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

High-resolution Climate Projections for Ireland – A Multi-model Ensemble Approach

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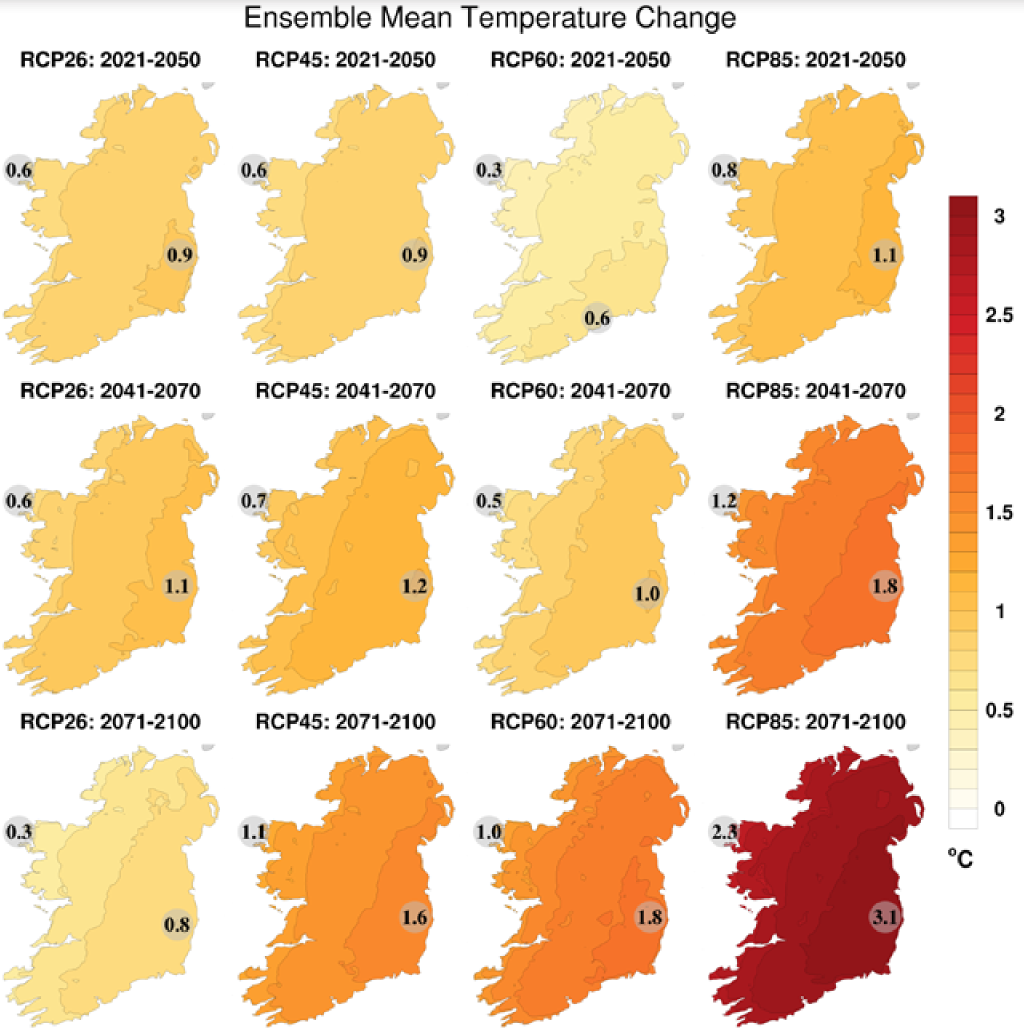

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Rialtas na hÉireann
Government of Ireland

ENVIRONMENTAL PROTECTION AGENCY

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

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- the contained use and controlled release of Genetically Modified Organisms *(GMOs)*;
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- Office of Environmental Sustainability
- Office of Environmental Enforcement
- Office of Evidence and Assessment
- Office of Radiation Protection and Environmental Monitoring
- Office of Communications and Corporate Services

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

EPA RESEARCH PROGRAMME 2014-2020

High-resolution Climate Projections for Ireland – A Multi-model Ensemble Approach

(2014-CCRP-MS.23)

EPA Research Report

Prepared for the Environmental Protection Agency

by

Irish Centre for High-End Computing (ICHEC) and Met Éireann

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Cover image: 21st century regional climate model (RCM) ensemble projections of 2-m temperature for the four Representative Concentration Pathways: RCP2.6, RCP4.5, RCP6.0 and RCP8.5. All RCM ensemble members were run with 4-km grid spacing. In each case, the future 30-year period is compared with the past period 1976–2005. The numbers included on each plot are the minimum and maximum projected changes, displayed at their locations.

This report is based on research carried out/data from January 2017 to December 2020. More recent data may have become available since the research was completed.

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

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Executive Summary

The method of regional climate modelling was employed to assess the impacts of a warming climate on the 21st-century climate of Ireland. The regional climate model (RCM) simulations were run at high spatial resolution (3.8 and 4 km), the first systematic study of its kind at this scale, thus allowing a better evaluation of the local effects of climate change. To address the issue of uncertainty, a multi-model ensemble approach was employed. Through the ensemble approach, the uncertainty in the projections can be partly quantified, thus providing a measure of confidence in the projections. Simulations were run for the reference period 1981–2000 and the future period 2041–2060. Differences between the two periods provide a measure of climate change. The Consortium for Small-scale Modeling–Climate Limited-area Modelling (COSMO-CLM) and Weather Research and Forecasting (WRF) RCMs were used to downscale the following Coupled Model Intercomparison Project – Phase 5 (CMIP5) global climate model (GCM) datasets: CNRM-CM5, EC-EARTH (four ensemble members), HadGEM2-ES, MIROC5 and MPI-ESM-LR. To account for the uncertainty in future greenhouse gas emissions, the future climate was simulated under both the Representative Concentration Pathway 4.5 (RCP4.5) and RCP8.5 scenarios.

The RCMs were validated by downscaling ERA-Interim global reanalyses and the GCM datasets for the period 1981–2000 and comparing the output with observational data. Extensive validations were carried out to test the ability of the RCMs to accurately model the climate of Ireland. Results confirm that the output of the RCMs exhibit reasonable and realistic features, as documented in the historical data record, and consistently demonstrate improved skill over the GCMs. Moreover, an increase in the spatial resolution of the RCMs resulted in a general increase in skill. However, it was found that although RCM accuracy increased with higher spatial resolution, reducing horizontal grid spacing below 4 km provided relatively little added value. The validation analysis confirms that the RCM configurations and domain size of the current study are capable of accurately simulating the current and past climate of Ireland.

The climate projections of the current report are in broad agreement with previous research, which adds a measure of confidence to the projections. Moreover, the current report presents projections of additional climate fields and derived variables that are of vital importance to sectors such as agriculture, health, energy, biodiversity and transport. It is envisaged that the research will inform policy and further the understanding of the potential environmental impacts of climate change in Ireland at a local scale.

Temperature Projections

Mid-century mean annual temperatures are projected to increase by 1–1.2°C and 1.3–1.6°C for the RCP4.5 and RCP8.5 scenarios, respectively. Temperature projections show a clear west-to-east gradient, with the largest increases in the east. Warming is enhanced for the extremes (i.e. hot days and cold nights), with the warmest 5% of daily maximum temperatures projected to increase by 1.0–2.2°C compared with the baseline period. The coldest 5% of daily minimum temperatures are projected to rise by 1–2.4°C. Heatwave events are expected to increase by the middle of the century; over the 20-year period (2041–2060), increases in heatwave events range from 1 to 8 for the RCP4.5 scenario and from 3 to 15 for the RCP8.5 scenario, with the largest increases in the south-east. Averaged over the whole country, the number of frost days (days when the minimum temperature is lower than 0°C) is projected to decrease by 45% and 58% for the RCP4.5 and RCP8.5 scenarios, respectively. Similarly, the number of ice days (days when the maximum temperature is lower than 0°C) is projected to decrease by 68% and 78% for the RCP4.5 and RCP8.5 scenarios, respectively. It is worth noting that periods of frost and ice are important environmental drivers that trigger phenological phases in many plant and animal species. Changes in the occurrence of these weather types may disrupt the life cycles of these species. The projected increase in heatwaves will have a direct impact on public health and mortality but this may be offset by the projected decrease in frost and ice days.

Precipitation, Snow and Surface Humidity Projections

Substantial decreases in precipitation are projected for the summer months, with reductions ranging from ≈0% to 11% for the RCP4.5 scenario and from 2% to 17% for the RCP8.5 scenario. Other seasons, and over the full year, show small projected changes in precipitation. However, the mid-century precipitation climate is expected to become more variable with substantial projected increases in both dry periods and heavy precipitation events.

The frequencies of heavy precipitation events show notable increases over the year as a whole and in the winter and autumn months, with "likely" projected increases of 5–19%.[1] The projected increase in evapotranspiration, noted for all seasons, may offset flooding events caused by the expected increases in heavy rainfall. However, it is recommended that additional hydrological modelling be undertaken to improve understanding of the potential impact on flooding. The number of extended dry periods (defined as at least 5 consecutive days for which the daily precipitation is less than 1 mm) is also projected to increase substantially by the middle of the century over the full year and for all seasons except spring. The projected increases in dry periods are largest for summer, with "likely" values of +11% and +48% for the RCP4.5 and RCP8.5 scenarios, respectively. The precipitation projections, summarised previously, were found to be generally robust with over 66% of the ensemble members in agreement.

Snowfall is projected to decrease substantially by the middle of the century with "likely" reductions of 51% and 60% for the RCP4.5 and RCP8.5 scenarios, respectively.

Specific humidity is projected to increase substantially (≈10%) for all seasons by the middle of the century. Relative humidity is projected to increase slightly (or show ≈0% change) for all seasons except summer. The largest increases are noted for spring (both RCP scenarios) and winter (RCP8.5). For summer, relative humidity is expected to decrease in the south-east and increase in the north-west (both RCP scenarios).

Wind Speed, Storm Tracks and Mean Sea Level Pressure Projections

Mid-century mean 10-m wind speeds are projected to decrease for all seasons. The decreases are largest for summer months under the RCP8.5 scenario. The summer reductions in 10-m wind speed range from 0.3% to 3.4% for the RCP4.5 scenario and from 2% to 5.4% for the RCP8.5 scenario. The frequency of "driving rain" events is projected to decrease for all seasons with the exception of the winter months (RCP8.5), when small increases are projected.

The projections indicate that the mean sea level pressure (MSLP) is projected to increase by ≈1 hPa by the middle of the century, with similar increases noted for all seasons. To assess the potential impact of climate change on extreme cyclonic activity in the North Atlantic, an algorithm was developed to identify and track cyclones as simulated by an ensemble of EURO-CORDEX 12-km downscaled CMIP5 RCMs. The results show an overall reduction of ≈10% in the numbers of storms affecting Ireland and suggest an eastward extension of the more severe wind storms over Ireland and the UK from the middle of the century. It should be noted that because extreme storms are rare events, the storm projections should be considered with a level of caution. Future work will focus on analysing a larger ensemble of downscaled CMIP6 data, thus allowing a more robust statistical analysis of extreme storm track projections.

Agricultural Impacts

The projections, outlined previously, of increases in temperature, heatwaves, heavy precipitation and dry periods/droughts along with decreases in frost and ice days will have direct and substantial effects on agriculture in Ireland by the middle of the century. In addition, the projections indicate an average increase in the length of the growing season by the middle of the century of 12% and 16% for the RCP4.5 and RCP8.5 scenarios, respectively. Similarly, the grazing season, crop heat units (CHUs) and growing degree days (GDDs) for a range of crops are projected to increase substantially by the middle of the century. The results suggest a warming climate may present some

1 A "likely" projection is defined as a projection for which at least 66% of the RCM ensemble members are in agreement. In this case, 66% of the ensemble members project increases in heavy precipitation events of at least 5–19% (spatially) over Ireland. See section 1.2.5 for a full description.

positive opportunities for farming. However, the results should be viewed in the context that a warming climate will also result in an increase in pests as a result of an increase in pest-GDDs and a decrease in frost and ice days, as cold conditions are a key control mechanism for the survival of pests. Furthermore, the projected increase in the frequency of both droughts and heavy rainfall events could be detrimental to the potential gains of a warming climate to the agricultural sector.

Energy Impacts

The energy content of the 120-m wind is projected to decrease for all seasons by the middle of the century. The decreases are largest for summer, with reductions ranging from 2.8% to 8.7% for the RCP4.5 scenario and from 6.5% to 14.1% for the RCP8.5 scenario. To assess the impacts of climate change on solar power in Ireland, projections of solar photovoltaic (PV) power were analysed. Results show a small expected decrease in PV by the middle of the century ranging from ≈0 to 4%. The largest decreases are noted in the north of the country and for the RCP8.5 scenario. The projected change in heating degree days (HDDs) shows that by the middle of the century there will be a greatly reduced requirement for heating in Ireland, with HDDs projected to decrease by 12–17% and 15–21% for the RCP4.5 and RCP8.5 scenarios, respectively. A clear north-to-south gradient is evident for both RCP scenarios, with the largest decreases in the south. The projections show that cooling degree days (CDDs) are expected to slightly increase, suggesting a small increase in air conditioning requirements by the middle of the century. However, the amounts are small compared with HDDs and therefore have a negligible effect on the projected changes in the total energy demand, calculated using the first-order approximation: energy degree days (EDD) = HDD + CDD.

1 Introduction

The objective of this study is to evaluate the effects of climate change on the future climate of Ireland using the method of high-resolution regional climate modelling. There is a lack of research in dynamically downscaled high-resolution (finer than 7-km grid spacing) climate modelling of Ireland, for projections in the medium term. Existing studies have either focused on analysing relatively small ensembles of regional climate model (RCM) simulations at a relatively low spatial resolution (7–12 km) (e.g. McGrath *et al*., 2005; McGrath and Lynch, 2008; Nolan *et al*., 2012, 2014, 2017; Gleeson *et al*., 2013; Nolan, 2015; O'Sullivan *et al*., 2015) or analysed a large ensemble of low-resolution RCM simulations (van der Linden and Mitchell, 2009; Jacob *et al*., 2014). The analysis presented in this study was undertaken to address this lack of research by analysing the output of three high-resolution (≈4 km) RCMs of Ireland, driven by an ensemble of eight global climate model (GCM) datasets, under the Representative Concentration Pathway 4.5 (RCP4.5) and RCP8.5 emission scenarios. Simulations were run for a reference period, 1981–2000, and a future period, 2041–2060. Differences between the two periods are used to provide a measure of the projected climate change.

The current research consolidates and expands on previous national RCM research (e.g. McGrath *et al*., 2005; McGrath and Lynch, 2008; Nolan *et al*., 2012, 2014, 2015, 2017; Gleeson *et al*., 2013; O'Sullivan *et al*., 2015) by running a large ensemble of downscaled simulations, using the most up-to-date RCMs and the RCP4.5 and RCP8.5 scenarios to simulate the future climate of Ireland. Additionally, the accuracy and usefulness of the model predictions are enhanced by increasing the model grid spacings to ≈4 km. Although uncertainty can never be eliminated in climate projections (see sections 1.1 and 1.2.5 for further comments), the large ensemble size (using different RCMs, GCMs and RCPs) allows for a robust quantification of climate projection uncertainty and a measure of confidence to be assigned to the projections. Nevertheless, RCM-downscaling studies will always be limited by the available resources to process large ensembles and will likely underrepresent the full range of possible climate futures.

The climate projections of the current report are in broad agreement with previous research, which adds another measure of confidence to the projections. Moreover, the current report presents projections of additional climate fields and derived variables that are of vital importance to sectors such as agriculture, health, energy, biodiversity and transport. It is envisaged that the research will inform policy and further the understanding of the potential environmental impacts of climate change in Ireland at a local scale.

1.1 Regional Climate Models

The impact of increasing greenhouse gases and changing land use on climate change can be simulated using GCMs. However, on account of computational constraints, long climate simulations using GCMs are currently feasible only with horizontal resolutions of ≈50 km or coarser. Because climate fields such as precipitation, wind speed and temperature are closely correlated to the local topography, this is inadequate to simulate the detail and pattern of climate change and its effects on the future climate of Ireland. Furthermore, and of particular relevance to Ireland, numerous studies have shown that, even at 50-km grid spacing, GCMs severely underresolve both the number and intensity of cyclones (e.g. Zhao *et al*., 2009; Camargo, 2013; Zappa *et al*., 2013).

To overcome these limitations, the RCM method dynamically downscales the coarse information provided by the global models and provides high-resolution information on a subdomain covering Ireland. The computational cost of running the RCM, for a given resolution, is considerably less than that of a global model. The approach has its flaws: all models have errors, which are cascaded in this technique, and new errors are introduced via the flow of data through the boundaries of the regional model. Nevertheless, numerous studies have demonstrated that high-resolution RCMs improve the simulation of fields, such as precipitation (Lucas-Picher *et al*., 2012; Kendon *et al*., 2012, 2014; Bieniek *et al*., 2015; Nolan, 2015, 2017) and topography-influenced phenomena and extremes with relatively small spatial or short temporal character (Feser *et al*., 2011; Feser and Barcikowska, 2012; Shkol'nik *et al*., 2012; IPCC, 2013a). An additional advantage is that the physically based RCMs explicitly resolve more small-scale atmospheric features and provide a better representation of convective precipitation (Rauscher *et al*., 2010) and extreme precipitation (Kanada *et al*., 2008; Nolan *et al*., 2017). Other examples of the added value of RCMs are improved simulations of near-surface temperature (Feser, 2006; Di Luca *et al*., 2016), European storm damage (Donat *et al*., 2010), strong mesoscale cyclones (Cavicchia and Storch, 2011), North Atlantic tropical cyclone tracks (Daloz *et al*., 2015) and near-surface wind speeds (e.g. Kanamaru and Kanamitsu, 2007; Nolan *et al*., 2014; Nolan, 2015), particularly in coastal areas with complex topography (Feser *et al*., 2011; Winterfeldt *et al*., 2011). The added value of RCMs in the simulation of cyclones is particularly important for the current study, as low pressure systems are the main delivery mechanism for precipitation and wind in Ireland. Furthermore, numerous studies have demonstrated that increased RCM spatial resolution results in a more accurate representation of the climate system. Low-resolution RCMs use parameterised convection schemes, meaning that the heaviest precipitation events (e.g. convective systems on hot summer days) may not be adequately represented in the simulations (Prein *et al*., 2013; Kendon *et al*., 2014). Zängl *et al*. (2015) investigated heavy rainfall events over the North-Alpine region and found that increasing the mesh size (9, 3 and 1 km) resulted in a stepwise improvement in skill. Similarly, Nolan *et al*. (2017) found that RCM accuracy increased with higher spatial resolution; however, reducing the horizontal grid spacing below 4 km provided relatively little added value.

The Intergovernmental Panel on Climate Change (IPCC) has concluded that there is "high confidence that downscaling adds value to the simulation of spatial climate detail in regions with highly variable topography (e.g., distinct orography, coastlines) and for mesoscale phenomena and extremes" (IPCC, 2013a).

1.2 Methods and Climate Models of the Current Study

1.2.1 Climate models and emission scenarios

The future climate of Ireland was simulated at high spatial resolution (3.8 and 4 km) using the Consortium for Small-scale Modeling–Climate Limited-area Modelling (COSMO-CLM; v4.0 and 5.0) and Weather Research and Forecasting (WRF; v3.8) RCMs. The COSMO-CLM RCM is the COSMO weather forecasting model in climate mode (Rockel *et al*., 2008).[2] The COSMO model[3] is the non-hydrostatic operational weather prediction model used by the German weather service (*Deutscher Wetterdienst*; DWD). A detailed description of the COSMO model is given by Doms and Schättler (2002) and Steppeler *et al*. (2003). The WRF model[4] is a numerical weather prediction system designed to serve atmospheric research, climate and operational forecasting needs. The WRF simulations of the present study adopted the Advanced Research WRF (ARW, v3.8.1) dynamical core, with development led by the US National Center for Atmospheric Research (NCAR) (Skamarock *et al*., 2008; Powers *et al*., 2017).

Projections for the future Irish climate were generated by downscaling the following Coupled Model Intercomparison Project Phase 5 (CMIP5; Taylor *et al*., 2012) global datasets:

- the UK Met Office's Hadley Centre Global Environment Model version 2 Earth System (HadGEM2-ES) configuration GCM (W.J. Collins *et al*., 2011);
- four realisations of the EC-Earth consortium GCM (Hazeleger *et al*., 2011);
- the CNRM-CM5 GCM developed by the Centre National de Recherches Météorologiques–Groupe d'études de l'Atmosphère Météorologique (CNRM-GAME) and the Centre Européen de Recherche et de Formation Avancée (Cerfacs) (Voldoire *et al*., 2013);
- the Model for Interdisciplinary Research on Climate (MIROC5) GCM developed by the MIROC5 Japanese research consortium (Watanabe *et al*., 2010);

2 www.clm-community.eu (accessed 29 May 2020).

3 www.cosmo-model.org (accessed 29 May 2020).

4 www.wrf-model.org (accessed 29 May 2020).

- the MPI-ESM-LR Earth System Model developed by the Max Planck Institute for Meteorology (Giorgetta *et al*., 2013).

To account for the uncertainty arising from the estimation of future global emission of greenhouse gases, downscaled GCM simulations based on two RCPs (RCP4.5 and RCP8.5) (Moss *et al*., 2010; van Vuuren *et al*., 2011) were used to simulate the future climate of Ireland.

1.2.2 Model domains and experiment setup

The RCMs were driven by GCM boundary conditions with the following one-way nesting strategies: GCM to 50 km to 18 km to 4 km (COSMO v4); GCM to 18 km to 4 km (COSMO v5); and GCM to 19 km to 3.8 km (WRF). The COSMO v4 50-, 18- and 4-km model domains are shown in Figure 1.1. The COSMO v5 (18 and 4 km) and WRF (19 and 3.8 km) domains are similar to the d02 and d03 domains of Figure 1.1. The advantage of high-resolution RCM simulations is highlighted in Figure 1.2, which shows how the

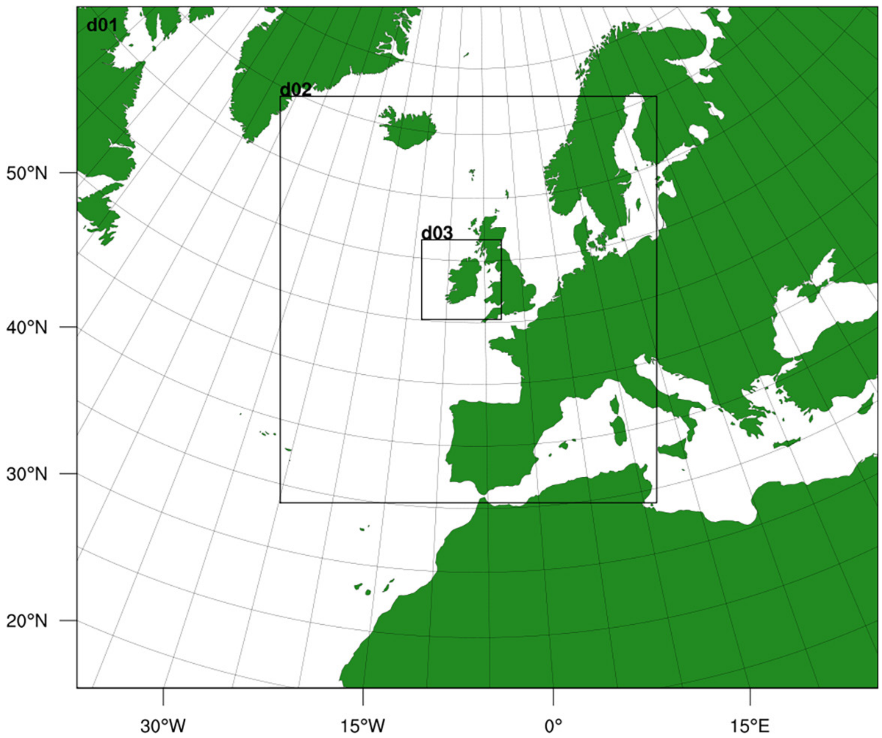

Figure 1.1. The COSMO4-CLM model domains. The d01, d02 and d03 domains have 50-, 18- and 4-km grid spacings, respectively.

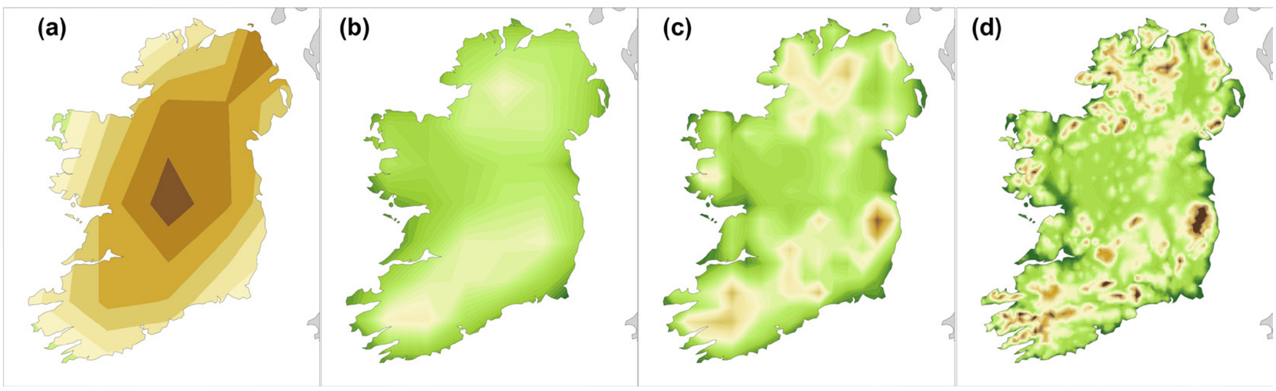

Figure 1.2. The topography of Ireland as resolved by the EC-Earth GCM and the COSMO4-CLM RCM for different spatial resolutions: (a) EC-Earth 125-km grid spacing, (b) COSMO4-CLM 50-km grid spacing, (c) COSMO4-CLM 18-km grid spacing and (d) COSMO4-CLM 4-km grid spacing.

surface topography is better resolved by the higher resolution data. For the current study, only 3.8-km and 4-km grid spacing RCM data are considered. The higher resolution data allow improved estimates of the regional variations of climate projections. The climate fields of the RCM simulations were archived at 3-h intervals. An overview of the COSMO-CLM archived fields are provided in Table 1.1. The WRF archived fields are similar.

The RCM simulations were run on the Irish Centre for High-End Computing (ICHEC) supercomputers. Running such a large ensemble of high-resolution RCMs was a substantial computational task and required extensive use of the ICHEC supercomputer systems over a period of 3–4 years. This archive of data will be made available to the wider research community and general public through the EPA and the Climate Ireland platform.[5]

Table 1.1. Archived data of the COSMO RCM simulations

Variable	Units	Variable	Units
Surface pressure	Pa	Surface lifted index	K
Mean sea level pressure	Pa	Showalter index	K
Surface temperature	K	Surface net downward SW radiation	$W m^{-2}$
2-m temperature	K	Average surface net downward SW radiation	$W m^{-2}$
2-m dew point temperature	K	Direct surface downward SW radiation	$W m^{-2}$
U-component of 10-m wind	$m s^{-1}$	Averaged direct surface downward SW radiation	$W m^{-2}$
V-component of 10-m wind	$m s^{-1}$	Averaged surface diffuse downward SW radiation	$W m^{-2}$
Surface roughness length	m	Averaged surface diffuse upward SW radiation	$W m^{-2}$
Maximum 10-m wind speed	$m s^{-1}$	Averaged downward LW radiation at the surface	$W m^{-2}$
Surface-specific humidity	$kg kg^{-1}$	Averaged upward LW radiation at the surface	$W m^{-2}$
2-m specific humidity	$kg kg^{-1}$	Averaged surface net downward LW radiation	$W m^{-2}$
2-m relative humidity	%	Averaged surface photosynthetic active radiation	$W m^{-2}$
Snow surface temperature	K	Surface albedo	0–1 (fraction)
Thickness of snow	m	Surface latent heat flux	$W m^{-2}$
Height of freezing level	m	Surface sensible heat flux	$W m^{-2}$
Total precipitation amount	$kg m^{-2}$	Surface evaporation	$kg m^{-2}$
Precipitation rate	$kg m^{-2} s^{-1}$	Soil temperature (eight levels)	K
Large-scale rainfall	$kg m^{-2}$	Soil water content (eight levels)	m
Convective rainfall	$kg m^{-2}$	Daily average 2-m temperature	K
Large-scale snowfall	$kg m^{-2}$	Daily maximum 2-m temperature	K
Convective snowfall	$kg m^{-2}$	Daily minimum 2-m temperature	K
Large-scale graupel	$kg m^{-2}$	Daily duration of sunshine	s
Surface runoff	$kg m^{-2}$	Daily relative duration of sunshine	s
Subsurface runoff	$kg m^{-2}$	Daily evapotranspiration	mm
Vertical integrated water vapour	$kg m^{-2}$	U-component of wind[a]	$m s^{-1}$
Vertical integrated cloud ice	$kg m^{-2}$	V-component of wind[a]	$m s^{-1}$
Vertical integrated cloud water	$kg m^{-2}$	Air density[a]	$kg m^{-3}$
Total cloud cover	0–1 (fraction)	Wind speed[a]	$m s^{-1}$
Low cloud cover	0–1 (fraction)	Cube wind speed[a]	$m^3 s^{-3}$
Medium cloud cover	0–1 (fraction)	Wind direction[a]	degree
High cloud cover	0–1 (fraction)	Monthly (1–48) Standardized Precipitation Index	–3 to 3
CAPE 3 km	$J kg^{-1}$		

Note: with the exception of the daily and monthly data, all variables are archived at 3-h intervals.
[a]Variables archived at 20, 40, ..200 m.
LW, longwave; SW, shortwave; U-component, zonal velocity; V-component, meridional velocity.

5 www.climateireland.ie (accessed 29 May 2020).

The choice of domain size, nesting downscaling ratio and grid spacing was decided upon following the recommendations of previous studies. For example, several studies found that the parent–grid ratio should be no larger than approximately 1:12 (e.g. Denis *et al*., 2003; Antic *et al*., 2006). Brisson *et al*. (2015) investigated the sensitivity of simulating precipitation over Belgium by downscaling ERA-Interim data. They concluded that an intermediate nesting ratio of approximately 3 was essential for the correct representation of precipitation. Rummukainen (2010) recommended that an RCM domain should be "large enough to allow for desired phenomena related to topographic influence and small-scale atmospheric processes to develop, but still sufficiently small so that the flow solution does not deviate too much from the driving model". The 50- and 18-km domains of the current study are large enough to allow changes to synoptic scales. Ideally, the domain for the finest grid size would be larger in order to allow the RCM to fully develop small-scale dynamical structures in the interior of the domain, superposed on the coarse-scale information that enters through the lateral boundaries. However, the size of the inner domains was constrained by available computational resources. Finally, the choice of grid spacing was determined by both computational constraints and a careful preliminary validation experiment (e.g. Nolan *et al*., 2017; Flanagan *et al*., 2019). A number of 1-month validation simulations were run using different physics schemes in order to determine the most accurate physics options to use for the current study. It was found that although the RCM accuracy increased with a higher spatial resolution, reducing the horizontal grid spacing below 4 km provided relatively little added value (Nolan *et al*., 2017). The results of the preliminary experiments determined the model configurations of the current study (Nolan *et al*., 2017; Flanagan *et al*., 2019).

An overview of the simulations is presented in Table 1.2. The GCM realisations result from running the same GCM with slightly different initial conditions, i.e. the starting date of historical simulations. Data from two time slices, 1981–2000 (the reference period) and 2041–2060 (the future period), were used for analysis of projected changes in the middle of the 21st-century Irish climate. These periods were chosen because they are the longest decadal time periods common to all RCM simulations. The historical period was compared with the corresponding future period for all simulations within the same RCM-GCM group. This results in future anomalies for each model run,

Table 1.2. Details of the ensemble RCM simulations

RCM	GCM (no. of ensemble members, realisations)	Nesting strategy (km)	Historical period	RCP4.5 (no. of ensemble comparisons)	RCP8.5 (no. of ensemble comparisons)
COSMO4	HadGEM2-ES (r1i1p1)	50, 18, 4	1980–2000	2020–2060 (1)	2020–2060 (1)
COSMO4	EC-Earth x3 (r1i1p1, r13i1p1 & r14i1p1)	50, 18, 4	1980–2005	2020–2060 (9)	2020–2060 (9)
COSMO5	EC-Earth (r12i1p1)	18, 4	1975–2005	2006–2100 (1)	2006–2100 (1)
COSMO5	MPI-ESM-LR (r1i1p1)	18, 4	1975–2005	2006–2100 (1)	2006–2100 (1)
COSMO5	CNRM-CM5 (r1i1p1)	18, 4	1975–2005	2006–2100 (1)	2006–2100 (1)
COSMO5	HadGEM2-ES (r1i1p1)	18, 4	1975–2005	2006–2100 (1)	2006–2100 (1)
COSMO5	MIROC5 (r1i1p1)	18, 4	1975–2005	2006–2100 (1)	2006–2100 (1)
WRF	MIROC5 (r1i1p1)	19, 3.8	1975–2005	2006–2100 (1)	2006–2100 (1)

The rows present information on the RCM used, corresponding downscaled GCM and number of realisations, nesting strategy, historical simulated period, future simulated period, RCP details and the number of ensemble comparisons.

i.e. the difference between future and past. In this study the ensemble members of the downscaled GCM simulations are treated as independent estimates of the climate system and are given equal weight. Only the differences between the simulations of the past and future climate for each model will be used in the analysis. While model biases may not be invariant under future scenarios of greenhouse gas emissions, this approach may reduce the impact of model bias.

1.2.3 Regional climate model validation

The RCMs were validated by downscaling ERA-Interim reanalyses and the GCM datasets for the period 1981–2000 and comparing the output with observational data. Extensive validations were carried out to test the ability of the RCMs to accurately model the climate of Ireland. Results confirm that the output of the RCMs exhibit reasonable and realistic features as documented in the historical data record (Nolan *et al*., 2017; Flanagan *et al*., 2019; Werner *et al*., 2019).

1.2.4 Model domains and experiment setup

Simulations were run for a reference period, 1981–2000, and a future period, 2041–2060. Differences between the two periods provide a measure of climate change. To provide a more comprehensive examination of climate change, projected changes in the standard deviation are considered in context with changes in the mean. Analyses of changes in the standard deviation provide information on projected changes in the shape (or variability) of the distribution of a climate field. In particular, analyses of changes in the mean and standard deviation provide a more comprehensive understanding of projections of extreme events.

To illustrate this concept, Figure 1.3 presents a schematic of past and future probability distributions of precipitation.[6] Figure 1.3a presents a future with increases in mean precipitation and no change in the standard deviation. In this future world, the total amount of precipitation increases, the amount of dry events decreases and the amount of wet events increases. Figure 1.3b presents a future with no change in mean precipitation and an increase in the standard deviation. In this future world, the total amount of precipitation remains constant, with an increase in both dry and wet events (i.e. increased variability). Conversely, Figure 1.3c shows that a decrease in variability, coupled with no change in mean precipitation, results in a decrease in both dry and wet events. Finally, Figure 1.3d illustrates how an increase in the mean and variability results in large increases in wet events.

To create a large ensemble, all RCM outputs were regridded to a common 4-km grid over Ireland using the method of bilinear interpolation. This results in 16 RCP4.5 and 16 RCP8.5 ensemble comparisons. The relatively large number of comparisons allows for the uncertainty of the projections to be partly quantified, providing a measure of confidence in the predictions.

1.2.5 Overview of climate projection uncertainty

Climate change projections are subject to uncertainty, which limits their utility. Fronzek *et al*. (2012) suggest that there are four main sources of uncertainty: (1) the natural variability of the climate system; (2) uncertainties on account of the formulation of the models themselves; (3) uncertainties in future regional climate because of the coarse resolution of GCMs; and (4) uncertainties in the future atmospheric composition, which affects the radiative balance of the Earth. The uncertainties arising from (1) and (2) can be addressed, in part, by employing a multi-model ensemble approach (Déqué *et al*., 2007; van der Linden and Mitchell, 2009; Jacob *et al*., 2014). The ensemble approach of the current project analyses the output of three RCMs, driven by several GCMs, to simulate climate change (see Table 1.2). Through the ensemble approach, the uncertainty in the projections can be partly quantified, providing a measure of confidence in the predictions. The uncertainty arising from (3) is addressed in the current work by running the RCM simulations at the high spatial resolution of ≈4-km grid spacings. To account for the uncertainty

6 Note: the figures are schematic representations of the distribution of standardised precipitation data. The distribution of raw precipitation data does not generally follow a normal distribution. The purpose of Figure 1.3 is simply to illustrate the concepts of how projected changes in the mean and variance can lead to substantial changes in the extremes.

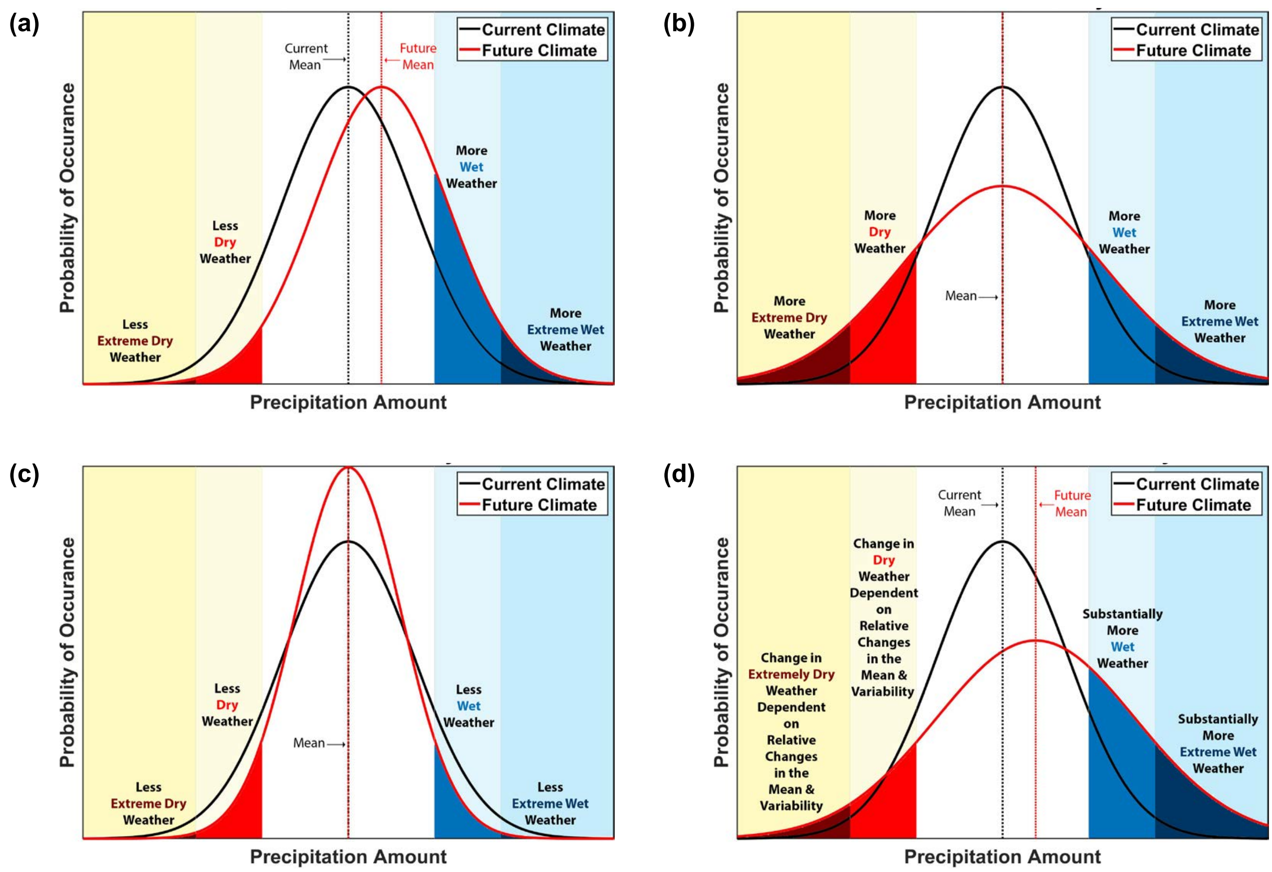

Figure 1.3. Schematic illustrating the effects of changes in the mean and standard deviation on the probability of low and high precipitation: (a) an increase in the mean with no change in the standard deviation, (b) an increase in the standard deviation with no change in the mean, (c) a decrease in the standard deviation with no change in the mean and (d) an increase in both the mean and standard deviation.

arising from (4), the future climate is simulated under both the RCP4.5 and RCP8.5 emission scenarios.

A disagreement between RCM ensemble projections can result in large individual outliers,[7] skewing the mean ensemble projection. For this reason, it can be informative to also consider percentiles when analysing an ensemble of future projections. The relatively large ensemble size of the current study allows the construction of a probability density function (pdf) of climate projections. Likelihood values can then be assigned to the projected changes. For example, if the mean (and median) ensemble projection is positive for a particular climate field, the 33rd percentile of the ensemble of projected changes is considered and is defined as the "likely" projected increase. This is a projection such that over 66% of the RCM ensemble members project greater increases. Similarly, if the mean (and median) ensemble projection is negative, the 66th percentile of the ensemble of projections is considered and is defined as the "likely" projected decrease. In this case, over 66% of the RCM ensemble members project greater decreases. In a similar manner, a "very likely" projection is defined as a projection for which at least 90% of the RCM ensemble members are in agreement; the "as likely as not" projection is defined as the 50th percentile (median) projection.

This method of analysing percentiles allows for a better understating of climate change uncertainty and allows for a quantification of conservative and robust ("likely") projections. Conversely, the likelihood method allows for policymakers to consider more "unlikely"

7 However, there is information in the outliers that may be of relevance in specific circumstances and so they cannot be entirely discounted. For example, analysis of the outliers allows policymakers to plan for "low-probability, high-impact" climate projections.

(and possibly high-impact) climate projections. These definitions, based on an ensemble of 16 members for each RCP, provide a statistically based descriptive measure of the climate change projection uncertainty.

Note that the accuracy of these statistical descriptions is based on the assumption that the ensemble members represent an unbiased sampling of the (unknown) future climate. It is also important to stress that the likelihood values presented in the current study (and similarly in studies such as Murphy *et al.*, 2009; IPCC, 2013b; and Lowe *et al.*, 2018) are derived from the most up-to-date evidence currently available. Therefore, the "likelihood" values only apply to the specific sets of high-resolution models and experimental design of the current study. Future improvements in modelling may alter the projections, as uncertainty is expected to be further reduced. Future work will focus on reducing this uncertainty by increasing the ensemble size and employing more up-to-date RCMs (including fully coupled atmosphere–ocean–wave models) to downscale recently completed CMIP6 GCMs under the full range of the Scenario Model Intercomparison Project (ScenarioMIP) "tier 1" Shared Socioeconomic Pathways (SSPs), namely SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5 (Riahi *et al.*, 2017).

2 Regional Climate Model Validations

The RCMs were validated by running 20-year simulations of the past Irish climate for the time period 1981–2000, driven by both ERA-Interim reanalysis (Dee *et al*., 2011) and the GCM datasets, and comparing the output against observational data. Uncertainty estimates (bias, absolute error and root mean square error – RSME) have been calculated for precipitation and 2-m temperature, utilising gridded datasets of observations made available by Met Éireann and the UK Met Office. The results of these analyses are presented in sections 2.1 and 2.2. The equivalent uncertainty estimates for 10-m winds and 2-m relative humidity have been calculated utilising station observations and are presented in sections 2.3 and 2.4.

2.1 RCM Precipitation Validations

Gridded datasets of (observed) accumulated daily precipitation, at 1-km resolution, covering Ireland (Walsh, 2012) for the period 1981–2000 were obtained from Met Éireann. Additionally, equivalent UK Met Office datasets covering Northern Ireland were acquired from the Centre for Ecology and Hydrology (Tanguy *et al*., 2016). The gridded datasets are available in monthly comma-separated values (CSV) files and require several processing steps before they can be used in any later analyses. These steps involve solutions that vary in complexity: the precipitation files contain spurious negatives that must be masked; easting and northing coordinates must be transformed to longitude and latitude pairs; and the gridded datasets are at 1-km resolution, whereas the modelled datasets are at 4 km (COSMO4 and 5) and 3.8 km (WRF). The latter step requires a degree of care, as there are differences in how the observed values and the model values have been calculated; the observed values are calculated for a given point, whereas the model values represent accumulations over the model grid cell. A routine has been developed that overlays the observed grid with the model grid. For each cell on the model grid, an average precipitation amount is calculated from those observed values that fall within the cell. This routine has been applied to the gridded observations for each model grid and the transformed observed datasets stored for comparison with the appropriate model outputs.

Figure 2.1a presents the annual observed precipitation averaged over the period 1981–2000. Figure 2.1b presents the downscaled ERA-Interim data as simulated by the COSMO5-CLM model with 4-km grid spacings. Note that the majority of the future

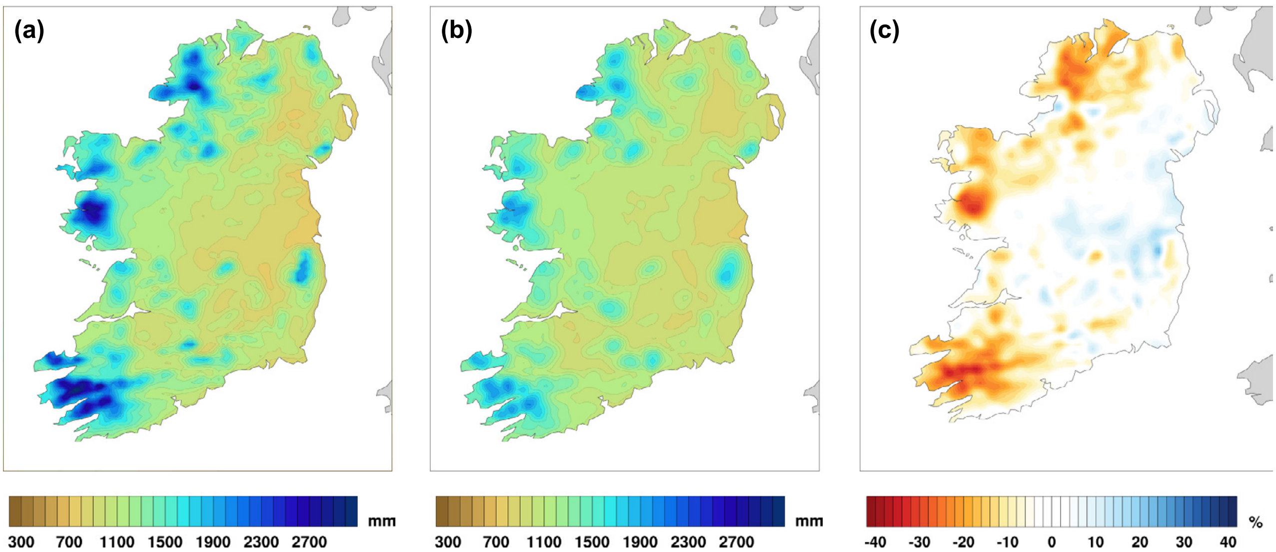

Figure 2.1. Mean annual precipitation for 1981–2000: (a) observations, (b) COSMO5-CLM-ERA-Interim 4-km data and (c) COSMO5-CLM-ERA-Interim error (%).

projections analysed for the current study use this configuration (see Table 1.2). It is noted that the RCM accurately captures the magnitude and spatial characteristics of the historical precipitation climate, e.g. higher rainfall amounts in the west and over mountains. The COSMO4-CLM RCM was found to give similar results (not shown). The WRF 3.8-km RCM was found to generally overestimate precipitation, whereas both COSMO4-CLM and COSMO5-CLM underestimate.

Figure 2.1c shows that the percentage errors range from approximately −30% to approximately +15% for COSMO5-CLM downscaled ERA-Interim data. The percentage error at each grid point (*i, j*) is given by:

$$per\_bias_{(i,j)} = 100 \times \left(\frac{bias_{(i,j)}}{\overline{OBS}_{(i,j)}} \right) \quad (2.1)$$

where

$$bias_{(i,j)} = \overline{RCM}_{(i,j)} - \overline{OBS}_{(i,j)} \quad (2.2)$$

and the $\overline{RCM}_{(i,j)}$ and $\overline{OBS}_{(i,j)}$ terms represent the RCM and observed values, respectively, at grid point (*i*, *j*), averaged over the period 1981–2000.

Figure 2.1c highlights a clear underestimation of precipitation over the mountainous regions. This is probably because the RCMs underestimate heavy precipitation; previous validations studies (e.g. Nolan *et al.*, 2017) have demonstrated a decrease in RCM skill with increasing magnitude of heavy precipitation events. To quantify the overall bias evident in Figure 2.1c, the mean was calculated over all grid points covering Ireland, resulting in an overall bias of −4.7%. The bias metric allows for the evaluation of the systematic errors of the RCMs but this can hide large errors, as positive and negative values can cancel each other out. For this reason, the percentage mean absolute error (MAE) metric was also used to evaluate the RCM precipitation errors:

$$per\_MAE_{(i,j)} = 100 \times \frac{MAE_{(i,j)}}{\overline{OBS}_{(i,j)}} \quad (2.3)$$

where

$$MAE_{(i,j)} = \left| \overline{RCM}_{(i,j)} - \overline{OBS}_{(i,j)} \right| \quad (2.4)$$

Again, the mean was calculated over all grid points covering Ireland, resulting in an overall MAE value of 8.3%. Additionally, the percentage RMSE metric was calculated:

$$per\_RMSE = 100 \times \left(\frac{RMSE}{\overline{OBS}} \right) \quad (2.5)$$

where

$$RMSE = \sqrt{\frac{1}{N} \sum_{i,j} \left(\overline{RCM}_{(i,j)} - \overline{OBS}_{(i,j)} \right)^2} \quad (2.6)$$

where *N* is the number of grid points covering Ireland. The COSMO5-CLM-ERA-Interim precipitation data, presented in Figure 2.1, has a *per_RSME* value of 14%.

The validations described previously were repeated for each RCM ensemble member (with 3.8- and 4-km horizontal grid spacings) outlined in Table 1.2. The mean bias (daily), absolute error (MAE) and RMSE (in both mm and as a percentage of observations) for each ensemble member has been calculated over the period 1981–2000. The results found for each ensemble member are presented in Table 2.1.

Percentage bias values found range from −0.26% (COSMO4-CLM-HadGEM2-ES) to 15.9% (COSMO5-CLM-MPI-ESM-LR), the percentage MAE values range from 8.75% (COSMO5-CLM-EC-Earth) to 17.99% (COSMO5-CLM-MPI-ESM-LR) and the percentage RMSE values range from 11.17% (COSMO5-CLM-EC-Earth) to 21% (COSMO5-CLM-MPI-ESM-LR).

It should be noted that the observed precipitation dataset has a margin of error of approximately ±10%, so the RCM validations should be considered within this context.

To assess the added value of high-resolution RCM models, and to quantify the improved skill of RCMs over the GCMs, precipitation data were compared with both RCM and GCM data for the period 1976–2005. The analysis was limited to Ireland and the COSMO5-CLM RCM simulations as outlined in Table 1.2. Results, presented in Table 2.2, demonstrate improved skill of the RCMs over the GCMs. Moreover, an increase in grid resolution of the RCMs (from 18- to 4-km grid spacings) results in a general increase in skill. Nolan *et al*. (2017) analysed a larger ensemble of RCMs (both COSMO-CLM and WRF) with different grid spacings (18, 7, 6, 4, 2 and 1.5 km) and found that the RCMs demonstrated a general stepwise increase in skill with increased model resolution. Furthermore, it was shown that heavy precipitation events are more accurately resolved by the higher spatial resolution RCM data. However, it was found that although the RCM accuracy increased with higher spatial

Table 2.1. Precipitation uncertainty estimates found for each RCM ensemble member through comparison with gridded observations

Precipitation (daily) validation statistics 1981–2000						
RCM ensemble member	**Bias (mm)**	**Bias (%)**	**MAE (mm)**	**MAE (%)**	**RMSE (mm)**	**RMSE (%)**
COSMO4-CLM-EC-Earth (r1i1p1)	0.01	2.61	0.33	9.48	0.47	12.0
COSMO4-CLM-EC-Earth (r13i1p1)	0.24	9.40	0.39	12.25	0.51	15.17
COSMO4-CLM-EC-Earth (r14i1p1)	0.11	5.33	0.33	9.91	0.47	12.57
COSMO4-CLM-HadGEM2-ES	–0.11	–0.26	0.40	11.21	0.61	14.05
COSMO5-CLM-CNRM-CM5	–0.20	–3.16	0.42	11.26	0.61	14.15
COSMO5-CLM-EC-Earth (r12i1p1)	–0.14	–1.98	0.32	8.57	0.49	11.17
COSMO5-CLM-HadGEM2-ES	–0.54	–14.48	0.56	15.17	0.74	17.30
COSMO5-CLM-MIROC5	0.15	8.08	0.45	14.09	0.57	17.04
COSMO5-CLM-MPI-ESM-LR	0.44	15.9	0.56	17.99	0.65	21.0
WRF-MIROC5	0.18	7.5	0.31	9.7	0.38	11.56

For each metric, the best- and worst-performing scores are highlighted in green and red, respectively.

Table 2.2. GCM and COSMO5-CLM MAE (%) uncertainty estimates through comparison with gridded observations for the period 1976–2005

30-year average annual rainfall MAE % error			
		COSMO5-CLM-GCM	
GCM	**GCM Data**	**18 km**	**4 km**
CNRM-CM5	16.5	14.1	11.8
EC-Earth (r12i1p1)	17.3	14.0	10.0
HadGEM2-ES	20.8	14.6	15.1
MIROC5	26.0	18.2	15.6
MPI-ESM-LR	25.1	24.8	21.6

For each metric, the best- and worst-performing scores are highlighted in green and red, respectively.

resolution, reducing the horizontal grid spacing below 4 km provided relatively little added value (Nolan *et al.*, 2017).

2.2 RCM 2-m Temperature Validations

Daily 1-km gridded observations of 2-m temperature for Ireland for the period 1981–2000 were obtained from Met Éireann and processed for comparison with each ensemble member. As with the gridded precipitation observations, the (observed) temperature data require coordinate transformation (easting and northing to longitude and latitude) and regridding (1-km model grids to 3.8-km/4-km model grids). Unlike precipitation, however, no spurious values needed to be masked and the calculation of temperature at specific grid points is relatively straightforward; a bilinear interpolant was used.

Figure 2.2a presents the observed 2-m temperature averaged over the 20-year period 1981–2000. Figure 2.2b presents the downscaled ERA-Interim data as simulated by the COSMO5-CLM model at 4-km resolution. It is noted that the COSMO5-CLM data accurately capture the magnitude and spatial characteristics of the observed temperature climate. This is confirmed by Figure 2.2c, which shows a small negative bias of a mean value of −0.32°C over Ireland. The corresponding MAE statistic has a value of 0.34°C.

In Table 2.3, we present the results (bias, MAE and RMSE) found for each RCM ensemble member (with 3.8- and 4-km horizontal grid spacings) outlined in Table 1.2. Bias values found range from −0.05°C (COSMO4-CLM-HadGEM2-ES) to −2.1°C (COSMO5-CLM-CNRM-CM5), MAE values range from 0.25°C (COSMO4-HadGEM2-ES) to 2.1°C

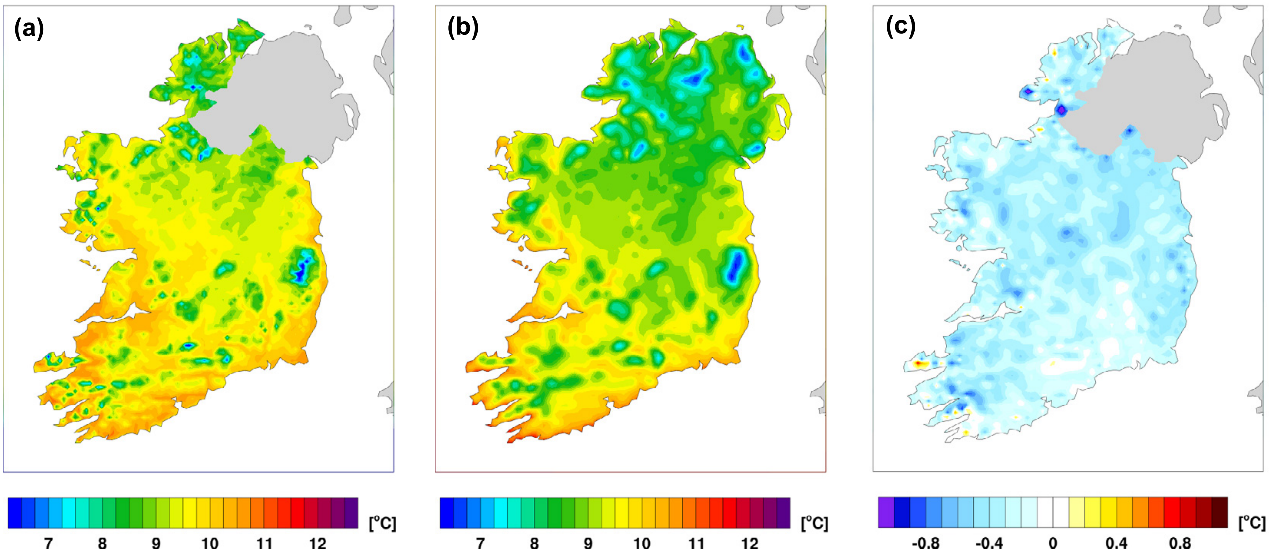

Figure 2.2. Mean annual 2-m temperature for 1981–2000: (a) observations, (b) COSMO5-CLM-ERA-Interim 4-km data and (c) COSMO5-CLM-ERA-Interim bias.

Table 2.3. 2-m temperature uncertainty estimates found for each RCM ensemble member through comparison with gridded observations

2-m temperature validation statistics 1981–2000			
RCM ensemble member	**Bias (°C)**	**MAE (°C)**	**RMSE (°C)**
COSMO4-CLM-EC-Earth (r1i1p1)	–1.52	1.52	1.56
COSMO4-CLM-EC-Earth (r13i1p1)	–1.93	1.93	1.96
COSMO4-CLM-EC-Earth (r14i1p1)	–1.62	1.62	1.66
COSMO4-CLM-HadGEM2-ES	–0.05	0.25	0.36
COSMO5-CLM-CNRM-CM5	–2.1	2.1	2.12
COSMO5-CLM-EC-Earth (r12i1p1)	–1.60	1.60	1.63
COSMO5-CLM-HadGEM2-ES	–0.49	0.53	0.59
COSMO5-CLM-MIROC5	–0.29	0.37	0.44
COSMO5-CLM-MPI-ESM-LR	–0.73	0.75	0.80
WRF-MIROC5	–1.0	1.05	1.10

For each metric, the best- and worst-performing scores are highlighted in green and red, respectively.

(COSMO5-CLM-CNRM-CM5) and RMSE values range from 0.36°C (COSMO4-CLM-HadGEM2-ES) to 2.12°C (COSMO5-CLM-CNRM-CM5).

The observed gridded 2-m temperature dataset has an estimated MAE of 0.19°C and an RMSE of 0.41°C, so the RCM validations should be considered within this context.

2.3 RCM 10-m Wind Speed Validations

Daily (00.00 Coordinated Universal Time – UTC) 10-m wind speed data from nine Met Éireann weather stations were utilised to validate model outputs. The data obtained were from Shannon Airport (Co. Clare), Roches Point (Co. Cork), Malin Head (Co. Donegal), Casement Aerodrome (Co. Dublin), Dublin Airport (Co. Dublin), Valentia Observatory (Co. Kerry), Belmullet (Co. Mayo), Claremorris (Co. Mayo) and Mullingar (Co. Westmeath) and covered time periods longer than 1981–2000. Although other Met Éireann station data exist, they typically do not extend back to 1981 and were therefore not used. The observed time series were trimmed to cover the required period (1981–2000) and units were converted from knots to $m\,s^{-1}$ for comparison with ensemble member values.

Before this latter step could be completed, time series of (daily) 10-m wind speeds were generated from each ensemble member at each station location. This was achieved by first estimating the (3-hourly) 10-m (zonal velocity – U, meridional velocity – V) wind components at each station location through bilinear interpolation and then calculating (3-hourly) 10-m wind speeds through the simple formula $W = \sqrt{U^2 + V^2}$.

For each ensemble member (m), mean (daily) 10-m wind speeds (both modelled – M – and observed – O) for the period 1981–2000 were calculated from each of the (nine in total) station (s) time series. The errors at each station location $\left(e_{s,m} = M - O\right)$ were then used to calculate:

overall bias $\left(\sum_{s=1}^{9} e_{s,m} / 9\right)$,

MAE $\left(\sum_{s=1}^{9} \left|e_{s,m}\right| / 9\right)$ and

RMSE $\left(\sqrt{\sum_{s=1}^{9} \left(e_{s,m}\right)^2 / 9}\right)$

for each ensemble member. The results of these calculations are given in Table 2.4; bias values range from −0.09 m s^{-1} (COSMO4-CLM-EC-Earth, r13i1p1) to −0.94 m s^{-1} (WRF-MIROC5); MAE ranges from 0.58 m s^{-1} (COSMO5-CLM-CNRM-CM5) to 1.09 m s^{-1} (WRF-MIROC5); and RMSE ranges from 0.73 m s^{-1} (COSMO4-CLM-EC-Earth, r13i1p1) to 1.32 m s^{-1} (WRF-MIROC5).

Initial test simulations showed that the WRF data exhibited a consistent overestimation in the wind speed. This overestimation was corrected by adapting the *topo_wind* parameterising scheme – a topographic correction for surface winds to represent extra drag from subgrid topography and enhanced flow at hill tops (Jimenez and Dudhia, 2012). However, adapting this parameterising scheme resulted in an underestimation of the WRF-MIROC5 wind speed (–0.94 m s^{-1} bias; see Table 2.4).

2.4 RCM 2-m Relative Humidity Validations

Hourly 2-m relative humidity data from the nine Met Éireann weather stations listed in section 2.3 were used for model validation. The data obtained have an earliest starting date of 1 January 1987, 01:00, and cover periods that extend beyond 2000. As with the daily data described in section 2.3, other Met Éireann station data exist but do not extend back to 1987 and were therefore not used. The observed time series were therefore systematically trimmed to cover the common period 1987–2000.

Bilinear interpolation was used to generate time series of 3-hourly 2-m relative humidity from each ensemble member at each station location. For each ensemble member (m), mean (3-hourly) 2-m relative humidities (both modelled – M – and observed – O) for the period 1987–2000 were calculated from each of the (nine in total) station (s) time series. As in section 2.3, the errors at each station location were then used to calculate overall bias, MAE and RMSE for each ensemble member. The results of

Table 2.4. 10-m wind speed validations calculated utilising Met Éireann daily station observations and estimations from each of the 10 ensemble members

Daily (mean) 10-m wind speed 1981–2000			
Model	**Bias (m s^{-1})**	**MAE (m s^{-1})**	**RMSE (m s^{-1})**
COSMO4-CLM-EC-Earth (r1i1p1)	-0.29	0.77	0.79
COSMO4-CLM-EC-Earth (r13i1p1)	-0.09	0.69	0.73
COSMO4-CLM-EC-Earth (r14i1p1)	-0.20	0.73	0.76
COSMO4-CLM-HadGEM2-ES	-0.57	0.86	0.93
COSMO5-CLM-CNRM-CM5	0.31	0.58	0.77
COSMO5-CLM-EC-Earth (r12i1p1)	0.72	0.86	0.97
COSMO5-CLM-HadGEM2-ES	0.59	0.74	0.86
COSMO5-CLM-MIROC5	0.36	0.61	0.76
COSMO5-CLM-MPI-ESM-LR	0.85	0.99	1.10
WRF-MIROC5	-0.94	1.09	1.32

For each metric, the best- and worst-performing scores are highlighted in green and red, respectively.

Table 2.5. 2-m relative humidity validations calculated utilising Met Éireann hourly station observations and estimations from each of the 10 ensemble members

2-m relative humidity validation statistics 1987–2000			
RCM ensemble member	**Bias (%)**	**MAE (%)**	**RMSE (%)**
COSMO4-CLM-EC-Earth (r1i1p1)	–4.07	4.07	4.25
COSMO4-CLM-EC-Earth (r13i1p1)	–3.94	3.94	4.16
COSMO4-CLM-EC-Earth (r14i1p1)	–3.77	3.77	3.99
COSMO4-CLM-HadGEM2-ES	–4.11	4.11	4.25
COSMO5-CLM-CNRM-CM5	–1.60	1.70	2.33
COSMO5-CLM-EC-Earth (r12i1p1)	–2.26	2.26	2.74
COSMO5-CLM-HadGEM2-ES	–2.75	2.75	3.12
COSMO5-CLM-MIROC5	–0.57	1.11	1.49
COSMO5-CLM-MPI-ESM-LR	–0.53	1.33	1.73
WRF-MIROC5	–0.15	1.37	1.62

For each metric, the best- and worst-performing scores are highlighted in green and red, respectively.

these calculations are given in Table 2.5; bias values range from −0.15% (WRF-MIROC5) to −4.11% (COSMO4-CLM-HadGEM2-ES); MAE ranges from 1.11% (COSMO5-CLM-MIROC5) to 4.11% (COSMO4-CLM-HadGEM2-ES); and RMSE ranges from 1.49% (COSMO5-CLM-MIROC5) to 4.25% (COSMO4-CLM-EC-Earth, r1i1p1 and COSMO4-CLM-HadGEM2-ES).

2.5 RCM Validation Summary

The RCMs were validated by downscaling ERA-Interim reanalyses and the GCM datasets for the period 1981–2000, and comparing the output with observational data. Extensive validations were carried out to test the ability of the RCMs to accurately model the temperature, precipitation, wind and humidity climate of Ireland. Results confirm that the output of the RCMs exhibit reasonable and realistic features as documented in the historical data record. The skill of the individual RCM datasets was dependent on the field under analysis (e.g. WRF performed well for precipitation but less well for wind speed). This variation in RCM skill stresses the importance of using an ensemble of RCMs to simulate climate change.

For an in-depth validation of additional climate fields, please refer to Nolan *et al*. (2014, 2015, 2017) and Flanagan *et al*. (2019). Additional experiments were carried out to assess the added value of high-resolution RCM models, the results of which demonstrated improved skill of RCMs over the GCMs. Moreover, an increase in the spatial resolution of the RCMs was found to result in a general increase in skill (e.g. Nolan *et al*., 2017). However, it was found that although the RCM accuracy increased with higher spatial resolution, reducing the horizontal grid spacing below 4-km provided relatively little added value (Nolan *et al*., 2017). Werner *et al*. (2019) completed a validation of agri-climate fields derived from downscaled ERA-Interim COSMO5-CLM5 and WRF datasets. The authors compared derived fields, such as evapotranspiration and soil moisture deficits, with observations and found that both RCMs exhibit high skill, with WRF slightly outperforming COSMO5-CLM.

The analysis presented in this chapter confirms that the RCM configurations and domain size of the current study are capable of accurately simulating the climate of Ireland.

Future validation work will focus on downscaling and analysing the more up-to-date and accurate ERA5 global reanalysis dataset from the European Centre for Medium-Range Weather Forecast (ECMWF), in place of ERA-Interim. ERA5 is the fifth generation of the ECMWF global climate reanalysis dataset (C3S, 2017). The ERA5 dataset was not available at the time that the current research was carried out. Furthermore, additional WRF historical simulations will be completed, which will allow for a robust quantification of the relative skill of the COSMO5-CLM and WRF RCMs.

3 Mid-century Climate Projections

3.1 Temperature Projections

Figure 3.1 presents the spatial distribution of annual temperature changes for 2041–2060 relative to 1981–2000. The mean annual temperature is projected to increase by 1–1.2°C and by 1.3–1.6°C for the RCP4.5 and RCP8.5 scenarios, respectively. Temperature projections show a clear west-to-east gradient, with the largest increases in the east.

The seasonal temperature projections are presented in Figure 3.2; winter temperatures show increases ranging from 0.9°C in the south-west to 1.2°C in the north-east for the RCP4.5 scenario (1.2°C in the south-west and 1.6°C in the north-east for RCP8.5). The patterns for spring are similar to winter, with a projected increase in temperature of 0.9°C to 1.0°C for RCP4.5 (1.0°C to 1.3°C for RCP8.5) with a south-west to north-east gradient. Summer temperatures show increases ranging from 1.0°C in the north-west to 1.3°C in the south-east for RCP4.5 (1.3°C in the north-west and 1.8°C in the south-east for RCP8.5). Autumn shows a west-to-east pattern with expected increases of 1.3°C to 1.5°C and 1.6°C to 1.9°C for the RCP4.5 and RCP8.5 scenarios, respectively. In summary, the temperature change gradient is from south-west to north-east in winter and spring, north-west to south-east in summer and from west to east in autumn and over the full year. These trends are consistent with previous studies (e.g. Gleeson *et al.*, 2013; Nolan, 2015; O'Sullivan *et al.*, 2015) and all RCM-GCM simulations, RCPs and future time periods assessed to date.

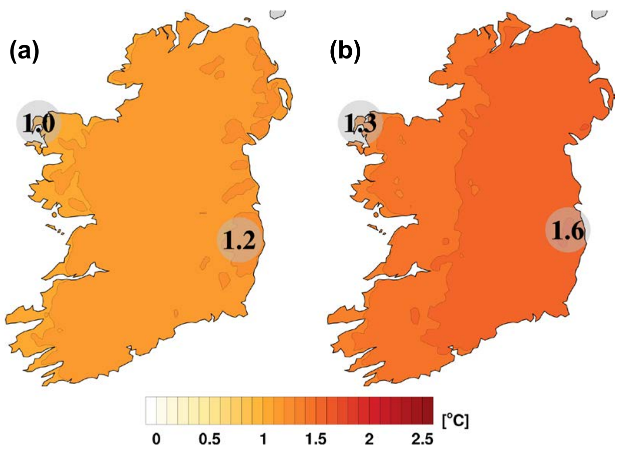

Figure 3.1. Ensemble mean of projections of 2-m temperature change for the (a) RCP4.5 and (b) RCP8.5 scenarios. In each case, the future period, 2041–2060, is compared with the past period, 1981–2000. The numbers included on each plot are the minimum and maximum projected changes, displayed at their locations.

As outlined in Chapter 1, a disagreement between RCM ensemble members can result in large individual outliers skewing the mean ensemble projection. For this reason, it can be more informative to consider percentiles when analysing an ensemble of future projections. The relatively large ensemble size of the current study allows the construction of a pdf of climate projections. Likelihood values can then be assigned to the projected changes. This method of analysing percentiles allows for a better understating of climate change uncertainty and it allows for a quantification of conservative and robust ("likely") projections. Conversely, the likelihood method allows for policymakers to consider more "unlikely" (and possibly high-impact) climate projections.

To this end, the 33rd, 50th and 66th percentiles of annual and seasonal mean 2-m temperature projections are presented in Figure 3.3. For example, the annual figures (top panels) show that over 67% (P33) of the ensemble members project an annual increase in temperatures of 0.8–1.1°C and 1.1–1.5°C for the RCP4.5 and RCP8.5 scenarios, respectively. That is to say, it is "likely" that increases in temperature will be greater than or equal to these values.[8] Similarly, the 50th percentile figures (P50) provides information on the "as likely as not" projection. The 66th percentile (P66) provides information on the "unlikely" projection and can be useful for the analysis of high-impact, low-probability projections.

8 Since all ensemble members project increases in temperature, the 33rd percentile is denoted the "likely" projection in this case (conversely, if projections are negative, the 66th percentile is denoted the "likely" projection).

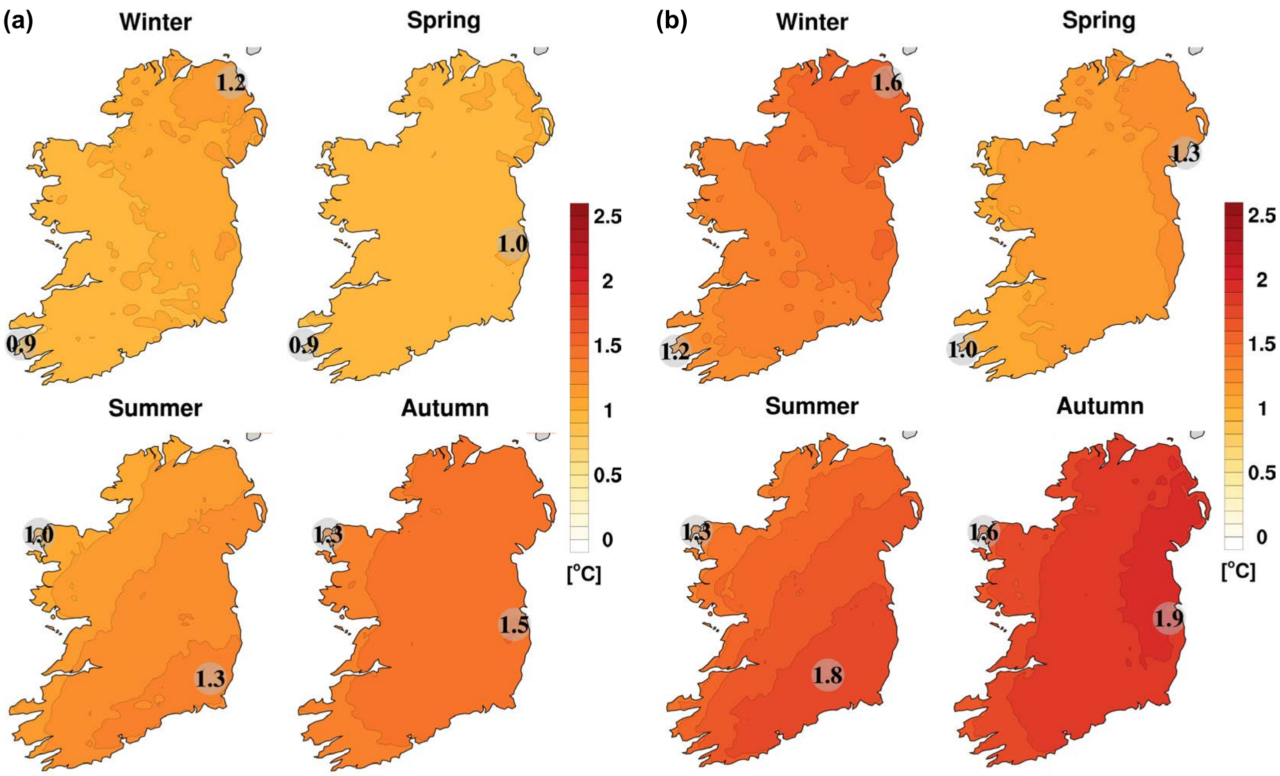

Figure 3.2. Mid-century seasonal projections of mean 2-m temperature change for the (a) RCP4.5 and (b) RCP8.5 scenarios. In each case, the future period, 2041–2060, is compared with the past period, 1981–2000. The numbers included on each plot are the minimum and maximum projected changes, displayed at their locations.

The warming gradient of the annual (Figure 3.1) and seasonal (Figure 3.2) mean projections are also evident in the percentile projections of Figure 3.3. Furthermore, there exists a small variation between the 33rd, 50th and 66th projection percentiles, which demonstrates good agreement (small spread) between ensemble members. Finally, the annual and seasonal warming gradients are similar for both the RCP4.5 and RCP8.5 scenarios. This agreement increases the confidence in the regional projections of temperature.

The annual change in the standard deviation (Figure 3.4) shows small changes of between ≈−0.1°C and ≈0.2°C for both the RCP4.5 and RCP8.5 scenarios.[9] Similarly, the seasonal projected changes in the standard deviation of temperature are small (Figure 3.5); small increases (decreases) are noted for summer (winter) for both RCPs and a mixed signal is noted for spring and autumn. It should be noted that large increases in the mean summer temperature (Figure 3.2) coupled with increases in the standard deviation will lead to enhanced increases in extreme high temperatures (refer to Figure 1.3d for a schematic example of such an outcome). Similarly, increases in mean winter temperature (Figure 3.2) coupled with a decrease in standard deviation will lead to enhanced decreases in extreme low temperatures. However, it should be noted that the projected changes in standard deviation are small for all seasons. The results suggest that although future temperatures will increase substantially for all seasons, the shape of the temperature distribution will remain broadly similar.

3.2 Extreme Temperature Projections

Changes in the daily maximum and daily minimum temperatures are arguably of more immediate importance, since extreme events have an abrupt and much larger impact on lives and livelihoods than a gradual change in mean values (Easterling *et al*., 2000; O'Sullivan *et al*., 2015). A sustained increase in the daily maximum temperature is associated

9 Please refer to section 1.2.4 for an overview of the effects of changes in the standard deviation on the distribution of a climate field.

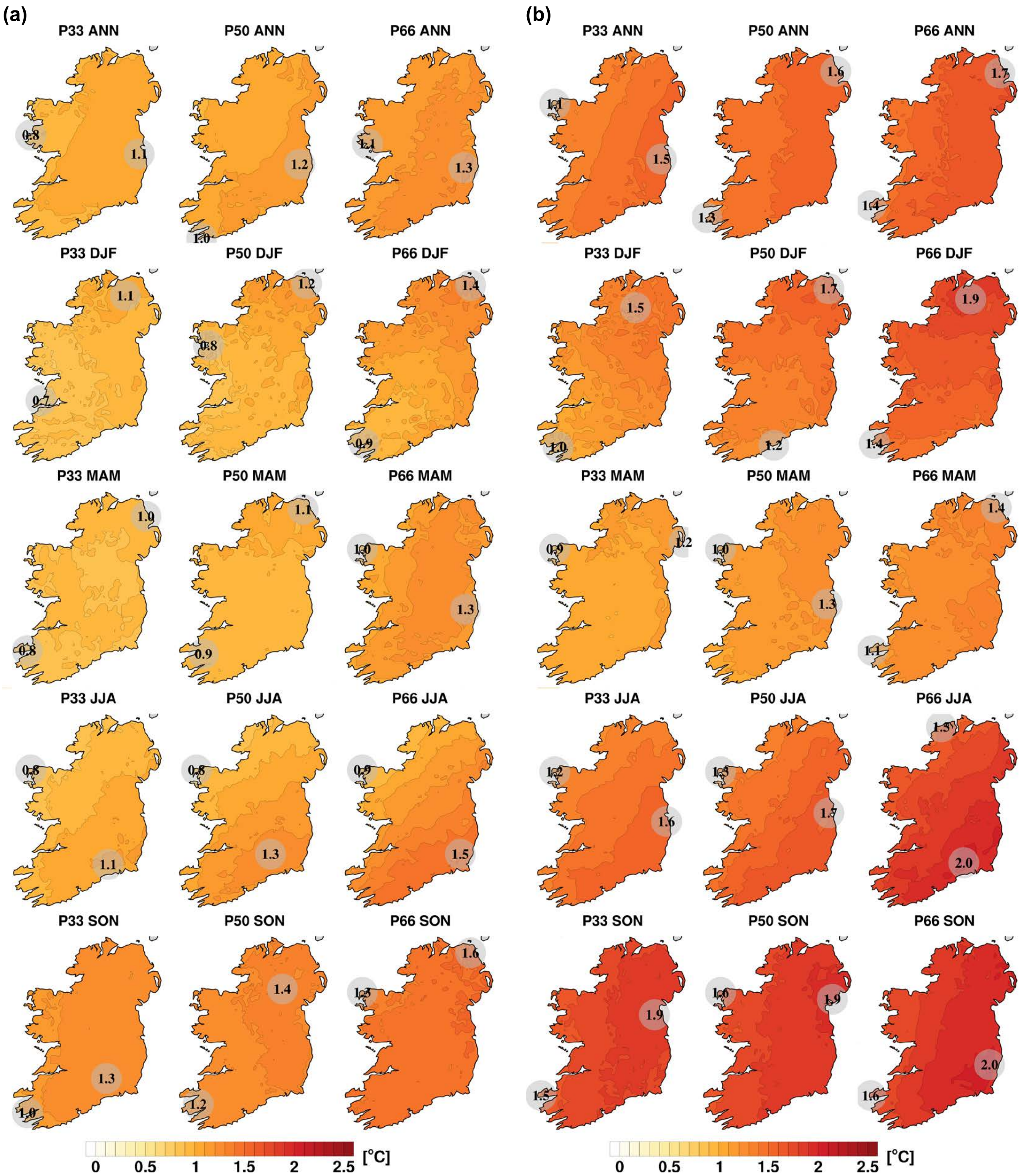

Figure 3.3. The 33rd, 50th and 66th percentiles of annual and seasonal mean 2-m temperature projections for the (a) RCP4.5 and (b) RCP8.5 scenarios. In each case, the future period, 2041–2060, is compared with the past period, 1981–2000. The numbers included on each plot are the minimum and maximum projected changes, displayed at their locations. ANN, annual; DJF, December, January, February; JJA, June, July, August; MAM, March, April, May; SON, September, October, November.

with heatwaves, whereas an increase in the daily minimum temperature will typically imply warmer nights. Figure 3.6a shows how the warmest 5% of daily maximum temperatures are projected to change (TMAX-95%). A strong warming is evident, which is greater than the projected mean summer increase (Figure 3.2), ranging from 1.0°C to 1.6°C for the RCP4.5 scenario and from 1.4°C to 2.2°C for the

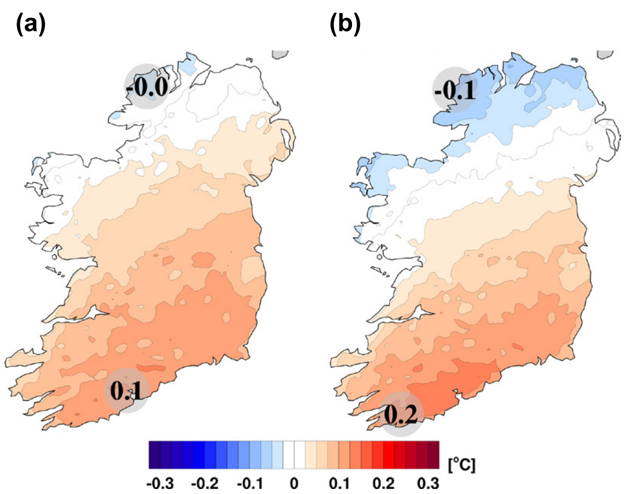

Figure 3.4. Annual projected change in the standard deviation of 2-m temperature for the (a) RCP4.5 and (b) RCP8.5 scenarios. In each case, the future period, 2041–2060, is compared with the past period, 1981–2000. The numbers included on each plot are the minimum and maximum projected changes, displayed at their locations.

RCP8.5 scenario. Warming is greater in the south than in the north.

Figure 3.6b shows how the coldest 5% of daily minimum temperatures are projected to change (TMIN-5%). Again, the projected increase of TMIN-5% is greater than the mean winter increase (Figure 3.2), ranging from 0.9°C to 1.8°C for the RCP4.5 scenario and from 1.2°C to 2.4°C for the RCP8.5 scenario. Warming is greater in the north than in the south.

3.3 Heatwaves

The large projected increase in high summer temperatures (TMAX-95%; Figure 3.6a) suggests an increase in the number of heatwave events by the middle of the century. This is confirmed by Figure 3.7, which presents the projected change in the number of heatwave events over the 20-year period 2041–2060. The increases range from 1 to 8 for the RCP4.5 scenario and from 3 to 15 for the RCP8.5 scenario. Both scenarios exhibit a north-west to south-east

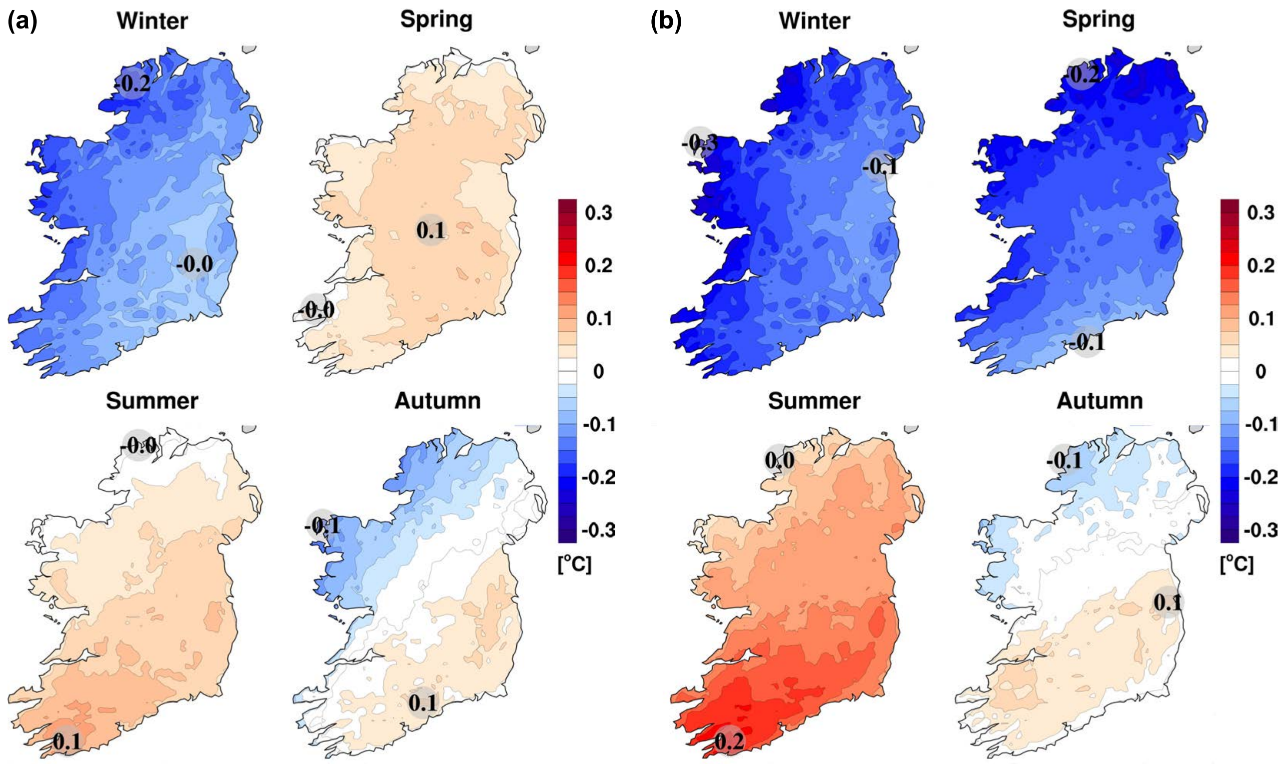

Figure 3.5. Seasonal projected change in the standard deviation of 2-m temperature for the (a) RCP4.5 and (b) RCP8.5 scenarios. In each case, the future period, 2041–2060, is compared with the past period, 1981–2000. The numbers included on each plot are the minimum and maximum projected changes, displayed at their locations.

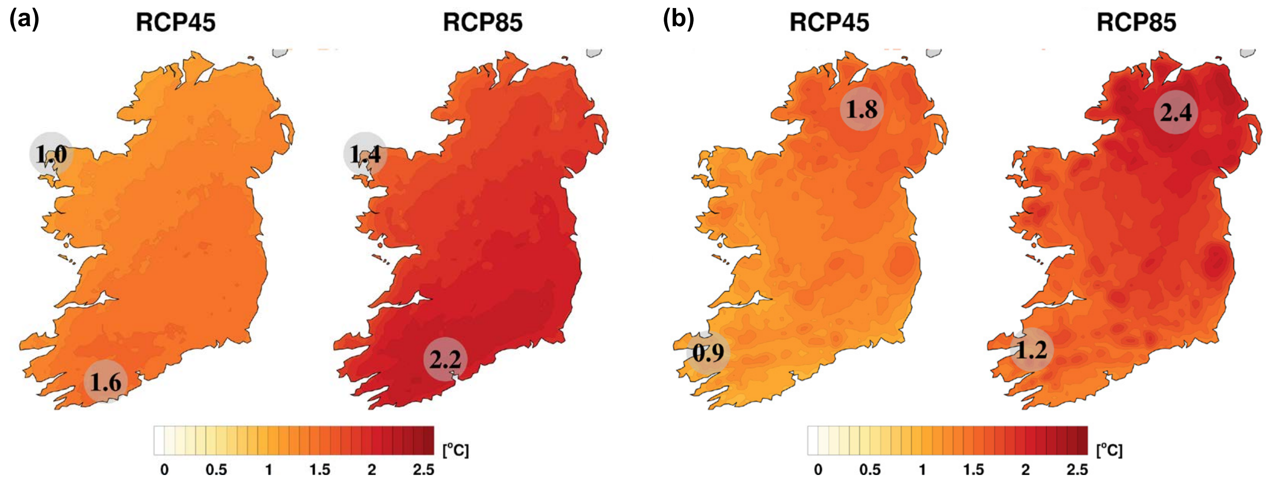

Figure 3.6. Projected changes in mid-century extreme 2-m temperature: (a) top 5% of daily maximum temperatures (warm summer days) and (b) bottom 5% of daily minimum temperatures (cold winter nights). In each case, the future period, 2041–2060, is compared with the past period, 1981–2000. The numbers included on each plot are the minimum and maximum projected changes, displayed at their locations.

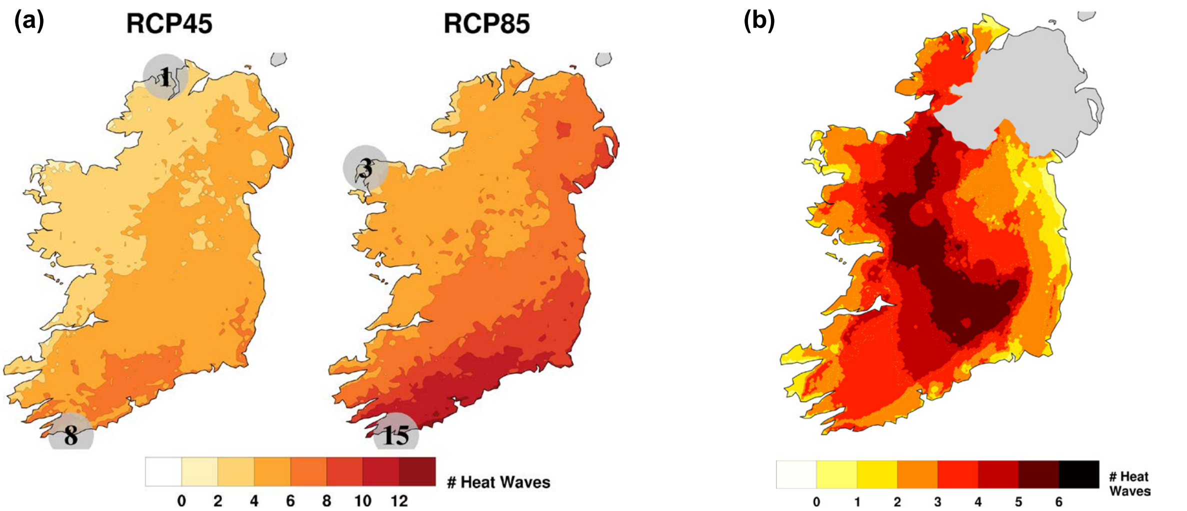

Figure 3.7. (a) The RCP4.5 and RCP8.5 projected change in the number of heatwave events over the 20-year period 2041–2060. In each case, the future period, 2041–2060, is compared with the past period, 1981–2000. The numbers included on each plot are the minimum and maximum increases, displayed at their locations. (b) The observed number of heatwave events over the period 1981–2000.

gradient. For comparison, the observed number of heatwave events over the period 1981–2000 is presented in Figure 3.7b (derived from daily maximum temperature data provided by Walsh, 2012). The projected increase in heatwaves will have a direct impact on public health and mortality, but this may be offset by the projected decrease in frost and ice days (see section 3.4).

For the analysis of the change in number of heatwaves, the following definition as described in Jacob *et al*. (2014) was used: heatwaves are considered as periods of more than 3 consecutive days exceeding the 99th percentile of the daily maximum temperature of the May-to-September season of the control period (1981–2000). Jacob *et al*. (2014) analysed a large ensemble of relatively low-resolution (12.5 km to 25 km) RCMs and showed small