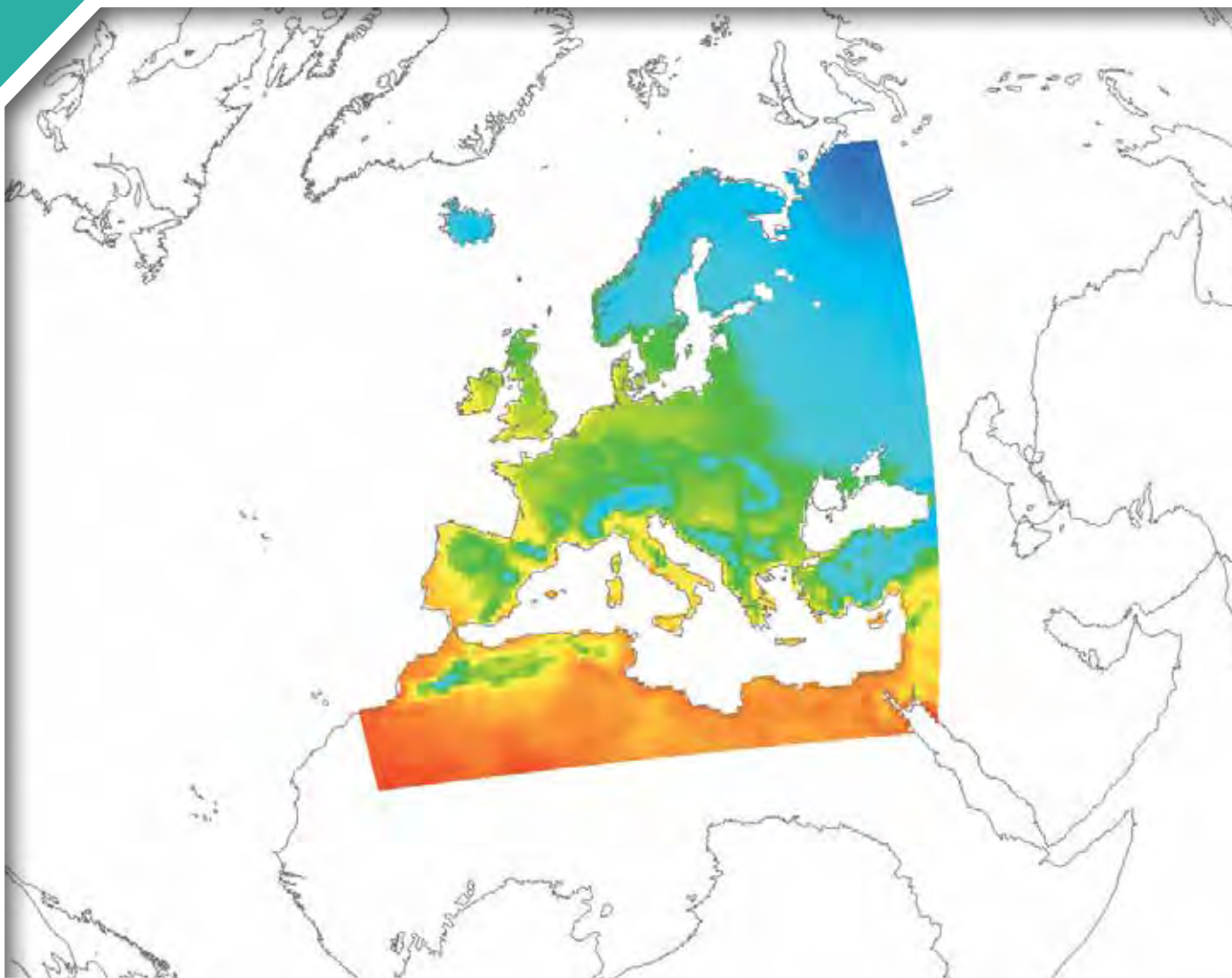


Regional Climate Model Simulations for Ireland for the 21st Century

Authors: Rowan Fealy, Cindy Bruyère and Catriona Duffy



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.*

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Our Responsibilities

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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;
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- Conducting an annual programme of audits and inspections of EPA licensed facilities.
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- 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.

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- Monitoring air quality and implementing the EU Clean Air for Europe (CAFÉ) Directive.
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- 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.

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- Advising Government on matters relating to radiological safety and emergency response.
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- Promoting radon testing in homes and workplaces and encouraging remediation where necessary.

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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.

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Regional Climate Model Simulations for Ireland for the 21st Century

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Executive Summary

The research outlined here details the application and use of the Advanced Research Weather Research and Forecasting (WRF) model (version 3.4.1), a regional climate model (RCM), to develop climate simulations for a European domain (~50 km resolution), based on boundary conditions provided by the EC-Earth earth system model for two representative concentrations pathways (RCPs), namely RCP2.6 and 8.5. The model simulations represent Ireland's contribution to the European component of the Coordinated Regional Downscaling Experiment (EURO-CORDEX), a World Climate Research Programme (WCRP) initiative to address climate information needs at the regional level. A key advantage to participation in the EURO-CORDEX initiative is that it provides access to a large ensemble of global climate models (GCMs) and RCMs, all of which adhere to a common framework and common specification guidelines. Where possible, these additional models, which represent an ensemble of opportunity, were incorporated into the current analysis. This also enabled additional RCPs (e.g. RCP4.5) to be included in the analysis.

The WRF RCM was initially evaluated with boundary conditions provided from the ERA-Interim Reanalysis data for a reference period (1981–2010). The WRF model was found to perform well and was capable of reproducing the essential features of the climate system over the European domain. Typical of all RCMs, model biases were evident in the model simulations, particularly associated with precipitation.

Following the model evaluation, boundary conditions from the EC-Earth earth system model were then employed to generate future climate simulations for the period 2006 to 2100 based on two RCPs, namely RCP2.6 and RCP8.5. These RCPs were selected to represent a future in which either significant adaptation (RCP8.5) or more manageable adaptation (RCP2.6) may be required to manage and reduce the potential impacts of future changes in the climate system. All changes were assessed relative to the baseline period of 1971–2000. The contrast between these pathways also represents the degree to which global versus national/regional action is required. In the absence of internationally binding agreements to mitigate global greenhouse gas emissions, the emphasis shifts

strongly to national and regional actors to develop appropriate adaptation options.

On the basis of a wider range of model simulations, available through participation in the EURO-CORDEX initiative, temperatures are simulated to increase across the European domain over the course of the present century; the amount of warming is largely dependent on the particular RCP employed. In addition, the greater the warming, the greater the range evident between individual GCM–RCM simulations, particularly evident during the winter season for the 2071–2100 period. Significant regional variations are evident in the rate of warming, with the extreme northern edge of Europe warming at a faster rate than more southern locations. This simulated warming rate is consistent with current observations for this region, which indicate that high northern-latitude land areas are warming at a rate faster than the global mean; this is largely attributed to changes in surface cover, with associated changes in albedo, and the transport of energy to the poles.

Marked differences are evident in both the magnitude and direction of the simulated changes in precipitation across Europe. Generally, wetter winters are simulated for central, northern and eastern Europe, with drier summers in western and southern Europe. Consistent with the findings for temperature, a larger range is evident between individual GCM–RCM simulations of precipitation for the higher forcing pathways.

Simulated changes in Ireland's climate

Temperature

By the middle of the present century, mean temperatures across Ireland are simulated to increase in all seasons (Table ES.1). In general, the largest seasonal increases are associated with RCP8.5, while the smallest increases are associated with RCP2.6. Spring is likely to experience the smallest increase by this period, of between 0.3 and 0.7 kelvin (K), depending on RCP, while autumn is likely to experience the largest increase, of between 0.8 K (RCP2.6) and 1.5 K (RCP8.5). This is consistent with the seasonal increases simulated for the end of the century; autumn is simulated to experience the

Table ES.1. Seasonal projected changes in temperature (K) for RCP2.6 and RCP8.5 based on the WRF341E simulations, employing EC-Earth as boundary conditions, for the periods 2021–2050 and 2071–2100. Values in brackets show the model ranges for selected models from EURO-CORDEX. 1K is equal to 1°C

Season	2021–2050		2071–2100	
	RCP2.6	RCP8.5	RCP2.6	RCP8.5
Winter (December to February)	0.8 (0.3–0.8)	1.0 (0.2–1.0)	0.9 (0.3–0.9)	2.1 (1.7–2.6)
Spring (March to May)	0.3 (0.3–0.6)	0.7 (0.2–1.0)	0.6 (0.2–0.9)	1.8 (1.2–2.6)
Summer (June to August)	0.8 (0.2–1.0)	1.2 (0.4–1.2)	0.9 (0.5–1.1)	2.8 (2.2–3.0)
Autumn (September to November)	0.8 (0.4–1.4)	1.5 (0.7–1.5)	1.1 (0.6–1.7)	3.1 (2.4–3.3)

Table ES.2. Seasonal projected changes in precipitation (percentage change) for RCP2.6 and RCP8.5 based on the WRF341E simulations, employing EC-Earth as boundary conditions, for the periods 2021–2050 and 2071–2100. Values in brackets show the model ranges for selected models from EURO-CORDEX

Season	2021–2050		2071–2100	
	RCP2.6	RCP8.5	RCP2.6	RCP8.5
Winter (December to February)	–1.8 (–1.8 to 10.4)	–2.3 (–2.2 to 10.7)	1.1 (1.0 to 8.0)	7.1 (7.0 to 22.9)
Spring (March to May)	7.6 (–2.3 to 7.6)	0.2 (–1.7 to 9.3)	8.7 (–12.3 to 8.7)	1.0 (–1.2 to 8.4)
Summer (June to August)	–13.6 (–13.6 to 4.8)	–6.4 (–19.0 to 0)	–5.5 (–8.0 to 6.4)	–13.7 (–35.5 to –9.0)
Autumn (September to November)	0.9 (–1.0 to 8.6)	–1.3 (–1.2 to 1.6)	–3.0 (–7.0 to 0)	9.4 (2.1 to 10.7)

largest increase in mean temperatures, of between 1.1 and 3.1 K with the smallest increase, of between 0.6 and 1.8 K, simulated for spring for this period. On a seasonal basis, the geographical variations in the simulated increases are small, typically less than 0.5 K.

Precipitation

Seasonal changes in precipitation are more marked, in both direction and magnitude, than changes in temperature but also location, of simulated changes. However, caution needs to be exercised with regard to interpreting the simulated changes in precipitation, particularly at the regional scale, as significant uncertainties exist at this scale (IPCC, 2013a).

Small/negligible changes are simulated in both winter and autumn precipitation by the middle of the century under both RCP2.6 and 8.5. Spring precipitation is simulated to increase by ~7% under RCP2.6, with a negligible change simulated under RCP8.5 for this season (Table ES.2). Decreases in summer precipitation are simulated under both RCPs; a decrease of ~13% is simulated under RCP2.6, with a smaller decrease of ~6% simulated under RCP8.5,

by the middle of the century relative to the baseline period. Spatially, the largest decreases in summer precipitation are simulated to occur along the south and east coasts (> 15%), under RCP2.6.

By the end of the century, an increase in winter precipitation of ~7% is simulated under RCP8.5. RCP2.6 simulates the largest spring increase, of ~8%. A decrease in summer precipitation is simulated under both RCPs of between ~5% and 13% for this period. For autumn, a small decrease is simulated under RCP2.6; this is in contrast to RCP8.5, which simulates an increase of ~9% for this season.

With the inclusion of a wider suite of models available from EURO-CORDEX, more marked differences in the direction of simulated changes are evident for the end of the century, particularly associated with spring precipitation in Ireland. For example, the range from the 25th percentile to 75th percentile of precipitation changes indicates both increasing and decreasing precipitation associated with this season. If the full model and RCP range is considered, a difference in the direction of simulated changes is also evident for summer precipitation.

Climatological indices and extremes

Simulated changes in a selection of climatological indices for Ireland were also examined. Of relevance to the agricultural sector, a simulated increase in seasonal temperatures will lead to an increase in the growing season length. The number of summer days or days experiencing temperatures of 18°C or greater is also simulated to increase across all time periods and RCPs. An increase in winter temperatures is also reflected in the reduction in heating degree-days or days with mean temperature less than 18°C, which is likely to impact on the seasonal demand for energy.

In terms of precipitation indices, the number of wet days (> 1 mm/day) is simulated to decrease across the country, particularly under RCP8.5. However, the frequency of heavy (> 10 mm/day) and very heavy (> 20 mm/day) precipitation days is simulated to increase. This reflects a potential shift in the distribution of precipitation, from long-duration, low-intensity precipitation characteristic of the Irish climate to more intense precipitation events, with potential consequences for water management.

Future work and recommendations

Recent research by Prein and Gobiet (2016) found significant differences between a number of commonly employed gridded observations of precipitation, including the E-Obs data utilised in this research. They found that the magnitude of the uncertainties associated with these gridded observational-derived products was similar to that of precipitation errors in RCMs. This highlights the need for improved gridded observational data and a greater understanding of the errors and uncertainties associated with these products.

The development of long-term, homogeneous, historical records, and their subsequent analysis, can provide key insights into past climate events, particularly extreme events. Future research focused on assessing the exposure of different sectors to the occurrence of extreme events in the historical climate archives would be very beneficial. This would potentially enable the development of more robust sectoral adaptation policies. If combined with an assessment of simulated future changes in extremes, it could assist in reducing the sensitivity of these adaptation measures to future uncertainties in climate model simulations.

Research is also required to more fully understand the coupling between the land surface and atmosphere; feedbacks between the land surface and atmosphere play a critical role in influencing the climate response and significantly contribute to model biases.

Observations (e.g. surface and remotely sensed) and modelling studies that support our understanding of the surface energy and water balance are required to further our understanding in this area. An improved understanding of the land–atmosphere coupling would also lead to an improved understanding of the occurrence of extreme events. High-resolution eddy covariance or flux towers (either on homogeneous land surface types or tall vertical towers measuring the planetary boundary layer) are essential tools to support these research activities. The development of a coordinated network of towers would also provide a direct measure of the effectiveness of policies that seek to mitigate greenhouse gas emissions.

Even if we had perfect knowledge of the climate system, uncertainties in future climate model simulations would remain (Wilby and Dessai, 2010). Therefore, the development of adaptation approaches that seek to minimise their sensitivity to uncertainty needs to be a research priority. Such an approach reflects the fact that, while the models generally agree that a change in radiative forcing will give rise to temperature increases, the amount of warming is dependent on the particular pathway considered more likely; for precipitation, differences in both the magnitude and direction of change mean that we cannot rely on climate model simulations alone to inform the decision-making process.

From a mitigation perspective, RCP2.6 represents a pathway that could result in a stabilisation of temperatures in Europe by 2060; in contrast, RCP4.5 and RCP8.5 simulate continued warming to the end of the century. A lower rate of warming is likely to provide greater opportunity for adaptation needs to be manageable, and thus minimise the potential negative impacts of climate change across a range of sectors. The development of *effective* mitigation strategies will be required to move to the lower RCP pathway. Research focused on assessing the geography of emissions, rather than necessarily a sector-based approach, would facilitate the development of spatially tailored mitigation strategies. Such strategies offer the potential to be more effective in mitigating emissions.

1 Introduction

Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, sea level has risen, and the concentrations of greenhouse gases have increased.

IPCC, 2013b: 2

1.1 Research Outline

This research presents model simulated changes in the climate of Ireland over the 21st century. To achieve this, a dynamical regional climate model (RCM), the Advanced Research Weather Research and Forecasting (WRF) model (version 3.4.1), developed by the National Centre for Atmospheric Research (NCAR) in Boulder, Colorado, was employed. While a primary objective of the research was to develop climate simulations for Ireland, an important secondary objective was to contribute to a global modelling initiative which seeks to develop high-resolution regional climate simulations for specified regions, globally. This global modelling initiative, entitled Coordinated Regional Downscaling Experiment (CORDEX) (section 2.4), is a programme of the World Climate Research Programme (WCRP). To fulfil both objectives, a European-wide model domain, in common to all modelling groups participating in CORDEX, was employed in this research. Results for the European domain are also presented. Details on the WRF model, the model domain and model set-up are described in section 3.2.

A number of climate simulations were performed as part of this research, representing the observational period from 1981 to 2010, required to evaluate the WRF model, a historical period from 1951 to 2005, and two future simulations representing the time period from 2006 to 2100. The climate simulations for the 2006–2100 period were undertaken for two plausible yet distinct futures, with changes in radiative forcing prescribed by different representative concentration pathways (RCPs), namely RCP2.6 and RCP8.5

(section 2.2). RCP2.6 represents a future in which atmospheric concentrations peak at ~490 parts per million (ppm) carbon dioxide equivalent (CO₂-eq) before 2100 and thereafter decline. RCP8.6 represents a future in which atmospheric concentrations continue to rise, with concentrations reaching in excess of 1370 parts per million by volume (ppmv) CO₂-eq in 2100. The selected RCP simulations potentially provide a basis to assess the (non-)implementation of policy interventions seeking to mitigate anthropogenic climate change over the course of the present century.

The WRF model was initially run with boundary conditions provided by the European Centre for Medium-Range Weather Forecasting (ECMWF) ERA-Interim Reanalysis data. The reanalysis data provide boundary condition data that are consistent with the observed climate for the period 1979–2010 and therefore provide a means to evaluate the model simulations against observed data. The selection of appropriate reanalysis data for the evaluation is an important step; ERA-Interim Reanalysis data, which replaced the previous ERA-40 Reanalysis data, are currently considered to be the most advanced reanalysis data available due to their ability to represent certain aspects of the climate system over similar reanalysis data products provided by other modelling centres (e.g. Troy and Wood, 2009; Mooney *et al.*, 2010; Screen and Simmonds, 2010).

These initial model simulations of the climate were then evaluated against comparable, gridded, observational data, obtained from the European Climate Assessment and Data (ECA&D). The following variables were evaluated – mean sea level pressure, minimum and maximum temperature and precipitation – on monthly, seasonal and climatological time periods. A more extensive evaluation of the land–atmosphere coupling and surface energy balance components, namely soil moisture and latent and sensible heat exchanges, for the summer period over 1989–2008, is outlined in Knist *et al.* (2016). Results from the evaluation period (1981–2010) are presented in section 3.3; the evaluation period excludes the year 1979 as this was employed for model spin-up (e.g. a period of time to allow the model to achieve

an equilibrium state). This initial evaluation focused on climatologically similar regions across Europe, providing a robust assessment of the model and its ability to simulate climate across a range of temporal and spatial scales over the evaluation period. Overall, the WRF model was found to reproduce the important spatial and temporal features of the climate system across the model domain.

Following the evaluation of the WRF model, boundary conditions from the EC-Earth earth system model (ESM) were employed to generate climate simulations for the 1951–2005 (historical) and 2006–2100 time periods. Details of the EC-Earth model, which represents a state-of-the-art ESM, are outlined in section 4.2. The historical climate simulations (1951–2005) were evaluated against the statistics of the gridded observational data to determine the presence of bias across the domain in the downscaled simulations. Additional model simulations, provided through the WCRP CORDEX initiative and representing different global and RCM simulations and RCPs (e.g. RCP4.5), were also included in the analysis of the historical (section 4.4) and future simulations (section 4.5) of temperature and precipitation. Importantly, these additional models provide a measure of spread in the climate simulations employed and could assist in characterising model uncertainty. While the range in outcomes is dependent on the models employed, the global climate model (GCM)–RCM combinations represent a sub-sample of the associated model uncertainty space. Ultimately, the models utilised in this report represent an ensemble of opportunity – selected because of their availability – rather than based on any selection criteria.

Section 5 of this report focuses on the evaluation and analysis of the WRF model simulations specifically for Ireland for both temperature and precipitation; section 6 presents simulated changes in selected climatological indices, including growing season length, heating degree-days, summer days index, wet days, heavy precipitation days, very heavy precipitation days and the maximum 1-day precipitation amount. The climate simulations detailed in this report, which represent one plausible set of outcomes, add to the existing knowledge base for Ireland; utilised in an appropriate manner they provide an additional tool to inform policy intervention and provide a means to assess developed adaptation

policies for sensitivity to climate model uncertainties. The report also identifies some potential impacts for Ireland, mainly associated with simulated changes in climate indices, which could lead to both positive and negative impacts for Ireland. Finally, section 7 outlines a potential approach for integrating the information provided in this report into the process of developing adaptation options.

1.2 Background

Changes in the global climate system have been observed in the instrumental records for a range of meteorological and environmental parameters, such as surface air temperature, atmospheric water vapour content, ocean heat content, snow cover and sea ice extent around the Arctic (e.g. IPCC, 2013a; Blunden and Arndt, 2015). Most notably, the globally average combined land and ocean surface temperature increased by 0.85°C (range: 0.65–1.06°C) (linear trend) over the period 1880–2012 (IPCC, 2013b); the rate of warming experienced over the period from 1951 to 2012 is estimated to be 0.12°C (0.08 to 0.14°C) per decade (IPCC, 2013) (Figure 1.1a). These findings, based on the instrumental records, are supported by independent temperature-sensitive proxy time series over a comparable time period (e.g. corals, ice cores, speleotherms, etc.) (e.g. Anderson *et al.*, 2013). Also evident in the instrumental records is the greater degree of warming experienced by mid- and high-latitude land areas in the northern hemisphere (Arctic amplification) (Figure 1.1b) during the early 20th century, while the recent warming phase appears more global in nature (IPCC, 2013a). However, a number of authors (e.g. Hansen *et al.*, 2006; Liu *et al.*, 2007; Cohen *et al.*, 2014; Francis and Skific, 2015) have indicated enhanced warming in high latitudes in the northern hemisphere in recent decades, in particular during the autumn and winter months.

1.3 Radiative Forcing

Long-term changes in the globally averaged surface temperatures are a direct response to an imbalance in the Earth's energy balance; to maintain equilibrium, the climate system responds by adjusting the planetary temperature. Radiative forcing provides a measure of the influence a factor has in altering the balance between incoming and outgoing energy, and hence the Earth's energy balance. Recent estimates

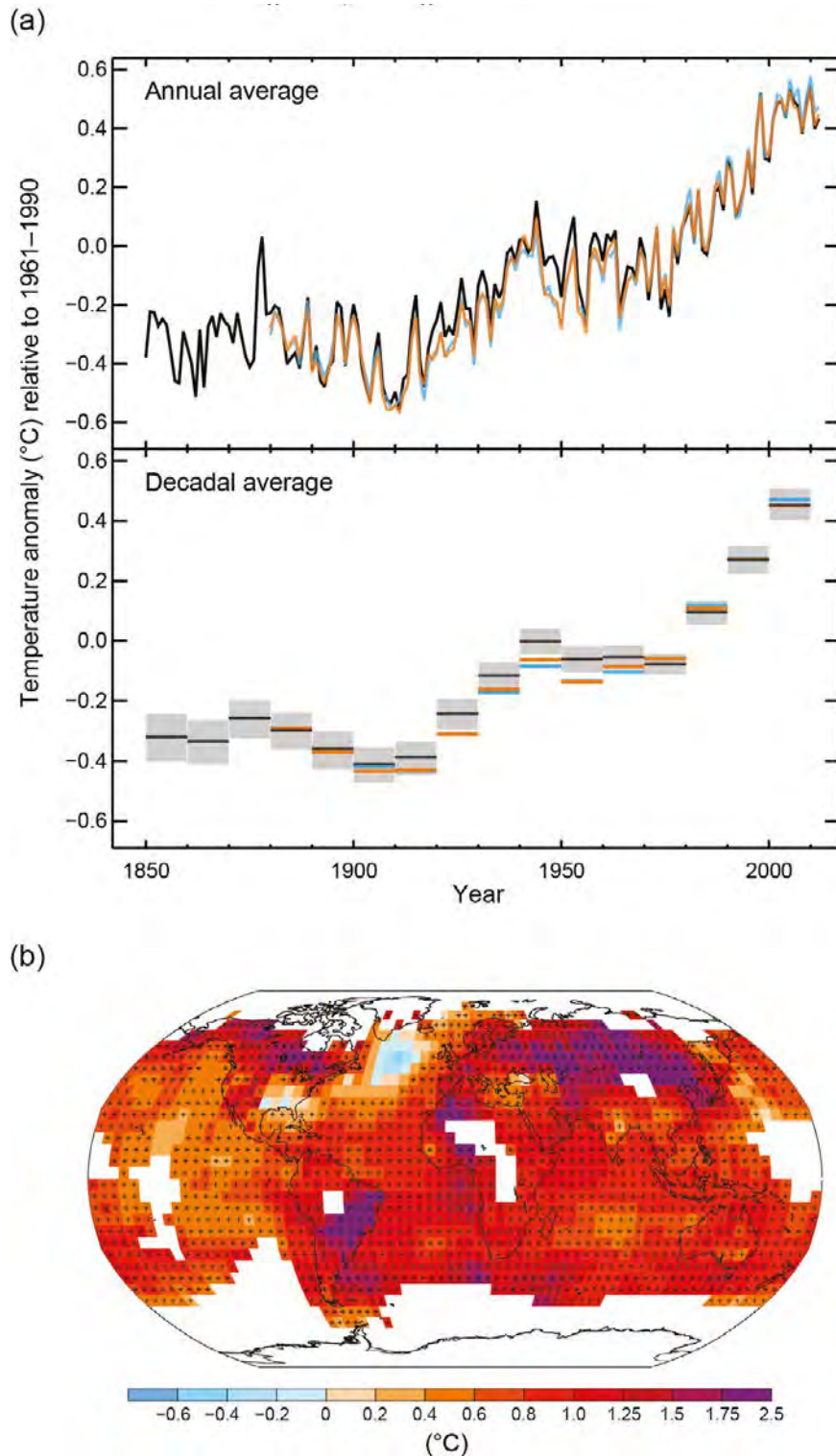


Figure 1.1. (a) Observed global mean combined land and ocean surface temperature anomalies, from 1850 to 2012, from three datasets. Top panel: annual mean values. Bottom panel: decadal mean values including the estimate of uncertainty for one dataset (black). Anomalies are relative to the mean of 1961–1990. **(b)** Map of the observed surface temperature change from 1901 to 2012 derived from temperature trends determined by linear regression from one dataset [orange line in panel (a)]. Trends have been calculated where data availability permits a robust estimate (i.e. only for grid boxes with greater than 70% complete records and more than 20% data availability in the first and last 10% of the time period). Other areas are white. Grid boxes where the trend is significant at the 10% level are indicated by a “+” sign. Figure and caption source: IPCC, 2013a: 6.

indicate that the total radiative forcing associated with anthropogenic activities is +2.29 (range: 1.13–3.33) W/m², relative to 1750 (IPCC, 2013b), of which the greenhouse gas CO₂ provides the largest contribution, estimated at 1.68 (1.33–2.03) W/m² (IPCC, 2013b) (Figure 1.2). The radiative forcing due to CO₂ (and other long-lived greenhouse gases) is due to the

accumulation of CO₂ in the atmosphere, and is proportional to the cumulative emissions of CO₂ over time, whereas the radiative forcing for short-lived gases, such as methane (CH₄), is due to the change in the rate of emissions.

Between 1971 and 2010, more than 90% of the increased energy accumulated because of the

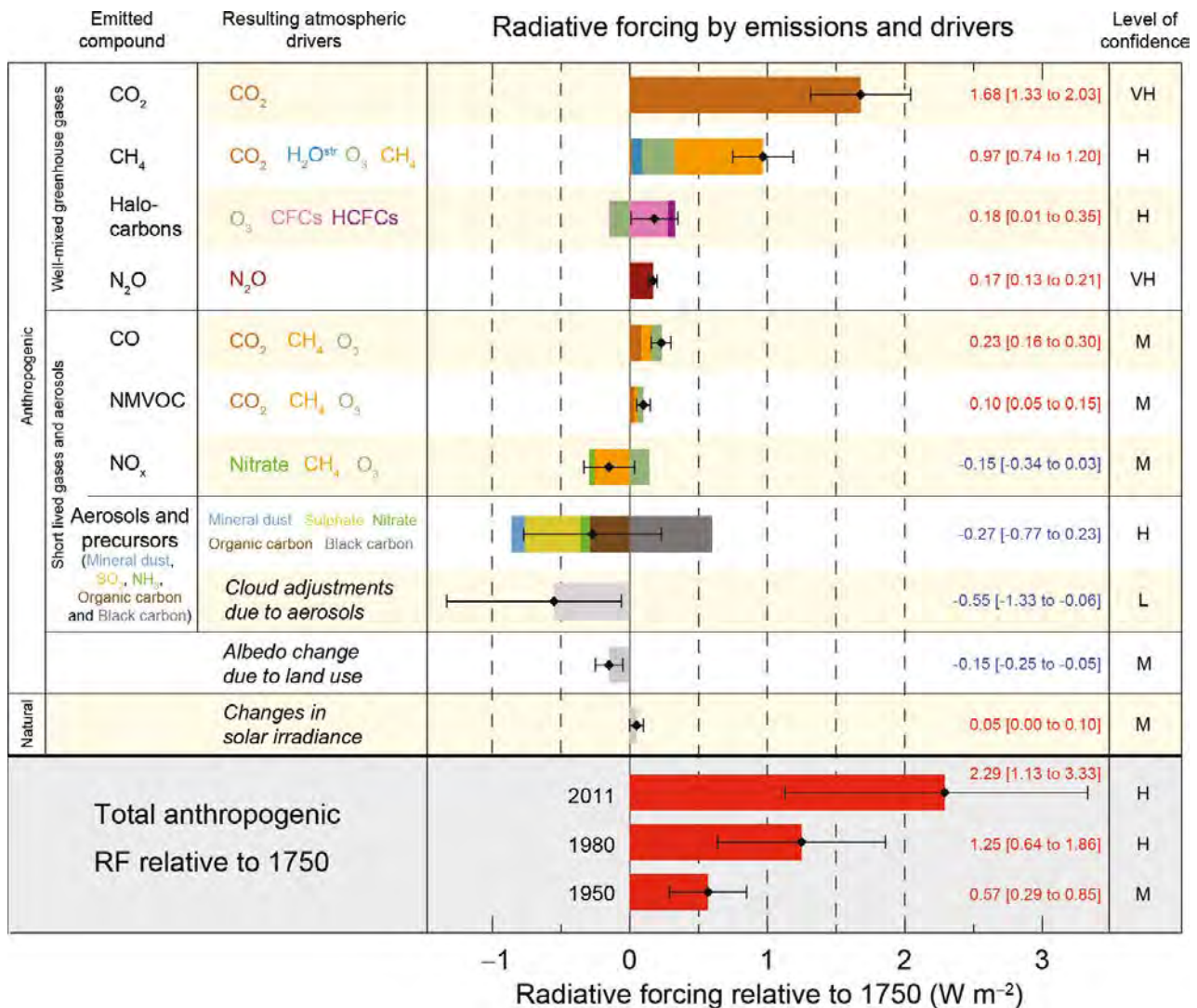


Figure 1.2. Radiative forcing estimates in 2011 relative to 1750 and aggregated uncertainties for the main drivers of climate change. Values are global average radiative forcing (RF14), partitioned according to the emitted compounds or processes that result in a combination of drivers. The best estimates of the net radiative forcing are shown as black diamonds with corresponding uncertainty intervals; the numerical values are provided on the right of the figure, together with the confidence level in the net forcing. Albedo forcing due to black carbon on snow and ice is included in the black carbon aerosol bar. Small forcings due to contrails (0.05 W/m², including contrail-induced cirrus), and hydrofluorocarbons, perfluorocarbons and sulfur hexafluoride (total 0.03 W/m²) are not shown. Concentration-based radiative forcings for gases can be obtained by summing the like-coloured bars. Volcanic forcing is not included as its episodic nature makes it difficult to compare with other forcing mechanisms. Total anthropogenic radiative forcing is provided for 3 years relative to 1750. VH, very high; H, high; M, medium; L, low. Figure and caption source: IPCC, 2013b: 14.

positive radiative forcing has been taken up by the oceans, with warming of the upper ocean (0–700 m) accounting for more than 60% of the total (IPCC, 2013a). The remainder is accounted for by warming of the atmosphere and land surface and melting of glacier and sea ice. These changes are being reflected in a variety of climate phenomena and in particular in the frequency and duration of extreme weather and climate events (Table 1.1).

1.4 National Context

Ireland experiences a mild maritime climate due to the moderating influence of the North Atlantic Ocean. As a consequence, Ireland does not experience the seasonal range of temperature associated with more continental locations at similar latitudes; mean

annual temperatures typically range from 8°C to 12°C (average 1981–2010) (source: Met Éireann, 2015). Precipitation receipts, by their nature, tend to be variable in Ireland and are strongly associated with the dominant airflow direction, maritime air advected from the Atlantic. Consequently, receipts tend to be higher in the west, associated with orographic enhancement, with mean annual receipts of 1000–1400 mm, declining to between 750 and 1000 mm on the east coast (source: Met Éireann, 2015). Prolonged periods of below average precipitation are also evident in the observational records. Recent research suggests that Ireland has experienced periods of consecutive years of rainfall deficiency and dry spells (e.g. 1850s, 1880 and 1970s) (Wilby *et al.*, 2016), based on a new long-term homogenised precipitation catalogue (Noone *et al.*, 2016).

Table 1.1. Global scale assessment of recent observed climate phenomena, direction of trend and human contribution

Phenomenon and direction of trend	Assessment that changes occurred	Assessment of a human contribution
Warmer and/or fewer cold days and nights over most land areas	<i>Very likely</i>	<i>Very likely</i>
	<i>Very likely</i>	<i>Likely</i>
	<i>Very likely</i>	<i>Likely</i>
Warmer and/or more frequent hot days and nights over most land areas	<i>Very likely</i>	<i>Very likely</i>
	<i>Very likely</i>	<i>Likely</i>
	<i>Very likely</i>	<i>Likely</i> (nights only)
The frequency and/or duration of warm spells/heat waves increases over most land areas	<i>Medium confidence</i> on a global scale	<i>Likely</i>
	<i>Likely</i> in large parts of Europe, Asia and Australia	Not formally assessed
	<i>Medium confidence</i> in many regions	More likely than not
Heavy precipitation events Increase in the frequency, intensity and/or amount of heavy precipitation	<i>Likely</i>	
	<i>Likely</i> more land areas with increases than decreases	<i>Medium confidence</i>
	<i>Likely</i> more land areas with increases than decreases	<i>Medium confidence</i>
Increases in intensity and/or duration of drought	<i>Likely</i> over most land areas	More likely than not
	<i>Low confidence</i> on a global scale	<i>Low confidence</i>
	<i>Likely</i> changes in some regions	<i>Medium confidence</i>
Increases in intense tropical cyclone activity	<i>Medium confidence</i> in some regions	More likely than not
	<i>Likely</i> in many regions since 1970	
	<i>Low confidence</i> in long-term (centennial) changes	<i>Low confidence</i>
Increased incidence and/or magnitude of extreme high sea level	<i>Virtually certain</i> in North Atlantic since 1970	<i>Low confidence</i>
	<i>Low confidence</i>	More likely than not
	<i>Likely</i> in some regions since 1970	
	<i>Likely</i> (since 1970)	<i>Likely</i>
	<i>Likely</i> (late 20th century)	<i>Likely</i>
	<i>Likely</i>	More likely than not

Adapted from IPCC (2013b) with permission.

*The IPCC define the following terms to indicate the assessed likelihood, using expert judgement, of an outcome or a result: *Virtually certain* >99% probability of occurrence, *Extremely likely* >95%, *Very likely* >90%, *Likely* >66%, *More likely than not* >50%, *Unlikely* <33%, *Very unlikely* <10%, *Extremely unlikely* <5%.

In spite of Ireland's maritime location, and the buffering effect it conveys on the climate, similar trends to those experienced globally have been observed for Ireland (e.g. McElwain and Sweeney, 2007; Dwyer, 2012; Walsh, 2013). Mean annual air temperature anomalies derived from five long-term stations, namely Valentia, Birr, Phoenix Park, Armagh and Malin Head, increased by approximately 0.8°C (linear trend) over the period 1900–2011 (Dwyer, 2012; Walsh, 2013 – which included the year 2012). However, even within the relatively small land area of Ireland, significant spatial variations are evident in the observed rates of warming. A study by Fealy *et al.* (2010) on the Burrishoole catchment in County Mayo found that, over the 50-year period from 1960 to 2009, mean annual air temperature anomalies (relative to the 1961–1990 average) in the catchment had increased by 1.48°C (compared with the national value of 0.9°C over a comparable time period of 1960–2005; Fealy *et al.*, 2010). Consistent with international studies on the global climate, national research efforts have also detected changes in other meteorological and environmental parameters, such as precipitation (McElwain and Sweeney, 2007; Dwyer, 2012); evaporation (Kiely *et al.*, 2010); number of frost days (Dwyer, 2012) and frost season length (McElwain and Sweeney, 2007); growing season (Donnelly *et al.*, 2006; Met Éireann, 2009a, 2009b); river flow (Kiely *et al.*, 2010; Murphy *et al.*, 2013); flora and fauna (Desmond *et al.*, 2009); phenology (Regan, 2013); and ecosystem response (Donnelly *et al.*, 2015).

Recent extreme weather events, such as the prolonged cold periods during the winter of 2009/10 and November/December 2010, widespread flooding episodes (e.g. August 2008, November 2009, winter 2015/16) (e.g. McGrath *et al.*, 2010), and the winter storms of 2013/14, the stormiest on record for the UK and Ireland (e.g. Matthews *et al.*, 2014), have alerted stakeholders, ranging from local authorities to insurance suppliers, that the repeated occurrence of such events can have severe negative impacts. While such events are consistent with the natural variability of the climate system, changes in the frequency, occurrence and duration of extreme weather events are likely to have significant and varying impacts on human and natural systems, including, *inter alia*, animal and human health, energy, agriculture, food security, transport and water resources.

1.5 Discussion

Globally, the scientific consensus is that anthropogenic activities now have a discernible and measurable effect on the Earth's climate system, largely assessed through the diagnostic of changes in the surface temperature record. Such detected changes are superimposed on the natural variability inherent in the climate system. In addition, both positive and negative feedbacks exist within the climate system; such feedbacks may operate in the direction of the original change (land surface changes resulting from warming tend to be positive as they lead to enhanced warming) or counter to the direction of the original perturbation (increased moisture in the atmosphere, due to warming which leads to an increase in low cloud cover, can result in cooling and therefore is negative). The climate system, much like any dynamical system that is sensitive to initial conditions, also displays chaotic behaviour, limiting the extent to which we can “predict” changes in the system.

As a result of the complexity of the climate system, scientific endeavour has pursued a range of approaches following various lines of enquiry, which seek to improve our scientific understanding of how the climate system operates. A central component of this international research effort has been the development of sophisticated computer models, which are routinely used in operational weather forecasting. While these models represent a pinnacle of scientific endeavour, they are imperfect; ultimately, they represent a simplification of a very complex system and are subject to uncertainties. Some uncertainties within our models may be reducible as our knowledge of the system increases and is incorporated into the model; others may simply be irreducible. This has significant implications for developing long-term climate simulations. While model simulations of weather over short time scales (~5–10 days) represent a forecast or prediction, in that probabilities can be attached to the forecast, because of the time scales involved, model outputs from longer term climate (statistics of weather) simulations should not be viewed as deterministic outcomes but rather interpreted as plausible outcomes or projections. Model simulations provide a means to assess the robustness of developed policy options and their potential sensitivity to uncertainties in the climate system response to a change in radiative forcing.

2 Modelling the Climate System

Since all models are wrong the scientist cannot obtain a “correct” one by excessive elaboration. On the contrary following William of Occam he should seek an economical description of natural phenomena.

Box, 1976: 792

2.1 Introduction

Climate models currently represent the best available scientific tools for undertaking scenario analyses of possible future changes in the climate system, for example if current atmospheric concentrations of greenhouse gases continue to increase. These state-of-the-art, dynamical models typically require prescribed information about future emissions, or atmospheric concentrations, of radiatively active species of gases to generate long-term climate projections, based on assumptions about future human activity or natural effects that could alter the energy balance of the climate system over time through changes to the radiative forcing. Until recently, future emissions scenarios were prescribed according to various storylines or pathways of future world development (e.g. socio-economic scenarios based on storylines of future economic development, energy production and use, and technology development, uptake and transfer) [e.g. Special Report on Emissions Scenarios (SRES), after Nakicenovic *et al.*, 2000]. However, identified shortcomings in the treatment of short- and long-lived gases in this approach led to the

development of a new suite of prescribed forcings, termed (RCPs) (e.g. Moss *et al.*, 2010), for use in global climate modelling.

2.2 Representative Concentration Pathways (RCPs)

RCP scenarios specify time-evolving emissions, concentrations and radiative forcing trajectories decoupled from any underlying socio-economic assumptions or storylines; each concentration pathway is one of many possible scenarios that could lead to a specific forcing characteristic (Moss *et al.*, 2010). Four primary trajectories or representative concentration pathways have been identified, namely RCP2.6, RCP4.5, RCP6.0 and RCP8.5 (see Table 2.1). Figure 2.1 illustrates the difference in radiative forcing between the new RCPs, employed in the Fifth Assessment Report (IPCC, 2013a), and earlier scenarios, employed in the Second (IPCC, 1995), Third and Fourth Assessment Reports (IPCC, 2001, 2007).

Consistent with previous findings based on the earlier SRES, temperatures increase because of increasing concentrations of greenhouse gases; the amount of warming projected is dependent on the particular concentration pathway (Table 2.2). The multi-model mean spatial pattern of temperature and precipitation of the RCP projections are also found to be consistent with those of the earlier SRES (Knutti and Sedláček, 2013). Yet, in spite of the similarities in the multi-model means, significant differences remain between

Table 2.1. Radiative forcing and CO₂-eq (CO₂ equivalent) associated with the four representative concentration pathways (RCPs) (after Moss *et al.*, 2010)

Name	Radiative Forcing	Concentration (ppm)	Pathway	Model providing RCP
RCP2.6	Peak at ~3 W/m ² before 2100 and then declines	Peak at ~490 CO ₂ -eq before 2100 and then declines	Peak and decline	IMAGE
RCP4.5	~4.5 W/m ² at stabilisation after 2100	~650 CO ₂ -eq (at stabilisation after 2100)	Stabilisation without overshoot	GCAM
RCP6.0	~6 W/m ² at stabilisation after 2100	~850 CO ₂ -eq (at stabilisation after 2100)	Stabilisation without overshoot	AIM
RCP8.5	>8.5 W/m ² in 2100	>1370 CO ₂ -eq in 2100	Rising	MESSAGE

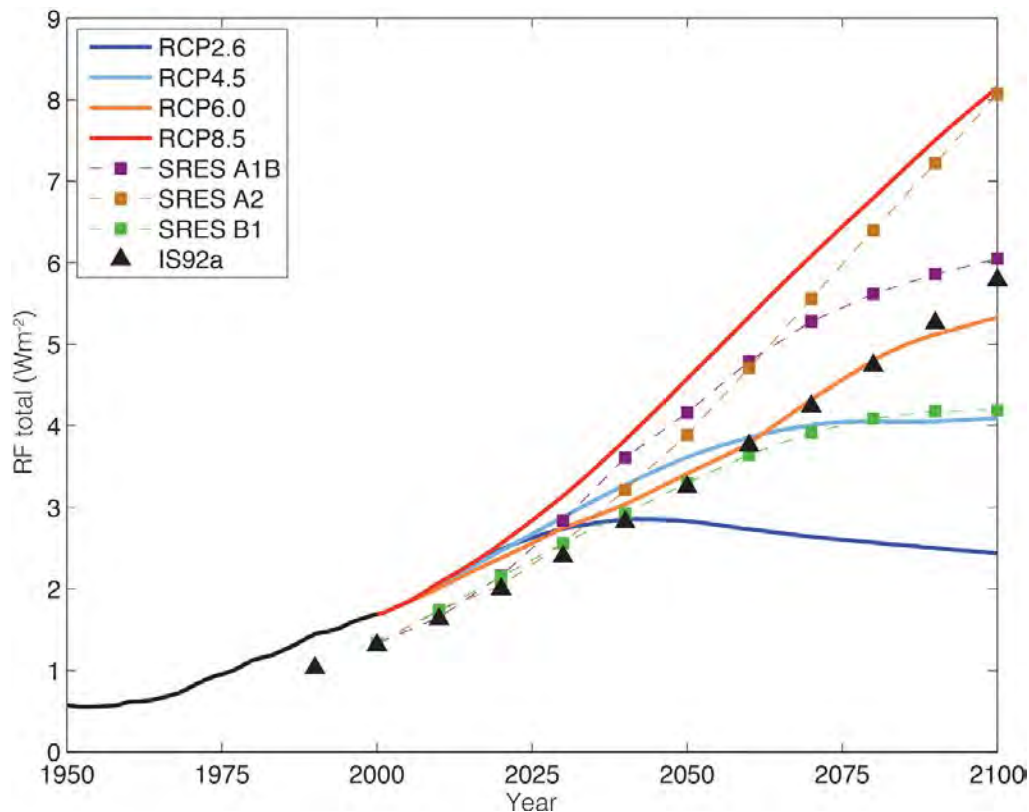


Figure 2.1. Historical and projected total anthropogenic radiative forcing (Wm^{-2}) relative to pre-industrial levels (about 1765) between 1950 and 2100. Previous Intergovernmental Panel on Climate Change (IPCC) assessments (SAR IS92a, TAR/AR4 SRES A1B, A2 and B1) are compared with representative concentration pathway (RCP) scenarios. The total radiative forcing of the three families of scenarios, IS92, SRES and RCP, differ, for example for the year 2000, resulting from the knowledge about the emissions assumed having changed since the Third Assessment Report and Fourth Assessment Report. Figure and caption source: IPCC, 2013a: 146.

Table 2.2. Projected change in global mean surface air temperature ($^{\circ}\text{C}$) for the mid and late 21st century relative to the reference period of 1986–2005. Table and caption source: IPCC, 2013b: 23.

Scenario	2046–2065		2081–2100	
	Mean	Likely range	Mean	Likely range
RCP2.6	1.0	0.4 to 1.6	1.0	0.3 to 1.7
RCP4.5	1.4	0.9 to 2.0	1.8	1.1 to 2.6
RCP6.9	1.3	0.8 to 1.8	2.2	1.4 to 3.1
RCP8.5	2.0	1.4 to 2.6	3.7	2.6 to 4.8

models in both the temporal and spatial projections of precipitation. Such differences are most pronounced at the regional scale, where differences in both the magnitude and direction of projected changes in precipitation are evident (IPCC, 2013a: 15).

2.3 Model Uncertainty

While significant developments have occurred in terms of increasing model complexity and resolution [e.g. from ~500 km (T21) (e.g. IPCC, 1990) to ~100 km (T159) (e.g. IPCC, 2013a)], the current global and ESMs simply cannot dynamically resolve processes occurring at a scale smaller than the model grid resolution. Consequently, important sub-grid scale processes are parameterised, or resolved, employing empirical equations or approximations. For example, sub-grid scale cloud formation is approximated employing an empirical relationship derived from observations. In addition, terrain representation effects can have significant impacts on regional and local scale climatic processes, particularly those associated with precipitation and over regions of complex topography.

A number of methodological approaches have been employed to generate higher resolution climate scenarios at the regional scale. These broadly fall into the following categories: statistical (e.g. Fealy and Sweeney, 2007, 2008); dynamical (e.g. McGrath *et al.*, 2005); and hybrid dynamical–statistical downscaling approaches (e.g. Bruyère *et al.*, 2012) (for a more comprehensive review of methods, see Mearns *et al.*, 2003; Wilby *et al.*, 2004; Fowler *et al.*, 2007). Statistical downscaling approaches are typically applied at a site or sites of interest (e.g. meteorological or surface environmental observation station); dynamical approaches, based on numerical weather prediction models, dynamically simulate climate over a spatial domain or region of interest (e.g. continental), thereby freeing up computational resources which can be directed towards increased model resolution. Dynamical–statistical approaches typically employ a combination of both approaches to generate higher resolution climate scenarios. While the use of RCMs can assist in resolving smaller scale processes than the parent climate model, similar issues prevail at the finer grid sizes. Irrespective of approach, all downscaling techniques are subject to uncertainties, in addition to those accruing in the parent climate model; while they may produce more precise outputs, they are not necessarily any more accurate.

Ultimately, all climate models, whether statistical or dynamical, represent a simplification of reality (e.g. Box, 1976), which gives rise to model differences arising from the various sources of uncertainty – model, emissions/forcing pathway and internal

variability – which vary depending on the time and space scale of interest (IPCC, 2013a). For the time scales of interest for near-term, or decadal, predictions, the correct specification of initial conditions is critical as the signal to noise ratio (climate change signal to natural variability) is considered small. Hence, uncertainties in both initial conditions (Cox and Stephenson, 2007) and model uncertainty (Hawkins and Sutton, 2009) contribute the largest proportion to “prediction” uncertainty over short-time horizons (Figure 2.2a). In contrast, as the signal to noise ratio increases, over century and longer time scales, as a result of the increasing dominance of the anthropogenic climate signal, model simulations become largely insensitive to initial conditions. Over these long time horizons, the largest contributors to “prediction” uncertainty arise from the prescribed pathway (e.g. emissions, concentrations, radiation forcing) scenario uncertainties (Cox and Stephenson, 2007) and model uncertainties (Hawkins and Sutton, 2009) (Figure 2.2a). In an analysis of the Coupled Model Intercomparison Project (CMIP) phase 3 (CMIP3) data to partition the various sources of uncertainty in climate model projections (e.g. internal variability, model uncertainty and emissions uncertainty), Hawkins and Sutton (2009) extended the analysis of Cox and Stephenson (2007) to the regional scale (Figure 2.2b). They found that the different sources of uncertainty varied with lead time and both spatial and temporal averaging scale.

Hawkins and Sutton (2009) also highlight the importance of internal variability for short time scales.

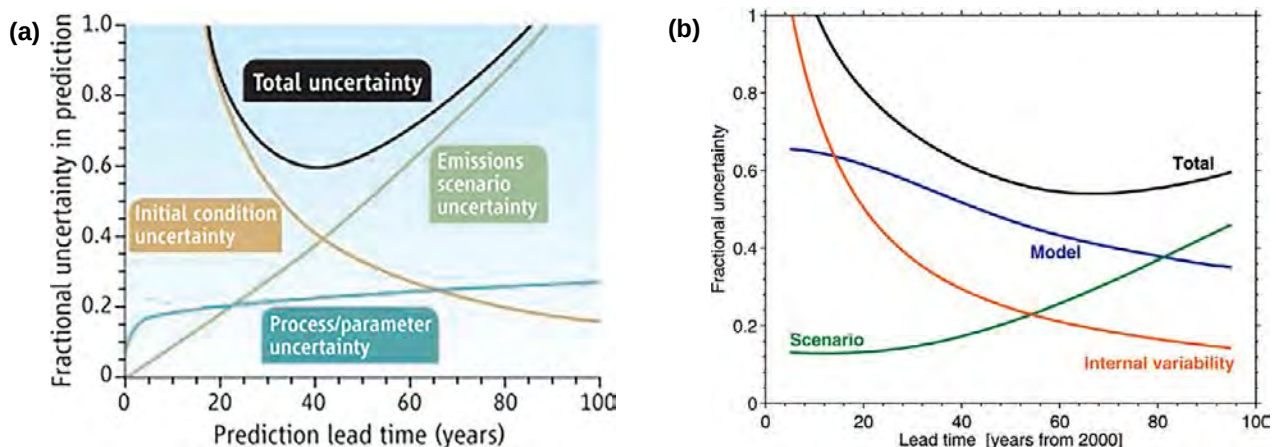


Figure 2.2. The “prediction problem”. (a) Relationship between lead time and fractional uncertainty (prediction error divided by its central estimate) (from: Cox and Stephenson, 2007. Reprinted with permission from AAAS.); (b) fractional uncertainty in decadal mean surface temperatures over Britain and Ireland (source: Hawkins and Sutton, 2009).

Importantly, the contribution of internal variability to uncertainty was found to increase at smaller spatial and temporal scales (Hawkins and Sutton, 2009). A “sweet spot” occurs around the middle of the century (lead time 60 years), where the accumulation of the three contributions to total uncertainty (model, scenario and internal variability) is minimised. For precipitation, internal model variability is estimated to contribute between 50% and 90% of the total uncertainty for the next decade and remains an important source of uncertainty for lead times up to 30 years (Hawkins and Sutton, 2011).

Projections of changes in extremes are also highly uncertain, particularly at scales of relevance for developing tailored, cost-effective adaptation strategies (Klein Tank *et al.*, 2009). Beniston *et al.* (2007), in an analysis of projected changes of extremes in Europe, found that, while the simulation of heat waves was robust to model formulation, changes in extreme precipitation and wind speeds were sensitive to the choice of regional climate model and driving global climate model. These findings are in contrast to Vautard *et al.* (2013), in an analysis of simulated heat waves in Europe from a large ensemble of RCMs, who found that results were sensitive to the microphysics parameterisation schemes employed and model convection. Model resolution was also found to affect the results, which the authors linked to the partitioning of energy (e.g. between sensible and latent heat–Bowen ratio). For precipitation, variations between climate models were found to exceed internal variability and variability between different emission scenarios (Beniston *et al.*, 2007). While for 10-metre wind, Pryor *et al.* (2012) found that domain-averaged simulated wind speed, 50-year return period wind speed and wind gust increased when the spatial resolution was increased from 50 km to 6 km.

These results present significant challenges to modelling the climate system at all spatial scales. From the point of view of adaptation planning, the findings of Smith *et al.* (2007) that the inclusion of data assimilation techniques improved model skill (which they attributed to improved internal variability) may offer new opportunities for developing “skilful” decadal predictions (Keenlyside *et al.*, 2008). While robust decadal “predictions” at the regional scale remain a goal of the international modelling community, through the development of high-resolution fully

coupled ESMS and increased convergence between numerical weather prediction and climate modelling techniques (referred to as “seamless prediction”), the current international research effort continues towards the provision of long-term, century-scale climate projections.

2.4 World Climate Research Programme (WCRP) Coordinated Regional Downscaling Experiment (CORDEX)

A number of international modelling efforts have developed downscaled regional climate projections, mainly focused on Europe [e.g. Prediction of Regional scenarios and Uncertainties for Defining European Climate change risks and Effects (PRUDENCE) (Christensen *et al.*, 2007; Jacob *et al.*, 2007; van der Linden and Mitchell, 2009)] and North America [e.g. North American Regional Climate Change Assessment Program (NARCCAP) (Mearns *et al.*, 2009)]. More recently, the WCRP initiated a new programme, CORDEX, to generate regional scale climate projections for impact and adaptation assessment.

The CORDEX programme has defined a number of regional model domains for investigation by modelling groups. These regions are the Arctic, North America, Central America, Europe (EURO), Mediterranean (MED), Middle East/North Africa (MENA), Africa, Central Asia, East Asia, South Asia, South-East Asia (SEA), Australasia, South America and Antarctica. The aim of CORDEX is two-fold: to provide a protocol for a set of common experiments for specified domains (Figure 2.3) (e.g. standard domain, resolution, boundary conditions), output variables (see Appendix 1) and time resolution that all modelling groups agree to adhere to; and to provide a framework to evaluate and benchmark model performance (Giorgi *et al.*, 2009). An important aspiration of CORDEX is to characterise some of the uncertainty space that accrues in modelling the climate at the regional scale, based on the large number of contributing GCM–RCM model combinations (Table 2.3) (e.g. Katragkou *et al.*, 2015). This approach may also facilitate the generation of probabilistic-based climate change information; however, the resultant probabilities are ultimately limited to the uncertainty space defined by the selected input models and, consequently, may only partially reflect the total uncertainty range.

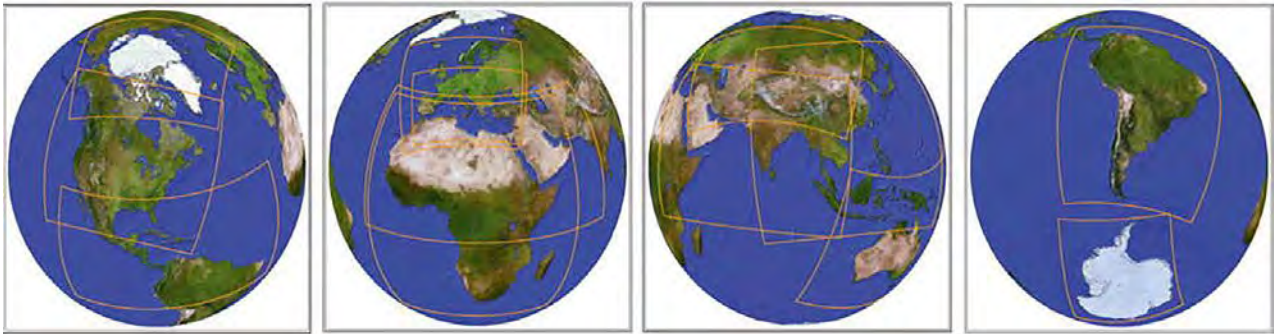


Figure 2.3. Locations of the COordinated Regional Climate Downscaling EXperiment (CORDEX) model domains: Arctic; North America; Central America; Europe; Mediterranean; Middle East/North Africa; Africa; Central Asia; East Asia; South Asia; South-East Asia; Australasia; South America; Antarctica (source: <https://rcmes.jpl.nasa.gov/content/cordex>). Figure reproduced by kind permission of RCMES and CORDEX.

Table 2.3. Matrix of GCM–RCM combinations for the EURO-CORDEX 0.44° resolution domain (EUR-44) for RCP8.5. RCMs are across the columns and GCMs are down the rows (source: EURO-CORDEX)

GCM	RCM									
	ALADIN	ARPEGE	CCLM	HIRHAM5	RACMO	RCA	RegCM	REMO2009	WRF	Total
ACCESS1-3									1	1
CanESM2						1				1
CCSM4						1				1
CNRM-CM5	2	1				1	1			5
CSIRO-Mk3-6-0						1				1
EC-EARTH				1	1	1			2	5
GFDL-ESM2M						1				1
HadGEM2-ES			1			1				2
IPSL-CM5A-MR						1			1	2
MIROC5						1				1
MPI-ESM-LR			1			1		2		4
NorESM1-M						1			1	2
Total	2	1	2	1	1	11	1	2	5	26

2.5 Discussion

ESMs represent the current state of the art in generating global model simulations of the climate system. Reflecting the complexity of the system they attempt to simulate, these models are complex and sophisticated. However, in common with all models, they are ultimately subject to uncertainties; even if we could devise and build the perfect climate model, future projections of climate would continue to remain highly uncertain because of uncertainties associated with future development, leading to uncertainties around future atmospheric greenhouse gas concentrations (Wilby, 2010). In an attempt to cater for some of the uncertainties that can occur in the modelling

framework, a number of international modelling initiatives have developed that provide a common set of protocols or standards for participating modelling groups to adhere to (e.g. CMIP, CORDEX). Adherence to these common protocols ultimately facilitates any subsequent comparison of model outputs.

However, caution needs to be exercised in interpreting the convergence of results from any ensemble of models; due to similarity in model code, design or parameterisation schemes, the individual models do not represent an independent assessment of the climate system. Consequently, the uncertainty represented by the ensemble is likely to underrepresent the total uncertainty space of the climate system.

3 Regional Climate Simulations using the Advanced Research Weather Research and Forecasting (WRF) Model

Climate models have improved since the AR4. Models reproduce observed continental-scale surface temperature patterns and trends over many decades, including the more rapid warming since the mid-20th century and the cooling immediately following large volcanic eruptions (very high confidence).

There has been some improvement in the simulation of continental-scale patterns of precipitation since the AR4. At regional scales, precipitation is not simulated as well, and the assessment is hampered by observational uncertainties.

IPCC, 2013b: 13

development and support for RCM applications. In addition, WRF was designed for use at scales from large eddy simulation to hemispherical applications (Leung *et al.*, 2006). WRF climate simulations have also been widely used in impacts and adaptation studies (e.g. Heikkilä *et al.*, 2011; Chotamonsak *et al.*, 2012).

As part of this research, the original WRF model source code was modified to read in prescribed trace gas concentrations, based on the new RCPs, an option that is activated at compilation time. The modified code was originally developed by Claire Carouge [Climate Change Research Centre (CCRC), Australia]. This option is now standard in WRF releases and is controlled via a runtime option. This was considered an important element for the simulations and previous (unpublished) work has demonstrated the importance of including trace gas concentrations for regional simulations, which previously was included only indirectly via the boundary data.

The top of the model atmosphere was set to 10 hectopascals (hPa) and comprised 61 eta levels in the vertical, the concentration of levels occurring in the lower troposphere to reflect the higher density of the atmosphere in this region. A significant advantage of the WRF model is the range of user-definable selection of options, particularly those associated with model physics. The physics options employed are shown in Table 3.1, selected on the basis of previous research which assessed the sensitivity of WRF to different parameterisation schemes (Mooney *et al.*, 2013).

The extent of the domain employed is illustrated in Figure 3.1 and is based on a rotated-pole coordinate system with 186 grids in the east–west direction and 143 grids in the north–south direction. The grid domain and set-up contains the EURO-CORDEX specified domain dimensions (103 × 106), with an additional boundary region to allow for relaxation of boundary conditions. The model grid resolution

3.1 Introduction

RCM simulations for Ireland were undertaken with a modified version of the WRF model (Skamarock *et al.*, 2008), version 3.4.1. Consistent with the requirements of WCRP CORDEX, evaluation simulations were performed for the period 1979–2010 employing the ERA-Interim reanalysis data (T255 spectral or ~80 km) for the specified European (EURO-CORDEX) domain (Figure 2.3). The simulations were then evaluated against gridded observational data, E-Obs, derived from data provided by meteorological agencies across Europe, including Met Éireann. The evaluation focuses primarily on an evaluation of mean sea level pressure, 2-metre mean temperature and precipitation, variables that represent different scales of climate processes.

3.2 Model Description and Set-up

The WRF model, version 3.4.1, is a non-hydrostatic atmospheric model developed at the NCAR in Boulder, Colorado. The WRF model has been widely used as an RCM (e.g. Bukovsky and Karoly, 2009; Caldwell *et al.*, 2009; Evans and McCabe, 2010; Mooney *et al.*, 2013; Katragkou *et al.*, 2015) because of its widespread availability and the NCAR's on-going

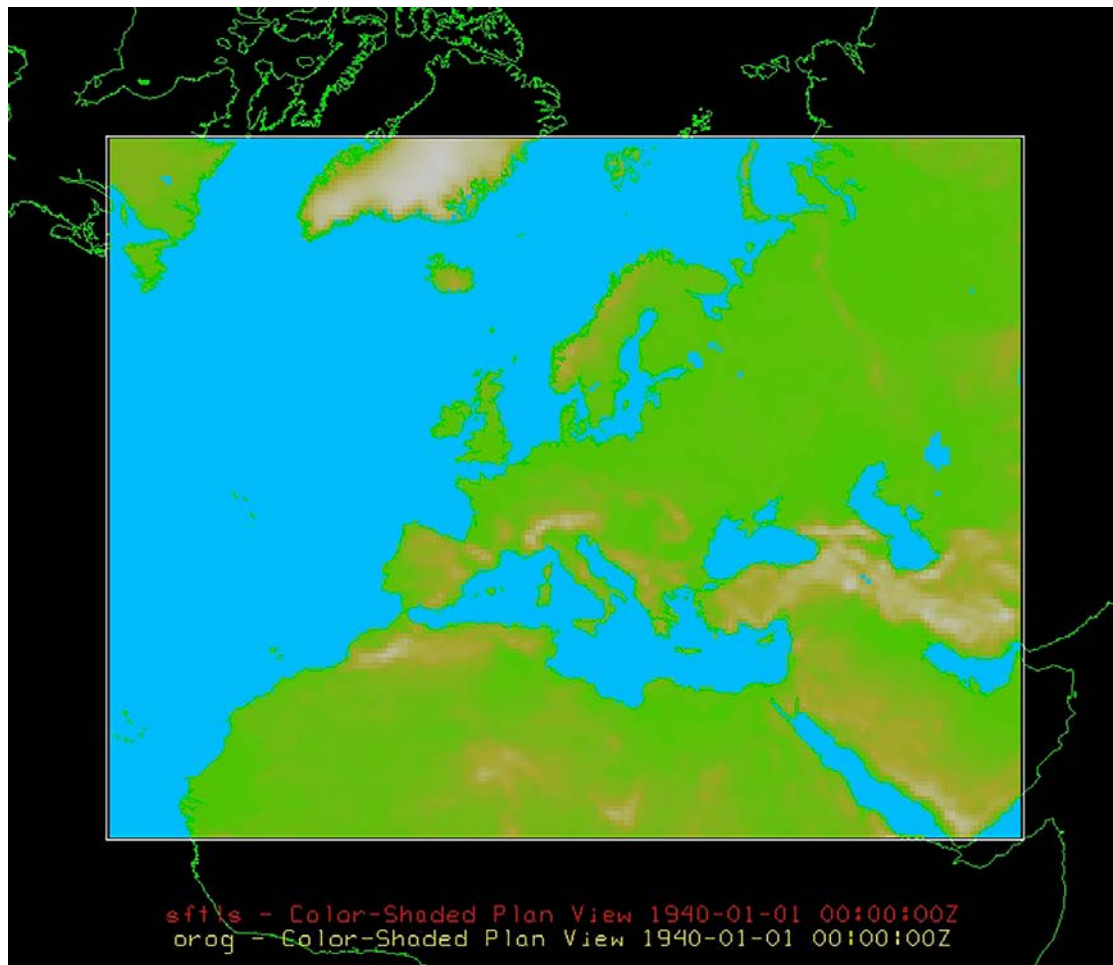


Figure 3.1. Model domain which includes the Euro-CORDEX domain.

Table 3.1. Model physics and the selected options employed for the WRF simulations

Parameterisation	Scheme
Microphysics	WSM-6-class graupel scheme
Longwave radiation	RRTMG scheme
Shortwave radiation	RRTMG scheme
Radiation update	30 minutes
Surface layer	MM5 Monim–Obukhov scheme
Land surface	Unified Noah land surface model
Boundary layer	YSU scheme
Cumulus	Tiedtke scheme

is 0.44° or ~ 50 km. A list of archived model outputs, consistent with the CORDEX specifications, is shown in Table 3.2. Different variables have been archived at various temporal resolutions (e.g. 3-hourly, 6-hourly and daily) according to the requirements of CORDEX. For a full list of variables and archived resolutions see http://is-enes-data.github.io/CORDEX_variables_requirement_table.pdf.

For the evaluation simulations, boundary conditions were supplied by the ERA-Interim Reanalysis data for the period 1979–2010. ERA-Interim data replaced the previous ERA-40 Reanalysis data and are the latest reanalysis data produced by the ECMWF. Recent studies (e.g. Troy and Wood, 2009; Mooney *et al.*, 2010; Screen and Simmonds, 2010) have shown that the ERA-Interim data are currently the most advanced reanalysis data available for this purpose, thanks to their ability to represent certain aspects of the climate system over other reanalysis data. Six-hourly ERA-Interim Reanalysis, at a spectral resolution of T255 (~ 80 km), were obtained on 60 vertical model levels (see Berrisford *et al.* (2011) and Dee *et al.* (2011) for a full description) for input to WRF. To allow for the WRF model to “spin up” (e.g. heating of soil layers, soil moisture, etc.), the WRF model-simulated data for 1979, based on boundary conditions provided from the ERA-Interim Reanalysis data, are removed from subsequent analysis.

Table 3.2. List of variables, and units, archived from the WRF simulations

Variable name	Units	Variable name	Units
Near-surface temperature	K	Convective precipitation	kg/m ² /s
Daily maximum near-surface temperature	K	TOA outgoing longwave radiation	W/m ²
Daily minimum near-surface temperature	K	TOA incident shortwave radiation	W/m ²
Precipitation	kg/m/s	TOA outgoing shortwave radiation	W/m ²
Surface air pressure	Pa	Eastward near-surface wind velocity	m/s
Sea level pressure	Pa	Northward near-surface wind velocity	m/s
Near-surface specific humidity	1	Daily maximum near-surface wind speed of gust	m/s
Near-surface wind speed	m/s	Surface temperature	K
Daily maximum near-surface wind speed	m/s	Height of boundary layer	m
Total cloud fraction	%	Water vapour path	kg/m ²
Duration of sunshine	s	Condensed water path	kg/m ²
Surface downwelling shortwave radiation	W/m ²	Ice water path	kg/m ²
Surface downwelling longwave radiation	W/m ²	Eastward wind	m/s
Surface upwards latent heat flux	W/m ²	Northward wind	m/s
Surface upwards sensible heat flux	W/m ²	Air temperature	K
Surface upwelling shortwave radiation	W/m ²	Specific humidity	1
Surface upwelling longwave radiation	W/m ²	Eastward wind	m/s
Evaporation	kg/m ² /s	Northward wind	m/s
Potential evapotranspiration	kg/m ² /s	Geopotential height	m
Total soil frozen water content	kg/m ²	Air temperature	K
Surface runoff	kg/m ² /s	Eastward wind	m/s
Subsurface runoff	kg/m ² /s	Northward wind	m/s
Total soil moisture	kg/m ²	Air temperature	K
Snow amount	kg/m ²	Geopotential height	m
Surface snow melt	kg/m ² /s	Snow depth	m
Daily maximum precipitation	kg/m ² /s	Snowfall flux	kg/m ² /s

3.3 Model Evaluation: Observations

WRF-simulated mean sea level pressure was compared with the ERA-Interim (ERAi) Reanalysis data to assess the model's ability to reproduce key large-scale circulation features of the driving data. Figure 3.2 illustrates the annual averaged mean sea level pressure for ERA-Interim (driving/boundary data) and WRF, and the difference between WRF and ERA-Interim (WRF–ERAi) for the period 1981–2010. The WRF model demonstrates good ability in reproducing the location and pressure associated with both the semi-permanent low-pressure system over Iceland (Icelandic Low) and the permanent high-pressure system over the Azores (Azores High). WRF was found to simulate above average mean sea level over North Africa of ~0.5 hPa. The largest departures in the simulated mean sea level pressure are found over northern Europe, where departures of 3.5 hPa are evident, particularly over high terrain, and over eastern

Europe. Overall, WRF appears to capture the strength of the dominant pressure systems and their locations; the main features of the airflow over the domain are also reproduced but slightly underestimated.

While reproduction of the large-scale climate features in the simulations is a necessary constraint, the model should also reproduce the small-scale features of the climate. Selected model-simulated meteorological fields for the European domain were therefore assessed for the evaluation period 1981–2010, using the ECA&D E-Obs, version 10 (Haylock *et al.*, 2008; van den Besselaar *et al.*, 2011). The ECA&D E-Obs data include gridded data for daily temperature (mean, maximum and minimum), daily precipitation sum and daily averaged sea level pressure, and exist on the same domain and resolution (e.g. 0.44°), with a similar grid definition (i.e. rotated grid) to the WRF model output (Figure 3.3). The ECA&D gridded data are derived from observational data which have

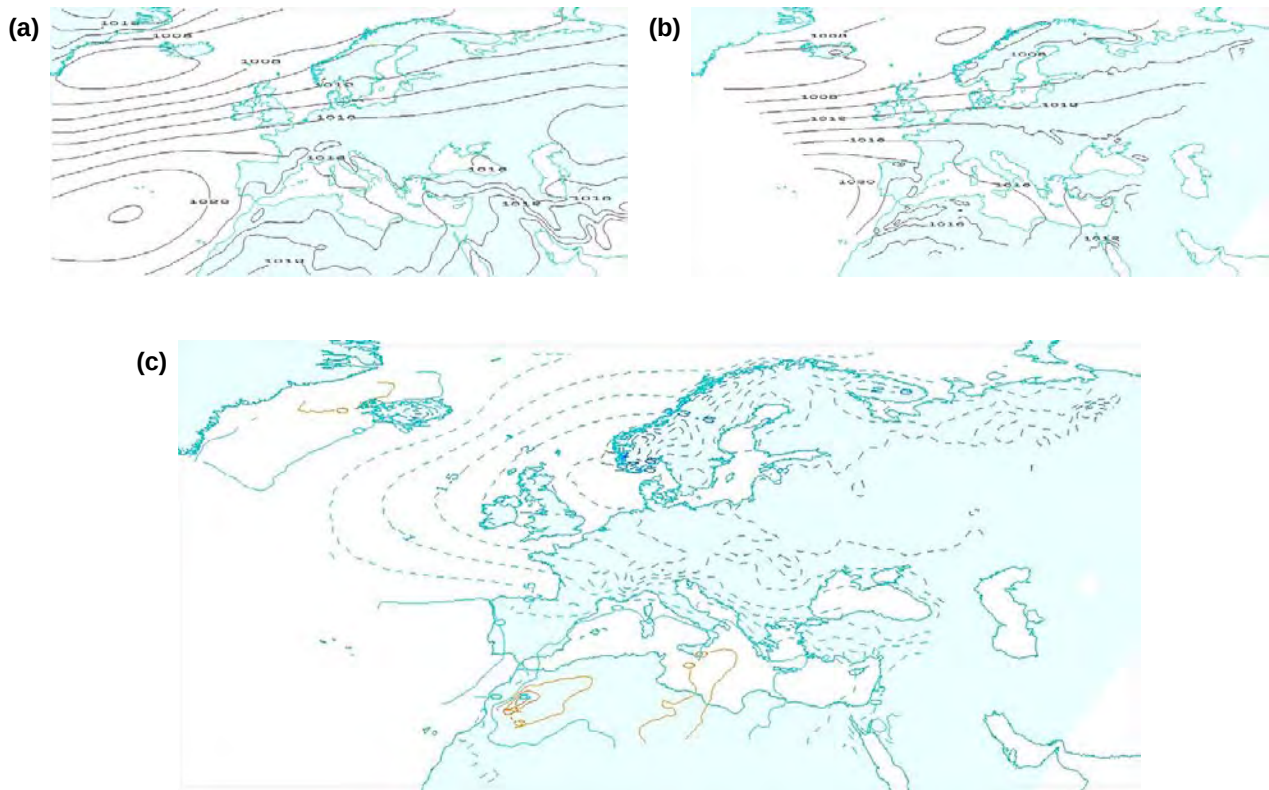


Figure 3.2. Annual averaged mean sea level pressure from (a) ERA-Interim (boundary conditions) and (b) WRF simulation and (c) difference between WRF and ERA-Interim. (WRF-ERAi) (bottom). The domain for the WRF simulation is identified by the green land area. The domain size for climate simulations should ensure that the dominant features of large-scale circulation do not depart significantly from the boundary conditions, provided by the ERA-Interim Reanalysis, while allowing for the development of small-scale features not present in the parent model. If the boundary domain size is too small, small-scale features of the model climate cannot fully develop as the boundary conditions dominate; conversely, if the domain is too large, the model climate can depart from the boundary (driving) conditions, leading to the development of large-scale circulation features that are different from the boundary conditions (Leduc and Laprise, 2009).

undergone a variety of interpolation techniques (see Haylock *et al.*, 2008, for further details) and are updated on a regular basis. Homogenisation of the observed data series is undertaken prior to interpolation. While the E-Obs data are based on observations, similar to all modelled data, the resultant gridded E-Obs data are subject to error in their own right (see Prein and Gobiet, 2016), in both instrumentation and interpolation. For the purposes of the current evaluation, the E-Obs data are considered to represent the best estimate of the “true” climate at a grid location.

Seasonal biases in mean sea level pressure, mean, maximum and minimum temperature and precipitation were assessed across the entire domain. Following this initial evaluation, the domain was then

decomposed into climatologically similar sub-domains (Figure 3.4), following Christensen and Christensen (2007), for further assessment. A more detailed evaluation was undertaken for these sub-regions, which included a temporal analysis of both the long-term and average monthly climatologies.

3.3.1 Seasonal mean bias

The seasonal mean bias was calculated as the difference between the WRF-simulated field and the E-Obs; a positive bias indicates that the WRF model simulated a higher value at that grid than E-Obs, while a negative bias indicates that the WRF model underestimated the grid value. Figure 3.5(a–c) shows the seasonal mean bias for mean sea level pressure (hPa), mean temperature (K) and precipitation

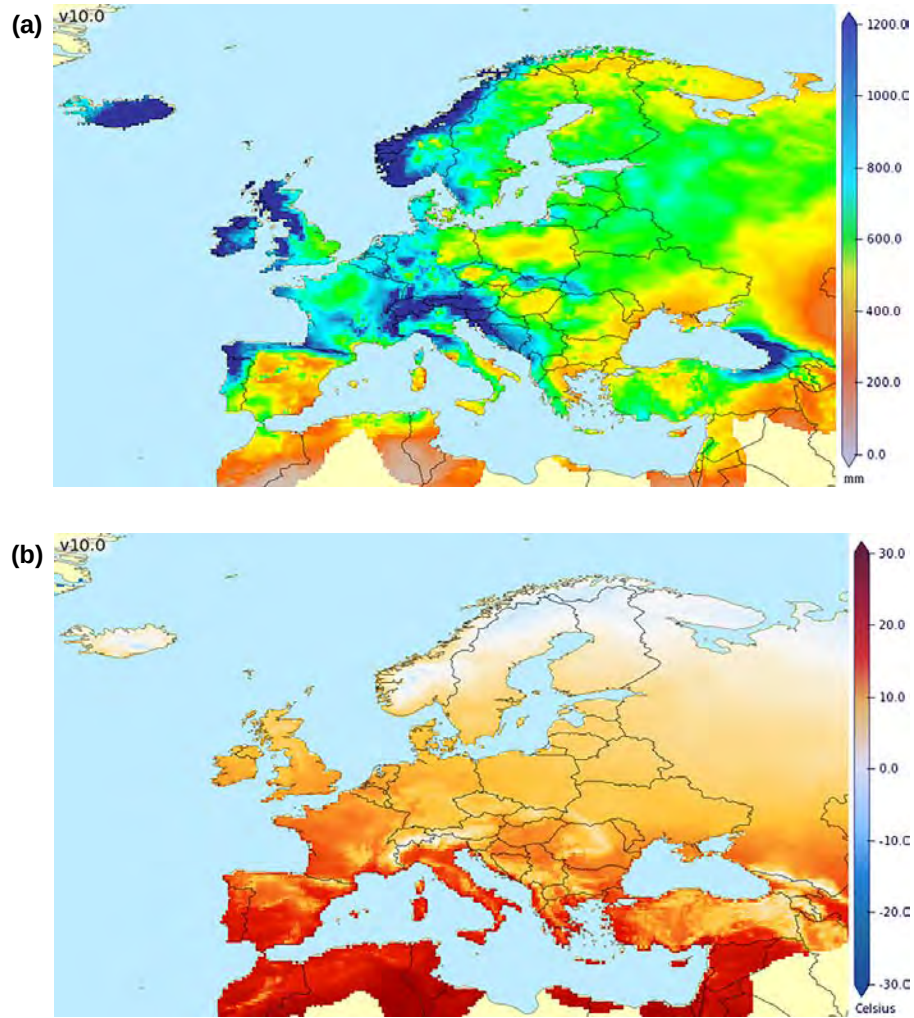


Figure 3.3. 1981–2010 annual climatology for (a) precipitation and (b) temperature from the ECA&D E-Obs version 10.0 data (source: cib.knmi.nl).

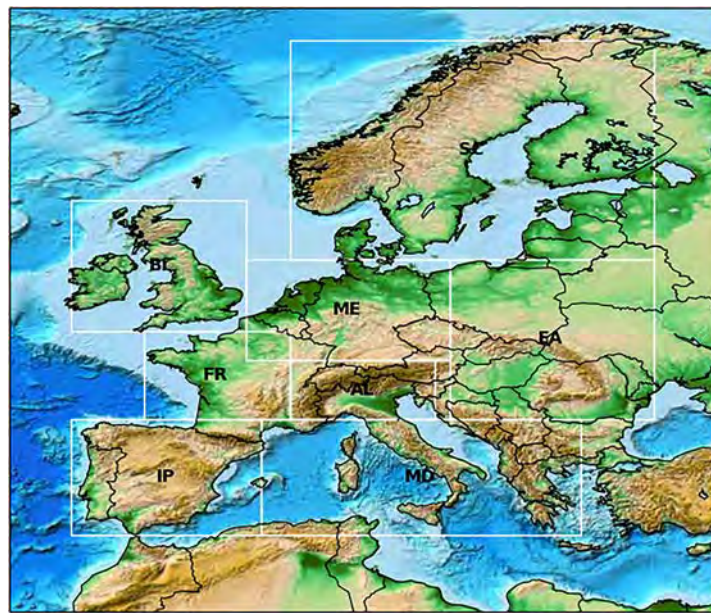


Figure 3.4. European sub-regions employed for model evaluation. AL, Alps; BI, British Isles; EA, Eastern Europe; FR, France; IP, Iberian Peninsula; MD, Mediterranean; ME, Mid-Europe; SC, Scandinavia.

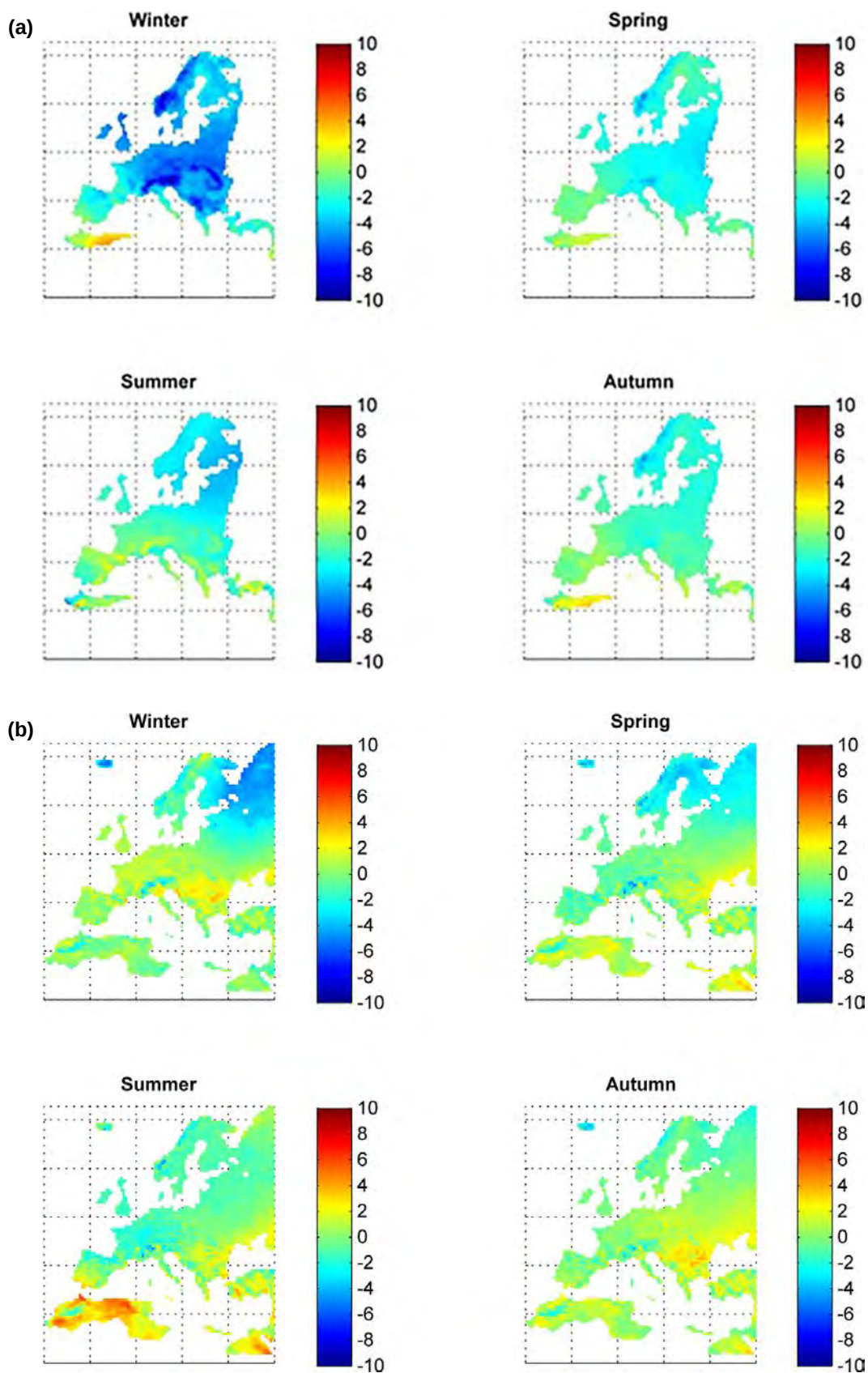


Figure 3.5. Seasonal mean bias for mean sea level pressure (hPa), mean temperature (K) and precipitation (mm) for the Euro-CORDEX domain for the period 1981–2010. (a) Seasonal mean bias for mean sea level pressure (MSLP) (hPa). (b) Seasonal mean bias for 2-metre mean temperature (K).

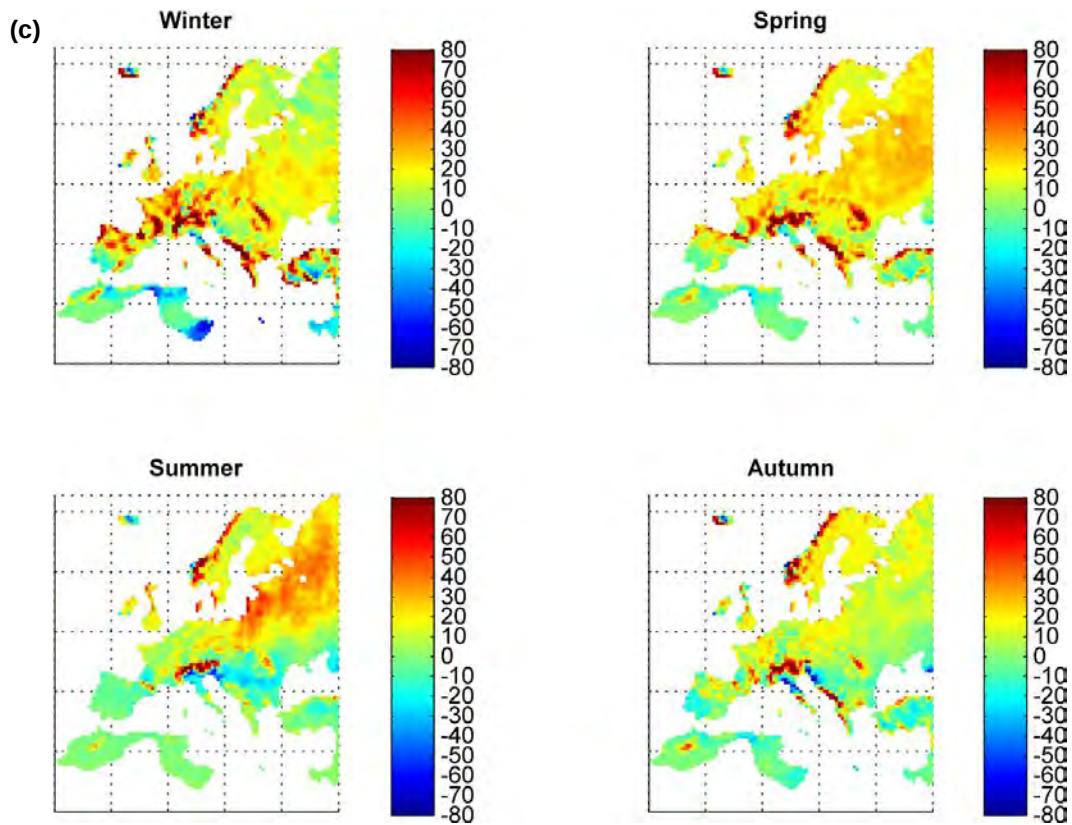


Figure 3.5. Continued. Seasonal mean bias for mean sea level pressure (hPa), mean temperature (K) and precipitation (mm) for the Euro-CORDEX domain for the period 1981–2010. (c) Seasonal mean bias for precipitation (mm).

(mm) for the Euro-CORDEX domain for the period 1981–2010. Bias plots for maximum and minimum temperature are shown in Appendix 2.

Mean sea level pressure

In all seasons, WRF simulates mean sea level pressure within $\pm 1\%$ (10 hPa) of the E-Obs data. Spatially, WRF displays a tendency to underestimate mean sea level pressure. The largest biases are evident over mountainous terrain, particularly in winter, spring and autumn, and are probably associated with orographic differences between the model elevation and the height of observed station locations; simulated pressure is consistently lower in the north-eastern part of the domain. Seasonal biases are smallest during the spring (March, April, May (MAM)), summer (June, July, August (JJA)) and autumn (September, October, November (SON)) periods, with the largest bias evident during the winter (December, January, February (DJF)) season. These findings are consistent with the bias evident in the annual averages over the

simulation period 1981–2010 (Figure 3.2) and with the analysis of Mooney *et al.* (2013), based on an assessment of parameterisation schemes and land surface model for the European domain.

2-metre mean temperature

A maximum winter cold bias is evident in the mean 2-metre air temperature for the extreme north-eastern part of the model domain over Russia. This reflects the underestimation of both maximum and minimum temperature (see Appendix 2). Katragkou *et al.* (2015) and Mooney *et al.* (2013) detected a similar underestimation for this region for the WRF model, which Mooney *et al.* (2013) attributed to the longwave radiation and microphysics schemes employed, while Katragkou *et al.* (2015) suggest the land–atmosphere interactions as the likely source. Overall, the WRF-simulated temperature reasonably captures the spatial detail of the E-Obs data. The number of observations contributing to E-Obs from this region is also likely to affect the gridded observations.

Precipitation

Throughout all seasons, precipitation is overestimated in regions of elevated terrain, relative to the E-Obs data. In winter, this overestimation extends to the northern half of Spain, most of France and parts of Germany. While the number of station observations in the E-Obs data is reduced for elevated regions, the station network for Germany is very dense, indicating that WRF is typically producing too much precipitation. This is confirmed by the monthly climatology for precipitation across the sub-regions.

3.3.2 European sub-regions: climatology

Mean sea level pressure

Relative to E-Obs, WRF underestimates mean sea level pressure in each of the regional sub-domains (Figure 3.6). The underestimation is most pronounced during the winter months, in particular for the Alps region (AL) (Figure 3.6a), with the smallest underestimations occurring during the summer months. The Alpine region represents a region of mountainous terrain and high elevation and it is likely that WRF model elevation and station density from the E-Obs are in part responsible for the underestimation in this sub-region.

2-metre mean temperature

WRF appears to capture the monthly mean 2-metre temperature climatology across all the sub-regions, with a tendency to overestimate temperature during the winter months with the exception of the Scandinavian sub-region, where WRF underestimates the mean temperature relative to the E-Obs data. The overestimation evident during the winter months is linked to the overestimation of minimum temperatures during these months. In general, WRF reproduces the maximum temperatures more faithfully during the winter months than during the summer months, when it tends to underestimate the mean monthly maximum temperatures. The Scandinavian region is an exception, with maximum temperatures being underestimated for all months. Previous research by Mooney *et al.* (2010), in a comparison of mean surface temperature derived from three reanalysis datasets

(National Centers for Environmental Prediction/NCAR; ERA-40 and ERA-Interim) with surface observations for Ireland, found a warm winter bias in the reanalysis data. The tendency of WRF to overestimate minimum temperatures during winter is a possible artefact of this.

Precipitation

In general, WRF overestimates precipitation during all months and for all regions, with the exception of the Iberian Peninsula and Mediterranean regions during the summer months. The largest overestimates are associated with the Alps region (AL), where the climatological mean monthly precipitation is overestimated by approximately 50 mm for the month of January, over the period 1981–2010. Across all sub-regions, the smallest differences in precipitation between E-Obs and WRF occur during the period between June and November.

3.3.3 European sub-domains: monthly evaluation

Results from an evaluation WRF on a monthly basis over the period 1981–2010 are illustrated in Figure 3.7(a–c), for mean sea level pressure (Figure 3.7a), mean temperature (Figure 3.7b) and precipitation (Figure 3.7c). On a monthly basis, WRF has a tendency to underestimate mean sea level pressure, relative to E-Obs, across all sub-regions. In spite of this, the month-to-month variability appears to have been well captured in the model simulations. The WRF-simulated mean monthly temperatures show a slight tendency to underestimate the annual range in temperature in the Alps (AL), Britain and Ireland (BI), France (FR) and Mediterranean (MD) regions. For Scandinavia (SC), WRF overestimates mean temperature during the winter months, relative to the E-Obs data, while it displays a tendency to underestimate winter temperatures in the Mediterranean (MD) region. For monthly precipitation, the WRF simulations display a tendency to overestimate receipts consistent with the discussion above (section 3.3.2). The largest overestimates are associated with the Alps (AL) region. This result is not surprising and is attributable to the difference between model and actual orography of the region.

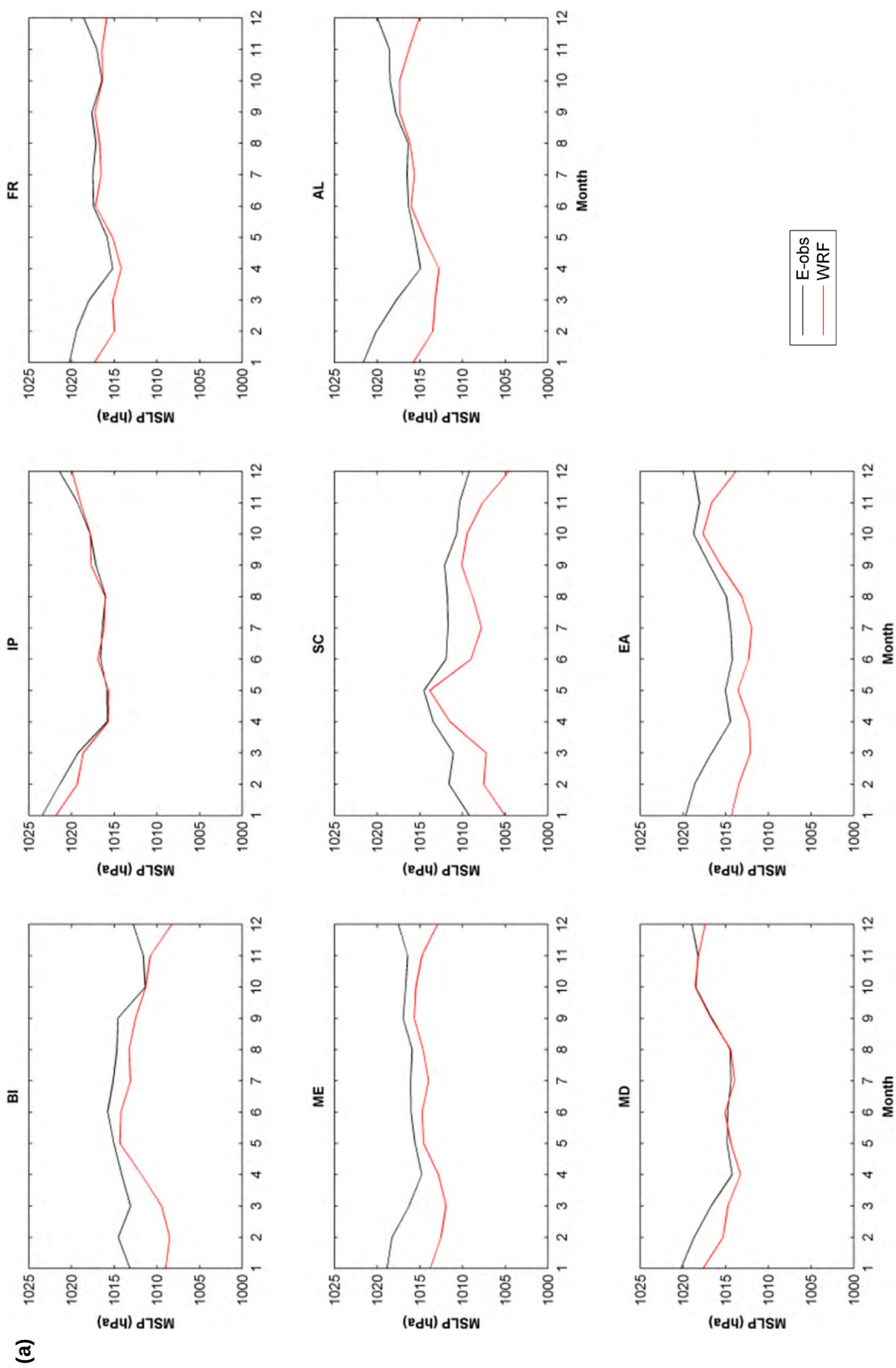


Figure 3.6. Climatological mean monthly sea level pressure, mean temperature and precipitation for the period 1981–2010 for the European sub-domains for E-Obs and WRF simulations employing ERA-Interim boundary conditions. (a) Climatological mean monthly sea level pressure (MSLP) (hPa). AL, Alps; BI, Britain and Ireland; EA, Eastern Europe; FR, France; IP, Iberian Peninsula; MD, Mediterranean; ME, Mid-Europe; SC, Scandinavia.

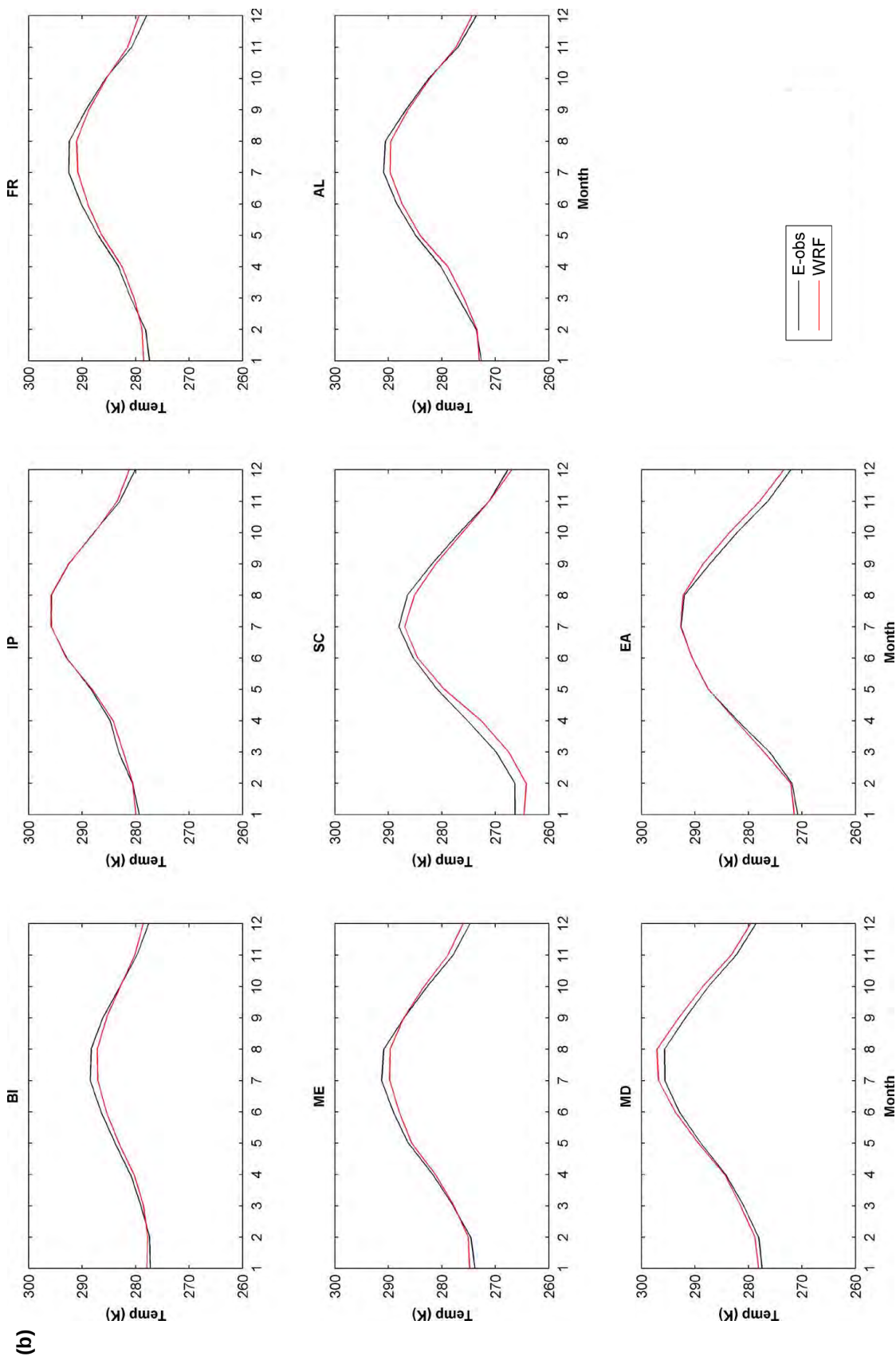


Figure 3.6. Continued. Climatological mean monthly sea level pressure, mean temperature and precipitation for the period 1981–2010 for the European sub-domains for E-Obs and WRF simulations employing ERA-Interim boundary conditions. (b) Climatological mean monthly mean temperature (K). AL, Alps; BI, Britain and Ireland; EA, Eastern Europe; FR, France; IP, Iberian Peninsula; MD, Mediterranean; ME, Mid-Europe; SC, Scandinavia.

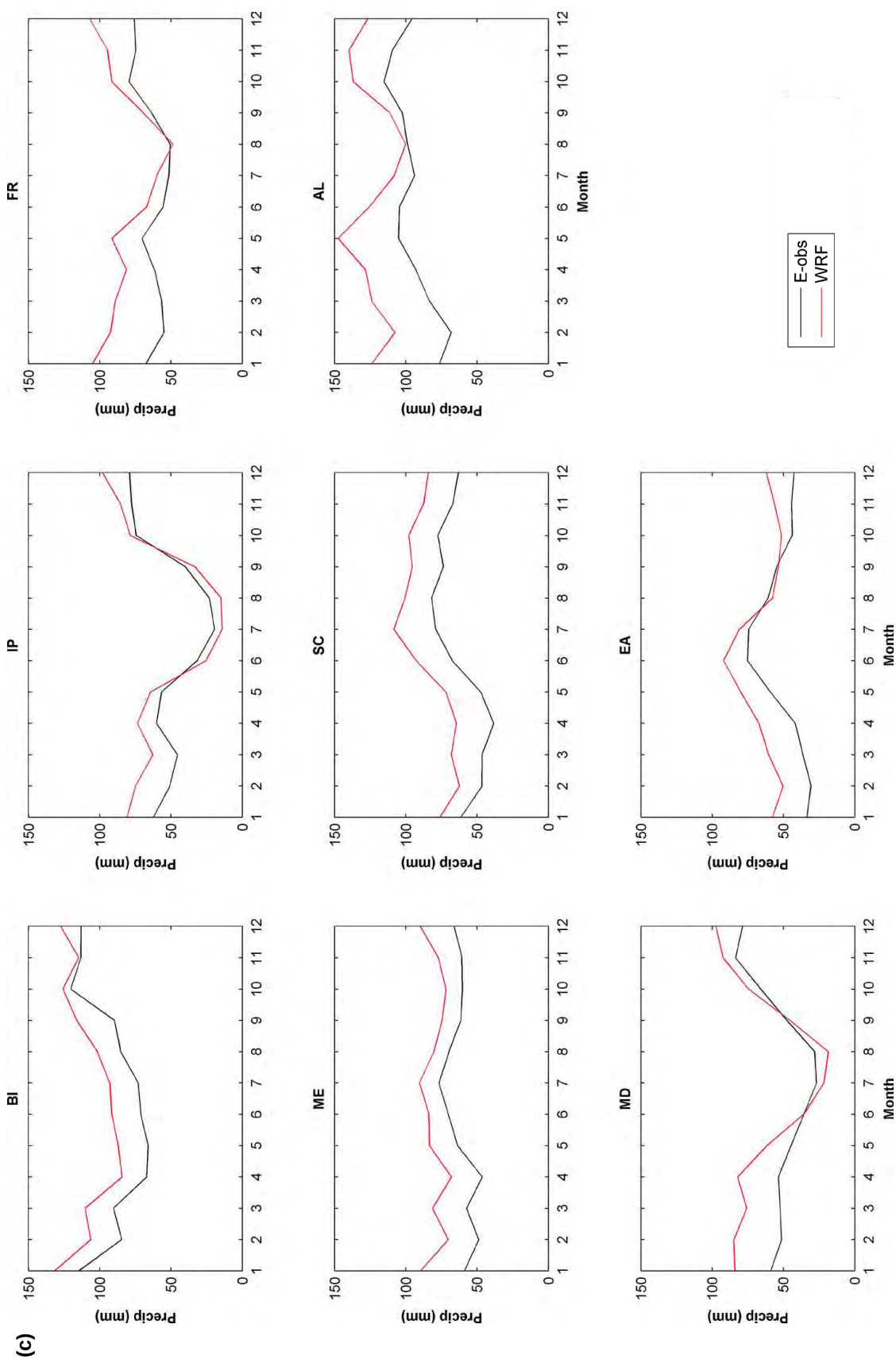


Figure 3.6. Continued. Climatological mean monthly sea level pressure, mean temperature and precipitation for the period 1981–2010 for the European sub-domains for E-Obs and WRF simulations employing ERA-Interim boundary conditions. (c) Climatological mean monthly precipitation (mm). AL, Alps; BI, Britain and Ireland; EA, Eastern Europe; FR, France; IP, Iberian Peninsula; MD, Mediterranean; ME, Mid-Europe; SC, Scandinavia.

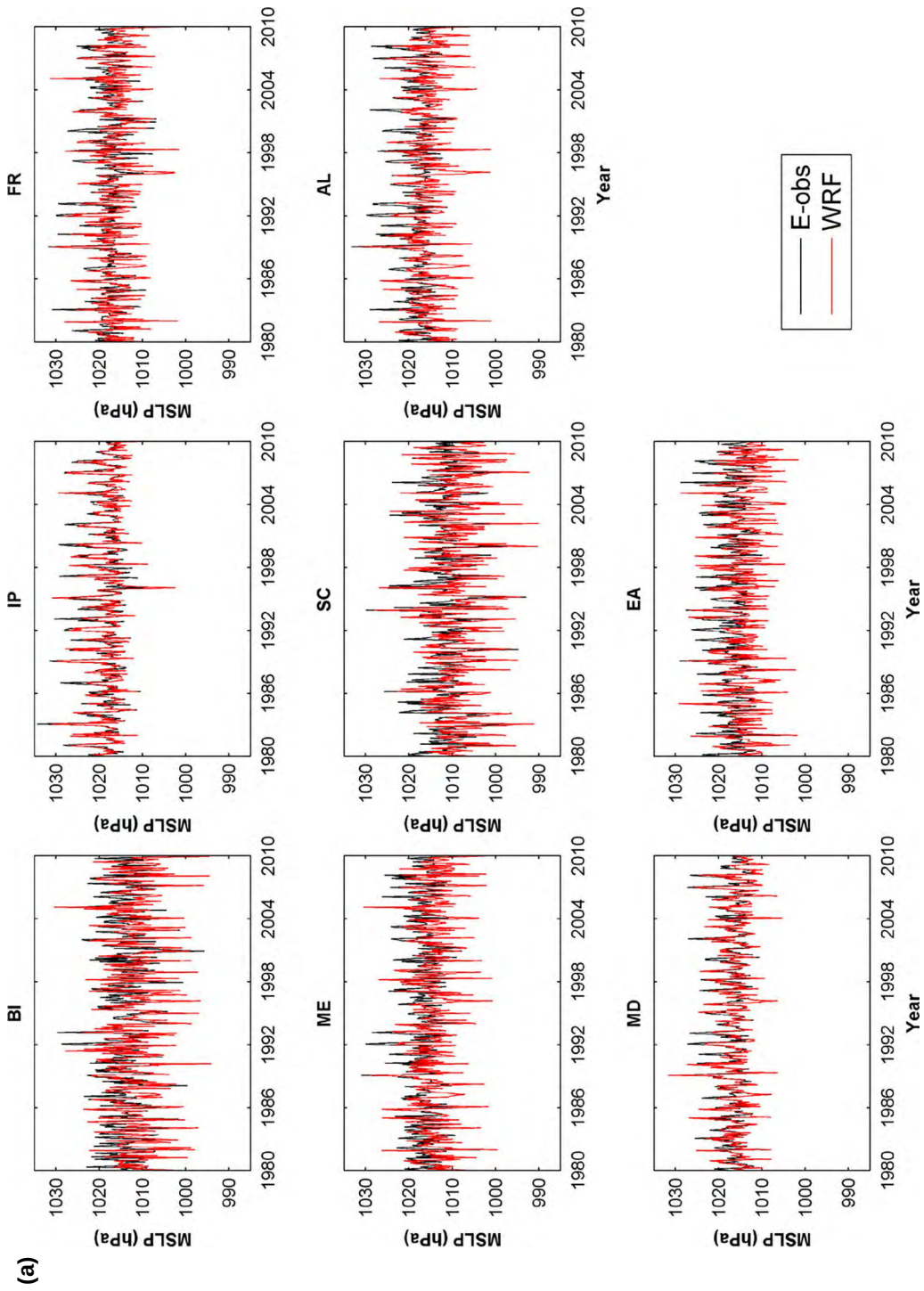


Figure 3.7. Monthly mean sea level pressure, mean temperature and precipitation for the period 1981–2010 for E-Obs and WRF for the European sub-domains. (a) Monthly mean sea level pressure (MSLP) (hPa). AL, Alps; BI, Britain and Ireland; EA, Eastern Europe; FR, France; IP, Iberian Peninsula; MD, Mediterranean; ME, Mid-Europe; SC, Scandinavia.

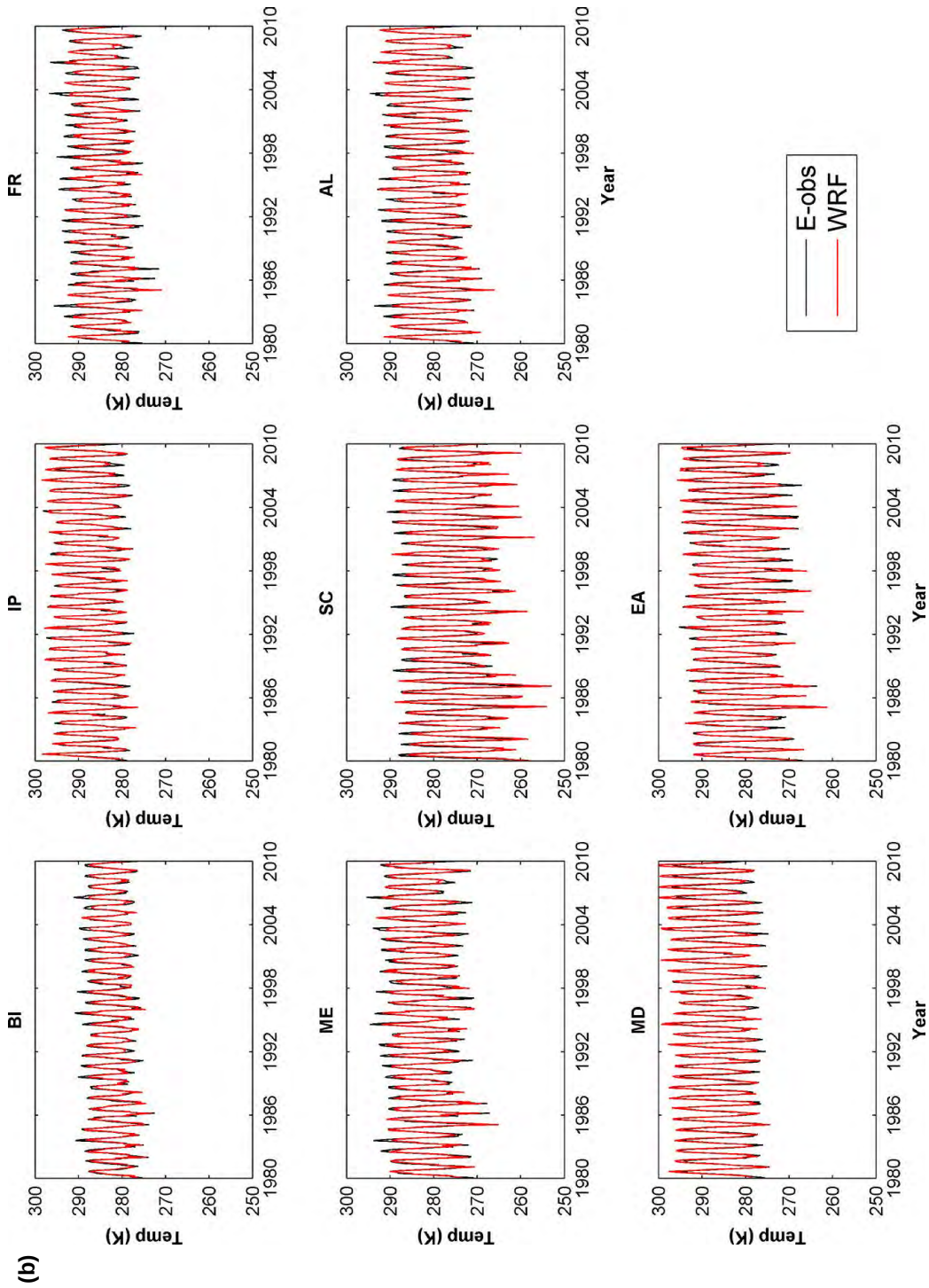


Figure 3.7. Continued. Monthly mean sea level pressure, mean temperature and precipitation for the period 1981–2010 for E-Obs and WRF for the European sub-domains. (b) Monthly mean temperature (K). AL, Alps; BI, Britain and Ireland; EA, Eastern Europe; FR, France; IP, Iberian Peninsula; MD, Mediterranean; ME, Mid-Europe; SC, Scandinavia.

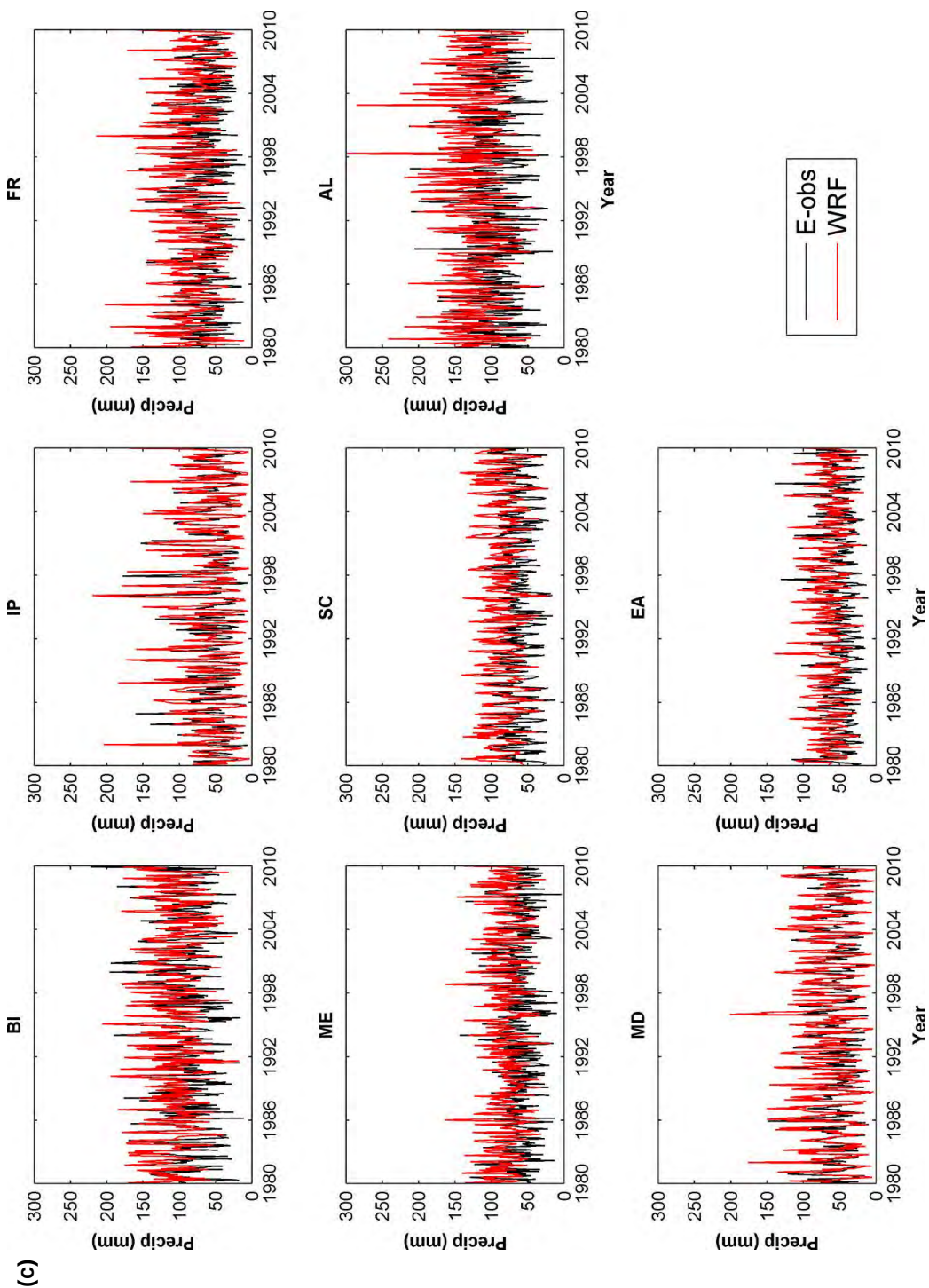


Figure 3.7. Continued. Monthly mean sea level pressure, mean temperature and precipitation for the period 1981–2010 for E-Obs and WRF for the European sub-domains. (c) Climatological mean monthly precipitation (mm). AL, Alps; BI, Britain and Ireland; EA, Eastern Europe; FR, France; IP, Iberian Peninsula; MD, Mediterranean; ME, Mid-Europe; SC, Scandinavia.

3.4 Discussion

Based on an initial evaluation of the WRF341E simulations, employing ERA-Interim Reanalysis data as boundary conditions, the model was found to reproduce the large-scale features of the boundary data over the 1981–2010 period, capturing both the locations and strength of the key pressure systems that influence the climate of Europe, namely the Azores High and the Icelandic Low. To further evaluate the model, the simulated fields of mean sea level pressure, mean daily temperature and precipitation were compared against the E-Obs gridded observational data on a seasonal basis for the model domain. The model was also evaluated for climatological (sub-)regions within Europe, to assess the ability of the model to reproduce the climatological mean values of the E-Obs data for these regions.

WRF demonstrated good ability to simulate mean sea level pressure, with simulated values falling within $\pm 1\%$ or ~ 10 hPa of the observed data. However, it tended to underestimate mean sea level pressure over mountainous terrain, in particular during the winter, spring and autumn seasons. This underestimation is probably attributable to differences in terrain height between that employed by the E-Obs data and the WRF model. However, these biases were also found to be consistent with Mooney *et al.* (2013).

In terms of temperature, a cold bias was evident in the daily mean temperature over the north-eastern part of the model domain, again consistent with other studies which attribute this to the physics schemes or land–atmosphere interactions. The climatological monthly means for the sub-regions show that WRF is able to adequately capture the annual cycle in temperature across the sub-regions and the seasonal minima and maxima.

Relative to E-Obs, WRF was found to consistently overestimate daily precipitation, particularly over regions of high relief. Again, this is partly attributable to a difference in the model versus E-Obs orography; the model orography is typically higher in Alpine regions. However, WRF also overestimates precipitation in regions where the model orography is lower than that of E-Obs (e.g. Scandinavia and northern Spain in winter). But the larger overestimates are likely associated with model relief. WRF underestimated precipitation in only two regions, namely the Iberian Peninsula and Mediterranean, and only during the summer months.

A more detailed evaluation was undertaken by Knist *et al.* (2016) for a selection of models participating in EURO-CORDEX to assess the interactions between the land surface and the atmosphere during the summer months, over the period 1989–2008, against the FLUXNET network (a network of micrometeorological tower sites across Europe). Overall, the WRF simulations outlined here were found to be broadly consistent with other model simulation studies for the domain.

Recent research by Prein and Gobiet (2016) found significant differences between a number of commonly employed gridded observations of precipitation, including the E-Obs data, indicating that the magnitude of the uncertainties associated with these gridded observational-derived products was similar to those of the RCM biases examined; hence caution should be exercised in interpreting the findings where only one observational dataset has been employed to evaluate the model simulations. A fuller evaluation of the model, with alternative observed data, is likely to reveal additional insight and would assist in quantifying and attributing the associated biases in the model simulations.

4 Historical and Future Model Simulations of the Climate over the EURO-CORDEX Domain

The credibility of downscaled information of course depends on the quality of the downscaling method itself, and on the quality of the global climate models providing the large-scale boundary conditions.

IPCC, 2013a: 816

4.1 Introduction

Regional climate model simulations, using the modified version of the Advanced Research Weather Research and Forecasting (WRF) model, version 3.4.1. (described in section 3.2), were undertaken for the European domain for a historical (1951–2005) and future (2006–2100) time period. Boundary conditions were provided by EC-Earth, an ESM, developed by a consortium of European research institutes and national meteorological agencies, including the national meteorological service Met Éireann and the Irish Centre for High-End Computing (ICHEC). Simulations for the 2006–2100 time period were undertaken for two RCPs, namely RCP2.6 and RCP8.5 (see section 2.2). Initially, an evaluation of the regional climate simulations is presented for the historical period from 1951 to 2000 to assess for model bias. Model bias was evaluated on climatological seasonal mean values of mean sea level pressure (hPa), 2-metre temperature (K) and mean daily precipitation (mm), where the resultant bias represents the difference between the observational data (E-Obs) and the individual models employed over the period 1951–2005. Timeseries of mean monthly climatologies derived for the EURO-CORDEX sub-regions, over the 1951–2005 period, are also included. Following this evaluation, simulations of the future climate are presented for the period 2006–2100. Results from additional global and regional climate model combinations participating in the EURO-CORDEX experiment are also presented for the historical and future simulations. These additional model simulations represent different boundary conditions, regional models and RCPs.

4.2 Description of the EC-Earth earth system model

EC-Earth represents a state-of-the-art ESM. It was developed, as part of a European-wide consortium of national weather centres and research institutes, from the operational seasonal forecast system (version 3) of the ECMWF (see Hazeleger *et al.*, 2012). EC-Earth contributed to the latest CMIP5 (phase 5), which provided the basis for the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report. EC-Earth is a fully coupled atmosphere–ocean (atmosphere – IFS; ocean – Nemo; sea ice – LIM2) climate model (AOGCM) and includes a dynamic vegetation module, a chemistry model and a biogeochemistry model for the oceans (Hazeleger *et al.*, 2010). Current developments of the EC-Earth model are in the vanguard of international research efforts to integrate numerical weather prediction and climate modelling techniques into a common modelling framework.

The EC-Earth model output is available on a standard T159 horizontal spectral resolution (corresponds to a spatial resolution of $1.125^\circ \times 1.125^\circ$ or ~ 125 km) configuration with 62 vertical levels for the atmosphere and $1^\circ \times 1^\circ$ resolution, with 42 levels, for the oceans. In a comparison of EC-Earth model with the predecessor CMIP3 models, it was found to perform well over both short- and long-term simulations (Hazeleger *et al.*, 2010). Importantly, internal variability in the model was found to be adequately captured, albeit with reduced variance (Hazeleger *et al.*, 2010). Additionally, the model demonstrates good performance from daily to interannual time scales and for long-term mean climate (Hazeleger *et al.*, 2010). While the model was found to perform well in simulating tropospheric fields, surface temperatures and fluxes were found to be less skilful when compared over the current climate.

The model is initialised with a pre-industrial spin up period of >500 years. Subsequently, historical/observed changes in atmospheric concentrations of greenhouse gases, aerosols and land use changes

are prescribed for the 20th century or control run (1850–2005). For the future climate simulations, the model employs the RCPs (RCP2.6, RCP4.5 and RCP8.5) which prescribe plausible future changes in radiative forcing for the period 2006–2100.

Hazeleger *et al.* (2012), in an analysis of the performance of EC-Earth, found that, although the annual deviations in mean sea level pressure over the period 1989 to 2009 were small relative to ERA-Interim (<2 hPa), small seasonal variations in bias were evident (Figure 4.1a). Over western Europe, EC-Earth tended to slightly underestimate mean sea level pressure during the winter months (DJF) and slightly overestimate it during the summer months. In terms of 2-metre surface temperature, the present-day EC-Earth simulation was found to be too cold in the tropics and over land, particularly during the boreal summer (JJA), when compared with both ERA-Interim and observational estimates (Figure 4.1b). During boreal winter (DJF), EC-Earth overestimated surface temperature over mid- to high-latitude land areas in the northern hemisphere, in particular over northern Canada, eastern Europe and northern Russia, and over the Southern Ocean (Hazeleger *et al.*, 2012). For precipitation, the main tropical rainbands, such as the Intertropical Convergence Zone (ITCZ) and the convergence zones in South Pacific and South Atlantic, are well represented, with a tendency to underestimate precipitation in the Pacific ITCZ (Figure 4.1c). While the model captures the Indian monsoon, it underestimates the strength of the Asian monsoon. Over central and western Europe, the model overestimates precipitation, with a larger bias in winter relative to summer, compared with the Climate Prediction Centre (CPC) Merged Analysis of Precipitation (CMAP) data.

Overall, the EC-Earth model was found to perform well when compared with models of similar complexity. The climate sensitivity, $\sim 1 \text{ K/W/m}^2$, lies within published ranges; changes in the hydrological cycle were also found to be consistent with published results (Hazeleger *et al.*, 2012). Between the pre-industrial and present-day conditions, total precipitation was found to increase by $\sim 1.1\%/K$, increasing to $\sim 1.8\%/K$ under warming conditions results (Hazeleger *et al.*, 2012).

4.3 EURO-CORDEX Model Domain: Historical Simulations

An evaluation of the WRF simulations, employing boundary conditions from the EC-Earth ESM, was undertaken initially for the historical simulation period, 1951–2005. As agreed model standards exist for all modelling centres participating in EURO-CORDEX, additional simulations, representing different global and regional climate model combinations, are also included where possible in the evaluation (Table 4.1). The inclusion of these additional models allows for a degree of intercomparison of both global and regional climate model simulations, where groups of models are employed in common. For example, four modelling centres employ EC-Earth as boundary conditions, namely the Danish Meteorological Institute (DMI), the Royal Netherlands Meteorological Institute (KNMI), Maynooth University (NUIM) and the Swedish Meteorological and Hydrological Institute (SMHI), providing a measure of difference in the regional climate simulations. Similarly, SMHI employs the RCA4 regional climate model with 10 different global models, providing a measure of difference in the

Table 4.1. List of global and regional climate model combinations participating in EURO-CORDEX employed in the analysis. Monthly data are available from these models for selected variables (mean sea level pressure, 2-metre temperature and precipitation) for the simulation period 1951–2005

GCM		Institute
CCCma-CanESM2	RCA4	SMHI
CNRM-CERFACS-CNRM-CM5	RCA4	SMHI
CSIRO-QCCCE-CSIRO-Mk3-6-0	RCA4	SMHI
ICHEC-EC-EARTH	HIRHAM5	DMI
ICHEC-EC-EARTH	RACMO22E	KNMI
ICHEC-EC-EARTH	RCA4	SMHI
ICHEC-EC-EARTH	WRF341E	NUIM
IPSL-IPSL-CM5A-MR	RCA4	SMHI
MIROC-MIROC5	RCA4	SMHI
MOHC-HadGEM2-ES	RCA4	SMHI
MPI-M-MPI-ESM-LR	CCLM4-8-17	CLMcom
MPI-M-MPI-ESM-LR	RCA4	SMHI
MPI-M-MPI-ESM-LR	REMO2009	MPI-CSC
NCC-NorESM1-M	RCA4	SMHI
NOAA-GFDL-GFDL-ESM2M	RCA4	SMHI

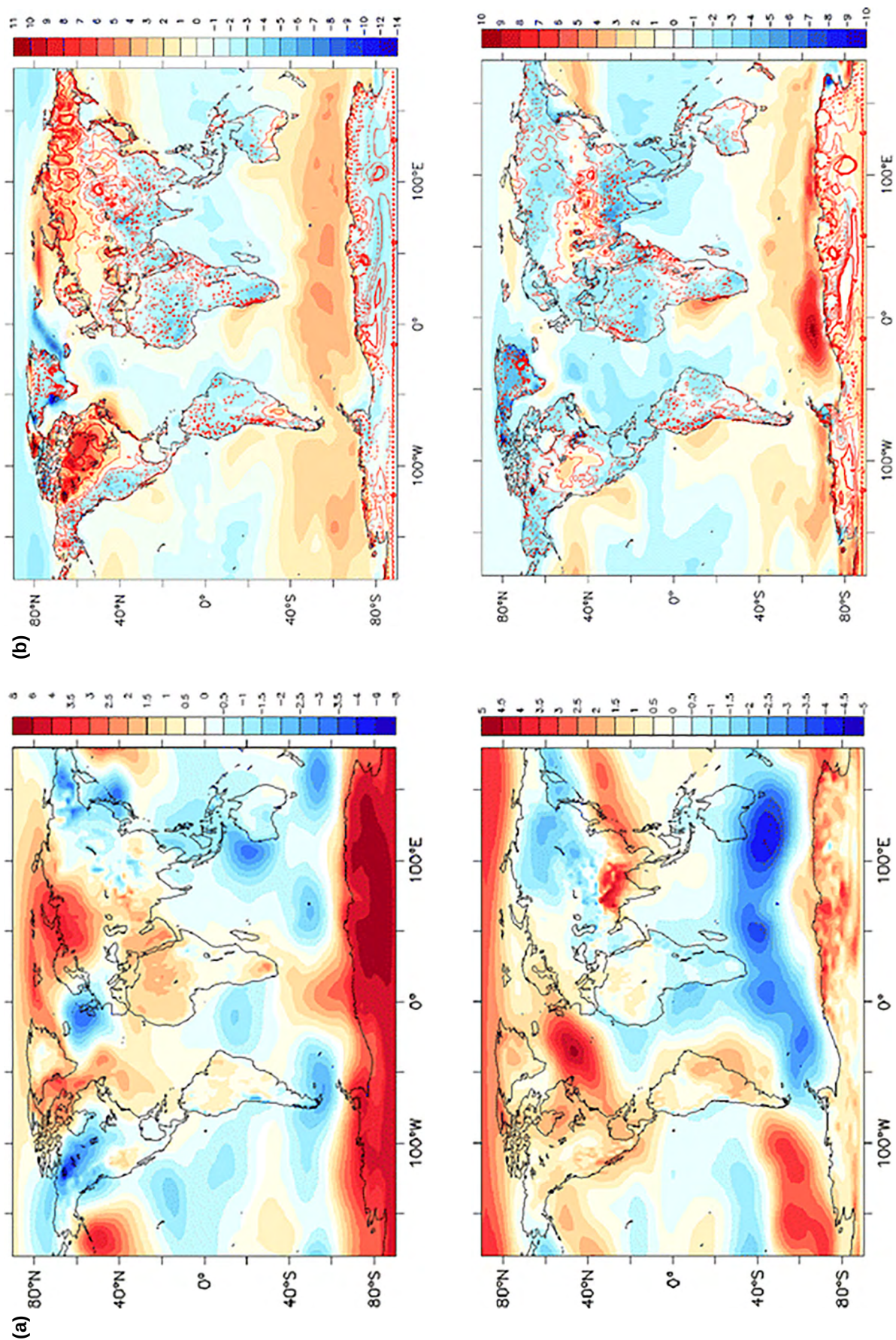


Figure 4.1. Difference between EC-Earth (present day) and ERA-Interim in (a) mean sea level pressure (hPa) for winter (top) and summer (bottom) and (b) 2-metre surface temperature (K) for winter (top) and summer (bottom). All figures from Hazeleger et al. (2012).

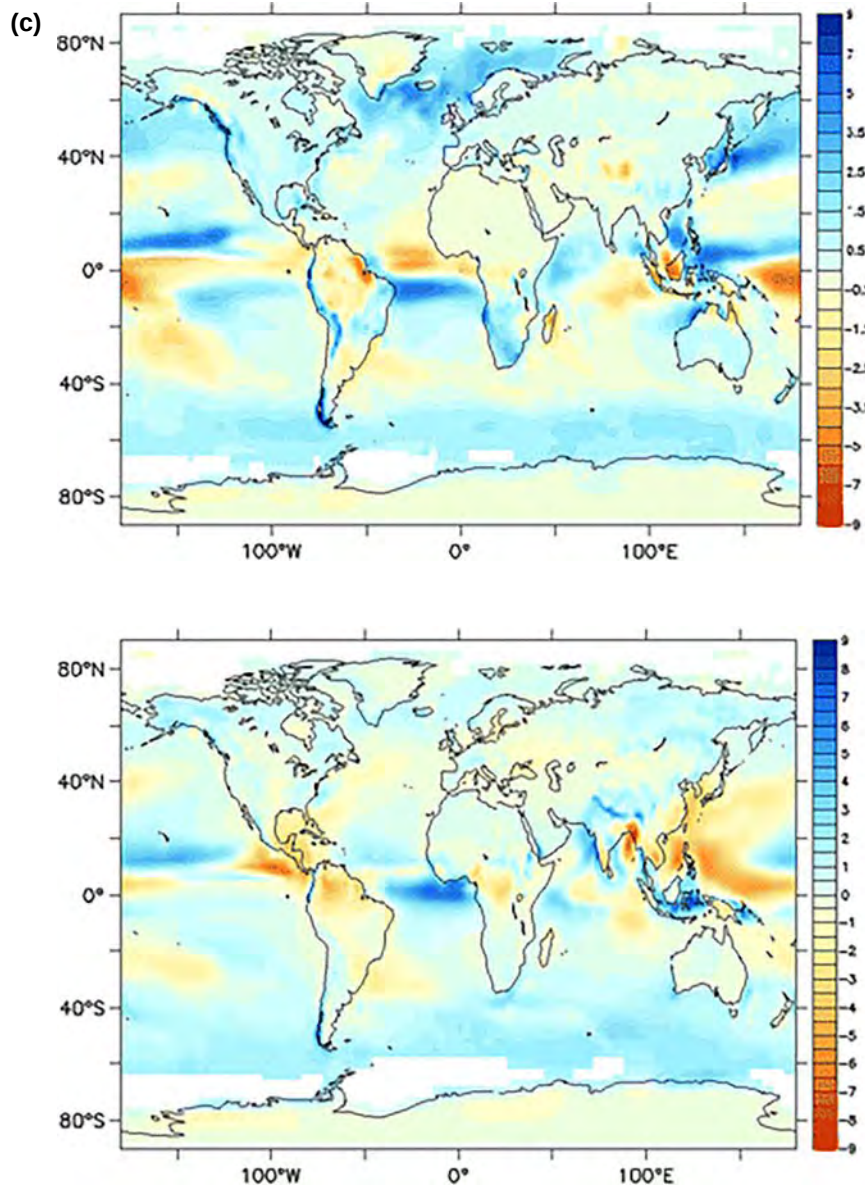


Figure 4.1. Continued. (c) Difference between EC-Earth (present day) and observational estimates from the Climate Prediction Centre Merged Analysis of Precipitation (CMAP) in mean daily precipitation (mm) for winter (left) and summer (right). All figures from Hazeleger *et al.* (2012).

boundary data. The models were chosen solely on account of their availability and therefore represent an ensemble of opportunity, rather than a comprehensive sampling of the spread of model outcomes. Consequently, caution needs to be exercised in interpreting the results.

4.4 Model Evaluation

Model biases are evident in both winter (Figure 4.2) and summer (Figure 4.3) with regard to the simulation of mean sea level pressure when evaluated against the observation over the historical period.

Across all models, the bias in winter lies within ± 6 hPa of the observations, while in summer the model bias across all models falls within ± 2.4 hPa of observations. Overall, the models display a tendency to underestimate mean sea level pressure during the winter months (Figure 4.2n) and overestimate mean sea level pressure during the summer months (Figure 4.3n), an exception being those simulations associated with the Max Planck Institute (MPI) ESM, MPI-M-MPI-ESM-LR, which tends to overestimate mean sea level pressure during the summer months. Relative to the other RCM simulations that employ the EC-Earth model for boundary conditions, the

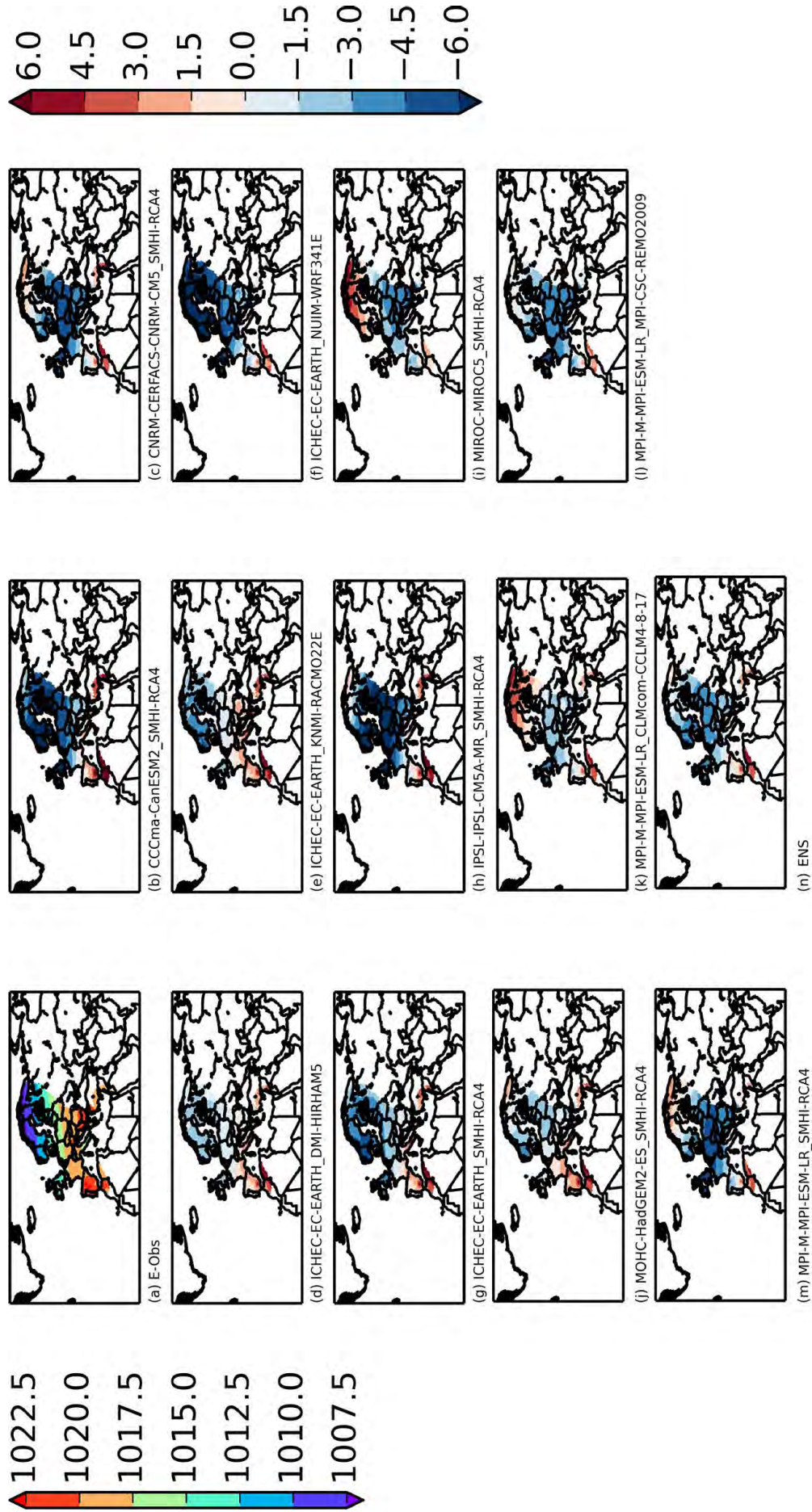


Figure 4.2. Comparison of mean sea level pressure in winter (DJF) for the period 1951–2005. (a) Observations from E-Obs and (b)–(m) values simulated by a selection of global and regional climate model combinations participating in EURO-CORDEX outlined in Table 4.1. Observations from E-Obs are absolute values (hPa). Model simulations (b)–(m) are the differences (bias) from observations. The ensemble mean bias of all simulations is also shown (n).

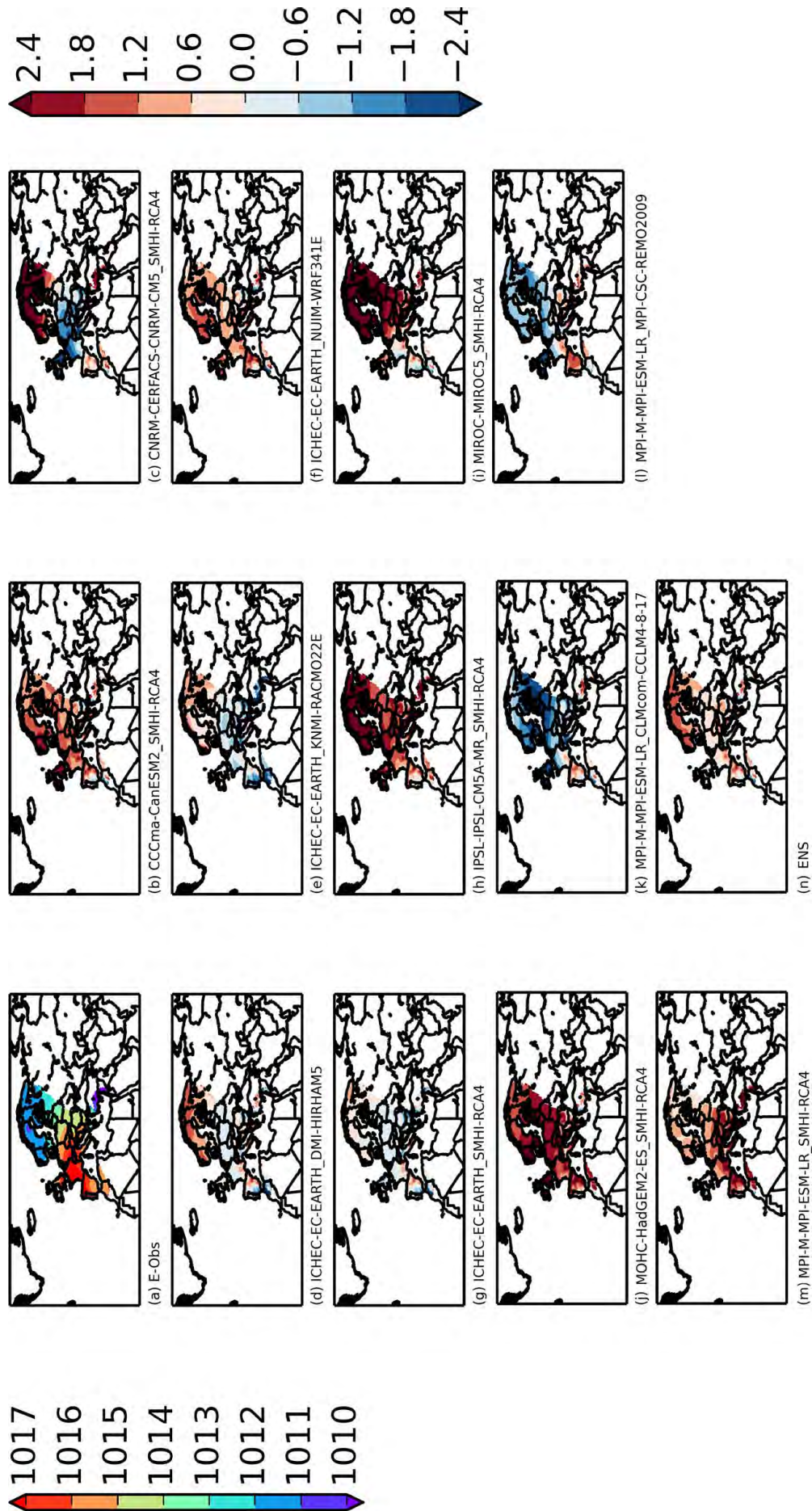


Figure 4.3. Comparison of mean sea level pressure in summer (JJA) for the period 1951–2005. (a) Observations from E-Obs and (b)–(m) simulated values from a selection of global and regional climate model combinations participating in EURO-CORDEX outlined in Table 4.1. Observations from E-Obs are absolute values (hPa). Model simulations (b)–(m) are differences (bias) from observations. The ensemble mean bias of all simulations is also shown (n).

ICHEC-EC-Earth NUIM-WRF341E simulations display a greater underestimation of mean sea level pressure during the winter months. This is consistent with earlier results which found that WRF, employing ERA-Interim as boundary conditions, underestimated sea level pressure when evaluated against the observations (Figure 3.5a). The larger negative bias in the NUIM-WRF341E simulations is likely due to underestimation of winter-time mean sea level pressure by both EC-Earth (Hazeleger *et al.*, 2012), which provides the boundary conditions, and WRF itself. The systematic underestimation of mean sea level pressure by the WRF model is consistent with findings from a number of authors. During the summer months, the ICHEC-EC-Earth NUIM-WRF341E simulations show a positive bias in mean sea level pressure across the entire domain, inconsistent with the other regional climate model simulations employing EC-Earth. While EC-Earth tends to slightly overestimate mean sea level pressure during the summer months over western and central Europe, the negative systematic bias in WRF does not appear to counteract this, producing a small positive bias in mean sea level pressure during the summer months.

A larger number of model simulations were available for the evaluation of simulated 2-metre temperature over the historical period from 1951 to 2005. Consistent with previous findings (e.g. Giorgi and Coppola, 2009; Dosio and Paruola, 2011), a number of models display a marked cold bias in northern Europe during the winter months, a feature which has also been identified in a number of CMIP5 models (Cattiaux *et al.*, 2013). The models also display a tendency to overestimate 2-metre temperature in central and eastern Europe during these months. Both the cold bias in northern European and warm bias in central Europe are reflected in the ensemble mean (Figure 4.4p) for this season. During the summer months, all models tend to underestimate 2-metre temperature, relative to the observations.

Overall, model biases range from ± 6 K in winter (Figure 4.4) to ± 4 K in summer (Figure 4.5). During the winter months, the ICHEC-EC-Earth NUIM-WRF341E simulations show a positive bias in 2-metre surface temperature across central Europe, broadly consistent with the other EC-Earth-driven regional simulations and the EC-Earth model (present-day) simulations. A larger negative bias is evident in the north-eastern part of the domain, over northern Finland and Russia. Consistent with the negative or cold bias in

EC-Earth over Europe during the summer months, all EC-Earth-driven regional climate simulations display a marked tendency to underestimate 2-metre surface temperature during these months (Figure 4.5e–h).

Model biases of mean daily precipitation (mm/day) for both winter (Figure 4.6) and summer (Figure 4.7) display a tendency to overestimate precipitation, relative to the observations, across all model simulations. An exception to this is evident in the simulations associated with the KNMI RACMO22E RCM (Figure 4.7f and k), which underestimate mean daily precipitation during the summer months over central and eastern Europe. With the exception of the KNMI RACMO22E RCM during the summer months, the models that employ EC-Earth as boundary conditions show a broad consistency in terms of bias, in both magnitude and spatial pattern. Overall, the ensemble mean of all model simulations for both seasons display an overestimation of mean daily precipitation.

Figures 4.8, 4.9 and 4.10 illustrate monthly climatologies of mean sea level pressure (Figure 4.8), 2-metre surface temperature (Figure 4.9) and mean daily precipitation (Figure 4.10) for the previously defined sub-regions, evaluated over the 1951–2005 period.

4.5 EURO-CORDEX Model Domain: Future Simulations

Model simulations for the EURO-CORDEX domain for the 2006–2100 period are presented as differences, or anomalies, from the corresponding model-specific simulated means over the 1971–2000 period, chosen here to represent baseline conditions. As is standard in meteorological and climatological reporting of averages, a 30-year period was selected to represent “normal” conditions, in preference to the 20-year periods chosen in the Fifth Assessment Report. Thirty-year periods representing climate normal are recommended by the World Meteorological Organization (WMO) to filter out interannual variation, while maintaining the longer climatic trend.

4.5.1 Simulated changes in temperature across the European domain

A selection of regional model simulations of 2-metre temperature were available, representing different combinations of earth system/global climate and

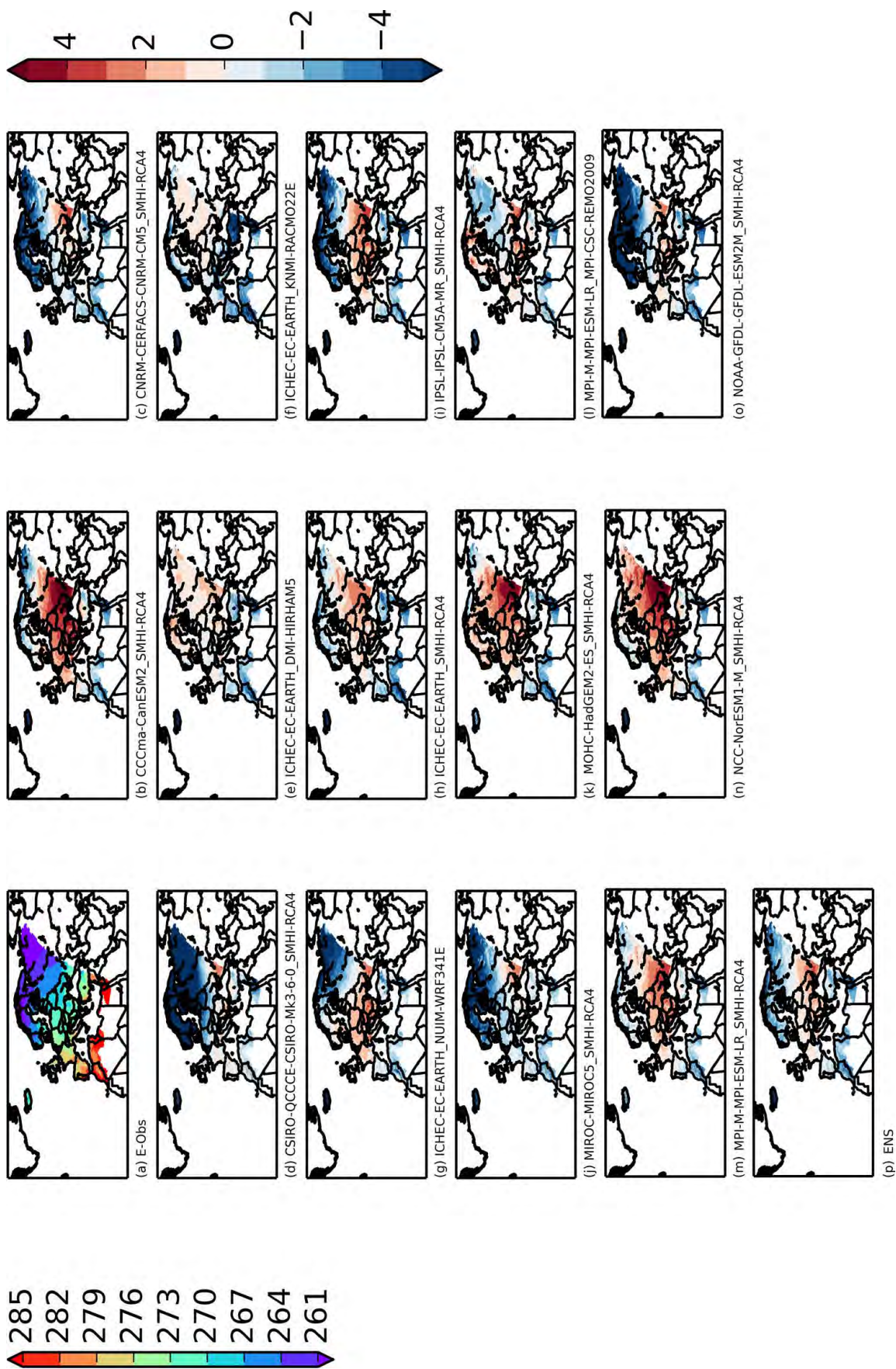


Figure 4.4. Comparison of 2-metre temperature in winter (DJF) for the period 1951–2005. (a) Observations from E-Obs and (b)–(o) simulated values from a selection of global and regional climate model combinations participating in EURO-CORDEX outlined in Table 4.1. Observations from E-Obs are absolute values (K). Model simulations (b)–(o) are differences (bias) from observations. The ensemble mean bias of all simulations is also shown (p).

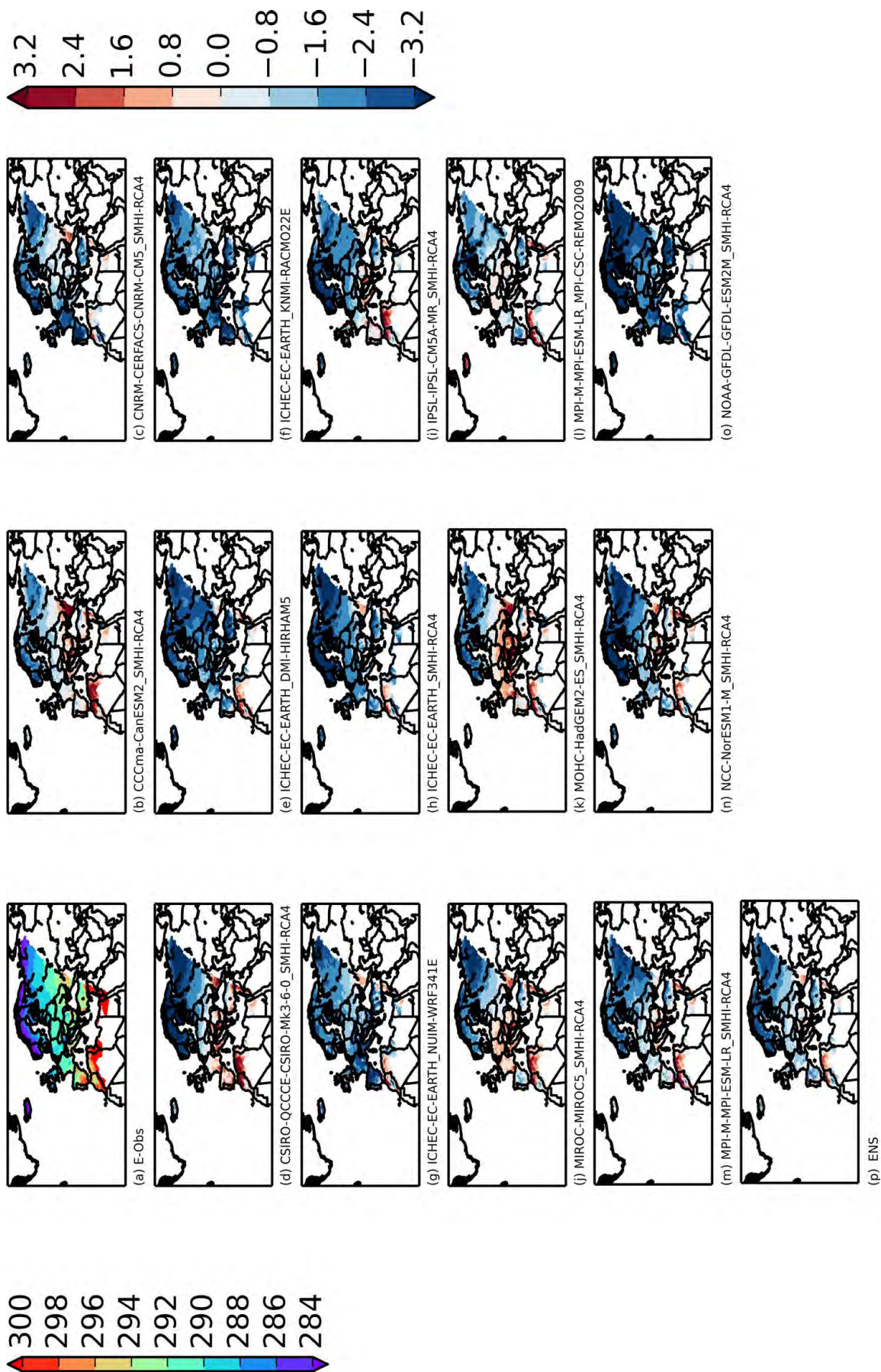


Figure 4.5. Comparison of 2-metre temperature in summer (JJA) for the period 1951–2005. (a) Observations from E-Obs and (b)–(o) simulated values from a selection of global and regional climate model combinations participating in EURO-CORDEX outlined in Table 4.1. Observations from E-Obs are absolute values (K). Model simulations (b)–(o) are differences (bias) from observations. The ensemble mean bias of all simulations is also shown in (p).

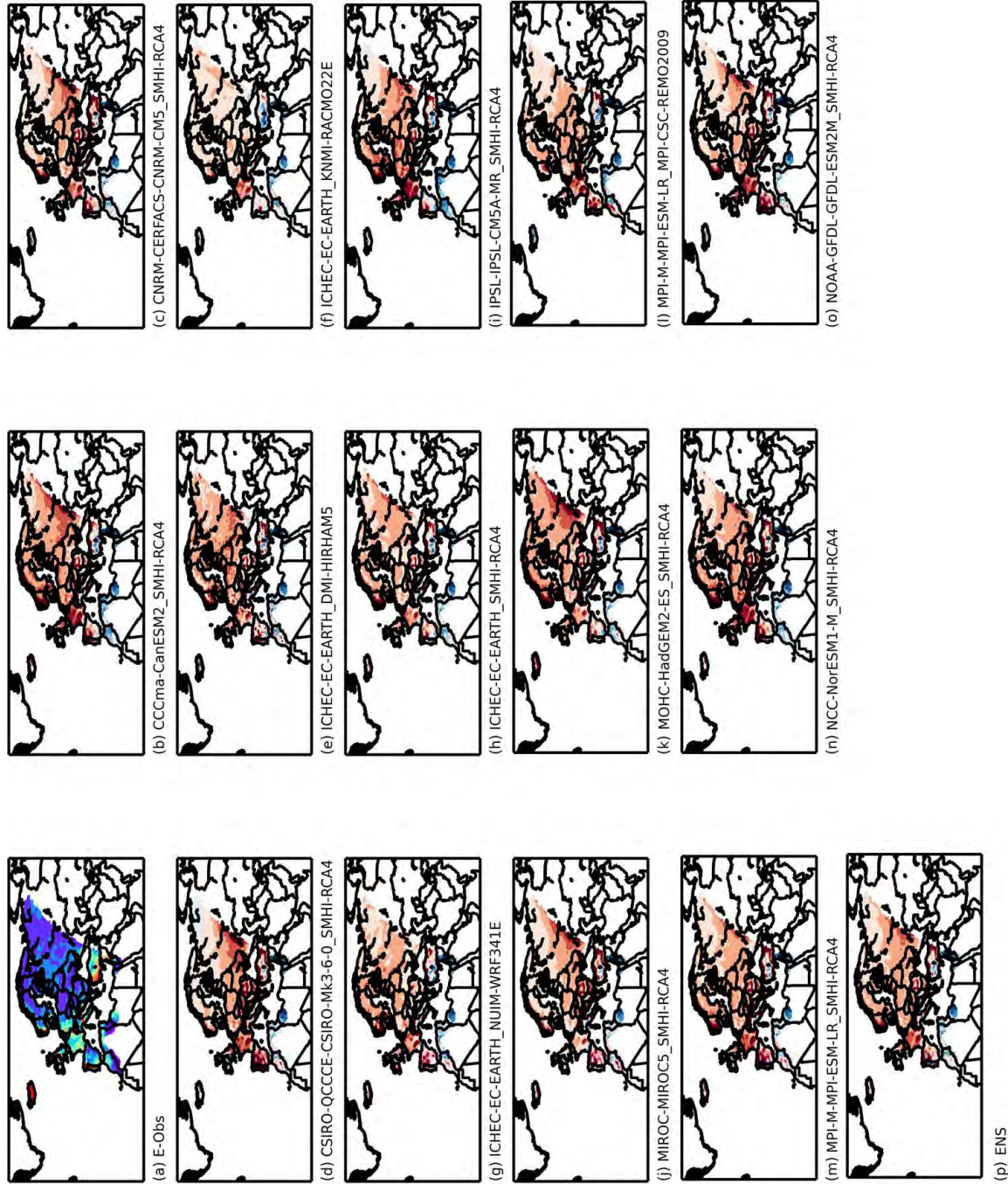
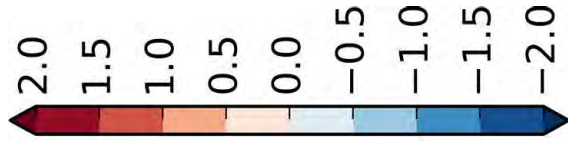


Figure 4.6. Comparison of precipitation in winter (DJF) for the period 1951–2005. (a) Observations from E-Obs and (b)–(o) simulated values from a selection of global and regional climate model combinations participating in EURO-CORDEX. Observations from E-Obs are absolute values (mm/day). Model simulations (b)–(o) are differences (bias) from observations. The ensemble mean bias of all simulations is also shown (p).

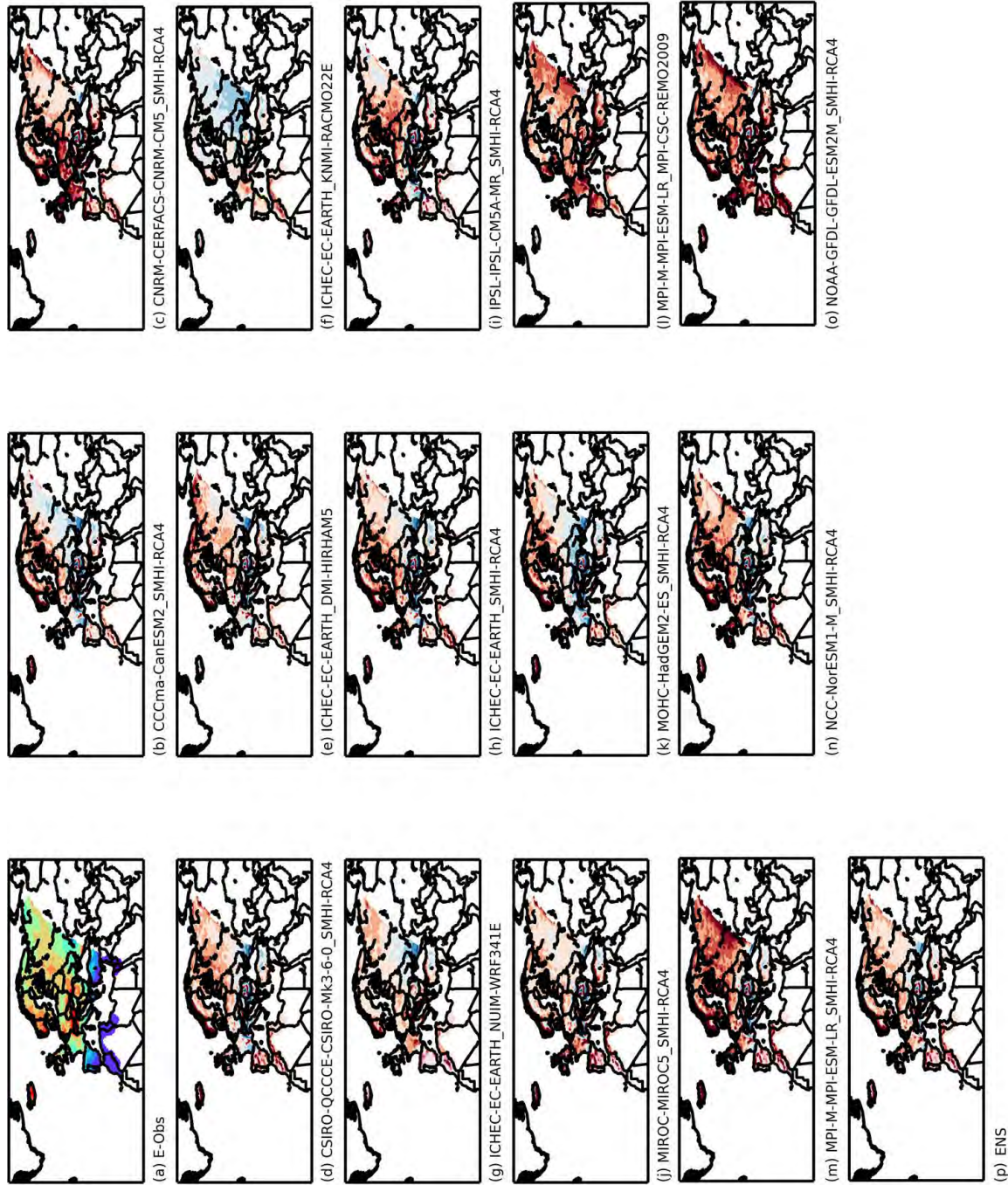
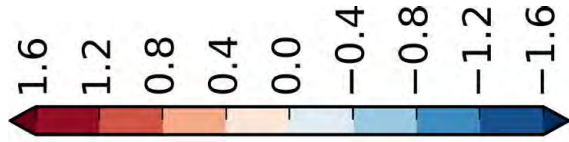


Figure 4.7. Comparison of precipitation in summer (JJA) for the period 1951–2005. (a) Observations from E-Obs and (b)–(o) simulated values from a selection of global and regional climate model combinations participating in EURO-CORDEX. Observations from E-Obs are absolute values (mm/day). Model simulations (b)–(o) are the differences (bias) from observations. The ensemble mean bias of all simulations is also shown (p).

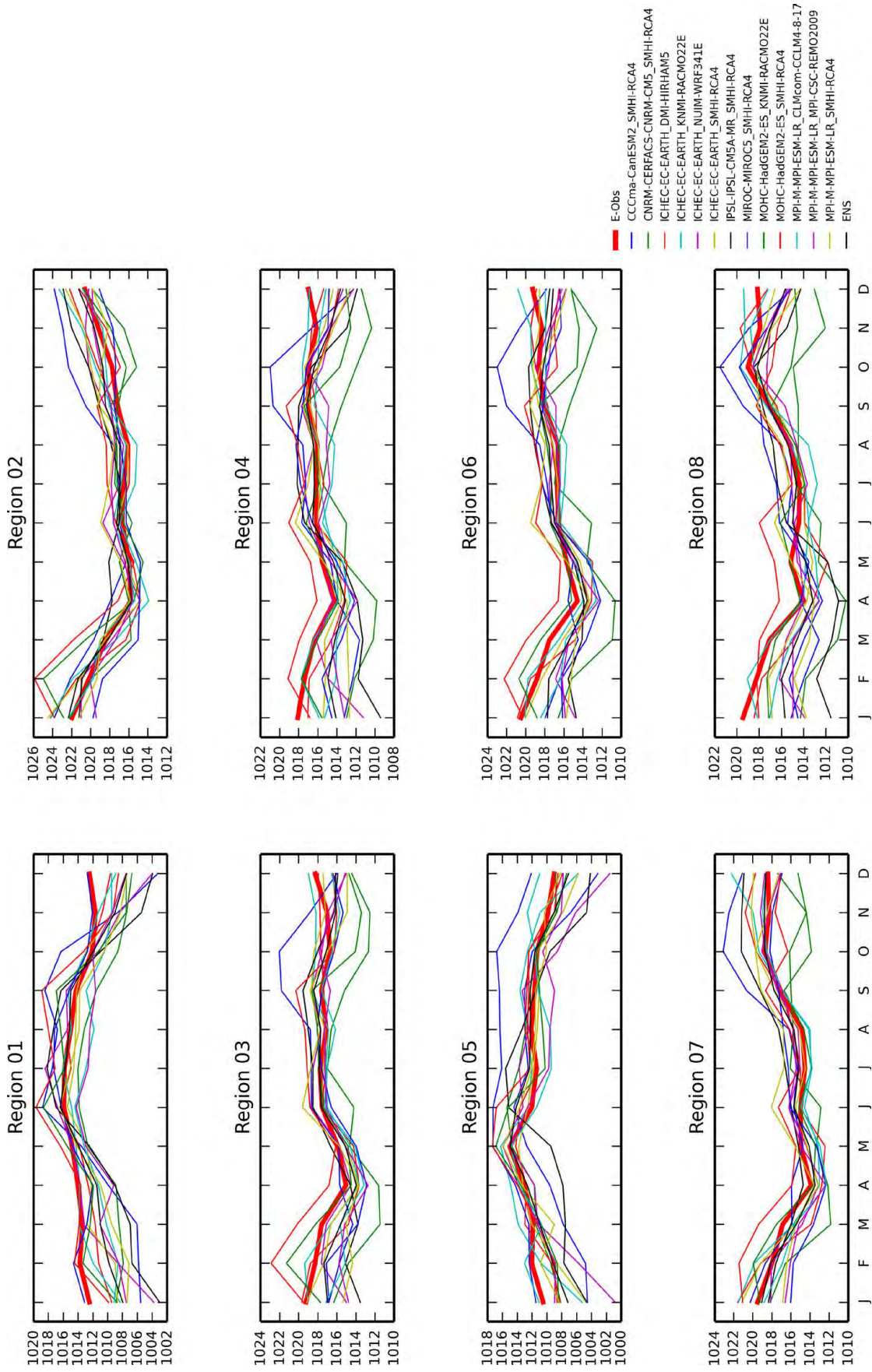


Figure 4.8. Monthly climatologies of mean sea level pressure (hPa) for the period 1951–2005 from E-Obs and a selection of regional climate model simulations participating in EURO-CORDEX for the European sub-regions. The sub-regions are Region 1 – Britain and Ireland (BI); Region 2 – Iberian Peninsula (IP); Region 3 – France (FR); Region 4 – Mid-Europe (ME); Region 5 – Scandinavia (SC); Region 6 – Alps (AL); Region 7 – Mediterranean (MD); Region 8 – Eastern Europe (EA). The ensemble mean of all simulations is also shown.

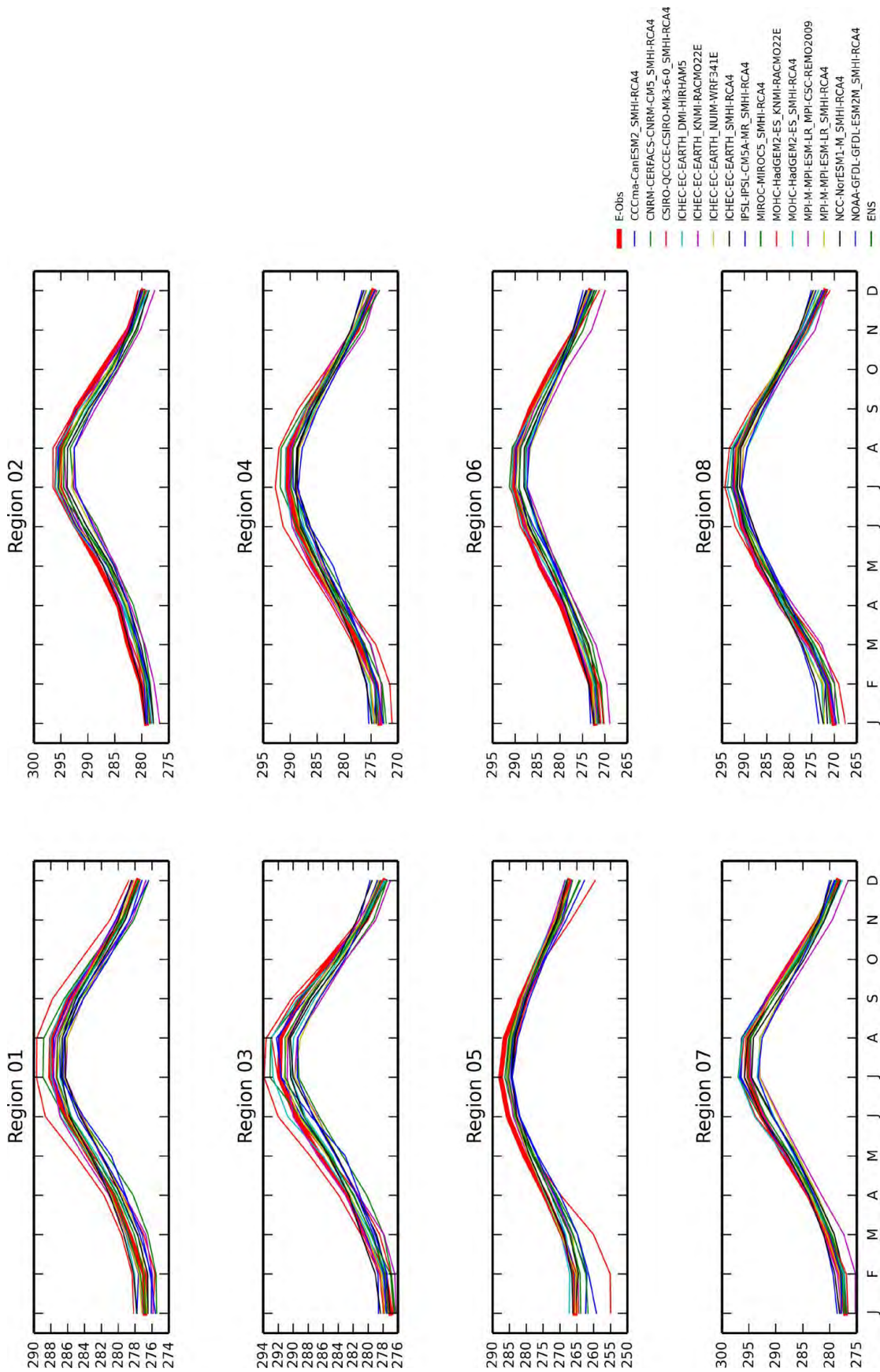


Figure 4.9. Monthly climatologies of mean daily 2-metre temperature (K) for the period 1951–2005 from E-Obs and a selection of regional climate model simulations participating in EURO-CORDEX for the European sub-regions. The sub-regions are Region 1 – Britain and Ireland (BI); Region 2 – Iberian Peninsula (IP); Region 3 – France (FR); Region 4 – Mid-Europe (ME); Region 5 – Scandinavia (SC); Region 6 – Alps (AL); Region 7 – Mediterranean (MD); Region 8 – Eastern Europe (EA). The ensemble mean of all simulations is also shown.

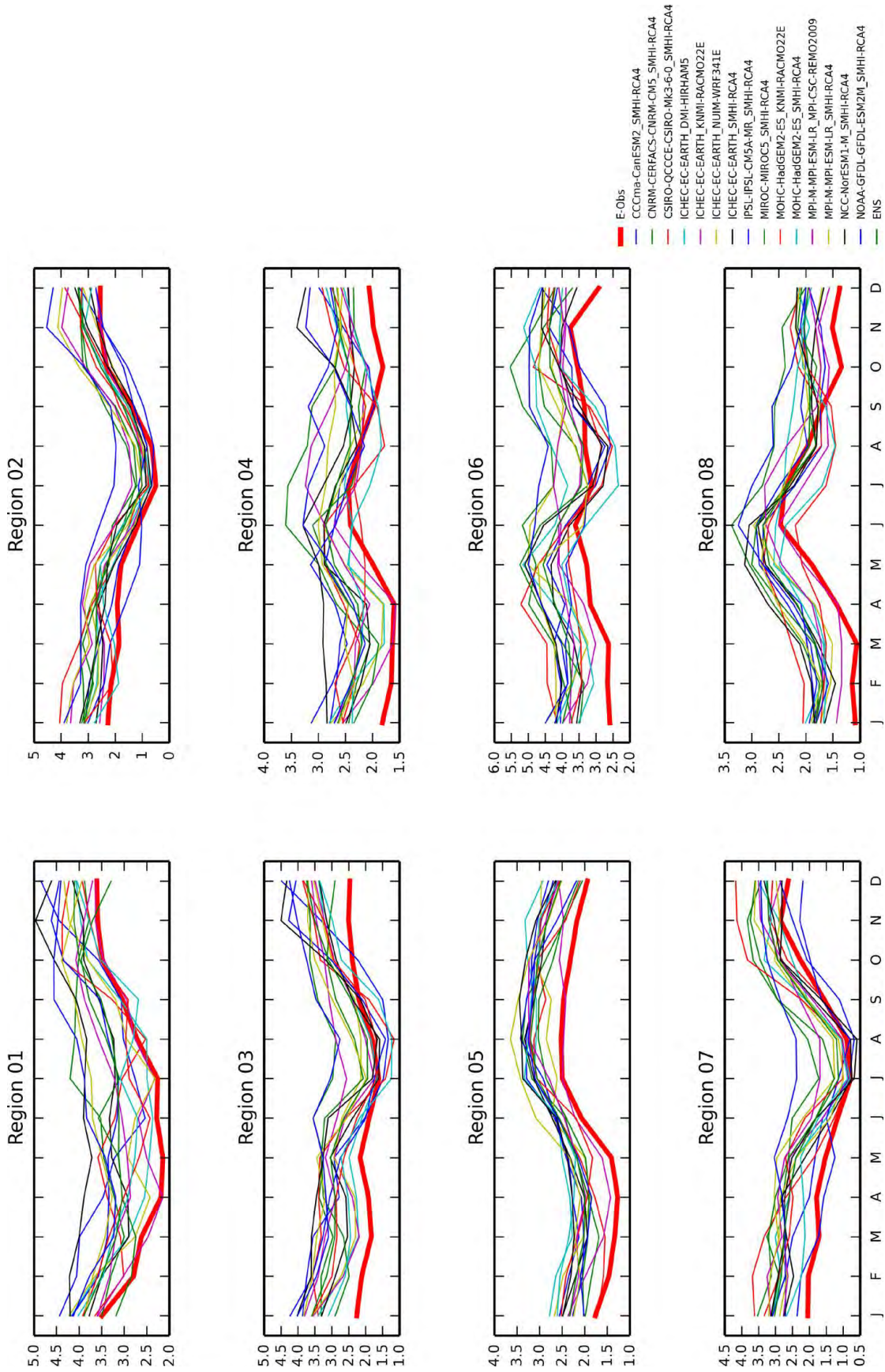


Figure 4.10. Monthly climatologies of mean daily precipitation (mm/day) for the period 1951–2005 from E-Obs and a selection of regional climate model simulations participating in EURO-CORDEX for the European sub-regions. The sub-regions are Region 1 – Britain and Ireland (BI); Region 2 – Iberian Peninsula (IP); Region 3 – France (FR); Region 4 – Mid-Europe (ME); Region 5 – Scandinavia (SC); Region 6 – Alps (AL); Region 7 – Mediterranean (MD); Region 8 – Eastern Europe (EA). The ensemble mean of all simulations is also shown.

regional climate models, for three RCPs, namely RCP2.6, RCP4.5 and RCP8.5. Results for 2-metre temperature are presented for annual average anomalies for the period 1951–2100, relative to the 1971–2000 period, for the EURO-CORDEX domain. Annual anomalies of observations, derived from E-Obs for a comparable domain and base period, are also shown for reference for the period 1951–2013. The data include only land areas in the EURO-CORDEX domain.

Across all model simulations, the magnitude of warming is related to the selected RCP (Figure 4.11); the lowest end-of-century warming is associated with RCP2.6 (Figure 4.12), the highest with RCP8.5 (Figure 4.13). Model-simulated changes in mean annual temperature for 2100 range from ~ 0.4 K to 6.2 K across Europe, relative to 1971–2000, depending on model combination and RCP choice. The influence of different RCPs is evident after 2050, with more marked divergence in the warming signal occurring after this point between the various pathways.

Also evident is that the greater the warming, the larger the spread in the model simulations, consistent with findings from the Fifth Assessment Report. For RCP2.6, the simulated domain-averaged annual temperature anomalies range from ~ 0.5 K to 1.0 K (Figure 4.12). For RCP4.5, the end-of-century annual temperature anomalies range from 2.0 K to 3.0 K (Figure 4.14); the end-of-century warming associated with RCP8.5 ranges from ~ 4.2 K to 6.2 K (Figure 4.12). However, annual anomalies mask both the seasonal and spatial variation evident in the simulations. Figures 4.15, 4.16 and 4.17 illustrate the ensemble mean seasonal anomalies across the domain for RCP8.5, RCP4.5 and RCP2.6, respectively.

Across all seasons and RCPs, the largest warming is projected to occur in northern Europe by the end of the century (Figures 4.15, 4.16 and 4.17), with mean winter values projected to increase by $\sim 8^\circ\text{C}$ for the extreme northern edge of the domain under RCP8.5. For RCP8.5, the largest seasonal mean increases are projected to occur in winter (4.8°C) and autumn (4.6°C), while summer increases of 4.4°C are projected (Figure 4.16). Projections for spring show the lowest seasonal increase, of 4.3°C . Significant spatial variation is evident, with projected warming for western and central Europe less than northern and eastern Europe and North Africa.

Similar spatial variations are evident for the ensemble mean seasonal temperatures for RCP4.5, with western and central Europe projected to warm less than northern and eastern Europe and North Africa (Figure 4.16). The largest seasonal mean warming for RCP4.5 is projected for winter (2.8°C), followed by spring and autumn (2.6°C), with summer mean temperatures projected to increase by 2.4°C , on average, across the domain. The spatial pattern of warming for RCP2.6 is broadly consistent with the other RCPs, with the exception of the autumn season, when the projected changes for central and eastern Europe are less than those projected for northern and western Europe and North Africa. For RCP2.6, the ensemble mean projected changes in seasonal mean temperature for both winter and spring are 1.5°C , with autumn projected to increase by 1.3°C . A mean summer increase of 1.2°C is projected on average across the domain (Figure 4.17). Projected seasonal changes in the ensemble mean temperature for Europe for the 2021–2050 period are shown in Appendix 4.

4.5.2 *Simulated changes in precipitation across the European domain*

Similar to the ensemble mean projected changes in temperature, results for the ensemble mean seasonal change in precipitation (percentage change) are presented based on the different models and RCPs. Consistent with the temperature analysis, the percentage changes for each model are calculated relative to the respective model baseline period of 1971–2000; this is partly to account for any systematic biases that may occur in the simulated fields. Because of the acknowledged difficulty in simulating precipitation at the regional scale (IPCC, 2013a), resulting in regional model simulations that differ not only in the magnitude of simulated changes but also in the direction of change, the ensemble mean results are presented with an additional indicator, highlighting where more than 80% of the utilised models agree on the direction (i.e. increase or decrease) of change. However, inter-model agreement in this instance should not be interpreted as an increased measure of confidence in the simulated changes; the models selected were based on an *ensemble of opportunity*, representing available models, and are not necessarily indicative of the full spread of possible model outcomes. Additionally, as the ensemble of models selected contain a number of driving and regional

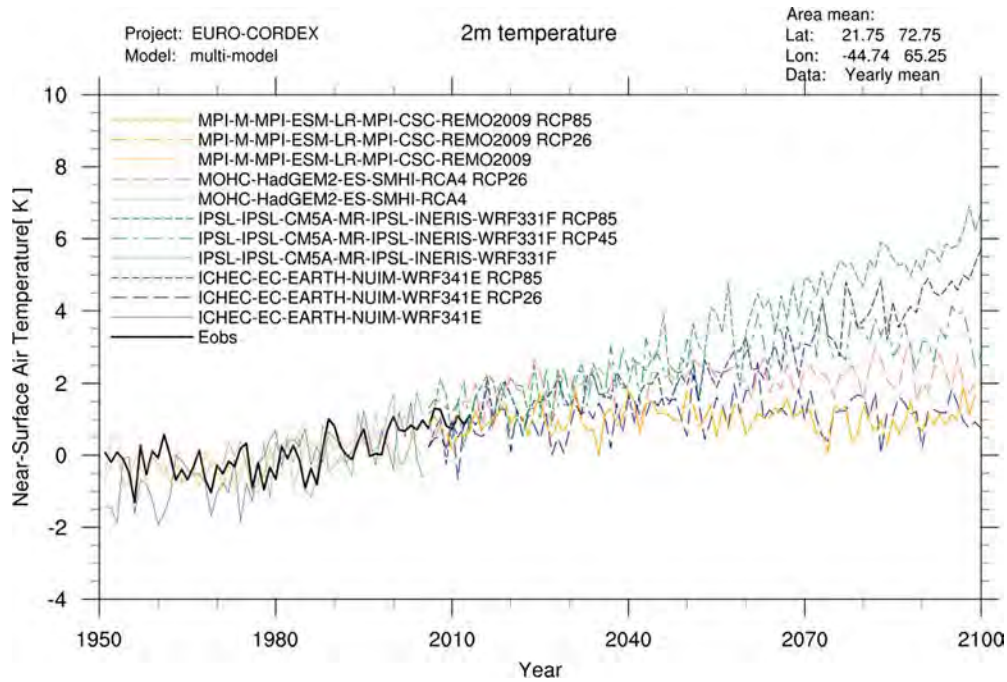


Figure 4.11. Multi-model timeseries of annual anomalies of 2-metre surface temperature (K) for all land areas in the EURO-CORDEX domain for a selection of models and RCPs for the period 1951–2100, relative to 1971–2000. Annual anomalies of observations, derived from the E-Obs data (black line), are also shown for reference for the period 1951–2013. Solid lines indicate historical simulations (1951–2005); dashed lines indicate RCP forcing scenarios (2006–2100). Models were selected for display on the basis of representing different combinations of earth system/global climate and regional climate models.

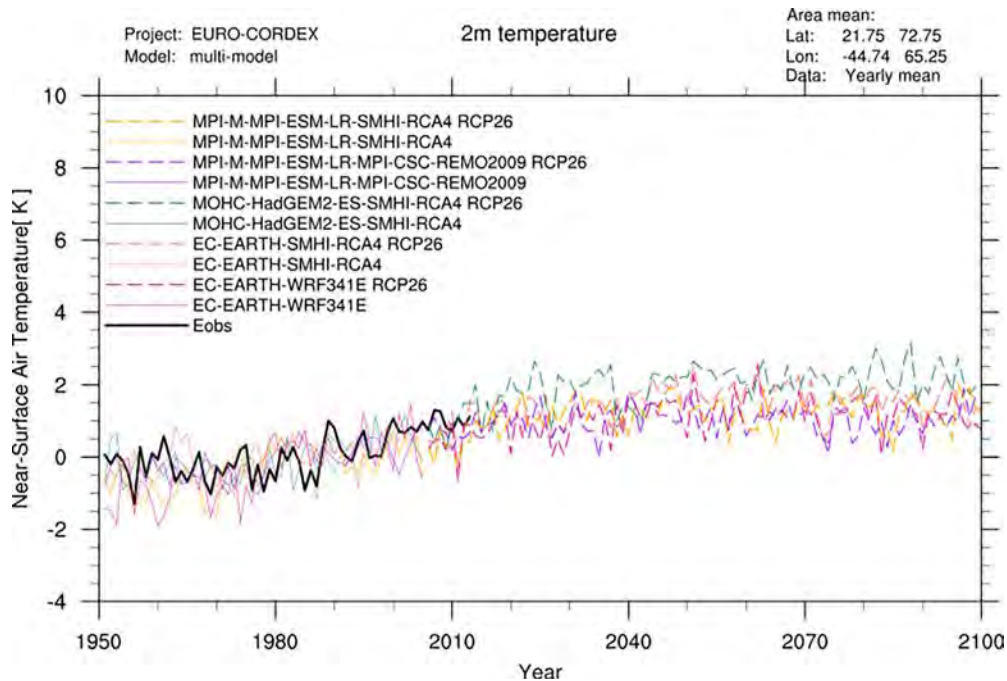


Figure 4.12. Multi-model timeseries of annual anomalies of 2-metre surface temperature (K) for all land areas in the EURO-CORDEX domain for a selection of models for RCP2.6 for the period 1951–2100, relative to 1971–2000. Annual anomalies derived from the E-Obs data (black line), are also shown for reference for the period 1951–2013. Solid lines indicate historical simulations (1951–2005); dashed lines indicate RCP forcing scenarios (2006–2100). Models were selected for display on the basis of representing different combinations of earth system/global climate and regional climate models.

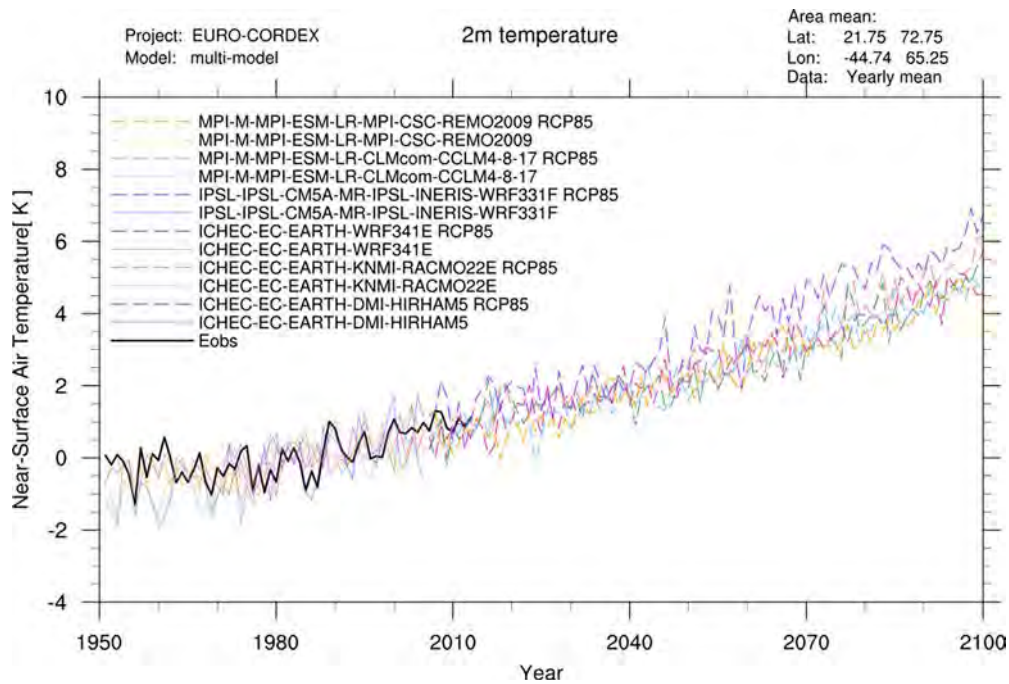


Figure 4.13. Multi-model timeseries of annual anomalies of 2-metre surface temperature (K) for all land areas in the EURO-CORDEX domain for a selection of models for RCP8.5 for the period 1951–2100, relative to 1971–2000. Annual anomalies of observations, derived from the E-Obs data (black line), are also shown for reference for the period 1951–2013. Solid lines indicate historical simulations (1951–2005); dashed lines indicate RCP forcing scenarios (2006–2100). Models were selected for display on the basis of representing different combinations of earth system/global climate and regional climate models.

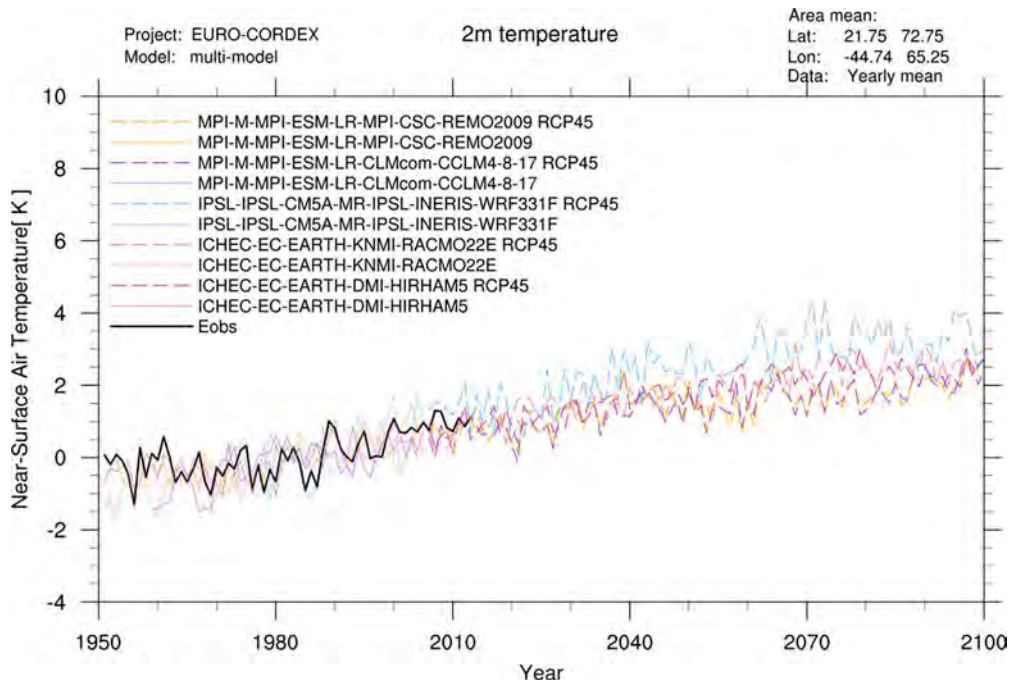


Figure 4.14. Multi-model timeseries of annual anomalies of 2-metre surface temperature (K) for all land areas in the EURO-CORDEX domain for a selection of models for RCP4.5 for the period 1951–2100, relative to 1971–2000. Annual anomalies derived from the E-Obs data (black line), are also shown for reference for the period 1951–2013. Solid lines indicate historical simulations (1951–2005); dashed lines indicate RCP forcing scenarios (2006–2100). Models were selected for display on the basis of representing different combinations of earth system/global climate and regional climate models.

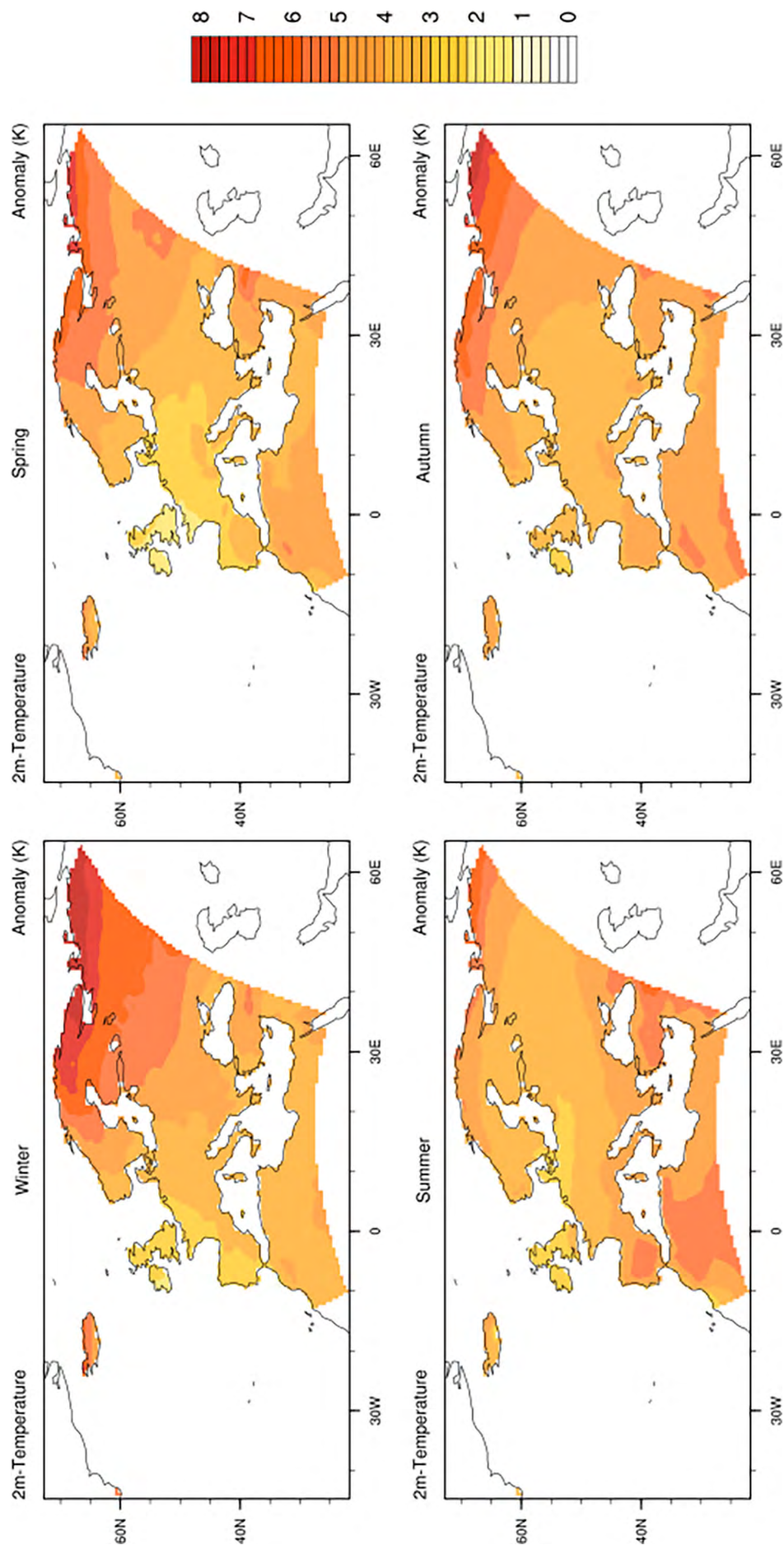


Figure 4.15. Multi-model ensemble mean of 2-metre temperature for RCP8.5 for the period 2071–2100. Values are shown as anomalies for the period, relative to 1971–2000. The multi-model mean is derived from six input models: ICHEC-EC-Earth DMI-HIRHAM5, -NUIM-WRFV341E, -RACMO22E; IPSL-IPSL-CM5A-MR-IPSL-INERIS-WRFV331F; MPI-M-MPI-ESM-LR -CLMcom-CCLM4-8-17, -MPI-CSC-REMO2009.

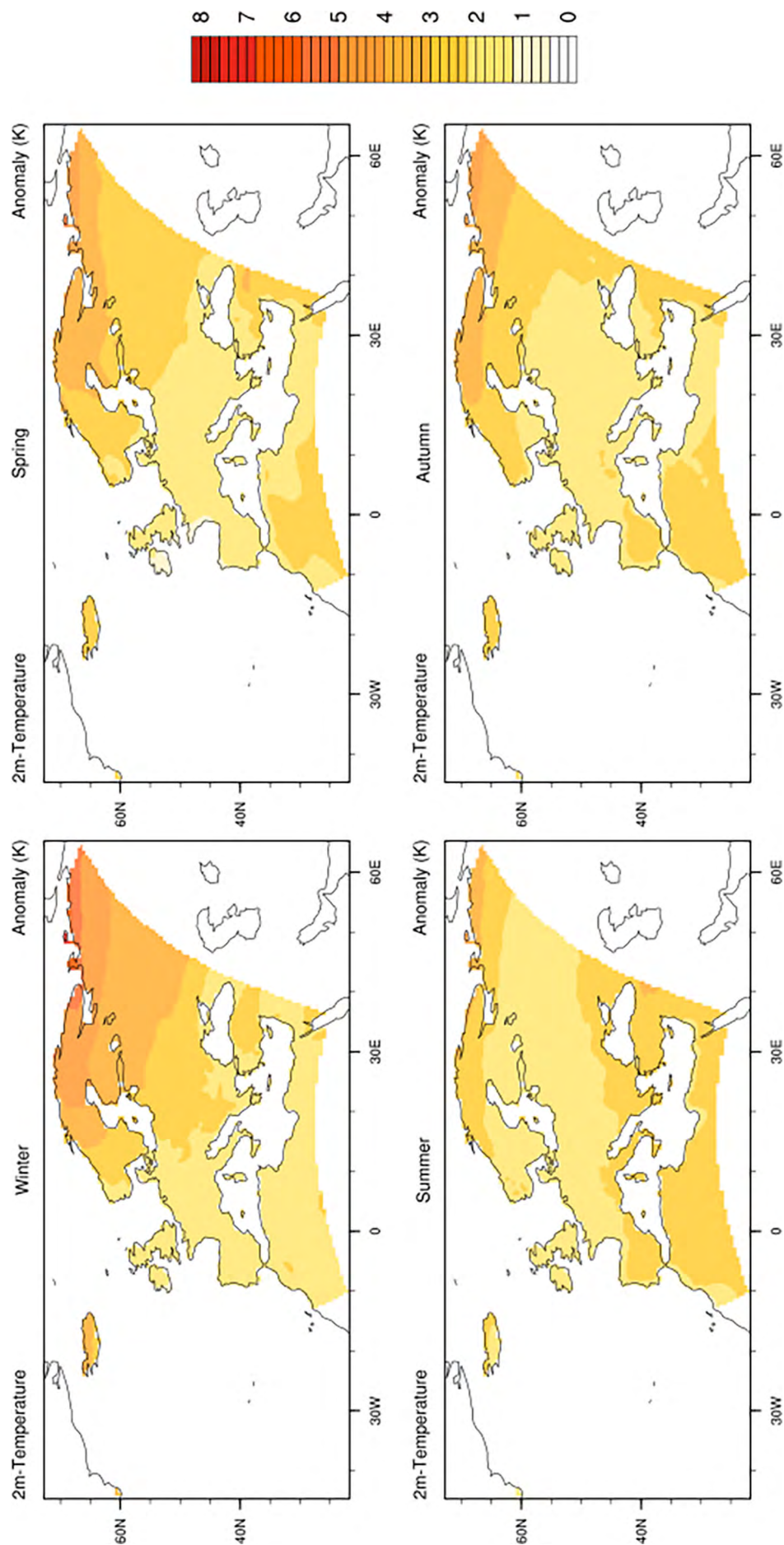


Figure 4.16. Multi-model ensemble mean of 2-metre temperature for RCP4.5 for the period 2071–2100. Values are shown as anomalies for the period, relative to 1971–2000. The multi-model mean is derived from five input models: ICHEC-EC-Earth – DMI-HIRHAM5, -RACMO22E; IPSL-IPSL-CM5A-MR-IPSL- INERIS-WRFV331F; MPI-M-MPI-ESM-LR –CLMcom-CCLM4-8-17, -MPI-CSC-REMO2009.

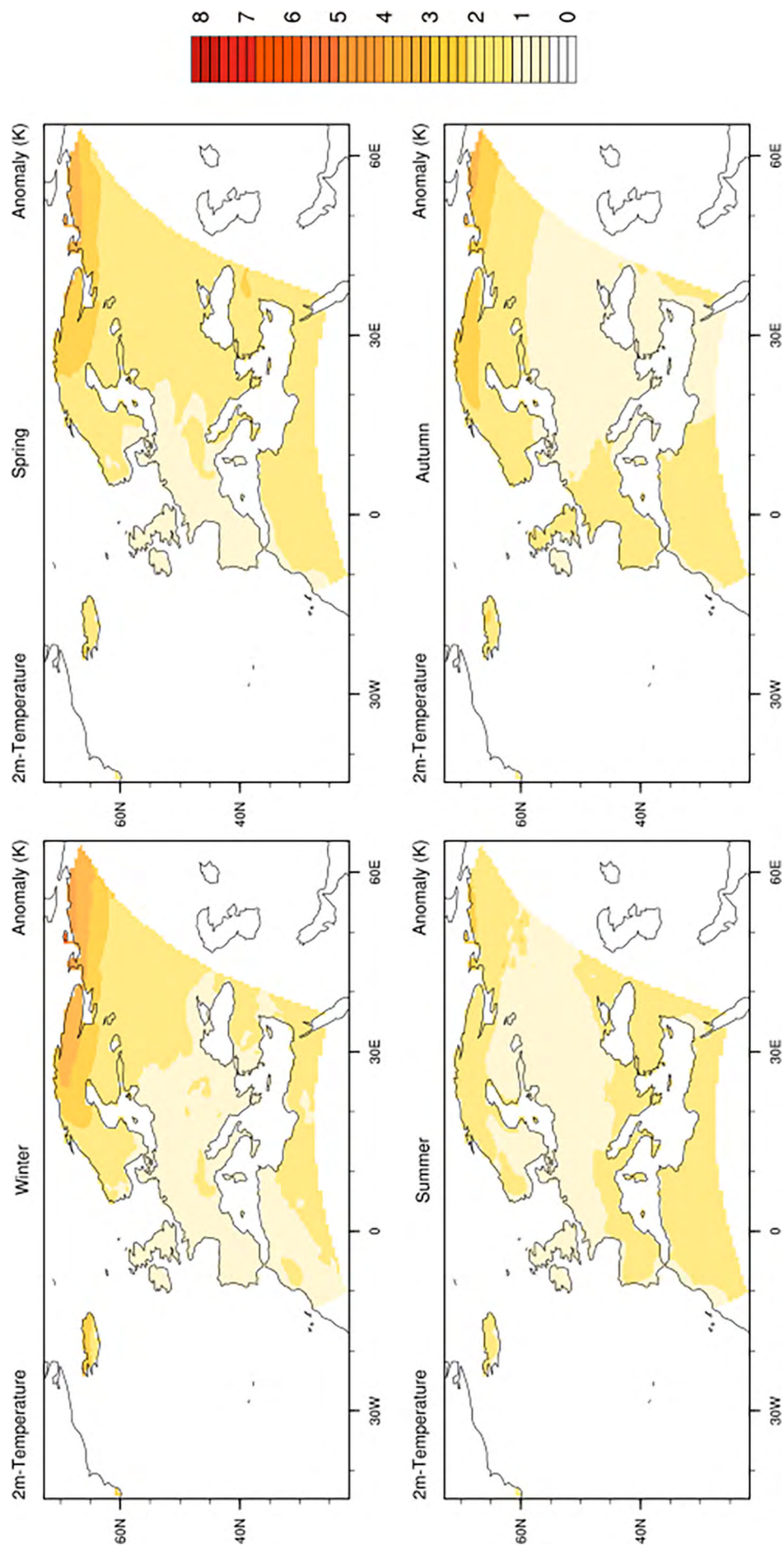


Figure 4.17. Multi-model ensemble mean of 2-metre temperature for RCP2.6 for the period 2071–2100. Values are shown as anomalies for the period, relative to 1971–2000. The multi-model mean is derived from five input models: ICHEC-EC-Earth -NUIM-WRFV341E, -SMHI-RCA4; MOHC-HadGEM2 -SMHI-RCA4; MPI-M-MPI-ESM-LR -MPI-CSC -REMO2009, -SMHI-RCA4.

climate models in common, the likelihood of model agreement is increased.

Representing precipitation change using the measure of percentage change may also lead to results that are not directly comparable between regions; a small change in simulated precipitation in a climatologically “dry” region may result in a large percentage change relative to a large or significant change in simulated precipitation in a climatologically “wet” region. However, the measures employed do provide a means to represent the simulated changes and to assess selected model agreement, and allow for comparability with previous studies that utilised a similar approach.

Based on the six available models, the end-of-century (2071–2100) ensemble mean simulated change in precipitation (% change) for RCP8.5 indicates that winters are likely to get wetter in central and northern Europe (>10% increase), with decreases in precipitation projected for southern Europe (decreases of less than –10%) and North Africa (less than –20%). While inter-model agreement is broadly consistent for these regions (indicated by the stippling), the models do not agree on the location of the transition zone between increasing and decreasing winter precipitation, reflected in the lack of agreement across a band of southern European countries. The largest winter precipitation increases are simulated for northern and eastern Europe, with the largest decreases simulated for the western part of North Africa.

During the summer months, precipitation is simulated to decrease across western and southern Europe, and parts of eastern Europe (less than –10%), while small increases (~10%) are indicated for northern Europe over the period 2071–2100. Similar to the winter months, the models do not agree on the location of the transition between decreasing and increasing precipitation, representing a swath through central Europe. Figures for changes in spring and autumn precipitation for RCP8.5 are shown in Appendix 5.

Simulated changes in precipitation for RCP4.5, based on five available models, show broad geographical agreement with those of RCP8.5 for winter; increased precipitation is simulated for northern Europe (up to ~10%) and eastern Europe (>20%), with decreases simulated for southern Europe (more than –10%)

and North Africa (less than –20%). RCP4.5 simulated precipitation tends to display a greater number of locations indicating agreement between the selected models during the winter months. This is in contrast to the summer precipitation changes, for which model agreement is less than that of the winter simulations. During the summer months, the selected models are in broad agreement that precipitation is likely to decrease over western Europe, North Africa and Turkey (less than –10%), while no model agreement is evident for much of central and eastern Europe and parts of northern Europe. Precipitation increases are projected for these regions, but model agreement is evident only for parts of Norway, Finland, Estonia and Latvia.

The multi-model ensemble mean precipitation change for RCP2.6, based on five available models, shows increasing winter precipitation across most of Europe (0–10%), with greater increases indicated for central and eastern Europe (10–20%), over the 2071–2100 period. Winter precipitation decreases are indicated for North Africa (ranging from no change to –40%). During the summer months over this period, precipitation decreases are evident across North Africa (less than –40%), western Europe and parts of central Europe (<0 to –10%). Increasing summer precipitation is indicated for eastern and northern Europe, with model agreement largely confined to northern Europe.

Boxplots of seasonal changes in 2-metre temperature (K) and precipitation (percentage change), for the period 2071–2100, are shown in Figure 4.24 for each RCP. Boxplot values are derived from the mean of each contributing model and represent a measure of spread in the model simulations for that season and RCP. Mean seasonal values derived from the NUIM-WRFV341E are also indicated, where available (e.g. RCP8.5 and RCP2.6). While all model simulations of 2-metre temperature show increased temperatures by the 2071–2100 period, relative to 1971–2000, there is marked variation evident in the boxplots, particularly associated with the model indicating the greatest warming. For precipitation, both the magnitude and direction of change are shown to vary across the selected models. This is a consistent finding for all seasons and RCPs. However, these derived values reflect the domain average of each model and consequently ignore the spatial dimension of the projected change.

4.6 Discussion

All models included in the analysis simulate increasing temperatures for Europe over the present century; the amount of warming is largely dependent on the particular RCP. In addition, the greater the warming, the greater the range evident between model projections, particularly evident during the winter season for the 2071–2100 period (Figure 4.24).

Based on RCP8.5, temperatures across Europe are simulated to continue to increase over the present century, reflecting the increase in prescribed radiative forcing over this period. The RCP8.5 projected end-of-century increase in annual temperatures across Europe ranges from $\sim 4.2\text{ K}$ to 6.2 K , relative to the 1971–2000 period. Under RCP4.5, annual temperatures are also simulated to increase over the course of the present century, but to a lesser extent than RCP8.5. For this pathway, end-of-century annual temperatures across Europe are simulated to be between 2.0 K and 3.0 K warmer than the 1971–2000 period. In marked contrast to both RCP4.5 and RCP8.5, temperature simulations associated with RCP2.6 are projected to stabilise around mid-century, following an increase of between $\sim 0.5\text{ K}$ and 1.0 K , relative to 1971–2000.

Significant regional variations were also evident in the multi-model mean ensemble temperature across the domain (Figures 4.15–4.17), with the extreme northern edge of Europe simulated to experience the greatest warming by the end of the present century, particularly under RCP8.5 and RCP4.5. This is consistent with current observations for this region, which are largely attributed to changes in the land surface cover, resulting in a lowering of the albedo and enhanced absorption of radiation, and increased transport of energy by advection.

For precipitation, modelled differences in both the magnitude and direction of projected changes were evident in all seasons and for all RCPs (Figure 4.24). However, this largely reflects the fact that the domain-wide averages act to mask the significant spatial variation that occurs in the simulated precipitation receipts. An assessment of the spatial and seasonal patterns of precipitation changes across Europe broadly indicates wetter winters in northern and eastern Europe, with drier summers in western and southern Europe and North Africa (Figures 4.18, 4.19, 4.20, 4.21, 4.22 and 4.23). Consistent with the findings for projected changes in temperature, larger simulated changes in precipitation are associated with the higher forcing pathways.

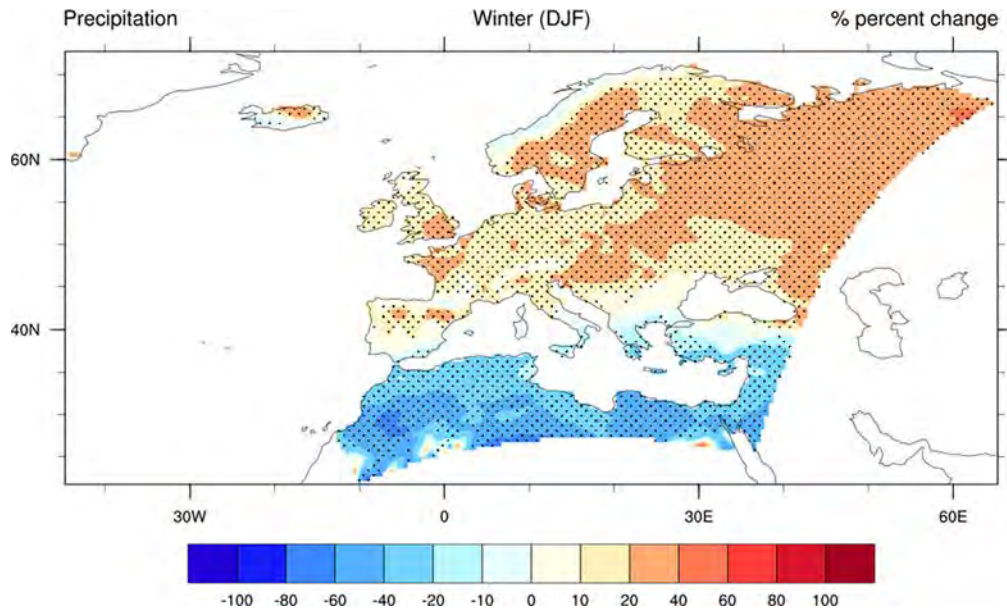


Figure 4.18. Multi-model mean ensemble of winter (DJF) percentage change in precipitation for all land areas in the EURO-CORDEX domain for a selection of models for RCP8.5 for the period 2071–2100, relative to 1971–2000. Stippling indicates areas where more than 80% of selected models agree on the sign of the change. Note that a number of regional climate models employed, selected on account of their availability, are forced with the same parent boundary conditions, and therefore model agreement cannot be interpreted independently of the input model selection. The multi-model mean is derived from six input models: ICHEC-EC-Earth -HIRHAM5, -WRF341E, -RACMO22E; IPSL-CM5A-WRF331F; MPI-M-MPI-ES -CCLM4-8-17, -REMO2009.

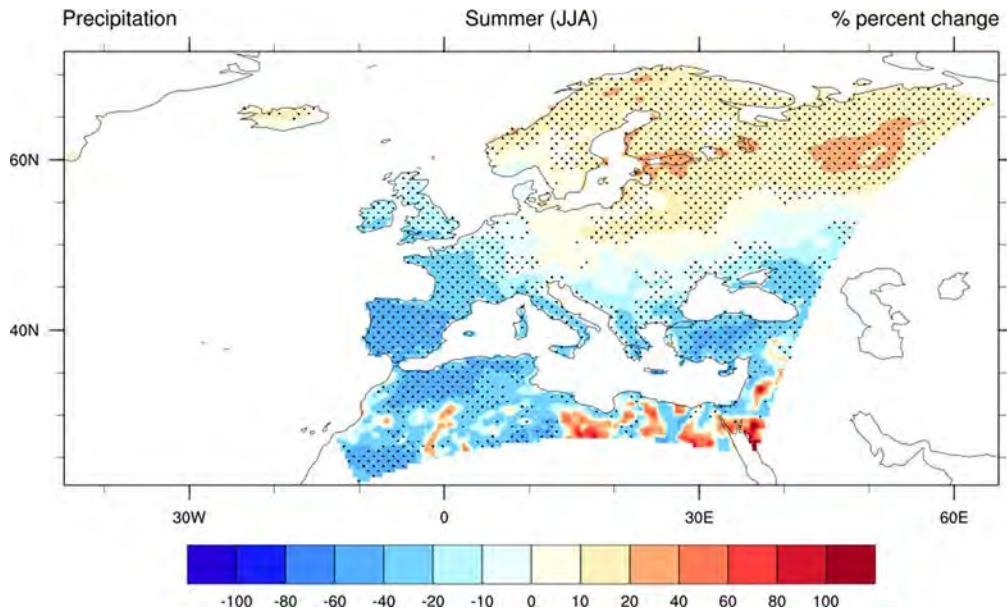


Figure 4.19. Multi-model mean ensemble of summer (JJA) percentage change in precipitation for all land areas in the EURO-CORDEX domain for a selection of models for RCP8.5 for the period 2071–2100, relative to 1971–2000. Stippling indicates area where more than 80% of selected models agree on the sign of the change. Note that a number of regional climate models employed, selected on account of their availability, are forced with the same parent boundary conditions, and therefore model agreement cannot be interpreted independently of the input model selection. The multi-model mean is derived from six input models: ICHEC-EC-Earth -HIRHAM5, -WRF341E, -RACMO22E; IPSL-CM5A-WRF331F; MPI-M-MPI-ES -CCLM4-8-17, -REMO2009.

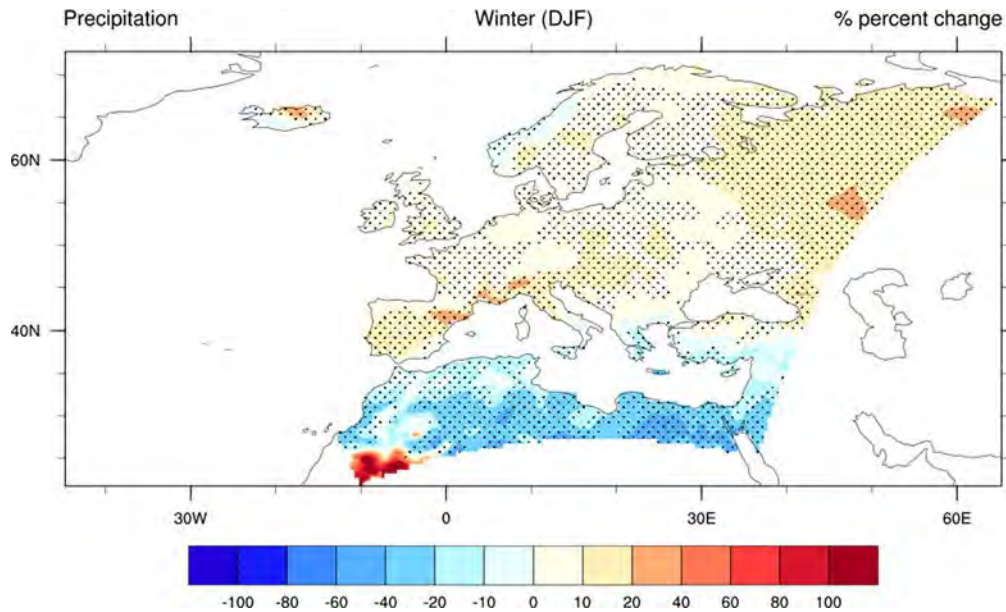


Figure 4.20. Multi-model mean ensemble of winter (DJF) percentage change in precipitation for all land areas in the EURO-CORDEX domain for a selection of models for RCP4.5 for the period 2071–2100, relative to 1971–2000. Stippling indicates area where more than 80% of selected models agree on the sign of the change. Note that a number of regional climate models employed, selected on account of their availability, are forced with the same parent boundary conditions, and therefore model agreement cannot be interpreted independently of the input model selection. The multi-model mean is derived from five input models: ICHEC-EC-Earth -HIRHAM5, -RACMO22E; IPSL-CM5A-WRF331F; MPI-M-MPI-ES -CCLM4-8-17, -REMO2009.

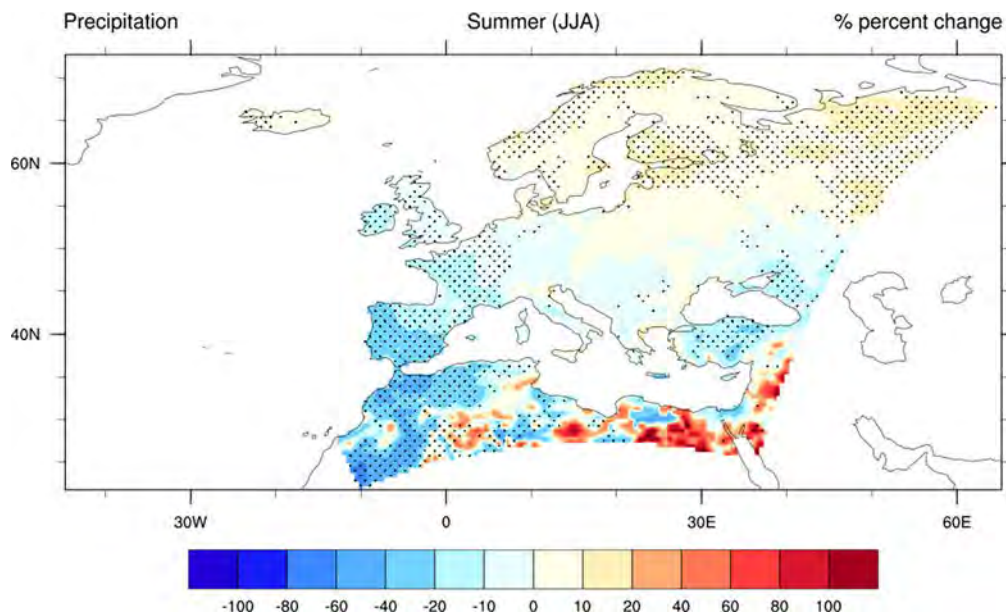


Figure 4.21. Multi-model mean ensemble of summer (JJA) percentage change in precipitation for all land areas in the EURO-CORDEX domain for a selection of models for RCP4.5 for the period 2071–2100, relative to 1971–2000. Stippling indicates area where more than 80% of selected models agree on the sign of the change. Note that a number of regional climate models employed, selected on account of their availability, are forced with the same parent boundary conditions, and therefore model agreement cannot be interpreted independently of the input model selection. The multi-model mean is derived from five input models: ICHEC-EC-Earth -HIRHAM5, -RACMO22E; IPSL-CM5A-WRF331F; MPI-M-MPI-ES -CCLM4-8-17, -REMO2009.

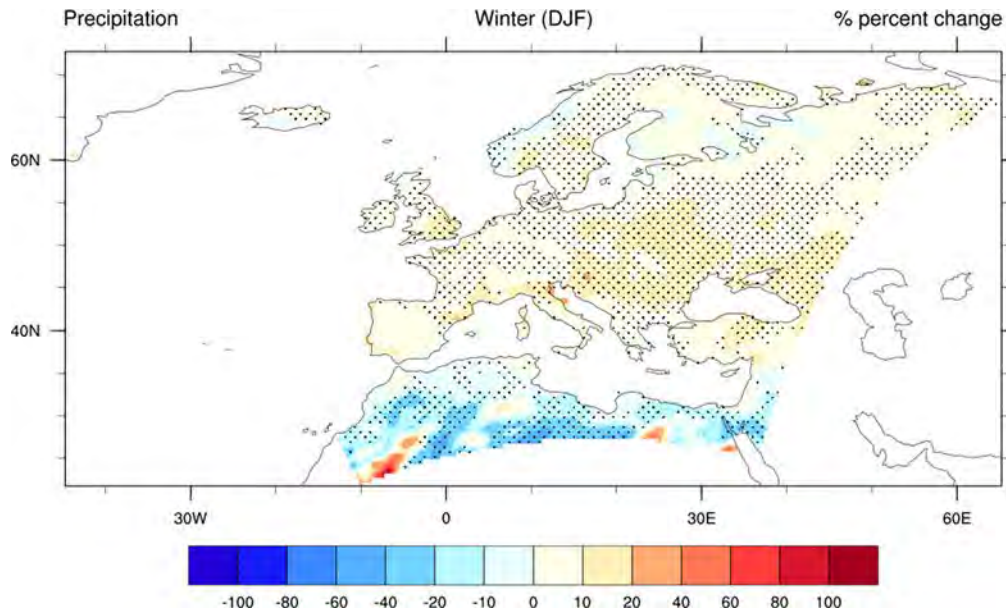


Figure 4.22. Multi-model mean ensemble of winter (DJF) percentage change in precipitation for all land areas in the EURO-CORDEX domain for a selection of models for RCP2.6 for the period 2071–2100, relative to 1971–2000. Stippling indicates area where more than 80% of selected models agree on the sign of the change. Note that a number of regional climate models employed, selected on account of their availability, are forced with the same parent boundary conditions, and therefore model agreement cannot be interpreted independently of the input model selection. The multi-model mean is derived from five input models: ICHEC-EC-Earth -WRFV341E, -RCA4; MOHC-HadGEM2-ES-RCA4; MPI-M-MPI-ES -RCA4, -REMO2009.

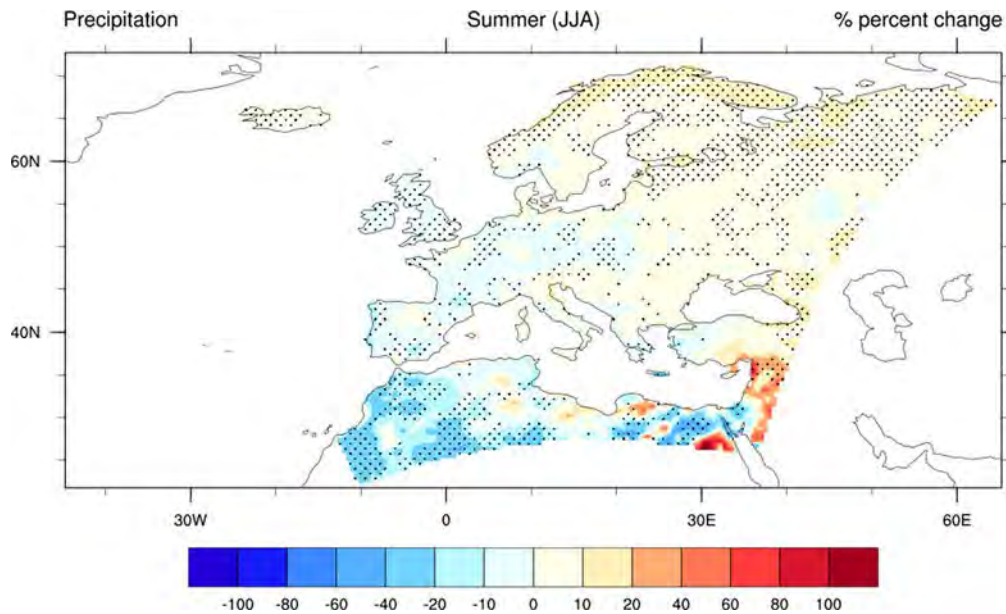


Figure 4.23. Multi-model mean ensemble of summer (JJA) percentage change in precipitation for all land areas in the EURO-CORDEX domain for a selection of models for RCP2.6 for the period 2071–2100, relative to 1971–2000. Stippling indicates area where more than 80% of selected models agree on the sign of the change. Note that a number of regional climate models employed, selected on account of their availability, are forced with the same parent boundary conditions, and therefore model agreement cannot be interpreted independently of the input model selection. The multi-model mean is derived from five input models: ICHEC-EC-Earth -WRFV341E, -RCA4; MOHC-HadGEM2-ES-RCA4; MPI-M-MPI-ES -RCA4, -REMO2009.

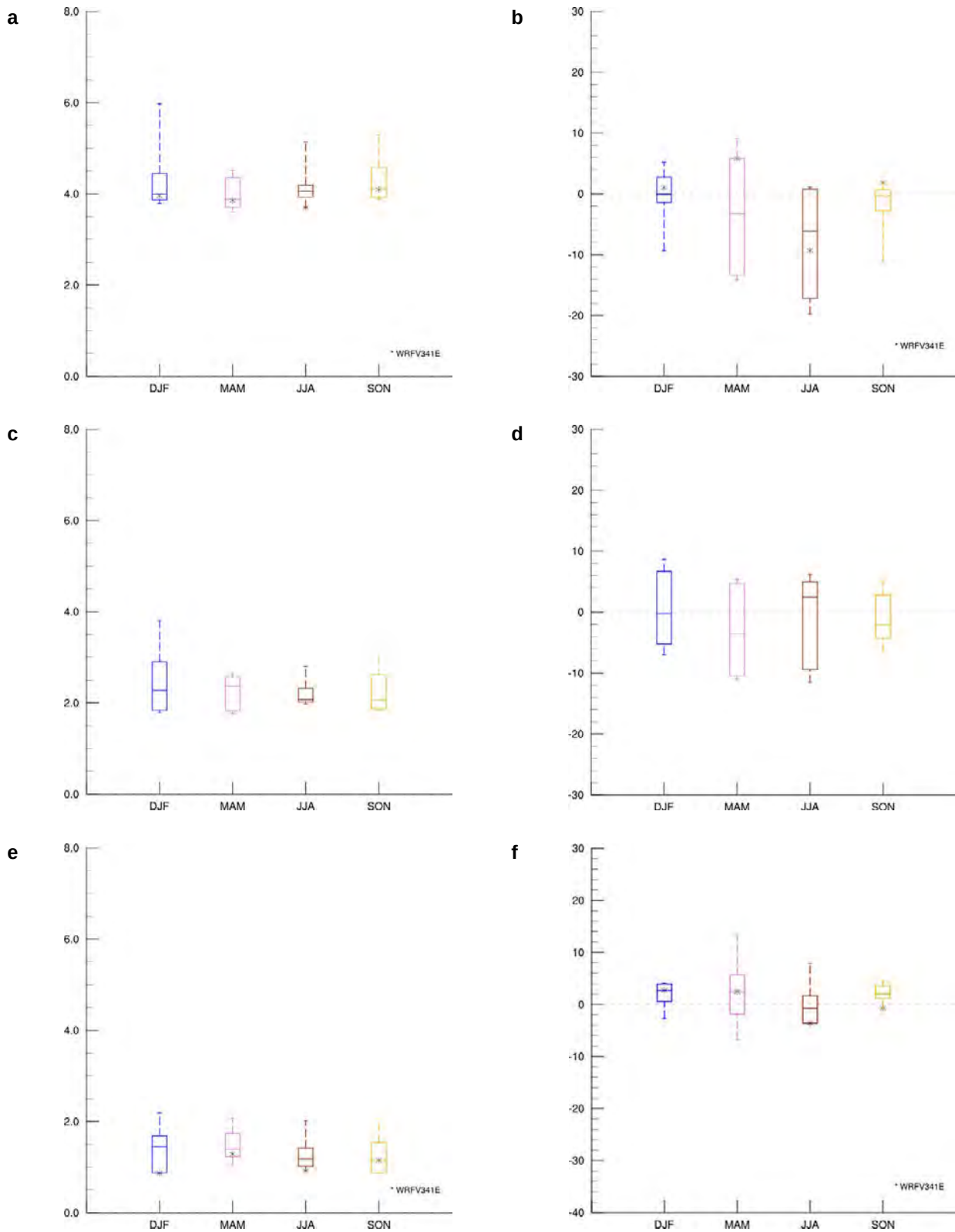


Figure 4.24. Seasonal boxplots of 2-metre temperature (K) (left column) and percentage change precipitation (right column), for the period 2071–2100. Seasonal values are derived from the domain average of each individual model; the average from each model contributes to the calculation of the boxplot statistics (lower whisker – minimum; lower box – 25th percentile; within box – median; upper box – 75th percentile; upper whisker – maximum). The number of models available for each RCP shown is reported in previous figures. The NUIM-WRF341E seasonal mean values for RCP8.5 and 2.6 are indicated by an asterisk (*).

5 Historical and Future Model Simulations of the Climate for Ireland

Climate change will result in a range of impacts across a number of sectors that are likely to exacerbate existing vulnerabilities. Adaptation actions will be required to avoid or reduce the adverse impacts of climate change and take advantage of any positive impacts. For Ireland, it is important to be able to build on positive opportunities that may be presented to respond effectively to reduce any negative impacts and to prepare for longer term consequences.

DECLG, 2012: 10

5.1 Introduction

This chapter presents model simulations for Ireland for both the historical and future periods, with a specific focus on the evaluation and model projections from the NUIM-WRF341E model. The NUIM-WRF341E simulations, which represent Ireland's contribution to EURO-CORDEX, were developed to provide high-resolution (~50 km) regional scenarios for Ireland, with boundary conditions provided by the EC-Earth ESM. An evaluation of the WRF model simulations, employing ERA-Interim boundary conditions, is initially presented for Ireland over the evaluation period of 1981–2010. In this initial analysis, the WRF model simulations are against the E-Obs gridded observational data. For graphical purposes, the Britain and Ireland BI) domain is illustrated, but only results for Ireland are discussed. Following this, an analysis of the WRF simulations, employing the EC-Earth ESM as boundary conditions, is presented for the historical period of 1951–2005. Again, the E-Obs gridded observational data are employed for comparison. Model results for the future simulations are then presented for various future time periods, representing either annual timeseries over the period 2006–2100 or time slices (2021–2050 and 2071–2100). Where feasible, the model simulations are placed in the context of available RCMs from EURO-CORDEX.

5.2 Model Simulations: Evaluation Period 1981–2010

An evaluation of the WRF341E model simulations, employing ERA-Interim boundary conditions, was undertaken for the period 1981–2010. Model simulations are compared against the E-Obs gridded observational data, employed previously for the larger evaluation over the EURO-CORDEX domain. Figure 5.1 illustrates the seasonal values of mean temperature (K) from E-Obs (Figure 5.1, left) and WRF341E (Figure 5.1, centre). Seasonal anomalies, representing the difference between the observed and model data (i.e. E-Obs minus WRF341E), are also shown (Figure 5.1, right). The anomalies have been adjusted to show a positive anomaly where WRF341E overestimates the value, relative to E-Obs, and a negative anomaly where WRF341E underestimates the value relative to E-Obs. The WRF341E simulations are shown to capture the broad spatial features of mean temperature, with temperature maxima located in the south and east of the domain and temperature minima located to the north of the domain.

During winter, the WRF simulations show a warm bias (~0.6 K) across Ireland. The largest biases are evident during spring and summer, with WRF341E underestimating temperatures in these seasons by approximately –0.6 K and –1.2 K respectively. The smallest biases are associated with autumn, with WRF341E underestimating temperatures by approximately –0.1 K across Ireland.

Figure 5.2 illustrates the seasonal mean precipitation (mm) from E-Obs (Figure 5.2, left) and WRF341E (Figure 5.2, centre). Again, the WRF341E simulations are shown to capture the broad spatial and temporal patterns of seasonal precipitation across Ireland, with precipitation maxima located on the west coast, reflecting the large-scale synoptic processes associated with precipitation. Seasonal anomalies are also shown in Figure 5.2 (right). Positive anomalies are associated with locations where WRF341E overestimates mean daily precipitation and

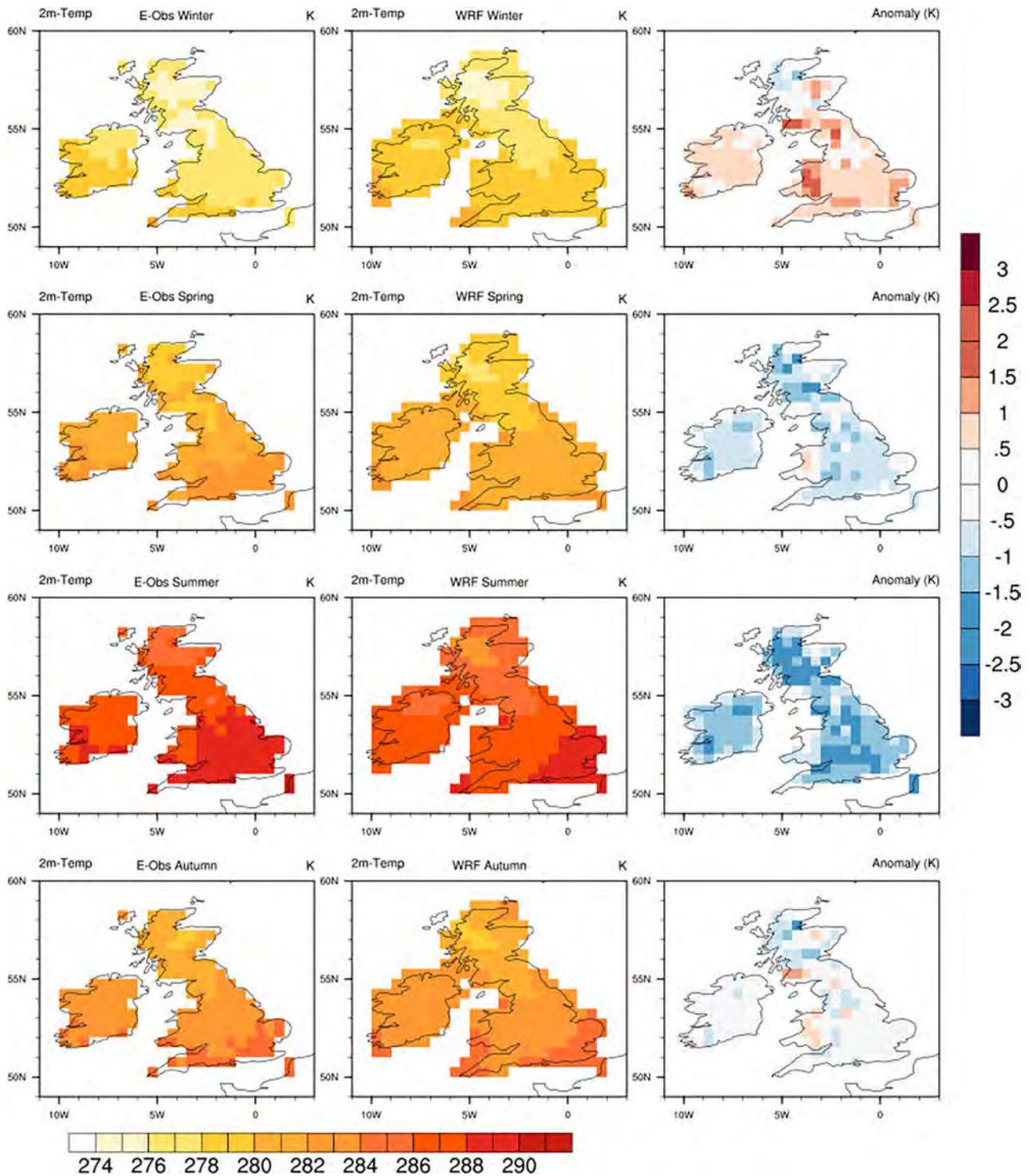


Figure 5.1. Difference in seasonal mean temperature between E-Obs (absolute values in K) (left) and WRF model simulations (K) for the evaluation period, employing ERA-Interim, for the period 1981–2010. The difference is calculated as E-Obs – model. Top to bottom: winter (DJF), spring (MAM), summer (JJA) and Autumn (SON). E-Obs values are shown in the left column, WRF model values in the centre and seasonal anomalies in the right column.

negative anomalies where it underestimates it. Overall, WRF341E overestimates mean daily precipitation across all seasons, with the largest bias evident during

the winter, spring and autumn seasons. The largest seasonal biases are located in the west and central parts of Ireland.

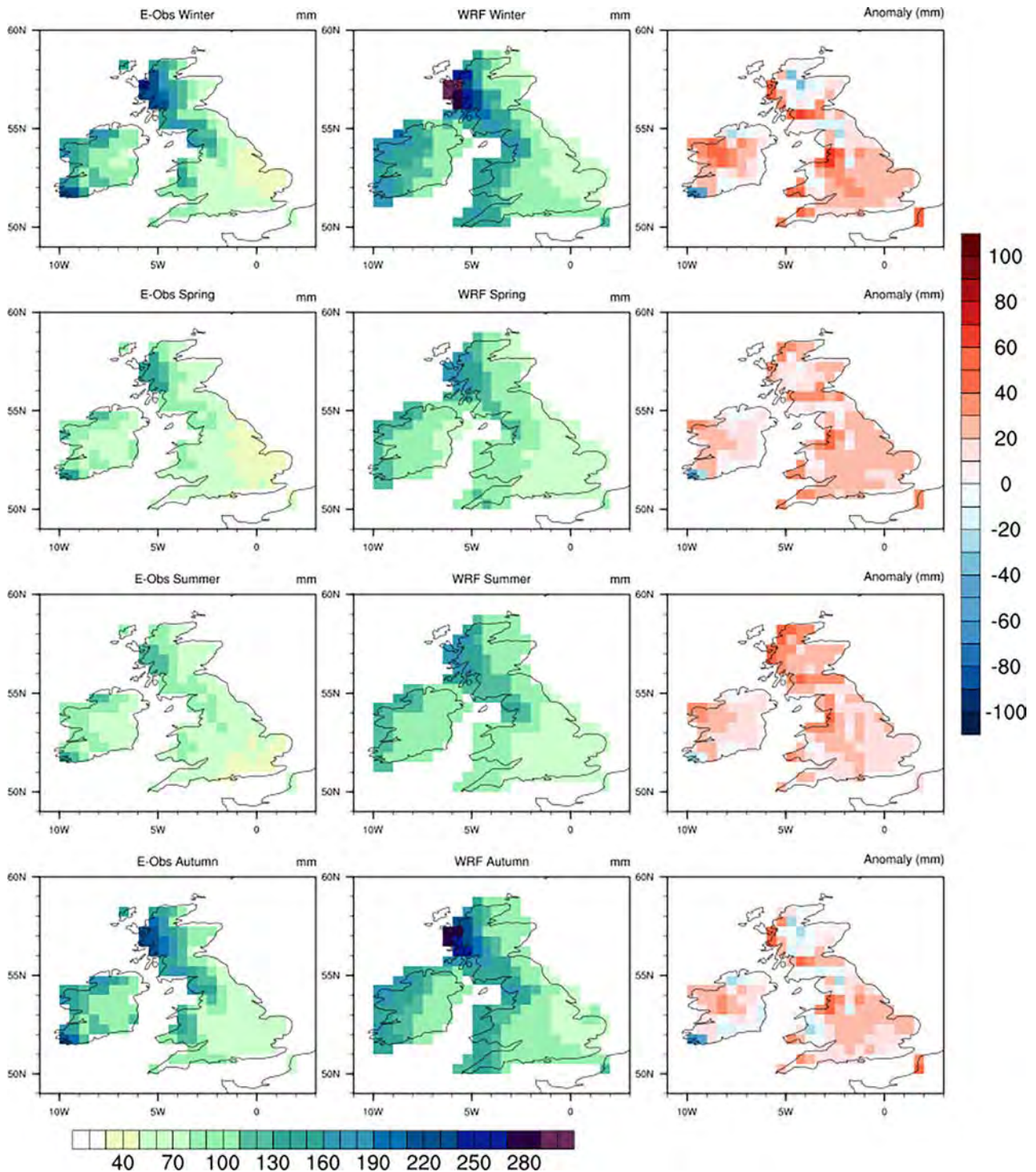


Figure 5.2. Difference in seasonal mean precipitation between E-Obs (values in mm) (left) and WRF model simulations (mm) for the evaluation period, employing ERA-Interim, for the period 1981–2010. The difference is calculated as E-Obs – model. Top to bottom: winter (DJF), spring (MAM), summer (JJA) and autumn (SON). E-Obs values are shown in the left column, WRF model values in the centre and the seasonal anomalies (mm) in the right column.

To assess the models' ability to reproduce the empirical distributions of both daily mean temperature and daily precipitation, a comparison between E-Obs and WRF341E for the evaluation period 1981–2010

was undertaken for each season. For temperature, this comparison broadly confirms the findings from the seasonal analysis outlined above. The WRF341E model appears to adequately capture the spread of

the observed data, with a tendency to underestimate the frequency of above average daily temperatures during summer and autumn (Figure 5.3). During winter, the model simulates the spread of the observed data, but is shown to overestimate the frequency of values just above the mean. For precipitation, the shape parameter (α) of a fitted gamma function is comparable between E-Obs and WRF341E for all seasons (Figure 5.4). However, during the summer and autumn seasons, the scale parameter (β) of the simulated mean daily precipitation is greater than that of the E-Obs data, indicating that the model produces

a higher frequency of more extreme daily precipitation compared with the E-Obs data.

Overall, the evaluation of the WRF model, employing ERA-Interim as boundary conditions, demonstrated that WRF is capable of reproducing the dominant spatial and temporal characteristics of the observed climate of Ireland as represented by the E-Obs data. The seasonal comparison showed reasonable model agreement, with small seasonal biases evident in both temperature and precipitation. The comparison of the distributions of the daily values of both temperature and precipitation, on a seasonal basis,

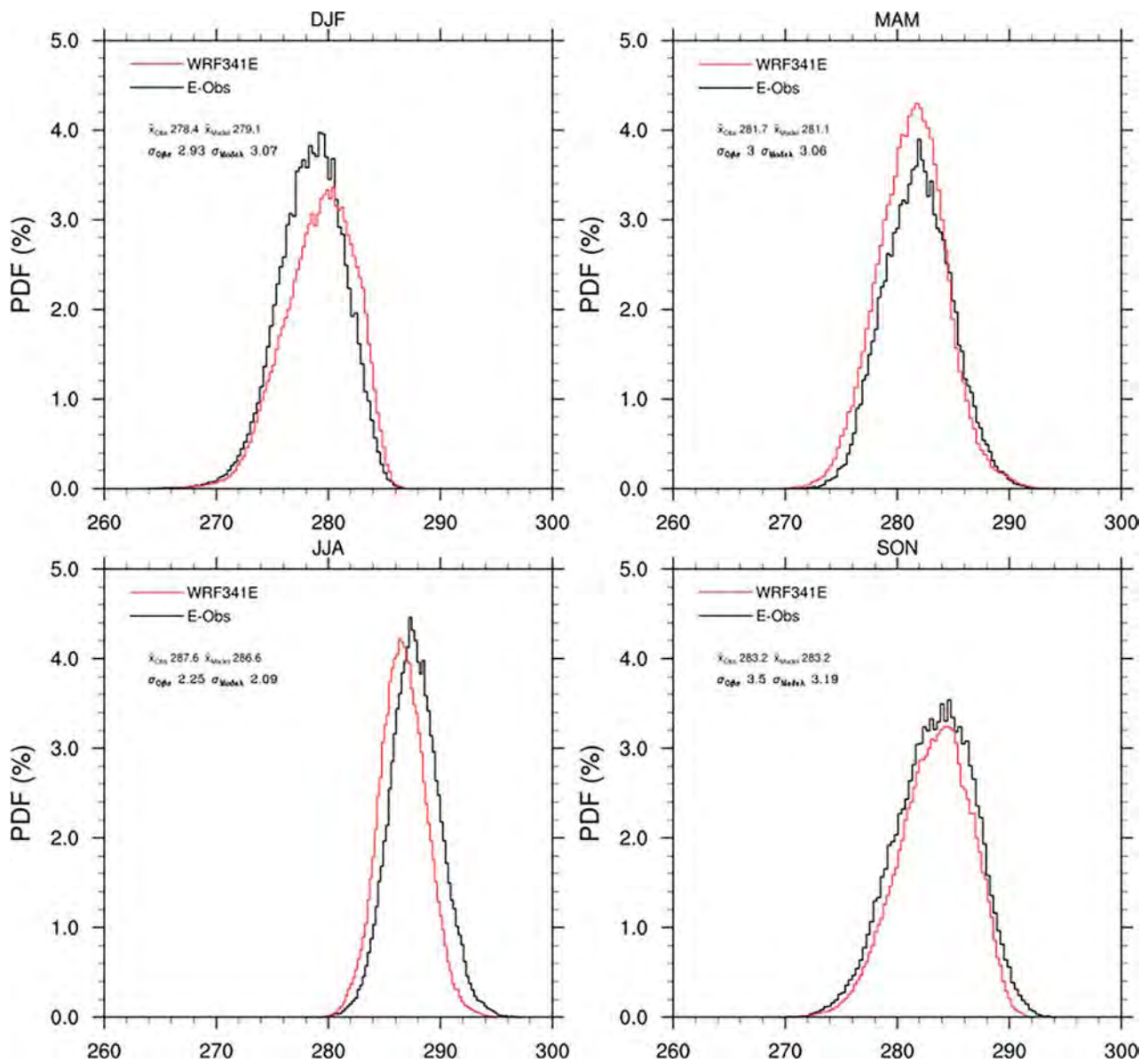


Figure 5.3. Empirical probability distribution function of mean daily temperature (K) from E-Obs and WRF341E simulations, employing ERA-Interim boundary conditions, for the evaluation period 1981–2010 for Ireland. The means ($\bar{x}$) and standard deviations (σ) are also shown for both E-Obs (obs) and WRF341E (model).

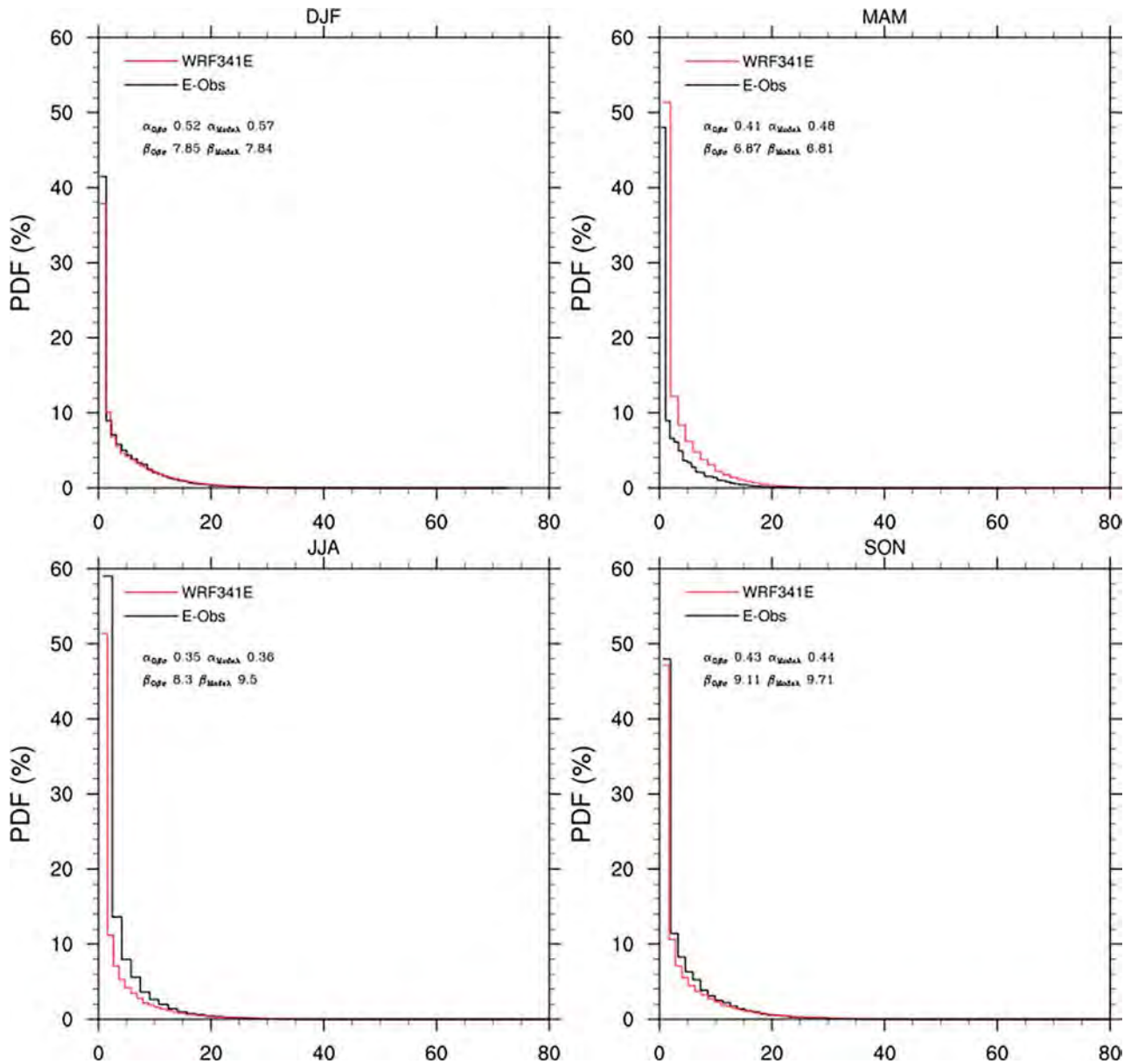


Figure 5.4. Empirical probability distribution function of mean daily precipitation (mm) from E-Obs and WRF341E simulations, employing ERA-Interim boundary conditions, for the evaluation period 1981–2010 for Ireland. The shape (α) and scale (β) of the fitted gamma function are also shown for both E-Obs (obs) and WRF341E (model). The threshold for precipitation was set at 0.

again demonstrated the ability of the WRF model to replicate the broad features of the E-Obs data, with a slight tendency to underestimate above average daily temperatures during summer and autumn. The opposite was the case for mean daily precipitation, with the WRF model tending to overestimate the frequency of higher daily precipitation amounts.

5.3 Model Simulations: Historical Period 1951–2005

Following evaluation of the WRF model employing ERA-Interim as boundary conditions, the historical

simulations, which employ the EC-Earth ESM as boundary conditions, were compared for the historical period 1951–2005. The WRF341E simulations are again compared with the gridded observational data, E-Obs. The anomalies represent WRF341E minus E-Obs; positive anomalies indicate where the WRF341E model overestimates values relative to the observed data and negative anomalies indicate where the WRF341E model simulations underestimate values relative to the observed data.

The WRF341E simulations, employing EC-Earth as boundary conditions, broadly reproduce the

observed spatial patterns of seasonal warming over the period 1951–2005 (Figure 5.5). Consistent with the evaluation period, the locations of the temperature maxima are in the south and east, with minima located to the north. As previously outlined, the EC-Earth

model underestimates 2-metre temperature in this region, and this is reflected in the underestimation of simulated mean temperature across all seasons in the WRF341E simulations (Figure 5.5, left). Winter displays the smallest underestimation (approximately

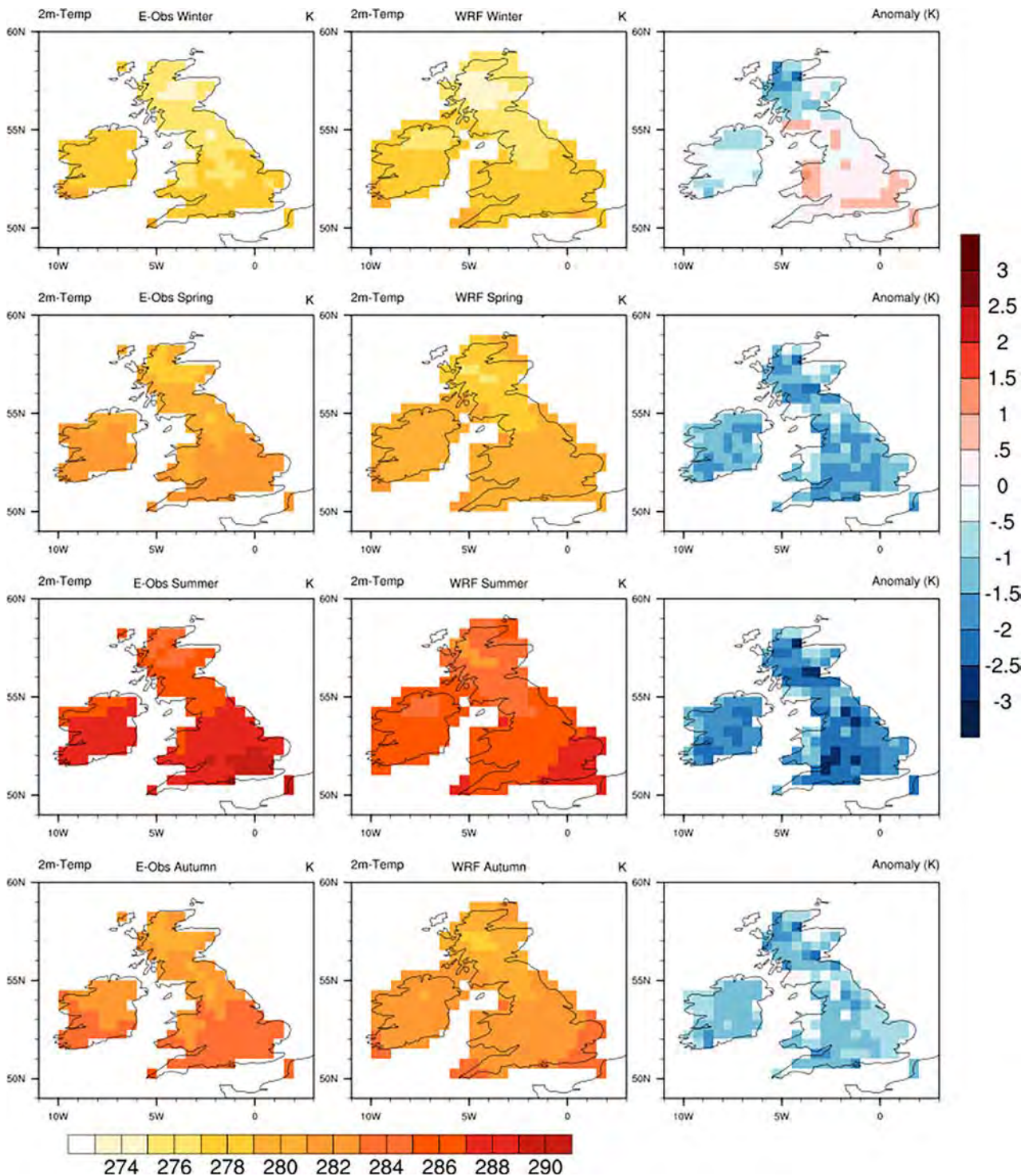


Figure 5.5. Difference in seasonal mean temperature between E-Obs (absolute values in K) (left) and historical model simulations for the ICHEC EC-Earth WRF simulations (K) for the period 1951–2005. The difference is calculated as E-Obs – model. Top to bottom: winter (DJF), spring (MAM), summer (JJA) and autumn (SON). E-Obs values are shown in the left column, WRF model values in the centre and the seasonal anomalies in the right column.

–0.4 K), followed by autumn (approximately –1.0 K) and spring (approximately –1.3 K). Summer displays the largest cold anomaly, underestimating the observed E-Obs data by approximately –1.8 K across Ireland.

A comparison of seasonal mean precipitation (mm) between E-Obs and WRF341E, employing EC-Earth as boundary conditions, over the period 1951–2005 is illustrated in Figure 5.6. The EC-Earth ESM overestimates precipitation over western Europe,

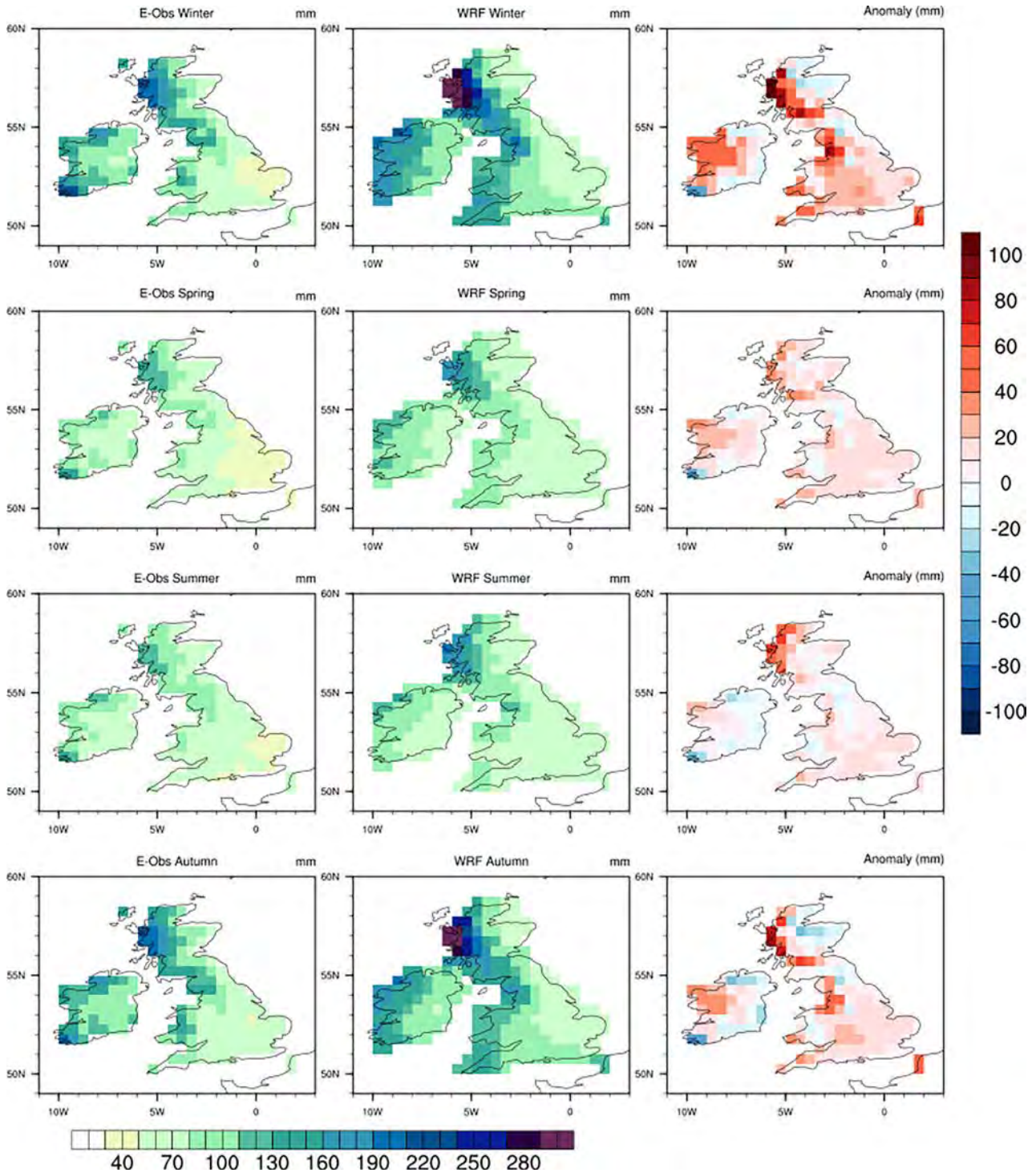


Figure 5.6. Difference in seasonal mean precipitation between E-Obs (values in mm) (left) and historical model simulations for the ICHEC EC-Earth WRF simulations (mm) for the period 1951–2005. The difference is calculated as E-Obs – model. Top to bottom: winter (DJF), spring (MAM), summer (JJA) and autumn (SON). E-Obs values are shown in the left column, WRF model values in the centre and the seasonal anomalies (mm) in the right column.

particularly in winter; this is reflected in the largest seasonal biases during this season. Coupled with WRF's tendency to overestimate precipitation in all seasons, positive biases are evident particularly during spring and autumn across Ireland.

To place these WRF biases in context, boxplots of the seasonal mean bias (in K for temperature and percentage change for precipitation) derived from all available model simulations contributing to EURO-CORDEX are shown in Figure 5.7, for the mean of model grids representing Ireland. For comparison, the mean values for comparable grid locations from the WRF341E simulations are also identified. For temperature, the WRF341E mean biases lie within the 25th–75th percentile range, with the exception of the summer mean bias. For precipitation, the WRF341E winter seasonal mean bias is the only season to lie outside the 25th–75th percentile range of models employed.

A comparison of the seasonal distributions of mean daily temperature (Figure 5.8) shows that the WRF model simulations, employing EC-Earth as boundary

conditions, underestimate mean daily temperatures in all seasons, consistent with the analysis of the seasonal mean biases. Winter is the only season in which the simulated distribution compares well with the observed data in terms of the standard deviation. During spring and summer, both the means and standard deviations are underestimated by WRF341E. During autumn, the model simulates the frequency of below average values, but underestimates the frequency of above-average values.

Figure 5.9 illustrates the comparison of mean daily precipitation between E-Obs and WRF341E. During winter and summer, the simulated frequency of low- and non-precipitation days is underestimated, relative to the observed frequency. In spite of this, the simulated precipitation for days on which precipitation occurred matches closely with the observed frequencies. During summer, the underestimation of non-precipitation days is also evident for days on which precipitation occurred. During spring and autumn, the simulated frequencies match the observations very closely, reflected in the similarity

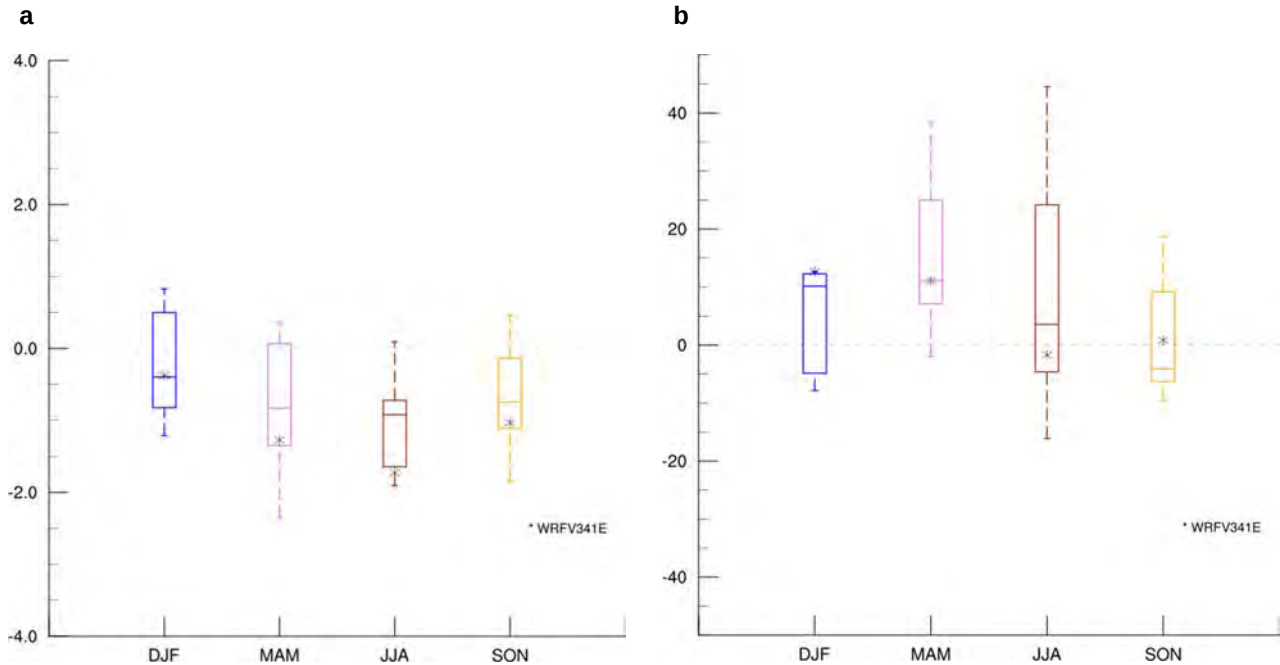


Figure 5.7. Multi-model seasonal mean bias statistics for temperature (K) (a) and precipitation (%) (b) represented as boxplots (lower whisker – minimum; lower box – 25th percentile; within box – median; upper box – 75th percentile; upper whisker – maximum). The multi-model statistics are derived from input models: ICHEC-EC-Earth -HIRHAM5, -RACMO22E, -WRF341E, -RCA4; IPSL-CM5A-WRF331F; MOHC-HadGEM2-ES-RCA4; MPI-M-MPI-ES -CCLM4-8-17, -REMO2009, -RCA4. The NUIM-WRF341E seasonal percentage values are indicated by an asterisk (*). Statistics are derived from the mean of the grid boxes representing Ireland in the models.

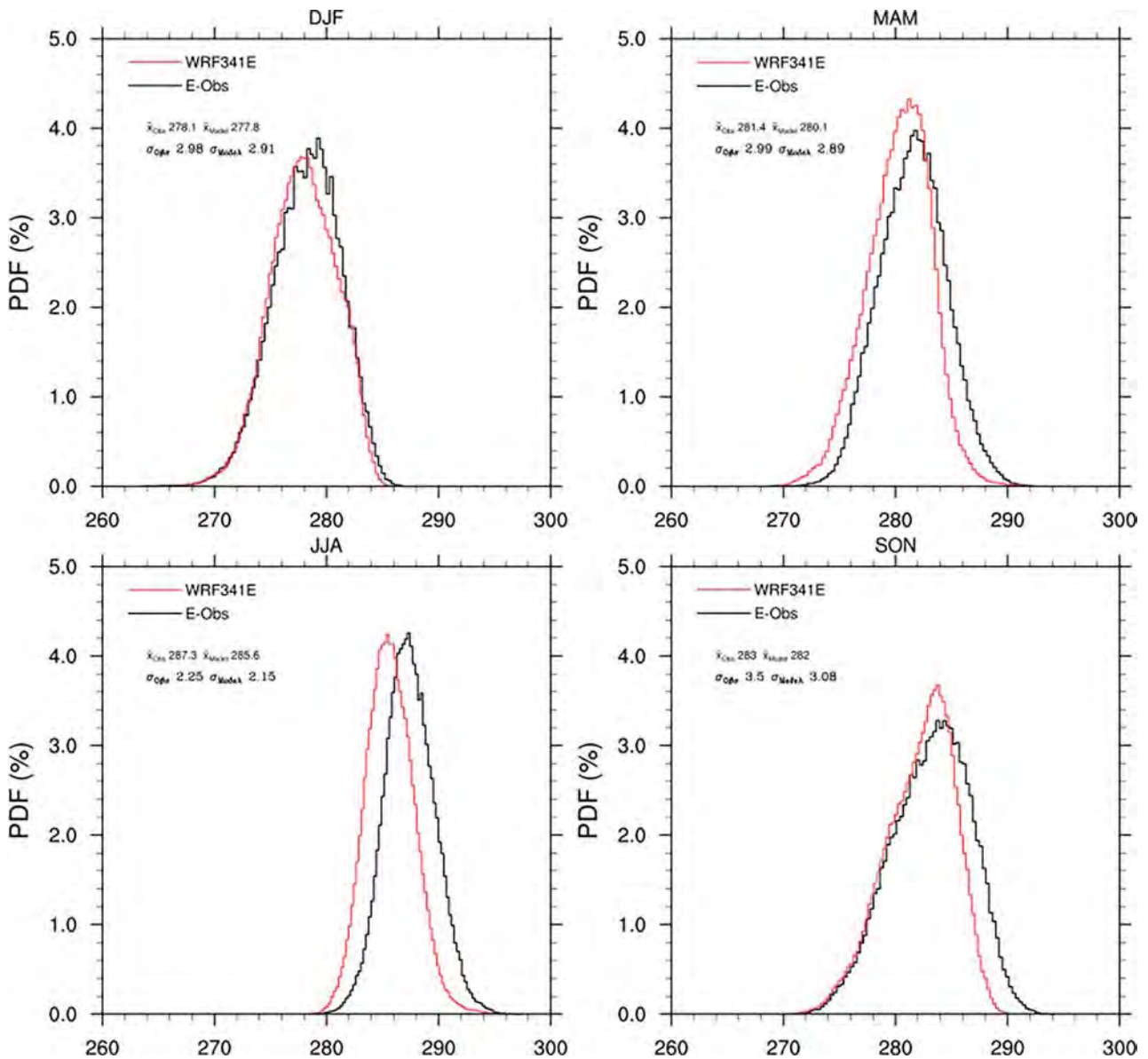


Figure 5.8. Empirical probability distribution function of mean daily temperature (K) from E-Obs and WRF341E simulations, employing EC-Earth boundary conditions, for the historical period 1951–2005 for Ireland. The means ($\bar{x}$) and standard deviations (σ) are also shown for both E-Obs (obs) and WRF341E (model).

between both the shape (α) and scale (β) parameters for these seasons.

The WRF341E simulations, employing EC-Earth as boundary conditions, are capable of reproducing the seasonal spatial patterns evident in the observed data. When compared with other available model simulations contributing to EURO-CORDEX, the mean biases for Ireland were found to lie within a comparable range of the models available. For temperature, the WRF341E simulations were found to underestimate the mean and spread of the observed data, with the exception of winter. This is

probably attributable to the cold bias evident in the boundary conditions for this region. On a seasonal basis, the model reproduced the spatial variations in the observed data, capturing the higher precipitation receipts on the west coast, evident in the observed data. Biases in the seasonal mean daily precipitation were generally small, but WRF341E does display a tendency to underrepresent the frequency of non-rain days during winter and summer. Overall, the model captures the shape and scale of the observed data, with the exception of summer, where the model underestimates the frequency of mean daily precipitation, relative to the observed frequencies.

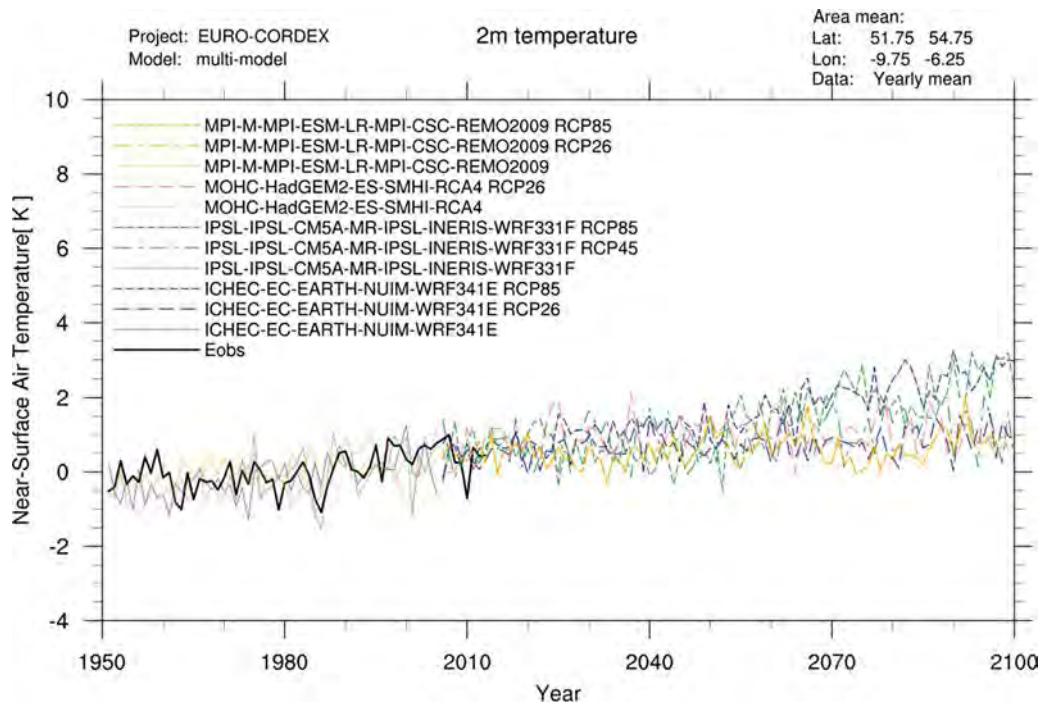


Figure 5.9. Empirical probability distribution function of mean daily precipitation (mm) from E-Obs and WRF341 simulations, employing EC-Earth boundary conditions, for the historical period 1951–2005 for Ireland. The shape (α) and scale (β) of the fitted gamma function are also shown for both E-Obs (obs) and WRF341E (model). The threshold for precipitation was set at 0.

5.4 Model Simulations: Future Simulations for Ireland

Figure 5.10 shows the annual mean temperature anomalies, relative to the 1971–2000 period, for a selection of RCPs and model simulations for the period 1951–2100. For comparison, annual anomalies of the gridded observed data from E-Obs are also shown for the period 1951–2013. The observed anomalies are relative to the same base period as the model simulations, 1971–2000. The values are based on the model grid cells representing the land area of Ireland in each of the model simulations. Depending on model and RCP choice, end-of-century warming for Ireland is projected to lie between ~0.5 K and 4.5 K. Consistent with previous studies, the influence of the different RCPs is most evident after the middle of the present century. As expected, the greatest warming is associated with the higher RCPs. Model spread also appears to increase with the higher RCPs, specifically RCP8.5 (Figure 5.11). For example, end-of-century warming associated with RCP8.5 ranges from ~2 K to 4.5 K (Figure 5.11), while for RCP4.5 warming ranges from ~1.0 K to 2.5 K (Figure 5.12) and for RCP2.6 it ranges from 0.5 K to 1.5 K (Figure 5.13).

To evaluate the spatial and seasonal projected changes in temperature and precipitation, seasonal and spatial anomalies for two future time periods were examined. The chosen time periods, 2021–2050 and 2071–2100, were selected to represent near and end-of-century changes in the climate of Ireland. The seasonal anomalies are calculated relative to the period 1971–2000, consistent with previous sections. The results presented here focus on the WRF341E simulations, employing EC-Earth as boundary conditions. Subsequent sections will assess the simulated changes in context of additional model simulations, obtained from the suite of available models participating in EURO-CORDEX.

Table 5.1 presents a summary of the projected changes in both temperature (K) and precipitation (percentage change), on a seasonal basis, for RCP2.6 and RCP8.5 for the selected time periods, based on the WRF simulations undertaken for this study. Table 5.2 presents results from available EURO-CORDEX models. The models chosen were based on availability and therefore represent an ensemble of opportunity, rather than necessarily representing the full sample space of future climate. The values in Table 5.1 are

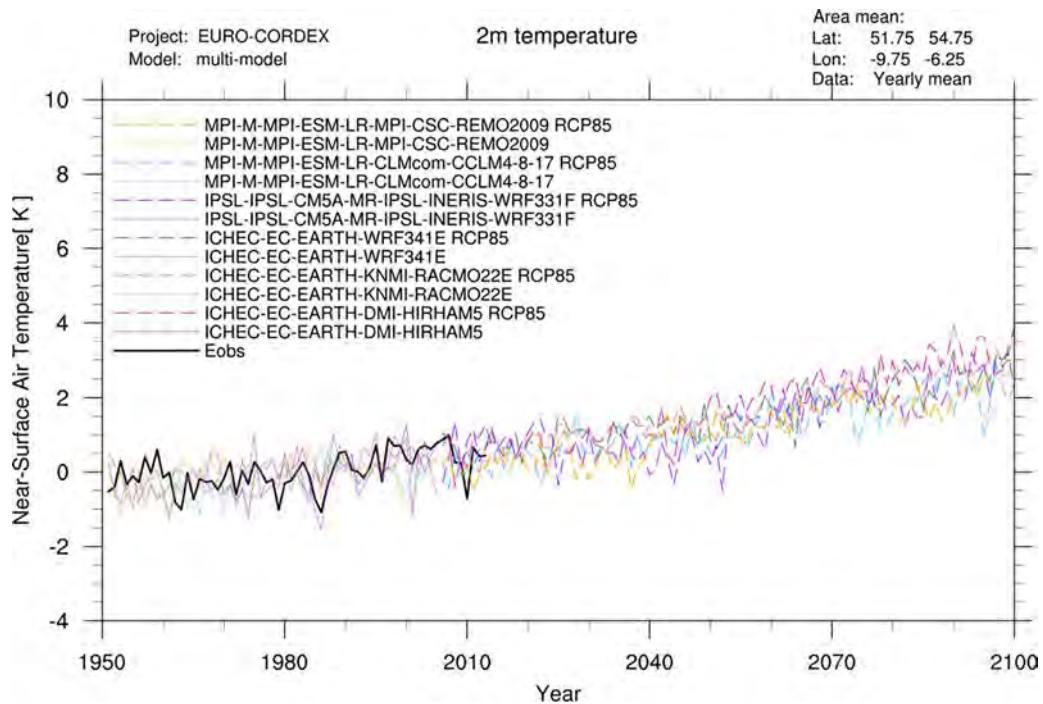


Figure 5.10. Multi-model timeseries of annual anomalies of 2-metre surface temperature (K) for the land area representing Ireland for a selection of models and RCPs for the period 1951–2100, relative to 1971–2000. Annual anomalies of observations, derived from the E-Obs data (black line), are also shown for reference for the period 1951–2013. Solid lines indicate historical simulations (1951–2005); dashed lines indicate RCP forcing scenarios (2006–2100).

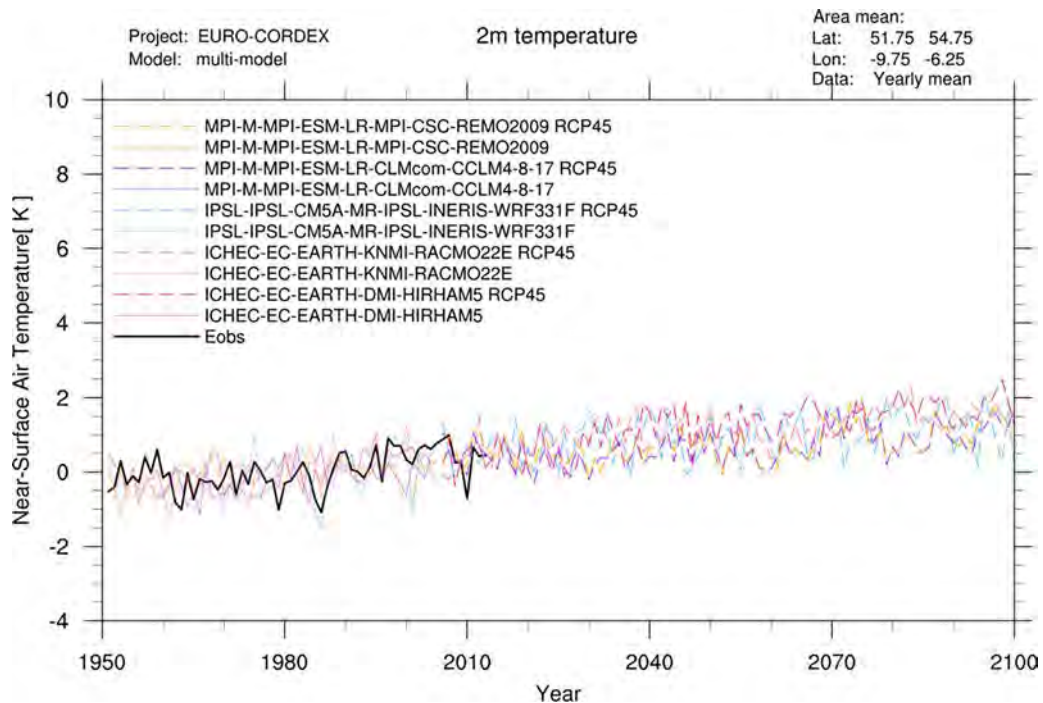


Figure 5.11. Multi-model timeseries of annual anomalies of 2-metre surface temperature (K) for the land area representing Ireland for a selection of models for RCP8.5 for the period 1951–2100, relative to 1971–2000. Annual anomalies of observations, derived from the E-Obs data (black line), are also shown for reference for the period 1951–2013. Solid lines indicate historical simulations (1951–2005); dashed lines indicate RCP forcing scenarios (2006–2100).

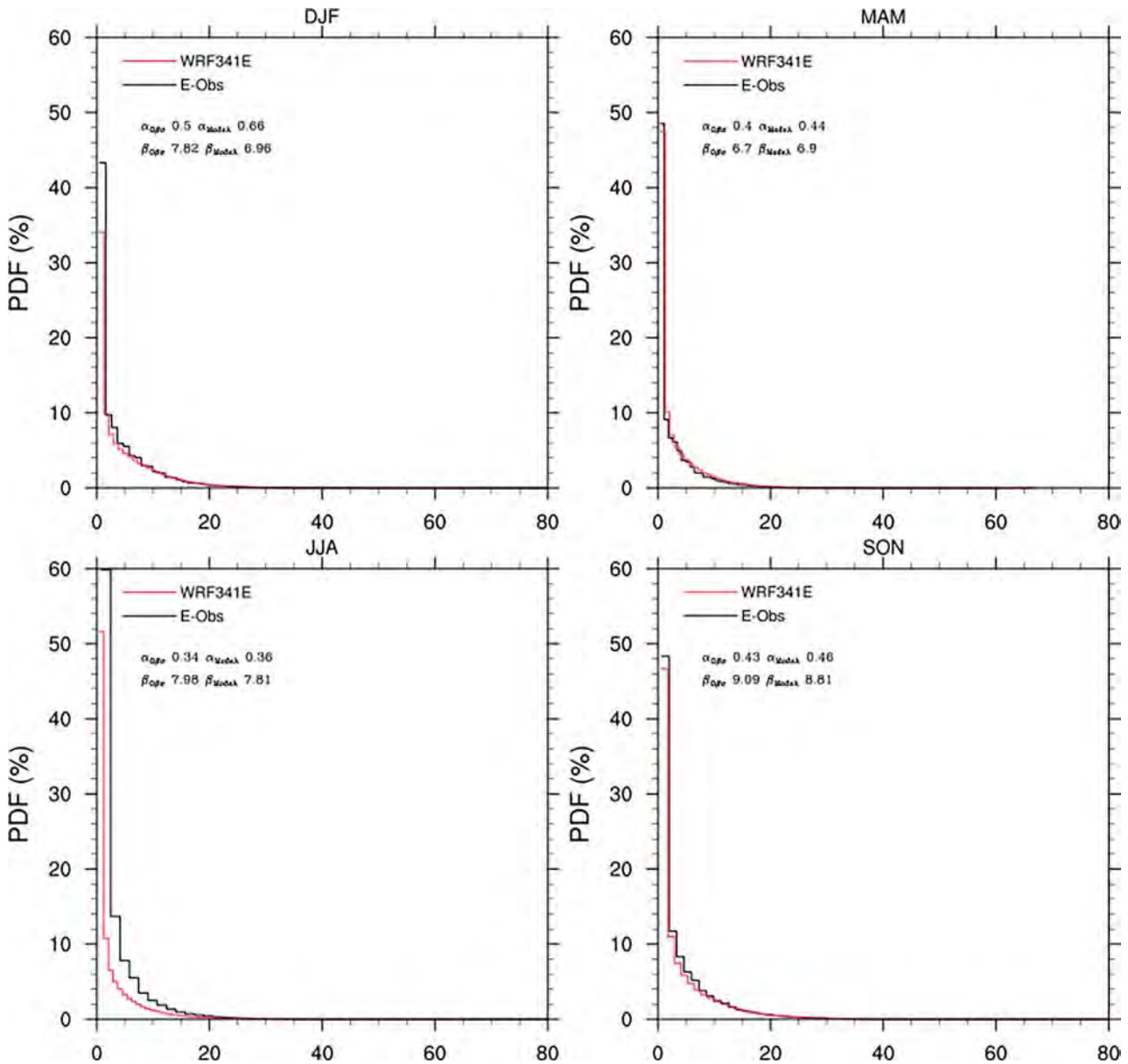


Figure 5.12. Multi-model timeseries of annual anomalies of 2-metre surface temperature (K) for the land area representing Ireland for a selection of models for RCP4.5 for the period 1951–2100, relative to 1971–2000. Annual anomalies of observations, derived from the E-Obs data (black line), are also shown for reference for the period 1951–2013. Solid lines indicate historical simulations (1951–2005); dashed lines indicate RCP forcing scenarios (2006–2100).

based on the land area for Ireland within the model simulations and represent nationally averaged values. To assess the projected spatial changes in temperature and precipitation, seasonal figures for both variables are also presented in Figures 5.14 and 5.15.

Over the 2021–2050 period, mean seasonal temperatures are simulated to increase in all seasons and for both RCPs. For RCP2.6, increases of between

0.3K and 0.8K are simulated, depending on season. Spring shows the lowest increase, of 0.3K, with all other seasons projected to warm by 0.8K. Greater seasonal differences are evident for RCP8.5 for this period, with spring simulated to show the smallest increase, of 0.7 K, followed by winter (1.0K) and summer (1.2K). Autumn is likely to experience the largest increase in temperature relative to 1971–2000, with mean temperatures for this season simulated to increase by 1.5K.

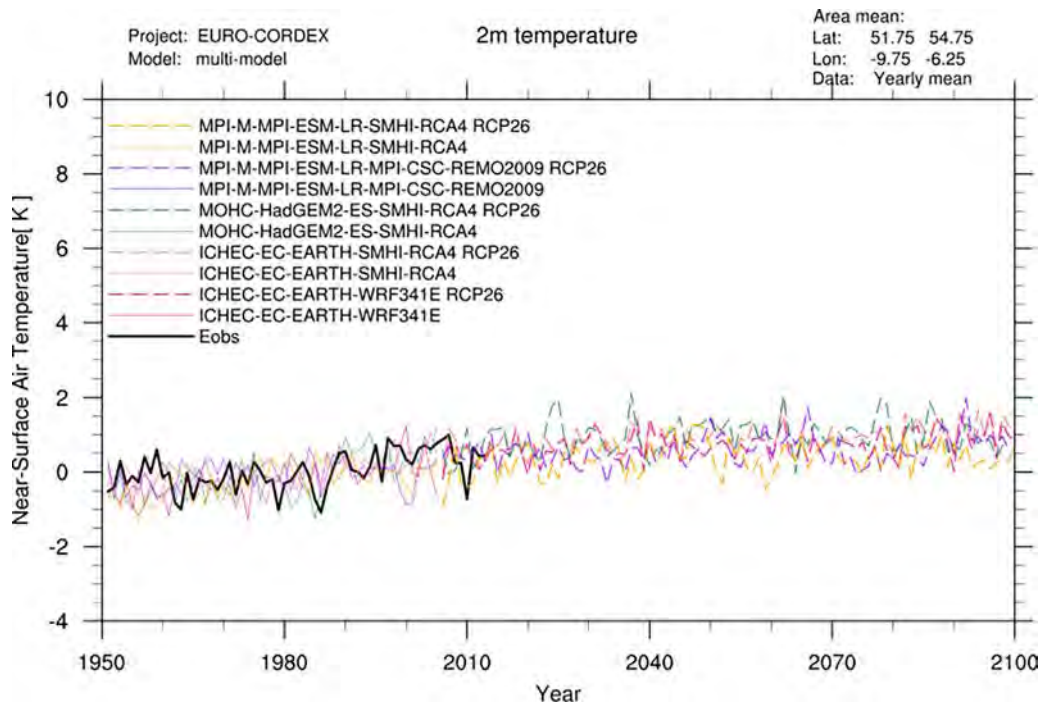


Figure 5.13. Multi-model timeseries of annual anomalies of 2-metre surface temperature (K) for all the land area representing Ireland for a selection of models for RCP2.6 for the period 1951–2100, relative to 1971–2000. Annual anomalies of observations, derived from the E-Obs data (black line), are also shown for reference for the period 1951–2013. Solid lines indicate historical simulations (1951–2005); dashed lines indicate RCP forcing scenarios (2006–2100).

Table 5.1. Simulated seasonal changes in temperature (K) and precipitation (percentage change) for RCP2.6 and 8.5 based on the WRF341E simulations derived for this study employing EC-Earth as boundary conditions, for the period 2021–2050 and 2071–2100, relative to 1981–2000. Values are based on the land area representing Ireland

Season	2021–2050		2071–2100	
	RCP2.6	RCP8.5	RCP2.6	RCP8.5
<i>Temperature (K)</i>				
Winter (December to February)	0.8	1.0	0.9	2.1
Spring (March to May)	0.3	0.7	0.6	1.8
Summer (June to August)	0.8	1.2	0.9	2.8
Autumn (September to November)	0.8	1.5	1.1	3.1
<i>Precipitation (% change)</i>				
Winter (December to February)	–1.8	–2.3	1.1	7.1
Spring (March to May)	7.6	0.2	8.7	1.0
Summer (June to August)	–13.6	–6.4	–5.5	–13.7
Autumn (September to November)	0.9	–1.3	–3.0	9.4

By the 2071–2100 period, RCP2.6 displays only small temperature increases when compared with the simulated increases for this pathway for the 2021–2050 period. Again, spring is simulated to show the smallest increases (0.6 K) relative to 1971–2000, with

mean temperature increases in autumn simulated to be greatest (1.1 K) under this RCP. Winter and summer both show increases of 0.9 K. For RCP8.5, the mean temperature increases for 2071–2100 are more than double those of the 2021–2050 period. Autumn is

Table 5.2. Multi-model ensemble, minimum and maximum values (brackets), derived from available models from EURO-CORDEX for the land area representing Ireland. The values are derived from five models for RCP2.6 and RCP4.5 and from six models for RCP8.5

Season	2021–2050		2071–2100			
	RCP2.6	RCP4.5	RCP8.5	RCP2.6	RCP4.5	RCP8.5
Temperature (K)						
Winter (December to February)	0.6 (0.3 to 0.8)	0.6 (0.2 to 1.1)	0.7 (0.2 to 1.0)	0.7 (0.3 to 0.9)	1.2 (0.9 to 1.6)	2.1 (1.7 to 2.6)
Spring (March to May)	0.4 (0.3 to 0.6)	0.5 (0.1 to 1.0)	0.6 (0.2 to 1.0)	0.5 (0.2 to 0.9)	1.0 (0.6 to 1.6)	1.8 (1.2 to 2.6)
Summer (June to August)	0.7 (0.2 to 1.0)	0.8 (0.5 to 1.2)	0.8 (0.4 to 1.2)	0.8 (0.5 to 1.1)	1.2 (1.0 to 1.6)	2.5 (2.2 to 3.0)
Autumn (September to November)	0.8 (0.4 to 1.4)	1.0 (0.8 to 1.3)	1.1 (0.7 to 1.5)	1.1 (0.6 to 1.7)	1.5 (1.3 to 1.7)	2.9 (2.4 to 3.3)
Precipitation (% change)						
Winter (December to February)	6.8 (−1.8 to 10.4)	3.4 (0 to 7.5)	1.6 (−2.2 to 10.7)	5.7 (1.0 to 8.0)	6.5 (3.6 to 10.6)	13.8 (7.0 to 22.9)
Spring (March to May)	3.5 (−2.3 to 7.6)	2.2 (−5.2 to 7.8)	2.8 (−1.7 to 9.3)	0.3 (−12.3 to 8.7)	−1.0 (−7.4 to 3.0)	1.7 (−1.2 to 8.4)
Summer (June to August)	−8.4 (−13.6 to 4.8)	−8.6 (−15.9 to 0)	−9.4 (−19.0 to 0)	−3.3 (−8.0 to 6.4)	−11.7 (−26.2 to −5.7)	−18.3 (−35.5 to −9.0)
Autumn (September to November)	1.8 (−1.0 to 8.6)	0.8 (−2.6 to 4.5)	0.4 (−1.2 to 1.6)	−3.3 (−7.0 to 0)	3.7 (0 to 10.6)	7.5 (2.1 to 10.7)

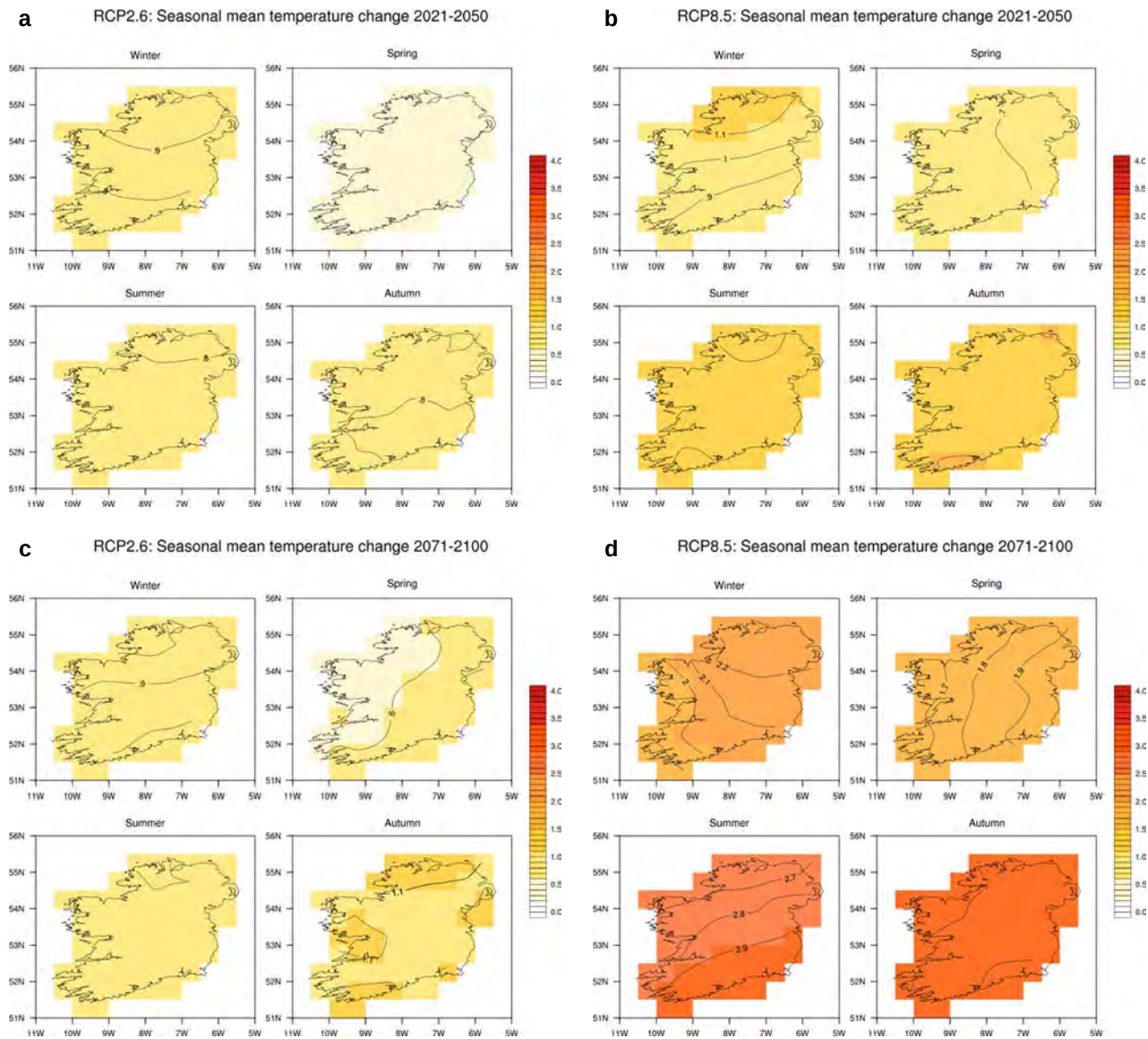


Figure 5.14. Projected changes in seasonal mean temperatures (K) for RCP2.6 (a, c) and RCP8.5 (b, d) for two future time periods, 2021–2050 (top) and 2071–2100 (bottom), based on the WRF341E simulations, employing EC-Earth as boundary conditions.

likely to experience the largest increases, with mean temperatures simulated to increase by $\sim 3.0\text{K}$ above the 1971–2000 period. Similar warming is simulated for the summer season. Winter mean temperatures are simulated to increase by $\sim 2.0\text{K}$, while spring experiences the lowest of the seasonal increases, with a simulated warming of 1.8K .

For both RCPs and future time periods, there is no marked spatial variation evident in the projected temperature increases for Ireland, with regional differences in the order of less than $\sim 0.3\text{K}$ across the country (Figure 5.14). This is in contrast to the projected changes in precipitation, which show

significant regional variation across Ireland (Figure 5.15). For the 2021–2050 period, a marginal decrease in precipitation is simulated for winter (approximately -1.8%), with a larger reduction simulated to occur during the summer months (approximately -13%), under RCP2.6. Spring precipitation is simulated to increase (approximately 7.6%), with a marginal increase during autumn. For RCP8.5, marginal decreases are simulated for winter (approximately -2.3%) and autumn (approximately -1.3%). Summer is again the season likely to experience the largest reductions under this forcing pathway, with decreases of approximately -6.4% simulated. There is a marked gradient evident in the simulated changes for both

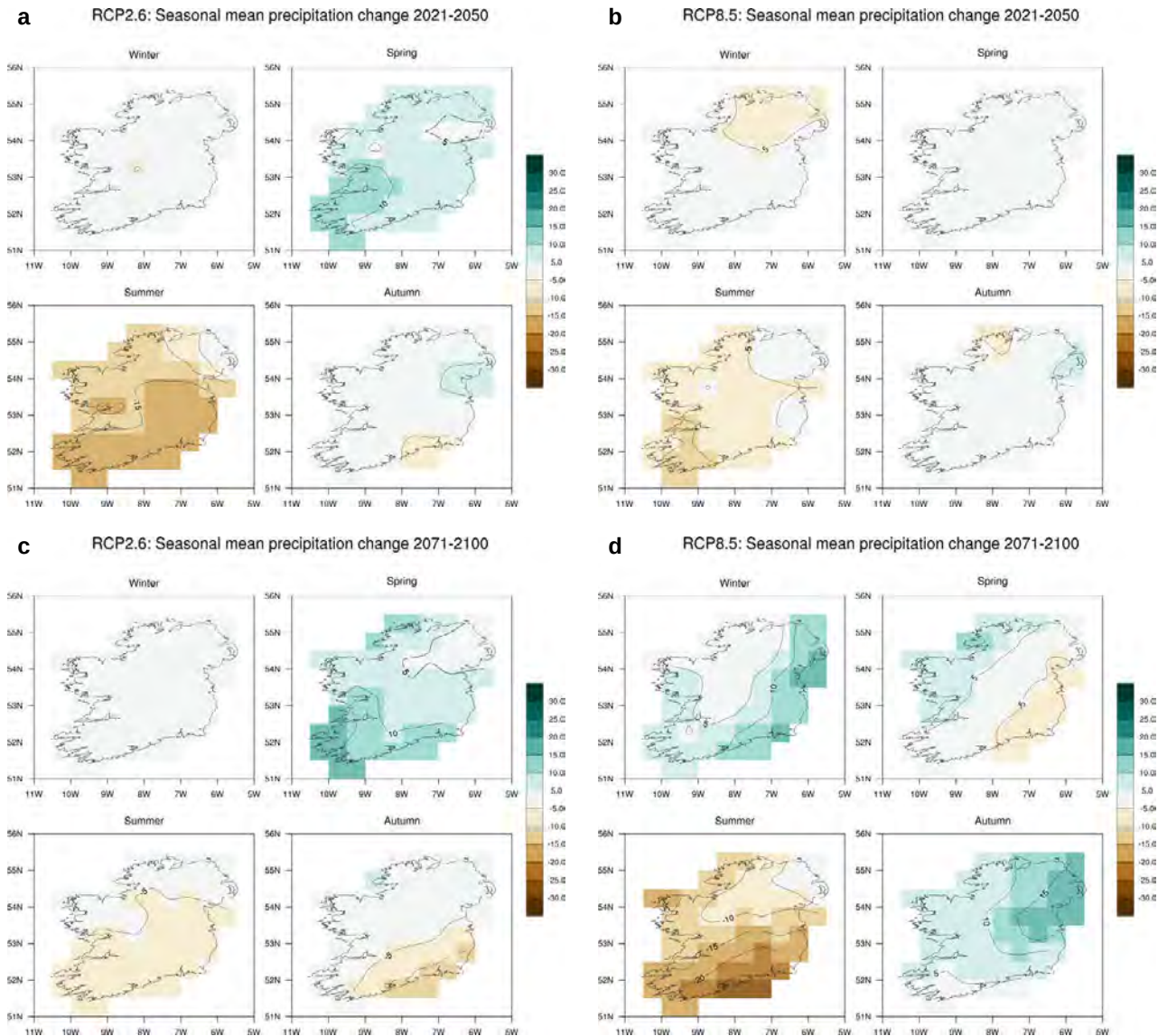


Figure 5.15. Projected changes in seasonal mean precipitation (percentage change) for RCP2.6 (a, c) and RCP8.5 (b, d) for two future time periods, 2021–2050 (top) and 2071–2100 (bottom), based on the WRF341E simulations, employing EC-Earth as boundary conditions.

spring and summer during this period under RCP2.6, with the greatest increase simulated to occur in the south-west of the country during spring (~10%). During summer, the largest reductions are simulated to occur along the south and east coasts, with a decrease of approximately –15% simulated for this region. The spatial variations evident in summer under RCP2.6 are in contrast to those of RCP8.5, which indicate that the smallest changes will occur on the east coast and that the largest decreases are simulated to occur in the south-west of the country.

For the 2071–2100 period, the summer season is simulated to experience decreased precipitation under both RCPs. Under RCP2.6, summer precipitation is

simulated to decrease by approximately –5.5%, with decreases also simulated to occur during autumn (approximately –3.0%). A marginal increase in winter precipitation (~1.1%) is simulated, with an increase of ~8.7% during spring. RCP8.5 shows the largest changes across all seasons, with the exception of spring. An increase in precipitation of ~7.1% during winter and ~9.4% during autumn is simulated under this forcing scenario. The largest decreases are simulated for the summer months, with seasonal precipitation simulated to decrease by ~13.7%.

Spatial variations are again evident in the simulated precipitation changes for this period. Under RCP2.6, spring shows the largest increases in the south and

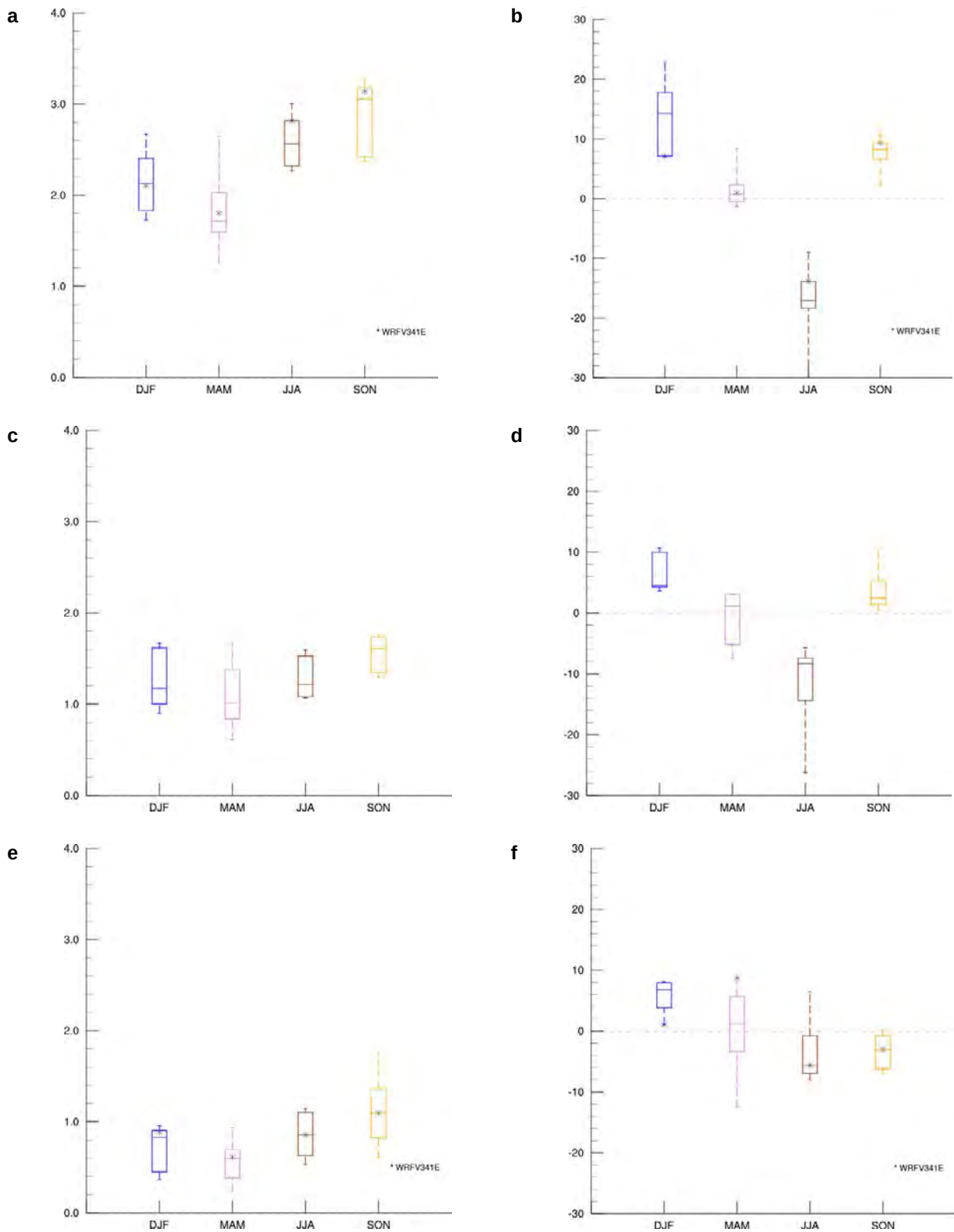


Figure 5.16. Multi-model seasonal mean statistics for temperature (K) (left) and precipitation (%) (right) for the 2071–2100 period for RCP8.5 (top), RCP4.5 (middle) and RCP2.6 (bottom). The grid area seasonal means are represented as boxplots (lower whisker – minimum; lower box – 25th percentile; within box – median; upper box – 75th percentile; upper whisker – maximum). The multi-model statistics are derived from models participating in EURO-CORDEX. The NUIM-WRF341E seasonal mean values are indicated by an asterisk (*). Statistics are derived from the aggregate of the grid boxes representing Ireland in the models.

west of the country, declining along a gradient towards the north and east. Regional variations are present for the remaining seasons, but are less marked. Under RCP8.5, spatial variations in precipitation change occur in all seasons for the 2071–2100 period. During winter, the largest simulated increases are projected to occur along the east and south coasts. During spring, precipitation over the north-west coast is projected to increase, with decreases projected for the south-east of the country. Based on Table 5.2, caution needs to be exercised when interpreting the results from a single model, particularly with regards to the magnitude, direction and regional simulated changes in precipitation. In addition, the statistical significance of these changes have not been assessed.

Figure 5.16 shows boxplots of seasonal mean temperature (K) and precipitation (percentage change) for the 2071–2100 period, for RCP2.6, RCP4.5 and RCP8.5, derived from the seasonal means of models participating in EURO-CORDEX. The mean values from WRF341E are also highlighted (asterisks). For temperature, the WRF341E simulated changes all lie either close to the multi-model median value or within the 25th–75th percentile range. With the exception of the projected changes in spring precipitation under RCP2.6, the WRF341E projections are within the 25th–75th percentile range of the multi-model means. Also apparent from these boxplots is the spread in values across the models employed. While all models simulate increasing temperatures for Ireland across all seasons, both the magnitude and direction of the projected changes in seasonal precipitation are shown to differ, particularly during spring.

5.5 Discussion

Results for the land area representing Ireland in the model domain were found to be broadly consistent with the findings for the European domain as a whole. Compared with the observational data, E-Obs, WRF was found to display seasonal biases in both temperature and precipitation. A warm bias is evident during the winter months, while a negative bias is evident during the spring and summer months. In an analysis of reanalysis data, including ERA-Interim Reanalysis, Mooney *et al.* (2010) found that the ERA-Interim data overestimated winter temperatures for selected stations in Ireland, which may explain the winter warm bias, while García-Díez *et al.* (2012)

found a cold bias in WRF simulations during the warm seasons across Europe, in common with other RCMs, which they tentatively attribute to deficiencies in the radiative exchanges. In terms of precipitation, WRF overestimates daily receipts across all seasons in Ireland, consistent with previous findings for the European-wide domain. Spatially, the larger biases are evident across the western and central parts of the country. In spite of these biases, WRF demonstrated that it is capable of reproducing the spatial and temporal characteristics of the observed climate in Ireland; more importantly, it was capable of reproducing the statistics of the observed climate on a seasonal basis.

For the historical simulation period, 1951–2005, a cold bias is evident across all seasons in the WRF simulations, probably attributable to biases associated with the parent climate model, EC-Earth, which displays a similar cold bias over this region. EC-Earth also overestimates precipitation for this region. In spite of this, WRF displays only small positive biases in precipitation on a seasonal basis. Placed in a broader context, the biases evident in WRF were generally found to lie between the 25th and 75th percentiles of available EURO-CORDEX models (Figure 5.8). The historical WRF simulations, forced with EC-Earth boundary conditions, also captured the broad spatial and seasonal patterns of the observed climate (Figures 5.5 and 5.6).

Consistent with the findings for the European domain, warming is projected to occur in all seasons over the course of the present century, the larger temperature increases associated with the higher radiative forcing of RCP8.5, relative to RCP2.6. Compared with the mean annual temperature increases projected for the wider European domain, based on the available climate models, lower mean annual temperature increases are simulated for Ireland. Mean annual temperature increases under RCP8.5 become more marked after the middle of the century, with projected end-of-century increases of ~2.0 K to 3.0 K relative to 1971–2000. Less marked increases are associated with RCP4.5, with end-of-century projected increases in annual temperatures for Ireland ranging from ~1.0 K to 1.5 K relative to the 1971–2000 period. The smallest increases in annual temperature are simulated for RCP2.6, with end-of-century mean annual temperatures projected to be between 0.5 K and 1.0 K warmer than the 1971–2000 period.

Seasonal and spatial variations in the simulated seasonal mean temperature increases were also assessed for two future time periods, 2021–2050 and 2071–2100; all changes were assessed relative to the 1971–2000 period. On a seasonal basis, autumn, summer and winter display the largest increases, with spring typically displaying the smallest seasonal changes across both RCP2.6 and RCP8.5 (Table 5.1). This finding is consistent with the multi-model ensemble mean derived from all available EURO-CORDEX models (Table 5.2 and Figure 5.16). Only small spatial variations are evident across the country in the projected seasonal mean temperatures for both future time periods, 2021–2050 and 2071–2100, and RCPs.

This is in contrast to the spatial variations evident in the simulated seasonal precipitation changes (Figure 5.15). Decreases in summer precipitation are simulated for all periods and RCPs, the largest decreases associated with the south and east of the country. In spite of the lower radiative forcing associated with RCP2.6, a larger decrease in precipitation is simulated in summer precipitation for the 2021–2050 period with this pathway, relative to RCP8.5. Seasonal contrasts become more evident in the 2071–2100 period, particularly associated with RCP8.5.

Based on the multi-model mean and associated inter-model ranges (Figure 5.16), all models indicate an increase in winter precipitation by the end of the century (2071–2100) under all RCPs and increased autumn precipitation under RCP4.5 and RCP8.5. Autumn precipitation under the RCP2.6 pathway is simulated to decrease across all models employed. During spring and summer, model divergence is evident in terms of both the direction and magnitude of simulated changes under RCP2.6 for the end of the century, while decreasing precipitation amounts are simulated for summer under RCP4.5 and RCP8.5, relative to 1971–2000.

While regional simulations of temperature have improved, modelling precipitation at the regional scale remains challenging (IPCC, 2013b), particularly at the scale of a small country such as Ireland. This is in part due to uncertainties in observational data (IPCC, 2013a), but also due to the ability of models to dynamically resolve sub-grid-scale processes important for simulating precipitation. The model results outlined here represent a small subset or ensemble of opportunity, and therefore are unlikely to represent the full spread of “plausible” futures. The magnitude, direction and location of simulated seasonal changes in temperature and precipitation outlined here should be employed with care.

6 Simulated Changes in Climatological Indices

A changing climate leads to changes in the frequency, intensity, spatial extent, duration, and timing of extreme weather and climate events, and can result in unprecedented extreme weather and climate events. Changes in extremes can be linked to changes in the mean, variance, or shape of probability distributions, or all of these [...].

IPCC, 2012: 7

6.1 Introduction

Simulated changes in the mean climate for Ireland were outlined in the previous chapter. The current chapter looks at simulated changes in a selection of climate indices, based on the WRFV341E simulations for Ireland. Previously, the WRF341E model, employing EC-Earth as boundary conditions, was shown to capture the main spatial and temporal patterns of climate over the historical period of 1951–2005 when compared with the E-Obs data, but some biases were evident in the simulations (Figures 5.8 and 5.9). The presence of such biases in the model simulations can be partially accounted for, if the assumption holds that these are systematic, rather than unsystematic, biases and that any such bias remains constant in time. Two key approaches to bias correction of climate model data have emerged; the first applies a correction technique to the boundary conditions that corrects the mean error in the boundary input fields (e.g. Bruyère *et al.*, 2014) while the second applies a correction technique (e.g. quantile mapping) to the simulated output fields from the RCM in order to improve the fit between the observed and simulated distributions. However, the application of a bias correction technique is non-trivial and can affect the higher-order moments of the distribution of the transformed variable (e.g. Lafon *et al.*, 2013). For temperature, a simple bias correction technique is applied as a number of the climate indices are calculated based on absolute values (e.g. grass

growing season length is the accumulation of degree-days above an absolute temperature threshold of 6°C). A number of techniques to bias correct precipitation were assessed, but were not found to result in significant improvement in the transformed distribution; consequently, precipitation was not bias corrected.

6.2 Bias Correction

For daily temperature, a number of bias correction techniques exist; however, the correction of biases in daily precipitation is non-trivial. For daily mean temperature, a simple bias correction technique was utilised for the current study, which applied the seasonal means and standard deviations of the E-Obs data over the period 1951–2005 to the standardised anomalies of the WRF341E simulated data. Figure 6.1 shows a comparison between the percentiles of daily temperature from the E-Obs data and WRF341E historical simulations, employing EC-Earth as boundary conditions, for the period 1951–2005. Consistent with Figure 5.8, the WRF341E simulations underestimate the observed percentiles in all seasons. After the bias correction technique has been applied, the bias in the WRF341E simulations is shown to decrease, with chosen percentiles matching more closely (Figure 6.2). The seasonal distribution of the bias-corrected daily temperature also compares more favourably with that of the E-Obs data (Figure 6.3).

Figure 6.4 shows the comparison between E-Obs and WRF341E simulated precipitation for the period 1951–2005. While the model was found to underestimate precipitation, the empirical probability distribution functions of both the E-Obs and WRF simulated precipitation compare favourably in all seasons (the parameters of the gamma function also show a close correspondence), except summer. In spite of this underestimation, the seasonal percentile plots show good agreement between the observed and simulated values (Figure 6.4). A number of techniques exist to bias correct daily precipitation, but these affect the simulated values (and higher order moments of the

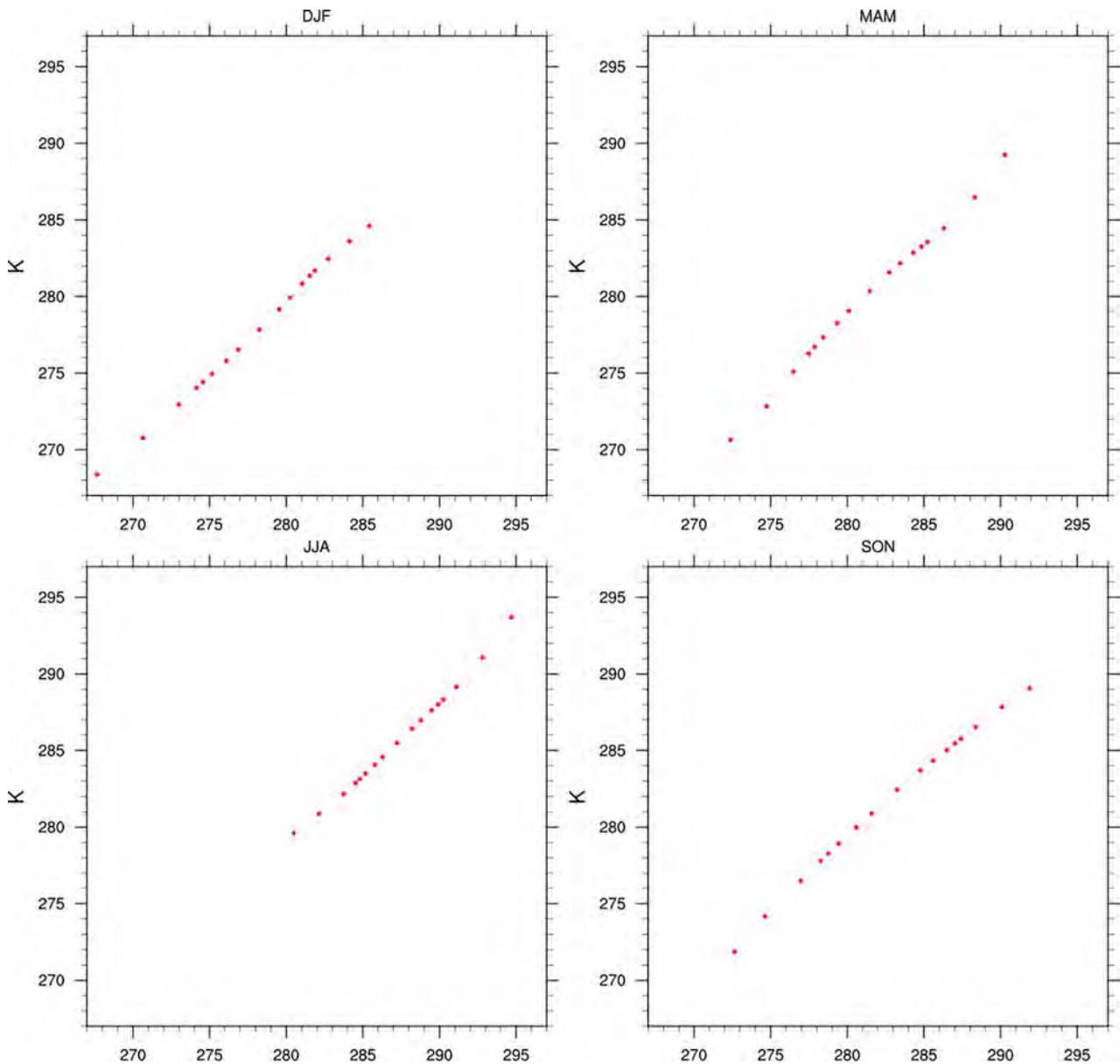


Figure 6.1. Comparison of percentiles for mean daily temperature (K) on a seasonal basis between E-Obs (x-axis) and the WRF341E historical simulations (y-axis), employing EC-Earth boundary conditions, for the period 1951–2005, for Ireland.

distribution) in different ways and introduce additional uncertainties (Lafon *et al.*, 2013).

Following Tye *et al.* (2014) a Weibull power transformation was tested, because of the similarity between both the Weibull and gamma distributions; however, the resultant bias-corrected daily precipitation values were found to be degraded relative to the observed values. Consequently, the simulated daily precipitation values were not bias corrected and results for precipitation are shown, where possible, as relative changes (i.e. future simulation relative to

historical simulation values) to account for systematic biases.

6.3 Simulated Changes in Climate Indices

A number of climate indices were selected to assess how climate change could affect different sectors over the course of the present century (Table 6.1). For example, growing season length (threshold $\geq 6^{\circ}\text{C}$) is an important indicator for grass growth in agriculture.

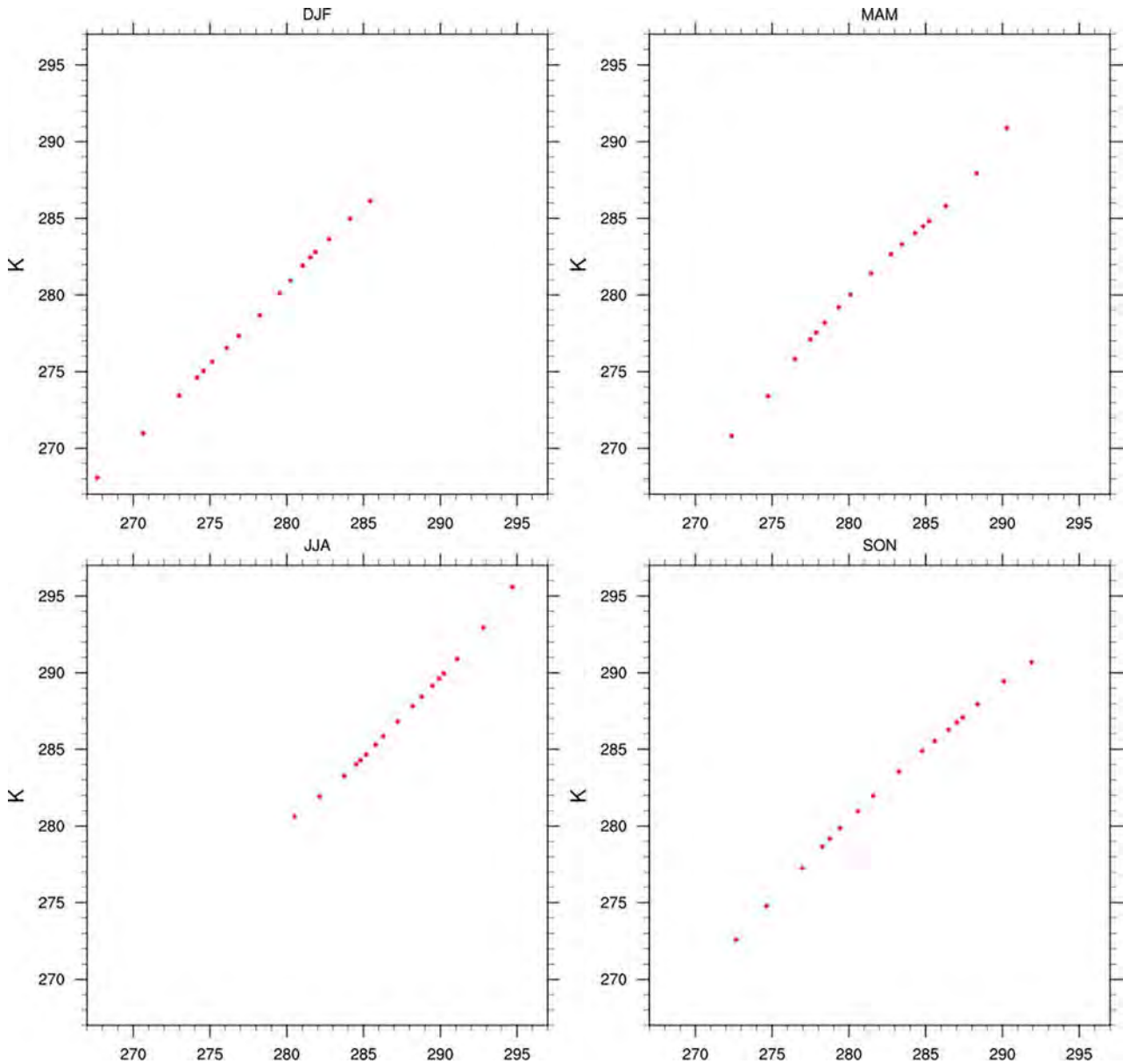


Figure 6.2. Comparison of percentiles for mean daily temperature (K) on a seasonal basis between E-Obs (x-axis) and the bias-corrected WRF341E historical simulations (y-axis), employing EC-Earth boundary conditions, for the period 1951–2005, for Ireland.

Heating degree-days is important as it indicates the potential for energy demand; an indoor temperature of $\sim 18^{\circ}\text{C}$ is considered optimum for human comfort. Similarly, the numbers of wet days and heavy precipitation days are important for water resource managers and flood engineers. As the significance of the findings detailed below was not assessed, the results need to be interpreted with caution; the findings for the temperature-based indices are likely to be more robust than the precipitation indices.

6.3.1 Temperature-based indices

Figure 6.5 shows the annual average growing season length calculated from E-Obs, and the historical (simulated) period, calculated from the WRF341E bias-corrected temperature series, for the period 1971–2000. Also illustrated are the simulated changes, in number of days, for the periods 2021–2050 and 2071–2100 for both RCP2.6 and RCP8.5. There is a marked spatial gradient in the average annual length of the growing season, with a longer period of growth

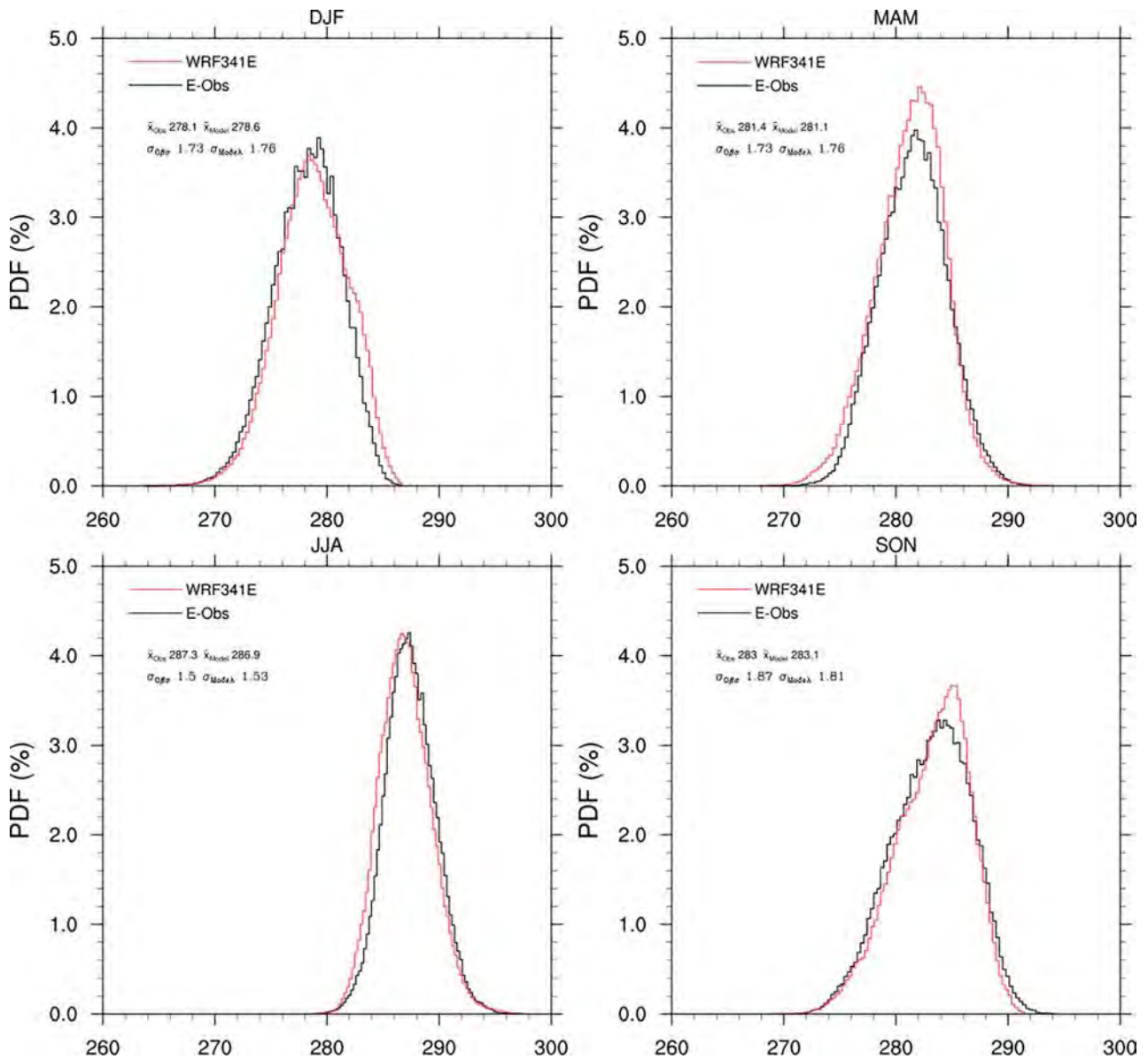


Figure 6.3. Empirical probability distribution function of mean daily temperature (K) from E-Obs and the bias corrected WRF341E simulations, employing EC-Earth boundary conditions, for the historical period 1951–2005 for Ireland. The means ($\bar{x}$) and standard deviations (σ) are also shown for both E-Obs (obs) and WRF341E (model).

evident in the south-west, declining to north-east. This gradient largely reflects both the latitudinal and maritime controls on Irish temperature. A similar gradient is evident in the historical simulations, with proximate length of the annual averaged growing season. Under all RCPs and time periods, the growing season length is expected to lengthen, consistent with the projected increase in seasonal temperatures. An increase in growing season length in the south-west is ultimately limited, as it is close to its possible maximum value; consequently, the largest increases are simulated to occur in the north of the country, with an

extension of up to 70 days simulated for some regions. The largest of these simulated changes are projected to occur under RCP8.5 and for the 2071–2100 period.

Heating degree-days provide a measure of potential energy demand to maintain indoor temperature at 18°C, a temperature considered optimal for human comfort. For every degree below this threshold, a heating degree-day is accumulated. For example, a day with a mean temperature of 14°C would result in 4 heating degree-days being accumulated. Again, reflecting the latitudinal and maritime controls on

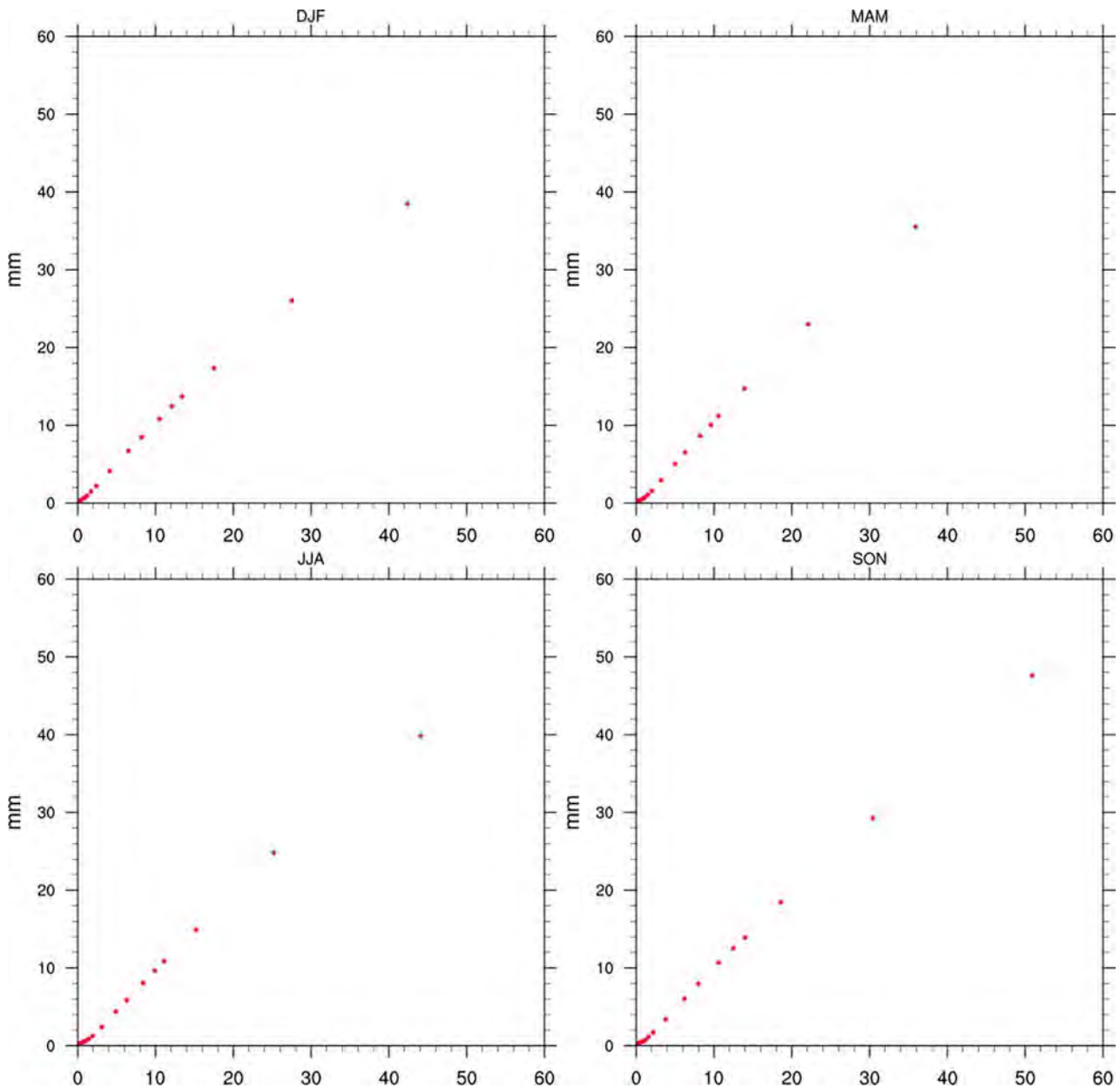


Figure 6.4. Comparison of percentiles for mean daily precipitation (mm) on a seasonal basis between E-Obs (x-axis) and the WRF341E historical simulations (y-axis), employing EC-Earth boundary conditions, for the period 1951–2005, for Ireland.

Table 6.1. List of climate indices, definition and units, employed

Index name	Definition	Units
Growing season length	The number of days between the first occurrence of 5 consecutive days on which mean temperature is $\geq 6^{\circ}\text{C}$ and the first occurrence of 5 consecutive days on which mean temperature is $< 6^{\circ}\text{C}$	Degree days
Heating degree-days	The sum of degree-days when the mean daily temperature is $< 18^{\circ}\text{C}$	Degree-days
Summer days Index	The number of days on which the mean daily temperature is $\geq 18^{\circ}\text{C}$	Days
Wet days	The number of days on which the mean daily precipitation is ≥ 1 mm	Days ^a
Heavy precipitation days	The number of days on which the mean daily precipitation is ≥ 10 mm	Days ^a
Very heavy precipitation days	The number of days on which the mean daily precipitation is ≥ 20 mm	Days ^a
Maximum 1-day precipitation amount	Highest 1-day precipitation amount, calculated for each month	mm

^aAs values for simulated changes in precipitation indices are shown relative to the historical period, the units employed are percentage days.

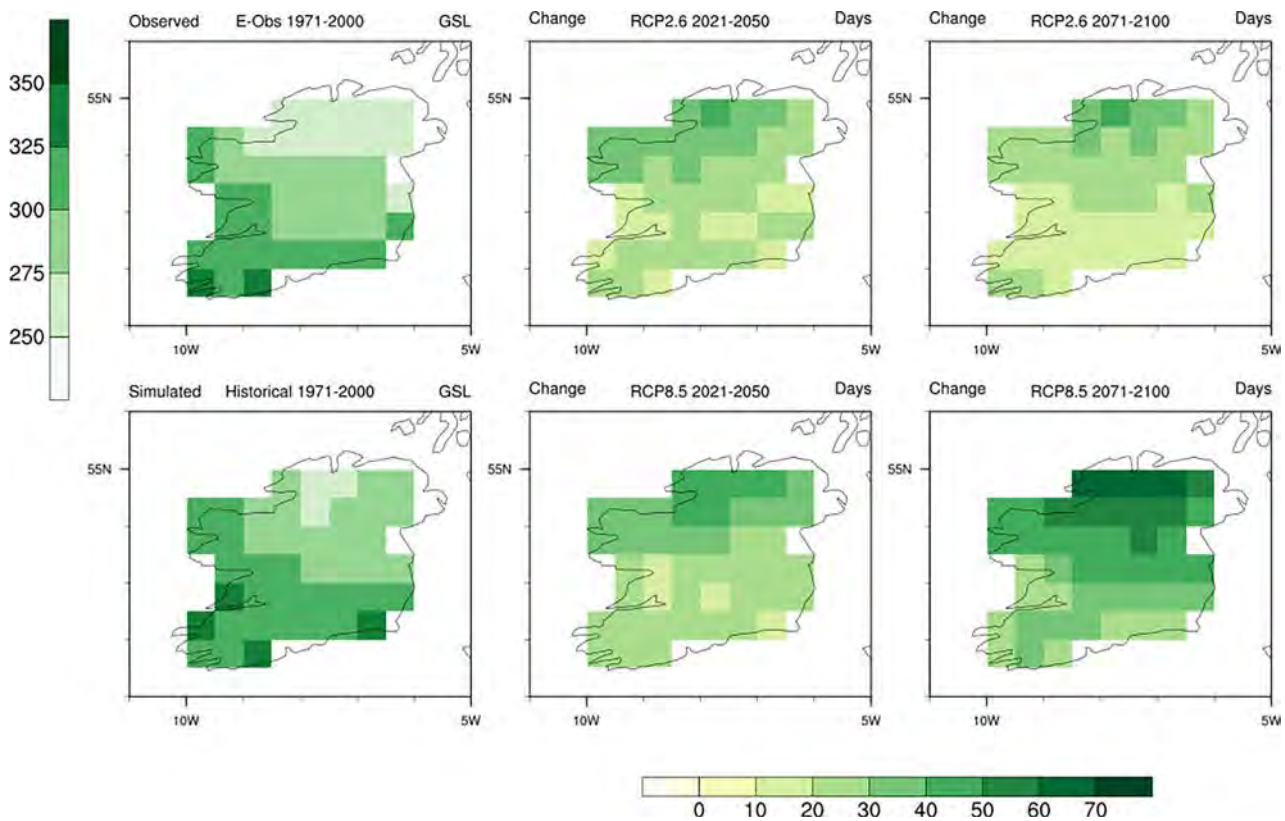


Figure 6.5. Annual average length of the growing season derived from E-Obs and the WRFV341 historical simulation (historical), for the period 1971–2000. The annual average change in growing season length (days) is shown for RCP2.6 (top) and RCP8.5 (bottom) for the 2021–2050 (centre) period and 2071–2100 period (right), relative to the historical period (left).

temperature, a marked gradient in heating degree-days is evident across Ireland, from the south-west to the north-east, with higher heating degree-days calculated for the north of the country. The historical WRF341E simulations largely replicate this gradient, but slightly underestimate heating degree-days in the north of the country (Figure 6.6). Consistent with warmer temperatures, the accumulated heating degree-days decrease across both RCPs and time periods. For RCP8.5, the simulated reduction in heating degree-days is >1000 degree-days in the midlands, with lower decreases likely to be experienced along the south and west coasts.

An index of summer days, defined as the number of days on which the daily mean temperature is $\geq 18^{\circ}\text{C}$, was also calculated (Figure 6.7). Based on the observational data, E-Obs, the highest annually averaged number of summer days (over the 1971–2000 period) occurred in the southern half of the island, from the west coast to the eastern midlands, with, on average, up to 10 days above the threshold.

While the historical WRF341E simulations broadly replicate the spatial pattern, they underestimate the higher number of warm days in the southern portion of the country by 1–2 days. Under RCP2.6, an increase in the number of summer days is projected to occur across the entire island, with the highest increases simulated for the southern half of the island. The largest increase is again simulated to occur under RCP8.5 for the end of the present century, with an increase in the number of summer days of ~45 days in the south-west and ~20 days in the north.

All selected temperature-based indices respond in a predictable way; increased temperatures give rise to an increase in the growing season length, a decrease in the number of heating degrees and an increase in the number of summer days. The simulated indices, calculated from the bias corrected mean daily temperature for the historical period (1971–2000), were found to be comparable to those calculated from the E-Obs data over the same period, with a slight tendency to underestimate the more extreme values.

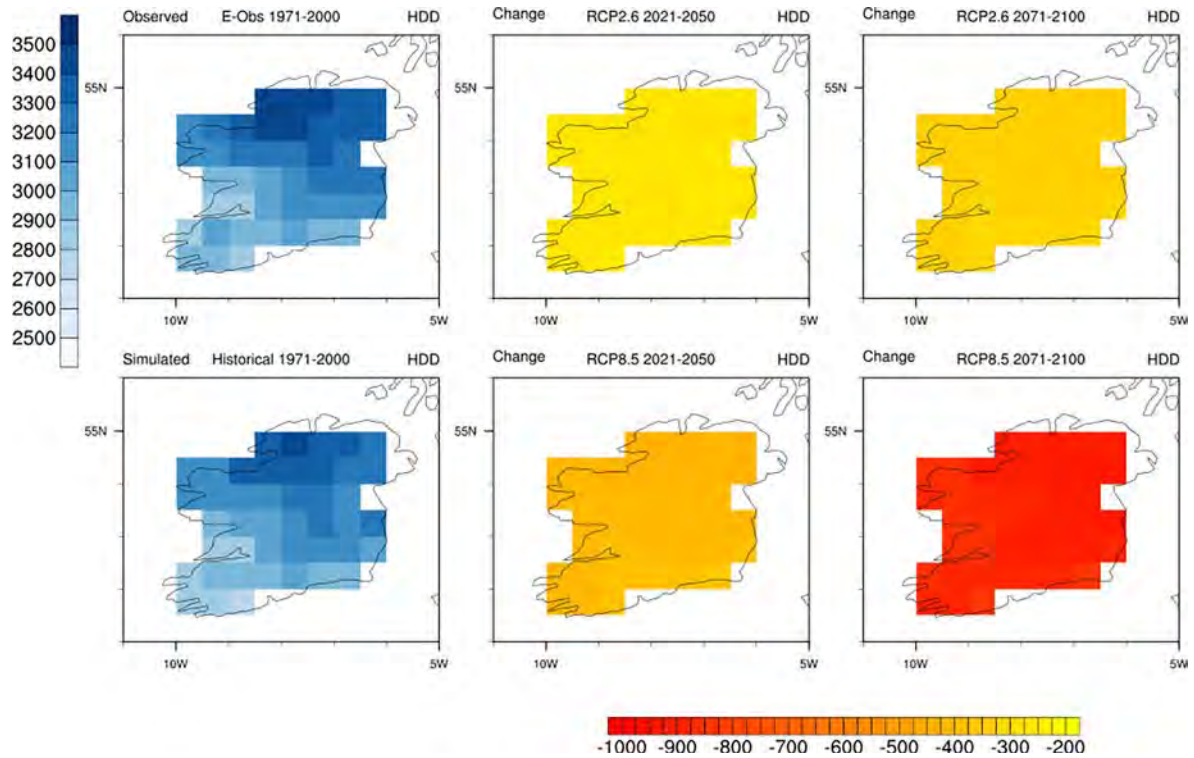


Figure 6.6. Annual average heating degree-days, calculated for the threshold of 18°C, derived from E-Obs and the WRFV341 historical simulation (historical), for the period 1971–2000. The annual average change in heating degree-days is shown for RCP2.6 (top) and RCP8.5 (bottom) for the 2021–2050 (centre) period and 2071–2100 period (right), relative to the historical period (left).

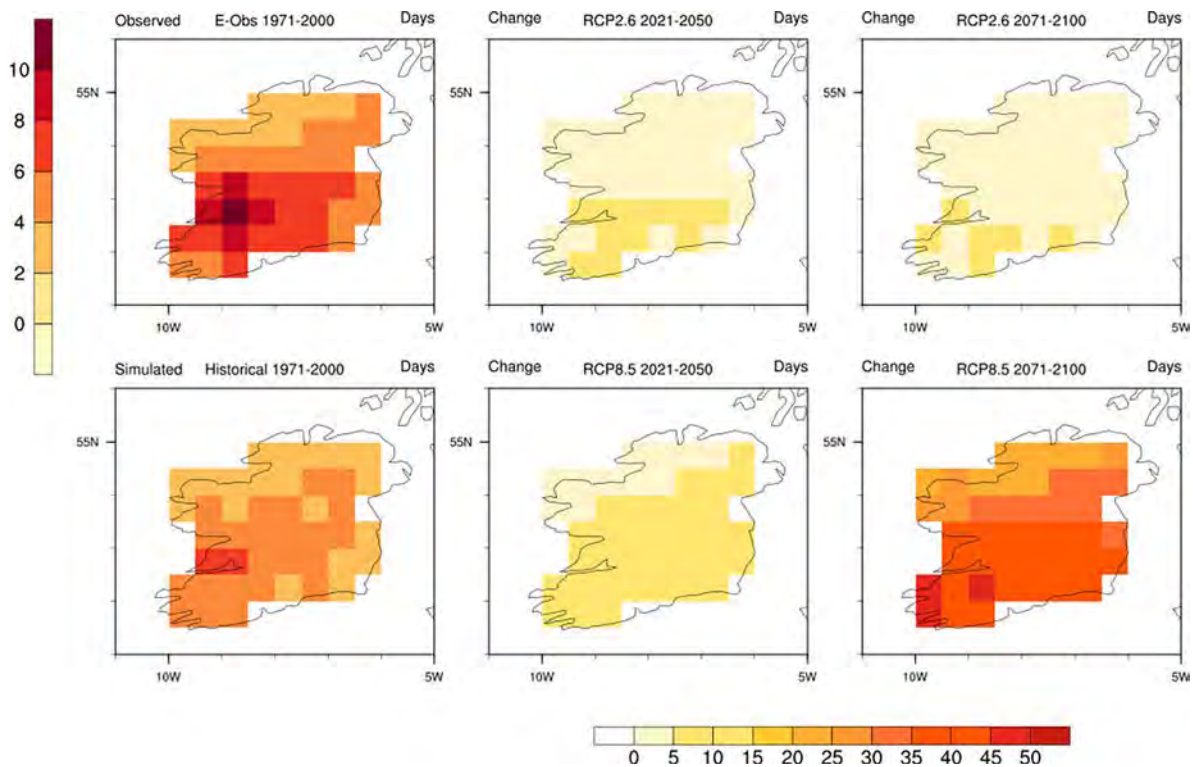


Figure 6.7. Annual average number of summer days, defined as a day with a mean daily temperature of $\geq 18^{\circ}\text{C}$, derived from E-Obs and the WRFV341 historical simulation (historical), for the period 1971–2000. The annual average change in the number of summer days (days) is shown for RCP2.6 (top) and RCP8.5 (bottom) for the 2021–2050 (centre) period and 2071–2100 period (right), relative to the historical period (left).

The larger calculated changes were found to occur under RCP8.5; the smallest changes were typically found for RCP2.6.

6.3.2 Precipitation-based indices

For precipitation, four indices were calculated: wet days, heavy precipitation days, very heavy precipitation days and monthly maximum 1-day precipitation amount. The highest number of wet days (daily precipitation ≥ 1 mm), averaged over the 1971–2000 period, occurs along the west and north coasts, reflecting the dominant controls on precipitation in Ireland, maritime airflow interacting with high relief (Figure 6.8). The WRF341E historical simulation captures the broad spatial pattern reflected in the E-Obs data, but tends to overestimate the number and extent of wet days across the midlands. Under RCP2.6, the number of wet days (percentage days relative to the historical simulations) in the west and north-east of the country is projected to

decrease marginally; increasing in spatial extent for the 2071–2100 period. Larger decreases in the number of wet days are simulated for the north-west and southern portion of the island for the 2021–2050 period, but these decreases reduce in spatial extent by the end of the century. A more marked decrease in the percentage of wet days is simulated under RCP8.5 for both the 2021–2050 and 2071–2100 periods. These decreases display a marked spatial gradient, with the largest decreases (reduction of ~ 10 days in the annual number of wet days) simulated to occur over the south-east of the country.

Figure 6.9 shows the annual average number of heavy precipitation days, defined as days with mean daily precipitation ≥ 10 mm, for the period 1971–2000. Also shown are the historical simulations for the same period and the simulated change (percentage days), relative to the historical period. Based on the observed data, E-Obs, heavy precipitation days are more frequent around the coast than in the interior of the island and occur more often on the west coast

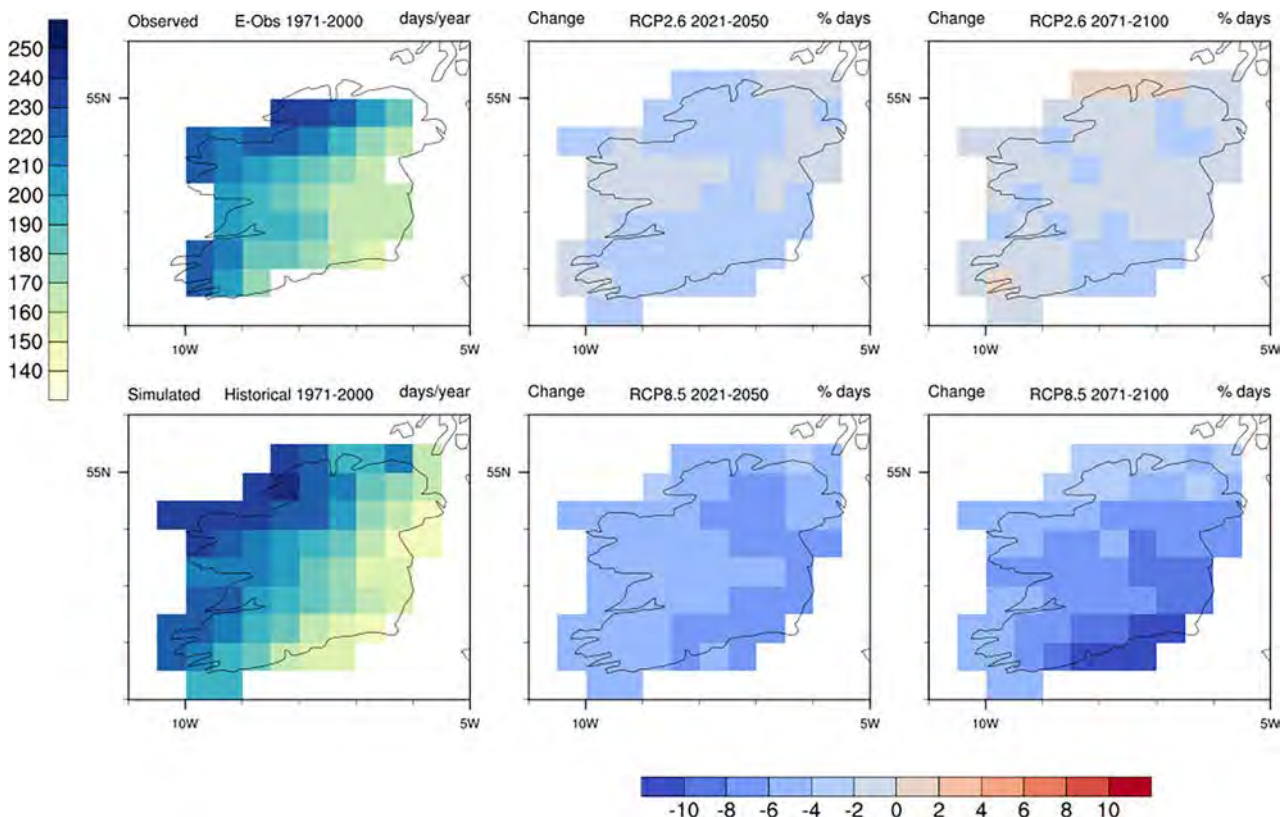


Figure 6.8. Annual average number of wet days, defined as any day with a mean daily precipitation ≥ 1 mm, derived from E-Obs and the WRFV341 historical simulation (historical), for the period 1971–2000. The annual average percentage change in the number of wet days is shown for RCP2.6 (top) and RCP8.5 (bottom) for the 2021–2050 (centre) period and 2071–2100 period (right), relative to the historical period (left).

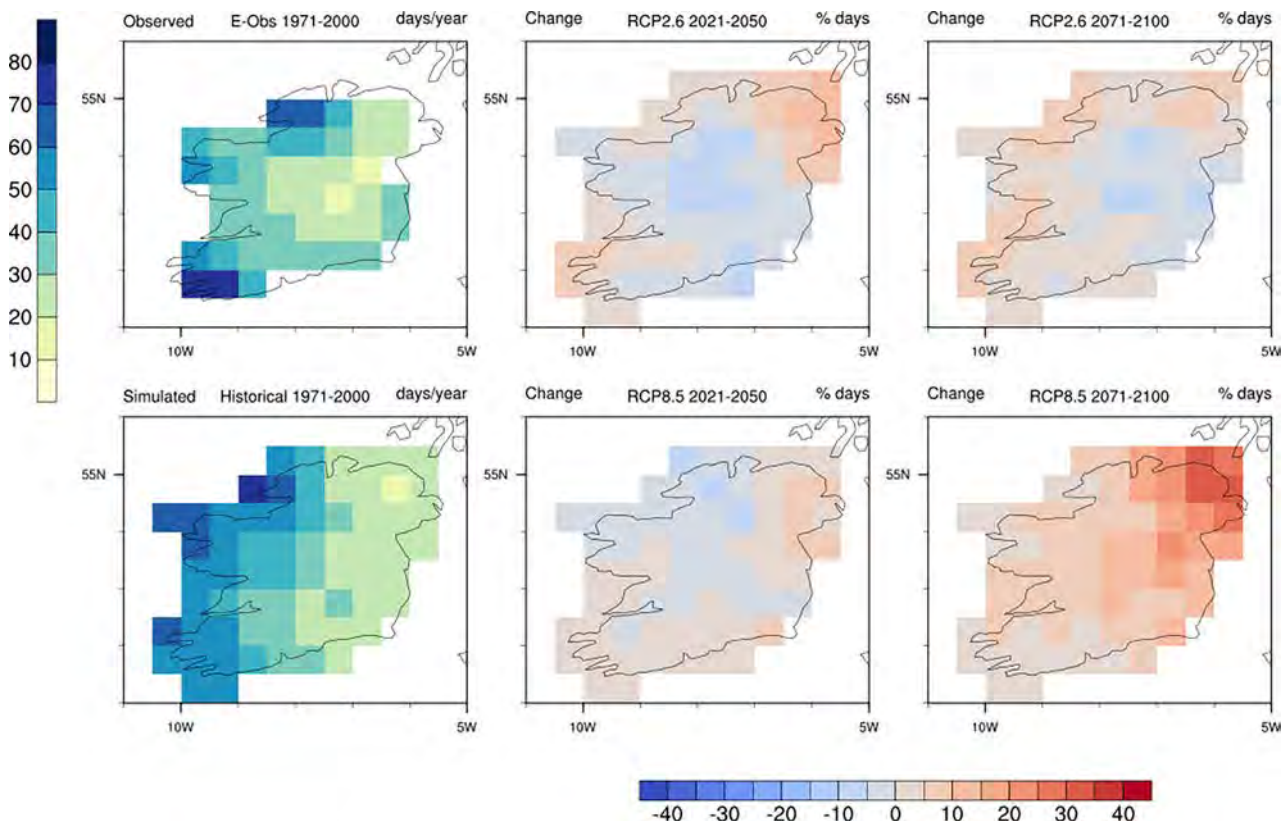


Figure 6.9. Annual average number of heavy precipitation days, defined as a day with mean daily precipitation $\geq 10\text{mm}$, derived from E-Obs and the WRFV341 historical simulation (historical), for the period 1971–2000. The annual average percentage change in the number of heavy precipitation days is shown for RCP2.6 (top) and RCP8.5 (bottom) for the 2021–2050 (centre) period and 2071–2100 period (right), relative to the historical period (left).

than on the east coast. The historical simulation displays a west–east gradient, with a higher frequency of heavy precipitation days on the west coast, rather than a coast–interior spatial pattern, as evident in the observed data. Under RCP2.6, the number of heavy precipitation days is simulated to increase, but these increases are mainly confined to coastal locations for both future time periods; a decrease in the number of heavy precipitation days is simulated to occur in the midlands for the 2021–2050 period, which decreases in spatial extent by the 2071–2100 period. For RCP8.5, a decrease in the number of heavy precipitation days is simulated for a wedge-like area from the north-west to the south-east coast for the period 2021–2050. For the period 2071–2100, a more marked spatial gradient from the south-west to the north-east is evident, with an increase in the number of heavy precipitation days in the order of $\sim 30\%$ simulated for the north-west.

Figure 6.10 shows the observed and historical simulations of very heavy precipitation days, defined

as days with mean daily precipitation $\geq 20\text{mm}$, annually averaged for the period 1971–2000. Simulated changes for RCP2.6 and RCP8.5 for the periods 2021–2050 and 2071–2100 are also shown. Consistent with the heavy precipitation days, the E-Obs data displays a coast–interior spatial pattern, with a higher frequency of very heavy precipitation days evident around the coast. The WRF341E historical simulation displays a broadly similar pattern, but overestimates the frequency of very heavy precipitation days in the interior of the country. Under RCP2.6, the frequency of very heavy precipitation days is simulated to decrease in the south-east of the country by the 2021–2050 period, with an increase evident in the south-west, west and northern portions of the country. By 2071–2100, this pattern shifts, with decreases simulated for the east coast and increases indicated along remaining coasts. No decreases are evident in the frequency of very heavy precipitation days under RCP8.5 for either time period. The largest increases are simulated to occur over the north-western part of the country during 2021–2050, with all

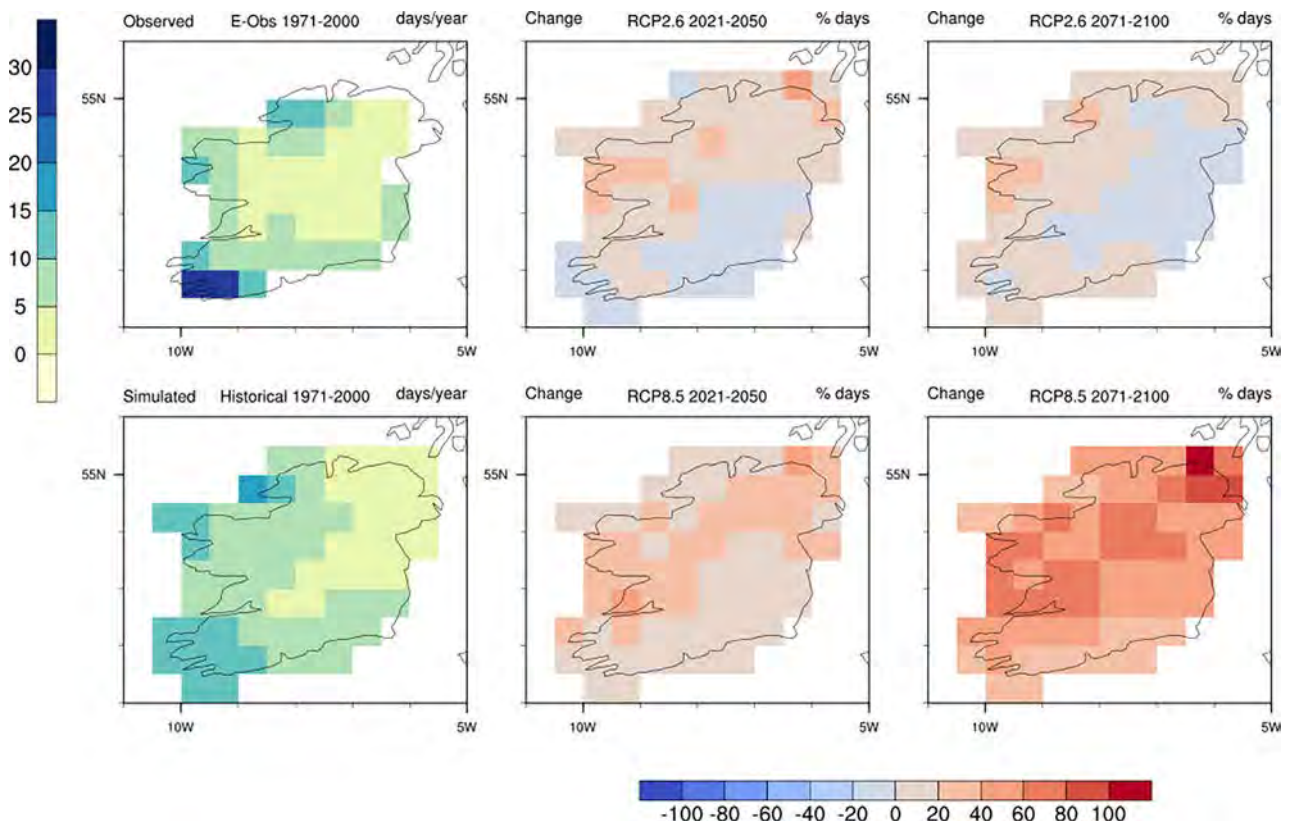


Figure 6.10. Annual average number of very heavy precipitation days, defined as any day with a mean daily precipitation ≥ 20 mm, derived from E-Obs and the WRFV341 historical simulation (historical), for the period 1971–2000. The annual average percentage change in the number of very heavy precipitation days is shown for RCP2.6 (top) and RCP8.5 (bottom) for the 2021–2050 (centre) period and 2071–2100 period (right), relative to the historical period (left).

regions simulated to experience an increase of $\geq 20\%$ in the number of very heavy precipitation days by 2071–2100.

Based on the selected precipitation indices, a general reduction in the frequency of wet days (> 1 mm) is evident in both RCPs, with an increase in the number of heavy (≥ 10 mm) and very heavy (≥ 20 mm) precipitation days. This suggests that precipitation is likely to become more intense, with an increase in the frequency of occurrence of heavy precipitation days simulated by WRF.

In terms of very extreme precipitation events, the maximum 1-day precipitation amount (mm) for each month was determined from E-Obs and the WRF341E historical simulations for the period 1971–2000 and for two future time periods, 2021–2050 and 2071–2100, for both RCP2.6 and RCP8.5 (Figure 6.11). The empirical distributions are calculated from the 1-day maximum precipitation from all the individual grid cells representing the land area of Ireland in the model

simulations, for each month, for the selected period. While the E-Obs and WRF341E historical simulation display similar means and standard deviations, the WRF341E simulations are shown to underestimate the frequency of occurrence of values around the mean, relative to E-Obs, over the period 1971–2000. This underestimation of extreme values is a finding consistent with other RCM simulations. However, the frequency of occurrence of the more extreme values of the distribution compares much more favourably with the observed frequencies. For RCP2.6 for both time periods and RCP8.5 for the 2021–2050 time period, there is little evidence to suggest that the extreme monthly maximum 1-day precipitation event increases based on the empirical distributions (e.g. similarity of mean and standard deviation), relative to the historical simulations. However, under RCP8.5 for the 2071–2100 period, a shift in the distribution is evident, with a tendency towards an increase in both the magnitude and frequency occurrence of maximum 1-day events.

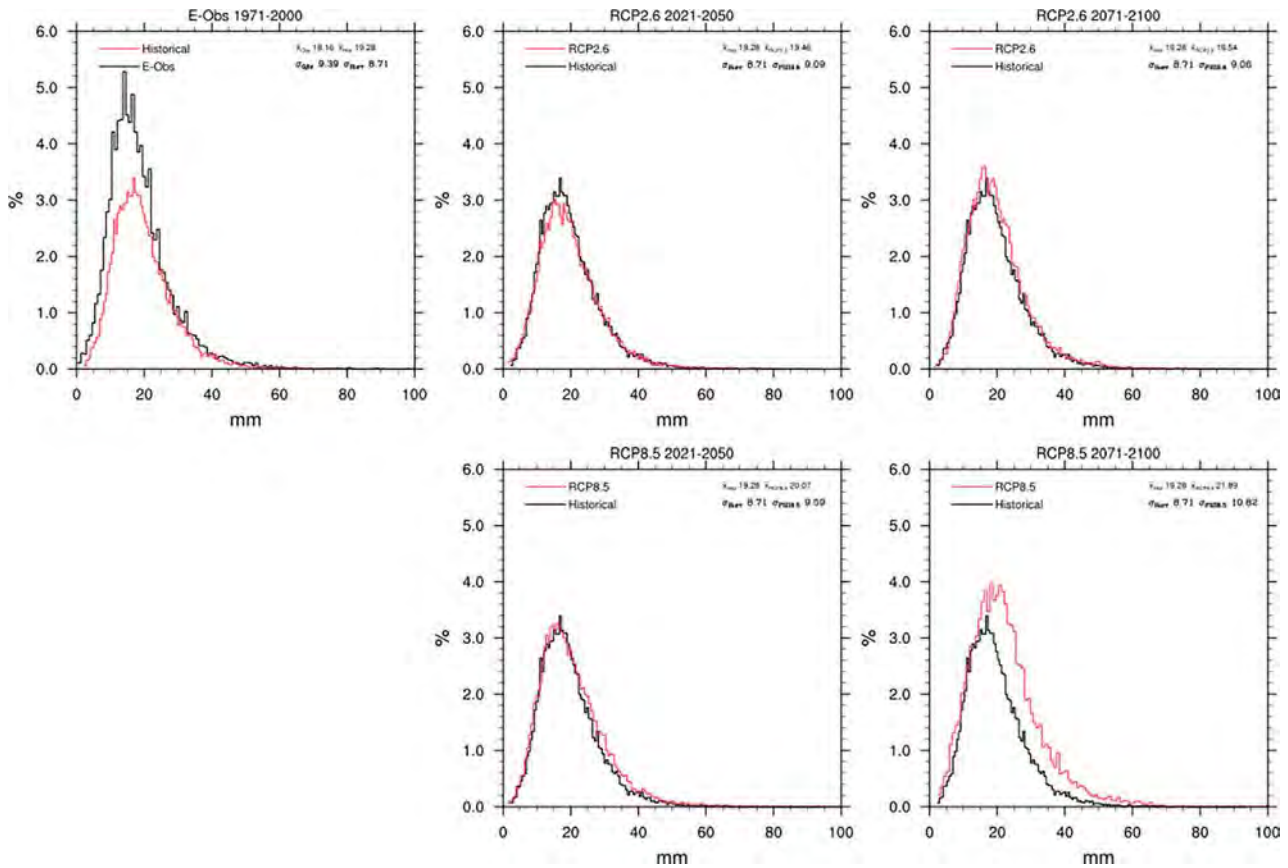


Figure 6.11. Probability distributions of maximum 1-day precipitation amount, defined as the largest daily precipitation amount to occur in a month, derived for the observational period from E-Obs and the WRFV341 historical simulation (historical), for all months over the period 1971–2000. Probability distributions of maximum 1-day precipitation amounts are shown for RCP2.6 (top) and RCP8.5 (bottom) for the 2021–2050 (centre) period and 2071–2100 period (right).

6.4 Discussion

A number of climate indices were selected for investigation for Ireland; while not comprehensive, the findings do indicate an alteration in the tails of the distributions of both temperature and precipitation, particularly with regards to extreme precipitation events in the 2071–2100 period under RCP8.5. For all time periods and RCPs, the annual number of growing degree-days is simulated to increase, the largest increase being associated with RCP8.5 for the northern portion of the country, where growing degree-days are currently thermally limited. If realised, some locations along the south coast will, by the end of the century, achieve sufficient thermal energy requirements to sustain grass growth throughout the year. Assuming soil trafficability, this may confer a competitive advantage on these regions. Significant reductions in energy use, consistent with increased temperatures, are also indicated, with a reduction in the number of heating degree-days, assuming that

maximum temperatures remain within the range of human comfort. If maximum temperatures exceed this, then energy demand is likely to reflect the increased need for chilling/air conditioning. More importantly, the seasonal demand in energy use is likely to alter, placing additional requirements on the seasonal production of energy.

On the basis of the selected indices, changes in the distribution of precipitation are simulated to occur. A reduction in the number of wet days, particularly evident along the east and south coasts under RCP8.5, is accompanied by an increase in the percentage of heavy precipitation days (>10mm) along eastern and northern coasts. In contrast, increases in very heavy precipitation days (>20mm) are simulated for southern, western and northern locations under RCP2.6. More marked increases in heavy precipitation days are simulated under RCP8.5, across the entire country.

7 Discussion and Recommendations

While (to quote Niels Bohr) “it is difficult to predict, especially the future” it might be useful [...] to pick out some recent developments which might be the forerunner of things to come.

Kac, 1973: 256

7.1 Discussion

While climate models represent a pinnacle of scientific endeavour and have proved critical in informing and motivating the international policy community to limit the impact of climate change (e.g. United Nations Framework Convention on Climate Change, IPCC), their utility in developing meaningful, robust adaptation at sectoral, local or regional level has yet to be fully demonstrated. In spite of the large number of climate impact assessments that have been undertaken, both nationally and internationally, a key limitation in the development of subsequent adaptation policy arises largely because of the uncertainty ranges typically associated with the outcomes of these studies, some of which have been outlined within this report. Traditional approaches to informing adaptation policy, employing climate model outputs as inputs to sectorally specific impact models (e.g. hydrology or crop models) with the intention of assessing exposure to climate change, are therefore subject to a cascade of uncertainty (that is, the accumulation of uncertainty with each additional modelling layer added to the framework). This renders the translation of the subsequent findings into policy as difficult, at best, or simply impossible.

A number of techniques have been developed that seek to quantify uncertainty within an ensemble of model outputs, based on either an assessment of model skill in replicating the present-day climate to weight their relative contributions to an ensemble mean or deriving statistical probabilities based on a measure of model convergence. No attempt was made to apply such techniques in the current study as the *ensemble of opportunity* employed comprises a number of RCM simulations employing boundary conditions from the same parent GCMs (e.g. EC-Earth,

MPI-M-MPI-ESM-LR), and is thus more likely to underrepresent the potential spread in model outputs than if a range of independent models were included in the analysis. In addition, model biases and errors may not be independent of one another, because of similarity in model design, code or specification of similar parameterisation or land surface schemes (e.g. NOAH land surface model). This may result in greater model convergence, where a group of models produce similar outcomes, and consequently lead to an assumed greater level of confidence in the simulations than should be ascribed to them.

Rather than employing climate model outputs as the sole basis on which to judge exposure to future changes in the climate system, the fact that uncertainty exists in models can be exploited to explore the sensitivity of a particular system, sector or, more importantly, policy, to a range of potential changes in the climate system (e.g. determining sensitivity thresholds). Used in combination with other approaches (e.g. climate analogues, historical climate information), models utilised in this way can provide valuable, additional information on which to assess the robustness of proposed adaptation options, in an attempt to develop adaptation options that are insensitive to uncertainty. Ultimately, this approach requires us to rethink how we utilise climate model outputs and reframe questions around the framework we employ to develop appropriate adaptation options (for example, see Wilby and Dessai, 2010).

For sectors or locations that have an existing exposure to climate or meteorological hazards, this exposure is likely to increase as a consequence of climate change. Changes in the mean climate state, accompanied by any changes in extremes, are also likely to lead to new exposures being identified. The resultant change in exposure, and consequently vulnerability, will in part be a function of the amount of change in the climate system (e.g. changing probability of hazard), which in turn appears to be largely dependent on the particular RCP or particular emissions pathway future development follows. From a national, European and international policy perspective, the results contained herein provide a strong motivation to implement

and support policies that are effective in reducing or mitigating anthropogenic impacts (e.g. land use change, greenhouse gas emissions) on the climate system.

For adaptation, we need to recognise that climate is one of many drivers that can influence exposure and consequently risk; thus, we need to consider climate change in the wider context of these factors (e.g. demographic change). The fact that uncertainty on future changes in the climate system will continue to remain, even with perfect knowledge of the system, also needs to be recognised and incorporated into our approach for developing robust adaptation policy, to develop adaptation options that are largely insensitive to uncertainty. While this is acknowledged in the policy approach to climate adaptation in Ireland, the practical implementation of this is not yet clear.

A “wait and see” approach is not an option for climate change adaptation; adaptation decisions, particularly those with long-term implications, need to be made now, on the basis of the best available, albeit to some extent incomplete, information, drawing on approaches to formulating strategies that are both prudent and robust to uncertainty.

DECLG, 2012: 14

The fact that a single optimum solution may not exist means we need to focus on a range of solutions that are likely to be sub-optimal but robust, particularly when faced with uncertainties about the future climate and other drivers of change. Alternative approaches to developing robust adaptation options still rely on climate model outputs; however, rather than being a point of departure for informing a single policy option, they are utilised to assess the robustness of a range of policy options which seek to reduce our exposure to existing and past changes in climate. This represents a “*policy first*” rather than a “*science first*” approach; such an approach begins with identifying a suite of possible adaptation options that are socially, economically and technically feasible, which can then be evaluated for robustness based on different narratives, including future changes in the climate system (Wilby and Dessai, 2010; Wilby, 2012). By assessing the degree to which we are resilient to both past and present changes in the climate system, we

can formulate policies which seek to increase our resilience to potential future changes in climate.

7.2 Recommendations

Prein and Gobiet (2016) highlighted the importance of understanding uncertainties in the observational data (e.g. IPCC, 2013b), which they found had a similar magnitude to precipitation errors found in RCM simulations. To assist in quantifying these uncertainties, a key research priority is to focus on the maintenance, and development, of our existing meteorological station network and undertaking analysis of the observational data. Precipitation is highly variable in Ireland; an expansion of the existing network of gauges and rainfall radar sites would greatly enhance our ability to resolve spatial and temporal variations, leading to improved estimates of precipitation. The integration of multiple observation data sources, including remotely sensed data (e.g. satellite), therefore should also be a focus of research effort. Data derived from a high-quality, integrated observational network provide a central means to improve our understanding of the climate system, leading to improved model formulation and evaluation; they are also essential for detecting and attributing measured changes. Appropriate recording and documentation of metadata (information about the data) would greatly assist these efforts.

The development of long-term, homogeneous, historical records, and their subsequent analysis, can provide key insights into past climate events, particularly extreme events. Such long-term historical records, in combination with other data sources including climate model simulations, can provide a very valuable basis for informing the development, and subsequent testing, of adaptation policy options to ensure that such policies are robust to uncertainties.

Research is also required to more fully understand the coupling between the land surface and atmosphere, feedbacks between which play a critical role in the climate response (e.g. Seneviratne *et al.*, 2006) and significantly contribute to model biases (e.g. Bauer *et al.*, 2015). The land surface represents a lower boundary condition in a climate model; adequately representing the exchanges or fluxes of heat, moisture and momentum between the land surface and atmosphere is central to improving model simulations. Observations and modelling studies that support

our understanding of the surface energy and water balance are required to contribute new knowledge in this important area. High-resolution eddy covariance or flux towers (either on homogeneous land surface types or on tall vertical towers measuring the planetary boundary layer) are essential tools to support these research activities.

The development of a coordinated flux tower network would also deliver significant additional benefits, providing direct measurements on the effectiveness of different greenhouse gas mitigation policies, and support for our international reporting obligations, and contributing to international research efforts.

Participation in international research efforts such as EURO-CORDEX, which this research has contributed to, can deliver significant benefits to the wider research and policy community. The availability of a large ensemble of model simulations, employing a range of global and regional climate models typically

beyond the resources of any one institution or country, provides a potentially valuable source of information to test the robustness or resilience of any developed adaptation policies. While the available model outputs do not represent a sample of the full uncertainty space, they are likely to be useful in identifying where particular policy options are more or less sensitive to future uncertainties in the climate system or where alternative approaches to policy development are required (i.e. approaches that do not rely on climate model simulations). For example, models that simulate both positive and negative changes for a particular location or season may be useful in this context. Incorporation of the model outputs from EURO-CORDEX in this, or a similar, manner offers the potential for the formulation and subsequent development of more robust adaptation policies, which in the absence of significant mitigation efforts is increasingly becoming a priority.

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Abbreviations

CMIP	Coupled Model Intercomparison Project
CO₂-eq	Carbon dioxide equivalent
CORDEX	Coordinated Regional Downscaling Experiment
DMI	Danish Meteorological Institute
ECA&D	European Climate Assessment and Data
ECMWF	European Centre for Medium-Range Weather Forecasting
E-Obs	Observational data
ESM	Earth system model
EURO-CORDEX	European component of the Coordinated Regional Downscaling Experiment
GCM	Global climate model
hPa	Hectopascals
KNMI	Royal Netherlands Meteorological Institute
MPI	Max Planck Institute
ppm	Parts per million
NCAR	National Center for Atmospheric Research
NUIM	National University of Ireland, Maynooth
RCM	Regional climate model
SMHI	Swedish Meteorological and Hydrological Institute
SRES	Special Report on Emissions Scenarios
WCRP	World Climate Research Programme
WRF	Weather Research and Forecasting

Appendix 1 Archived Variable List

Table A1.1. List of variables for the Euro-CORDEX simulations. Those highlighted in bold are not available from the WRF model and therefore not archived

No.	Variable name	Variable long name	Variable standard name	Units
1	tas	Near-surface temperature	Air temperature	K
2	tasmax	Daily maximum near-surface temperature	Air temperature	K
3	tasmin	Daily minimum near-surface temperature	Air temperature	K
4	pr	Precipitation	Precipitation flux	kg/m ² /s
5	ps	Surface air pressure	Surface air pressure	Pa
6	psl	Sea level pressure	Air pressure at sea level	Pa
7	huss	Near-surface specific humidity	Specific humidity	1
8	sfcwind	Near-surface wind speed	Wind speed	m/s
9	sfcwindmax	Daily maximum near-surface wind speed	Wind speed	m/s
10	clt	Total cloud fraction	Cloud area fraction	%
11	sund	Duration of sunshine	Duration of sunshine	s
12	rsds	Surface downwelling shortwave RADIATION	Surface downwelling shortwave flux in air	W/m ²
13	rlds	Surface downwelling longwave radiation	Surface downwelling longwave flux in air	W/m ²
14	hfls	Surface upwards latent heat flux	Surface upwards latent heat flux	W/m ²
15	hfss	Surface upwards sensible heat flux	Surface upwards sensible heat flux	W/m ²
16	rsus	Surface upwelling shortwave radiation	Surface upwelling shortwave flux in air	W/m ²
17	rlus	Surface upwelling longwave radiation	Surface upwelling longwave flux in air	W/m ²
18	evspsbl	Evaporation	Water evaporation flux	kg/m ² /s
19	evspsblot	Potential evapotranspiration	Potential water evaporation flux	kg/m ² /s
20	mfrso	Total soil frozen water content	Soil frozen water content	kg/m ² /s
21	mrros	Surface runoff	Surface runoff flux	kg/m ² /s
22	mrro	Subsurface runoff	Runoff flux	kg/m ² /s
23	mrso	Total soil moisture	Soil moisture content	kg/m ²
24	snw	Snow amount	Surface snow amount	kg/m ²
25	snm	Surface snow melt	Surface snow melt flux	kg/m ² /s
26	prhmax	Daily maximum precipitation	Precipitation flux	kg/m ² /s
27	prc	Convective precipitation	Convective precipitation flux	kg/m ² /s
28	rlut	TOA outgoing longwave radiation	TOA outgoing longwave flux	W/m ²
29	rsdt	TOA incident shortwave radiation	TOA incoming shortwave flux	W/m ²
30	rsut	TOA outgoing shortwave radiation	TOA outgoing shortwave flux	W/m ²
31	uas	Eastward near-surface wind velocity	Eastward wind	m/s
32	vas	Northward near-surface wind velocity	Northward wind	m/s
33	wsgsmax	Daily maximum near-surface wind speed of gust	Wind speed of gust	m/s
34	tauu	Surface downwards eastward wind stress	Surface downwards eastward stress	Pa
35	tauv	Surface downwards northward wind stress	Surface downwards northward stress	Pa
36	ts	Surface temperature	Surface temperature	K
37	zmla	Height of boundary layer	Atmosphere boundary layer thickness	m
38	prw	Water vapour path	Atmosphere water vapour content	kg/m ²

Table A1.1. Continued

No.	Variable name	Variable long name	Variable standard name	Units
39	clwvi	Condensed water path	Atmosphere cloud condensed water content	kg/m ²
40	clvi	Ice water path	Atmosphere cloud ice content	kg/m ²
41	ua850	Eastward wind	Eastward wind	m/s
42	va850	Northward wind	Northward wind	m/s
43	ta850	Air temperature	Air temperature	K
44	hus850	Specific humidity	Specific humidity	Range 0–1
45	ua500	Eastward wind	Eastward wind	m/s
46	va500	Northward wind	Northward wind	m/s
47	zg500	Geopotential height	Geopotential height	m
48	ta500	Air temperature	Air temperature	K
49	ua200	Eastward wind	Eastward wind	m/s
50	va200	Northward wind	Northward wind	m/s
51	ta200	Air temperature	Air temperature	K
52	zg200	Geopotential height	Geopotential height	m
53	clh	High cloud cover	Cloud area fraction in atmosphere layer	%
54	clm	Medium cloud cover	Cloud area fraction in atmosphere layer	%
55	cil	Low cloud cover	Cloud area fraction in atmosphere layer	%
56	snc	Snow area fraction	Surface snow area fraction	%
57	snd	Snow depth	Surface snow thickness	m
58	sic	Sea ice fraction	Sea ice fraction	%
59	prsn	Snowfall flux	Snowfall flux	kg/m ² /s

Appendix 2 Seasonal Mean Bias: Maximum and Minimum Temperature

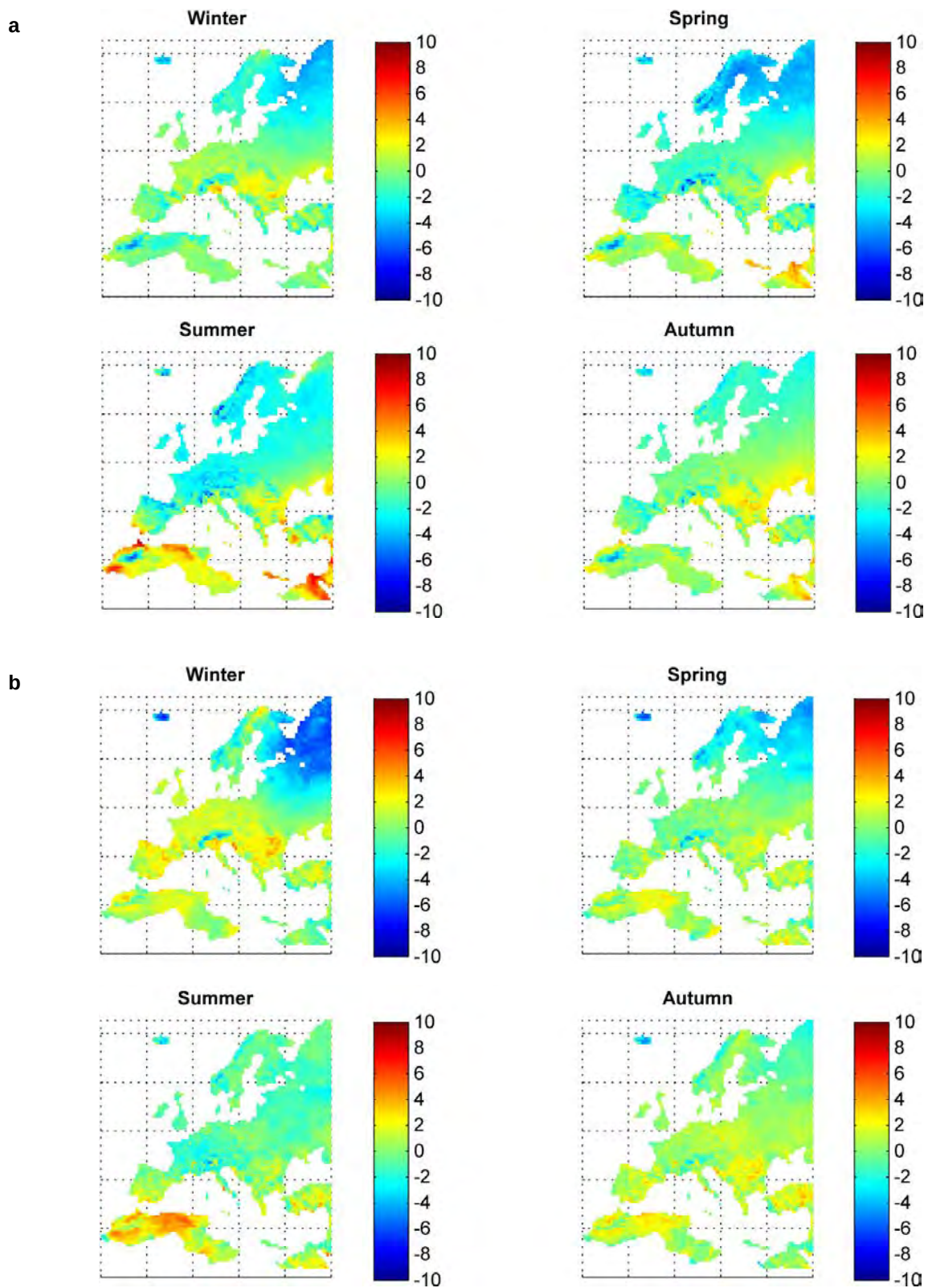
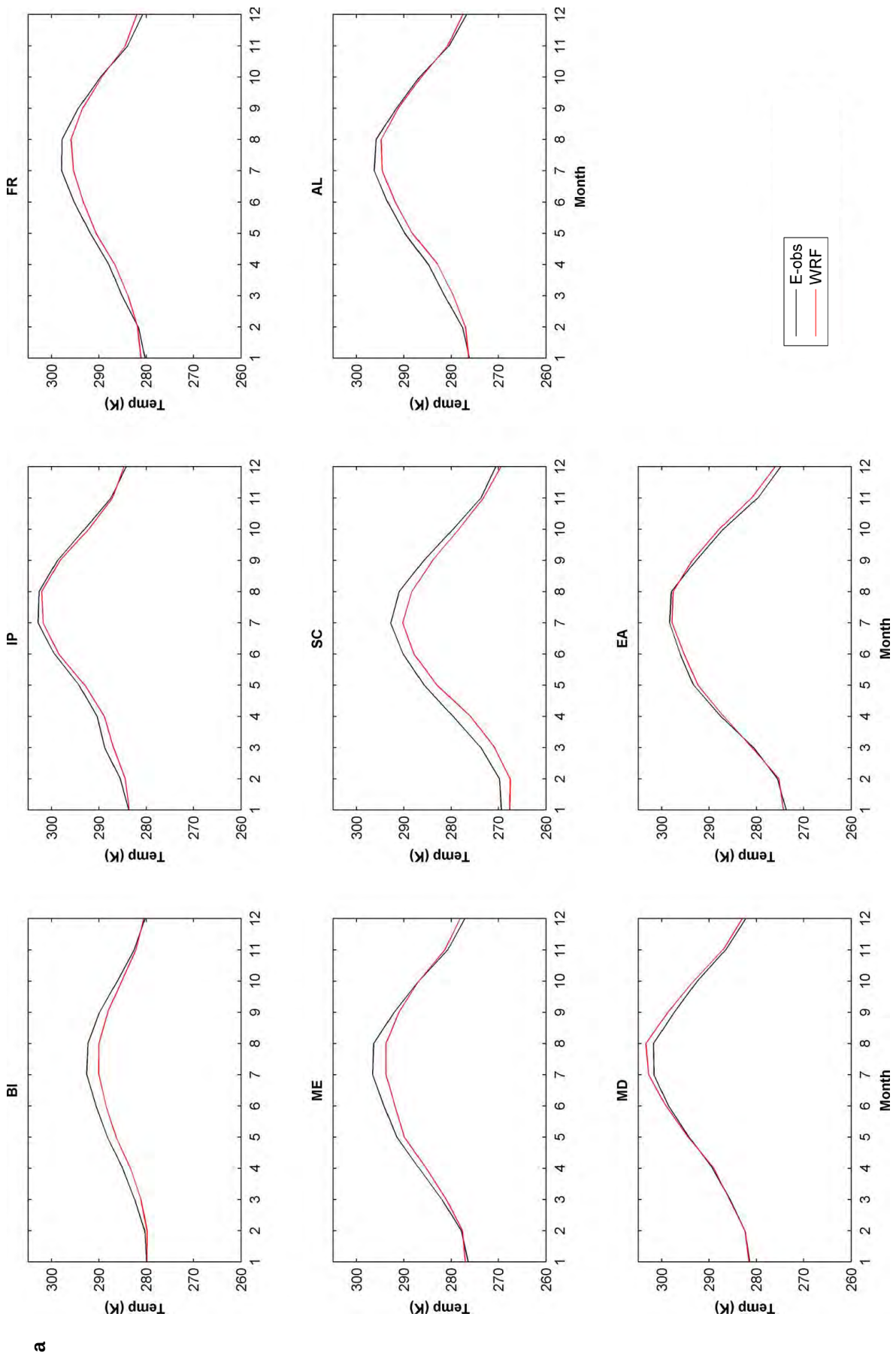


Figure A2.1. Seasonal mean bias for (a) maximum and (b) minimum temperature (K) for the period 1981–2010.

Appendix 3 Rockel Regions: Maximum Temperature and Minimum Temperature



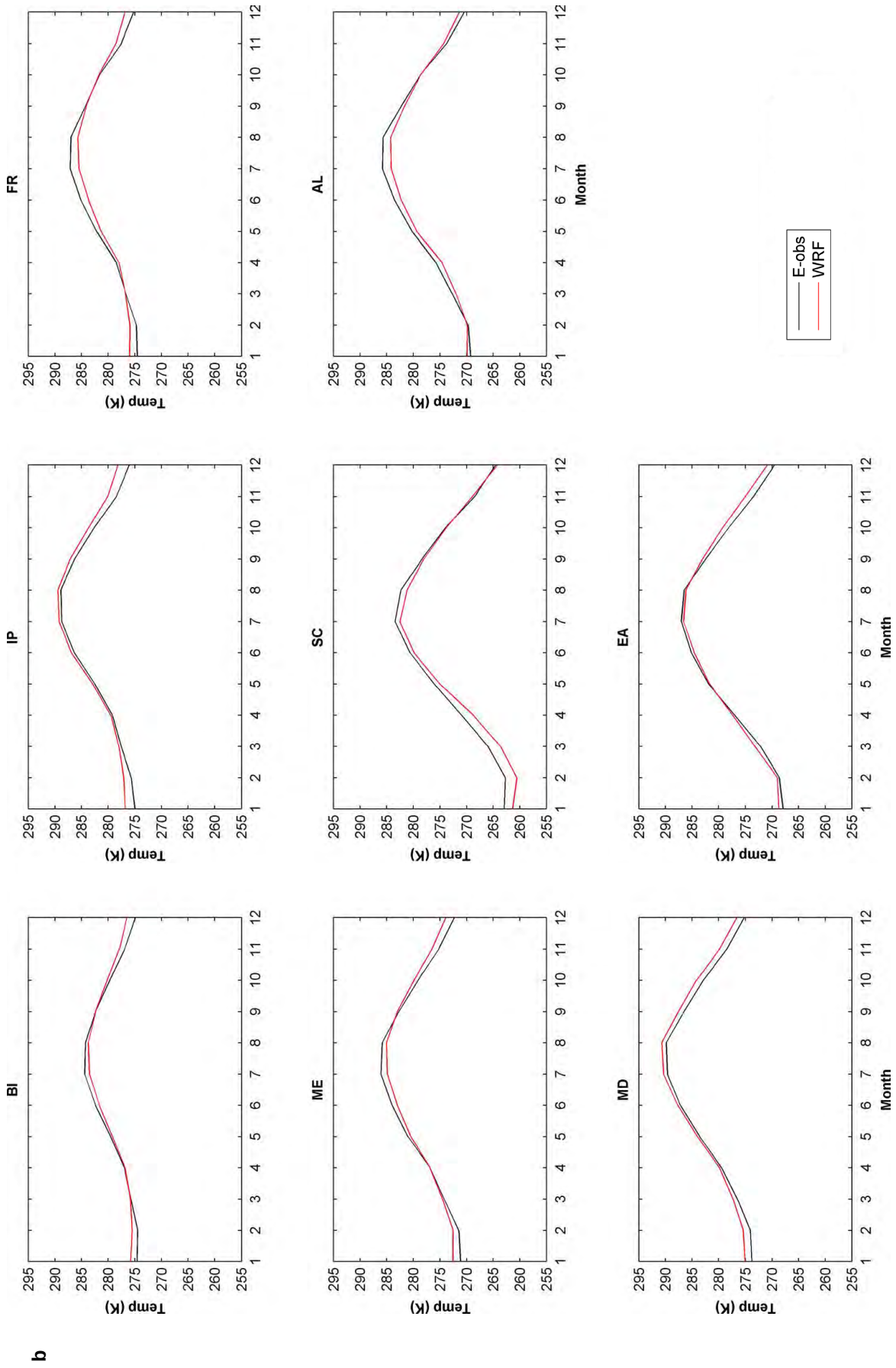


Figure A3.1. Climatological mean monthly (a) maximum temperature and (b) minimum temperature for the period 1981–2010 for the European sub-domains for E-Obs and WRF simulations employing ERA-Interim boundary conditions.

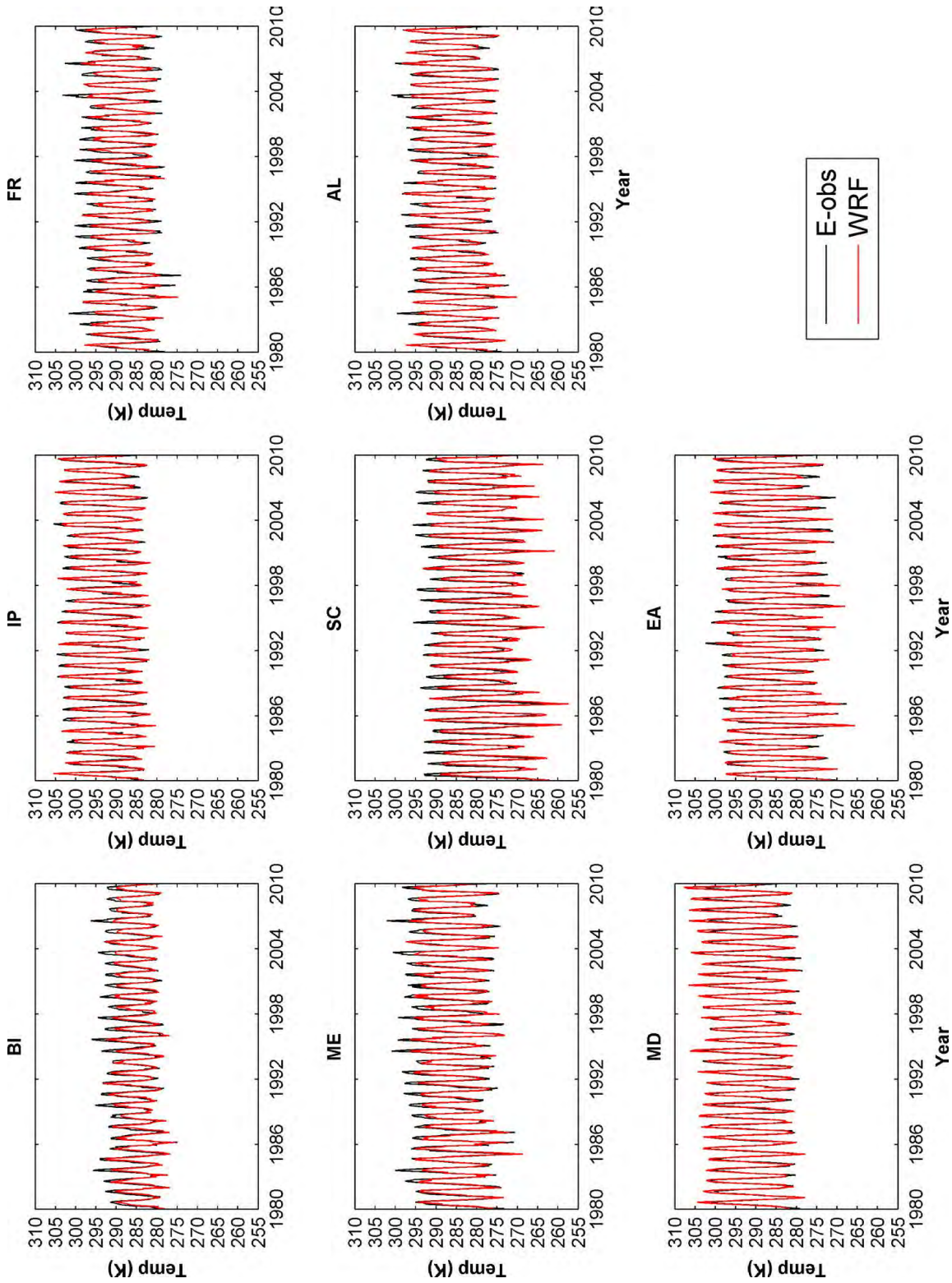


Figure A3.2. Monthly mean maximum temperature for the period 1981–2010 for E-Obs and WRF for the British Isles (BI); Iberian Peninsula (IP); France (FR); Mid-Europe (ME); Scandinavia (SC); Alps (AL); Mediterranean (MD) and Eastern Europe (EA).

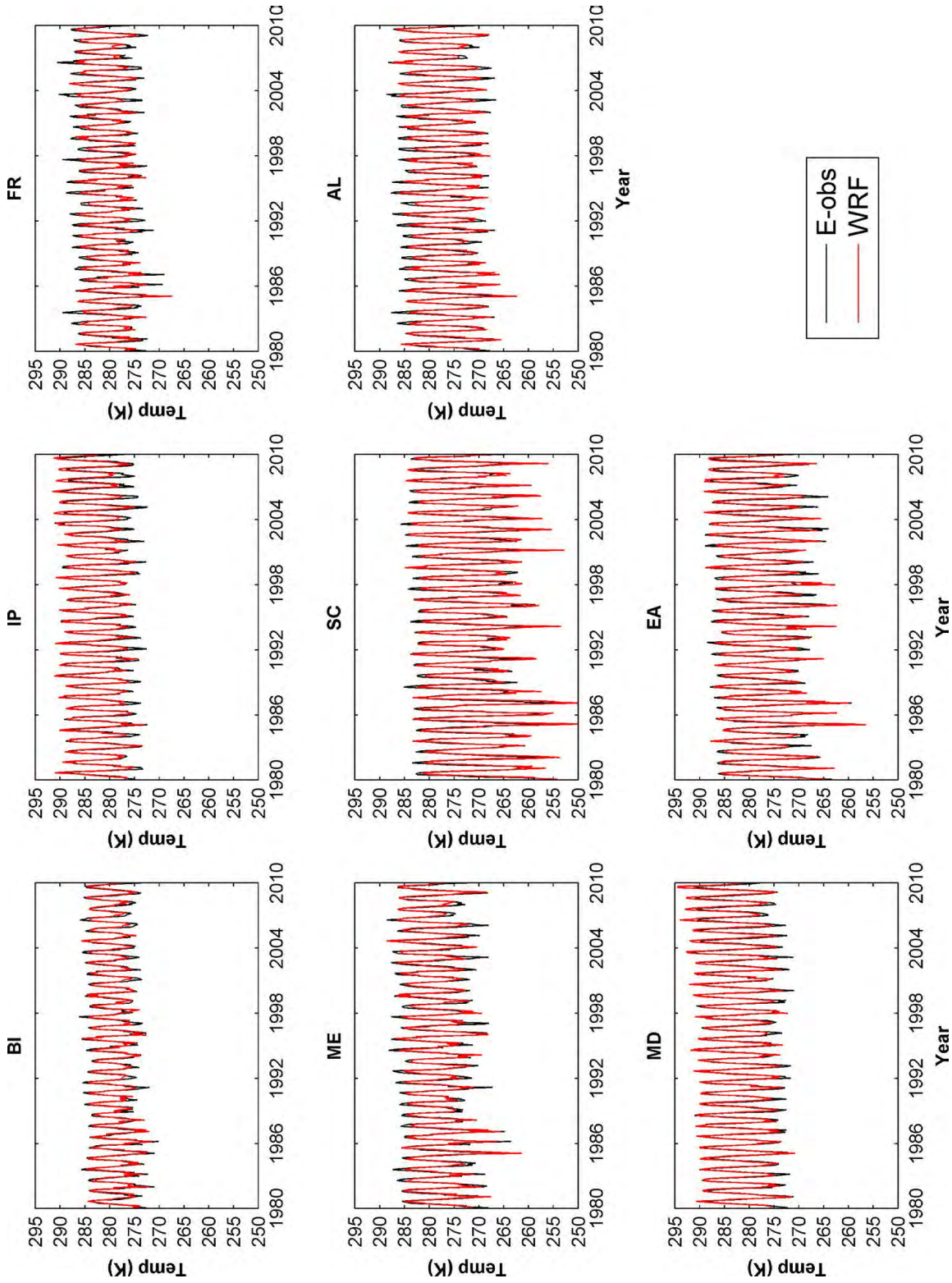


Figure A3.3. Monthly mean minimum temperature for the period 1981–2010 for E-Obs and WRF for the British Isles (BI); Iberian Peninsula (IP); France (FR); Mid-Europe (ME); Scandinavia (SC); Alps (AL); Mediterranean (MD) and Eastern Europe (EA).

Appendix 4 Seasonal Ensemble Mean Temperature

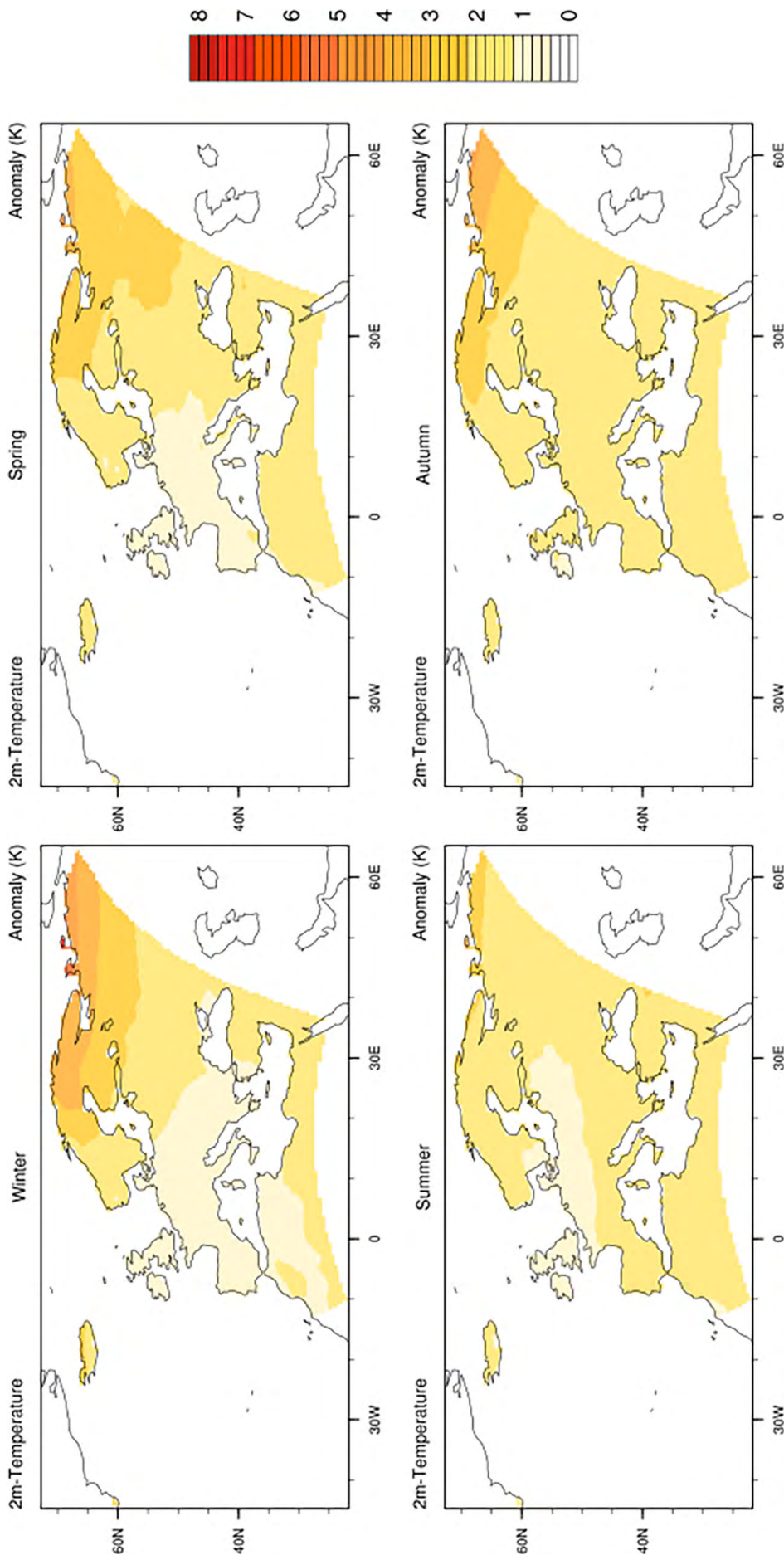


Figure A4.1. Multi-model ensemble mean of 2-metre temperature for RCP8.5 for the period 2021–2050. Values are shown as anomalies for the period, relative to 1971–2000. The multi-model mean is derived from seven input models: ICHEC-EC-Earth -DMI-HIRHAM5, -KMNI-RACMO22E, -NUIM-WRFV341E; IPSL-IPSL-CM5A-MR-IPSL-INERIS-WRFV331F; MOHC-HadGEM2-ES-KMNI-RACMO22E; MPI-M-MPI-ESM-LR -CLMcom-CCLM4-8-17, -MPI-CSC-REMO2009.

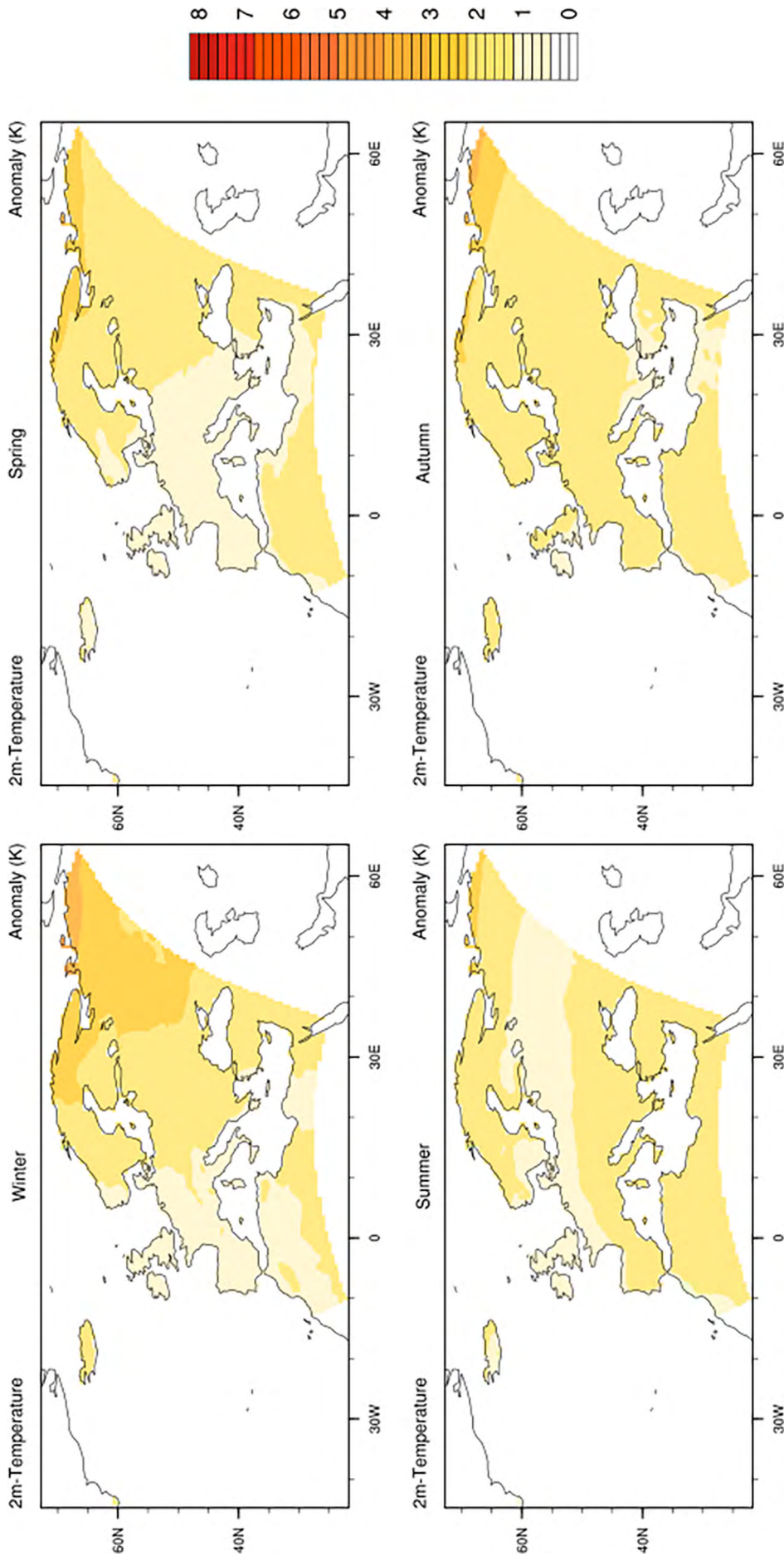


Figure A4.2. Multi-model ensemble mean of 2-metre temperature for RCP4.5 for the period 2021–2050. Values are shown as anomalies for the period, relative to 1971–2000. The multi-model mean is derived from six input models: ICHEC-EC-Earth -DMI-HIRHAM5, -KNMI-RACMO22E; IPSL-IPSL-CM5A-MR-IPSL-INERIS-WRFV331F; MOHC-HadGEM2-ES-KNMI-RACMO22E; MPI-M-MPI-ESM-LR -CLMcom-CCLM4-8-17, -MPI-CSC-REMO2009.

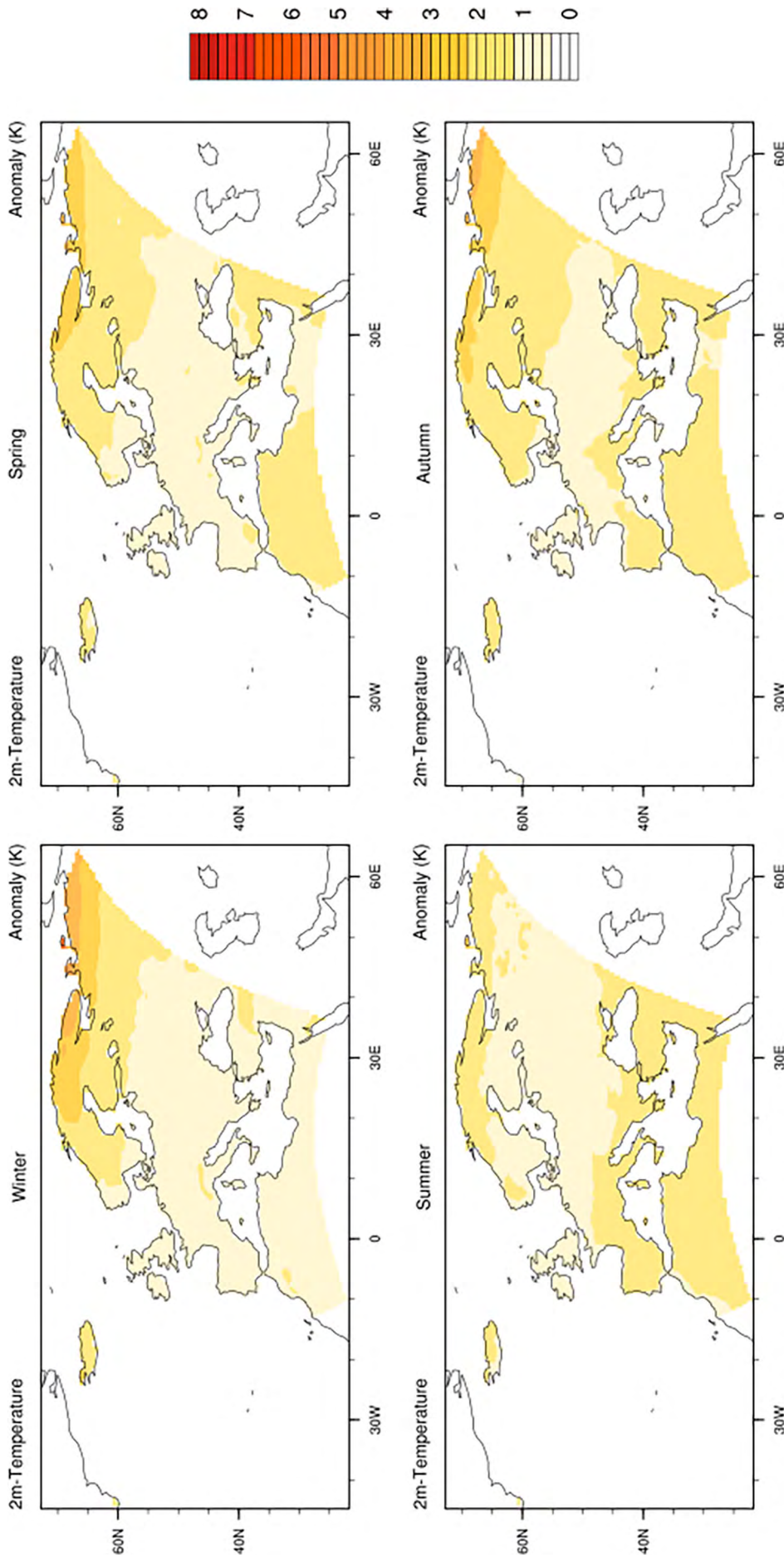


Figure A4.3. Multi-model ensemble mean of 2-metre temperature for RCP2.6 for the period 2021–2050. Values are shown as anomalies for the period, relative to 1971–2000. The multi-model mean is derived from five input models: ICHEC-EC-Earth -NUIM-WRFV341E, -SMHI-RCA4; MOHC-HadGEM2 -SMHI-RCA4; MPI-M-MPI-ESM-LR -MPI-CSC-REMO2009, -SMHI-RCA4.

Appendix 5 Spring and Autumn Ensemble Mean Precipitation

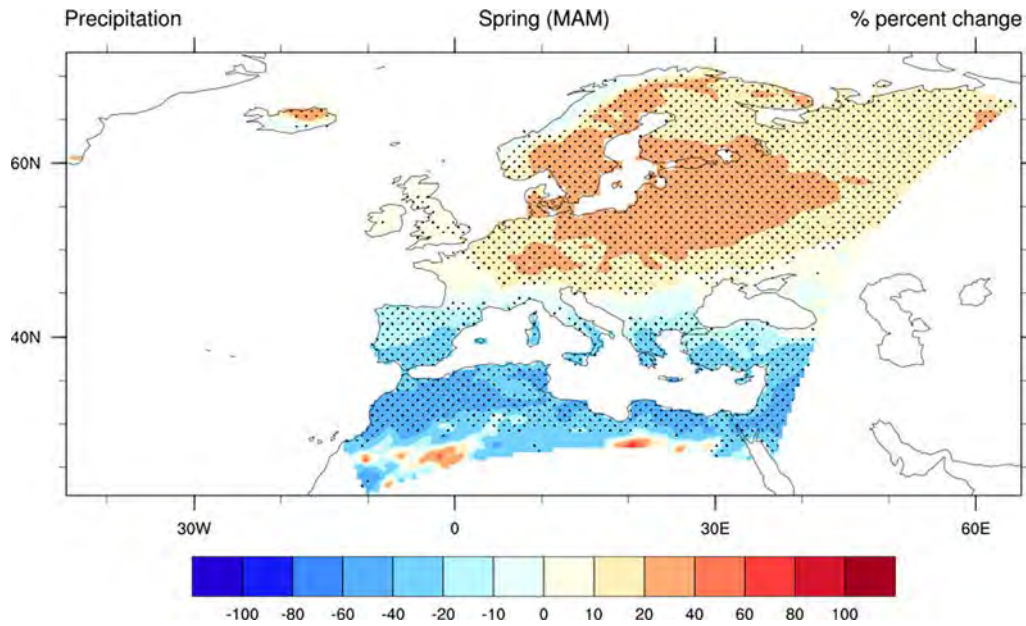


Figure A5.1. Multi-model mean ensemble of spring (MAM) percentage change in precipitation for all land areas in the EURO-CORDEX domain for a selection of models for RCP8.5 for the period 2071–2100, relative to 1971–2000. Stippling indicates area where more than 80% of selected models agree on the sign of the change. Note that a number of regional climate models employed, selected on account of their availability, are forced with the same parent boundary conditions, and therefore model agreement cannot be interpreted independently of the input model selection. The multi-model mean is derived from six input models: ICHEC-EC-Earth -HIRHAM5, -RACMO22E, -WRF341E; IPSL-CM5A-WRF331F; MPI-M-MPI-ES -CCLM4-8-17, -REMO2009.

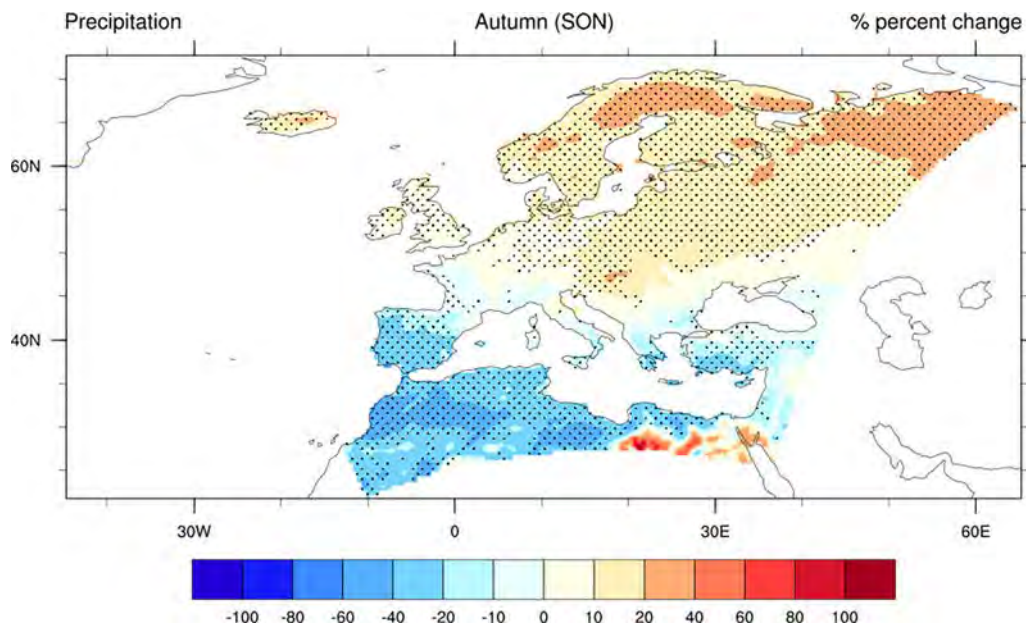


Figure A5.2. Multi-model mean ensemble of autumn (SON) percentage change in precipitation for all land areas in the EURO-CORDEX domain for a selection of models for RCP8.5 for the period 2071–2100, relative to 1971–2000. Stippling indicates area where more than 80% of selected models agree on the sign of the change. Note that a number of regional climate models employed, selected on account of their availability, are forced with the same parent boundary conditions, and therefore model agreement cannot be interpreted independently of the input model selection. The multi-model mean is derived from six input models: ICHEC-EC-Earth -HIRHAM5, -RACMO22E, -WRF341E; IPSL-CM5A-WRF331F; MPI-M-MPI-ES -CCLM4-8-17, -REMO2009.

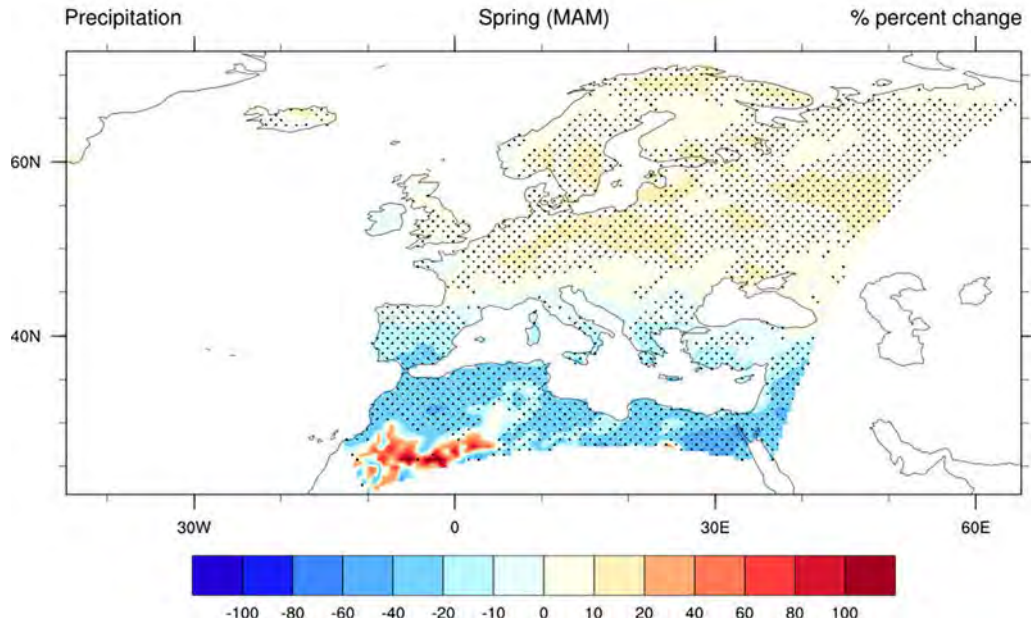


Figure A5.3. Multi-model mean ensemble of spring (MAM) percentage change in precipitation for all land areas in the EURO-CORDEX domain for a selection of models for RCP4.5 for the period 2071–2100, relative to 1971–2000. Stippling indicates area where more than 80% of selected models agree on the sign of the change. Note that a number of regional climate models employed, selected on account of their availability, are forced with the same parent boundary conditions, and therefore model agreement cannot be interpreted independently of the input model selection. The multi-model mean is derived from five input models: ICHEC-EC-Earth -HIRHAM5, -RACMO22E; IPSL-CM5A-WRF331F; MPI-M-MPI-ES -CCLM4-8-17, -REMO2009.

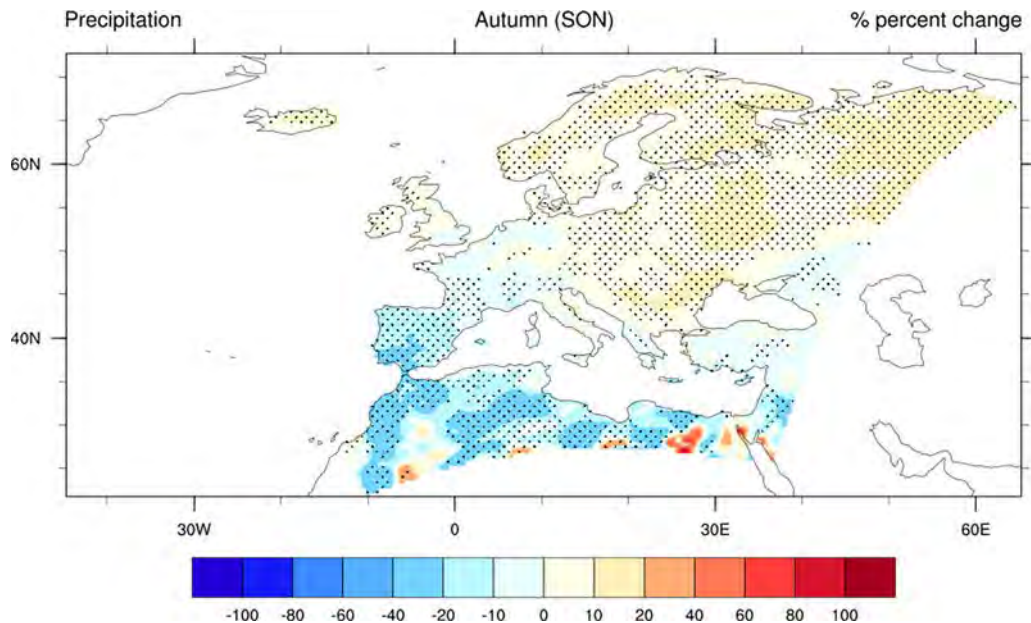


Figure A5.4. Multi-model mean ensemble of autumn (SON) percentage change in precipitation for all land areas in the EURO-CORDEX domain for a selection of models for RCP4.5 for the period 2071–2100, relative to 1971–2000. Stippling indicates area where more than 80% of selected models agree on the sign of the change. Note that a number of regional climate models employed, selected on account of their availability, are forced with the same parent boundary conditions, and therefore model agreement cannot be interpreted independently of the input model selection. The multi-model mean is derived from five input models: ICHEC-EC-Earth -HIRHAM5, -RACMO22E; IPSL-CM5A-WRF331F; MPI-M-MPI-ES -CCLM4-8-17, -REMO2009.

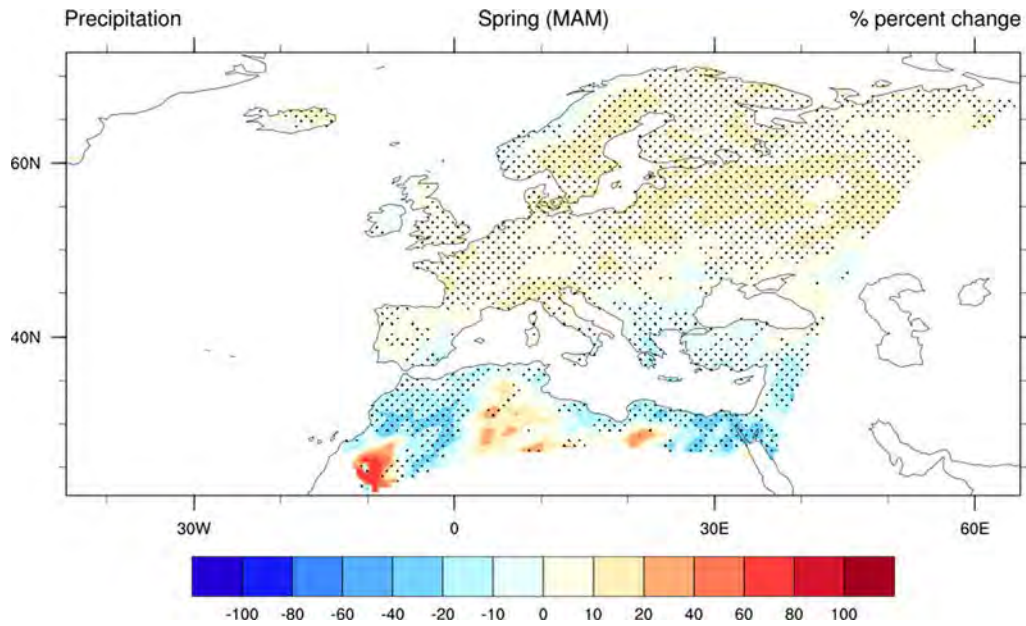


Figure A5.5. Multi-model mean ensemble of spring (MAM) percentage change in precipitation for all land areas in the EURO-CORDEX domain for a selection of models for RCP2.6 for the period 2071–2100, relative to 1971–2000. Stippling indicates area where more than 80% of selected models agree on the sign of the change. Note that a number of regional climate models employed, selected on account of their availability, are forced with the same parent boundary conditions, and therefore model agreement cannot be interpreted independently of the input model selection. The multi-model mean is derived from five input models: ICHEC-EC-Earth -WRFV341E, -RCA4; MOHC-HadGEM2-ES-RCA4; MPI-M-MPI-ES -RCA4, -REMO2009.

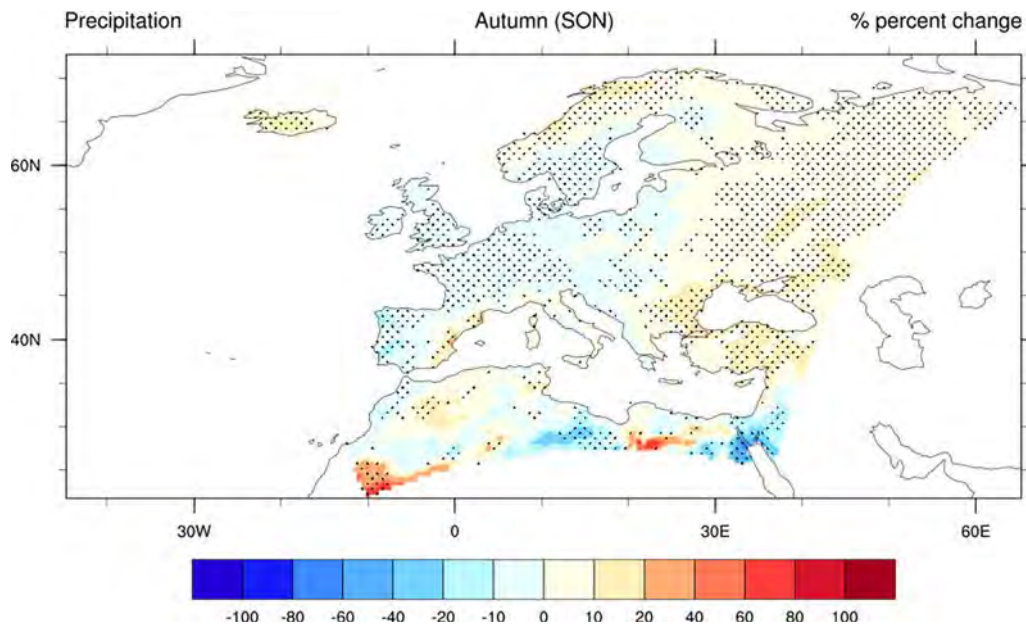


Figure A5.6. Multi-model mean ensemble of autumn (SON) percentage change in precipitation for all land areas in the EURO-CORDEX domain for a selection of models for RCP2.6 for the period 2071–2100, relative to 1971–2000. Stippling indicates area where more than 80% of selected models agree on the sign of the change. Note that a number of regional climate models employed, selected on account of their availability, are forced with the same parent boundary conditions, and therefore model agreement cannot be interpreted independently of the input model selection. The multi-model mean is derived from five input models: ICHEC-EC-Earth -WRFV341E, -RCA4; MOHC-HadGEM2-ES-RCA4; MPI-M-MPI-ES -RCA4, -REMO2009.

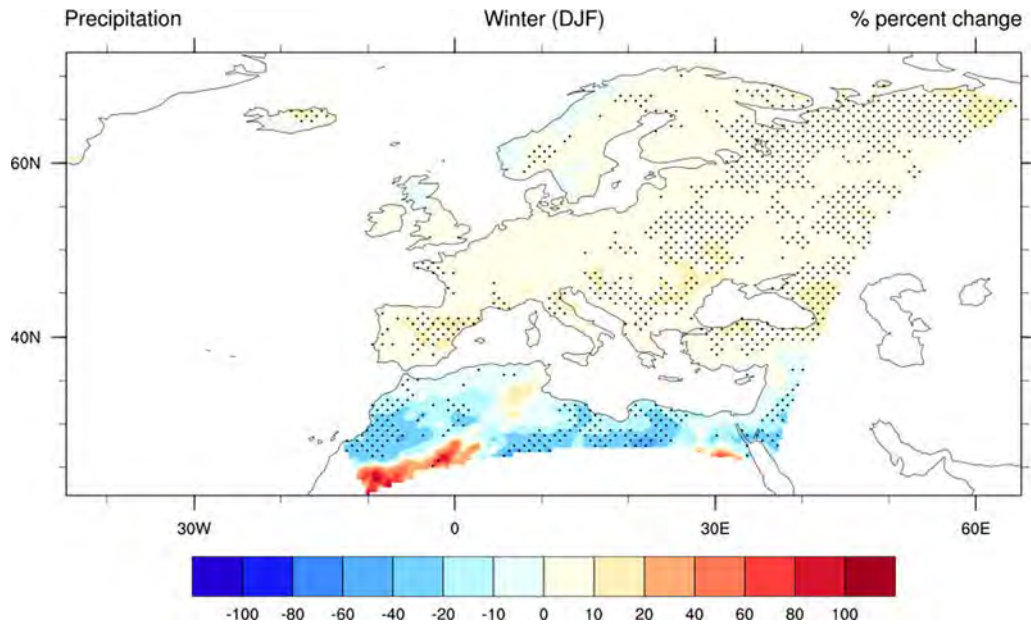


Figure A5.7. Multi-model mean ensemble of winter (DJF) percentage change in precipitation for all land areas in the EURO-CORDEX domain for a selection of models for RCP8.5 for the period 2021–2050, relative to 1971–2000. Stippling indicates area where more than 80% of selected models agree on the sign of the change. Note that a number of regional climate models employed, selected on account of their availability, are forced with the same parent boundary conditions, and therefore model agreement cannot be interpreted independently of the input model selection. The multi-model mean is derived from six input models: ICHEC-EC-Earth -HIRHAM5, -RACMO22E, -WRF341E; IPSL-CM5A-WRF331F; MPI-M-MPI-ES -CCLM4-8-17, -REMO2009.

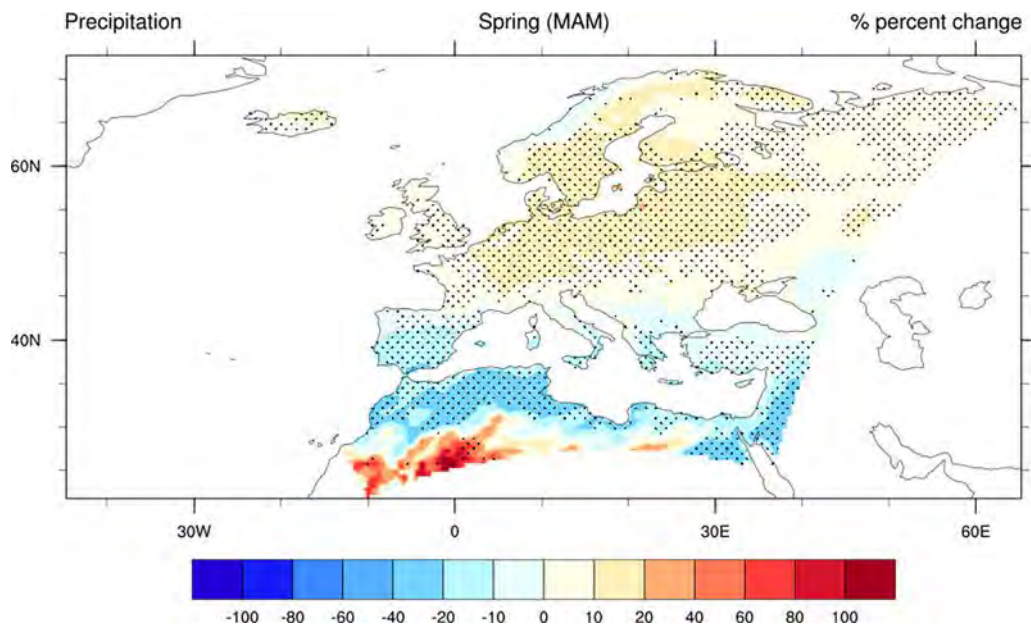


Figure A5.8. Multi-model mean ensemble of spring (MAM) percentage change in precipitation for all land areas in the EURO-CORDEX domain for a selection of models for RCP8.5 for the period 2021–2050, relative to 1971–2000. Stippling indicates area where more than 80% of selected models agree on the sign of the change. Note that a number of regional climate models employed, selected on account of their availability, are forced with the same parent boundary conditions, and therefore model agreement cannot be interpreted independently of the input model selection. The multi-model mean is derived from six input models: ICHEC-EC-Earth -HIRHAM5, -RACMO22E, -WRF341E; IPSL-CM5A-WRF331F; MPI-M-MPI-ES -CCLM4-8-17, -REMO2009.

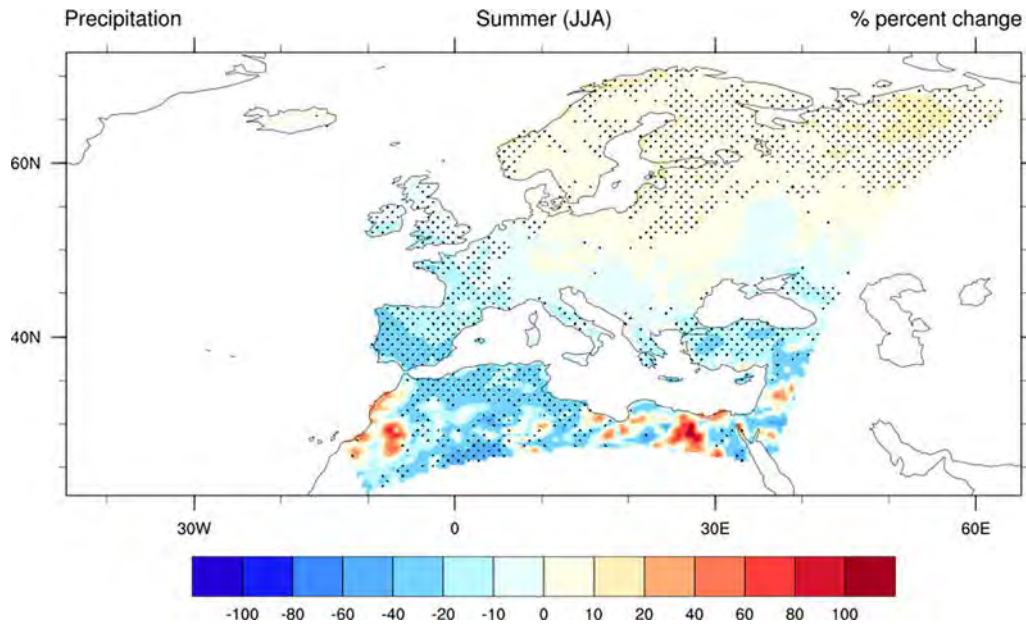


Figure A5.9. Multi-model mean ensemble of summer (JJA) percentage change in precipitation (%) for all land areas in the EURO-CORDEX domain for a selection of models for RCP8.5 for the period 2021–2050, relative to 1971–2000. Stippling indicates area where more than 80% of selected models agree on the sign of the change. Note that a number of regional climate models employed, selected on account of their availability, are forced with the same parent boundary conditions, and therefore model agreement cannot be interpreted independently of the input model selection. The multi-model mean is derived from six input models: ICHEC-EC-Earth -HIRHAM5, -RACMO22E, -WRF341E; IPSL-CM5A-WRF331F; MPI-M-MPI-ES -CCLM4-8-17, -REMO2009.

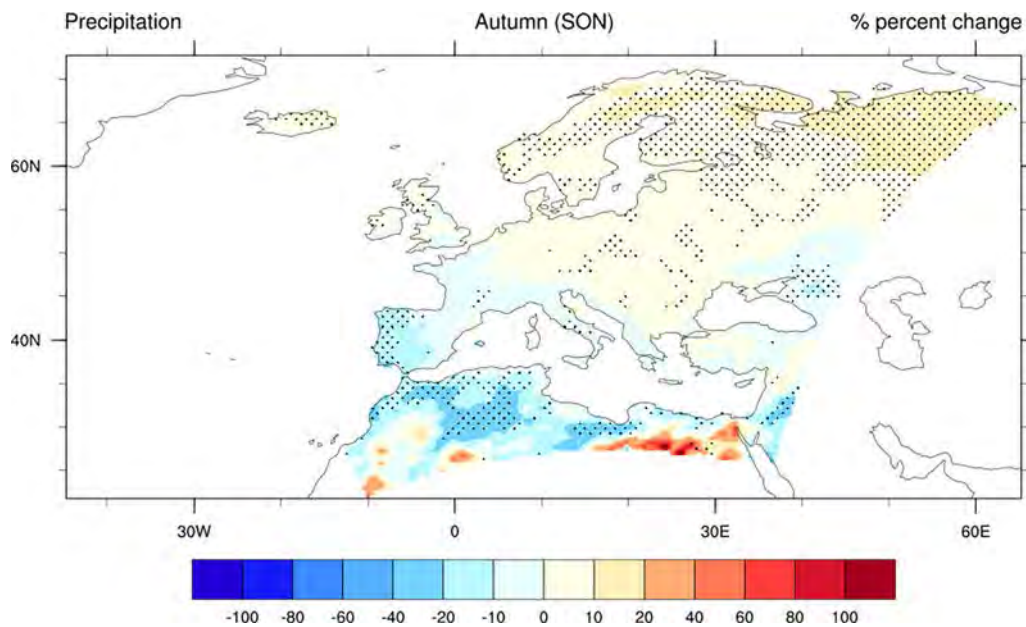


Figure A5.10. Multi-model mean ensemble of autumn (SON) percentage change in precipitation for all land areas in the EURO-CORDEX domain for a selection of models for RCP8.5 for the period 2021–2050, relative to 1971–2000. Stippling indicates area where more than 80% of selected models agree on the sign of the change. Note that a number of regional climate models employed, selected on account of their availability, are forced with the same parent boundary conditions, and therefore model agreement cannot be interpreted independently of the input model selection. The multi-model mean is derived from six input models: ICHEC-EC-Earth -HIRHAM5, -RACMO22E, -WRF341E; IPSL-CM5A-WRF331F; MPI-M-MPI-ES -CCLM4-8-17, -REMO2009.

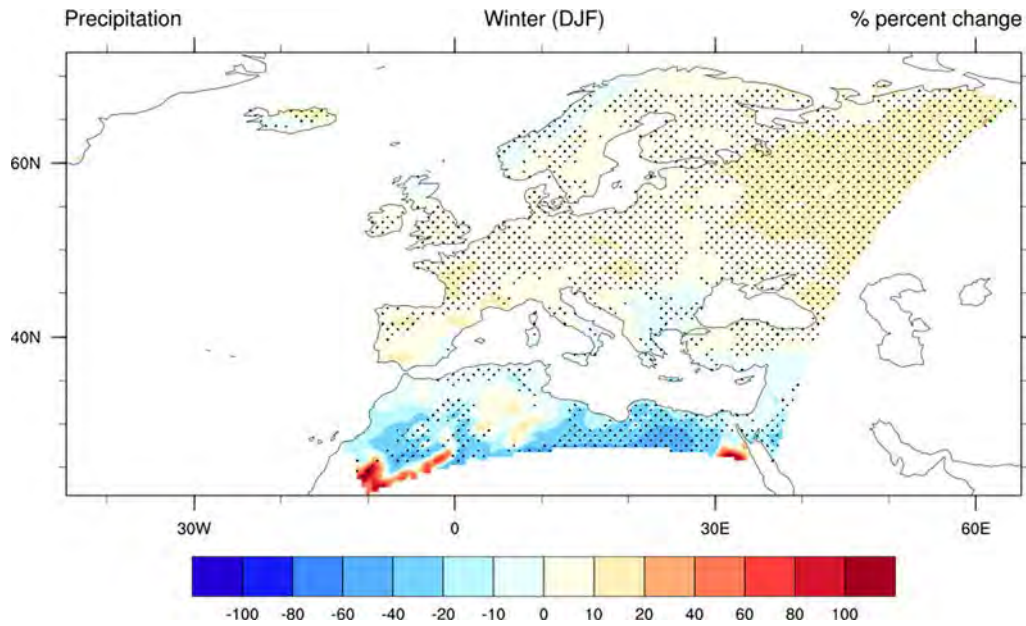


Figure A5.11. Multi-model mean ensemble of winter (DJF) percentage change in precipitation for all land areas in the EURO-CORDEX domain for a selection of models for RCP4.5 for the period 2021–2050, relative to 1971–2000. Stippling indicates area where more than 80% of selected models agree on the sign of the change. Note that a number of regional climate models employed, selected on account of their availability, are forced with the same parent boundary conditions, and therefore model agreement cannot be interpreted independently of the input model selection. The multi-model mean is derived from five input models: ICHEC-EC-Earth -HIRHAM5, -RACMO22E; IPSL-CM5A-WRF331F; MPI-M-MPI-ES -CCLM4-8-17, -REMO2009.

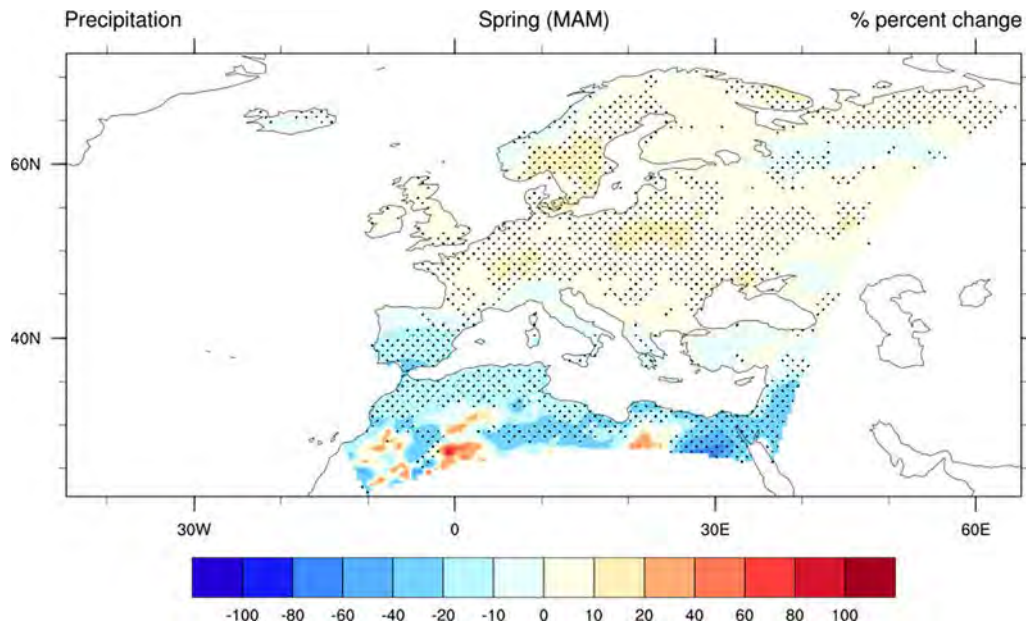


Figure A5.12. Multi-model mean ensemble of spring (MAM) percentage change in precipitation for all land areas in the EURO-CORDEX domain for a selection of models for RCP4.5 for the period 2021–2050, relative to 1971–2000. Stippling indicates area where more than 80% of selected models agree on the sign of the change. Note that a number of regional climate models employed, selected on account of their availability, are forced with the same parent boundary conditions, and therefore model agreement cannot be interpreted independently of the input model selection. The multi-model mean is derived from five input models: ICHEC-EC-Earth -HIRHAM5, -RACMO22E; IPSL-CM5A-WRF331F; MPI-M-MPI-ES -CCLM4-8-17, -REMO2009.

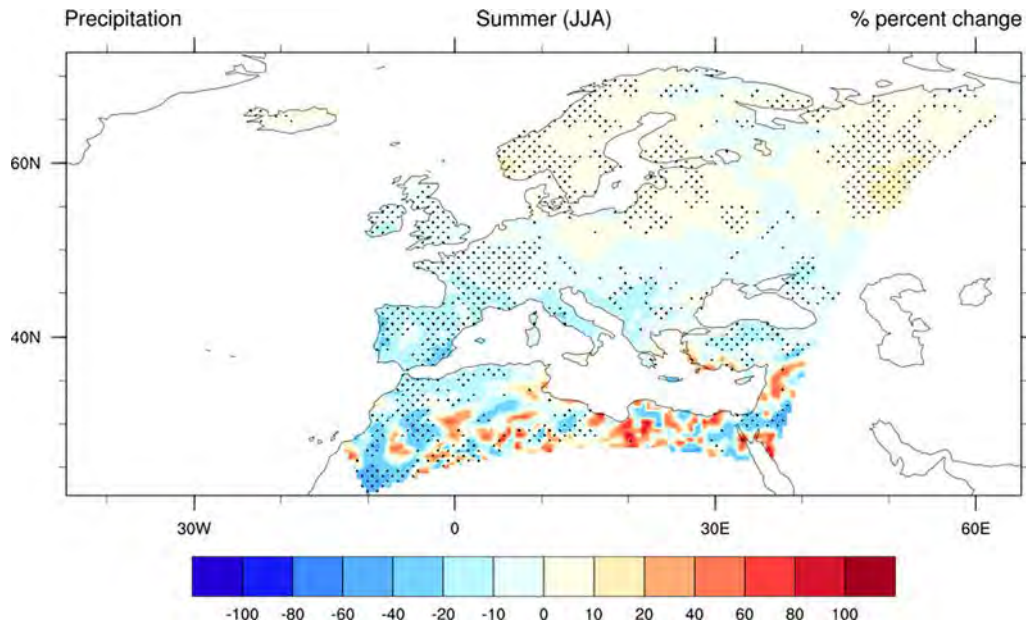


Figure A5.13. Multi-model mean ensemble of summer (JJA) percentage change in precipitation for all land areas in the EURO-CORDEX domain for a selection of models for RCP4.5 for the period 2021–2050, relative to 1971–2000. Stippling indicates area where more than 80% of selected models agree on the sign of the change. Note that a number of regional climate models employed, selected on account of their availability, are forced with the same parent boundary conditions, and therefore model agreement cannot be interpreted independently of the input model selection. The multi-model mean is derived from five input models: ICHEC-EC-Earth -HIRHAM5, -RACMO22E; IPSL-CM5A-WRF331F; MPI-M-MPI-ES -CCLM4-8-17, -REMO2009.

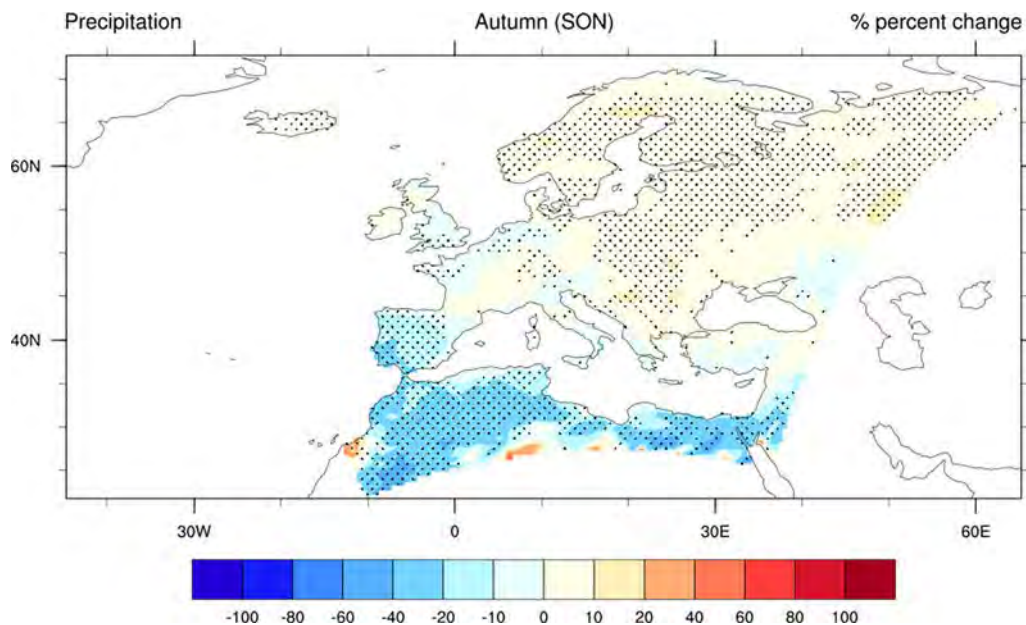


Figure A5.14. Multi-model mean ensemble of autumn (SON) percentage change in precipitation for all land areas in the EURO-CORDEX domain for a selection of models for RCP4.5 for the period 2021–2050, relative to 1971–2000. Stippling indicates area where more than 80% of selected models agree on the sign of the change. Note that a number of regional climate models employed, selected on account of their availability, are forced with the same parent boundary conditions, and therefore model agreement cannot be interpreted independently of the input model selection. The multi-model mean is derived from five input models: ICHEC-EC-Earth -HIRHAM5, -RACMO22E; IPSL-CM5A-WRF331F; MPI-M-MPI-ES -CCLM4-8-17, -REMO2009.

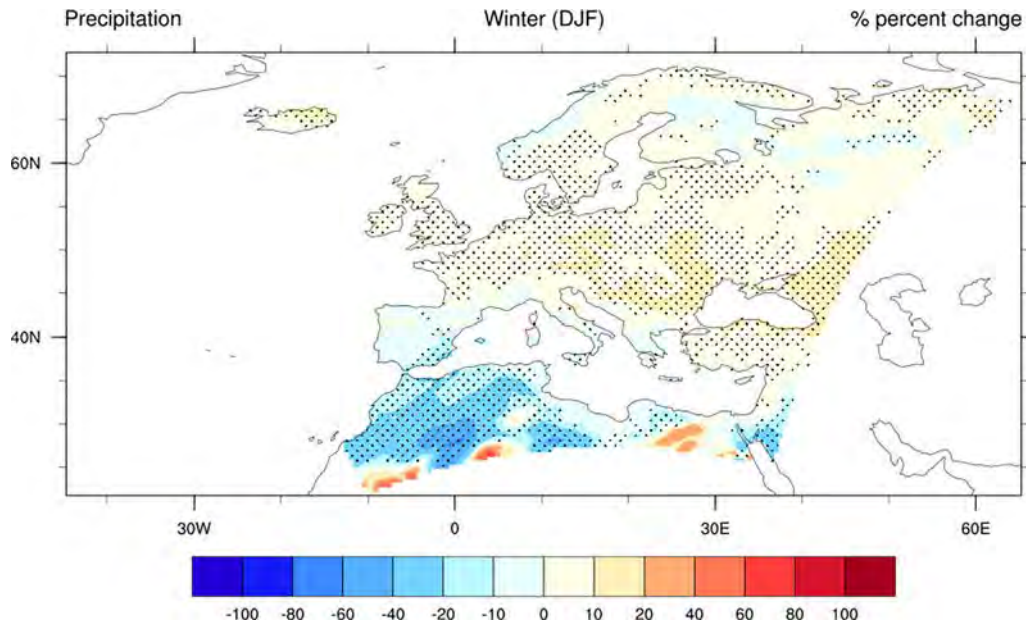


Figure A5.15. Multi-model mean ensemble of winter (DJF) percentage change in precipitation for all land areas in the EURO-CORDEX domain for a selection of models for RCP2.6 for the period 2021–2050, relative to 1971–2000. Stippling indicates area where more than 80% of selected models agree on the sign of the change. Note that a number of regional climate models employed, selected on account of their availability, are forced with the same parent boundary conditions, and therefore model agreement cannot be interpreted independently of the input model selection. The multi-model mean is derived from five input models: ICHEC-EC-Earth -WRFV341E, -RCA4; MOHC-HadGEM2-ES-RCA4; MPI-M-MPI-ES -RCA4, -REMO2009.

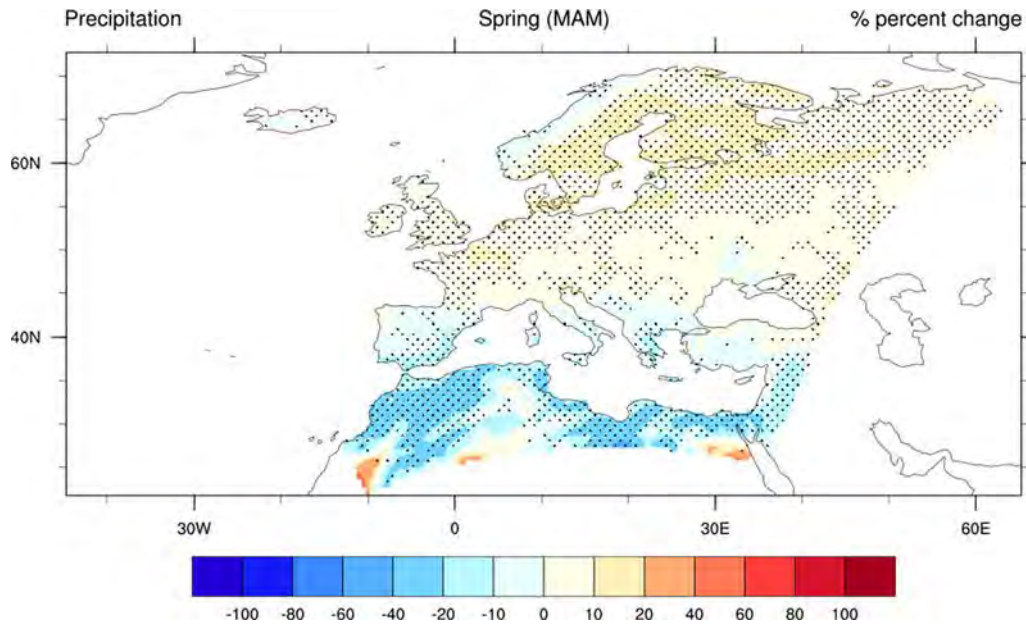


Figure A5.16. Multi-model mean ensemble of spring (MAM) percentage change in precipitation for all land areas in the EURO-CORDEX domain for a selection of models for RCP2.6 for the period 2021–2050, relative to 1971–2000. Stippling indicates area where more than 80% of selected models agree on the sign of the change. Note that a number of regional climate models employed, selected on account of their availability, are forced with the same parent boundary conditions, and therefore model agreement cannot be interpreted independently of the input model selection. The multi-model mean is derived from five input models: ICHEC-EC-Earth -WRFV341E, -RCA4; MOHC-HadGEM2-ES-RCA4; MPI-M-MPI-ES -RCA4, -REMO2009.

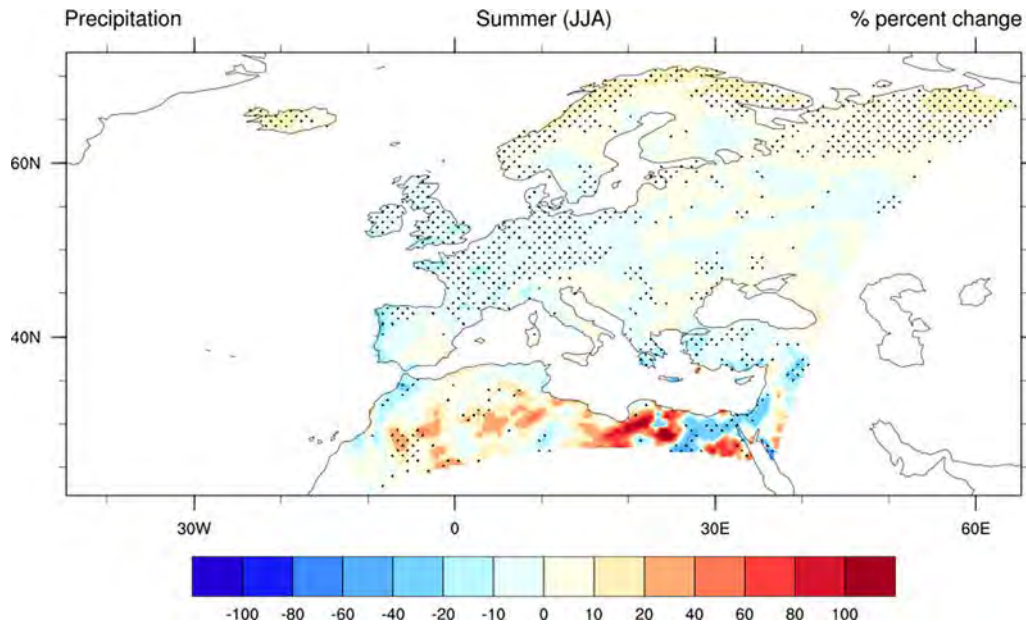


Figure A5.17. Multi-model mean ensemble of summer (JJA) percentage change in precipitation for all land areas in the EURO-CORDEX domain for a selection of models for RCP2.6 for the period 2021–2050, relative to 1971–2000. Stippling indicates area where more than 80% of selected models agree on the sign of the change. Note that a number of regional climate models employed, selected on account of their availability, are forced with the same parent boundary conditions, and therefore model agreement cannot be interpreted independently of the input model selection. The multi-model mean is derived from five input models: ICHEC-EC-Earth -WRFV341E, -RCA4; MOHC-HadGEM2-ES-RCA4; MPI-M-MPI-ES -RCA4, -REMO2009.

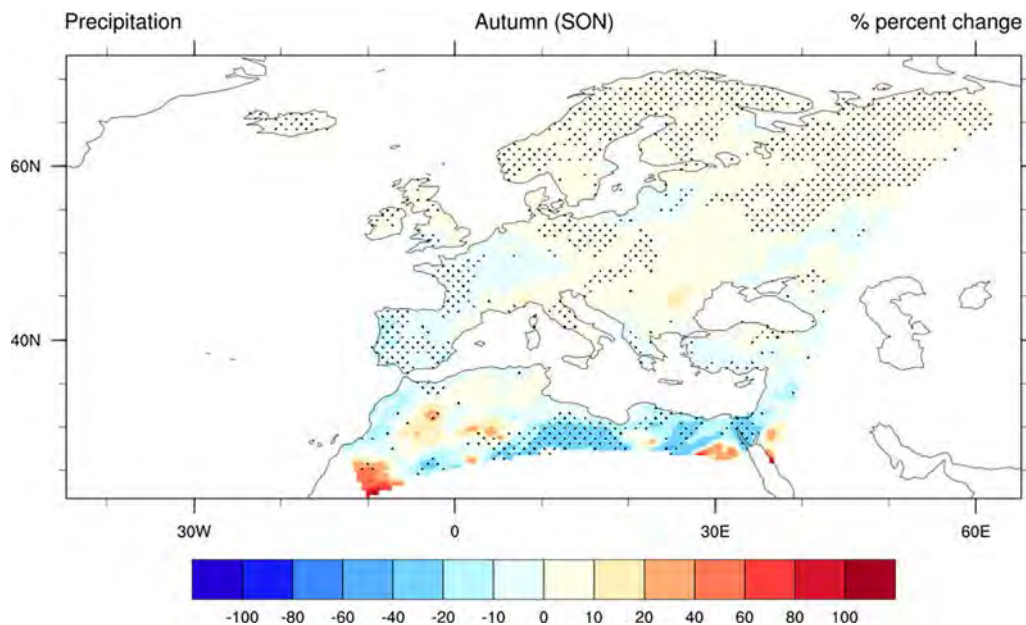


Figure A5.18. Multi-model mean ensemble of autumn (SON) percentage change in precipitation for all land areas in the EURO-CORDEX domain for a selection of models for RCP2.6 for the period 2021–2050, relative to 1971–2000. Stippling indicates area where more than 80% of selected models agree on the sign of the change. Note that a number of regional climate models employed, selected on account of their availability, are forced with the same parent boundary conditions, and therefore model agreement cannot be interpreted independently of the input model selection. The multi-model mean is derived from five input models: ICHEC-EC-Earth -WRFV341E, -RCA4; MOHC-HadGEM2-ES-RCA4; MPI-M-MPI-ES -RCA4, -REMO2009.

AN GHNÍOMHAIREACHT UM CHAOMHNÚ COMHSHAOIL
Tá an Gníomhaireacht 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 maithhe comhshaoil a sholáthar agus chun díriú orthu siúd nach gcloíonn leis na córais sin.

Eolas: Soláthraímid sonraí, faisnéis agus measúnú comhshaoil atá ar ardchaighdeán, spriocdhírithhe 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 peitрил;
- 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 idíonn 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 shainaitheint, 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. mórfhleananna 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 comhshaoil 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 inmí agus le comhairle a chur ar an mBord.

Authors: Rowan Fealy, Cindy Bruyère and Catriona Duffy

Identifying Pressures

The EU recognises the need for a two-tiered approach to improving resilience to climate change, requiring both mitigation and adaptation strategies to be put in place; in the absence of binding, global, agreements on emissions targets, adaptation strategies are increasing in priority. Due to the range of different climate impacts likely to be experienced across the European Union, tailored adaptation strategies are required at a country or regional level. The development of National Adaptation Strategies, required under Article 4 of the UNFCCC, reflect the need for a coordinated approach to policy formulation at EU level. An essential element of developing National Adaptation Strategies is the requirement for climate information of the past, present and possible future evolution of the climate system. The current research generated climate scenarios for two plausible future climates, described by the representative concentration pathways (RCPs), namely RCP2.6 and RCP8.5. These RCPs were selected to represent a future in which either significant adaptation (RCP8.5) or more manageable adaptation (RCP2.6) may be required to manage and reduce the potential impacts of future changes in the climate system.

Informing Policy

Climate is one of many drivers that can influence exposure and consequently risk; thus, climate change needs to be considered in the wider context of these factors. The fact that uncertainty about future changes in the climate system will continue to remain, even with perfect knowledge of the system, also needs to be recognised and incorporated into our approach for developing robust adaptation to climate change.

Climate model outputs provide a basis to assess the robustness of a range of policy options which seek to reduce our exposure to existing and past changes in climate. This represents a “policy first” rather than a “science first” approach; such an approach begins with identifying a suite of possible adaptation options that are socially, economically and technically feasible, which can then be evaluated for robustness based on different narratives, including future changes in the climate system. An assessment of the degree to which we are resilient to both past and present changes in the climate system is essential if we are to formulate effective policies which seek to increase our resilience to potential future changes in climate.

Developing Solutions

The current research utilised a start of the art regional climate model to dynamically downscale climate simulations from EC-Earth, an earth systems model, developed by a consortium of European research institutes and national meteorological agencies, including the national meteorological service Met Éireann and the Irish Centre for High-End Computing (ICHEC). The model simulations represent Ireland’s contribution to the European component of the Coordinated Regional Downscaling Experiment (EURO-CORDEX), a World Climate Research Programme (WCRP) initiative to address climate information needs at the European, national and regional level.