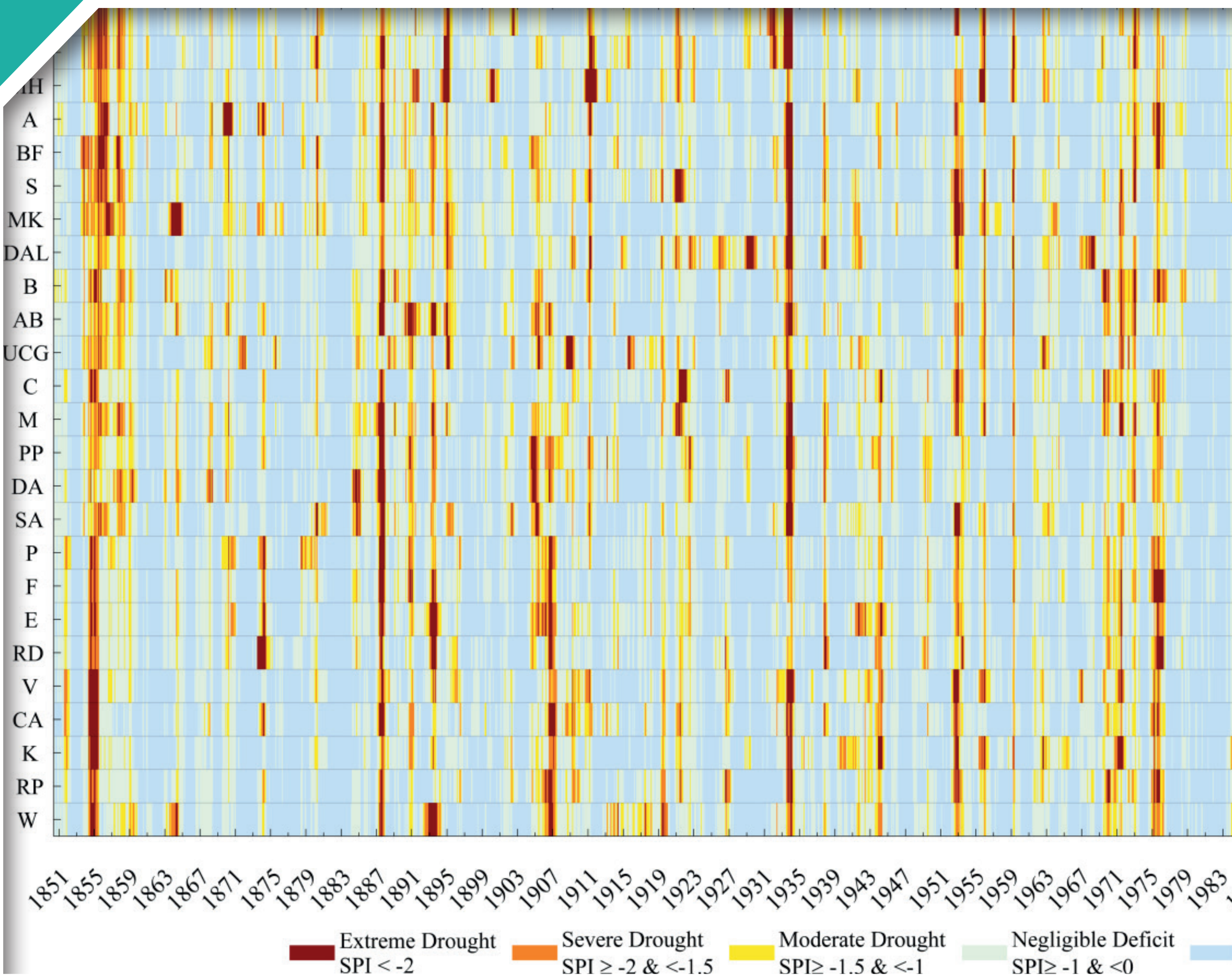
Report No. **277**

epa Research
Climate - Water - Sustainability
Identifying pressures • Informing policy • Developing solutions

Irish Climate Futures: Data for Decision-making

Authors: Conor Murphy, Ciaran Broderick, Tom K.R. Matthews, Simon Noone and Ciara Ryan



www.epa.ie

Rialtas na hÉireann
Government of Ireland

ENVIRONMENTAL PROTECTION AGENCY
The Environmental Protection Agency (EPA) is responsible for protecting and improving the environment as a valuable asset for the people of Ireland. We are committed to protecting people and the environment from the harmful effects of radiation and pollution.

The work of the EPA can be divided into three main areas:

Regulation: *We implement effective regulation and environmental compliance systems to deliver good environmental outcomes and target those who don't comply.*

Knowledge: *We provide high quality, targeted and timely environmental data, information and assessment to inform decision making at all levels.*

Advocacy: *We work with others to advocate for a clean, productive and well protected environment and for sustainable environmental behaviour.*

Our Responsibilities

Licensing
We regulate the following activities so that they do not endanger human health or harm the environment:
- waste facilities *(e.g. landfills, incinerators, waste transfer stations)*;
- large scale industrial activities (*e.g. pharmaceutical, cement manufacturing, power plants)*;
- intensive agriculture *(e.g. pigs, poultry)*;
- the contained use and controlled release of Genetically Modified Organisms *(GMOs)*;
- sources of ionising radiation *(e.g. x-ray and radiotherapy equipment, industrial sources)*;
- large petrol storage facilities;
- waste water discharges;
- dumping at sea activities.

National Environmental Enforcement
- Conducting an annual programme of audits and inspections of EPA licensed facilities.
- Overseeing local authorities' environmental protection responsibilities.
- Supervising the supply of drinking water by public water suppliers.
- Working with local authorities and other agencies to tackle environmental crime by co-ordinating a national enforcement network, targeting offenders and overseeing remediation.
- Enforcing Regulations such as Waste Electrical and Electronic Equipment (WEEE), Restriction of Hazardous Substances (RoHS) and substances that deplete the ozone layer.
- Prosecuting those who flout environmental law and damage the environment.

Water Management
- Monitoring and reporting on the quality of rivers, lakes, transitional and coastal waters of Ireland and groundwaters; measuring water levels and river flows.
- National coordination and oversight of the Water Framework Directive.
- Monitoring and reporting on Bathing Water Quality.

Monitoring, Analysing and Reporting on the Environment
- Monitoring air quality and implementing the EU Clean Air for Europe (CAFÉ) Directive.
- Independent reporting to inform decision making by national and local government *(e.g. periodic reporting on the State of Ireland's Environment and Indicator Reports)*.

Regulating Ireland's Greenhouse Gas Emissions
- Preparing Ireland's greenhouse gas inventories and projections.
- Implementing the Emissions Trading Directive, for over 100 of the largest producers of carbon dioxide in Ireland.

Environmental Research and Development
- Funding environmental research to identify pressures, inform policy and provide solutions in the areas of climate, water and sustainability.

Strategic Environmental Assessment
- Assessing the impact of proposed plans and programmes on the Irish environment *(e.g. major development plans)*.

Radiological Protection
- Monitoring radiation levels, assessing exposure of people in Ireland to ionising radiation.
- Assisting in developing national plans for emergencies arising from nuclear accidents.
- Monitoring developments abroad relating to nuclear installations and radiological safety.
- Providing, or overseeing the provision of, specialist radiation protection services.

Guidance, Accessible Information and Education
- Providing advice and guidance to industry and the public on environmental and radiological protection topics.
- Providing timely and easily accessible environmental information to encourage public participation in environmental decision-making *(e.g. My Local Environment, Radon Maps)*.
- Advising Government on matters relating to radiological safety and emergency response.
- Developing a National Hazardous Waste Management Plan to prevent and manage hazardous waste.

Awareness Raising and Behavioural Change
- Generating greater environmental awareness and influencing positive behavioural change by supporting businesses, communities and householders to become more resource efficient.
- Promoting radon testing in homes and workplaces and encouraging remediation where necessary.

Management and structure of the EPA
The EPA is managed by a full time Board, consisting of a Director General and five Directors. The work is carried out across five Offices:
- Office of Environmental Sustainability
- Office of Environmental Enforcement
- Office of Evidence and Assessment
- Office of Radiation Protection and Environmental Monitoring
- Office of Communications and Corporate Services

The EPA is assisted by an Advisory Committee of twelve members who meet regularly to discuss issues of concern and provide advice to the Board.

EPA RESEARCH PROGRAMME 2014–2020

Irish Climate Futures: Data for Decision-making

(2014-CCRP-MS-16)

EPA Research Report

Prepared for the Environmental Protection Agency

by

Maynooth University

Authors:

Conor Murphy, Ciaran Broderick, Tom K.R. Matthews, Simon Noone and Ciara Ryan

ENVIRONMENTAL PROTECTION AGENCY
An Ghníomhaireacht um Chaomhnú Comhshaoil
PO Box 3000, Johnstown Castle, Co. Wexford, Ireland

Telephone: +353 53 916 0600 Fax: +353 53 916 0699
Email: info@epa.ie Website: www.epa.ie

ACKNOWLEDGEMENTS

This report is published as part of the EPA Research Programme 2014–2020. The EPA Research Programme is a Government of Ireland initiative funded by the Department of Communications, Climate Action and Environment. It is administered by the Environmental Protection Agency, which has the statutory function of co-ordinating and promoting environmental research.

The authors would like to acknowledge the expert input of many people, including members of the project steering committee, namely Margaret Desmond, Philip O'Brien and Professor Robert Wilby of Loughborough University for their advice throughout. Professor Christel Prudhomme of the Centre for Ecology and Hydrology and Professor Peter Thorne of ICARUS, Maynooth University, together with Mary Curley and Seamus Walsh of Met Éireann, also offered valuable feedback. Thanks are also extended to Karen O'Regan for assistance with editing and Margaret Desmond and Marc Kierans for their patient project management.

Cover image: DNA of Irish drought (image based on Figure 2.2 from https://rmets.onlinelibrary.wiley.com/doi/epdf/10.1002/joc.4999, with permission of the Royal Meteorological Society. © 2017 Royal Meteorological Society).

DISCLAIMER

The EPA Research Programme addresses the need for research in Ireland to inform policymakers and other stakeholders on a range of questions in relation to environmental protection. These reports are intended as contributions to the necessary debate on the protection of the environment.

EPA RESEARCH PROGRAMME 2014–2020
Published by the Environmental Protection Agency, Ireland

ISBN: 978-1-84095-832-4 June 2019

Price: Free Online version

Project Partners

Dr Conor Murphy
Irish Climate Analysis and Research UnitS (ICARUS)
Department of Geography
Maynooth University
Maynooth
Ireland
Tel.: +353 1 708 3494
Email: conor.murphy@mu.ie

Dr Ciaran Broderick
Irish Climate Analysis and Research UnitS (ICARUS)
Department of Geography
Maynooth University
Maynooth
Ireland

Dr Tom K.R. Matthews
School of Natural Sciences and Psychology
Liverpool John Moores University
Liverpool
UK

Dr Simon Noone
Irish Climate Analysis and Research UnitS (ICARUS)
Department of Geography
Maynooth University
Maynooth
Ireland

Ms Ciara Ryan
Irish Climate Analysis and Research UnitS (ICARUS)
Department of Geography
Maynooth University
Maynooth
Ireland
and
Met Éireann
Dublin 9
Ireland

Contents

List of Figures

List of Tables

Executive Summary

The realisation of a climate-resilient Ireland over the coming decades depends on decisions taken at all scales to adapt to climate change. Good decisions depend on the types and quality of information used to inform planning. Building resilience requires the diversification of the types of information used for understanding past and future climate variability and change, and a better understanding of the range of plausible changes. This work seeks to develop and expand the types of data available for decision-making. The following sections detail the key outcomes from this work.

Historical Data for Decision-making

Historical climate records that take full advantage of the rich history of weather observing on the island of Ireland offer a valuable approach to meeting the challenges of adaption. Ranges of climate variability and extreme events within historical records can be useful for discovering vulnerabilities. They also assist in contextualising recent extremes, tracking emerging signals of change and ground-truthing climate model projections. We present a long-term, quality-assured Island of Ireland Precipitation (IIP) network comprising 25 stations and a composite series for the island covering the period 1850–2015. These records reveal increasing winter and decreasing summer rainfall over this period. Analysis of drought from these long records shows that Ireland is drought prone, but recent decades are unrepresentative of the longer term drought climatology. During the years 1850–2015, seven major drought-rich periods were identified, with an island-wide fingerprint: 1854–60, 1884–96, 1904–12, 1921–23, 1932–35, 1952–54 and 1969–77. These events resulted in social and economic disruption and exhibited substantial diversity in terms of their development, severity and spatial occurrence. The resulting drought catalogue challenges prevailing perceptions about drought in Ireland while strengthening the evidence base for future drought and water resource planning across the island. Finally, we present a continuous monthly rainfall series representing the island of Ireland from 1711 to present. The series reveals considerable variability in Irish rainfall climatology. Remarkably wet winters are found during the 1730s, with the driest winter decade coinciding with the Laki eruption of 1783–84. Unusually wet summers occurred in the 1750s, consistent with proxy (tree ring) reconstructions of summer precipitation in the region. In the annual series, the most recent decade (2006–2015) is found to be the wettest in over 300 years. The new series reveals multi-centennial trends in winter (increasing) and summer (decreasing) precipitation. Importantly, we show that the years 1940 to present – the period with the most widely available digitised records for informing decision-making – can be unrepresentative of long-term changes in all seasons, highlighting the importance of long-term records.

Irish Climate Futures: A Framework for Climate Services

Projections of climate change from global climate models are an important tool in the armoury for adaptation. Given the increasing demand for climate change projections for adaptation, a key challenge is the provision of climate information in a way that facilitates the needs of end users charged with developing adaptation strategies. In an attempt to meet these challenges, we developed the Irish Climate Futures (ICF) framework. The ICF framework offers flexibility in assessing future climate risks with climate model projections and tailors information (basic, intermediate and advanced levels) to user needs. We show how the framework can be used to develop simple narrative descriptions of change that represent plausible ranges of change from the Coupled Model Intercomparison Model Phase 5 (CMIP5) ensemble of global climate models, and how the framework can be used to stress test system vulnerability or adaptation options, by allowing users to determine ranges of change in temperature and precipitation for exploring their own system's responses. The framework can also be used for impact assessment and is extendable, using a weather generator, to explore climate change signals in combination with natural variability, at monthly to daily timescales. Although this work is limited to developing a prototype exemplar of the framework, the workflow is designed and implemented in such a way that it is extendable to other locations, climate variables and units of analysis (grids, catchments, etc.). The prototype version of the framework can be viewed at https://mu-icarus.shinyapps.io/climate_futures_dashboard_18012018/

Changing Seasonal Extremes

We use historical data and information from the ICF framework to show how the datasets that we develop can be used to inform adaptation planning by examining memorable seasonal extremes. Direct personal experience of extreme weather events results in greater public engagement and policy response to climate change. Based on this premise, we present a set of future climate scenarios for Ireland, communicated in the context of recent, observed extremes. Specifically, we examine the changing likelihood of extreme seasonal conditions in the long-term observational record and explore how frequently such extremes might occur in a changed Irish climate, according to the latest model projections. Over the period 1900–2014, records suggest a greater than 50-fold increase in the likelihood of the warmest recorded summer (1995), whereas the likelihood of the wettest winter (1994/95) and driest summer (1995) has doubled since 1850. The most severe end-of-century climate model projections suggest that summers as cool as that in 1995 (currently the hottest summer on record) may occur only once every ~7 years, whereas winters as wet as that in 1994/95 and summers as dry as that in 1995 may increase by factors of ~8 and ~10, respectively. It is hoped that framing future climate scenarios in the context of extremes from living memory will help communicate the scale of the challenge that climate change presents, and in doing so bridge the gap between climate scientists and wider society.

Rainfall Extremes in a Changing Climate

Finally, we evaluate changes in extreme rainfall with future climate change by using the largest ensemble of regional climate models available [Coordinated Regional Climate Downscaling Experiment (CORDEX) ensemble]. Model performance is assessed against observed daily precipitation (1976–2005) and future changes are examined for mid- and end century. Sixteen different indices of rainfall extremes are examined, representing changes in the duration, frequency, mean and intensity of summer and winter precipitation. It is shown that no single model uniformly performs best for all seasons, highlighting the importance of using large ensembles of climate models. Deficiencies found that were common to the majority of CORDEX models include the underestimation of wet (winter) and dry (summer and winter) spell lengths and the underestimation of the spatial variability of most rainfall indices, particularly for summer. Projections indicate an amplification of the precipitation regime, with wetter winters and drier summers occurring. Changes in rainfall extremes are likely to be experienced right across the island, highlighting the strength of the climate signal spatially. Most models project significant increases in the intensity of winter precipitation, accompanied by increases in the number of heavy events (e.g. > 20 mm/day). Despite probable reductions in average receipts, increases in the intensity of summer rainfall are suggested, although there is greater uncertainty associated with the magnitude and significance of changes for this season.

1 Introduction

1.1 The Imperative of Adaptation

That the world has warmed since the 19th century is unequivocal. Evidence for warming includes changes in surface, atmospheric and oceanic temperatures; glaciers; snow cover; sea ice; and sea level and atmospheric water vapour. We know that humans have been the main cause of this warming through emissions of greenhouse gases. We also know that continued emissions of greenhouse gases will cause further warming and changes in all components of the climate system, and at all scales from local to global. How much warming will be experienced over the course of this century depends on future emissions of greenhouse gases. If we continue on a business-as-usual course, Earth's average temperature is likely to increase by between 2.6°C and 4.8°C above today's levels, with associated increases in extreme events and sea level rise. For Ireland, such changes would probably mean more frequent wet winters, dry summers and hot summers, which would pose challenges for water and flood risk management, agriculture and tourism.

Recent national-scale extreme events, from the winter storms of 2013/14 to the flooding of the Shannon and other catchments associated with Storm Desmond, serve to highlight Ireland's vulnerability to extreme events. Much work has been completed by different research groups from Irish universities and Met Éireann on exploring future impacts. These works show that we are likely to experience wetter winters, drier summers and more frequent extreme weather events, with associated implications across multiple sectors.

In responding to climate change there are two broad policy options: mitigation and adaptation. Mitigation concerns treating the cause of the problem, adaptation concerns making changes to avoid the adverse impacts of a changing climate. Mitigation is about reducing our emissions of greenhouse gases to limit the amount of warming that happens over the coming decades. Ultimately, mitigation means reducing our dependence on fossil fuels in all aspects of our lives. All actors, from individuals, households, businesses and governments to the international community and international corporations, have an important role to play in mitigation.

Adaptation recognises that some degree of climate change will happen and revolves around making plans to reduce the possible negative implications of climate change and making the most of any opportunities that may arise. In essence, this means adjusting the systems and services on which we depend to accommodate changes in climate. Too often mitigation and adaptation are treated as independent strategies; in reality, even if we could somehow stop all greenhouse gas emissions right now, some degree of warming will still result. Additionally, even at 1.5°C and 2°C warming, impacts will still be felt. Therefore, it is critical that society adapts to future impacts of climate change.

1.2 Climate Data for Adaptation

The need to adapt to climate change has meant that there is now a demand from a variety of different users and sectors for actionable climate information or climate services. For instance, in the Irish context, Gray (2016) provides guidance for local authorities for developing and implementing adaptation plans. In particular, climate information is required for (1) assessing the current adaptation baseline (which involves identifying extremes in the historical record and examining vulnerabilities/impacts from these); (2) assessing future climate risks; and (3) identifying, assessing and prioritising adaptation options.

Key challenges are confronted in implementing these tasks, particularly in the kinds of climate data that are required for implementation. This research aims to address these challenges. In constructing adaptation baselines, long records of key climate variables that extend beyond the last 20–30 years are often lacking. This is a key gap as knowledge of the range of variability and change, together with historical extreme events, is critical for contextualising recent extremes, informing discussions around vulnerability and identifying emerging changes and trends. It is also critical that such records are quality assured and fit for purpose. In addition, given that the climate change signal at the local scale will probably remain within the bounds of natural variability until at least mid-century, the availability of long-term quality-assured data for key climate variables, which capture the range of natural variability, can also serve an important function in stress testing adaptation decisions against the range of historically experienced conditions.

Climate model projections are also an important tool in the armoury of adaptation planning and decision-making. However, they are often used without due acknowledgement of their challenges and limitations. Projections of future climate change are inherently uncertain, which has been a major obstacle in adaptation planning. Uncertainties in projections of climate variables are associated with future emissions pathways, model structure and parameterisation, initialisation, boundary conditions and downscaling techniques (e.g. Dobler *et al.*, 2012). In addition, there is now a multitude of global climate model outputs and results available for application at different scales using various downscaling techniques. Such factors give rise to a model selection issue (Whetton *et al.*, 2012). Using a small set of best-performing models or a "best-guess" assessment is a less than ideal solution and can result in poor and even dangerous adaptation decisions. There is currently no consensus around robust methods for selecting a few "best" models (Knutti *et al.*, 2010). Good model performance for past and current climate is no guarantee of such performance under future, changed conditions (Murphy *et al.*, 2011), whereas applying model weights tends to focus on specific impacts and is complex to implement and interpret.

1.3 Aims of the Report

With the above challenges in mind, this report has the following aims:

1. To provide long-term quality-assured data for key climate variables, particularly precipitation, for creating adaptation baselines and for exploring vulnerability to the range of climate variability and extremes across multiple sectors.
2. To present a framework and develop its prototype implementation to better use climate change projections for supporting adaptation decisions. This framework – the Irish Climate Futures (ICF) framework – is designed to take advantage of the most up-to-date climate model ensembles, with multiple end users in mind, and climate information is tailored to different uses.
3. To demonstrate how historical data and climate change projections from (1) and (2) above can be used to understand how the frequency of past memorable extremes has changed in the historical record and how these extremes are likely to change in frequency in future.
4. To examine changes in daily rainfall extremes from a large ensemble of regional climate model (RCM) projections for Ireland.

1.4 Structure of the Report

The remainder of the report is structured as follows. Chapter 2 presents work on developing long-term, quality-assured records of precipitation from across the island of Ireland for use in climate change planning. The chapter presents key insights from the Island of Ireland Precipitation (IIP) network – a homogeneous network of 25 monthly rainfall stations from across the island with data from 1850 to 2016. The IIP network is interrogated to identify historical droughts and the key findings from this work are reported. The chapter also highlights the island of Ireland 1711 monthly rainfall series, which represents monthly and seasonal rainfall variability for the island dating back to 1711. This represents one of the longest continuous rainfall records anywhere in the world.

Chapter 3 introduces the ICF Framework, a proposed new approach to delivering climate change projections for adaptation planning. The ICF Framework exploits the opportunities presented by large ensembles of climate models, particularly the Coupled Model Intercomparison Project (CMIP) Phase 5 (CMIP5), which underpins the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (Taylor *et al.*, 2012). The framework is designed to be transparent to uncertainties in future climate projections, while at the same time providing clear and easily communicable information to different end users, classified as basic, intermediate and advanced.

Chapter 4 presents a case study of how historical data and basic-level information from the ICF Framework can be used to inform adaptation planning by examining memorable seasonal extremes. Direct personal experience of extreme weather events results in greater public engagement and policy response to climate change. Based on this premise, we present a set of future climate scenarios for Ireland communicated in the context of recent, observed extremes. Specifically, we examine the changing likelihood of extreme seasonal conditions in the long-term observational record and explore how frequently such extremes might occur in a changed Irish climate according to the latest model projections. Over the period 1900–2014, records suggest a greater than 50-fold increase in the likelihood of the warmest recorded summer (1995), whereas the likelihood of the wettest winter (1994/95) and driest summer (1995) have both doubled since 1850. The most severe end-of-century climate model projections suggest that summers as cool as that in 1995 (currently the hottest summer on record) may occur only once every ~7 years, whereas winters as wet as that in 1994/95 and summers as dry as that in 1995 may increase by factors of ~8 and ~10, respectively. Contrary to previous research, we find no evidence for increased wintertime storminess as the Irish climate warms, but caution that this conclusion may be an artefact of the metric employed. It is hoped that framing future climate scenarios in the context of extremes from living memory will help communicate the scale of the challenge that climate change presents, and in doing so bridge the gap between climate scientists and the wider society.

Chapter 5 moves on to explore changes in extreme rainfall events with climate change over the course of the century. Given that global climate models do not operate at a scale that is sufficient to resolve extreme rainfall events, we analyse the Coordinated Regional Climate Downscaling Experiment (CORDEX) ensemble of RCMs. Specifically, CORDEX comprises a 19-member ensemble derived using 13 RCMs run at a ~11 km resolution and forced using one or more of six different CMIP5 global climate models (GCMs). It thus provides the most complete analysis of daily climate extremes undertaken for Ireland to date. Outputs from the entire ensemble are evaluated using gridded observed daily precipitation (1976–2005) and future changes are examined for two 30-year periods (mid-century: 2040–69; late century: 2070–99) for two representative concentration pathways (RCPs 4.5 and 8.5). A total of 16 different indices of rainfall extremes are examined, representing changes in the duration, frequency, mean and intensity of summer and winter precipitation.

Finally, Chapter 6 provides key conclusions from across the report and distils key recommendations for future work, in terms of both addressing limitations of the work presented here and advancing new and better approaches for providing climate data for decision-making.

2 Historical Data for Decision-making

2.1 Introduction

Assembling high-quality long-term records of key climate variables is a critical but often laborious task. It is also an essential activity if we are to have the robust evidence basis from which to make smart, climate-ready decisions. There has been a recent focus by the climate science community on the collection and refinement of observational evidence for climate change through historical global temperature records extending back to the mid-19th century and beyond. There is now a growing realisation that improvements in the quantity, quality and resolution of instrumental and documentary historical observations and proxy/palaeo climate data, together with developments in both reconstruction methodologies and dynamical historical reanalyses, can provide new baselines for global and regional weather and climate. The reconstruction of regionally specific historical extreme weather events and investigations of the social responses to these events are of crucial significance to assess how different communities in different contexts might be affected by, and respond to, future events and to understand the nature of the events that might take place in the future. Historical data rescue, climate reconstruction and the compilation of climate databases have the potential to assist immensely in understanding past climate events and increasing the information base for managing future climate risk (McGregor, 2015).

In this chapter an overview is given of the work undertaken to establish and quality assure long-term records of key climate variables for Ireland. In each case a summary of the relevant dataset and how it was produced is given, together with a link to where the data can be obtained and how they might be used in decision-making for adaptation. The interested reader is encouraged to access these publications when full details are provided.

2.2 Island of Ireland Precipitation Network

Long-term precipitation series are critical for understanding emerging changes to the hydrological cycle. Noone *et al*. (2016) constructed a homogenised IIP network comprising 25 stations and a composite series covering the period 1850–2010 (IoI_1850), providing the second-longest regional precipitation archive in the British–Irish Isles. The location of stations included in the dataset is provided in Figure 2.1. The availability of long-term records was expanded through the digitisation and transcription of monthly records held in paper form in the archives of Met Éireann. All metadata for the 25 rainfall stations across the island were also collated, including details on station location and moves, corrections applied to the data and notes made by the original observers.

Statistical homogenisation procedures were applied to the data to identify any inconsistencies and to correct for them by scrutinising collated metadata. The homogenisation process was also used to extend all series to a common start year of 1850. A total of 25 breakpoints were detected across 14 stations and the majority ($n=20$) are corroborated by metadata. Assessment of variability and change in homogenised and extended precipitation records reveals positive (winter) and negative (summer) trends. Trends in records covering the typical period of digitisation (1941 onwards) are not always representative of longer records. Furthermore, trends in post-homogenisation series change magnitude and even direction at some stations, emphasising the importance of data quality to trend interpretation. Although cautionary flags are raised for some series, confidence in the derived network is high given the attention paid to the metadata, the coherence of behaviour across the network and the consistency of findings with those of other long-term climatic series, such as England and Wales precipitation.

The full paper detailing the construction of the IIP network is published in the *International Journal of Climatology* (Noone *et al*., 2016). Data for each of the stations in the IIP network, together with a composite series representing the island of Ireland, are available from https://www.met.ie/news/display.asp?ID=337. Since its initial publication, the IIP network and composite series representing the entire island have been updated to 2016 and have proven very valuable

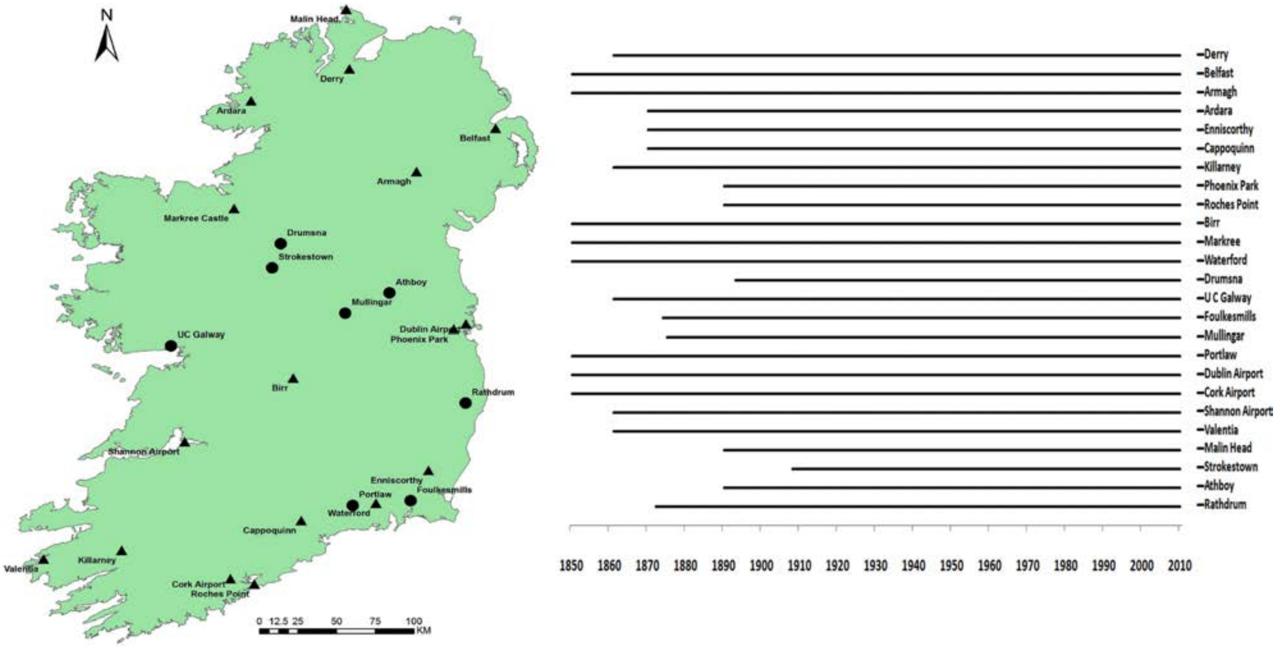


Figure 2.1. Location of and updated record length (before extension to common start of 1850) for 25 stations used in the construction of the IIP network.

in contextualising recent extremes such as the wet December of 2015 (McCarthy *et al*., 2016), together with exploring the changing nature of precipitation (Matthews *et al*., 2016; see also case study in Chapter 4) and exploring the nature of historical drought events.

Take-home messages from the IIP network are as follows:

- Trends in shorter records, even those available back to the 1940s, are not always representative of long-term changes, as evidenced from the IIP network.
- The long-term trend from 1850 to the present is towards wetter winters and drier summers.
- The IIP network offers a high-quality dataset for contextualising recent extremes and exploring the nature of past wet and dry months, seasons and years.
- Local planners can easily access individual stations to examine past extremes and variability.

2.3 Island of Ireland Drought Catalogue

Using the homogenised data from the IIP network, Noone *et al*. (2017) compiled an historical drought catalogue for Ireland from 1850 to 2015 and extended this to 1766 using reconstructed precipitation series. Drought conditions were identified by employing the widely used Standardised Precipitation Index (SPI). This index was selected as it is applicable to monthly series, does not require additional climatological variables and is recommended as a key drought indicator (WMO, 2011). The SPI is calculated by summing precipitation over specified accumulation periods (typically 1, 3, 6, 9, 12 and 24 months) and fitting accumulation series to a parametric distribution, from which probabilities are transformed to the standard normal distribution. SPI values give standard deviations from typical accumulated precipitation for a given location and time of year. This allows the frequency, duration, intensity and magnitude of drought events to be quantified and compared, even across climatologically different regions. Choice of accumulation period, reference period and statistical distribution are key methodological decisions when applying the SPI. Shorter accumulation periods (1–6 months) are useful for examining agricultural drought, whereas longer durations (6–24 months) are more indicative of hydrological drought and water scarcity. Given the objective of examining impacts across multiple sectors, the SPI-12 (12-month accumulation period) was derived. Following previous analyses, drought start is defined as the month in which the SPI-12 falls below −1.00, with the return to positive values indicating the month of drought termination (see Noone *et al.*, 2017 for full details).

Noone *et al*. (2017) also used documentary sources from newspaper archives spanning the last 250 years, together with other historical sources, to add confidence to the quantitative detection of drought episodes and gain insight into the socio-economic impacts of historical droughts. The results show that Ireland is drought prone but that recent decades are unrepresentative of the longer-term drought climatology. A large decline in 30-year accumulated SPI-12 values is evident from around the 1990s onwards. During the years 1850–2015, seven major drought-rich periods were identified with an island-wide fingerprint; these were in 1854–60, 1884–96, 1904–12, 1921–23, 1932–35, 1952–54 and 1969–77. These events exhibit substantial diversity in terms of drought development, severity and spatial occurrence. Two exceptionally long events are found in the record: the continuous drought of 1854–60 and the drought of 1800–09 (in fact, a series of three droughts with brief interludes). Over the last 250 years, droughts have resulted in agricultural hardship, water resource crises and failures and preceded some of the major famines of the 18th and 19th centuries. This work shows that newspaper archives can be used to trace the progression of drought events and impacts and we thus advocate their wider use in corroborating quantitative assessments. The resulting catalogue challenges prevailing perceptions about drought in Ireland, while strengthening the evidence base for future drought and water resource planning across the island.

Figure 2.2 shows the "DNA of Irish drought". In this figure the SPI-12 values for all 25 stations in the IIP network are plotted (along the y-axis), with values colour coded based on drought severity. It is clear that many drought events identified in the IIP series have been island-wide in extent (i.e. extend across all stations). Also evident is the tendency for severe droughts to cluster in time. The relative paucity of droughts in recent decades is also evident

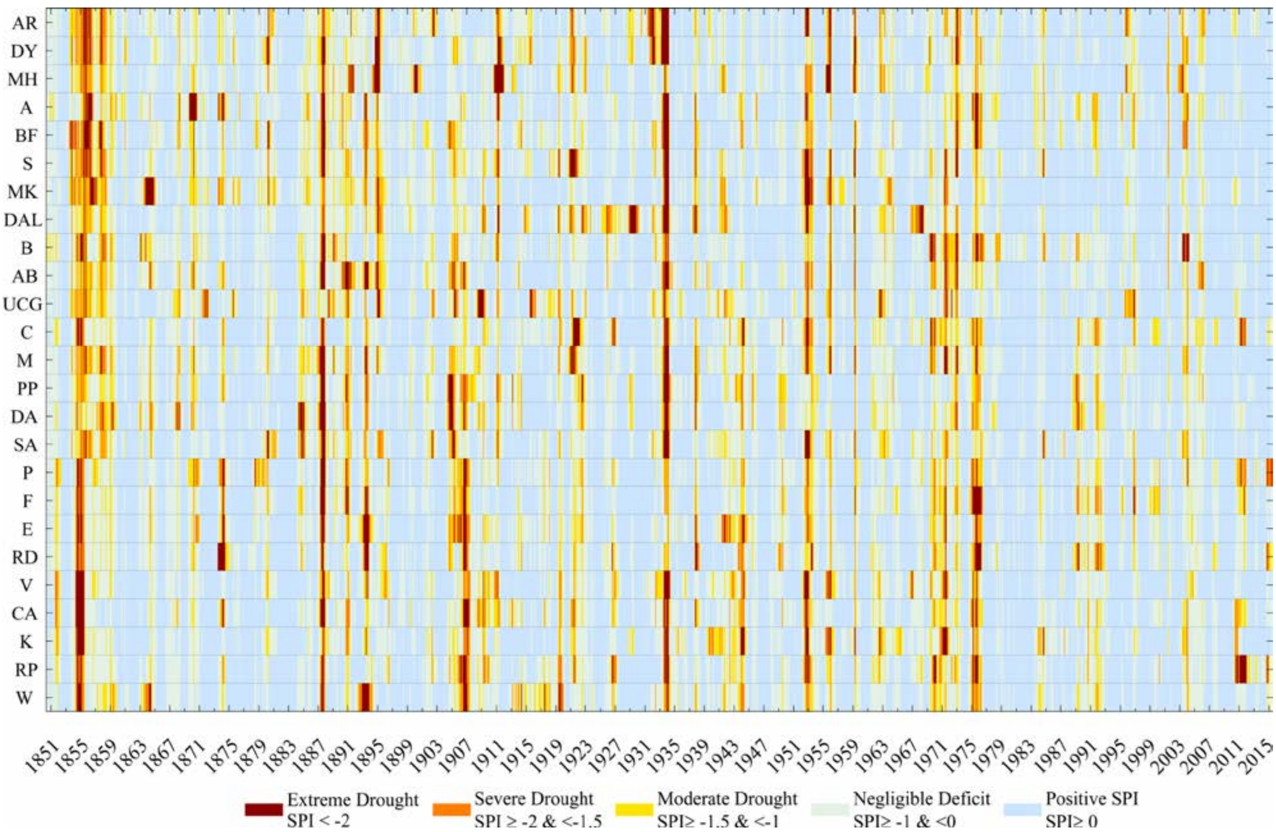


Figure 2.2. SPI-12 values for all 25 stations in the IIP network. Negative SPI-12 values are colour coded according to severity thresholds to highlight periods of moderate to extreme drought conditions.

across individual stations. This reflects a return to generally stormier and wetter summers since the 1990s (Matthews *et al*., 2015). Nonetheless, there is no room for complacency about drought risk given increasing water demands. As Irish Water embarks on a period of major investment in water infrastructure, stress testing designs against episodes with negative rainfall anomalies lasting up to nine seasons (relative to 1961–90) offers an altogether different risk assessment than the ability to cope with single-season deficiencies. Using Markov models to interrogate the IIP network rainfall data, Wilby *et al*. (2015) also show that there is a relatively high likelihood ($p = 0.125$) of a continuous 5-year (10-season) dry spell in Dublin, a region in which population growth and aging infrastructure have resulted in a water system operating at the edge of its capacity.

A detailed drought catalogue for each of the 25 stations in the IIP network is provided by Noone *et al*. (2017), in which all drought events for each station are listed, along with information on the duration of the drought and mean, total accumulated and minimum SPI-12 values for each event. Code is also available from the authors to derive any other SPI accumulations that might be of interest (e.g. SPI-3 for investigation of agricultural drought or as a proxy for soil moisture deficits).

Using the definition of a drought-rich period as years in which at least 40% of the stations in the IIP network experience unusually dry conditions lasting at least 18 months, the following periods are noted as drought rich: 1854–60, 1884–96, 1904–12, 1921–23, 1932–35, 1952–54 and 1969–77. Figure 2.3 shows the progression and spatial distribution of these events in more detail. Of note is the diversity of drought signatures in terms of their severity and spatiotemporal development. For instance, the events of 1884–96 and 1969–77 are marked by intermittent periods of extreme and moderate drought conditions, whereas the events in 1854–60, 1932–35 and 1952–54 are characterised by prolonged, severe drought conditions. The "long drought" of 1854–60, previously identified in the IIP network (Wilby *et al.*, 2015) and UK series (Marsh *et al.*, 2007) , is evident. However, in the south and south-east, this event appears more intense but shorter in duration. The drought period of 1921–23 is the least spatially extensive of those considered and falls just short of meeting the criteria set out for drought identification. However, we include it in our analysis as it has been recorded as an event of note in other work covering Ireland (Cook *et al*., 2015) and the UK (e.g. Lennard *et al*., 2014). For this period, extreme drought conditions are noted as persisting for a relatively long period at a small number of stations.

Findings from the Irish drought catalogue have significant implications for future infrastructure and water resource planning, while also facilitating resilience assessment of critical services under severe drought conditions. When advising Irish local authorities that are developing climate change adaptation strategies, Gray (2016) recommends adopting a 30-year window as appropriate to identify weather extremes and climatic trends in assessing resilience to climate variability. This work clearly shows that, where vulnerability to drought is an issue, such guidance would result in considerable maladaptation with potentially serious consequences.

The combination of droughts of various duration, evolution and intensity identified here provides a diverse set of conditions under which to stress test current and planned infrastructure, particularly in the water sector. To this end, findings from the Irish drought catalogue are being shared with Irish Water as they seek to reduce vulnerability to water shortages over the coming decades. Visualising historical drought in the form of the plots in Figure 2.3 provides an accessible means of communicating and re-imagining vulnerabilities. The same historical hydro-climatic information can also be used to appraise adaptation and investment plans in future. Testing designs against persistent, multi-season drought episodes from long records offers an altogether different risk assessment than the ability to cope with single-season droughts (such as the summer of 1995).

The full paper detailing the island of Ireland drought catalogue is published in the *International Journal of Climatology* (Noone *et al*., 2017). Wilby *et al*. (2015) assess the likelihood of the occurrence of protracted droughts across the IIP network in another paper in the same journal. Data on the magnitude, duration and intensity of each identified drought are published in the Supplementary Information for the Noone *et al*. (2017) paper. Any further information can be requested from the authors.

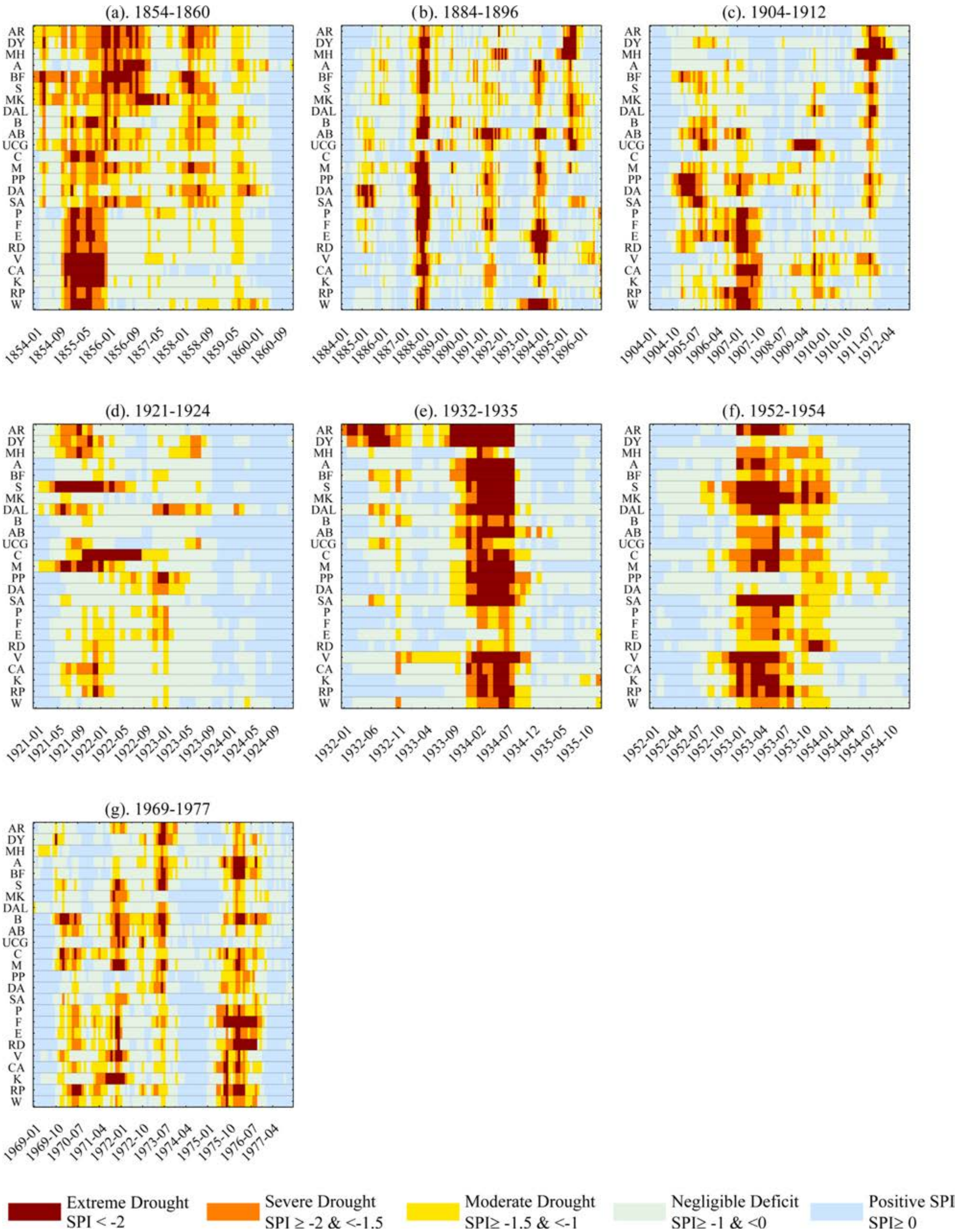


Figure 2.3. Drought signatures showing SPI-12 values for all stations in the IIP network for the seven drought periods identified with island-wide impact. Negative SPI-12 values are colour coded according to severity thresholds to highlight periods of moderate to extreme drought conditions.

Take-home messages from the island of Ireland drought catalogue are as follows:

- Historically, Ireland has been more prone to long and severe drought events than is evident in records since the mid-1970s.
- The social and economic impacts of droughts have been significant and newspaper articles offer a valuable insight into historical drought impacts and responses.
- Decision-makers can use the drought catalogue to identify historical droughts of interest and to stress test plans for performance against historical droughts.

2.4 Island of Ireland Monthly Rainfall 1711–2016 (IoI_1711)

Continuous observations of precipitation in the British–Irish Isles can be traced back to 1677, the year the first known rain gauge was developed by Richard Towneley of Burnley, Lancashire, in north-west England. Since the early 1700s, at least three precipitation gauges have operated somewhere in the British–Irish Isles every year (Jones and Briffa, 2006). The earliest meteorological observations in Ireland can be traced to the end of the 17th century (Shields, 1983). However, these early instrumental records, taken in Dublin by William and Samuel Molyneux, have been lost. Although discontinuous records exist, systematic weather observing did not begin in Ireland until 1789, when Richard Kirwan set up a series of instruments in Dublin (Shields, 1983). However, with the exception of Butler *et al*. (1998), who analysed the record for Armagh Observatory (commencing in 1838), there has been little work on Irish precipitation measurements prior to 1850, primarily because of the lack of suitable digitised data. There have also been few assessments of qualitative descriptions from weather diaries pre 1850. Exceptions from the 18th century include analyses of the diary of Thomas Neve from Derry for the period 1711–25 (Dixon, 1959), the diary of Isaac Butler from Dublin for the period 1716–34 (Sanderson, 2017) and Joshua Wight from Cork for the period June 1753 to September 1756 (Tyrrell, 1995). Thus, Irish rainfall climatology of the last 300 years remains poorly understood.

Murphy *et al*. (2018) were able to derive a continuous monthly rainfall series representing the island of Ireland for the period 1711–2016 (IoI_1711) (Figure 2.4). This was facilitated by bridging a previously unpublished UK Meteorological Office note that collated early Irish rainfall measurements and weather diaries with the island of Ireland composite series of Noone *et al*. (2016). Following the merging of these sources, Murphy *et al*. (2018) undertook quality assurance of the series through comparison with other long observational records (e.g. England and Wales precipitation and other long records for individual sites in the UK – Kew Gardens, Oxford, Spalding, Carlisle), reconstructed precipitation records (e.g. tree ring reconstructions), observations on atmospheric circulation from ship logs books (e.g. Westerly Index), observations of sea level pressure and reconstructions of the North Atlantic Oscillation Index.

Remarkably, for both spring and autumn, decadal mean totals from IoI_1711 show strong coherence with other long-term series throughout the full period of record. Confidence is low in the winter IoI_1711 series prior to 1790, when conditions are probably overly dry for the period 1740–90. Much of this part of the record is informed by qualitative descriptions in weather diaries or data from the UK used to represent Irish rainfall. Although confidence in actual rainfall totals is low, it is probable that much of this period was indeed very dry. Jones and Briffa (2006) highlight the exceptional cold and dryness of the early 1740s for the British–Irish Isles, with the impacts on Irish society and “the Forgotten Famine”, well documented by Dickson (1997) and Engler *et al*. (2013). The 1740s are noted as being exceptionally dry in the IoI_1711 winter and annual series, while 1740 stands out as being exceptionally dry in the early annual totals from Cork taken by Dr Timothy Tucker.

The weather diary of Joshua Wight from Cork offers further insight into conditions of the 1750s. In his analysis of that diary, Tyrrell (1995) notes the severe cold of winters during the years 1753–56, and in particular the notably low frequency of wet days during the winter of 1754–55, citing a higher frequency of northerly and easterly winds during the winter half year (October to March) for this period, typically associated with fewer wet days and longer dry spells. Tyrrell (1995) also notes that the middle and high latitudes were strongly affected by volcanic activity during the 1750s, with Lamb’s Dust Veil Index for these latitudes peaking between 1753 and 1756 following the eruption of Katla in 1755–56.

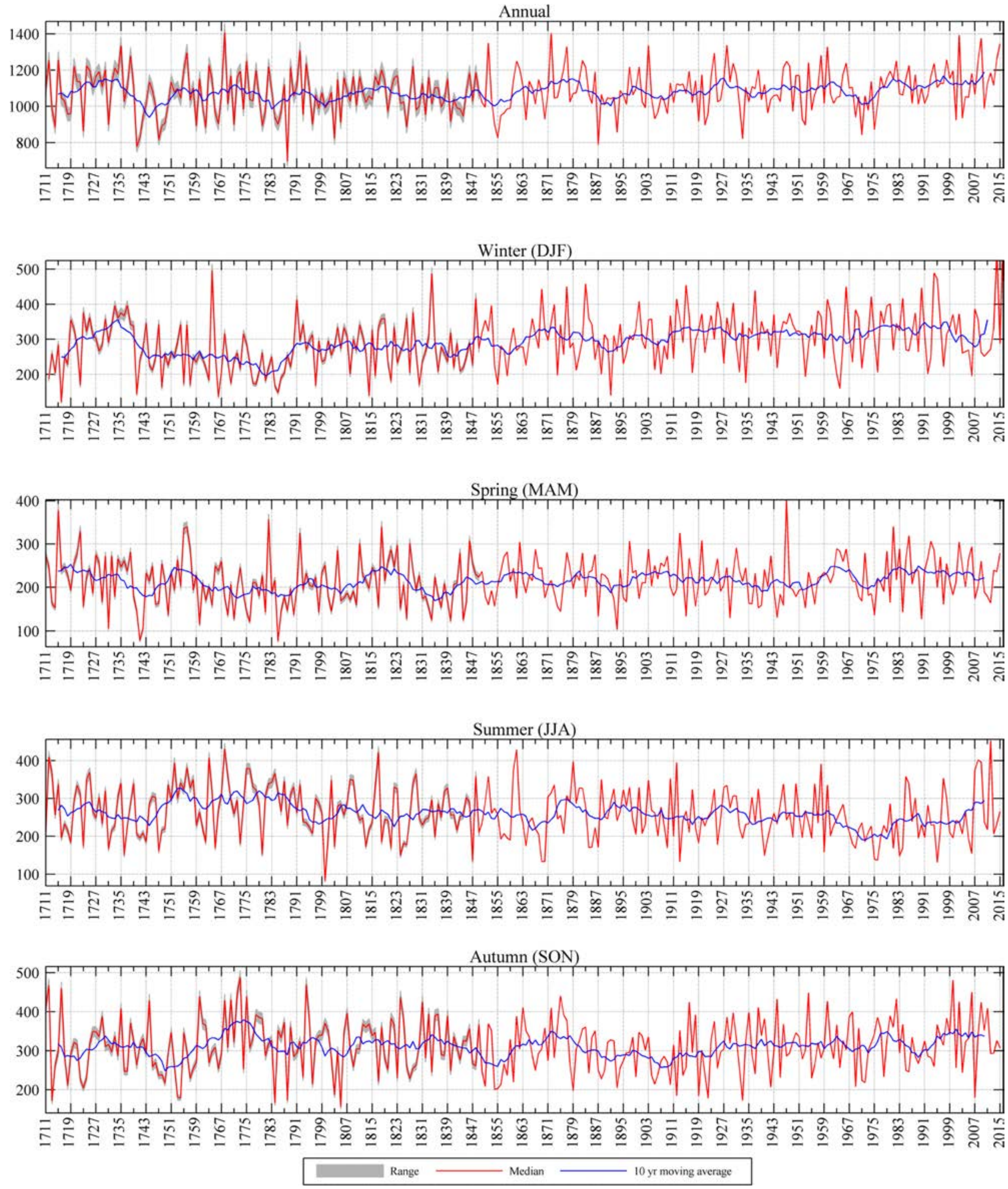


Figure 2.4. Reconstructed IoI_1711 precipitation series showing annual and seasonal totals. The grey shading shows the uncertainty in the reconstruction from resampling of the baseline used to derive the annual average rainfall. The red line is the median of the 1000 resamples. From 1850 onwards the data are the IoI_1850 series (see section 2.2) produced by Noone *et al*. (2016). The blue line represents a 10-year moving average.

While the 1740s are the driest decade in the IoI_1711 annual series, the years 1777–86 mark the driest winter decade. These years are also driest in a number of long-term precipitation records in the UK [e.g. England and Wales precipitation – EWP (1776–85), Carlisle (1776–85), Oxford (1781–90)]. Additionally, this period is marked by relatively low values of the Westerly Index, strongly negative North Atlantic Oscillation (NAO) conditions and exceptional cold in the Central England temperature (CET) record, thus favouring reduced rainfall. This period is also coincident with the Laki eruption of 1783–84, with winters following the eruption being amongst the most severe on record in Europe and North America (Thordarson and Self, 2003). Rather than volcanic forcing, some have argued that the exceptional conditions of these years was due to natural variability, related primarily to a combined negative phase of the NAO and an El Niño–Southern Oscillation (ENSO) warm event, similar to conditions during the cold and snowy European winter of 2009–10 (D'Arrigo *et al*., 2011). Still others have argued that a combination of volcanic forcing and natural variability may have played a role (Schmidt *et al*., 2012). The winters of 1784–85 and 1785–86 both rank among the 10 driest winters in the entire IoI_1711 record and are also notable in the EWP series (1784 ranks in the top 10 driest winters, with 1785 ranked as 13th for the period 1766–2016).

Within the entire 305-year IoI_1711 winter series, the 1730s are identified as the wettest decade. Rather than an individual year in the 1730s standing out as remarkable, the decade is notable for persistently wet conditions. Confidence in the 1730s being exceptionally wet is heightened given concurrent and almost unprecedented warmth in the CET (Jones and Briffa, 2006), glacial advance throughout Scandinavia (Nesje *et al*., 2008) and notably enhanced westerly air flow (Barriopedro *et al*., 2014), all consistent with a wintertime NAO-type forcing. After 1790, when early Irish observations become available, IoI_1711 shows improved consistency with other long-term observational and proxy records. In summer, exceptionally wet conditions of the mid- to late 1700s stand out, as do the very dry summers of the 1970s near the end of the record. The exceptional summer wetness of the IoI_1711 series in the mid-1700s is supported by oxygen isotope tree ring reconstructions for southern England (Rinne *et al*., 2013). The period is also documented as being exceptionally wet in tree ring reconstructions (based on tree ring widths) by Wilson *et al*. (2013), who note the mid-1700s as among the five wettest 20-year periods since 950 AD for the months March–July in southern-central England. The Old World Drought Atlas (Cook *et al*., 2015) also identifies the mid-1700s as notably wet in the context of the last 1000 years. Relative to other long-term precipitation observations (e.g. at Kew), this wet period seems to be greater in magnitude and duration in the IoI_1711 series. In his analysis of Joshua Wight's diary, Tyrrell (1995) highlights that summers of the mid-1750s were wetter than those in recent years, noting in particular that the number of wet days reported for summer 1756 was significantly higher than the average for the modern regime. Multiple lines of evidence thus add confidence to the very wet summers of this period in the IoI_1711 series.

The IoI_1711 series significantly extends our understanding of the rainfall regime of Ireland. Monotonic trends derived for the IoI_1711 series reveal large variability in both magnitude and direction, depending on the period of record assessed (Figure 2.5). Winter records commencing before the 1850s show statistically significant (0.05 level) increasing trends. Tests commencing between 1850 and 1900 show non-significant increasing trends. Weak non-significant decreasing trends are evident for tests commencing after 1900. It is thus evident that the finding of statistically significant increasing trends in winter rainfall is dependent on cold and dry conditions in the pre-1850 record. The early records in both IoI_1711 and EWP draw on descriptions from weather diaries and early and experimental rain gauges that may be prone to undercatch, particularly during cold, snowy conditions. It is therefore possible that biases in measurements during cold conditions affect the magnitude and significance of trends in winter rainfall in long-term rainfall series. We intend to explore this potential temperature-dependent bias and potential influences on winter rainfall trends using physically based models in a future study. Summer rainfall reveals statistically significant (0.05 level) decreasing trends, but only for tests commencing before the 1900s. Trends derived from records that represent the typical availability of digitised data (i.e. 1940s onwards) reveal results that are unrepresentative of the long term, thus illustrating the importance of long records.

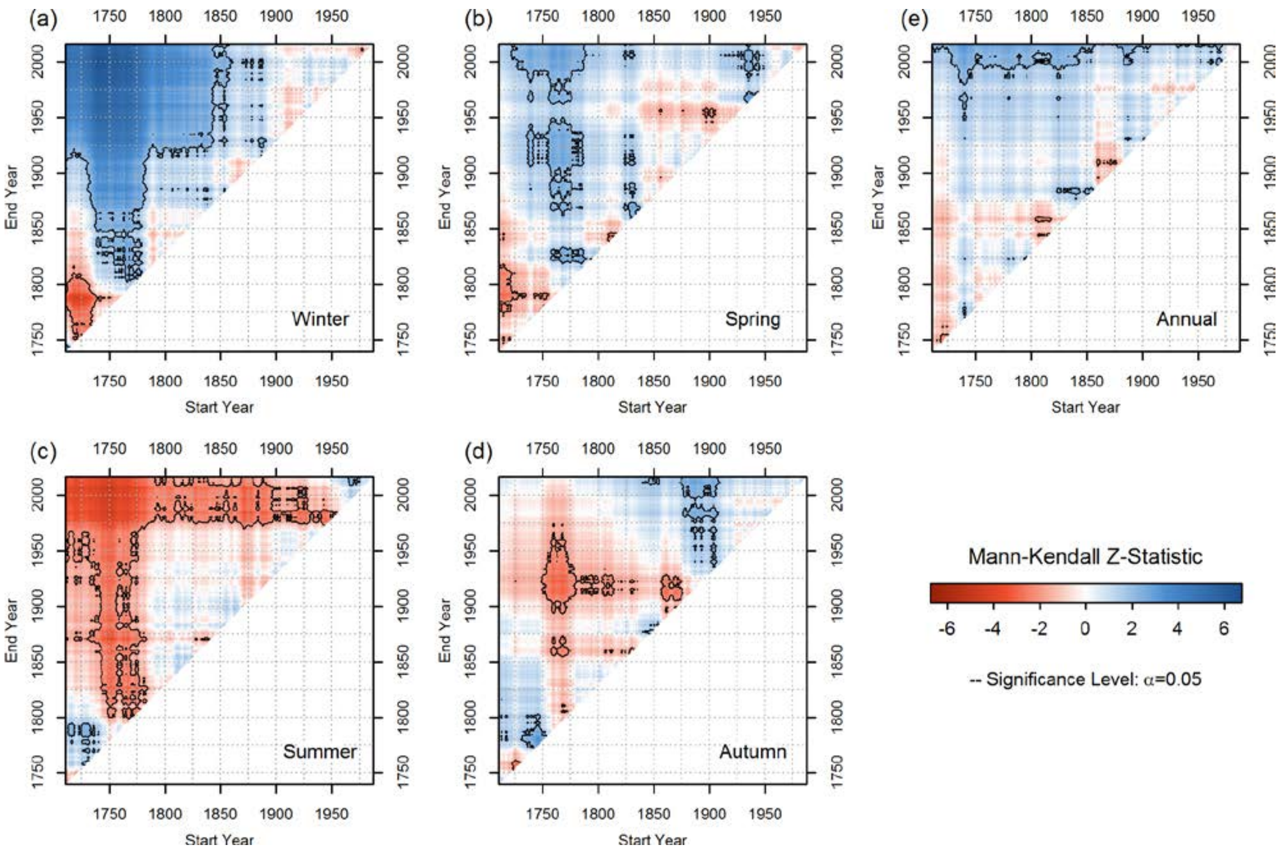


Figure 2.5. Mann–Kendall Zs values for IoI_1711 seasonal and annual series for all possible combinations of start and end years, with minimum length of 30 years. Contours represent periods for which trends are significant at the 0.05 level.

The full paper detailing the IoI_1711 rainfall series is published in *Climate of the Past* (https://www.clim-past.net/14/413/2018/). The dataset is available from Dr Conor Murphy.

Take-home messages from the IoI_1711 rainfall series are as follows:

- The 18th century shows remarkable decadal climate variability relative to the recent centuries. This information provides valuable insights for assessing vulnerabilities.
- The dataset provides insights into how different climate forcings, such as volcanic eruptions, solar activity and greenhouse gases, have affected Irish rainfall in the past and may do so again in the future.
- The IoI_1711 series also reaffirms the trend of wetter winters and drier summers.

2.5 Conclusions and Ongoing Work

Together, the IIP network, drought catalogue and IoI_1711 rainfall series add considerably to our knowledge of the rainfall climatology of Ireland, reaching right back to the beginning of meteorological observations. As outlined above, each dataset has utility in tracking emerging changes in climate; contextualising recent extremes; identifying past events that have had significant societal impact; and ground-truthing climate models. The datasets are already being used in different sectors to “stress test” infrastructure and build resilience to future extremes. At the regional scale, such as in Ireland, future climate projections are dominated by natural variability until mid-century. Having long-term quality-assured datasets such as these facilitates researchers and decision-makers in more confidently quantifying natural variability in developing adaptation plans.

Although much has been achieved in this work, much remains to be completed. For instance, we currently lack the equivalent datasets for temperature. Work is ongoing at the National University of Ireland Galway, where a PhD project is attempting to address this, and its completion will make a valuable contribution. In addition, the datasets above are for monthly precipitation totals. Given the concern of increasing extremes, it is of high priority to develop a long-term, quality-assured daily rainfall network for the island. Such work is ongoing at the Irish Climate Analysis and Research Units (ICARUS,) at Maynooth University, where researchers, together with Met Éireann, are working with students to transcribe pre-1940 daily rainfall records currently held in the archives at Met Éireann. Thus far, this work has successfully transcribed in excess of 2600 years of daily rainfall data, together with associated metadata, across the island. Over the next year or two, the quantity of data transcribed will be increased and the data will be quality assured to produce one of the longest daily rainfall networks in the world. Such a dataset will be invaluable for examining changes in rainfall intensity and extremes.

In addition to the rainfall and temperature, the Irish Reference Network (IRN) (Murphy *et al*., 2013) of river flow stations provides a valuable resource for monitoring, detecting and attributing climate-driven changes in river flows. Stations within this network are specifically identified as being of high quality and experiencing minimum disturbances so that the identification of climate-driven changes, across the full flow regime, can be undertaken with greater confidence. The IRN needs updating, in terms of both of record length and the stations included in the network. This process is currently underway, in tandem with wider hydrometric network reviews being undertaken by the Office of Public Works and the Environmental Protection Agency.

Given the critical vulnerabilities in Ireland to hydrological extremes, an important avenue of work currently underway at ICARUS is the reconstruction of river flows. In Ireland, most of our hydrological records commence in the early to mid-1970s. Although a number exist that date back to the 1940s, these are often heavily affected by arterial drainage. Long-term global reanalysis datasets such as the 20th century Reanalysis, which extends back to 1850, together with ERA-20C, which extends back to 1900, offer exciting possibilities to help develop probabilistic river flow reconstructions. These could then be used to explore hydrological drought and changing flood occurrences.

Given the dominance of natural climate variability relative to the projected anthropogenic climate change signal over the coming decades, the past is very much the key to the future in terms of adaptation planning. Too often we assume that climate models are the only tool at our disposal for dealing with climate change. This is patently not the case. To develop a climate-resilient Ireland, a critical step is making the most of our rich heritage of meteorological observations to better understand the nature of historical climate variability and change. The work reported here makes a major step forward in this regard and has spawned ongoing work to maintain that momentum. It is our hope that the datasets developed will be taken up and used by both researchers and decision-makers.

3 Irish Climate Futures: A Framework for Climate Services Based on User Needs

3.1 Introduction

Climate services that provide timely, tailored information and knowledge to decision-makers play an important role in improving the capacity to manage climate risks. Climate services focus on meeting the needs of user communities, operating at the boundary between climate sciences, policy and practice (Guston, 2001) and providing stakeholders and organisations with knowledge and information that can be used to reduce climate-related losses and enhance benefits. A key component of the effective provision of climate services is the production of long-term climate projections (Vaughan and Dessai, 2014). However, utilising climate change projections to inform decision-making in adapting to climate change has presented challenges for regional climate projection science. The main challenges presented are threefold and are discussed briefly in the following paragraphs.

First, projections of future climate change are inherently uncertain, which has been a major obstacle in adaptation planning (challenge 1). Uncertainties in projections of climate variables are associated with future emissions pathways, model structure and parameterisation, initialisation, boundary conditions and downscaling techniques (e.g. Dobler *et al.*, 2012). In addition, there is now a multitude of global climate model outputs and results available for application at different scales using various downscaling techniques. Such factors give rise to a model selection issue (Whetton *et al.*, 2012). Using a small set of best-performing models or a “best-guess” assessment is a less than ideal solution. There is currently no consensus around robust methods for selecting a few “best” models (Knutti *et al.*, 2010). Good model performance for past and current climate is no guarantee of such performance under future, changed conditions (Murphy *et al.*, 2011), whereas applying model weights tends to focus on specific impacts and is complex to implement and interpret. Additionally, Dessai *et al.* (2009) highlight that the exclusion of models deemed to be of low reliability may exclude consideration of low likelihood but high-impact conditions. Conversely, using a wide selection of models and scenarios typically results in large uncertainties that propagate and expand in downscaled regional climate change scenarios and impacts. The decision-maker is then left with a bewildering range of possibilities and often defaults to “low regret” decisions (World Bank, 2012). Such large ranges of uncertainty have not been welcomed by policymakers and can lead to inertia in furthering adaptation policy (Murphy *et al.*, 2011). The notion that “best guess” climate model output can be used in a deterministic sense to direct adaptation decisions is increasingly hard to defend in the face of recognised uncertainties in global and regional climate modelling, both statistical and dynamical (Stakhiv, 2011; Pielke and Wilby, 2012).

Second, climate information is required for multiple sectors as diverse as agriculture, water resource management, flood risk reduction, transportation and health (challenge 2). Such sectors often have diverse information requirements for contextualising decision-making (Vaughan and Dessai, 2014). These requirements range from the types of climate variables that are important, the spatial scale at which information is required and the timescales over which information is important. Traditional top-down approaches to adaptation have shortcomings in recognising and meeting these diverse needs (Wilby *et al.*, 2014). In such approaches a small number of climate variables are produced through statistical and/or dynamic downscaling [often using a small number of parent global climate models (GCMs)], with emphasis typically on producing projections of a small number of variables at high spatial resolution. In Ireland, with a few exceptions (e.g. Bastola *et al.*, 2011), impacts assessment for specific sectors have used a small subset of downscaled climate projections, thus under-representing the range of possible future impacts. Furthermore, different subsets of scenarios have been used in different sectors, often confusing broader interpretation of national-scale vulnerability or comparison of vulnerabilities across sectors.

Third, in many cases the connections between climate science users and providers are weak and/or non-existent (challenge 3; Changnon, 2004), resulting in an information gap. In most instances, climate projections for the coming decades are produced and distributed in raw form or as generalised data products for end users to interpret, rather than being packaged to meet the information needs of decision-makers. Indeed, in many instances, end users of climate scenarios have traditionally been seen as other scientists, particularly in the impact assessment field, rather than decision-makers. As a result, providers often do not fully understand the contexts in which decisions are made (McNie, 2007), with information provided in formats that prospective users find difficult to understand and/or incorporate into the decision-making process (Vaughan and Dessai, 2014). In such situations, inappropriate use of climate information can increase risk exposure and lead to bad decisions or maladaptation (Dilling and Lemos, 2011).

In meeting these challenges, novel approaches to the provision of climate services are required. Such approaches need to be decision-centric, relevant and tailored to the needs of end users, while dealing transparently and efficiently with the challenge of uncertainty so that adaptation decisions can be tested for robustness to the range of projected changes. The use of representative climate futures (RCFs) (Whetton *et al.*, 2012) presents such a novel approach for balancing user needs for simplicity and interpretability with the need to include cutting-edge climate projections. In producing robust climate services, the RCFs approach can act as a bridge between the climate research community and end users (Whetton *et al.*, 2012).

Rather than basing climate change assessments on output from modelling chains, RCFs are employed as “boundary objects” to anchor discussion and decision-making. Typologies/classifications of future climate that determine the key drivers of change are established through discussion with end users. For example, when temperature and precipitation change are key drivers, matrices of simple narratives such as warmer and wetter, or much hotter and much drier, are derived. Model projections from large datasets, such as the CMIPs, and/or previously downscaled scenarios for the region of interest are then classified within these narratives. Likelihoods for specific RCFs can be established based on the number of scenarios falling into each RCF classification or more formal weighting based on model performance in representing past climate. RCFs of little interest to adaptation can be neglected, with attention focused on populating relevant RCFs with climate datasets from one or more representative GCM. These can be downscaled using appropriate methodologies that are consistent with user needs. In addition, the representation of important RCFs using a subset of climate scenarios allows the possibility of deriving internally consistent, multivariate datasets when more detailed impact or risk assessments may be required.

The merits of a climate futures approach in addressing the key challenges outlined above are significant when (1) scenarios and information provision are developed with user needs to the fore; (2) the complexity associated with the use of emissions pathways and models is removed for end users, i.e. there is no need for end users to understand the complex modelling chains that underlie particular scenarios; (3) multiple layers of information can be contained, with users needing only to access the level of detail required for a particular decision; and (4) the number of narratives used to represent future climate impacts can remain small and stable in the face of proliferating climate model results. An additional benefit of the RCF approach is that pre-existing downscaled scenarios can be included, maintaining the relevance of previous research (Whetton *et al.*, 2012).

Systematic application of the RCF approach has a number of methodological challenges, in particular (1) the identification of an efficient and effective way to characterise or classify climate scenarios for a region into a particular climate future; (2) the calculation of relative likelihoods – based on either qualitative or quantitative procedures; and (3) the selection by end users of a subset of climate futures that requires development based on their understanding of current vulnerabilities of the system in question. This is a particular challenge if the RCF approach is employed for the generation of national climate change scenarios.

3.2 The Irish Climate Futures Framework

Here, we develop a framework for exploring ICF that is inspired by, but different from, the RCF approach. We base our framework on the GCM runs comprising CMIP5. Our analysis includes between 68 and 98 different climate scenarios for each of the following

RCPs for three future time periods: RCP 2.6, 4.5, 6 and 8.5 and the 2020s (2010–39), the 2050s (2040–69) and the 2080s (2070–99). For each scenario, changes in temperature and precipitation are derived seasonally relative to the baseline period 1976–2000 using the simple change factor approach.

The methods adopted are intended to be flexible in terms of user needs with regard to approaches to adaptation planning. First, scenarios are derived for climatological and synoptic weather stations across Ireland and 35 catchments within the IRN (Murphy *et al.*, 2013). The workflow is just as easily extended to grids or to any unit of analysis deemed necessary for adaptation planning (e.g. county level or region, e.g. Greater Dublin Region). Attention was also given to ensuring that the approaches developed could be used for climate change communication and adaptation planning, in particular for:

1. Developing narratives or simple story lines of future change that are informed by the range of climate projections that also underpin the IPCC Fifth Assessment Report. Such narratives may be beneficial for communicating climate change impacts to the general public, policymakers and planners or for vulnerability assessment.
2. Deriving ranges of potential future changes for developing sensitivity testing of systems and adaptation decisions for both climate and non-climate factors in a wide range of different sectors.
3. Providing downscaled climate projections for underpinning impact assessments that represent the full range of uncertainty from the most up-to-date climate model ensemble.

The ICF framework is based on three levels of interaction/dissemination (basic, intermediate and advanced), depending on specific needs of potential users. In the following sections each level of interaction/dissemination is described, together with the methods that underpin the development of climate information. We also highlight potential uses that the data/information can be put to in developing adaptation plans. In all aspects we pay particular attention to the need for transparency surrounding uncertainties in future projections. The framework we develop is a prototype and will need to be rolled out on a wider basis before being operational, which depends on future funding. The current phase of work set out to scope a framework to better deliver climate services for Ireland. For those interested in viewing a sandbox user interface in which output for each level is derived for three locations (Cork, Dublin and Armagh) see https://mu-icarus.shinyapps.io/climate_futures_dashboard_18012018/.

3.3 Irish Climate Futures: Basic Level

3.3.1 Target audience

The target audience is widespread, with potential users from members of the public interested in climate change to advanced users charged with conducting vulnerability assessments and adaptation plans through to researchers. In particular, we highlight this level of interaction as particularly useful for planners, policymakers, local authorities and politicians.

3.3.2 What it does

The basic level is structured around changes in seasonal temperature and precipitation, as derived from the CMIP5 archive. Seasonal change factors estimated for mean daily temperature and precipitation are classified by the combined changes in the two variables, with the data presented as simple histograms for each variable, showing the range of projected changes. A scatterplot showing the individual projected changes in temperature and precipitation is also derived. Finally, the projected changes in seasonal temperature and precipitation are presented as climate futures – simple narratives describing the nature of future change. The climate futures used are described in Table 3.1. The resultant classifications provide a clear visual display of the spread and clustering of climate change projections for different time periods of interest (i.e. 2020s, 2050s, 2080s) and different greenhouse gas concentration pathways. This provides model consensus information for each climate future and makes it easy for users to identify information that is of most importance to their impact assessment. This represents a unique way of exploring regional climate projections by allowing users to explore the projected changes in two climatic variables simultaneously.

Table 3.1. Descriptions of climate futures used in the development of heat plots under the basic level of interaction

Precipitation climate futures	Temperature climate futures
• Much wetter: > 15% increase in rainfall	• Slightly warmer: < 1°C increase in temperature
• Wetter: 5–15% increase in rainfall	• Warmer: 1–2°C increase in temperature
• Little change: –5% to +5% change in rainfall	• Hotter: 2–3°C increase in temperature
• Drier: 5–15% reduction in rainfall	• Much hotter: > 4°C increase in temperature
• Much drier: > 15% reduction in rainfall	

3.3.3 Example output

Figure 3.1 shows output from the basic level for Cork Airport. Here, we show the winter (DJF) season changes relative to present under the business-as-usual, emissions-intensive RCP 8.5. The same output can be selected through dropdown menus in the user interface for any RCP, season or future time period. The output consists of (1) a histogram of projected temperature change from the full range of CMIP5 model simulations; (2) a histogram of precipitation change from the full range of CMIP5 model simulations; (3) a scatterplot of the above changes in temperature and precipitation from each climate scenario and (4) a heat map of consensus among climate scenarios around simple future climate change narratives (descriptions of future changes; see Table 3.1). The colour ramps detail the percentage of future climate projections from the CMIP5 archive that fall within each climate future. Each plot can be easily downloaded, as can the data behind the plots, for presentation purposes.

Such functionality makes it very simple to derive detailed information for any location of interest. Each climate scenario is equally likely and thus none can be discounted. Not focusing on an ensemble means that the user/decision-maker can identify which part of the scenario space may be of interest and might cause stress for the system in question.

Figure 3.2 shows the climate futures plot for winter (DJF) and summer (JJA) for the 2050s and 2080s for Dublin under business-as-usual emissions (RCP 8.5). The evolution from more moderate to extreme climate futures is evident when progressing from mid-century to end of the century. The uncertainty in future projections is easily visualised and understood. For instance, by the end of the century, more than half of the projected winters are likely to be much hotter (> 4°C hotter than in the baseline period 1976–2000), with an equal number of scenarios being wetter (5–15% increase in precipitation) and much wetter (> 15% increase in precipitation). The majority of climate models project that summers in Dublin by the end of the century will be much hotter (> 4°C hotter than in the baseline period 1976–2000) and much drier (> 15% reduction in rainfall relative to the baseline period 1976–2000). Equally important is that the user can readily see where other climate projections lie and the relative likelihood of these, if likelihood is counted as the level of agreement among climate models. Viewing climate model projections in this way thus offers a very transparent way of assessing future climate risk that allows the user to easily examine the full range of projected changes, and how they agree or disagree, in assessing vulnerabilities, devising adaptation plans and even communicating risk to non-experts.

3.3.4 How might the basic level be useful for adaptation planning?

This type of information (from viewing climate model projections) is relevant to assessing vulnerabilities across all sectors, especially the water, agricultural and health sectors, and could easily be used for scoping vulnerability. The narratives could also be used in appraising future adaptation strategies. Chapter 4 combines the long observational records from Chapter 2 with the change factors in seasonal temperature and precipitation derived using the basic-level functionality of the ICF framework to assess how past seasonal extremes have changed over the period of record and how they are likely to change in the future. Such analogue methods that identify extremes within living memory and ask how they are likely to change in future offer a valuable means of assessing vulnerabilities across all sectors and provide a powerful method of communicating the impacts of climate change.

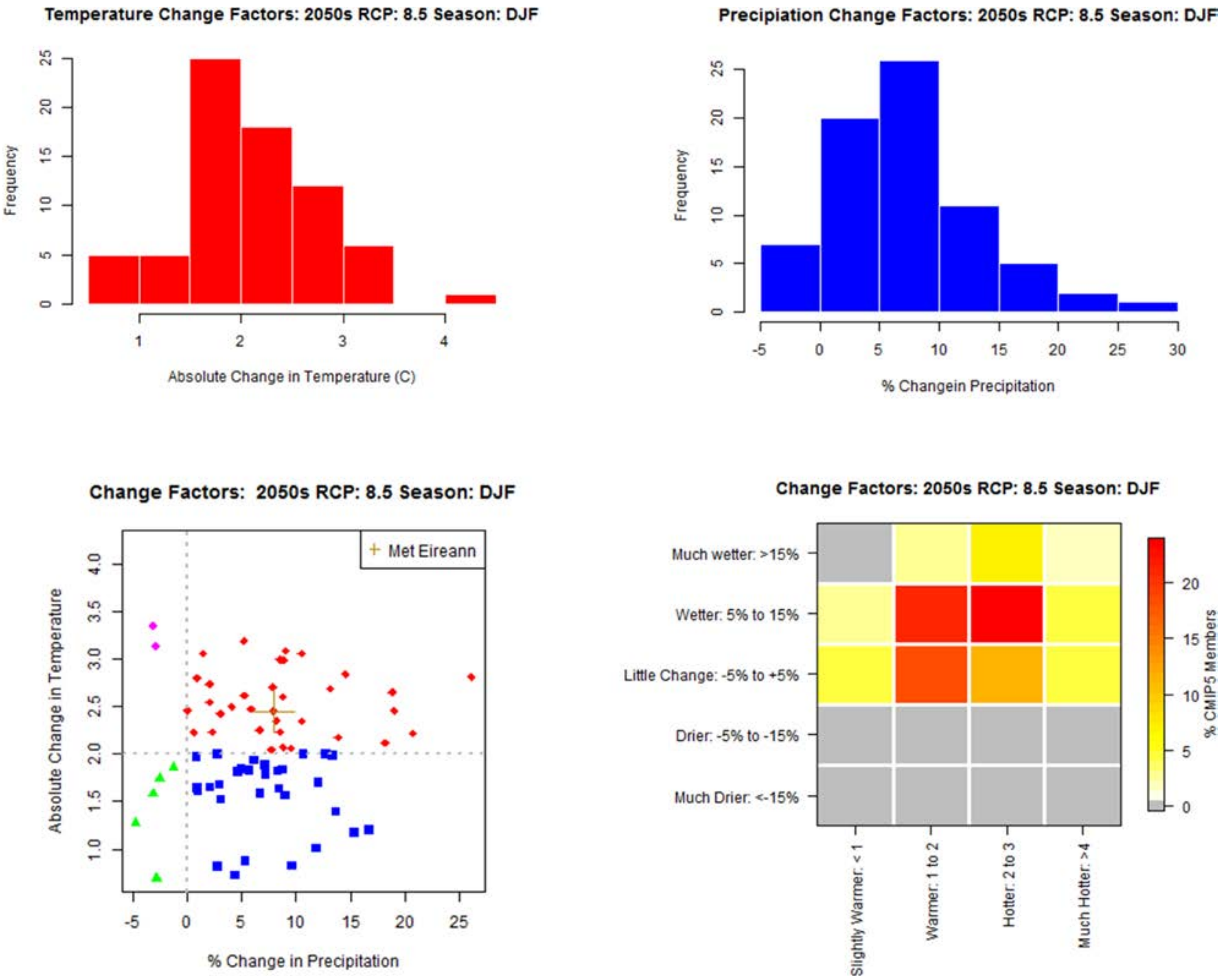


Figure 3.1. Output provided for each station, season and RCP for the basic level of the ICF framework. This example case is for winters in the 2050s for Cork Airport under business-as-usual emissions (RCP 8.5). Top left: histogram of temperature changes projected. Top right: histogram of precipitation changes projected. Bottom left: scatterplot of temperature and precipitation changes. The dotted vertical line represents zero rainfall change and the dotted horizontal line represents a 2°C change relative to baseline. Scenarios falling within each quadrant are coloured. The cross-hair shows the location of EC-Earth, the climate model currently run by Met Éireann. Bottom right: heat map of climate scenarios for narratives of future changes of temperature and precipitation. The percentage of CMIP5 models comprising each future narrative is colour coded.

3.4 Irish Climate Futures: Intermediate Level

3.4.1 Target audience

The intermediate level is aimed at those responsible for assessing vulnerability to climate change in different sectors, including local authorities, consultants and engineers. Often, this will require running system models to assess vulnerability or the implementation of different adaptation options. In many cases, this necessitates integrated assessment whereby climate change is only one factor of future change that needs to be accounted for. For example, in developing water plans, water managers will need to develop models of future water availability that account for changes in population, water demand and possible land use, as well as climate change. In assessing future system vulnerabilities and the effectiveness of potential adaptation options, it is critical that the full range of potential changes in key climate variables is included to avoid potentially expensive over- or underspend on adaptation. Including hundreds of climate scenarios in modelling studies is often not

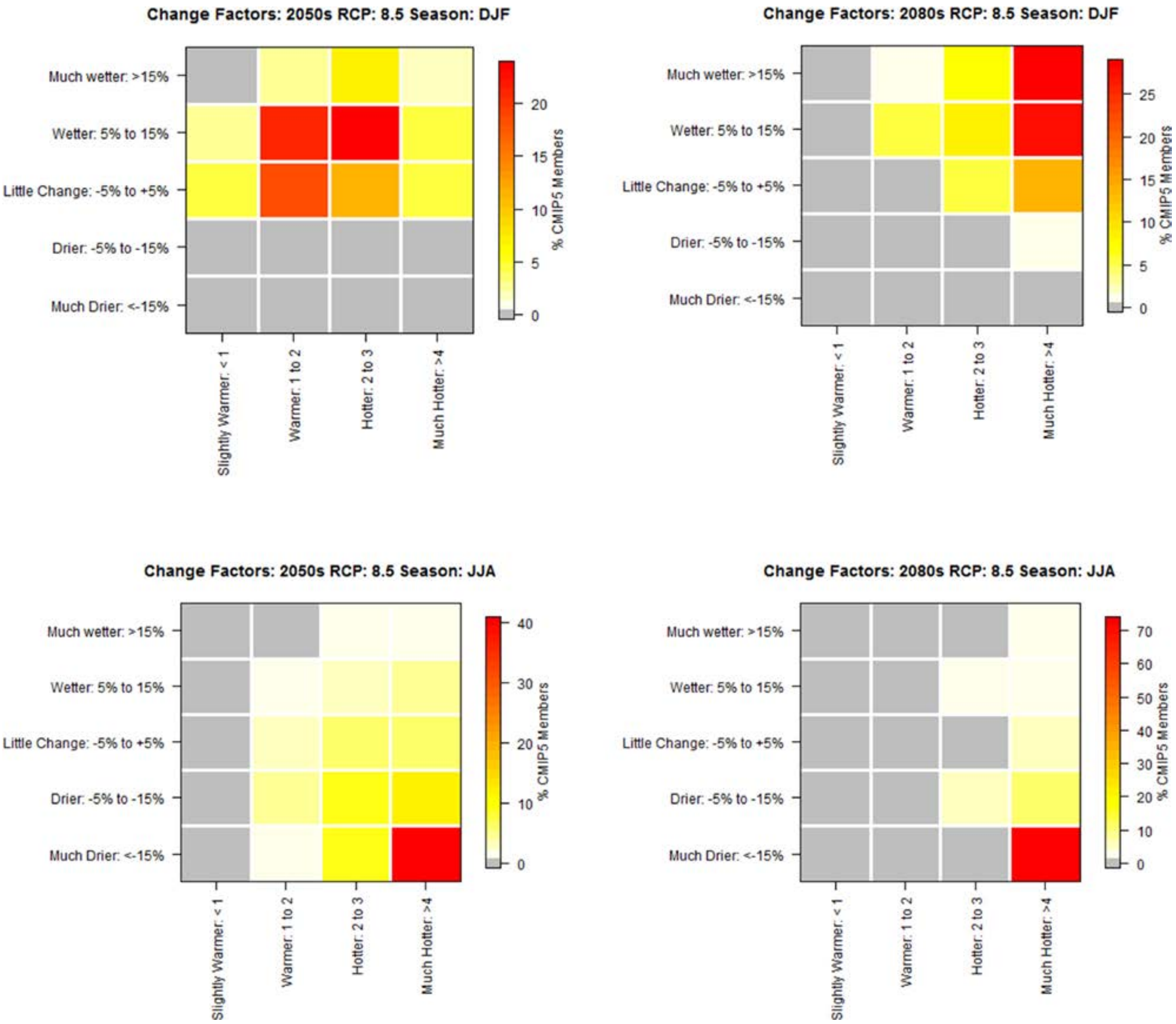


Figure 3.2. Climate future heat plots for Dublin Airport showing the proportion (%) of climate model scenarios from the CMIP5 ensemble that comprise each climate future for winter (DJF) (top) and summer (JJA) (bottom) for the 2050s (left) and 2080s (right) under the business-as-usual emissions RCP 8.5.

an option because of the expertise needed and the computational expense. The intermediate level of the ICF framework aims to reduce the complexity of large climate ensembles (CMIP5) into a small and manageable set of climate futures that represent unique and equally plausible climate change signals that encompass the range of projected changes from the parent ensemble.

3.4.2 What it does

To avoid poor adaptation decisions, best practice dictates robust sampling of key climate and model uncertainties (Clark *et al*., 2016). Hence, the outputs from large-scale model experiments, such as CMIP (Taylor *et al*., 2012), represent a valuable resource for adaptation planning. However, such experiments rely on the support of autonomous modelling groups, which differ in the number of simulations conducted, the specific model(s) employed and the particular component(s) of uncertainty considered (e.g. parameterisations, initial conditions). This is complicated by GCMs developed by different groups sharing a similar formulation and hence many of the same errors/biases, an issue that also affects successive model generations (Masson and Knutti, 2011). Furthermore, models may share the same parameterisations or be “tuned” using the same (possibly biased) observational data. Consequently, the usefulness of ensemble experiments is limited by their biased representation of constituent uncertainties, with several studies highlighting the effects that data redundancy and model interdependence have on the effective ensemble size (Knutti *et al*., 2010; Pennell and Reichler, 2011).

Deriving unbiased distributions of future climate and predictive uncertainty is strictly conditional on the independence of ensemble members (Greene *et al*., 2006; Déqué and Somot, 2010; Masson and Knutti, 2011; Mendlik and Gobiet, 2016). Here, biased sampling leads to disproportionate weighting of the respective model biases and sensitivities, resulting in a skewed statistical interpretation of probable changes. Hence, ensemble bias has direct implications for our understanding of climate risk and the robustness of planning decisions. Addressing this requires the identification of an independent subset of ensemble members that captures the original ensemble spread and ensures that, in omitting certain projections, minimal information is lost. In addition, by minimising data redundancies, sub-selection lessens the burden of considering the full ensemble, which, on the part of decision-makers, may force poor ensemble member selection (or at worst lead to inaction). Furthermore, planning decisions may be complicated by the necessity of considering additional stressors (e.g. land use change, population growth and socio-economic scenarios) alongside climate change. Hence, identifying key climate narratives via objective down-selection helps to better communicate climate risk. Such narratives can be used to define ranges with which to stress test system vulnerability (Prudhomme *et al*., 2010; Whateley *et al*., 2014).

In the intermediate level, the ICF framework employs principal component analysis in conjunction with a *k*–means clustering algorithm applied to the rotated component loadings to identify a reduced set of objective and independent climate change signals that characterise the uncertainty in the CMIP archive. To maintain internal consistency between temperature and precipitation, the procedure is applied to the concatenated climate signals of both variables. Example output is provided in the following section for Cork Airport.

3.4.3 Example output

Using the example of Cork Airport for the 2050s and RCP 8.5, Figure 3.3 identifies seven independent ensemble members that capture distinct signals of projected change and 90% of the range of projections from the CMIP archive. Thus, the approach robustly refines the CMIP5 ensemble to seven independent climate change signals and reduces the number of simulations required to efficiently capture the ensemble spread. In Figure 3.3 the blue columns

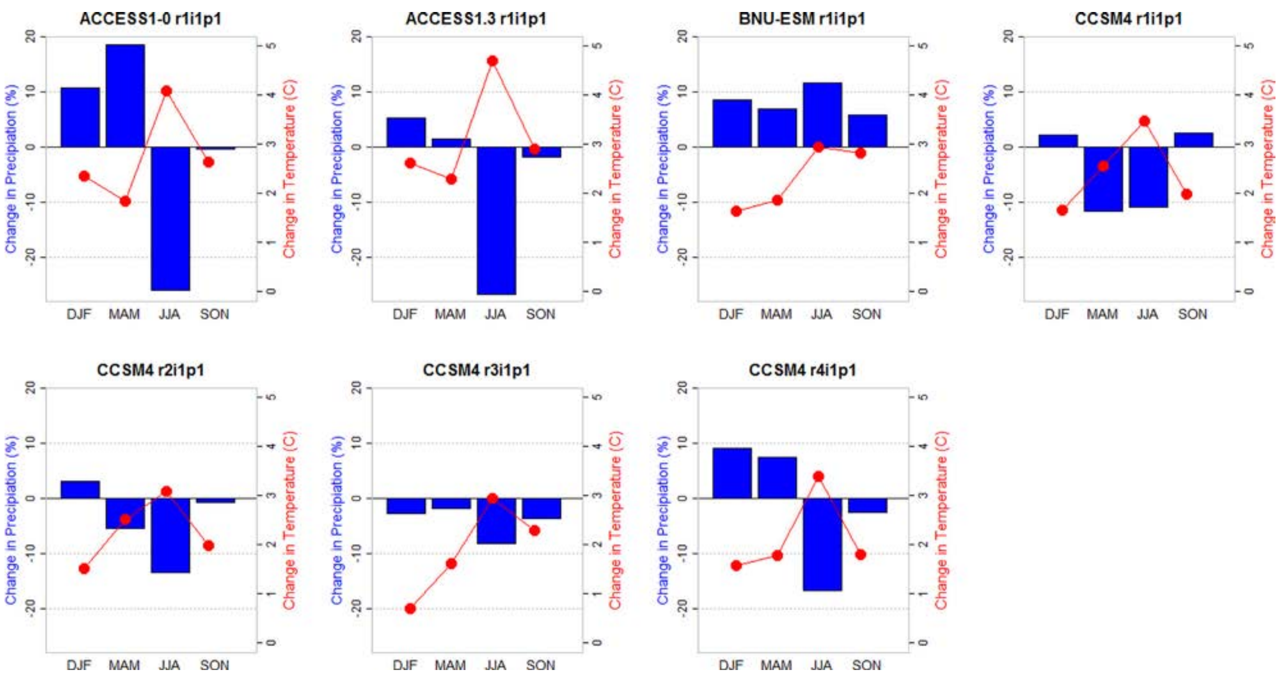


Figure 3.3. Intermediate level output: independent and equally plausible climate change signals for Cork Airport (2050s under RCP 8.5) identified from the CMIP5 archive of GCM output. These seven signals were selected to span 90% of the range of the parent CMIP5 ensemble.

represent seasonal rainfall changes and the red lines represent seasonal temperature changes. Equally plausible changes range from increasing rainfall in all seasons (EM BNU-ESM) with little temperature change, to large increases in seasonality of rainfall (wetter winters and drier summers) and large increases in summer temperatures (EM ACCESS 1.0). Given the independent and equally plausible nature of such changes, it is critical that vulnerabilities and adaptation options be assessed for functionality under the range of these projections. The approach also allows identification of different narratives to communicate changes and test adaption decisions under a range of plausible future scenarios.

3.4.4 How might the intermediate level be useful in adaptation planning?

The intermediate level is particularly useful for adaptation planning when systems need to be assessed for future vulnerabilities or the assessment of adaptation options. A case in point is the water sector. In many cases, water managers will have a working model of a water supply system that might represent the major sources, abstractions, discharges, demands on water, etc. Climate change is only one pressure on water resource provision and water managers may also be interested in examining how the system responds to increased population, changing water demands, land use change within the catchment area, changes in pricing of water, etc. Such complexity necessitates the use of a smaller number of climate change projections that can be used in such integrated assessments. The intermediate-level approach can provide such reduced scenario numbers, but maintain their representativeness of the uncertainties and distinct climate signals from the larger set of climate projections. The intermediate level may also be useful for identifying/selecting climate model projections that may be subject to dynamical downscaling.

3.5 Irish Climate Futures: Advanced Level

3.5.1 Target audience

The advanced level is aimed at researchers, planners and consultants who may be interested in further exploring uncertainties in future climate projections as a result of natural variability and who require daily climate simulations for their analysis. This may be the case when adaptation planning using the basic- or intermediate-level data reveals vulnerability in the system of interest and deeper assessment of that vulnerability may be required to inform planning and decision-making.

3.5.2 What it does

The advanced level applies a weather generator (WG) to climate futures identified in the intermediate level. WGs produce climate data of unlimited length that have the same statistical features (e.g. mean, variance) as the observed data but with a different sequencing of weather events. Their stochastic basis means that WGs have the benefit of capturing natural variability in local-scale conditions, which is critical for design considerations where high-frequency variability is an issue (e.g. flood defences). By altering their parameters using large-scale weather predictors, WGs can be adapted to downscale GCM projections (Kilsby *et al*., 2007; Jones *et al*., 2011; Bastola *et al*., 2012). For this study we employ the WeaGETS (Weather Generator of the École de Technologie Supérieure) single-site stochastic WG developed by Chen *et al*., (2012). Numerically, WeaGETS is similar to the widely applied WG model but is altered to improve the simulation of low-frequency climate variability (Chen *et al*., 2010). WeaGETS was selected based on its flexibility, parsimonious structure and concurrent simulation of precipitation and temperature, with the last being important when modelling systems that require the physical and temporal relationship between both variables to be maintained (e.g. crop modelling). For this study the WG parameters are perturbed by refitting the model to observed climate data that has been rescaled using change factors from the intermediate-level output. For precipitation the model was found to perform best using a third-order Markov chain for wet/dry day occurrence and two-parameter gamma distribution to simulate rainfall amount. The use of Fourier harmonics to smooth the temporal transition between parameters was found to improve performance (Chen *et al*., 2010). Additional tests were conducted to determine the number and length of simulations required to capture the full range of internal variability.

3.5.3 Example output

Example output is provided for Cork Airport in Figure 3.4. For each of the independent scenarios identified in the intermediate level in Figure 3.3, the WG is applied to explore the ranges of natural variability in addition to the climate change signals. It is evident that the ranges of change expand considerably. The output is provided graphically and in the form of CSV files for users who need to download the data for impact assessment of adaptation planning.

3.5.4 How might the intermediate level be useful in adaptation planning?

It is envisaged that the advanced level will be accessed only by advanced users who have high-level capabilities in assessing climate change risks. In particular, the output from the advanced level could be used at advanced levels of adaptation planning for stress testing adaptation decisions. For instance, in flood management the output from the WG could be deployed to assess the effectiveness

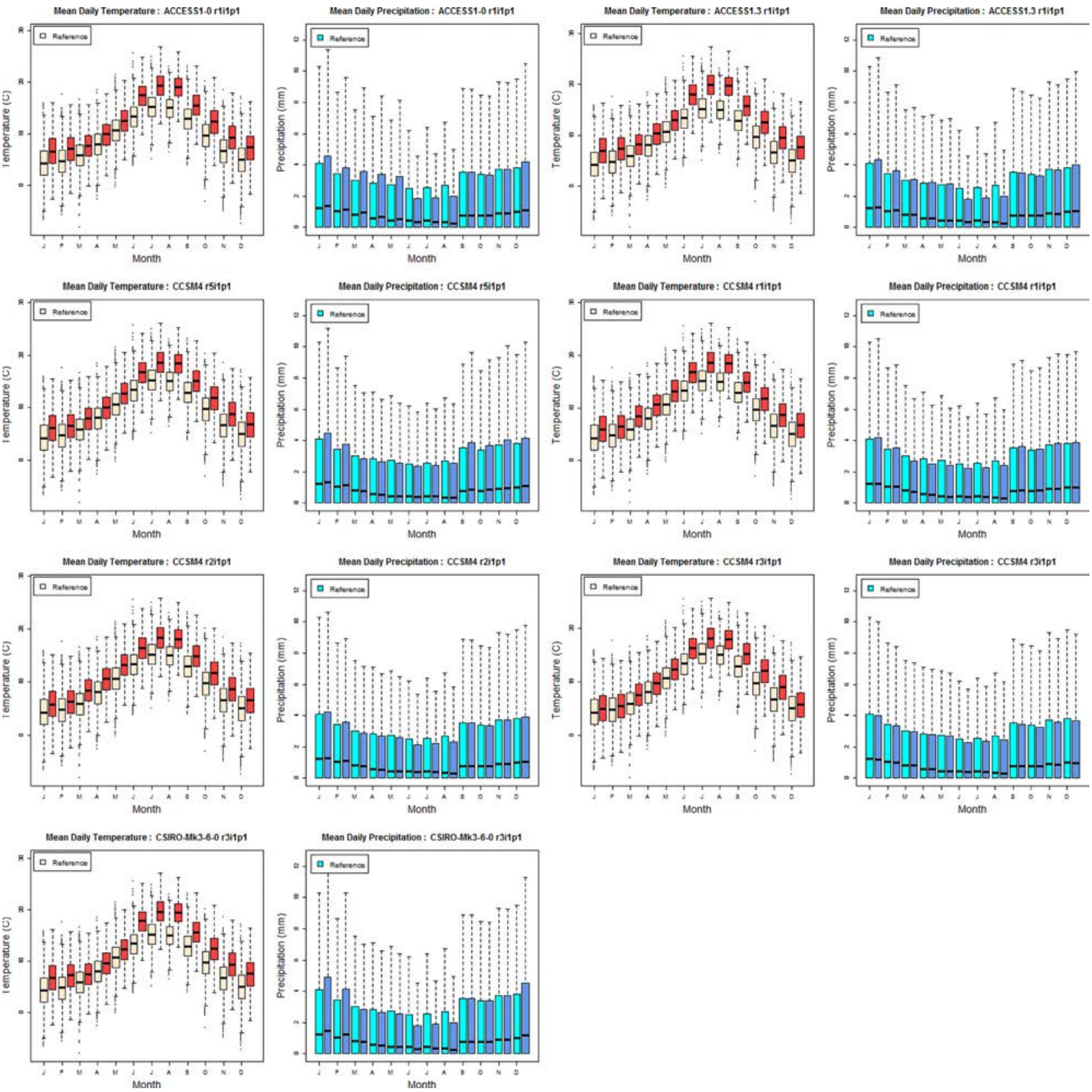


Figure 3.4. Case study output from the advanced level for Cork Airport, detailing the output from the WG when applied to the climate futures identified in the intermediate level. The box plots represent the range of changes in temperature (red) and precipitation (blue) for each scenario.

of design allowances in the construction of flood defences.

3.6 Conclusions and Next Steps

The ICF framework presented in this chapter offers a pathway to integrating climate change information into decision-making in a way that is more sensitive to user needs and the types of information required and, critically, is transparent in the presentation of uncertainties that are present when assessing future climate risks. In particular, potential end users have been welcoming of the basic and intermediate levels. At present, the framework is a prototype, with the methods for each level developed and assessed. There are, of course, limitations associated with all approaches. The greatest caveat is that even the largest set of future climate change projections, as represented by the CMIP5 archive, is probably underdispersive (i.e. does not capture the full range of probable outcomes in the future) and surprise events/outcomes should be expected. If this approach is deemed useful for adaptation planning and communication of climate change risks, it will need to be expanded to other stations and output units of interest (e.g. catchments, grid points). It is also possible to extend the framework to examine other climate variables simulated GCMs.

4 Past and Future Climate Change in the Context of Memorable Seasonal Extremes

4.1 Introduction

Assessments of climate change impacts can be difficult to communicate to the general public and decision-makers. One of the challenges is that climate change may seem temporally, personally and geographically remote and in essence distant from people's lives (Moser, 2010; Pidgeon, 2012). In attempting to bridge this gap we argue that a focus on memorable extremes in both the historical records and as an analogue using future projections may be helpful. By focusing on memorable extremes, individuals can use their grounded memories to gain an insight into key vulnerabilities and impacts that may not be available using conventional approaches. Therefore, we try to make Irish climate change projections more tangible by grounding them in memorable seasonal extremes.

We first identify the wettest, stormiest winters and the driest, hottest summers in observational datasets, before assessing how unusual these events are in the long-term context. These extremes are of particular interest given the magnitude of the social, environmental and economic impacts that they have had previously; additionally, they provide a reference for stress testing existing management plans under likely future conditions. We then assess how the likelihoods of these extreme seasons may have already changed during the period of observation, before employing output from a suite of climate model experiments to explore projected future change. [Paragraph reproduced from Matthews *et al*. (2016).

Here we provide a synthesis of key findings from Matthews *et al*. (2016) and the interested reader is encouraged to consult the full paper in the journal *Climate Risk Management*.

4.2 Key Findings

4.2.1 Changing seasonal extremes from observations

In terms of dry summers, 1995 stands out as the most exceptional since 1850, with a return period value of 84 years (Figure 4.1). The second and third driest summers occurred in 1913 and 1869, respectively, both of which had estimated return periods of 73 years. For wet winters, the most extreme on record occurred in 1994, with a corresponding return period estimate of 63 years. Ranked second and third were the years 1995 and 1883, registering a return period of 40 years and 28 years, respectively. The hottest summer in the observational record was in 1995, with a return period of 441 years. The summers of 2006 and 1976, with return periods of 94 years and 85 years, were ranked second and third, respectively. In terms of storminess, 2013/14 ranks as first with 1914/15 ranking second and 1935/36 ranking third in long-term records. The stormiest winter, 2013/14, is found to have a return period of 2198 years.

Our analysis finds that with the exception of winter storminess, all extreme seasons show signs of an increasing likelihood of occurrence over time. We find that the chance of a summer as warm as 1995 has increased 56-fold over the course of the available records. In the early 1900s, a summer as warm as 1995 would have a return period of approximately 6400 years. Between 1985 and 2014, the return period for a summer as warm as 1995 has reduced to 114 years. Both summer and winter precipitation show an increasing likelihood of extreme seasons (Figure 4.2). For both the wettest winter and driest summer, return periods have halved from the beginning to the end of the record. The trends over time are significant in winter. Our analysis finds that the likelihood of a winter

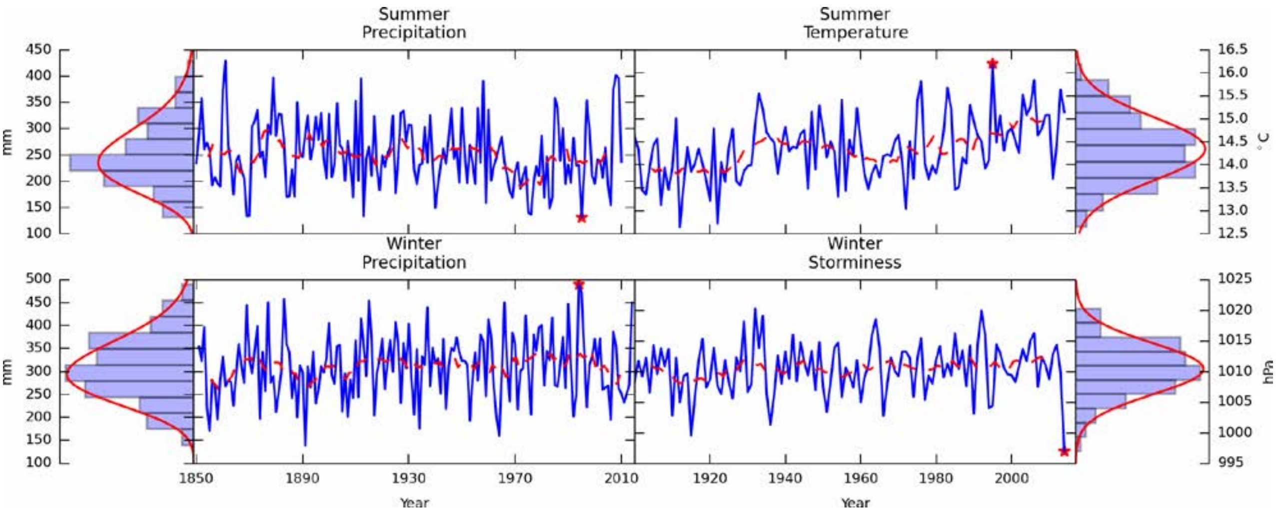


Figure 4.1. The line plots provide time series of the respective variables, in which the dotted line is a 10-year (centred) moving average. The seasons classified as most extreme (wettest winter, driest summer, hottest summer, and winter with lowest mean sea-level pressure – the "stormiest") are highlighted by red stars. Histograms show the distribution of the variables, with fitted gamma (winter/summer precipitation) and normal (winter storminess and summer temperature) distributions overlain (red line). Reproduced from Matthews *et al*. (2016). This is an Open Access article distributed in accordance with the terms of the Creative Commons Attribution (CC BY-NC-ND) license, which permits the copying and redistribution of the material in any medium or format, provided the original work is properly cited. See: http:// creativecommons.org/licenses/by-nc-nd/4.0/

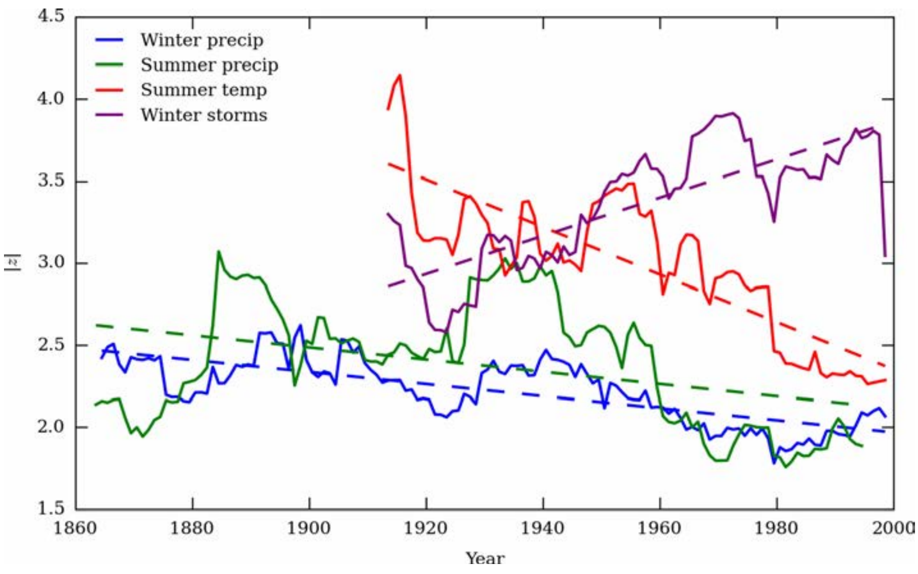


Figure 4.2. *Z*-scores for top-ranked seasons when distributions (gamma = precipitation; normal = storminess and air temperature) are fitted to sliding 30-year samples. Note that here we plot |*z*|, hence a decrease equates to an increasing likelihood of occurrence. The *x*-co-ordinate corresponds to the centre year of the 30-year sample. Reproduced from Matthews *et al*. (2016). This is an Open Access article distributed in accordance with the terms of the Creative Commons Attribution (CC BY-NC-ND) license, which permits the copying and redistribution of the material in any medium or format, provided the original work is properly cited. See: http://creativecommons.org/licenses/by-nc-nd/4.0/

as stormy as 2013/14 has decreased significantly since 1900. However, this may be an artefact of the storminess metric employed.

4.2.2 Changes in the mean and/or variance?

We investigated trends in the mean and variance of each respective variable with trends in the mean calculated from annual series and variance assessed using the 30-year running samples. The change in mean summer air temperature is the only trend that is statistically significant at the 0.05 level, reflecting 0.93°C warming over the period 1900–2014. For both summer and winter precipitation, our analysis finds that trends in the mean have an ~20% chance of being drawn from a population with no trend and highlight that the increase in winter precipitation (+25.7 mm) over the period investigated essentially compensated for the decrease in summer precipitation (–25.6 mm). Our analyses also indicate that the trends in mean sea level pressure and variability for all variables are too weak to approach statistical significance at the 0.05 level or even at the 0.10 level. The variance and mean have increased for wintertime precipitation and summer temperature, so both factors contribute to the increasing likelihood of extreme seasons throughout the observational record (Figure 4.3). For summer air temperature, the changes in the mean are of much greater importance in driving the increase in the likelihood of such warm summers. The growing risk of wetter winters is more driven by a combination of increasing mean winter precipitation and variance (Figure 4.4).

4.2.3 Changing seasonal extremes from model projections

The nature of changing seasonal extremes from future model projections was assessed using the CMIP5 archive of global climate models. Modelled historical series from the CMIP5 archive show broad agreement with observations in terms of the direction of change, but large spread is apparent between the magnitude of change across individual model runs (Figure 4.5). The median changes across the ensemble of climate models tends to be more modest than from observations (Figure 4.6). For summer precipitation in particular it is noted that low frequency variability is not captured well by the climate models, with variability in

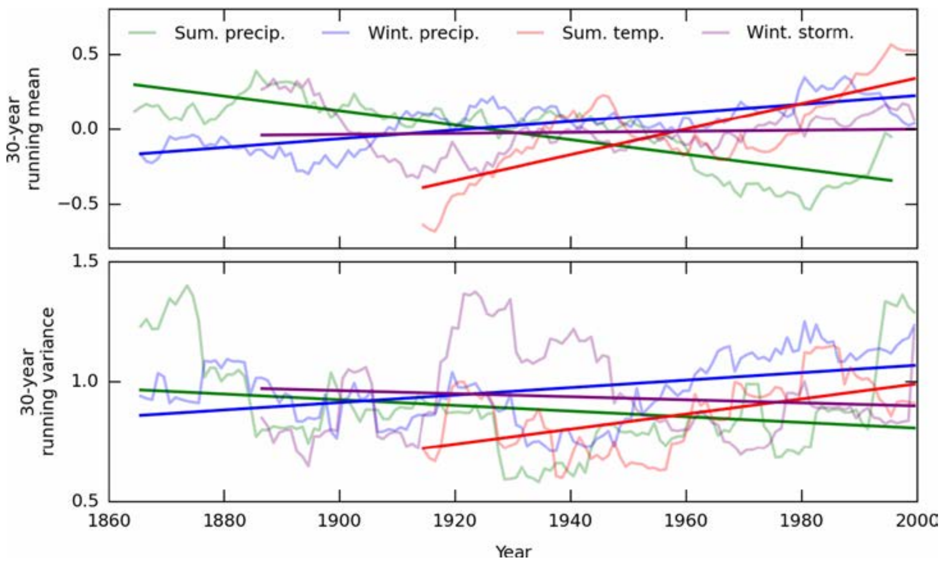


Figure 4.3. Running 30-year means (top) and variances (bottom). Prior to calculating running statistics, all variables were standardized by subtracting the mean and dividing by the standard deviation. Darker lines are least-squares trend lines fitted to the smoothed data to indicate the direction of change. Trends in [...] means utilize the raw annual series; smoothed data are shown here only for clarity of illustration. Reproduced from Matthews *et al*. (2016). This is an Open Access article distributed in accordance with the terms of the Creative Commons Attribution (CC BY-NC-ND) license, which permits the copying and redistribution of the material in any medium or format, provided the original work is properly cited. See: http://creativecommons.org/licenses/by-nc-nd/4.0/

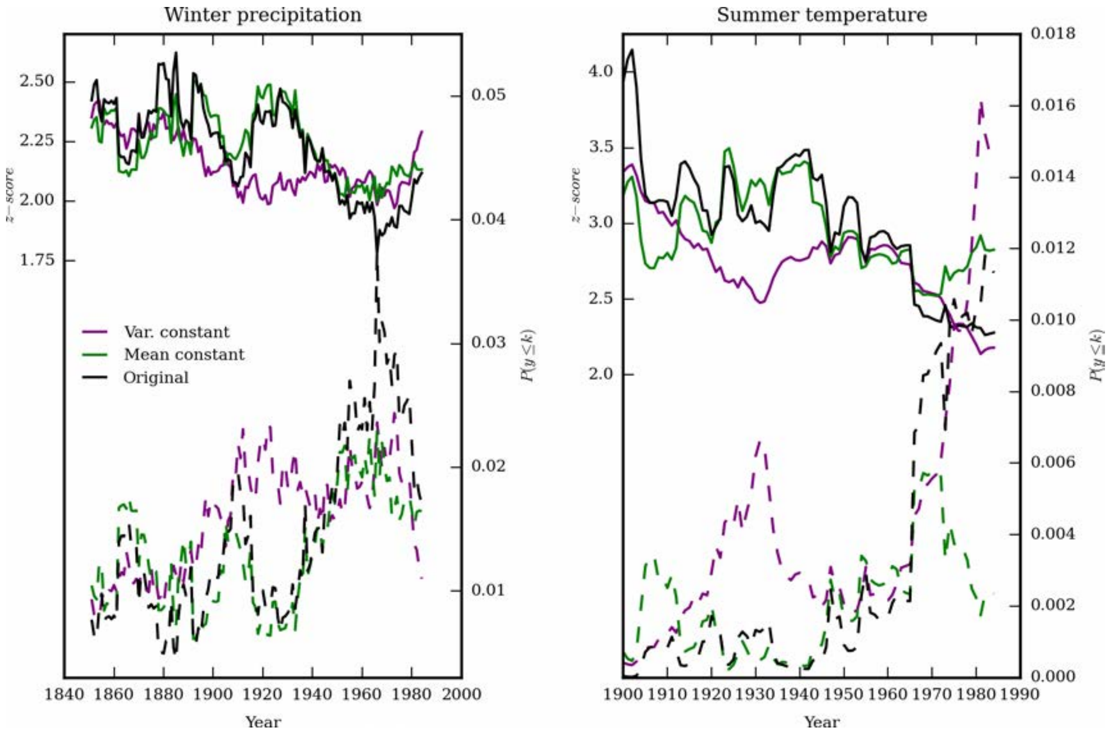


Figure 4.4. Time-evolving *z*-scores (solid lines, left axes) and corresponding *p*-values (dotted lines, right axes) for the top-ranked seasons, when distributions are fitted to sliding 30-year samples. Each line corresponds to a different experiment, in which the mean or variance is held constant, whilst the other is allowed to evolve [...]. Reproduced from Matthews *et al*. (2016).

the observations being far more pronounced than in the model runs.

When we assess the changing likelihood of future seasonal extremes using the CMIP5 climate models forced with different greenhouse gas emissions profiles, as represented by the RCPs, we find substantial changes for all series except winter storminess (Figure 4.7). In particular, we find a very large change in the likelihood of a summer as warm as that in 1995. Under a business-as-usual RCP 8.5 there is an 85% likelihood of summer temperatures exceeding 1995 levels. By the end of the century it is plausible that temperatures as cool as those in 1995 (the hottest in the observations) would be expected to occur on average only once in 7 years. For a 30-year period at the end of the century under RCP8.5, 25–26 years would be expected to be hotter than the hottest summer on record. This represents an almost 250-fold increase in the likelihood of a summer as warm as that in 1995. By this time, the hottest summer on record would be conceived as an usually cool summer.

For dry summers and wet winters the median model runs for the end of the century under RCP 8.5 indicate the precipitation totals associated with the driest summer on record (1995) and the wettest winter (1994/95) are likely to become 8–10 times more likely. For each seasonal extreme indicator examined projected changes become more conservative under RCP 4.5, indicating the importance of avoiding RCP 8.5. Projections of our storminess metric give no suggestion of increasing likelihood for extreme seasonal conditions. It is also important to note that there are large uncertainties in future projections of seasonal extremes. For instance, for summer precipitation under RCP 8.5 there is more than a 5% chance that summers as dry as 1995 will be less probable by the end of the century. By contrast, there is more than a 95% chance that summers as hot as that in 1995 and winters as wet as that in 1994 will be more probable by the end of the 21st century under RCP 8.5. When we assess the relative importance of changes in the mean and variance in driving chances

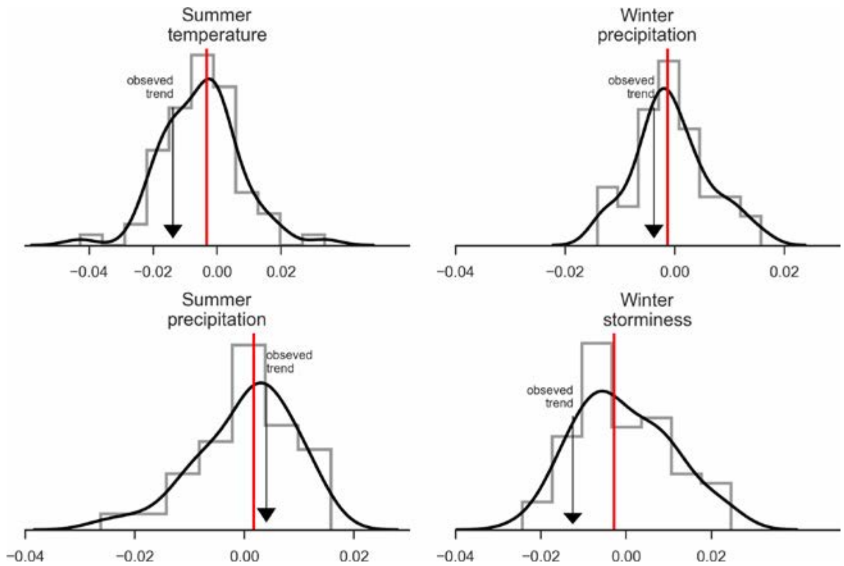


Figure 4.5. Least-squares trends in *z*-scores (per year) during the historical CMIP5 experiments (1901–2005). The black line is the kernel density estimate, providing a smoothed illustration of the density summarised in the underlying histogram (grey outline). The red line highlights the median of this distribution whilst the arrow indicates the gradient of the trend lines plotted in Figure 4.2. Reproduced from Matthews *et al*. (2016). This is an Open Access article distributed in accordance with the terms of the Creative Commons Attribution (CC BY-NC-ND) license, which permits the copying and redistribution of the material in any medium or format, provided the original work is properly cited. See: http://creativecommons.org/licenses/by-nc-nd/4.0/

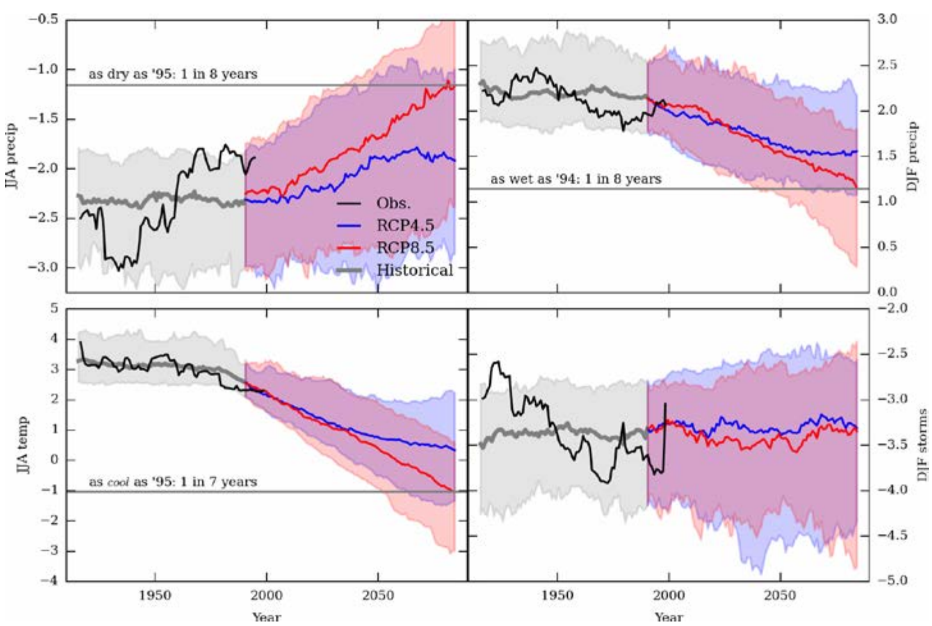


Figure 4.6. Evolution of *z*-scores in the historical and RCP experiment calculated for centred, 30-year sliding windows. The shaded region of the CMIP5 ensemble spans the 5th–95th percentiles, whilst the solid lines provide the median. The discontinuity between the historical and the RCP 8.5 medians is because only a subset of historical model runs continues to RCP 8.5. Note that the observed series are also displayed in each panel and the different scaling on the respective *y*-axes. Reproduced from Matthews *et al*. (2016). This is an Open Access article distributed in accordance with the terms of the Creative Commons Attribution (CC BY-NC-ND) license, which permits the copying and redistribution of the material in any medium or format, provided the original work is properly cited. See: http://creativecommons.org/licenses/by-nc-nd/4.0/

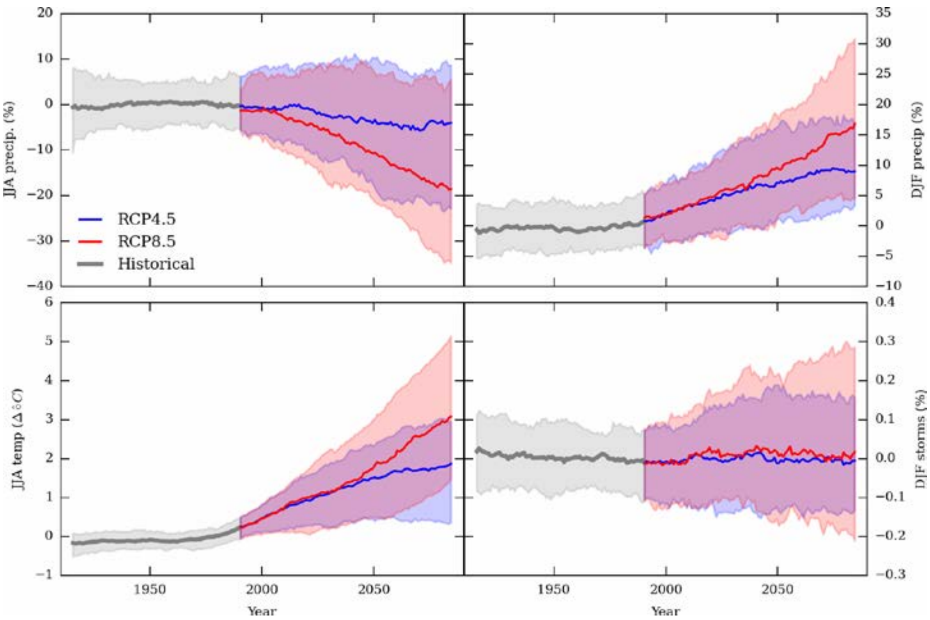


Figure 4.7. Centred 30-year running means of the respective variables, expressed as anomalies from 1901 to 2005. Reproduced from Matthews *et al.* (2016). This is an Open Access article distributed in accordance with the terms of the Creative Commons Attribution (CC BY-NC-ND) license, which permits the copying and redistribution of the material in any medium or format, provided the original work is properly cited. See: http://creativecommons.org/licenses/by-nc-nd/4.0/

in seasonal extremes from the CMIP5 archive we find that for all indicators considered that changes in variance are of secondary importance to changes in the mean.

4.3 Implications and Conclusions

This research shows that over the course of the last 100 years the likelihood of extremely wet winters and hot summers increased significantly. The largest increase was found for hot summers, with the likelihood of a summer as hot as that in 1995 increasing by a factor of 50 over the observed record. When combined with further large increases in the likelihood of extremely hot summers from climate model projections, results give cause for concern. Pascal *et al*. (2013) have previously shown that excess mortality increased during the summer of 1995, while others have shown that mortality rates in Ireland are temperature dependent (Goodman *et al*., 2004; Gleeson *et al*., 2013; Pascal *et al*., 2013).

In comparison with changes in summer air temperature, projected changes in the likelihood of extremely dry summers and wet winters are more subtle, but still potentially challenging. For instance, drought and water resources management were a particular challenge during the summer of 1995. For summer in particular it is important to note the lack of skill of the current generation of climate modes in capturing low-frequency variability in summer precipitation. The Atlantic Multidecadal Oscillation (AMO) plays an important role in determining Irish summer precipitation (McCarthy *et al*., 2015). Given that models are unable to capture the AMO signal, we advise that the CMIP5 ensemble is unlikely to represent decadal scale fluctuations in precipitation driven by sea surface temperatures. Projection of summer precipitation change for the region from CMIP5 models are therefore likely to be too constrained and this should be accounted for in adaptation planning. While our findings show that the likelihood of a winter as stormy as 2013/14 is low by the end of the century, this contradicts other work. In the full paper (Matthews *et al*., 2016) we provide discussion as to why this may be so.

In closing, Irish climate has experienced substantial change in the occurrence of extreme seasonal temperatures and rainfall that, in the earlier half of the 20th century, would have been considered highly exceptional. These changes are largely consistent with climate model projections of future Irish climate. We show that such events are likely to become less the exception and more the norm as further warming is experienced. This is most apparent in the almost 250-fold (RCP 8.5; relative to 1901–2005) increase in the likelihood of a summer as warm as that in 1995 – the warmest currently on record.

5 Rainfall Extremes in a Changing Climate

5.1 Introduction

The extent to which human activity has altered the global climate system is evident in the changing nature of weather and climate extremes (Rummukainen, 2012). Climate change signals are manifest through shifts in the duration, frequency, timing and spatial extent of extreme precipitation and related events such as fluvial flooding and hydrological drought (Trenberth *et al*., 2003; Min *et al*., 2011; Habeeb *et al*., 2015; Blöschl *et al*., 2017). Given the significant human, environmental and financial costs involved across sectors as diverse as agriculture, water quality, flooding and urban drainage, understanding changes in extremes is critical for minimising future risk, particularly to vulnerable populations and infrastructure (Nissen and Ulbrich, 2017).

Despite contrasts in the rate of change across individual components of the regime (e.g. total receipts, upper quantiles), as well as discontinuities in the signal both spatially (e.g. wet vs dry areas, ocean vs land) and temporally (e.g. daily, sub-hourly), evidence indicates an ongoing intensification of the global hydrological cycle (Alexander *et al*., 2006; Westra *et al*., 2013; Wu *et al*., 2013; Asadieh and Krakauer, 2015; Donat *et al*., 2016). Changes shown to occur globally are mirrored by increases in extremes at continental and regional scales (van den Besselaar *et al*., 2012; Wagner *et al*., 2013; Vautard *et al*., 2014; Blöschl *et al*., 2017). Much research has examined past and current trends in observed records as an indicator of possible future conditions (Easterling *et al*., 2000; Murphy *et al*., 2013). Further to this, studies have focused on the attribution of trends and on quantifying their human component. Climate model experiments also constitute a significant strand of current research. Experiments such as CMIP5 (Taylor *et al*., 2012) and CORDEX (Jacob *et al*., 2014) aid process understanding and support the findings of observation-based studies. Additionally, by providing an insight into future behavior, their predictions inform much of the adaption planning necessary to reduce climate change risk (Frei *et al*., 2006; Russo *et al*., 2014; Vautard *et al*., 2014; Nissen and Ulbrich, 2017).

The Clausius–Clapeyron (CC) relation, which suggests that specific humidity and hence atmospheric moisture increase approximately exponentially with temperature (6.5%/K) (Boer, 1993), provides a theoretical basis for understanding changes in rainfall extremes under a warming climate. Although this cannot be translated directly into increases in intensity locally, it provides a basis for understanding the changing patterns found in observed data (Groisman *et al*., 2005; Shiu *et al*., 2012) and model-simulated data (Groisman *et al*., 2005; Sun *et al*., 2006). However, studies suggest that under certain atmospheric conditions the relation may be conservative, with evidence supporting a doubling of the CC rate in extreme hourly intensities (Lenderink and van Meijgaard, 2008; Blenkinsop *et al*., 2015; Bao *et al*., 2017; Lenderink *et al*., 2017). Similarly, studies highlight the importance of rainfall type (convective versus stratiform) and circulation pattern for the scaling between temperature and precipitation intensity (Berg *et al*., 2009). This underlines the complex nature of extremes and the uncertainty in extrapolating changes using simple scaling techniques alone.

This study examines changes in precipitation extremes for the island of Ireland using RCM simulations from the CORDEX project (Giorgi *et al*., 2009; Jacob *et al*., 2014). RCMs allow higher resolution climate information for a limited domain to be dynamically downscaled from the coarser simulations of planetary-scale GCMs. Their greater resolution means that RCMs provide an improved spatiotemporal representation of climate variability and are better able to resolve the local-scale features (e.g. orography, land–sea interactions) and finer scale atmospheric processes (e.g. convection, cloud formation) associated with extremes (Wilby and Wigley, 1997; Ayar *et al*., 2016). However, despite significant model advances, climate projections remain subject to much uncertainty. This is related to factors including model limitations (parameterisation of system processes, coarse scale), the chaotic nature of the system and the indeterminate trajectory of future emissions. Addressing uncertainty necessitates using multiple realisations of future climate from perturbed physics and/or multi-model ensembles run using different emission scenarios. Hence, the availability and use of ensemble datasets is critical from a planning perspective, where poor model sampling can lead to overconfidence in a particular climate outcome, potentially undermining adaptation efforts.

This chapter considers a 19-member ensemble from the CORDEX experiment, developed using 13 highly resolved RCMs run at 11° resolution and forced using lateral boundary conditions from one or more of six different CMIP5 GCMs (Taylor *et al.*, 2012). The ability of climate models to accurately simulate future changes highlights their utility for impact assessment. Hence, using a series of indices relating to extreme rainfall, the analysis first investigates model performance for the island of Ireland with respect to historical simulations. Following this, projected future changes are examined.

5.2 Data and Methods

5.2.1 Data

Model validation of the ability of climate models to capture observed rainfall is conducted using 1 × 1 km gridded datasets of observed daily precipitation for the island of Ireland obtained from Met Éireann (Walsh, 2012). Daily precipitation from 19 different GCM–RCM combinations, which comprise part of the CORDEX ensemble, is analysed (Table 5.1). To develop the ensemble, eight different participant agencies ran their RCMs at a 0.11° (~12.5 km) horizontal grid resolution for a European-wide domain, taking lateral boundary conditions from one of five different GCMs. The ensemble used includes historical GCM runs (1976–2005) alongside future projections (2010–2100), relating to two different RCPs (+4.5 and +8.5 W/m^2). Each RCP is indicative of the possible

Table 5.1. Ensemble members from the CORDEX project used in the present study

Modelling group	GCM	Ensemble member	RCM	RCM version	Abbreviation
Climate Limited-area Modelling Community (CLMcom)	CNRM-CERFACS-CNRM-CM5	r1i1p1	CLMcom-CCLM4-8-17	v1	C1
	ICHEC-EC-EARTH	r12i1p1	CLMcom-CCLM4-8-17	v1	C2
	MOHC-HadGEM2-ES	r1i1p1	CLMcom-CCLM4-8-17	v1	C3
	MPI-M-MPI-ESM-LR	r1i1p1	CLMcom-CCLM4-8-17	v1	C4
Centre National de Recherches Météorologiques (CNRM)	CNRM-CERFACS-CNRM-CM5	r1i1p1	ALADIN53	v1	A1
Danish Meteorological Institute (DMI)	ICHEC-EC-EARTH	r3i1p1	DMI-HIRHAM5	v1	D1
	NCC-NorESM1-M	r1i1p1	DMI-HIRHAM5	v2	D2
Institut Pierre Simon Laplace (IPSL-INERIS)	IPSL-IPSL-CM5A-MR	r1i1p1	IPSL-INERIS-WRF331F	v1	I1
Koninklijk Nederlands Meteorologisch Instituut (KNMI)	ICHEC-EC-EARTH	r12i1p1*	KNMI-RACMO22E	v1	K1
	MOHC-HadGEM2-ES	r1i1p1	KNMI-RACMO22E	v2	K2
	ICHEC-EC-EARTH	r1i1p1	KNMI-RACMO22E	v1	K3
Helmholtz-Zentrum Geesthacht, Climate Service Center, Max Planck Institute for Meteorology (MPI-CSC)	MPI-M-MPI-ESM-LR	r1i1p1	MPI-CSC-REMO2009	v1	M1
	MPI-M-MPI-ESM-LR	r2i1p1	MPI-CSC-REMO2009	v1	M2
Royal Meteorological Institute of Belgium and Ghent University (RMIB-Ugent)	CNRM-CERFACS-CNRM-CM5	r1i1p1	RMIB-UGent-ALARO-0	v1	R1
Swedish Meteorological and Hydrological Institute, Rossby Centre (SMHI)	CNRM-CERFACS-CNRM-CM5	r1i1p1	SMHI-RCA4	v1	S1
	ICHEC-EC-EARTH	r12i1p1	SMHI-RCA4	v1	S2
	IPSL-IPSL-CM5A-MR	r1i1p1	SMHI-RCA4	v1	S3
	MOHC-HadGEM2-ES	r1i1p1	SMHI-RCA4	v1	S4
	MPI-M-MPI-ESM-LR	r1i1p1	SMHI-RCA4	v1a	S4

Data related to daily precipitation downscaled using RCMs run at a 0.11° resolution. Asterisk (*) denotes ensemble member without an RCP 4.5 simulation.

range of radiative forcing by the year 2100 relative to preindustrial levels. For additional information on the RCMs used and their configuration, refer to Jacob *et al*., (2014). It is noted that the ensemble does not provide a systematic sampling of the model space, but is rather assembled on the basis of opportunity (Stone *et al*., 2007). It is to a certain extent affected by an over/under-representation of certain models and by biases in the particular GCM–RCM combinations used. This is further complicated by the use of different realisations (e.g. ICHEC-EC-Earth realisation #12 and #3) from the same parent GCM, as well as differences in the particular RCM version employed. Despite such limitations, the ensemble provides a suite of high-resolution climate projections that are suitable for investigating changes in extremes locally while addressing issues of model and forcing uncertainty.

5.2.2 Indices of extremes

Sixteen different statistical measures (Table 5.2) are used to characterise precipitation extremes. Included are a number from the benchmark suite of internationally agreed indices recommended within the STARDEX (Statistical and Regional dynamical Downscaling of Extremes for European regions; https://crudata.uea.ac.uk/projects/stardex/) project and by the ETCCDI (Expert Team on Climate Change Detection and Indices; http://www.wcrp-climate.org/etccdi/) (Klein Tank *et al*., 2009). Four

Table 5.2. Definitions of the 16 indices used to examine observed and RCM-simulated precipitation extremes

Indices	Abbreviation	Description	Units
Mean and intensity indices			
Average precipitation	Ave	Daily average precipitation	mm/day
Precipitation intensity	SDII	Average precipitation on wet days (> 1 mm)	mm/day
Wet-day percentile	RW95p	The 95th percentile of precipitation on wet days (> 1 mm)	mm/day
All-day percentile	RA975p	The 97.5th percentile of precipitation on all days	mm/day
Quotient of heavy precipitation: wet-day threshold	PFLW95	Fraction of total precipitation occurring on days > RW95p threshold	%
Quotient of heavy precipitation: all-day threshold	PFLA975	Fraction of total precipitation occurring on days > RA975p threshold	%
Heavy precipitation amount: wet-day threshold*	PTLW95	Total precipitation from events occurring on days > RW95p threshold – reported as a seasonal average	mm
Heavy precipitation amount: all-day threshold*	PTLA975	Total precipitation from events occurring on days > RA975p threshold – reported as a seasonal average	mm
Duration indices			
Average 3-day wet-spell length	PWSAV3	Average wet-spell length – defined as a spell with a minimum 3-day duration (> 1 mm)	Days
Average 3-day dry-spell length	PDSAV3	Average dry-spell length – defined as a spell with a minimum 3-day duration (< 1 mm)	Days
Extended 3-day wet spell	PWEXT3	The 95th percentile of wet-spell length – defined as a spell with a minimum 3-day duration (> 1 mm)	Days
Extended 3-day dry spell	PDEXT3	The 95th percentile of dry-spell length – defined as a spell with a minimum 3-day duration (< 1 mm)	Days
Frequency indices			
Wet-day occurrence	R1mm	Frequency occurrence of wet days (> 1 mm) – reported as a percentage of the series length	%
Heavy precipitation occurrence	R20mm	Frequency occurrence of heavy rainfall days (> 20 mm) – reported as a percentage of the series length	%
Count of heavy precipitation days: wet-day threshold*	PNLW95	Count of heavy rain days (> RW95p) – reported as the seasonal average of occurrence	Days
Count of heavy precipitation days: all-day threshold*	PNLA975	Count of heavy rain days (> RA975p) – reported as the seasonal average of occurrence	Days

In calculating the relative future changes, those indices marked with an asterisk (*) use the baseline percentile as the threshold value.

of the (frequency) indices are estimated based on exceedance of a fixed threshold and eight relate to precipitation mean and intensity; also adopted are four duration-based measures. In the case of percentile values, indices are estimated both for the full series (all days; RA975p) and using wet days (> 1 mm; RW95p) only. This is because of the sensitivity of wet-day percentiles to changes in the frequency of wet/dry days, which is shown to produce artificial increases in extreme precipitation (Abiodun *et al*., 2017). Furthermore, from an impacts perspective, this indicator complicates interpretation of projected changes. Here, changes in the complete distribution of daily precipitation is more applicable, particularly in the case of specification for infrastructure design and engineering (Schär *et al*., 2016). Hence, it is advocated that all-day-based percentiles are used for impact-orientated assessments. However, indices that consider wet-day percentiles are useful for model evaluation and comparison. Because of model and data limitations, the indices used relate to moderate rather than rare or exceptional extremes. The relatively short series length (30 years) limits the robustness of extreme distribution fitting and the accurate extrapolation of exceptional events. Similarly, the spatial degradation associated with interpolation means that gridded observations will not capture extremes with the same fidelity as point-scale measurements. In addition, given their current limitations (e.g. spatial resolution, parameterisation of convective precipitation), such events are more likely to exceed the reliable operational capability of the CORDEX RCMs (Diaconescu *et al*., 2015).

Indices are examined for two different 30-year periods (2050s: 2040–69; 2080s: 2070–99) and two different RCP scenarios (4.5 and 8.5). Future differences are quantified relative to the corresponding 1976–2005 historical simulation. For all indices, the percentage change between the baseline and each future period is examined. For those measures based on the exceedance of percentile thresholds, the corresponding baseline value is used when analysing each future period and RCP (see Table 5.2). Following Diaconescu *et al*. (2015), who highlight the advantage of using a last-step remapping procedure for preserving the statistical characteristics of the original field, indices are first applied to the observed and RCM datasets on their native grid. Values are then linearly interpolated to a 0.125° × 0.125° resolution latitude–longitude grid. This common grid is used for model evaluation and spatial ensemble averaging.

5.2.3 Estimation of uncertainty and model performance

Performance of the CORDEX ensemble members in capturing extremes is examined by comparing indices estimated from the simulated and observed data. Three statistical measures including (1) the domain area mean, (2) the standard deviation and (3) the spatial correlation coefficient (Pearson’s *r*) are used. Metrics are selected such that they compare model bias and variability alongside similarity in spatial patterns. In establishing the significance of change signals, the internal variability of the climate system as a source of uncertainty must be addressed. This is similarly important in evaluation where unforced (natural) variability has a confounding influence on the robust assessment of model performance. Hence, to incorporate a measure of variability a non-parametric bootstrap technique is employed (Frei *et al*., 2006; Rajczak *et al*., 2013). For this, 50 time series are generated by sampling with replacement 30 individual years from the original grid point time series. To preserve the spatial pattern all grid points are sampled concurrently using the same years. The procedure is applied to the observed and model-simulated data for each season, RCP and 30-year time slice. Using the resamples, the median – considered the most likely estimate – and confidence bounds are calculated. Changes in climate (Pdiff) are calculated as the percentage difference between the baseline and the future period:

$$\text{Pdiff} = \frac{(\text{future} - \text{baseline})}{\text{baseline}} \times 100 \qquad (5.1)$$

Significance in the strength of projected changes is investigated by comparing all combinations (1225) of the 50 30-year bootstrapped historical and future samples using equation 5.1 (i.e. applied 1225 times). Following Frei *et al*. (2006), changes are deemed significant if the majority – either 90% or 95% dependent on significance level – of comparisons are ≥0% (indicating no difference relative to the baseline). This criterion thus requires that the projected climate is sufficiently outside the bounds of natural variability experienced over the baseline period as to represent a clearly defined shift in the precipitation regime.

5.3 Results

5.3.1 Model validation

Figure 5.1 displays results from the domain area (Ireland) assessment of seasonal performance of each model for all indices. As they are the least correlated with other measures and/or are important from an impacts perspective, three indices are examined in greater detail. This includes precipitation intensity (SDII), wet-day occurrence (R1mm) and the quotient of heavy precipitation (PFLW95). Taylor plots relating to each of these are shown in Figure 5.2. Taylor plots provide an easily interpretable statistical summary of how well the spatial patterns of the observed and simulated fields match each other in terms of their correlation, mean difference and the ratio of their variances.

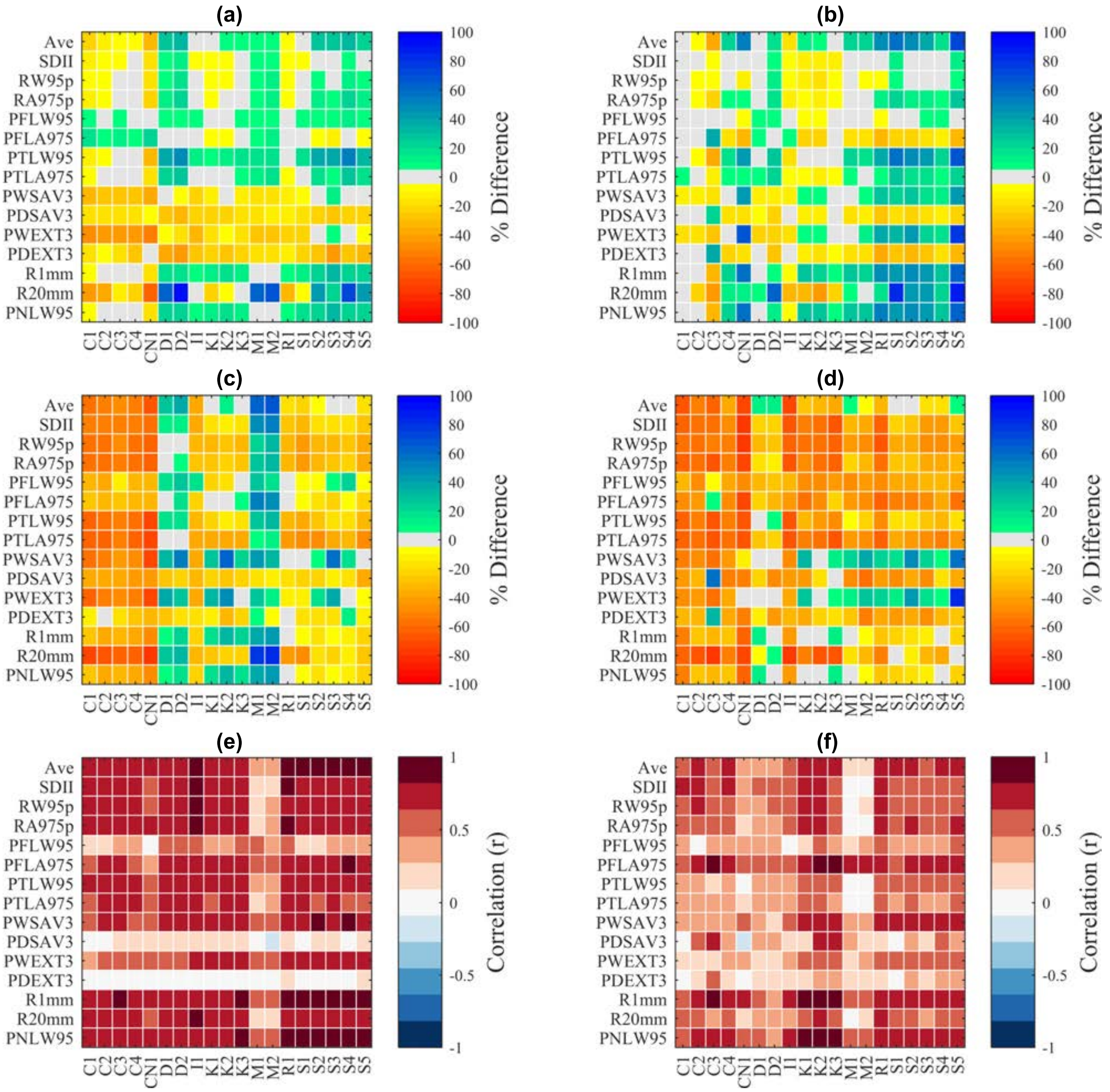


Figure 5.1. Ensemble member performance with respect to differences (%) in the domain area average (a and b) and standard deviation (c and d). Also shown is the spatial correlation (e and f). Plots are developed using the median of the bootstrapped sampled observed and model-simulated datasets. The left-hand column relates to winter (DJF; a, c and e) and the right-hand column relates to summer (JJA; b, d and f).

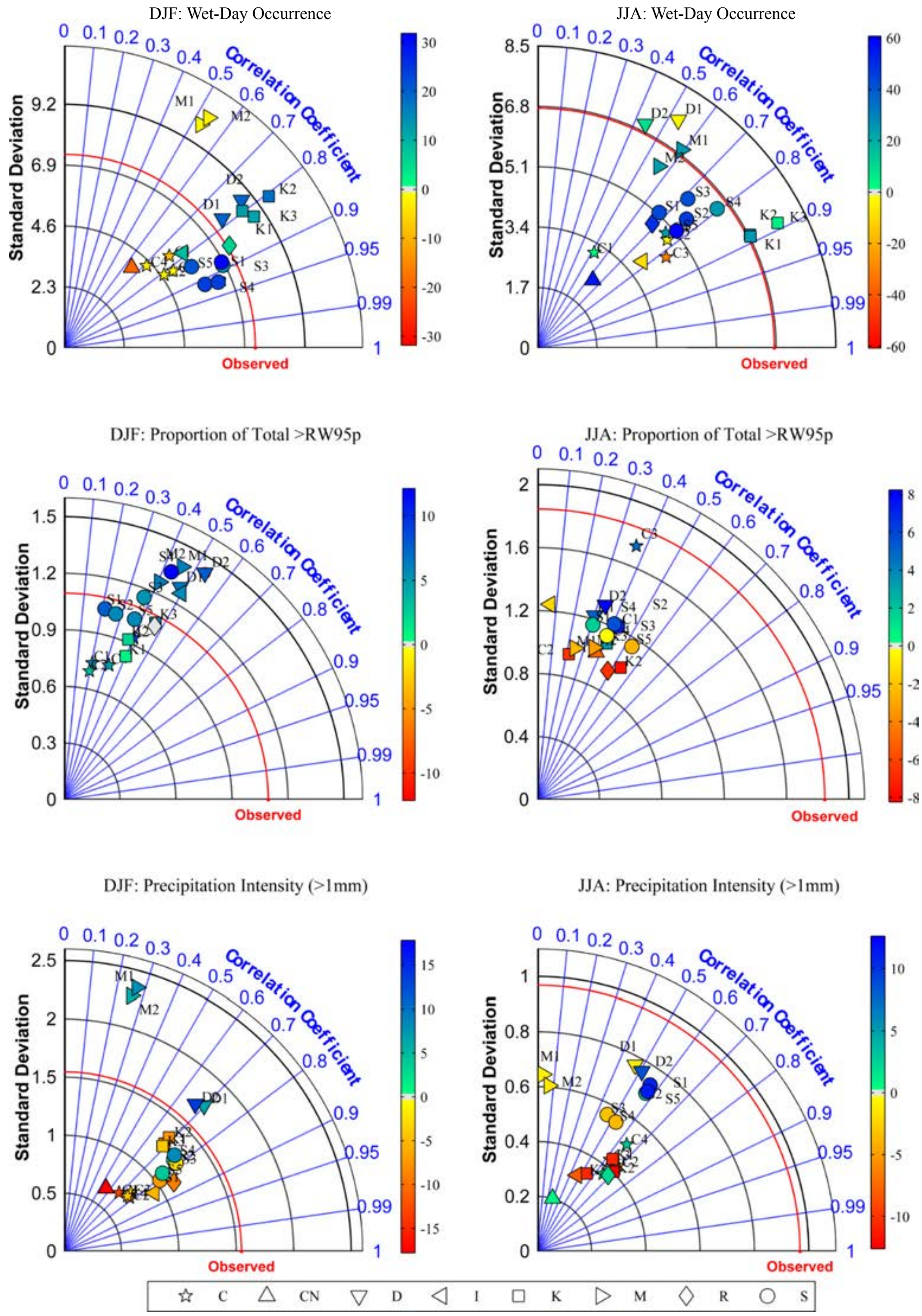


Figure 5.2. Taylor plots showing the correspondence between the gridded observed and model-simulated fields. The proximity of each point to the red line (observed) shows how well models reproduce the spatial variability (standard deviation). Blue lines show values for the correlation coefficient (Pearson's *r*). Values further from/closer to 0/1 are indicative of lesser/greater skill in reproducing the observed spatial pattern. Skill in reproducing the domain average value (mean % bias) is shown using colour shading of individual points and interpreted using the colour bar. Comparisons are made using the median estimate from the bootstrapped samples. Plots are developed for the mean winter/summer wet-day occurrence (1-day length; R1mm), precipitation intensity (SDII) and quotient of heavy precipitation (PFLW95).

The observed data show a number of notable spatial patterns relating to the distribution of precipitation intensity and occurrence. As shown in the supplementary maps in Appendix 1 (Figure A1.1), the south-west and uplands are characterised by high-intensity events. In the case of precipitation occurrence (Figure A1.2) the north-west experiences a high proportion of wet days and is more conspicuous nationally. Conversely, for the proportion of total precipitation from heavy events (Figure A1.3), relative contributions are greatest along the south-west and eastern seaboard, particularly during the summer. The existence of such differences highlights the importance of using multiple indices capable of capturing distinct components of the island's precipitation regime. It also highlights their significance for investigating different aspects of model performance.

The results highlight the degree to which no one ensemble member performs similarly across indices and model diagnostics. Additionally, comparison between figures highlights the extent to which domain averaging can mask spatial disparities in performance. Models both over- and underestimate (particularly C1–C4) the domain-averaged winter precipitation (Ave), but generally tend only to overestimate this indicator in summer (particularly S5). The majority of ensemble members underestimate the length of dry and wet spells during winter; however, they tend only to underestimate the dry spell during summer. In addition, all show poor skill (R ~0) in simulating spatial patterns in the length of winter dry spells. In the case of precipitation intensity (SDII), differences in spatial correlations are most notable for ensemble members contributed by the Max Planck Institute (M1 and M2); this is evident for both seasons. Similarly, in contrast to other members, M1 and M2 overestimate the standard deviation associated with all indices in winter except PDEXT3. They also both tend to overestimate the domain average. Both simulations from the Danish Meteorological Institute are notable for overestimating (with the exception of spell length) most indices, particularly during winter. However, both show high spatial correlations with the observed data. Based on Figure 5.2, all ensemble members underestimate the standard deviation of summer intensity and the proportion of rainfall from heavy events. The same is not evident in winter patterns. The results highlight that the models are better able to simulate indices relating to average and intensity as opposed to duration-based metrics. In cases in which GCM–RCM combinations differ only in the GCM realisation used (M1 and M3; K1 and K3), the downscaled simulations tend to exhibit the same biases, highlighting the importance of the parent model.

5.3.2 Model projections: domain (Ireland) average

Figure 5.3 and 5.4 show the seasonal CORDEX projections for two different time horizons (2040–69; 2070–2099) and each RCP scenario. For each of the 16 indices used, the results are presented as the percentage difference estimated relative to the baseline (1976–2005). Both figures relate to the domain area (island of Ireland) average. Projections are highlighted as significant (outside natural variability) if the signifier of no change (0% difference) is located outside the 95% and 90% prediction bands calculated by comparing all bootstrapped samples. The majority of model projections show an increase/decrease in average winter/summer precipitation, commensurate with an increasingly amplified seasonal regime. For winter, projections suggest a clear increase in precipitation intensity. This trend is most pronounced by the end of the century and under the more emission-intensive RCP 8.5 scenario. Here, the ensemble average indicates a 16% increase in wet-day receipts. However, projections for individual members range between ~7% and ~25%. All simulations differ significantly from the baseline climate indicating robustness in the signal with respect to natural variability. Uniform increases are also noted in the magnitude of events associated with the upper wet-day and all-day percentiles (RW95p, RA975p). Similarly, by the 2080s all projections suggest an increase in the frequency of heavy events (R20mm, PNLA95rel and PNLW975rel).

According to the ensemble mean there is a projected doubling (~100% increase) in the number of days with receipts of > 20 mm (2080s, RCP 8.5). Additionally, the total amount (PTLA95rel and PTLW975rel), as well as the quotient (PFLA95rel and PFLW975rel), of precipitation from heavy events is projected to increase significantly. Similar to intensity, the signal becomes more pronounced over successive horizons and under RCP 8.5. Changes in the intensity indices are contrary to those relating to spell duration. In this case, some projections show little difference; however,

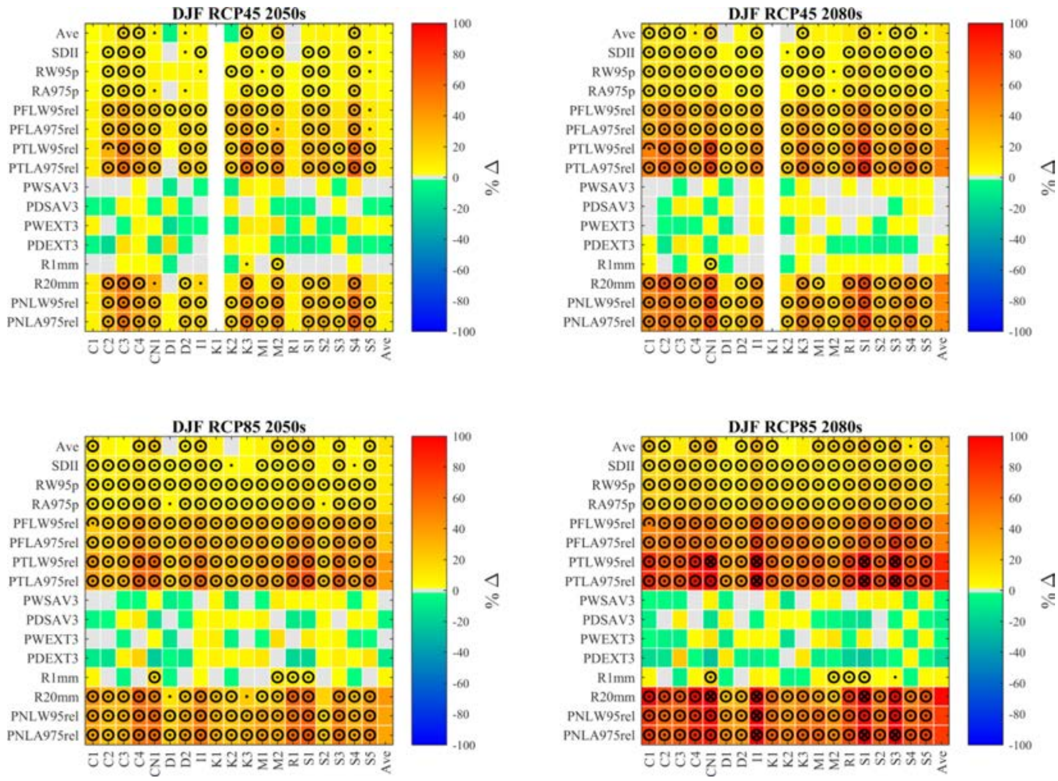


Figure 5.3. Winter (DJF) precipitation simulations from the CORDEX ensemble assessed for changes in 16 indices of extremes. Percentage changes are quantified for two different RCP scenarios (4.5 and 8.5 W/m²) and time horizons (2040–69, 2070–99) relative to the 1976–2005 baseline. Black circles and dots denote changes that are significant at the 95% and 90% level, respectively. For plotting purposes, values >100% are identified with a cross. Indices with the suffix "rel" are estimated using the baseline threshold. Also shown is the ensemble average (Ave).

when a change is registered, disagreements exist in both magnitude and direction. Overall, the ensemble mean suggests an increase in the number of wet days (R1mm, 5.5%, 2080s, RCP 8.5). However, by the same measure the mean duration of wet and dry spells (minimum of 3 days consecutively) is shown to decrease. Based on the ensemble mean, the greatest difference in duration measures is associated with a decrease in the extended wet spell (~15%, 2080s, RCP 8.5).

Summer projections are subject to greater uncertainty, with larger inter-model differences in the strength, magnitude and direction of change evident. However, for the majority of ensemble members a general increase in precipitation intensity is evident. For SDII, the ensemble average suggests increases of between 5% (2050s, RCP 4.5) and 10% (2080s, RCP 8.5). Similarly, increases are shown in the frequency of heavy rainfall events (R20mm). This is mirrored by increases in the proportion and total amount of precipitation contributed by heavy rainfall. In addition to intensity, simulations show an increase in the magnitude of events associated with upper percentiles. Here, an increase of 15% in the 95th percentile of wet-day events is suggested by the ensemble mean (2080s, RCP 8.5). Unlike winter, there is a greater degree of concordance between simulations with regard to changes in spell length, albeit that few are registered as being significant. In the majority of cases the duration of dry/wet spells is shown to increase/decrease. Similar trends are shown for the 95th percentile of spell length. Additionally, the number of wet summer days is projected to decrease. This trend is most pronounced for the 2080s under RCP 8.5. Results for summer show the extent to which individual ensemble members can disagree on the direction of change. For example, K1 projects a ~10% decrease in R20mm; however, for the same period and scenario, S1 returns a ~50% increase. Uncertainty in how the local climate may respond to similar changes in global forcing highlights the value of using a multi-model

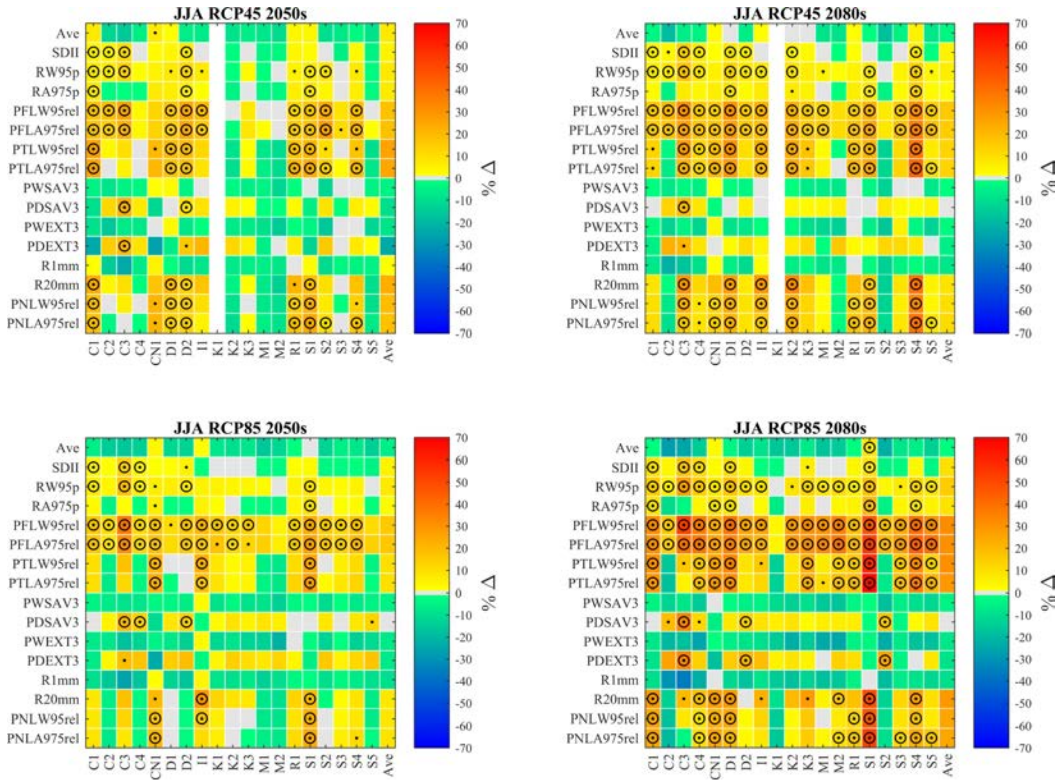


Figure 5.4. Summer (JJA) precipitation simulations from the CORDEX ensemble assessed for changes in 16 indices of extremes. Percentage changes are quantified for two different RCP scenarios (4.5 and 8.5 W/m²) and time horizons (2040–69, 2070–99) relative to the 1976–2005 baseline. Black circles and dots denote changes that are significant at the 95% and 90% level, respectively. Indices with the suffix "rel"are estimated using the baseline threshold. Also shown is the ensemble average (Ave).

ensemble. Similarly, from an impacts and adaption perspective it underlines the potential pitfalls of relying on a single projection or ensemble of limited size.

5.3.3 Model projections: spatially discrete

Figures 5.5 and 5.6 show box plots of the projected changes in four indices (SDII, RA95p, R1mm and PDEXT3/PWEXT3) developed using the percentage difference between the baseline and the future period for each grid point. Grid point values are estimated from the median of the bootstrap samples. The box plots are supplemented by the plots shown in Figures A1.7–A1.10 (see Appendix 1), which map changes in rainfall intensity and occurrence projected by individual ensemble members; also shown is the ensemble average.

The results show the extent to which projected changes vary across the island. Winter precipitation intensity is shown to increase almost uniformly, with an up to ~25% (2080s, RCP 8.5) increase projected by some models. As it cancels out pronounced changes, the ensemble average is more a conservative estimate; however, for the same scenario increases of ~15% are suggested. A similar pattern is shown for RA975p. For both indices the signal is clearer for the 2080s and under RCP 8.5. In the case of wet-day occurrence and spell length, much greater inter-model variability is evident. In the case of CN1 there are significant increases in the percentage of wet days (~20%); however, a number of ensemble members show progressive decreases, most notably C3. Similar patterns are registered for the extended wet spell, albeit that the signal is weaker and more uncertain in the direction of change. As indicated by Figure 5.6, changes in summer intensity are less spatially uniform. A similar pattern of change is shown for the 95th percentile (RA975p). In the case of wet-day occurrence, the majority of ensemble members project reductions across the island. The stronger spatial signal for this indicator is reflected in the ensemble mean, for which an up to 20% reduction in wet days is projected by the end of the century (RCP 8.5).

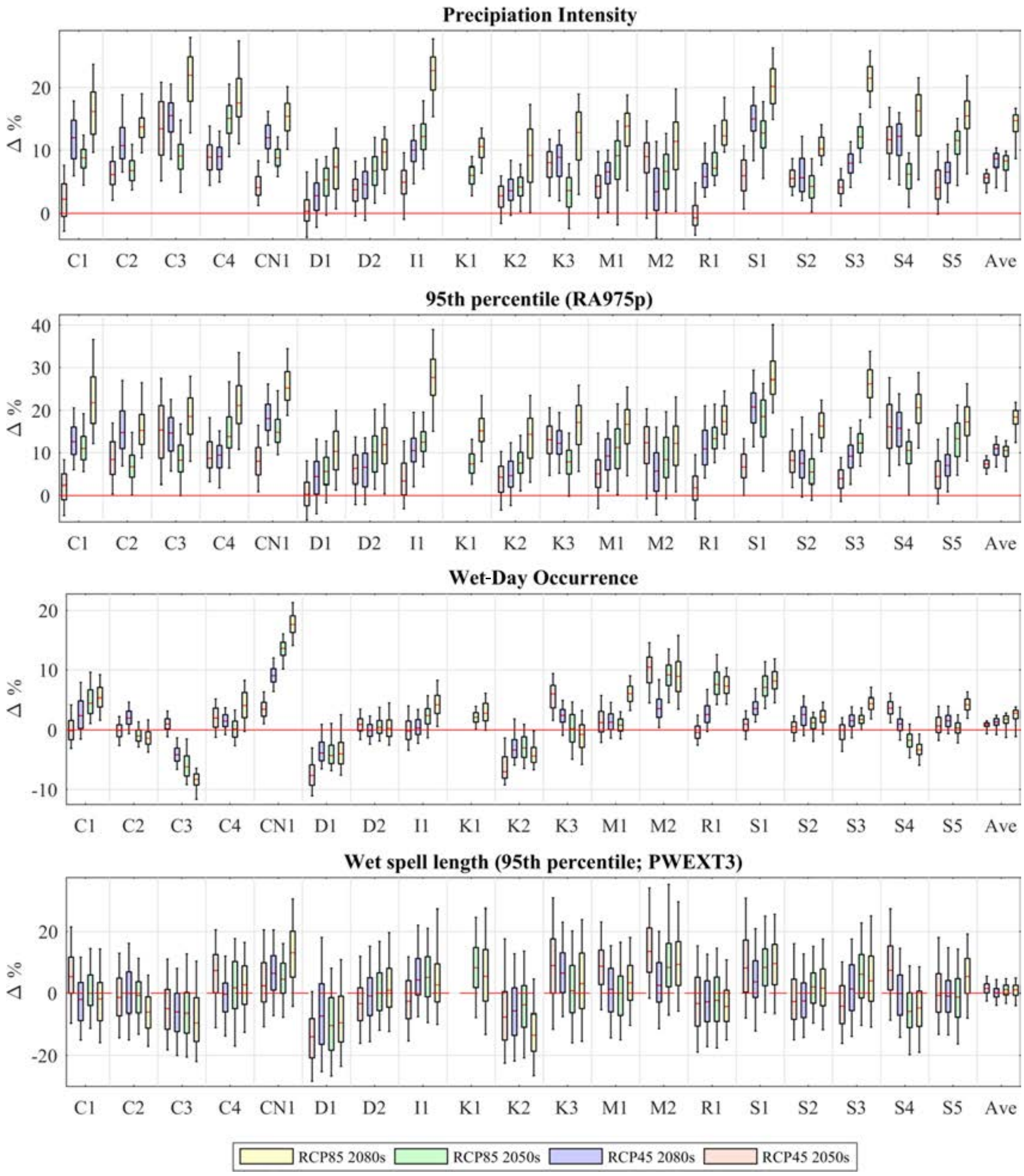


Figure 5.5. Box plots showing the percentage difference between CORDEX-simulated baseline and future conditions estimated on a grid point basis for winter (DJF). Changes are quantified for two different RCP scenarios (4.5 and 8.5 W/m^2) and time horizons (2040–69, 2070–99) relative to 1976–2005. Also shown is the ensemble average (Ave). Box plot whiskers represent the 5th and 95th percentiles. Also shown are the median and 25th and 75th percentiles.

5.4 Conclusion

To examine changes in precipitation extremes for the island of Ireland an ensemble of 19 climate simulations developed within the CORDEX project was analysed. Ensemble members were derived by eight participant meteorological organisations that undertook to run their RCMs at a spatial resolution of 11° for a European-wide domain, taking boundary conditions from one or more of six different CMIP5 GCMs. This study uses historical and future simulations for two different RCPs (+4.5 and +8.5 W/m^2). Sixteen different indices relating to moderate extremes are used to assess precipitation simulations for winter (DJF) and summer (JJA). Included are measures that quantify the duration, frequency and intensity of events. The analysis first examines the accuracy of ensemble members in simulating a 30-year reference period

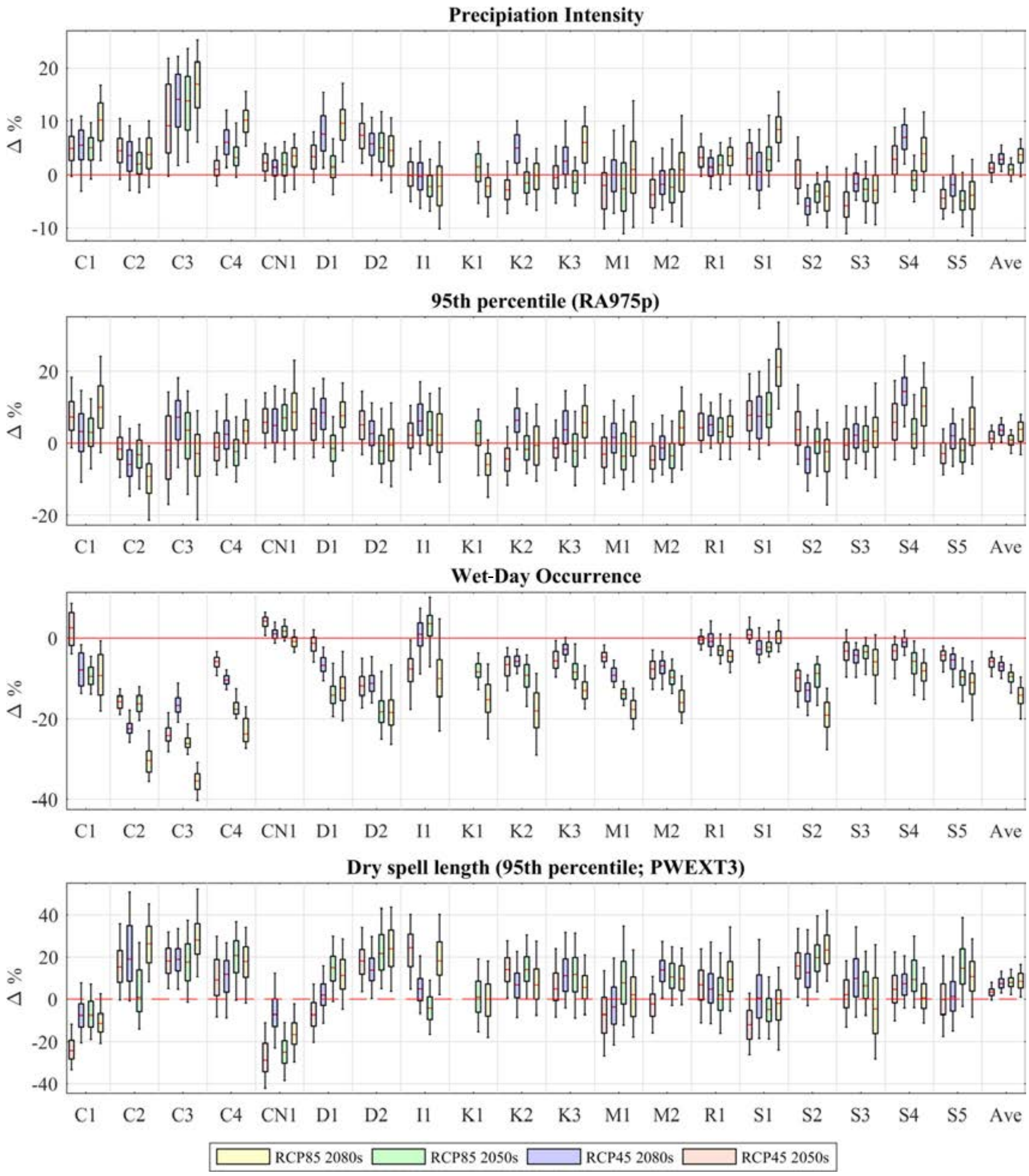


Figure 5.6. Box plots showing the percentage difference between CORDEX-simulated baseline and future conditions estimated on a grid point basis for summer (JJA). Changes are quantified for two different RCP scenarios (4.5 and 8.5 W/m²) and time horizons (2040–69, 2070–99) relative to 1976–2005. Also shown is the ensemble average (Ave). Box plot whiskers represent the 5th and 95th percentiles. Also shown are the median and 25th and 75th percentiles.

(1976–2005). Subsequently, future projections are examined for each indicator using a resampling technique to determine signal significance.

It is shown that no single ensemble member uniformly performs best for all seasons and according to each component of the precipitation regime. Deficiencies found that are common to the majority of CORDEX members include the underestimation of wet (winter) and dry (summer and winter) spell lengths. Additionally, models tend to underestimate the spatial variability of most indices, particularly for summer. However, ensemble members show good performance in capturing spatial patterns, highlighting their ability to resolve topographical forcing, particularly along Ireland’s western seaboard. The degree of difference shown in model skill underlines the importance of using multi-model ensembles. It is universally accepted that adopting an ensemble approach is superior to relying on any single projection in isolation. As no one model provides a complete representation of the climate, using ensembles ensures that those that capture components of the system differently or more skillfully can contribute projections to the collective. Furthermore, ensembles are important for capturing uncertainty in how the climate might respond to altered forcing and, as demonstrated in this study, they provide a reference for understanding the range of current model capabilities.

Model projections indicate an amplification of the precipitation regime, with wetter winters and drier summers occurring. As is the case with most indicators, projected changes become more pronounced as the century progresses and for the most greenhouse gas-intensive RCP 8.5 scenario. Results indicate that changes are likely to be experienced (albeit to differing degrees) right across the island, highlighting the strength of the climate signal spatially. Most models project significant increases in the intensity of winter precipitation accompanied by increases in the number of heavy events (e.g. >20 mm/day). Despite probable reductions in average receipts, increases in the intensity of summer rainfall are suggested, albeit that there is greater uncertainty associated with the magnitude and significance of changes for this season. Although we can be more confident about rainfall intensity, there is less certainty regarding changes in wet-day occurrence. This also applies to changes in dry- and wet-spell lengths. In comparison to winter, it is suggested that summers will experience an increase in the number of dry days accompanied by longer extended dry periods. However, findings for summer are less robust.

In using the CORDEX projections for climate assessment and planning there are a number of limitations that must be considered. First, although ensemble members generally agree as to the direction of the climate signal, there is considerable uncertainty regarding the exact magnitude and timing of future changes. Such uncertainty stems from the limitations of climate models and differences in their numerical representation of system processes. This is compounded by a lack of certainty regarding the exact trajectory of future greenhouse gas emissions and the chaotic nature of the climate system, the latter of which complicates identification of anthropogenic signals. Similarly, the ensemble is limited in its utility for assessing exceptionally rare or localised events with a long return period. This directly impacts the utility of the CORDEX data for designing long-lived and strategically important infrastructure, which must remain resilient to future exceptional extremes.

Although significant improvements in computing capacity have made it possible to produce highly resolved multi-model ensembles such as those undertaken for CORDEX, relative to the highly detailed spatiotemporal scales on which some physical processes occur, models remain limited. This particularly applies in the case of convective precipitation, which is parameterised in larger scale models (>10 km) and represents a significant source of uncertainty. Higher resolution convection-permitting models (<4 km) offer a means to address these shortcomings. In addition, these models provide an improved representation of orography and are thus better able to resolve areas with complex topography. Deficiencies in model skill with respect to convection suggest that the CORDEX simulations may underestimate changes in summer intensities when convective processes are more active. However, convection-permitting models have a high computational demand, which restricts their deployment in large model experiments such as CORDEX. Despite their limitations, the trajectory of computing and model developments means that future studies will benefit from the improved technology that these models will offer for multi-model assessments (Prein *et al*., 2015).

Despite its limitations, the CORDEX ensemble is a valuable resource for climate impact and adaption planning. Projections should be interpreted with caution and supplemented with other lines of investigation, including using insights from observational datasets alongside ongoing and past model experiments (Nolan *et al*., 2017). Although ensemble members disagree as to the extent of the changes, most are in agreement that Ireland’s rainfall regime will probably undergo significant changes, characterised by an increase in the intensity, duration and frequency of extreme events. As such, the results mirror signals already present in observed data and support evidence for an ongoing intensification of the hydrological cycle observed at a regional and global scale.

6 Conclusion and Recommendations

6.1 Introduction

Recent extreme events have served to highlight the vulnerability of various sectors of Irish society to climate change. Given the imperative of successfully adapting to climate change, this work sought to further develop and expand the types of data available for decision-making in adapting to climate change. In delivering on this ambition our project had the following aims:

1. To provide long-term quality-assured data for key climate variables, particularly precipitation, for creating adaptation baselines and for exploring vulnerability to the range of climate variability and extremes across multiple sectors.
2. To present a framework and develop its prototype implementation for better using climate change projections for supporting adaptation decisions. This framework – the ICF framework – is designed to take advantage of the most up-to-date climate model ensembles, with multiple end users in mind, and climate information is tailored to different uses.
3. To demonstrate how historical data and climate change projections from (1) and (2) above can be used to understand how the frequency of past memorable extremes has changed in the historical record and how these extremes are likely to change in frequency in future.
4. To examine changes in daily rainfall extremes from a large ensemble of RCM projections for Ireland.

In this report, Chapters 2–5 deliver on each of the above aims. In the following sections we distil the key contributions and insights gained from each chapter. In section 6.6 we offer overall conclusions and recommendations for future work.

6.2 Historical Data for Decision-making

Traditionally, climate model information has been viewed as the primary source of information for assessing future climate risks and for informing adaptation decisions. Recently, the value of the long-term quality-assured observations for informing climate risk management, in the form of adaptation and decision-making, has become increasingly recognised. In developing adaptation plans, human memory of past extremes can be short lived. Thus, having high-quality historical datasets is a critical tool in developing resilience across multiple sectors. A key challenge in successfully adapting to climate change is creating resilient systems that are capable of functioning within plausible ranges of change, often beyond the experience of recent decades. A key requirement, then, for building resilience is to understand the range of plausible changes. To successfully capture plausible ranges of variability, time series that extend beyond 100 years are required. For instance, a key mode of variability that impacts Irish climate is the AMO, which varies over periods of 60–70 years. Obviously, records of shorter duration are not able to capture the full range of variability.

Historical climate records that take full advantage of the rich history of weather observing on the island offer a valuable approach to meeting the challenges of adaption. Ranges of climate variability and extreme events within historical records can be useful for discovering system vulnerabilities by prompting questions such as “If this event were to occur again, how might components of our system fail?”. They also assist in contextualising how rare recent extremes have been and tracking emerging signals of change and ground-truthing climate model projections.

In this work we presented three datasets based on historical precipitation records that extend to the commencement of rainfall observations in Ireland: the IIP network (1850–2016), the Irish drought catalogue of historical drought extending to 1766 and a monthly rainfall series that extends to 1711 (IoI_1711 series). These resources provide valuable datasets for understanding Irish rainfall climatology and historical extremes for informing adaptation. These datasets can be used for interrogating system vulnerability and for stress testing the effectiveness of adaptation options. Indeed, Irish Water are already using these datasets to do exactly that in developing water plans for the island. Further work is required to extend the range of variables for which we have such long-term, quality-assured records and to diversify information sources (see section 6.6).

6.3 Irish Climate Futures

Projections of climate change from GCMs are an important tool in the armoury for adaptation. Given the increasing demand for climate change projections for adaptation, a key challenge is the provision of climate information in a way that facilitates the needs of end users charged with developing adaptation strategies. In particular, climate model information needs to be presented:

- at a level of complexity that is warranted by the decision at hand, i.e. there is no need for detailed regional scenarios when high-level information at a national scale is required; conversely, when potentially expensive (socially and economically) decisions are required, more detailed information should be available;
- in a way that is fully transparent about the uncertainties associated with future climate change and allows end users to attempt to quantify realistic ranges of potential future changes from the full set of available climate models;
- in a way that limits scientific jargon and in transparent and simple terms, but in a way that is scientifically robust;
- in a way that is decision centric and allows decision-makers to choose the type of information necessary for a decision at hand and to construct their own information based on expert knowledge of systems or sectors in question.

In an attempt to meet these challenges, this work puts forward an ICF framework that provides:

- a novel, flexible and cutting-edge framework in which complex climate information can be tailored to the needs of decision-makers and decision-makers can tailor climate information to their own needs;
- a framework in which full advantage can be taken of cutting-edge modelling outputs (e.g. CMIP5) for informing decision-making in Ireland, using the best possible information;
- a framework in which uncertainty in climate change projections can be an enabler of more informed decision-making rather than a barrier to adaptation;
- a framework in which pre-existing and ongoing national research (e.g. regionalised EC-EARTH and CORDEX outputs) can be incorporated and readily updated as new outputs come on stream;

The prototype version of the framework can be viewed at https://mu-icarus.shinyapps.io/climate_futures_dashboard_18012018/.

The ICF framework presented in Chapter 3 offers a pathway to integrating climate change information into decision-making in a way that is more sensitive to user needs and the types of information required, and in a way that is transparent in the presentation of uncertainties when assessing future climate risks. In moving away from traditional impacts-led adaptation, the ICF framework offers flexibility in assessing future climate risks with climate model projections and tailors information (basic, intermediate and advanced levels) to user needs. We have shown how the framework can be used to develop narrative descriptions of change that represent plausible ranges of change from the CMIP5 ensemble of GCMs and how the framework can be used to stress test system vulnerability or adaptation options, by allowing users to determine ranges of change in temperature and precipitation for exploring their own systems responses. The framework can also be used for traditional top-down approaches to impact assessment and is extendable, using a WG, to exploring climate change signals in combination with natural variability, at monthly to daily timescales. Although this work is limited to developing a prototype exemplar of the framework, the workflow is designed and implemented in such a way that it can be easily extended to other locations and units of analysis (grids, catchments, etc.). The extension of the framework in this way will require additional funding support. A caveat, however, is that even the CMIP5 ensemble of climate models is likely to under-represent the plausible ranges of future change, and users of climate model information for decision-making should be made aware of this fact.

6.4 Changing Seasonal Extremes

Chapter 4 illustrates the value of the work completed in building historical datasets and the basic level of interaction of the ICF framework. This work examined how the probability of memorable extreme events has changed in the past and how frequent such extremes are likely to become in the future. Key findings from the research show that over the period 1900–2014 records suggest that a summer as warm as that in 1995 has become 50 times more likely, whereas the probability of a winter as wet as that in 1994/95 (the wettest winter on record until winter 2015/16) has doubled. The likelihood of the driest summer (1995) has also doubled since 1850. Under the business-as-usual (RCP 8.5) scenario, climate model projections suggest that our hottest summer historically may be seen as an unusually cool summer in the future. By the end of the century, summers as cool as that in 1995 may occur only once every 7 years or so. Winters as wet as that in 1994/95 and summers as dry as that in 1995 may become 8 and 10 times more frequent, respectively. Insights into what these changes mean for Irish society is afforded by examining the impacts that these extremes had. The hot and dry summer of 1995 was associated with increased mortality (especially among the elderly and infirm) in Ireland. Rainfall deficits and water shortages in summer 1995 also adversely impacted the agricultural sector. The effects of the latter have the potential to be felt internationally through Ireland's agricultural exports. The possibility of summer temperatures as warm as those in 1995 occurring almost 90% of the time by the end of this century under a business-as-usual scenario must be of concern.

6.5 Changing Rainfall Extremes

Chapter 5 examined changes in precipitation extremes for the island of Ireland using an ensemble of 19 climate simulations developed within the CORDEX project. Ensemble members were derived by eight participant meteorological organisations that undertook to run their RCMs at a spatial resolution of 11° for a European-wide domain, taking boundary conditions from one or more of six different CMIP5 GCMs. This study uses historical and future simulations for two different RCPs (+4.5 and +8.5 W/m^2). Sixteen different indices relating to moderate extremes are used to assess precipitation simulations for winter (DJF) and summer (JJA). Measures that quantify the duration, frequency and intensity of events are included. The analysis first examines the accuracy of ensemble members in simulating a 30-year reference period (1976–2005). Subsequently, future projections are examined for each indicator using a resampling technique to determine signal significance.

It is shown that no single ensemble member uniformly performs best for all seasons and according to each component of the precipitation regime. Deficiencies found that were common to the majority of CORDEX members include the underestimation of wet (winter) and dry (summer and winter) spell lengths. Additionally, models tend to underestimate the spatial variability of most indices, particularly for summer. However, ensemble members show good performance in capturing spatial patterns, highlighting their ability to resolve topographical forcing, particularly along Ireland's western seaboard. The degree of difference shown in model skill underlines the importance of using multi-model ensembles. It is universally accepted that adopting an ensemble approach is superior to relying on any single projection in isolation or a limited selection of projections. As no one model provides a complete representation of the climate, using ensembles ensures that those that capture components of the system differently or more skillfully can contribute projections to the collective.

Projections from the CORDEX ensemble indicate an amplification of the precipitation regime, with wetter winters and drier summers occurring. The results indicate that changes are likely to be experienced (albeit to differing degrees) right across the island, highlighting the strength of the climate signal spatially. Most models project significant increases in the intensity of winter precipitation, accompanied by increases in the number of heavy events (e.g. > 20 mm/day). Despite probable reductions in average receipts, increases in the intensity of summer rainfall are suggested, albeit that there is greater uncertainty associated with the magnitude and significance of changes for this season. Although we can be more confident about rainfall intensity, there is less certainty regarding changes in wet-day occurrence. This also applies to changes in dry- and wet-spell lengths. In comparison to winter, it is suggested that summers will experience an increase in the number of dry days, accompanied by longer extended dry periods. However, findings for summer are uncertain.

In using the CORDEX projections for climate assessment and planning there are a number of limitations that must be considered. First, although ensemble members generally agree as to the direction of the climate signal, there is considerable uncertainty regarding the exact magnitude and timing of future changes. Such uncertainty stems from the limitations of climate models and differences in their numerical representation of system processes. This is compounded by (1) the fact that CORDEX, in attempting to get to a higher resolution than is possible in the CMIP5 archive, is only forced by up to six GCMs; (2) a lack of certainty regarding the exact trajectory of future greenhouse gas emissions; and (3) the chaotic nature of the climate system, which complicates identification of anthropogenic signals. Similarly, the ensemble is limited in its utility for assessing exceptionally rare or localised events with a long return period. This directly impacts the utility of the CORDEX data for designing long-lived and strategically important infrastructure, which must remain resilient to future exceptional extremes.

6.6 Key Recommendations

Although this research adds considerably to the range of climate data of utility for decision-making in adapting to climate change, much valuable work remains to be done. Below, we identify what we see as four priorities for ensuring that we have the range of information needed to realise a climate-resilient Ireland in the decades ahead:

1. Perhaps the greatest value of this work to adaption decision-making are the long-term records of precipitation that have been developed. However, we have only scratched the surface of what is possible, given the rich history of weather observing in Ireland. Many data remain hidden from scientific scrutiny on paper records and it should be a priority to support the digitisation, quality assurance and analysis of these data. A number of projects are ongoing to this end (see Chapter 2), but there is room for additional work, particularly for climate variables beyond temperature and precipitation that are important to decision-makers.
2. Documentary sources of climate information can also play an important role in establishing ranges of variability and change historically, and importantly can shed light on how society was impacted by, and responded to, historical extremes. To this end, more could made of existing weather diaries and archives (including newspaper archives) that help to bring forgotten hazards back to life in surveying current vulnerabilities (see, for example, Murphy *et al.*, 2018).
3. It should also be a priority to temporally extend our understanding of climate variability and change further back in time. Ireland has a vibrant paleo-climate community and the data that it produces, in the form of climate reconstructions from various sources, including tree rings and peat records, can offer value to adaptation decision-making. This is especially the case in understanding plausible ranges of variability for assessing vulnerability and stress testing adaptation options, especially in summer, for which uncertainties in future projections of precipitation are considerable. Such work could greatly expand our understanding of the spatiotemporal history of droughts and floods and help bound the ranges of variability that are plausible for stress testing decisions.
4. Finally, we recommend that the ICF framework that we have developed here for tailoring climate model projections to meet the needs of end users be extended to become operational. This will require further ground testing with decision-makers, expansion of the methods across the island and integration with existing climate services platforms. The prototype ICF Dashboard can be viewed here: https://mu-icarus.shinyapps.io/climate_futures_dashboard_18012018/.

References

Abiodun, B.J., Adegoke, J., Abatan, A.A., Ibe, C.A., Egbebiyi, T.S., Engelbrecht, F. and Pinto, I., 2017. Potential impacts of climate change on extreme precipitation over four African coastal cities. *Climatic Change* 143: 399–413.

Alexander, L.V., Zhang, X., Peterson, T.C., Caesar, J., Gleason, B., Tank, A.K., Haylock, M., Collins, D., Trewin, B., Rahimzadeh, F. and Tagipour, A., 2006. Global observed changes in daily climate extremes of temperature and precipitation. *Journal of Geophysical Research* 111(D5).

Asadieh, B. and Krakauer, N.Y., 2015. Global trends in extreme precipitation: climate models versus observations. *Hydrology and Earth System Sciences Discussions* 19: 877–891.

Ayar, P.V., Vrac, M., Bastin, S., Carreau, J., Déqué, M. and Gallardo, C., 2016. Intercomparison of statistical and dynamical downscaling models under the EURO- and MED-CORDEX initiative framework: present climate evaluations. *Climate Dynamics* 46: 1301–1329.

Bao, J., Sherwood, S.C., Alexander, L.V. and Evans, J.P., 2017. Future increases in extreme precipitation exceed observed scaling rates. *Nature Climate Change* 7: 128–132.

Barriopedro, D., Gallego, D., Alvarez-Castro, M.C., García-Herrera, R., Wheeler, D., Pena-Ortiz, C. and Barbosa, S.M., 2014. Witnessing North Atlantic westerlies variability from ships' logbooks (1685–2008). *Climate Dynamics* 43: 939–955.

Bastola, S., Murphy, C. and Sweeney, J., 2011. The sensitivity of fluvial flood risk in Irish catchments to the range of IPCC AR4 climate change scenarios. *Science of the Total Environment* 409: 5403–5415.

Bastola, S., Murphy, C. and Fealy, R., 2012. Generating probabilistic estimates of hydrological response for Irish catchments using a weather generator and probabilistic climate change scenarios. *Hydrological Processes* 26: 2307–2321.

Berg, P., Haerter, J.O., Thejll, P., Piani, C., Hagemann, S. and Christensen, J.H., 2009. Seasonal characteristics of the relationship between daily precipitation intensity and surface temperature. *Journal of Geophysical Research* 114(D18).

Blenkinsop, S., Chan, S.C., Kendon, E.J., Roberts, N.M. and Fowler, H.J., 2015. Temperature influences on intense UK hourly precipitation and dependency on large-scale circulation. *Environmental Research Lett*ers 10: 054021.

Blöschl, G., Hall, J., Parajka, J., Perdigão, R.A., Merz, B., Arheimer, B., Aronica, G.T., Bilibashi, A., Bonacci, O., Borga, M. and Čanjevac, I., 2017. Changing climate shifts timing of European floods. *Science* 357: 588–590.

Boer, G.J., 1993. Climate change and the regulation of the surface moisture and energy budgets. *Climate Dynamics* 8: 225–239.

Box, J.E., 2002. Survey of Greenland instrumental temperature records: 1873–2001. *International Journal of Climatology* 22: 1829–1847.

Butler, C.J., Coughlin, A.D.S. and Fee, D.T., 1998. Precipitation at Armagh Observatory 1838–1997. *Biology and Environment* 98B(2): 123–140.

Changnon, D., 2004. Improving outreach in atmospheric sciences: assessment of users of climate products. *Bulletin of the American Meteorological Society* 85: 601–606.

Charlton, R., Fealy, R., Moore, S., Sweeney, J. and Murphy, C., 2006. Assessing the impact of climate change on water supply and flood hazard in Ireland using statistical downscaling and hydrological modelling techniques. *Climatic Change* 74: 475–491.

Chen, J., Brissette, F.P. and Leconte, R., 2010. A daily stochastic weather generator for preserving low-frequency of climate variability. *Journal of Hydrology* 388: 480–490.

Chen, J., Brissette, F.P. and Leconte, R., 2012. Downscaling of weather generator parameters to quantify hydrological impacts of climate change. *Climate Research* 51: 185–200.

Clark, P.U., Shakun, J.D., Marcott, S.A., Mix, A.C., Eby, M., Kulp, S., Levermann, A., Milne, G.A., Pfister, P.L., Santer, B.D. and Schrag, D.P., 2016. Consequences of twenty-first-century policy for multi-millennial climate and sea-level change. *Nature Climate Change* 6: 360–369.

Compo, G.P., Whitaker, J.S., Sardeshmukh, P.D., Matsui, N., Allan, R.J., Yin, X., Gleason, B.E., Vose, R.S., Rutledge, G., Bessemoulin, P. and Brönnimann, S., 2011. The Twentieth Century Reanalysis project. *Quarterly Journal of the Royal Meteorological Society* 137: 1–28.

Cook, E.R., Seager, R., Kushnir, Y., Briffa, K.R., Büntgen, U., Frank, D., Krusic, P.J., Tegel, W., van der Schrier, G., Andreu-Hayles, L. and Baillie, M., 2015. Old World megadroughts and pluvial during the Common Era. *Science Advances* 1(10): e1500561. https://doi.org/10.1126/sciadv.1500561.

D'Arrigo, R., Seager, R., Smerdon, J.E., LeGrande, A.N. and Cook, E.R., 2011. The anomalous winter of 1783–1784: was the Laki eruption or an analog of the 2009–2010 winter to blame? *Geophysical Research Letters* 38: L05706.

Déqué, M. and Somot, S., 2010. Weighted frequency distributions express modelling uncertainties in the ENSEMBLES regional climate experiments. *Climate Research* 44: 195–209.

Dessai, S., Hulme, M., Lempert, R. and Pielke Jr, R., 2009. Climate prediction: a limit to adaptation? In Adger, W.N., Lorenzoni, I., O'Brien, K.L. (eds.), *Adapting to Climate Change: Thresholds, Values, Governance*. Cambridge University Press, Cambridge, pp. 64–78.

Diaconescu, E.P., Gachon, P. and Laprise, R., 2015. On the remapping procedure of daily precipitation statistics and indices used in regional climate model evaluation. *Journal of Hydrometeorol*ogy 16: 2301–2310.

Dickson, D., 1997. *Arctic Ireland: The Extraordinary Story of the Great Frost and Forgotten Famine of 1740–41*. White Row Press Ltd., Belfast, pp. 96.

Dilling, L. and Lemos, M.C., 2011. Creating usable science: opportunities and constraints for climate knowledge use and their implications for science policy. *Global Environmental Change* 21: 680–689.

Dixon, F.E., 1959. An Irish weather diary of 1711–1725. *Quarterly Journal of the Royal Meteorological Society* 85(366): 371–385.

Dobler, C., Hagemann, S., Wilby, R.L. and Stätter, J., 2012. Quantifying different sources of uncertainty in hydrological projections in an Alpine watershed. *Hydrology and Earth System Sciences Discussions* 16(11): 4343–4360.

Donat, M.G., Lowry, A.L., Alexander, L.V., O'Gorman, P.A. and Maher, N., 2016. More extreme precipitation in the world's dry and wet regions. *Nature Climate Change* 6: 508–513.

Easterling, D.R., Evans, J.L., Groisman, P.Y., Karl, T.R., Kunkel, K.E. and Ambenje, P., 2000. Observed variability and trends in extreme climate events: a brief review. *Bulletin of the American Meteorological Society* 81: 417–425.

Engler, S., Mauelshagen, F., Werner, J. and Luterbacher, J., 2013. The Irish famine of 1740–1741: famine vulnerability and "climate migration". *Climate of the Past* 9: 1161–1179.

Frei, C., Schöll, R., Fukutome, S., Schmidli, J. and Vidale, P.L., 2006. Future change of precipitation extremes in Europe: intercomparison of scenarios from regional climate models. *Journal of Geophysical Research* 111(D6).

Giorgi, F., Jones, C. and Asrar, G.R., 2009. Addressing climate information needs at the regional level: the CORDEX framework. *World Meteorological Organisation Bulletin* 58: 175.

Gleeson, E., Caffarra, A., Coleman, M., Dias, F., Dijkstra, H., Donnelly, A., Drijfhout, S., Dwyer, N., Gallagher, S., Gault, J., Goodman, P., Gray, S., Livina, V., Martin, D., McGrath, R., McKinstry, A., Murphy, C., Nolan, P., O'Dowd, C., O'Dwyer, B., O'Sullivan, J., Regan, E., Semmler, T., Sweeney, C., Tiron, R., Walsh, S. and Zottele, F., 2013. *Ireland's Climate: The Road Ahead*. Met Éireann, Dublin.

Goodman, P.G., Dockery, D.W. and Clancy, L., 2004. Cause-specific mortality and the extended effects of particulate pollution and temperature exposure. *Environmental Health Perspectives* 112: 179–185.

Gray, S., 2016. *Local Authority Adaptation Strategy Development Guideline.* Environmental Protection Agency, Johnstown Castle, Ireland.

Greene, A.M., Goddard, L. and Lall, U., 2006. Probabilistic multimodel regional temperature change projections. *Journal of Climate* 19: 4326–4343.

Groisman, P.Y., Knight, R.W., Easterling, D.R., Karl, T.R., Hegerl, G.C. and Razuvaev, V.N., 2005. Trends in intense precipitation in the climate record. *Journal of Climate* 18: 1326–1350.

Guston, D.H., 2001. Boundary organizations in environmental policy and science: an introduction. *Science, Technology and Human Values* 26: 399–408.

Habeeb, D., Vargo, J. and Stone, B., 2015. Rising heat wave trends in large US cities. *Natural Hazards* 76: 1651–1665.

Hall, J., 2007. Probabilistic climate scenarios may misrepresent uncertainty and lead to bad adaptation decisions. *Hydrological Processes* 21: 1127–1129.

Jacob, D., Petersen, J., Eggert, B., Alias, A., Christensen, O.B., Bouwer, L.M., Braun, A., Colette, A., Déqué, M., Georgievski, G. and Georgopoulou, E., 2014. EURO-CORDEX: new high-resolution climate change projections for European impact research. *Regional Environmental Change* 14: 563–578.

Jones, P.D. and Conway, D., 1997. Precipitation in the British Isles: an analysis of area-average data updated to 1995. *International Journal of Climatology* 17: 427–438.

Jones, P.D. and Briffa, K.R., 2006. Unusual climate in northwest Europe during the period 1730 to 1745 based on instrumental and documentary data. *Climatic Change* 79: 361–379.

Jones, P.D., Horton, E.B., Folland, C.K., Hulme, M., Parker, D.E. and Basnett, T.A., 1999. The use of indices to identify changes in climatic extremes. *Climatic Change* 42: 131–149.

Jones, P.D., Harpham, C., Goodess, C.M. and Kilsby, C.G., 2011. Perturbing a weather generator using change factors derived from regional climate model simulations. *Nonlinear Processes Geophysics* 18: 503–511.

Kilsby, C.G., Jones, P.D., Burton, A., Ford, A.C., Fowler, H.J., Harpham, C., James, P., Smith, A. and Wilby, R.L., 2007. A daily weather generator for use in climate change studies. *Environmental Modelling & Software* 22: 1705–1719.

Klein Tank, A.M.G., 2009. Guidelines on analysis of extremes in a changing climate in support of informed decisions for adaptation. *Climate Data and Monitoring WCDMP-No. 72.* World Meteorological Organization, Geneva.

Knutti, R., Furrer, R., Tebaldi, C., Cermak, J. and Meehl, G.A., 2010. Challenges in combining projections from multiple climate models. *Journal of Climate* 23: 2739–2758.

Lenderink, G. and van Meijgaard, E., 2008. Increase in hourly precipitation extremes beyond expectations from temperature changes. *Nature Geoscience* 1: 511–514.

Lenderink, G., Barbero, R., Loriaux, J.M. and Fowler, H.J., 2017. Super-Clausius–Clapeyron scaling of extreme hourly convective precipitation and its relation to large-scale atmospheric conditions. *Journal of Climate* 30: 6037–6052.

Lennard, A.T., Macdonald, N.E. and Hooke, J.A., 2014. Analysis of drought characteristics for improved understanding of a water resource system. *Proceedings of the International Association of Hydrological Sciences* 364: 404–409.

McCarthy, G.D., Gleeson, E. and Walsh, S., 2015. The influence of ocean variations on the climate of Ireland. *Weather* 70: 242–245.

McCarthy, M., Spillane, S., Walsh, S. and Kendon, M., 2016. The meteorology of the exceptional winter of 2015/2016 across the UK and Ireland. *Weather* 71(12): 305–313.

McGregor, G., 2015. Climatology in support of climate risk management: a progress report. *Progress in Physical Geography* 39: 536–553.

McNie, E.C., 2007. Reconciling the supply of scientific information with user demands: an analysis of the problem and review of the literature. *Environmental Science and Policy* 10: 17–38.

Marsh, T., Cole, G. and Wilby, R., 2007. Major droughts in England and Wales, 1800–2006. *Weather* 62(4): 87–93.

Masson, D. and Knutti, R., 2011. Spatial-scale dependence of climate model performance in the CMIP3 ensemble. *Journal of Climate* 24: 2680–2692.

Matthews, T., Murphy, C., Wilby, R.L. and Harrigan, S., 2014. Stormiest winter on record for Ireland and UK. *Nature Climate Change* 4: 738–740.

Matthews, T., Murphy, C., Wilby, R.L. and Harrigan, S., 2015. A cyclone climatology of the British-Irish Isles 1871–2012. *International Journal of Climatology* 36: 1299–1312.

Matthews, T., Mullan, D., Wilby, R.L., Broderick, C. and Murphy, C., 2016. Past and future climate change in the context of memorable seasonal extremes. *Climate Risk Management* 11: 37–52.

Mendlik, T. and Gobiet, A., 2016. Selecting climate simulations for impact studies based on multivariate patterns of climate change. *Climatic Change* 135: 381–393.

Met Éireann, 2006. The Weather of Summer 2006. Available online: https://www.met.ie/climate/past-weather-statements (accessed 18/02/2019).

Met Éireann, 2014. Annual Summary 2014. Available online: https://www.met.ie/climate/past-weather-statements (accessed 18/02/2019).

Min, S.K., Zhang, X., Zwiers, F.W. and Hegerl, G.C., 2011. Human contribution to more-intense precipitation extremes. *Nature* 470: 378–381.

Moser, S.C., 2010. Communicating climate change: history, challenges, process and future directions. *Wiley Interdisciplinary Reviews: Climate Change* 1: 31–53.

Murphy, C., Bastola, S., Hall, J., Harrigan, S., Murphy, N. and Holman, C., 2011. Against a "wait and see" approach in adapting to climate change. *Irish Geography* 44: 81–95.

Murphy, C., Harrigan, S., Hall, J. and Wilby, R.L., 2013. Climate-driven trends in mean and high flows from a network of reference stations in Ireland. *Hydrological Sciences Journal* 58: 755–772.

Murphy, C., Broderick, C., Burt, T.P., Curley, M., Duffy, C., Hall, J., Harrigan, S., Matthews, T.K., Macdonald, N., McCarthy, G. and McCarthy, M.P., 2018. A 305-year continuous monthly rainfall series for the Island of Ireland (1711–2016). *Climate of the Past* 14: 413–440.

Nesje, A., Dahl, S.O., Thun, T. and Nordli, Ø., 2008. The "Little Ice Age" glacial expansion in western Scandinavia: summer temperature or winter precipitation? *Climate Dynamics* 30: 789–801.

Nissen, K.M. and Ulbrich, U., 2017. Increasing frequencies and changing characteristics of heavy precipitation events threatening infrastructure in Europe under climate change. *Natural Hazards and Earth System Sciences* 17: 1177–1190.

Nolan, P., O'Sullivan, J. and McGrath, R., 2017. Impacts of climate change on mid-twenty-first-century rainfall in Ireland: a high-resolution regional climate model ensemble approach. *International Journal of Climatology* 37: 4347–4363.

Noone, S., Murphy, C., Coll, J., Matthews, T., Mullan, D., Wilby, R.L. and Walsh, S., 2016. Homogenisation and analysis of an expanded long-term monthly rainfall network for the Island of Ireland (1850–2010). *International Journal of Climatology* 36: 2837–2853.

Noone, S., Broderick, C., Duffy, C., Matthews, T., Wilby, R.L. and Murphy, C., 2017. A 250-year drought catalogue for the island of Ireland (1765–2015). *International Journal of Climatology* 37: 239–254.

NRC (National Research Council), 2009. *Informing Decisions in a Changing Climate – Panel on Strategies and Methods for Climate-Related Decision Support*. National Academies Press, Washington, DC.

NRC (National Research Council), 2010. America's Climate Choices: Panel on Advancing the Science of Climate Change. National Academies Press, Washington, DC.

Pascal, M., Sweeney, J., Cullen, E., Schwartz, J. and Goodman, P., 2013. Heatwaves and mortality in Ireland, planning for the future. *Irish Geography* 46: 203–211.

Pennell, C. and Reichler, T., 2011. On the effective number of climate models. *Journal of Climate* 24: 2358–2367.

Pidgeon, N., 2012. Public understanding of, and attitudes to, climate change: UK and international perspectives and policy. *Climate Policy* 12: 85–106.

Pielke, R.A. Sr. and Wilby, R.L., 2012. Regional climate downscaling – what's the point? *Eos* 93: 52–53.

Prein, A.F., Langhans, W., Fosser, G., Ferrone, A., Ban, N., Goergen, K., Keller, M., Tölle, M., Gutjahr, O., Feser, F. and Brisson, E., 2015. A review on regional convection-permitting climate modeling: demonstrations, prospects, and challenges. *Reviews of Geophysics* 53: 323–361.

Prudhomme, C., Wilby, R.L., Crooks, S., Kay, A.L. and Reynard, N.S., 2010. Scenario-neutral approach to climate change impact studies: application to flood risk. *Journal of Hydrology* 390: 198–209.

Rajczak, J., Pall, P. and Schär, C., 2013. Projections of extreme precipitation events in regional climate simulations for Europe and the Alpine Region. *Journal of Geophysical Research: Atmospheres* 118: 3610–3626.

Rinne, K.T., Loader, N.J., Switsur, V.R. and Waterhouse, J.S., 2013. 400-year May–August precipitation reconstruction for Southern England using oxygen isotopes in tree rings, *Quaternary Science Reviews* 60: 13–25.

Rummukainen, M., 2012. Changes in climate and weather extremes in the 21st century. *Wiley Interdisciplinary Reviews: Climate Change* 3: 115–129.

Russo, S., Dosio, A., Graversen, R.G., Sillmann, J., Carrao, H., Dunbar, M.B., Singleton, A., Montagna, P., Barbola, P. and Vogt, J.V., 2014. Magnitude of extreme heat waves in present climate and their projection in a warming world. *Journal of Geophysical Research: Atmospheres* 119: 12,500–12,512.

Sanderson, M.G., 2017. Daily weather in Dublin 1716–1734: the diary of Isaac Butler. *Weather* 99(99): 1–4.

Schmidt, A., Thordarson, T., Oman, L.D., Robock, A. and Self, S., 2012. Climatic impact of the long-lasting 1783 Laki eruption: inapplicability of mass-independent sulfur isotopic composition measurements, *Journal of Geophysical Research* 117(D23): D23116.

Shields, L., 1983. The beginning of scientific weather observation in Ireland (1684–1708). *Weather* 38: 304–311.

Shiu, C.J., Liu, S.C., Fu, C., Dai, A. and Sun, Y., 2012. How much do precipitation extremes change in a warming climate? *Geophysical Research Letters* 39(17).

Stakhiv, E.Z., 2011. Pragmatic approaches for water management under climate change uncertainty. *Journal of the American Water Resources Association* 47: 1183–1196.

Stone, D., Allen, M.R., Selten, F., Kliphuis, M. and Stott, P.A., 2007. The detection and attribution of climate change using an ensemble of opportunity. *Journal of Climate* 20: 504–516.

Sun, Y., Solomon, S., Dai, A. and Portmann, R.W., 2006. How often does it rain? *Journal of Climate* 19: 916–934.

Taylor, K.E., Stouffer, R.J. and Meehl, G.A., 2012. An overview of CMIP5 and the experiment design. *Bulletin of the American Meteorological Society* 93: 485–498.

Thordarson, T. and Self, S., 2003. Atmospheric and environmental effects of the 1783–1784 Laki eruption: a review and reassessment. *Journal of Geophysical Research* 108: AAC 7-1–AAC 7-29.

Trenberth, K.E., Dai, A., Rasmussen, R.M. and Parsons, D.B., 2003. The changing character of precipitation. *Bulletin of the American Meteorological Society* 84: 1205–1217.

Tyrrell, J.G., 1995. Paraclimatic statistics and the study of climate change: the case of the Cork region in the 1750s. *Climatic Change* 29: 231–245.

van den Besselaar, E.J.M., Klein Tank, A.M.G. and Buishand, T.A., 2012. Trends in European precipitation extremes over 1951–2010. *International Journal of Climatology* 33: 2682–2689.

van Vuuren, D.P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G.C., Kram, T., Krey, V., Lamarque, J.F. and Masui, T., 2011. The representative concentration pathways: an overview. *Climatic Change* 109: 5–31.

Vaughan, C. and Dessai, S., 2014. Climate services for society: origins, institutional arrangements, and design elements for an evaluation framework. *Wiley Interdisciplinary Reviews: Climate Change* 5: 587–603.

Vautard, R., Gobiet, A., Sobolowski, S., Kjellström, E., Stegehuis, A., Watkiss, P., Mendlik, T., Landgren, O., Nikulin, G., Teichmann, C. and Jacob, D., 2014. The European climate under a 2°C global warming. *Environmental Research Letters* 9: 034006.

Wagner, S., Berg, P., Schädler, G. and Kunstmann, H., 2013. High resolution regional climate model simulations for Germany: part II—projected climate changes. *Climate Dynamics* 40: 415–427.

Walsh, S., 2012. Long term rainfall averages for Ireland. *National Hydrology Seminar*, Office of Public Works, Tullamore.

Westra, S., Alexander, L.V. and Zwiers, F.W., 2013. Global increasing trends in annual maximum daily precipitation. *Journal of Climate* 26: 3904–3918.

Whateley, S., Steinschneider, S. and Brown, C., 2014. A climate change range-based method for estimating robustness for water resources supply. *Water Resources Research* 50: 8944–8961.

Whetton, P., Hennessy, K., Clarke, J., McInnes, K. and Kent, D., 2012. Use of representative climate futures in impact and adaptation assessment. *Climatic Change* 115: 433–442.

Wilby, R.L., 2008. Constructing climate change scenarios of urban heat island intensity and air quality. *Environment and Planning B: Planning and Design* 35: 902–919.

Wilby, R.L. and Quinn, N.W., 2013. Reconstructing multi-decadal variations in fluvial flood risk using atmospheric circulation patterns. *Journal of Hydrology* 487: 109–121.

Wilby, R.L. and Wigley, T.M.L., 1997. Downscaling general circulation model output: a review of methods and limitations. *Progress in Physical Geography* 21: 530–548.

Wilby, R.L., Dawson, C.W., Murphy, C., Connor, P.O. and Hawkins, E., 2014. The statistical downscaling model – decision centric (SDSM-DC): conceptual basis and applications. *Climate Research* 61: 259–276.

Wilby, R.L., Noone, S., Murphy, C., Matthews, T., Harrigan, S. and Broderick, C., 2015. An evaluation of persistent meteorological drought using a homogeneous Island of Ireland precipitation network. *International Journal of Climatology* 36: 2854–2865.

Wilson, R., Miles, D., Loader, N.J., Melvin, T., Cunningham, L., Cooper, R. and Briffa, K., 2013. A millennial long March–July precipitation reconstruction for southern-central England, *Climate Dynamics* 40: 997–1017.

WMO (World Meteorological Organization), 2011. *Guide to Climatological Practices (WMO/No 100)*. WMO, Geneva.

World Bank, 2012. *Adapting to Climate Change: Assessing World Bank Group Experience*. World Bank Group, Washington, DC.

Wu, P., Christidis, N. and Stott, P., 2013. Anthropogenic impact on Earth's hydrological cycle. *Nature Climate Change* 3: 807–810.

Abbreviations

AMO	Atlantic multidecadal oscillation
CC	Clausius–Clapeyron
CET	Central England temperature
CMIP	Coupled Model Intercomparison Project
CMIP5	Coupled Model Intercomparison Project Phase 5
CORDEX	Coordinated Regional Climate Downscaling Experiment
EWP	England and Wales precipitation
GCM	Global climate model
ICARUS	Irish Climate Analysis and Research Units
ICF	Irish Climate Futures
IIP	Island of Ireland Precipitation
IoI_1711	Island of Ireland monthly rainfall 1711–2016
IPCC	Intergovernmental Panel on Climate Change
IRN	Irish Reference Network
NAO	North Atlantic Oscillation
RCF	Representative climate future
RCM	Regional climate model
RCP	Representative concentration pathway
SPI	Standardised Precipitation Index
WeaGETS	Weather Generator of the École de Technologie Supérieure
WG	Weather generator

Appendix 1 Chapter 5 Supplementary Maps

A1.1 Maps of Results for Historical Validation of RCM Simulation

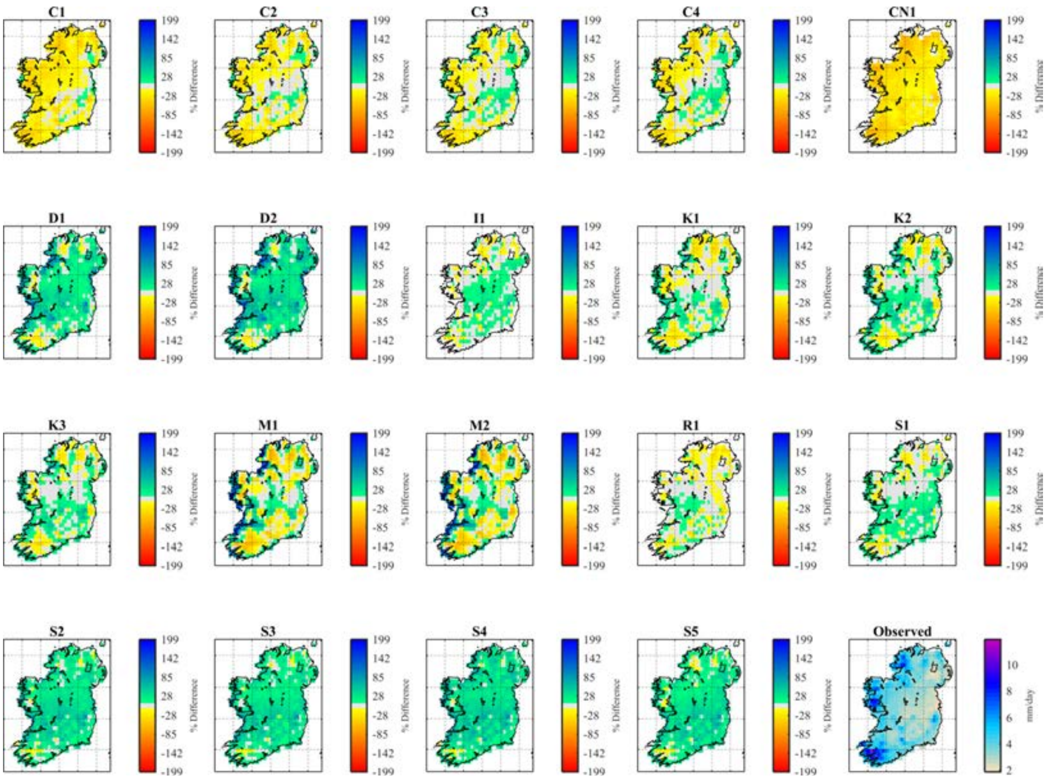


Figure A1.1. Percentage bias in mean winter (DJF) precipitation (Ave) simulated by each CORDEX ensemble member. For RCM abbreviations see Table 5.1. Also shown is the observed (mm/day) mean winter (DJF) precipitation (1976–2005).

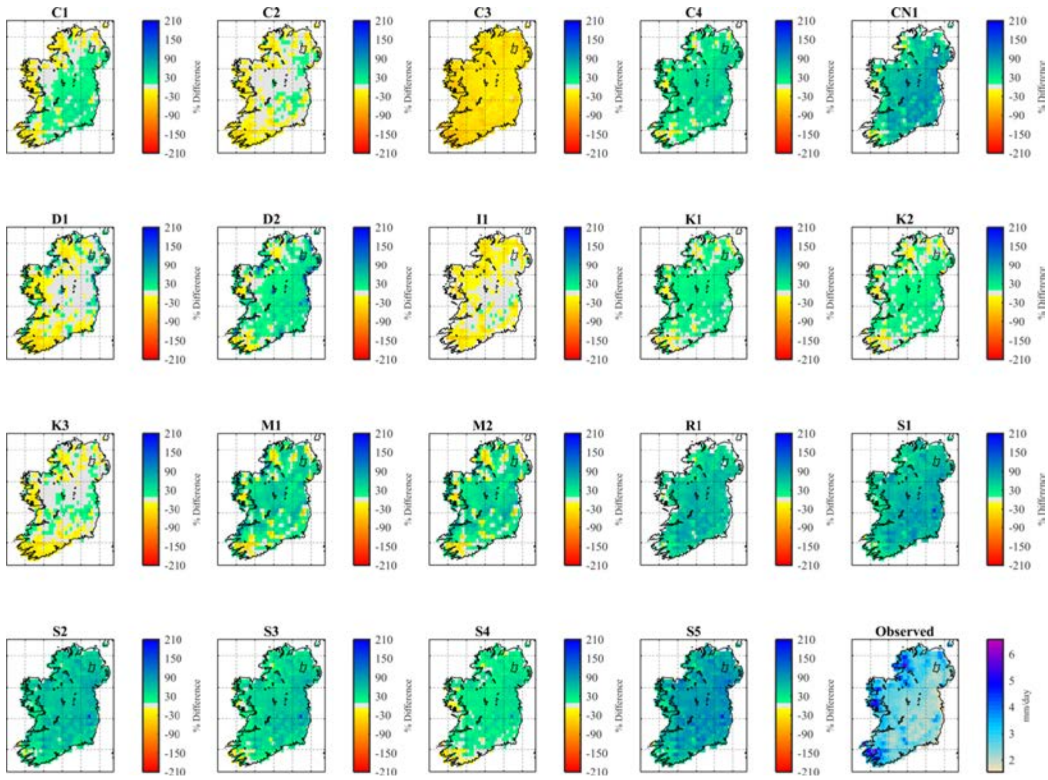


Figure A1.2. Percentage bias in mean summer (JJA) precipitation (Ave) simulated by each CORDEX ensemble member. For RCM abbreviations see Table 5.1. Also shown is the observed (mm/day) mean summer (JJA) precipitation (1976–2005).

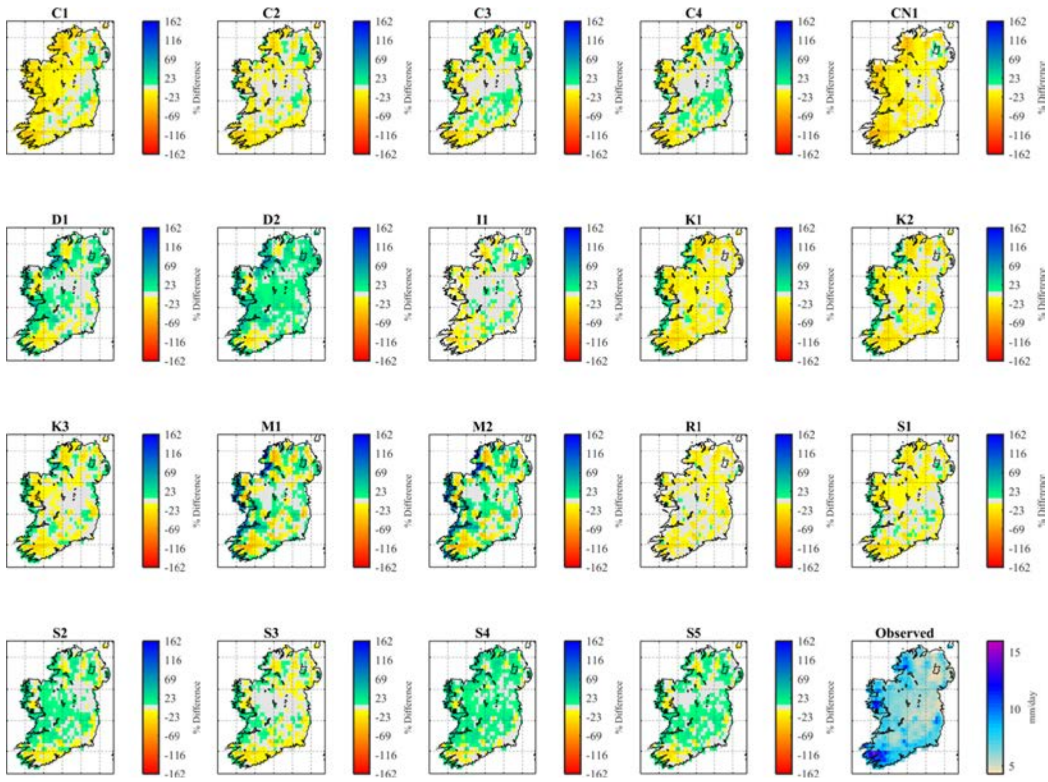


Figure A1.3. Percentage bias in mean winter (DJF) precipitation intensity (SDII) simulated by each CORDEX ensemble member. For RCM abbreviations see Table 5.1. Also shown is the observed (mm/day) mean winter (DJF) precipitation intensity (1976–2005).

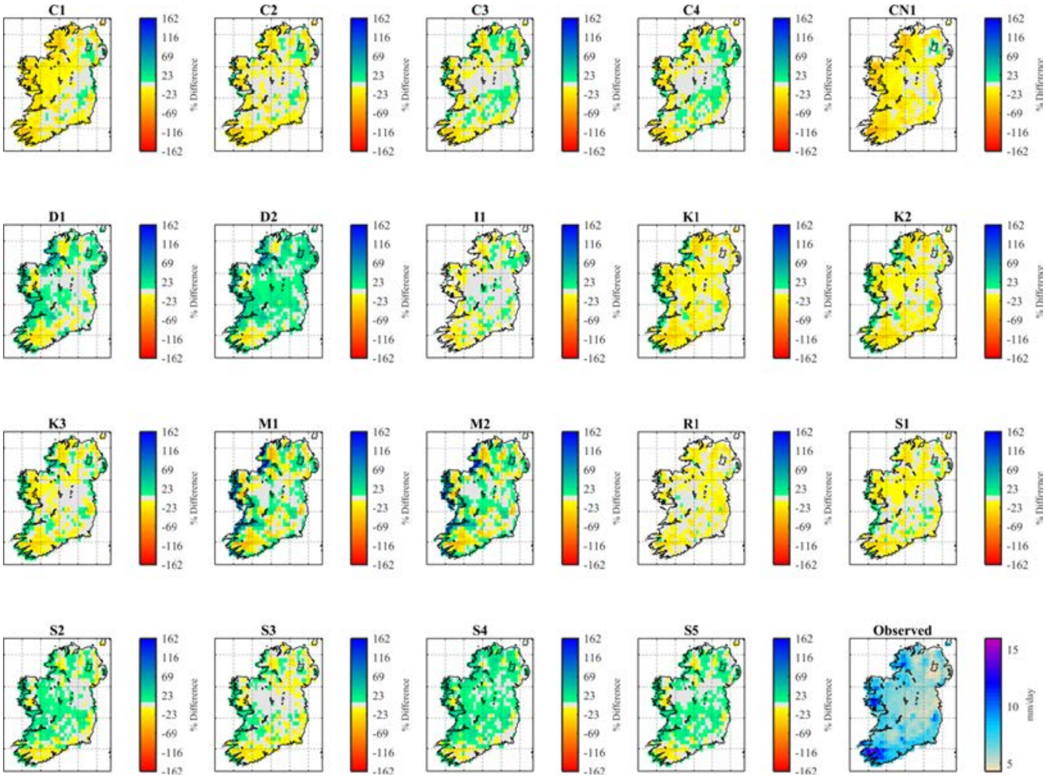


Figure A1.4. Percentage bias (%) in mean summer (JJA) precipitation intensity (SDII) simulated by each CORDEX ensemble member. For RCM abbreviations see Table 5.1. Also shown is the observed (mm/day) mean summer (JJA) precipitation intensity (1976–2005).

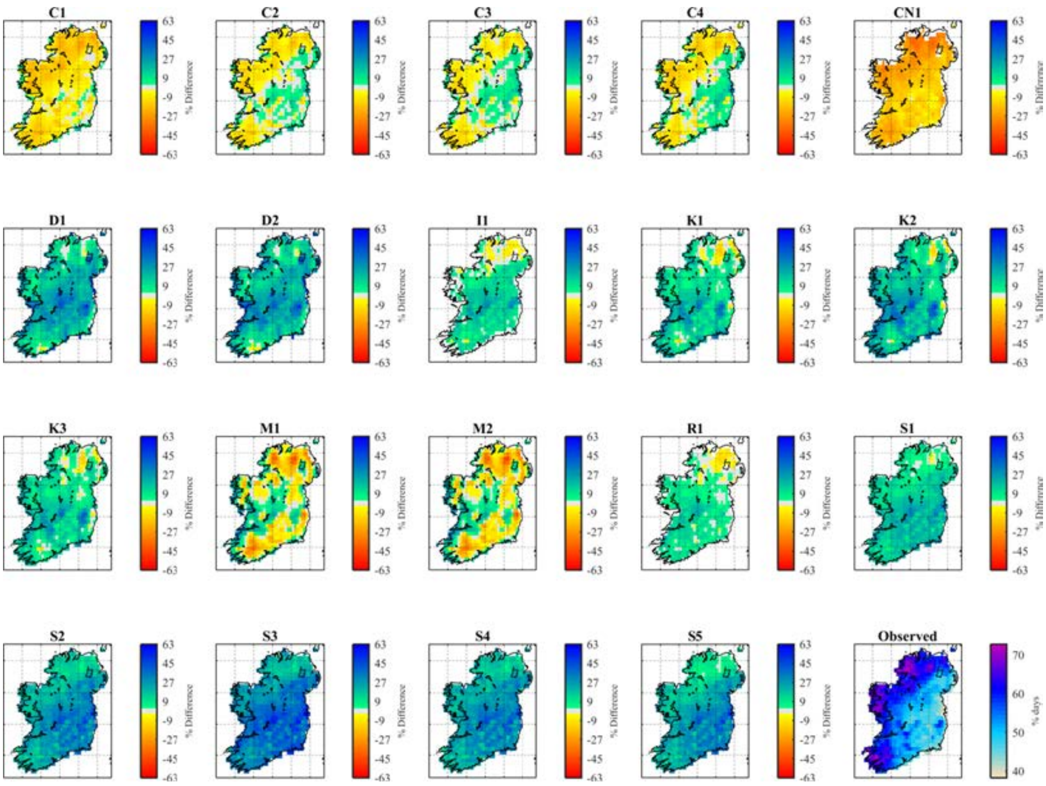


Figure A1.5. Percentage bias in mean winter (DJF) precipitation occurrence (R1mm) simulated by each CORDEX ensemble member. For RCM abbreviations see Table 5.1. Also shown is the observed (% days) mean winter (DJF) precipitation occurrence (1976–2005).

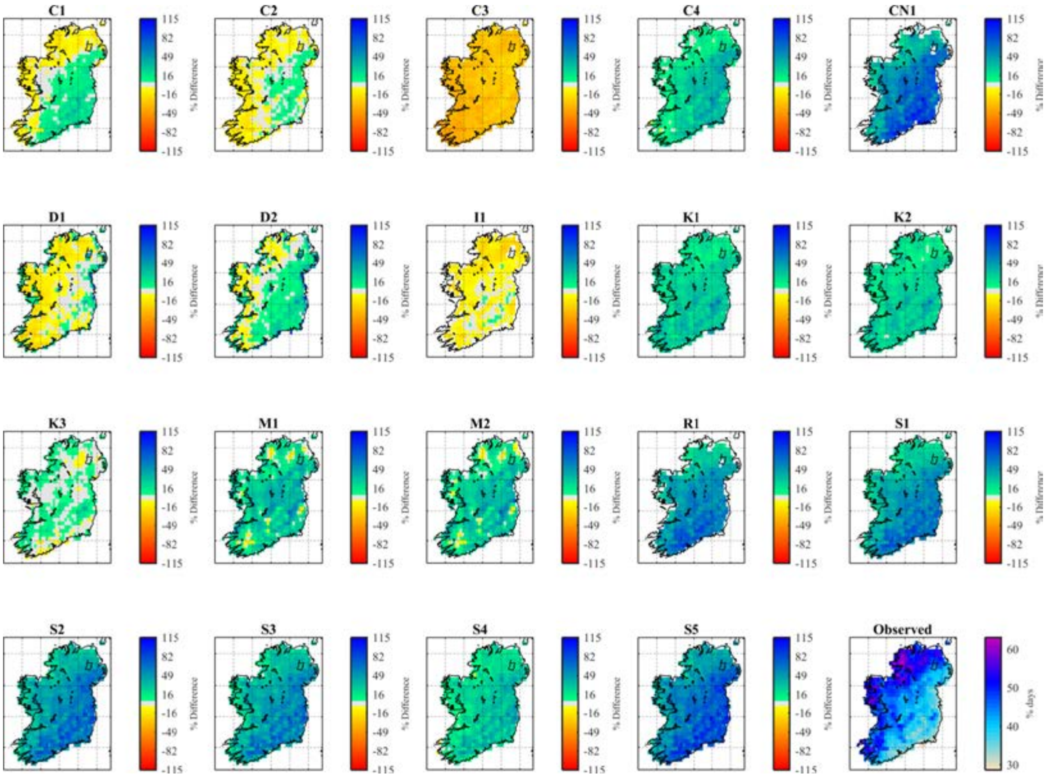


Figure A1.6. Percentage bias in mean summer (JJA) precipitation occurrence (R1mm) simulated by each CORDEX ensemble member. For RCM abbreviations see Table 5.1. Also shown is the observed (% days) mean summer (JJA) precipitation occurrence (1976–2005).

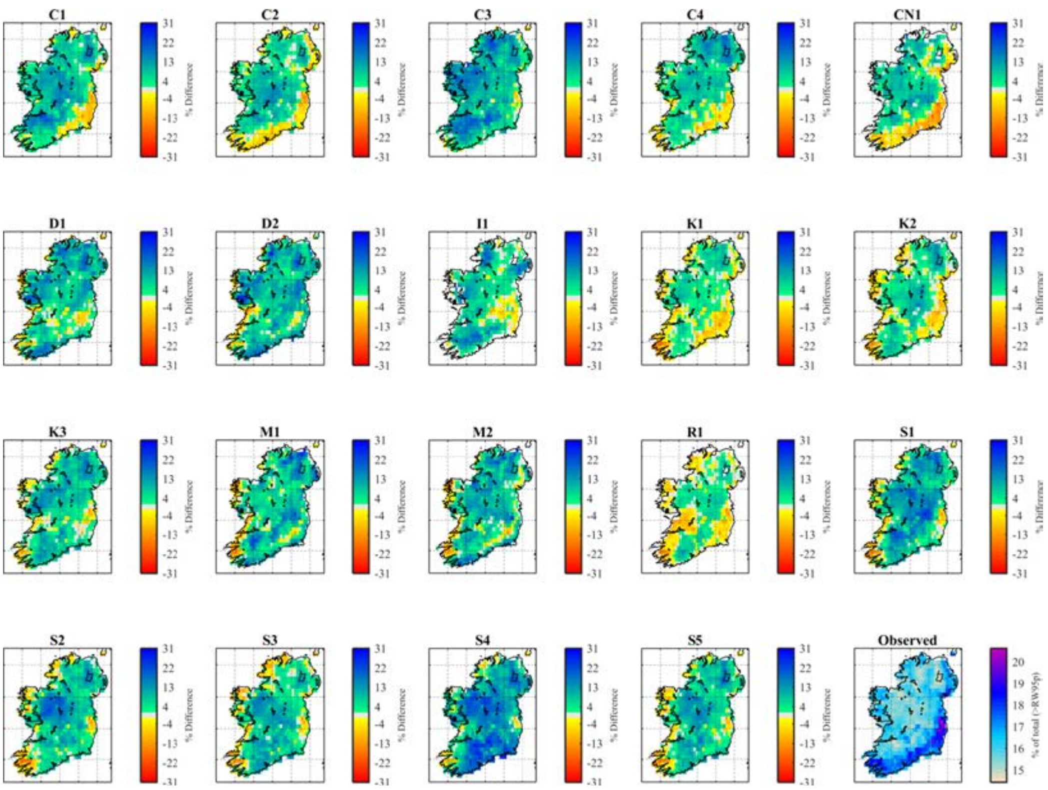


Figure A1.7. Percentage bias in the quotient of winter (DJF) precipitation originating from heavy events (>RW95p) simulated by each CORDEX ensemble member. For RCM abbreviations see Table 5.1. Also shown is the observed (% of total >RW95p) quotient of winter (DJF) precipitation originating from heavy events (1976–2005).

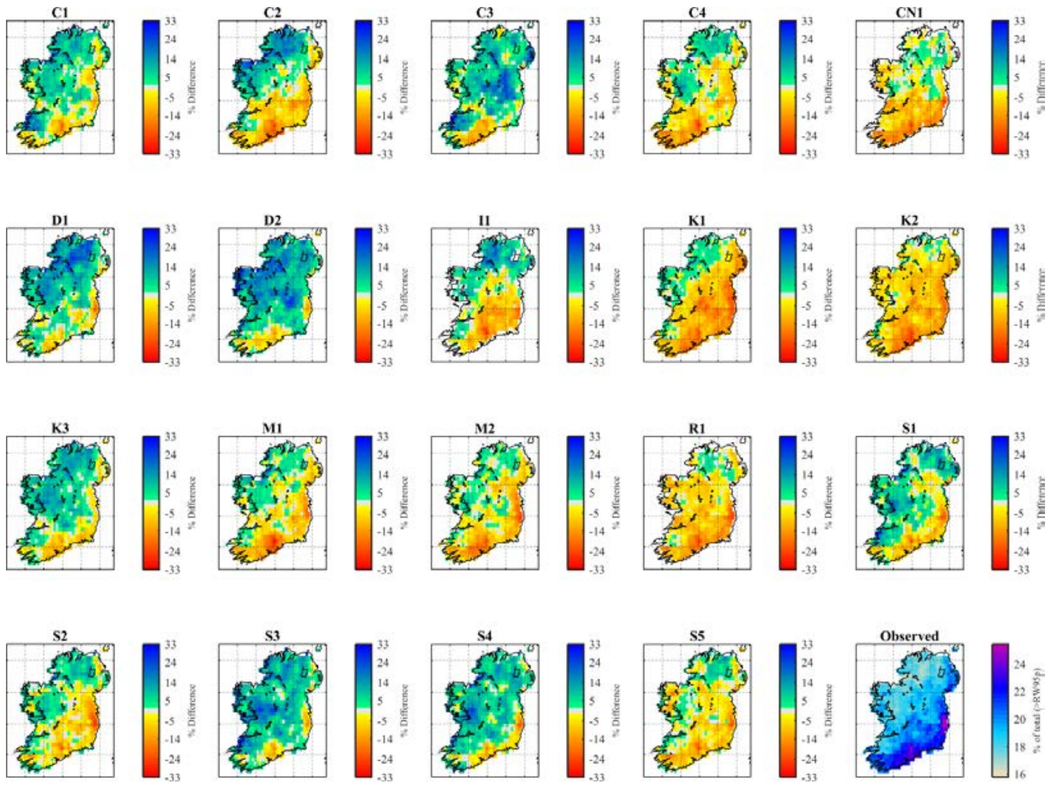


Figure A1.8. Percentage bias in the quotient of summer (JJA) precipitation originating from heavy events (>RW95p) simulated by each CORDEX ensemble member. For RCM abbreviations see Table 5.1. Also shown is the observed (% of total >RW95p) quotient of summer (JJA) precipitation originating from heavy events (1976–2005).

A1.2 Maps of Projected Changes for Key Precipitation Indices

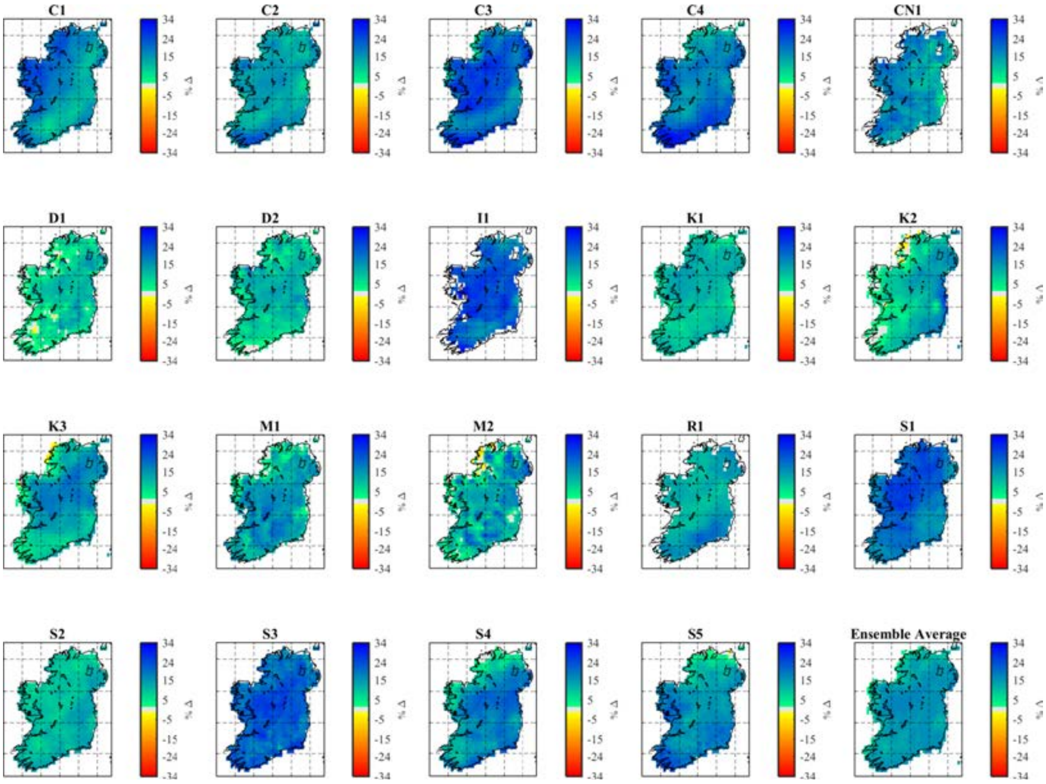


Figure A1.9. Percentage changes in the intensity of winter (DJF) precipitation simulated by each CORDEX ensemble member. For RCM abbreviations see Table 5.1. Changes are estimated for the 2080s (2070–99) under RCP 8.5 relative to the 1976–2005 baseline.

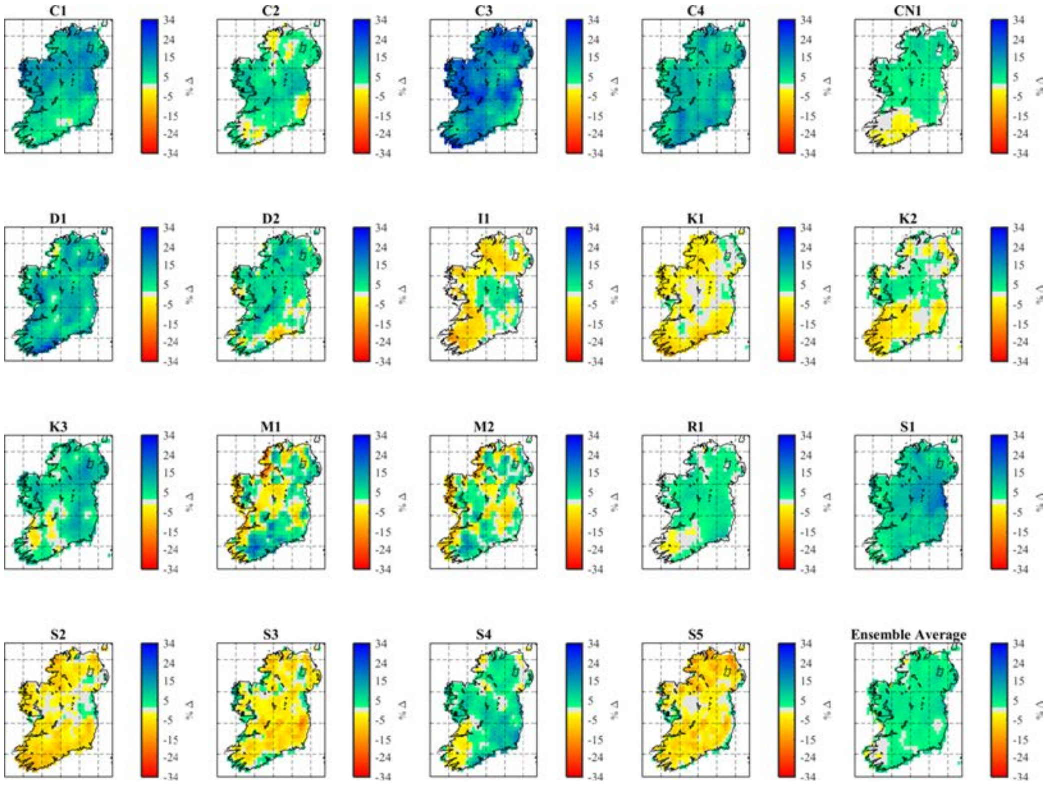


Figure A1.10. Percentage changes in the intensity of summer (JJA) precipitation simulated by each CORDEX ensemble member. For RCM abbreviations see Table 5.1. Changes are estimated for the 2080s (2070–99) under RCP 8.5 relative to the 1976–2005 baseline.

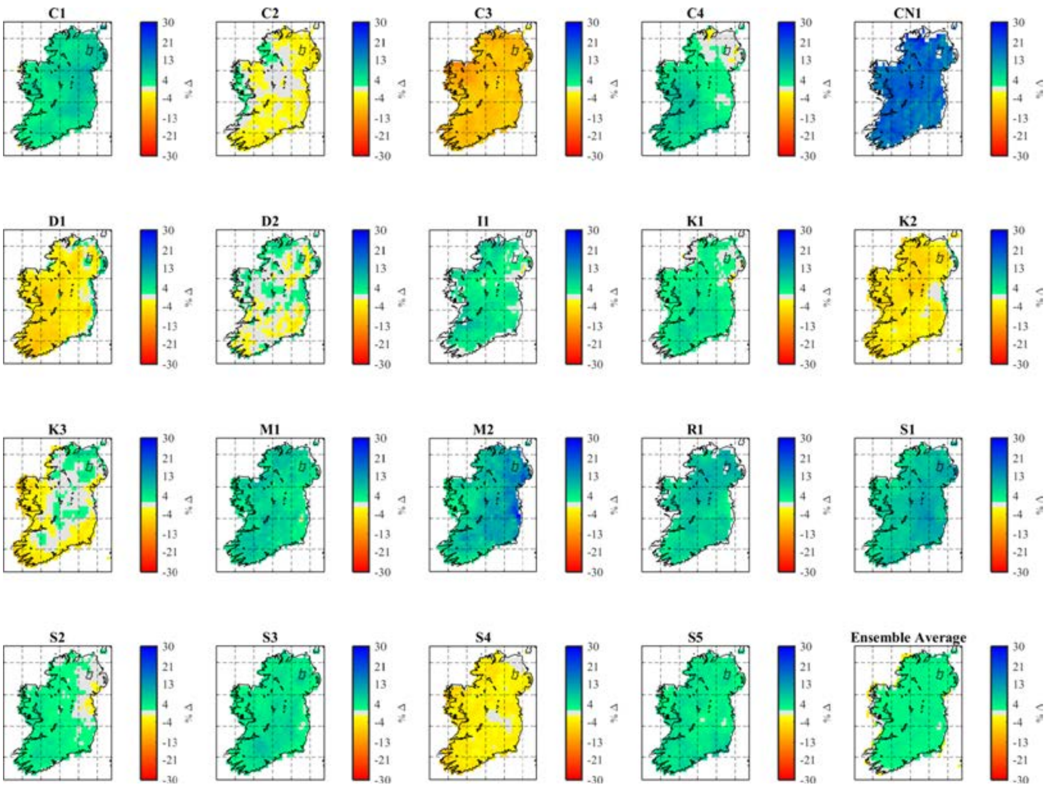


Figure A1.11. Percentage changes in winter wet-day occurrence (>1 mm) simulated by each CORDEX ensemble member. For RCM abbreviations see Table 5.1. Changes are estimated for the 2080s (2070–99) under RCP 8.5 relative to the 1976–2005 baseline.

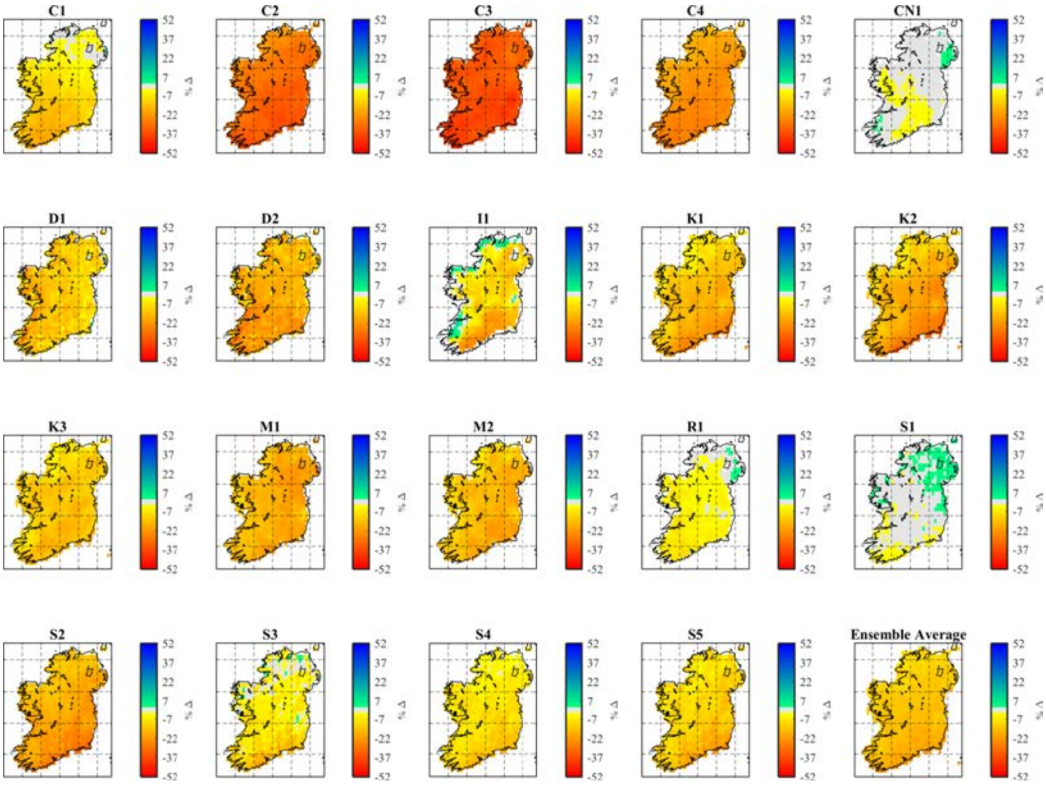


Figure A1.12. Percentage changes in summer wet-day occurrence (>1 mm) simulated by each CORDEX ensemble member. For RCM abbreviations see Table 5.1. Changes are estimated for the 2080s (2070–99) under RCP 8.5 relative to the 1976–2005 baseline.

AN GHNÍOMHAIREACHT UM CHAOMHNÚ COMHSHAOIL
Tá an Ghníomhaireacht um Chaomhnú Comhshaoil (GCC) freagrach as an gcomhshaol a chaomhnú agus a fheabhsú mar shócmhainn luachmhar do mhuintir na hÉireann. Táimid tiomanta do dhaoine agus don chomhshaol a chosaint ó éifeachtaí díobhálacha na radaíochta agus an truaillithe.

Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

Rialú: *Déanaimid córais éifeachtacha rialaithe agus comhlíonta comhshaoil a chur i bhfeidhm chun torthaí maithe comhshaoil a sholáthar agus chun díriú orthu siúd nach gcloíonn leis na córais sin.*

Eolas: *Soláthraímid sonraí, faisnéis agus measúnú comhshaoil atá ar ardchaighdeán, spriocdhírithe agus tráthúil chun bonn eolais a chur faoin gcinnteoireacht ar gach leibhéal.*

Tacaíocht: *Bímid ag saothrú i gcomhar le grúpaí eile chun tacú le comhshaol atá glan, táirgiúil agus cosanta go maith, agus le hiompar a chuirfidh le comhshaol inbhuanaithe.*

Ár bhFreagrachtaí

Ceadúnú
Déanaimid na gníomhaíochtaí seo a leanas a rialú ionas nach ndéanann siad dochar do shláinte an phobail ná don chomhshaol:
- saoráidí dramhaíola *(m.sh. láithreáin líonta talún, loisceoirí, stáisiúin aistrithe dramhaíola)*;
- gníomhaíochtaí tionsclaíocha ar scála mór *(m.sh. déantúsaíocht cógaisíochta, déantúsaíocht stroighne, stáisiúin chumhachta)*;
- an diantalmhaíocht *(m.sh. muca, éanlaith)*;
- úsáid shrianta agus scaoileadh rialaithe Orgánach Géinmhodhnaithe *(OGM)*;
- foinsí radaíochta ianúcháin *(m.sh. trealamh x-gha agus radaiteiripe, foinsí tionsclaíocha)*;
- áiseanna móra stórála peitril;
- scardadh dramhuisce;
- gníomhaíochtaí dumpála ar farraige.

Forfheidhmiú Náisiúnta i leith Cúrsaí Comhshaoil
- Clár náisiúnta iniúchtaí agus cigireachtaí a dhéanamh gach bliain ar shaoráidí a bhfuil ceadúnas ón nGníomhaireacht acu.
- Maoirseacht a dhéanamh ar fhreagrachtaí cosanta comhshaoil na n-údarás áitiúil.
- Caighdeán an uisce óil, arna sholáthar ag soláthraithe uisce phoiblí, a mhaoirsiú.
- Obair le húdaráis áitiúla agus le gníomhaireachtaí eile chun dul i ngleic le coireanna comhshaoil trí chomhordú a dhéanamh ar líonra forfheidhmiúcháin náisiúnta, trí dhíriú ar chiontóirí, agus trí mhaoirsiú a dhéanamh ar leasúchán.
- Cur i bhfeidhm rialachán ar nós na Rialachán um Dhramhthrealamh Leictreach agus Leictreonach (DTLL), um Shrian ar Shubstaintí Guaiseacha agus na Rialachán um rialú ar shubstaintí a ídíonn an ciseal ózóin.
- An dlí a chur orthu siúd a bhriseann dlí an chomhshaoil agus a dhéanann dochar don chomhshaol.

Bainistíocht Uisce
- Monatóireacht agus tuairisciú a dhéanamh ar cháilíocht aibhneacha, lochanna, uiscí idirchriosacha agus cósta na hÉireann, agus screamhuiscí; leibhéil uisce agus sruthanna aibhneacha a thomhas.
- Comhordú náisiúnta agus maoirsiú a dhéanamh ar an gCreat-Treoir Uisce.
- Monatóireacht agus tuairisciú a dhéanamh ar Cháilíocht an Uisce Snámha.

Monatóireacht, Anailís agus Tuairisciú ar an gComhshaol
- Monatóireacht a dhéanamh ar cháilíocht an aeir agus Treoir an AE maidir le hAer Glan don Eoraip (CAFÉ) a chur chun feidhme.
- Tuairisciú neamhspleách le cabhrú le cinnteoireacht an rialtais náisiúnta agus na n-údarás áitiúil *(m.sh. tuairisciú tréimhsiúil ar staid Chomhshaol na hÉireann agus Tuarascálacha ar Tháscairí)*.

Rialú Astaíochtaí na nGás Ceaptha Teasa in Éirinn
- Fardail agus réamh-mheastacháin na hÉireann maidir le gáis cheaptha teasa a ullmhú.
- An Treoir maidir le Trádáil Astaíochtaí a chur chun feidhme i gcomhair breis agus 100 de na táirgeoirí dé-ocsaíde carbóin is mó in Éirinn.

Taighde agus Forbairt Comhshaoil
- Taighde comhshaoil a chistiú chun brúnna a shainaithint, bonn eolais a chur faoi bheartais, agus réitigh a sholáthar i réimsí na haeráide, an uisce agus na hinbhuanaitheachta.

Measúnacht Straitéiseach Timpeallachta
- Measúnacht a dhéanamh ar thionchar pleananna agus clár beartaithe ar an gcomhshaol in Éirinn *(m.sh. mórphleananna forbartha)*.

Cosaint Raideolaíoch
- Monatóireacht a dhéanamh ar leibhéil radaíochta, measúnacht a dhéanamh ar nochtadh mhuintir na hÉireann don radaíocht ianúcháin.
- Cabhrú le pleananna náisiúnta a fhorbairt le haghaidh éigeandálaí ag eascairt as taismí núicléacha.
- Monatóireacht a dhéanamh ar fhorbairtí thar lear a bhaineann le saoráidí núicléacha agus leis an tsábháilteacht raideolaíochta.
- Sainseirbhísí cosanta ar an radaíocht a sholáthar, nó maoirsiú a dhéanamh ar sholáthar na seirbhísí sin.

Treoir, Faisnéis Inrochtana agus Oideachas
- Comhairle agus treoir a chur ar fáil d'earnáil na tionsclaíochta agus don phobal maidir le hábhair a bhaineann le caomhnú an chomhshaoil agus leis an gcosaint raideolaíoch.
- Faisnéis thráthúil ar an gcomhshaol ar a bhfuil fáil éasca a chur ar fáil chun rannpháirtíocht an phobail a spreagadh sa chinnteoireacht i ndáil leis an gcomhshaol *(m.sh. Timpeall an Tí, léarscáileanna radóin)*.
- Comhairle a chur ar fáil don Rialtas maidir le hábhair a bhaineann leis an tsábháilteacht raideolaíoch agus le cúrsaí práinnfhreagartha.
- Plean Náisiúnta Bainistíochta Dramhaíola Guaisí a fhorbairt chun dramhaíl ghuaiseach a chosc agus a bhainistiú.

Múscailt Feasachta agus Athrú Iompraíochta
- Feasacht chomhshaoil níos fearr a ghiniúint agus dul i bhfeidhm ar athrú iompraíochta dearfach trí thacú le gnóthais, le pobail agus le teaghlaigh a bheith níos éifeachtúla ar acmhainní.
- Tástáil le haghaidh radóin a chur chun cinn i dtithe agus in ionaid oibre, agus gníomhartha leasúcháin a spreagadh nuair is gá.

Bainistíocht agus struchtúr na Gníomhaireachta um Chaomhnú Comhshaoil
Tá an ghníomhaíocht á bainistiú ag Bord lánaimseartha, ar a bhfuil Ard-Stiúrthóir agus cúigear Stiúrthóirí. Déantar an obair ar fud cúig cinn d'Oifigí:
- An Oifig um Inmharthanacht Comhshaoil
- An Oifig Forfheidhmithe i leith cúrsaí Comhshaoil
- An Oifig um Fianaise is Measúnú
- Oifig um Chosaint Radaíochta agus Monatóireachta Comhshaoil
- An Oifig Cumarsáide agus Seirbhísí Corparáideacha

Tá Coiste Comhairleach ag an nGníomhaireacht le cabhrú léi. Tá dáréag comhaltaí air agus tagann siad le chéile go rialta le plé a dhéanamh ar ábhair imní agus le comhairle a chur ar an mBord.

EPA Research Report 277

Irish Climate Futures: Data for Decision-making

Authors: Conor Murphy, Ciaran Broderick, Tom K.R. Matthews, Simon Noone and Ciara Ryan

epaResearch
Climate - Water - Sustainability
Identifying pressures • Informing policy • Developing solutions

Identified Pressures

The realisation of a climate-resilient Ireland over the coming decades depends on decisions taken at all scales to adapt to climate change. Good decisions depend on the type and quality of information used to inform planning. Building resilience requires the diversification of the types of information used to understand past and future climate variability and change, and improved insight into the plausible range of changing conditions that will need to be addressed.

Informed Policy

The need to adapt to climate change means that there is a demand from a variety of different users and sectors for actionable climate information. For instance, in the Irish context, guidance is provided for sectors and local authorities in developing and implementing adaptation plans. In particular, climate information is required to (1) assess the current adaptation baseline, which involves identifying extremes in the historical record and examining the vulnerabilities and impacts of these; (2) assess future climate risks; and (3) identify, assess and prioritise adaptation options. A key challenge to undertaking these tasks is identifying the kinds of climate data that are required for the development and implementation of adaptation planning. This challenge is explored and aspects are addressed as part of this research. Outputs from this work have been used to inform the Citizen's Assembly deliberations on climate change, the National Adaptation Framework and the Oireachtas Joint Committee on Climate Action.

Developed Solutions

This work draws together long-term, quality-assured records of precipitation and historical droughts that extend back to the 1700s. These records can be used to interrogate vulnerability to climate extremes in adaptation planning in a range of water-sensitive sectors. In addition, a Climate Futures framework is proposed that allows climate model information to be tailored for different user needs, ranging from basic research users to intermediate and advanced research users. To aid in the communication of risks from past and future climate change, recent seasonal extremes are used as climate change analogues and an assessment is provided of how these extremes have become more likely over the past century and are likely to become even more frequent in the coming decades. Finally, changes in rainfall extremes are assessed using output from the CORDEX ensemble of regional climate models.

EPA Research: McCumiskey House,
Richiew, Clonskeagh, Dublin 14.

Phone: 01 268 0100
Twitter: @EPAResearchNews
Email: research@epa.ie

www.epa.ie

EPA Research Webpages
www.epa.ie/researchandeducation/research/