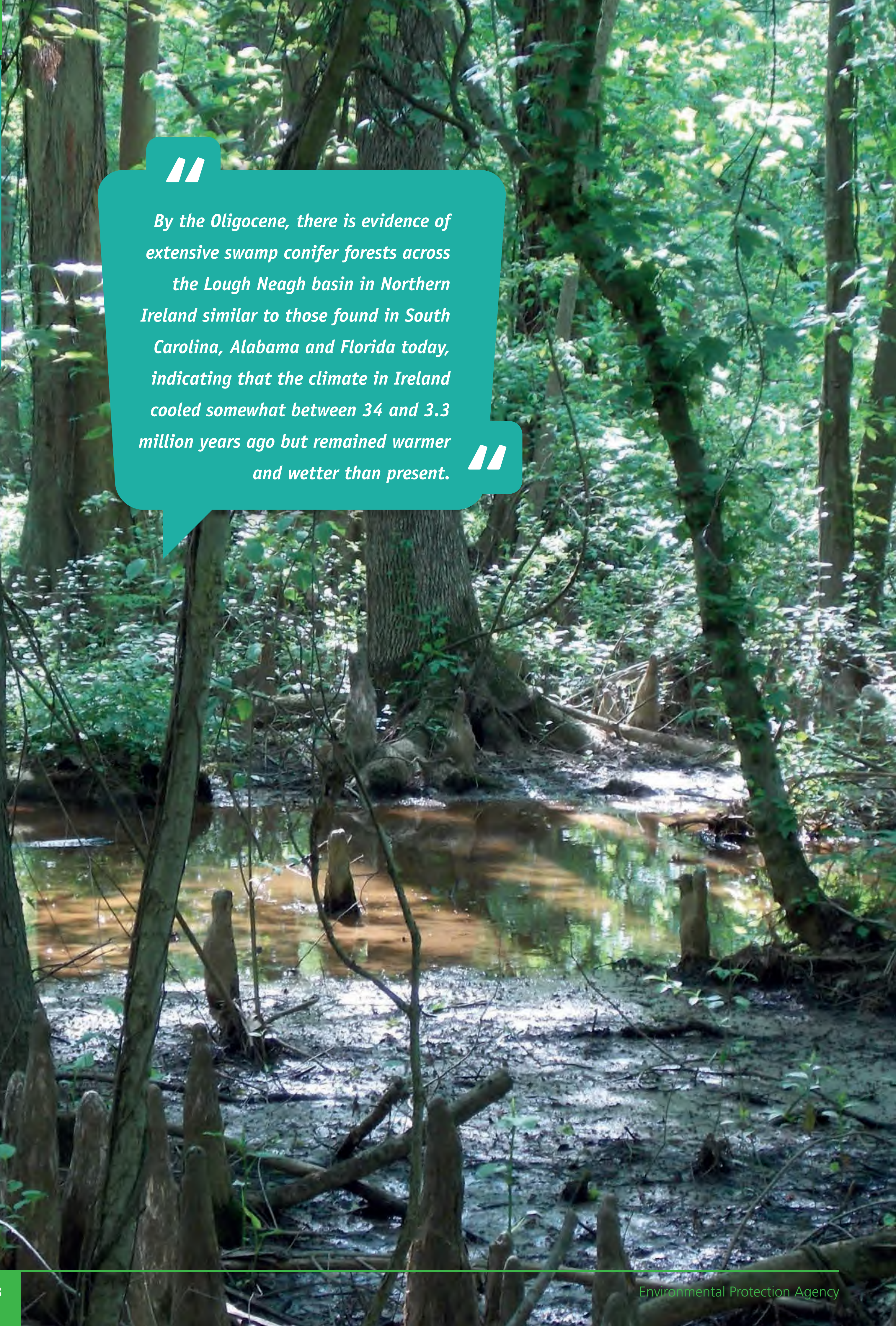


Figure 3.12 Projected changes in the recurrence times (or return periods) of Ireland-averaged TNn values that had recurrence times of 2, 5 and 10 years during the past reference period of 1976–2005 based upon downscaled CMIP5 output. The symbols joined by dashed lines show values from the medium-sensitivity model ensemble, while the shading spans the range between the low- and high-sensitivity ensembles. Panel (a) presents the Early action scenario, (b) the Middle action scenario and (c) the Late action scenario. Note the logarithmic scale on the y-axis. Source: Figures prepared by TRANSLATE contributing authors specifically for this report.

3.5 Recommendations

3.1	Met Éireann's long-term climatological stations must be maintained and developed, and the data continue to be made available to support monitoring of our changing climate. Periodic reprocessing using state-of-the-art techniques to assess quality control and homogeneity and create improved observationally based products, including spatially interpolated products, needs to be supported on a sustained basis.
3.2	The many environmental data records currently available in only hard copy or image format need to be rescued and digitised to enable exploitation. There are millions of observations that remain in hard copy or image format and are thus inaccessible for further research. Efforts are required to inventory, scan and rescue these records, which exist in a variety of public and private repositories; some of which predate Irish independence may rest in UK-based repositories. There is substantial potential to engage citizens in this effort, via either participatory citizen science projects or engagement as part of experiential learning techniques, the latter of which Irish researchers have pioneered in secondary and tertiary educational settings. Rescuing the records would greatly inform estimates of long-term historical changes.
3.3	It is imperative that the newly developed national station and gridded products for the 27 ETCCDI indices, currently in the process of finalisation by Met Éireann, be supported and maintained for the long term. These will complement the Europe-wide E-OBS product and will potentially in future benefit from access to additional data sources and improved local knowledge, leading to improved interpolation into data void regions.
3.4	To support climate services provision it is necessary to undertake additional climate model experiments to better understand the interplay of internal variability, model uncertainty, climate sensitivity and scenario choices in projections of future changes, particularly in extreme indices, which are sensitive to such choices. This requires careful experimental design to tease apart these sources of uncertainty, and may benefit from consideration of using ESMs run with very large ensembles to sample from, to drive the RCMs used in TRANSLATE in follow-on activities, including TRANSLATE-2 and the new national climate services programme.
3.5	Observed changes in the hottest night have exceeded those of the hottest day and have been greater in the west than the east. This is the opposite of projected behaviour in the TRANSLATE ensemble where it is projected that the hottest days will warm more than the hottest nights and changes will be greatest in the east. Further research is necessary to ascertain whether this reflects a probable change in behaviour of temperature extremes moving forwards, model limitations or residual observational homogeneity issues.



> *By the Oligocene, there is evidence of extensive swamp conifer forests across the Lough Neagh basin in Northern Ireland similar to those found in South Carolina, Alabama and Florida today, indicating that the climate in Ireland cooled somewhat between 34 and 3.3 million years ago but remained warmer and wetter than present.*

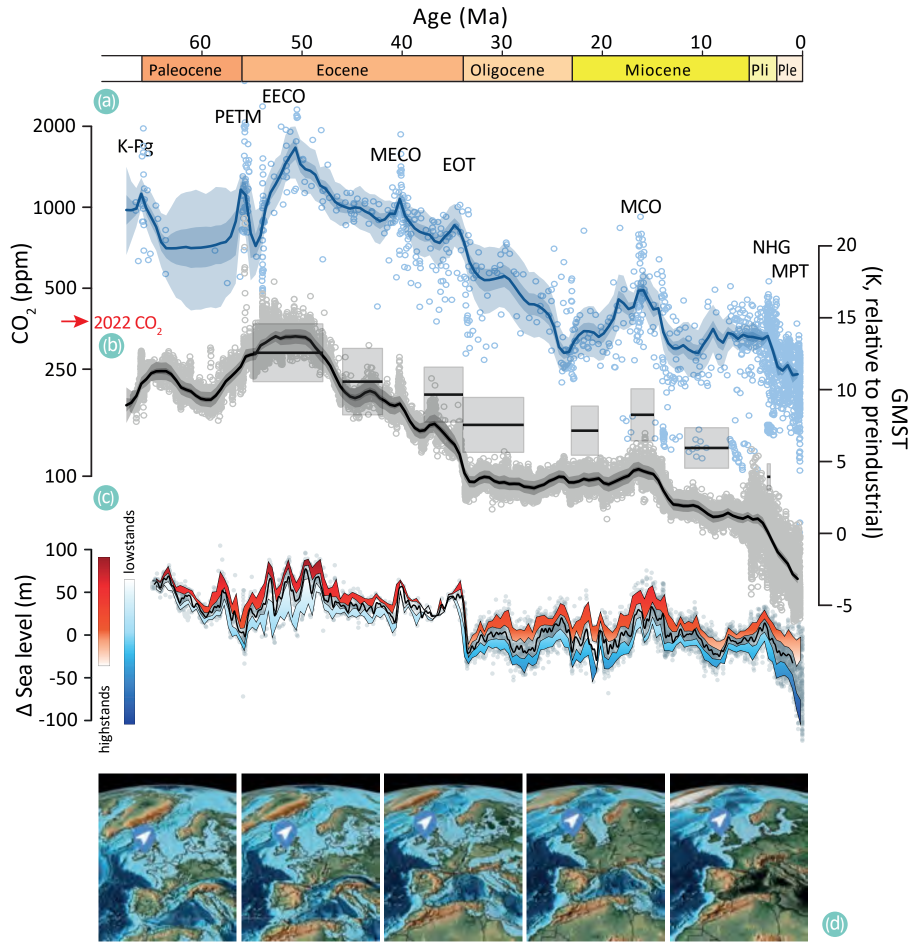
CROSS-CHAPTER BOX 2

IRELAND'S CLIMATE THROUGH THE AGES

Detailed study of proxy climate records, including temperature and atmospheric carbon dioxide (CO_2), reveal the evolution of Earth's dynamic and changing climate over the past 66 million years – a geological time interval known as the Cenozoic. New compilations of deep-ocean temperature estimates from fossil phytoplankton have been used together with Earth surface temperature proxies to calculate trends in global mean surface temperature (GMST) over deep time (Westerhold et al. 2020; Ring et al., 2022). Similar large-scale compilation efforts have been under way to vet all known proxy CO_2 estimates from fossil leaves, marine algae, liverworts, soils and marine boron isotopes, resulting in a 66-million-year consensus record of atmospheric CO_2 (www.paleo-co2.org; Hoenisch, 2021; Hoenisch et al., 2023, in press, 2023). Taken together, they enable us to provide a deep-time context for Ireland's current and future climate.

The paleo-proxy records show that global temperature and atmospheric CO_2 concentrations have declined over the Cenozoic, from warmhouse and hothouse climate states with GMSTs of >5°C and >10°C higher than pre-industrial levels, respectively, between 66 and 34 million years ago (Cross-chapter Box 2, Figure 1a). During these warmhouse and hothouse states the poles were ice free and much of the landmass of Ireland was below sea level (Cross-chapter Box 2, Figure 1d). At around 34 million years ago at the Eocene/Oligocene boundary, global climates transitioned to a coolhouse state characterised by a significant drop in GMST (Cross-chapter Box 2, Figure 1b; Westerhold et al., 2020) and a strong decline in atmospheric CO_2 concentration (Cross-chapter Box Figure 1a; Hoenisch et al., 2023, in press). Large ice sheets expanded on Antarctica at this time, global sea levels dropped precipitously (Cross-chapter Box 2, Figure 1c; Miller et al., 2020) and Ireland's familiar geography emerged as its land mass was now mostly above sea level (Cross-chapter Box 2, Figure 1d; Scotese and McKerrow, 1994). The coolhouse climate characterised by the presence of Antarctic ice and GMST greater than pre-industrial levels but less than 5°C warmer lasted until 3.3 million years ago, after which an icehouse climate prevailed (Westerhold et al., 2020). Icehouse climates are characterised by waxing and waning of ice sheets in the Arctic and have widely fluctuating GMSTs, much colder than present during the glacials when northern hemisphere ice sheets expand, and similar or warmer than present during the interglacials when ice sheets contract.

Although limited proxy temperature estimates have been obtained from fossils and sediments across the island of Ireland and our geographical position was not identical to that of today (see Cross-chapter Box 2, Figure 1d), it is possible to highlight the general paleo-environmental conditions of some key fossil localities that occur along this long 66-million-year timeline which corroborate the climatic transitions from hothouse to icehouse observed at a global scale. Fossil leaves from Paleocene-aged sediments within the Antrim basalts near the Giant's Causeway (Baily, 1869) and across the North Atlantic region (Willard et al., 2019) suggest a mixed conifer/broadleaved forest adapted to warm temperate and even subtropical climates in Ireland at a time when warmhouse climates prevailed globally. Evidence of fossil palms and baobab trees (found today in Madagascar) within the paleo-Arctic Circle provide strong support for a warmhouse climate in the broader Atlantic region (Willard et al., 2019). By the Oligocene, there is evidence of extensive swamp conifer forests across the Lough Neagh basin in Northern Ireland similar to those found in South Carolina, Alabama and Florida today, indicating that climate in Ireland cooled somewhat between 34 and 3.3 million years ago but remained warmer and wetter than present. Globally, coolhouse climates prevailed. Swamp conifer forests were still evident in Galway in the Pliocene around 5 to 2.5 million years ago (Coxon, 2001) but went extinct from the island of Ireland as the global climate transitioned from coolhouse to icehouse in the Pleistocene (Quaternary).



Cross-chapter Box 2 Figure 1 Trends in global temperature, sea level, atmospheric CO_2 concentration and Antarctic glaciation state over the past 66 million years (Cenozoic) together with an illustration of Ireland's changing paleogeographical position and proportion of land area above sea level. (a) Global trends in atmospheric CO_2 concentration (category 1 paleo-CO_2 record) from the CO_2-PIP consortium of paleo-CO_2 proxies (Hoenisch, 2021; Hoenisch et al., 2023, in press). The record is generated from hundreds of individual proxy CO_2 concentration estimates measured from fossilised leaves, liverworts, marine algae, soils and marine boron isotopes (blue symbols) that are correlated using a random walk model between successive time steps (solid line with 95% confidence intervals). Major climate events, including those that are used as analogues for Earth's climate future (Tierney et al., 2020) are highlighted (K/PG, Cretaceous/Paleogene boundary; PETM, Paleocene–Eocene Thermal Maximum; EECO, Early Eocene Climatic Optimum; MECO, Middle Eocene Climatic Optimum; EOT, Eocene/Oligocene Transition; MCO, Miocene Climatic Optimum; NHG, onset of northern hemisphere glaciation; MPT, Mid-Pleistocene Transition). Current atmospheric CO_2 level (average of year 2022) of 418ppm is indicated in red . (b) GMST estimates relative to pre-industrial levels over the past 66 million years, based on oxygen and carbon isotope analysis of deep-ocean dwelling foraminifera (Westerhold et al., 2020) and surface temperature proxies (Ring et al., 2022). (c) Sea level after Miller et al. (2020). Grey dots are raw data; the solid black line reflects median sea level in a 1-million-year running window. High (red) and low (blue) stands are defined within a 400,000-year running window, with high stands defined by the 75th (lower bound) and 95th (upper bound) percentile in each window, and low stands defined by the 5th (lower bound) and 25th (upper bound) percentile in each window. (d) Paleogeographical maps of the North Atlantic region by C. R. Scotese (Scotese and McKerrow, 1994), Paleomap Project. From left to right: maps of Paleocene (62 million years ago (Mya)), Eocene (51Mya), Oligocene (30Mya) and Miocene (7Mya). Location arrow on all maps is Dublin, Ireland (Moore, 2012). Pl and Quat refer to Pliocene and Quaternary, respectively.

[19] Data from Dr Pieter Tans, NOAA/GML (gml.noaa.gov/ccgg/trends/), and Dr Ralph Keeling, Scripps Institution of Oceanography (scrippsco2.ucsd.edu/).

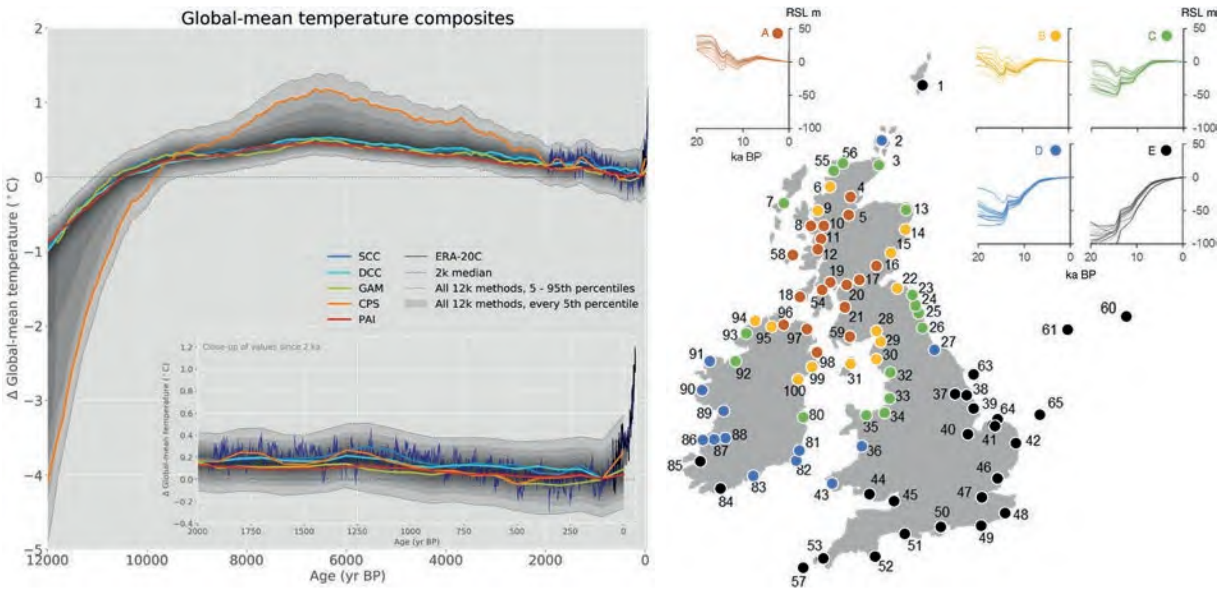
At the start of the Quaternary Period and the Pleistocene Epoch c.2.6 million years ago, the geographical position of the continents were in their current configuration. Global and Irish climates started to alternate between cold glacial periods, with significant ice on the northern hemisphere continents beyond Greenland, and warmer intervals, called interglacials, with little or no continental ice in the northern hemisphere (Shackleton et al., 1984; Past Interglacial Working Group of PAGES, 2016). For reference, we are currently in an interglacial phase of the Pleistocene Epoch called the Holocene. During maximum glacial phases of the Quaternary, the British–Irish ice sheets extended over the entire landscape of Ireland, as far south as the Celtic Sea shelf and west into the Porcupine Bank (Peters et al., 2015; Clark et al., 2018), and relative sea level was up to 60m lower than at present (Shennan et al., 2018) (Cross-chapter Box 2, Figure 2a). Eleven interglacial phases are recognised over the past 2.6 million years, including our current interglacial (Past Interglacials Working Group of PAGES, 2016), some of which were warmer than present and others cooler (Coxon et al., 2017). Although interglacial records of the Irish paleoclimate are generally less well preserved than those of continental Europe (Coxon et al., 2017), Ireland has a particularly rich archive of peatland, lake, cave and marine deposits spanning the last c.12,000 years (Holocene), and these records provide valuable insight into Ireland's baseline climate conditions over multiple millennia; examples include Crag Cave in County Kerry (McDermott 2001), An Loch Mór on Inis Oírr (Holmes et al., 2007), Glendalough, County Wicklow (Mitchell and Maldonado-Ruiz, 2018), and many others reviewed in Swindles et al. (2013).

Holocene proxy temperature records from the Irish continental shelf are being studied to assist future projections of storm intensities and trajectories (Curran et al., 2019). This 8,000-year marine record demonstrates higher than present bottom water temperatures (winter season) during the transition from the middle to late Holocene around 4,200 years ago, in good agreement with GMST records (Kaufman et al., 2020), and again in the Roman Warm Period between c.2,500 and 1,600 years ago (Curran et al., 2019). It has been hypothesised that these warmer temperatures are attributable to an increasing contribution of Atlantic waters with a subtropical origin and an eastward shift of a low-pressure system that influences the direction of storms, called the Icelandic low (Curran et al., 2019). Curran et al.'s study highlights the complexity of both atmospheric and oceanic factors and their interactions within the North Atlantic in shaping Ireland's climate history.

On land, compilations of proxy records from Irish and continental European peatlands document a pattern of distinct lowering of water table depths indicative of peatland drying in Ireland, Britain and Scandinavia over the past 300 years (Swindles et al., 2019). Although the primary driving force for these major hydrological changes in peatlands cannot be easily disentangled, the records demonstrate clearly that the most recent drying is greater in magnitude than previous hydrological shifts (Swindles et al., 2019), which has implications for future restoration (Volume 3). Although many paleoclimate records across Ireland lack concordance owing to limitations of dating and resolution, some document congruence in their climatological and hydroclimate signals, indicating a common forcing. For example, a strong warming observed in Irish Atlantic marine records (Curran et al., 2019) in the Roman Warm Period coincides with lowering peatland water table depth (Swindles et al., 2013) and establishment of pine and oak trees on Irish bogs (reviewed in Edvardsson et al., 2016). Many other cooling/wetting and warming/drying events, such as the Little Ice Age (LIA; between c.550 and 250 years before present) and the Medieval Warm Period (MWP; between c.1000 and 700 years before present), are detected in multi-proxy climate records from Irish sedimentary archives and historical annals (Kelly, 2020; Campbell and Ludlow, 2020); however, it has recently been concluded that past climatic extremes of the last two millennia such as the LIA and MWP are not global events occurring on the same time frame (Neukom et al., 2019). They represent regional climatic events caused by variability within the climate system (Neukom et al., 2019). In contrast, only the warming of the post-industrial era has a global expression, as it has been forced by a global anthropogenic driver – enhanced greenhouse gas emissions (Neukom et al., 2019) (Chapter 1).

Paleoclimate records thus provide vital insights on the role of natural climate forcing, such as volcanic emissions, solar insolation and Atlantic circulation, before human intervention in the climate system. They provide past temperature and precipitation estimates to validate Earth System Models (Otto-Bliesner et al., 2021). Equally, Irish Holocene paleoarchives provide one of the only means of establishing long-term baseline information required to inform future climate adaptation (Volume 3)/mitigation (Volume 2) policy that is tailored to our needs, such as on peatland hydrological status (Swindles et al., 2013), fire history (Hawthorne and Mitchell, 2018; O'Connell, 2021) and past explosive volcanic events (Watson et al., 2015), landscape-scale woodland cover and degree of openness (Fyfe et al., 2013; Baillie, 2014; Edvardsson et al., 2016; O'Connell, 2021), rate and magnitude of relative sea level change (Shennan et al., 2018), historical incidence of disease outbreak (Flynn and Mitchell, 2019), prevailing wind direction and position of ocean currents (Comas-Bru and McDermott, 2014; Orme et al., 2017) and modes of climate variability at different spatial and temporal scales (Hernandez et al., 2020), to name but a few.

By looking back at our climates of the past, both the deep (pre-Pleistocene) and more shallow (e.g. the Holocene) past, we can place future climate trajectories into context. If we follow the trajectory of SSP5–8.5 (Late action; Cross-volume Box 1) we will transition to a warmhouse state not experienced in Ireland or globally since the Eocene (>35 million years ago). A future climate following the projection of SSP5–3.4-OS (middle action; Cross-volume Box 1) has not been experienced in Ireland or globally since the Middle Miocene Climate Transition (MMCT) around 14 million years ago. North Atlantic Ocean proxy temperature estimates from the Porcupine basin off the coast of Cork indicate surface sea temperatures 13°C warmer than present during the Middle Miocene Climate Optimum and 10°C warmer than present at the MMCT (Sangiorgi et al., 2021). Only Early action (SSP1–1.9 or SSP1–2.6; Cross-volume Box 1) would keep GMST rise within the bounds of our and our ancestors' (e.g. genus Homo) past experience. Current atmospheric CO_2 levels are higher than any time since the MMCT according to the latest consensus atmospheric CO_2 record from the CO_2PIP consortium (Hoenisch et al., in prep., 2023). In other words, although Ireland and the world generally is currently within an interglacial phase of an icehouse state, we are transforming the planet's climate to a coolhouse/warmhouse mode more similar to that of our deep past.



Cross-chapter Box 2 Figure 2 Global mean surface temperature (GMST) change based on multiple paleotemperature sources compiled from marine, land and freshwater archives over the past 12,000 years relative to 1800–1900 (on left; from Kaufman et al., 2020) and relative sea level changes over the past 20,000 years in Ireland and the UK (from Shennan et al., 2018). Different coloured lines in GMST anomalies indicate different statistical methods of compilation as follows: standard calibrated composite (SCC), dynamic calibrated composite (DCC), composite plus scale (CPS), pairwise comparison (PAI) and generalised additive model (GAM). All GMST estimates, irrespective of the statistical method used in their compilation, show warming in the mid-Holocene around 8,000–6,000 years before present. The uncertainties for each method (grey shading) take into account different sources of errors. See Kaufman et al. (2020) for all methods. See Shennan et al. (2018) for geographical location of relative sea level data. Figure reproduced with permission from Shennan et al. (2018) and Kaufman et al. (2020).

Cross-chapter box recommendations

CCB.1	CCB.1 Multiple pre-Pleistocene fossil localities and sediment archives on the island of Ireland are amenable to reconstruction of paleotemperature and paleo-CO_2 using proxies, such as the inter-basaltic fossil-bearing sediments of Antrim and new Pleistocene interglacial sequences. Historically these fossil localities have not been studied with state-of-the-art paleoclimatic methods. Quantitative mean annual temperature estimates for these fossil localities could help to constrain biotic thresholds or tipping points and elucidate the nature of climatic transitions in Ireland's deep past.
CCB.2	Ireland's location in the north-east Atlantic makes it ideally placed for investigating the time course of changes in ocean and atmospheric circulation on climate and thus provides a sound basis for modelling the impact of possible changes in these systems today and in the future. Key archives that provide numerous proxies that are available to address this are the diversity of near-shore marine sediments in both shallow and deep water; extensive deep peat deposits; widespread lake deposits (including annually laminated lakes); a full Holocene tree ring record from bog oak and pine; and speleothems and written archives (c.1,200 years). A well-resourced and centralised repository of Irish paleoclimate and paleoenvironmental data would facilitate their integration across space and time towards this goal.

4

Precipitation Changes

Key messages

Annual precipitation was 7% higher in the period 1991 to 2020, compared to the 30-year period 1961 to 1990. Regions where trends in precipitation since 1950 are significant have generally experienced overall annual increases.

Regional projections of precipitation for Ireland are highly uncertain because they are dominated by model uncertainty and internal variability, even at the end of the century. Precipitation projections exhibit a much greater sensitivity to the choice of Earth System Model (ESM) than temperature projections. Limitations in the ability to sample from the full range of ESMs mean that the true uncertainty may be substantially undersampled in the TRANSLATE ensemble, in spite of careful experimental design.

Projected changes in national precipitation are more uncertain than those for temperatures. While winters tend to get wetter and summers tend to get drier, this is not consistently found across all global ESMs. There is also substantial sensitivity to the choice of ESM used to drive the national simulations. Changes averaged across the island of Ireland show a slight increase of <10% in annual mean accumulated precipitation amounts but with large sensitivity to choice of driving ESMs.

The natural variability in extreme precipitation in Ireland is significant. Therefore, analysis of local observations does not reveal evidence of a clear climate change signal in extreme precipitation indices. Regions where trends are significant have generally experienced overall annual increases. There are regions where a reduction has occurred over this period, but, in most cases, these changes are not significant. Overall, when aggregated, there has been a slight tendency to increased preponderance of wet extremes across a range of indicators.

Projections of changes in precipitation extremes are even more affected by model uncertainty and internal variability than annual average precipitation. It is likely that the available model projections considerably under-represent the range of possible outcomes for extreme precipitation indices. Intense precipitation extremes become more frequent and extreme with further warming in most regions across a range of extreme precipitation indices.

Extreme precipitation events are projected to become more frequent, with changes in rarer 50-year events being more marked than 10- and 20-year return periods. Under the Late action scenario, the annual maximum daily rainfall that used to occur once every 50 years, on average, will become approximately twice as frequent. The shortening of recurrence times that is projected out to mid-century or so can be stabilised or even reversed under the Early action scenarios by the end of the century.

4.1 Observed changes in mean precipitation

Precipitation (rain, snow, sleet or hail that falls to or condenses on the ground) plays a vital role in the water cycle and water balance and thus directly affects all of life on the island of Ireland. Changes in precipitation drive changes in the water supply. Analysis of gridded precipitation observations from Met Éireann for the period 1941 to the present indicate increasing trends in annual precipitation totals since the 1980s (Cámaro García et al., 2021). IPCC AR6 WGI (Douville et al., 2021) assessed medium confidence[20] for the observed increase in mean precipitation in mid-latitudes of the northern hemisphere and high confidence that internal climate variability dominates multi-decadal trends in precipitation at regional scales. Given the large interdecadal variability of Irish precipitation, analysis of long-term records is critical to identify robust changes. Noone et al. (2016) developed a quality-assured precipitation series for the island dating back to 1850. Their results show the large variability that has been experienced in annual and seasonal precipitation totals. Overall, they found that increasing trends in winter rainfall are evident for records commencing before 1860. In summer, there have been decreasing trends in rainfall since 1850. These seasonal trends have become much more pronounced and significant since the 1970s (Noone et al., 2016). Nationally averaged annual precipitation was 7% higher in the period 1991 to 2020, compared to the 30-year period 1961 to 1990 (Cámaro García et al., 2021; updated).

There can be high variability in precipitation amounts over space and time, particularly so in summer when convective (tens of kilometres) rather than synoptic (hundreds to thousands of kilometres) scale precipitation is more frequent. During convective events, places a matter of a kilometre apart can be either totally dry or extremely wet. Therefore, a dense network of national measurement stations is required to capture trends and variability. With the advent of radar capabilities in recent decades, and with an adequate sampling of well-situated radars, spatial distributions of precipitation can be inferred. Despite the availability of (sub-) hourly precipitation observations from a number of stations and 5-minute resolution radar data, there thus far exists little to no investigation of changes in sub-daily precipitation nationally. Divergent long-term trends can also occur because the variability of precipitation is highly dependent upon start and end dates of the time series studied (Gulev et al., 2021). Shifting the start or end date by even a year or two if it includes/excludes a particularly wet or dry year can change even the sign of the trends locally.

Precipitation has been measured systematically in Ireland since the late 19th century, with a peak of over 800 official rainfall stations in the late 1950s. Today, there are 25 synoptic, 384 manual and 78 automatic climate stations measuring rainfall, maintained by Met Éireann. Murphy et al. (2018) developed a 300-year precipitation series for the island and found that annual totals in recent decades are the wettest in the entire series. The continuous 305-year (1711–2016) monthly rainfall series (IoI_1711) was created for the island of Ireland using observational and documentary records. The derived series, one of the longest continuous records in Europe, offers valuable insights for understanding multi-decadal and centennial rainfall variability in Ireland. Figure 4.1 shows the annual IoI_1711 series. Annually, the period 2006–2015 is the wettest decade in the record. The IoI_1711 series reveals significant multi-centennial trends in winter (increasing) and summer (decreasing) seasonal precipitation. However, long-term trends in winter precipitation may be a result of changes in measurement practice around the 1860s and the inclusion of snow as part of precipitation totals (Murphy et al., 2019). Nonetheless, exceptional winter rainfall totals in recent years (2013–14 and 2015–16) stand out in the long-term records.

Spatial trends from E-OBS (used for consistency with the temperature analysis in Chapter 3) show very spatially heterogeneous trends over 1950–2021 (Figure 4.2), which for very many parts of the island of Ireland are not statistically significant. The regions which do exhibit significant trends extend across parts of the Midlands and mid-west and parts of Ulster, and exhibit increasing trends in annual accumulations. Most areas showing drying; even though the trends are in many instances large, are not significant. Using a distinct dataset or a distinct period of record would possibly yield a different picture. Trends are sensitive to the precise period of record, station inclusion and choice of interpolation, which matters considerably more for precipitation (small spatial scales, orders of magnitude variations) than for temperature (large spatial scales, small variations) (Gulev et al., 2021; Blair Trewin, Bureau of Meteorology, personal communication, 2022).

[20] In the IPCC, confidence and likelihood statements have very specific meanings. Confidence statements are based upon the number of lines of evidence and their degree of agreement. Likelihood statements have specific probabilistic interpretations. More information is available in https://www.ipcc.ch/site/assets/uploads/2017/08/AR5_Uncertainty_Guidance_Note.pdf

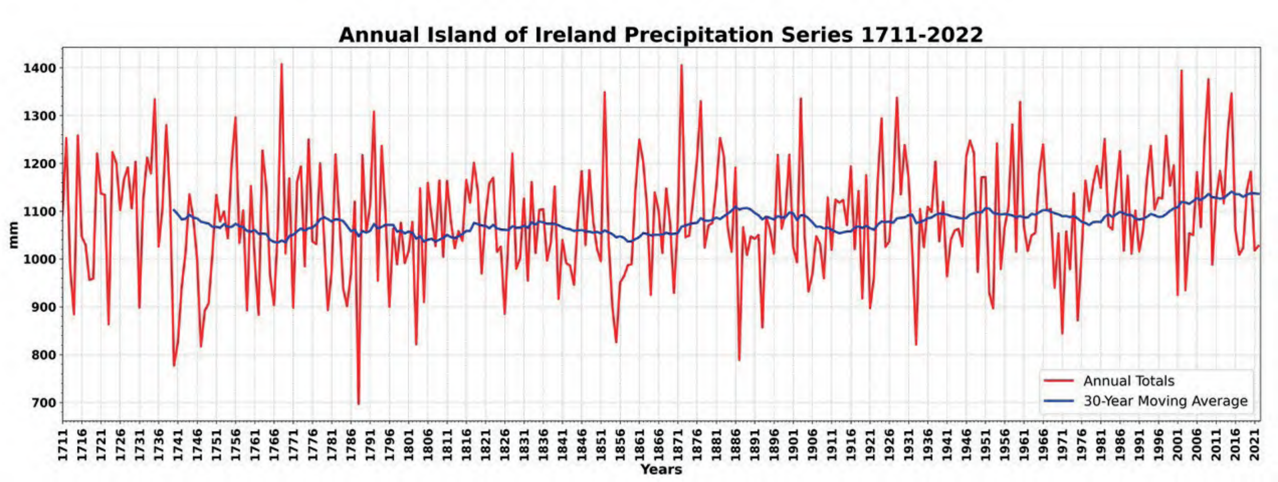


Figure 4.1 Reconstructed precipitation series over the island of Ireland since 1711, based upon Murphy et al. (2018) showing annual totals. From 1850 onwards, the data are the island of Ireland 1850 series produced by Noone et al. (2016). The blue line represents a 30-year moving average. Data post-2015 are based upon 12 well-separated sites maintained by Met Éireann for which real-time data are available. Source: Plot provided by Simon Noone for this report.

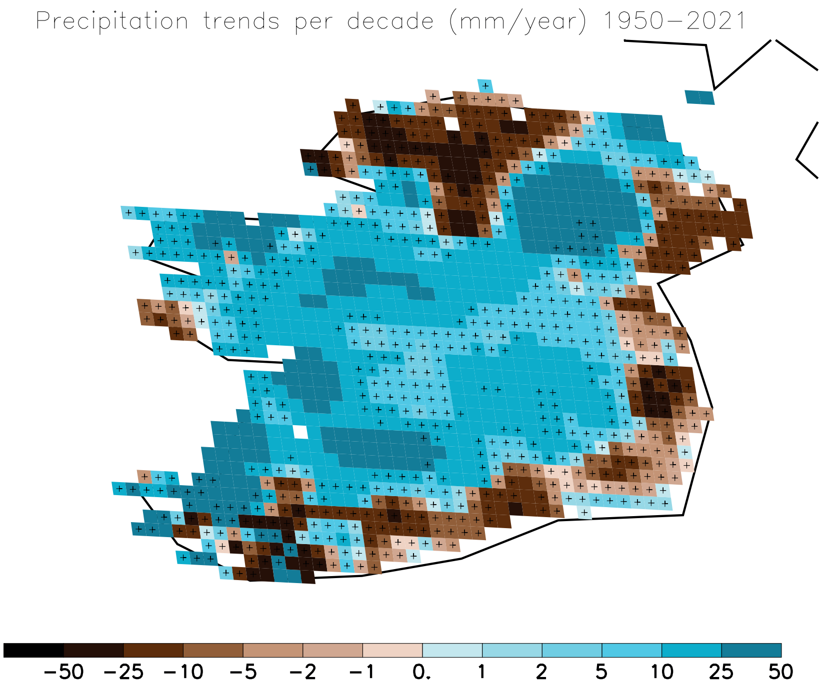


Figure 4.2 Trends in annual precipitation accumulations from the E-OBS dataset. Trends and their significance have been calculated using the method of Santer et al. (2008). Hatched areas denote non-significance accounting for autocorrelation effects. We acknowledge the E-OBS dataset and the data providers in the European Climate Assessment & Dataset (ECA&D) project (https://www.ecad.eu, Cornes et al., 2018). Source: Plotted by the authors.

4.2 Future changes in mean precipitation

It is much more challenging to project changes in precipitation than in temperature (Figure 4.3). Following the approach to apportioning sources of uncertainty to projections of Lehner et al. (2020), and considering the CMIP6 ensemble of ESMs, the response to different scenarios despite showing variability clearly separates for decadal temperature projections after mid-century (Figure 4.3, top left), whereas for decadal precipitation projections there is no separation (Figure 4.3, bottom left). For temperature, there is a clear demarcation between periods as to the dominance of different sources of uncertainty, with internal variability dominant on very short time horizons, model uncertainty dominant until beyond the mid-century and scenario uncertainty dominating by the end of the century (Figure 4.3, top right (also used as the right-hand panel in Figure 1.14)). For precipitation, on the other hand, the dominant contribution is always either internal variability (up until mid-century) or model choice (after mid-century), with scenario choice having very little influence at any time horizon. Indeed, Lee et al. (2021) show (see Figure 8.2e,f in Chapter 8) that over almost all the globe, including Ireland, the sign of the maximum and minimum trends sampled from across CMIP6 models differs.

Given that the RCMs used in the TRANSLATE project are driven by boundary conditions from ESMs similar to those shown in Figure 4.3, it might be reasonable to expect that the choice of ESMs will matter substantially for precipitation in a way that might not be the case for temperature. As noted in Box 3.1, the TRANSLATE model runs were selected from ESMs chosen to have realistic storm tracks, which should reduce a degree of artificial spread in Figure 4.3 arising from those ESMs with gross errors (e.g. models with climatological storm tracks displaced very far north or south). Nevertheless, it should be expected that, for the relatively small ensembles arising from TRANSLATE that model uncertainty and internal variability may be dominant in precipitation projections over the forced response at the scale of the island of Ireland, even for integrated metrics such as decadal mean precipitation. Limitations in the ability to sample from the full range of ESMs mean that the true uncertainty may be substantially undersampled in the TRANSLATE ensemble in spite of the careful experimental design. Such considerations would be expected to become even more acute at the local scales and for extreme indices (Lehner et al., 2020).

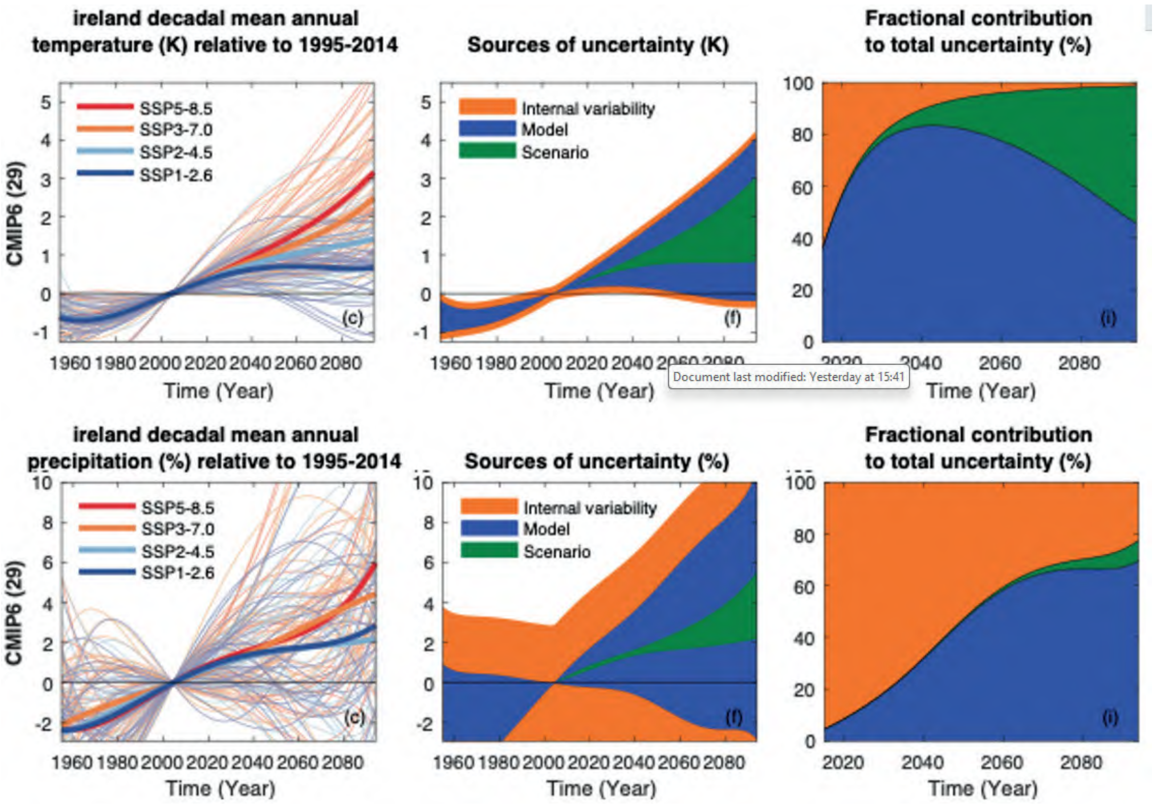


Figure 4.3 Summary of quantification of sources of uncertainty in projected changes relative to 2005 and their relative contributions from the CMIP6 multi-model ensemble of ESMs over the island of Ireland for temperature and precipitation. Left panels show traces (one line per model) of projections (decadally smoothed) from individual models coloured by scenario with multi-model means in bold. Middle panels show total contributions by source (internal climate system variability, model choice or scenario choice). Right panels denote fractional contributions by the same sources. Top row is for decadal mean temperature; bottom row is for decadal mean precipitation. Source: Based on Lehner et al. (2020), with plots provided by Flavio Lehner for this report using the same data as in the original analysis.

"It is much more challenging to project changes in precipitation than in temperature (Figure 4.3)."

Projections of annual precipitation totals are highly uncertain and sensitive to the driving ESM(s) used (Figure 4.4). The substantial sensitivity to both scenario and ESM equilibrium climate sensitivity may point to uncertainty principally arising from the driving ESMs selected and/or internal variability (see Figure 4.3 and its discussion). Because absolute climatological values are largest in the west the largest absolute changes in precipitation may be in the west and not the east in these projections. Decision makers need to be aware that there is substantial uncertainty in precipitation projections for the island as a whole, which become much more acute locally even at the scale of total annual accumulations averaged over multi-decadal time slices. By the end of the century, there is some tentative indication that under Late action scenarios total annual precipitation accumulations may increase across much of Ireland.

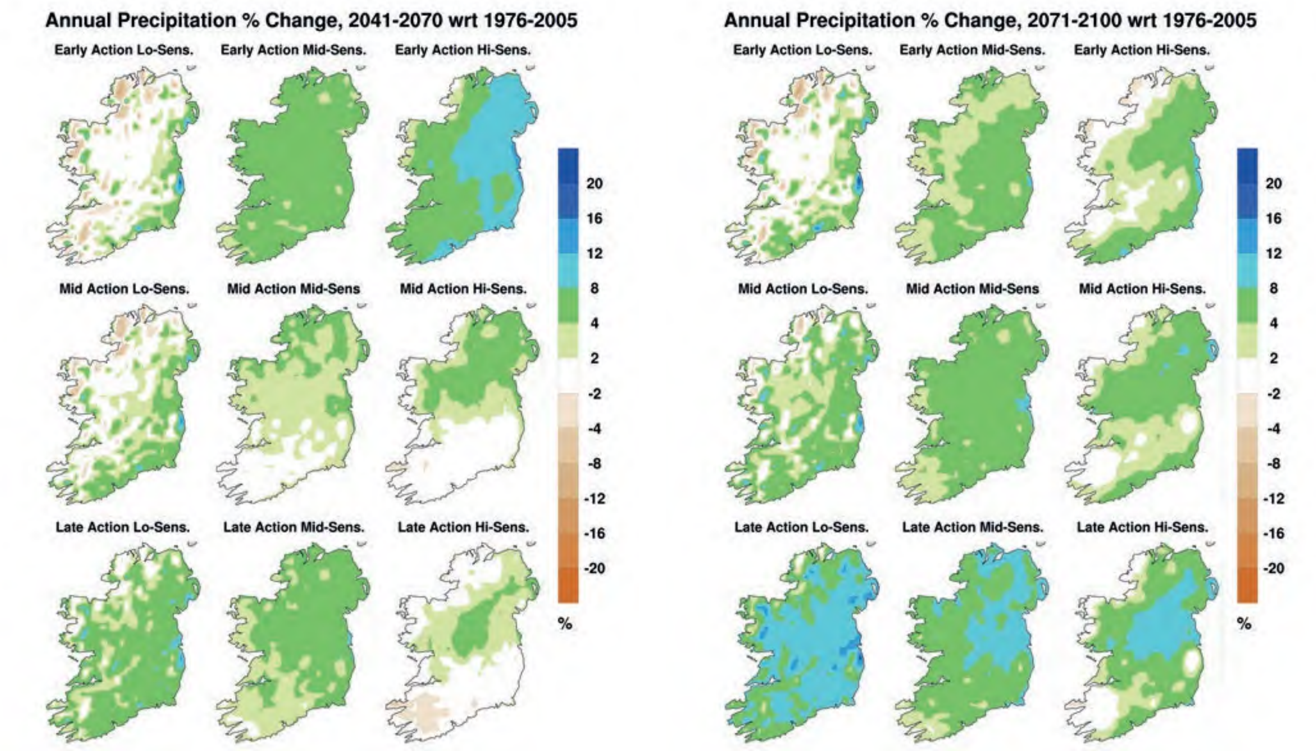


Figure 4.4 Annual mean precipitation projected changes (as a percentage change on recent past annual accumulations) relative to 1976–2005 in the mid-century (top set of panels) and late-century (bottom set of panels). Projections are differentiated by local transient climate sensitivity of the driving ESMs (columns) and scenario (rows). Changes are denoted as percentages of climatology over the period 1981–2010. For further details on ensemble design and how to interpret these figures, see Box 3.1. Source: Figures prepared by TRANSLATE contributing authors specifically for this report.

The annual mean precipitation changes averaged across the island of Ireland relative to the recent past (1976–2005) show a much more complex response to both mitigation choice and climate sensitivity (or model selection; see Figure 4.3 and associated discussion) than is the case for mean temperature changes (Table 4.1, cf. Table 3.1). Changes generally tend to a slight increase of <10% in annual mean accumulated precipitation amounts but with large sensitivity to choice of driving ESMs.

Table 4.1 Areally averaged changes in annual mean surface precipitation (as a ratio to present-day mean accumulations) from the TRANSLATE ensembles across the island of Ireland with a land–sea mask applied. Averages are the ensemble mean in each case and the differences between the 30-year means for end of century and a recent 30-year period (1976–2005). The use of ensemble averages here implies that values may fall above or below the values given because of natural variability

Scenario	Low sensitivity	Mid-sensitivity	High sensitivity
Mid-century (2041–2070)			
Early action	1.02	1.05	1.11
Middle action	1.03	1.04	1.01
Late action	1.05	1.05	1.01
Late century (2071–2100)			
Early action	1.03	1.05	1.07
Middle action	1.05	1.05	1.04
Late action	1.10	1.09	1.05

Source: Results provided by TRANSLATE contributing authors for this report.

Winters (defined as December to February) are generally projected to get wetter by the end of the century across much of Ireland, although there are more complex potential behaviours of change suggested by mid-century, including some simulations showing potential wintertime drying in the north-west (Figure 4.5). For both time slices, there is substantial heterogeneity based upon the driving ESMs, even at the end of the century, that presumably speaks principally to the model uncertainty rather than being likely real geophysical signals (see Figure 4.3 and discussion). There is somewhat better concordance based upon scenario, with progressively somewhat larger signals of increasing precipitation changes with delays in global mitigation actions. Relative changes also appear to be greater in the south-east than in the north-west in both time slices in some but by no means all cases. As noted previously, given the climatological gradients in precipitation, absolute changes may be larger in the north-west despite this.

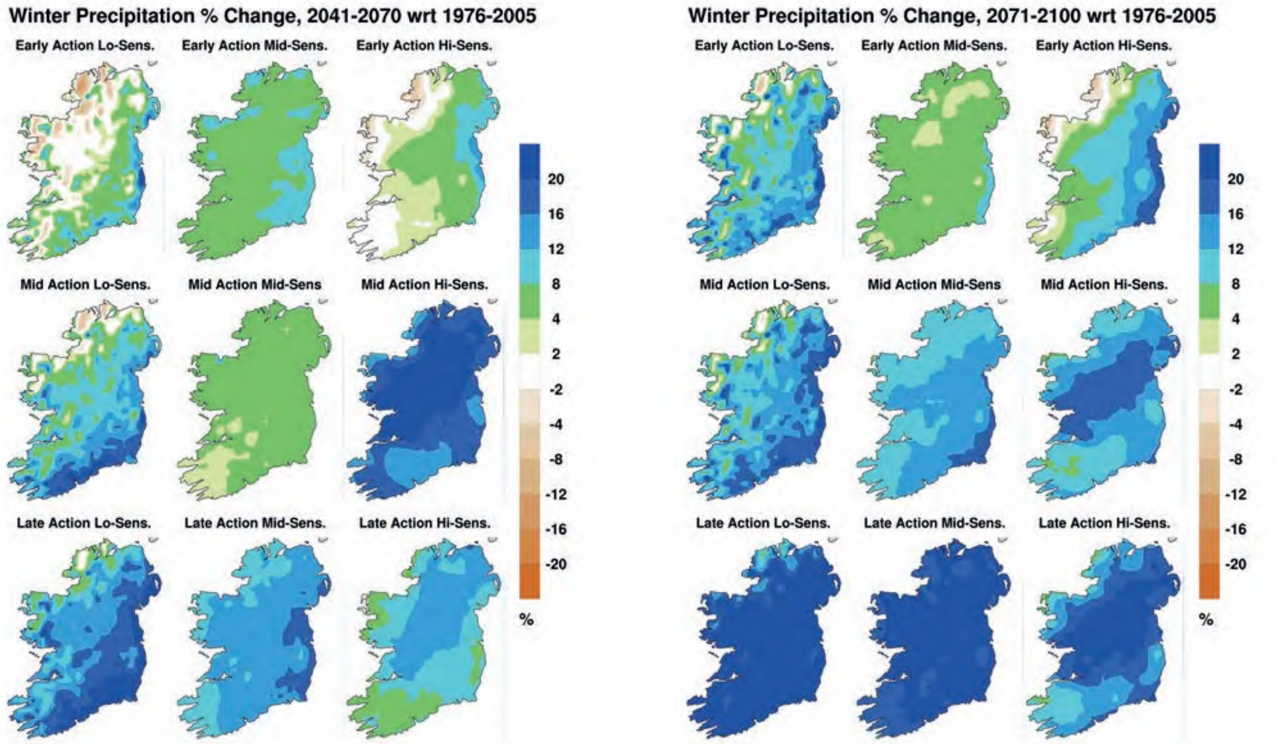


Figure 4.5 Seasonal mean precipitation projected changes for winter (December–February as a percentage change on recent past winter accumulations) relative to 1976–2005 in the mid-century (top set of panels) and late-century (bottom set of panels). Projections are differentiated by local transient climate sensitivity of the driving ESMs (columns) and scenario (rows). Changes are denoted as percentages of climatology over the period 1981–2010. For further details on ensemble design and how to interpret these figures, see Box 3.1. Source: Figures prepared by TRANSLATE contributing authors specifically for this report.

Summers are generally projected to get drier overall at both mid-century and the end of the century (Figure 4.6). There is a notable exception for the Early action ensemble for high sensitivity where summers get wetter, particularly in mid-century. This behaviour has been carefully cross-checked and verified and is a feature arising from the underlying ESM simulations, highlighting the substantial potential role of internal variability even in long-term seasonal precipitation changes. The variability across and within ensembles serves as a reminder that, despite overall tendencies towards wetter winters (see Figure 4.5 and discussion) and drier summers, such outcomes cannot be taken as a given in the presence of substantial uncertainties arising from model choice and internal variability (see Figure 4.3 and associated discussion). There is little by way of coherency for any expected spatial patterns for summer precipitation changes. Drying trends tend to get stronger under Late action scenarios in both timeslices.

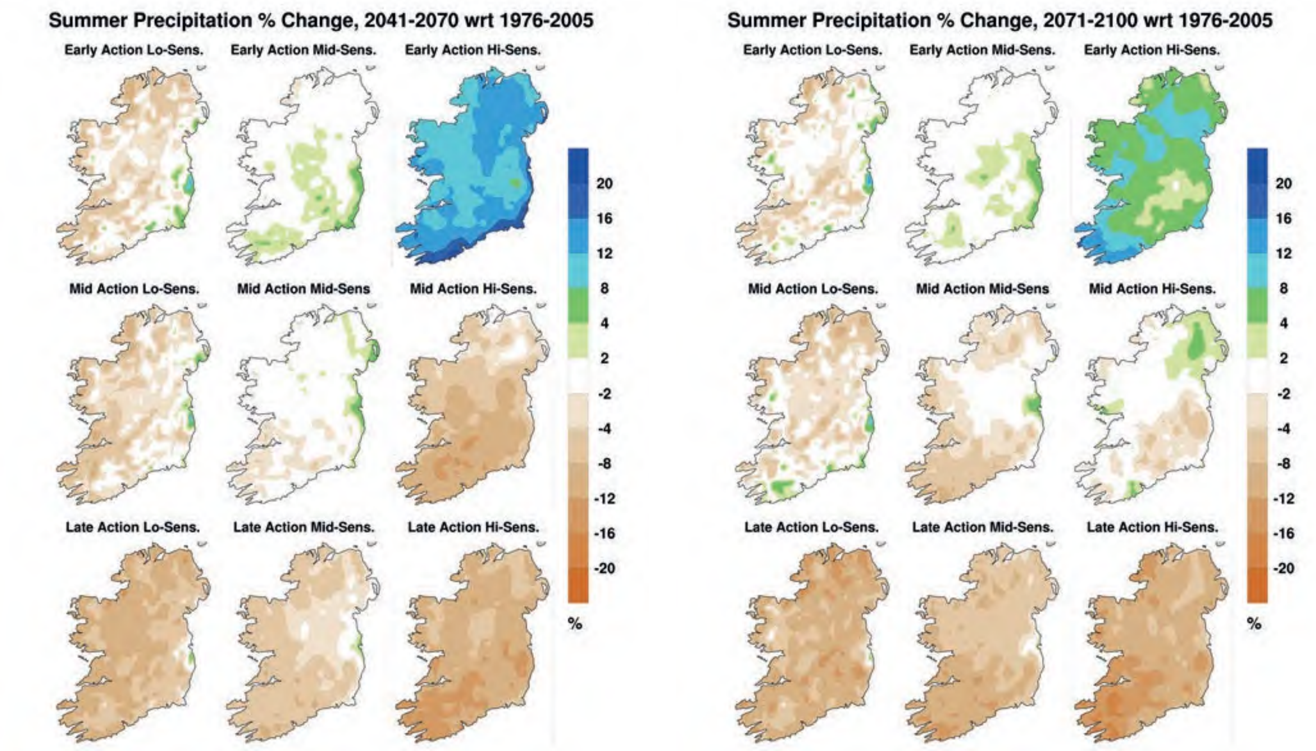


Figure 4.6 Projected percentage changes in summer (June–August) precipitation for mid-century (top set of panels) and the end-of-century period (2071–2100; bottom set of panels) relative to 1976–2005. Each array of nine maps shows projections for the different action scenarios (rows) and for the different model ensemble local transient climate sensitivities (columns). For further details on ensemble design and how to interpret these figures, see Box 3.1. Source: Figures prepared by TRANSLATE contributing authors specifically for this report.

In comparing the seasonal trends (Figures 4.5 and 4.6) with the annual mean changes (Figure 4.4), there is little coherent tendency to annual precipitation accumulations, but any changes tend, in most but by no means all cases, to be the result of countervailing tendencies to increased winter precipitation and decreased summer precipitation. The largest changes are projected for the late action scenario and at the end of the century. There is, however, very substantial uncertainty in precipitation changes, and even the sign of the changes both annually and seasonally is uncertain. It is clear that in the presence of such substantial uncertainty great care is required in the interpretation and use of precipitation projections. It is likely that the TRANSLATE ensembles would need to be substantially larger and the ensemble spread used proactively to get a comprehensive picture of the true uncertainty in projections for seasonal and annual precipitation changes.

4.3 Observed changes in extreme precipitation events

Several extreme precipitation metrics relating to intensity, duration and totals have been adopted by the WMO. These include several metrics for measuring dry spells. Harrigan (2016), in an analysis of daily precipitation records from the 1950s onwards, found increases in precipitation intensity consistent with expectations of a warming atmosphere (Douville et al., 2021), particularly in the east and south-east of the island in summer. Cámaro García et al. (2021) found increasing trends in the length of wet spells across the island over the period 1961 to present. Ryan et al. (2021) evaluated changes in precipitation extremes in rescued precipitation data using the WMO metrics for a dense network of stations across the island, dating back to the late 19th century in order to place these findings in a long-term context.

Few studies have evaluated changes in meteorological drought in Ireland. One exception is Vicente-Serrano et al. (2020) who evaluated long-term variability and trends in meteorological droughts (using the Standardised Precipitation Index) for western Europe over the period 1851–2018, including stations that were quality assured by Noone et al. (2016). The largest increases in summer droughts over this period were found for Ireland and Britain.

Spatial trends in precipitation extreme indices, in general, show that for many regions of Ireland the trends are not significant. Figure 4.7 shows:

- Rx1day (maximum daily precipitation in the year) and Rx5day (the maximum consecutive 5-day precipitation in the year);
- R99p (total annual precipitation from events exceeding the 99th percentile of occurrence);
- R20mm (frequency of occurrence of days of precipitation with greater than 20mm a day in a calendar year);
- SDII (number of wet days in the year);
- CDD (maximum number of consecutive dry days in a year).

Note that for several of these indicators the colour bar is flipped such that browns are always associated with drying/a reduction in precipitation and blues are always associated with wetting/increases in precipitation.

For R20mm, there is an overall tendency towards increased frequency of occurrence, and most areas that are significant are showing such increases. However, there are many regions that exhibit decreases, most notably much of Ulster. Similar findings extend to various wetness (Rx1day, Rx5day) and dryness (CDD) indicators that are shown in Figure 4.7. The overall picture for observed changes since 1950 in these precipitation-related extremes, like for mean annual accumulations (Figure 4.2), is one of little significant change across most of the country, with trends of opposite signs in different regions. Overall, nationally, there has been a slight tendency to an increased preponderance of wet extremes across a range of indicators. Given the spatial and temporal scales and episodic nature of many precipitation extremes, a robust signal at the local level would be expected to take considerable time to emerge from natural climatic variability, which is substantial for such indices.

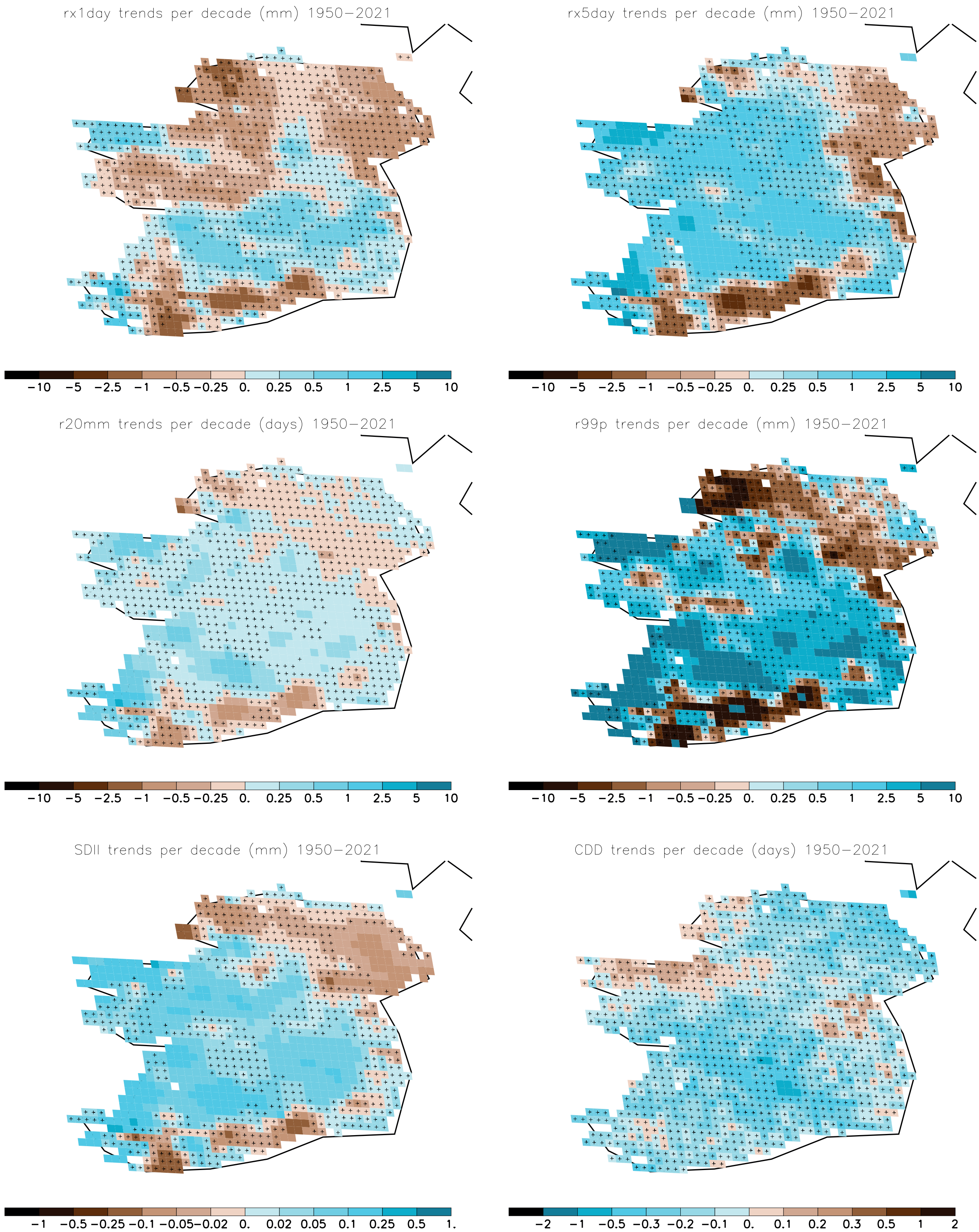


Figure 4.7 Changes in Rx1day, Rx5day, R20mm, R99p, SDII and CDD between 1950 and 2021. Trends and their significance have been calculated using the method of Santer et al. (2008). Hatched areas denote non-significance accounting for autocorrelation effects. Note that the units differ by parameter (given in plot titles) as do colour bar scales. For each indicator, the colour bar is arranged such that increased wetness is associated with blue colours and increased dryness with brown colours for intuitive interpretation. This means that for some indicators the colour bar is flipped. We acknowledge the E-OBS dataset and the data providers in the European Climate Assessment & Dataset (ECA&D) project (https://www.ecad.eu, Cornes et al., 2018). Source: Plotted by authors.

4.4 Future precipitation extremes projections

The water holding capacity of the atmosphere increases with temperature (Brown, 1951); hence, under warming conditions increases in precipitation extremes are expected. IPCC WGI AR6 (Seneviratne et al., 2021) assessed with high confidence that heavy precipitation has intensified at a global scale over land, and that it is likely that anthropogenic influence is the main cause. Similarly, intense rainfall events are likely to become more intense in Ireland as a result of additional warming. A warmer world will also increase soil evaporation, thus exacerbating ecological and agricultural droughts even in the absence of reduced precipitation (Seneviratne et al., 2021).

For each time period – 2041–2070 but especially for 2071–2100 – there is a broad pattern of increasing maximum daily precipitation (Rx1day) values across much of the country (Figure 4.8). The substantial variability between climate sensitivity cases highlights the substantial role of model uncertainty and internal variability (see Figure 4.3 and associated discussion). By the end of the century maximum, daily precipitation does not change much from mid-century and may even be reduced in some places under Early action, highlighting that ambitious action on global emissions reductions now can potentially stabilise important aspects of our climate system, such as extreme precipitation within the lifetimes of today's children. Some of the changes projected, particularly under Late action at the end of the century, are very substantial, with potentially up to 50% increases in the maximum daily precipitation over much of the country, particularly for the high climate sensitivity ensemble (Figure 4.8).

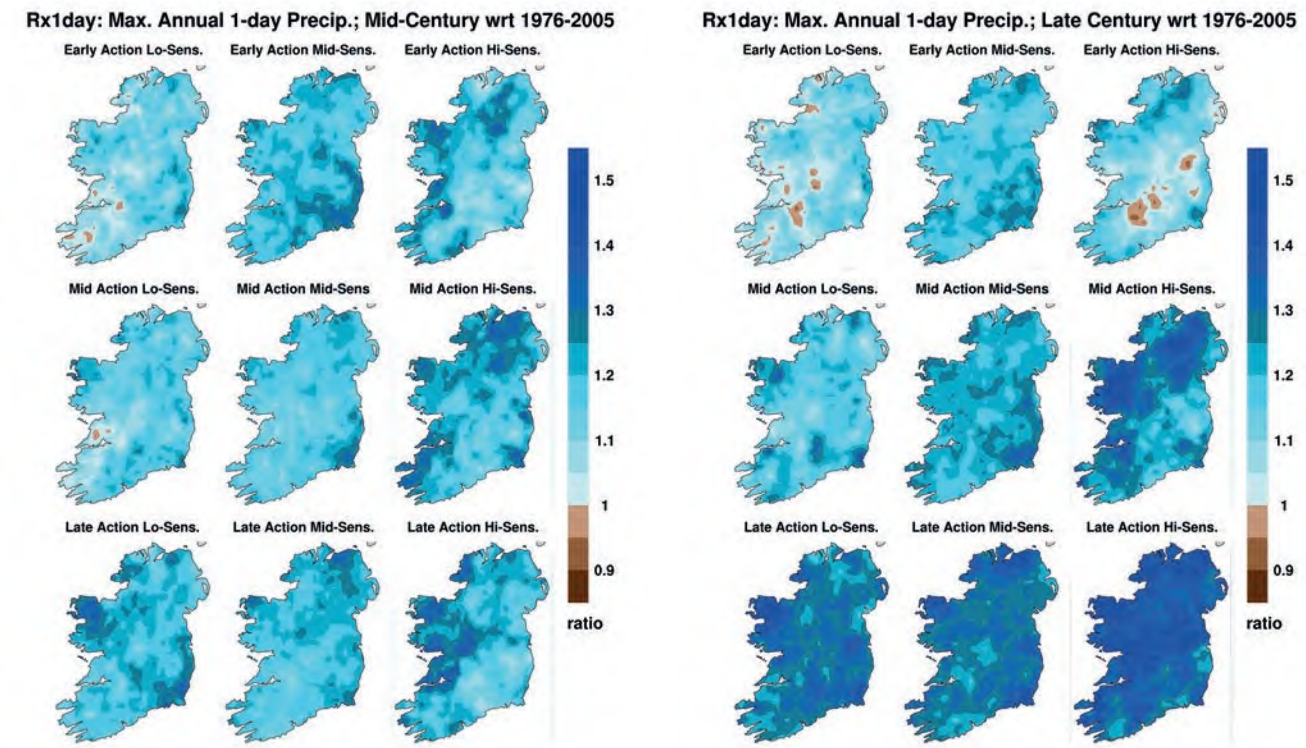


Figure 4.8 As in Figure 3.4, but for projected changes to the Rx1day index (where Rx1day is the precipitation amount on the single wettest day of each year). For further details on ensemble design and how to interpret these figures, see Box 3.1. Source: Figures prepared by TRANSLATE contributing authors specifically for this report.

For Rx5day (Figure 4.9), proportional changes are considerably smaller than for Rx1day and of considerably more mixed sign (cf. Figure 4.8). This has potentially important implications for catchment hydrology (Volume 3), as larger catchments tend to respond more to multi-day precipitation events and vice versa. Again, there is substantial model uncertainty present in the TRANSLATE ensemble results. Overall, there is a tendency for changes in this metric to increase both with delays in mitigation action and with climate sensitivity. Over much of the east of the island of Ireland, the maximum 5-day precipitation accumulation increases, particularly so under scenarios of delayed action and for the high-sensitivity simulations. The high local transient climate sensitivity ensemble shows more widespread increases in Rx5day than the low-sensitivity ensemble, and for delayed action shows considerable increases in Rx5day by the end of the century. As with other precipitation-based changes, there is little further change for the Early action scenario after the mid-century.

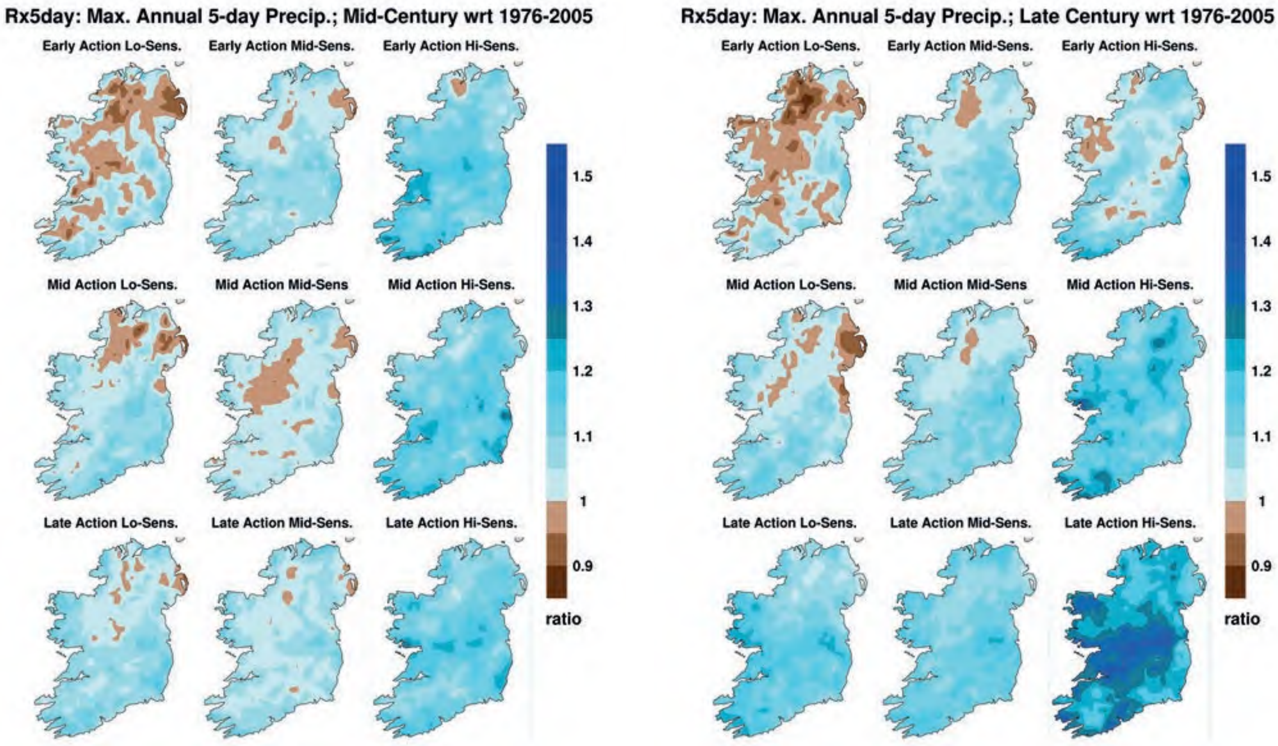


Figure 4.9 As in Figure 3.4, but for projected changes to the Rx5day index, where Rx5day is the maximum consecutive 5-day precipitation. For further details on ensemble design and how to interpret these figures, see Box 3.1. Source: Figures prepared by TRANSLATE contributing authors specifically for this report.

Changes in R20mm (Figure 4.10) show overall increases in the frequency of occurrence of days with precipitation exceeding 20mm across much of the country under all scenarios, with the exception of the low-sensitivity ensemble under Early action. For this particular metric, there is somewhat less sensitivity to model selection than other precipitation-related extreme indices. Under Early action, particularly for low local transient climate sensitivity, changes are relatively small and again stabilise after mid-century. Under Late action scenarios, by the end of the century, changes could be locally large with broad areas projected to see a 50–150% increase in frequency of occurrence for the high climate sensitivity ensemble.

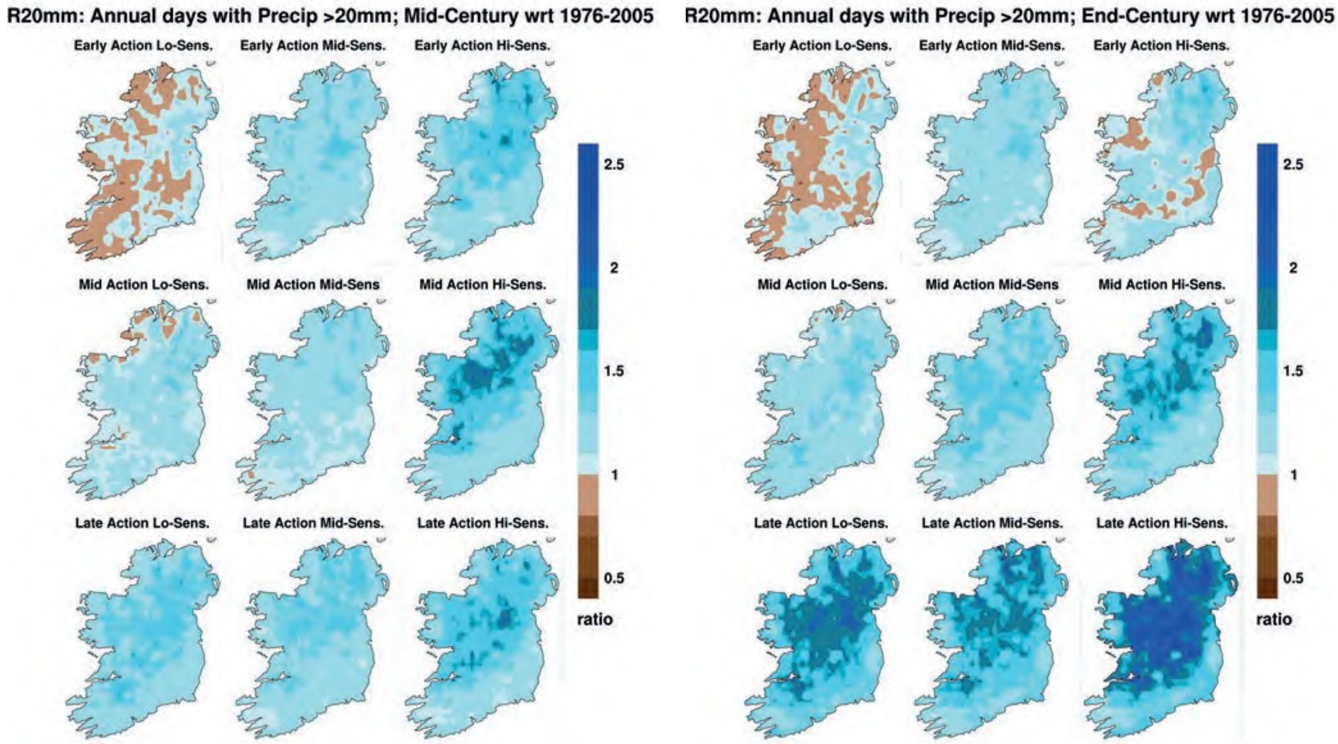


Figure 4.10 As in Figure 3.4, but for projected changes to the R20mm index, where R20mm is the number of days per year with precipitation >20mm. While the changes are still expressed as ratios relative to the reference period 1976–2005, the basic unit is number of days, not mm of precipitation. For further details on ensemble design and how to interpret these figures, see Box 3.1. Source: Figures prepared by TRANSLATE contributing authors specifically for this report.

Similar findings extend to dryness indicators such as CDD (Figure 4.11). The preponderance for long dry spells is overall projected to decrease across much of the island of Ireland, although changes are relatively small and there is evidence of substantial model sensitivity. There is an overall tendency for CDD spells to get shorter in the east, with a more mixed signal in the west. There is little apparent sensitivity to scenarios for this metric even by the end of the century, at least by comparison with other extreme precipitation metrics considered previously. Most changes are within ±20% under all scenarios, even by the end of the century.

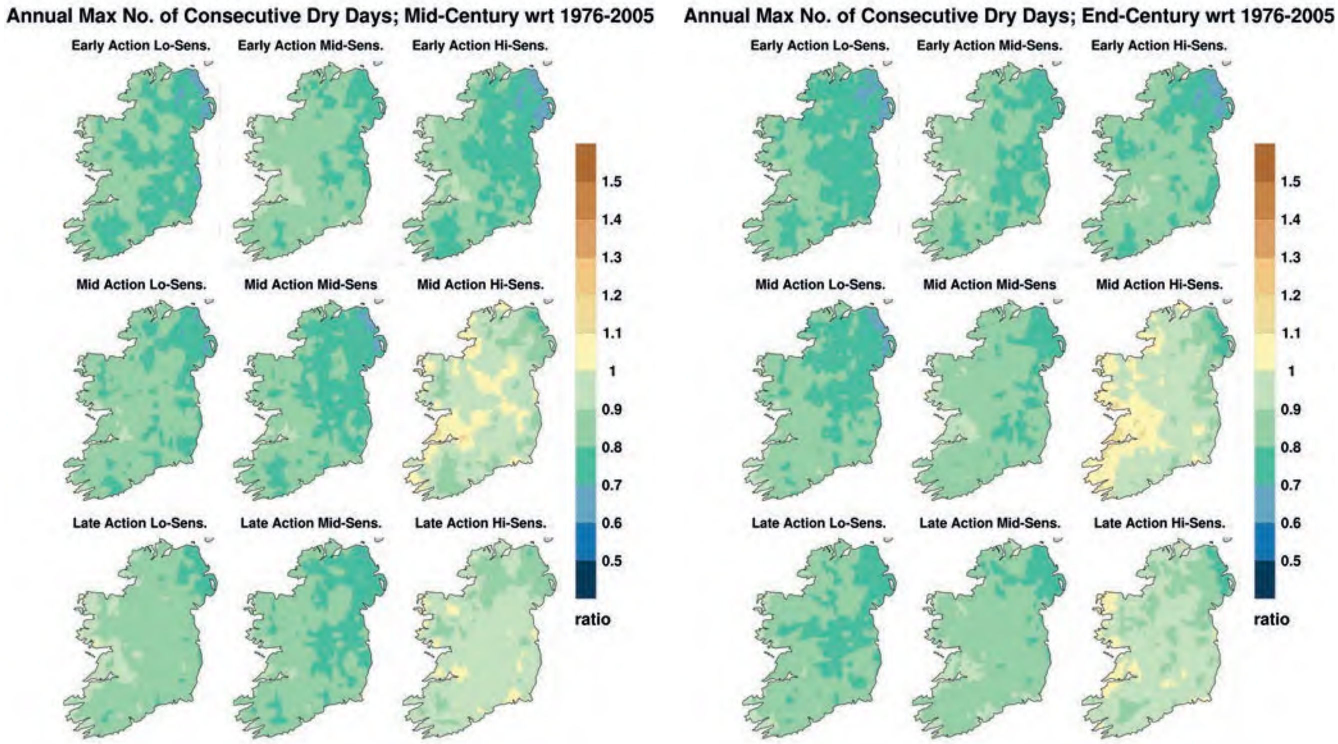


Figure 4.11 As in Figure 3.4, but for projected changes to the CDD index, where CDD is the maximum length of consecutive dry days (rainfall rate <1mm). While the changes are still expressed as ratios relative to the reference period 1976–2005, the basic unit is number of days, not mm of precipitation. For further details on ensemble design and how to interpret these figures, see Box 3.1. Source: Figures prepared by TRANSLATE contributing authors specifically for this report.

In addition to changes in magnitude, the recurrence times, or frequency, of precipitation extremes over Ireland are also expected to change. Figure 4.12 shows the projected changes to the recurrence times for annual maximum daily precipitation amounts that fell on average every 10, 20 and 50 years in the past. For all return periods considered, extreme precipitation events are projected to become more frequent, with rarer 50-year event changes being more marked than 10- and 20-year return periods. This is consistent with the global scale analysis in IPCC WGI AR6 (Senevartine et al., 2021). Under the Late action scenario, the annual maximum daily rainfall that used to occur once every 50 years, on average, will become a once in every 22- to 26-year event by the end of the century (or twice as frequent). The shortening of recurrence times in the Early action scenario that is projected over the next generation or so can be stabilised or reversed by the end of the century. This is not the case for late action scenarios where the recurrence time for the 50-year extreme precipitation events keep shortening all through this century.

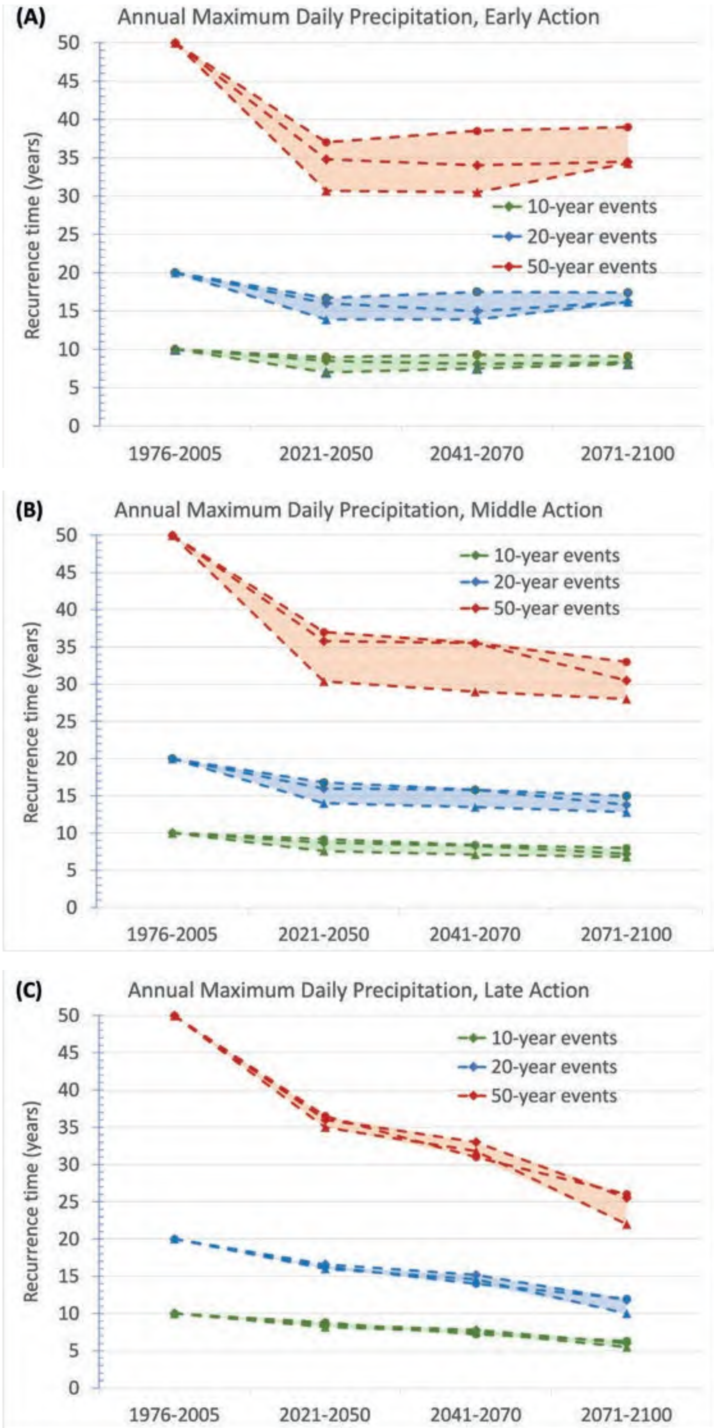


Figure 4.12 Projected changes in the recurrence times (or return periods) of Ireland-averaged Rx1day values that had recurrence times of 10, 20 and 50 years during the past reference period of 1976–2005, based upon downscaled CMIP5 output and split into three subsets according to the local transient climate sensitivity of the driving ESMs used. The symbols joined by dashed lines show values from the model ensembles with different climate sensitivities, while the shading spans the range between them all (not necessarily from lowest to highest sensitivity). Panel (a) shows the Early action scenario, (b) shows the Middle action scenario and (c) shows the Late action scenario. Source: Figures prepared by TRANSLATE contributing authors specifically for this report.

4.5 Recommendations

4.1	*In situ* precipitation measurement networks must be maintained and expanded in areas of poor coverage. Given the smaller spatial scales of precipitation variability, a denser network is required than for temperature. The new expanded radar network under procurement and deployment must be maintained for multiple decades to augment the *in situ* network.
4.2	There is considerable potential to create merged products from rain gauges, radar and satellites, building upon the strengths of each data type. Modern spatially complete field estimates can be used to train analyses to create physically plausible historical estimates of changes in historically unsampled regions. This requires sustained support for archiving, post-processing and reprocessing to maintain a long-term homogeneous product. There is particular value in looking at daily and sub-daily resolution precipitation records that have been underexploited to date.
4.3	There is a requirement for research on the impacts of ESM selection for downscaling of precipitation and precipitation indices and to quantify more comprehensively the uncertainty in precipitation projections for Ireland.
4.4	Further research on the geological and historical context for extreme precipitation events in Ireland and their impacts (floods and droughts) that occurred prior to instrumental records from a combination of paleo and documentary sources would be extremely useful for anticipating the impacts of future precipitation changes. Due care should be given to understanding the impacts of more recent human interventions in drainage and river course management when making inferences.
4.5	Changes in storminess and winds have not been able to be comprehensively assessed at this time. Further analysis of the quality and homogeneity of historical wind and pressure records, including the creation of gridded products, is required prior to their use in such an assessment. Work is also required to understand and appropriately analyse the projections arising from ESMs and the TRANSLATE project over Ireland. Work to bring these aspects in is technically feasible in the time frame of any subsequent assessment report.

5

The Changing Shelf Seas around Ireland

Key messages

Shelf and coastal currents around Ireland ameliorate local marine conditions near our coasts. Changes in shelf and coastal currents which could directly impact coastal communities are poorly modelled and understood, and substantial changes cannot at this point be ruled out.

Both sea surface temperatures (SSTs) and ocean heat content (OHC) have increased in Ireland's territorial waters, consistent with globally observed changes. Both will further increase under additional global greenhouse gas emissions.

Recent studies have highlighted higher rates of sea level rise since the late 20th Century in Cork and Dublin than the global average. The reasons remain unclear and under investigation. There are a range of processes that can lead to local sea level changes diverging to a certain extent from global changes over a broad range of timescales.

Global sea level increases will be modified locally around the island of Ireland by ongoing isostatic rebound – the north-east of the island is slowly rising and the south-west slowly sinking (<0.2mm per year in most regions); multi-decadal ocean basin variability (order of several centimetres in a decade); and the relative contributions to sea level change arising from the Greenland and Antarctic ice sheets over time. Larger relative contributions from Greenland would result in smaller increases for Ireland and vice versa due to the gravitational effects of the two ice sheets.

Storm surges and extreme waves pose an ever-increasing threat to Ireland as sea levels continue to rise, including to many of our coastal cities, such as Cork, Dublin, Galway and Limerick, and to critical infrastructure. Particularly at risk are soft sediment shorelines. Projections of changes in storminess are highly uncertain and translate into large uncertainties in future frequency and intensity of extreme waves.

Consistent with global open ocean changes, Irish coastal and territorial waters have experienced a long-term decrease in pH (acidification) due to uptake of anthropogenic atmospheric CO_2.

In Irish waters, there have been substantial changes in marine ecosystems, including changes in seasonality and abundance of many species, including phytoplankton and zooplankton at the base of the food web. Many of these changes are consistent with a changing climate.

5.1 Ocean currents

Circulation in Ireland's offshore waters is dominated by the subpolar gyre and AMOC (section 2.4.2) variations (Figure 5.1). Closer to the shelf (the shallow seas <200m depth), the European slope current delineates a separation between the open ocean and shelf seas. Even closer to the coast there exists a set of coastal currents (McCarthy et al., 2023a).

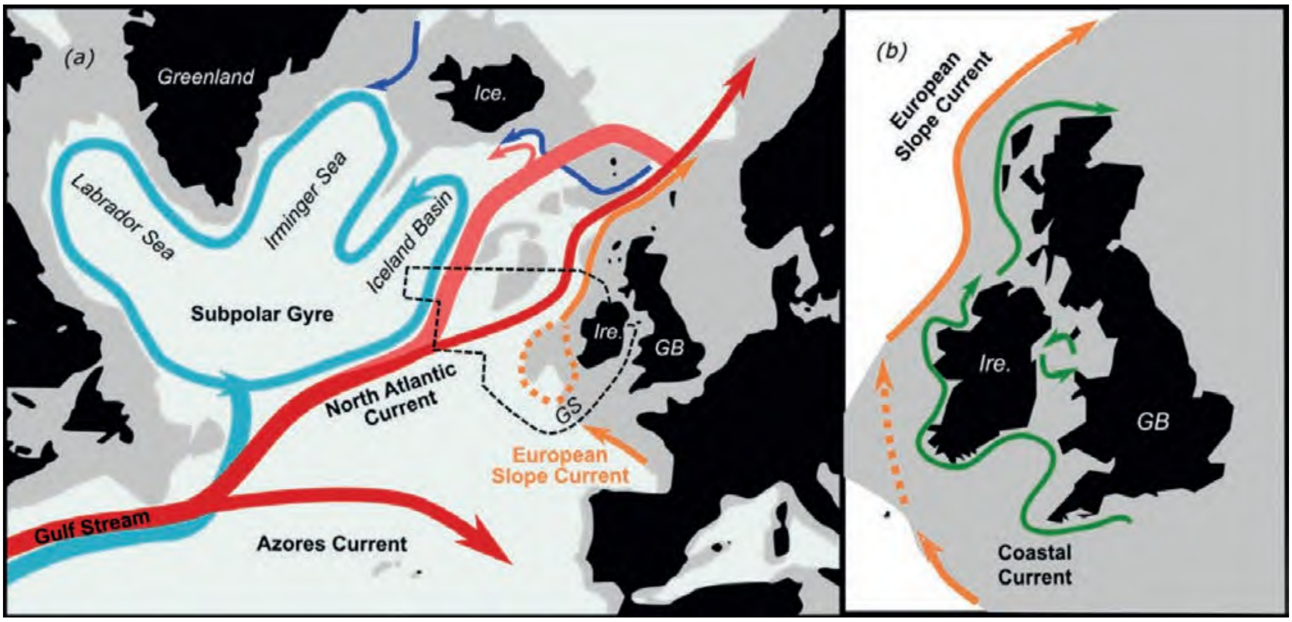


Figure 5.1 (a) Circulation of the North Atlantic showing the main ocean currents (bold text) and geographical features (italics). Warm currents, such as the Gulf Stream and North Atlantic Current, are shown in red. Cold currents, such as those of the subpolar gyre, are shown in blue. (b) Slope (orange) and coastal (green) circulation around Britain and Ireland, modified from Hill et al. (2008). Dashed orange line in (a) denotes the disputed path of the slope current near Goban Spur (GS). Dashed black line in (a) denotes the so-called Real Map of Ireland – the limits of Irish waters used for calculations in Figure 5.2. Grey shaded areas indicate the continental shelf (depth <200m). Source: McCarthy et al. (2023a; their figure 3.1).

The subpolar gyre has been observed to expand and contract on multi-decadal timescales, with expansions associated with cool periods and contractions associated with warm periods in the region (McCarthy et al., 2023a). Periods of expanded subpolar gyre have been associated with drier summers in north-west Europe (Sutton et al., 2018). The subpolar gyre is currently in an expanded state (McCarthy et al., 2023a). There is little evidence of change in the subtropical gyre, although there is evidence of a broadening of the North Atlantic Current (Andres, 2016). The subtropical gyre is expected to expand polewards under warming, including a poleward extension of the North Atlantic Current in response to changes in atmospheric circulation (Yang et al., 2016), but there is no evidence of this having occurred to date.

The European slope current marks the separation of Irish and continental shelf waters from the open Atlantic and is a relatively shallow current at 500–1,000m (although consideration as a continuous feature is an over-simplification; McCarthy et al., 2023a). The current is stronger in winter than in summer and strengthens with increasing latitude, which is associated with significant transport of heat (Xu et al., 2015). There is substantial ambiguity regarding pathways around the south-west of Ireland (Xu et al., 2015; Moritz et al., 2021). Closest of all to the coast is the Irish coastal current, which is driven by a time-varying mix of winds, tides and density gradients (owing to salinity differences; McCarthy et al., 2023a). Salinity-related aspects of coastal current variations are largest in summer (Hill et al., 2008). Summertime circulation is an important driver of movement of harmful algal material (Raine, 2014). How these more local currents may alter under climate change has received much less attention than possible changes in overall North Atlantic Circulation and is much harder to model, leading to very large uncertainties (McCarthy et al., 2023a). Potentially substantial changes cannot be ruled out.

5.2 Sea surface temperature and ocean heat content changes

Local SSTs are influenced by a number of factors, including ocean currents, and hence are expected to exhibit substantial interannual to interdecadal variability. OHC and SSTs in Ireland's waters show larger decadal variability than the global average (Figure 5.2), linked in part to AMV (section 1.3.3), with recent years showing a relatively cool phase (McCarthy et al., 2023a). Irish SST and OHC experienced warm periods from the 1940s to the late 1950s and from the mid-1990s to the mid-2000s (McCarthy et al., 2023a). The highest SSTs in Irish waters occurred in 2007, averaging over 0.8°C warmer than in 1960–1990, and the highest OHC occurred in 2005 (McCarthy et al., 2023a). Despite recent reductions in SST and OHC in Irish waters, both remain substantially elevated relative to the mid-20th century. Understanding of OHC change relies on continued Irish contributions to key international programmes, especially the Euro-Argo programme.

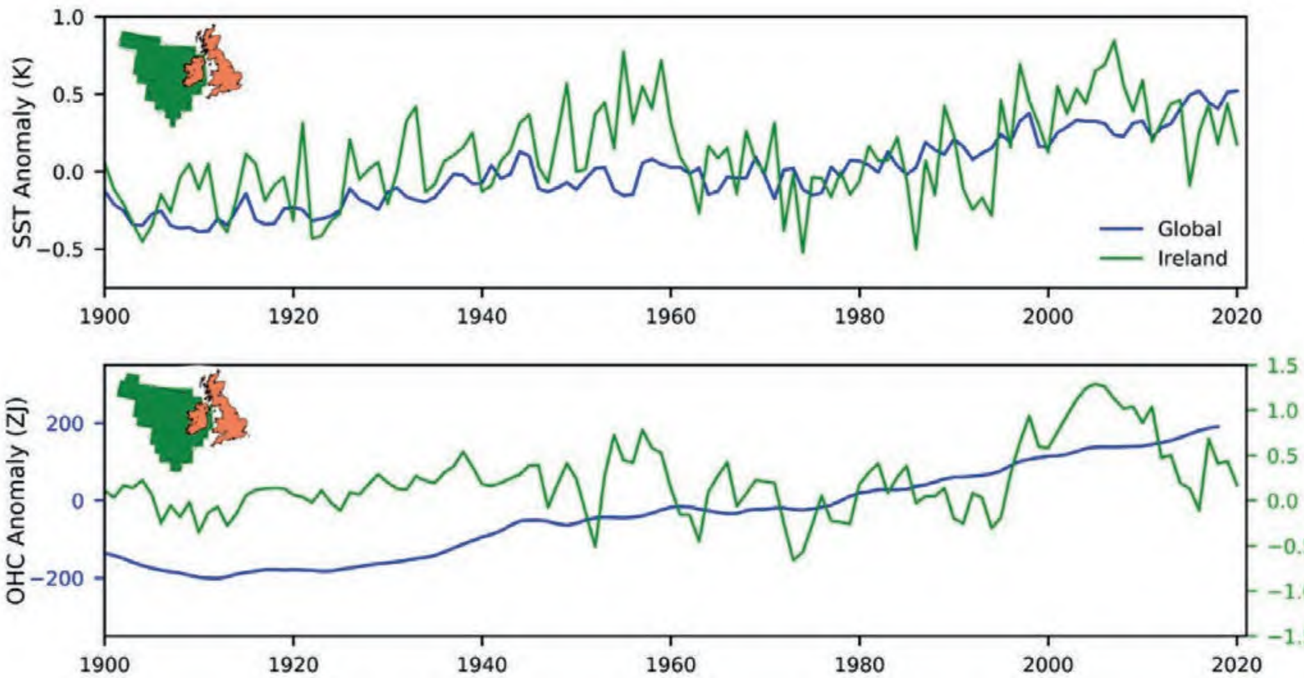


Figure 5.2 Top: global (blue) and Irish (green) waters SST anomaly from HadISST (Rayner et al., 2003). Bottom: global (blue) and Irish (green) waters OHC from EN_4 (Zanna et al., 2019). Anomalies are calculated relative to the period 1960–1990. Inset highlights in green denote the 'Real Map of Ireland' – the limits of Irish waters that are used here. Source: McCarthy et al. (2023a; their figure 3.3).

Future SSTs and OHC in Irish waters will likely be dominated by the same combination of global responses to changes in radiative forcing arising from emissions of GHGs and internal climate variability as is evident in the historical record. SST in Irish coastal regions and shelf seas could rise by several degrees Celsius (Dabrowski et al., 2023) as is evident in the geological past (see Cross-chapter Box 2). OHC globally will take hundreds of years to reach a new equilibrium (Fox-Kemper et al., 2021) and this will also be the case for Ireland's shelf seas and territorial waters.

5.3 Sea level changes

Measuring sea level relies on a number of high-precision measurements of both sea and land at the same time. The Marine Institute routinely collects data on sea level in addition to temperature, salinity, currents and tidal patterns (Figure 5.3; Nolan et al., 2021). Prior to the early 1990s, observational evidence for sea level rise was reliant on coastal tide gauge data. Ireland has a historical geographical bias in the location of these gauges, with long-term observations being confined to north-east of an axis from Dublin to Malin Head (McCarthy et al., 2023b). A comprehensive, all-Ireland tide gauge network was established in the 2000s, but this time period is shorter than the necessary 40 years (Hogarth et al., 2021) for assessing mean sea level trends.

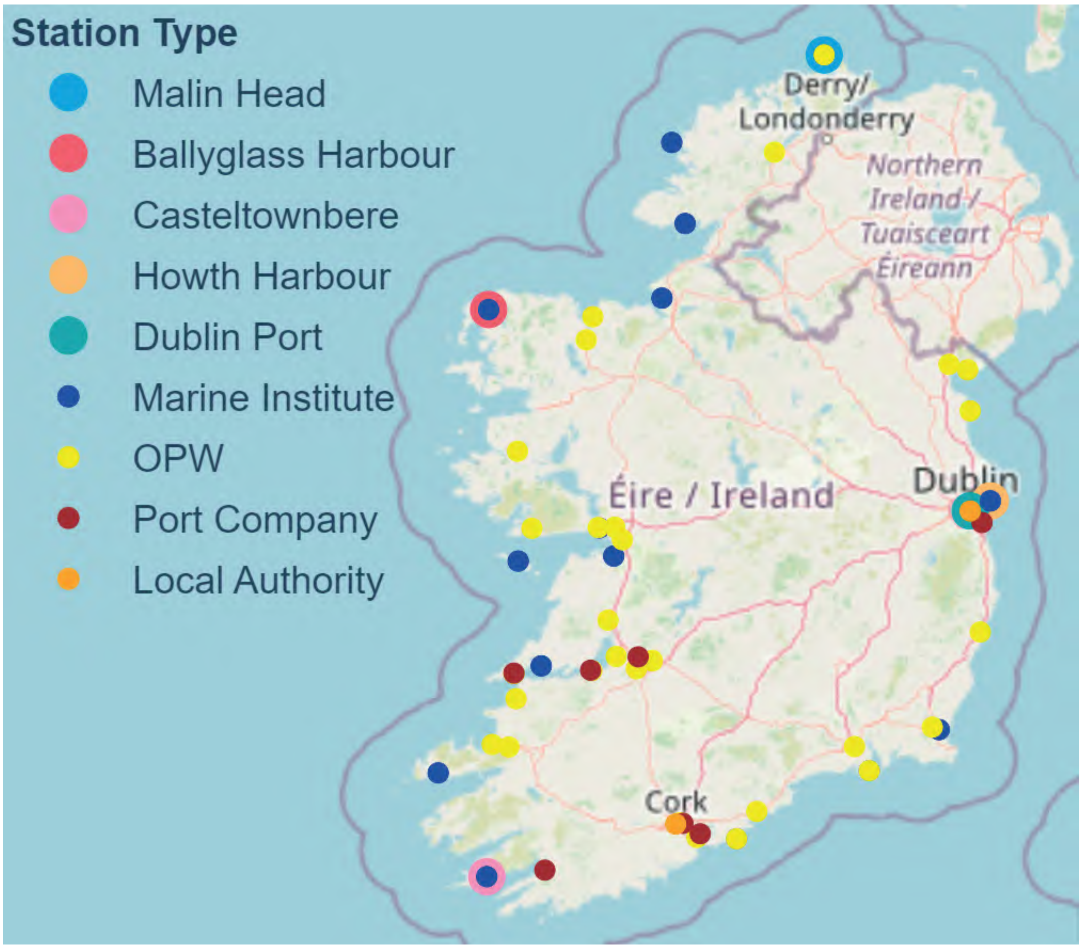


Figure 5.3 Location of stations measuring relative sea levels. Measurements of sea level rely on high-precision contemporaneous measurements of sea and land level. Measurements are taken mainly by a network of tide gauges around the Irish coast, which are operated by a number of different bodies, including the Marine Institute (MI) (blue), the Office of Public Works (OPW) (yellow), local authorities (orange) and port companies (brown). The EPA Gauging Station Register is a national inventory of all gauges, including tide gauges. The longest continuous records for Ireland are from Dublin Port (orange inner, green outer), where a tide gauge has been in operation since at least 1923, with digitised records available from 1938, and from Malin Head, County Donegal (yellow inner, blue outer), in operation since 1958. In addition, there are many long-forgotten gauges that can extend records further back in time, although not continuously. Source: Climate Ireland.

Cámaro García et al. (2021) concluded that sea level around Ireland has risen by 2–3mm per year since the early 1990s. In addition, there has been substantial renewed interest in reconstructing long-term sea level changes around Ireland and understanding them (Pugh et al., 2021; Shoari Nejad et al., 2022). Shoari Nejad et al. (2022) present a newly rescued and extended record for Dublin Port which accounts for apparent biases arising from various instrument relocations and other changes (Figure 5.4). These biases had led to recent changes being overestimated in the raw data. Using this dataset (Figure 5.2), they estimate a rate of sea level rise for Dublin Bay of 1.1mmyr^{-1} during 1953–2016 (95% range 0.6^{-1}.6mmyr^{-1}) and a rate of 7mmyr^{-1} during 1997–2016 (95% range 5–8.8mmyr^{-1}). Substantial multi-decadal variability, along with accelerating global sea level rise (section 1.4.2.2), has led to higher rates of rise in recent years.

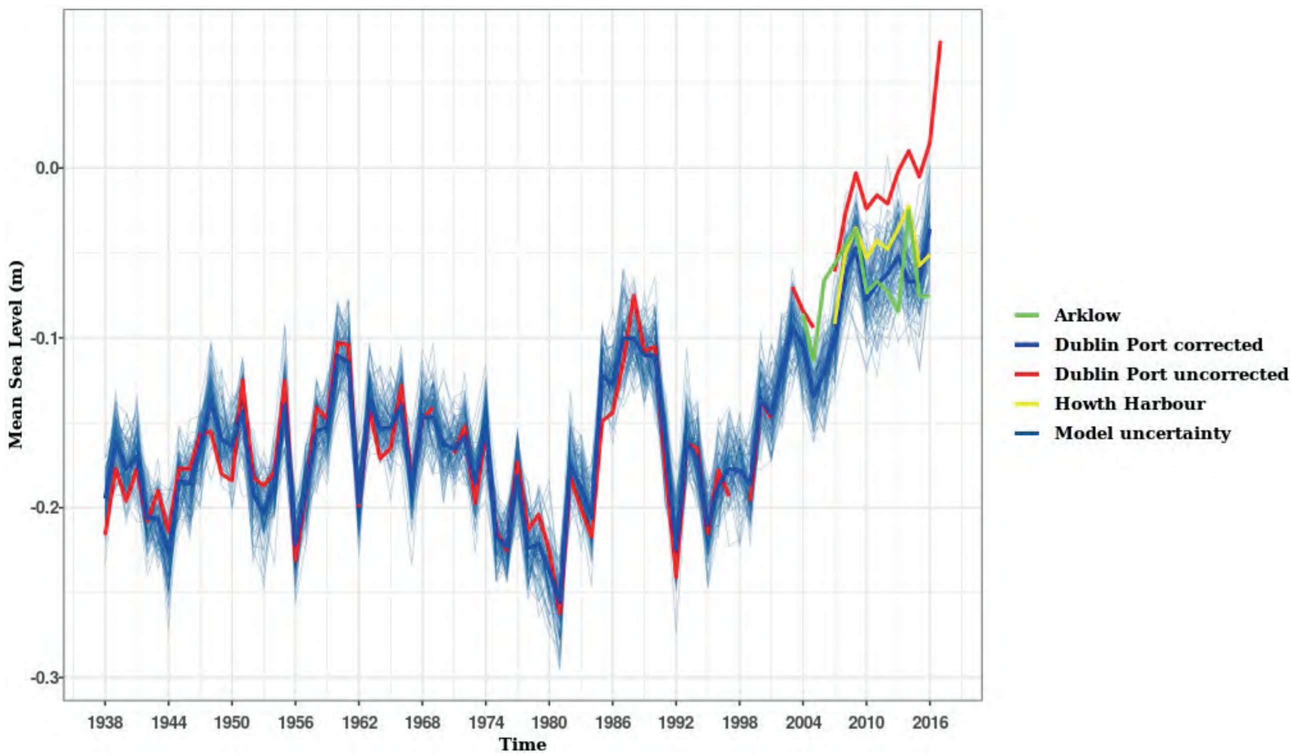


Figure 5.4 Sea level time series for Dublin Port following the reconstruction by Shoari Nejad et al. (2022), showing the need to adjust the recent record to account for apparent inhomogeneities that lead to an overestimate of the long-term trend. Source: Shoari Nejad et al. (2022; their graphical abstract). Reproduction licensed under the Creative Commons Attribution CC BY 4.0 licence (https://creativecommons.org/licenses/by/4.0/).

It is also possible to reconstruct longer-term regional changes for selected areas from fragmented records in combination with modern measurements, as shown by Pugh et al. (2021) for Cork and environs (Figure 5.5). Pugh et al. (2021) found a mean sea level rise of 40cm in the greater Cork Harbour area from 1842 to 2019, larger than would be expected from global mean sea level trends plus local glacial isostatic adjustment (south-west Ireland is still slowly sinking as a result of the melting of the Eurasian ice sheet 18,000–12,000 years ago; Stockamp et al., 2015). Investigation into the regional differences in rates of sea level rise around Ireland is ongoing work. A new project, Retro, funded by the Marine Institute, will contribute to this understanding through data archaeology south-west of the Dublin–Malin axis and offer a better picture of Irish sea level rise (McCarthy et al., 2023b).

Future sea level around Ireland will be determined principally by changes in global mean sea levels, which are projected to rise under all scenarios and to continue to do so for hundreds to thousands of years into the future (section 2.4.1). Locally, these global-scale changes will be attenuated by basin-scale (pan-Atlantic) and local shelf sea variability, and isostatic rebound, and influenced by the mix of sources of global mean sea level contributions.

Temporal variability in ocean dynamics dominates regional sea level patterns on annual to decadal timescales (Fox-Kemper et al., 2021). Interannual to decadal variations in tide gauges in north-west Europe are anti-correlated with those on the eastern seaboard of North America (Church et al., 2013; Rhein et al., 2013). When sea levels are anomalously elevated in New York City relative to global mean sea level they are anomalously low in Newlyn, England (Figure 5.6). While they can substantially alter local sea level change on decadal timescales by several centimetres, they do not meaningfully alter longer-term, globally driven trends. In shelf seas, these basin-wide processes can be further modified by the complex seabed topography and coastline, leading to even more local and somewhat more pronounced signals (Fox-Kemper et al., 2021).

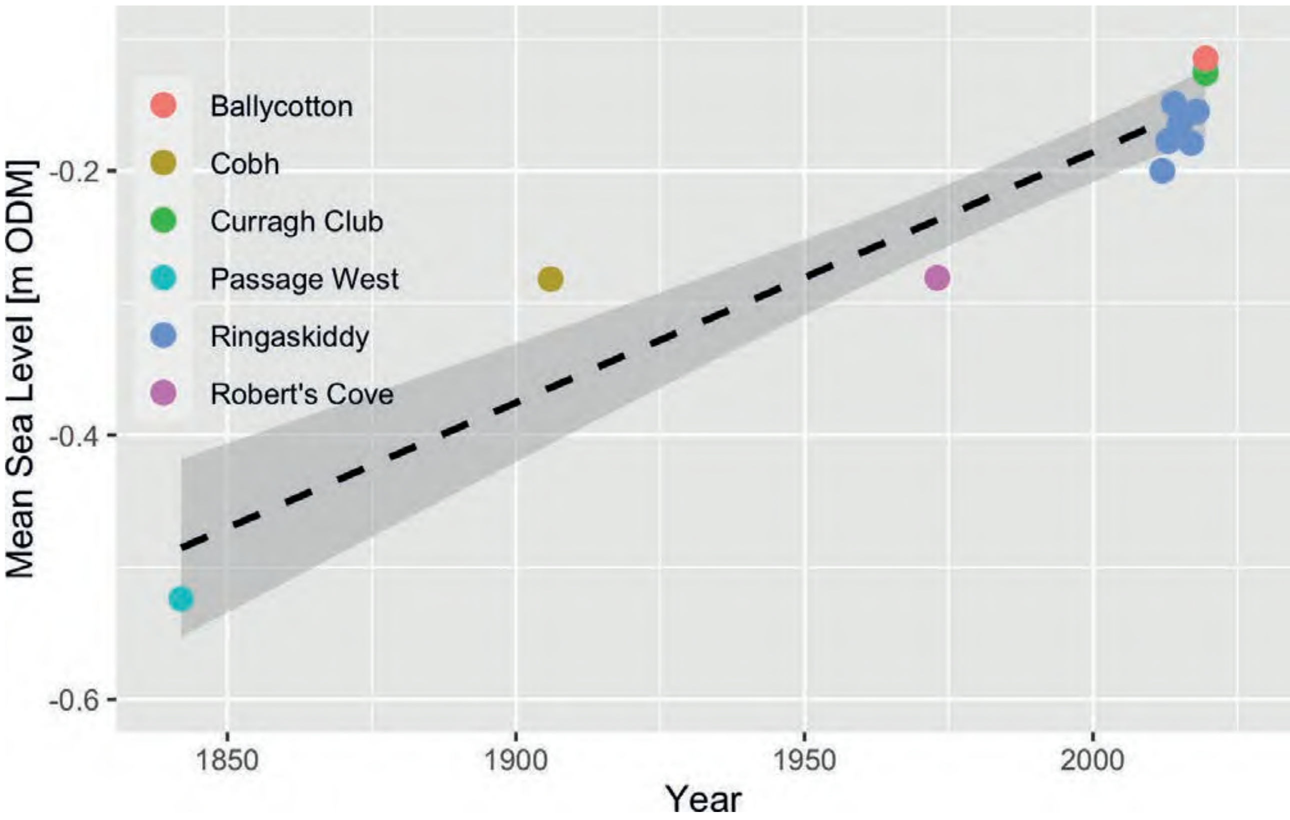


Figure 5.5 Regional multi-site-based reconstruction for the Cork region extending back to 1842. Observations from given dates and locations have been combined to form an estimate of the longest-term changes in this regional composite. Source: Pugh et al. (2021, their graphical abstract figure). Reproduction licensed under the Creative Commons Attribution CC BY 4.0 licence (https://creativecommons.org/licenses/by/4.0/).

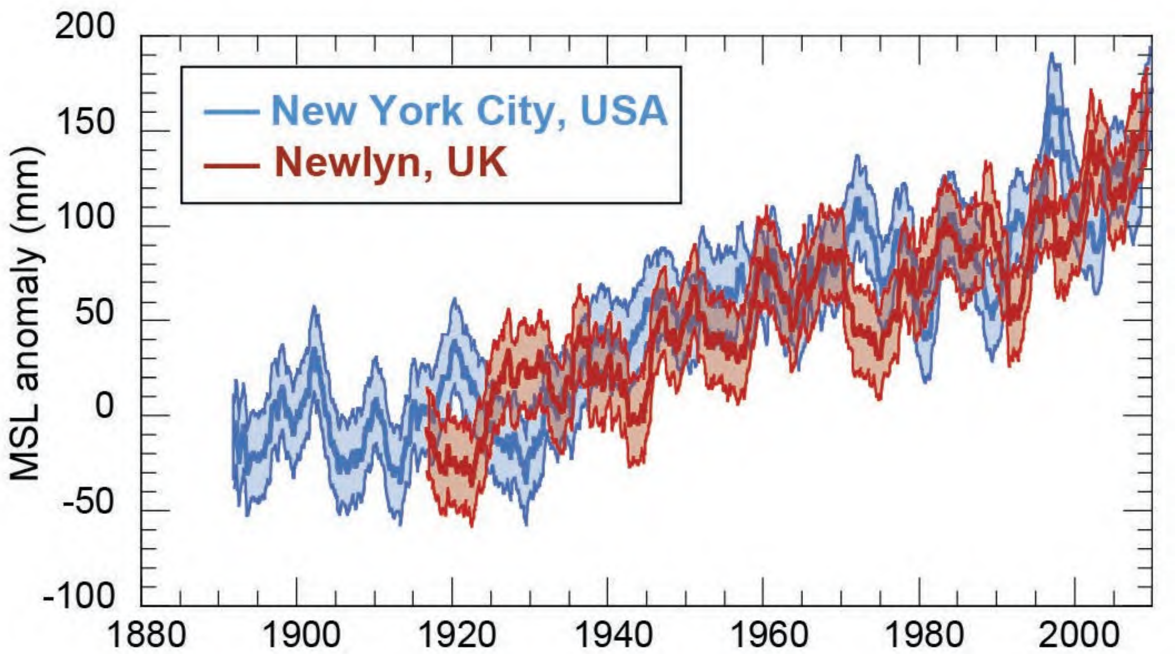


Figure 5.6 Multi-decadal tide gauge records from Newlyn and New York City showing out of phase multi-annual to multi-decadal departures from the long-term rising trend at the two locations. Source: Rhein et al. (2013; their figure 3.12a).

Isostatic rebound results from changes in the loading of tectonic plates (Milne and Shennan, 2013). Until about 12,000–18,000 years ago much of north-west Europe, including portions of Ireland, was covered by ice sheets up to several kilometres thick (Fretwell et al., 2008). This depressed the crust in these areas while elevating the surrounding crust – a bit like placing a heavy ball in a lump of plasticine. The crust is slowly rebounding where the ice sheets once were and slowly sinking where they were not. For Ireland, that means that land roughly south and west of a line from Dublin to Mayo is sinking, while everything north and east, where ice sheets were present during the last glacial maximum, is rising. The rates are much slower than both ongoing and projected changes in global mean sea level (generally <0.2mmyr^{-1} although locally higher in the extreme north-east and south-west (Stockamp et al., 2015); cf. c.3mmyr^{-1} global mean sea level increases) and yet will either enhance or ameliorate local sea level changes.

Current ice sheets influence sea level through melting ice and via their gravitational effects (Fox-Kemper et al., 2021). Both contemporary Greenland and Antarctic ice sheets are so massive that their gravitational effects ameliorate sea levels around the world (the ocean is not actually flat, and local sea level across the world varies considerably from such an assumption (Fox-Kemper et al., 2021)). How national sea levels will evolve therefore depends on where the ice sheet contributions to future sea levels arise from. If the predominant ice sheet contribution to global sea level rises in the future were to arise from Greenland, then the reduction in gravitational pull would mean locally lower sea level increases throughout much of the North Atlantic (Bamber and Riva, 2010; Brunnabend et al., 2015). Conversely, were the predominant source of sea level rise contributions to be from Antarctica, its reduced gravitational effects would lead to northern hemisphere local sea level increases being significantly enhanced (Bamber and Riva, 2010; Brunnabend et al., 2015). The relative contributions and timings of Greenland and Antarctic ice sheet melt to future sea level change remain uncertain (Fox-Kemper et al., 2021).

5.4 Extreme sea levels and storm surges

Ireland's position in the North-east Atlantic makes it prone to significant waves (O'Brien et al., 2013; Tiron et al., 2015) and storm surges, with significant variations in risk due to the complex coastline (Gallagher et al., 2014). Wave behaviour (height, period and direction) is highly correlated with the phase of the NAO (section 1.3.1; Gallagher et al., 2014; Glesson et al., 2017). Positive phases of the NAO are generally associated with increased significant wave activity.

Storm surges, particularly in combination with extreme waves, pose an ever-increasing risk to Ireland, including major cities such as Galway, Cork and Dublin. Both Galway and Dublin have experienced significant wave overtopping in recent years (McCarthy et al., 2023a), and Cork has experienced repeated nuisance flooding (Underwood, 2018) at high tides. Several recent storm surges have coincided with neap or low tides, meaning that impacts have been avoided.

Continuing rising sea levels will serve to exacerbate the risk of storm surges and significant waves, particularly on sandy shorelines (Ranasinghe et al., 2021). Impacts in the second half of this century are substantially more acute under delayed action than Early action scenarios, and that extends generally to Europe (Ranasinghe et al., 2021). Significant wave heights (the highest third of all waves) are projected to decrease around Ireland during the remainder of the century (Dabrowski et al., 2023). However, the future behaviour of extreme waves around Irish coasts is considerably less certain, with studies showing everything from decreases to increases in wave heights (Dabrowski et al., 2023). These differences principally relate to changes in storminess in the North Atlantic sector, which remain highly uncertain (Seneviratne et al., 2021).

5.5 Shelf sea chemistry

Repeat sampling on an annual basis has been undertaken on key aspects of ocean chemistry since 2006 across the western Irish shelf and Rockall Trough (Büscher et al., 2023). Irish offshore waters have become more acidic, with an overall reduction in pH of 0.02 units per decade (McGrath et al., 2012). The reduction in pH is also evident in deeper waters (1,500–2,000m) when 2010 is compared to the 1990s (Büscher et al., 2023). The mechanisms underlying this acidification relate to ocean–atmosphere carbon exchanges and are well understood and documented (section 2.4.3). Short-term variations in pH in the coastal seas can be an order of magnitude larger that the observed signal in the open ocean (Fox-Kemper et al., 2021; Gulev et al., 2021) and have been observed in Irish coastal seas (Büscher et al., 2023).

Ocean acidification also results in reduced calcium carbonate saturation states, which impacts the ability of organisms to form shells and skeletons. The aragonite saturation horizon (ASH), which is the depth below which unprotected aragonitic calcium carbonate tends to dissolve, has become shallower. As this continues over the course of this century, benthic ecosystems on the shelf slopes will be at risk (Büscher et al., 2023). In coastal embayments the ASH may be strongly influenced by local geology, highlighting the potential for emerging local hotspots as ocean acidification continues (Büscher et al., 2023).

Measurements of pCO_2 on board the national research vessels have yielded insights into the nature of marine CO_2 sources and sinks in Irish waters in recent years (Büscher et al., 2023). Irish coastal waters have been observed to act as a sink of CO_2. The seas to the north and west of Ireland have been observed to act as a sink year round, while in autumn and winter the Celtic Sea has often acted as a CO_2 source to the atmosphere. The data will continue to be collected and analysed in a regional and global context on an ongoing basis.

Concentrations of various marine nutrients essential for plant growth, including dissolved inorganic nitrogen, silicate and phosphate, can be altered by climate change, principally through changes in stratification, which influences replenishment of surface nutrients through deep-ocean mixing (Büscher et al., 2023). Climate change is, however, just one of a number of human-based interventions affecting the concentration of these nutrients in our shelf seas. There is little evidence to date for a climate signal in marine nutrient concentrations, although projections show that climate change under all scenarios is projected to decrease nutrient availability (Büscher et al., 2023).

5.6 Marine ecosystems

Phytoplankton are the base of the marine food chain and include several harmful algal species that impact the seafood sector and potentially humans (Clarke et al., 2023). An expansion of the phytoplankton growth season has been observed for some species in Irish waters, while others have changed considerably in abundance, including an overall increase in diatom and dinoflagellate occurrence throughout the year (Figure 5.7; Clarke et al., 2023). There has also been an increase in the frequency of occurrence and abundance of various potentially toxic or harmful algal blooms (Clarke et al., 2023). Observed changes to date in plankton and algal blooms are consistent with observed climate changes to date and are expected to be exacerbated by further climate change (Clarke et al., 2023).

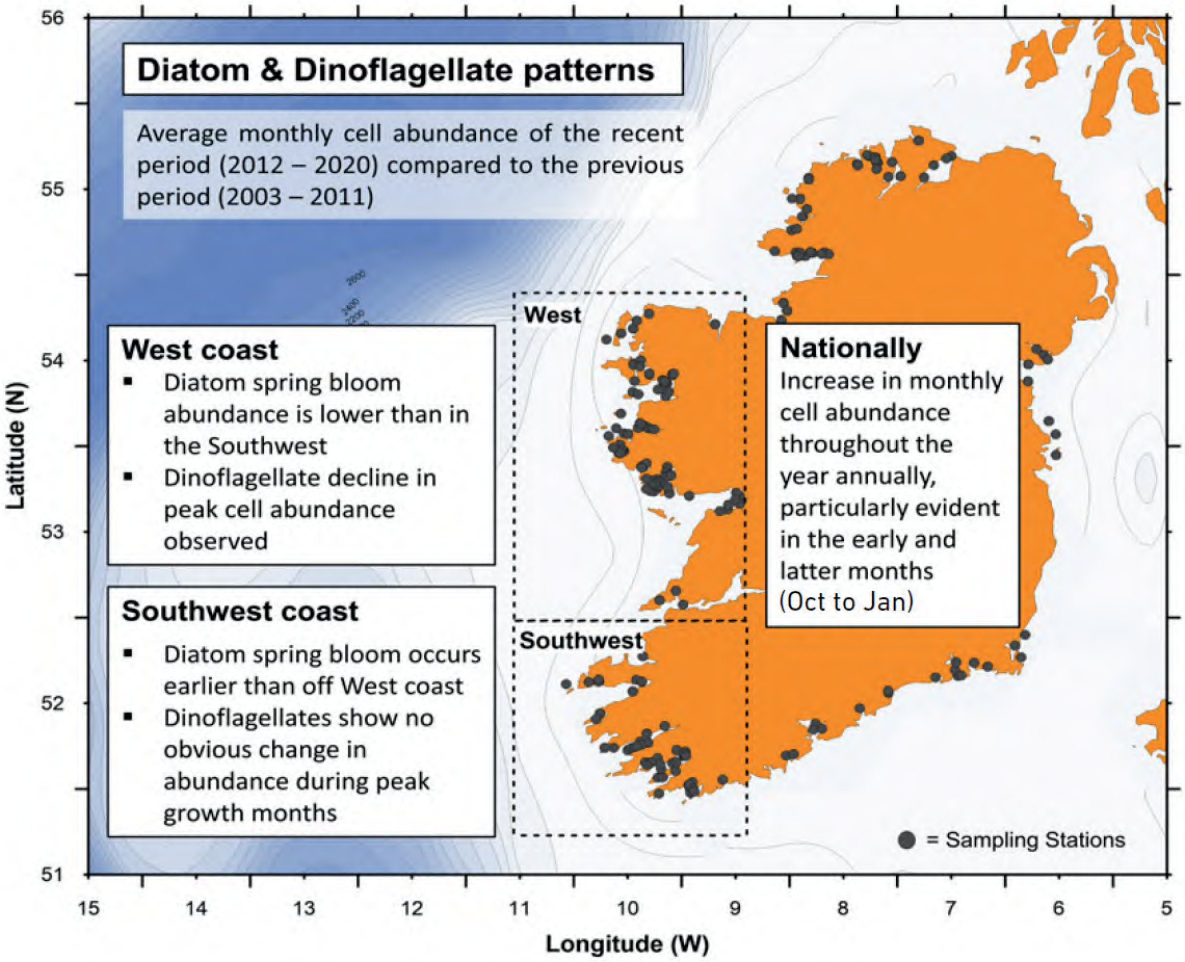


Figure 5.7 Summary of changes in diatom and dinoflagellate abundance and occurrence, 2003–2020. Source: Clarke et al. (2023; their figure 5.2).

Changes in marine ecosystems have also been observed higher up the marine food chain, including in commercial fish and shellfish species (Vaughan et al., 2023). Linking changes in commercial fish species to climate change is problematic because the confounding influence of changes in exploitation through time often overwhelms any climate signal (Vaughan et al., 2023). Nevertheless, climate change is already affecting marine taxa through changes in ranges, abundance, productivity, mortality, maturity and growth (Rijnsdorp et al., 2008; Pinnegar et al., 2017). Many species are shifting polewards and/or to deeper waters as the ocean continues to warm (Figure 5.8; Gulev et al., 2021; Vaughan et al., 2023).

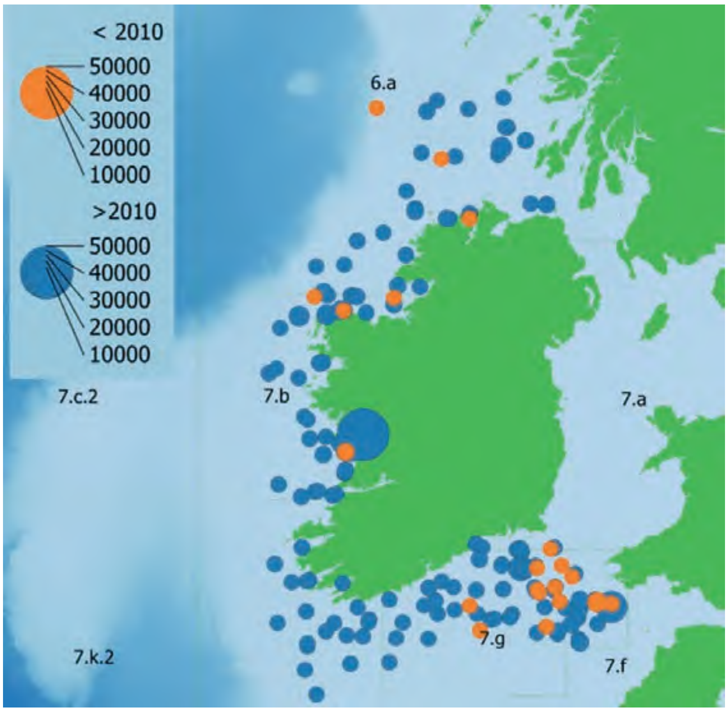


Figure 5.8 The distribution (no./km2) of European anchovy (Engraulis encrasicolus) from the Irish Groundfish Survey from 2003–2009 (orange circles) and 2010–2020 (blue circles). Abundance of anchovy has increased, as has its geographical prevalence. Source: Vaughan et al. (2023; their figure 6.4).

5.7 Recommendations

5.1	Maintenance of coastal sensors and the national buoy network is essential for both national and global ocean monitoring. Ireland is also a member of the Euro-Argo programme and deploys Argo floats, which contribute to the global ocean monitoring network. Ireland's participation in such networks is crucial for gathering information on local and global ocean properties.
5.2	Currently, there is no long-term ocean current monitoring system being operated by Ireland. If such a system were to be put in place it would not only be key to understanding the seas around Ireland but also fill a large gap in the data for ocean currents in the North-east Atlantic. Such data would be extremely valuable for understanding the impacts of AMOC changes and variability in the Nordic and Atlantic seas.
5.3	Ongoing pCO_2 and related measurements around the Irish coast from observatories and research vessels are necessary to help us build up a clearer picture of how different regions of the Irish coastal and shelf waters are contributing to, and responding to, carbon uptake from the atmosphere.
5.4	It is important that the current network of tide gauges is maintained and coordinated so that it meets the need for reliable, relevant and up-to-date information on sea level variability and change around Ireland on a sustained basis.
5.5	It would be beneficial to support research to collect, collate and digitise historical tide gauge observations to enable the reconstruction of longer-term changes around our coasts to place modern measurements in an appropriate longer-term context.

6

Increasing Human Influence on Climatic Extremes in Ireland

Key messages

Many notable recent Irish events have not yet been formally studied in the context of the rapidly emerging science of event attribution using state-of-the-art approaches. However, recent changes in heat extremes and heavy precipitation events in Ireland can be linked, albeit indirectly, to human-induced climate change. The potential for human-induced climate change influencing the frequency or intensity of other types of extreme events in Ireland, such as windstorms, is not evident from observations and analysis to date.

For heatwaves, such as those experienced in the summer of 2022, there is consistent evidence that these have been made more likely and more frequent due to climate change. The July heatwave of 2022 saw temperatures reach 33°C (at Phoenix Park) for the first time nationally in over a century and may constitute the hottest temperature reliably recorded, given the uncertainties recently documented about the long-standing national heat record.

Intense short-lived rainfall events such as those at New Ross in August 2022 or in County Donegal in August 2017 have often, but not always, been shown to be made more likely and more severe due to climate change. These types of extreme summer convective events are becoming more frequent and intense across much of north-west Europe.

There is evidence for human influences making many multi-day rainfall events, such as those culminating in Storm Desmond in December 2015, more likely and more intense.

Several windstorms have occurred in recent years, including the intense windstorm in August 2020 and ex-Hurricane Ophelia in 2017. In general, the attribution of windstorms has proven incredibly challenging and remains a topic of active research.

The Intergovernmental Panel on Climate Change Working Group I Sixth Assessment Report makes clear that many of the most extreme events will scale with the global temperature response to greenhouse gas emissions. That is to say, those recent events that have been impacted by human-induced climate change, such as heatwaves and extreme rainfall, are a foretaste of what will likely occur in future with increased frequency and intensity under further warming. The most rare extreme events that impact entire communities and regions are the events that will see the largest relative increases in frequency and intensity (see also Chapters 1, 3 and 4).

Compound events are combinations of multiple climate impact drivers that occur at the same time, in the same area or both. Such events are caused by weather events which may have been altered in their likelihood and/or intensity by human influence. The likelihood of both concurrent heatwave and drought conditions and storm surges with heavy precipitation have been observed to increase to date in Europe and are projected to further increase with additional warming.

6.1 Explaining recent Irish extreme events

Met Éireann has a long history of recording extreme weather events in Ireland, dating back to the Night of the Big Wind in 1839 when hurricane force winds caused many shipwrecks and major infrastructure damage across Ireland. Documented events cover a broad range of impacts, including heatwaves, cold waves, high rainfall, drought, windstorms and even snow extremes (see https://www.met.ie/climate/major-weather-events). Recent research has focused on whether or not human activity has influenced the probability of particular weather or climate events or, in some cases, the strength or intensity of the event. Event attribution (section 1.6.1) can be used to answer this question.

6.1.1 Direct observations of memorable extremes and their attribution

Direct observations over the past century or so have enabled the characterisation of a range of meteorological extreme events. The first definitive event attribution study statistically linking extreme weather to human-induced climate change was the European heatwave in 2003 (Stott et al., 2004; Otto, 2017). This study, using data from Ireland and other European countries, estimated that the likelihood of the heatwave, which saw temperatures in Ireland reach 30°C, was doubled due to human influence (Stott, 2004). Since then, event attribution has been applied to a variety of different types of extreme events globally, such as heatwaves, heavy precipitation, droughts and storms (e.g. Herring et al. (2020) and precursor and following editions of the explaining extreme events series[21]). Despite uncertainties arising from event definition, data quality and model processes (van Oldenborgh et al., 2021), there is consistent evidence for human influence in attribution findings for temperature-related extreme events such as heatwaves (more likely and more intense) and cold waves (less likely and less intense) (Seneviratne et al., 2021). The consistency is slightly lower for precipitation-related events such as extreme precipitation and droughts that are additionally influenced by regional variability in land surface feedback mechanisms (e.g. changes in vegetation cover) (NAS, 2016). The more complex the underlying mechanism (e.g. for severe convective storms and hurricanes), the more difficult attribution becomes, requiring high-resolution model simulations that can adequately represent the processes. Therefore, there is considerably less consistent signal for human influences in their attribution (NAS, 2016).

Consistent with globally observed trends (Hawkins et al., 2020), many parts of Europe report increases in temperature and rainfall extremes, along with increasingly documented evidence linking specific extreme events to climate change (e.g. King et al., 2015; Mitchell et al., 2016; Schaller et al., 2016). Table 6.1 provides a synthesis of some of the notable recent attribution studies carried out for different classes of extreme events in Europe. The geographical proximity and the homogeneity in climate of Ireland with the UK and near-continent allows for making qualitative assessments, albeit indirectly, about the role of anthropogenic climate change on climate/weather extremes for Ireland based on evidence available for the UK and neighbouring regions. Notably, the summer of 2022 saw the UK break 40°C for the first time in recorded history, which was deemed extremely unlikely without human influence (Zacharia et al., 2022) and happened much sooner than had been expected by Christdis et al. (2020; Table 6.1).

These studies show that, albeit with variations in the magnitude of the effect, climate change has considerably increased the likelihood of hot extremes and heavy precipitation events in north-western Europe, which is expected to become more common as warming increases (Seneviratne et al., 2021). IPCC WGI AR6 shows how these scale directly with global warming levels (the amount of warming since 1850–1900) for such event types, such that current changes will be further magnified with further warming (Arias et al., 2021).

[21] https://www.ametsoc.org/ams/index.cfm/publications/bulletin-of-the-american-meteorological-society-bams/explaining-extreme-events-from-a-climate-perspective/

Table 6.1 Synthesis of some notable past attribution studies on different types of extreme events in Europe in general and in the UK

Event	Source	Method	Findings
Winter rainfall (December–February) 2013–14, UK	Schaller et al. (2016)	Used simulations of factual (actual) and counterfactual (natural) worlds from large ensemble model project weather@home to calculate the increase in risk of the 2013–14 rainfall event due to climate change	The risk of the event is increased by 43% due to anthropogenic warming Two-thirds of this increase is caused by thermodynamic changes and one-third by circulation changes
Heavy rainfall during Storm Desmond 4–6 December 2015, UK	Otto et al. (2017)	Followed a multi-method approach based on historical observed trends, coupled climate model simulations and a large ensemble of regional model simulations	The precipitation event is made 40% more likely by climate change
Temperature above 40°C in the UK	Christidis et al. (2020)	Used natural, actual and future projections from 16 atmosphere-only climate models that are part of CMIP5	The return period of summers with temperature above 40°C somewhere in the UK is a 1-in-100- to 1-in-300-year occurrence at present, but will be a frequent 1-in-3.5-year event by the year 2100, in the absence of efforts to mitigate GHG emissions
Summer warm spell in Europe, 2018	Leach et al. (2020)	Employed two approaches using (1) historical (1960–2013) ensemble, and factual and counterfactual ensembles for the year 2018 from Hadley Centre Global Environment Model version 3, an atmosphere-only model and (2) trend-based analysis of historical ensembles from EURO-CORDEX	Climate change made seasonal anomalously high temperatures 10–100 times more likely

6.1.2 Selected recent memorable Irish events from the past decade and their likely human contributions

Regrettably, many notable recent Irish events have not yet been formally studied in the context of event attribution. In part, this speaks to a lack of current national[22] capacity in the area of event attribution, which could be addressed in future by investment and collaboration with international partners. For very recent events it also speaks to the lack of operational attribution capabilities more generally, with only selected global events being able to be assessed in close to real time (https://www.worldweatherattribution.org/). Nevertheless, the existing literature gives firm pointers, albeit indirectly, as to whether human influence could have made these events more or less likely.

For heatwaves such as those experienced in the summer of 2022, there is consistent evidence across numerous studies that these have been made more likely and more frequent due to climate change (Christidis et al., 2020; Zacharia et al., 2022; numerous studies in the annual series of explaining recent events from a climate perspective reports). The July heatwave saw temperatures reach 33°C for the first time in over a century and may constitute the hottest ever temperature reliably recorded, given the uncertainties recently documented about the long-standing national heat record (Dooley et al., 2023). Met Éireann is currently reassessing the maximum temperature record of 33.3°C recorded at Kilkenny Castle in June 1887, including rescuing and digitising additional temperature measurements from the period, and will update the national record, if necessary, on completion of this assessment. The two heatwaves in 2022, separated by a month, were distinct in characteristics. The July heatwave was more intense but much shorter in duration. The August event was longer lasting

[22] It is not just national but also more EU-wide capacity that is lacking in this area, reflected by several EU funding calls to build capacity.

but less severe. Various studies have highlighted that both the duration and intensity of heatwaves have increased due to climate change, leading the IPCC to conclude that this is virtually certain[23] to be due to human-caused emissions of GHGs (Seneviratne et al., 2021).

Intense short-lived precipitation events, such as those at New Ross in August 2022 or in County Donegal in August 2017, have often, but not always, been shown to be made more likely and more severe due to climate change (Ciavarella et al., 2021; Cotterill et al., 2021; numerous examples in explaining extreme events series). These types of extreme summer convective events are becoming more frequent and intense across much of north-west Europe (Ranasinghe et al., 2021). Similarly, there is evidence for human influences making many multi-day precipitation events, such as that culminating in Storm Desmond in December 2015, more likely and more intense (Stott and Christidis, 2015; Christidis and Stott, 2022; Schaller et al., 2016).

For cold events, such as the 'Beast from the East' in 2018, the causes are harder to disentangle (Overland et al., 2020). Climate change almost certainly made the temperature less of a cold extreme (Seneviratne et al., 2021). What impact climate change had on the snowfall, or the likelihood of the event type, is much less clear, as there is little guidance in the available literature.

Several notable recent windstorms have occurred, including the unseasonably intense windstorm in August 2020 and, perhaps most notably, ex-Hurricane Ophelia in 2017 (Figure 6.1). In general, attribution of windstorms has proven incredibly challenging, with most attempts unable to draw definitive conclusions (see various papers in the explaining extreme events series). Ophelia was interesting in numerous aspects, including forming much further north and east than any tropical disturbance has done in the over 40-year satellite observational record and maintaining tropical features to much further north than had been the case previously (Stewart, 2018). Certainly, warmer seas, in part due to human-induced climate change, were part of the cause. Interactions with a particularly anomalous mid-latitude jet stream, bringing anomalously cold surrounding air and divergence aloft, enabled tropical characteristics to be maintained for considerably longer than would otherwise have been the case (Stewart, 2018). Given the complexity in this case, in particular the phasing with mid-latitude weather systems, it would be hard to conclude that there is a definitive link to human-induced climate changes.

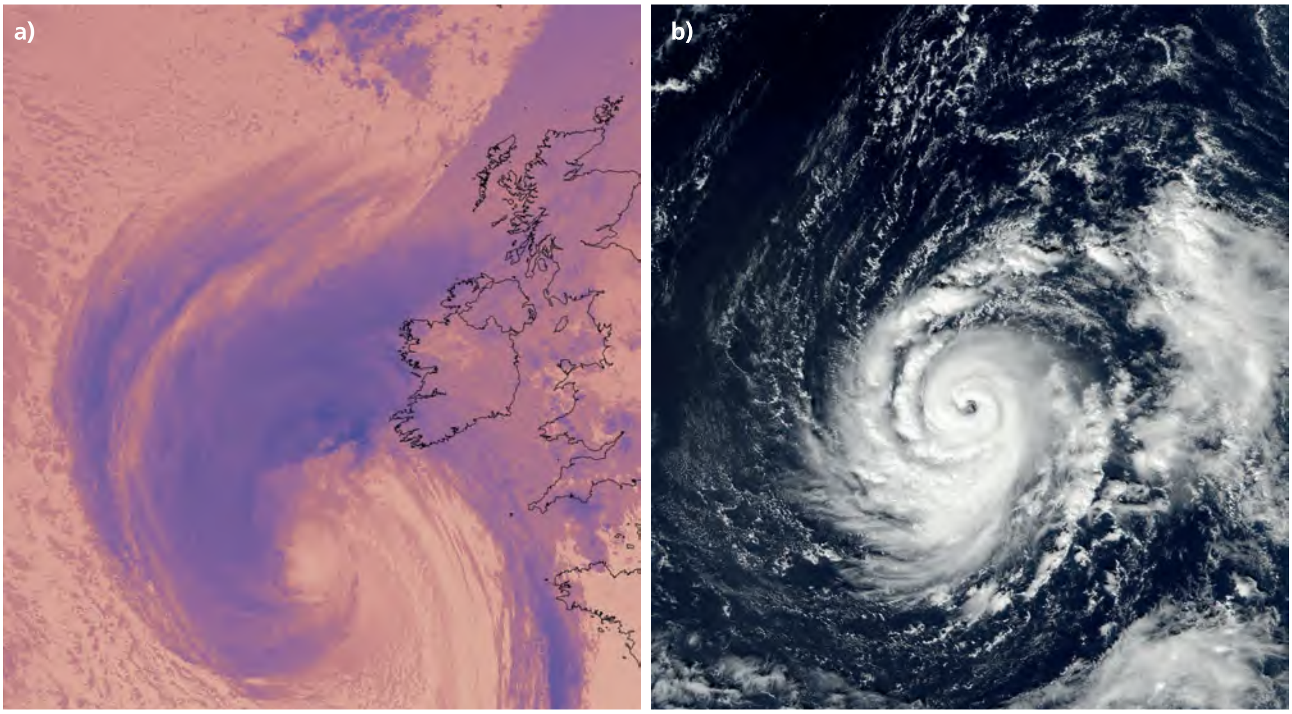


Figure 6.1 Ophelia satellite images. Images from NASA–NOAA's Suomi NPP satellite: (a) thermal image of Hurricane Ophelia from over Ireland on 16 October 2017 at 02:54 UTC; and (b) visible light image of Ophelia over the Atlantic on 12 October at 15:30 UTC. Source: NASA.

[23] Here, virtually certain has a very specific meaning of being > 99% likelihood using the carefully calibrated IPCC confidence and likelihood framework.

The droughts in 2018 and 2020 were a major wake-up call for many sectors in Irish society, as substantial nationwide droughts had not occurred since 1976. In the longer term, however, Ireland has gone through periods of frequent and severe drought in the past (Noone et al., 2017). Droughts have not always been attributed to human-induced climate changes, but several notable examples of attribution do exist (Senevaritne et al., 2021; see explaining extreme events series).

6.2 Projections of future changes in memorable events

IPCC WGI AR6 makes clear that many of the most extreme events will scale with the temperature response (Seneviratine et al., 2021; see also event return period analyses for heat and precipitation extremes in Chapters 3 and 4). Recent events that have been impacted by human-induced climate change are therefore probably a foretaste of what will likely occur in future, but with increasing frequency and intensity with each degree of additional warming (IPCC, 2021a).

The most extreme of extremes – those events that impact entire communities and regions – are the events that will see the largest increases in frequency and intensity under further warming (Seneviratne et al., 2021). It is unlikely that in Ireland we have yet experienced an event that would have been impossible without human interference. However, some other parts of the world have done so (Ciavarella et al., 2021; NESP, 2020; Philip et al., 2022), and if the planet were to continue to warm the probability of such an event in Ireland would rapidly increase (Seneviratne et al., 2021; Figure 6.2).

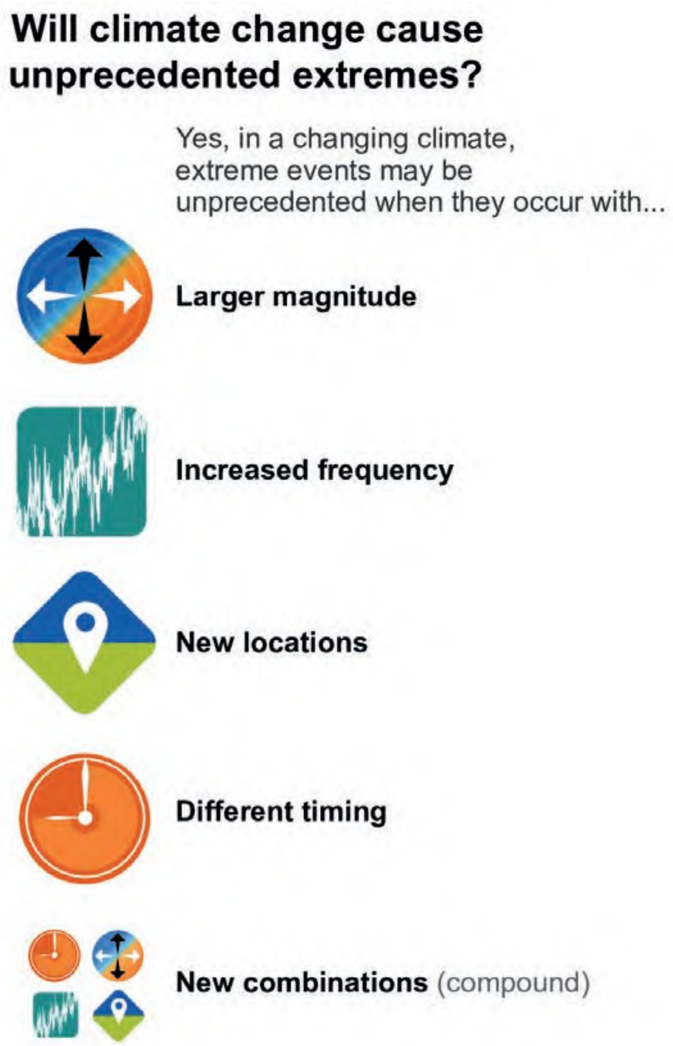
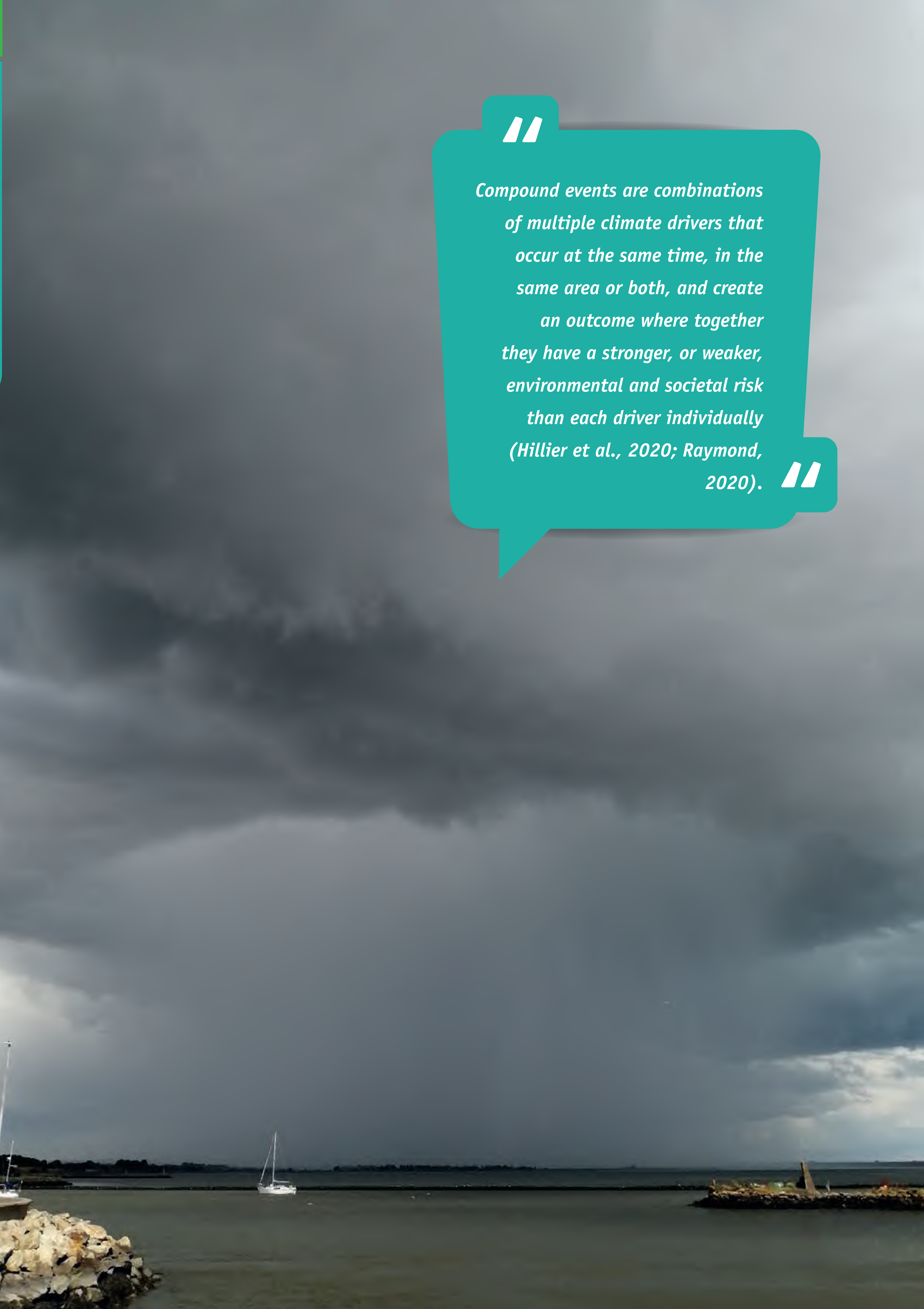


Figure 6.2 Climate change and extreme events: new types of unprecedented extremes that will occur as a result of climate change. Extreme events will occur in the future with unprecedented magnitudes. Future extreme events will also occur more frequently. Extreme events may occur in regions that have not encountered those types of events before and may also be unprecedented in their timing. Compound events, where multiple extreme events of either different or similar types occur simultaneously and/or in succession, may be more probable or severe in the future. Source: Senevartine et al. (2021; their FAQ 11.2 figure 1).



> *Compound events are combinations of multiple climate drivers that occur at the same time, in the same area or both, and create an outcome where together they have a stronger, or weaker, environmental and societal risk than each driver individually (Hillier et al., 2020; Raymond, 2020).*

6.3 Compound events

Compound events are combinations of multiple climate drivers that occur at the same time, in the same area or both, and create an outcome where together they have a stronger, or weaker, environmental and societal risk than each driver individually (Hillier et al., 2020; Raymond, 2020). An example of such a compound event in Ireland are the winter storms experienced in 2013/2014, where strong winds and heavy rainfall combined to cause substantial damage in Irish towns and cities (e.g. Matthews et al., 2014).

Compound events are broadly classified into four categories (Zscheischler, 2018):

(1) Pre-conditioned events are so called because the impact of one hazard is made more extreme by the prior presence of another hazard. Such a case could occur when heavy rain follows a period of snowfall, where the effect of the rain is compounded by rapid melting of the snow and frozen ground, leading to flooding.

(2) Multivariate events occur when two hazards happen at the same time or place. An example of this in Ireland is coastal flooding where a storm surge, high winds and high river discharges occur at the same time (Moftakhari et al., 2017).

(3) Temporally compounded events occur when multiple hazards of the same or different types occur in close succession, such as the 'Beast from the East' followed by drought in 2018, which had major implications for the agricultural sector in Ireland.

(4) Spatially compounded events are when multiple hazards occur in the same region and can lead to greater vulnerability in locales at risk of multiple hazards, such as coastal towns in Ireland.

Climate change impacts on temperature, precipitation and other variables can serve to modify the likelihood and intensity of compound events. The most relevant compound events in a national context are likely to be heat and drought/fire and compound flooding events at our coasts arising from storm surges and heavy precipitation. Consistent with overall global trends, there has been an increasing frequency of coincidence of heatwave and drought conditions in Europe (Orth et al., 2016; Sedlmeier et al., 2017). Ridder et al. (2018) found increasing frequency of co-occurrence of heavy precipitation and storm surges in a Dutch context with probable broader applicability across north-western European coasts, including Ireland (Bevacqua et al., 2019). The increasing co-presence of both factors has been found to increase the frequency of exceedance at least twofold for the highest warning levels in European case studies (van den Hurk et al., 2015). The increases in both types of compound events are projected to continue under further warming (Seneviratne et al., 2021).

6.4 Recommendations

6.1	A national operational event attribution capability is necessary to inform climate services and policymakers and raise public awareness of the impacts of climate change as they further develop. Such a capability could cooperate with similar European services and undertake analyses on international events in countries of strategic importance under Department of Foreign Affairs guidance.
6.2	There is a need to better study and understand the changing risks of compound events for Ireland. This is likely to require additional simulations to sample plausible future climates sufficiently to identify the changing risk of such rare events.

7

Climate Change, Biodiversity and Ireland’s Natural Landscape

Key messages

Climate change and biodiversity loss are linked challenges, both globally and nationally. Climate change can have direct impacts upon biodiversity by shifting species or the timing of key life cycle events. Biodiversity changes can ameliorate or exacerbate the impacts of climate change through altering surface characteristics and the efficacy of the terrestrial carbon sink.

The main impacts of climate change on Irish species and habitats observed to date have been changes in species abundance and distribution, phenology, community composition, and habitat structure and ecosystem processes. These changes are in addition to much larger impacts on Ireland's biodiversity and habitats arising from other direct human interventions.

Peatlands are among Ireland's critically important landscapes. Covering less than 3% of the global land surface, peatlands represent a significant global carbon store. Ireland is a global hotspot for peatlands, with up to 20% of its land cover characterised by peatland or peat soils. However, given that most Irish peatlands have been drained or degraded, it is probable that the majority of Ireland's peatlands are currently significant sources of carbon emissions to the atmosphere, thereby contributing to global warming. With careful management this could be reversed, they could become an important carbon sink once again, aiding attainment of global net zero emissions ambitions and biodiversity restoration targets.

The land use, land use change and forestry (LULUCF) sector in Ireland is currently a net source rather than a net sink of greenhouse gas emissions. This is anomalous in a European context.

The changing frequency of climate extremes (temperature and rainfall) can be expected to lead to a change in the likelihood of natural wildfires in Ireland, with consequences for biodiversity and carbon stocks. Wildfires are a major source of short-lived climate forcer emissions, and fire events occurring near populated areas cause severe air pollution episodes.

7.1 Irish biodiversity: trends in habitat and species in Ireland

Biodiversity data are a key requirement for understanding our natural surroundings, for tracking change in our environment and for gaining a greater insight into how we benefit from, and impact upon, the ecosystem goods and services provided by biological diversity (National Biodiversity Data Centre: https://biodiversityireland.ie). Ireland has a diversity of internationally important habitats, such as wetland, peatland, limestone, dunes and grassland (NPWS, 2019; WWF, 2020; Stroh et al., 2023). These habitats provide the environments in which internationally and ecologically significant species can survive (e.g. Atlantic salmon, white-clawed crayfish, Irish whitebeam and Irish marsh orchids), many of which are also climate sensitive (Wyse Jackson, 2007; NPWS, 2019; WWF, 2020; Stroh et al., 2023). Biodiversity is at risk in Ireland because of habitat loss and damage. The third Irish report on the status of habitats and species protected under the EU Habitats Directive (NPWS, 2019) found that most (85%) Irish habitats listed in the Habitats Directive have unfavourable (inadequate or bad) status, while almost half are demonstrating ongoing declines. Declining trends are particularly notable in marine, peatland, grassland and woodland habitats. A significant decline has been observed in the number of pristine rivers in Ireland, falling from 500 to 20 sites in the space of 30 years (EPA, 2020), which is compounding biodiversity loss within freshwater habitats (Biggs et al., 2017). One of the species of concern from this trend is the pollution-sensitive freshwater pearl mussel; only a few rivers have populations that include young individuals – and those populations without young individuals are likely to die out (NPWS, 2019).

Regional climate determines the distribution and abundance of biodiversity in Ireland along with the ecosystem services they provide, and are potentially sensitive to climate changes (e.g. Scheffers et al., 2016). The frequency and intensity of rainfall affect vegetation and crops, runoff and its nutrient and particulate load, as well as streamflow in lakes and rivers, while temperature dictates the timing of growing seasons and sea level rise impacts our coastal ecosystems (e.g. García Molinos et al., 2015; Dublin Bay Biosphere Partnership, 2016). Climate change will therefore compound negative trends in global (IPBES, 2019) and Irish (NPWS, 2019) biodiversity that are already apparent due to land use change and direct human pressure.

Almost two-thirds (63%) of Ireland's common bird species are in severe to moderate decline and have been red or amber listed. This is above the global trend of nearly a 50% decline in bird populations, with one in eight bird species globally currently threatened with extinction (BirdWatch Ireland, 2021; BirdLife, 2022). Farmland birds such as the iconic curlew, lapwing, snipe, kestrel and skylark are the fastest worsening group in terms of extinction threat in Ireland, with upland birds and lowland wetland birds also in significant decline. More than half of Ireland's native plant species have declined in frequency since 1987, whereas the prevalence of the majority of newly introduced species has increased (Stroh et al., 2023).

One-third of wild bee species are also threatened with extinction in Ireland, which is again due to habitat loss and the drastic reduction in the amount of food (flowers) and safe nesting sites in our landscapes for pollinators (EPA, 2020; National Biodiversity Data Centre, undated). This is a significant trend for Ireland, as pollinators provide the basis for plant fertilisation and reproduction, thereby sustaining entire ecosystems and supporting a steady supply of food for people. The All-Ireland Bumblebee Monitoring Scheme further confirms the impacts of factors such as land use and climate change on the Irish bumblebee population. This citizen science scheme tracked population trends of 14 bumblebee species from 2012 to 2021, and found a yearly decline of 4.1% (FitzPatrick and Stanley, 2022). The study found that the large carder bee (*Bombus muscorum*) has moved into serious decline, while the common carder bee (*Bombus pascuorum*) remains in moderate decline. The scheme also acknowledged that a longer-term dataset will be necessary to smooth out the fluctuating impacts of Irish weather. High nature value (HNV) landscapes with high biodiversity and habitat richness sequester more carbon in soils than low biodiversity landscapes (Yang et al., 2019; Delaby et al., 2020; Xu et al., 2020; Furey and Tilman, 2021; Di Sacco et al., 2021). They are also more resistant to climate extremes (Isbell et al., 2015; IPBES, 2019; Hossain et al., 2022; Lüscher et al., 2022). Managing Irish landscapes for the protection and restoration of biodiversity will thus benefit their ability to buffer future climate change and enhance their carbon storage potential (Haughey, 2021). Currently, HNV farmland in Ireland covers approximately 33% of the agricultural land, and 50% of these areas coincide with Natura 2000 land (Moran et al., 2021). This coverage of HNV areas, and the ecosystem services they provide, is under significant threat because of the dual forces of intensification and land abandonment, which are often driven by wider societal issues, such as ageing rural populations, rural depopulation and declining farm incomes (Moran et al., 2021).

In Ireland, as globally, we are presented with the twin crises of climate change and biodiversity loss (as first acknowledged by Dáil Éireann in 2019). The two are tightly linked in presenting both challenges and opportunities in Ireland. Ireland's biodiversity is very vulnerable to the impacts of climate change, but it is also key to building Ireland's adaptive capacity. By understanding, protecting and enhancing biodiversity in Ireland, we can improve our ability to adapt to global and national climate change. It is therefore essential that we tackle these crises in tandem with one another.

7.2 Key climate drivers affecting Ireland's species and ecosystems

There are many mechanisms by which climate change can impact biodiversity (Pörtner et al., 2021). Increasing temperatures, changes in seasonality, changes in precipitation patterns and extreme events all place pressure on the functioning of ecosystems and the species they contain (e.g. Grimm et al., 2013; Scheffers, 2016; Mori et al., 2021). However, these interactions are often highly complex, and the impacts of climate change on biological organisms and ecosystem processes are likely to vary significantly within and across biomes and taxonomic groups (Nunez et al., 2019).

Ecological processes, biological activity and chemical reactions are usually faster in higher temperatures (Ockendon, 2014). Higher temperatures of freshwater lead to lower levels of dissolved oxygen in lakes and rivers, with substantive consequences for aquatic life (e.g. Adrian, 2009). Increased temperature also increases soil microbial activity, increasing soil nitrogen mineralisation rates and decomposition of organic matter (Greaver, 2016; Jansson, 2020). Increasing sea levels (see sections 1.4.2.2, 2.4, 5.3) are hugely important for Ireland's coastal habitats and organisms through the destruction of dune and shoreline habitats (e.g. Jackson and Cooper, 2011). Some of our most threatened species are coastal, and have undergone population decline due to the direct pressure of human disturbance and development in coastal areas (NPWS, 2019; Power et al.,, 2023; Stroh et al., 2023). Climate change is acting as a compounding pressure on already dwindling populations of a number of native species. For example, 89% of seabirds impacted by climate change are also affected by human pressures, such as overfishing, hunting/trapping and disturbance, which are key threats to seabirds worldwide (Dias et al., 2019). This is an important indicator, as seabirds have been widely used to infer diverse aspects of the health of marine environments (Furness and Camphuysen, 1997; Mallory et al., 2010), including the state of fish populations, the occurrence of pollution and climate change (Vaughan et al., 2023). Over half of Ireland's native plant diversity has declined in range and frequency since 1987, mainly due to habitat loss and degradation, according to the Plant Atlas 2020 (Stroh et al., 2023). Although, to date, climate impacts have had a lesser impact than direct habitat destruction on these floral trends (Stroh et al., 2023), future changes in temperature and precipitation highlighted in Chapters 3 and 4, particularly under late action and high ECS scenarios, will further alter the ecology and diversity of the Irish flora.

Temperature also strongly impacts the life cycles (phenology) of plants and animals in Ireland, including the start of the growing season and the timing of bud burst. Earlier budding makes plants prone to later season frosts – a phenomenon seen increasingly across Europe and North America in fruit crops in recent years, which is projected to increase (Lamichhane, 2021). Shifting annual cycles of plants and animals can lead to mismatches in the interactions between species (Gulev et al., 2021), such as between predators and their prey and between plants and their pollinators. This can cause structural changes in the functioning of ecosystems. Wingler et al. (2022) found that the start of the season advanced by an average of 0.09 days per year between 1990 and 2018 in deciduous woodlands across Ireland. Start of season generally also showed an advance of 1.18 days per degree Celsius of rising temperature, which affected first flight dates of moths and butterflies over the decade from 2008 to 2018, the arrival of migratory birds generally, and woodland spring phenology. Increasing temperatures throughout the year in Ireland may encourage more species from southern Europe and Africa to make a home in northern and western European habitats, including pests and pathogens (Berry et al., 2002; Coll et al., 2013; see also Volume 3). According to expert groups, rising temperatures may facilitate the establishment of invasive alien species in Ireland (Lucy and Davis, 2020). Certain species require cooler winters for their life cycles or feeding (particularly commercial fish, such as cod, and some of our native trees and wildflowers (Stroh et al., 2023), along with migratory birds) and so may find Ireland's terrestrial habitats and its shelf seas increasingly less suitable (Coll et al., 2013; Garcia Molinos et al., 2015; Lewis et al., 2019; Stroh et al., 2023). The increased presence of species that are shifting their northern range or increasing in abundance in Ireland may also outcompete some of our current native flora and fauna, driving them to rarity or local extinction (Berry, 2002; Stroh et al., 2023).

Lewis et al. (2019) noted that, due to Ireland's position at the western edge of the wintering range for many waterbird species that breed in northern Europe, Scandinavia and Arctic Russia, it is likely that the effects of climate change, including increasing winter temperatures, are making Ireland a less hospitable location for many species to migrate to. Moreover, bioclimatic modelling (of species and habitat distributions) projects that under future climate scenarios many species in Ireland will experience significant changes in their ranges (Coll et al., 2013). Species most vulnerable to climate change may include those in Ireland with arctic, boreal and boreo-arctic montane distributions that are adapted to generally colder climates (Coll et al., 2013). Many of these species occur today in Counties Mayo, Sligo and Donegal in populations that represent the most southerly and/or westerly reaches of their entire ranges (Preston and Hill, 1997; Figure 7.1).

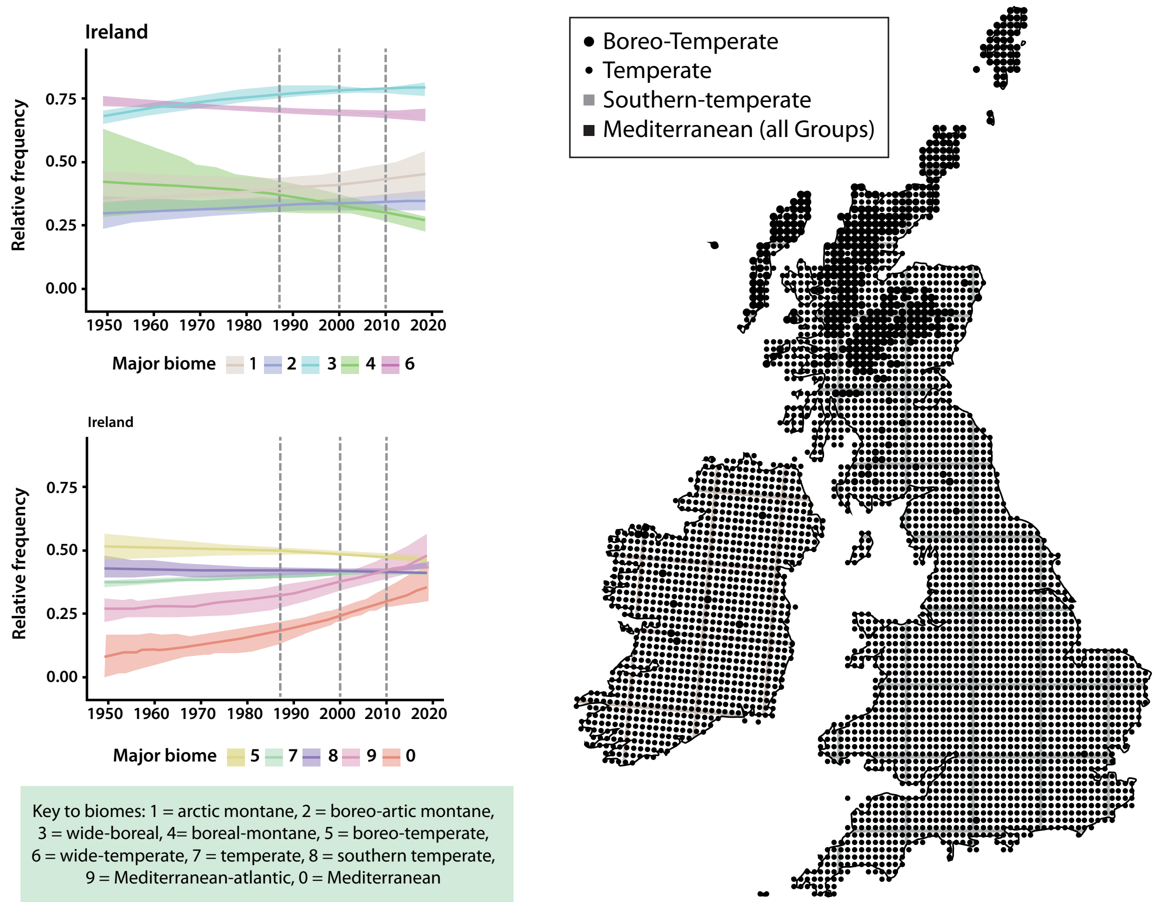


Figure 7.1 Left: temporal trends in Irish plant species grouped by their wider distribution in Europe (biome or biogeographic range) from the Plant Atlas 2020. Source: Reproduced with permission from Stroh et al. (2023). Right: map illustrating the location in Ireland of terrestrial plant species that have biogeographic ranges in the boreo-temperate, temperate, southern temperate and Mediterranean regions. Source: Redrawn from Preston and Hill (1997).

Habitats indicated as most vulnerable to climate change impacts in Ireland include upland habitats, peatlands and coastal habitats, which have the additional threat of sea level rise and associated coastal squeeze, as habitats are prevented from extending landwards because of the presence of fixed or artificial boundaries (Coll et al., 2013). Climate change may benefit some species in Ireland which have a more Mediterranean distribution (Figure 7.1). Data from Ireland's Plant Atlas 2020 Survey demonstrates that native plant species with Mediterranean distributions are indeed expanding their ranges northwards under recent climate change, and species with arctic montane distributions are showing range contraction in line with expectations (Stroh et al., 2023). Other groups of plant species, however, are showing unexpected trends with climate change (Stroh et al., 2023), highlighting the fact that predictions of species responses to climate change are complex and that further research is required (Urban et al., 2016; Åkesson, 2021) now that regional downscaled climate projections are available through projects such as TRANSLATE (O'Brien and Nolan, 2023).

Water availability is crucial for all aspects of life in Ireland. Changes in the frequency and intensity of rainfall (see section 4.1 of this volume and Volume 3, Chapter 5) have implications for life on land, in lakes and rivers, and at our coasts (Muluneh, 2021). The scale of the impact of precipitation changes on plant life, in particular, is expected to depend on seasonal variation in rainfall patterns and how it relates to the growing season of the vegetation (e.g. Li et al., 2019). Increasing levels of winter precipitation have the potential to increase nutrient runoff that can impact soil erosion, and negatively impact salmon- and trout-spawning areas (Climate Ireland: https://climateireland.ie/). Dry spells and droughts could amplify the stress caused by novel pests and diseases, such as ash dieback, and exert considerable stress on Irish forests, leading to premature leaf ageing and dieback (Schnable et al., 2022). Our native tree species have different tolerances to drought (oak > ash > alder), which could influence the species make-up of future naturally regenerating forests, shifting dominance to more drought-tolerant species if drought were to become more prevalent (Leuzinger et al., 2005; Ray et al., 2009) (see Chapter 4). Repeated droughts impact carbon dynamics in forests can result in legacy effects impacting growth, which reduce the reserves of mature trees to withstand subsequent droughts (Schnable et al., 2022). The frequency and severity of droughts over the coming century in Ireland will thus determine if our forests act as carbon sinks or sources, and ultimately this will influence how forest stocks are accounted for within our national carbon budget (see Volume 2).

7.3 Non-climate drivers of biodiversity loss

Globally, around one-quarter of the animal and plant species assessed as part of the 2019 Intergovernmental Science–Policy Platform on Biodiversity and Ecosystem Services' assessment on biodiversity were found to be threatened and at risk of extinction unless action is taken to reduce pressures (IPBES, 2019). At the same time, it is widely accepted that the global crises of climate change and biodiversity loss are inextricably interlinked, and limiting global warming and the protection of biodiversity are reinforcing objectives (Pörtner et al., 2021).

Globally, the drivers of biodiversity loss include:

- land use change/habitat loss;
- over-exploitation;
- climate change;
- pollution;
- invasive species.

These same processes operate across the breadth of Ireland's ecosystems, where they exert pressure on native biodiversity, causing the loss of species and habitats (NPWS, 2019; Gorman et al., 2023; Stroh et al., 2023). These negative drivers of change cause ecosystem degradation and reduce the capacity of ecosystems to absorb, recover from and adapt to climatic shocks and perturbations, eroding ecosystem resilience (Côté and Darling, 2010; Kefi et al., 2019; Yang et al., 2019). These drivers of change therefore do not operate in isolation but drive change through synergistically detrimental effects (Donohue et al., 2016; Kefi et al., 2019).

In Ireland, habitat change, which includes the loss, fragmentation or degradation of natural and semi-natural habitats, occurs because of changing patterns of land use, including fragmentation of the rural landscape (NPWS, 2019; Chetcuti et al., 2022). The primary driving factors are urban sprawl, grey infrastructure and one-off developments; homogenisation and loss of habitat caused by agricultural intensification and land abandonment; and intensively managed forests (EPA, 2020) (see Volumes 2 and 3 for further details). These non-climatic drivers are currently the predominant drivers of biodiversity changes on the island of Ireland (NPWS, 2019; EPA, 2020; Stroh et al., 2023; National Biodiversity Data Centre, undated).

7.4 A focus on Ireland's peatlands

Over 20% of land cover in Ireland is characterised by peatland or peat soils which are internationally important habitats. Peatlands are a wetland ecosystem characterised by the accumulation of organic matter under waterlogged conditions that prevent plant material from fully decomposing (Feehan et al., 2008; Zhong et al., 2020). In this type of ecosystem, the production of organic matter exceeds its decomposition, resulting in a net accumulation of peat and carbon (Page and Baird, 2016). The limiting factor for this process of decomposition is the availability of water or the position of the water table within the peat profile (Laiho, 2006). There are three types of peatlands in Ireland, which are distinguished as fens, raised bogs and blanket bogs (Hammond, 1984; Figure 7.2). Fens are minerotrophic, meaning that they receive nutrients from surface water or groundwater and precipitation, while bogs are ombrotrophic, receiving nutrients from precipitation only. Blanket bogs simply blanket the landscape with peat, while raised bogs are dome-shaped masses of peat occupying former lakes or shallow depressions, and their formation is a continuous development following a fen stage. Blanket bogs can be further classified into two categories: Atlantic blanket bogs and mountain blanket bogs (Feehan et al., 2008).

Peatlands are home to a high proportion of Ireland's biodiversity; since they are composed of a unique combination of habitats, they can form a mosaic of ecosystems with a unique genetic and species diversity. They represent a considerable national biodiversity resource, with some species being endemic and rare at a global scale (Renou-Wilson et al., 2018, 2019). For example, peatlands are home to two-thirds of the breeding population of curlews in Ireland, our largest wader, which is now almost extinct. The population of curlews decreased by 96% between 1980 and 2018 to an estimated 138 pairs (O'Donoghue et al., 2019; EPA, 2020). Long-term assessment of peatland water table depth across Europe using proxy methods has shown that 76% of peatlands in Ireland, Britain, Scandinavia and the Baltic countries have undergone significant drying over the last 400 years due to both direct (e.g. drainage) and indirect (e.g. climate change) human pressure (Swindles et al., 2019) (Cross-chapter Box 2).

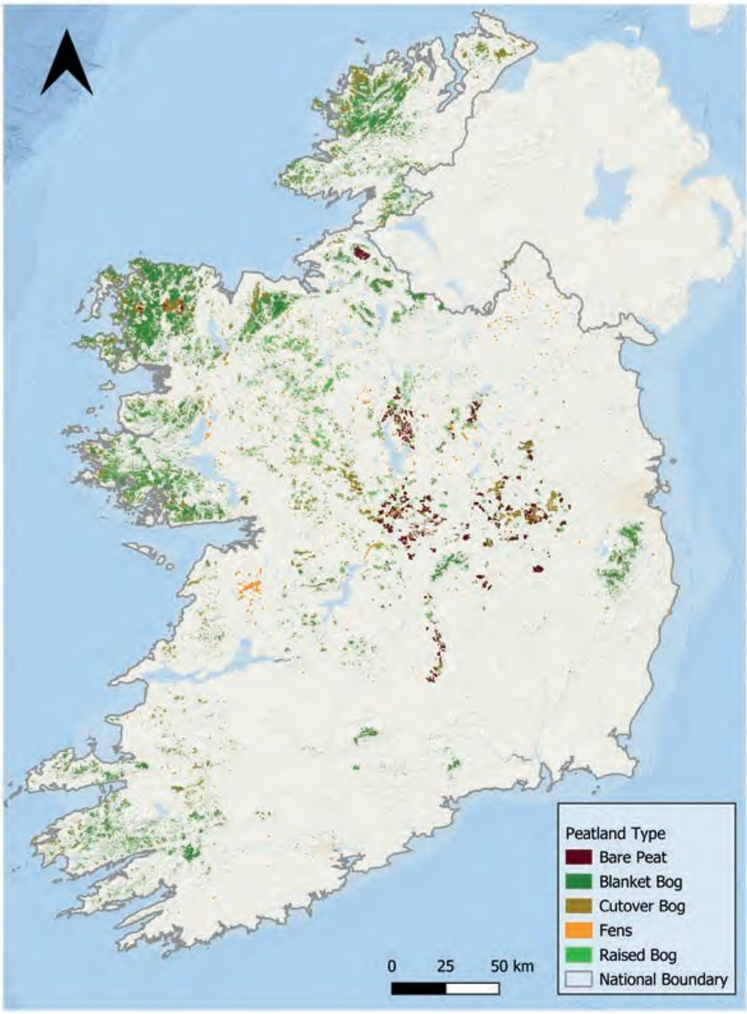
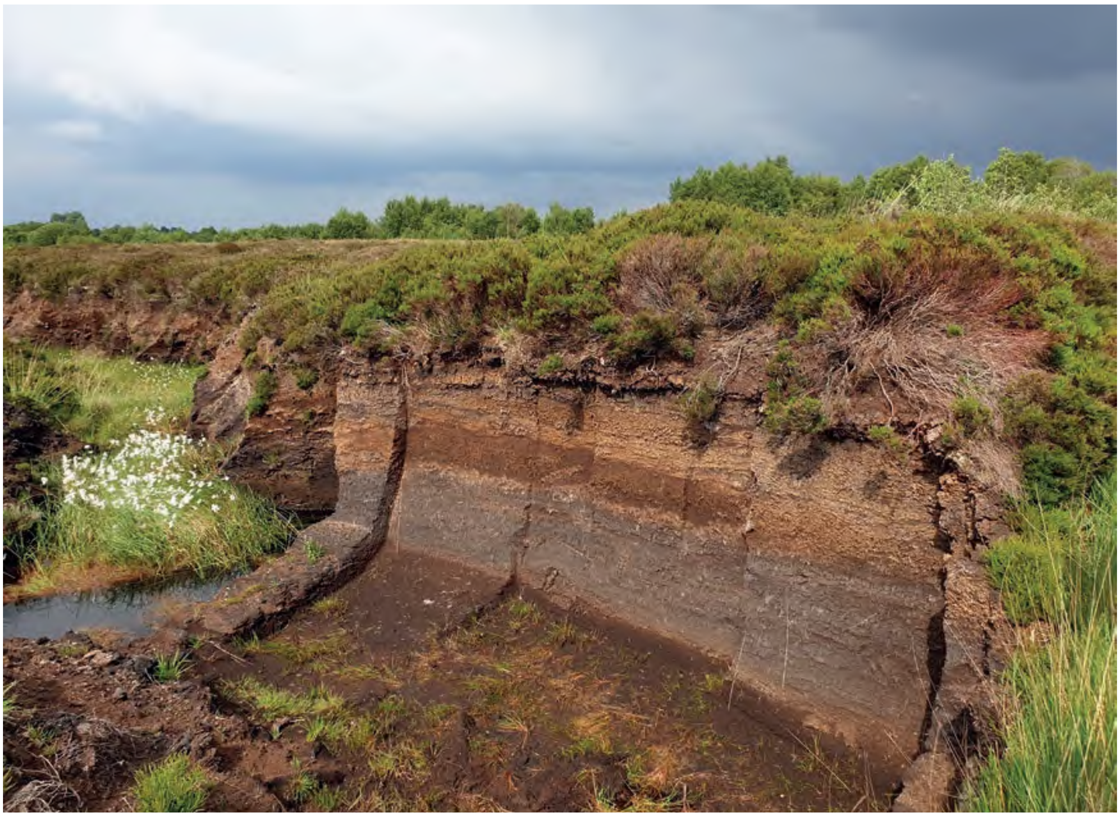


Figure 7.2 Map of the distribution of peatlands based on EPA and Tailte Éireann National Landcover Map of Ireland (2023). Source: Datasets extracted and map drafted by Sate Ahmad, Trinity College Dublin, for this report.

Box 7.1 GHG emissions from drained peatlands, rehabilitated areas and restored bogs

Covering less than 3% of the global land surface, peatlands represent a significant global carbon store, accounting for substantially more than the carbon stock contained in the entire global forest biomass (Joosten, 2016). Ireland is a global hotspot for peatlands, with up to 20% of land cover characterised by peatland or peat soils (Connolly and Holden, 2014). Over millennia, peatlands have been drained and/or converted to a variety of land uses, primarily agricultural grassland, peat extraction and forestry, and more recently for renewable energy generation (predominantly wind power). Peat has been extensively extracted for domestic use for hundreds of years (Feehan et al., 2008), while industrial extraction for energy and horticultural use, beginning in the mid-1900s, largely focused on the Midlands peatlands (Connolly, 2018). Irish peatlands contain an estimated 2.2 billion tonnes of carbon (Renou-Wilson et al., 2022). Where peatlands retain their structural and functional characteristics (high water table, peat accumulation), research has shown that they are generally small annual carbon sinks (Roulet et al., 2007; McVeigh et al., 2014), where the amount of carbon sequestered as CO_2 by the peatland plants is greater or equal to the amount of carbon lost from the peatland as CH_4 and in dissolved form to adjacent water bodies.

However, once a peatland is drained, it rapidly becomes a net carbon source and will remain so until all the peat is oxidised or the peatland is rewetted. Given that most Irish peatlands have been drained or degraded, it is probable that the majority of Ireland's peatlands are currently significant sources of carbon emissions to the atmosphere (Aitova et al., 2023), thereby contributing to global warming (Box 7.1, Figure 1; Loisel et al., 2020).



Box 7.1 Figure 1 Bellair bog, County Offaly. Cutover bog showing different peat types that have accumulated since the last ice age, c.10,000 years ago. Photo credit: Florence Renou-Wilson.

The impact of rewetting on carbon dynamics in formerly drained grassland and forested sites is unclear given the paucity of studies to date. Work by Renou-Wilson (2018) showed significant emission reductions following rewetting of nutrient-poor grassland in Donegal (Box 7.1, Figure 2), while Rigney et al. (2018) reported that CO_2 emissions from the rewetted forested blanket bog and raised bog sites were, in some cases, greater than those reported from drained sites (Jovani-Sancho et al., 2021) due to the large volume of brash left behind on site after clear-felling.

Box 7.1 Figure 2 Moyarwood bog, County Galway. The bog is growing again, 10 years after rewetting (Renou-Wilson et al., 2019). Photo credit: Florence Renou-Wilson.

Research in this area has ramped up considerably in recent years, driven by the substantial emissions reported from drained grassland areas, with new data expected over the next decade from a wide range of drained and rewetted peatland sites. While peatland restoration and rewetting have been seen as a cost-effective nature-based solution for climate (as well as co-benefiting water quality and biodiversity) (Renou-Wilson et al., 2019; Farrell et al., 2021), the scale of restoration in Ireland remains limited (Anderson et al., 2016). It is critical to understand the need for a site-by-site and/or catchment approach (due to unique peatland properties) for future management schemes (Farrell et al., 2022; Renou-Wilson et al., 2022).

7.5 Overall land use, land use change and forestry (LULUCF) emissions

LULUCF sector emissions in Ireland are anomalous in a European context[24] in being a substantial net source of GHG emissions, rather than a net sink (Climate Change Advisory Council, 2022). The latest estimate is that in 2021 the LULUCF sector was responsible for 7.8MtCO_2 equivalent emissions[25] nationally, although this number is highly uncertain (Climate Change Advisory Council, 2022). In addition to peatlands (section 7.4), other sources and sinks are grasslands, mineral soils, forestry, wetlands and salt marshes. Grasslands are the largest current net source, with a significant contribution from wetlands. These principally relate to historical and ongoing drainage practices (Climate Change Advisory Council, 2022). Ireland's forestry stock is currently a diminishing net sink, as mature forestry is being harvested and replanting rates are, at least temporarily, insufficient to counterbalance harvesting (Climate Change Advisory Council, 2022). Uncertainty in many aspects of the calculation of LULUCF emissions remains very substantial, with significant changes in estimates of current and historical emissions expected in coming years as improved estimates become available (Climate Change Advisory Council, 2022). Work by Teagasc and across academia to better measure and understand LULUCF emissions will lead to improved estimates in future.

7.6 Wildfires: a future threat to Ireland's carbon stocks and biodiversity?

Wildfires contribute to GHG emissions (Canadell et al., 2021). Wildfires are also a major source of SLCF emissions (see section 2.2), and fire events occurring near populated areas cause severe air pollution episodes (Marlier et al., 2020). When associated with deforestation, they cause significant ecosystem disturbance and also reduce the potential of vegetation to act as a carbon store (Burton et al., 2021). Climate change has the potential to enhance national wildfire activity, which can disturb active carbon cycle storage in vegetation and soils and may impact the viability of offsetting approaches that rely upon such sequestration (Volume 2). Changes in temperature and precipitation with further climate change will generally increase the risk of fire (Jones et al., 2020), but the occurrence of fires and their emissions in the future strongly depends on additional non-climatic factors, such as population density, land use, human behaviour and fire management (Veira et al., 2016).

Wildfires can have highly destructive effects on habitats and the biota they support, and land managers frequently use prescribed burning to reduce the extent of wildfires and to benefit biodiversity (Pastro et al., 2011). However, most fires in Ireland are a result of human causes, whether deliberate or unintentional (Arnell, 2021). Fires are often set by landowners to clear gorse, but uncontrolled fires can spread to adjacent areas and give rise to extensive wildfires (Ponkshe, 2015). In summer drought conditions, subsurface peatland fires, which release carbon from the peat, may also occur (Davies et al., 2013). Data on vegetation fires in Ireland are not compiled centrally by the fire services. However, burned area estimates, based on assessments of known fires, are generated annually by the DAFM and are reported to the European Commission.

Satellite data are used internationally to make regional and global estimates of fire disturbance (Chuvieco et al., 2020). Figure 7.3 shows satellite-derived fire detection data for the period 2002–2017, from which we can see that peatlands, particularly upland heaths and blanket bogs and lowland blanket bogs, have the strongest association with wildfires (vegetation and peat fires). The annual burned area of all land cover types is thought to range between 4,000 and 6,000ha annually, with the bulk of fire activity taking place between March and June each year. Satellite surveys conducted by the DAFM during 2017 found that 10,600ha of land had been affected by fire in that year. Although assessments of future fire danger due to climate change have not been carried out for Ireland, a recent assessment for the UK has predicted that higher temperatures, lower relative humidity and lower precipitation all combined will increase fire danger in the UK in the future, particularly in the south and east (Arnell et al., 2021), but a high level of uncertainty in the predictions was noted. The study found that reducing carbon emissions to levels in line with the Paris Agreement on climate change reduces the increase in fire danger significantly, but does not eliminate it.

[24] Only Denmark and the Netherlands also report being net sources. Both, like Ireland, have a large proportion of drained/managed land and low afforestation rates (Climate Change Advisory Council, 2022).

[25] This method of accounting uses international reporting using the GWP_{100} metric (see section 2.3.4) to combine the various different GHG emissions.

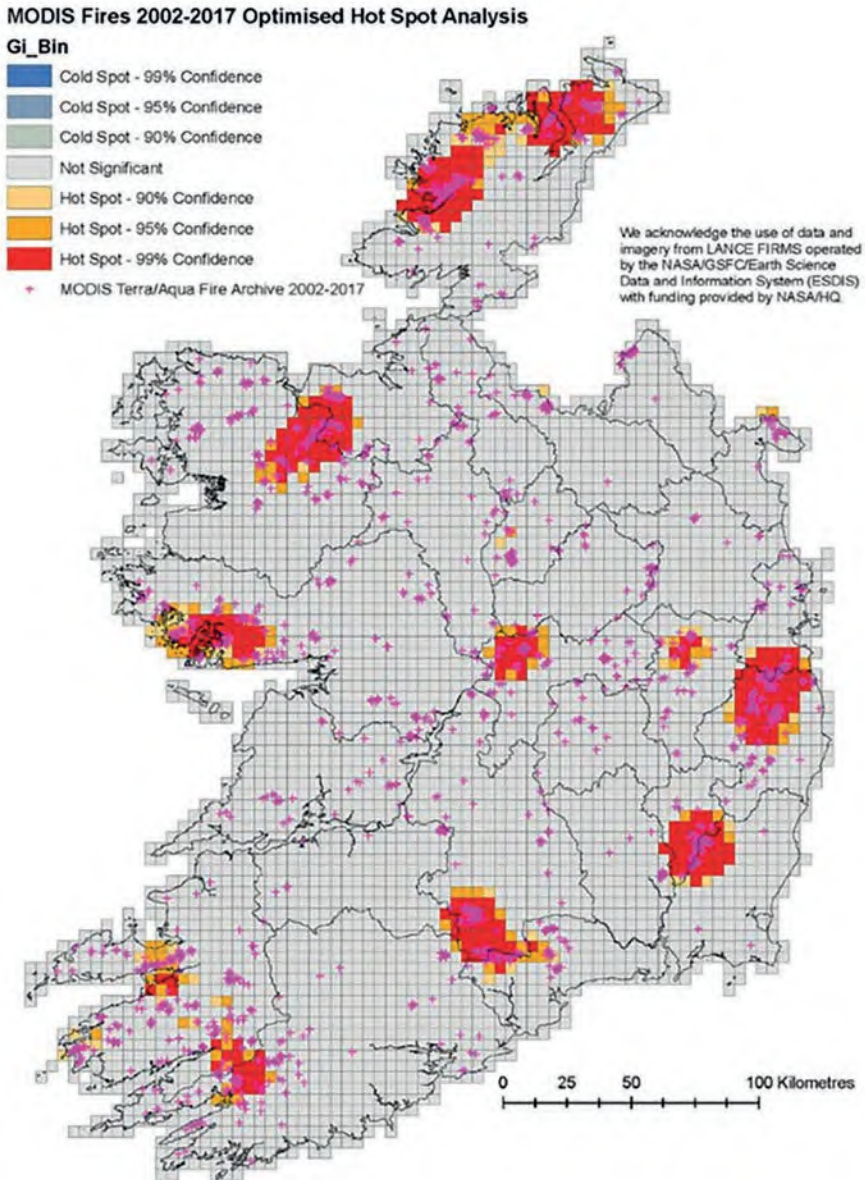


Figure 7.3 Optimised hotspot analysis of fire detection locations in Ireland (2002–2017), based on fire locations identified from satellite imagery. Location of individual fires detected by satellite shown as pink crosses. Source: DAFM.

7.7 Recommendations

7.1	Consistent with global accounting, national GHG emissions accounting is most uncertain in the LULUCF sector. There is a need to improve estimates of stocks and flows nationally as a contribution to global understanding. This will become increasingly critical in the coming decades in terms of verifying whether net zero emissions targets have been reached. Sustained investments in infrastructure and research are required to close this gap in understanding.
7.2	7.2 An all-island approach to ecosystems and land use is required to both monitor and effectively plan for climate change impacts on biodiversity in Ireland. Cross-border monitoring of ecosystems and biodiversity and the sharing of information and data is necessary to fully capture the effects of climate change on Ireland's natural landscape. Citizen science efforts in Ireland have been an excellent example of this and should be maintained.
7.3	Phenological monitoring should be prioritised and maintained to help inform practices that will prevent maladaptation, support mitigation and determine the impact of climate change on interactions between, for example, plants, birds and insects. Future maintenance and coordination of citizen science projects, data collections and phenological equipment, in addition to liaison with recorders at the international phenological gardens in Ireland, require continued support. It would also be beneficial to coordinate phenological activities at the national level and publish phenological observations in an open and easily accessible format at a central site.
7.4	Further research is required in species distribution modelling under future climate change scenarios. This would improve our understanding in predicting species' ranges under varying temperature and precipitation scenarios, the complexity of their interactions with other species, as well as the likely introduction of non-native species to the island. With an increased likelihood of shifting species distributions, it is important that we closely monitor and understand the impacts of invasive flora and fauna and both the nature and consequences of their interactions with native species.
7.5	Prioritising the restoration of our internationally important habitats, which are also in decline, would halt the loss of biodiversity and ecosystem services from these ecologically significant areas. For example, a national peatland restoration strategy would provide an appropriate framework to determine the best return for resources in terms of peatland rewetting and restoration for climate and other co-benefits.
7.6	Further research is required into the carbon dynamics of peatlands after rewetting. This would provide important insights into the mitigation potential of rewetted peatlands in Ireland, which is currently uncertain and understudied. Further research here would be greatly beneficial to assessing both when and where such mitigation initiatives would have the greatest impact in Ireland.

PART C

Possible Low-likelihood High-impact Outcomes

This part of the report looks at possible climate surprises or low-likelihood high-impact outcomes which, although unlikely, cannot be ruled out. Low-likelihood high-impact outcomes are those whose probability of occurring is either low or not well known, but whose potential impacts on ecosystems and society could be very high. While climate model projections provide insight into possible future changes, these insights are limited by the fact that models do not include all of the complex known processes of our planet's system and that their ability to simulate such tipping points is unproven.

8

Low-likelihood High-impact Climate Futures

Key messages

Low-likelihood high-impact climate outcomes for Ireland are important to explore because they may be associated with high levels of risk. The aim of assessing these possible climate futures is to better inform risk assessment and decision making for all sectors in Irish society.

The upper bound of equilibrium climate sensitivity (ECS) is poorly constrained. If the true ECS lies in the highest end of the plausible range, then even under early action considerable additional warming would occur. With delayed action, there would be very substantial warming and there would be associated impacts across the climate system. Because the Coupled Model Intercomparison Project 6 Earth System Models (ESMs) have a broad range of ECS, it is possible to draw out individual simulations from ESMs with a very high ECS to inform low-likelihood high warming outcomes. For Ireland, a low-likelihood high warming global outcome would likely lead to larger warming and commensurate larger changes in precipitation and associated extremes than the equivalent best estimate for any given scenario.

Climate system tipping points represent thresholds beyond which components of the Earth system permanently switch to new states. Tipping points would have considerable impacts, including sea level rise from collapsing ice sheets, dieback of the Amazon rainforest and carbon release from thawing permafrost. Several such tipping points would have implications for Ireland either through further shifting global climate or altering the regional climate in the North Atlantic and north-western Europe.

For Ireland, the Atlantic Meridional Overturning Circulation (AMOC) is the most immediately important potential tipping point for the Irish climate, given the importance of the North Atlantic in determining our climate and agricultural productivity. The AMOC will almost certainly weaken over the 21st century, and a full collapse cannot be ruled out. If there were to be a collapse in the AMOC, as has occurred repeatedly in the past during rapid climate transitions of past glacial phases, winters would become considerably colder and summers warmer, and there would likely be an increase in storminess and potential implications for sea levels. These would have very profound implications for the Irish climate and society.

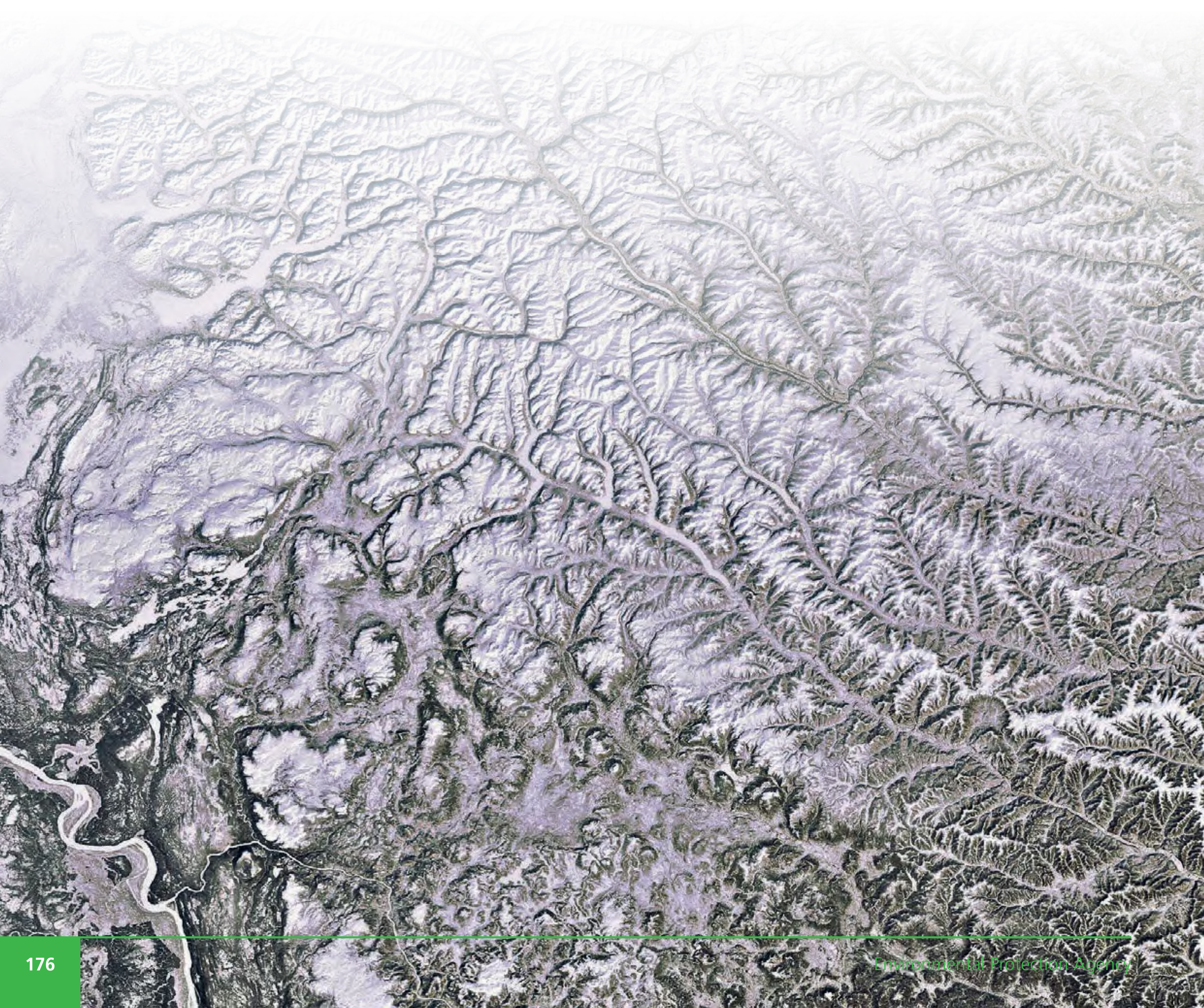
Future global sea level rise projections over the coming centuries have large uncertainties. Particular concern relates to retrograde ice sheets where much of the ice sheet is grounded below present-day sea level, which could reach tipping points whereby they become committed to collapsing over a multi-centennial period. The largest such ice sheet is the West Antarctic Ice Sheet (WAIS), which alone could contribute several metres of sea level rise. Historical global emissions may have already committed it to its long-term collapse. Both the Greenland and Antarctic ice sheets have been considerably smaller in past warm periods, but proxies cannot determine the pace of past ice sheet collapse. Under Late action scenarios, highly uncertain ice sheet instabilities mean that 2m of sea level rise this century cannot be ruled out.

The Arctic has warmed at more than four times the global rate over the past 50 years. A seasonally ice-free Arctic Ocean has occurred in the past and has the potential to significantly impact the Irish climate, but details of any likely impacts remain elusive. The probability of attaining a seasonally ice-free Arctic Ocean on a sustained basis is considerably higher under late action scenarios.

Loss of tropical or temperate forests would have the potential to alter both the efficacy of terrestrial carbon sinks and regional to global climate patterns, with broad-scale climate implications.

Currently, thawing permafrost is losing carbon to the atmosphere. Based on high agreement across model projections, fundamental process understanding and paleoclimate evidence, it is inevitable that permafrost extent and volume will shrink as the global climate warms, releasing further greenhouse gases into the atmosphere. Complete thawing of permafrost cannot be ruled out, and this would emit more carbon than humans have emitted to date into the atmosphere, leading to substantial additional warming.

Unpredictable and rare natural events not related to human influence on climate may lead to low-likelihood high-impact outcomes. For example, a sequence of large explosive volcanic eruptions within decades has occurred in the past, causing substantial global and regional climate perturbations over several decades. A future with such a sequence of eruptions over the coming decades would increase the stress on ecosystems and society. Short-term volcanic cooling will not mitigate long-term human-induced climate changes. Even the most extreme volcanic activity scenario in the 21st century causes little reduction in temperatures at the end of the century.



8.1 Low-likelihood high-impact outcomes

In IPCC WG1 AR6, certain low-likelihood outcomes are described and assessed because they may be associated with high levels of risk, and therefore the greatest risks may not be associated with the most expected outcomes (Lee et al., 2021). The aim of assessing these possible futures is to better inform risk assessment and decision making across all sectors for applications where risk-averse decision making is necessary (see also Volume 3).

Two types of low-likelihood outcomes are considered here:

(1) Low-likelihood high warming scenarios describe the climate in a world with very high ECS (section 2.3.3), beyond the range of high sensitivity considered in prior sections of this report.

(2) Low-likelihood high-impact events – tipping points (Lenton, 2021) – are deemed to have a low likelihood of occurring but would cause large potential impacts on society or ecosystems were they to occur. Tipping points, once triggered, lead to a sustained change in the climate system. Tipping points are frequently associated with policy-relevant impacts, including substantial sea level rise from collapsing ice sheets, dieback of the Amazon rainforest and carbon release from thawing permafrost.

8.2 Low-likelihood high warming scenarios

It has recently been argued that a climate assessment that is too narrowly focused on the likely range potentially ignores the changes in the physical climate system associated with the highest risks (Sutton, 2019). Our uncertainty over ECS (section 2.3.3) is not symmetrical – the constraint on the low end of ECS is much more robust than that on the upper end (Forster et al., 2021). Because the CMIP6 ESMs have a broad range of ECS, it is possible to draw out individual simulations from ESMs with a very high ECS to inform low-likelihood high warming outcomes in a physically consistent manner (Lee et al., 2021). The resulting estimates of future change under given scenarios can be compared with those models with ECS closer to the best estimate to yield an estimate of the impacts of a ‘high warming storyline’ (Sutton, 2019; Lee et al., 2021).

Figure 8.1 shows the high warming storylines for changes in mean temperature globally. For the very high warming models, end-of-century warming under the Early action scenario is broadly equivalent to the best estimate of warming under the most pessimistic Late action scenario considered in CMIP6 (compare panel (c) of Figure 8.1 with panel (d)) (Lee et al., 2021). If the real-world ECS is as high as implied by the most sensitive ESMs in CMIP6 (Figure 8.1c,f), then even Early action would commit us to very strong warming through the remainder of the century.

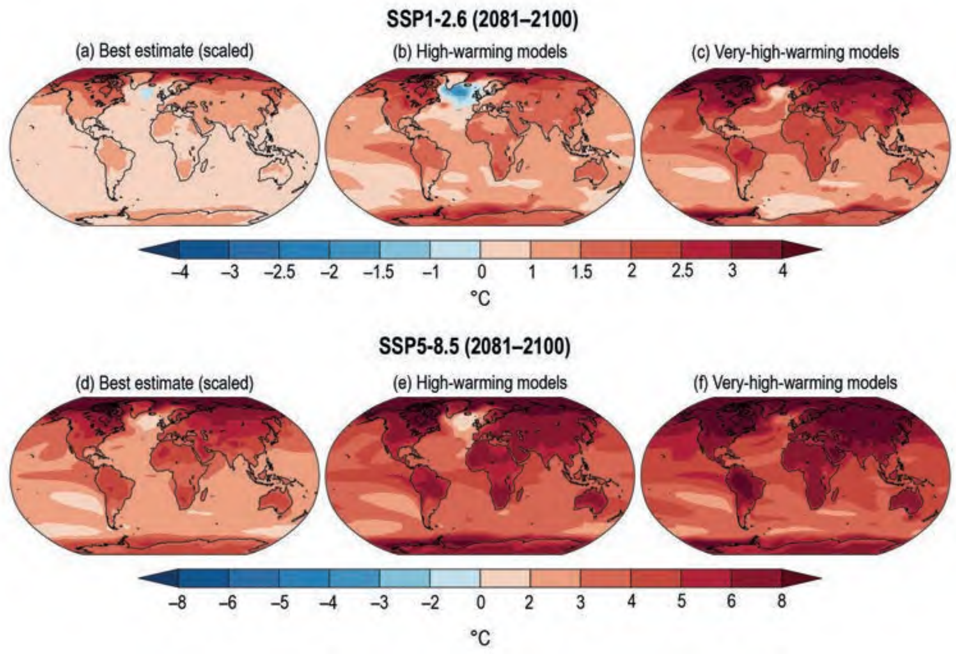


Figure 8.1 Global patterns of warming for an Early action scenario (SSP1–2.6) and Late action scenario (SSP5–8.5) for, from left to right, the best estimate of the change that might occur, a set of models at the upper tail of the assessed likely IPCC AR6 ECS range (high warming models) and a subset of models with ECS beyond this range but that cannot be absolutely ruled out (very high warming models). Source: Arias et al. (2021; their box TS 3 figure 1).

Such low-likelihood high warming storylines are also associated with changes in the hydrological cycle (Figure 8.2; Lee et al., 2021). The general patterns of precipitation changes seen under the best estimate response are amplified in models at the upper end of the assessed very likely ECS range, and further exacerbated in models with even higher ECS (Lee et al., 2021)[26]. Several of the very high warming models have a substantial proportion of the global land area experience in excess of 100% increases in precipitation under a late action scenario (Figure 8.2).

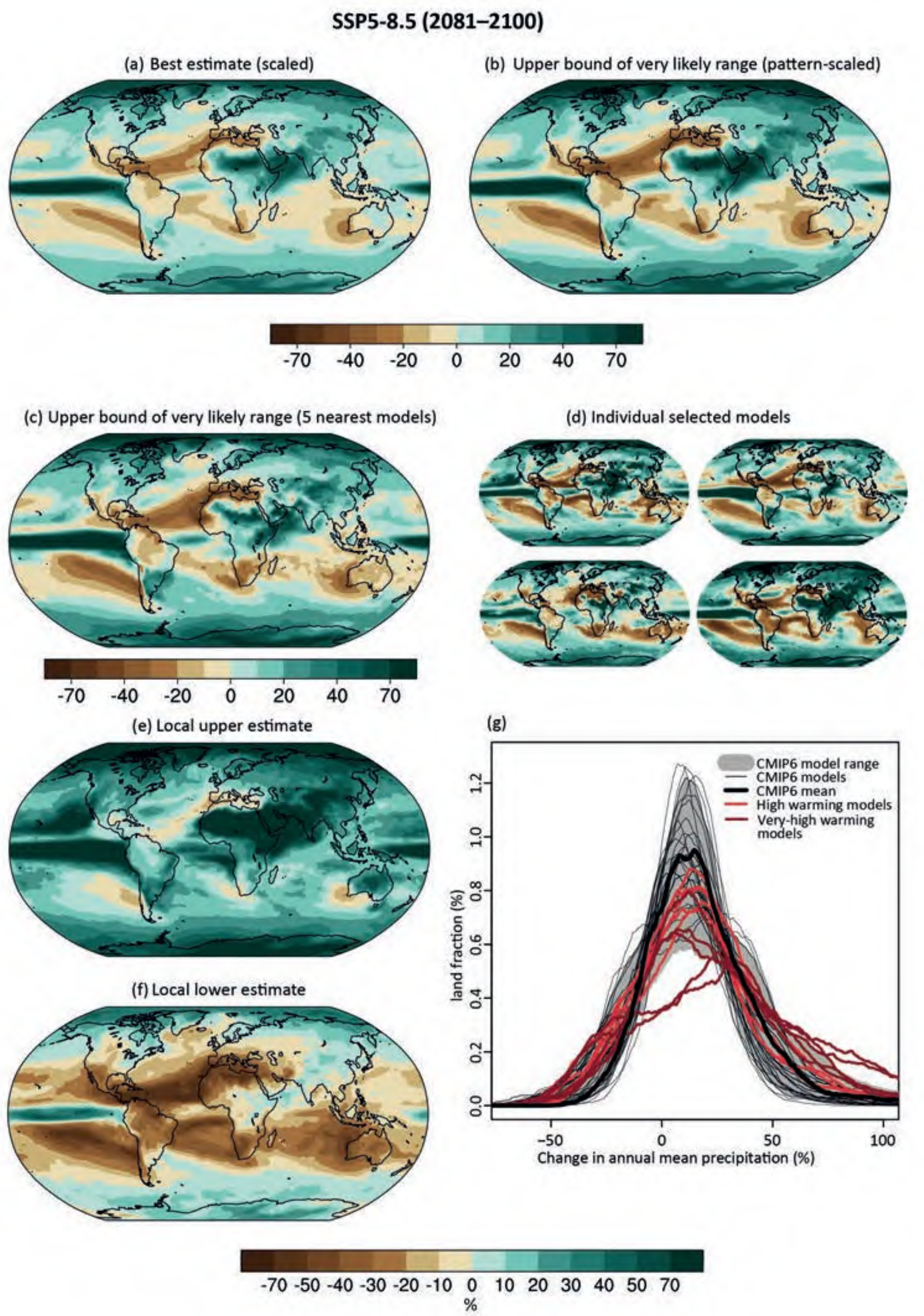


Figure 8.2 High-sensitivity storylines for global annual mean precipitation changes. Panel (a) shows the best estimate. Panel (b) shows models at the upper bound of the assessed likely range scaled according to IPCC methodology. Panel (c) shows the average of five ESMs with ECS closest to the assessed upper bound of the very likely range of ECS, with individual estimates for four of these shown in panel (d). Panels (e) and (f) show local maxima and minima in changes across the models (and as such should not be interpreted as a globally realisable pattern), while panel (g) shows how the global distribution of precipitation changes over land differ according to model sensitivity, including those models with very high sensitivities beyond the assessed very likely range. All results are shown for the Late action SSP5–8.5 scenario. Source: Lee et al. (2021; their figure 4.42).

26 Similar to the observed increase in impacts with increasing global warming levels, as assessed in IPCC (2021).

High warming storylines would increase the risk of rapid ice sheet melt arising from poorly understood marine ice cliff instability and marine ice shelf instability processes (Fox-Kemper et al., 2021). Such processes would affect both the Antarctic and Greenland ice sheets. Substantial uncertainties and low levels of agreement in quantifying their future evolution arise from limited understanding of the processes involved and limited availability of observations of these phenomena (Fox-Kemper et al., 2021). Fundamentally, mechanical stress within ice sheets means that ice cliffs beyond a certain height cannot be maintained and are vulnerable to collapse. Despite low confidence in the processes, there is very high confidence that the risks associated scale rapidly with warming, such that either high emissions or high climate sensitivity (or both) would rapidly increase the risk (Fox-Kemper et al., 2021).

Rapid ice sheet melting could lead to global sea level rises that are substantially in excess of the assessed very likely[27] range in IPCC WGI AR6, such that by 2100 global sea level could have increased by in excess of 1.5m and a 2m rise cannot be ruled out (see lower left panel Figure 1.15d). This would have very substantial implications for our coastline, including our major coastal cities.

Such a high warming storyline would also manifest itself in other climate variables (Sanderson et al., 2011), such as Arctic Sea ice and both atmospheric and ocean circulation changes. These high warming storylines imply changes in many aspects of the climate system that exceed the patterns associated with the best estimate of global surface air temperature changes by up to more than 50%. Therefore, these low-likelihood high warming storylines cannot be ruled out for users where decisions are risk intolerant. Such potential future warming storylines should be taken into account to stress-test decisions in such cases.

Overall, for Ireland, a low-likelihood high warming outcome is likely to lead to greater warming and commensurately larger changes in precipitation and associated extremes than the equivalent best estimate for any given scenario.

[27] Here, very likely has a very specific meaning of being a 5–95% range.

8.3 Low-likelihood high-impact events (tipping points)

Different parts of the Earth system exhibit critical thresholds, sometimes called 'tipping points', many of which are depicted in Figure 8.3 (e.g. Lenton et al., 2008; Collins et al., 2013; Kopp et al., 2016). Such tipping points represent a source of growing scientific, policy and public concern (Lenton, 2021). Tipping points are thresholds whereby a tiny additional change could push a component of the climate system into a completely new state. Several such tipping points would have implications for Ireland, either through further shifting the global climate or altering the regional climate in the North Atlantic and north-western Europe. Tipping elements are large-scale components of the Earth system that may pass a tipping point. Going past a tipping point may not yield an immediate climate system response, but it does commit to some sustained change in the climate system, with long-lasting consequences (Lenton, 2021). For many tipping points, it may not be apparent that they have been passed until considerably after the fact. The paleo-record shows considerable evidence of such tipping points having been reached in the past (e.g. Lenton, 2012; Barker and Knorr, 2016).

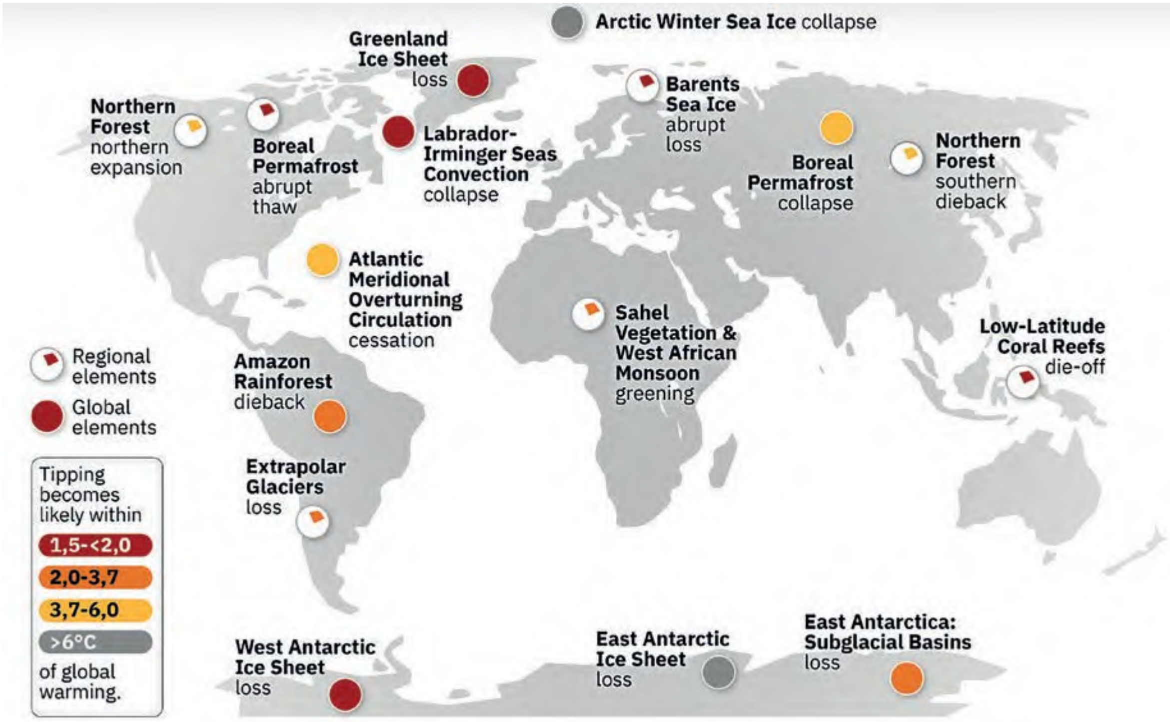


Figure 8.3 Map of the most important tipping elements in the Earth system and the latest assessment of when they might be passed by global warming level from Armstrong McKay et al. (2022). Source: Potsdam Institute for Climate Impact Research). Reproduction licensed under the Creative Commons Attribution CC BY 4.0 licence (https://creativecommons.org/licenses/by/4.0/).

The IPCC explains that "Abrupt responses and tipping points of the climate system, such as strongly increased Antarctic ice sheet melt and forest dieback, cannot be ruled out" (IPCC, 2021a). Examples of abrupt biogeochemical changes in models include tropical rainforest dieback (Cox et al., 2004; Brando et al., 2014) and temperate and boreal forest dieback (Joos et al., 2001; Scheffer et al., 2012). Transitions can be prompted by climate extremes. For example, the tropical forest dieback seen in some ESM projections is accelerated by longer and more frequent droughts over tropical land (Good et al., 2013). Transitions from one state to another can also occur if a critical threshold is exceeded, known as a bifurcation tipping point (Ashwin et al., 2012). The new state is defined as irreversible on a given timescale if the recovery from this state takes substantially longer than the timescale of interest, which is decades to centuries for the projections presented herein.

The tipping point concept is most commonly framed for systems in which the forcing changes slowly. However, this is not the case for most scenarios of human-induced forcing projected for the 21st century (Cross-volume Box 1). Systems with inertia lag behind rapidly increasing forcing, which can lead to the failure of early warning signals or even the possibility of temporarily overshooting a bifurcation point without provoking tipping (Ritchie et al., 2019). New research suggests that even attaining the Paris Agreement goal of limiting warming to well below 2°C and preferably 1.5°C is not safe, and that going above 1.5°C risks crossing multiple tipping points (Armstrong McKay et al., 2022). In the remainder of this subsection, we concentrate upon a subset of tipping points which, were they to occur, might have the most profound direct impacts upon Ireland.

8.3.1 Potential for a shutdown of the Atlantic Meridional Overturning Circulation

The AMOC (see section 2.4.2) is the most important potential tipping point for Irish climate, given the importance of the North Atlantic in determining our climate (Chapters 2 and 5). There is copious evidence from the paleo-record that in past periods the AMOC has varied considerably in strength, including periods of rapid climate transitions in past glacial phases when it was significantly weakened or shut down entirely (Fox-Kemper et al., 2021; Gulev et al., 2021). The AMOC is projected to weaken over the 21st century, with best estimates ranging from 34% to 45%, depending on the emission scenario (Weijer et al., 2020) (Figure 8.4). There is also increasing evidence that the AMOC has already started to slow down over the course of the 20th century (e.g. Caesar et al., 2018; Latif et al., 2022), even though it has not been determined yet whether this is due to external forcing, feedbacks such as increased freshwater input from melting of the Greenland ice sheet (GrIS) or natural variability. While a shutdown of the AMOC before 2100 is thought to be unlikely, it is not impossible, as there is substantial uncertainty in the quantitative (not the qualitative, as all models predict an AMOC decline) projections of AMOC decline in the 21st century (Fox-Kemper et al., 2021).

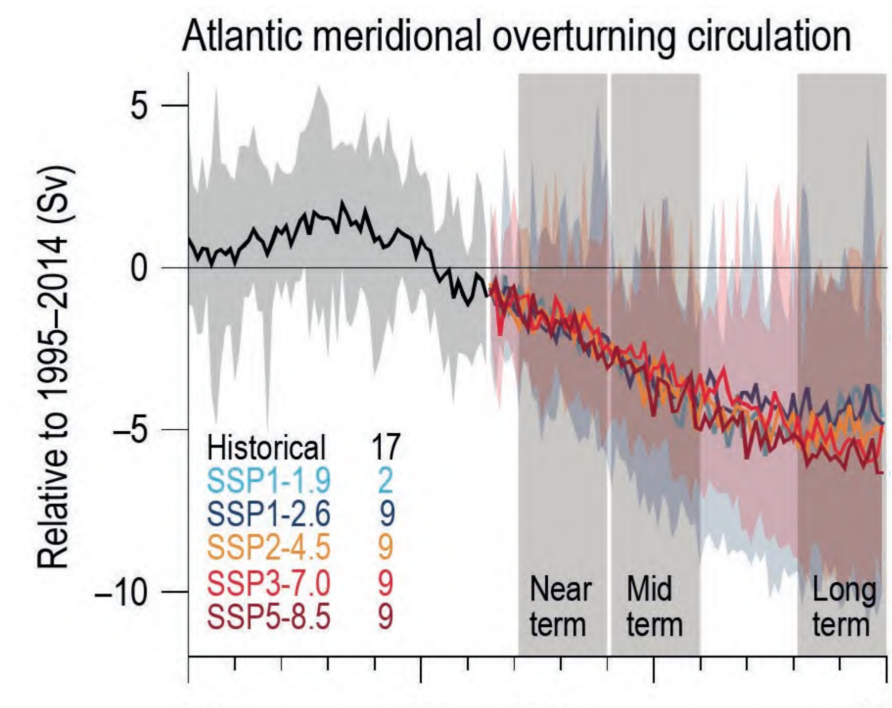


Figure 8.4 CMIP6 annual mean AMOC strength change in historical (black) and scenario (coloured) simulations. Changes are given in Sverdrup (1Sv = $10^6 m^3 s^{-1}$) and are relative to the 1995–2014 averages (c.17Sv; McCarthy et al., 2015a). The curves show ensemble averages and the shadings the 5–95% ranges across the different scenarios. SSP1–1.9 and SSP1–2.6 constitute Early action scenarios, SSP2–4.5 Middle action and SSP3–7.0 and SSP5–8.5 Late action. Source: Lee et al. (2021; their figure 4.6).

A partial or complete collapse of the AMOC would cause global climate impacts, many of which would affect Ireland (Jackson et al., 2015). The consequences of a substantial AMOC reduction or collapse would include widespread cooling throughout the North Atlantic and northern hemisphere in general; less precipitation in the northern hemisphere mid-latitudes; large changes in precipitation in the tropics and a strengthening of the North Atlantic storm track (Jackson et al., 2015; Gastineau et al., 2016). Conversely, it is suspected that cold SSTs in the subpolar North Atlantic in the summer can enhance the possibility of European heatwaves (Duchez et al., 2016). The changes in ocean circulation would also impact sea level rise on both sides of the North Atlantic, yet the sign of the change varies locally (McCarthy et al., 2015c).

For marine ecosystems, a disruption of the AMOC could have severe consequences, reducing the upper ocean nutrient concentrations in the North Atlantic and therefore decreasing plankton stocks (Schmittner, 2005) and general ocean productivity (Osman et al., 2019). Specifically, a strong correlation was found between Barents Sea temperatures and cod stocks (Årthun et al., 2018), stressing the potential impact of temperature variations caused by AMOC weakening on fisheries in the North Atlantic. On land, ESMs have shown a reduction in grass crop productivity in spring and summer of up to 50% in Ireland and by 10–20% in western Britain due to a disruption of the AMOC (Jackson et al., 2015).

To summarise, we know that a partial or complete collapse of the AMOC would have very substantial impacts upon Ireland's climate. Winters would become considerably colder and summers warmer, and there would likely be an increase in storminess. Worryingly, very recent research by Michel et al. (2022) using paleo-records suggests that recent enhanced decadal variability may signal a tipping point in the AMOC being approached.

8.3.2 Antarctic or Greenland ice sheet collapse

Ice sheet collapse would lead to substantially faster sea level rises than are currently projected (Fox-Kemper et al., 2021). Particular concern relates to retrograde ice sheets where much of the ice sheet is grounded below present-day sea level. These ice sheets are potentially susceptible to the marine ice sheet instability mechanism, whereby, once no longer buttressed, the position of the grounding line is inherently unstable until it reaches an upwards sloping bed, potentially committing it to long-term and irreversible melting (Fox-Kemper et al., 2021). Under Late action scenarios, highly uncertain ice sheet instabilities mean that 2m of sea level rise this century cannot be ruled out (Fox-Kemper et al., 2021). The largest such ice sheet is the WAIS, which alone could contribute almost 3.5m of sea level change (Bamber et al., 2009). The IPCC assessments carried out in the AR6 cycle, including the Special Report on 1.5°C and the Special Report on ocean and cryosphere in a changing climate, building on a suite of literature, point to the likelihood that instability will be triggered between 1.5°C and 2°C (Fox-Kemper et al., 2021). This ice is vulnerable to collapse over centuries to millennia due to a range of feedbacks involving ocean–ice sheet–bedrock interactions (Clark et al., 2016). Paleo evidence points to multiple periods over the last several million years (when the continents have been broadly similar to current configurations) when the WAIS has been absent and beyond that when the Earth was completely ice free (Gulev et al., 2021) (Cross-chapter Box 2). However, paleo-records are generally not sufficiently dated to discriminate between progressive long-term retreat and much faster ice sheet instability mechanisms (Fox-Kemper et al., 2021).

Less is known about the potential for instability of the East Antarctic ice sheet, the largest ice sheet in the world. Recent research suggests that warmer waters are flowing towards the East Antarctic ice sheet (Herraiz-Borreguero and Naveira Garabato, 2022). In Antarctica as a whole, the amount of ice that sits on bedrock below sea level is enough to raise the GMSL by 23m (Fretwell et al., 2013). The movement of warm waters is expected to worsen throughout the 21st century, further threatening the ice sheet's stability (Herraiz-Borreguero and Naveira Garabato, 2022).

The GrIS exhibits multiple stable states as a result of feedback involving the elevation of the ice sheet, atmosphere–ocean–sea ice dynamics and albedo (Fox-Kemper et al., 2021; Gulev et al., 2021). Much of the GrIS is prograde (the ground elevation increases away from the coast), making it less prone to sudden collapse than the WAIS (Fox-Kemper et al., 2021). Nevertheless, warming to date has committed the GrIS to substantial melting for hundreds to thousands of years to come (Fox-Kemper et al., 2021).

Past warm and cold periods have experienced very distinct ice sheet configurations from present (Figure 8.5). At the last glacial maximum, 18,000 years ago, in addition to large Eurasian and North American ice sheets, both the GrIS and Antarctic ice sheet expanded. During the past interglacial, the most recent period during which global surface temperatures were last plausibly as warm as today, both ice sheets were diminished compared with present-day conditions, with most of the WAIS absent (Fox-Kemper et al., 2021).

The mid-Pliocene warm period, when CO_2 concentrations were last as high as today on a sustained basis, had greatly diminished the WAIS and GrIS (Fox-Kemper et al., 2021). Much of the uncertainty in ice sheet evolution relates to the rate of change and not the final state. It is certain that by the time the ice sheets have caught up with past and future emissions both ice sheets will be diminished, contributing to at least several metres of sea level rise (Fox-Kemper et al., 2021). Our future emissions will determine whether that becomes tens of metres of rise (see Figure 2.14).

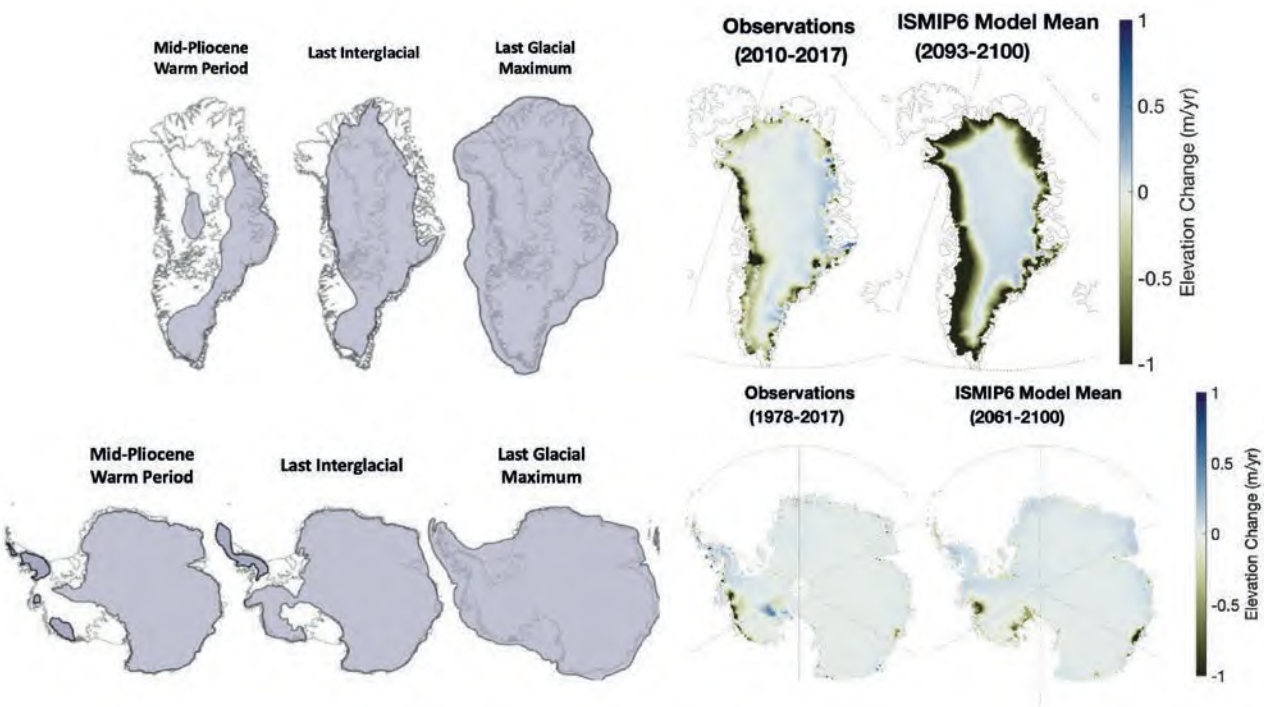


Figure 8.5 Present observed (rightmost) and past cold (last glacial maximum, 18,000 years ago, third panel) and warm period (last interglacial (125,000 years ago, second panel) and mid-Pliocene warm period (3.3 million years ago, left-hand panel) ice sheet extent reconstructions for Greenland (top) and Antarctica (bottom). Source: Fox-Kemper et al. (2021; subsets of their figures 9.17 and 9.18, modified with permission).

8.3.3 Arctic sea ice disappearance

The Arctic has warmed at more than four times the global rate over the past 50 years, with the greatest increase during the cold season (Rantanen et al., 2022). Several mechanisms are responsible for the enhanced warming of the Arctic, including ice–albedo and cloud feedbacks (Doblas-Reyes et al., 2021). The Arctic sea ice may exhibit abrupt state shifts into summer ice-free or year-round ice-free states (Lindsay and Zhang, 2005). The paleo-record has numerous examples of past warm climate states associated with either seasonally or perennially ice-free Arctic conditions (Feng et al., 2019, where ice-free is defined as less than 1 million km2 of cover) (Cross-chapter Box 2). During past intervals when the Arctic was ice free, warm adapted flora and fauna species have existed as far north as the Canadian archipelago (Eberle and Greenwood., 2011; Gulev et al., 2021).

Climate model simulations (Figure 8.6) have historically underestimated the rate of Arctic sea ice loss (Fox-Kemper et al., 2021). This is likely due to insufficient representation of positive feedback mechanisms (that accelerate warming) in the models associated with the inadequate representation of critical sea ice processes (Stroeve et al., 2014; Shu et al., 2015). The observed fluctuations of the Arctic sea ice cover arise from changes in natural external forcing and anthropogenic forcing, internal variability and climate system feedbacks (e.g. Notz and Stroeve, 2018; Halloran et al., 2020). The most recent models shown in Figure 8.6 somewhat better capture key processes but may still underestimate sensitivity to warming (Fox-Kemper et al., 2021). The probability of attaining a seasonally ice-free Arctic Ocean on a sustained basis is considerably higher under late action scenarios.

There is considerable scientific ambiguity in the relative contribution of Arctic warming and sea ice loss to mid-latitude atmospheric changes compared with other drivers. The linkages between the Arctic warming and the mid-latitude circulation is an example of contrasting lines of evidence that still need to be reconciled (Doblas-Reyes et al., 2021). As summarised by Doblas-Reyes et al. (2021), some studies contend that there could be significant impacts on mid-latitude weather via modifications that could already be occurring and that could become more severe in mid-latitude circulation as a result of sea ice loss, while other studies dispute the links made and suggest that other mechanisms may be at play. As there have been no ice-free conditions directly observed, these ambiguities are difficult, if not impossible, to reconcile without extensive and robust paleoclimate records from Arctic ice-free periods in the geological past (see Cross-chapter Box 2). Therefore, the impacts of Arctic sea ice disappearing on the Irish climate remain unclear.

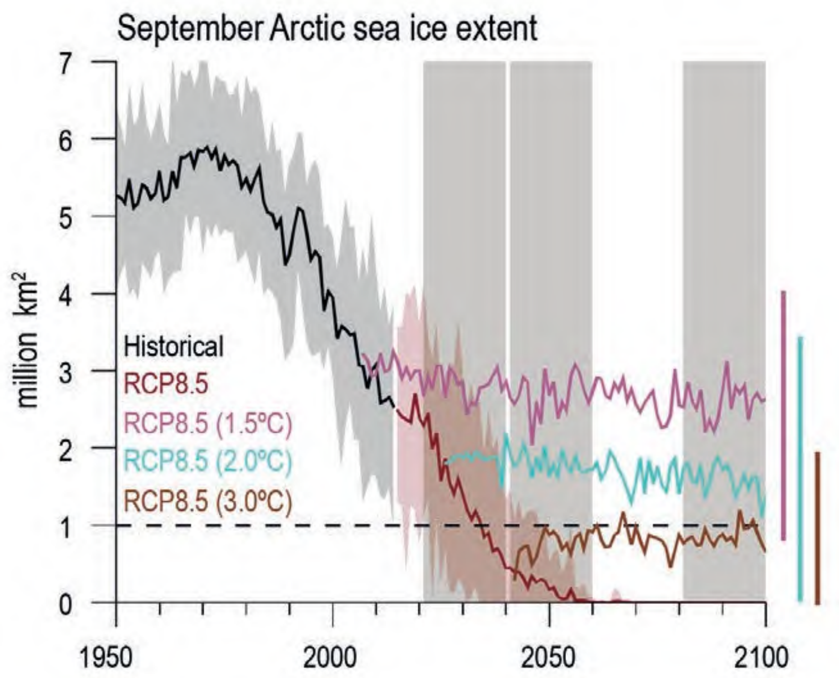


Figure 8.6 Arctic sea ice extent in September in a large initial condition ensemble of observationally constrained simulations of an ESM (CanESM2). The black and red curves are averages over 20 simulations following historical forcings to 2015 and late action extensions to 2100, respectively. The coloured curves are averages over 20 simulations each after global surface temperature has been stabilised at the indicated degree of global mean warming relative to 1850–1900. The bars to the right are the minimum to maximum ranges over 2081–2100 (Sigmond et al., 2018). The horizontal dashed line indicates a practically ice-free Arctic. Source: Lee et al. (2021; their figure 4.5).

8.3.4 Amazon and boreal forest dieback

Potential tipping elements also exist in large-scale ecosystems. Of most relevance is the potential for large-scale dieback of either tropical or temperate forests, which would radically alter large-scale surface characteristics and resulting climate locally, with potentially global implications, particularly through knock-on effects on the effectiveness of terrestrial carbon sinks (Canadell et al., 2021). Forests are vulnerable to tipping points induced by some combination of changes in mean climate (Scheffer et al., 2012; Zemp et al., 2017), changes in temperature and precipitation extremes (Scheffer et al., 2012; Pavlov, 2015; Zemp et al., 2017) and changes in fire activity (Staver et al., 2011; Lasslop et al., 2016).

The Amazon rainforest is a huge but weakening net CO_2 sink due to climate change and deforestation, and could already have changed from a carbon sink to a carbon source (Gatti et al., 2021). ESMs predict further temperature seasonal cycle amplitude increases, suggesting that drying will continue with future climate change, potentially triggering the system into tipping into an alternative state (Cox et al., 2013; Zemp et al., 2017). The possibility of Amazon dieback has long been debated. On the one hand, there is evidence to suggest a greater agreement among the latest CMIP6 generation of climate models, with c.70% of CMIP6 models with dynamic vegetation displaying localised abrupt areas of dieback over the Amazon region caused by elevated CO_2 levels alone (Parry et al., 2022). Furthermore, models may underplay the role of other stressors (Nobre et al., 2016). On the other hand, the models greatly simplify the complexity of tropical forest ecosystem dynamics and may underestimate resilience (Levine et al., 2016; Sackschewski et al., 2016) and adaptability to increased temperatures (Mercado et al., 2018). Pollen records from the past demonstrate that high diversity Amazonian forests have great antiquity over tens of millions of years and have survived the slow climate changes associated with past glacial–interglacial cycles and were resilient at times of past high GHG concentrations (Hoorn et al., 2010). The length of the dry season and the accompanied prolonged fire season (Fu et al., 2013) over southern Amazonia has increased in recent decades. Amazon dieback could lead to substantial net emissions of carbon. It is estimated that as much as 50PgC (where 1Pg = 1,015 tonnes (1Gt) of carbon)could be released from tropical forests per degree Celsius of warming (Cox et al., 2013; Wenzel et al., 2014). Further impacts of large-scale Amazon dieback would include changes in the global atmospheric water budget via a large-scale reduction in evapotranspiration. The changed surface characteristics of the savannah would fundamentally change energy partitioning across tropical South America, with implications for global circulation and thus climate even potentially as far afield as Ireland (Betts et al., 2008).

Huge swathes of the northern hemisphere mid-latitudes consist of forested lands. These forest ecosystems could be disrupted either directly by changes in climate (Scheffer et al., 2012) or indirectly via fire disturbance (Lasslop et al., 2016) or pests modified by climate changes (Flower and Gonzalez-Meler, 2015). Pine beetle infestations have already had a non-negligible impact in North American temperate and boreal forests facilitated by climate change (Audley et al., 2020; Sambaraju and Goodsman, 2021). Large-scale temperate forest dieback would have substantial implications for mid-latitude climates by altering the surface characteristics and exchanges of energy and water over a large area of the mid-latitudes. Both the magnitude and the nature of the changes experienced by Ireland would be dependent upon the location and nature of the mid-latitude forest dieback (Schnabel et al., 2022). Dieback may also be too simplistic a paradigm in that boreal forests may expand into prior areas of tundra and be replaced on their southern flank by temperate forests (Canadell et al., 2021).

8.3.5 Permafrost thaw

In the Arctic, large amounts of organic carbon are stored in permafrost ground that remains frozen throughout the year (Figure 8.7; Hugelius et al., 2014; Strauss et al., 2017; Mishra et al., 2021). The permafrost region has been a historic carbon sink over centuries to millennia (Loisel et al., 2014; Lindgren et al., 2018). Currently, though, thawing soils due to human-induced warming are losing carbon to the atmosphere (Hicks Pries et al., 2013). If significant areas of permafrost were to thaw as the climate warms, it could release CO_2 and CH_4 at rates capable of elevating concentrations by an additional 1ppm CO_2 per year and 10ppb CH_4 per year (compare to current rates of c.3ppm and 10ppb, respectively (section 1.2); Canadell et al., 2021). The volume of carbon stored in permafrost globally (1,460–1,600Pg) far exceeds the historical human emissions to date, so if all this stored carbon were released, substantial additional warming would occur. Based on high levels of agreement across CMIP6 and older model projections, fundamental process understanding and paleoclimate evidence, it is virtually certain that the permafrost extent and volume will shrink as global climate warms, releasing further heat-trapping GHGs into the atmosphere (Canadell et al., 2021; Fox-Kemper et al., 2021). The additional GHGs would exacerbate warming arising from human-caused GHG emissions, making the resulting climate changes more pronounced everywhere, including Ireland.

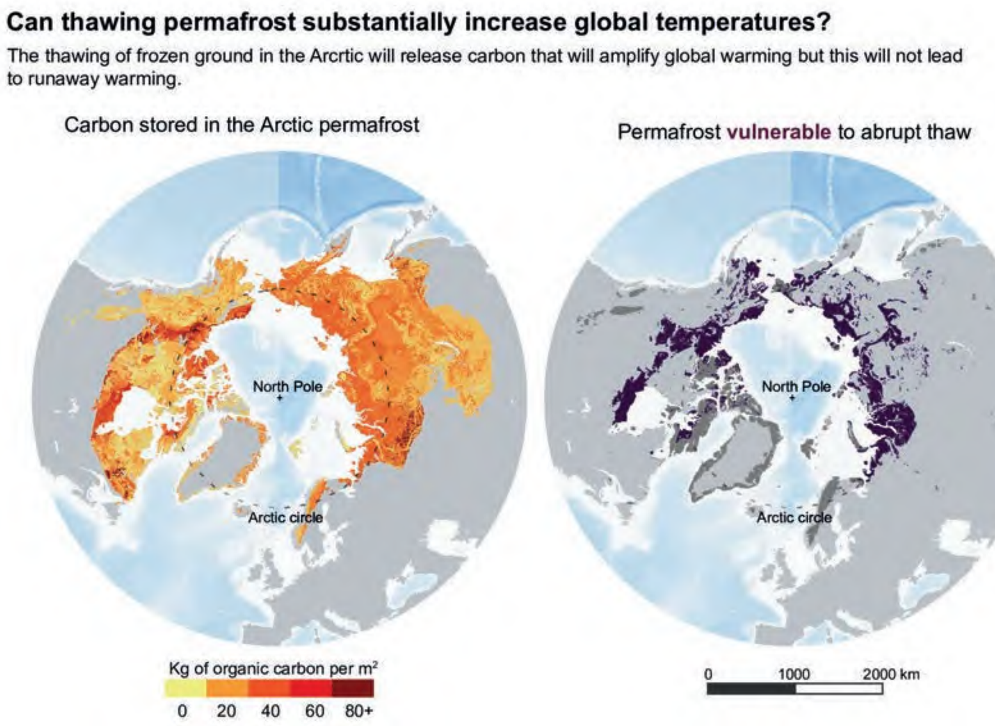


Figure 8.7 Permafrost thaw. The Arctic permafrost is a big pool of carbon that is sensitive to climate change. Quantity of carbon stored in the permafrost, to 3m depth (NCSCDv2 dataset) (left-hand panel) and area of permafrost vulnerable to abrupt thaw (Circumpolar Thermokarst Landscapes dataset) (right-hand panel). Source: Canadell et al. (2021; their FAQ 5.2 figure 1).

8.4 Volcanoes: the wildcard in the pack

Low-likelihood outcomes need not be limited to human-induced climate change and associated feedbacks. Our geological record contains self-evident large-scale climate perturbations, including, for example, large Earth impacts such as that which contributed to the demise of dinosaurs and led to the rise of mammals (Hildebrand et al., 1991). Such events are so rare and catastrophic that they are treated as exceedingly unlikely and not of immediate policy relevance. However, there are plausible natural events, such as a sequence within a relatively short order of highly explosive volcanic eruptions, which are sufficiently plausible to be worth due consideration (IPCC, 2021a).

Volcanic forcing is regarded as the dominant driver of forced variability in preindustrial surface air temperature (Schurer et al., 2013) (see section 1.2). Every few decades or so, there is an explosive volcanic eruption, larger or similar in size to Mount Pinatubo in the Philippines in June 1991, that throws out a climatically significant volume of particles to a great height (McCormick et al., 1995). The eruption of Tambora in Indonesia in 1815 cast a veil of aerosols over the Earth (Raible et al., 2016). A weather-wise extreme year followed, with frost destroying crops in Europe and North America. The year 1816 has been termed 'the year without a summer', with impacts causing great suffering across societies worldwide (Luterbacher and Pfister, 2015). Further back in time, the eruption of Samalas was associated with even greater impacts and hardship (Guillet et al., 2017). Proxy records show that large volcanic eruptions with the potential for substantial climate impacts occurred, on average, twice a century throughout the last 2,500 years, the most recent being Pinatubo in 1991 (Gulev et al., 2021). Ash layers from past volcanic eruptions are found in Irish peat deposits, demonstrating their extensive geographical impact (Kalliokoski et al., 2020). Typically, three in every four centuries have experienced at least one large explosive eruption (equivalent to Mount Pinatubo in 1991 or larger). During the 20th century, the volcanic aerosol burden was 14% lower than the average of the preceding 2,500 years, whereas the 13th century was among the most volcanically active, with four eruptions exceeding that of Mount Pinatubo in 1991 (Sigl et al., 2015).

Volcanic eruptions are a wildcard for future climate projections and are rarely included in simulations of future climate because eruptions are inherently unpredictable (Bethke et al., 2017). A future with higher volcanic activity than in the recent past would cause a 21st century future that was much more variable and challenging than one without such a sequence of eruptions (Bethke et al., 2017). This would increase the stress on ecosystems and society, as has been the case for past eruptions (Bethke et al., 2017). Short-term volcanic cooling will not mitigate long-term human-induced climate changes. Even the most extreme plausible volcanic activity in the 21st century causes little reduction in temperatures at the end of the century; it just makes the journey that much more extreme (Bethke et al., 2017).

In simulations of a single model with multiple plausible volcanic forcing futures (Bethke et al., 2017; Figure 8.8) there is:

- an increase in the frequency of extremely cold individual years;
- an increased likelihood of decades with negative global surface temperature trend (decades with negative global surface temperature trends become 50% more commonplace);
- later anthropogenic signal emergence (the mean time at which the signal of global warming emerges from the noise of natural climate variability is delayed almost everywhere); and
- a 10% overall reduction in global land monsoon precipitation and a 20% overall increase in the ensemble (group of models) spread (Mann et al., 2021).

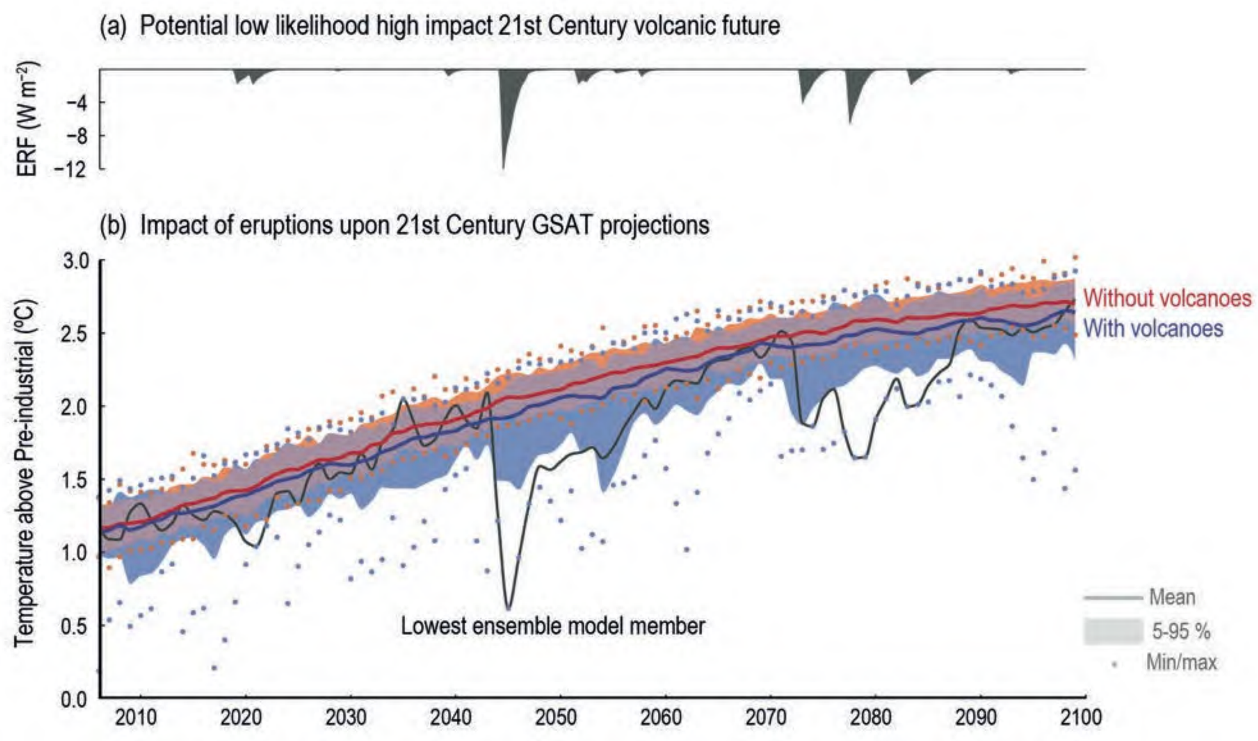


Figure 8.8 Volcanic impact. Panels (a) and (b) show the potential impact of volcanic eruption on future global temperature change. CMIP5 projections of possible 21st century futures under a Middle action scenario after a Samalas-magnitude volcanic eruption in 2044 are from Bethke et al. (2017). Source: Lee et al. (2021; their cross-volume box 4.1, figure 1).

8.5 Recommendations

8.1	Targeted studies using paleo-records may be able to elucidate upon the climate impacts of past periods when certain relevant tipping points were reached, such as AMOC shutdown or seasonally/perennially sea ice-free Arctic Ocean conditions. This requires investment in paleo-based research, including the identification of candidate sites for proxy-based analyses, target periods for investigation and the identification of proxies with sufficient chronological sequencing to distinguish slow processes from more rapid tipping behaviour. Such studies would inform critical regional and global reconstructions.
8.2	Efforts should be made to better understand and quantify the effects of both very high warming storylines and various important tipping points specifically on Irish climate. This will require the study of various global and regional models as well as various theoretical approaches.
8.3	Future downscaling simulations could regionalise projected changes in those tipping points and climate surprises for which relevant ESM simulations exist. For example, the ensemble of volcanic futures created by Bethke et al. (2017) could be downscaled to inform potential effects of uncertain volcanic futures.
8.4	There would be considerable benefits in undertaking targeted efforts to improve the representations of key processes related to potential tipping points of importance nationally, such as the AMOC and Arctic sea ice, in ESMs followed by downscaling of these results to better inform policymakers and decision makers.

Annex

Collated Recommendations

Introduction

This annex provides a compilation of all recommendations made within the chapters of this volume. The recommendations are for actions within the scope of the volume (other volumes contain recommendations within their respective scopes) and hence focus upon the national scientific research, infrastructures and expertise required to further our understanding of Ireland in a changing climate. Key overall thematic areas arise from this as follows.

1. Sustaining and enhancing Ireland's climate observational capabilities

There is a need to sustain and enhance national observational capabilities of our changing climate system providing a strong evidence base for decision making. This needs to be consistent with a sustained and strong national contribution to the Global Climate Observing System (GCOS), including of our waters within our exclusive economic zone and the broader North Atlantic. Substantial progress has been made, not least through the national GCOS committee. Much remains to be done, including the development of a strategic approach that is aligned with national needs and requirements. This should include enhanced participation in relevant European research infrastructures, including in the European Strategy Forum on Research Infrastructures (ESFRI) process, and related regional and global networks. The work of the national GCOS committee needs to be strengthened and sustained with adequate funding support for relevant agencies and institutions.

2. Enhanced provision and utilisation of past and current climate observations

Enhanced capacity and resources are required to enable better provision and utilisation of past and current observations to better understand Ireland's changing climate and its drivers. As scientists learn more about observations and new techniques and insights emerge, it is critical to periodically reassess understanding of historical and ongoing observations, reanalyse them and produce new and improved products and knowledge. This includes activities such as data rescue of historical holdings of various types not yet available in digitised form and better exploitation of space-based observations.

3. Sustaining and enhancing Ireland's climate modelling capability

There is a need for a sustained and enhanced modelling capability to provide a range of nationally relevant downscaled results, including contributions to the Coupled Model Intercomparison Project (CMIP) and EURO-CORDEX. This includes quantification and provision of uncertainty estimates in a usable manner via portals such as climateireland.ie, which should be maintained to promote and enable exploitation by stakeholders and users.

4. Scaling up support for strategic climate research activities

Substantial scientific uncertainties remain across the ocean, atmosphere and terrestrial domains that still need to be strategically and rigorously addressed. Supports through climate research programmes are needed that transcend short-term projects. This should enable capacity building through the training and retention of the excellent researchers necessary to address these cross- and trans-disciplinary challenges. Particularly important current uncertainties identified in the present volume include, but are not limited to: diurnal temperature changes, precipitation changes, changes in storminess and sea level changes.

5. Increasing Ireland's participation in climate-related European and international scientific activities

There is a need to increase participation in relevant European and international scientific activities to have a stronger contribution to and influence in the development of these activities. These provide expanded access to expertise, opportunities for collaboration, including on internationally funded projects, and learning and sharing of knowledge and best practices, which has important benefits in terms of provision of advice to policymakers. This includes participation in relevant European-level programmes such as the European Space Agency, Horizon Europe and Joint Programming Initiatives, and various research infrastructures. Internationally, participation should be sought in IPCC and Intergovernmental Science–Policy Platform on Biodiversity and Ecosystem Services (IPBES) reports and in relevant international activities such as those undertaken by the World Meteorological Organization and through its (co-sponsored) programmes, including the World Climate Research Programme and GCOS.

It is notable how often 'sustained' appears across the recommendations and in their summary above. This points to perhaps the single most fundamental issue to be addressed. We must recognise that the climate crisis is a long-term problem and plan accordingly by ensuring that infrastructure and expertise is adequately resourced for the long term in a manner that supports effective planning and decision making in the context of evolving understanding. This requires long-term commitments and focus in a coordinated manner across government and engaging with academia and the private sector alike.

Collated recommendations

1.1	Irish participation in IPCC reports should be more actively sought. In several other countries, the government actively tenders for nominations for every Special Report and Working Group report and nominates multiple individuals per report. Strong participation would ensure an Irish voice at the table as well as acting as an opportunity for significant career advancement and building of international research collaboration networks for Irish researchers. Sufficient support for authors needs to be put in place to enable relief from other duties. For those appointed coordinating lead authors, funding should be made available to support a full-time chapter scientist position, as is done by many other countries.
1.2	Much of the Mace Head research is funded through short-term competitive funding. While there is undoubtedly a role for such funding, it is imperative that the long-term monitoring capabilities (including necessary personnel) be given sustained and guaranteed funding support for this critical national contribution to European and global monitoring. This is even more important now that Mace Head is officially part of the Integrated Carbon Observation System Research Infrastructure.
1.3	Sustained and guaranteed support for both national supercomputing capability and modelling research is vital to underpin our national climate research ambitions. Producing ESM and RCM simulations is a continuous and long-term task that requires substantial expertise, high-performance computing and storage resources to run the models, analyse, package up and share the resulting large datasets. It is essential that climate modelling research and the national supercomputing centre (ICHEC) are adequately resourced into the future on a sustained basis in terms of both personnel and hardware.
2.1	It is key that Ireland plays its full part in understanding the changes in the global climate system. This requires investment in research capabilities that take a more global and regional perspective upon our changing climate system. Ireland should play its full part by partaking in relevant global bodies such as the IPCC, the World Climate Research Programme, the Global Climate Observing System (GCOS) and the Global Ocean Observing System, and at the EU level in relevant research infrastructures (such as ICOS, which Ireland recently formally joined) and pan-European projects. Researchers across academia and government agencies need to be encouraged and enabled to participate in such activities.
3.1	Met Éireann's long-term climatological stations must be maintained and developed, and the data continue to be made available to support monitoring of our changing climate. Periodic reprocessing using state-of-the-art techniques to assess quality control and homogeneity and create improved observationally based products, including spatially interpolated products, needs to be supported on a sustained basis.
3.2	The many environmental data records currently available in only hard copy or image format need to be rescued and digitised to enable exploitation. There are millions of observations that remain in hard copy or image format and are thus inaccessible for further research. Efforts are required to inventory, scan and rescue these records, which exist in a variety of public and private repositories; some of which predate Irish independence may rest in UK-based repositories. There is substantial potential to engage citizens in this effort, via either participatory citizen science projects or engagement as part of experiential learning techniques, the latter of which Irish researchers have pioneered in secondary and tertiary educational settings. Rescuing the records would greatly inform estimates of long-term historical changes.
3.3	It is imperative that the newly developed national station and gridded products for the 27 ETCCDI indices, currently in the process of finalisation by Met Éireann, be supported and maintained for the long term. These will complement the Europe-wide E-OBS product and will potentially in future benefit from access to additional data sources and improved local knowledge, leading to improved interpolation into data void regions.

3.4	To support climate services provision it is necessary to undertake additional climate model experiments to better understand the interplay of internal variability, model uncertainty, climate sensitivity and scenario choices in projections of future changes, particularly in extreme indices, which are sensitive to such choices. This requires careful experimental design to tease apart these sources of uncertainty, and may benefit from consideration of using ESMs run with very large ensembles to sample from, to drive the RCMs used in TRANSLATE in follow-on activities, including TRANSLATE-2 and the new national climate services programme.
3.5	Observed changes in the hottest night have exceeded those of the hottest day and have been greater in the west than the east. This is the opposite of projected behaviour in the TRANSLATE ensemble where it is projected that the hottest days will warm more than the hottest nights and changes will be greatest in the east. Further research is necessary to ascertain whether this reflects a probable change in behaviour of temperature extremes moving forwards, model limitations or residual observational homogeneity issues.
CCB.1	Multiple pre-Pleistocene fossil localities and sediment archives on the island of Ireland are amenable to reconstruction of paleotemperature and paleo-CO_2 using proxies, such as the inter-basaltic fossil-bearing sediments of Antrim and new Pleistocene interglacial sequences. Historically these fossil localities have not been studied with state-of-the-art paleoclimatic methods. Quantitative mean annual temperature estimates for these fossil localities could help to constrain biotic thresholds or tipping points and elucidate the nature of climatic transitions in Ireland's deep past.
CCB.2	Ireland's location in the north-east Atlantic makes it ideally placed for investigating the time course of changes in ocean and atmospheric circulation on climate and thus provides a sound basis for modelling the impact of possible changes in these systems today and in the future. Key archives that provide numerous proxies that are available to address this are the diversity of near-shore marine sediments in both shallow and deep water; extensive deep peat deposits; widespread lake deposits (including annually laminated lakes); a full Holocene tree ring record from bog oak and pine; and speleothems and written archives (c.1,200 years). A well-resourced and centralised repository of Irish paleoclimate and paleoenvironmental data would facilitate their integration across space and time towards this goal.
4.1	In situ precipitation measurement networks must be maintained and expanded in areas of poor coverage. Given the smaller spatial scales of precipitation variability, a denser network is required than for temperature. The new expanded radar network under procurement and deployment must be maintained for multiple decades to augment the *in situ* network.
4.2	There is considerable potential to create merged products from rain gauges, radar and satellites, building upon the strengths of each data type. Modern spatially complete field estimates can be used to train analyses to create physically plausible historical estimates of changes in historically unsampled regions. This requires sustained support for archiving, post-processing and reprocessing to maintain a long-term homogeneous product. There is particular value in looking at daily and sub-daily resolution precipitation records that have been underexploited to date.
4.3	There is a requirement for research on the impacts of ESM selection for downscaling of precipitation and precipitation indices and to quantify more comprehensively the uncertainty in precipitation projections for Ireland.
4.4	Further research on the geological and historical context for extreme precipitation events in Ireland and their impacts (floods and droughts) that occurred prior to instrumental records from a combination of paleo and documentary sources would be extremely useful for anticipating the impacts of future precipitation changes. Due care should be given to understanding the impacts of more recent human interventions in drainage and river course management when making inferences.

4.5	Changes in storminess and winds have not been able to be comprehensively assessed at this time. Further analysis of the quality and homogeneity of historical wind and pressure records, including the creation of gridded products, is required prior to their use in such an assessment. Work is also required to understand and appropriately analyse the projections arising from ESMs and the TRANSLATE project over Ireland. Work to bring these aspects in is technically feasible in the time frame of any subsequent assessment report.
5.1	Maintenance of coastal sensors and the national buoy network is essential for both national and global ocean monitoring. Ireland is also a member of the Euro-Argo programme and deploys Argo floats, which contribute to the global ocean monitoring network. Ireland's participation in such networks is crucial for gathering information on local and global ocean properties.
5.2	Currently, there is no long-term ocean current monitoring system being operated by Ireland. If such a system were to be put in place it would not only be key to understanding the seas around Ireland but also fill a large gap in the data for ocean currents in the North-east Atlantic. Such data would be extremely valuable for understanding the impacts of AMOC changes and variability in the Nordic and Atlantic seas.
5.3	Ongoing pCO_2 and related measurements around the Irish coast from observatories and research vessels are necessary to help us build up a clearer picture of how different regions of the Irish coastal and shelf waters are contributing to, and responding to, carbon uptake from the atmosphere.
5.4	It is important that the current network of tide gauges is maintained and coordinated so that it meets the need for reliable, relevant and up-to-date information on sea level variability and change around Ireland on a sustained basis.
5.5	It would be beneficial to support research to collect, collate and digitise historical tide gauge observations to enable the reconstruction of longer-term changes around our coasts to place modern measurements in an appropriate longer-term context.
6.1	A national operational event attribution capability is necessary to inform climate services and policymakers and raise public awareness of the impacts of climate change as they further develop. Such a capability could cooperate with similar European services and undertake analyses on international events in countries of strategic importance under Department of Foreign Affairs guidance.
6.2	There is a need to better study and understand the changing risks of compound events for Ireland. This is likely to require additional simulations to sample plausible future climates sufficiently to identify the changing risk of such rare events.
7.1	Consistent with global accounting, national GHG emissions accounting is most uncertain in the LULUCF sector. There is a need to improve estimates of stocks and flows nationally as a contribution to global understanding. This will become increasingly critical in the coming decades in terms of verifying whether net zero emissions targets have been reached. Sustained investments in infrastructure and research are required to close this gap in understanding.
7.2	An all-island approach to ecosystems and land use is required to both monitor and effectively plan for climate change impacts on biodiversity in Ireland. Cross-border monitoring of ecosystems and biodiversity and the sharing of information and data is necessary to fully capture the effects of climate change on Ireland's natural landscape. Citizen science efforts in Ireland have been an excellent example of this and should be maintained.
7.3	Phenological monitoring should be prioritised and maintained to help inform practices that will prevent maladaptation, support mitigation and determine the impact of climate change on interactions between, for example, plants, birds and insects. Future maintenance and coordination of citizen science projects, data collections and phenological equipment, in addition to liaison with recorders at the international phenological gardens in Ireland, require continued support. It would also be beneficial to coordinate phenological activities at the national level and publish phenological observations in an open and easily accessible format at a central site.

7.4	Further research is required in species distribution modelling under future climate change scenarios. This would improve our understanding in predicting species' ranges under varying temperature and precipitation scenarios, the complexity of their interactions with other species, as well as the likely introduction of non-native species to the island. With an increased likelihood of shifting species distributions, it is important that we closely monitor and understand the impacts of invasive flora and fauna and both the nature and consequences of their interactions with native species.
7.5	Prioritising the restoration of our internationally important habitats, which are also in decline, would halt the loss of biodiversity and ecosystem services from these ecologically significant areas. For example, a national peatland restoration strategy would provide an appropriate framework to determine the best return for resources in terms of peatland rewetting and restoration for climate and other co-benefits.
7.6	Further research is required into the carbon dynamics of peatlands after rewetting. This would provide important insights into the mitigation potential of rewetted peatlands in Ireland, which is currently uncertain and understudied. Further research here would be greatly beneficial to assessing both when and where such mitigation initiatives would have the greatest impact in Ireland.
8.1	Targeted studies using paleo-records may be able to elucidate upon the climate impacts of past periods when certain relevant tipping points were reached, such as AMOC shutdown or seasonally/perennially sea ice-free Arctic Ocean conditions. This requires investment in paleo-based research, including the identification of candidate sites for proxy-based analyses, target periods for investigation and the identification of proxies with sufficient chronological sequencing to distinguish slow processes from more rapid tipping behaviour. Such studies would inform critical regional and global reconstructions.
8.2	Efforts should be made to better understand and quantify the effects of both very high warming storylines and various important tipping points specifically on Irish climate. This will require the study of various global and regional models as well as various theoretical approaches.
8.3	Future downscaling simulations could regionalise projected changes in those tipping points and climate surprises for which relevant ESM simulations exist. For example, the ensemble of volcanic futures created by Bethke et al. (2017) could be downscaled to inform potential effects of uncertain volcanic futures.
8.4	There would be considerable benefits in undertaking targeted efforts to improve the representations of key processes related to potential tipping points of importance nationally, such as the AMOC and Arctic sea ice, in ESMs followed by downscaling of these results to better inform policymakers and decision makers.

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Abbreviations and symbols

AMOC	Atlantic Meridional Overturning Circulation
AMV	Atlantic Multi-decadal Variability
AR6	Sixth Assessment Report
ASH	aragonite saturation horizon
CDR	carbon dioxide removal
CFC	chlorofluorocarbon
CH_4	methane
CMIP	Coupled Model Intercomparison Project
CO_2	carbon dioxide
DAFM	Department of Agriculture, Food and the Marine
ECS	Equilibrium Climate Sensitivity
ECV	essential climate variable
ERF	effective radiative forcing
ESM	Earth System Model
ESFRI	European Strategy Forum on Research Infrastructures
ETCCDI	Expert Team on Climate Change Detection and Indices
EURO-CORDEX	European Coordinated Regional Climate Downscaling Experiment
GCOS	Global Climate Observing System
GHG	greenhouse gas
GMSL	global mean sea level
GrIS	Greenland ice sheet
GWP	Global Warming Potential
HCFC	hydrochlorofluorocarbon
HFC	hydrofluorocarbon
HNV	high nature value
IAM	integrated assessment model
ICHEC	Irish Centre for High-End Computing
ICOS	Integrated Carbon Observation System
IPCC	Intergovernmental Panel on Climate Change
LULUCF	land use, land use change and forestry
N_2O	nitrous oxide

NAM	Northern Annular Mode
NAO	North Atlantic Oscillation
OHC	ocean heat content
pCO_2	partial pressure of CO_2
ppb	parts per billion
ppm	parts per million
QDM	quantile delta mapping
RCB	Remaining Carbon Budget
RCM	regional climate model
RCP	representative concentration pathway
SLCF	short-lived climate forcer
SSP	shared socioeconomic pathway
SST	sea surface temperature
TCRE	transient climate response to cumulative CO_2 emission
UTC	Coordinated Universal Time
WAIS	West Antarctic Ice Sheet
WG	working group
WMO	World Meteorological Organization

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