Ireland's Climate: the road ahead

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Edited by Emily Gleeson, Ray McGrath, Mairéad Treanor

Met Éireann, Dublin
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Acknowledgements

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Image of Common Blue butterfly taken in Malahide Estuary, Dublin, supplied by Mary Twomey, LIPF. ©Mary Twomey

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Editors: Emily Gleeson, Met Éireann
Ray McGrath, Met Éireann
Mairéad Treanor, Met Éireann

Authors: Amelia Caffarra, Mary Coleman, Frederic Dias, Hank Dijkstra, Alison Donnelly, Sybren Drijfhout, Ned Dwyer, Sarah Gallagher, Jeremy Gault, Emily Gleeson, Patrick Goodman, Stefan Gray, Valerie Livina, Damien Martin, Ray McGrath, Alastair McKinstry, Conor Murphy, Paul Nolan, Colin O'Dowd, Barry O'Dwyer, John O'Sullivan, Eugenie Regan, Tido Semmler, Conor Sweeney, Roxana Tiron, Séamus Walsh, Fabio Zottele.

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Foreword

It gives me great pleasure to welcome this report which documents recent research on Irish climate change.

The timing of the report is particularly appropriate as it coincides with the launch of the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change. While AR5 addresses climate change on global scales, this report looks closer to home and provides an up-to-date assessment of Irish climate trends.

Over many decades Met Éireann staff have compiled measurements of temperature, pressure and other weather parameters, and these now provide essential "ground truth" for monitoring the Irish climate. More recently, as a partner in the EC-Earth climate modelling consortium, Met Éireann has made important contributions to international projects and local research initiatives. In both its monitoring and modelling activities, Met Éireann plays a key role in implementing Ireland's National Climate Change Adaptation Framework.

We are pleased to facilitate the publication of this collaborative report, which draws together contributions from a wide range of experts and highlights the quality and scope of Irish climate research. On-going scientific work of this calibre will be essential if Ireland is to respond effectively to the challenges ahead.

Liam Campbell
Director
Met Éireann

Summary

New global climate model simulations carried out in Ireland provide an update on the expected changes in the Earth's climate over the 21st century. The global results form part of Ireland's contribution to the science underpinning the IPCC AR5 report.

Data from this new model, and other global models, have been downscaled over Ireland to update the projections for the future Irish climate.

Key results from the global and European simulations

- Mean global land temperatures are expected to rise by 2.7 degrees for the period 2071-2100 under a medium-low emission scenario (RCP4.5) and by up to 5.4 degrees under a high emission scenario (RCP8.5). Warming is greatest at high latitudes, leading to an accelerated loss of Arctic sea-ice cover.
- The estimated warming may be conservative, as "global brightening" associated with a reduction in air pollution may lead to enhanced warming.
- Global mean annual precipitation amounts over land are projected to increase by 4.4 % under RCP4.5 and by up to 7.6% for RCP8.5 by 2071-2100. Under the more extreme RCP8.5 forcing there is a strong signal for wetter winters and drier summers for Europe.
- Cold extremes are predicted to warm faster than warm extremes by about 30% on average with the excessive warming of the cold extremes mainly confined to regions with retreating snow and sea-ice cover.
- There is an overall increase in rainfall extremes over the tropics and extratropics and a decrease over the subtropics.
- Declining Arctic sea ice may increase the likelihood of cold continental air outbreaks over Ireland during winter.

Key results for the Irish climate

- The observed warming over the period 1981-2010 is expected to continue with an increase of ~1.5 degrees in mean temperatures by mid-century; the strongest signals are in winter and summer.
- Warming is enhanced for the extremes (i.e. hot or cold days) with highest daytime temperatures projected to rise by up to 2 degrees in summer and lowest night-time temperatures to rise by up to 2-3 degrees in winter.
- Milder winters will, on average, reduce the cold-related mortality rates among the elderly and frail but this may be offset by increases due to heat stress during summer.
- Winters are expected to become wetter with increases of up to 14% in precipitation under the high emission scenarios by mid-century; summers will become drier (up to 20% reduction in precipitation under the high emission scenarios).
- The frequency of heavy precipitation events during winter shows notable increases of up to 20%.
- Changes in precipitation are likely to have significant impacts on river catchment hydrology.
- The models predict an overall increase (0 to 8%) in the energy content of the wind for the future winter months and a decrease (4-14%) during the summer months.
- A small decrease in mean wave heights is expected around Ireland by the end of the century, while in winter and spring, storm wave heights are likely to increase.
- Expected increases in temperature will further affect the ecologies of Irish butterflies, in particular their flight periods, voltinism, and abundances.
- Birch tree simulations suggest that the advance in bud burst with increasing temperature will be greater in the northeast than the southwest resulting in more homogeneous bud burst across the country towards the end of the century.

Introduction

The distinction between weather and climate is well known: the former is concerned with short-term detail while the latter relates to the statistical details over extended periods (e.g. averages over 30 years). Whereas a short-range weather forecast for Ireland is barely influenced by the weather thousands of kilometres away, climate always has a global context; the impacts of rising greenhouse gases on the Irish climate can only be assessed by using a global model that realistically simulates all of the physical processes that make up the climate system.

Interest in the Irish climate has considerably increased in recent years due to international concerns regarding climate change and the linkage with greenhouse gas emissions. In response, several reports have been produced by Irish researchers that provide projections of the future Irish climate in the coming decades, based on IPCC scenarios of greenhouse gas emissions. Until recently a lot of this work has depended on global climate model simulations produced outside Ireland.

In the lead-up to the latest Fifth Assessment Report (AR5) of the IPCC[1], a major international effort has been on-going over the past few years to update global climate projections. The models have become more refined in terms of detail, more inclusive of physical processes that are important for the climate system and more accurate in representing these processes.

For the first time, Ireland has engaged in this global modelling process by contributing to the scientific development of a new global climate model (named EC-Earth), performing centennial-scale simulations with the model and contributing the data to CMIP5[2] for assessment by IPCC in AR5. The global modelling work was carried out by Met Éireann and ICHEC (Irish Centre for High-End Computing) as partners in the EC-Earth international consortium. Apart from supporting the international community, this work also provides independent information on the future Irish climate in support of the National Climate Change Adaptation Framework (2012)[3].

With the imminent release of the AR5 report, it is timely to provide an update on the projections for the Irish climate. This report, based on the contributions from a broad spectrum of collaborating researchers from Ireland and abroad, documents key results and impacts, and also provides details for the user community regarding access to the data for further research. The report is preliminary in nature and focused to a large extent on the EC-Earth simulations downscaled to Ireland. It is a summary report and its projections will be further refined as the enormous archives of data produced to support the IPCC AR5 are analysed in the future.

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[1] The Fourth Assessment Report (AR4) was launched in 2007.

[2] CMIP5 - Coupled Model Intercomparison Project Phase 5. It acts as a focal point for global coupled modelling activities and a data portal.

[3] Department of the Environment, Community and Local Government. (2012) National climate change adaptation framework: building resilience to climate change, Dublin: DECLG. Available at: *http://www.environ.ie/en/Environment/Atmosphere/ClimateChange/NationalAdaptationFramework/* (accessed 05 Sep 2013).

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1. The path to climate information: global to local scale

Emily Gleeson[1], Paul Nolan[2], Ray McGrath[1]

Global climate simulations with the EC-Earth model are described for the spin up period, the historical period (1850-2005) and the future period (2006-2100). The future simulations are based on prescribed RCP emission scenarios. For the local Irish climate it is necessary to downscale the global data. This is performed using a variety of regional climate models to process the EC-Earth and other global projections. This Multi-Model Ensemble approach provides the basic data to assess the impacts of climate change on Ireland.

The EC-Earth model

Global Earth System Models such as EC-Earth are essential for providing society with fundamental information on the future climate. The EC-Earth consortium consists of research institutes from 10 European Countries (Figure 1) that collaborate on the development of the model and the running of climate simulations. The most recent set of experiments carried out by the consortium was a series of simulations for CMIP5 (Coupled Model Intercomparison Project; Taylor et al., 2012) which fed into this year's IPCC AR5 report.

The simulations were performed using EC-Earth version 2.3, a model consisting of an atmosphere-land surface module coupled to an ocean and sea-ice model (Hazeleger et al., 2010; Hazeleger et al., 2012). Future versions will include other components such as a more complete atmospheric chemistry and aerosol description, dynamic vegetation, a carbon cycle and river routing. Met Éireann and ICHEC were the two Irish institutions involved in both the development of the model and the running of simulations on supercomputers at the European Centre for Medium-Range Weather Forecasting (ECMWF) and the Irish Centre for High-End Computing (ICHEC).

Future versions will include other components such as a more complete atmospheric chemistry and aerosol description, dynamic vegetation, a carbon cycle and river routing.

Before running the CMIP5 experiments, the EC-Earth model first had to be spun up to allow the atmosphere and ocean to adjust and reach equilibrium (Sterl et al., 2012). Greenhouse-gas concentrations for the year 1850 were used during this phase. In all, the model was spun up for over 2000 calendar years, with the final 450 years termed the experiment "control run". The entire spin up for the EC-Earth consortium was carried out by Met Éireann. In total, 14 historical simulations were performed by the EC-Earth community, 3 of these by Met Éireann. To provide an ensemble of simulations, 14 different points in the control run, typically separated by 15 years, were used as starting points for historical simulations; these were then extended into the future using prescribed emission scenarios (RCP4.5 and RCP8.5; see text box Emission scenarios). The historical simulations extend from 1850 to 2005 and include observed greenhouse-gas and aerosol concentrations, and estimated emissions associated with volcanic eruptions. The future simulations run from 2006 to 2100 based on the RCP4.5 and RCP8.5 emission scenarios. Table 1 summarises the global simulations.

The entire spin up for the EC-Earth consortium was carried out by Met Éireann.

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[1] Research, Environment and Applications Division, Met Éireann, Glasnevin, Dublin 9.

[2] ICHEC, Trinity Technology & Enterprise Campus, Grand Canal Quay, Dublin 2 and formerly Meteorology & Climate Centre, School of Mathematical Sciences, UCD, Belfield, Dublin 4.

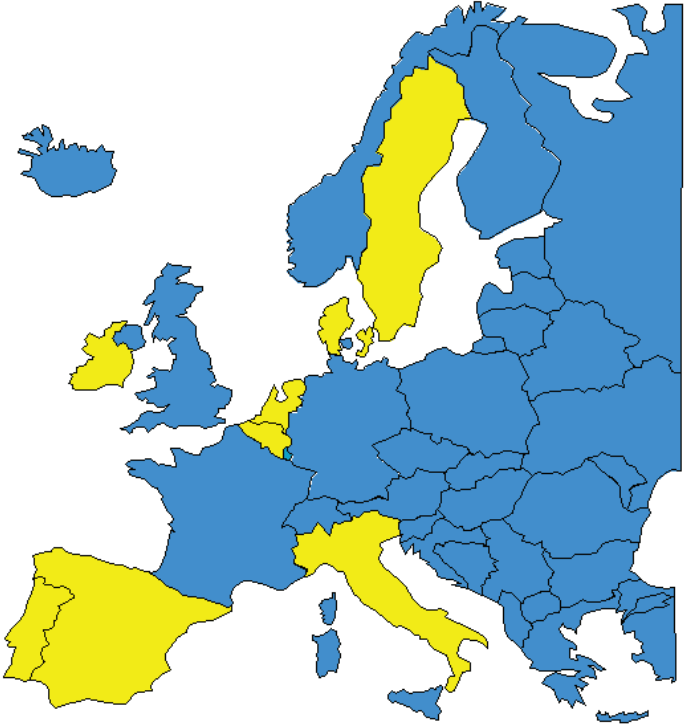

Figure 1. EC-Earth partner countries (highlighted in yellow).

simulation	number of years	years	experiment information
Spin up	1750	Arbitrary	1850 greenhouse-gas concentrations
Control	450	Last 450 years of spin up	1850 greenhouse-gas concentrations
Historical	156	1850 to 2005	Historical greenhouse-gas concentrations
Future	95	2006 to 2100	RCP4.5 and RCP8.5 emission scenarios

Table 1. Details of the global simulations performed by Met Éireann.

Emission scenarios: Representative Concentration Pathways (RCPs)

To estimate future changes in the climate we need to have some indication as to how global emissions of greenhouse gases (and other pollutants) will change in the future. In previous IPCC reports this was handled using Special Report on Emissions Scenarios (SRES e.g. A2 scenario) that were based on projected emissions, changes in land-use and other relevant factors. The new Representative Concentration Pathways (RCP) scenarios are focused on radiative forcing - the change in the balance between incoming and outgoing radiation via the atmosphere caused primarily by changes in atmospheric composition – rather than being linked to any specific combination of socioeconomic and technological development scenarios. Unlike SRES, they explicitly include scenarios allowing for climate mitigation.

Global modelling groups that provided input to CMIP5 agreed to use one or more of these scenarios for their simulations of the future climate. There are 4 such scenarios (RCP2.6, RCP4.5, RCP6.0 and RCP8.5) named with reference to a range of radiative forcing values for the year 2100 or after i.e. 2.6, 4.5, 6.0, and 8.5 W/m2, respectively (van Vuuren et al., 2011). EC-Earth primarily focused on the RCP4.5 (medium-low) and RCP8.5 (high) scenarios[3].

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[3] Some simulations were performed with RCP2.6.

125 km resolution

50 km resolution

18 km resolution

4 km resolution

Figure 2. Ireland and UK as seen by climate models with different horizontal resolutions (image produced by John O'Sullivan).

Downscaling to Ireland

The computational cost of running complex global climate models increases rapidly with the level of climate detail required. To achieve reasonable execution speeds, the model grid is set relatively coarse in comparison with operational weather forecast models. In effect, the climate "pixels" are rather large (see Figure 2), and wash out some of the detail. The relatively coarse grid (125km) used in the EC-Earth global simulations underestimates extremes and local effects, which are important for precipitation and wind modelling in particular.

To capture local climate details it is necessary to downscale the data to a finer grid. This was done over Ireland using the Max Planck Institute's ECHAM5 global climate model (GCM), the UK Met Office's HadGEM2-ES GCM, the CGCM3.1 GCM from the Canadian Centre for Climate Modelling and the EC-EARTH GCM. The EC-EARTH GCM data were provided by Met Éireann. Data from these global climate model simulations (EC-Earth, ECHAM5, HadGEM2-ES and CGCM3.1) were downscaled at the UCD Meteorology and Climate Centre using three different Regional Climate Models (RCMs): COSMO-CLM versions CLM3 and CLM4 (Deutscher Wetterdienst, German Meteorological Service) and WRF (National Center for Atmospheric Research, US). The COSMO-CLM simulations were run at 50km, 18km, 7km and 4km resolutions. The WRF simulations were run at 54km, 18km and 6km resolutions. Simulations were performed on the ICHEC supercomputer. The RCMs were validated by performing 30-year simulations of the Irish climate (1981-2010), and comparing the output to observations.

The sets of global/regional simulations used in the temperature, precipitation and wind analysis studies for Ireland are listed in Table 2. The grid resolution of the downscaled data and the

Global Model (GCM)	Regional Model (RCM)	Grid Resolution (km)	Scenario/Forcing
EC-Earth (me41)	CLM4	4	RCP4.5
EC-Earth (me42)	CLM4	4	RCP4.5
EC-Earth (me43)	CLM4	4	RCP4.5
EC-Earth (me81)	CLM4	4	RCP8.5
EC-Earth (me82)	CLM4	4	RCP8.5
EC-Earth (me83)	CLM4	4	RCP8.5
EC-Earth (me41)	WRF	6	RCP4.5
EC-Earth (me43)	WRF	6	RCP4.5
EC-Earth (me81)	WRF	6	RCP8.5
EC-Earth (me83)	WRF	6	RCP8.5
HadGEM2-ES	CLM4	4	RCP4.5
HadGEM2-ES	CLM4	4	RCP8.5
CGCM3.1	CLM4	4	A1B
CGCM3.1	CLM4	4	A2
ECHAM5 (1)	CLM3 (1)	7	B1
ECHAM5 (2)	CLM3 (1)	7	B1
ECHAM5 (1)	CLM3 (1)	7	A1B
ECHAM5 (2)	CLM3 (1)	7	A1B
ECHAM5 (1)	CLM3 (2)	7	A1B
ECHAM5 (2)	CLM3 (2)	7	A1B
ECHAM5 (1)	CLM4 (1)	7	A1B *
ECHAM5 (2)	CLM4 (1)	7	A1B *
ECHAM5 (1)	CLM4 (2)	7	A1B *
ECHAM5 (2)	CLM4 (2)	7	A1B *

Table 2. Details of the regional simulation datasets used in this report. Simulations marked with an asterisk do not have precipitation data available.

future emission scenario used are also included. The numbers/letters in brackets after the model name are indicative of the ensemble number.

To create a large ensemble, all of the data were regridded to a common 7km grid over Ireland. The simulations carried out using RCP4.5 and the B1 scenario were used to create a "medium-low emission" ensemble while the RCP8.5, A1B and A2 simulations were used to create a "high emission" ensemble. This Multi-Model Ensemble (MME) approach enables the uncertainty in RCM projections to be quantified, providing a measure of confidence in the predictions.

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2. Setting the scene: the climate of Ireland 1900-2012

Séamus Walsh[1]

The availability of high-quality observational data is a key element in future climate modelling and climate research. High-quality observations obtained from our nationwide network are quality controlled and used to describe the climate of Ireland and to identify trends in temperature, precipitation and other parameters where possible. The data have also been used to produce gridded datasets which provide a baseline for climate change studies and verification of climate models including EC-Earth.

The observational network

Underpinning climate research and modelling the future climate there is a fundamental need for high-quality observation data. The earliest evidence of scientific weather observations in Ireland dates from as far back as the 1700s, but it wasn't until the end of the 19th century, under the direction of the 'Meteorological Department' led by Admiral Fitzroy of the Royal Navy that an operational network of observing stations was established. Over the next 80 years or so, the Meteorological Office (now the UK Met Office) managed and developed the observation network in Ireland until the Irish Meteorological Service (now Met Éireann) took responsibility when it was founded in 1936.

The network consists of three main strands; the synoptic network where observations of a wide range of parameters are made at hourly intervals or less, the climate network where observations of precipitation and temperature are made once a day, and the precipitation network where readings of precipitation are made once a day. Currently there are 25 synoptic stations, and approximately 70 climate and 450 precipitation stations, but the number has varied considerably over the years.

While it is important to have a dense network that is representative of the climate, long-term time series are particularly important in assessing climate trends. There are several locations in Ireland with good quality, long time series (e.g. Valentia Observatory and the Phoenix Park), which have quality observation data dating back to the mid-19th century.

The national climate database

Met Éireann maintains the National Climate Database. All observations received by Met Éireann are quality controlled and stored in this database. These observations are the building blocks upon which all climate research is based. Observations of precipitation have been digitised back to 1941 and temperature to 1961. Temperature data from some significant long-term stations have also been digitised. There are also substantial paper records. When the data have been quality controlled they are analysed and used to calculate long-term climate averages or 'normals'. These are 30-year averages of weather elements which define the climate of Ireland. Inhomogeneities may exist in climate data due to changes in station exposure, location and instrumentation or in the observing regime. Work is currently underway to produce homogenised datasets of precipitation and temperature. Gridded datasets at 1km resolution are also produced using geostatistical techniques. These grids are used in climate change studies for verification and as a baseline climatology against which changes can be quantified.

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[1] Climatology and Observations Division, Met Éireann, Glasnevin, Dublin 9.

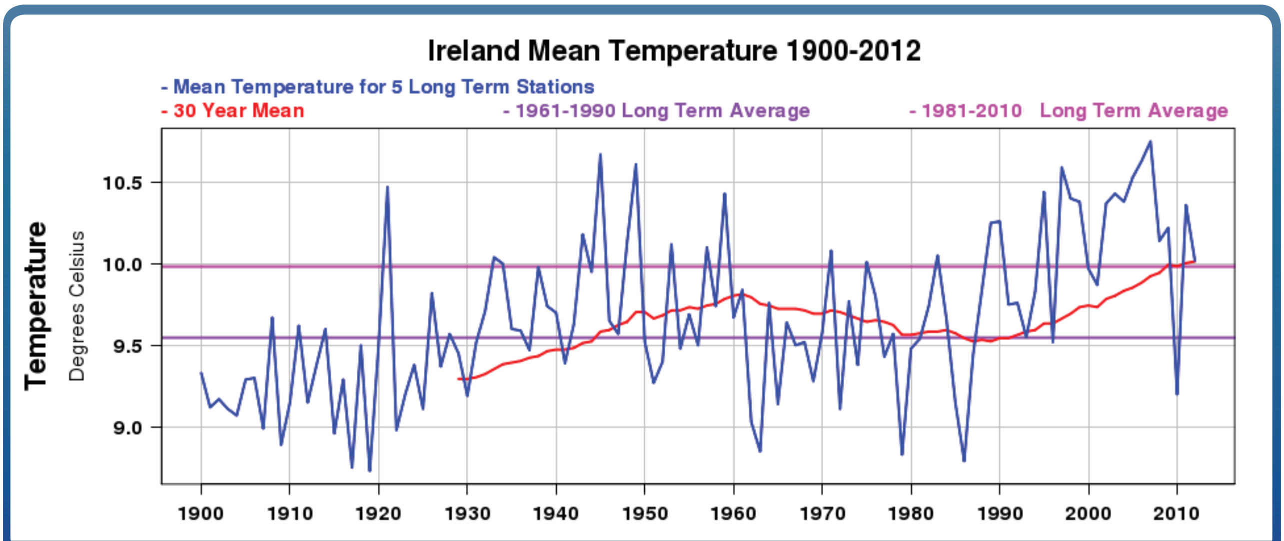

Figure 1. Time series of mean temperatures for 1900-2012 using data from 5 long-term stations, a 30-year running mean (red) and fixed 30-year long-term averages (purple and pink)

Temperature

A time series which is an average of 5 long-term stations is used as an indicator of long-term temperature trends in Ireland. This time series, 1900-2012, shows that the mean annual temperature has increased by approximately 0.8 degrees over that time period (Figure 1). This is consistent with the global rise in air temperatures. The recently published 1981-2010 long-term averages (Walsh, 2012) shows a 0.5 degree increase in mean annual air temperature over Ireland compared with the 1961-1990 long-term averages. All seasons show an increase in temperature with the highest increases occurring in the spring and summer. Analysis of all available digitised station data indicates an increasing trend in the number of warm days (days when maximum temperature exceeds 20 degrees) and a decreasing trend in the number of frost days per year.

The recently published 1981-2010 long-term averages show a 0.5 degree increase in mean annual air temperature over Ireland compared with the 1961-1990 long-term averages.

Precipitation

Precipitation by its nature shows great variation in space and time. Long-term precipitation trends have been calculated for individual stations.

All seasons show an overall increase in precipitation but there are some regional variations, with a decrease in winter precipitation in the south and east.

A national precipitation time series has been derived averaging gridded data over Ireland (Figure 2). The recently published 1981-2010 long-term averages show a 5% increase in mean annual precipitation over Ireland compared with the 1961-1990 long-term averages, with higher precipitation increases over the western half of the country.

Trends in precipitation show greater regional variation than temperatures with occasional conflicting trends from stations which are geographically relatively close. However, there is evidence of an increase in the number of days with heavy rain (10 mm or more) in the west and northwest.

Other parameters

A wide range of additional climate parameters is also observed. They include wind speed and direction, water vapour, upper air temperature and wind, air pressure and radiation. In the case of wind, no long-term trend can be determined with confidence because changes in site exposure and instrumentation make it difficult to obtain consistent wind speed data for periods of more

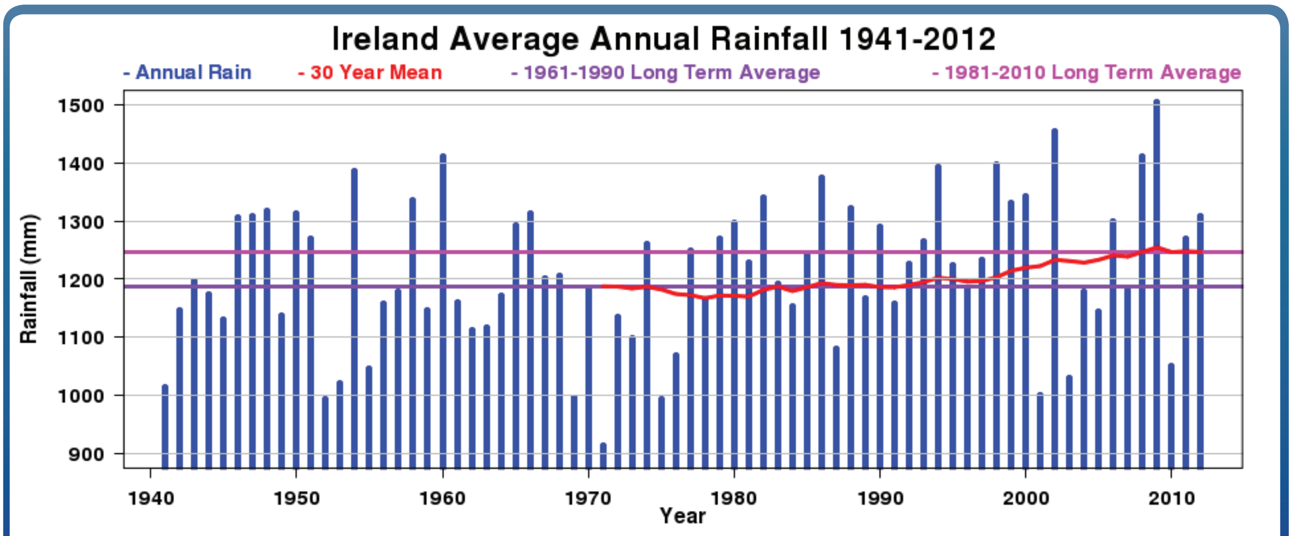

Figure 2. Rainfall time series for Ireland (1941-2012) showing annual totals (blue), a 30-year running mean (red) and fixed 30-year long-term averages (purple and pink).

than 15 to 20 years. In the case of the other parameters either the time series are not long enough or further analysis is required to detect any long-term trends. See Dwyer, 2012 and Walsh, 2012 for further information

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3. Mining the seam of climate data

Alastair McKinstry[1]

Running the climate models is the easy part. Storing and sifting through the data to make them accessible to the user community can be a fraught experience. This article describes the work involved and the international infrastructure that supports climate modelling initiatives.

Climate modelling, particularly when it involves the global climate, creates vast amounts of data. Even in an era when a good laptop computer will be branded as having "terrabyte storage", climate modellers nowadays tend to speak in terms of "petabytes" (PB), the next kilo rung in the storage ladder. EC-Earth, for example, generated around half a petabyte of data.

A petabyte of average MP3 encoded music would take about 2000 years to play.

Not all of the data are saved. Climate modelling focuses on the information contained in the statistics, the creation of which is as challenging a task as running the climate model itself. While daily snapshots of the climate will have little relevant information in isolation, they contribute to the production of statistics such as the means and extreme values taken over decadal periods. Even when the statistical information is extracted, there is still a need to retain a large component of the original data to support climate-related applications; a regional climate model, for example, will ideally require data from the global model at 6-hour intervals.

The second big issue for climate modellers is making the data accessible. It is very costly to run climate models but the end product is a valuable resource that extends our knowledge of climate change and informs policy makers and developers. It also acts as a focal point for further research in the academic community. Having put so much effort into generating this information it is vital that the basic data are made available both nationally and internationally. The national effort is described in more detail in Chapter 15; here, we describe our collaboration with the international community. The focal point for this collaboration is CMIP5.

CMIP5: coordinating global climate modelling

CMIP5 is the Coupled Model Inter-comparison Project, phase 5. It was established to compare global climate models against each other for an agreed set of greenhouse-gas emission scenarios, and against historical observations for the period 1850 to 2005. CMIP5 is closely linked with the current IPCC AR5 report as the global climate model simulations feed into the scientific investigations underpinning the report. Planning and synchronising the EC-Earth modelling experiments to meet the reporting deadline for AR5 turned out to be extremely challenging for the EC-Earth community.

The essence of CMIP5 is simple: agree a set of scenarios to be modelled, have each global model run these scenarios and compare the results. At a meeting in 2008, 20 climate modelling groups in the World Climate Research Programme (WCRP) agreed to run a set of standard experiments. Today, CMIP5 provides a framework for coordinating this international work and includes simulations that were used for assessment in the AR5. The large ensemble of climate simulations that feed into CMIP5 enables researchers to estimate the uncertainty

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[1] ICHEC, Trinity Technology & Enterprise Campus, Grand Canal Quay, Dublin 2

associated with future climate projections.

To ensure consistency and to facilitate comparison of model simulations CMIP5 requested modellers to produce a minimum extensive list of climate products. It also required detailed documentation of model simulations and standardised the units used for physical quantities (e.g. Celsius for temperature). Details of the geographical layout of gridded data, and of the numerical model and how it handles the physics and dynamics of the climate system, also had to be supplied.

The benefit of this standardisation is that it facilitates automated comparisons across model simulations.

Ireland's contribution to CMIP5

For CMIP5, Met Éireann ran a "pre-Industrial control" simulation, 3 ensemble members each for the historical, RCP4.5 and RCP8.5 scenarios (see Chapter 1 for further details) and a set of decadal-prediction simulations.

ICHEC acted as the "data hub" for EC-Earth.

The number-crunching was shared between ICHEC's Stokes supercomputer (Figure 1) and the ECMWF supercomputer in Reading, UK. In total, 14 ensemble member-sets were run across the EC-Earth consortium on a range of systems. All of the resulting data needed to be analysed for correctness and then converted to standard formats. ICHEC acted as the "data hub" for EC-Earth.

Moving all of the data across international networks for conversion and standardisation required a substantial effort; new conversion software had to be written and the storage facilities secured. Once the model simulations were complete, the results needed to be checked for errors, converted and "published" (i.e. details advertised and user access allowed).

Figure 1. The ICHEC Stokes supercomputer.

The data were published using the Earth System Grid (ESG), a schematic of which is shown in Figure 2. This is a federated infrastructure for making climate data and software available - researchers can get accounts giving access to CMIP5 data. Portal websites enable dataset searching e.g. to discover which variables are available for which experiments and to enable data downloads. The federation consists of a core of sites (initially PCMDI, the Program for Climate Model Diagnostics and Intercomparison, based at Lawrence Livermore, California; BADC, the British Atmospheric Data Centre and the World Data Centre for Climate, at DKRZ in Germany). These hold a core of about 500 TB of climate data and act as a gateway to about 5 PB of further climate data held on data nodes at local sites including ICHEC.

In 2008, the e-INIS initiative was established to provide the e-Infrastructure for Ireland. Funded under the Programme for Research in Third Level Institutions (PRTLI), this combined existing resources such as the Stokes computer at ICHEC, the upgraded optical fibre network (10 Gbit/s) from HEAnet connecting Irish universities and the Grid software infrastructure from Grid Ireland, with a new storage system capable of storing 1 PB of data across multiple locations; this was managed by DIAS. It was decided that

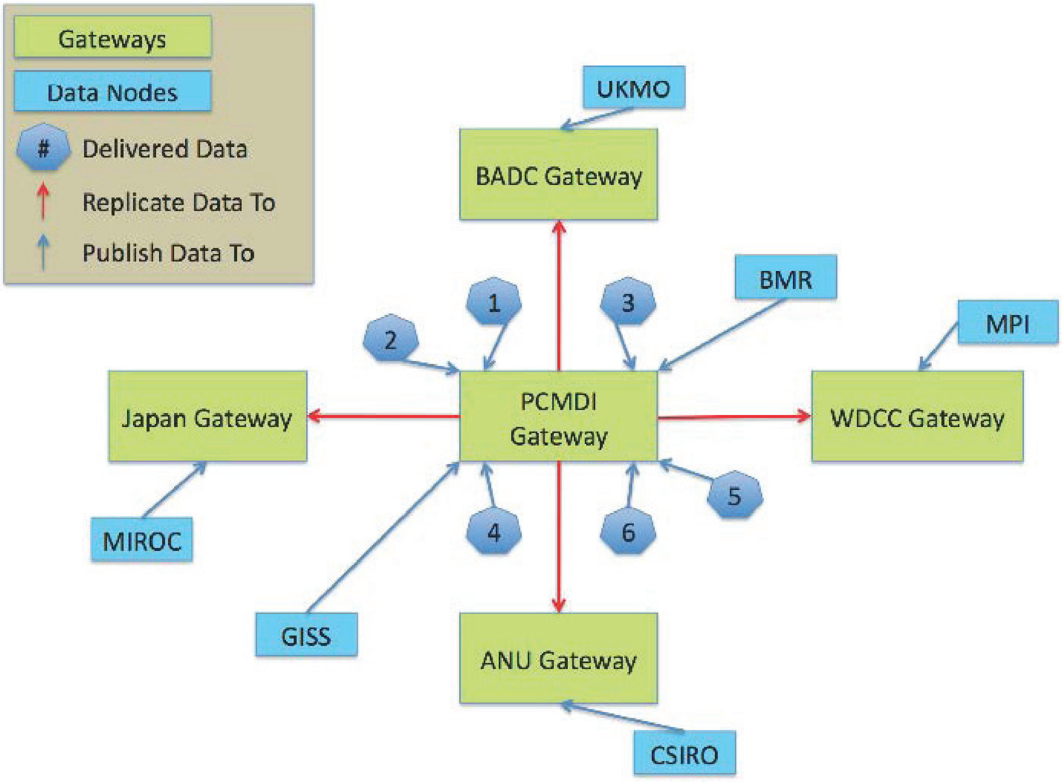

Figure 2. Structure of the Earth System Grid network: The ICHEC data node uploads to BADC, which replicates to the main centres around the world, in particular the PCMDI. Smaller model datasets may be sent by tape; larger modeling centres such as the UK Met Office (UKMO) and ICHEC run data nodes holding all of the data for their models (HadGEM and EC-Earth respectively), with the BADC and PCMDI holding caches of the most frequently used datasets.

ICHEC would use this storage infrastructure to publish the CMIP5 data for the EC-Earth consortium.

ICHEC and e-INIS agreed to set up and host a data node for the Earth System Grid, one of only twelve or so around the world. This was then connected to the BADC gateway. When data were published, they were made public on the ESG node, becoming visible on the search engines at BADC and PCMDI. A core of these data was cached elsewhere on the Earth System Grid but most of the data were made available via e-INIS.

As previously mentioned, not all data can be saved due to pressure on storage facilities. Forecasts for the most common weather elements (wind, temperature, pressure, precipitation, cloud cover, etc.) were saved at 3-hour or 6-hour intervals, together with daily and monthly statistical averages. Datasets were organised into "priority groups" to minimise the storage space needed at any time for processing and to speed up the publishing of the most important data.

Data were then sent to ICHEC from the EC-Earth partners. All ocean data were processed at ICHEC. Given the slower timescales in ocean models, only monthly averages were required and the data volumes were smaller. The atmospheric data from the Met Éireann ensemble runs, and two other institutions, were also processed at ICHEC.

The processing of data for CMIP5 took over 18 months. Approximately 130 TB were finally published but nearly 2 PB of data were transported over the e-INIS network for processing (sometimes multiple times, as issues were discovered in quality control). The largest datasets took 2-3 months to download as bandwidth needed to be limited to avoid operational issues at national meteorological centres.

It is fair to say that the amount of effort involved in coordinating and actually carrying out the post-processing work was underestimated by the EC-Earth community. For example, eventually, over 8 million files were processed, well in excess of the 200,000 originally planned. Nevertheless, the project has successfully delivered a large body of climate simulation data for users and valuable lessons have been learned for the future (e.g. for participation in CMIP6).

Current status of the archive

The CMIP5 archive for the IPCC AR5 report was "closed" on 15 March 2013; all data to be used in papers in the IPCC report needed to be in the archive by this date. Experience from previous CMIP experiments has shown that the data will be used at an exponentially growing rate for many years to come, up until the CMIP6 round. For this reason further data will be accepted into the archive until 2014 and it is planned to make the data available for as long as possible. The EC-Earth data are currently being used for downscaling experiments for Ireland and it is hoped that the CMIP5 archive will continue to be a valuable asset in studying climate change.

Acknowledgements

The work of Honoré Tapamo at ICHEC in porting and optimising the EC-Earth model at the beginning of the project is acknowledged, and also the work of Keith Rochford (e-INIS system) and David Callaghan, formerly of TCD.

4. The earth's climate at the end of the century

Emily Gleeson[1] , Tido Semmler[2],
Conor Sweeney[3], Ray McGrath[1]

Local climate is dependent on the global climate. Here, a global picture on climate change is presented using predictions from the EC-Earth simulations for the end of the century. The results indicate a general rise in annual mean temperature everywhere: 2-4 degrees (global average), 1-6 degrees (over Europe) and 1-4 degrees (Ireland). Changes in precipitation are more varied: large increases (>100%) at high northern latitudes and in the equatorial Pacific but decreases of more than 50% over the subtropics; winters in Europe are predicted to be up to 20% wetter and summers up to 20% drier. Changes in extremes are also presented in this chapter.

Introduction

Climate change not only means changes in the average climate but also changes in the frequency and intensity of extreme weather and climate events. It is recognised that extreme events such as severe flooding, droughts, and heat/cold waves can have important socioeconomic consequences. Changes in their frequency and intensity are therefore of particular interest to policymakers and stakeholders. Numerous studies have shown that the scale and frequency of extreme events are changing and will change further due to climate change (IPCC 2012).

As already mentioned in Chapter 1, Met Éireann ran 3 of the 14 EC-Earth historical simulations which span the years 1850 to 2005; these included observed greenhouse gas and aerosol concentrations, and contributary emissions from volcanic eruptions. Met Éireann also ran 6 of the 28 simulations of the future climate (2006-2100) carried out under the RCP4.5 and RCP8.5 greenhouse-gas emission scenarios (medium-low and high emission scenarios respectively) (van Vuuren et al., 2011); see also Chapter 1.

Here we present potential future changes in global temperature and precipitation, as well as changes in extremes, which could have more significant consequences. In this analysis, 16 of the EC-Earth ensemble simulations of the future climate were used with all projected changes calculated relative to the reference 30-year period 1961-1990. For the extremes, changes in the highest daytime temperatures, lowest night-time temperatures and highest daily precipitation amounts were analysed.

Past, present and future temperatures

The EC-Earth model temperature data compare reasonably well with available observation data including the CRU TS3.1 (Mitchell and Jones, 2005) and E-OBS (Haylock et al., 2008) datasets. For example, the EC-Earth annually averaged global mean temperature anomaly[4] over land (relative to the period 1961-1990), a commonly quoted parameter when it comes to climate change, agrees with the CRU dataset mostly to within 0.3 degrees as shown in Figure 1.

The EC-Earth model temperature data compare reasonably well with available observation data including the CRU TS3.1 (Mitchell and Jones, 2005) and E-OBS (Haylock et al., 2008) datasets.

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[1] Research, Environment and Applications Division, Met Éireann, Glasnevin, Dublin 9.
[2] Alfred Wegener Institute, (Building F-115), Bussestrasse 24, D-27570 Bremerhaven, Germany.
[3] Meteorology & Climate Centre, School of Mathematical Sciences, UCD, Belfield, Dublin 4.
[4] The temperature anomaly referred to in this chapter is the temperature relative to the average temperature during the period 1961-1990.

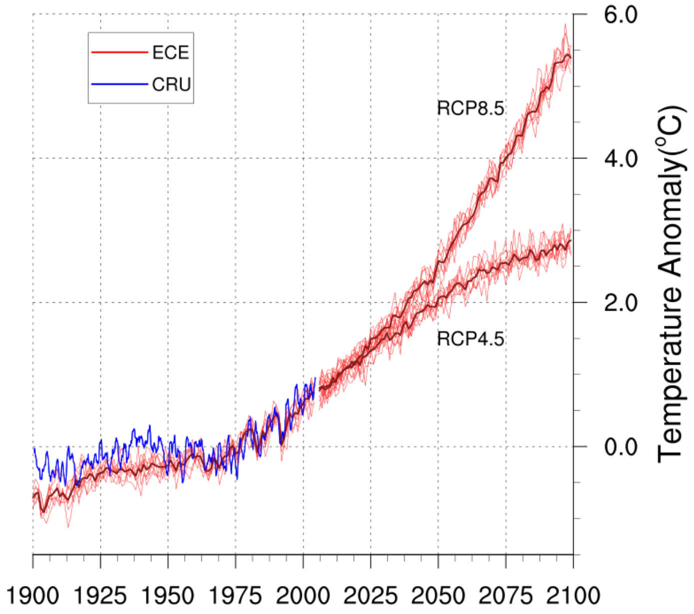

Figure 1. Mean temperature anomaly [°C] over land for an EC-Earth ensemble (ECE) compared to the CRU TS3.1 dataset (CRU). The observation dataset covers the period 1901-2004 and the EC-Earth future projections span the years 2006-2100 for the RCP4.5 and RCP8.5 scenarios.

The geographical patterns of past 2m temperatures also compare very well to observations with the biases within +/- 2 degrees over most of Europe and to within 1 degree over Ireland. The EC-Earth model tends to underestimate the highest temperatures and overestimate the lowest temperatures, with larger biases for these extremes (up to 5 degrees over many parts of Europe[5]) . Finally, performance indices by Reichler and Kim show that the EC-Earth model is very competitive with other global climate models in terms of performance (Hazeleger et al. 2012).

Future projections of the annual mean global land temperature anomalies are also shown in Figure 1. Under the RCP4.5 scenario the EC-Earth ensemble predicts changes of about 2.7 degrees for the period 2071-2100 and changes of about 5.4 degrees under the RCP8.5 scenario.

Under the RCP4.5 scenario the EC-Earth ensemble predicts changes of about 2.7 degrees for the period 2071-2100 and changes of about 5.4 degrees under the RCP8.5 scenario.

Figure 2 shows the changes in the mean JJA (June, July, August) and DJF (December, January, February) temperatures for the period 2071-2100 compared to the reference period 1961-1990. Note that both land and ocean areas are included in this case. When including sea areas, temperature increases are smaller because the sea tends to warm up more slowly than the land, as can be seen in Figure 2. Areas in the Arctic Ocean with sea-ice coverage during the Northern Hemisphere winter and around the Antarctic continent during the Southern Hemisphere winter are exceptions. The globally averaged mean land and sea temperature changes are approximately 2 to 2.5 degrees under the RCP4.5 scenario and between 3.5 and 4 degrees for the RCP8.5 scenario. Mean temperatures over Europe are predicted to mostly rise by between 1 and 4 degrees under RCP4.5, with Ireland nearer the lower end of

The globally averaged mean land and sea temperature changes are approximately 2 to 2.5 degrees under the RCP4.5 scenario and between 3.5 and 4 degrees for the RCP8.5 scenario.

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[5] A gridded dataset of temperature maxima and minima and daily precipitation was only available over Europe (E-OBS dataset). Hence, the analysis of past extremes was confined to the area covered by this dataset.

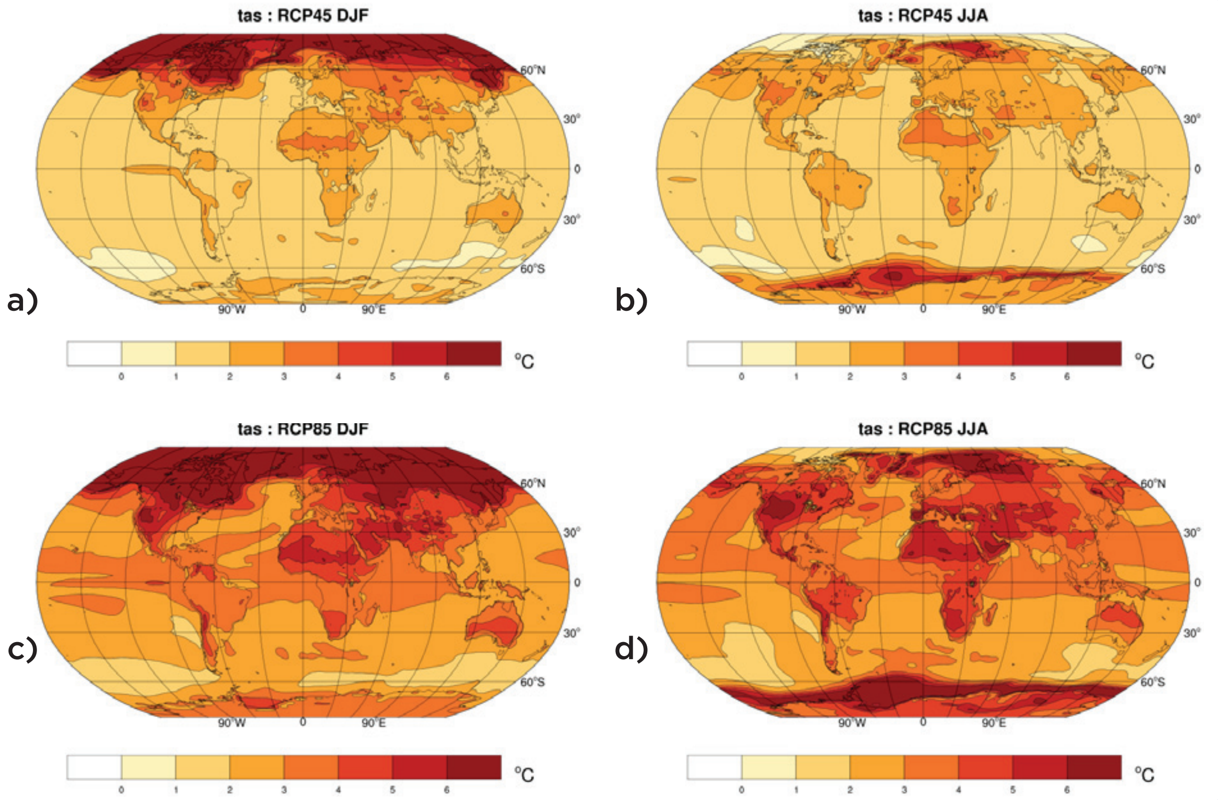

Figure 2. Changes in 2071-2100 mean 2m temperature [°C] relative to 1961-1990 for the following cases (a) DJF RCP4.5 (b) JJA RCP4.5 (c) and (d) similar to (a) and (b) but for RCP8.5.

these changes. The projected increases are even greater for the RCP8.5 projections as shown in Figure 2(c) and (d).

This means that extreme summer maximum temperatures could exceed 35 degrees by the end of this century.

In all regions of the globe, the EC-Earth model simulates increases in the highest daytime temperatures (Figure 3(a) and 3(b) for JJA). The ensemble predicts global mean changes of ~2 degrees and ~3.5 degrees under RCP4.5 and RCP8.5 respectively. In the more extreme RCP8.5 case, the projected changes over the Arctic region are over 20 degrees in places due to sea-ice reductions and/or complete removal. The increases in the lowest night-time temperatures are slightly greater (Figure 3(c) and 3(d) for DJF) than the increases in extreme daily maxima, with the greatest changes over high northern and southern latitudes due to projected changes in sea-ice cover. For Europe the highest summer temperatures are predicted to rise by 2-5 degrees under RCP4.5 but by up to 8 degrees under RCP8.5 in parts of southern Europe. Over Ireland the EC-Earth ensemble predicts increases of 2-3 degrees in the highest summer temperatures under the medium-low scenario RCP4.5 but by up to 4-5 degrees under RCP8.5. This means that extreme summer maximum temperatures could exceed 35 degrees by the end of this century (see Chapter 5 regarding heat waves and mortality). The changes in the lowest wintertime temperatures are more pronounced, particularly for eastern Europe where increases of up to 10 degrees are predicted while for Ireland the changes in lowest night-time winter temperatures are between +2

The EC-Earth ensemble predicts changes of 2.7 and 4.6 degrees in global mean temperatures over land by 2071-2100 for the RCP4.5 and RCP8.5 scenarios with corresponding global annual precipitation increases of 4.4% and 7.6%.

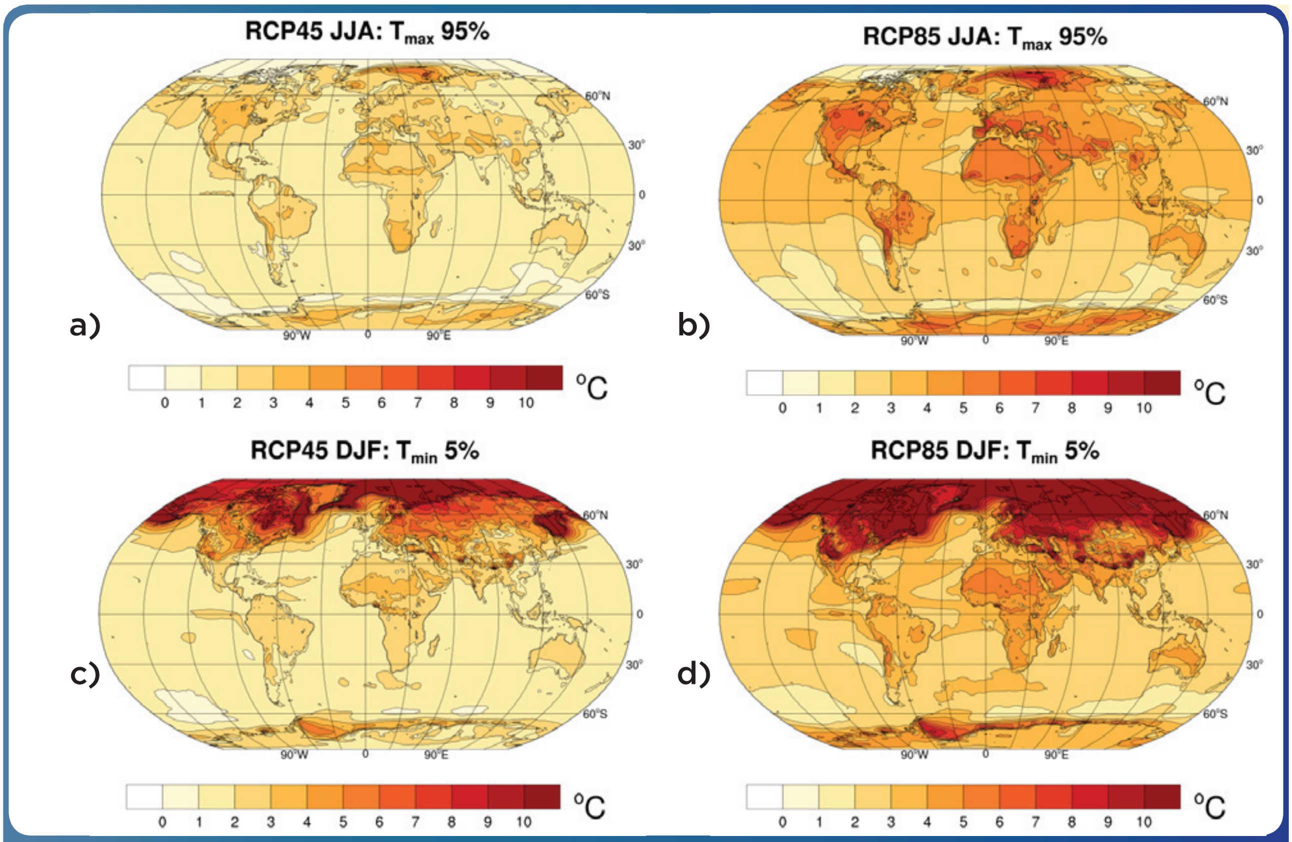

Figure 3. Changes in 2071-2100 highest daytime temperatures [°C] relative to 1961-1990 for the following cases (a) JJA RCP4.5 (b) JJA RCP8.5. (c) and (d) are similar to (a) and (b) but show lowest night-time temperatures for DJF.

and +4 degrees. However, cold winters will still be possible due to the natural variability in the climate system (see also Chapters 5 and 13).

Global precipitation: past, present and future

Global annual precipitation amounts compare quite well to the CRU and GPCC (Rudolf and Schneider, 2005) observation datasets as shown in Figure 4 with the geographical patterns of past precipitation also comparing very well to observations. As a percentage of global average precipitation over land, the biases between the EC-Earth data and the observation datasets are mostly between 3% and 8%. The EC-Earth model tends to overestimate highest daily precipitation amounts by 20-40% over parts of western and southern Europe during summer but underestimates it in many of these areas during winter. While there are notable biases, for example in areas with complex topography, it is important to note that the EC-Earth ensemble does reproduce peaks of extreme precipitation over the Alps and Norway.

Global mean annual precipitation amounts over land are projected to increase by 4.4% under RCP4.5 by 2071-2100 and by 7.6% for RCP8.5 (Figure 4). Changes in annual mean precipitation (land and sea areas included) for the period 2071-2100 relative to 1961-1990 are depicted in Figure 5. For both RCP scenarios there are increases over the Arctic and Antarctic and equatorial regions and decreases over the subtropics. For the extratropics, including most of Europe, the signal is more varied. Under RCP4.5 there is an indication of a slight increase in winter precipitation and a slight decrease in summer. However, under the more extreme RCP8.5 forcing, there is a stronger signal for wetter winters and drier summers for Europe.

Projected changes in highest daily precipitation amounts are shown in Figure 6 where similar trends in wetter/drier areas can be seen. For the

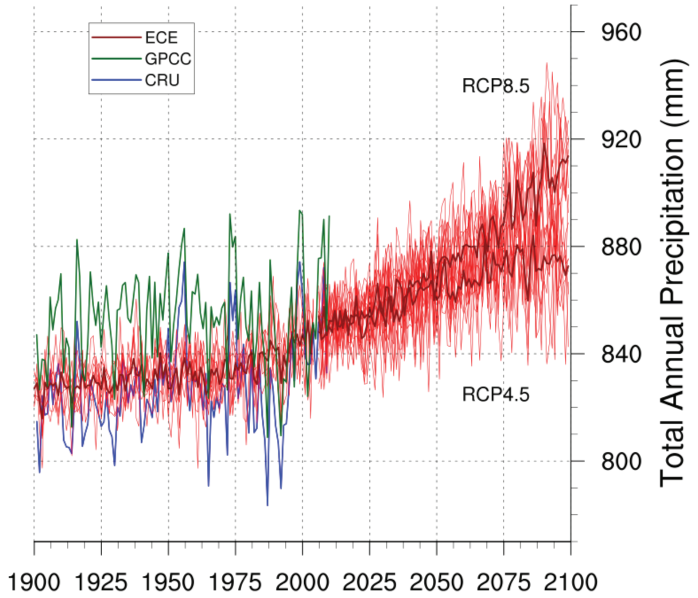

Figure 4. Mean annual precipitation [mm] over land compared to the CRUTS3.1 and GPCCv6.0 datasets. The observation datasets cover the period 1901-2004 and the EC-Earth future projections span the years 2006-2100 for the RCP4.5 and RCP8.5 scenarios.

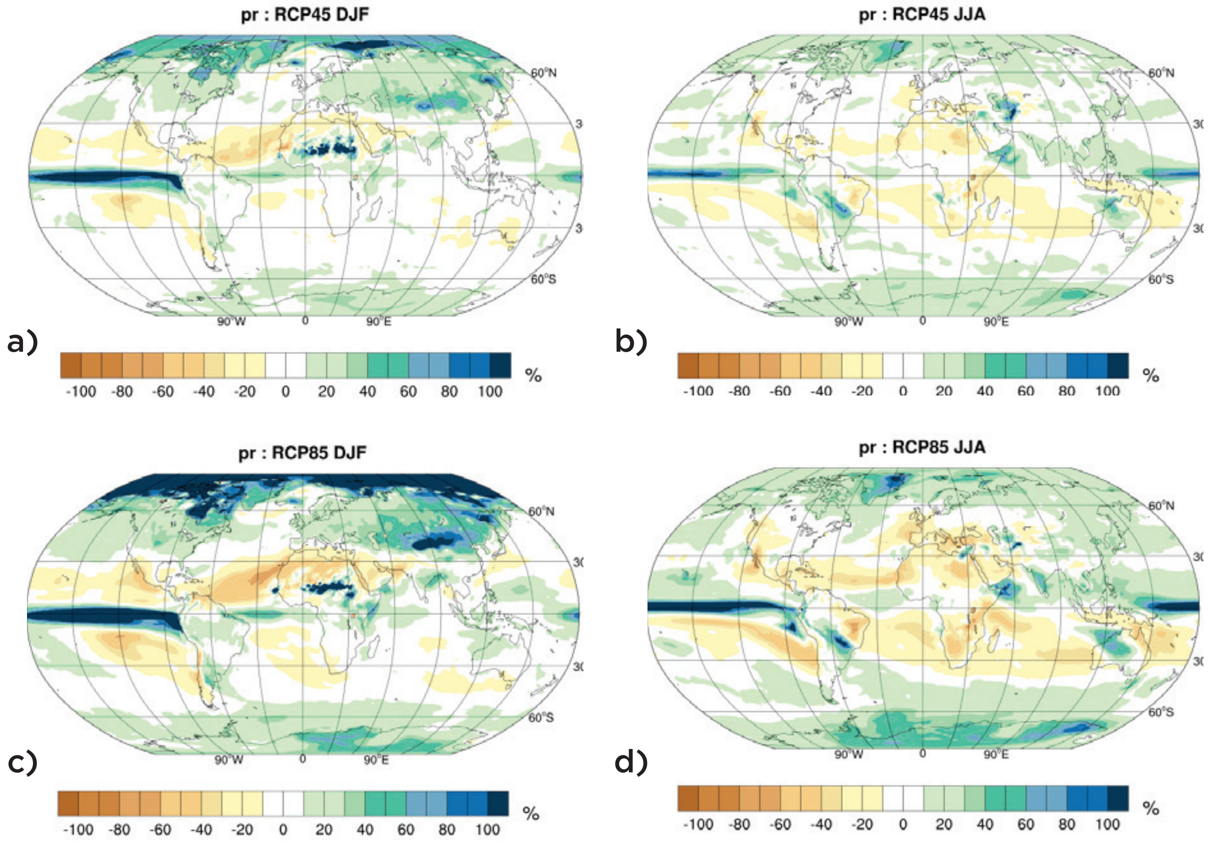

Figure 5. Changes in 2071-2100 precipitation [%] relative to 1961-1990 for the following cases (a) DJF RCP4.5 (b) JJA RCP4.5. (c) and (d) as (a) and (b) but for RCP8.5.

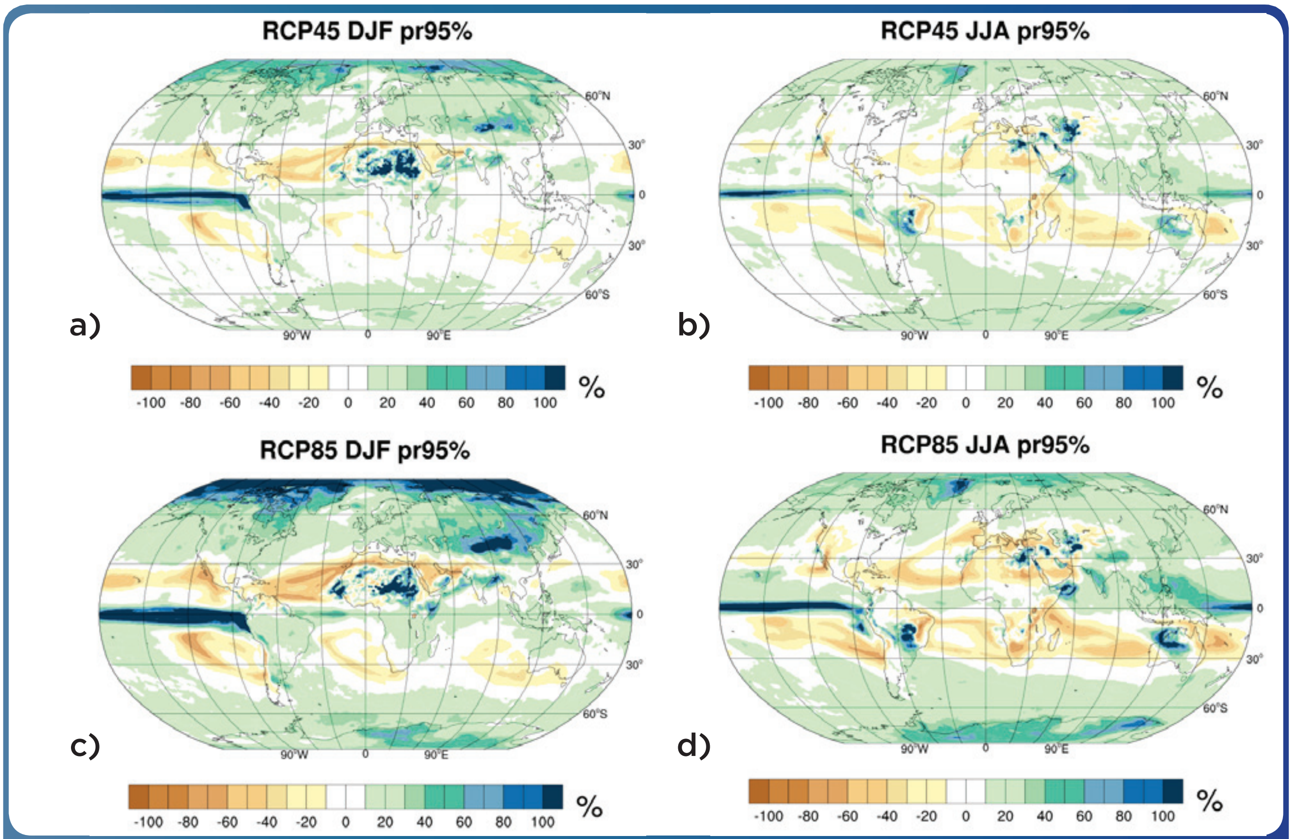

Figure 6. Changes in the highest daily precipitation [%] relative to 1961-1990 for the following cases (a) DJF RCP4.5 (b) JJA RCP4.5. (c) and (d) as (a) and (b) but for RCP8.5.

For Ireland, there are suggested increases in extreme precipitation in winter but there is no strong signal for summer.

RCP8.5 case the most notable changes are the increases in highest daily precipitation amounts over the Arctic and equatorial Pacific by over 100% and the strong decreases in the subtropical zones. For Ireland, there are suggested increases in extreme precipitation in winter but there is no strong signal for summer. However, the global model does not provide an accurate description of precipitation over geographically small areas; within the model, surface features such as Irish mountains and valleys are not fully resolved and the smoothed features compromise the quality of the simulated precipitation. A more accurate description is provided by downscaling the global data to a finer grid. See Chapter 9 for more detail and the expected changes in precipitation for Ireland.

Conclusions

Depending on the emission scenario, the EC-Earth suite of global climate simulations predicts increases of ~3 degrees (RCP4.5) and ~5 degrees (RCP8.5) in global mean temperatures over land by 2071-2100 with corresponding global annual precipitation increases of ~5% (RCP4.5) and ~8% (RCP8.5). Cold extremes are predicted to warm faster than warm extremes by about 30%, globally averaged. Rainfall extremes are projected to increase over the tropics and extratropics and decrease over the subtropics with wetter winters and drier summers predicted over much of Europe, particularly under the RCP8.5 scenario.

Mean temperatures over Ireland are predicted to increase by 1-3 degrees under RCP4.5 and 2-4 degrees under RCP8.5. Warm extremes are expected to rise by 2-3 degrees (RCP4.5) but by up to 5 degrees under RCP8.5 with similar

increases in cold extreme temperatures (ie. less cold). Under RCP4.5 there is no strong signal for changes in precipitation over Ireland for winter but for summer a decrease in the order of 20% is signalled. Under RCP8.5 an increase in winter precipitation of up to 40% is predicted for Ireland while the decrease during summer is still signalled. Both scenarios show increases in extreme precipitation during winter but there is no signal during summer.

Acknowledgements

We would like to acknowledge the Irish Centre for High-End Computing (ICHEC) and the European Centre for Medium-Range Weather Forecasting (ECMWF) for the use of their computing facilities and the EC-Earth consortium for the use of their CMIP5 global simulation data. We also acknowledge the E-OBS dataset from the EU-FP6 project ENSEMBLES *(http://ensembles-eu.metoffice.com)* and the data providers in the ECA&D project (*http://eca.knmi.nl*). The GPCC Precipitation data were provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA through their web site at *http://www.esrl.noaa.gov/psd/*. We would also like to acknowledge the University of East Anglia Climatic Research Unit (CRU) for the use of the CRU Time Series (TS) high resolution gridded datasets and Alastair McKinstry, ICHEC, for technical support.

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5. Climate change: impacts on Irish temperatures

Paul Nolan[1], Pat Goodman[2], John O'Sullivan[3],
Conor Sweeney[3], Emily Gleeson[4],
Ray McGrath[4]

The impacts of climate change on air temperatures over Ireland are assessed for mid-century using downscaled climate simulations based on medium-low and high emission scenarios. Projections indicate a rise of ~1.5 degrees in mean temperatures, with the strongest signals in winter and summer. The changes also show regional variation. Warming is enhanced for the extremes (i.e. hot or cold days) and pronounced in winter night-time temperatures. Milder winters will, on average, reduce the cold-related mortality rates among the elderly and frail but this may be offset by increases due to heat stress in the warmer summers.

Introduction

The full impact of rising greenhouse gas concentrations on the global climate is difficult to evaluate due to the interactions and dependencies between the numerous physical processes that make up the system. However, basic physics provides a direct link between temperatures and greenhouse-gas concentrations. With rising concentrations the atmosphere becomes more opaque at infrared wavelengths, reducing the heat lost to space; the net result is that the earth is absorbing more energy than it radiates and this imbalance (~0.5Wm^{-2}; Hansen et al., 2011) warms the planet. The warming is evident in the Irish observational records (see Chapter 2).

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The effect is well marked in the global model simulations when the radiative forcing associated with greenhouse gases is increased. The warming is not regionally uniform and is amplified at the Arctic latitudes, for example.

In addition to changes in mean temperatures, there are also impacts on the extremes. This is reflected in the observational record in recent decades and is expected to continue in the future (Seneviratne et al., 2012) with consequences for human health and mortality.

The current study aims to assess the impacts of climate change on air temperatures over Ireland. To address the issue of model uncertainty, a large ensemble of simulations were run. The models were run at high resolution, up to 4 km, thus allowing us to better assess the regional variations in temperature increases. Details regarding the different global climate datasets, the greenhouse-gas emission scenarios and the downscaling models used to produce the ensemble of climate projections for Ireland are summarised in Chapter 1. The consequences of rising temperatures on human health and mortality in Ireland are also assessed.

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[1] ICHEC, Trinity Technology & Enterprise Campus, Grand Canal Quay, Dublin 2 and formerly Meteorology & Climate Centre, School of Mathematical Sciences, UCD, Belfied, Dublin 4.

[2] School of Physics, Dublin Institute of Technology, Kevin Street, Dublin 8.

[3] Meteorology & Climate Centre, School of Mathematical Sciences, UCD, Belfield, Dublin 4.

[4] Research, Environment and Applications Division, Met Éireann, Glasnevin, Dublin 9.

[5] References are to air temperatures (i.e. 2m above the ground).

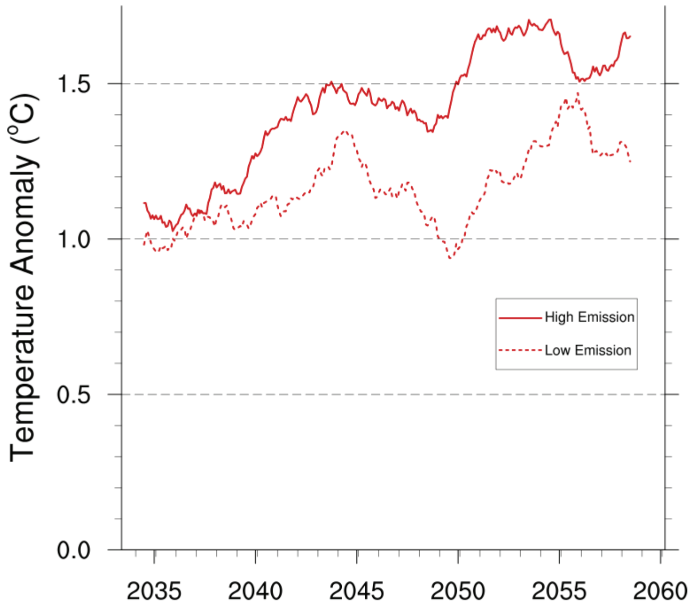

Figure 1. Ensemble mean of average monthly temperature anomaly for Ireland for the years 2035-2060 for the high and medium-low emission scenarios.

Changes in mean temperatures

Projected changes in temperature for Ireland (based on an ensemble sample), spatially averaged, are shown in Figure 1. Results are presented as an "anomaly" relative to the average temperature over the period 1981-2000, which is used as a reference. As expected, and consistent with the global EC-Earth model projections, there is a general upward trend in temperature which is more pronounced for the high emission scenario. Note, however, the large variability over short periods; the warming trend is essentially superimposed on the background or natural variability, of the climate, which is expected to continue in the presence of rising greenhouse-gas concentrations.

Figure 2 shows the areal distribution of temperature changes for 2041-2060 relative to 1981-2000, stratified by season. As the spatial patterns are similar for the high and medium-low emission scenarios only the results for the former are shown.

Spring shows a projected increase in temperature of around 1 degree for both the high and medium-low emission scenarios, with more warming expected in the east than in the west. Autumn shows a similar east-west pattern, but with greater warming: up to 1.5/1.4 degrees for the high/medium-low emission scenario.

The patterns are different for summer and winter. Summer temperatures show increases from 1 degree in the northwest to 1.5 degrees in the southeast (0.8 and 1.3 degrees respectively for the medium-low scenario). Winter temperatures, on the other hand, show increases ranging from 1.2 degrees in the southwest to 1.7 degrees in the northeast (0.8 to 1.2 degrees respectively for medium-low scenario). The temperature gradient is therefore from northwest to southeast in summer but from southwest to northeast in winter.

Changes in temperature extremes

Changes in the daily maximum and daily minimum temperatures are arguably of more immediate importance to people, since extreme events have an abrupt and much larger impact

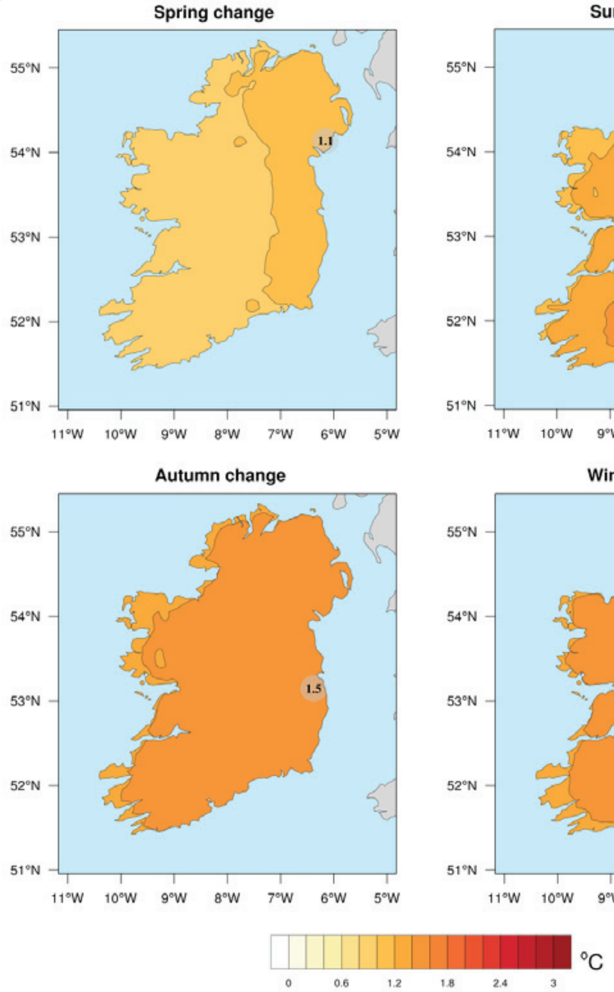

Figure 2. Projected increase in mean temperature for the four seasons for 2041-2060 relative to 1981-2000 for the high emission scenario.

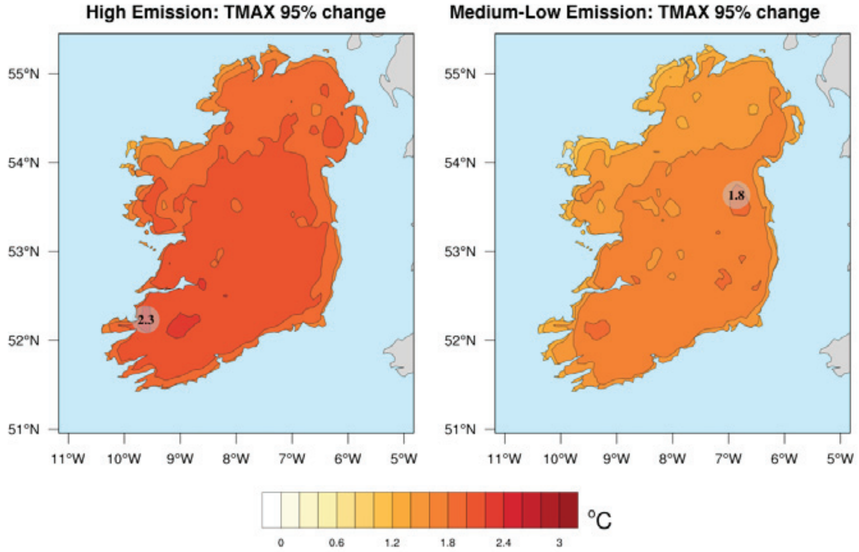

Figure 3. Projected changes in the top 5% of highest daytime summer temperatures for high and medium-low emission scenarios.

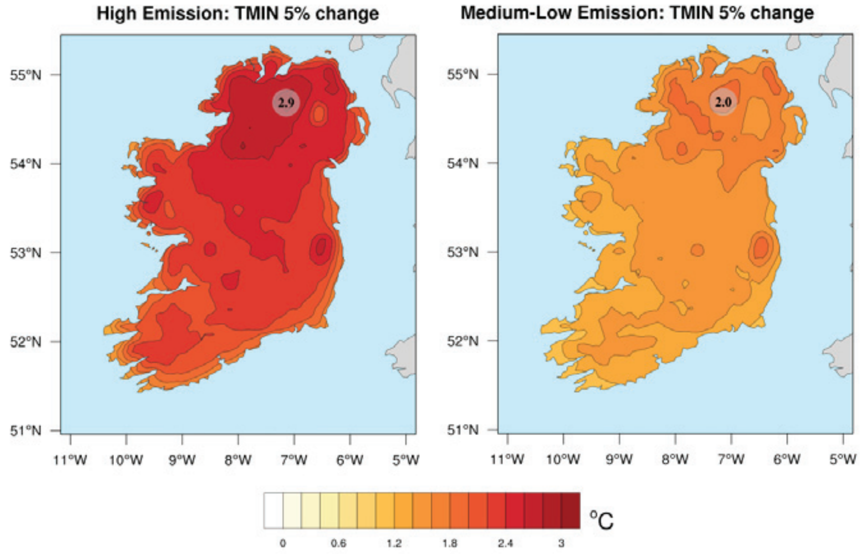

Figure 4. Projected changes in the lowest 5% of winter night-time temperatures for the high and medium emission scenarios.

on lives and livelihoods than a gradual change in mean values. A sustained increase in the daily maximum temperature is associated with heatwaves while an increase in the daily minimum temperature will typically imply warmer nights.

Figure 3 shows how the warmest 5% of daily maximum summer temperatures are projected to change (TMAX 95%). We see a stronger warming compared to the average seasonal temperatures (Figure 2). Most regions experience an increase of 1.8-2.2 degrees (1.4-1.8 degrees for the medium-low emission scenario). Warming is greater in the south and east than in the northwest. Figure 4 shows how the coldest 5% of lowest night-time temperatures in winter are projected to change (TMIN 5%). Both high and medium-low emission scenarios lead to greater warming in the north than in the south.

Minimum temperatures are projected to increase by around 2 degrees in the southeast and by around 2.9 degrees in the north on average (1.4 to 2.0 degrees for medium-low emission scenario). This suggests that the north of Ireland in particular will see milder nights during future winter months, with fewer frost and ice days.

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Temperature and mortality

Weather has a very strong association with human health. In particular there is an increase in mortality among the elderly and frail during temperature extremes related to heat and cold. Here we focus on the Irish situation and on the direct effects of temperature on health, as opposed to indirect effects which might be due to new insects and disease arising from a changing climate. In IPCC reports on climate change (e.g. Confalonieri et al., 2007) there are significant sections which relate to human health and climate change. Specifically on temperature extremes, the recent IPCC Special Report on Extremes (Seneviratne et al., 2012) commented:

> "It is *virtually certain* that increases in the frequency and magnitude of warm daily

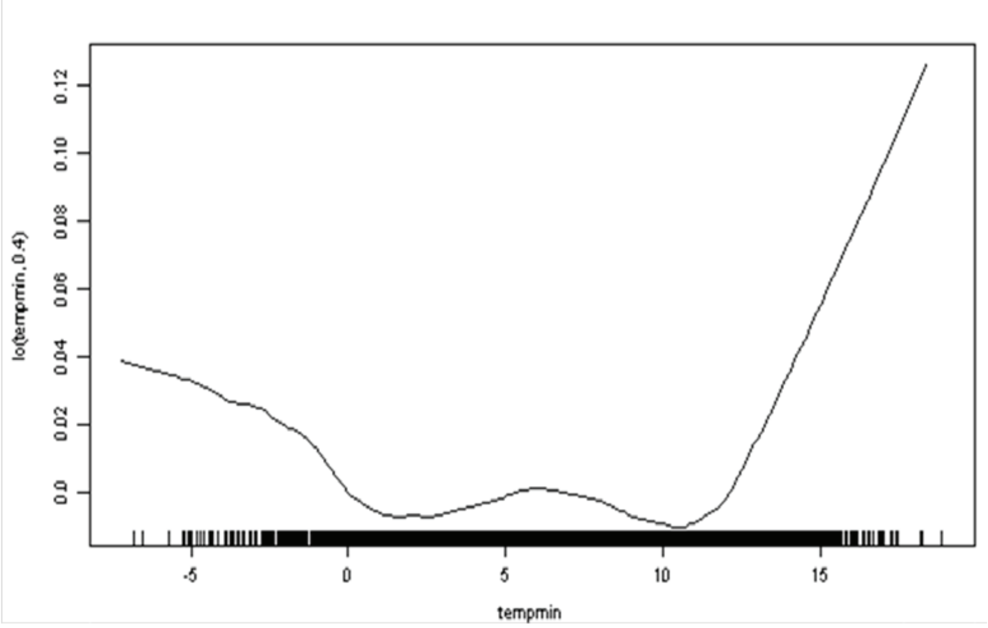

Figure 5. Mortality and minimum temperature for Dublin

> temperature extremes and decreases in cold extremes will occur in the 21st century at the global scale. It is *very likely* that the length, frequency, and/or intensity of warm spells or heat waves will increase over most land areas."

As discussed above, the warming trends projected for Ireland are consistent with this global picture.

If we consider the relationship between ambient temperatures and mortality, we see that we get what is often referred to as a classical "U" or "J" shape relationship, where mortality increases as temperatures move to either extreme, and where the bottom of the curve is the "optimum" or comfort temperature for that population group.

The data in Figure 5 are based on 20 years of mortality and temperature data for Dublin, where daily minimum temperature was used in the model. It shows that the optimum minimum temperatures are between 2 and 12 degrees, and that when one moves to lower or higher temperatures, mortality is seen to increase. Similar graphs can be produced for most population centres and it is seen that the optimum temperatures in warmer countries are significantly different to those for Ireland.

Figure 6 shows the seasonal variation in mortality based on 7 years of data for Dublin. It is very clear that there is a significantly higher mortality in winter than in summer, and the excess is observed every winter. In fact, in Ireland the differences in mortality rates between winter and summer are some of the largest in Europe.

With mean night-time temperatures expected to rise faster than mean daytime temperatures, there is likely to be a reduction in winter mortality in Ireland but this may be offset by an increase in the frequency and severity of heatwaves.

In 2003 Europe experienced a severe heatwave with many thousands of excess deaths. Key points to note are that both the maximum and the minimum temperatures were elevated during this event, and although the signal of increasing deaths can be observed as soon as the temperatures start to rise, the majority of deaths occurred only after a number of consecutive days of high temperatures. From a health perspective it appears that a number of days of sustained high temperatures are required to cause an increase in excess mortality.

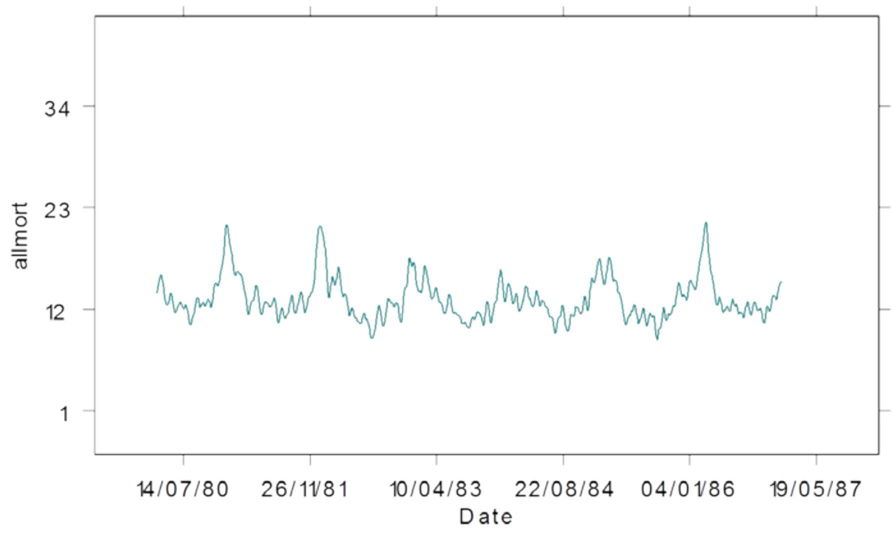

Figure 6. Variation in mortality (non-accidental) between winter and summer in Dublin showing the seasonal pattern (arbitrary units on vertical axis).

Translating this into an Irish context, Pascal et al., 2013 looked at data from 1980 up to 2008 for their study on heat-related mortality in Ireland. They identified increased mortality during spells of sustained hot weather and suggested that a maximum temperature above 25 degrees for at least 3 days could be considered a heatwave. They noted that this should be used as a warning to the elderly, the very young, and people who are already ill (e.g. with heart conditions, diabetes, respiratory conditions). The study recommended that a warning system should be put in place to warn vulnerable groups when such temperatures are expected and to advise them of the appropriate actions to take to reduce their risk.

From a health perspective it appears that a number of days of sustained high temperatures are required to cause an increase in excess mortality.

Clearly, the EC-Earth and downscaled projections indicate that temperatures in Ireland of over 30 degrees can be expected to arise more often in the future, and this poses a challenge. If these changes are gradual there is scope for the population to adapt.

The study recommended that a warning system should be put in place to warn vulnerable groups when such temperatures are expected and to advise them of the appropriate actions to take to reduce their risk.

Conclusions

An ensemble of downscaled high-resolution climate simulations, based on medium-low and high emission scenarios, was employed to assess the impacts of climate change on mid-century air temperatures over Ireland. Projections indicate a rise of ~1.5 degrees in mean temperatures, with the strongest signals in winter and summer. Warming is enhanced for the extremes (i.e. hot or cold days) and pronounced in winter night-time temperatures. The expected changes in temperatures are consistent with the findings from previous studies (e.g. McGrath et al., 2008). However, this is a preliminary study and more work is needed to quantify the impacts of rising temperatures both on the environment (see Chapter 7) and on human health. In particular, the projected changes in the extremes (e.g. frequency, duration and severity of hot/cold spells) need to be further evaluated by extending the research to include more CMIP5 and other (e.g. CORDEX) datasets.

Acknowledgements

This research was supported and funded by the Environmental Protection Agency CCRP STRIVE Programme. The authors wish to acknowledge the SFI/HEA Irish Centre for High-End Computing (ICHEC) and ECMWF for the provision of computational facilities and support. We are also grateful to Eoghan Harney, an undergraduate intern who worked on this project, and Dr. Mathilde Pascal who worked on the mortality and heatwave study.

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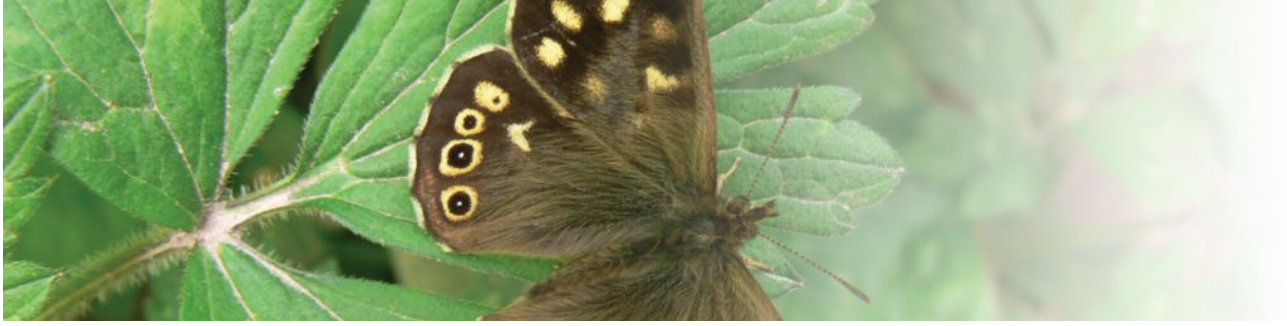

6. Mercury rising: what climate change will mean for butterflies in Ireland

Eugenie Regan[1]

Butterflies respond quickly to changes in their environment. In this chapter, recent changes in the Irish butterfly population are documented. Increasing temperatures may favour the expansion of the butterfly population and the arrival of new migrant species, but may be thwarted by habitat loss and other ecological changes induced by climate change.

Insects account for over one third of Ireland's species biodiversity and play an essential role in ecosystem functioning including pollination, nutrient recycling and pest control. Butterflies are some of the most documented, easily identified and monitored, and popular groups of insects and as such, they are good biological indicators. Butterflies react quickly to change and occur in a wide range of habitat types. They have been proposed as a good and viable indicator in the Streamlining EU Biodiversity Indicators (SEBI) process and are considered to be a valuable way of monitoring progress towards the EU target of halting the loss of biodiversity and degradation of ecosystem services by 2020. A standard method of monitoring based on regular walks along butterfly transects has been well described and proven to be scientifically sound. This has been adopted in at least 19 countries or regions across Europe, including Ireland. As a result butterflies are the only invertebrate taxon for which it is currently possible to estimate rates of decline among terrestrial insects in many countries.

Butterflies are some of the most documented, easily identified and monitored, and popular groups of insects and as such, they are good biological indicators.

There are 34 resident and regular migrant species of butterflies in Ireland.

There are 34 resident and regular migrant species of butterflies in Ireland. The species richness of our island is the lowest of any European Union country. Nevertheless, the Irish butterfly fauna exhibit some interesting features and hold important populations of certain species, including the Marsh Fritillary which is legally protected under the EU Habitats Directive.

Butterflies are an ideal group for studying the effects of climate change because, as poikilothermic organisms, their life-cycle, activity, distribution and abundance are affected by temperature. There are numerous ways that butterflies respond to temperature changes including abundance changes, range changes, phenology changes, changes in voltinism, changes in habitat, new residents and new species. The impact of climate change on Irish butterflies is difficult to predict partly because of the uncertainties about how the climate of Ireland will be affected and partly because the impact will be different for each species and each habitat. However, more and more information is becoming available on Irish butterflies and some of this information is presented here.

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[1] National Biodiversity Data Centre, Beechfield House, WIT West Campus, County Waterford, now working at the United Nations World Convservation Monitoring Centre.

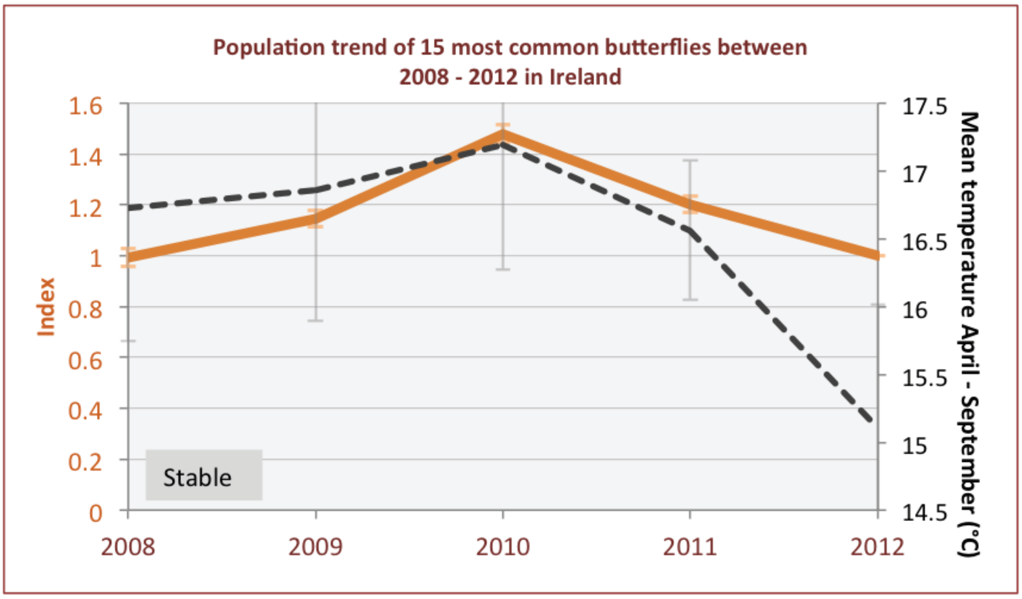

Figure 1. The populations of Irish butterflies are closely correlated with summer temperatures (Regan and Staats, 2013). Orange line: butterfly abundance index. Dashed black line: mean April-September temperature.

Changes in butterfly abundances

The Irish Butterfly Monitoring Scheme is a citizen science project, established by the National Biodiversity Data Centre in 2007 with the aim of monitoring changes in Irish butterfly populations. It is the largest insect monitoring scheme in Ireland and contributes data to a pan-European butterfly population index. For the scheme, each volunteer undertakes the same walk (1-2km) every week from April to September and counts the butterflies following a standard methodology. The data are then collated by the National Biodiversity Data Centre. The scheme started with only six transects in 2007 and has now grown to over 150 transects across the country.

For the scheme, each volunteer undertakes the same walk (1-2km) every week from April to September and counts the butterflies seen following a standard methodology.

Changes in abundance of Irish butterflies have been clearly observed in the Irish Butterfly Monitoring Scheme data. Analysis of the population data of the 15 most common butterflies between 2008 and 2012 shows a close correlation with temperature (specifically the mean April-September temperature). This is consistent with findings from other countries (including the Netherlands and Britain). Warm, dry weather during the summer positively affects the populations of most Irish butterfly species, in particular the double brooded species in Figure 1 (Regan and Staats, 2013); see also Chapters 5 and 9.

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Warm, dry weather during the summer positively affects the populations of most Irish butterfly species, in particular the double brooded species.

Changes in butterfly distributions

Climate change has a profound effect on the distribution of numerous plant and animal species. The composition of European butterfly communities has shifted northwards during the period 1990-2008 by 114 km. However, during the

Figure 2. Speckled Wood butterfly (Photograph: Deirdre Heaphy).

same period, the northward shift in temperature in Europe was even faster, so that the climatic debt of butterflies corresponds to a 135km lag behind climate (van Swaay et al., 2010).

> *The composition of European butterfly communities has shifted northwards during the period 1990-2008 by 114km.*

In Ireland, we have also seen a northward shift in the butterfly community with some species that were once confined to the southern half of the country expanding their range. One such example is the Speckled Wood butterfly (Figure 2). Although there are insufficient data to draw firm conclusions, it is clear that this species has expanded its range in Ireland over the past 30 years (Figure 3). This range expansion has also been observed in Britain and Europe. The European range of the Speckled Wood butterfly has also extended northwards over the past 30-100 years and these changes have been attributed to two factors: long-term fluctuations in climate and habitat change (Asher et al., 2001).

Changes in butterfly flight periods and numbers of generations

The timing of the flight period of butterflies (or phenology) is closely linked with temperature. The emergence date of adults can vary by a number of weeks depending on the current temperature. Temperature changes with latitude, and so too does the phenology of Irish butterflies. One such example is the flight period of the Common Blue butterfly derived from the Irish Butterfly Monitoring Scheme 2009-2012. Figure 4 shows the grid reference northing (equivalent to latitude) of each Common Blue record plotted against the date of the sighting. In this plot (termed a phenogram) the horizontal lines are at 50km grid intervals of the National Grid of Ireland, so the y-axis spacing is 0.5 degrees or 50km. The size of each dot represents the number of adult butterflies recorded on a particular date. The clear picture that emerges is the transition from two flight periods in the south to a single flight period in the north. The zone of transition is at a latitude of 54°N, which stretches roughly between Dundalk and Blacksod Bay. There is also a slight trend showing that the flight periods occur at later dates in the north.

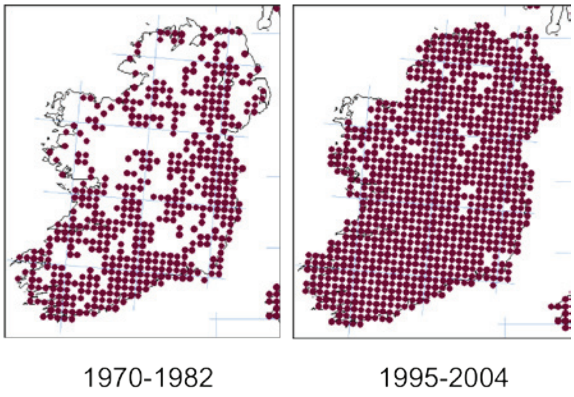

Figure 3. The changing distribution of the Speckled Wood butterfly in Ireland between 1970 and 2004. (Data source: Butterfly Conservation UK).

The latitude at which the Common Blue butterfly changes from a double to a single generation each year might be expected to shift in response to climatic factors (Asher et al. 2001). Increasing temperatures might result in the latitude of this transition zone shifting further north.

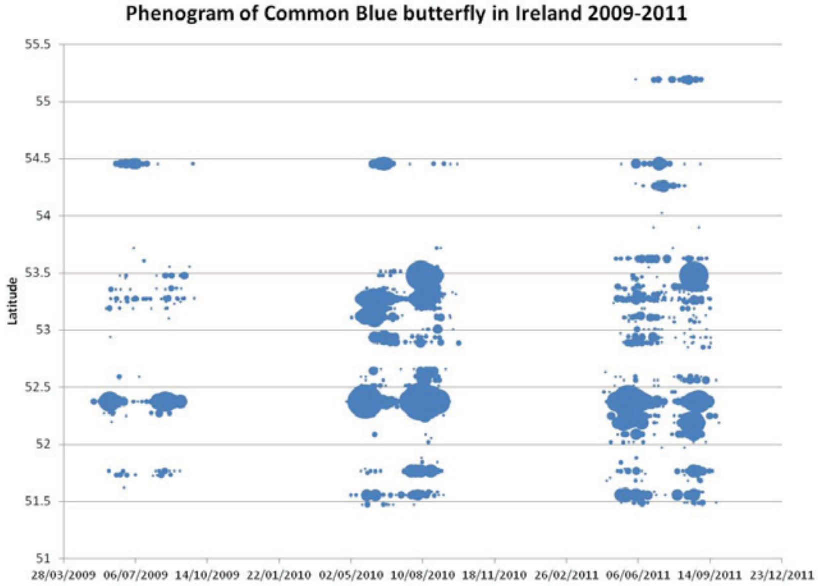

Figure 4. Phenogram for the Common Blue butterfly in Ireland showing the transition from double to single flight periods. (Data source: Irish Butterfly Monitoring Scheme 2009-2012).

New resident butterflies and new species to Ireland

Irish winters have historically been too cold for the overwintering of some of our migrant species. Instead these species recolonise our island each year. In recent years two regular migrants, the Red Admiral and Clouded Yellow (Figure 5) have been observed to successfully overwinter (Smyth and Nash, 2008; Nash et al., 2012). There is also evidence that both of these species have successfully overwintered in Britain (Asher et al., 2001). However, this is still an unusual event involving a small number of individuals with an unknown, and likely to be small, contribution to the annual population. It is, therefore, premature to regard the Red Admiral or Clouded Yellow as resident species, although they appear to be shifting in that direction.

Two new species recently added to the Irish butterfly list are the Essex Skipper (Figure 6) and the Small Skipper (Wilson et al., 2007; Harding, 2008; Wilson et al., 2009; Nash et al., 2012). The origin and year of arrival of both species are unknown but it is thought they may have been transported to Ireland in fodder or imported grass seed (Nash et al., 2012). Warmer weather conditions have undoubtedly made Ireland more habitable for accidentally-introduced species.

Warmer weather conditions have undoubtedly made Ireland more habitable for accidentally-introduced species.

What changes might be expected in the future?

Figure 5. The Clouded Yellow is a migrant species which has been observed overwintering in Ireland in recent years and has the potential to become a resident species with warmer winters (Photograph: Chris Wilson).

The Clouded Yellow is a migrant species which has been observed overwintering in Ireland in recent years and has the potential to become a resident species with warmer winters.

Figure 6. The Essex Skipper was first recorded in Ireland in 2006 in County Wexford (Photograph: Chris Wilson).

As a result of climate change, the northern limit of the global distribution of many butterfly species is moving northwards. Ireland has a low number of butterfly species compared with other countries (for example 59 species in Britain and 250 species in France). With the distributions of species across Europe expanding northwards, there is the potential for new species to arrive and become resident in Ireland as long as the species' food plant and habitats are present here. Another expected change is for migratory species such as the Clouded Yellow and Red Admiral to become overwintering residents.

It is clear that the ecologies of native species are changing with environmental change. Further increases in annual temperatures in Ireland will further affect the ecologies of Irish butterflies, in particular their flight periods, voltinism, and abundances (see Chapters 5 and 9 regarding future changes in temperature and precipitation). The distributions of native species may also change, including species such as the Gatekeeper, Holly Blue and Comma.

The continuation of the Irish Butterfly Monitoring Scheme over the long term will provide much needed information on Irish butterfly populations, how they are changing and what conservation measures can be put in place.

Further increases in annual temperatures in Ireland will further affect the ecologies of Irish butterflies, in particular their flight periods, voltinism, and abundances.

Conclusions

It appears that many Irish butterflies will be positively affected by increased temperatures by increasing their distributions, the number of generations per year and their populations. However, the recent Irish Red List of Butterflies and analysis of the Irish Butterfly Monitoring Scheme data have shown that Irish butterflies are in decline. It is possible that any benefit of a warming climate may be overridden by habitat loss and change. Recent research also shows that butterflies living in fragmented habitats may be unable to keep pace with large-scale environmental changes and may become more prone to local extinction.

Butterflies reflect a wider change in the Irish insect fauna. The effects of climate change in Ireland have been observed for dragonflies (Nelson and Thompson, 2004; Nelson et al., 2011), mayflies (Kelly-Quinn and Regan, 2012) and moths (Bond and Gittings, 2008). It is assumed that other insect groups are also being affected by climate change, including pests and disease vectors. It is certain that Ireland's insect communities are changing and climate change is a major factor. However, we have very little data on how the communities are changing and what impacts this will have on various ecosystem services (such as pollination and pest control) and the spread of vector-borne diseases. Insects are an integral part of our ecosystems and make up the vast majority of our biodiversity. It is, therefore, imperative that we develop a better understanding of their ecologies and conservation and that they are fully addressed in any biodiversity policies.

It is possible that any benefit of a warming climate may be overridden by habitat loss and change.

Insects are an integral part of our ecosystems and make up the vast majority of our biodiversity.

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7. Irish wildlife in a warmer climate

Alison Donnelly[1], Amelia Caffarra[2],
Fabio Zottele[3], Emily Gleeson[4]

Spring warming in recent years has had a significant impact on Irish wildlife by advancing the timing of key phenological phases of a wide range of organisms, including trees, birds and insects. This chapter demonstrates how phenological data from across Ireland has become an important tool in climate change research.

Knowing how Irish wildlife will respond to future warmer temperatures is not a trivial matter. In order to attempt a meaningful estimate of how species might respond to rising temperature we first need to establish a link between ambient temperature and species' responses. One common way to do this is by examining changes in the timing of temperature-dependent developmental stages in plants and animals over time. Temperature increases in spring trigger bud burst and leaf unfolding on deciduous trees. In addition, these warmer temperatures stimulate insect activity and bird migration. The study of the timing of these recurring life-cycle events in plants and animals is called phenology and the events themselves are called phenological phases, or phenophases for short. Once the relationship between temperature and phenology is established and mathematically modelled, it is then possible to use future temperature projections, such as those produced by the EC-Earth global climate model, to simulate the future timing of key phenophases such as bud burst.

Bud Burst

When bud scales begin to part and the leaf within becomes visible.

Leaf Unfolding

This phase follows on from bud burst and is observed when the leaf has emerged from the bud.

Linking temperature and wildlife phenology

In recent years, the number of studies of data series from a range of plant and animal species has grown substantially, and phenology has become established as an important tool in climate change research. Analysis of phenological data from across Ireland has clearly demonstrated that the timing of key phenological phases of trees (Donnelly et al., 2006; Gleeson et al., 2013), birds (Donnelly et al., 2009; Stirnemann et al., 2012) and insects (O'Neill et al., 2011) has already been affected by rising spring temperature. Over a 40-year period (1967-2004), the timing of leaf unfolding of a suite of deciduous trees advanced by up to 3 weeks. In addition, the arrival time of a selection of sub-Saharan migrant birds also advanced significantly over the period 1969-1999, while the timing of spring departure of a short-distance winter visitor, the Whooper Swan (Cygnus cygnus) (Figure 1) was also significantly earlier. Furthermore, sightings of a range of moth species across the country have become significantly earlier since records began in 1980 indicating earlier emergence times. These advancing trends, similar to those observed in different countries across the world are due, at least in part, to rising spring temperature (Peñuelas and Filella, 2001; Menzel et al. 2006).

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[1] Department of Geography, University of Wisconsin-Milwaukee, WI 53201, USA.
[2] Centre de Recherche de Climatologie – UMR Biogéosciences, uB/CNRS 6262 Université de Bourgogne, 6, bd Gabriel, F-21000 Dijon, France.
[3] Centre for the Technology Transfer, Fondazione Mach, 38010 San Michele all'Adige, Italy.
[4] Research, Environment and Applications Division, Met Éireann, Glasnevin, Dublin 9.

Figure 1. Whooper Swan (Cygnus cygnus), Iceland (Photograph: Emily Gleeson).

Even though an earlier start to spring has been established for each of these groups of organisms there has, as expected, been considerable intra- and inter-species and site variation in phenological response to temperature. Studies have shown that not all groups responded to the same environmental stimulus (i.e. rise in temperature) at the same rate. This is a very important point since organisms depend on one another for survival and any disruption to previously synchronous relationships could greatly affect overall ecosystem dynamics (Donnelly et al., 2011). For example, moth caterpillars feed on newly emergent leaves, and migratory birds depend on moth caterpillars as their primary food source. If spring temperatures cause caterpillars to emerge before leaves have unfolded many caterpillars will perish. In addition, if birds arrive after the peak timing in availability of caterpillars, fewer chicks will survive and more leaves will be consumed by the herbivores. This illustrates the fine balance at work within an ecosystem and how this balance may be disrupted in a warmer world.

If spring temperatures cause caterpillars to emerge before leaves have unfolded many caterpillars will perish. In addition, if birds arrive after the peak timing in availability of caterpillars, fewer chicks will survive and more leaves will be consumed by the herbivores.

Simulating phenological response to future temperature

Using experimentally-derived phenological data coupled with historical data on the timing of bud burst of birch (Betula pubescens) (Figure 2) in Ireland and a range of other European countries a process-based phenological model was constructed (Caffarra et al., 2011). This model (DORMPHOT) simulates the timing of birch bud burst based on temperature and photoperiod. This means that if future temperature simulations are available it is possible to estimate the timing of bud burst for birch trees into the future. Given the well-established reports of variation in phenological response to a range of environmental drivers between species, phenological models tend to be species specific.

Figure 2. Birch (Betula pubescens) leaves at the National Botanic Gardens, Dublin (Photograph: Emily Gleeson).

In order to simulate the timing of birch bud burst in Ireland up to the end of the current century the DORMPHOT model was applied to future temperature projections from a 19-member ensemble of regional climate simulations (on a 25km grid). Results are shown in Figure 3 (Caffarra et al., 2013).

The DORMPHOT model was spatially enabled in order to investigate the spatial variability of the bud burst. The resulting maps indicated that the previously reported trend towards earlier timing of birch bud burst would continue to the end of the century (Figure 3). Interestingly, the trend varied across the country with a distinctive

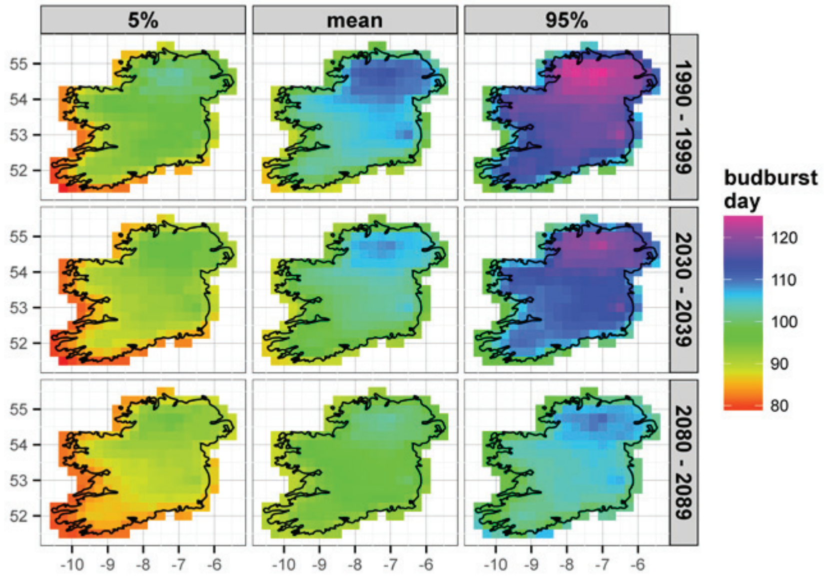

***Figure 3.* Ensemble mean, 5th and 95th percentiles (i.e. lowest and highest 5% of values) of the timing of bud burst (day of year) over Ireland, for (a) 1990-1999 (b) 2030-2039 and (c) 2080-2089. Reproduced from Caffarra et al., 2013.**

northeast-southwest gradient. Simulations suggest that the advance in bud burst will be greater in the northeast than the southwest resulting in more homogeneous bud burst across Ireland towards the end of the century. In the northeast of the country the timing of birch bud burst will be expected to be 10 days earlier in the 2080s compared to the 1990s whereas little change is expected in the southwest.

Simulations suggest that the advance in bud burst will be greater in the northeast than the southwest resulting in more homogeneous bud burst across Ireland towards the end of the century.

These results have been produced using a 19-member ensemble of climate simulations generated as part of the EU ENSEMBLES Project. The ensemble of EC-Earth climate simulations yielded similar temperature projections for Ireland to the ensemble used in this study. Therefore, the bud burst projections using EC-Earth temperature data would be expected to be similar to those shown in Figure 3. However, the EC-Earth data are available at a much finer resolution, having been downscaled to 4km over Ireland, compared to 25km in the data used here (see Chapter 5 for further details regarding temperature changes).

Conclusions

There is no doubt that a spring warming in recent years has had a significant impact on Irish wildlife by advancing the timing of key phenological phases of a wide range of organisms, including trees, birds and insects. In addition, the response to warming varied according to species and location. Whereas tangible evidence for future trends exists for only one of these groups (i.e. trees), indicating a continuation of this advancing trend, it would be remiss to ignore the other species. As yet there are no comparable computer models available to simulate what might happen to birds and insects in the future but based on past data we can expect trends towards both earlier arrival and earlier appearance dates in spring to continue into the near future. Furthermore, it will be important to continue to monitor and record phenological data in Ireland as it provides an early warning for potential disruption between interdependent phenophases and potential

A spring warming in recent years has had a significant impact on Irish wildlife by advancing the timing of key phenological phases of a wide range of organisms, including trees, birds and insects.

irreversible consequences for change in ecosystem dynamics.

It will be important to continue to monitor and record phenological data in Ireland as it provides an early warning for potential disruption between interdependent phenophases and potential irreversible consequences for change in ecosystem dynamics.

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8. Air pollution and climate change interactions

Colin O'Dowd[1], Mary Coleman[1],
Damien Martin[1]

Air pollution emissions controls have resulted in reduced aerosol pollution levels and have been correlated with an increase in surface incoming solar radiation to the tune of ~20% over the last decade. The inverse correlation between aerosol mass concentrations and incoming solar radiation corroborates the concept of global brightening as air pollution policies improve air quality. European-scale climate projections are presented for the RCP6.0 emission development out to the year 2100 using the regional climate model REMOTE.

Introduction

Atmospheric aerosols (suspended dust, smoke, sulphates, organics, sea-spray or similar particles of about a millionth of a metre in size) are major contributors to air pollution (O'Dowd, 2012). In the air quality research community, aerosol particles are termed "Particulate Matter" (PM). Aerosol air pollution is typically measured as the total mass of particles smaller than a particular size (e.g. 10 μm for PM10 and 2.5 μm for $PM_{2.5}$). Air quality is regulated in terms of exposure to a particular PM standard. Air pollution has been a serious problem since the eighteenth century when the invention of the steam engine increased the amount of coal-burning. Prior to that, air pollution was a problem due to wood and coal-burning, although it was not as severe. In 1905, the term "smog" was coined and it described the combination of smoke and fog that was visible in many industrialised cities e.g. London. Dublin, as recently as 1982, also experienced severe smog events with smoke concentrations exceeding 700 μg m^{-3}, and excess deaths of approximately 20 per day. This is to be compared with a current EU yearly exposure limit of 25 μg m^{-3} for $PM_{2.5}$ and 50 μg m^{-3} sustained over a 24-hour period, 35 times in one year for PM_{10}.

Air pollution is injurious to health. The EU's Clean Air for Europe (CAFE) programme estimates that 348,000 premature deaths occur per year in Europe due to exposure to $PM_{2.5}$. Figure 1 illustrates the estimated loss in life expectancy attributable to exposure to $PM_{2.5}$ from anthropogenic emissions in Europe (EEA, 2007). The data are calculated from emissions for the year 2000 and for targeted emission reductions by the year 2020.

While air pollution, particularly aerosol air pollution, has been steadily decreasing in the developed world, it has become an increasing problem in developing countries, not only on urban megacity scales but also on regional and almost hemispheric scales. Inter-continental and hemispheric transport of pollution is now regarded as a serious concern, affecting local- and regional-scale air quality.

In terms of climate impacts, these aerosol haze layers reduce the amount of solar energy transmitted through the atmosphere as the haze reflects some of the sun's incoming rays to space. In addition to forming haze layers, aerosols are essential for the formation of clouds as they provide condensation nuclei on which cloud water drops and ice particles can form. Without these nuclei, there would be no clouds, no precipitation and no hydrological cycle. Furthermore, these clouds provide the most reflecting layers in the atmosphere, also reducing

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[1] School of Physics & Centre for Climate and Air Pollution Studies, Ryan Institute, National University of Ireland Galway, University Road, Galway.

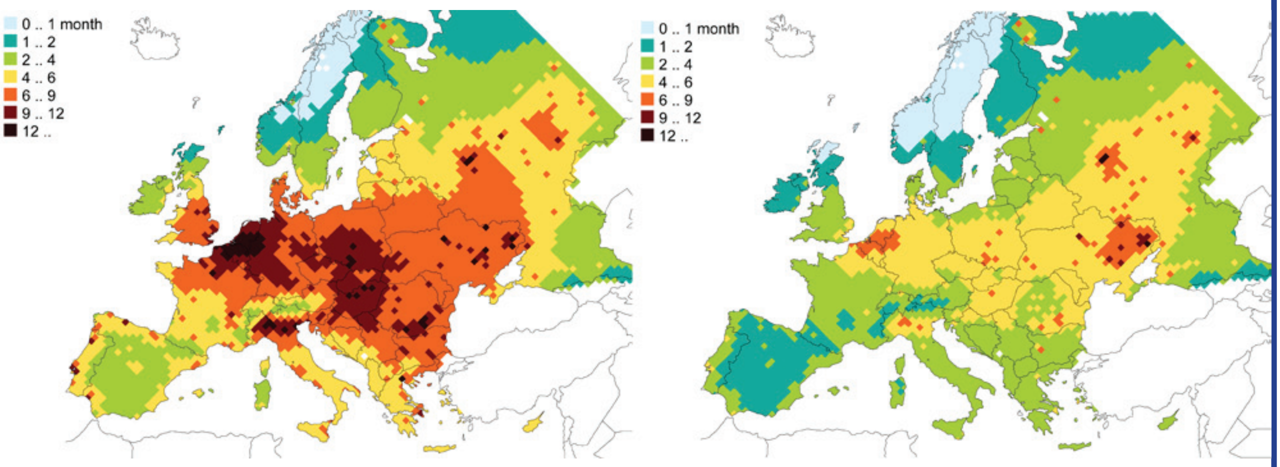

***Figure 1.** Estimated loss in life expectancy attributable to exposure to fine particulate matter ($PM_{2.5}$) from anthropogenic emissions for the year 2000 (left) and projected reduced emissions for the year 2020 (right). Graphics were regenerated based on data from EEA Report No. 2/2007. Courtesy of Dr. Zbigniew Klimont and Dr. Markus Amann.*

the amount of solar energy transmitted through the atmosphere. These reflecting layers have the net effect of cooling the planet. Changes in the abundance of these aerosols lead to changes in the reflection, or cooling efficiency, of these haze and cloud layers. The Inter-governmental Panel on Climate Change (IPCC, 2007) Assessment Report 4 (AR4) concluded that the aerosol contribution to radiative forcing amounted to a cooling effect that partly off-set the warming induced by the accumulation of greenhouse gases (GHGs) in the atmosphere. This suggests that aerosols have been obscuring the true rate of global warming, or, specifically, the climate-temperature sensitivity to CO_2-induced global warming. One would intuitively expect a lower level of brightness, or dimming, if more solar radiation is reflected to space. Over the past 40 years, both dimming and brightening trends have been observed, the explanation of which converges towards an aerosol influence on climate.

Dimming is a term associated with a decadal decrease in surface solar radiation, while brightening refers to an increase in surface solar radiation. Studies (Lieipert, 2002; Wild et al., 2005; Wild, 2009) have shown a widespread decrease in surface solar radiation at a variety of locations worldwide between 1960 and 1990.

However, the period from 1990 to the present shows a reversal of the trend into a brightening trend (Wild et al., 2005). The dimming effect appeared to have been obscuring, or suppressing, greenhouse warming with reduced, or even negative, trends for global temperatures over the period as greenhouse gases continued to accumulate. In Europe, as the trend reversed from dimming to brightening, rapid temperature rise became evident after the mid-1980s when, thereafter, the decadal rise in temperature was +0.38 degrees per decade, significantly higher than in any other period since the pre-industrial era (Philipona et al., 2009). The brightening has been associated with reduced aerosol pollution since the 1980s, as developed countries implemented policies to clean up air pollution.

This study examines the observational records linking aerosol emissions to air pollution and radiation trends at the Mace Head Atmospheric Research station and utilises a Regional Climate Model to predict temperature changes over Europe under the RCP6.0 emission scenario to 2100.

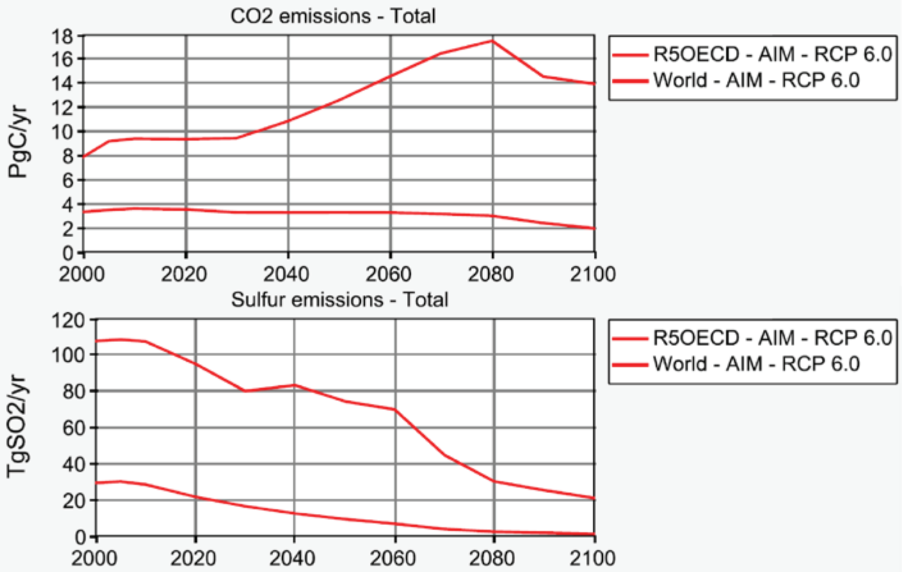

Figure 2. OECD countries and world emissions of CO2 and SO2 under the RCP6.0 emission scenario.

Methods

Mace Head Atmospheric Research station

For details regarding the site and the associated observational programmes see http://www.macehead.org. Ten years of total and speciated $PM_{2.5}$ aerosol measurements were conducted at the station along with combined direct and diffuse (global) radiation at 2m, for the years 2002 to 2011.

Emission storyline

The RCP pathway chosen for this study is a stabilisation pathway in which radiative forcing peaks at approximately 6W/m^2 at 2100 and stabilises thereafter. In this stabilisation pathway, global emissions are due to rise until mitigation takes effect (around 2050), after which time emissions decrease resulting in improved air quality (Moss et al., 2007). The expected trajectories for CO_2 and sulfur emissions are shown in Figure 2.

Model overview

The online climate-chemistry/aerosol model REMOTE is a regional climate three-dimensional model which predicts the physical, photochemical and aerosol characteristics of the atmosphere at every time step (Varghese et al., 2011; Stier et al., 2005).

Numerical simulations are carried out with the REMOTE model for the domain comprising Europe and North East Atlantic with a horizontal resolution of 0.5° (~50km), 81×91 grid points. The model domain covers an area from 10^{o}W to 30^{o}E at the southern boundary of about 30^{o}N and from 40^{o}W to 60^{o}E in the north at about 70^{o}N. Simulations were performed for 2006, 2030, 2050 and 2100.

Future anthropogenic emissions of SO_x, NO_x, NH_3, CO, VOCs and $PM_{2.5}$ are taken from the RCP6.0 emission scenario. In addition to anthropogenic emissions, other land and sea-based emissions are included.

Results

Emission and pollution trends

Partly as a result of the CAFE air pollution strategy, ozone precursor and aerosol primary emissions along with secondary precursor emissions have been reducing for at least 10 years. The Irish-scale emission trends are illustrated in Figure 3 for NOx, which influences ozone levels as well as nitric acid and nitrate aerosol; for SOx which influences the levels of sulphate aerosols, and for $PM_{2.5}$ which also includes primary emissions of soot (black) carbon (O'Dowd et al., 2012).

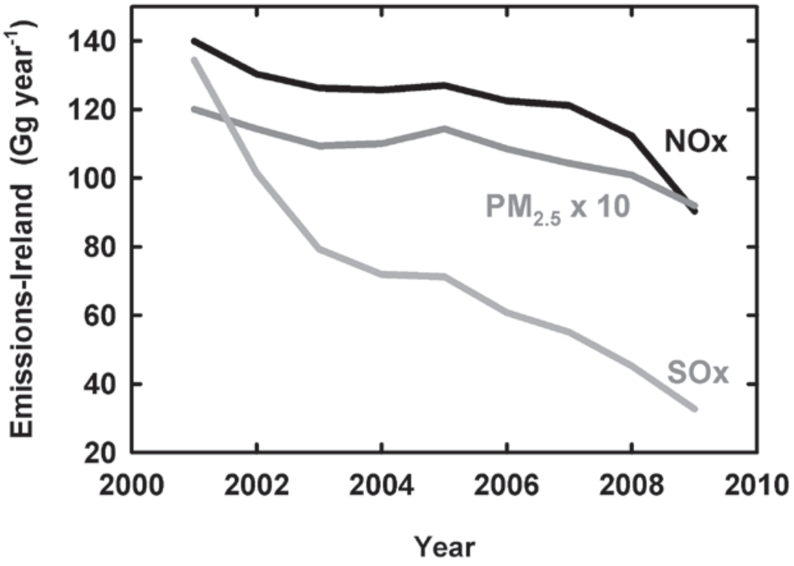

Figure 3. NOX, SOX and PM$_{2.5}$ emissions from Ireland from 2001-2009.

The most rapid reduction trend is seen for SOx. Analysis of data from the Mace Head station for monitoring essential climate variables and regional-scale air pollution reveals a reduction in aerosol pollution, with reduced emissions resulting in an increase in surface solar radiation.

Sulphate is selected for demonstration purposes as it is typically regarded as the major pollutant from fossil fuel combustion.

Future aerosol and climate projections

Figure 4 illustrates the current sulphate mass loadings, along with temperature fields, over Europe for August 2006, and future trends based on the RCP6.0 emission and economic development pathway for the time-slice years 2050 and 2100 (Coleman et al., 2013). As the time-slice years progress, sulphate air pollution reduces further and regional-scale temperatures increase. Similar regional-scale temperature increases are seen across various locations in Europe. The projected increase in temperature results from the combined effect of increased CO_2 concentrations and reduced aerosol concentrations.

These results should be compared with the projected temperature rises expected from the ensemble of downscaled EC-Earth and other global models (see also Chapter 5 and Chapter 1) based on RCP4.5 and RCP8.5; the REMOTE projections are higher, perhaps reflecting the more detailed treatments of aerosols. Based on these findings, regional-scale temperature increases of the magnitude close to the upper range of the global average projections are not to be unexpected.

Conclusions

- Aerosol air pollution has been obscuring the full extent of greenhouse gas-induced global warming
- Aerosol emissions are being reduced to improve air quality and public health
- This will reduce aerosol abundance, which will lead to less cooling but to improved human health
- Less cooling from cleaner air leads to increased net warming from greenhouse gases
- Reductions in greenhouse gas emissions and air quality pollutants are essential and must be undertaken in concert, in order to mitigate global warming and improve public health and the environment.

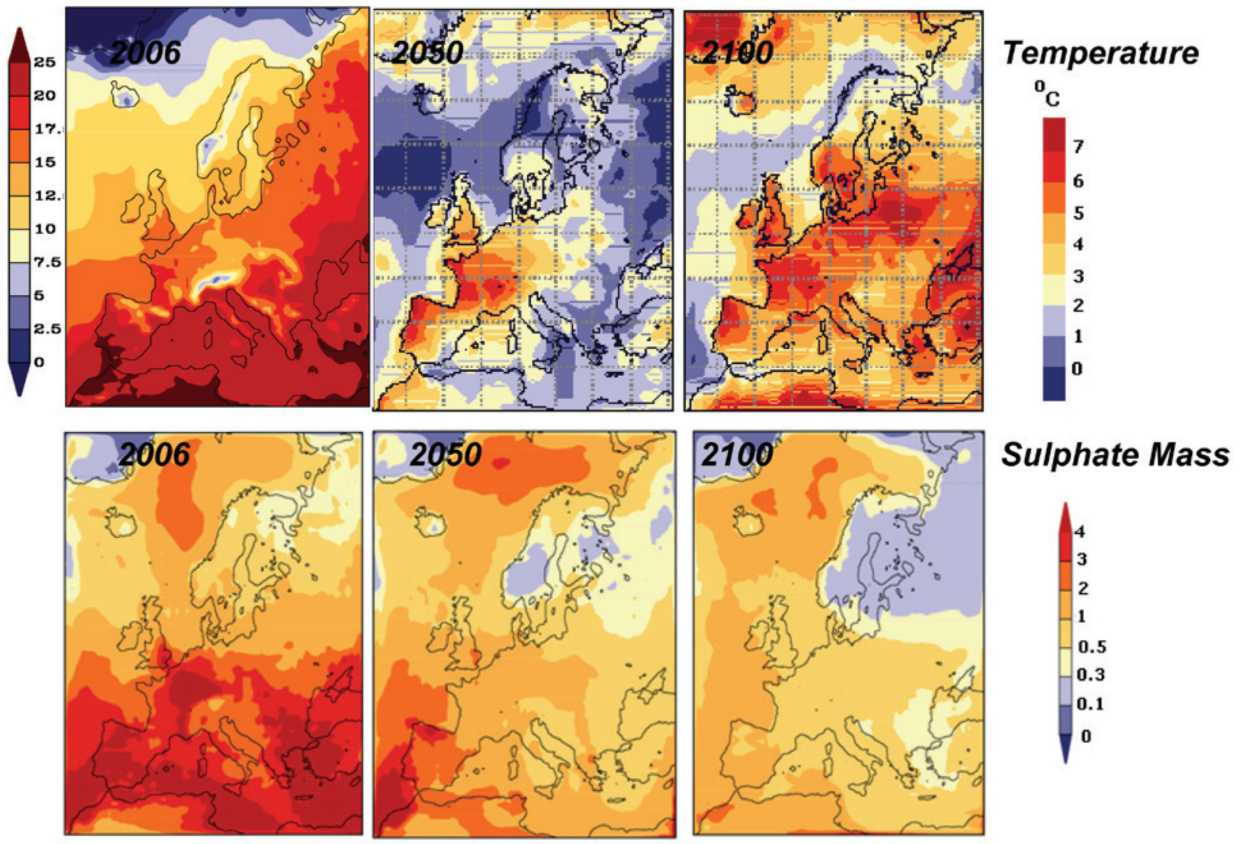

Figure 4. Regional Climate Model projection of temperature changes and sulphate mass concentrations over Europe into the future using the RCP6.0 emissions scenario projection. Time-slice years are taken for 2006, 2050 and 2100. Colour bar on left-hand side represents temperature for 2006, while upper-right colour bar represents temperature change for 2050 and 2100 relative to 2006. Lower-right colour bar represents sulphate ($PM_{2.5}$) mass (-g m^{-3}) for time-slice years 2006, 2050 and 2100.

Acknowledgements

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9. Impacts of climate change on Irish precipitation

Paul Nolan[1], Ray McGrath[3], Emily Gleeson[3], Conor Sweeney[2]

An ensemble of climate simulations for Ireland using medium-low and high future emission scenarios indicates that while the average annual precipitation shows only a slight decrease by mid-century there are substantial seasonal changes predicted with wetter winters and drier summers. The frequencies of heavy precipitation events also show notable increases, particularly in winter. Regional variations remain statistically elusive.

The simulation of precipitation is a major challenge for global climate models because of the nature of the interacting physical processes that lead to precipitation, and the lack of sufficient resolution in the models (Ma et al. 2013). The latter leads to a sacrificing of the fine details by introducing simplified "parameterization" physical schemes; it also smoothes the influence which surface features have in forcing precipitation. Cloud processes (which are linked to convection) and interactions with the boundary layer are a major source of uncertainty for the models.

Dynamical downscaling attempts to remedy some of these problems by employing a regional, and usually quite different, climate model with a higher resolution that processes input from the 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, high-resolution regional models demonstrate improved skill in simulating precipitation. [4]

The chaotic nature of weather (natural variability), which is particularly noticeable in precipitation, requires an ensemble approach to support the statistical significance of climate modelling results. Not only are the models imperfect, and handle the physical processes in different ways, but there is also uncertainty in future concentrations of greenhouse gases and aerosols. This uncertainty can be quantified to some extent by having simulations carried out with different models and different emission scenarios. Details regarding the different global datasets and the downscaling models used to estimate the impacts of climate change are summarised in Chapter 1. Here, we present a subset of results which we believe are robust for Ireland.

Linkage with temperature changes

The global model simulations indicate that the tropical regions will become wetter in the future, the subtropics drier and the higher latitudes also wetter. There are different physical mechanisms behind the changes; at the high latitudes the effects are linked to the ability of a warmer atmosphere to hold more moisture. Basic physical arguments (Trenberth et al., 2003) indicate that water vapour content should increase by ~7% for every degree rise in temperature but not all of the extra moisture goes into precipitation; other constraints suggest an increase in precipitation of 1-3% per degree

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[1] ICHEC, Trinity Technology & Enterprise Campus, Grand Canal Quay, Dublin 2 and formerly Meteorology & Climate Centre, School of Mathematical Sciences, UCD, Belfield, Dublin 4.

[2] Meteorology & Climate Centre, School of Mathematical Sciences, UCD, Belfield, Dublin 4.

[3] Research, Environment and Applications Division, Met Éireann, Dublin 9.

[4] A better solution would be to have a global climate model with a resolution ~few km to remove the need for regional downscaling. Such models exist for weather forecasting but the computational resources required to run long simulations (e.g. hundreds of years) at this level of detail are currently prohibitive.

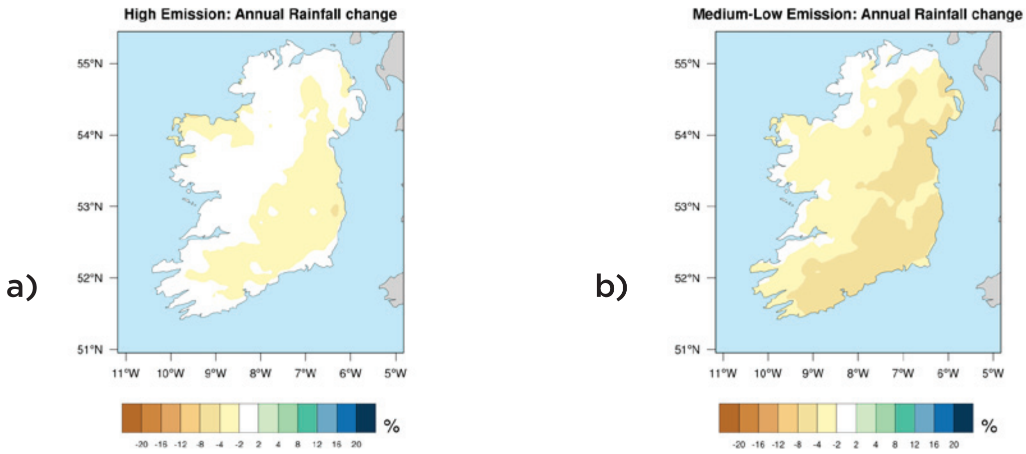

Figure 1. Mean annual change (%) in precipitation for the medium-low emissions ensemble (left) and high emissions ensemble (right). Changes for mid-century (2041-2060) are shown relative to the past (1981-2000).

warming (O'Gorman and Allan, 2012; Wild and Leipert, 2010). For short-period extreme precipitation events there is some evidence that the increase is much larger, perhaps double the 7% (Lenderink and Van Meijgaard, 2008). At a local scale, and over relatively small geographical regions, there is likely to be considerable variation in the climate change pattern.

Results: mean precipitation

Figure 1 shows the mean annual change (%) in precipitation for the 20-member precipitation ensemble used. There is an indication of a small reduction in the overall annual precipitation (mostly 0-8% for the medium-low emission ensemble, 0-4% for the high emission ensemble). However, there is a large spread in the simulations and the results may not be statistically significant.

Stratified by season the results are more robust. Figure 2 shows the change (%) in precipitation under medium-low emission scenarios with the corresponding plots for high emissions shown in Figure 3. The strongest signals are seen in the summer (decrease) and winter (increase) with the largest impacts for the higher emissions. Winter values typically show increases of 0-8% (medium-low emissions) rising to mostly between 4 and 14% for high emissions. In the summers, the reductions are typically 4-16% (medium-low emissions) and up to 20% for high emissions. Spring is also drier (0-8%). The signal for winter should be viewed with medium confidence as all ensemble members, with the exception of three, show either small changes or substantial increases. Similarly, the projections for spring have a medium level of confidence. The signal for summer can be viewed with very high confidence as all ensemble members, bar one, show decreases. It should be noted that, in all cases, the data outliers were small in magnitude. The regional details in Figures 1-3 are not reliable as there is a very wide spread in the ensembles (not shown).

> ***Winter values typically show increases of 0-8% (medium emissions) rising to mostly between 4 and 14% for high emissions.***

> ***The increased frequency of very wet days (>20%) is well marked in winter, particularly for the high emissions case but the regional distributions may not be robust.***

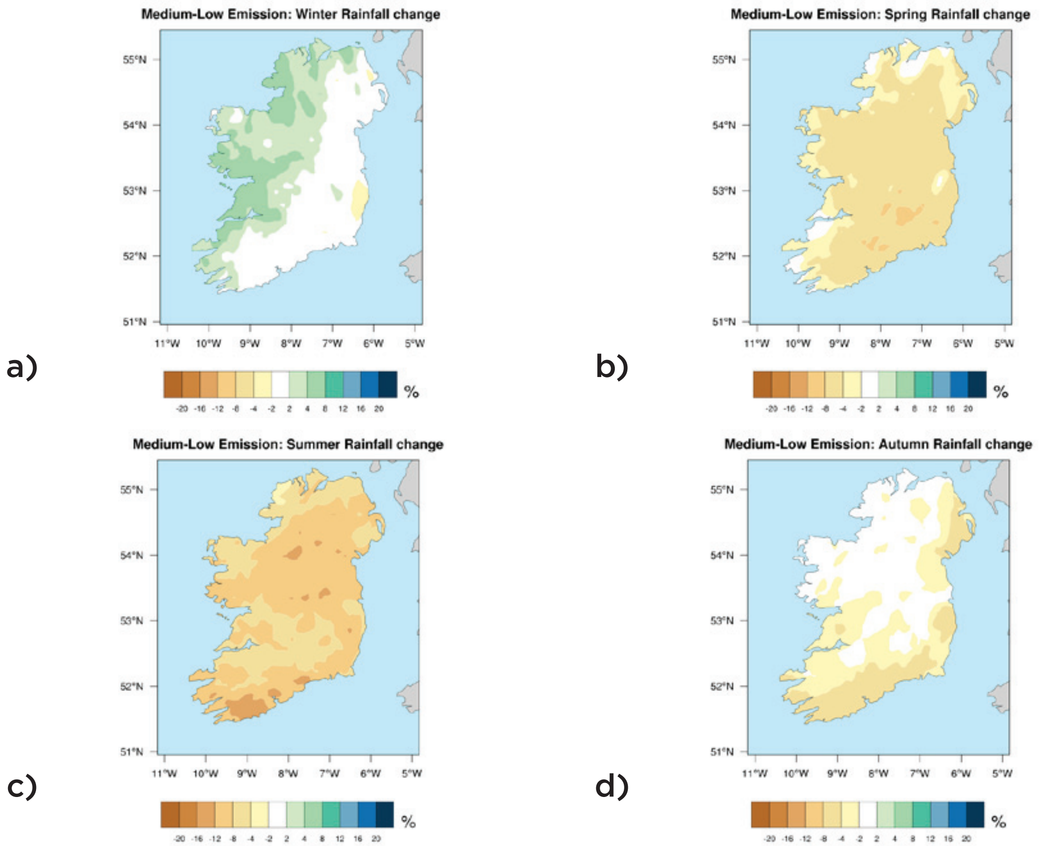

Figure 2. Seasonal changes (%) in precipitation for the medium-low emissions ensemble for (a) winter, (b) spring, (c) summer and (d) autumn. Changes for mid-century (2041-2060) are shown relative to the past (1981-2000).

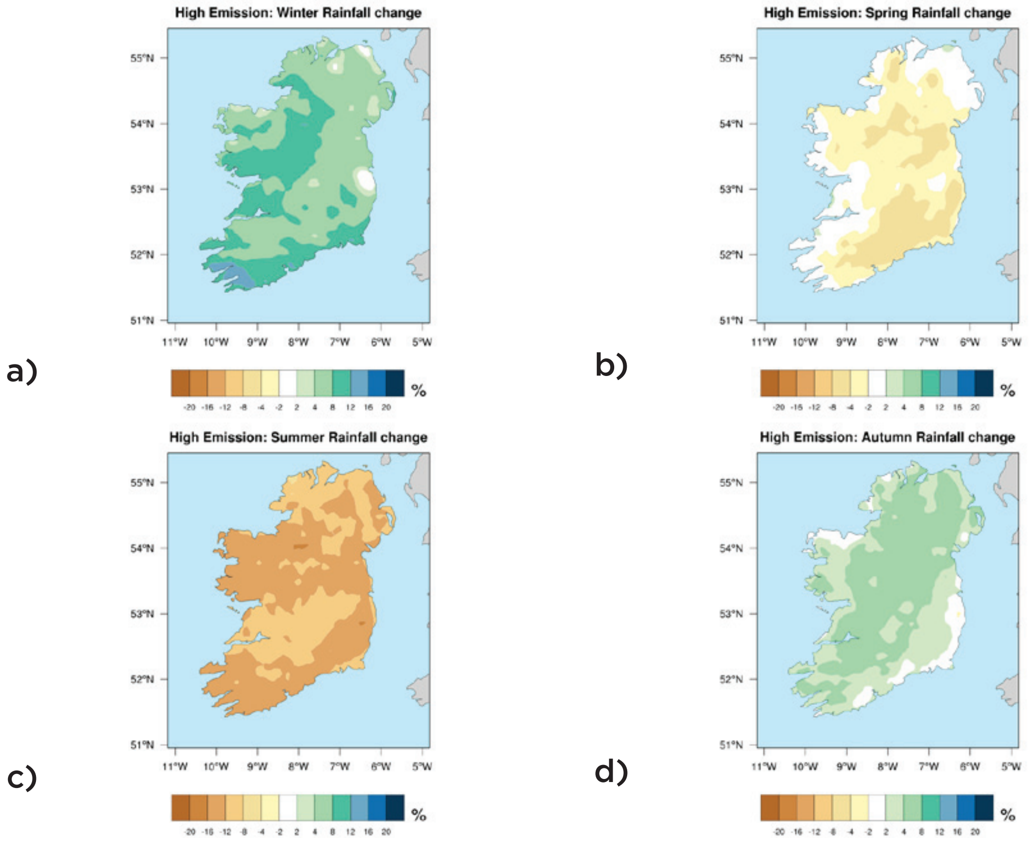

Figure 3. As for Figure 2 but for the high emissions ensemble.

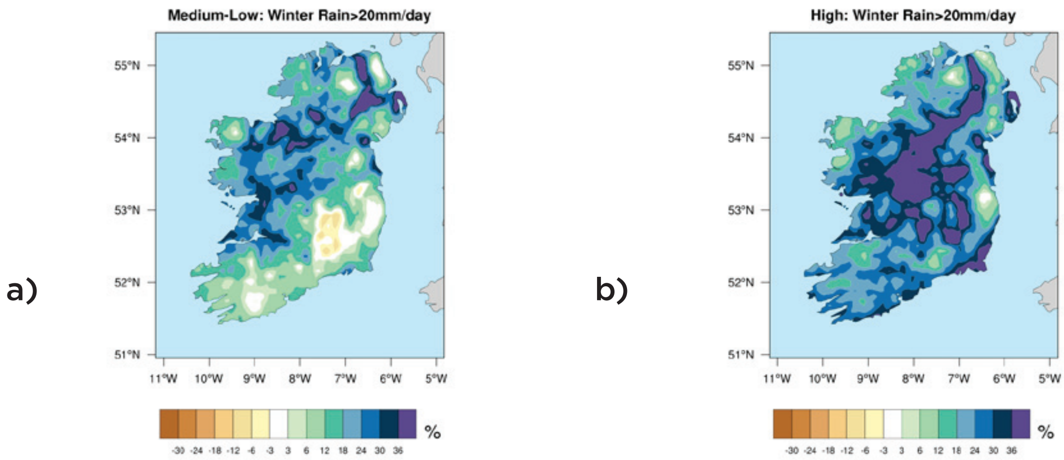

Figure 4. Seasonal change (%) in the frequency of very wet days (>20mm of precipitation) for winter for (a) medium-low emissions and (b) high emissions. Changes for mid-century (2041-2060) are shown relative to the past (1981 2000).

Results: heavy precipitation

Changes in the occurrence of extreme rainfall are particularly important because of the link with flooding. Figure 4 shows the change (%) in the frequency of very wet days (>20mm of precipitation) for the winter season for mid century (for both medium and high emission scenarios). The increased frequency of very wet days (>20%) is well marked in winter, particularly for the high emissions case but the regional distributions may not be robust. There is no obvious trend for summer.

Conclusions

Expected changes in Irish precipitation for mid-century are broadly consistent with the expected changes in temperatures (see Chapter 5). Winters are generally wetter and summers drier. They are also broadly consistent with results from the previous C4I modelling study (McGrath and Lynch, 2008).

Changes in extremes (e.g. very wet days) are more pronounced and are consistent with a study by Lenderink and Van Meijgaard (2008), which found an enhanced response in short-period precipitation extremes linked to rising temperatures.

Regional characterisation of the changes has been difficult to evaluate due to a large spread in the ensembles. However, a substantial body of climate simulation data has been generated in support of the new IPCC AR5 e.g. in the CMIP5 archive. With suitable downscaling and statistical analysis of the data it should be possible to refine the results presented here and provide sharper estimates of the impacts of climate change on Irish precipitation.

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10. Climate change and catchment hydrology

Conor Murphy [1]

Climate change is expected to alter catchment hydrology through changes in extremes of flooding and drought. River catchments are complex, dynamic systems and it is important to develop our understanding of how these systems are likely to respond to changes in climate. Work is ongoing in using EC-Earth simulations to further our understanding of how climate change will affect catchment hydrology and flood risk. In Ireland, the importance of this task is emphasised given the widespread socio-economic impacts of recent flood events. This chapter reviews recent Irish research concerning the hydrological impacts of climate change.

Observed trends in river flows

Hydrometric Stations

There are 703 active hydrometric stations in the Republic of Ireland operated by various bodies. Continuous water level records are maintained at 680 of these sites.

Detection of climate-driven trends from observations of river flows is a challenging task due to the many confounding factors (e.g. urbanisation, land-use change etc.) that can impede the analysis and interpretation of trends. To help detect and attribute trends in river flows more confidently many countries have identified Reference Hydrometric Networks (RHNs) to help limit these factors (Whitfield et al., 2012). In Ireland, Murphy et al. (2013a) have capitalised on the existing Irish hydrometric network to identify the Irish Reference Network (IRN); a subset of 35 gauges from the national hydrometric register that can be used for monitoring and detecting climate change signals. This flow archive, together with eight river flow stations that comprise the UK Benchmark Network (Hannaford and Marsh, 2006) has been analysed for changes in the full range of flow conditions (Murphy et al., 2013a; Murphy et al., 2013b).

High Flow indicators are dominated by increasing trends, with these becoming significant since 2000 in many stations.

Indicators of high flows from the IRN are dominated by increasing trends, a large proportion of which are statistically significant (5 percent level). Spatially, increasing trends in high flows are distributed throughout the country with the exception of the northwest and northeast where clusters of decreasing trends are evident.

Annual and seasonal mean flows are subject to large interannual variability making it difficult to detect trends. Trends in summer flows are not in line with projections from climate models.

For winter mean flows, there is some evidence of increasing trends in long records but these are not statistically significant. However, shorter records suggest decreasing trends. Summer mean flows are dominated by increasing trends with the recent spate of wet summers having a large influence on trends even for longer records. However, even when these recent wet summers are removed, increasing trends in summer mean flows remain prevalent. Trends in summer mean flows are heavily influenced by the historical development of the monitoring network with monitoring beginning for many stations around the early 1970s, a period of marked drought conditions, thereby hardwiring an increasing trend.

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[1] Irish Climate Analysis and Research Unit (ICARUS), Department of Geography, National University of Ireland, Maynooth.

It is difficult at this stage to attribute observed trends in observations of Irish river flows to anthropogenic climate change.

While there is considerable evidence of variability and change in the hydrological indicators derived from the flow records in the IRN, it is difficult at this stage to attribute changes to greenhouse-gas induced climate change. High flows show the greatest number of significant and persistent trends and are strongly correlated with the North Atlantic Oscillation (NAO), particularly in western areas. However, how the NAO itself will respond to anthropogenic climate change remains an open question (Osborn, 2004; Stephenson et al. 2006; Dong et al., 2011). More complete research on attributing changes in the IRN to drivers beyond the NAO should be a priority for future work.

Projected changes in catchment hydrology

Future projections of climate change impacts at the catchment scale are subject to large uncertainties.

Uncertainties in future impacts need to be quantified to ensure that the best quality information is available for decision making processes.

Seasonal flows

A broad signal of wetter winters and drier summers is evident from a number of independent studies.

Murphy and Charlton (2008) used statistically downscaled output from three Global Climate Models (GCMs) forced by the SRES A2 and B2 emissions scenarios (described in Chapter 1) to assess the impacts for nine Irish catchments. Results indicated increases in winter flow and decreases in summer. Murphy and Charlton also highlighted the importance of catchment properties in modulating the response to anthropogenic climate change. McGrath et al. (2008) and Steele-Dunne et al. (2008) used dynamically downscaled scenarios from the Rossby Centre Atmosphere Model (RCA3), forced using the European Centre Hamburg Model Version 5 (ECHAM5) to assess catchment scale impacts using the HBV hydrological model. Their results suggest an amplification of the seasonal cycle of runoff across the country driven by increased winter precipitation and decreased summer precipitation.

A small number of Irish studies have attempted to produce probabilistic climate change scenarios, built from a wider sample of GCM output (Fealy, 2010; Bastola et al., 2012). Bastola et al. (2012) derived probabilistic scenarios for the IPCC's AR4 CMIP3 climate model set. This dataset comprises 17 global climate models used in the IPCC's Fourth Assessment Report. Each of the 17 GCMs was run with the A1B, A2 and B1 SRES emissions scenarios and comprised 51 future scenarios (17 GCMs X 3 SRES scenarios). Figure 1 shows the probability density functions (PDFs) representing percentage changes in seasonal mean flows relative to present conditions for the Blackwater, Boyne, Moy and Suck catchments for the period 2070-2099 as simulated for the CMIP3 probabilistic scenarios produced by Bastola et al. (2012). The density is calculated on the basis of the proportion of daily future stream flow lying within the specified interval. Results are presented relative to natural variability in the period 1971-1990. In winter and spring PDFs are shifted to the right relative to estimates of climate variability, indicating increases in flows for these seasons. Summer and autumn flows on the other hand show a shift to the left relative to climate variability indicating a decrease in flows. However, uncertainties in response are large.

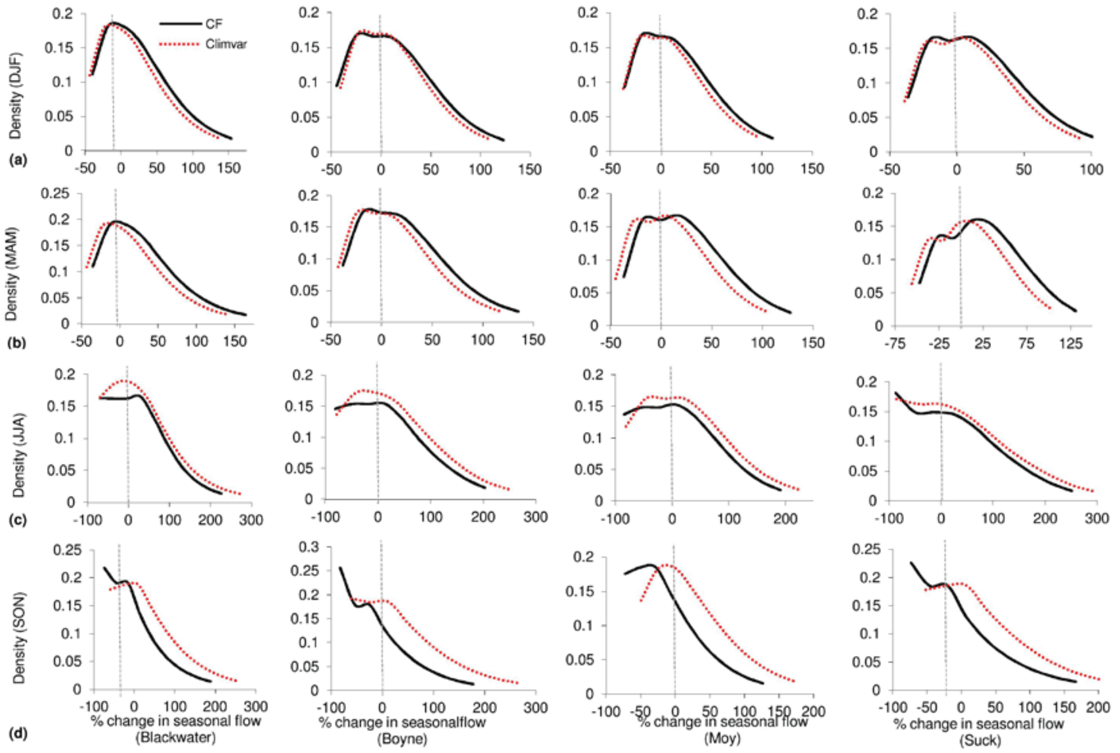

Figure 1. Probability distribution of seasonal mean flows as simulated using 17 CMIP3 global climate models relative to estimates of climate variability for (a) winter, (b) spring, (c) summer and (d) autumn for the Blackwater, Boyne, Moy and Suck catchments.

High flows

Increases in winter flows, coupled with likely increases in extreme precipitation events, are likely to lead to an elevated risk of flooding.

Uncertainties in future simulations are greater for low frequency (rarer) flood events than for high frequency (common) events.

Catchment response is critical in determining the changing nature of extremes.

Catchments with a fast response time show increases in flood risk for all return periods

Steele-Dunne et al. (2008) showed that increases in winter flows, coupled with likely increases in extreme precipitation events led to an elevated risk of flooding. Their work also showed that catchment response is critical in determining the changing nature of extremes; catchments with a fast response time show increases in flood risk for all return periods, while for other catchments little change or marginal decreases in flood risk were found. Increased risk is significantly marked in the southwest of the country for those catchments with fast response times. For example, in the Munster Blackwater the flow associated with a 40-year return period in the past is expected to have a return period of ~9.8 years in the period 2021–2060. The risk of extremely high winter flows is expected to almost double in the Feale and Suir, and is also likely to increase in the Boyne.

Return period

Refers to a flood of a magnitude that is expected to occur on average once in a specified number of years. For example, a flood with a one hundred year return period is expected to occur once on average every one hundred years. Therefore it has a probability of 0.01 of occurring in any one year.

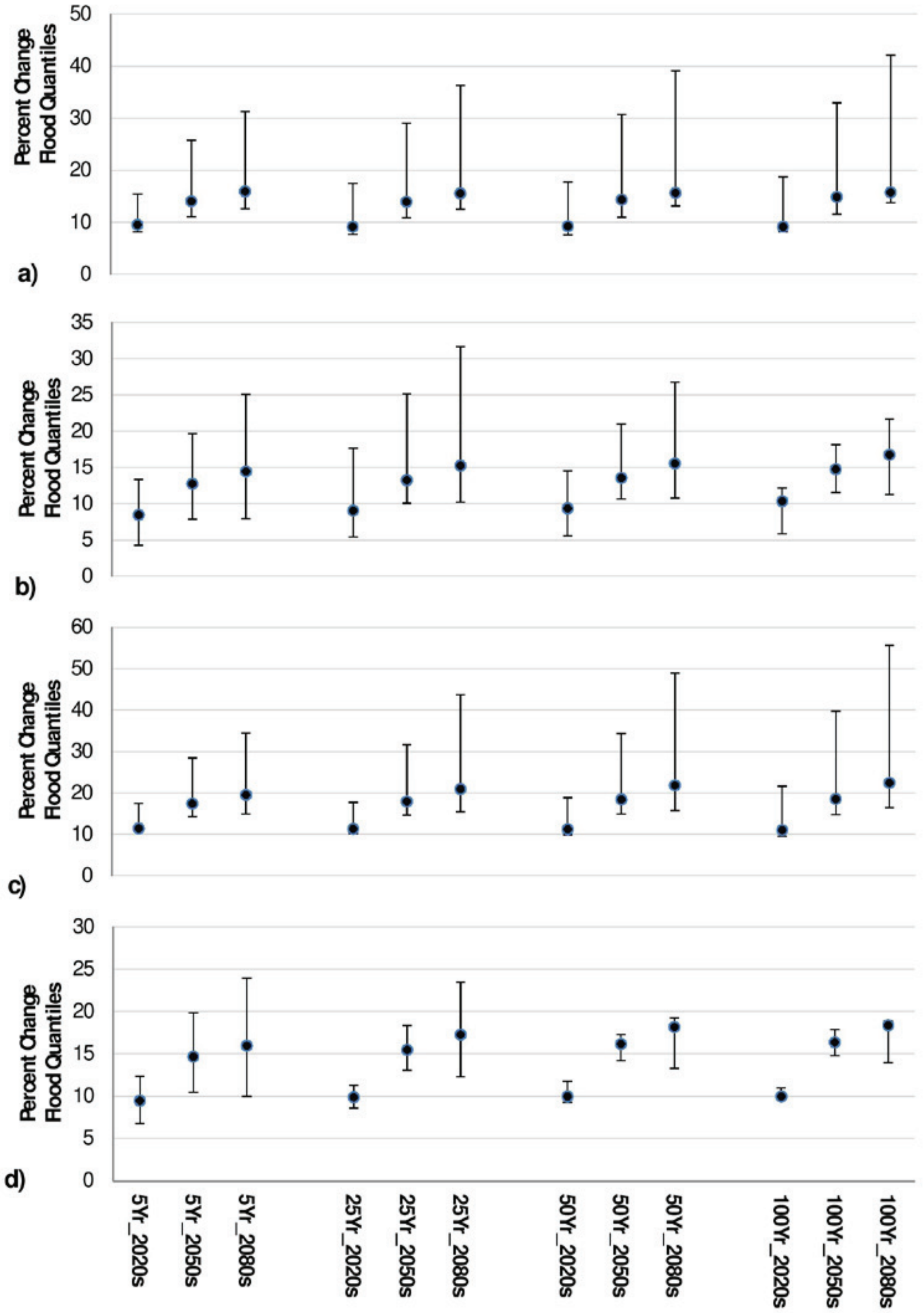

Figure 2. Simulation results showing percentage change in peak flows associated with current 5, 25, 50 and 100-year return period events for three future time periods. Catchments are a) Munster Blackwater b) Boyne c) Moy d) Suck. The black dot represents the median of simulations while the upper and lower error bars mark the 5th and 95th percentiles of future changes respectively.

Bastola et al. (2011) examined changes in flood risk using 17 global climate models that took part in the CMIP3 study and reported in the IPCC Fourth Assessment Report. Each of these models was forced with three SRES emissions scenarios (A1F1, A2, B1) resulting in 51 scenarios of future climate. Changes in flood risk were assessed for three future periods – the 2020s (2011-2040), the 2050s (2041-2070) and the 2080s (2071-2100). The scenarios were used to force structurally different hydrological models resulting in 20,000 simulations of future flood risk for four catchments – the Munster Blackwater, the Boyne, the Moy and the Suck.

Figure 2 shows the results simulated for each catchment in terms of the percentage change in each flood quantile analysed by Bastola et al. (2011). The impact of climate change is not as

great for flood peaks with smaller return periods. Consequently, for low frequency (very heavy precipitation) events, the risk of exceeding design allowances is greater with considerable implications for critical infrastructure. For individual catchments the uncertainties in future flood risk were greatest for the Moy and Blackwater and smallest for the Boyne and Suck. A progressive increase in the peak flow associated with the 5-, 25-, 50- and 100-year return periods was found when moving from the 2020s to the 2080s for all catchments. However, the magnitude of change varies between catchments.

Adapting to an uncertain future

Approaches to developing effective adaptation strategies must take uncertainty into account.

The application of a process-oriented "vulnerability thinking" instead of an "impacts thinking" approach in adaptation planning is promoted.

Rather than basing adaptation decisions on wide ranges of uncertainty, climate scenarios can be used to stress-test decisions to the range of possible future impacts.

Adaptation must be approached as context specific; a successful set of adaptation options may work well in one region but may not be applicable in another.

Adaptation is necessary to position Ireland to be better able to cope with the impacts of climate change (See Chapter 15). However, uncertainties surrounding future impacts are large and approaches to developing effective adaptation strategies must take this uncertainty into account. In the scenarios presented above, only climatic uncertainties are incorporated. Non-climatic factors such as changes in human behaviour, economic uncertainty and change in population dynamics should also be factored. Internationally, such uncertainties have precipitated a move away from traditional "predict and provide" approaches in adapting to climate change, where impacts derived from selected climate change scenarios are used to provide a narrow projection of future conditions on which to base adaptation decisions.

Recently this has been replaced with a bottom-up approach where broad ranges of climate scenarios that sample representative uncertainties are used to stress-test adaptation options which are identified by engagement with stakeholders. In such approaches emphasis is placed on identifying adaptation options that are robust to the inherent and irreducible uncertainties associated with future impacts (e.g. Wilby and Dessai, 2010). Where investment in new infrastructure is required, it is recommended that such infrastructure be subjected to a sensitivity analysis of performance under the full range of uncertainty associated with climate change. In Ireland a number of studies have begun to move in this direction and offer a starting point from which such approaches to adaptation can be developed.

Hall and Murphy (2011, 2012) conducted a vulnerability analysis of future public water supply for selected catchments over the coming decades by accounting for current and future pressures within the water supply system. Potential adaptation options were screened for robustness using exploratory modelling to assess the effectiveness and robustness of different adaptation options. In many cases simple options such as leakage and demand reduction were sufficient to avoid shortfalls in water provision under the range of impacts considered. However, in other systems, particularly those operating close to the maximum of capacity under current conditions, such adaptation options were found not to be sufficient in avoiding problems with water supply.

In the context of flooding, Bastola et al. (2011) use a large ensemble of climate scenarios to stress-test policy decisions in adapting to increases

in flood risk. Taking the example of providing additional safety margins on the design of flood defences, the study tests the effectiveness of such allowances given the uncertainties in future flood risk. Using risk response surfaces, the study shows that an allowance of 20% increases in peak discharges in designing flood defences to cater for future climate change may not be sufficient in some catchments.

Such work highlights the importance of considering uncertainties in developing adaptation plans, particularly the utility of using climate scenarios to stress-test current policies or preferred options. They also raise fundamental questions as to the acceptable levels of risk for instances where the economic cost of protecting against the full range of future impacts are not practical. Such studies also suggest that adaptation must be approached as context specific; different risks and different sensitivities of catchments to change mean that a set of adaptation options may work well in one catchment but may not be successful in another.

Future research needs

- It is crucial that the next generation of climate change scenarios are run for Irish hydrological conditions to help refine understanding of future impacts and our understanding of uncertainty ranges. Research is ongoing between Met Éireann and NUI Maynooth in assessing the hydrological impacts of the new EC-Earth scenarios for Irish catchments.
- Further research is required to better understand the links between large-scale atmospheric variables and flood risk in Ireland. While trends in high flows are correlated with changes in the North Atlantic Oscillation, this is a crude index. Additionally, there is large disagreement among climate models as to how the NAO will respond to increases in greenhouse gases. It is therefore crucial that future research better understands the hydro-climatic drivers of change in flood risk.
- Given the wide range of uncertainties that are inherent to local-scale impacts, new approaches to using climate change scenarios for stress-testing and appraisal of adaptation options are emerging in the international literature. Further development of such approaches for Ireland offers real direction in helping water managers and decision makers to incorporate climate change considerations into operational activities (see, for example, Brown and Wilby, 2012).
- Most studies to date only incorporate climatic changes into future impacts assessment. In the real world, climate change will take place in the context of other non-climatic drivers of change in catchment hydrology such as land-use change, population growth, changes in policy, etc. It is important that future work takes more account of the co-evolution of climate change with internal catchment changes.

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11. Impact of climate change on surface winds over Ireland

Paul Nolan[1], Emily Gleeson[2], Ray McGrath[2]

Downscaled global simulation data from several models were used to provide an assessment of the impacts of a warming climate on the wind energy resource of Ireland. The future climate was simulated using both medium-low (B1, RCP4.5) and high (A1B, A2, RCP8.5) emission scenarios. Results show an overall increase (0 to 8%) in the energy content of the wind for the future winter months and a decrease (4 to 14%) during the summer months.

Introduction

Under the EU Directive on the Promotion of the Use of Renewable Energy (2009/28/EC), Ireland is committed to ensuring that 16% of the total energy consumed in heating, electricity and transport is generated from renewable resources by 2020 (Department of Communications, Energy and Natural Resources, 2010). The Irish Government has also set a target of 40% electricity consumption from renewable sources by 2020. Wind energy is expected to provide approximately 90% of this target.

In 2012 wind energy in Ireland accounted for 15.5% of our electricity needs. From a climate perspective, Ireland is ideally located to exploit the natural energy associated with the wind. Mean annual speeds are typically in the range 6-8.5m/s at a 60m level over land, values that are sufficient to sustain commercial enterprises with current wind turbine technology.

The wind energy potential of the past Irish climate has been well documented (Troen et al., 1989, SEI, 2003). However, climate change may alter the wind patterns in the future; a reduction in speeds may reduce the commercial returns or pose problems for the continuity of supply and an increase in the frequency of severe winds (e.g. gale/storm gusts) may similarly affect supply continuity. Conversely, an increase in the mean wind speed may have a positive effect on the available power supply.

There is some evidence of a slight reduction in surface winds over past decades both over land and coastal areas around Ireland but the results are not robust (Vautard et al., 2010); see Chapter 2 section entitled “Other parameters”. Likewise, while future projections by the global climate models suggest a pole-ward shift in the jet stream and Atlantic storm tracks, the signals are not conclusive and natural variability may be the dominant feature in the coming decades. Nevertheless, a recent study with a very high resolution version of the EC-Earth model (Haarsma, et al., 2013) suggests an increase in the frequency of extreme wind storms affecting Western Europe in future autumn seasons due to global warming.

Details regarding the different global climate datasets, the greenhouse-gas emission scenarios and the downscaling models used to produce the ensemble of climate projections for Ireland are summarised in Chapter 1. The projections outlined in the current study agree with previous studies (Nolan et al., 2011, Nolan et al., 2012) in the sense that they show significant increases in the future wind energy resource over Ireland during winter and decreases during summer. Expected

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[1] ICHEC, Trinity Technology & Enterprise Campus, Grand Canal Quay, Dublin 2 and formerly Meteorology & Climate Centre, School of Mathematical Sciences, UCD, Belfield, Dublin 4.

[2] Research, Environment and Applications Division, Met Éireann, Glasnevin, Dublin 9.

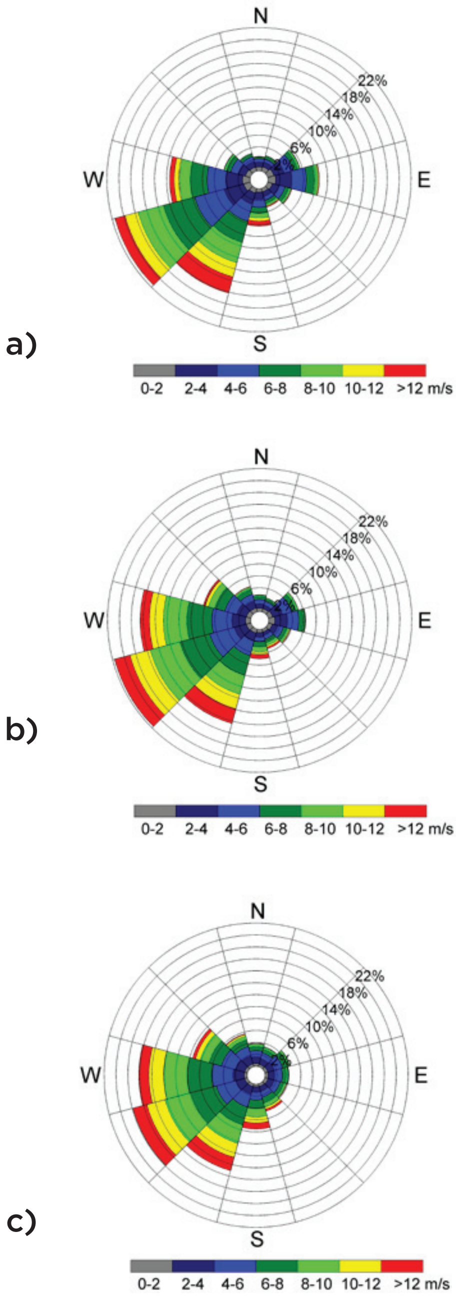

Figure 1. The 10m wind roses at Casement Aerodrome for the period 1981-2000 (a) observed, (b) WRF-ECEARTH ensemble 6km resolution (c) WRF-ECEARTH ensemble 18km resolution. Each sector shows the percentage breakdown of the wind speed in intervals of 2m/s.

changes in the annual mean wind speed are small. The current research aims to address the issue of model uncertainty by employing a large ensemble of simulations to study climate change. In addition, the model resolution was increased, up to a resolution of 4km, thus allowing us to better assess the local effects of climate change on the wind energy resource.

Validation

The Regional Climate Models (RCMs) were validated using 20-year simulations of the past Irish climate (1981-2000), driven by both ECMWF ERA-40 global re-analysis and the Global Climate Model (GCM) datasets and comparing the output against observational data. Extensive validations were carried out to test the skill of the CLM and WRF models in accurately modelling the wind fields (Nolan P. et al., 2012). Results confirm that the output of both models exhibit reasonable and realistic features as documented in the historical data record.

As in the case of precipitation (see Chapter 9), near-surface winds are strongly influenced by local features e.g. hills and valleys and an accurate description of these effects requires high-resolution climate modelling. To accurately model these effects in investigating the impacts of climate change a two-stage process is used whereby the global model data are downscaled using high-resolution regional climate models. The impacts of resolution are evident in Figure 1, which shows the 10m wind roses at Casement Aerodrome located north of the Wicklow Mountains. The observed wind rose in Figure 1a demonstrates that the mountains act as a barrier, preventing south and south-easterly winds. This is better represented by the high resolution (6km) simulation (Figure 1b). The 18km simulation (Figure 1c) underestimates the south-westerly and easterly wind.

Future projections

Since the typical height of wind turbines is approximately 60m, we focus on wind projections at this height. The projected percentage change in the annual 60m mean wind speed was found to show a small (0 to 1%) decrease. In order to investigate the effects of climate change on the energy content of the wind, the projected changes in the 60m mean cube wind speed were calculated. Again, only small decreases (0 to 2%) are projected. However, when stratified

per season, we see substantial changes in the mean wind speed, particularly for the winter (December, January and February) and summer (June, July and August) months. Figure 2 shows the seasonal percentage change in the 60m mean cube wind speed for the high emission scenarios (see Chapter 1 for a description of the emission scenarios). The corresponding medium-low emission results are presented in Figure 3. The strongest signals are noted for the summer (decrease) and winter (increase) months for the high emission simulations. The projected increases for winter range from ~0% (medium-low emission) to ~8% (high emission). For summer, decreases range from ~4% (medium-low emission) to ~14% (high emission). Reductions are also noted for spring, ranging from 0% to 6%. There is no obvious trend for autumn. The signals for annual, summer and spring are robust as all ensemble members are in general agreement for both the high and medium-low emission scenarios, thus increasing our confidence in the projections. However, a small number of the ensemble members showed an opposite signal for winter. The climate change signal for winter should therefore be viewed with caution.

Hereafter, the analysis will focus on the high emission simulations. In all cases, the medium-low emission projections were found to have a weaker but similar signal.

Figure 4 shows a contour plot of the diurnal cycle of mean cube 60m wind speed per month at Arklow wind farm and seventeen locations

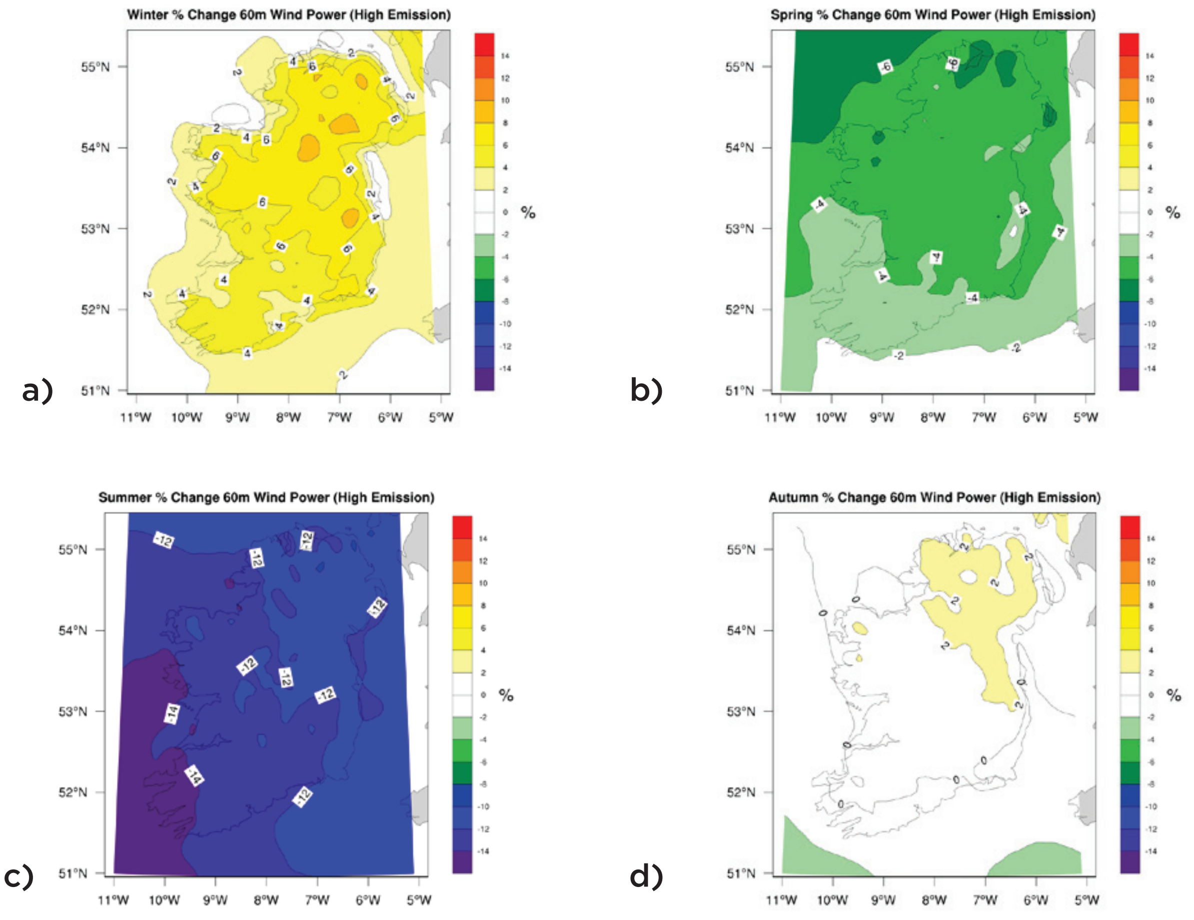

Figure 2. High emission: The ensemble projected change (%) in the 60m mean wind power for (a) winter, (b) spring, (c) summer and (d) autumn. In each case, the future period 2041-2060 is compared with the control period 1981-2000.

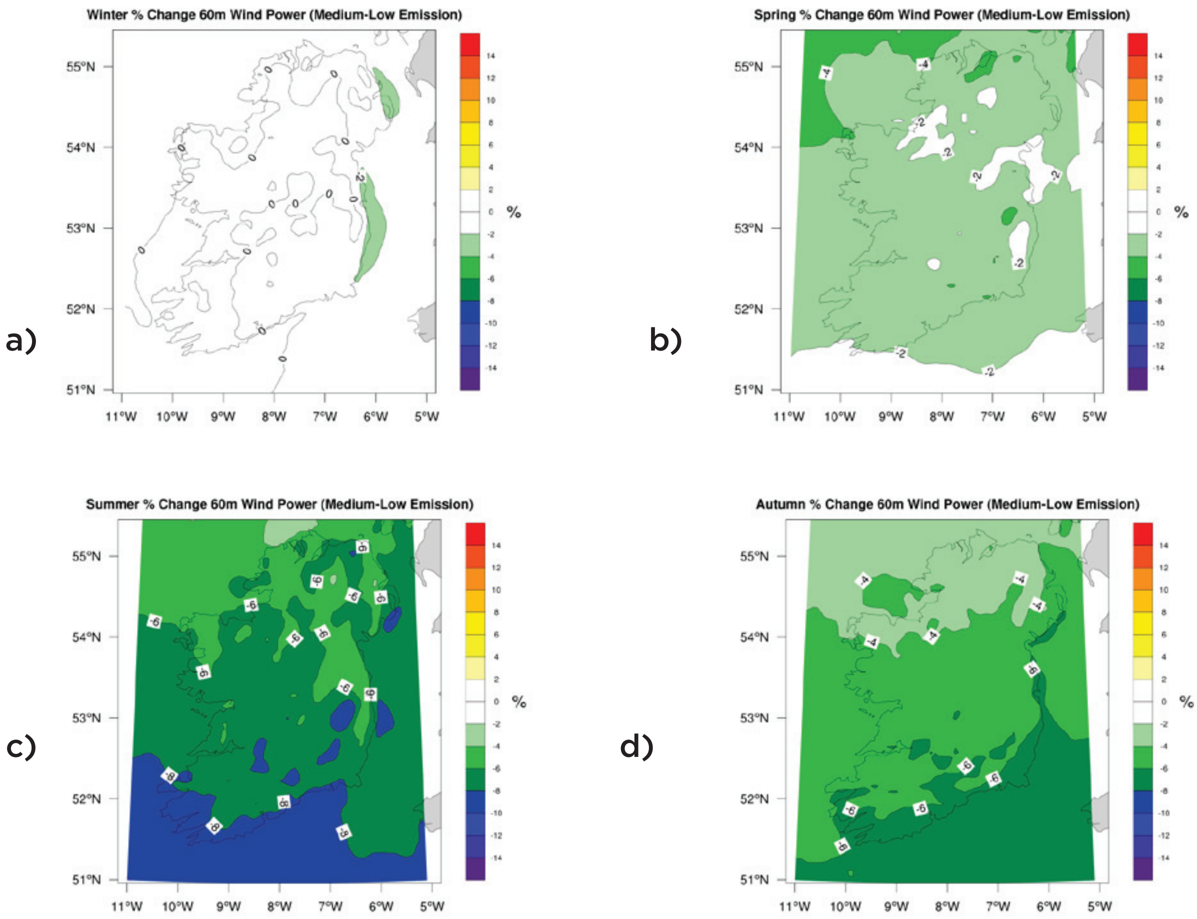

Figure 3. Medium-low emission: The ensemble projected change (%) in the 60m mean wind power for (a) winter, (b) spring, (c) summer and (d) autumn. In each case, the future period 2041-2060 is compared with the control period 1981-2000.

spanning Ireland. The ensemble of past and high emission simulations are presented in Figures 4(a) and 4(b) respectively. As expected, the energy content of the wind is at a maximum during the middle of the day in winter and minimum during night-time summer. The percentage difference is presented in Figure 4(c). The largest projected decreases are noted during the months of July and August particularly during morning and afternoon. Increases are noted during October and the winter months with no obvious diurnal trend.

Since wind farms are designed and constructed to make optimal use of the prevailing wind direction, it is important to assess the potential effects of climate change on future wind directions over Ireland. Figure 5 shows 60m wind roses at Arklow wind farm and various locations spanning Ireland for (a) the past winter ensemble control runs (1981-2000), (b) the winter ensemble of high emission future simulations, (c) the past summer ensemble control runs and (d) the summer ensemble of high emission future simulations. Although changes in wind speed for the future winter and summer months are projected, the general wind directions do not change substantially. For the winter months, a small increase in south-westerly winds is noted. For the future summer months, the wind directions show only minor changes. Given that near-surface wind speeds are strongly influenced by the local topography, it is not surprising that the projected change in wind directions is small.

To quantify the projected change in extreme wind speeds, the percentage change in the top

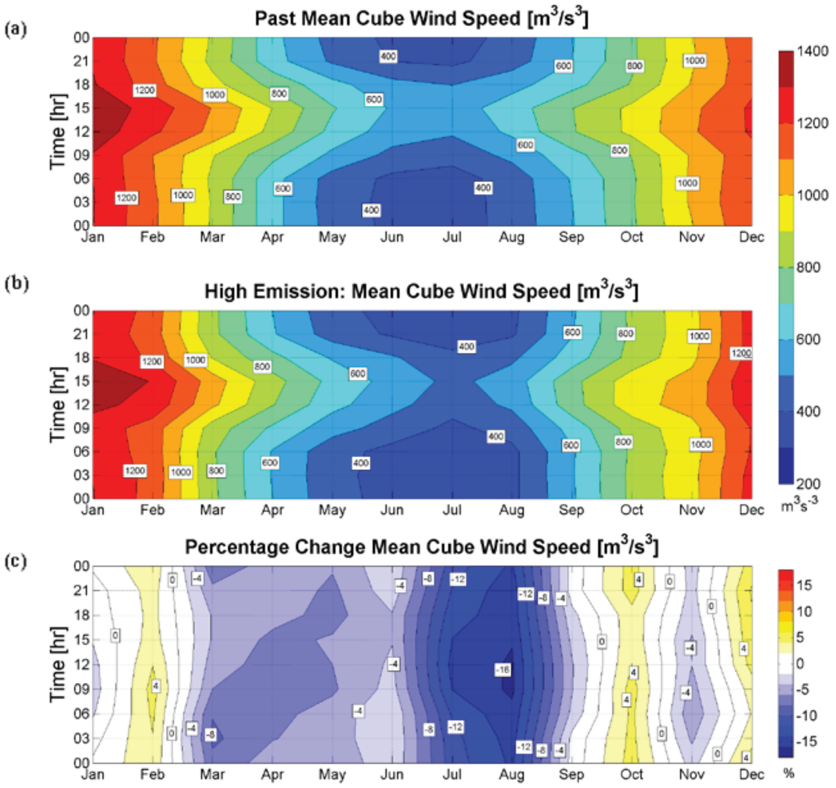

Figure 4. The annual diurnal 60m mean cubed wind speed at Arklow wind farm and seventeen locations spanning Ireland is shown for (a) ensemble of past simulation, (b) ensemble of high emission future simulations and (c) the projected percentage change.

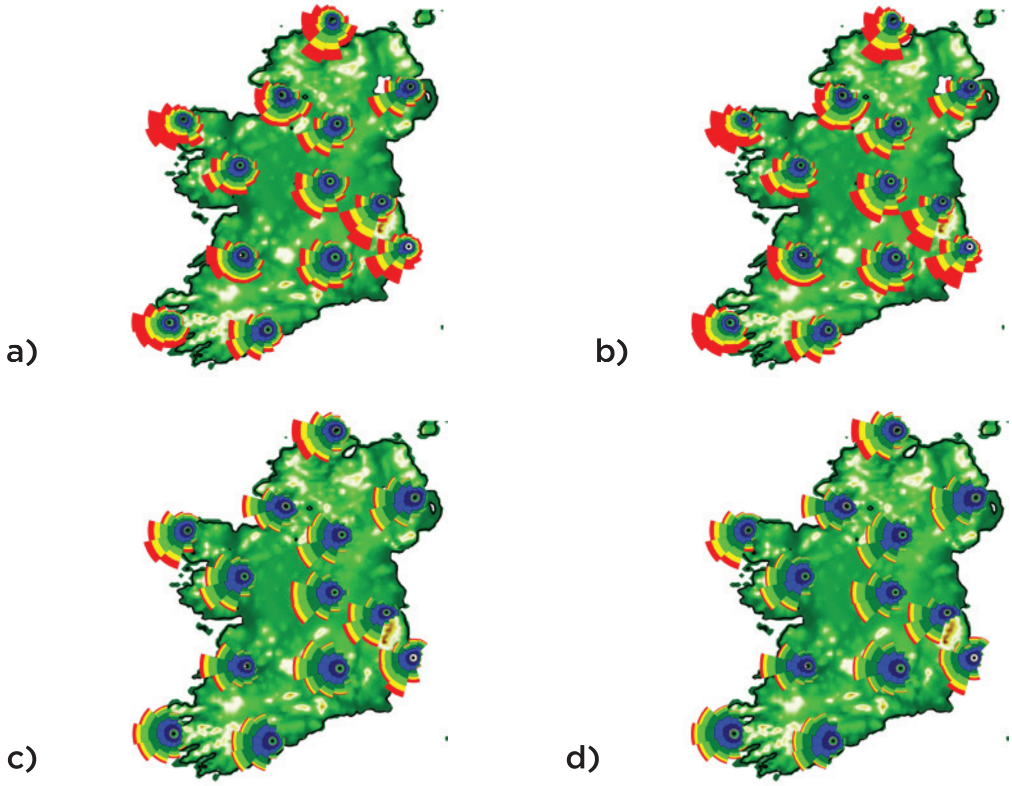

Figure 5. Wind roses at 60m at various locations spanning Ireland (a) the winter ensemble of past simulations 1981-2000, (b) the winter ensemble of high emission future simulations 2041-2060, (c) the summer ensemble of past simulations 1981-2000, (b) the summer ensemble of high emission future simulations 2041-2060.

1% of 60m winds was calculated for the medium-low and high emission scenarios. Results show slight increases in extreme wind speeds (~0.5%) over Ireland.

Conclusions

We have examined the impact of simulated global climate change on the wind energy resource of Ireland using the method of Regional Climate Modelling. In view of unavoidable errors due to model (regional and global) imperfections, and the inherent limitation on predictability of the atmosphere arising from its chaotic nature, isolated predictions are of very limited value. To address this issue of model uncertainty, an ensemble of RCMs was run.

In view of unavoidable errors due to model (regional and global) imperfections, and the inherent limitation on predictability of the atmosphere arising from its chaotic nature, isolated predictions are of very limited value. To address this issue of model uncertainty, an ensemble of RCMs was run.

The future climate was simulated using both medium-low and high emission scenarios. Results show an overall increase (0 to 8%) in the energy content of the wind for the future winter months and a decrease (4 to 14%) during the summer months. Reductions were noted for spring, ranging from 0% to 6%. All ensemble members show little or no changes over the year as a whole. There is no obvious trend for autumn. The signals for annual, summer and spring are robust as all ensemble members are in general agreement for both the high and medium-low emission scenarios, thus increasing our confidence in the projections. However a small number of the ensemble members showed an opposite signal for winter. The climate change signal for winter should therefore be viewed with caution. Expected changes in extreme wind speed and wind direction show no substantial change.

Results show an overall increase (0 to 8%) in the energy content of the wind for the future winter months and a decrease (4 to 14%) during the summer months.

Acknowledgements

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12. Predicting the future wave climate of Ireland: 2031-2060

Sarah Gallagher[1], Roxana Tiron[1],
Frédéric Dias[1]

The impact of rising greenhouse gas emissions on the future wave climate of Ireland is preliminarily assessed by using the new EC-Earth global climate simulations to drive a wave model. Overall, the results suggest a slight decrease in mean significant wave heights around Ireland in the future but there is some evidence of an increase in the more extreme wave heights in the north and northwest.

Introduction

Due to its location in the northeast Atlantic, Ireland possesses one of the most energetic wave climates in the world. Atlantic swells propagate eastward towards the coastline of Ireland, often originating at the other side of the ocean, thousands of kilometres away.

Given the considerable importance of the sea to the people of Ireland (for recreation, marine industries and renewable energy capabilities), it is important to know how climate change will affect the wave climate resource of Ireland. Can Ireland expect higher or lower wave heights in the future? Will changes in the Atlantic storm tracks bring more storms to our shores, enhancing coastal hazards and coastal erosion?

Figure 1. Surfer on Aileen's wave © Cliffs of Moher Visitor Experience

In this study we examine a likely future wave climate projection for Ireland using one of Met Éireann's global EC-Earth simulations, which covers the period 1850 to 2100. The 1961-1990 period was chosen for the historical analysis. The years 2031-2060, under RCP4.5 (Taylor et al., 2012; see Chapter 1 for further details), were used for analysis of the future wave climate. The 10m winds were used to drive a basin-scale wave model (North Atlantic) in order to capture distant swells that propagate from the other side of the ocean. These were then used to force two higher resolution nested grids focusing on Ireland (see Figure 2). The primary goal was to estimate the future wave climate around Ireland and the expected changes relative to the current climate.

Can we predict the "giants" among Irish waves?

O'Brien et al. (2013) revealed a long history of large waves around Ireland from large storm waves to the more destructive freak waves. The former can be linked to the prevalent strong winds in Ireland (Malin Head, for example, experienced an average of 66 "gale days" per annum during the period 1961-1990). Freak waves have only recently been accepted as a distinct wave class, and can loosely be defined as large and highly powerful waves that seem to appear from nowhere, with heights 2-3 times larger than the surrounding sea state (Kharif & Pelinovsky, 2003). They also have short "life-spans" and

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[1] School of Mathematical Sciences, UCD, Belfield, Dublin 4.

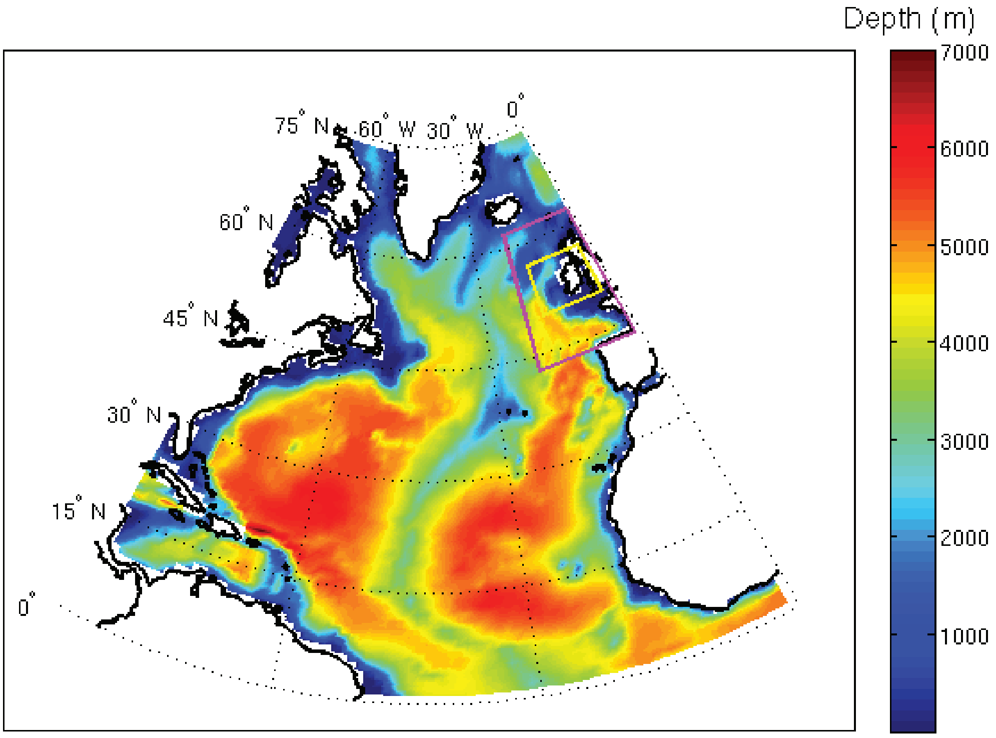

Figure 2. Model domains for the 3 nested grids used in the WAVEWATCH III wave model simulations. Grid 1: largest area, Grid 2: outlined in magenta and Grid 3: outlined in yellow.

are localised in space, which makes them hard to predict. However, even with very few buoys and with a relatively short observational record interval (of about 10 years), massive waves have been measured in Irish waters. On 13 December 2011, the M4 buoy located 75km off the Belmullet peninsula (Figure 3) registered a 20.4m wave in a sea state with mean wave heights of about 13m.

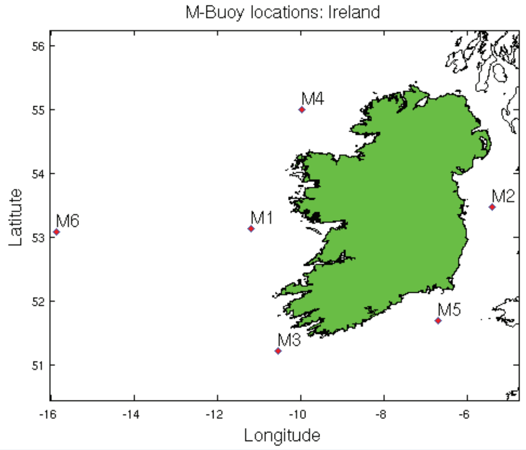

Figure 3. Location of Irish Buoys

Can a wave-forecasting model capture such formidable waves? Wave forecasting is an area that has experienced considerable progress in recent decades (Cavaleri et al., 2007). This has been aided by improvements in the understanding of the underlying physical processes that govern wave generation and propagation, and also by the increasing volume of observations available at a global scale (including satellite measurements), which allow a thorough validation and calibration of the models. Nonetheless, a key limitation is the dramatic disparity between the scales these models need to address (i.e. the scale of ocean basins, which are thousands of kilometres in extent and the scale of the waves themselves, which are generally measured in tens of metres). Wave forecasting models cannot predict individual waves. Rather, they target the evolution of the sea state, which in a sense represents the statistical properties e.g. the average height of the waves over a set time-frame (typically 30 minutes). While there is ongoing effort to gather information about the frequency of extreme waves and the meteorological conditions with which they are associated, freak waves and steep storm waves are currently largely unpredictable.

The most common measure of sea states is the significant wave height (Hs), which in technical terms represents the mean wave height (trough to crest) of the highest third of the waves. This measure is chosen because it tends to be the height of the waves that is most readily observed by the human eye (WMO, 1998) and, perhaps more importantly, the larger waves are usually more significant than the smaller waves. As such, this study focuses on quantifying the spatial and temporal changes in Hs around Ireland that are expected to occur in the future.

The wave model

We employ the WAVEWATCH III wave model (Tolman, 2009) used for operational forecasting by the National Oceanic and Atmospheric Administration (NOAA). The wave model consists of 3 nested grids (Figure 2): -

- Grid 1: North Atlantic: 1° x 1° latitude/longitude
- Grid 2: Eastern North Atlantic: 0.333° x 0.333° latitude/longitude
- Grid 3: Ireland: 0.1° x 0.1° latitude/longitude (about 10km)

The wave directional spectra are discretised into 32 frequencies (logarithmically spaced starting from 0.0373 Hz) and 24 equally-spaced geographical directions. The 1-minute gridded global relief dataset (ETOPO1) was used for the bathymetry of the model.

Wave climate averages for Ireland: 1981-2009

As a first step we determined the averages for the Irish wave climate by running a 29-year wave model historical simulation (1981-2009) with wind forcing from the ERA-Interim re-analysis dataset (Dee et al., 2011) provided by the European Centre for Medium-Range Weather Forecasts (ECMWF). This historical simulation (hindcast) can be considered as a best guess of the past climate and focuses on Ireland at high resolution. We also performed an historical climate run (or control run) for the same period, forced with historical EC-Earth winds and cross checked its climate statistics with the ERA driven historical simulation. This historical run can be imagined as a "parallel universe" where day-to-day values do not match observations, but long-term trends and averages should follow the real climate. The quality of the 29-year historical simulation was verified using observational data from the M3, M4 and M6 wave buoys from the Irish Marine Weather Buoy Network run by Met Éireann and the Marine Institute (Figure 3). As seen in Table 1, the ERA-driven hindcast compares very well with the wave buoy measurements at the three locations off the west coast.

Given the relative "youth" of the Irish Marine Weather Buoy Network (first deployments took place in 2000), the available measurements are still not sufficient to capture long-term changes in the climate. Therefore, the historical simulation, which was validated with existing data, is a valuable tool to investigate wave climate variability around Ireland.

The annual and seasonal means of the significant wave height for the historical simulation are shown in Figure 4 (left panels). This shows that the annual means vary significantly from season to season, with a maximum of over 5m off the west coast in winter and of under 1m on the east coast in summer. The right panels display the interannual variability of the means as the normalised standard deviation (%). This is a measure of how much the annual means vary from year to year. The annual mean significant wave height does not vary much around the coast. When looking at the individual seasons, however, a more interesting picture emerges. On the Atlantic west coast in winter and spring the mean significant wave height varies to a greater extent than in summer and autumn. On the east coast, the Irish Sea has increased variability compared to the Atlantic; however, this is relative

	M3 Buoy (2003 - 2010)	M4 Buoy (2006 - 2010)	M6 Buoy (2006 - 2010)
Mean (m)	**2.9**	**3.1**	**3.47**
Bias (m)	**0.07**	**-0.04**	**0.02**
RMSE (m)	**0.56**	**0.49**	**0.51**
Scatter Index	**0.19**	**0.16**	**0.14**
Correlation Coefficient	**0.94**	**0.96**	**0.96**

Table 1. Statistical comparison of the significant wave height (Hs) data from the M3, M4 and M6 buoys against the wave model values (ERA-driven historical run).

to low mean significant wave height values of about 1m.

The wave climate averages for the 29-year ERA-driven historical simulation and the 29-year historical EC-Earth-driven simulation were compared. This was carried out to evaluate if the wave model forced with the EC-Earth wind data could recreate the past wave climate of Ireland to a high quality. The relative differences in the mean significant wave height between both datasets, taken over the highest resolution grid (0.1° x 0.1°) focused on Ireland, are less than 5% (and less than 2% for the Irish Sea). This result demonstrates the realism of the EC-Earth climate simulations and justifies the use of the data to estimate the future wave climate.

Changes in the future wave climate: 2031-2060

This result demonstrates the realism of the EC-Earth climate simulations and justifies the use of the data to estimate the future wave climate.

To ascertain the changes in the wave climate, the 30-year (2031-2060) future wave climate projection was compared with the historical EC-Earth driven run (1981-2009), for both mean and highest sea states. Consistent with recent global wave climate projection studies (Hemer et al., 2013), our study reveals annual decreases in both mean significant wave heights and storm wave heights for the North Atlantic in general (Figure 5) and Ireland in particular (Figure 6). As can be seen in Figure 5, there is a small decrease in annual mean significant wave height in the proximity of Ireland with the largest decrease occurring in winter. Large areas of increase in winter off the northeast coast of North America and south of Greenland are likely related to the retreat of Arctic ice cover in the future. Summer mean values exhibit a small decrease around Ireland. However, there are areas of increased significant wave height off the coast of Spain and to the north, around the Icelandic coast.

Figure 6 presents the differences between the future and past/current climate on the finest resolution grid focused on Ireland. The largest decrease in the mean values (over 20cm) can be seen off the southwest coast in winter i.e. a decrease of about 4% in the mean significant wave height of about 5m. When we look at storm wave heights (highest 5% of significant wave heights), annual values show a small decrease around Ireland in the future but if we break this down by season, considerable increases become evident. Spring becomes stormier in the north and northwest, with increases of over 20cm. Note also that large decreases can be seen off the southwest coast (same order of magnitude). A small increase in the north can also be seen in the winter.

Figure 7 shows that the highest significant wave heights taken over the entire simulation period occur in the future run, despite an overall

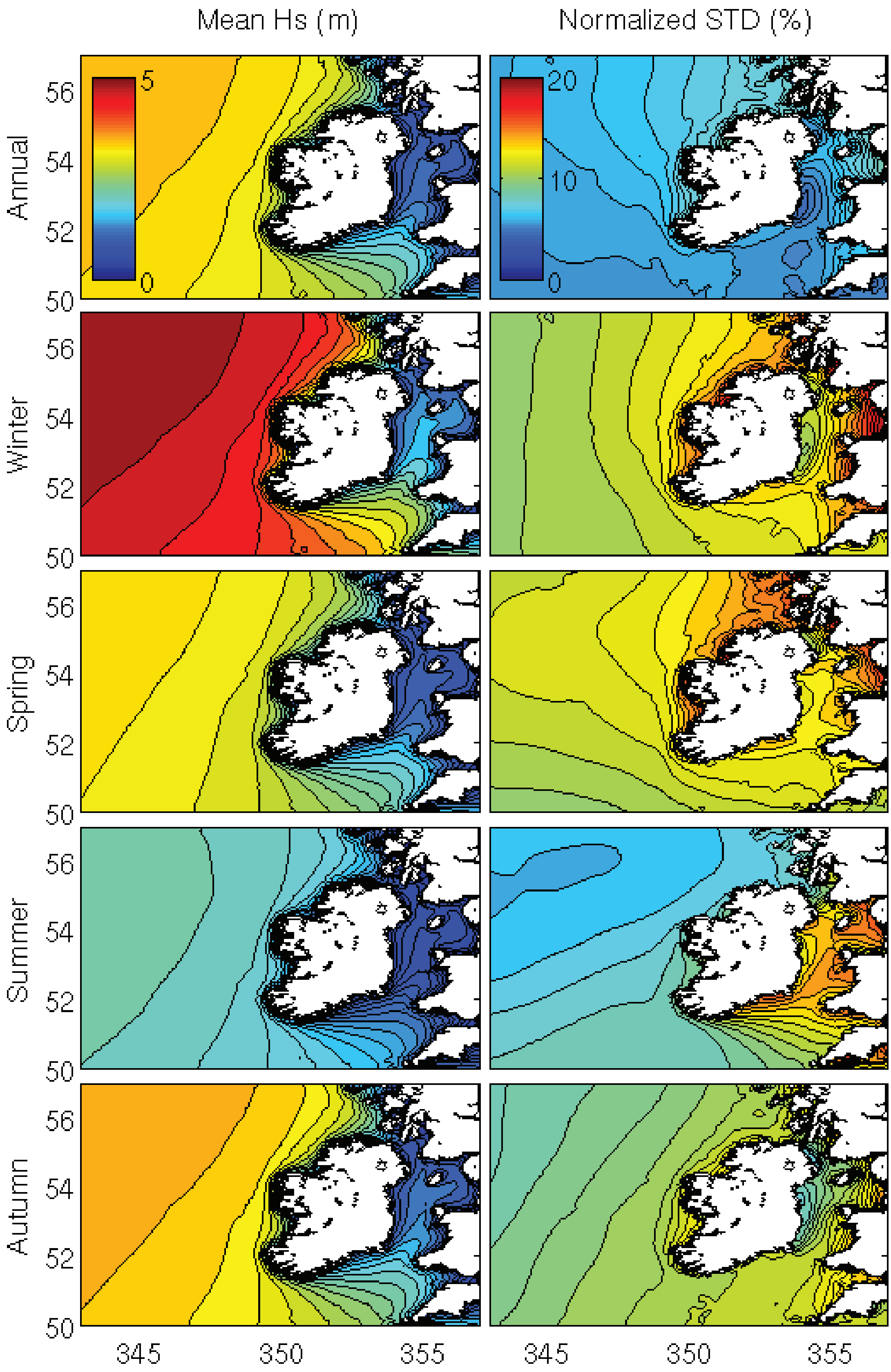

Figure 4. The simulated past wave climate of Ireland (1981-2009) driven by ERA-Interim re-analysis data. Left panels: annual and seasonal mean significant wave height. Right panels: normalised standard deviation of the means (%), which represents the interannual variability.

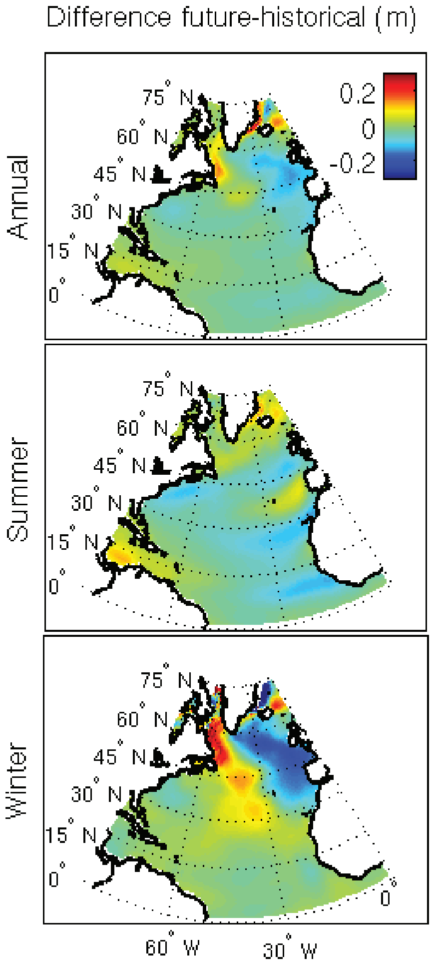

Figure 5. Difference in the mean significant wave heights for the future period (2031-2060) relative to the past period (1981-2009). Annual (top panel), summer (middle panel) and winter (bottom panel).

decrease in the mean of the highest 5% of sea states (Figure 6). This statistic is not robust; the highest 5% of sea states is a much more representative characteristic of the overall storminess of the ocean. However, other studies with a very high resolution version of the EC-Earth model (Haarsma et al., 2013) also suggest an increase in the frequency of extreme storms affecting Western Europe in future autumn seasons.

Conclusions

In this study we have used one EC-Earth ensemble member (with RCP4.5 future radiative forcing) to examine the impacts of rising greenhouse gas emissions on the future wave climate. An overall decrease in mean significant wave heights was found around Ireland (for the period 2031-2060 with respect to 1981-2009), with a maximum decrease of over 20cm in the winter mean. An increased storminess in winter and spring was found in the north and northwest.

The decrease in mean wave heights projected for the future could hint at a slight reduction in the wave energy resource. However, this is expected to have a minimal impact on the overall potential for wave energy exploitation in Ireland, particularly along the west coast. At the same time, our study reveals a significant interannual variability in the Irish wave climate, which should be taken into account when estimating the wave energy resource.

Our study reveals a significant interannual variability in the Irish wave climate, which should be taken into account when estimating the wave energy resource.

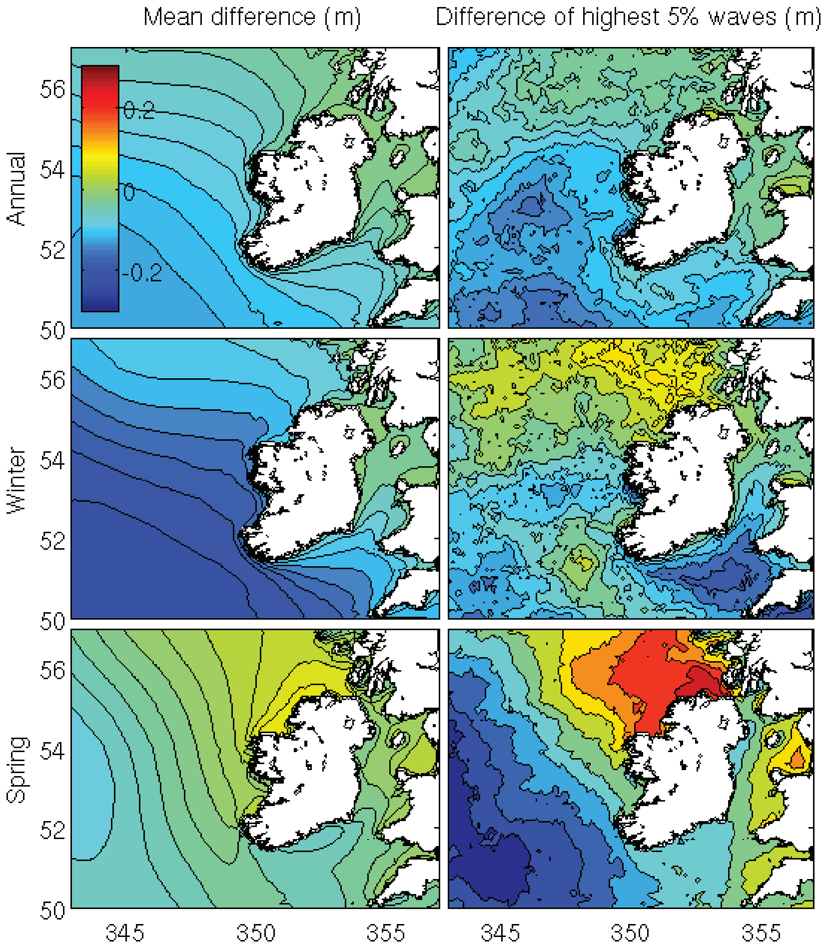

Figure 6. Annual and seasonal Hs changes between the future (2031-2060) and the past (1981-2009) simulations: mean (left panels) and highest 5% (right panels) of significant wave heights (metres).

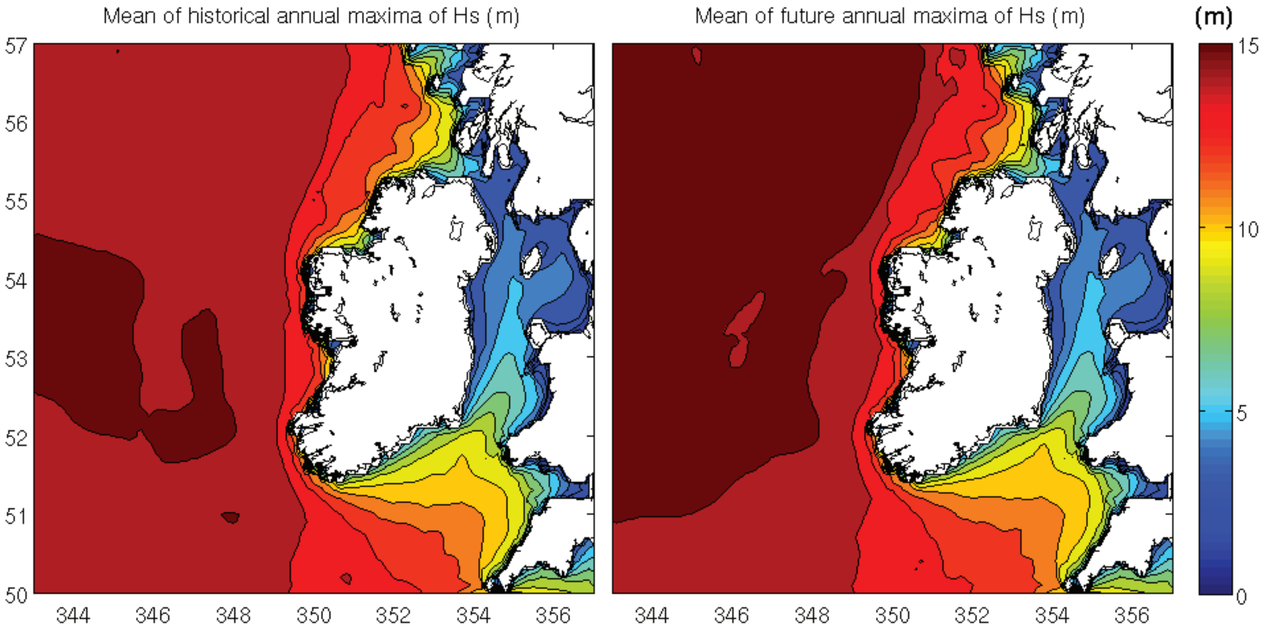

Figure 7. Historical (1981-2009) versus future (2031-2060) maximum significant wave height (Hs).

We stress that our findings should be interpreted with caution for the following reasons: firstly, to account for uncertainty and variability of the climate model, an ensemble of realisations should be investigated. Furthermore, other forcing scenarios should be explored in order to address the uncertainty in future global greenhouse gas emissions. Finally, to resolve the variability of the wave climate in the nearshore, a higher resolution downscaling will be required around Ireland. This work is currently underway by the UCD Wave Group in collaboration with Met Éireann.

Acknowledgements

We would like to thank Emily Gleeson and Ray McGrath at Met Éireann for providing the EC-Earth global climate data. The simulations were conducted on the Rosa cluster at the Swiss National Computing Centre under the PRACE DECI 10 project "Nearshore wave climate analysis of the west coast of Ireland".

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13. The impact of vanishing Arctic sea ice on the climate of Ireland

Tido Semmler[1]

Coupled climate models with increasing greenhouse gas concentrations and changing aerosol concentrations indicate an increase in the westerly airflow in mid-latitudes in winter as well as more extreme storms and precipitation events. However, declining Arctic sea ice may alter this projection. A sensitivity experiment run with the EC-Earth global model with Arctic sea ice removed shows a weakening of the westerly flow over Ireland. Such a change would increase the likelihood of cold continental air outbreaks over Ireland during winter.

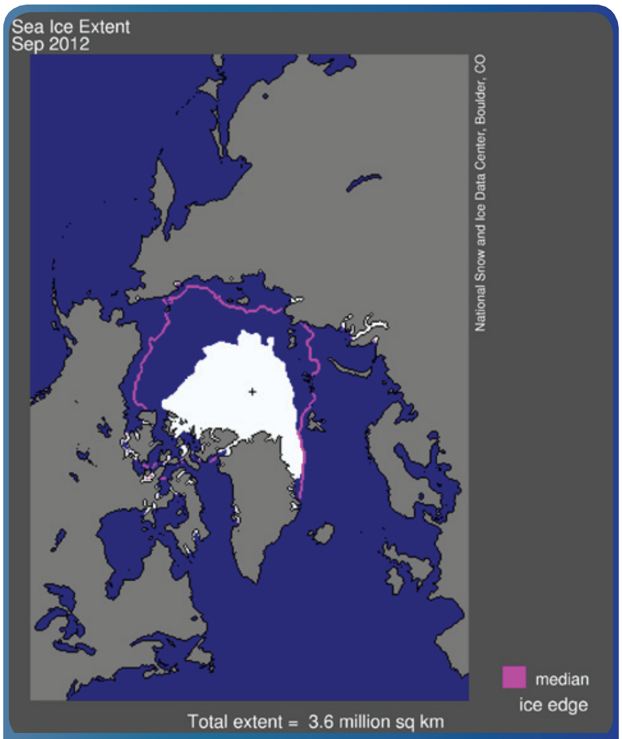

Figure 1. Arctic sea-ice extent in September 2012. Magenta line: Median September sea ice for the period 1979-2000. (Courtesy: National Snow and Ice Data Center, Boulder, Colorado).

Introduction

Arctic sea-ice coverage has been declining at an unprecedented rate over recent decades and faster than predicted by climate models (Figure 1). A record-breaking September minimum occurred in 2007 and 2012 (Parkinson and Comiso, 2013). According to the National Snow and Ice Data Center (NSIDC) in Boulder, Colorado, satellite observations over the 6-year period 2007-2012 recorded the lowest sea-ice coverage since 1979 (NSIDC, 2013). In addition, old multi-year sea ice is being increasingly replaced by fresher 1-year sea ice, which is prone to melting especially in situations with strong storms such as in August 2012 (Parkinson and Comiso, 2013). The Arctic could be ice-free during late summer by the middle of this century or even earlier (Serreze et al., 2007). It is important to study the role of Arctic sea ice in the climate system to understand its implications for the climate of the mid-latitudes and, more specifically, Ireland. Jaiser et al. (2012) found, from a record of atmospheric data over the past 30 years, that the winters following summers with low Arctic sea-ice extent show on average a weaker south-westerly flow at the surface and up to a height of 5km over Ireland meaning that less of the mild maritime air masses are transported over Ireland. Therefore, according to their study, Arctic sea-ice decline could lead to more frequent winter outbreaks of continental cold air over Ireland.

Therefore, according to their study, Arctic sea-ice decline could lead to more frequent winter outbreaks of continental cold air over Ireland.

Since many different physical processes interact with each other in coupled climate model

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[1] Alfred Wegener Institute, (Building F-115), Bussestrasse 24, D-27570 Bremerhaven, Germany.

simulations it is difficult to isolate the influence of the Arctic. Therefore, it is worthwhile carrying out idealised sensitivity experiments with atmosphere-only models prescribing different Arctic sea ice and surface temperature conditions as a lower boundary while leaving the ocean in other regions of the globe unchanged. The aim is to isolate the impact of Arctic sea-ice cover and sea-ice surface temperatures on the atmosphere of the Arctic region and Northern mid-latitudes without the complication of atmosphere-ocean feedbacks in a coupled atmosphere-ocean model. (Semmler et al., 2012)

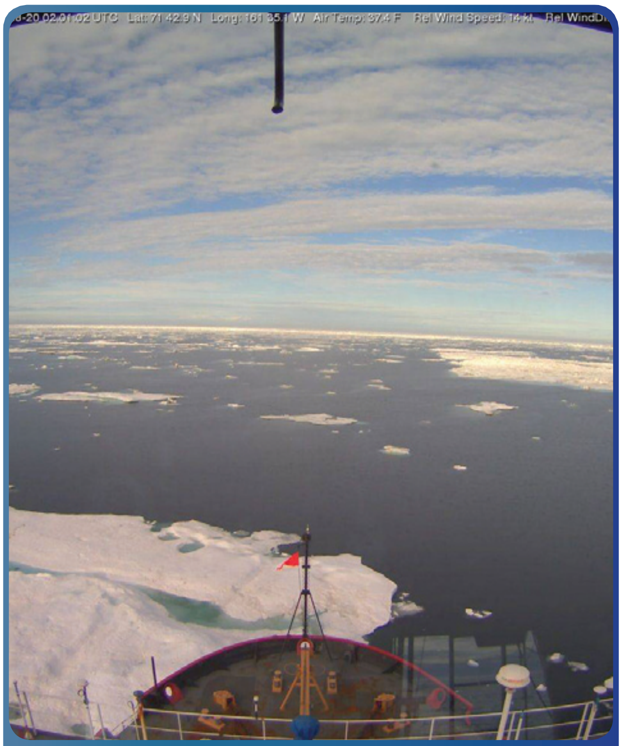

Figure 2. Scattered ice flows northwest of Barrow, Alaska in August 2012. (Courtesy: U.S. Coast Guard).

Set-up of experiments and methodology

The model used in this study was the atmospheric component of the EC-Earth model (Hazeleger et al., 2012). Three different 40-year experiments (1960-2000) were performed with a high horizontal resolution of 79km globally. The reference simulation (REF) was driven by observed sea-surface temperatures, sea-ice concentrations and sea-ice surface temperatures from 1960-2000. The first sensitivity experiment was conducted with a reduced Arctic sea-ice concentration and increased sea-ice surface temperature, referred to as IR. At times and in areas with a sea-ice surface temperature of more than 10 degrees below the freezing point[2], the sea-ice surface temperature was increased by 10 degrees to mimic the effect of thinner sea-ice cover and more heat transport from the underlying ocean to the surface. Otherwise, if the sea-ice surface temperature was higher than this threshold, the sea ice was removed and the sea-surface temperature set to the freezing point. The second sensitivity experiment was quite extreme with no Arctic sea ice throughout the year (IF).

Results

The prescribed changes in the Arctic sea-ice concentration and surface temperature have the largest impact on the large-scale circulation in winter in both sensitivity experiments compared to the reference experiment. This is because the prescribed Arctic surface temperature shows the strongest increase in winter and therefore, the meridional temperature gradient, which drives the large-scale circulation, is substantially weakened. As can be seen from Figure 3, both the IR and the IF experiments show higher mean sea-level pressure over Siberia and Northeastern Europe and lower mean sea-level pressure over the Western Arctic and the Canadian Archipelago compared to REF.

In the Northern Hemisphere the wind roughly follows the lines of equal mean sea-level pressure with the high pressure system to the right and the low pressure system to the left. According to Figure 3(a) the mean wind over Ireland in winter therefore comes from the west in the REF simulation. As can be seen from Figures 3(b) and 3(c), showing the differences in the IR and IF simulations compared to the REF simulation, the IR simulation does not show a pronounced

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[2] The freezing point of Arctic seawater is ~-1.8 degrees Celsius.

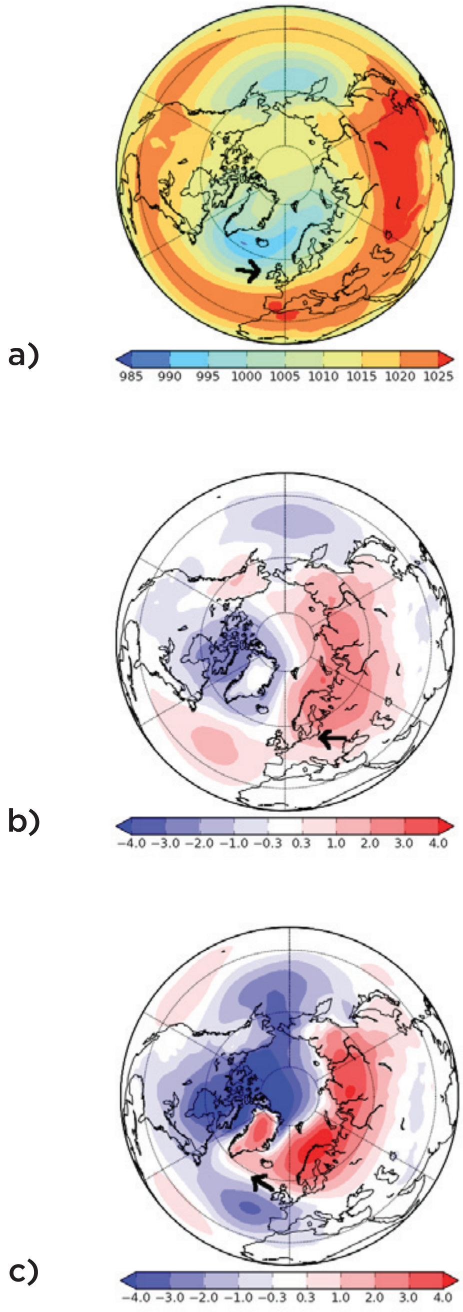

Figure 3. ***(a) Mean sea-level pressure [hPa] over the Arctic and the Northern mid-latitudes as climatological seasonal means for winter 1960-2000 for the reference experiment (REF), (b) mean sea-level pressure difference [hPa] for ice-reduced (IR) case minus the reference experiment for winter 1960-2000, (c) mean sea-level pressure difference [hPa] for ice-free (IF) case minus the reference experiment for winter 1960-2000. The black arrow west of Ireland in (a) indicates the resulting mean wind direction; in (b) and (c) the black arrows indicate the direction of the wind vector difference between the sensitivity experiment and the reference experiment.***

change over Ireland while the IF simulation shows a change towards a more easterly (or less westerly) flow over Ireland leading to more transport of cold continental (or less mild maritime) air to Ireland.

At an altitude of about 5km, as seen in the 500 hPa geopotential height map in Figure 4, the situation looks quite similar for Ireland. Also, here the air flow roughly follows the lines of equal 500hPa geopotential height with the high height to the right and the low height to the left. From Figure 4(a) the mean westerly flow in winter over Ireland can be clearly recognised. Figures 4(b) and 4(c) show that the difference between the IR and REF experiments is relatively weak over Ireland while the IF experiment shows a weakened westerly flow indicated by the easterly component in the difference between IF and REF. Close to the surface, and at an altitude of 5km, the westerly airflow is weakened mainly in Northern and Eastern Europe for the IR experiment while the weakening also extends to Ireland for the IF experiment.

Conclusions

The sensitivity experiments on reduced and removed Arctic sea-ice cover and increased Arctic surface temperature using an atmospheric circulation model show an important impact of sea ice on the large-scale circulation at Northern mid-latitudes which has implications for Ireland especially in winter. These idealised experiments should not be mistaken as predictions for future climate. Coupled climate models with increasing greenhouse gas concentrations and changing aerosol concentrations indicate an increase in the westerly flow at mid-latitudes in winter as well as more extreme storms and precipitation events. Our sensitivity experiment with removed

Our sensitivity experiment with removed Arctic sea ice shows a weakening of the westerly flow over Ireland. Such a change would increase the likelihood of cold continental air outbreaks over Ireland during winter.

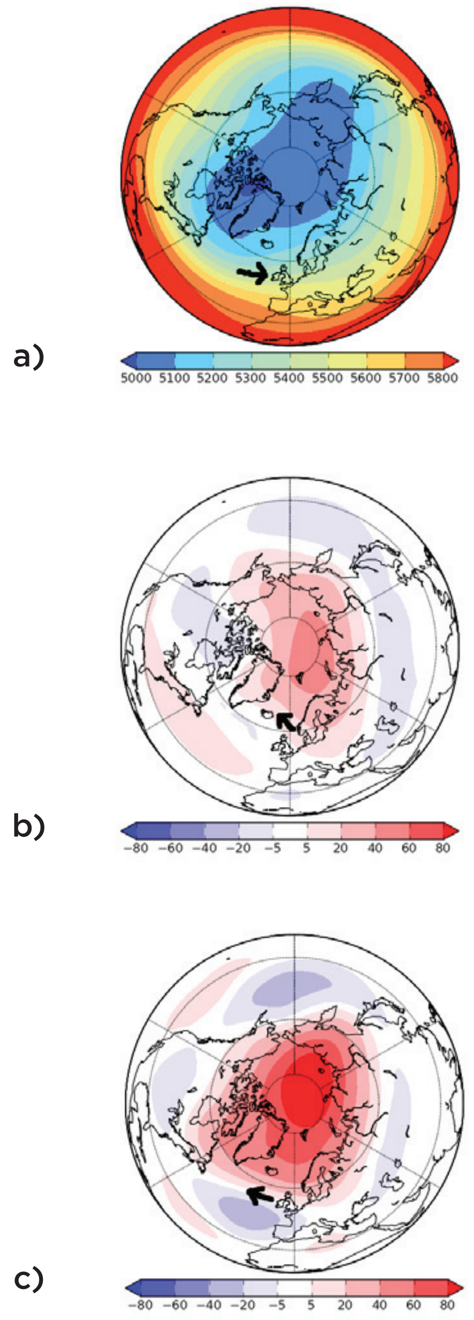

***Figure 4.* (a) 500 hPa geopotential height [m] over the Arctic and Northern mid-latitudes as climatological seasonal means for winter 1960-2000 for the reference (REF) experiment, (b) difference in 500 hPa geopotential height [m] for the ice-reduced (IR) case relative to the reference experiment for winter 1960-2000, (c) difference in 500 hPa geopotential height [m] for the ice-free (IF) case relative to the reference experiment for winter 1960-2000. The black arrow west of Ireland in (a) indicates the resulting mean wind direction at an altitude of about 5km; in (b) and (c) the black arrows indicate the direction of the wind vector difference between the sensitivity experiment and the reference experiment.**

Arctic sea ice shows a weakening of the westerly flow over Ireland. Such a change would increase the likelihood of cold continental air outbreaks over Ireland during winter.

The complex coupled climate model predictions consider many other influencing factors such as changes in ocean currents, and temperature increases in the tropical upper troposphere. This leads to a stronger meridional temperature gradient in the upper troposphere above 5km in altitude and, therefore, an intensified westerly flow over the mid-latitudes in winter.

However, if the Arctic sea ice continues to decrease in extent and thickness at the current rate and therefore continues to exceed rates predicted by coupled climate models, the effect of the Arctic sea-ice loss might counteract the effect of the upper tropospheric heating in the tropics. In this case an intensification of the comparably mild maritime westerly flow over Ireland in winter would become less likely and therefore Irish winters would not warm as much as predicted from coupled climate models.

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14. EC-Earth's "Little Ice Age"

Emily Gleeson[1], Sybren Drijfhout[2 3],
Henk Dijkstra[4], Valerie Livina[5]

During the spin-up phase of the EC-Earth global climate model, a period of abrupt Northern Hemisphere cooling occurred 450 years into the simulation and lasted for about a century. This spontaneous abrupt cooling event had a temperature anomaly similar to that of the Little Ice Age. Temperatures over Northern Europe were on average up to 8 degrees cooler for the period November to March, and up to 3 degrees cooler over Ireland. In addition, sea ice was present at much lower latitudes. This type of performance reflects well on the realism of the EC-Earth model and its ability to simulate the essential features of the global climate.

This spontaneous abrupt cooling event had a temperature anomaly similar to that of the Little Ice Age.

As mentioned in Chapter 1, before a climate model can be used to simulate past, present and future climate it must be spun up so that a balanced or close to balanced state is achieved. In the EC-Earth spin-up simulation the greenhouse gas concentration was held constant at the 1850 level of 280ppmv (parts per million by volume) and the ocean was initialised using the World Ocean Database Levitus climatology (Sterl et al., 2012). The entire spin-up simulation, spanning almost 2000 years of annual temporal resolution, was carried out by Met Éireann on behalf of the EC-Earth consortium, using computers at the European Centre for Medium-Range Weather Forecasts (ECMWF) and ICHEC (Irish Centre for High-End Computing).

Abrupt Cooling

In the following description, times are relative to the (arbitrary) start time of the simulation. During this spin-up simulation a period of abrupt cooling occurred 450 years into the simulation and lasted for about a century. The signal was first detected in the Atlantic Multidecadal Oscillation (AMO), which is a mode of natural variability in the sea-surface temperatures (SST) of the North Atlantic Ocean. The North Atlantic cooled by 0.5 degrees on average during this period as shown in Figure 1 where 10-year moving averages of the AMO Index (defined as the 10-year average SST over an area spanning 60°W to 5°W and 0°N to 60°N minus the average SST over that area for the entire time series considered) are shown.

A study of 50-year periods before (years 41-90), during (years 461-510) and after (651-700) the cold event showed that the mean sea-level pressure was lower over western Europe but higher over an area around southern Greenland. There was a stronger westerly component to the 10m wind over western Europe (not shown) and a stronger northerly airflow over an area stretching from Svalbard to Iceland and south Greenland (Figure 2).

The 2m temperature decreased by up to 12 degrees in places as shown in Figure 3 and the sea-ice cover extended further south as shown in Figure 4. In all cases, the difference between the cold event period and pre-cold event period were similar to those for the cold event period and post-cold event period.

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[1] Research, Environment and Applications Division, Met Éireann, Glasnevin, Dublin 9.
[2] Royal Netherlands Meteorological Institute, De Bilt, the Netherlands.
[3] National Oceanography Centre, Southampton, United Kingdom.
[4] Institute for Marine and Atmospheric Research Utrecht, the Netherlands.
[5] National Physical Laboratory, Teddington, United Kingdom.

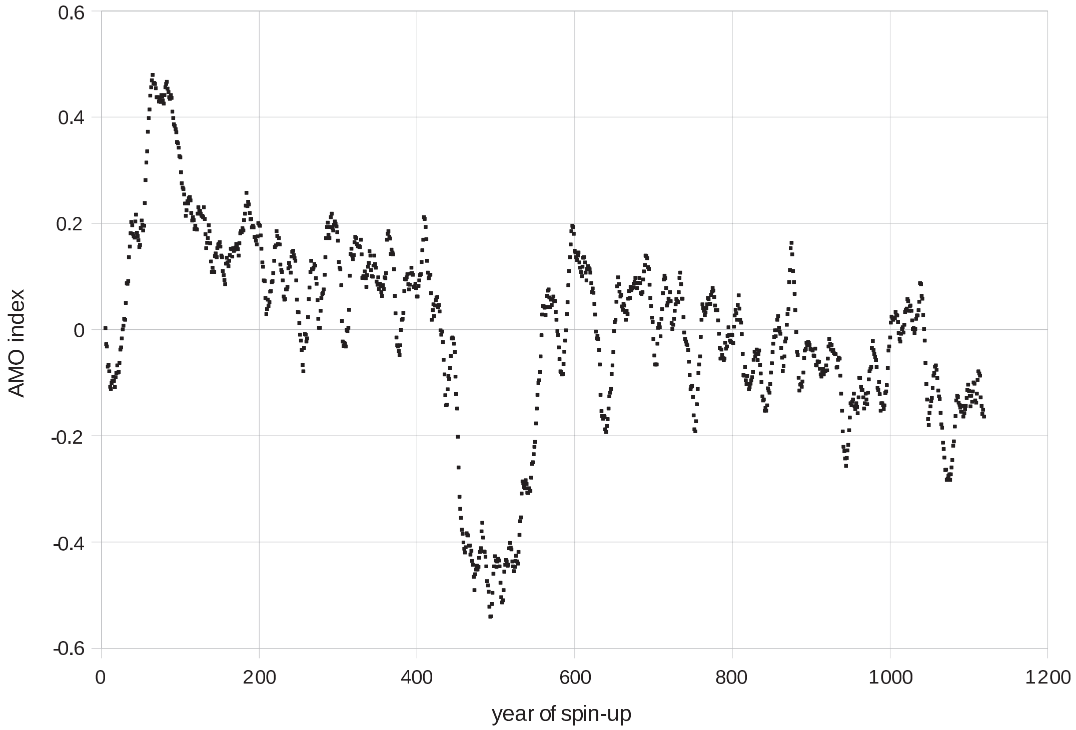

Figure 1. Time series of a 10-year running mean of the AMO index for the following area of the North Atlantic Ocean: 60°W to 5°W and 0°N to 60°N.

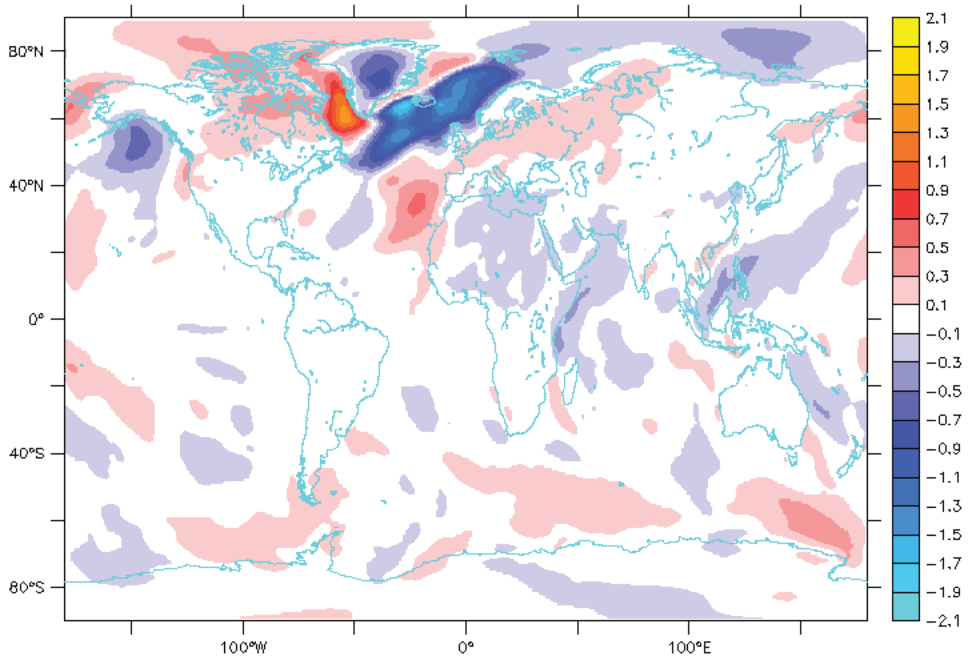

Figure 2. Mean difference between the v-component (north-south component) of 10m wind for the cold event period and pre-cold event period. The months of November to March were included in the calculation. Positive differences imply stronger southerly winds during the cold event while negative differences mean stronger northerly differences during the cold event.

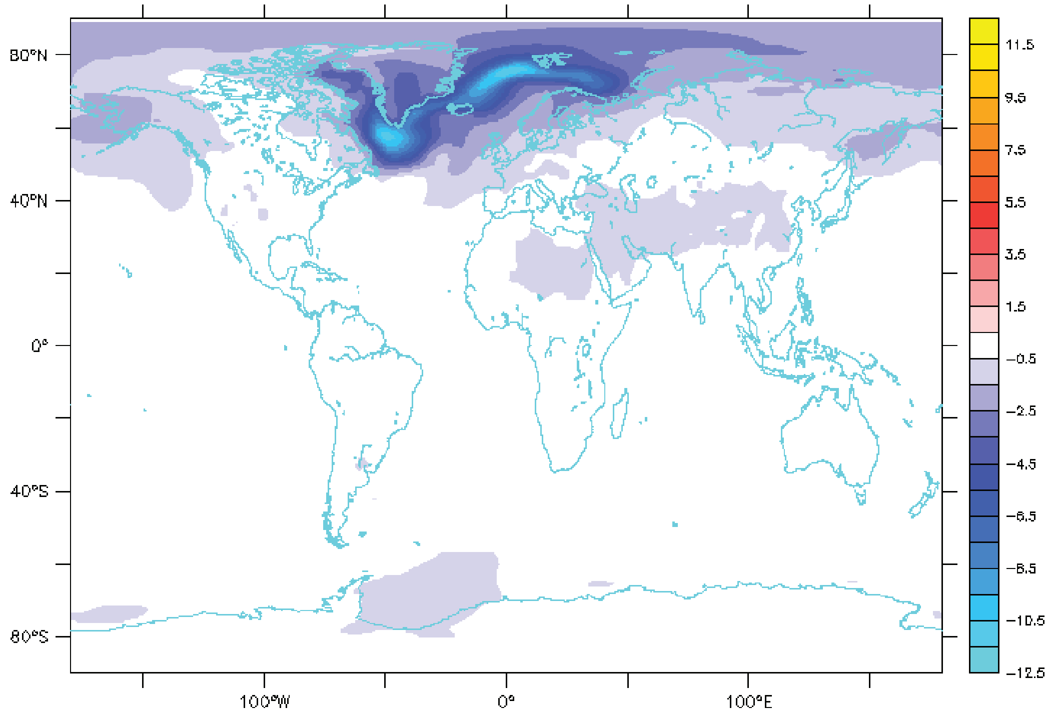

Figure 3. ***Mean difference between the 2m temperature for the cold event period and pre-cold event period. The months of November to March were included in the calculation.***

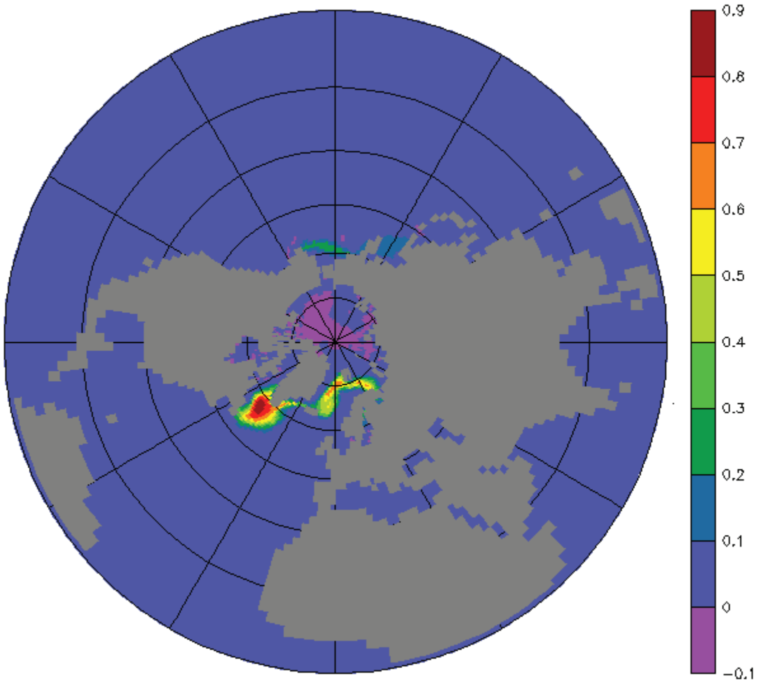

Figure 4. ***Mean difference between the sea-ice cover for the cold event period and pre-cold event period. The months of November to March were included in the calculation.***

Summary and conclusion

There are many periods of abrupt climate change evident in geological records but there are only a few cases where abrupt cooling occurs in climate model simulations. In this case the abrupt cooling started with a period of enhanced high-pressure blocking near Greenland which allowed the sea ice to progress southwards and was maintained by the strong coupling between the sea-level pressure anomaly and sea-ice concentration.

It is remarkable that the EC-Earth model, without any forcing (e.g. from changing greenhouse gases), is capable of displaying such events. This is in contrast to the well documented Little Ice Age (ca. 1250-1850 AD) which is thought to have been linked to volcanism and an increase in sulfates (Crowley et al., 2008; Miller et al., 2012). Only models with sufficient resolution to capture atmospheric blocking events and which have a sensitive sea-ice component are capable of capturing events like this. A full description of these results is currently in press (Drijfhout et al., 2013).

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15. Enabling climate adaptation in Ireland - Ireland's Climate Information Platform

Barry O'Dwyer[1,] Stefan Gray[1],
Jeremy Gault[1], Ned Dwyer[1]

Internationally and for Ireland, it is now recognised that there is an urgent need for the preparation of adaptation responses to the impacts of current and expected climate change and this is reflected in the recent publication of Ireland's National Climate Change Adaptation Framework (2012). Recent developments in climate modelling allow us to better identify how the future climate might evolve and to begin to identify and quantify the uncertainties in these projections. Ireland's Climate Information Platform is employing these data as part of a web-based resource to inform a wide audience about the implications of climate change for Ireland and potential adaptation options. Specific, targeted tools are being developed to allow decision-makers to employ the most up-to-date climatic information and data and begin the process of adaptation planning.

Introduction

Regardless of our attempts to mitigate against climatic changes, our long history of greenhouse gas emissions, and latencies in the response of the global climate system means that many of the impacts of climate change in the short- to medium-term are now unavoidable. Adaptation to these changes is now considered as a matter of urgency.

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Adaptation refers to the adjustment or preparation of natural or human systems to a new or changing environment with the aim of moderating harm or exploiting any opportunities that may arise. Adaptation responses are determined by the vulnerability of the system to climate change (physical or social) and its ability to adapt (Figure 1). The aim of adaptive measures is typically to address climate change impacts, and also to increase future adaptive capacity in responding to as yet unknown levels of future climate change. Such measures can be broadly categorised as "Grey", "Green" or "Soft" (EEA, 2013). Grey actions refer to technological and engineering solutions, such as the building of coastal defences. Green actions involve ecosystem-based approaches that employ the services of nature, while soft actions involve managerial, legal and policy approaches that alter human behaviour and styles of government. It is now widely recognised that the earlier we start to plan our adaptation responses, the better equipped we will be to avoid the unacceptable risks and to exploit the many opportunities provided by climate change. There is now a clear urgency to make progress on adaptation, as evidenced by a proliferation of policy responses at both national and international levels.

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The National Climate Change Adaptation Framework

Adaptation policy in Europe is relatively novel and is being progressed through the EU Strategy on adaptation to climate change (EC, 2013). A key objective of this strategy is to encourage all member states to adopt adaptation strategies to provide the policy context for developing

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[1] Coastal and Marine Research Centre, Environmental Research Institute, University College Cork, Cork.

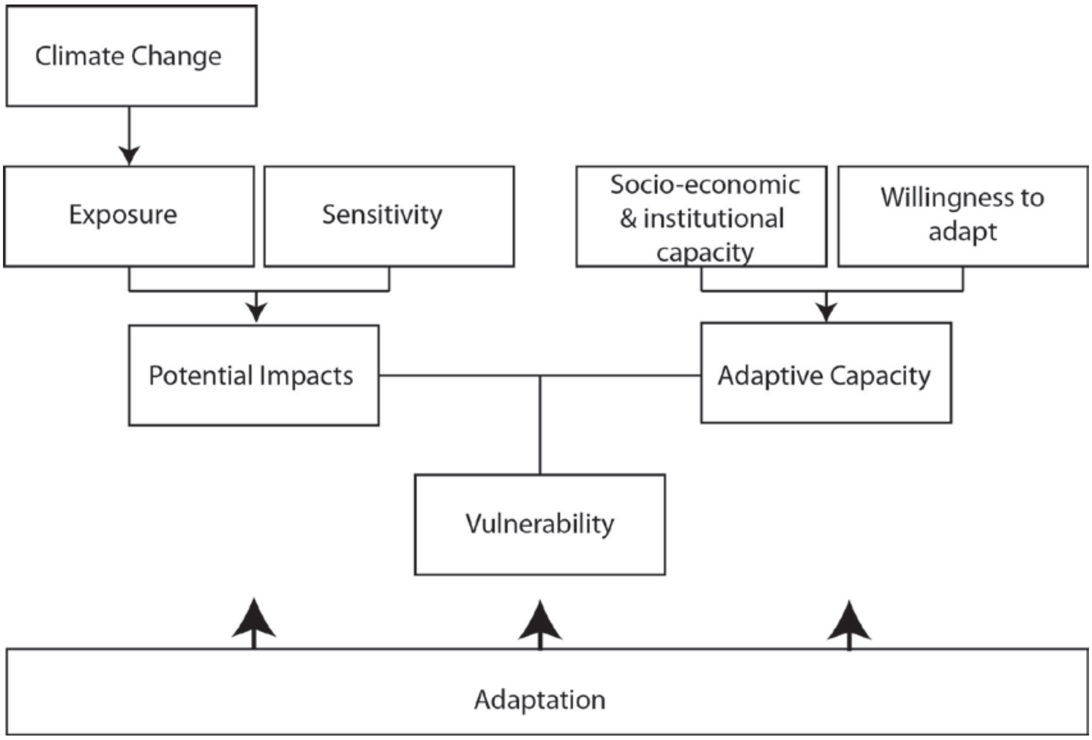


Figure 1. Climate change adaptation: Potential impacts, adaptive capacity and vulnerability (DECLG, 2012)

adaptation plans and integrating adaptation measures into sectoral policies. Currently, 16 EEA member countries, including Ireland, have developed national adaptation strategies (EEA, 2013). Ireland's National Climate Change Adaptation Framework (NCCAF) (2012) provides a strategic policy response to ensure that adaptation measures are taken across all sectors and levels of governance to reduce Ireland's vulnerability to climate change. More specifically, under the NCCAF, the relevant Government Departments, State Agencies and all Local Authorities will commence the preparation of sectoral and local adaptation plans.

Until recently, decision makers in Ireland tended to rely on past records of climate to plan for the future. However, in the context of planning for global climate change, past records prove inadequate, and information is now required on how human-induced warming may affect key climatic parameters and the effects these changes will have for Ireland. Arriving at an understanding of current and future climate change impacts at this scale is a major challenge for decision makers and requires consideration of a wide range of potential impacts, where and when these may occur and how different elements of the social, ecological and economic communities might respond. These complexities, and the necessarily ambitious aims of adaptation, place a premium on the provision of high-quality information, tailored variously to the needs of societal, political and managerial decision making at scales appropriate to their needs.

Recent developments in the projection of future climate achieved through EC-Earth and other model simulations, and the down-scaling of these simulations for Ireland (see Chapters 5, 9 and 11), form a key support for the development

Recent developments in the projection of future climate achieved through EC-Earth and other model simulations, and the down-scaling of these simulations for Ireland (see Chapters 5, 9 and 11), form a key support for the development of adaptation plans in Ireland.

of adaptation plans in Ireland. Moreover, due to the ensemble approach employed in developing these projections, we can now begin to quantify the uncertainties inherent in these projections and employ this information to better inform our adaptation responses.

Ireland's Climate Information Platform

These recent developments in climate modelling add to an already existing large body of work on current and anticipated impacts of climate change for Ireland, and it is considered that there is now a robust knowledge base on which to begin the process of adaptation planning (Desmond et al. 2009). However, this information remains spread out amongst a large number of institutions and agencies and it is extremely difficult for decision makers and citizens alike to access it in a timely and effective way.

Contemporary international experience demonstrates that centralised (e.g. national and international) online platforms providing harmonised scientific information adapted to end-users' needs can effectively support practical decision making. On this basis, the Environmental Protection Agency's (EPA) Climate Change Research Programme (2007-2013) has identified the need for a national climate change information system for Ireland, and work has commenced on its development. Ireland's Climate Information Platform (ICIP) involves a two-phased development approach, the first of which is now nearing completion.

A key aim of this first phase of work has been to develop an online resource of relevant and authoritative climate information to form a key support for local and national level planners in their assessments of climate change, and in meeting their obligations under the NCCAF. In addition, the first phase of development aimed to provide information to key stakeholders working on climate adaptation and to foster awareness and understanding of climate impacts and adaptation responses. Importantly, in order to bridge the gap between climate science and decision-making, ICIP has adopted a partnership approach and is being developed in close collaboration with data-providers and end-users to provide an authoritative, reliable and understandable source of climatic and adaptation information for Ireland.

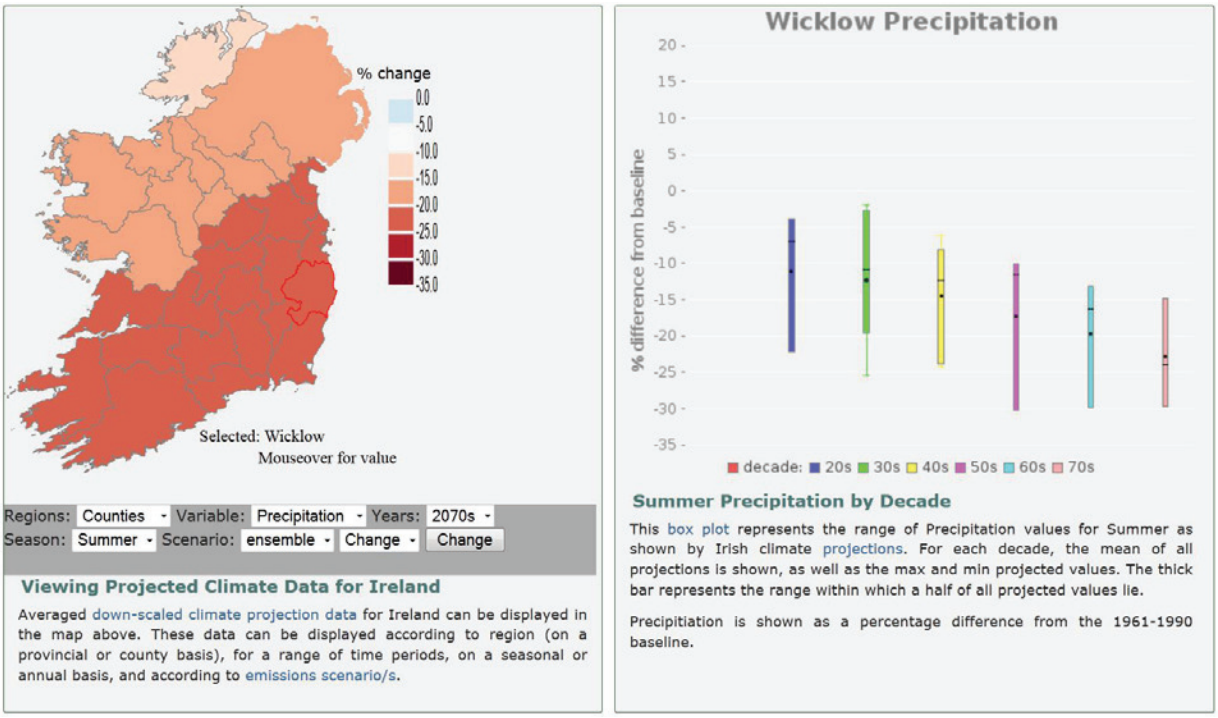
Climate change explained

Climate and adaptation science is complex. In order to raise awareness and make the science more accessible, ICIP provides comprehensive information on climate change and adaptation, with special attention paid to the intelligibility and user-friendliness of this information. Through its "Climate Change Explained" resource, ICIP provides:

- Reliable and diverse information on the evidence of climate change at global and national levels
- Descriptions of how projections of future climate and the impacts of these changes are developed
- A wide variety of information on adaptation including information on adaptation responses, policy and how to go about developing an adaptation plan

Climate Information Provision

In planning climate adaptation, information on current and expected climatic change is a key requirement. In order to allow users to examine existing and available downscaled projected climate change information for Ireland (e.g. McGrath et al., 2009; Sweeney et al., 2008), including those produced as part of the EC-Earth model simulations (see Chapters 5, 9 and 11), ICIP has developed a "Climate Information Tool" which allows users to familiarise themselves and query current and anticipated climate



Regions: Counties Variable: Precipitation Years: 2070s
Season: Summer Scenario: ensemble Change
Change

Viewing Projected Climate Data for Ireland

Averaged down-scaled climate projection data for Ireland can be displayed in the map above. These data can be displayed according to region (on a provincial or county basis), for a range of time periods, on a seasonal or annual basis, and according to emissions scenario/s.

Summer Precipitation by Decade

This box plot represents the range of Precipitation values for Summer as shown by Irish climate projections. For each decade, the mean of all projections is shown, as well as the max and min projected values. The thick bar represents the range within which a half of all projected values lie.

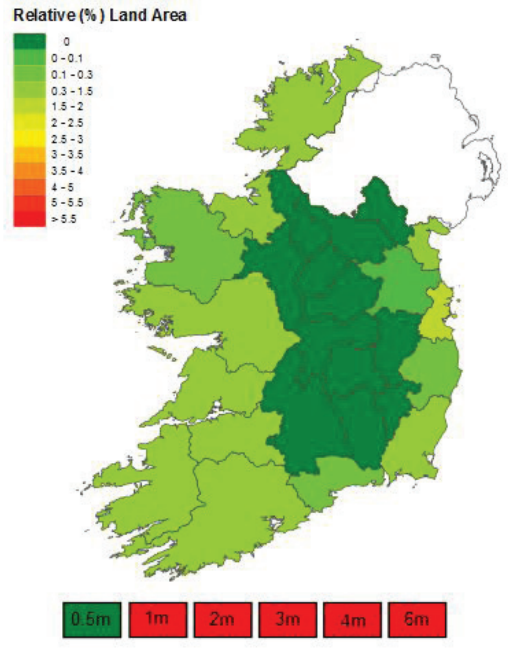
Precipitiation is shown as a percentage difference from the 1961-1990 baseline.

Figure 2. An example of the "Climate Information Tool" developed through ICIP. The left panel allows users to examine and begin to understand projected climate change for Ireland according to their specific requirements while the right panel displays the ranges of projected changes in the variable of interest for the coming decades.

information through maps, graphs and tables (Figure 2). The tool allows users to examine the full range of existing and available projected climatic information according to their county/province[2], variable and time period of interest.

Facilitating planning for climate adaptation

A key aim of ICIP is to allow decision makers to effectively employ projected climatic data in their management and planning processes. In adaptation planning, the present is seen as the starting point for any examination of future vulnerability to climate change. ICIP offers decision makers a variety of tools that bridge a common division between scientific information and practical decision making. These include a "Climate Hazard Scoping Tool", which draws on an appropriately targeted and relevant subset of current and projected climate and socio-economic information to allow users to quickly grasp their current vulnerability to climate impacts, and on this basis, to begin to



Map showing percentage land area per county at risk of innundation at a sea level rise of 0.5m. This projection does not account for isostatic rebound or the existence of coastal defences (Flood et al. 2011)

Figure 3. An example of the "Climate Hazard Scoping Tool" illustrating potential land losses from a range of projected sea level rise scenarios.

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[2] It should be noted that there are uncertainties in each of the projections but using a large ensemble of climate simulations helps to quantify the uncertainty by providing a range of possible outcomes.

understand how future climate change might affect them.

Conclusion

Recent developments in climate modelling allow us to better understand how Ireland's climate might evolve and this information is of utmost importance in the context of planning for climate adaptation. In order to make this information available to decision makers and the general public, the EPA has funded the development of ICIP, a web-based resource of climatic information and data, including results from current and future climate modelling initiatives, with specialised tools. Development involves a two-phased approach; the first phase of development is nearing completion and a prototype ICIP is now available for restricted user testing at *http://www.climateireland.ie*.

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List of acronyms

AMO	Atlantic Multidecadal Oscillation
AR5	The Fifth Assessment Report of the IPCC
BADC	British Atmospheric Data Centre
CAFE	Clean Air For Europe
CGCM3.1	A Global Climate Model from the Canadian Centre for Climate Modelling and Analysis
CMIP3	Coupled Model Intercomparison Project Phase 3
CMIP5	Coupled Model Intercomparison Project Phase 5
CORDEX	Coordinated Regional Climate Downscaling Experiment
COSMO-CLM	COSMO Community Land Model in climate mode; a regional climate model developed from the Local Model (LM) of the German Meteorological Service by the CLM-Community
C4I	Community Climate Change Consortium for Ireland
DECLG	Department of Environment, Community and Local Government
DIAS	Dublin Institute for Advanced Studies
DJF	December, January, February (Winter)
DKRZ	Deutsches Klimarechenzentrum (German Climate Computing Centre)
DORMPHOT	Birch phenological model
e-INIS	The Irish National e-Infrastructure
EC-Earth	An earth-system model developed by a consortium of European research institutions and researchers, based on state-of-the-art models for the atmosphere, the ocean, sea ice and the biosphere
ECHAM	An atmospheric general circulation model, developed at the Max Planck Institute for Meteorology
ECMWF	European Centre for Medium-Range Weather Forecasts
EEA	European Economic Area
EPA	Environmental Protection Agency
ERA-40	An ECMWF re-analysis of the global atmosphere and surface conditions for 45 years
ESG	Earth System Grid
EUCAARI	European Integrated project on Aerosol, Cloud, Climate, and Air Quality Interactions
GCM	Global Climate Model
GHGs	Greenhouse Gases
HadGEM2-ES	Hadley Global Environment Model 2 - Earth System Model developed at the Met Office Hadley Centre, UK
HBV	Hydrologiska Byråns Vattenbalansavdelning; A computer simulation used to analyse river discharge and water pollution
HEAnet	Ireland's National Education and Research Network
ICHEC	Irish Centre for High-End Computing
ICIP	Ireland's Climate Information Platform
IPCC	Intergovernmental Panel on Climate Change
IRN	Irish Reference Network
JJA	June, July, August (Summer)
MAM	March, April, May (Spring)
MME	Multi-Model Ensemble
NAO	North Atlantic Oscillation
NCCAF	National Climate Change Adaptation Framework
NSIDC	National Snow and Ice Data Center
PCMDI	Program for Climate Model Diagnostics and Intercomparison
PDF	Probability Density Function
PPM	Parts Per Million
PRTLI	Programme for Research in Third-Level Institutions
RCA3	Rossby Centre Regional Climate model
RCM	Regional Climate Model
RCP	Representative Concentration Pathways
REMOTE	Regional Climate Three-Dimensional Model
RHN	Reference Hydrometric Network
SEBI	Streamlining EU Biodiversity Indicators
SON	September, October, November (Autumn)
SRES	Special Report on Emissions Scenarios
SST	Sea Surface Temperature
UNEP-WCMC	United Nations Environment Programme-World Conservation Monitoring Centre
UNFCC	United Nations Framework on Climate Change
WAVEWATCH	Wave model developed at NOAA/NCEP
WCRP	World Climate Research Programme
WRF	Weather Research and Forecasting model version 3 developed at the National Center for Atmospheric Research (NCAR), United States

Author Contact Details

Surname	First Name	Title	Institute	Contact email
Caffarra	Amelia	Dr	Université de Bourgogne	amelia.caffarra@gmail.com
Coleman	Mary	Dr	NUI Galway	eiliscoleman@gmail.com
Dias	Frederic	Prof.	University College Dublin	frederic.dias@ucd.ie
Dijkstra	Hank	Dr	Institute for Marine and Atmospheric Research Utrecht	h.a.dijkstra@uu.nl
Donnelly	Alison	Dr	Trinity College Dublin & University of Wisconsin-Milwaukee	alison.c.donnelly@gmail.com
Drijfhout	Sybren	Prof.	KNMI & National Oceanography Centre	sybren.drijfhout@knmi.nl
Dwyer	Ned	Dr.	University College Cork	n.dwyer@ucc.ie
Gallagher	Sarah	Ms	University College Dublin	sarah.gallagher.3@ucdconnect.ie
Gault	Jeremy	Mr	University College Cork	j.gault@ucc.ie
Gleeson	Emily	Dr	Met Éireann	emily.gleeson@met.ie
Goodman	Patrick	Prof.	Dublin Institute of Technology	patrick.goodman@dit.ie
Gray	Stefan	Mr	University College Cork	s.gray@ucc.ie
Livina	Valerie	Dr	National Physical Laboratory	valerie.livina@npl.co.uk
Martin	Damien	Dr	NUI Galway	damien.martin@nuigalway.ie
McGrath	Ray	Mr	Met Éireann	ray.mcgrath@met.ie
McKinstry	Alastair	Mr	Irish Centre for High-End Computing	alastair.mckinstry@ichec.ie
Murphy	Conor	Dr	NUI Maynooth	conor.murphy@nuim.ie
Nolan	Paul	Dr	Irish Centre for High-End Computing & University College Dublin	paul.nolan@ichec.ie
O'Dowd	Colin	Prof.	NUI Galway	colin.odowd@nuigalway.ie
O'Dwyer	Barry	Dr	University College Cork	b.odwyer@ucc.ie
O'Sullivan	John	Mr	University College Dublin	john.o-sullivan.2@ucdconnect.ie
Regan	Eugenie	Dr	National Biodiversity Data Centre & UNEP-WCMC	eugenie.regan@unep-wcmc.org
Semmler	Tido	Dr	Alfred Wegener Institute	tido.semmler@awi.de
Sweeney	Conor	Dr	University College Dublin	conor.sweeney@ucd.ie
Tiron	Roxana	Dr	University College Dublin	roxana.tiron@ucd.ie
Walsh	Séamus	Mr	Met Éireann	seamus.walsh@met.ie
Zottele	Fabio	Mr	Fondazione Edmund Mach	fabio.zottele@fmach.it

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