

Ireland in a Warmer World

Scientific Predictions of the Irish Climate in the Twenty-First Century

Editors: Ray McGrath, Met Éireann and Peter Lynch, UCD

Authors: Susan Dunne, Jenny Hanafin, Peter Lynch, Ray McGrath, Elisa Nishimura, Paul Nolan, J. Venkata Ratnam, Tido Semmler, Conor Sweeney, Saji Varghese and Shiyu Wang

June 2008

Community Climate Change Consortium for Ireland (C4I)

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Acknowledgements

The Community Climate Change Consortium for Ireland (C4I) project was supported and co-funded by Environmental Protection Agency, Sustainable Energy Ireland and the Higher Education Authority with resources provided by the Irish Government's National Development Plan (NDP) 2000-2006. The work was also supported by Met Éireann and by the CosmoGrid project, the latter funded under the Programme for Research in Third Level Institutions (PRTLII) administered by the Higher Education Authority under the National Development Plan and with partial support from the European Regional Development Fund.

We would like to thank the model and data group at Max-Planck-Institute for Meteorology in Hamburg, Germany for the ECHAM5-OM1 data, and the Rossby Centre at the Swedish Meteorological and Hydrological Institute in Norrköping, Sweden, for the RCA3 model.

Support from ECMWF and the SFI/HEA Irish Centre for High-End Computing (ICHEC) for the provision of computational facilities is also gratefully acknowledged.

The support received from Met Éireann, particularly from the IT and Climate and Observations Divisions, is also gratefully acknowledged.

The project benefited from the work of several students who assisted in analyzing outputs: Michelle Dillon, Emily Gleeson, Steffi Gleixner, Emilia Main, Gillian Whelan and Renate Wilcke.



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ISBN: 9 780952 123255

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Summary

The challenge of global climate change, and its potentially devastating consequences, are now widely acknowledged. Climate scientists throughout the world are working to increase our knowledge of climate processes and our ability to anticipate the nature and magnitude of changes resulting from increased concentrations of greenhouse gases. In Ireland, the C4I Project (Community Climate Change Consortium for Ireland) has been in operation for five years. A substantial national climate modelling capability has been built, and a comprehensive data-base of results on the future climate of Ireland is now available on the C4I website (<http://www.c4i.ie>) for the benefit of Irish scientists, policy makers and other users.

This report describes Ireland's changing climate, based on a comprehensive series of computer simulations. The computations were carried out by the C4I team of scientists at Met Éireann and at the UCD Meteorology & Climate Centre. The first phase of the C4I Project finished in December, 2007, but the collaborative work is continuing.

The background to the project, and the regional climate model (RCM) approach to predicting changes in the climate, are reviewed in the opening chapter. Using a regional climate model, a range of climate simulations for the twenty-first century has been completed. Uncertainties in the predictions are reduced by combining several different model simulations in an ensemble. This ensemble procedure is reviewed in Chapter 2. The EU-funded ENSEMBLES Project is also described.

A complete review of the principal results emerging from the Project is presented in Chapter 2. For a brief summary of the key results and conclusions, see box following this summary on page (v).

The impact of climate change on storm surges is discussed in Chapter 3. Surge data were produced using the Regional Ocean Model System (ROMS) of Rutgers University. This model consistently reproduces the sea level variability in Irish waters. The results show an increase in storm surge events around Irish coastal areas in a warmer climate. In Chapter 4, the impact of climate change on North Atlantic wave heights is investigated, with a particular focus on coastal regions surrounding Ireland. While the impact is seasonally dependent, there is evidence that extreme wave heights may increase by up to 10% in some Irish waters.

Chapter 5 describes an investigation into the impact of warmer ocean temperatures on storminess. The results show an increase in the frequency of very intense cyclones, and also increases in the extreme values of wind and precipitation associated with them. This implies an increased risk of storm damage and flooding in vulnerable Irish coastal areas.

The observed trends in sea level and sea surface temperature around Ireland are studied in Chapter 6. Since the 1980s there has been a general warming trend of 0.3-0.7°C per decade in Irish waters, comparable to the trend over land. This is consistent with what has been observed globally and is expected to continue over the coming decades. Sea level rise will also exacerbate the impacts of changing storm surge and wave patterns in coastal areas and may also affect water tables through salt intrusion.

The impacts of climate change on hydrology are considered in Chapter 7. Nine Irish river catchments are modelled, and an amplification of the seasonal cycle across the country, with a rise in winter stream flow and a reduction in summer flow, is found. Increased winter flow means an elevated risk of flooding. Decreases in summer stream flow will have significant consequences for water availability, water quality, fisheries and recreational water use.

A comparison between statistical downscaling and dynamical downscaling is presented in Chapter 8. The two methods are directly compared for their ability to predict precipitation over Ireland. There are differences in detail of the results produced by the two approaches, but the overall signal of wetter winters and drier summers is reflected consistently by both methods.

Renewable energy sources are of growing importance. The impact of climate change on available wind energy is considered in Chapter 9. The simulations show an increase of about 10% in available wind power in future winter months in the middle of the century and a decrease of a comparable magnitude in the summer months. Increasing the horizontal resolution of the downscaling grid has a positive impact on the quality of the winds, since local effects, such as the distortion of the airflow by surface features, are better resolved.

Chapter 10 describes some high-resolution experiments using the MM5 model, a limited-area non-hydrostatic model. The benefits of higher resolution for these simulations was not as clear as expected, and suggest that much more work to develop parameterization schemes suitable for this resolution is required. Until this is done, the substantial additional computational cost of the highest resolution simulations is probably not justified.

The influence of climate change on ozone concentrations and ultra-violet radiation in Ireland is described in Chapter 11. This study relates ozone concentrations to stratospheric circulation and temperature patterns. It suggests that the recovery in the atmospheric ozone may be slower than anticipated from a reduction in CFC emissions. Risk of skin cancer in Ireland will remain significant. Moreover, a warmer Irish climate is likely to increase outdoor leisure activities and potentially increase the exposure to damaging UV-B. The following chapter investigates the influence of climate change on heating and cooling energy demand in Ireland. Energy demand has already slightly decreased in the south of the country. A clear, continuing decrease in demand is predicted for the rest of this century.

In Chapter 13, the expertise that has been developed through the C4I Project, and the climate modelling capability that has been built, is reviewed. Strong international links have been made with other climate-related projects, such as ENSEMBLES and the EC-Earth Project. Met Éireann, in collaboration with the UCD Meteorology and Climate Centre and the Irish Centre for High-End Computing (ICHEC), will continue the collaborative modelling work to predict Ireland's future climate with increasing precision and confidence. Some of the key scientific issues to be addressed in future work are reviewed in this chapter.

A full list of publications, conference presentations, and other outputs of the C4I Project, completes the report. The primary output is the comprehensive data-base of model results, which can be accessed on the C4I website (<http://www.c4i.ie>). This provides a wide range of simulation data (e.g. time series and maps of weather elements for individual simulations). We plan to develop and extend the range of products in this resource as the climate modelling collaboration continues.

Editors:

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Peter Lynch, UCD

Key Results

- ▶ The climate will continue to warm, particularly in the summer and autumn seasons: possible increases of 3 to 4°C towards the end of the century. The greatest warming will occur in the south and east of the country.

- ▶ Autumn and winter seasons will become wetter: increases in the range 15-25% towards the end of the century. Summers will become drier: 10-18% decrease towards the end of the century. Regional details remain elusive, due to the large uncertainty in local projections.

- ▶ Mean windspeeds are not expected to change significantly over the coming decades, but there is likely to be an overall reduction in strengths towards the end of the century, particularly in summer (4-5%).

- ▶ The frequency of very intense cyclones affecting Ireland is likely to increase.

- ▶ The seas around Ireland have been warming at the rate of 0.3-0.4°C per decade since the 1980s; over the Irish Sea a greater warming has been observed (0.6-0.7°C per decade). The trends are consistent with what has been observed globally and are predicted to continue over the coming decades.

- ▶ Sea levels are rising on average about 3.5 cm per decade around Ireland.

- ▶ Ocean modelling results indicate an increase in the frequency of storm surge events around Irish coastal areas; in the northwest the increase in surge heights between 50 and 100 cm is around 30% by mid century. Extreme wave heights are also likely to increase in most regions.

- ▶ Changes in precipitation and temperature are likely to lead to a rise in winter stream flows (increasing the risk of flooding), and a reduction in summer flows.

- ▶ Changes in the climate may impede the recovery of the ozone layer; together with a warmer climate, there may be negative health consequences due to a greater exposure to UV radiation.

- ▶ Demand for heating energy is likely to reduce significantly as the climate warms.

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1 Project Overview

The primary objectives of the project were to build a capability for carrying out regional climate modelling in Ireland and to use this resource to deliver information on the impacts of future climate change at regional level to planners and developers. A key component was the establishment of a Regional Climate Analysis, Modelling and Prediction Centre (RCAMPC) in Met Éireann to develop critical expertise in climatology, dynamical meteorology, numerical analysis and advanced parallel computing. Outside of these core activities, the aim was to support the community of environmental scientists by providing free access to developed software and simulation results, to drive climate related applications.

As described in this report, the project has adhered closely to its original goals¹. A high level of expertise has been developed in regional climate modelling and an ensemble of climate simulations has been produced to map out the likely impacts of climate change for Ireland over the 21st century. The project has also developed close links with the climate modelling community: it became a partner in the international ENSEMBLES and EC-EARTH projects and has strong links with the Rossby Centre in Sweden, The Spanish State Meteorological Agency and a number of Irish universities.

It has also supplied climate data to support other projects:

- ▶ EPA ILLUMINATE project.
- ▶ COFORD CLIMIT project.
- ▶ CMRC wave modelling work.
- ▶ RPS Consulting Engineers- Flood Risk Management Plan for River Dodder Catchment.

The data remain accessible for other applications/projects.

On the educational side, it has provided research projects and supervision for several MSc students, in collaboration with UCD. A doctoral student has been with the project since its inception.

This is the second major report from the project.

The modelling approach

Ideally, the modelling of current and future climate scenarios should be handled on a global domain to ensure that interactions between the different climate regimes around the world are appropriately addressed. Atmosphere-Ocean General Circulation Models (AOGCM) are the basic tools for this purpose, with the various components of the climate system, their processes and interactions, mathematically represented on a three-dimensional grid in computer software.

¹ Climate modelling requires substantial computing resources. In the initial project proposal, Grid Computing - making use of a network of geographically dispersed computers - was seen as a mechanism for delivering this power. A computational scientist was recruited to the project to adapt the climate model to run over the network of Irish computers under the CosmoGrid project. This software project, run out of UCD, was successful but was never implemented for any substantial climate simulations; in tests, it was found to be much more efficient to run the original model on a single supercomputer. Resources were diverted from Grid Computing to statistical downscaling. The main climate simulations were eventually performed on a range of computers at ECMWF, UCD and CosmoGrid/ICHEC.

The computational requirements for running these models are very demanding, and for operational reasons the information they generate is relatively coarse-grained compared with operational weather forecast models (see box). The primary outputs do not provide sufficient detail to distinguish between the different climate regimes in Ireland. Extreme events (e.g. storms and heavy precipitation), for example, may not be captured or the intensity may be unrealistically low. Even with relatively fine grids it is difficult to capture local effects: topographic features need to be resolved with several grid points before their impact on modelled precipitation and wind fields is fully revealed. This is particularly important for modelling the hydrological cycle. What is required is a mechanism to 'downscale' the AOGCM data to provide the local detail.

Statistical downscaling is one such approach: available climate observations are statistically linked to interpolated forecast weather elements from an AOGCM, providing a predictive model that is trained to match, as closely as possible, the observations. The derived statistical relationships are then assumed to apply to the future data, providing a mechanism for predicting the future climate at the observation sites.

C4I has focused on a *dynamical downscaling* approach: a regional climate

model (RCM) is forced at its lateral boundaries with data provided by the AOGCM. The RCM in many respects is similar to a global model but its working grid is limited to a portion of the globe; in a sense it 'nests' within the global model.

As the model is configured to run over a subset of the globe the computational cost is smaller relative to the AOGCM, allowing finer grids to be used; the more detailed descriptions of coastlines and land elevations enable the regional model to provide local detail not available from the AOGCM. While the regional model can also be a coupled atmosphere-ocean system, only the atmospheric component was used by C4I; oceanic information provided by the AOGCM in the form of sea surface temperature fields, is passively handled by the regional model (i.e. unaltered), although the data do have a strong impact on the regional simulations.

Compared with statistical downscaling the dynamical method provides a full and consistent set of meteorological/climate data over the integration volume, allowing greater scope for applications and for testing the sensitivity of the climate system with idealized experiments. The strengths and weaknesses of both methods are summarized in the accompanying box.

Statistical downscaling is particularly well suited to situations where there is a dense network of observing stations that provide information to train the model to reproduce the observed data using large-scale weather elements. To be successful, the training or calibration data set must be large enough to span the range of natural variability so that the statistical relationships are robust (Wilby et al., 2004; Zorita and von Storch, 1999). Both methods have a role in predicting climate change (Kidson and Thompson, 1998; Boe et al., 2007; Schmidli et al., 2007): a

Advance of the models

FAR
~500 km (T21)

SAR
~250 km (T42)

TAR
~180 km (T63)

AR4
~110 km (T106)

Mid-1970s
Rain

Mid-1980s
Clouds

FAR
Swamp Ocean

SAR
Volcanic Activity

TAR
Carbon Cycle

AR4
Interactive Vegetation

Top left: how Ireland and Europe appear to the global climate models. Geographic resolution has increased with each release of the IPCC Assessment Reports - FAR (1990), SAR (1996), TAR (2001a), and AR4 (2007). However, even for AR4 the horizontal resolutions are typically ~200km for the century-long simulations. Vertical resolutions (atmosphere and ocean) have increased in line with the horizontal resolution (typically about thirty levels in both cases for AR4). In contrast, global operational weather forecast models typically deliver data on a 25 km grid.

Top right: the range of processes incorporated into the models has increased over the decades improving the realism of the models.

However "... models do not provide a perfect simulation of reality, because resolving all important spatial or time scales remains far beyond current capabilities, and also because the behaviour of such a complex nonlinear system may in general be chaotic."

Source: IPCC, 2007.

Extracting local detail from the AOGCM Statistical or Dynamical Downscaling?

Statistical downscaling

- ▶ Computationally cheap;
- ▶ Can provide fine-scale information e.g. with a dense network of stations;

Disadvantages:

- ▶ Statistical relationships derived from the current climate may not be applicable in a future climate;
- ▶ The method is restricted to available observations;
- ▶ Future projections may lack coherency among multiple climate variables.

Dynamical downscaling

- ▶ Not limited by available observations;
- ▶ Full model outputs - amenable to climate sensitivity studies or to drive applications requiring synoptic scale atmospheric data (e.g. storm surge).
- ▶ Potential for capturing mesoscale nonlinear effects and providing coherent information among multiple climate variables.

Disadvantages

- ▶ Computationally expensive (particularly at high resolution).
- ▶ Regional model physics may not be tuned for a future climate.

In both approaches the quality of the climate forecasts is strongly dependent on the accuracy of the AOGCM.

judicious combination of dynamical, followed by statistical, downscaling may be the best approach for weather elements such as precipitation.

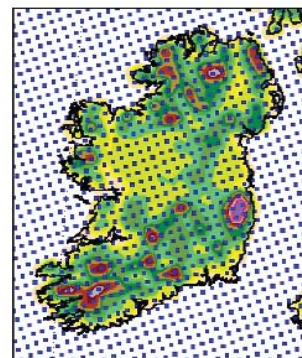
The regional climate model (RCM) used by C4I was developed from the HIRLAM (High Resolution Limited Area Model) forecast model used by Met Éireann, a HIRLAM partner, for operational weather forecasting. The basic model was amended and greatly expanded by the Rossby Center, with further contributions from C4I. In this report the model will be referred to as RCA3.

The choice of the area used to perform the downscaling was guided by a desire to cover at least all Irish coastal areas and the Irish Sea. A basic area, used for many of the simulations is shown in the accompanying box. However, for applications involving the marine (storm surges, wave/swell) a much larger area was used to ensure that essential processes were captured.

Addressing uncertainty

It is not possible to capture the full extent of the complexity of the climate system with an AOGCM. While the models are becoming more capable in their ability to describe the essential climate processes, all forecasts will have a measure of uncertainty that is difficult or impossible to quantify. Models may be assessed by their ability to replicate the current climate but there is no guarantee they will perform as well in a future climate; inevitably, models are tuned to the current climate. This is particularly an issue with some weather elements (e.g.

Integration area (left) used for climate simulations by C4I. The horizontal grid around Ireland is also shown (the grid spacing is about 14km). Either 40 or 31 levels were used in the vertical in the main simulations. Other, larger areas, were also used in specific applications.



rainfall). The prediction of changes in weather extremes is especially difficult given the inherent uncertainty and the limited duration of the simulations.

These issues are not unique to climate modelling. Operational weather forecast models face similar problems. Uncertainty is accepted as an essential feature and addressed by running many forecasts with the same model, starting from slightly different initial conditions. The spread in the ensemble of forecasts provides a measure of the reliability of the forecasts. A similar approach is used in climate modeling: different AOGCMs are run and perhaps downscaled with different RCMs. This multi-model, or *ensemble*, approach delivers probability information on the likelihood of future climate scenarios, rather than a single deterministic forecast. However, there is no guarantee that the ensemble members properly sample the future climate.

The ensemble approach – link with ENSEMBLES

The C4I project used an ensemble approach to assess the uncertainty in local climate predictions. An ensemble approach to climate modeling is essential to address the uncertainty in climate predictions. Attempts by C4I to generate an ensemble of forecasts with the RCM by perturbing the parameters in the physical parameterization scheme were unsuccessful; the spread in the forecasts was found to be too small. The RCM is strongly constrained by the GCM and any errors in the global data (e.g. biases in the zonal flow) are echoed by the RCM; the errors are not amenable to correction by the RCM and a statistical sampling of the uncertainty using a perturbation method will also be biased. What is required is a multi-model ensemble approach based on combinations of different GCMs and RCMs. In pursuit of this C4I, through Met Éireann, became a partner in the international ENSEMBLES project in late 2004.

The only certainty is uncertainty

Sources of uncertainty in forecasting the future climate:

- ▶ Limitations of the model.
- ▶ Uncertainty in future greenhouse gas emissions (becomes more of an issue in the 2nd half of the century).
- ▶ The natural variability of the climate system, even if correctly modelled, may mask or exaggerate changes forced by emissions.
- ▶ Some weather elements are inherently very variable (e.g. rainfall).

In applications that use climate model outputs, errors in the application model will also contribute to the uncertainty i.e. a cascade of uncertainty.

An ensemble approach may reduce the uncertainty provided the individual forecasts adequately sample the (unknown) future climate (i.e. are unbiased and representative of the full range of possible future outcomes).

ENSEMBLES is funded by the European Union under the 6th Framework Programme to assess the future impacts of climate change over Europe. It is supported by the European Commission as a 5 year Integrated Project (2004-2009) under the Thematic Sub-Priority “Global Change and Ecosystems”. The project was established to develop an ensemble climate forecast system spanning timescales from seasonal to decadal and beyond. The spatial focus extends from global to local. The project aims to:

- ▶ Develop an ensemble prediction system for climate change based on the principal state-of-the-art, high resolution, global and regional Earth System models developed in Europe, validated against quality controlled, high resolution gridded datasets for Europe, to produce for the first time, an objective probabilistic estimate of uncertainty in future climate at the seasonal to decadal and longer timescales

Figure 1



ENSEMBLES reference simulation area. Simulations are performed on a 25 km horizontal grid.

- ▶ Quantify and reduce the uncertainty in the representation of physical, chemical, biological and human-related feedbacks in the Earth System (including water resource, land use, and air quality issues, and carbon cycle feedbacks).
- ▶ Maximise the exploitation of the results by linking the outputs of the ensemble prediction system to a range of applications, including agriculture, health, food security, energy, water resources, insurance and weather risk management.

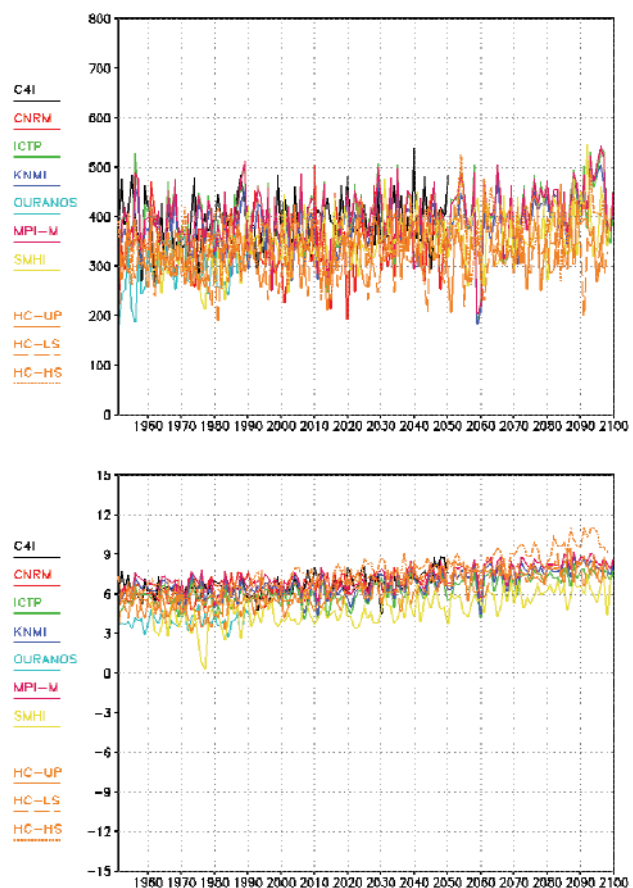
A particular focus of the work is to generate an ensemble of simulations, downscaled from AOGCMs onto a reference European grid with a 25 km horizontal resolution (see Figures 1 and 2). Production was shared among participating members. C4I contributed two substantial simulations using the RCA3 regional model: a 100-year simulation (1951-2050) forced by ECHAM5/OM1 (A2 scenario) and a 150-year simulation forced by HadCM3 (A1B scenario). To date, several future simulations have been produced; the work is ongoing and eventually about 16 future simulations should be available.

C4I has also contributed in the following areas:

- ▶ Investigation of the benefits of very high resolution downscaling using MM5 as a regional climate model;
- ▶ Comparison of statistical and dynamical downscaling;
- ▶ Validation of simulations in the current climate using HOAPS satellite data.

The ensemble simulations produced by this project represent the best available knowledge currently available on future climate change over Europe (including Ireland) and the uncertainty in the projections. As a partner in the project, we are entitled to full access to all of the data.

Figure 2



10 ensemble simulations of winter (DJF) precipitation (top; mm) and 2 m temperatures (bottom; °C) averaged over Ireland/UK area 1950-2100. The simulations were performed on a 25 km grid covering Europe with a mix of RCMs forced with a mix of GCMs. The future simulations mostly use the A1B emission scenario. Note the relatively large spread in the precipitation ensemble.

ENSEMBLES - Achievements to date

(Condensed version of a presentation at the Conference of the Parties
13th meeting (CoP13), in Bali, 2007)

Development of global ensemble climate prediction system, based on European earth system climate models

- ▶ New stochastic physics and perturbed parameter ensemble systems developed to sample modelling uncertainties in seasonal to decadal climate prediction.
- ▶ A new set of Earth System models has been constructed, tested and provided for use in simulations of future climate change.
- ▶ Methods to quantify uncertainties in decadal to centennial climate change have been developed, based on perturbed parameter ensembles sampling uncertainties in atmosphere, ocean, sulphur cycle and carbon cycle processes.

Development of a high resolution regional climate model (RCM) ensemble system for Europe

- ▶ A regional climate model system, of 10 different models, for use in multidecadal simulation experiment ensembles at 25 km.
- ▶ Performance-based weighting of the ENSEMBLES regional climate models, focusing on temperature and precipitation, as a means to advance probabilistic climate change projections on regional scale.

Production of sets of simulations at seasonal-decadal and centennial timescales using the global ensemble prediction system

- ▶ A first set of multi-model seasonal, annual and multi-annual hindcast simulations has been produced over a 10 year period (1991-2001), from 7 coupled GCMs each with 9 ensemble members, in order to sample uncertainties.

Production of regional climate scenarios for impacts assessments with high resolution RCM ensemble system

- ▶ Production of transient climate change projections (1950-2050/2100) for Europe.

Climate variability, predictability and the probability of extreme events

- ▶ Developed a new statistical method to optimally link local weather extremes to large-scale atmospheric circulation structures

Evaluation of the prediction system against observations

- ▶ Development of a gridded data set of daily observed data for Europe

Assessment of the impacts of climate change

- ▶ Impacts on mortality, due to heat stress; impacts on labour productivity, crop growth/yields, etc.



2 Climate Change for Ireland: principal results

Running regional climate model simulations and analysing the outputs has been a core activity of the C4I project. In total, 8 substantial simulations were run using different AOGCM datasets with different emission scenarios (Table 1). Two of these were in support of the ENSEMBLES project and covered the whole of Europe. Other datasets are being produced by other ENSEMBLES partners and, eventually, about 16 datasets covering Ireland will be available. The assessment in this report is based on those from Table 1.

Most of the simulation results have been posted on <http://www.c4i.ie>, where the user can access a wide range of weather parameters and view the expected changes in the coming decades. Here we focus on the main weather elements. As all models (regional and global) suffer from systematic errors, climate change is evaluated by comparing the future simulations against the same models run in the current climate (i.e. over a reference period). The period 1961-1990 is usually taken as the reference but as the climate has warmed since 1990, the period 1961-2000 is chosen instead. Two periods are examined: 2021-2060 and 2060-2099.

According to the IPCC (IPCC, 2007) the extent of climate change is crucially linked with future greenhouse gas emissions; however, short-term change is not particularly sensitive to the chosen emission scenario. Projections for the period 2060-2099 are therefore likely to be less robust than those for 2021-2060.

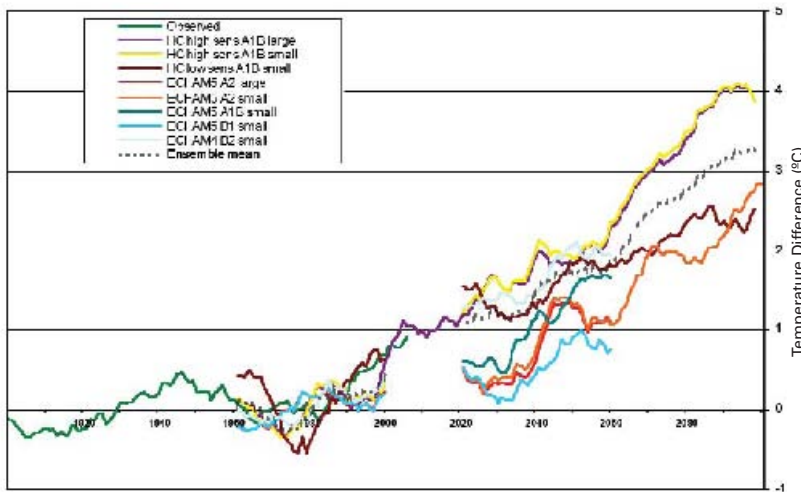
Table 1:
List of climate simulations performed by C4I.

AOGCM Model	Emission Scenario	Period	Area	Horizontal Resolution
ECHAM4	B2	1961-2000, 2021-2060	Irl/UK	14 km
ECHAM5	A2	1961-2000, 2021-2100	Irl/UK	14 km
ECHAM5	A1B	1961-2000, 2021-2060	Irl/UK	14 km
ECHAM5	B1	1961-2000, 2021-2060	Irl/UK	14 km
HadCM3L	A1B	1961-2000, 2021-2100	Irl/UK	14 km
HadCM3H	A1B	1961-2000, 2021-2100	Irl/UK	14 km
ECHAM5	A2	1950-2060	Europe	25 km
HadCM3H	A1B	1950-2100	Europe	25 km

Temperatures (Figures 1-3)

As expected, the climate is warming, particularly in the summer and autumn (1.2-1.4°C in mid century, increasing up to 3.4°C towards the end of the century). The warming is greatest in the south and east of the country.

Figure 1 *Impact of climate change on Irish temperatures.*



Green plot shows the annual mean observed air temperatures, relative to the 1961-1990 average, at 5 Irish stations (up to 2007). The other plots show the ensemble climate simulations, listed in the legend, interpolated to the sites. The gray line shows the mean of the ensembles. All data are smoothed using a 9-year running mean. The spread in the ensembles gives a measure of the uncertainty in the predictions. For the second half of the century the projections are sensitive to the greenhouse gas emission scenario.

Figure 2

Seasonal warming: mean of 8 ensemble simulations showing the temperature change (°C) between periods 2021-2060 and 1961-2000 for winter, spring, summer and autumn (from left to right). Note the general pattern of a warming trend from the SE, with less warming for Ireland relative to the UK (influence of Atlantic). The warming is greatest in the summer/autumn (1.2-1.4°C).

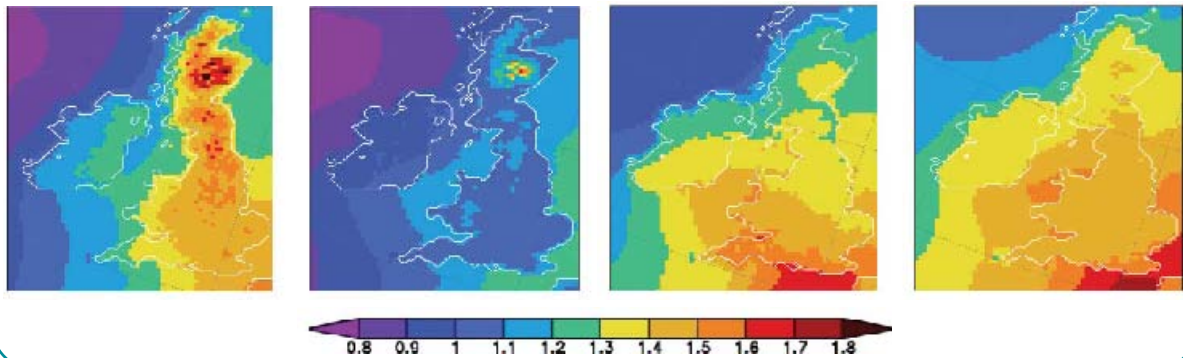
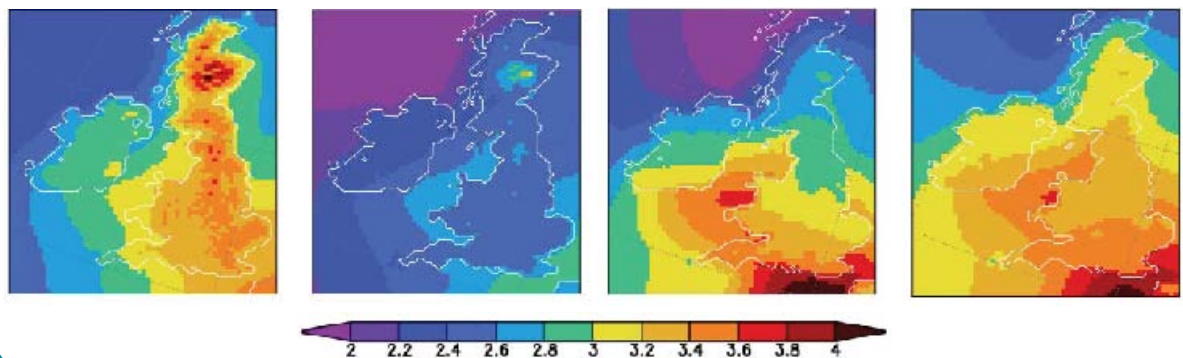


Figure 3

Seasonal warming: temperature change (°C) between periods 2060-2099 and 1961-2000 for winter, spring, summer and autumn (from left to right). Similar to Figure 2 (but note different scale), the warming is greatest in the summer/autumn (3.0-3.4°C in the autumn). These are mostly based on the A1B emission scenario but include one A2 scenario.



Precipitation (Figures 4 and 5)

Autumn and winter are becoming wetter: 5-10% increase in mid century, increasing 15-25% towards the end of the century. Summers are drier: 5-10% decrease for 2021-2060; 10-18% decrease towards the end of the century. While Figures 4 and 5 show regional detail the spread in the ensemble of simulations is large, implying that the accuracy of the detail is questionable. For example, early simulations suggested the largest winter increases would occur in the NW; later simulations showed a bias in favour of the E/SE. Only the general assessment is robust.

Figure 4

Seasonal changes in precipitation: mean of 8 ensemble simulations showing the percentage change between periods 2021-2060 and 1961-2000 for winter, spring, summer and autumn (from left to right). Autumn and winter are wetter (5-10%), summer drier (5-10%); spring is also slightly drier (2-5%). Unlike the temperature signal there is no clear regional trend; the spread in the ensembles (not shown) is also large.

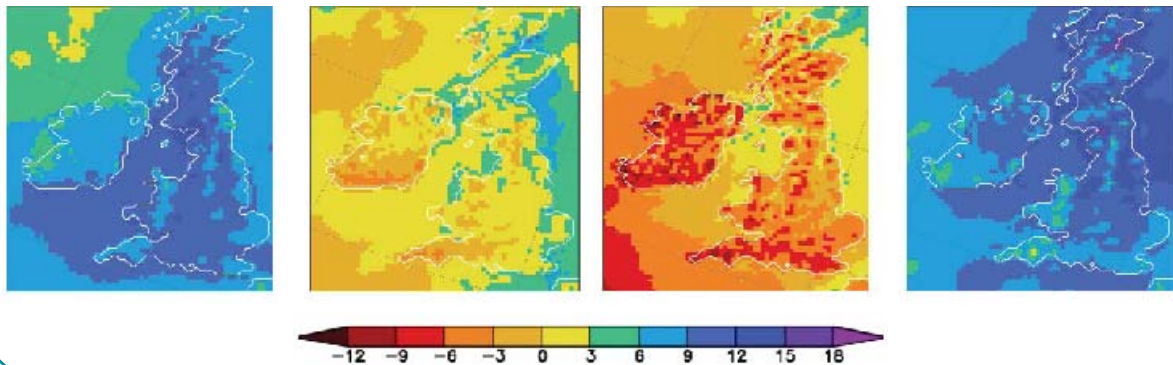
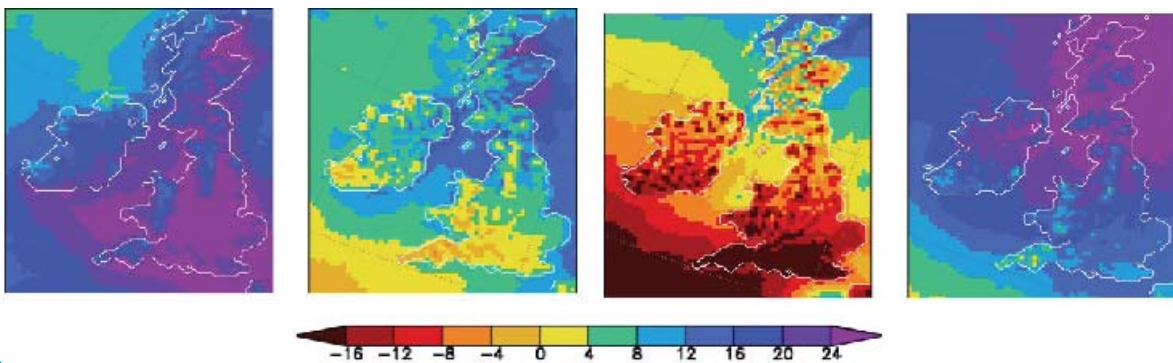


Figure 5

Percentage change in precipitation between the periods 2060-2099 and 1961-2000 for winter, spring, summer and autumn (from left to right). Autumn and winter are wetter: increases of 15-20% generally but 20-25% in the northern half of the country in autumn. Summer is drier (10-18%). Spring is least affected. There is no clear regional trend.



Wind speeds (Figures 6 and 7)

The ensemble set shows slight increases in winter wind speeds (1-2%) and decreases in summer (2-3%) for 2021-2060. However, towards the end of the century there is an overall decline in speeds, particularly in summer (4-5%). The latter is consistent with the predicted movement of storm tracks towards polar areas (IPCC, 2007); fewer storms may affect Ireland, although the influence of rising sea surface temperatures is likely to lead to more extreme storms. It should be noted that the Irish observational records indicate that average annual wind speeds decreased in the 1990s, with this trend continuing in the early years of the 21st century.

Figure 6

Seasonal changes in wind speeds: mean of 8 ensemble simulations showing the percentage change between periods 2021-2060 and 1961-2000 for winter, spring, summer and autumn (from left to right). The changes are small: increases in winter (1-2%) and decreases in summer (2-3%).

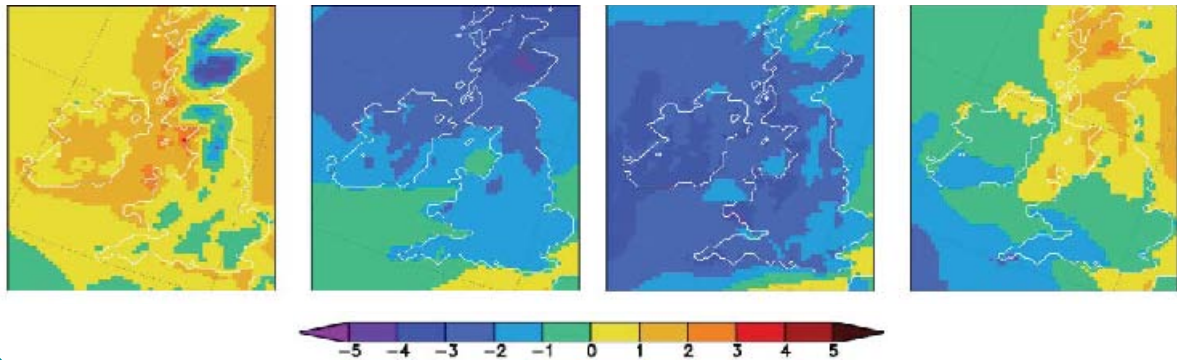
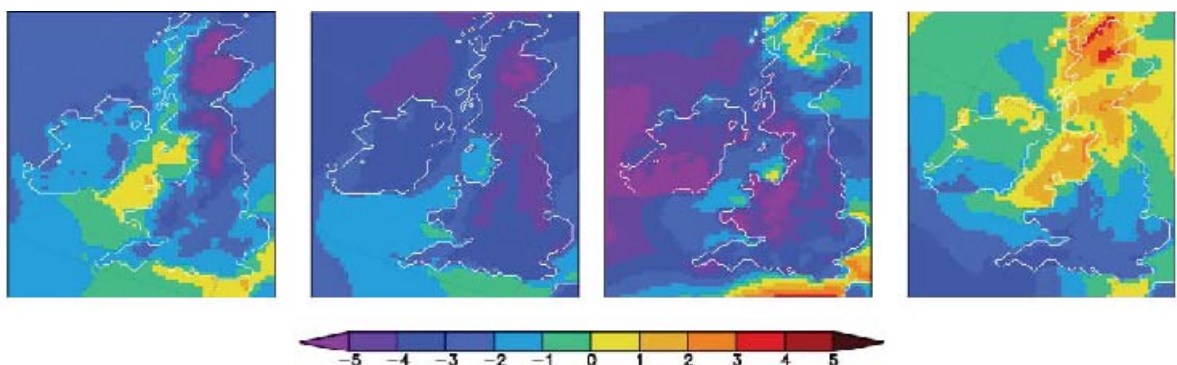


Figure 7

Percentage change in windspeeds between periods 2060-2099 and 1961-2000 for winter, spring, summer and autumn (from left to right). There is an overall decline in speeds, particularly in summer (4-6%).



Sunshine/cloudiness

No significant trends. However, these elements are particularly difficult to model.

Relative humidity

No significant trends.

Weather extremes

Modelling the sensitivity of the climate system to Atlantic sea surface temperatures suggests that there will be an increase in the frequency of the very intense cyclones with maximum wind speeds of more than 30 m/s; and increases in the extreme values of wind and precipitation associated with the cyclones. This will translate into an increased risk of storm damage and flooding.

The consensus among different modelling approaches is that extreme rainfall events are likely to increase in frequency in autumn and winter. However, there is still considerable uncertainty in these projections and further research is required.

Sea temperatures

Sea temperature and sea level around Irish coastlines have been rising slowly in recent decades. Since the 1980s satellite and in situ observations show a general warming trend of 0.3-0.4°C per decade in Irish waters, mirroring temperature trends over land. However, over the Irish Sea the satellite measurements suggest a more rapid warming rate (0.6-0.7°C per decade). The trends are consistent with what has been observed globally and are predicted to continue over the coming decades with possibly large impacts on marine ecology.

Sea level rise

Rising sea levels in recent decades are primarily linked to the warming of the oceans and resulting thermal expansion of seawater, and the influx of water from melting land ice. Satellite measurements show that sea levels are rising on average about 3.5 cm per decade around Ireland, well in excess of the ongoing isostatic adjustment of the land. This sustained trend would lead to sea level rises that are consistent with the IPCC (2007) global projections for the end of the century, although these estimates are probably conservative as they do not include current uncertainties in ice flow processes (melting glaciers, etc.).

Storm surges and waves

Ocean modelling results indicate an increase in the frequency of storm surge events around Irish coastal areas. There is also a significant increase in the height of extreme surges (in excess of 1 m) along the west coasts, with most of the extreme surges occurring in wintertime. The impacts on wave heights are seasonally dependent: there is some evidence of significant increases (up to 30 cm) in some months. Extreme wave heights (e.g. the 10-year return values) also show an increase - up to 10% around the northwest coast.

River catchment flooding

Modelling results (one ensemble member only) suggest an amplification of the seasonal cycle across the country, with increased winter precipitation leading to a rise in winter stream flow, and the combination of increased temperature and decreased precipitation causing a reduction in summer stream flow. Change to the seasonal cycle will have an impact on water supply management and design. Increased winter flows, coupled with the predicted increase in extreme precipitation events lead to an elevated risk of flooding. This is particularly significant in the southwest of the country, and those catchments with fast response times. The decrease in summer stream flow will impact on water availability, water quality, fisheries and recreational water use.

Ozone / skin cancers

The concentration of naturally occurring stratospheric ozone, which blocks harmful ultraviolet light reaching the surface, is linked with atmospheric circulation and temperature patterns. While the ozone layer is expected to reverse its decline due to the banning of CFC emissions in 1989, modelling results suggest the recovery may be slower than anticipated due to climate change. While in the long term the concentrations will recover, the risk of skin cancer in Ireland will not necessarily decrease. Social factors may also play a role. A warmer Irish climate (with drier summers) is likely to increase outdoor leisure activities and potentially increase the exposure to the damaging components of sunshine. Changing circulation patterns may also impact on air quality.

Impacts on future energy use

Ignoring mitigation initiatives and social/economic influences, heating energy demand is closely related to air temperatures (so called 'degree days'). Modelling the impact of climate change on this crude linkage suggests a decreasing heating energy demand: ~10% decrease in heating degree days is predicted for 2021-2060 and ~22% decrease for 2061-2100, compared to 1961-2000. Whereas air conditioning is not an issue in Ireland's current climate, a weak demand might develop towards the end of this century in the southeast of the country in summer.



3 The impact of climate change on storm surges over Irish waters

Evaluating the impact of climate change on storm surges requires, at a minimum, spatial fields of pressure and wind that can in turn be used to drive an ocean or surge model. As extreme surges are associated with depressions/storms with very low pressures and/or strong winds, it is essential that such features are adequately captured by the climate models used to produce the data. Pressure and wind data from global climate models (AOGCMs) are not suitable for this purpose as they are too coarse-grained. Here, a regional climate modelling approach is used; the global data are dynamically downscaled onto a finer grid covering an area large enough to support the application. The surge data were produced using the Regional Ocean Model System (ROMS) of Rutgers University.

Two experiments were performed to confirm the validity of the approach: the first focused on hindcasting the surge generated by a storm in early 2002 while the second provided surge statistics by running the model for the period 1990-2002; in both cases ROMS was driven with ERA-40 forcing fields. The results show that the model is capable of simulating both specific surge events and surge climate statistics with reasonable accuracy (order of 10 cm). Model outputs were also compared spatially against satellite altimetry data, corrected for long wavelength errors, from 1993 to 2001. The ROMS model consistently reproduces the sea level variability in the Irish Sea, and over the waters to the south and west of Ireland.

To investigate the impact of the climate change on storm surges, the same configuration of ROMS was driven by atmospheric forcing fields downscaled from ECHAM5/OM1 data for the past (1961-1990) and future (2031-2060; A1B greenhouse gas scenario). The results show an increase in the frequency of storm surge events around Irish coastal areas in the future projection with the strongest increases in the northwest. There is also a significant increase in the height of the extreme surges along the west coast, with most of the extreme surges occurring in wintertime.

1 Introduction

Storm surges are occasionally severe enough to lead to a significant loss of life and damage to property in coastal areas (McRobie, 2005; Wolf, 2005). With a warming climate there are concerns that such events may increase in frequency and intensity due to a combination of rising sea level and an increase in the frequency of extreme weather, including storms (IPCC, 2007). According to the IPCC report, there is likely to be an increase in the number of intense cyclones and associated strong winds, particularly in winter over the North Atlantic; a slight poleward shift of the storm tracks is also likely. These changes will have a direct impact on storm surges, which are primarily caused by low pressure and strong winds. Rising sea levels will enhance the impact of surges. In the same report, global sea level is projected to rise 18-59 cm (depending on the emission scenario) towards the end of this century, although some researchers argue that the range is underestimated and that the rise could reach 1.4m (Rahmstorf, 2007). Local changes will be more difficult to predict but any rise in sea level will exacerbate the impact of storm surges.

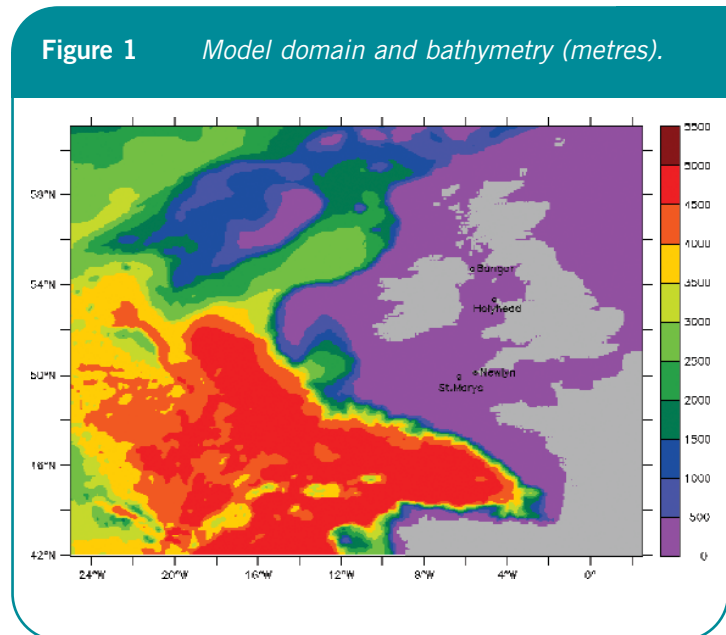
In Ireland, flooding is associated mainly with heavy rainfall which can lead to enhanced river-flow and over-topping of river banks. However, coastal flooding events are often more serious, particularly those associated with storm surge events that occur in combination with spring tides. The effects may be enhanced locally by the coastal topography (Wells, 1997).

Several early studies on storm surge have been carried out over the NE Atlantic area. The WASA project (Waves and Storms in the North Atlantic; WASA 1998), for example, analyzed available storm data and found that the climate has

undergone significant variation on time scales of several decades. Flather and Smith (1998) found that under enhanced greenhouse gas conditions extreme wind speeds could increase by 10% in the North Sea resulting in a similar increase in the extreme storm surge. Lowe et al. (2001) employed a dynamical approach similar to Flather and Smith (1998) with some improvements, including longer time slices, higher temporal (3-hour) and spatial resolutions (35 km) of the atmospheric forcing fields. Their results showed a statistically significant increase in extreme storm surge along the UK coastline, under assumed future climate conditions. Woth et al. (2005) applied an ensemble method for the surge study, using 6-hourly atmospheric forcing fields from 4 different regional climate models (horizontal resolution around 50km) to drive a high resolution surge model (horizontal resolution around 10km). Their results suggest that storm surge extremes may increase along the North Sea coast towards the end of this century; based on a comparison between the results of the different ensemble members, it was found that the increase is significantly different from zero at the 95% confidence level for most of the North Sea coast. All of the studies confirm the dependence on the underlying driving fields: in order to reach reliable conclusions regarding the impact of climate change, it is necessary to run long time-slice experiments to cover the natural variability of the Atlantic weather.

While the above studies show the uncertainties in predicting future storm surges, nevertheless the numerical storm surge models, driven with accurate atmospheric fields, can produce surge information in good agreement with observed data. They can also be used to generate information at arbitrary locations and for periods without observation. However, the atmospheric forcing fields must also be available with high temporal resolution; the 12 or 6 hour data typically available from global models are insufficient to capture rapid storm developments associated with surge extremes. Because of the local characteristic of the surge, a high spatial resolution is also required of the surge model, particularly near complex coastlines (e.g. in the Irish Sea). The integration area must also be large enough to capture the essential ocean processes. Flather et al. (2000a), for example, point out that the tides in shelf and coastal seas are responses to oscillations generated primarily in the deep oceans and that changes in sea level can also modify the dynamics of the tides and surges. To allow the least constrained resonant response to the lateral tidal forcing, the model domain should also be large enough to accommodate the major Atlantic cyclone systems that move over the area, while capturing the shallow-water characteristics of the Irish Sea.

In previous climate change studies of storm surge in the Atlantic Ocean, most of the research has focused on the North Sea. In Irish coastal areas and the Irish Sea most of the studies have used two dimensional surge models driven with relatively coarse spatial or temporal resolution data (Flather, 1998, 2000b). Kauker and Langenberg (2000) compared the performance of a 3D ocean model and 2D storm surge model; they found that the 2D surge model produces less variability than the 3D ocean model. The 2D studies could also be viewed as deficient either through the lack of sufficient resolution in the basic model or driving data, or the lack of a proper treatment of the inverted barometer effect in the lateral boundaries. In our study, we follow and extend the approach used in previous studies. A high resolution regional climate model (25km horizontal resolution) is run to generate the hourly atmosphere forcing field for the surge model. Considering Flather's experience, a large domain was selected, covering an area from the middle of the Atlantic Ocean to the North Sea and including the Rockall Trough and the Bay of Biscay (Figure 1). The 3D ROMS model also includes the interaction due to the non-linear dynamical processes in shallow water.



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Li et al (2006) used the ROMS model to study the storm surge induced by a hurricane in a semi-enclosed bay. Their results show that the model has excellent predictability for the storm surge as verified against the real-time data recorded on the observation systems. However, compared to a semi-enclosed bay, the Irish Sea is a much more

complex shelf area, prompting an initial validation of the model over the area before the climate change simulations were performed.

The layout of this chapter is as follows: following the methodology and model setup in section 2, the validation of the ROMS model is presented in section 3, and the impact of the climate change study on the storm surge is given in section 4.

2 Methodology

2.1 The GCM scenario data and regional climate model

The climate change scenario used in this downscaling experiment was obtained from ECHAM5/OM1 model, with the future simulations based on the A1B emission scenario. The regional climate model used to downscale the GCM data is the Rossby Centre Regional Atmospheric Model (RCA3) developed from the High Resolution Limited Area Model (HIRLAM). Most HIRLAM parameterisations have been retained in RCA3. However, RCA3 hosts a new land surface scheme and some new hydrological processes are included (Rummukainen et al., 2001; Jones, 2001), which improve the simulation of precipitation and evaporation; these two parameters are used to calculate the fresh water fluxes for the ocean model. In order to cover the selected domain areas for the ocean modelling, the RCA3 model domain was set up on a 0.22° (25 km), rotated latitude/longitude grid, covering a slightly bigger area than that shown in Figure 1. RCA3 has been validated extensively using ECMWF ERA-40 reanalysis data (Uppala et al., 2005) to simulate the present day climate; it has also been used to simulate the future climate using ECHAM4 (Roeckner et al., 1996) and ECHAM5 (Roeckner et al., 2003) scenario data. The results suggest that the model is well able to capture the characteristics of the present day climate and is suitable for dynamical downscaling of future climate scenarios (Wang et al., 2006; McGrath et al., 2005).

In this study, the downscaling consists of two 30-year time-slice periods (1961-1990 and 2031-2060) using boundary data at 6-hour intervals from ECHAM5/OM1. In order to drive the storm surge model and to catch the fast moving cyclone systems, the meteorological forcing fields were saved every hour; these included the 10-metre u and v component of wind speed, mean sea level pressure, net long-wave and short-wave radiation fluxes, precipitation, evaporation, latent and sensible heat fluxes.

2.2 The surge model

The ROMS model is a three-dimensional, hydrostatic, primitive equation ocean model originally developed by Rutgers University (Shchepetkin and McWilliams, 2003, 2005). It incorporates a free surface, enabling simulation of surface elevation changes due to tides and surges. Stretched, terrain-following, coordinate transformations are used in the vertical, while orthogonal curvilinear coordinate transformations are used in the horizontal.

As mentioned in the introduction, the model domain enclosed a large part of the north-west European continental shelf with a horizontal resolution of 4 minutes (about 7km) and 16 vertical levels. As a large part of the Atlantic Ocean is included in our model domain, open boundary conditions are used in the horizontal. For the sea surface elevation boundary condition, the inverted barometer effect (the change in sea level related to the atmospheric pressure, calculated using the hydrostatic assumption) was used. This gives a reasonable approximation to the sea level on the open ocean where coastal effects are not felt. It was used as a boundary condition to approximate changes to sea level, related to pressure changes associated with atmospheric systems approaching the model domain. In this set up, the model does not include the direct effects of global sea level rise due to the thermal expansion of seawater or fresh water influx from melting ice or glaciers; the changes in sea level and storm surge are primarily due to the impact of the atmospheric wind and mean sea level pressure. Sea level rise associated with climate change may affect surge heights in shallow water due to changes in bathymetry, but the impact is likely to be small (Lowe, 2001; de Ronde, 1993).

A Flather boundary condition (Flather, 1976) was used for the tidal currents and a radiation condition for the momentum, salinity and temperature. The salinity and temperature data are taken from the monthly ECHAM5/OM1 data sets. For the tidal forcing, data were derived from the barotropic tidal data assimilation system of Oregon State University (TPX06.2) (Egbert and Erofeeva, 2002); it includes eight primary (M_2 , S_2 , N_2 , K_2 , K_1 , O_1 , P_1 , Q_1) and two long period (M_f , M_m) harmonic constituents. These data are mainly assimilated from 364 cycles of Topex/Poseidon satellite data.

Because surges are superimposed on the normal astronomical tides, generated by variations in the gravitational attraction of the Moon and Sun, the surge height was computed following Flather and Williams (2000b):

$$\text{Sea level elevation} = \text{predicted tide level} + \text{storm surge height}$$

In order to include the effects of interactions due to non-linear dynamical processes in shallow water, two simultaneous simulations were run on separate, but identical, grids. One was driven with all the forcings (tides, inverted barometer effect and wind forcing); the other was driven with tidal forcing only. The surge heights were determined by subtracting the tide-only run from the tide plus meteorological forcing run.

2.3 Validation run

On 1 February, 2002, an intense cyclone formed over the northwest of Ireland with a central pressure of about 928hPa recorded at 18 UTC (Burt, 2007). The low pressure, in combination with strong surface winds and coinciding with high tides, caused serious coastal flooding, particularly along the east and south coasts of Ireland and parts of England and Wales. This storm was chosen to evaluate the performance of the ROMS model in hindcasting extreme surge events. The model simulation was run for a total of 45 days from 00 UTC on 1 January, 2002 to 00 UTC on 15 February, 2002. The first 15 days of results were disregarded to allow for model spin-up.

To assess the stability of the ROMS model to simulate multi-decadal climate runs, a second and much longer validation run (1990-2002) was carried out. In both cases the model was driven with 6-hour ERA40 reanalysis data.

For an independent assessment of the performance of ROMS, satellite altimetry data, corrected for long wavelength errors by SSALTO/ DUACS (Segment Sol multimissions d'ALTimétrie, d'Orbitographie et de localisation précise/Data Unification and Altimeter Combination System) using a 2D gravity wave model (MOG2D-G), by a dynamic atmospheric correction (DAC) method were used (Carrere and Lyard, 2003). Data are available from the SSTALTO/DUACS system at 6-hour intervals on a 0.25°x0.25° global grid.

2.4 Surge extreme analysis

The surge elevations are fitted using a Generalized Extreme Value distribution $GEV(\mu, \sigma, \kappa)$, where μ is the location parameter, σ the scale parameter and κ the shape parameter. For reliable estimates of the parameters long term series are required (Martins, 2000). In this study, as the 30-year time slice is still relatively short for the long-term return period estimation, the 5 largest maxima per year are used in the analysis. To make sure these data are independent, a 48-hour time window was applied for the selection of the yearly maxima.

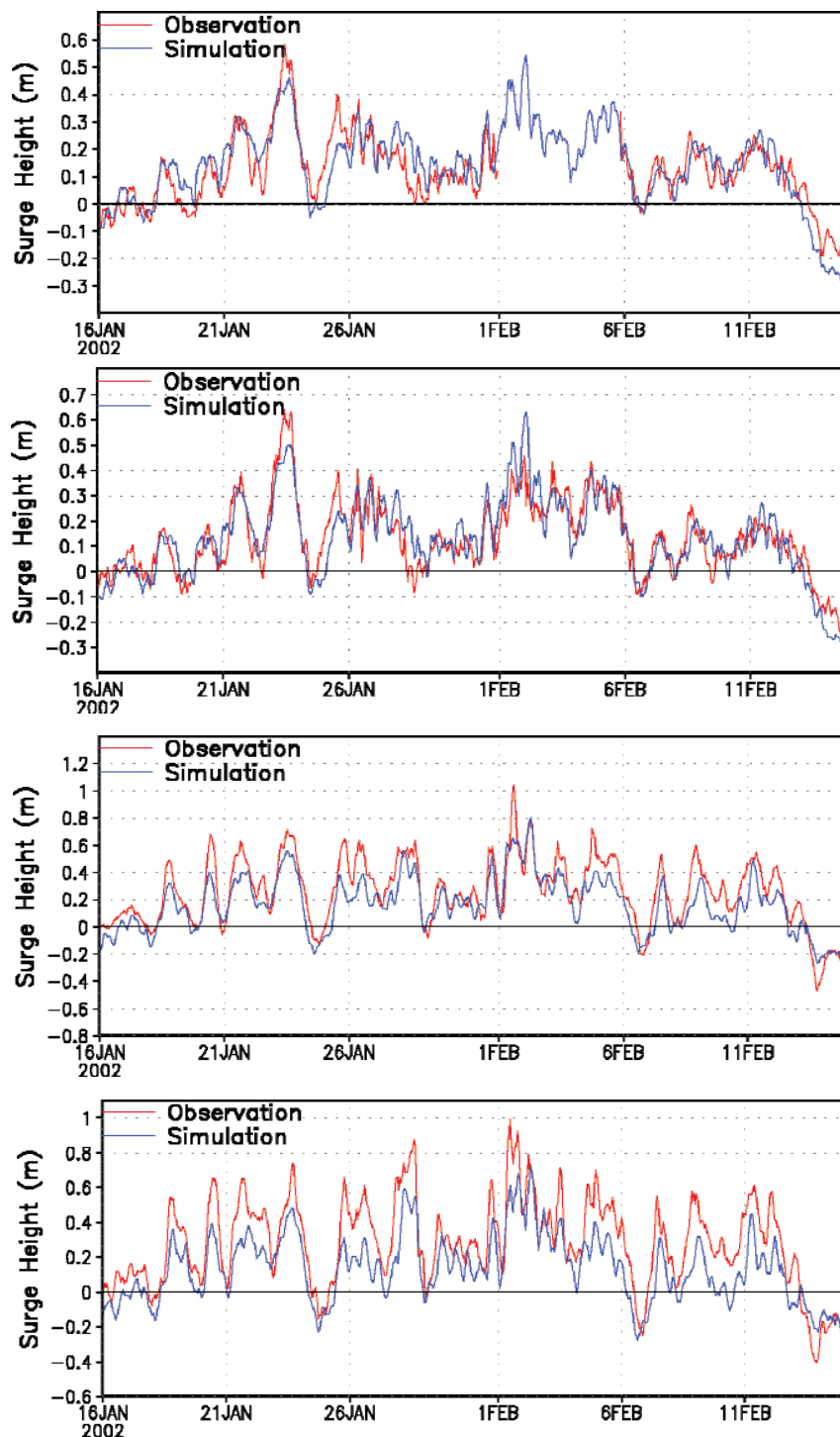
3 Validation of the storm surge for present day

3.1 Station data analysis

For the 2002 storm surge event, Figure 2 shows the simulated and observed surge for 4 selected stations (St. Mary's, Newlyn, Holyhead and Bangor – see Figure 1). The model is clearly reproducing both the magnitude and time of surge events in general. Agreement is better at the Newlyn and St. Mary's stations, which are less influenced by the topographic and dynamical effects of the semi-enclosed Irish Sea basin. However, some extreme surges, in particular a large event on the 22-23 January, were underestimated by up to 20 cm in the simulation, even at these stations. For Holyhead and Bangor, there is still a high degree of consistency between the modelled and observed time series, but the amplitude of the surge is systematically underestimated at both stations.

The accuracy of the simulation may be compromised by the use of 6-hour ERA-40 data to drive the ocean model; this frequency is too low to capture the full effects of fast-moving cyclone systems across the narrow Irish Sea basin. Another factor is the accuracy of the ERA-40 10-metre wind speed. From Flather's (1998) study, the model was found capable of capturing the extreme storm surge events when the precise wind forcing was used at 6-hour resolution. Comparing the ERA-40 data with synoptic surface observations, we find that the reanalysis wind strengths in this case are biased low, in general, but the bias is particularly evident for the strongest winds. Both of these factors will lead to weaker surges in the simulation compared with the observations. Another issue is the resolution of the ocean model; at approximately 7km it is too coarse to capture the detailed flow in the Irish Sea, particularly in the North Channel (Jones, 2006).

Figure 2 The simulated and observed surge at (top to bottom) St. Mary's, Newlyn, Holyhead and Bangor.



According to the research of *Lowe et al.* (2001), along the south Irish Sea coast the surge height is dominated by the inverted barometer effect, with the wind forcing providing only 16% of the surge height. In the north Irish Sea, on the other hand, the wind forcing contributes 72% of the surge height. A sensitivity study was carried out in which the ERA-40 winds were modified to provide better agreement with synoptic observations; the results confirmed that the wind bias is the main reason that the model performs better in the south Irish Sea (not shown).

For the 12-year simulation run (1990-2002), the hourly observed surge data from the British Oceanographic Data Center for 8 stations were used for validation. Summary statistics are listed in Table 1: the standard deviation error (STD), the root-mean-square error (RMSE), the RMS difference between the observed and simulated surges, and the correlation coefficient. For Bangor, the hourly data only cover about 5 years; data for the other stations cover at least 7 years.

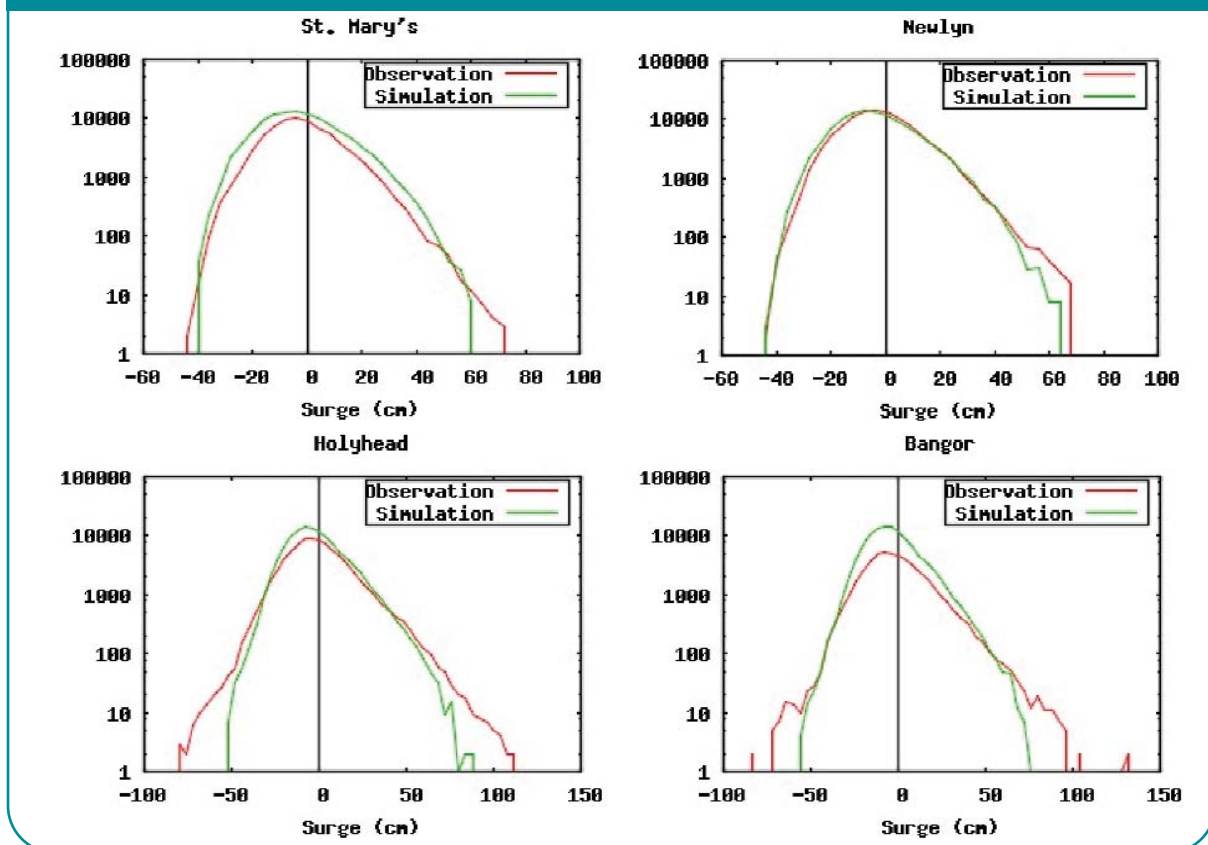
In the Irish Sea, the simulated surges have a relatively large error in the northern end compared to the south. The correlation coefficients are generally high for all the stations. Both the RMSE and STD figures show that the model is able to reproduce the surge variability with reasonable accuracy (order of 10 cm) in this region.

Table 1: Error statistics of the simulated and observed surge elevation at different stations (heights are in centimeters).

	Sample Size	RMSE	STD	RMS difference	Correlation
St.Mary's	70494	9.42	9.41	-1.16	0.75
Portpatrick	103280	12.83	12.6	4.07	0.75
Port Erin	62069	12.25	12.03	3.7	0.73
Port Ellen	97514	13.01	12.85	4.8	0.75
Fishguard	106900	9.05	8.7	0.77	0.84
Newlyn	108646	9.52	9.36	-0.48	0.76
Holyhead	79716	10.31	10.23	2.15	0.80
Bangor	46738	12.32	12.07	3.3	0.71

To investigate extreme surge events, Figure 3 shows the histogram distributions for the same 4 stations. For moderate surges, the model simulation is quite reasonable, while for the maximum surge there is an underestimation for all stations although agreement with observations is quite good for Newlyn. This is not surprising, in view of the underestimated wind speed, but the relatively coarse horizontal resolution of the ocean model may also be a factor, as discussed above. The simulation of the higher storm surge events in the south Irish Sea area is much better than in the north Irish Sea area.

Figure 3 Histogram distribution of the surge events for St. Mary's, Newlyn, Holyhead and Bangor.



3.2 Spatial variation comparison

The aim of the 12-year simulation was to evaluate the capability of the model to perform long climate simulations. To facilitate comparison with the satellite altimetry data for the period 1993-2001, ROMS output from a small inner domain (49-55°N and 1-12°W) was saved. As the satellite data are weekly averages the ROMS output was similarly converted.

The spatial and temporal variability of both sets of data were compared for the period 1993-2001 over the ocean area adjacent to Ireland, stratified into latitude/longitude bins as indicated in Table 2.

Table 2: Differences between ROMS and satellite-derived data.					
Area	Latitude	Longitude	RMS difference (cm)	R2	Mean difference (cm)
North	56.6-57.1°N	8-9°W	13.0	0.25	4.1
West	51.6-52.3°N	10.6-11.6°W	4.4	0.87	4.3
South	50-50.6°N	8-9°W	8.1	0.70	-0.4

Time series for the western area are shown in Figure 4. The ROMS model is in good agreement with the satellite-derived data in this domain. In the southern area the results are similar but agreement is poor for the northern domain (not shown). These results are also confirmed in the scatterplots shown in Figure 5.

The correlation coefficient and RMS difference fields (Figures 6a and 6b) show similar features from year to year. High correlations are observed in the southern part of the domain, with values exceeding 0.7 around much of Ireland, and more than 0.9 off the southwest coast. The RMS difference fields show a similar pattern, with values of 4-12 cm around the coasts and over most of the area, apart from the extreme north and northwest.

Figure 4 Time series of (a) dynamic atmospheric correction, calculated by MOG2D-G model for correction of altimetric sea level anomalies; (b) surge generated by ROMS model; (c) DAC-ROMS residuals. Data shown are weekly data from the West region (see Table 2) from January 1993 to December 2001.

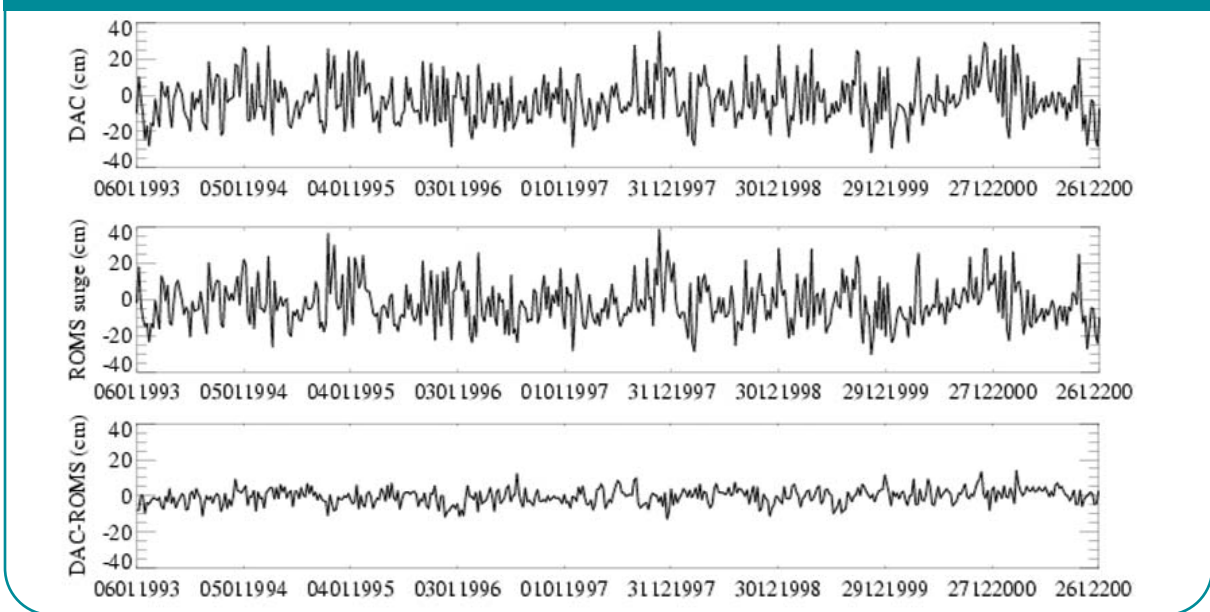


Figure 5 Scatterplots of ROMS surge and DAC for the north, south and west regions defined in Table 2.

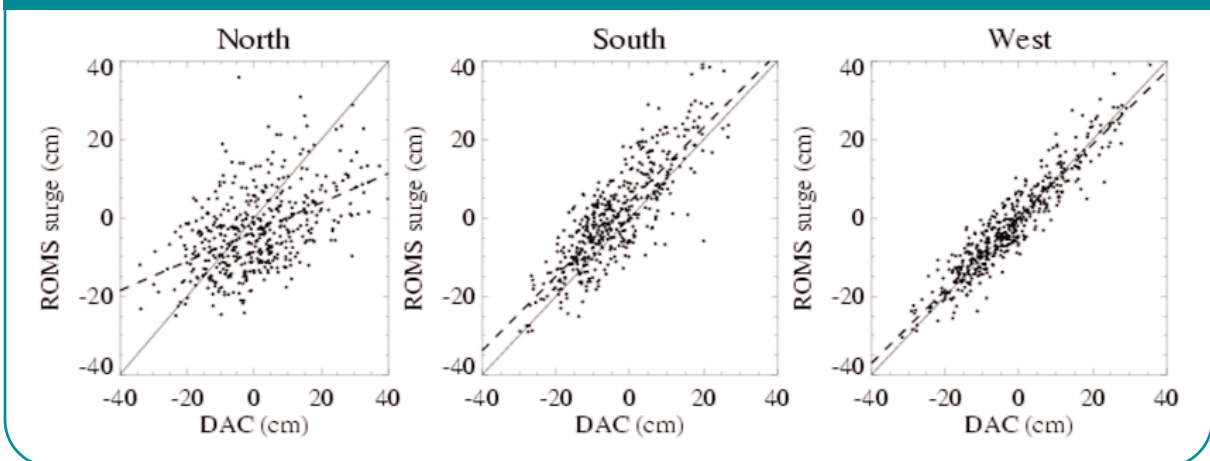
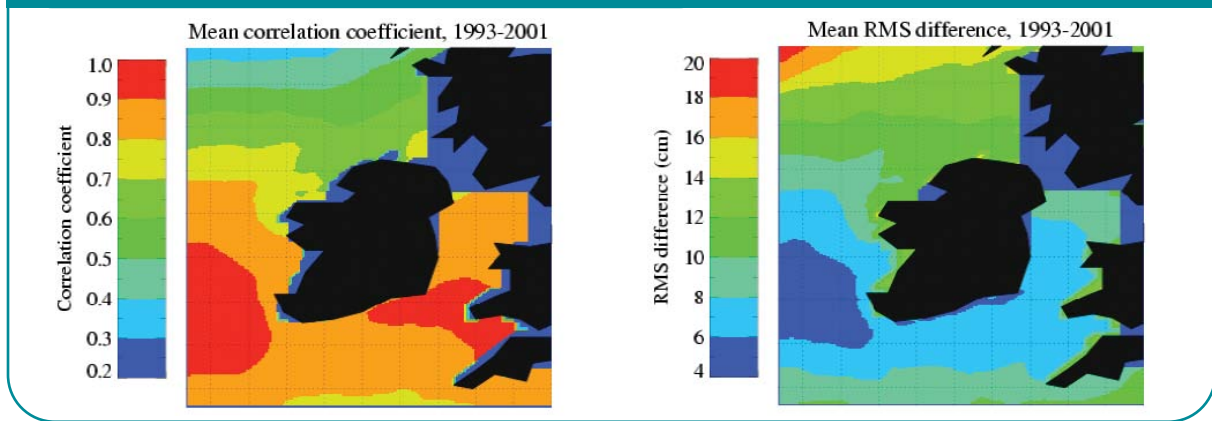


Figure 6 (a) Correlation coefficient between DAC and ROMS surge calculated for all weekly data between 1993 and 2001 and (b) RMS difference.



Low correlations and high RMS values north of Ireland indicate a systematic difference between the two sets of data in this area. The consistency of the spatial patterns from year to year points towards a bathymetric effect. This may be due to the bathymetry in the ROMS model having insufficiently high resolution or accuracy in the area adjacent to the Erris-Slyne trough, off the north-west of Ireland. It could also be due to inconsistencies in the bathymetry used in the models.

Generally, the above analysis shows that the ROMS model is capable of reproducing storm surge events with reasonable accuracy, supporting its use as a suitable tool in climate change studies.

4 The impact of climate change on storm surge

4.1 Station data analysis

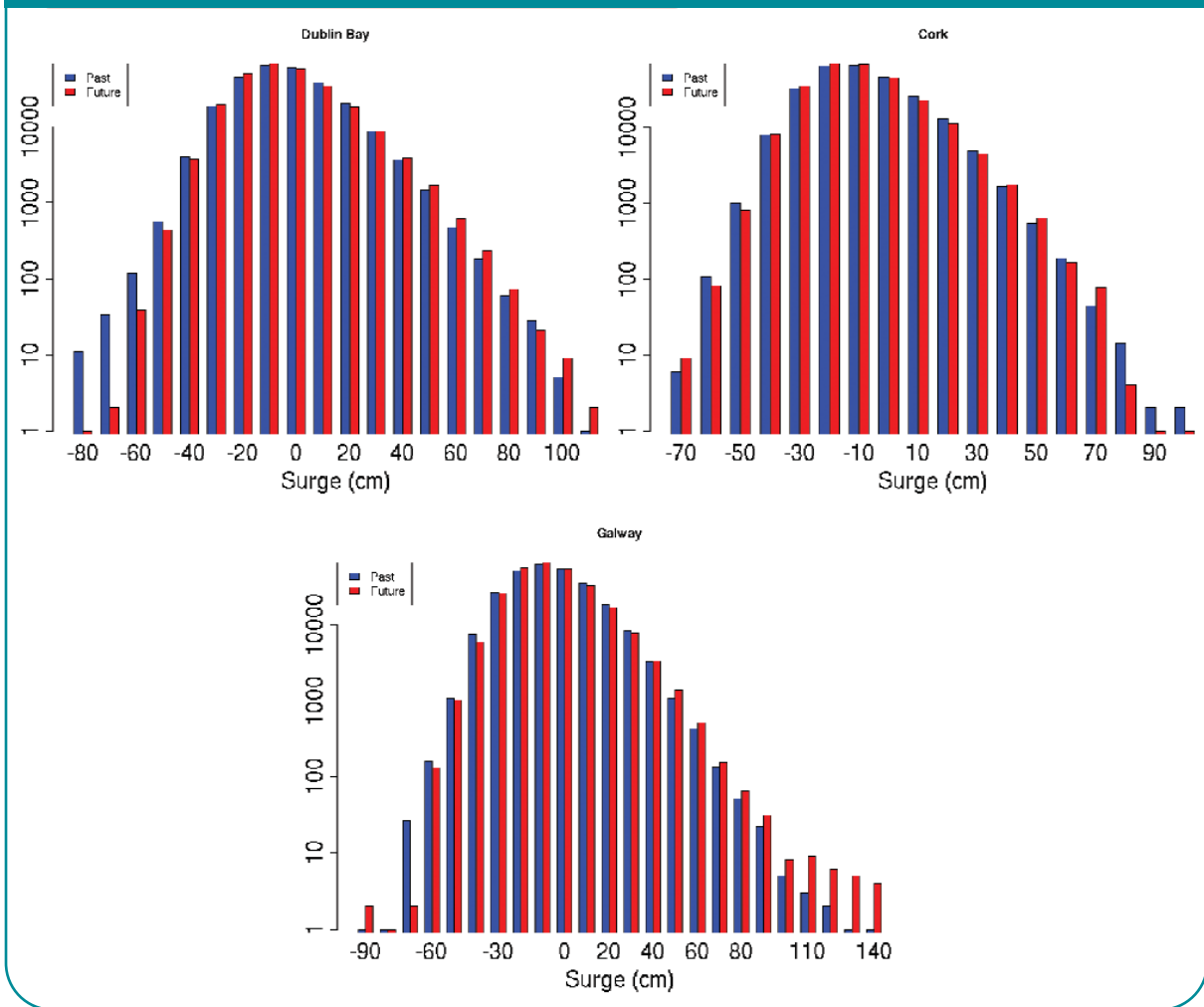
Ireland is particularly exposed to Atlantic storms due to its location on the west of Europe. To evaluate the impact of a changing climate on future storm surges, statistics were created for 13 coastal sites. Results for these sites are summarized in Table 3, which shows the simulated changes (2031-2060 relative to 1961-1990) in surge heights. The range 50-100 cm is chosen as being typical of surges associated with coastal flooding in Ireland. The results show increases in the frequency of such occurrences at all sites in the future simulation, especially along the western coastline of Ireland (more than 30% increase in the northwest). There are similar changes in the extremes (99% percentile); with the exception of Cork all show increases. For the maximum surge height, the changes are more variable and probably not robust, but some sites show a large increase (e.g. Galway).

Table 3: Differences in the surge elevation between the future (2031-2060) and control run (1961-1990).

Station Name	50 cm<Hsurge<100 cm % Change in frequency	99 percentile % Change in height	Maximum Surge % Change in height
Dublin Bay	14.7%	5.45%	5.6%
Wicklow	21.9%	2.22%	13.98%
Arklow	20.1%	2.27%	11.1%
Wexford Bay	18.98%	2.44%	12.36%
Waterford	20.6%	2.44%	-7.69%
Cork Harbour	10.6%	0.01%	-17.76%
Dingle Bay	24.93%	2.33%	20.88%
Shannon Estuary	25.50%	4.76%	10%
Sligo Entrance	30.53%	6.38%	-5.08%
Lough Swilly	19.2%	3.7%	-10.88%
Donegal Bay	24.80%	6.12%	6.87%
Clew Bay	31.20%	6.38%	6.42%
Galway Bay	25.93%	6.52%	73.2%

Histogram plots of the surge heights for Dublin Bay, Cork Harbour and Galway Bay are shown in Figure 7 and generally confirm the findings in Table 3. The increase in extreme surges is consistent with an increase in the frequency of intense cyclones over the area (McGrath, 2004; Sweeney, 2000; Lozano, 2002). Bijl (1997) showed that an increase in the storm intensity would have a relatively large effect on the surge maxima.

Figure 7 Histogram distribution of the surge events for Dublin Bay, Cork Harbour and Galway Bay.



To further investigate the extreme events, the cumulative probability of the Generalized Extreme Value (GEV) distribution was calculated for Dublin, Cork and Galway (Figure 8). Note that this probability is based on the annual maximum surge heights. These three stations are representative of the extremes for Ireland and are consistent with the histogram plots in Figure 7. The data confirm the local character of the surge climate, especially in shallow water where the surge events are strongly affected by the local bathymetry.

4.2 The spatial distribution analysis

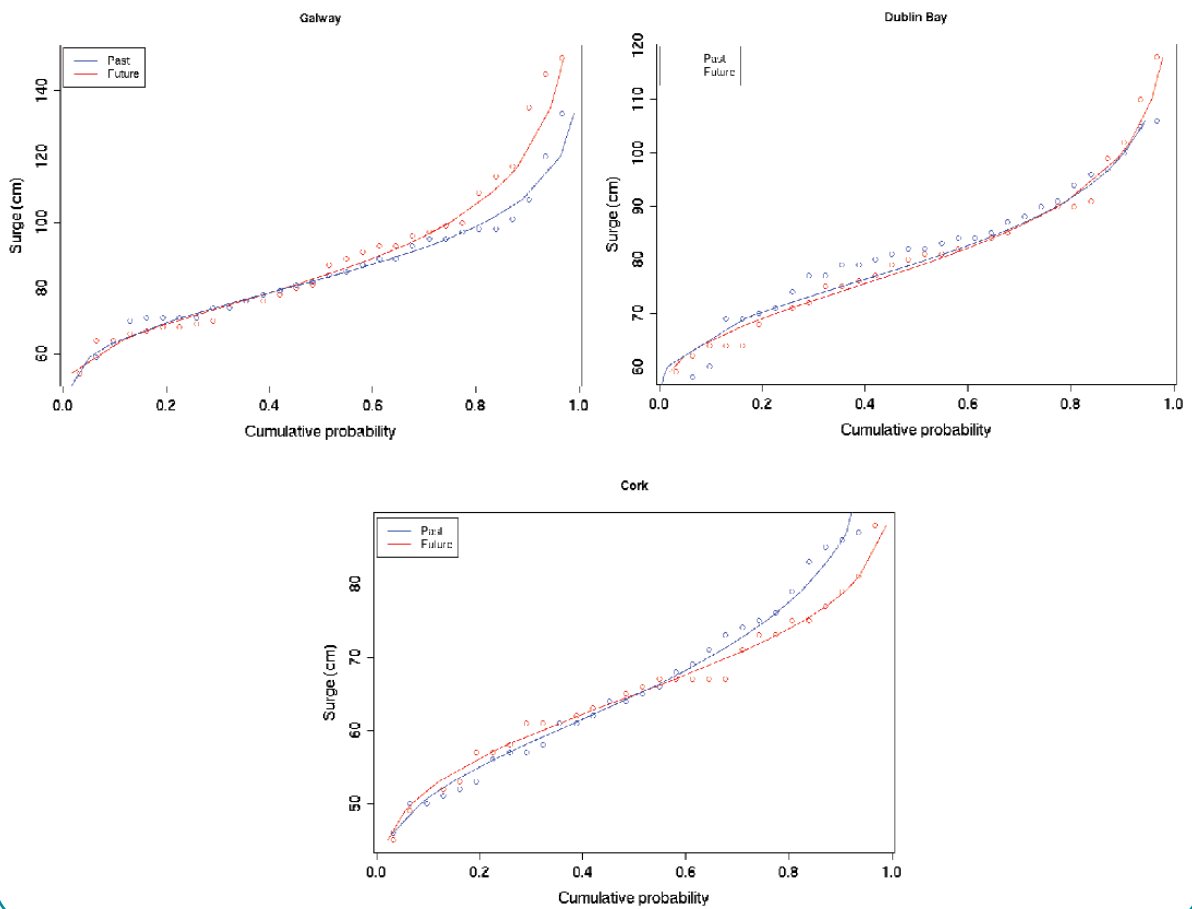
4.2.1 The wind speed and mean sea level pressure

As discussed before, the wind speed and mean sea level pressure are two main factors for generating the storm surge. Changes (%) in the annual mean wind speed (Figure 9) are relatively small; there is an increasing tendency along the west and north-west coast of Ireland and part of the UK coast, but a decrease over the open sea in the ROMS integration area. These results are similar to the findings in Debernad's (2002) study, which concludes that the largest changes are expected in high latitude areas.

For the relative changes of mean sea level pressure (PMSL) (Figure 10), the distribution pattern shows an increase around Ireland and southwards, and a decrease to the northwest. This is consistent with an increase in the frequency of intense cyclones over the area in the future.

While the annual mean wind speed does not change much, it is interesting to investigate the variation in the maximum speeds, which are often implicated in the strongest surges. Figure 11 shows the relative change in the 10-year and 50-year return values. Around the northern coastline of Ireland, the 10-year return value has increased 6-10% (Figure 11a). For the 50-year return value (Figure 11b), the spatial pattern is similar, with a slightly higher

Figure 8 Cumulative probability distribution of the annual maximum surge for Dublin Bay, Cork Harbour and Galway Bay.

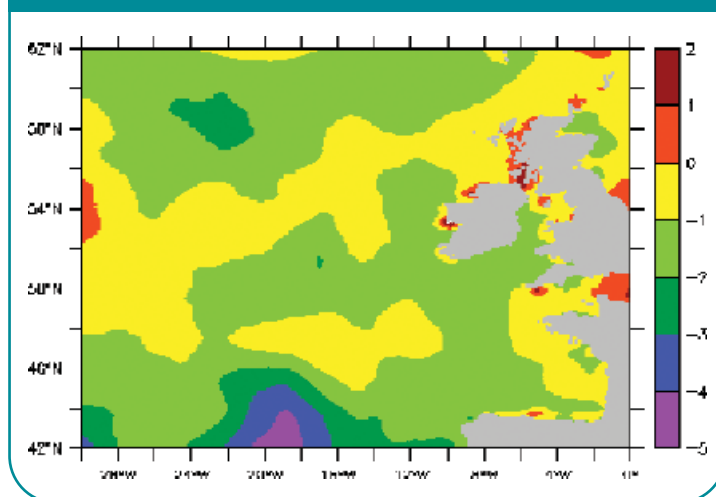


increase around the northern area. In both cases there is a slight decrease along the south coast. Stratification of the data by season shows that the increase in winds occurs mainly in winter; summer values show a slight decrease.

4.2.2 The extreme value analysis of the surge height from the control run

Apart from the wind speed, the wind direction is also a very important factor in the generation of extreme surges. Along the west coast of Ireland the prevailing westerly and south-westerly winds are associated with the strongest surges. However, over the Irish Sea, the tidal streams are propagated from both the north and south, and meet southwest of the Isle of Man, enhancing surge heights around this area. The 10-year return value of the extreme storm surge from the control run shows that the maximum surge heights occurs in the Solway Firth area (Figure 12a), similar to the findings of Flather et al. (1998). The 50-year return value of surge heights from the ROMS simulation is shown in Figure 12b. The spatial distribution is very similar to Flather's equivalent map (Flather, 1987) which is based on a sample of 16 storms constrained by observations. These results show that the ROMS model is capable of producing reliable surge extremes when it is forced by suitable meteorological fields.

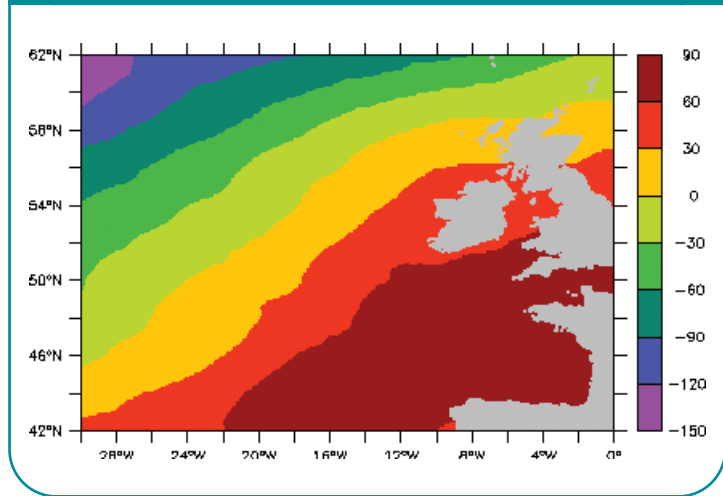
Figure 9 Relative changes (%) in the annual mean wind speed between the future and control run periods.



4.2.3 The effect of future scenario changes on the storm surge extremes

The relative changes in the 10-year and 50-year return period of the surge heights between the future and control simulation show that along most of the Irish coastline the trend is for increasing surge height (Figure 13a, b). However, the spatial pattern of the change is far from uniform. It is interesting to compare the changes with the corresponding changes in extreme wind speed (Figure 11). There is some correlation between changes in the maximum wind speed and changes in extreme surge heights but this does not apply everywhere; in the 50-year return values (Figure 13b) the extreme storm surge heights decreased along the north coast while the maximum wind speed increased; changes in the wind direction may be a factor in this case.

Figure 10 *Relative changes (Pa) in the annual mean sea level pressure between the future and control run periods.*



As discussed before, there is a strong seasonal variation for the maximum wind speed. This will have a strong impact on the extreme storm surges. Figure 14 shows the 10-year return value of the annual extreme storm surge distribution for the four seasons. In general these show increases in winter and spring, and decreases in summer and autumn.

Figure 11 *Relative changes (%) in the 10-year (a) and 50-year (b) return value of annual maximum wind speed between the future and past control run.*

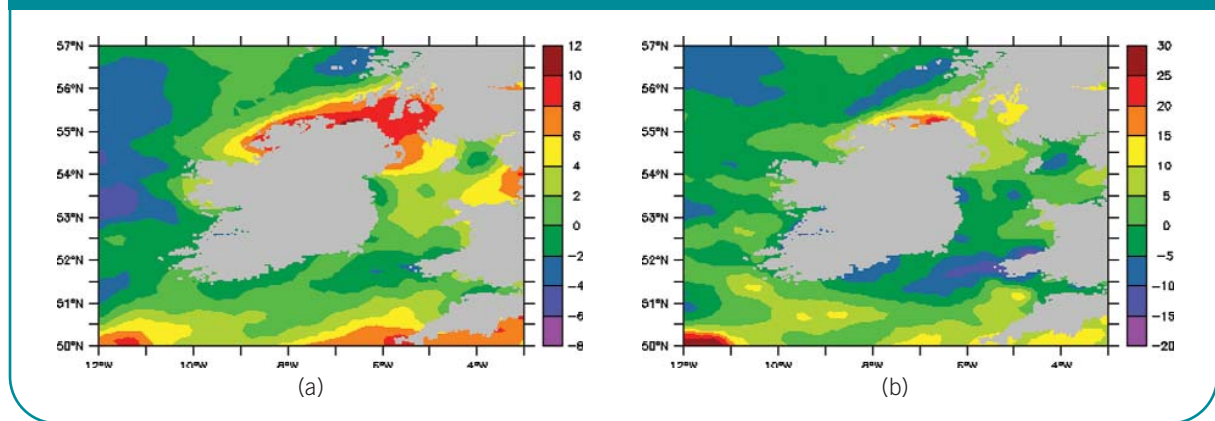


Figure 12 *10-year (a) and 50-year (b) return values (cm) of the annual maximum surge height for the control run.*

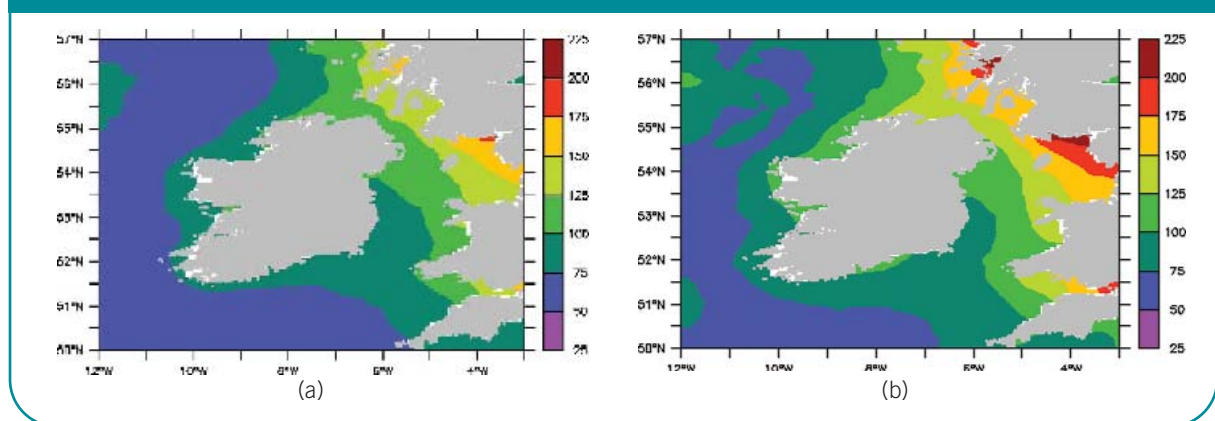


Figure 13 *Relative changes (%) in the return values of annual maximum storm surge between the future and past control run: 10-year (a) and 50-year (b).*

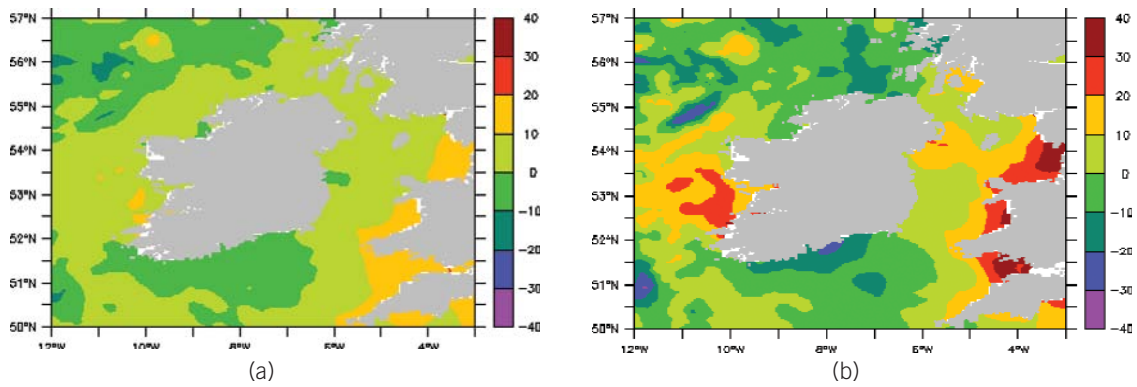
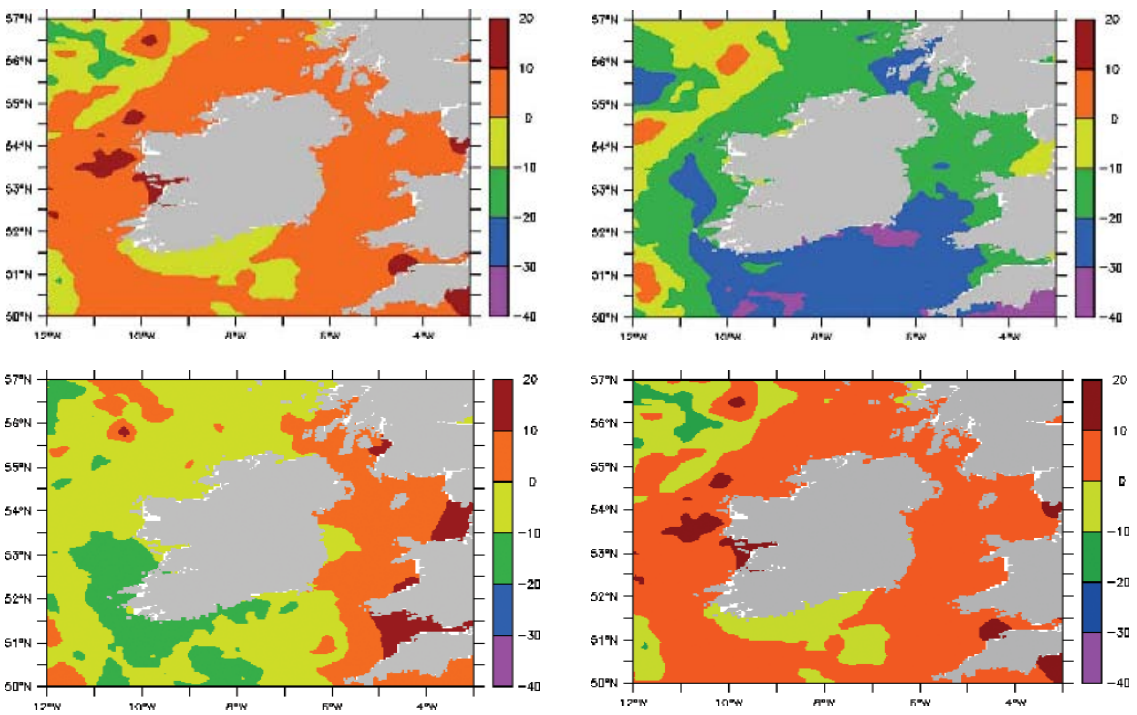


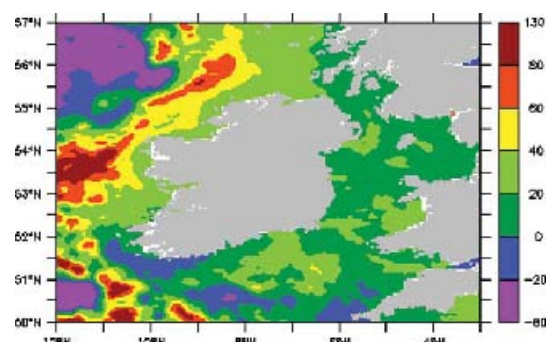
Figure 14 *Relative changes (%) in the 10-year return values of seasonal maximum storm surge between the future and past control run. Top: spring (left), summer (right). Bottom: autumn (left), winter (right).*



4.2.4 Combined storm surges and tides

In the discussions so far the surge has been analysed in isolation from the tides. However, a high surge may have little impact if it occurs at low tide, while a relatively minor surge may be damaging if it occurs on a Spring tide. A simple analysis was implemented to estimate the total impact of surge and tide. The average of all positive tide heights over the simulation period was used to provide a reference tidal level. The % change in the number of events with surge height exceeding 50cms, and the corresponding tide height exceeding the reference level, is

Figure 15 *Relative changes (%) in the occurrence of storm surge heights exceeding 50 cm in combination with high tides between future and control run.*



shown in Figure 15. Except in the southwest, it shows a general increase in Irish coastal waters, particularly in the northwest areas.

5 Conclusions and discussion

Coastal flooding and coastal erosion are issues with serious economic and social impacts. Recent studies have aimed at understanding and quantifying changes in the surge climatology and, in particular, surge extremes. Such studies usually require model simulations extending over many decades. An initial requirement is to validate the capability of the model to realistically reproduce the storm surges and to evaluate whether the model performance is robust over runs of long duration.

In this study, a regional ocean model ROMS was validated against observations in a short and long term study. For the short term validation, the ROMS model is shown to be capable of reproducing the general surge variation, especially in the south Irish Sea. However, due to the systematic under-prediction of the wind strengths in the ERA-40 data and the coarse temporal frequency (6-hourly) of the driving data, the simulated surge in the north Irish Sea has a relatively large error. To improve the accuracy of the simulations, and especially to capture the peak values, it is important to have accurate wind data for driving the model.

For the long-term validation run, comparison against station data show that the model is able to reproduce the surge variability with reasonable accuracy (order of 10 cm) over the chosen area. It also performs well when validated against satellite altimetry data corrected with the MOG2D-G model; time series values from both datasets show high correlation around Irish coastal areas and the Irish Sea, except in the northwest region. These results show that the ROMS model is reliable and suitable for studies of surge climatology in Irish waters.

For the climate change study, the ROMS model was run for two 30 year time-slice periods (1961-1990 and 2031-2060), forced by hourly meteorological data produced by dynamically downscaling ECHAM5/OM1 A1B scenario data using the Rossby Center Regional climate model.

Analysis of the results shows that storm surge heights in the range 50-100 cm are likely to increase in frequency around all Irish coastal areas; up to 30% in the northwest. Extreme surges also show an increase in most areas, particularly along the west coast, with most of the extreme surges occurring in wintertime. Changes in extreme surge heights also appear to be related to changes in extreme wind speeds and mean sea level pressure. There are also significant changes in the return values of surge heights.

This study has been based on a single future scenario from an AOGCM. Uncertainty in the atmospheric forcing data will be reflected in the surge outputs. To quantify this uncertainty the study needs to be repeated using other AOGCM scenario data.

Acknowledgments

Dynamic Atmospheric Corrections were produced by CLS Space Oceanography Division using the MOG2D model from Legos. The altimeter products were produced by SSALTO/DUACS and distributed by AVISO, with support from CNES. The tide gauge data were provided by the British Oceanographic Data Center.



4 The impact of climate change on Atlantic Wave Heights

Ocean waves are primarily produced by surface winds, and extreme wave heights are associated with intense weather systems. It is essential that such weather features are realistically simulated by the climate models, if the data are to be used to investigate the influence of climate change on the wave climatology. As in the case of storm surges, wind data from global climate models (AOGCMs) are not suitable for this purpose as they are too coarse-grained. Here, a regional climate modelling approach is used; the global data are dynamically downscaled onto a finer grid covering an area large enough to support the application. The output winds are then used to drive a state-of-the-art wave model.

While the primary focus of this study is on the coastal regions around Ireland, the area over which the simulations are performed needs to be chosen carefully; local swell, for example, can often originate from distant storms. As there is no information on sea/swell energy at the boundaries, it is assumed that no energy flows into the area from the outside, a strategy that is justified by experimentation with the simulation area. Ideally, as large an area as possible, covering the North Atlantic, should be chosen but the computational costs associated with running the models make this unrealistic. The eventual choice was determined by running a 1-year simulation on two areas in the current climate and using observed wave heights to evaluate the outputs.

To investigate climate change, two 30-year simulations were performed (1961-1990, 2031-2060). Preliminary results show that the impacts on monthly mean wave heights are seasonally dependent: there is some evidence of significant increases in some months. Extreme wave heights show an increase of up to 10%, except in parts of the south and west.

1 Model description and setup

The wave model used in this study is the ECMWF third generation Wave Model (ECWAM – see the ECMWF IFS 2007 documentation for a full description). The model computes the evolution of the two-dimensional wave spectrum explicitly through integration of the spectral energy balance equation. Model wave spectra have 30 frequencies, logarithmically spaced from 0.04177 to 0.66265 Hz, over 24 equally spaced geographical directions. Bathymetry data are taken from the 2-Minute Gridded Global Relief Data (ETOPO2) database at a resolution of 2 minutes of latitude and longitude.

ECWAM can be run either as a global model or over a limited domain. In the case of the latter the geographical boundaries become an issue in future climate simulations as the global climate models do not provide information on wave energy; influences outside the region must be ignored and no energy allowed to flow into the region.

For the selection of an appropriate domain area for running ECWAM, wind fields at 6-hour intervals from the ECMWF ERA-40 reanalysis data (Uppala et al., 2005) were used. For the main climate impact study, global ECHAM5/OM1 data for the past (1961-1990) and future (2031-2060; A1B greenhouse gas scenario) were downscaled using RCA3 onto the selected domain; the wind fields, available at 1-hour intervals, were used to drive ECWAM.

2 Choice of a simulation area/resolution

Two domains, shown in Figure 1, were chosen for experimentation: domain1 – covering most of the North Atlantic – and domain2, a subset of domain1. Three simulations, designated as EXP1, EXP2 and EXP3, were run with ECWAM for a 1-year period in 2001, using wind data from the ERA-40 archive: EXP1 and EXP2 were run on the larger area with a horizontal resolution of 0.5° and 0.25° respectively; EXP3 was run on the smaller area with the same resolution as EXP2 (0.25°).

To confirm the validity of this approach the ECMWF re-analysis wave data were used. The data, available on a 1.5° grid, are linked to the atmospheric re-analysis archive (the ERA-40 reanalysis system used a coupled atmosphere-wave model). While of high quality, it is known that wave heights are underestimated for medium to large values (Caires and Sterl, 2005).

Figure 2 shows the monthly mean ERA-40 significant wave heights for January and July, 2001, together with the corresponding results from the EXP1, EXP2 and EXP3 simulations. EXP2 and EXP3 produce very similar results. Away from the boundaries the agreement with the ERA-40 reanalysis wave heights is reasonable although the maximum significant wave height is slightly underestimated. The simulated wave height in the Caribbean area is not well captured compared with the high latitudes of the North Atlantic area, probably due to the zero inward energy flux requirement at the lateral boundary. It may also be due to errors in the bathymetry data (experience with the ROMS ocean model showed that these data are not very reliable in some shallow coastal areas). Comparing the outputs from EXP1 and EXP2 shows that the model resolution does not have a significant effect on the wave height simulation.

Comparing the results from EXP3 with EXP2 shows that, away from the boundaries, there is good agreement between the simulations, but the maximum wave height is also slightly underestimated. This is to be expected as the smaller domain will exclude more energy propagated by long-period swells in the North Atlantic, compared with the larger domain.

Figure 3 shows the time evolution of the wave heights at seven arbitrary locations (shown in Figure 1). In the southern part of the model domain (STA1 to STA3), the wave height is seriously underestimated, especially for the smaller domain. For the other locations, the simulations are consistent with the ERA-40 simulations, except that some of the peak values are slightly underestimated. The results confirm that the EXP3 simulation is a good template to use in assessing the impact of future climate change.

Use of 6-hourly wind fields to drive the wave model is probably too crude to capture fast moving cyclone systems or extreme events. For the future climate simulations, hourly wind fields, provided by the regional climate model, are used.

3 The effect of climate change on the wave height

Figure 4 shows the changes in the monthly mean significant wave height for different months. The spatial distribution of the changes is quite variable and dependent on the month. The most pronounced increases occur in January and October, while decreases are more prominent in March and April (reaching around 30 cm around Ireland). For other months, the changes are smaller and around 10 cm, in good agreement with the variation of the wind speed (not shown). Averaged over the whole year, differences are generally below 2 cm.

Figure 1 Experiment domains.

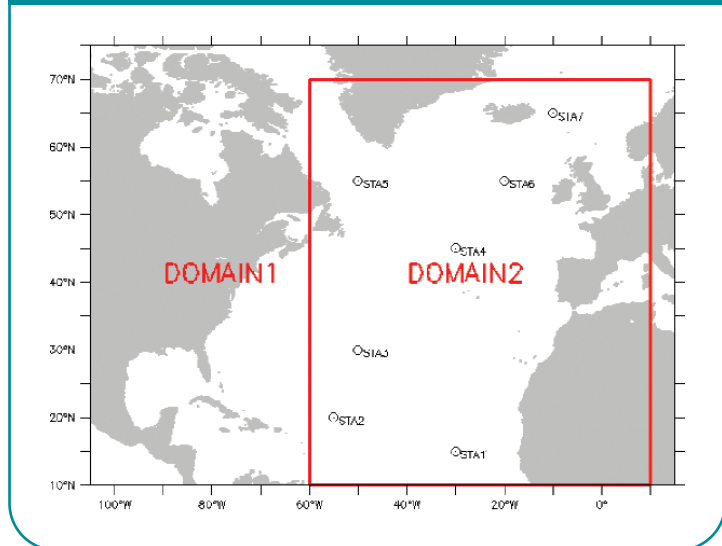
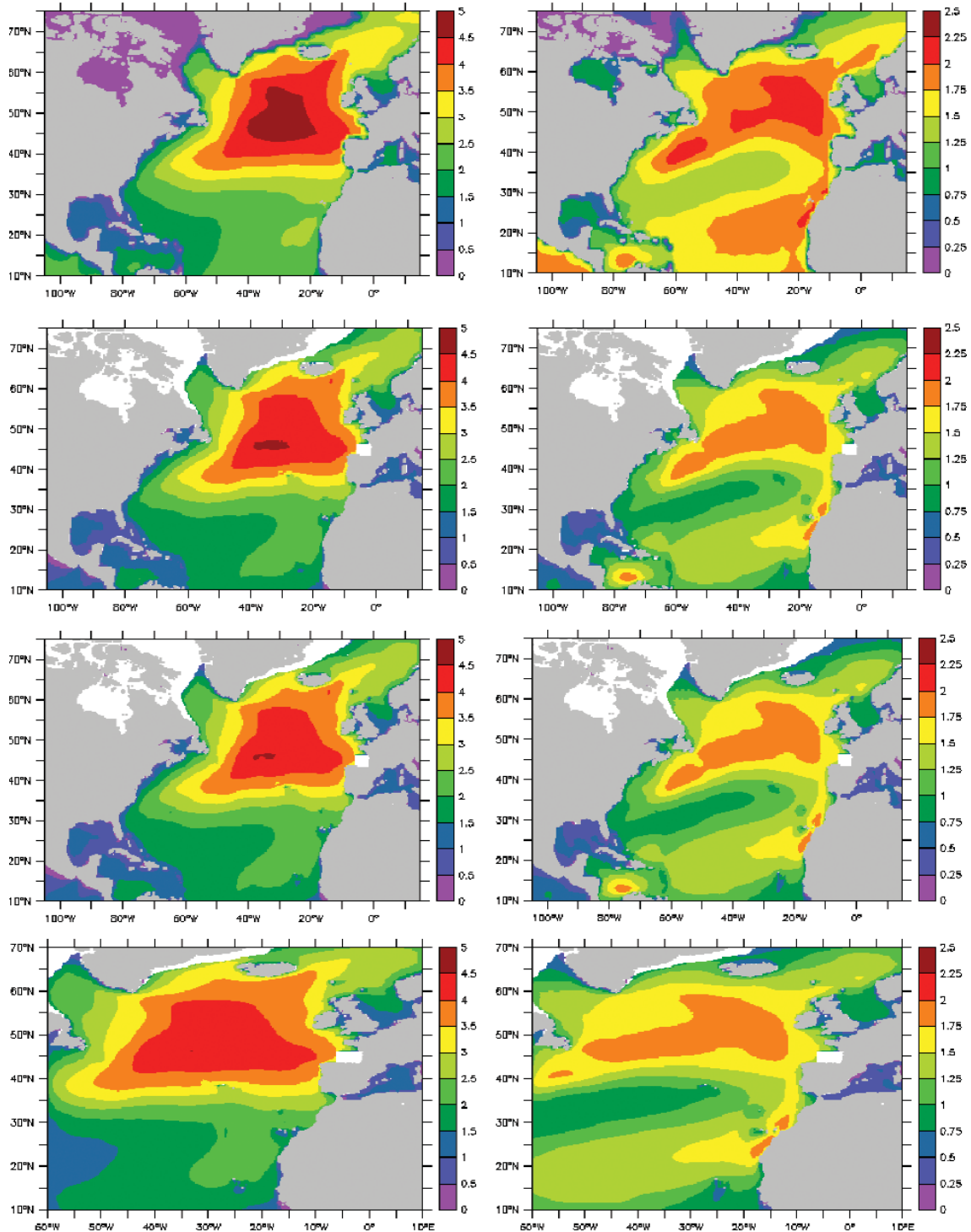


Figure 2 Top row: ERA-40 monthly mean significant wave heights for January (left) and July (right), 2001. The remaining rows, in sequence, show the corresponding results for simulations over the large area for EXP1, EXP2, and for the smaller area for EXP3.



For the extreme events, Figure 5 shows the relative changes in the 10-year return values of the annual maximum significant wave height between the future and past. Changes of 20-30% are notable over the central and southern parts of the area. Around Irish waters, the simulations suggest increases up to 10%, except in parts of the south and west, which show slight decreases. There is some consistency between these results and the corresponding results for extreme storm surges (see chapter 3 in this report); however, in some western coastal areas the simulations show a slight increase in extreme surge heights but a slight decrease in the extreme wave heights over the same period. Differences are to be expected as storm surge is mostly dependent on the surface pressure and wind fields, while

Figure 3 Time series plots: STA1-4 (left panel: top to bottom); STA5-7 (right panel: top to bottom).

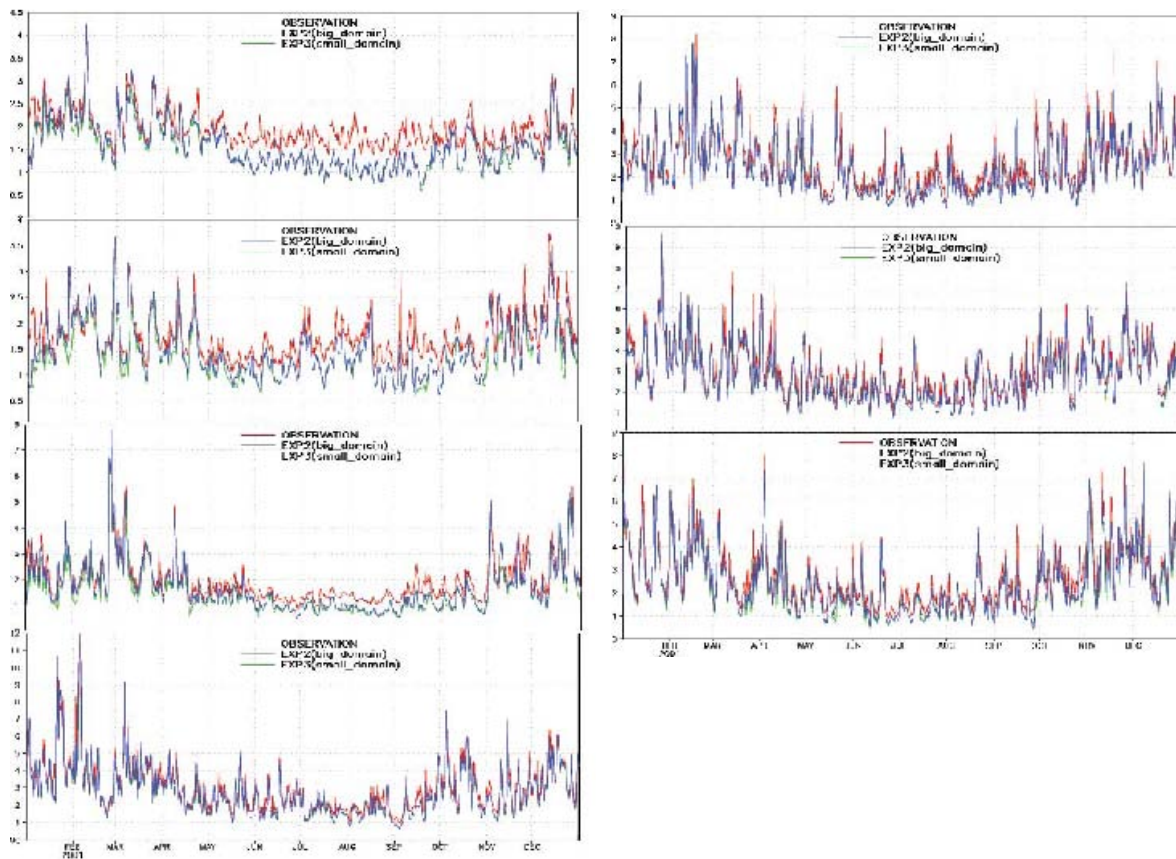
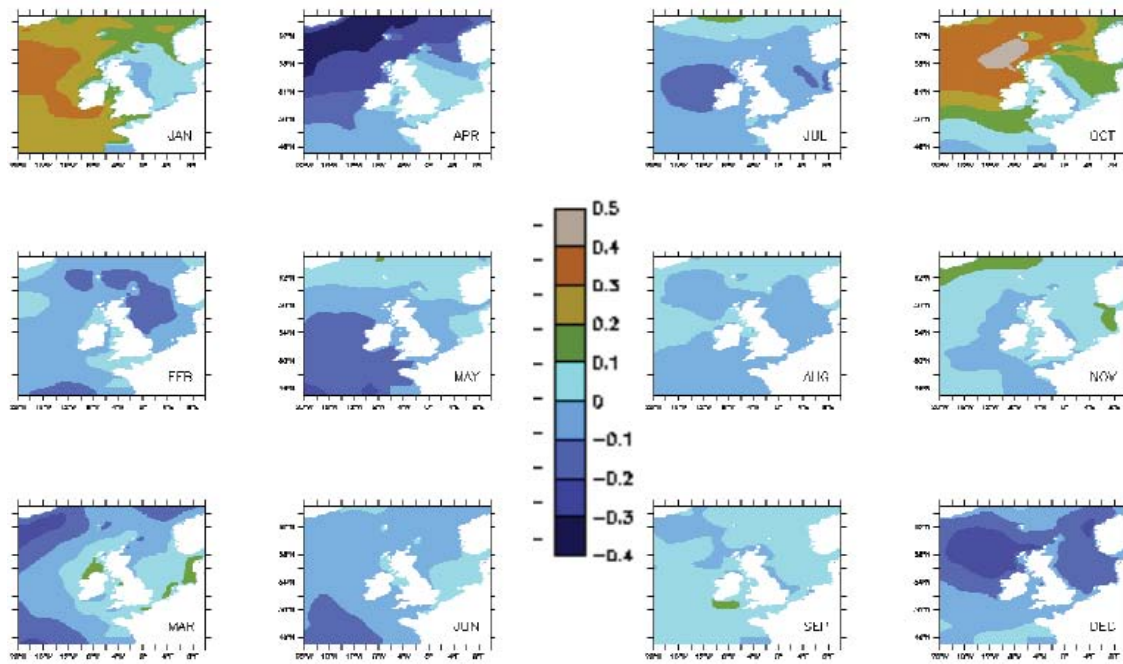


Figure 4 Changes in the monthly mean significant wave height (in meters) between the future (2031-2060) and past (1961-1990) simulations, for each month.

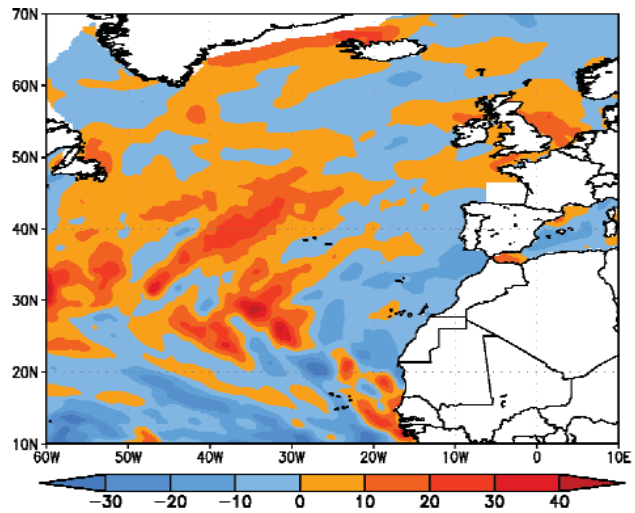


wave heights are dependent mostly on surface winds. Furthermore, extreme wave heights can respond quickly to extreme wind speeds while the storm surge needs more time to build up.

These results are based on the data from one AOGCM and one future greenhouse gas emission scenario and should therefore be treated with caution. Also, the resolution of the data (0.25°) is too coarse for a detailed analysis around the Irish coastline. In spite of these limitations, the basic data do provide a qualitative description of the possible impacts of climate change on wave heights around Irish coastal waters.

To support a more refined analysis, wave spectra from the model run were saved over a subset of the main area allowing an option to run a high resolution (~0.05°) simulation in the future. This work is being done by the Coastal & Marine Resources Centre (CMRC), University College Cork, in collaboration with Met Éireann.

Figure 5 *Relative changes (%) in the 10-year return value of annual maximum significant wave height between the future (2031-2060) and past (1961-1990) control run.*





5 On the impact of an increased sea surface temperature on storminess

Ireland's climate is heavily influenced by the North Atlantic Ocean. As sea surface temperatures (SST) are projected to rise due to global warming the impact on cyclone activity is investigated using two pairs of climate simulations performed with the Rossby Centre regional climate model RCA3. The results show an increase in the frequency of the very intense cyclones with maximum wind speeds of more than 30 m/s, and also increases in the extreme values of wind and (around Ireland) precipitation associated with the cyclones. This will translate into an increased risk of storm damage and flooding, with elevated storm surges along Irish coasts.

1 Introduction

The warming of the Earth's atmosphere in recent decades is a noticeable feature of climate change. The oceans are also warming, and while the temperature changes are more subdued relative to the atmosphere, the net heat uptake by the oceans considerably exceeds that of the atmosphere. This warming is predicted to continue into the future in most regions (IPCC, 2007). The increase in SSTs, and the associated increase in atmospheric moisture, may increase the intensity or frequency of cyclones with possible consequences for the Irish climate. Also, the environment may become more favorable for tropical cyclones to survive into higher latitudes, raising the possibility that Western Europe could be affected by a larger number of transitioned tropical cyclones. For these reasons it is very relevant to study changes induced purely by increased SSTs as well as changes induced by other factors.

The influence of SST on the development of extratropical and tropical cyclones has been studied widely. Gyakum and Danielson (2000) found that the combination of warm SST anomalies with cold air masses over the Western North Pacific leads to enhanced sensible and latent heat fluxes from the ocean into the atmosphere, favoring explosive cyclogenesis. According to Sanders and Gyakum (1980) explosive extratropical cyclogenesis is found preferably over regions with strong SST gradients. Emanuel (1987) showed that the maximum possible pressure drop towards the eye of a hurricane can be expressed as a function of the SST, the ambient relative humidity and the thermodynamic efficiency, which is proportional to the difference between the SST and a weighted mean temperature in the upper atmosphere. These studies, and many others, suggest that the SST is one of the key factors influencing the development of cyclones.

The topic has attracted a lot of scientific investigation, with AOGCMs providing a useful investigative tool. However, the results are dependent on the methodology and the AOGCM used (König *et al.*, 1993, Hall *et al.*, 1994, Zhang and Wang, 1997, Sinclair and Watterson, 1999). It is very important to reduce these uncertainties to achieve a better understanding of cyclone characteristics in a future climate.

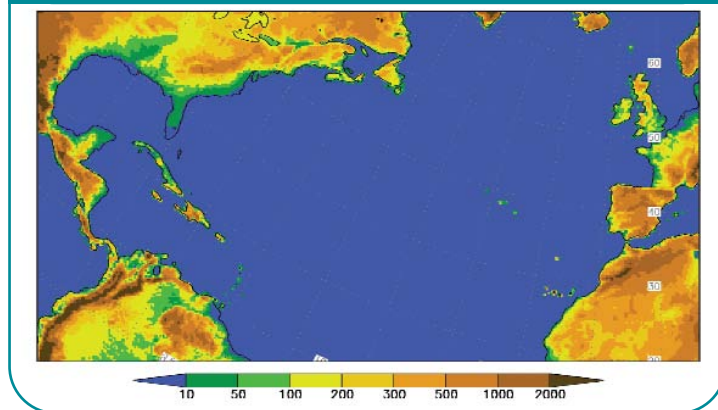
2 Model setup

In this study the regional climate model RCA3 (Rossby Centre regional Atmospheric Climate model version 3) (Kjellström *et al.*, 2005; Jones *et al.*, 2004) is used on a model domain including large parts of the North Atlantic to allow the increased SST to have an impact on the development of cyclones. Western Europe and North West Africa are included in the east of the model domain with Ireland, the UK and the Iberian Peninsula being far enough away from the lateral boundaries (Figure 1). The area is sufficiently large, particularly in the western side of the domain, to allow the simulation of tropical cyclones making landfall or travelling across the North Atlantic towards Western Europe while transforming into extratropical cyclones.

Two pairs of simulations were performed for the period May to December 1985 to 2000. The first pair was driven by the 40-year reanalysis data (ERA-40: Uppala *et al.*, 2005) from the European Centre for Medium-Range Weather Forecasts

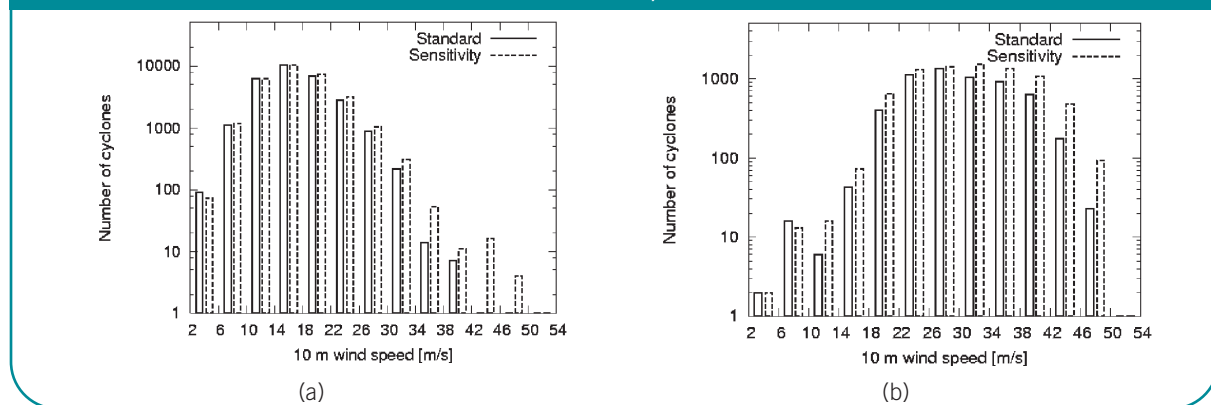
(ECMWF) at the lateral and lower boundaries. The model was initialized each year on the 1st of May and continuously run until the end of December to ensure that we simulate the strongest tropical storms and their journey across the North Atlantic, including their transition into extratropical storms. The model was run on a rotated latitude/longitude grid with a horizontal resolution of 0.25° (around 28 km) with 31 non-equally spaced vertical levels. One simulation of the first pair used the original SST from ERA-40 as lower boundary values (standard experiment), whereas the other one used an SST increased by 1K (sensitivity experiment). In the sensitivity experiment the atmospheric temperature was increased by 1K in the lateral boundary data at all model levels to maintain the vertical structure of the atmosphere. The specific humidity was also increased such that the relative humidity remained the same as in the standard experiment at all model levels. According to model projections (Knutson and Tuleya, 2004) it is realistic to assume the relative humidity in a warmer climate will be similar to the one observed today, whereas the vertical temperature structure is likely to change.

Figure 1 Orography [m] in the simulation domain.



The second pair of simulations was run on the same model domain, driven by data from the AOGCM ECHAM5-OM1 (Roeckner et al., 2003) from May to December 1985-2000 (control experiment), and from May to December 2085-2100 assuming the SRES A2 emission scenario (scenario experiment). This second pair of simulations was carried out to investigate differences to the idealized first pair, which could arise from changes in the general circulation, the vertical structure of the atmosphere, or the spatial pattern of SST.

Figure 2 Total number of (a) extratropical and (b) tropical cyclones in the standard and sensitivity experiment for simulation period May to December 1985-2000. All cyclones are counted using 3-hour model outputs and categorized in intensity classes with a width of 4 m/s maximum wind speed (first class: 2-6 m/s).

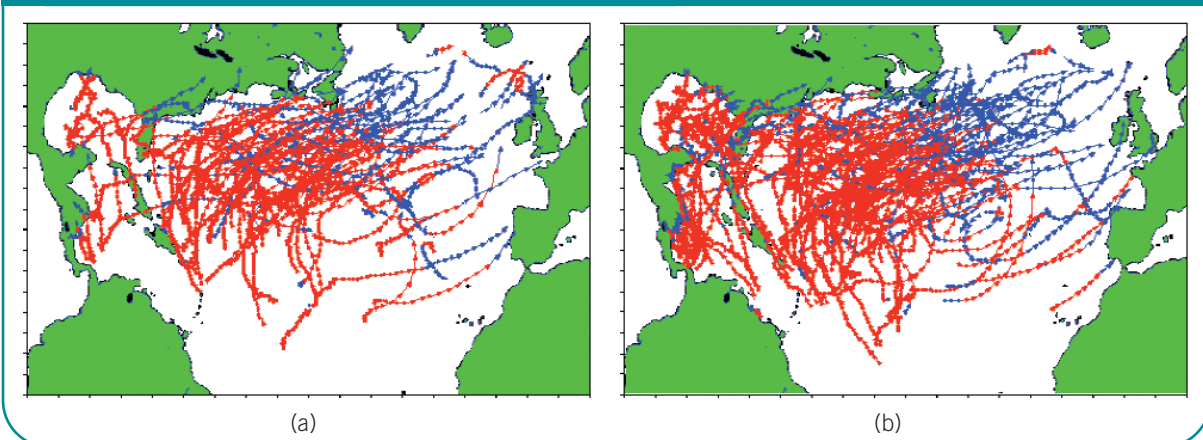


3 Results

3.1 Standard/sensitivity experiments

Figure 2 shows the number of extratropical and tropical cyclones grouped into intensity classes for the standard and the sensitivity experiment. All cyclones were counted using 3-hour model outputs. The frequency of the less intense extratropical cyclones does not change very much with increasing SST while the occurrence of more intense extratropical cyclones is increased. An increase in the number of tropical cyclones can be seen in nearly all intensity classes, except for the weak classes. For cyclones with maximum wind speeds exceeding 18 m/s, the increase due to the enhanced SST is 9% for the major extratropical cyclones and 39% for the tropical ones. The differences are most evident in the very strong intensity classes. The number of extratropical cyclones attaining maximum wind speeds of more than 30 m/s in the standard and the sensitivity experiment are 240 and 387 respectively. The number of hurricanes with wind speeds of more than 42 m/s (category 2 on the Saffir-Simpson Hurricane Scale) increases from 196 to 570.

Figure 3 Cyclone tracks of storms with maximum wind speed exceeding 18 m/s undergoing extratropical transition during their lifetime: (a) the standard experiment; (b) the sensitivity experiment. (Red arrows - cyclone classified as tropical; blue arrows - cyclone classified as extratropical). Only cyclones which sustain a minimum wind speed of 18 m/s over at least two time steps are tracked. The simulation period is May to December 1985-2000.

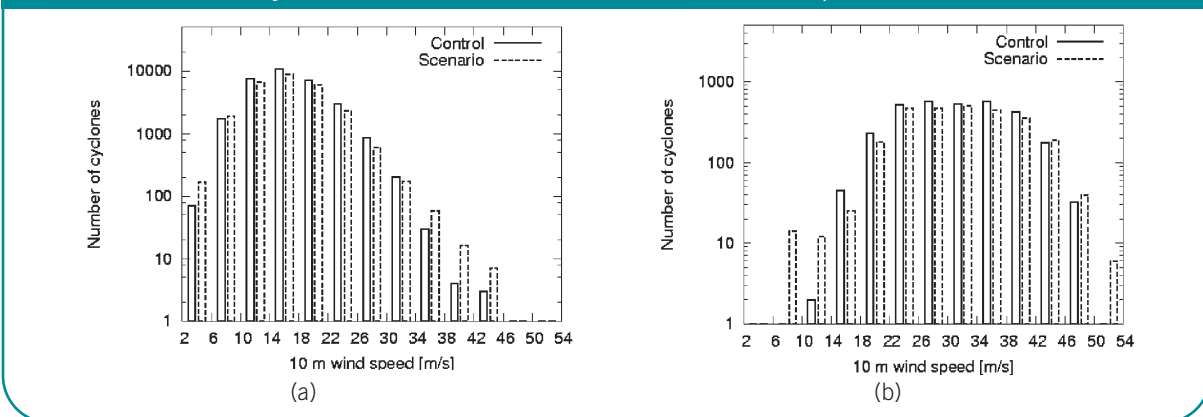


The simulations also show that under enhanced SST more tropical cyclones undergo extratropical transition when they move from tropical to extratropical regions (48% in the sensitivity experiment, compared to 44% in the standard experiment) and that substantially more cyclones re-intensify after their extratropical transition (24% compared to 12%). With a warmer ocean more major cyclones of tropical origin reach the vicinity of Western Europe (Figure 3).

3.2 Control/scenario experiments

Both experiments are based on downscaled ECHAM5-OM1 data: the scenario experiment covers the period 2085-2100 (A2 emission), where factors other than the SST are considered; the control experiment is the period 1985-2000. In the future simulation the number of extratropical cyclones decreases for many intensity classes compared to the control run (Figure 4). However, for intensity classes beyond 34 m/s the scenario experiment shows increases in the extratropical cyclone numbers, although these increases are smaller than in the first pair of experiments. Because of a weakening of the warm North Atlantic current (the extension of the Gulf stream) according to the ECHAM5-OM1 simulation the SST does not increase very much over the northeastern part of the Atlantic – in a small region southwest of Ireland and northwest of Spain it even mildly decreases (Figure 5). But even in the region of tropical cyclones, where the SST clearly increases by more than 2 K in large regions, the frequency of intermediate and strong cyclones with maximum wind speeds of up to 42 m/s slightly decreases. However, the frequency of the very strong cyclones with maximum wind speeds of more than 42 m/s still increases, as does the maximum intensity: in the scenario experiment the maximum wind speed exceeds 50 m/s which is not the case in the control experiment.

Figure 4 Total number of (a) extratropical and (b) tropical cyclones as in the control experiment for May to December 1985-2000 and in the scenario experiment for May to December 2085-2100. All cyclones are counted using 3-hour model outputs and categorized in intensity classes with a width of 4 m/s maximum wind speed (first class: 2-6 m/s).



Comparing the AOGCM-based and idealized experiment pairs, the reason for the relative decrease in the frequency of cyclones with intermediate intensity, and the slightly lesser increase in the frequency of the very intense cyclones, lies in changes of the vertical structure of the atmosphere. All over the North Atlantic a strong warming of up to 6° C is simulated to a height of about 5 km in the AOGCM simulation, whereas the surface warming as depicted in Figure 5 is clearly smaller. This means that the atmosphere is becoming more stable. Nevertheless, an increase in the frequency of severe storms is evident.

In terms of the proportion of cyclones undergoing extratropical transition while travelling from tropical to extratropical regions, a 2% increase is found similar to the first pair of experiments. 49% of all tropical cyclones undergo extratropical transition in the scenario experiment compared to 47% in the control. Furthermore, in the scenario experiment 24% of the cyclones re-intensify after their extratropical transition compared to 15% in the control, which is again consistent with the first pair of experiments. It is worth noting that not only the maximum wind speed related to intense cyclones is increasing; the extreme precipitation is also intensifying in some regions (Gulf of Mexico and Caribbean Sea areas but also around Ireland), and weakening over others. Figure 6 shows the ratio of the 99.9 percentile of daily precipitation from the second AOGCM-driven pair of experiments. Values exceeding (less than) 1 indicate an increase (decrease) in extreme precipitation.

Figure 5 Difference in the underlying SST: scenario experiment (ECHAM5-A2 driven, May to December 2085-2100) minus control experiment (ECHAM5 driven, May to December 1985-2000).

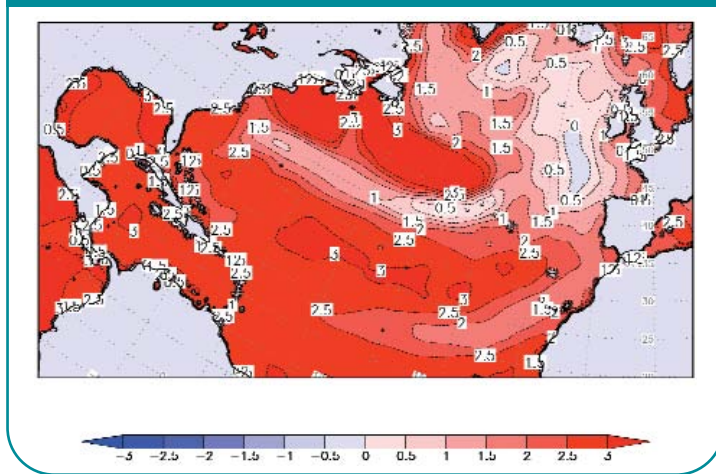
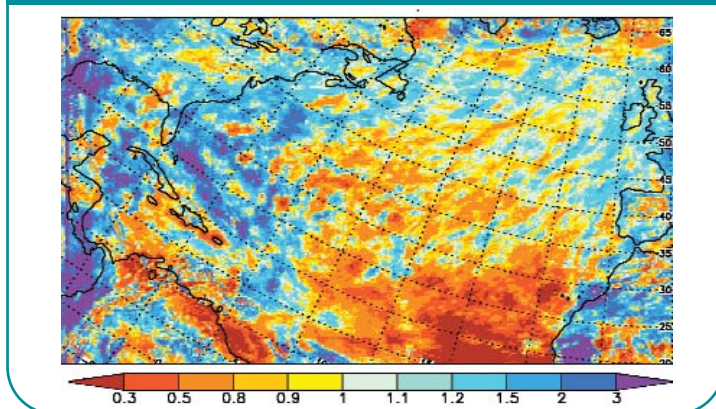


Figure 6 Ratio of the 99.9 percentile of daily precipitation (scenario experiment divided by control experiment).



4 Conclusions

With numerous interacting components running on different timescales, it is difficult to isolate the influence of a single element in the climate system. This study has focused on the influence of SST on the frequency and intensity of cyclones in the North Atlantic by running an idealised experiment with elevated SST values, using a regional climate model. The results have been compared with a more conventional downscaling experiment using current/future AOGCM scenario data.

While there are differences between the results, (which can be attributed to differences in the vertical structure of the atmosphere), the study confirms the important role of SST in cyclone development, particularly for Ireland: a warming ocean will increase the frequency of very intense cyclones, with corresponding increases in the extreme values of precipitation.



6 Observed trends in sea temperature and sea level around Ireland

Sea temperature and sea level around Irish coastlines have been rising slowly in recent decades. Since the 1980s satellite and *in situ* coastal observations show a general warming trend of 0.3-0.4°C per decade in Irish waters, mirroring temperature trends over land. However, over the Irish Sea the satellite measurements suggest a more rapid warming rate (0.6-0.7°C per decade). The trends are consistent with what has been observed globally and are predicted to continue over the coming decades with possibly large impacts on marine ecology.

Rising sea levels in recent decades are primarily linked to the warming of the oceans and resulting thermal expansion of seawater, and the influx of water from melting land ice. Satellite measurements show that sea levels are rising on average about 3.5 cm per decade around Ireland, well in excess of any ongoing isostatic adjustment of the land. This trend will continue in line with rising sea temperatures and will increase the risk of flooding in low-lying coastal areas and accelerate the erosion of vulnerable soft coastlines and wetlands.

Changes in sea level will also worsen the impacts of changing storm surge and wave patterns in coastal areas (see articles in this report) and may also affect water tables through salt intrusion.

Introduction

The net heat uptake by the oceans since 1960 is about 20 times that of the atmosphere (IPCC, 2007) i.e. most of the heat energy associated with global warming has found its way into the oceans. The expansion of the water in response to the heat and the influx of fresh water due to the melting of land-based ice and snow, contribute in roughly equal measure to rising sea levels (changes in salinity also play a minor part). Globally, this has led to an average sea level rise of 3.5 mm per year in 1993-2003, compared to 1.8 mm per year between 1960 and 2003. There are large regional variations.

The aim of this study was to investigate what trends have been observed in both sea level and sea surface temperature (SST) around Ireland in recent decades. Both satellite and *in situ* observations were used, where available. Each type of observation technique has its own error and bias characteristics, which is reflected in the range of estimates presented here.

Data

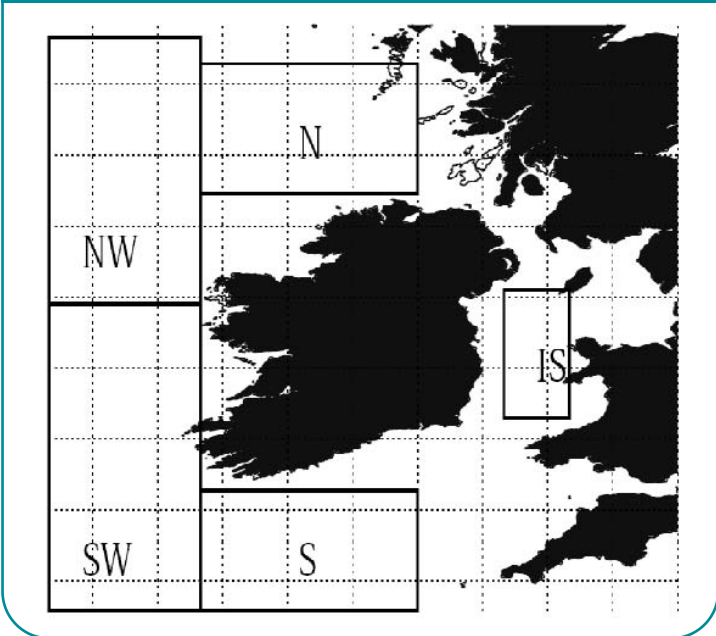
Sea surface height

Sea surface heights measured from satellites were analysed to investigate changes in sea level. The height of the sea surface as observed by satellites can change on scales of tens to hundreds of years due to thermal expansion or changes in large scale circulation. There is a strong signal with a period of one year, due to expansion and contraction of the water column with seasonal changes in water temperature. Higher frequency changes (with periods from hours to months) are also observed due to tides, ocean eddies and atmospheric weather systems.

Sea surface height anomalies (SSHA), observed by satellite-borne altimeters and processed by the SSALTO/ DUACS (Segment Sol multimissions d'ALTimétrie, d'Orbitographie et de localisation précise/Data Unification and Altimeter

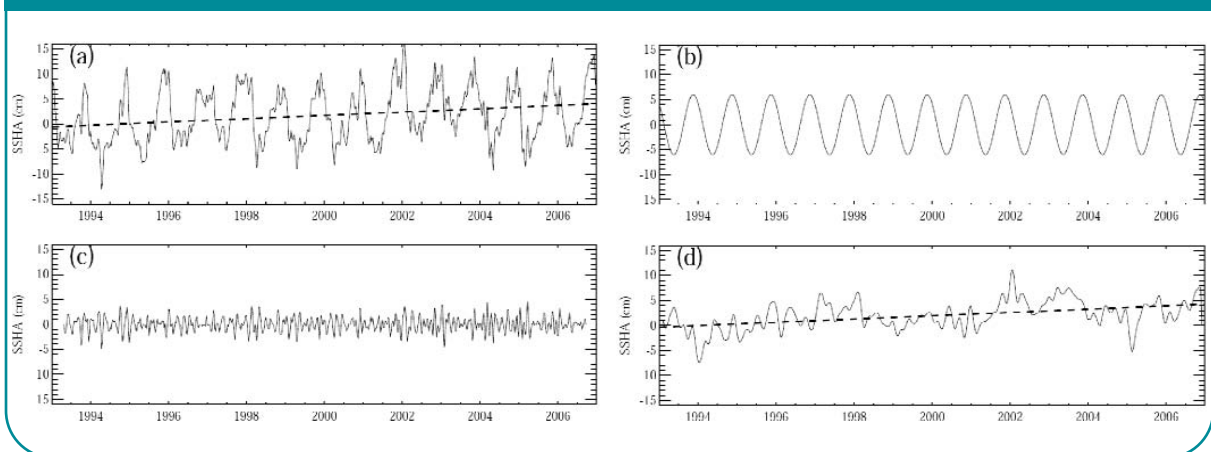
Combination System) were used in this study. This processing gives the most accurate estimate of the sea surface by merging data from a number of satellites and applying consistent corrections for various sources of error identified for each satellite platform (Le Traon et al., 1998). Models of height changes due to ocean tides and atmospheric signals are used to correct for tidal and inverse barometric effects (Carrere and Lyard, 2003). The resulting 'reference' data product was used in this analysis as it is the most stable and consistent in time and is available over 14 years. Data are available once a week over the global oceans on a $1/3^\circ$ latitude/longitude grid. The areas studied here covered Atlantic areas to the north, south, northwest and southwest of Ireland and the Irish Sea, as indicated in Figure 1.

Figure 1 Sea areas studied: northern (N), northwestern (NW), southwestern (SW) and southern (S) Atlantic coasts and the Irish Sea (IS).



The sea surface height anomaly is calculated as the difference between the observed sea surface height and the long term mean at the location of each gridpoint. This removes signals due to changes in bottom topography, for example, which would otherwise be aliased into the results. The long term mean for these data was calculated over the period from January 1993 to December 1999 for the reference satellite, so the sea surface height anomalies plotted in Figure 2 can be interpreted as changes in the mean sea surface height over the region relative to mid-1996.

Figure 2 a) Total, b) annual, c) high frequency and d) interannual sea surface height anomaly signal from 1993-2006 for the northern region.



Sea surface temperature

Two sets of data were analysed for SST trends: water temperature observations from the Met Éireann Malin Head synoptic station; and merged satellite-observed SSTs over the region. The synoptic observations are available since 1958, and are very valuable in providing a continuous, long-term record of temperatures at the same location. The merged SSTs are only available since 1982, but they provide SST at regular intervals on a global grid, giving additional spatial information.

The shore-based Malin Head observations have been made in different ways over the years as techniques and instrumentation developed, so careful analysis was required to ensure that an appropriate time series was used for

the deduction of trends over the period. Up until 1991, a thermometer was lowered into a well in the pier at Malin Head, which was connected by a pipe to the water outside. From 1991 to the present day, two techniques have been used at different times. One involved lowering an electronic temperature sensor into the water beside the pier and the other involved measuring the temperature of seawater extracted by a bucket. Dual observations were made at various times to check for systematic differences with a view to homogenization of the data. The observations were also made at different times of day over the period in question, so only those made before 12:00pm (noon) were included here to limit the effects of diurnal heating. Some 12:00pm observations were, however, included when the number of morning observations per month was low (below 10). These were normalised using the mean ratio of the 12:00pm temperatures to the 10am temperatures per calendar month, calculated over the entire dataset. These ratios introduced differences of 0 to -5% in the 12:00pm observations. Observations have only been taken at 10am since 2002, so there is no possibility of diurnal heating biasing the temperatures in recent years. Unfortunately, the location of the observations also changed during the period: from a side of the pier open to the ocean to a shallower and more sheltered location. This change may have introduced a slight bias in the temperatures. In view of these issues, caution must be used in inferring trends from the data.

The Optimal Interpolation SST (OISST) data product is available from the NOAA Climate Diagnostics Centre on a global 1° longitude/latitude grid at weekly time intervals from October 1981 to present. The OISST is produced using input from both satellite sensors (the Advanced Very High Resolution Radiometer flying on the NOAA-n operational polar-orbiting series) and *in situ* observations from buoys and ships (Reynolds et al., 2002). While satellites provide excellent coverage in space and time, they measure the ‘skin’ temperature of the top millimeters of water. This can differ from the ‘bulk’ temperature at depths of centimeters to tens of meters, which would be comparable to the Malin Head water temperatures. The *in situ* observations are used to convert the satellite skin SST to a bulk SST. The dataset has been reprocessed to be as consistent as possible in time, removing sources of error such as differences in calibration between sensors on different satellite platforms and changing sensor response over time, which can introduce spurious trends. The spatial errors are largest in areas of sea ice or where the SST changes rapidly over a short distance, for example over the Gulf Stream; inadequate detection of cloud cover by the satellite will also impact on the quality of the data.

Trend analysis

Two methods were used to estimate trends from these datasets. As both SSHA and SST time series are dominated by an annual cycle, θ_A , (Figure 2 (b)) the trends can be calculated from either annual means or by estimating and removing the annual cycle, leaving the interannual variability (θ_I). Both time series also have a high frequency component (θ_H) reflecting changes in SST and SSHA from day to day or week to week.

$$\theta_T = \theta_A + \theta_I + \theta_H$$

The time series of each dataset were smoothed using a boxcar filter to estimate the interannual signal (θ_I). This was subtracted from the original time series to give the residual, θ_R , and the annual cycle was then estimated by a sine wave. The amplitude (A) and phase (φ) of the sine wave were determined iteratively by minimising θ_R :

The annual cycle determined was then subtracted from the total signal, to produce a signal composed of the interannual components. As the annual signal dominates over the interannual and high frequency components of the SST time series, contributing up to 90% of the observed variance, monthly means were used for those data; this smooths the high frequency component. The SSHA annual component only contributes 45-70% to the observed variance, so the interannual signal was digitally filtered with a cutoff of about 6 weeks to remove the high frequency component after the annual component had been removed for those data. The magnitudes of the three components of the SSHA are shown in Figure 2.

Results

Trends in sea surface height

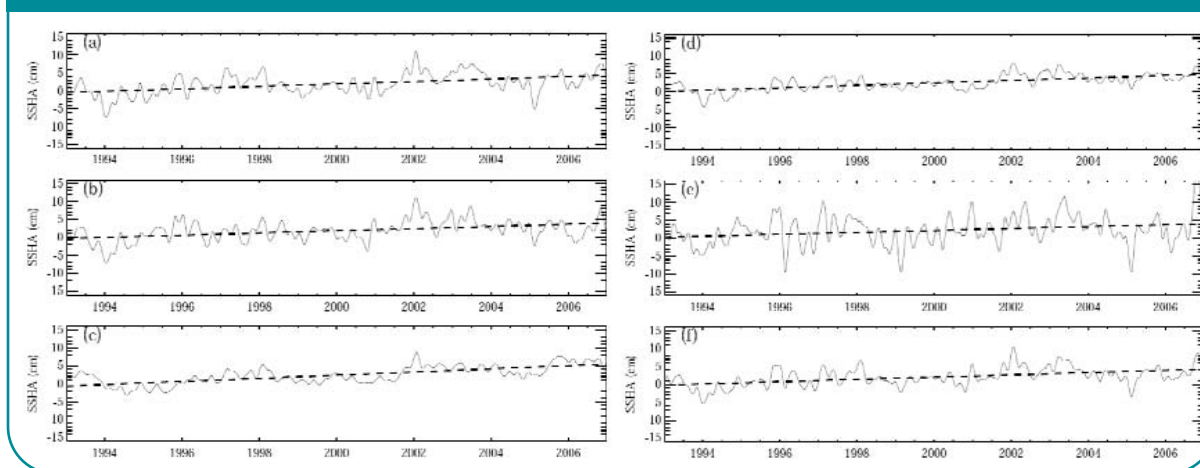
All regions show two main features in SSHA. First is an annual cycle, with amplitude of 6.9 to 23 cm (Table 1), the magnitude of which depends primarily on the mean water depth of the area. The annual cycle has a maximum in late autumn and a minimum in spring. It is primarily due to thermal expansion of seawater, following the annual cycle

in ocean temperature (Ferry *et al.*, 2000). The amplitude is larger on the continental shelf than in deeper water and largest in the shallow basin of the Irish Sea as the interaction of bottom topography with tides and currents adds to the surface variability. It should be noted that the tidal model used to remove the tidal component of the signal is less accurate in shallow water, so the errors are likely to be larger in shelf regions.

Table 1: Changes in sea level as measured by satellite altimetry for the regions indicated in Figure 1. The annual cycle has a maximum amplitude in late autumn (minimum in spring) and is primarily driven by the seasonal thermal expansion of seawater. The 'net trend' is the adjusted trend, allowing for the isostatic adjustment of the Earth's crust.

Region	Trend (mm/year)	Net trend (mm/year)	Annual Amplitude (cm)	Phase (week of year)
Northern	3.4	2.7 - 3.3	11.9	45
Northwestern	4.4	4.3 - 4.7	6.9	41
Southwestern	3.5	3.9 - 4.0	7.9	43
Southern	3.0	3.1 - 3.5	13.6	45
Irish Sea	2.7	2.3 - 2.7	23.0	45
All	3.1	3.3 - 3.6	11.2	44

Figure 3 Interannual sea surface height anomaly (solid lines) and trends (dashed line) for a) northern, b) southern, c) northwestern, d) southwestern, e) Irish Sea and f) all regions. All areas show a clear trend towards rising sea levels. See Table 1 for rates of sea level rise.



The second is highlighted in Figure 3, which shows the interannual signal (θ) for each region marked in Figure 1 and for all data available in the region depicted in Figure 1. The dashed line is a least squares fit to the 14 year dataset, showing a trend to positive sea surface height anomalies, i.e. rising sea level. The trends for each region are summarised in the first column of Table 1 and range from 2.7 mm/year in the Irish Sea to 4.4 mm/year in the northwest. The magnitude of the contribution of each component to the overall variance is outlined in Table 2. The annual signal is dominant, contributing 46-71%, followed by the interannual signal (23-36%). The high frequency component accounts for 4-14% of the variability in the open ocean areas, but increases to 27%, equal to the interannual component, in the semi-enclosed Irish Sea.

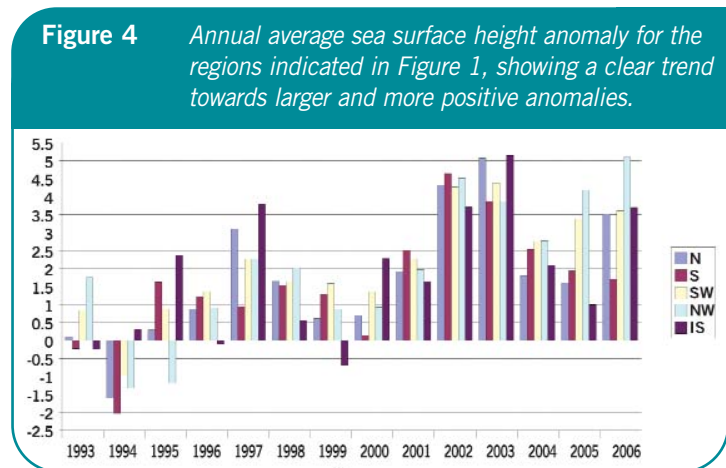
Table 2: Percentage of variance explained by each component of the total sea surface height anomaly signal

Region	Annual (%)	Interannual (%)	High Frequency (%)
North	65	26	9
Northwestern	60	36	4
South	59	27	14
Southwestern	71	23	6
Irish Sea	46	27	27

An issue arises with the use of satellite data to measure SSHA, as the continental crust is undergoing post-glacial adjustments following the last ice age. Northern coastlines are experiencing isostatic rebound and are still rising in adjustment to the loss of weight following the retreat of the ice sheet, whereas the southern and southwestern part of the country is subsiding in compensation.

The change in 'relative' sea level at the coast, as observed by tide gauges, will differ from the 'absolute' change observed by satellites as a result of this vertical land movement. The second column of Table 1 gives the change in relative sea level, taking isostatic rebound into account as estimated by Brooks et al (2008): coasts on the northern and eastern seaboard are rising, in general, at a rate of ~ 0.7 mm/year in the northeast, while coasts on the western and southern seaboards are subsiding, with a maximum rate of approximately -0.5 mm/year in the southwest. Note that the land effects are small: only about 10% that of the steady rise observed in sea level.

Another way of deducing trends from datasets with significant annual cycles is to look at annual averages. Figure 4 shows the annual averages for each region over the 14 year period. It is clear that while the annual average anomalies were small and occasionally negative over the first half of the time series, they have been larger and consistently positive from 2000 through to 2006 for all areas. It is also clear that the different regions are well correlated and there is some evidence of a decadal scale oscillation affecting all ocean regions around Ireland. This decadal scale variation in North Atlantic sea surface height has been attributed to the North Atlantic Oscillation (Yan et al., 2004).



Trends in sea surface temperature

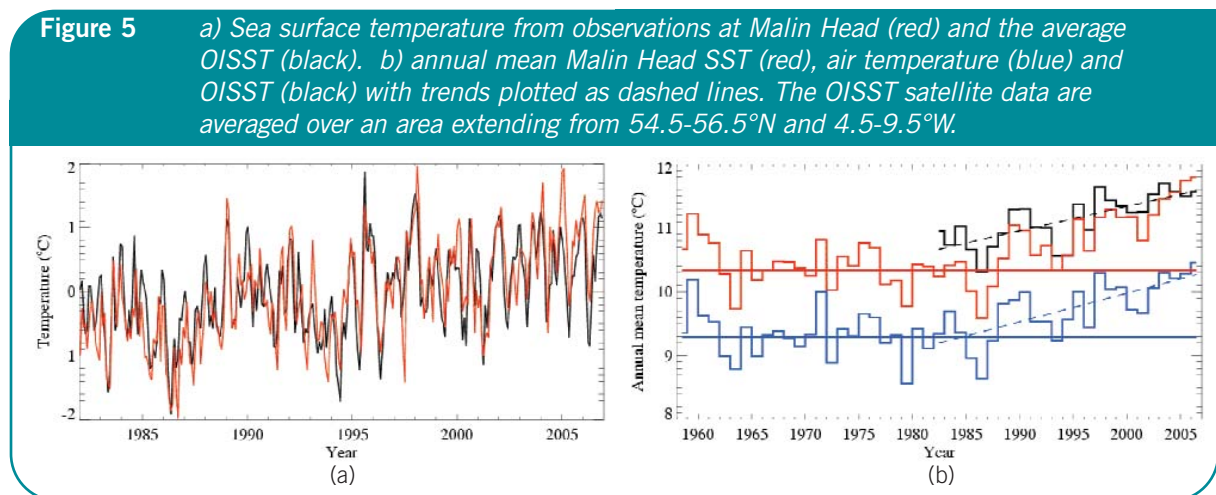


Figure 5(a) shows the interannual component of the Malin Head SST observations and the OISST for the period where they overlap (1982-2006, inclusive). The OISST value shown has been averaged over the area 54.5° to 56.5° latitude by 5° to 10° longitude, i.e. the entire northern seaboard. The plot shows a very good correlation between the two datasets both at monthly and decadal timescales. This shows that the temperature observed at the pier at Malin Head is forced by the same physical mechanisms as the ocean area to the north of Ireland.

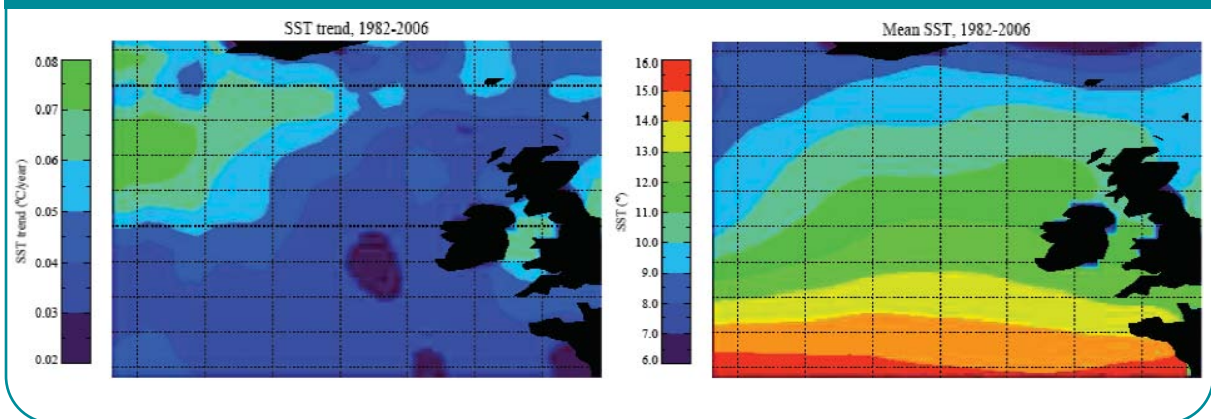
Figure 5(b) shows the full Malin Head record going back to 1958, with the 1960-1990 mean overlaid for comparison. The annual mean water temperature is in red, the annual mean air temperature is in blue and the OISST is in black. The positive trend in all temperatures in recent decades is very apparent, with water temperature

above the long term mean for all years since 1988. This is in stark comparison with the previous four decades, which show oscillations with 5-10 year cycles, but no significant trend. However, the OISST data do not show such a large trend in this area. This is apparent from Figure 5(b), where the trend as calculated from the annual averages is plotted as a dashed line, and Table 3. This trend is only 0.37°C/decade for the OISST, compared to 0.52°C/decade using the Malin Head temperatures. Only data from 1982 to 2001 were used to estimate the Malin Head temperature trend. After 2001, the temperatures increase much more rapidly than either the OISST or the air temperature. Due to the changes in location of the water temperature observation, the depth of the observation may have changed, and a slightly different water mass is sampled on the shallower, calmer side of the pier. Either of these changes may have biased the temperatures relative to the rest of the record, and could explain the apparent increase in the water temperature observation in recent years. The trend in air temperature falls between the two different water temperature estimates at 0.43°C/decade.

Table 3: Trends calculated from sea and air temperature observations at Malin Head and from the optimally interpolated SST from the CDC. The trends were calculated in two different ways, as outlined in the text. The spread in the results gives an indication of the level of statistical uncertainty involved in trend analysis, which is independent of the level of error in the original data.

Trend (°C/decade)	Annual mean	Interannual
Malin Head SST	0.52	0.54
Malin Head T _a	0.43	-
OISST	0.37	0.38

Figure 6 *Left: trends in satellite OISST from January 1982 to December 2006; right: mean sea surface temperature from the OISST data set.*



To look at the spatial trend patterns, the trend for all gridpoints was determined using the interannual method as described in section 2 from the 25 years of data available. This is shown in Figure 6(b) and ranges from 0.02 to 0.08°C/year over the northeast Atlantic area. Values of 0.03-0.04°C/year are seen over most of Irish territorial waters, with trends of up to 0.07°C/year in the Irish Sea. Higher values are also seen over the Iceland Basin, which lies south and southwest of Iceland, possibly due to shifts in the mean path of the Gulf Stream.

Discussion

The current rates of sea level rise, extrapolated over the coming decades, are consistent with global predictions from the IPCC (2007). However, these estimates may be conservative as they do not include current uncertainties in ice flow processes (melting glaciers, etc.). Changes in sea level will also worsen the impacts of changing storm surge and wave patterns in coastal areas (see articles in this report) and may also affect water tables through salt intrusion (Steinich et al., 1998).

The extrapolated OISST rates suggest that in 50 (100) years time the Atlantic Ocean around Ireland may be 1.75°C (3.5°C) warmer, compared with present day conditions; the corresponding figures for the Irish Sea are larger although other factors (e.g. currents) may come into play to reduce the development of a strong thermal gradient between the Sea and the Ocean. From the spatial pattern of the mean SST in Figure 6(a), we can see that conditions currently

experienced along the south coast of Ireland will be common along northern coasts, with southern coasts having conditions more similar to those currently common around Brittany. How such a shift in temperature will affect the marine life remains to be seen.

The output of three different runs of the Hadley Centre CM3 coupled ocean-atmosphere global climate model was analysed for comparison with these results over the same region. The three runs have been designed to span the anticipated range of climate sensitivity from low to high sensitivity and the third was run with unperturbed physics (Collins et al., 2006). Climate sensitivity refers to the level of response of the climate system to the expected rise in atmospheric temperature due to greenhouse gas emission. The unperturbed run represents the climate sensitivity as currently used in global climate models; the response is damped in the low sensitivity run and increased in the high sensitivity run. All three models show a decrease in SST in Irish waters from 1950 to 1980, followed by a steady rise in temperature till the end of this century. The unperturbed run lies between the high and low sensitivity runs, which predict temperature rises of 0.03° and 0.022°C per year respectively. As the observations show a minimum rise of 0.03-0.04°C per year since 1982 over the same area, this would suggest that the climate run with high sensitivity is more appropriate for this model, as it is more in line with observations. This has implications for the validity of the results of global climate modelling to date, as the changes that the models have been predicting will be underestimated if the climate sensitivity is higher than that used in the model physics.

Acknowledgements

The altimeter products were produced by Ssalto/Duacs and distributed by Aviso, with support from CNES. NOAA_OI_SST_V2 data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at <http://www.cdc.noaa.gov/>.

7 The impacts of climate change on hydrology in Ireland

A study of nine Irish catchments is carried out to quantify the expected impact of climate change on hydrology in Ireland. A regional climate model is used to generate downscaled AOGCM precipitation and temperature data, which in turn are used to drive a conceptual rainfall-runoff model (HBV-Light) to simulate stream flow. This is done for a reference (1961-2000) and future (2021-2060) period (SRES-A1B scenario). An important aspect of the study is to address the issue of uncertainty in the rainfall-runoff model; a Monte Carlo approach to calibration is used to obtain 100 parameter sets which reproduce observed stream flow well.

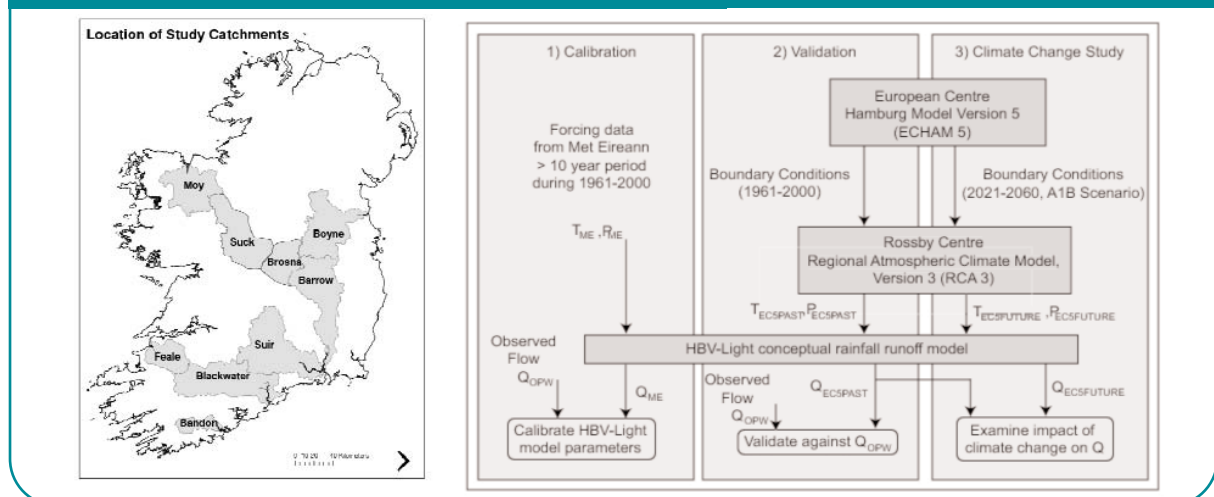
Results suggest an amplification of the seasonal cycle across the country, with increased winter precipitation leading to a rise in winter (DJF) stream flow, and the combination of increased temperature and decreased precipitation causing a reduction in summer (JJA) stream flow. Change to the seasonal cycle will have an impact on water supply management and design. Increased winter flows, coupled with the predicted increase in extreme precipitation events lead to an elevated risk of flooding. This is particularly significant in the southwest of the country, and those catchments with fast response times. The decrease in summer stream flow will impact on water availability, water quality, fisheries and recreational water use.

The study is based on a single set of downscaled AOGCM data; it does not address the uncertainty associated with the AOGCM predictions (particularly for precipitation) and needs to be extended by using an ensemble of climate simulations.

1 Introduction

A warming climate and the consequent rise in atmospheric water vapour have led to an increase in mean precipitation over northern Europe as well as an increase in the frequency of heavy precipitation events over most land areas (IPCC, 2007). It is expected that global average surface air warming will continue during this century, and that heat waves and heavy precipitation events will continue to increase in frequency. The objective of this project is to examine how the predicted climate change will impact on hydrology in Ireland.

Figure 1 Locations of study catchments and experiment set-up for each catchment.



In this study boundary conditions from a general circulation model are used to drive a regional climate model, to produce dynamically downscaled precipitation and temperature data. These data are used to force a hydrology model which simulates run-off during a reference (1961-2000) and future (2021-2060) period for a given future climate scenario.

This research differs from previous studies on climate impacts on hydrology in several respects. Previous C4I work used the HBV model from the Swedish Meteorological and Hydrological Institute (SMHI) in a study of the Suir catchment (Wang (2006)). This model is usually calibrated using a manual trial and error approach. Here, the HBV-Light model is used as it allows a Monte-Carlo approach to calibration. This enables us to include information on the impact of parameter uncertainty in the analysis. The second difference is that a significant bias has been identified in and removed from the downscaled ECHAM5-OM1/RCA3 precipitation data. Finally, the scope of the study has been broadened to include nine catchments (Figure 1(a)) and the focus has shifted from extreme flooding events to include changes in seasonal flows.

Details of the experiment, including the models and data used are provided in Section 2. In Section 3, the conceptual hydrology model is forced with observed precipitation and temperature data from Met Éireann, and calibrated using a Monte Carlo approach. The performance of the hydrology model is validated in Section 4 when it is forced with downscaled ECHAM5-OM1/RCA3 data in the reference period (1961-2000) and the simulated stream flow is validated against observations. A significant bias is identified in the downscaled precipitation data, and two methods are presented to remove it. Temperature and precipitation data from the downscaled ECHAM5-OM1/RCA3 simulations are presented in Section 5 to illustrate how climate is expected to change in Ireland in the future. Then, the impact of climate change on hydrology is simulated by comparing simulated stream flow in the future (2021-2060) to that in the reference period. Finally, the implications of the expected climate change and future research activities are discussed in Section 6.

2 Experiment Set-up

Figure 1(b) illustrates the experiment set-up for each catchment which requires the use of three models. A general circulation model (GCM) is first required to simulate the global climate. Here we use scenario data from the ECHAM5-OM1 AOGCM (Roeckner et al. (2003)). The resolution of these data is too coarse to capture the fine scale variability in precipitation due to orography and land cover, and so can not provide useful data to simulate stream flow at catchment scale. The coarse resolution climate model data is therefore dynamically downscaled, using the RCA3 regional climate model (Kjellström et al. (2005); Jones et al. (2004), onto a grid with a horizontal resolution of about 13 km. Details of the model setup and validation are listed in Wang et al. (2006) and Semmler et al. (2006).

Finally, the dynamically downscaled precipitation and temperature data provide the required forcing data for the HBV-Light conceptual rainfall run-off model which is used here to simulate stream flow in nine study catchments (Figure 1(a), Table 1). The original HBV model was developed by SMHI (Bergström (1992)) and includes soil and snow routines, evaporation, linear reservoir equations and channel routing. Groundwater recharge and actual evaporation are functions of actual water storage in a soil box, runoff formation is represented by three linear reservoir equations and channel routing is simulated by a triangular weighting function. The HBV light model (Seibert (2005)) used here has identical physics to the model of Bergström (1992), with two small changes. The first is the inclusion of a spin-up period rather than requiring prescribed initial states, and secondly the MAXBAS routing parameter can assume non-integer values. It is used here because its interface permits Monte-Carlo simulations.

Table 1: Study catchments, Stream flow gauge station and location, and catchment area upstream of the gauge station.

Catchment	Stream flow gauge station	Latitude (deg N)	Longitude (deg E)	Area (km ²)
Moy	Rahans	54.10	-9.16	1803
Boyne	Slane Castle	53.71	-6.56	2452
Blackwater	Ballyduff	52.14	-8.05	2302
Suck	Bellagill	53.36	-8.24	1219
Brosna	Ferbane	53.27	-7.83	1210
Feale	Listowel	52.44	-9.48	648
Barrow	Royal Oak	52.70	-6.98	2381
Suir	Clonmel	52.35	-7.70	2138
Bandon	Curranure	51.77	-8.68	431

In Section 4, it will be shown that the dynamically downscaled precipitation data includes a significant bias in the mean monthly and annual precipitation. It will be demonstrated that this bias adversely affects the simulated stream flow and so must be removed before the data can be used in any impact study.

3 HBV-Light model calibration

The HBV-Light model is first calibrated by forcing it with observed precipitation and temperature data. Temperature data from the nearest synoptic station to the catchment are used, while precipitation data from 8-12 rain gauges in the catchment are used to derive a time series of mean area daily precipitation using Theissen polygons. Simulated daily mean flow is compared to observed stream flow data provided by the Office of Public Works (OPW (2007)).

The HBV and HBV-Light model parameters are physically based, but are effective parameters for the catchment and may not bear any semblance to measurements from the field. In the User's Manual for the original HBV model (Bergström (1992)) it is recommended that the model be calibrated manually using a trial and error approach, seeking the unique optimal parameter set that best simulates runoff during the calibration period. However, conceptual models are often over-parameterized, so that very different parameter sets can give similarly good results during calibration (e.g. Mein and Brown (1978), Beven and Binley (1992), Duan et al (1992), Beven (1993), Freer et al (1996), van der Perk and Bierkens (1997), Seibert (1997a)). Furthermore, interactions between model parameters may result in them being inter-correlated (Jakeman and Hornberger, (1993) and Gaume et al. (1998)). The run-off may be sensitive to change in one uncertain parameter value, but the impact of the change may be compensated for by other uncertain parameters.

Badly-defined parameters introduce subjectivity in both manual and automatic calibration approaches. In a manual calibration, the user may choose initial values or try to limit the range of possible parameters based on their knowledge of the physical parameters of the catchment. Automatic calibration methods will yield different final parameter sets depending on starting point (Kite and Kouwen (1992)), and the user must then subjectively decide which is most reasonable.

Lindstrom (1997) argued that if several parameter sets yield the same run-off in calibration, that any one of them could be used for the model application. This assumes that the simulated runoff using each of these parameter sets is 'similar'. Harlin and Kung (1992) demonstrated that sets of parameters which give similarly good results during a calibration period may yield different results in other time periods. This occurs because model parameters determine the states of the various submodels, i.e. the soil routine, snow routine, routing routine etc., and so the states of the various submodels may differ depending on choice of parameter set. This is particularly significant in a climate impact study as the changes in weather conditions will impact on some subroutines more than others. For example, the impact of the change in temperature will be determined by the parameters of the evaporation parameterization and soil moisture routine. Seibert (1997) argues that using a Monte-Carlo approach to calibration allows the interaction between parameters to be taken into account as whole parameter sets vary, rather than varying individual parameters. Furthermore, simulations yield an ensemble² of possible results so expected changes can be expressed as a range rather than a single result.

In this study, an ensemble of 10 000 parameter sets is generated by sampling from a uniform distribution within the full range of physically reasonable values for each parameter (Booij (2005), Seibert (1997), Seibert (1999)). For each parameter set, HBV-Light was used to simulate runoff and the quality of the calibration was assessed using the Nash-Sutcliffe efficiency, R2:

$$R2 = 1 - \frac{\sum (Q_{obs} - Q_{sim})^2}{\sum (Q_{obs} - \overline{Q_{obs}})^2}$$

The best 100 parameter sets (i.e. the 99th percentile) were then selected for the HBV simulations. Table 2 shows the mean R2 value calculated across all 10 000 parameter sets, the maximum ("best") R2 value obtained and the 99th percentile value for each catchment. Only values above the 99th percentile are used in the HBV simulations in the

² In these sections the use of "ensemble" refers to the range of parameters used in the HBV model - not to be confused with climate ensembles.

following sections. The best and worst calibrations were obtained in the Moy and Bandon catchments, where the 99th percentile values were 0.9471 and 0.7133 respectively.

Calibration results for the Boyne catchment shown in Figure 2 demonstrate the merits of using a Monte Carlo approach. Usually, when the HBV model is calibrated using a trial and error approach, one parameter is varied within a certain range, while all other parameters are held constant. A parameter was considered sensitive if it yielded very different stream flows at different values. Furthermore, the parameter was considered well-defined if the quality of the calibration deteriorated as the parameter value deviated from some optimum value. For each of the parameters calibrated, Figure 2 shows the values of the best 100 parameter sets and the R2 value associated with that calibration. Clearly, excellent simulations ($R2 > 0.9$) are possible over wide ranges of most model parameters.

From Seibert (1997), it is the upper boundaries of the scatter plots that are of real interest, as for any value of a given parameter, poor simulations may occur due to the values of the other parameters. For a well-defined parameter, the upper boundary should have a distinct peak while in ill-defined parameters the upper boundary will have a broad plateau. In the Boyne catchment LP, PERC and MAXBAS are the best defined parameters. It is noteworthy that the list of well-defined parameters varies by catchment.

Table 2: HBV-Light calibration quality indicators for each catchment. R2 refers to the modified Nash-Sutcliffe efficiency parameter. For each catchment, 10 000 ensemble members were run in the calibration.

Catchment	Mean(R2)	Max(R2)	99th percentile
Moy	0.7682	0.9626	0.9471
Boyne	0.7355	0.912	0.8885
Blackwater	0.7081	0.8394	0.8246
Suck	0.7461	0.9235	0.9124
Brosna	0.7338	0.8992	0.8726
Feale	0.4861	0.7797	0.7276
Barrow	0.761	0.9229	0.9051
Suir	0.7341	0.8736	0.853
Bandon	0.5235	0.7314	0.7133

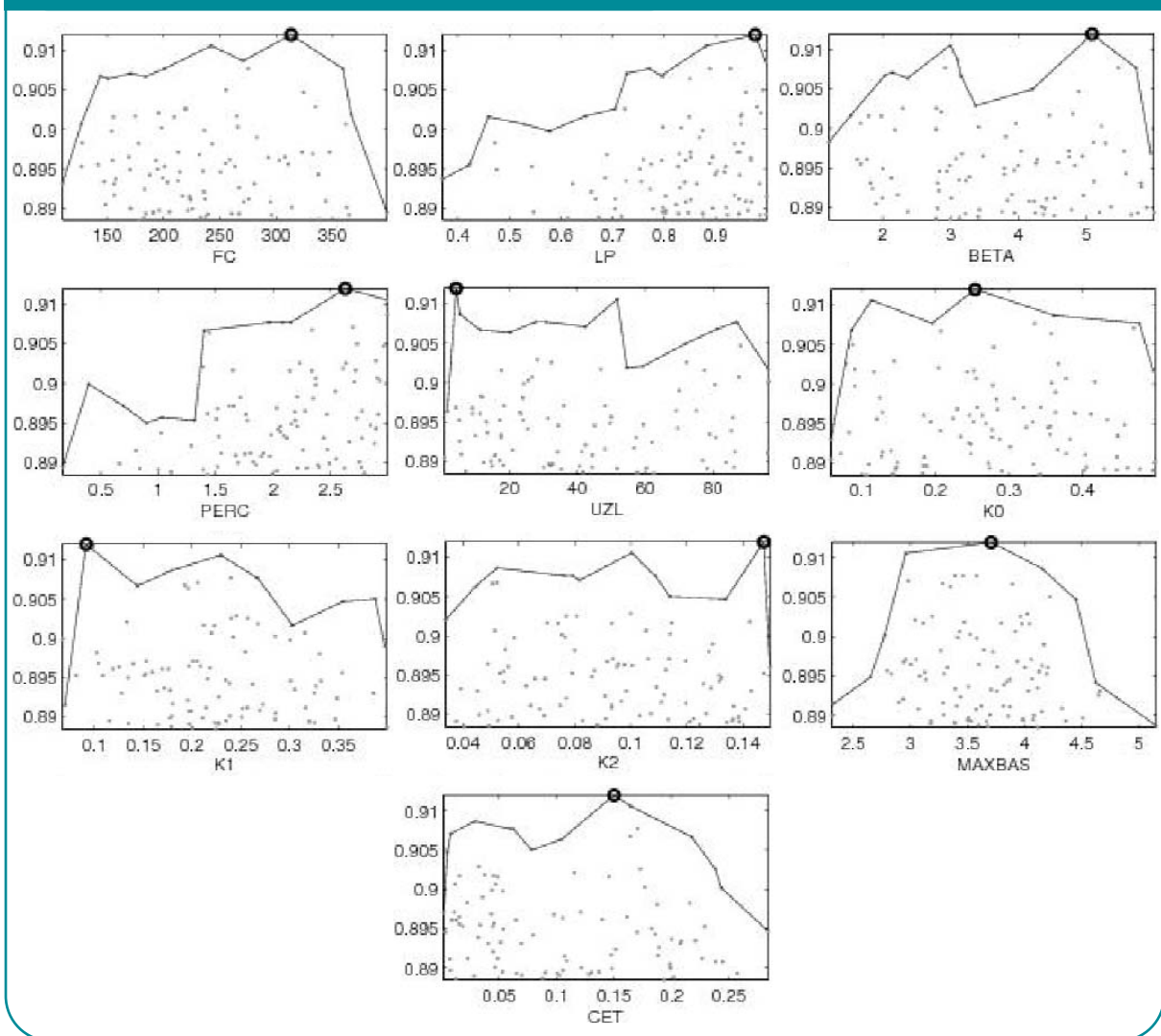
Table 3: Mean HBV-Light parameter values across best 100 ensemble members for each catchment..

	Mean FC	Mean LP	Mean BETA	Mean CET	Mean KO	Mean K1	Mean K2	Mean MAXBAS	Mean PERC	Mean UZL
Moy	277.3	0.64	3.75	0.137	0.261	0.078	0.085	3.31	1.77	81.4
Boyne	234.1	0.82	3.68	0.107	0.273	0.227	0.093	3.63	2.04	41.6
Blackwater	184.5	0.80	2.54	0.137	0.240	0.266	0.102	2.87	1.67	61.6
Suck	131.4	0.74	3.69	0.135	0.256	0.195	0.100	5.62	1.40	65.0
Brosna	285.0	0.75	4.21	0.116	0.265	0.193	0.072	3.17	2.11	45.4
Feale	217.1	0.75	2.83	0.153	0.353	0.293	0.079	2.45	1.10	12.8
Barrow	265.1	0.82	3.59	0.113	0.271	0.234	0.100	4.04	1.67	52.9
Suir	256.1	0.81	3.66	0.142	0.257	0.193	0.098	3.10	1.76	52.9
Bandon	95.2	0.72	3.69	0.179	0.282	0.296	0.097	2.94	1.20	41.5

For each parameter, the mean value across the 100 ensemble members used in the climate simulations is shown in Table 3. This set of values is not the optimal parameter set, but merely provides a way of classifying the catchments. FC, BETA, LP and CET are parameters of the soil moisture routine. FC(mm) is the maximum value of the soil moisture storage. For a given soil moisture, BETA (dimensionless) determines the portion of rainfall and snowmelt which contributes to groundwater storage, i.e. it determines the relative contribution to run-off from precipitation:

$$\frac{\text{Recharge}}{P} = \left(\frac{SM}{FC} \right)^{BETA}$$

Figure 2 Values for HBV-Light parameters from the best 100 ensemble members from calibration of the Boyne catchment.



Large values of FC and BETA are associated with more damped and even hydrographs (e.g. Brosna, Moy, Suir, Boyne, Barrow). However, steep slopes and the absence of extensive aquifers can explain large values of BETA in the smaller river catchments like the Bandon, because BETA can also be interpreted as a measure of the extension of relative contributing area (Seibert, 2000). The soil moisture value above which actual evapotranspiration equals potential evapotranspiration is given as a fraction, LP (dimensionless), of FC. CET is the correction factor for evaporation, lower values of which are associated with more damped and even hydrographs (e.g. Boyne, Barrow and Brosna). The recession coefficients (K0, K1 and K2, all with units of day^{-1}), PERC (mm/day) and UZL(mm) are the response function parameters. The recession coefficients can be expected to decrease with increasing catchment size because of a more damped and even hydrograph in a larger catchment. This is at least true for K1 which has its highest values in the Bandon and Feale, and much lower values in larger catchments such as the Boyne and Suir. PERC is the maximum rate of recharge between the upper and lower groundwater boxes. Flow from the lower groundwater box is limited to PERC, so small values (e.g. Feale, Bandon) result in a larger response from the upper groundwater box. UZL is the threshold for K0 outflow. Finally, MAXBAS (days) is the length of the triangular weighting function used in the routing routine. It can be expected to increase with increasing catchment size because of the increasing channel length (e.g. Suck, Boyne, and Barrow)

4 Validation of past climate (1961-2000)

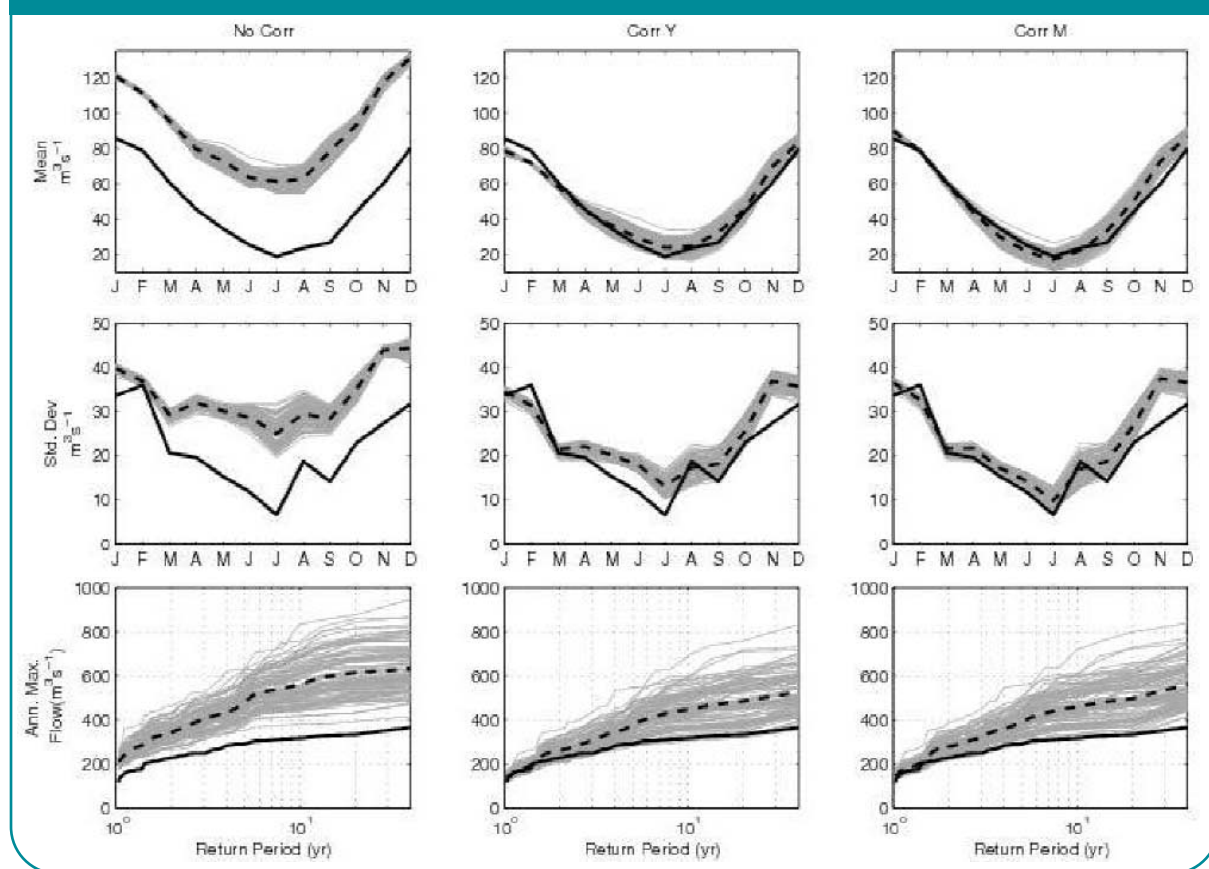
As argued in the previous section, calibration yields a number of parameter sets which produce satisfactory agreement between simulated and observed flow during the calibration period. However, this does not guarantee that simulated flow in other time periods, or forced with other data, will agree with observations. When the HBV-Light

model parameters for a catchment have been found, the stream flow generated using the past climate data (1961-2000) is validated against observations. Boundary conditions from the ECHAM5-OM1 model during the reference period 1961-2000 are used to drive the RCA3 model to produce the dynamically downscaled precipitation and temperature data required to run the HBV-Light model.

4.1 Precipitation Bias

If the precipitation data from the ECHAM5-OM1/RCA3 simulations is used to force the rainfall run-off model without any bias correction, the streamflow is grossly overestimated. In Figure 3, simulated and observed streamflow values are shown for the Suir catchment at Clonmel. Mean monthly flows are about $40 \text{ m}^3\text{s}^{-1}$ greater than those observed for each month. This translates to an error of 50% in winter flows and 200% for summer flows, rendering this data useless in any impact study.

Figure 3 Impact of bias correction on simulated streamflow in the River Suir at Clonmel (1961-2000). Simulated monthly mean flows (top), interannual variability of simulated monthly flows (middle) and annual maximum daily mean flow (bottom) are compared to observations (solid black line).



Two simple methods were tested to remove the bias in precipitation. Figure 4 shows the cumulative distribution function (CDF) for daily precipitation calculated using all daily values from 1961-2000 at Kilkenny (Met Éireann Synoptic Station 3613), one of the seven synoptic stations used to provide long term precipitation and temperature data in this study. The greatest divergence between the uncorrected precipitation data and the observed is at the low precipitation values. In the observed data, 66% of days have less than 1mm rainfall, compared to just 40% in the simulated data. The distributions converge for higher values of daily precipitation. The number of large events in the simulated precipitation compares favorably with that observed.

4.1.1. Correction using data from the full year (Corr Y)

For each of the seven synoptic stations, the percentage of zero precipitation days observed ($<0.1\text{mm}$) was noted (47% at Station 3613, Figure 4). In the simulated precipitation data, a cut-off threshold was found such that 47% of

values were less than the cut-off. At station 3613, this corresponded to 1.16mm/day. Values for all seven synoptic stations are given in Table 5. All precipitation values less than this cut-off amount were set to zero to ensure the correct number of dry days. However, a substantial bias remains even after this correction. It was assumed that the remaining bias occurred evenly across all non-dry days. The values of the remaining bias, to be subtracted from each non-wet day, are given in Table 5. In general, the cut-off rain rate is about 1mm/day while there is greater variability in the remaining bias.

This method is referred to as Corr Y as data for the full year are used to calculate the CDFs. From Table 4, it is clear that implementing this simple scheme reduces the bias in annual mean precipitation by at least 90%. Results, not shown, demonstrate that this correction reduces the bias across the year, but in general fails to capture the seasonal cycle.

Figure 4 Cumulative Distribution function for daily precipitation using all values at Station 3613 from 1961-2000.

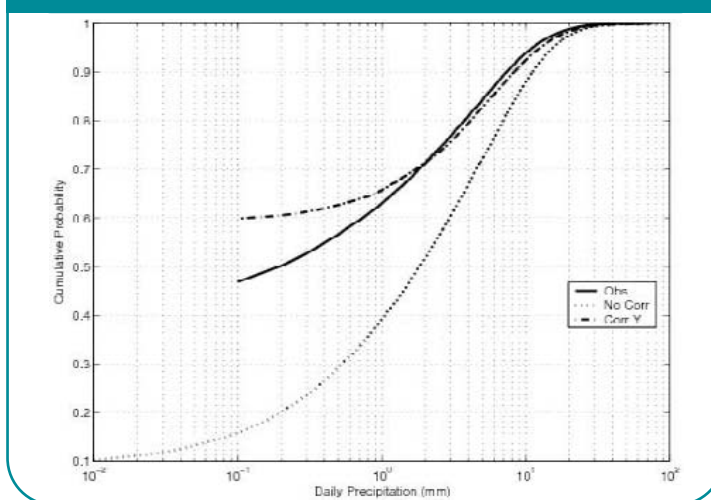


Table 4: Mean annual precipitation for ECHAM5/RCA3 simulated climate 1961-2000, compared to Met Éireann observed gauge data at seven synoptic stations.

Station Number	Station Name	Met Éireann Gauge Data (mm)	ECHAM5/RCA3 No Correction (mm)	ECHAM5/RCA3 Corrected Method Y (mm)	ECHAM5/RCA3 Corrected Method M (mm)
3613	Kilkenny	839.7	1495.1	898.4	897.9
532	Dublin Airport	739.0	1274.6	782.0	787.5
2922	Mullingar	942.8	1598.1	999.1	995.0
518	Shannon Airport	950.9	1480.6	985.1	987.1
1004	Roche's Point	933.2	1424.5	967.3	975.0
2727	Claremorris	1190.2	1766.4	1208.2	1230.1
3904	Cork Airport	1220.0	1612.8	1233.3	1239.5

4.1.2. Correction sorted by month (Corr M)

A second method was used, whereby precipitation was sorted by month, so a CDF was calculated for each month using all data from the period 1961-2000.

From Table 4, it seems that in almost all cases, the corrected mean annual precipitation is greater than that calculated using a single CDF for each station. However this method is more successful in reproducing the seasonal cycle of mean monthly precipitation.

Figure 3 shows the impact that correcting the precipitation bias has on simulated streamflow during the reference period.

Table 5: Thresholds used to correct bias calculated using data from seven synoptic stations, and bias in mean annual precipitation for ECHAM5 simulated climate 1961-2000 after bias has been removed.

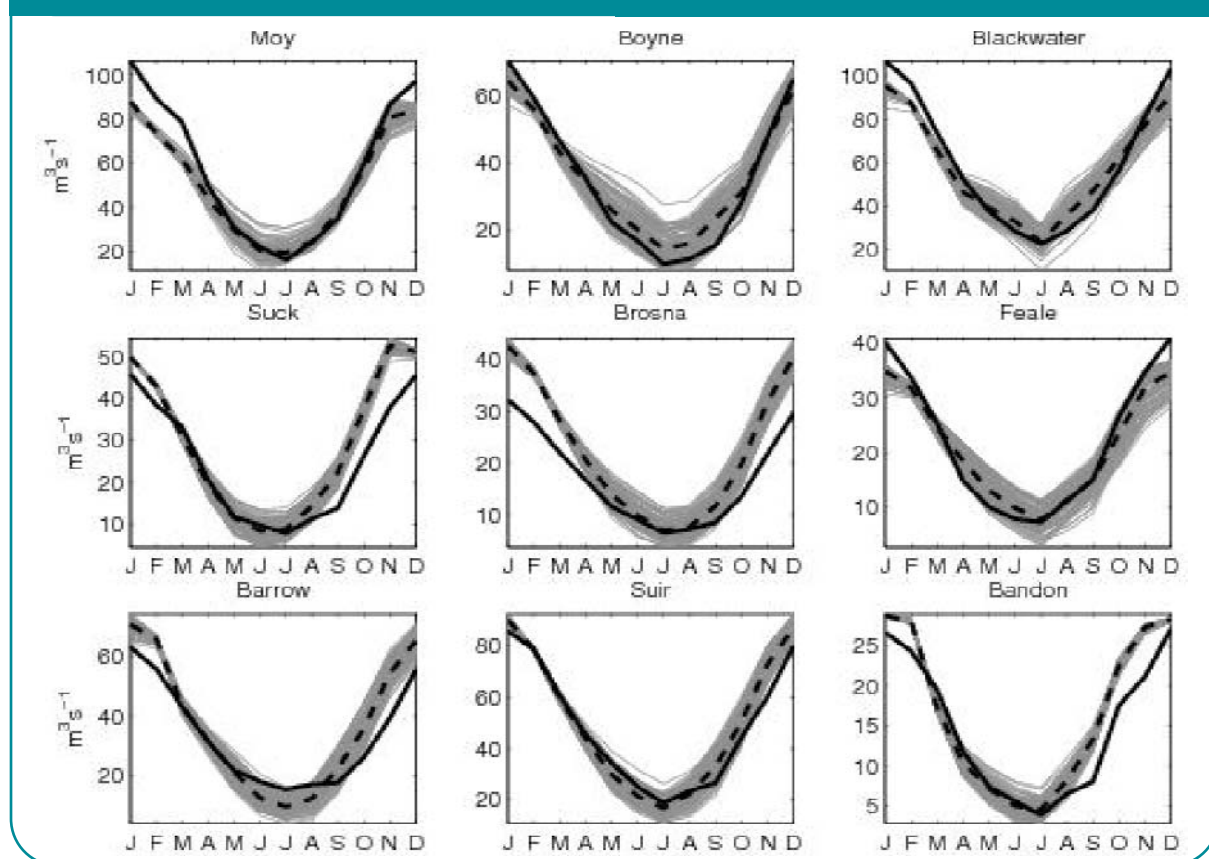
Station	Name	Cut-off (mm/day)	Remaining Uniform Bias (mm/day)
3613	Kilkenny	1.16	2.8329
532	Dublin Airport	1.03	2.3780
2922	Mullingar	1.01	2.6396
518	Shannon Airport	0.97	2.1502
1004	Roche's Point	1.03	2.2034
2727	Claremorris	0.90	2.3031
3904	Cork Airport	0.91	1.5959

Using the simplest correction scheme (Corr Y) based on a single CDF of all daily precipitation, the bias in streamflow is almost entirely removed. The observed streamflow falls within the ensemble of simulated flows in general. Sorting the precipitation into monthly CDFs (Corr M) further improves our ability to capture the seasonal cycle. In this case the truth lies within the ensemble of simulated streamflow for all months except November. The observed precipitation is also generally closer to the ensemble mean than in the previous two cases. The inter-annual variability of streamflow is also overestimated if the bias is not corrected, resulting in an overestimation of the inter-annual variability in streamflow in these months. If the bias in precipitation is uncorrected, the annual maximum daily mean flow for any return period is up to twice that observed. Removal of the bias using either method reduces the error in annual maximum daily mean flow, particularly at larger return periods. However a substantial bias remains. This is likely due to the residual bias shown in Table 4.

4.2. Validation results

The simulated flow is compared to that observed by the OPW for the reference period. In any catchment, parameter uncertainty causes the flow predictions to vary considerably. Uhlenbrook et al. (1999) argued that model predictions, particularly in applied studies should be given as ranges rather than as single values, so all 100 ensemble members are shown here.

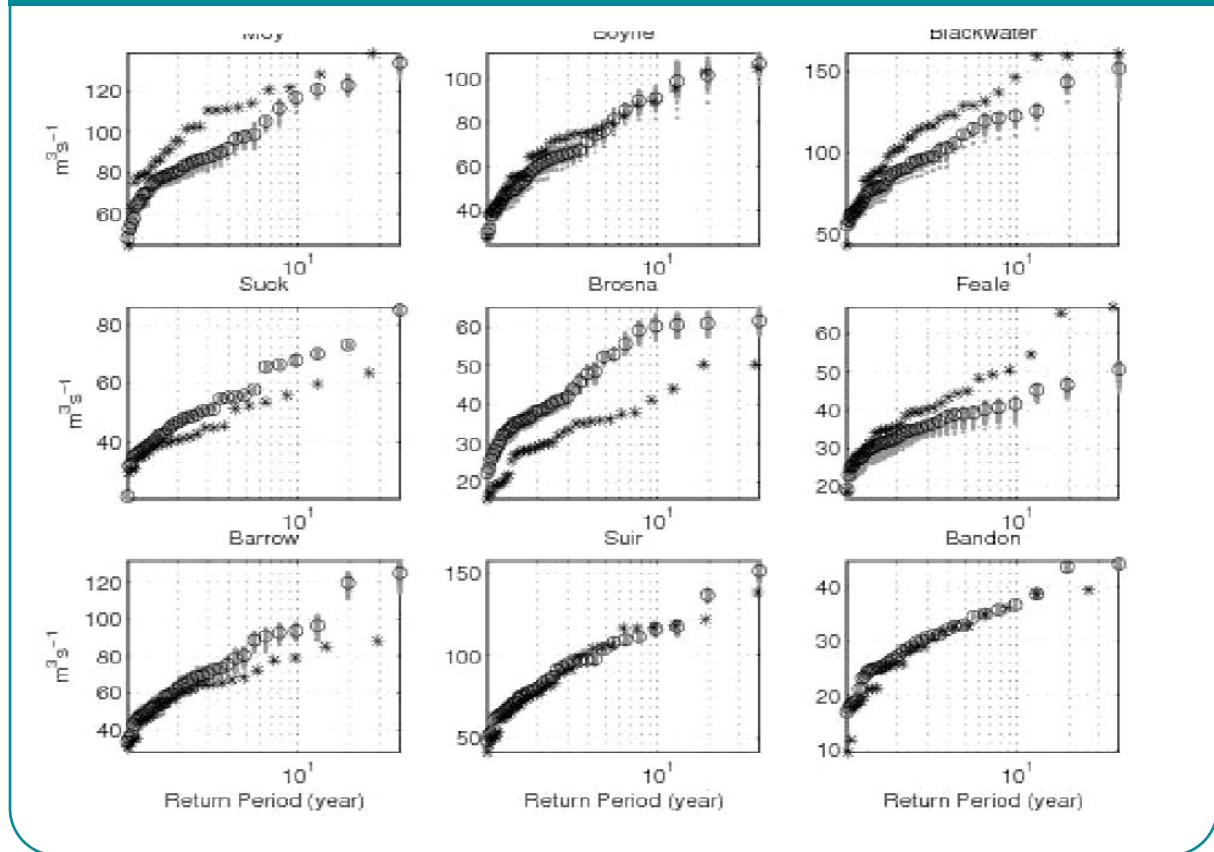
Figure 5 Validation of seasonal cycle of stream flow in each of the nine study catchments. Simulated ensemble members are shown in grey, with the ensemble mean as a black dashed line. Stream flow from OPW observations are shown as a solid black line.



In Figure 5 an ensemble of the seasonal cycle of mean monthly flow in each catchment is validated against observations from OPW stream flow data. The seasonal cycle is generally well captured, particularly in the Suir catchment. Ensemble spread is higher in summer than winter due to parameter uncertainty. In winter, precipitation is sufficiently high that the soil column is generally saturated. In the summer, the evaporation parameters determine how quickly the soil column dries out due to evaporation while the soil parameters ensure variability in how much storage there is as well as how quickly water is redistributed to the groundwater storage layers. In summer, the observed monthly stream flows generally fall within the ensemble, but in winter all ensemble members are generally

biased with respect to the observed. Winter flows are well captured in the Suir and Boyne, just slightly over- and under- estimated respectively. Winter flows are considerably overestimated in the Suck, Barrow, Brosna and Bandon and significantly underestimated in the Moy, Blackwater and Feale. Summer flow is generally better modeled than winter flow, with the only serious discrepancies in the Boyne (overestimated) and the Barrow (underestimated).

Figure 6 Validation of mean winter flow. Daily mean flow is averaged over winter (DJF) for each year and shown in m^3s^{-1} . Ensemble members in grey, ensemble mean as a black circle, and OPW observations are shown as black asterisks.



In Figure 6 the modeled mean winter (DJF) stream flow is plotted as a function of return period for each of the catchments and compared against observations from the OPW. If some winter flow Q_{20} has a return period of 20 years, then mean winter flow is likely to exceed this amount on average once every 20 years. Equivalently, in any year there is a 5% chance that mean winter flow will exceed this amount. This quantity is very reliably estimated, with excellent agreement in the Suir, Boyne and Bandon catchments. Risk is overestimated in the Suck, Barrow and Brosna. Recall from Figure 5 that these were the catchments in which mean monthly flows were overestimated in winter. Risk is underestimated in the Moy, Blackwater and Feale, the catchments in which summer monthly flows were underestimated. Ensemble spread is typically just 10-15% of the range of all values indicating that parameter uncertainty is pretty low in this quantity. However, in the biased results the observations typically lie outside the ensemble. Errors are as high as 50% (Brosna).

Figure 7 shows the modeled mean summer (JJA) stream flow as a function of return period. If some summer flow Q_{10} that has a return period of 10 years, then summer flow will only be less than this value once in 10 years, or equivalently there is a 10% chance that in any given year the mean summer flow will be less than this amount. Ensemble spread is generally much greater than for the mean winter flow case, due again to the impact of greater parameter uncertainty on summer flows. In all catchments, observations fall within the ensemble spread, though the spread in this case is much larger than in the case of the winter flows. Agreement is generally good, though risk is underestimated in the Boyne, Suck and Feale and overestimated in the Suir and Barrow.

The annual maximum daily mean flow is plotted against return period in Figure 8. The most striking difference between this and Figure 6 is that ensemble spread is significantly greater here. This indicates that while parameter

Figure 7 Validation of mean summer flow. Daily mean flow is averaged over summer (JJA) for each year and shown in m^3s^{-1} . Ensemble members in grey, ensemble mean as a black circle, and OPW observations are shown as black asterisks.

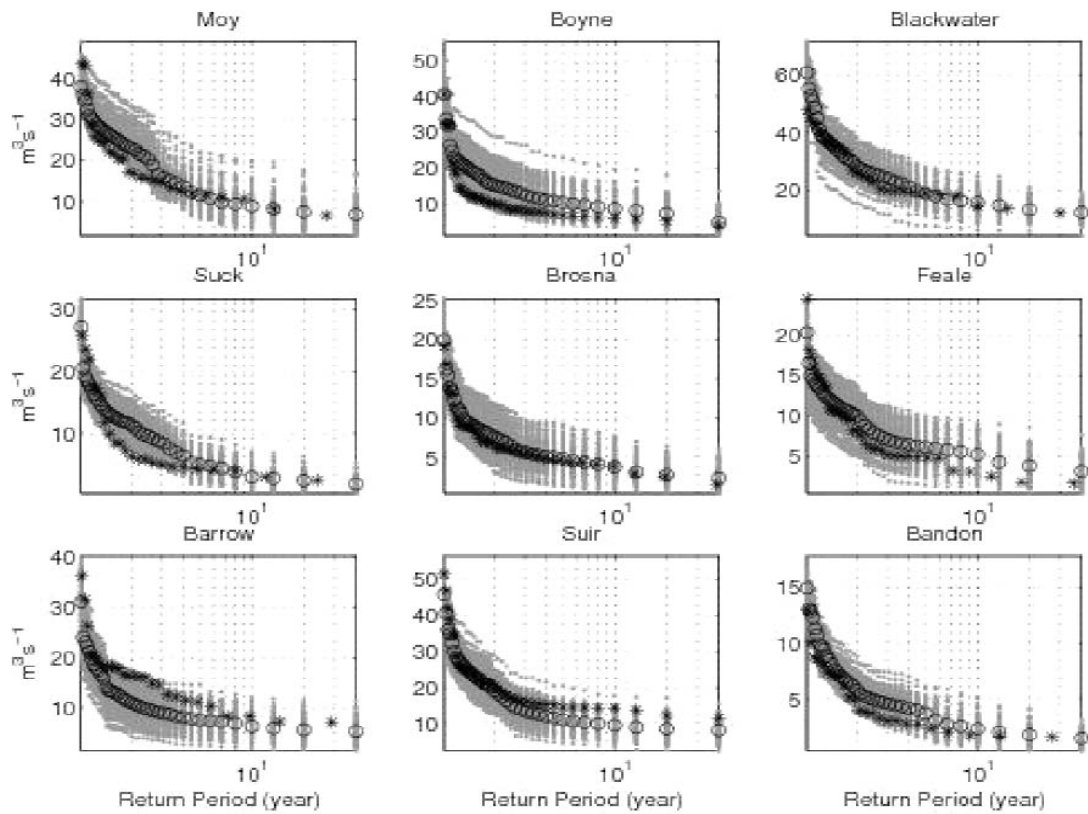
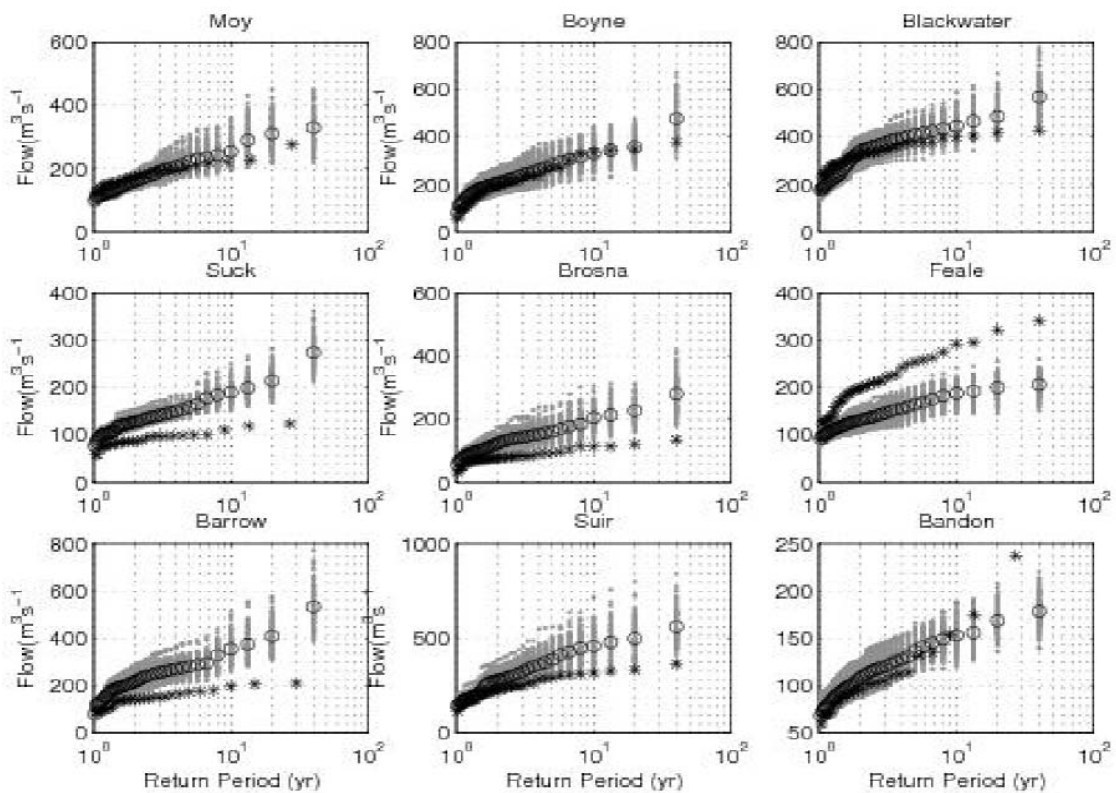


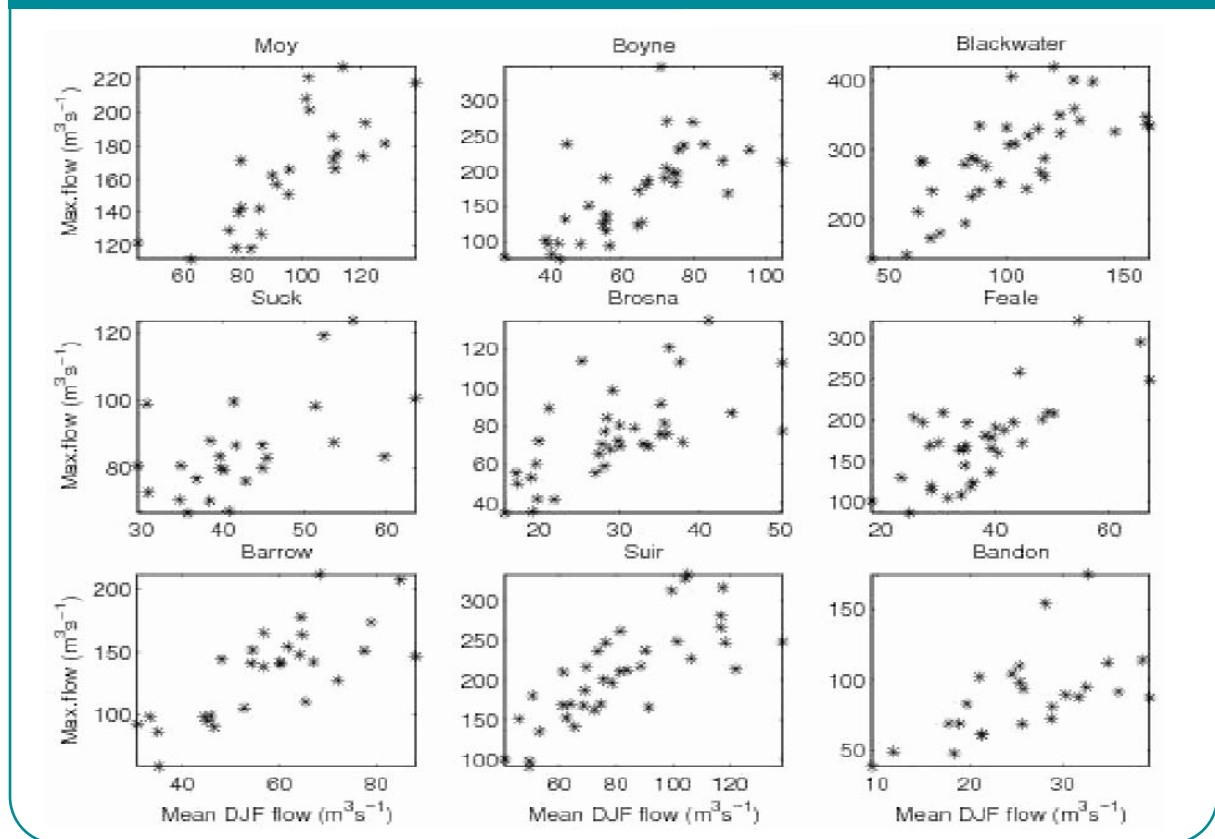
Figure 8 Validation of annual maximum daily mean flow in each of the nine study catchments. Ensemble members are shown as grey dots, with ensemble mean as black circles. OPW observed values are shown as black asterisks.



uncertainty had little impact on our ability to simulate mean winter flow, it has a large influence on simulations of single events such as the annual maximum daily mean flow. This makes sense as a mean over 90 days will integrate some of the differences in model parameters as it is an averaged quantity. The maximum value depends on the states of the model and its various subroutines on a single day.

Despite the large spread, observations fall outside the ensemble in half of the catchments (Suck, Barrow, Brosna, Feale). The best results are obtained for the Boyne and Bandon, which from Figure 6 were the most reliable simulations of mean winter flow return period. Despite excellent agreement with observations in Figures 5 and 6, simulated annual maximum daily mean flow in the Suir is overestimated in Figure 8, probably due to the empirical bias correction method. In general, with the exception of the Feale, risk is generally overestimated. This is despite results from Figure 5 indicating that half of the catchments overestimated and half underestimated mean winter flow.

Figure 9 Relationship between winter (DJF) average flow and maximum daily flow (DJF) from observed stream flow data.



In Figure 9, observed data from the OPW is used to demonstrate the relationship between the mean and maximum daily mean flow during winter (DJF). The mean refers to the average of all daily mean flow values from December to February, and the maximum refers to the highest value of daily mean flow recorded in this period. Obviously, the maximum daily mean flow is likely to be higher in wetter winters. However, there is not a simple relationship between these quantities. The considerable variability indicates that the annual maximum daily flow is influenced by factors other than the mean background flow. The main driver is of course the magnitude of the precipitation event responsible for the peak.

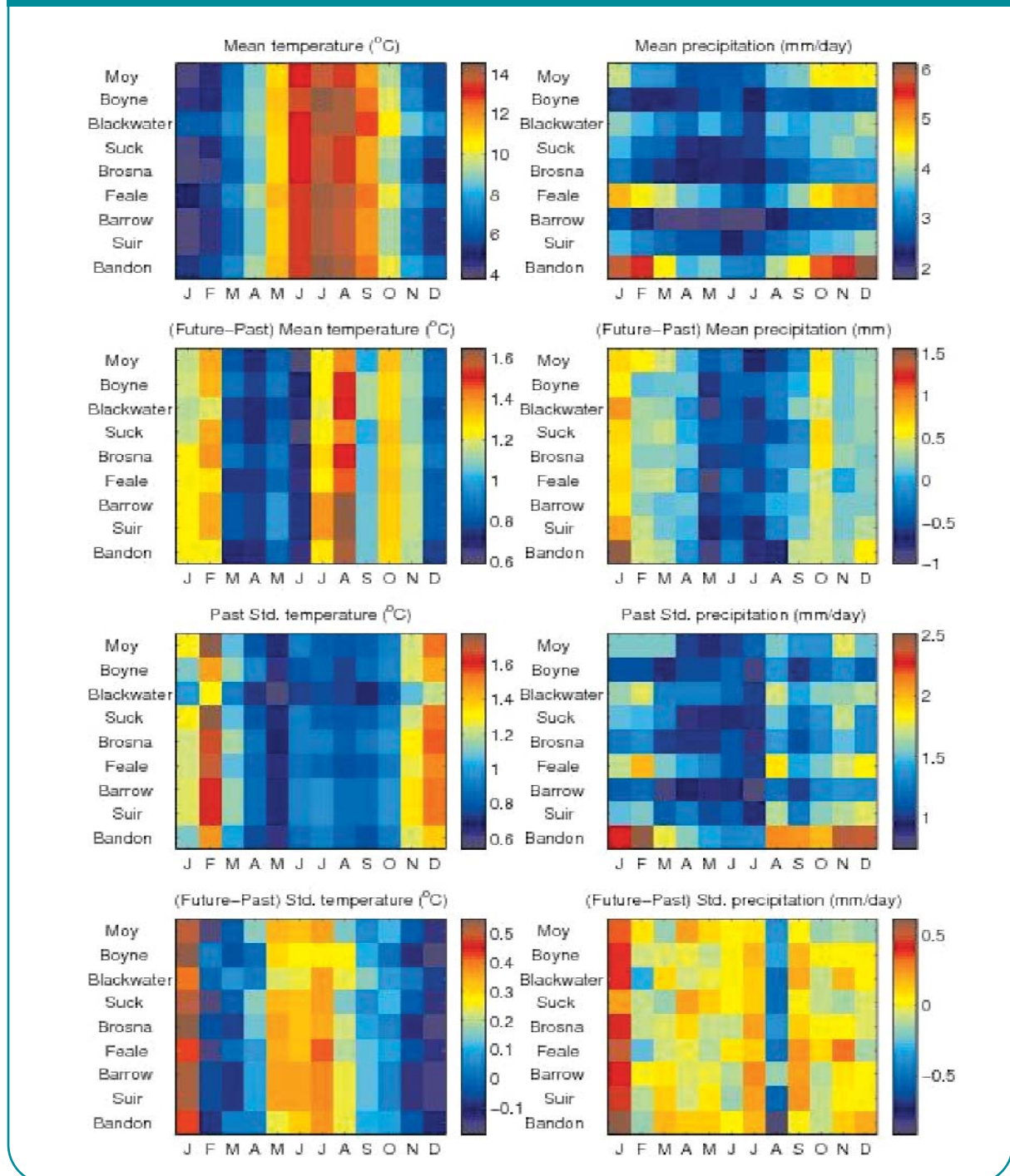
In Figure 8, all ensemble members have the same precipitation forcing, but the response of the various subroutines will vary depending on the model parameters. So, assuming that the peak occurs on the same day in each ensemble member (which is the case), the ensemble spread is due entirely to parameter uncertainty. The discrepancy between the observations and the ensemble members occurs because the single precipitation event which gave rise to the observed maximum was not simulated with the same magnitude or at the same time in the climate model. In short, it is unreasonable to expect the experiment set-up to reproduce single events such as annual maximum daily mean flow as reliably as it can reproduce averaged quantities such as seasonal flows.

5 Climate Change and its impact on hydrology

5.1 Expected Climate change

For each of the nine study catchments, Figure 10 shows the mean monthly temperature and precipitation in the reference period (1961-2000), the expected increase/decrease in these quantities in the period (2021-2060) compared to the reference period, as well as the expected change in inter-annual variability in these quantities between the two periods.

Figure 10 Expected change in temperature (left) and precipitation (right) due to climate change under SRES-A1B scenario. Mean quantities (1961-2000) are shown in the top panel. The expected change in mean quantities are shown in the middle. The expected change in inter-annual variability is shown on the bottom.



In the reference period 1961-2000, the Blackwater and Bandon are the warmest catchments, while the Brosna is the coolest, although the range of mean daily temperature across catchments is just 8.91°C to 10.04°C. There is a strong seasonal cycle in daily mean temperature. In all catchments, maximum daily mean temperatures occur in July (from 13.7°C in Moy and Suck to 14.5°C in Boyne) and minimum daily mean temperatures occur in January (from 3.8°C in Brosna to 6.2°C in Blackwater).

Inter-annual variability in the daily mean temperature for each month is calculated as the standard deviation in monthly average daily mean temperature across the 40 years of the reference period. Inter-annual variability in mean daily temperature (not shown) is highest in the Barrow and Suir, and lowest in the Blackwater and exhibits a strong seasonal cycle. It is highest in February, varying from 1.3°C in the Blackwater to 1.8°C in the Moy and Suck. Inter-annual variability in the summer months is approximately half that in the winter, and is lowest in May with little variation between the catchments.

Under the A1B scenario, temperature is expected to increase in all months in all catchments. The greatest increase is expected in the Barrow and Suir, and the lowest in the Blackwater, though the range across catchments is small. The greatest increase occurs in August (from 1.4°C in the Moy and Suck to 1.65°C in the Barrow and Suir). The smallest increase occurs in June and is on the order of 0.6-0.7°C in all catchments.

In general, inter-annual variability increases between April and October. In winter, there is a decrease in November, December and February, while there is an increase of about 0.5°C in January. The greatest decrease is in December (-0.07°C in Blackwater to -0.19°C in Boyne). Increased inter-annual variability in mean daily temperature affects potential evapotranspiration, which in turn influences summer low flows and autumn soil moisture.

Mean annual precipitation, as well as the timing and amplitude of the seasonal cycle vary with geographical location. The wettest catchments are the Bandon (1679mm) and the Feale (1469mm) in the southwest. In these catchments the minimum and maximum mean daily precipitation are in July (3.13mm/day, 2.62mm/day) and December (6.11mm/day, 5.08mm/day) respectively. The Barrow (849mm) and Boyne (941mm) are the driest catchments. In the southeast the minimum is earlier in June. In the west, the cycle is shifted further with the minimum in April and maximum in November. The Boyne has a very irregular seasonal distribution with a minimum (2.2mm/day) in February and maximum (2.86) in August.

Inter-annual variability in mean precipitation (not shown) is highest, and has the greatest amplitude in seasonal cycle in the wetter catchments. Minimum inter-annual variability is in April/May in the west (Suck (0.88mm/day), Brosna (1.0mm/day), Moy (0.98mm/day)), and June/July everywhere else. Maximum inter-annual variability is in February in the southeast (Bandon (2.51mm/day), Blackwater (1.76mm/day) and Feale 2.00mm/day)), but in November/December everywhere else. Again, the Boyne has a somewhat irregular cycle with the maximum inter-annual variability in August (1.36mm/day).

Under the A1B scenario, there is a general increase in winter precipitation and decrease in summer precipitation. The decrease in precipitation extends from April to August in the southwest, and May to September in the west, and May to July/August in the east and southeast. In all catchments the greatest increase is expected in January (from 0.62mm/day in Boyne to 1.56mm/day in Bandon). The largest decrease is generally expected in May (from -0.59mm/day in the Barrow and Brosna to -1.0mm/day in the Feale) but occurs later in July for the Moy and Suck.

The expected change in inter-annual variability in precipitation shows little trend, increasing or decreasing by up to 0.2mm/day. However, all catchments show an expected decrease in August (from -0.16mm/day in the Barrow to -0.92mm/day in Bandon) and an increase in January (from 0.24mm/day in Suck to 0.62mm/day in Bandon).

5.2 Impacts of climate change on hydrology

When the simulated stream flow derived from the ECHAM5-OM1/RCA3 data has been validated, future stream flow (2021-2060) is simulated based on the A1B SRES emission scenario to examine the impact of the expected climate change on hydrology in the nine study catchments.

Figure 11 shows the expected change in monthly stream flow (as a percentage of the past flow). These results suggest an amplification of the seasonal cycle in stream flow in all catchments. Due to the predicted increase in

Figure 11 *Change in monthly mean daily flow due to climate change under the SRES A1B scenario. Ensemble members are shown in grey, with the ensemble mean shown as a black dashed line.*

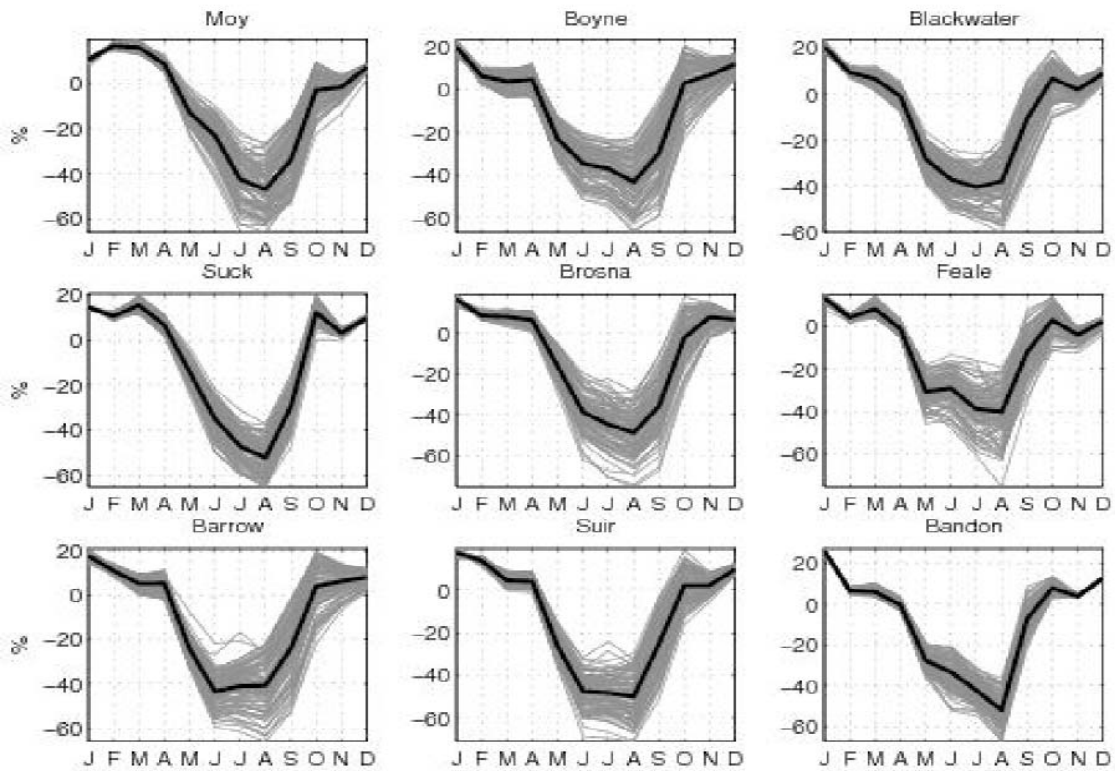
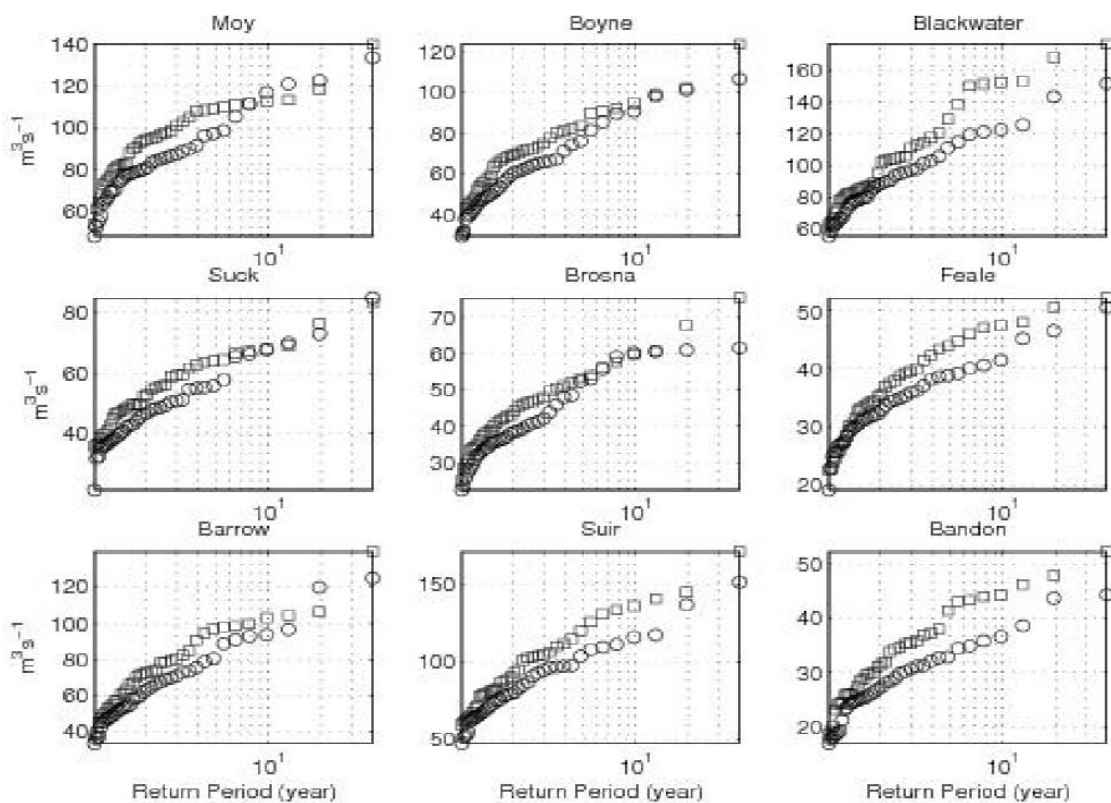


Figure 12 *Change in mean winter flow due to climate change under the SRES A1B scenario. Daily mean flow is averaged over winter (DJF) for each year and shown in $m^3 s^{-1}$. Ensemble mean in the reference period (1961-2000) is shown as black circles, while ensemble mean in future (2021-2060) is shown as black squares.*



winter precipitation, stream flow is expected to increase by up to 20% from October to April. The greatest increase in flow is generally in January, except in the Moy (February/March) and Suck (January/March). With a combination of reduced summer precipitation, increased temperature and consequent increased evaporation, stream flow is expected to decrease by up to 60% from May to September.

The impact of parameter uncertainty is very different in winter and summer. Recall that ensemble spread is greater in summer as storage is influenced by the parameters from the evaporation parameterization, and the soil moisture routine and stream flow is affected by the run-off routine. In winter, the soil is close to saturated in all ensemble members and evaporation is low due to the lower temperatures. This means that taking account of parameter uncertainty, we can be more confident in the predicted changes in winter flow than summer flow.

The expected change in mean winter flow (DJF) under the A1B scenario is plotted in Figure 12. The greatest increase in risk is expected in the Blackwater and Bandon catchments, where the flow associated with a 40-year return period in the past is expected to have a return period of 9.8 and 8.5 years respectively in the period 2021-2060. Recall that these were the wettest catchments in the reference period (1961-2000), and were expected to have the biggest increase in mean precipitation and interannual variability in January precipitation.

The risk of extremely high DJF flows is expected to almost double in the Feale and Suir, and will increase in the Boyne also. While precipitation is expected to decrease in November in the Feale, the catchment response is dominated by the Q0 response, and so the impact of the December and January increase will be more pronounced than in other catchments. Mixed results were obtained for the Moy, Suck, Barrow and Brosna, where the flow associated with some return periods in the past are expected to have a greater return period in the future. These catchments are characterized by damped and even hydrographs so the response to a change in precipitation will be on a longer time scale than faster responding catchments.

Figure 13 *Change in mean summer flow due to climate change under the SRES A1B scenario. Daily mean flow is averaged over summer (JJA) for each year and shown in m^3s^{-1} . Ensemble mean in the reference period (1961-2000) is shown as black circles, while ensemble mean in future (2021-2060) is shown as black squares.*

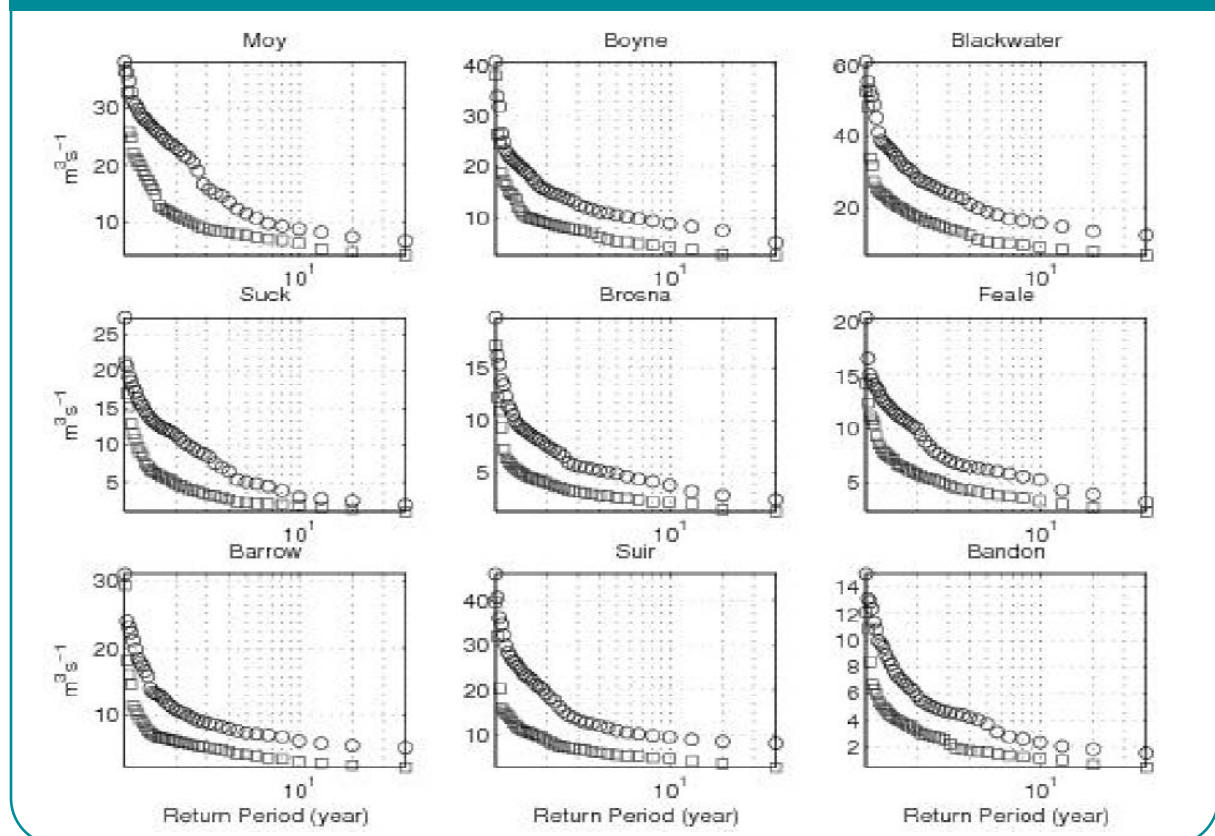
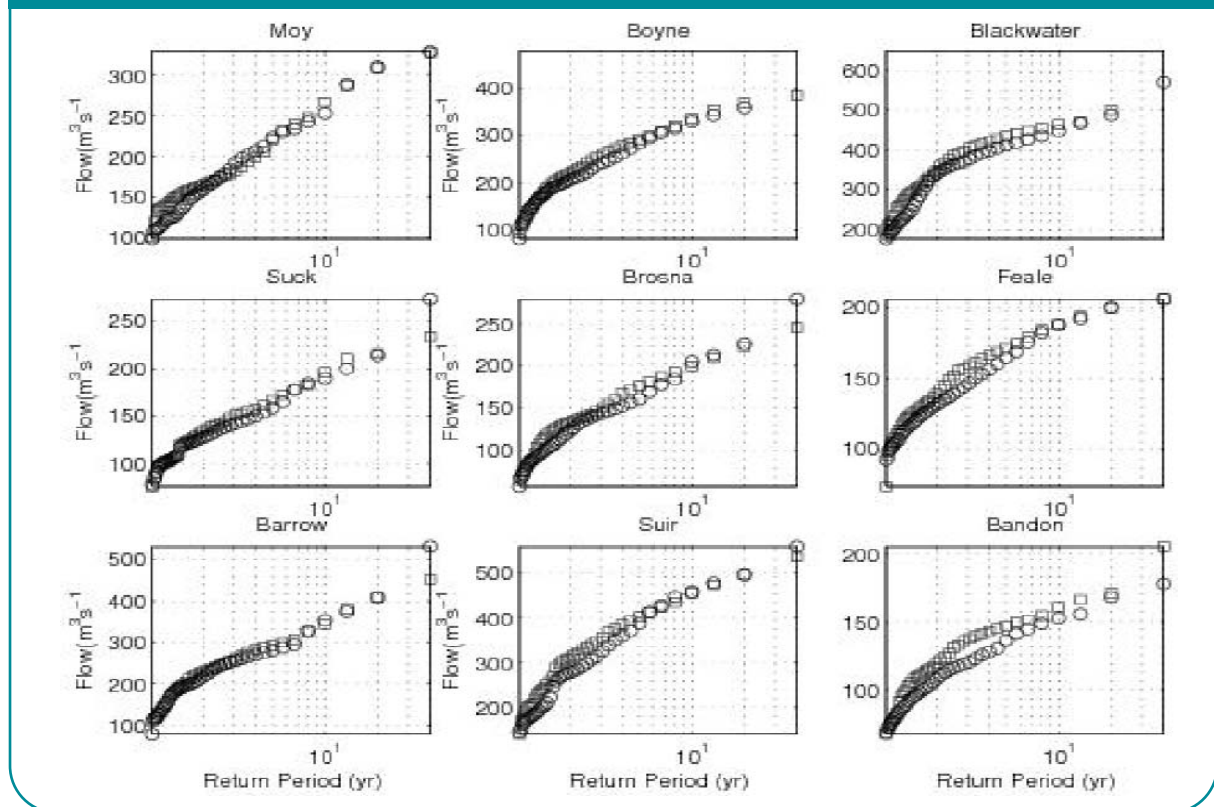


Figure 13 shows that a significant increase in the risk of extremely low summer flow is expected in all catchments and at all return periods. The greatest increase in risk is in the Suir and Barrow catchments where the greatest increase in temperature is predicted. It is noteworthy that in the past simulations there is little interannual variability in summer flow in these catchments, so that the flow with a 40 year return period is only slightly less than that with a return period of 5 years etc. In the future, there will be a further reduction in the inter-annual variability because possible stream flow values are limited by the lower end of the dynamic range.

Figure 14 *Change in Annual Maximum Daily Mean Flow due to climate change under SRES scenario A1B. Ensemble mean from the reference period (1961-2000) is shown as black circles, while ensemble mean in the future is shown as black squares.*



The return period associated with annual maximum daily mean flow in the past and future are compared in Figure 14. For clarity, only the ensemble mean values are shown. A definite increase in annual maximum daily mean flow at all return periods is apparent only in the Bandon and Blackwater catchments. For events with past return periods less than 20 years, an increase in risk is also expected in the Boyne and Suck. No change is expected in the Barrow, Feale, Suir and Moy, and a marginal decrease in risk is expected in the Brosna.

6 Conclusions & Discussion

Nine Irish catchments have been studied to investigate the impact that climate change will have on their hydrology. Boundary conditions from the ECHAM5-OM1 general circulation model were used to drive the RCA3 regional climate model to produce dynamically downscaled precipitation and temperature data, required by the HBV-Light conceptual rainfall runoff model.

A Monte-Carlo approach to calibration was used, in which the 99th percentile of an ensemble of 10,000 parameter sets were selected for use in the impact study. Use of this approach allows the inclusion of parameter uncertainty in the study, and provides a range of possible values rather than a single value. This allows us to include a statement on our confidence in the outcome.

The HBV-Light model was validated for a reference period (1961-2000) to ensure that stream flow was modeled correctly. A persistent positive bias in the downscaled precipitation was accounted for and removed to improve the

agreement between modeled and observed stream flow. It was shown that the impact of parameter uncertainty on the validation of seasonal (DJF and JJA) flows was less significant than in the annual maximum daily mean flow. This is intuitive as the seasonal flows are integrated values rather than single events which result from a combination of antecedent flow, the magnitude of a single storm event and a response determined by uncertain parameters.

Comparisons of simulated flow from the future (2021-2060) and the reference period suggest an amplification of the seasonal cycle, with increased winter precipitation leading to a rise in winter (DJF) stream flow, and the combination of increased temperature and decreased precipitation causing a reduction in summer (JJA) stream flow. Change to the seasonal cycle will have an impact on water supply management and design. Increased winter flows, coupled with the predicted increase in extreme precipitation events lead to an elevated risk of flooding. This is particularly significant in the southwest of the country, and those catchments with fast response times. The decrease in summer stream flow will impact water availability, water quality, fisheries and recreational water use. Given the magnitude of the predicted decrease in summer flows, further research on these sectors and their ability to respond to the predicted change is warranted.

The use of an ensemble of parameter sets in this study allowed us to examine the impact of parameter uncertainty in the calibration stage on the outcome of the validation and impact study. However, parameter uncertainty is by no means the only source of uncertainty in this study. As discussed by Semmler et al. (2006) and Murphy et al. (2006) for example, there is a cascade of uncertainty associated with climate impact studies. Additional *climate ensemble members* should be included in future to represent the choice of general circulation model, regional climate model, and climate scenarios.

Acknowledgements

The HBV-Light model used in this study was kindly provided by Prof. Jan Seibert of Stockholm University.



8 Statistical downscaling of precipitation over Ireland using air flow indices: comparison with dynamical downscaling

Statistical and dynamical downscaling methods are widely used to extract local information from General Circulation Model (GCM) simulations. Here, both methods are directly compared for their ability to predict precipitation over Ireland. Although not widely used, vertical velocity from the GCM is used as a predictor in the statistical approach. Predictors are also constrained to increase the weight for strong precipitation events, which are typically underpredicted. For the current climate, the method is shown to perform better than dynamical downscaling although it can only be applied at the location of the rainfall stations.

A first assessment of future Irish rainfall using this statistical downscaling method indicates a higher frequency of rain days in winter and autumn, and a lower frequency in summer, compared with the current climate. Mean intensity and extreme values are predicted to increase in both summer and autumn, however, which may offset the reduction in summer rainfall frequency.

1 Introduction

The methodology and relative merits of statistical downscaling (SD) and dynamical downscaling (DD) are discussed elsewhere in this report.

One approach to SD is to bin together instances of similar weather types or circulation patterns, which serve to characterize the large-scale atmospheric state. This involves classification of the flow into a set of types or patterns. A number of different approaches have been taken to categorise the classes and create relationships with observed surface variables. Subjective (Lamb, 1972) and objective (Goodess and Palutikof, 1998; Jones et al., 1993; Trigo and DaCamara, 2000) analyses of weather types have been based on mean sea level pressure (MSLP) and on a combination of MSLP and geopotential height (James, 2007).

In this study, Irish daily rainfall observations over the period 1961-2000 were linked with GCM data using multiple linear regression. Linear regressions have been shown to underestimate the variance of the predicted dataset, particularly for extremes (Schmidli et al., 2007), so metrics were included to evaluate the performance of the models in this regard. To assess possible changes in future rainfall patterns, the developed regressions were applied to GCM outputs for the A1B and A2 scenarios for 2061-2100 and compared to a chosen reference period (1961-2000).

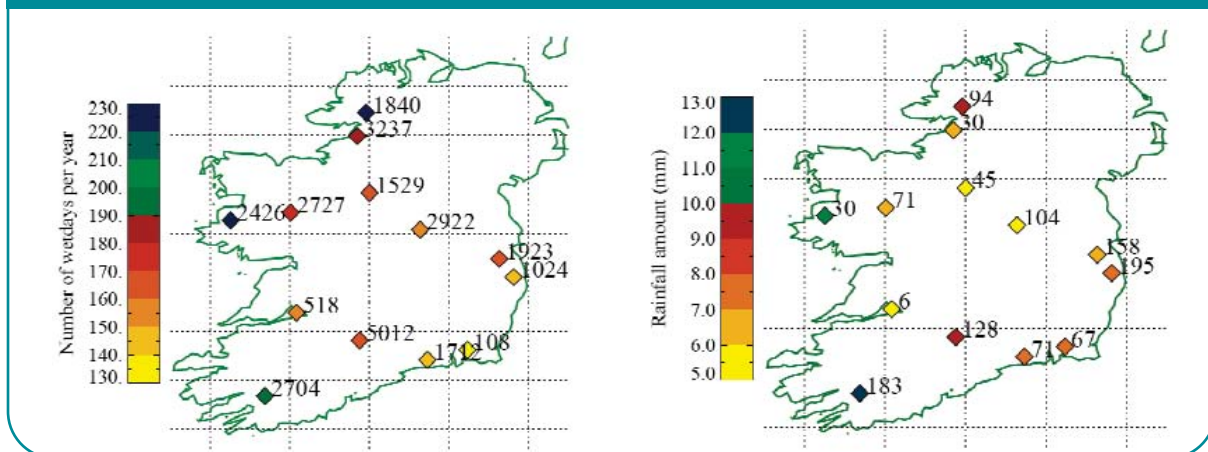
2 Observations and model data

2.1 Rainfall observations

Daily rainfall observations (from 09 UTC to 09 UTC next day) from the Met Éireann archive were used. A rigorous quality control procedure was carried out to examine extreme daily falls and dry months at each station and to remove faulty data. Missing days were estimated by using up to 6 neighbouring stations with similar annual average rainfall; these were ranked and the first to have a complete record for the missing period was substituted for the missing data. For stations without neighbouring stations of similar annual averages, the ratios of monthly means compared to the

missing station was calculated for 3 neighbouring stations and the weighted mean of the 3 estimates was reduced to daily time series by reference to the nearest station. Thirteen of these stations, known to be of good quality, with good geographic coverage, limited missing data and sampling parts of the island with different mean rainfall regimes, were chosen as validation stations.

Figure 1 *Left: location of 13 rainfall stations, labelled with station numbers and coloured by the average number of rain days per year observed. Right: rainfall stations labelled with station elevation (m) and coloured by the mean intensity of rainfall (mm/day) falling on rain days.*

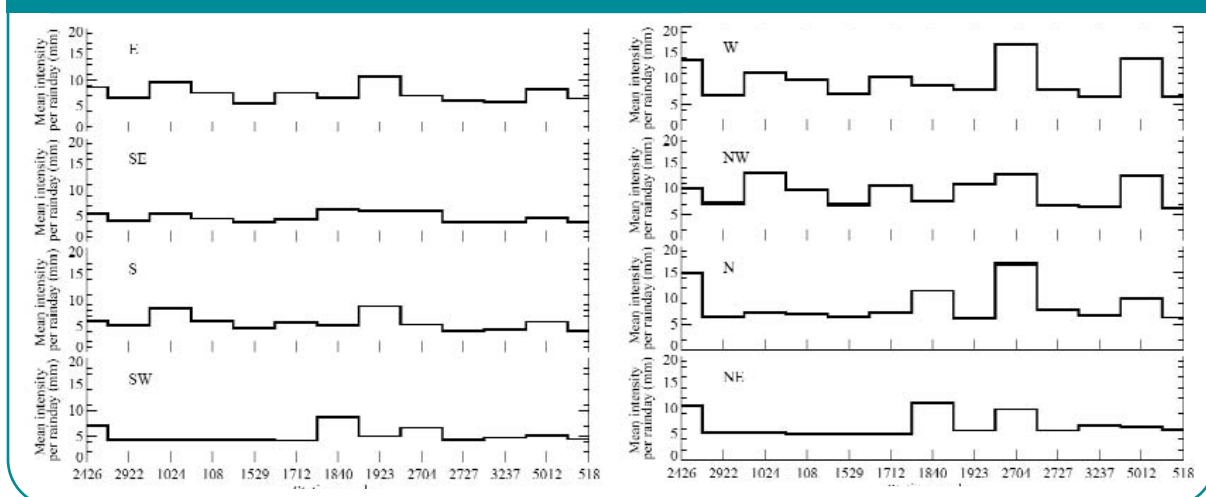


The characteristics of the stations are summarized in Figure 1 and Table 1. Figure 1 identifies the location of each station number and shows the mean annual number of rain days (defined as days when the total rainfall amount is greater than 1 mm) for each station over the period 1961-2000; it also shows the mean intensity of rainfall over all rain days (mm/day) and gives the elevation (m) of each station. Table 1 gives the location in latitude and longitude, elevation, mean intensity, mean number of rain days and also the 70th and 90th percentile of rainfall intensity calculated over the 40-year period. The mean intensity per rain day at each station, binned into the direction of the large scale flow based on MSLP, is shown in Figure 2. Each station shows a different response to the synoptic conditions, depending on its location, elevation, exposure and other local factors.

Table 1: Details of rainfall stations calculated over the 40-year period, 1961-2000...

Station Number	Latitude	Longitude	Elevation (m)	Mean intensity per rainday	No of raindays	70th percentile	90th percentile
2426	53.6314	-9.74722	30	11.1845	227.875	13	24.6
2922	53.5372	-7.36222	104	5.8219	156.2	6.6	12.3
1024	53.0528	-6.18611	195	7.93328	147.975	8.5	18.3
108	52.3111	-6.76667	67	7.04585	136.85	8.2	15.7
1529	53.9111	-8.00000	45	5.74954	169.975	6.5	12.3
1712	52.2097	-7.27083	71	7.34022	148.05	8.3	16.4
1840	54.7306	-8.04167	94	9.84307	229.675	11.8	21.4
1923	53.2389	-6.36667	158	6.84255	162.1	7.3	14.8
2704	51.8389	-9.31389	183	12.476	198.475	14.2	29.7
2727	53.7111	-8.99139	71	6.40305	177.15	7.3	13.6
3237	54.4917	-8.15278	30	6.1435	185	7.1	12.7
5012	52.4069	-8.12222	128	9.08972	167.475	10	21.1
518	52.6903	-8.91806	6	5.82938	157.575	6.8	12.4

Figure 2 Mean intensity of rainfall per rain day for all rainfall stations separated into the large-scale flow direction bins used in this study.



2.2 ERA-40 reanalysis

The statistical model was calibrated using predictor fields from the ERA40 re-analysis dataset (Uppala et al., 2005). The predictor fields used here were vorticity, divergence, vertical velocity, relative humidity, specific humidity and temperature at 1000, 850 and 500 hPa. These fields were chosen to span dynamic and moisture components. The fields are available at 6 hour intervals on a 1.125° by 1.125° grid over the region. Daily averages of these fields, corresponding to the 09 UTC observations, were interpolated to the station locations. The MSLP field was used to determine the synoptic-scale air flow indices, described in section 3.

2.3 Dynamical downscaling model

The Rossby Centre Regional Climate Model, RCA3 (Kjellström et al., 2005; Jones et al. 2004) was run over the European region, as defined for the ENSEMBLES project, at a ~ 25 km resolution. RCA3 was driven by ERA40 forcing fields (ERA40-DD).

2.4 Global climate model

The GCM used here was ECHAM5, in the configuration used for the IPCC Fourth Assessment Report (IPCC, 2007) experiments. This model was developed at the Max Planck Institute (MPI), Germany and has 31 vertical levels, a horizontal resolution of $1.9^\circ \times 1.9^\circ$ (Roeckner et al., 2003) and is coupled to the MPI ocean model with a $1.5^\circ \times 1.5^\circ$ horizontal resolution and 40 vertical levels (Marsland et al., 2003). An evaluation of the models used in the IPCC FAR (van Ulden and van Oldenborgh, 2006) found that the ECHAM5 model was one of the better performing models for both global and European MSLP fields when compared to the ERA-40 re-analysis.

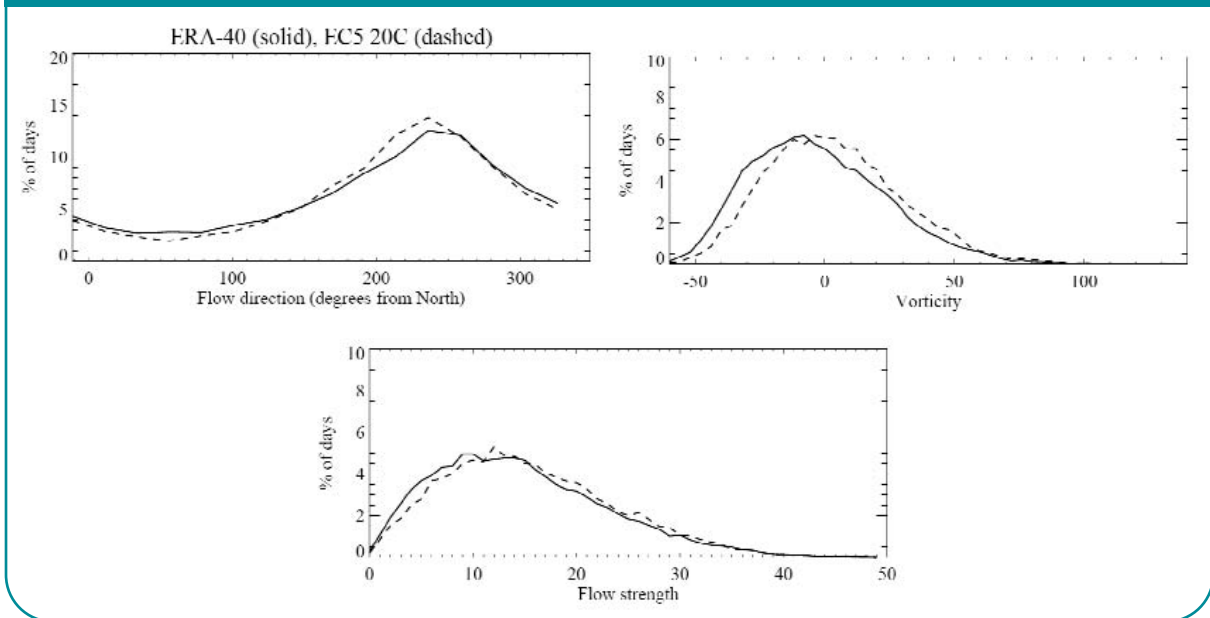
GCM predictor fields used for downscaling should follow some basic guidelines (Hewitson and Crane, 1996): they should be capable of representing current climate conditions at the spatial scale used for the downscaling model; the predictor-predictand relationship should be time-invariant; the set of predictors chosen should incorporate the range of the future climate change signal; and their future values should not lie outside the climatology used to calibrate the model (Wilby et al., 2004).

2.5 GCM validation – air indices, vertical velocity

As the observations show very distinct rainfall patterns at different stations for different large-scale flow directions (Figure 2; Sweeney, 1992), air indices (Conway et al., 1996) were used as indicators of the large-scale flow. While it has been established that ECHAM5 is one of the better GCMs at reproducing MSLP fields, it is of interest here to assess the quality of the GCM air indices. Figure 3 shows the frequency distribution of large-scale vorticity, flow direction and strength calculated from ERA40 and ECHAM5 MSLP fields. While the comparison is good in general, the GCM has more instances of southerly/southwesterly flow and fewer easterly/northeasterly cases. Table 2 shows

that the differences for most of the flow direction bins used in this study are less than 1%, apart from the southwesterly flows. It tends also towards more positive vorticity (cyclonic flows) and higher flow strengths.

Figure 3 *Intercomparison of ERA-40 and ECHAM5 air indices over 1961-2000. Frequency distribution of the percentage of days associated with flow direction, vorticity and flow strength.*



One of the predictor fields used in this study was vertical velocity, which is a diagnostic model variable, calculated from the divergence and u and v velocity fields. As such, it is a product of the dynamic fields which are a strength of GCMs, while being highly correlated with the probability of precipitation. It has a limited range, so is not likely to change so much in the future that it will lie outside the model calibration range of values. It has not generally been used in statistical downscaling models, however, so a validation of how well the GCM reproduces this variable was carried out. The mean and standard deviation of the 850 hPa vertical velocity field from both ECHAM5 and ERA40 over the period 1980-1989 is shown in Figure 4. The GCM reproduces the reanalysis data very well, particularly in the spatial pattern of the standard deviation. The means differ slightly, but as the 20th century ECHAM5 run used here is not based on observational data (as is the case with ERA40), this is less important than the standard deviation. The distributions of vertical velocity values from both models for this period display a high correlation over the range -0.5 to 0.5 Pa/s, representing over 99% of the data (not shown). ECHAM5 underestimates the ERA40 values by 0-10% over most of this range.

Table 2: Frequency of occurrence of days with flow direction in the bins used in this study for ERA-40 and ECHAM-5.

Flow direction bin	Percentage occurrence	
	ERA-40 1961-2000	ECHAM5 1961-2000
E	5.82	4.82
N	8.62	7.74
NE	5.59	4.72
NW	14.11	13.54
S	13.24	14.21
SE	8.30	7.55
SW	20.60	23.83
W	23.73	23.60

3 Statistical downscaling method

The predictand used was daily rainfall amount from 12 stations. As local factors, such as orography, exposure and elevation, play a large role in the amount of rain received at any particular station, an objective approach, based on air indices and weather type classification, was used (Conway and Jones, 1998).

To weight the regressions towards the larger events, which are typically underestimated in SD and DD efforts, thresholds were developed to minimise the number of dry days and maximise the number of days with heavier rainfall. A combination of the ERA40 vertical velocity ($<0.01\text{Pa/s}$) and vorticity ($>-2.3\times 10^{-5}/\text{s}$) fields, interpolated to the station locations, and the large scale vorticity ($>-10\text{ hPa}/10^\circ\text{latitude}$), Z , computed from the ERA40 MSLP field after Jones et al. (1993) and Conway and Jones (1998) was found which removed 87-92% of the dry days while retaining 70-80% of the events above the 40-year 70th percentile for each station.

The data from each station were then divided into 8 bins according to the large-scale direction of flow (see Figure 2). Separate regressions were carried out for each flow direction bin for each station, using stepwise multiple linear regression. New predictor fields were selected as long as they improved the correlation coefficient by more than 1%. A summary of the results of this predictor selection process are described in the following section.

4 Results

4.1 Predictor selection

By far the most frequent predictor selected by the regression procedure was the 850 hPa vertical velocity, which was the first predictor in 64% of the cases. As mentioned above, this predictor is not commonly used in SD efforts. Overall, vertical velocity at the three levels represented 38% of predictor fields, with vorticity at 24% and relative humidity at 16%. These three predictors alone cover 78% of those selected. Temperature was selected only 3% of the time and divergence and specific humidity were selected 10.5% and 8.5% respectively. The dynamic effects of divergence are already represented in the diagnostic vertical velocity parameter, which these results show is clearly a better indicator of rainfall probability.

The selection of relative humidity over specific humidity has implications for statistical modelling of climate change. While the specific humidity is likely to increase in the future with rising atmospheric temperature and may have a different distribution to that with which the model was calibrated, the relative humidity range is constrained. As long as the relative humidity is well-represented in the GCM, it is recommended above the specific humidity for statistical downscaling of rainfall. Upper level (500 hPa) humidity fields were selected more frequently than the lower level (1000 and 850 hPa) fields, as opposed to the dynamical fields, where the lower levels were more highly correlated with rainfall than higher levels.

4.2 SD and DD Model Validation – daily precipitation modelling

Table 3 shows a series of validation metrics for both the SD and DD, driven by ERA-40 data calculated over a chosen validation period (1971-1990). The SD performs better than the DD for all stations, with higher correlation coefficients for all stations: 0.61-0.76, compared to 0.25-0.49. The biases and RMSE are lower for the SD for almost all stations. The Percentage Forecast Correct and Critical Success Indices (Wilks, 1995) are also consistently higher for the SD model. Similar statistics were generated for a version of the SD model which was run without using the thresholds described above. Including the thresholds consistently improves the model prediction of both occurrence and intensity at all stations by a few percent in most cases.

4.3 Comparison of ERA-40 and ECHAM5 forcings: station-level, seasonal and annual

A number of metrics were used to compare the performance of the downscaling models when forced by ERA40 and ECHAM5 fields. The mean intensity and number of rain days reflect their ability to predict intensity and occurrence. The standard deviation and 70th and 90th percentiles are a measure of how well the models reproduce the distribution, particularly of heavy rainfall. Figures 5-8 show how the ERA40-DD, ERA40-SD and EC5-SD reproduce the observed rainfall for each station for four seasons and also annually.

Performance of all 3 models for the mean intensity is very good for both SD models at station level, and much better than the DD model for the stations with higher rainfall returns, which the RCM consistently underestimates. The summer rainfall tends towards lower temporal and spatial coherence and the results show the strength of the SD model in reproducing the mean local statistics, given a very sporadic field, which the DD cannot match. The ECHAM5 forced model tends to underestimate the mean intensity for all stations and has a larger spread across the stations, compared to the ERA40 forced models.

Table 3: Comparison of ERA-40 forced SD and DD with observed rainfall over the validation period.

Station number	Model	Correlation	Bias	RMS	PFC	CSI
2426	ERA40-SD	0.72	-0.69	7.02	0.79	0.72
	ERA40-DD	0.25	3.75	10.53	0.67	0.54
2922	ERA40-SD	0.65	0.08	3.36	0.76	0.56
	ERA40-DD	0.44	-0.85	5.01	0.70	0.54
1024	ERA40-SD	0.72	-0.07	4.75	0.76	0.57
	ERA40-DD	0.42	-2.03	7.79	0.67	0.50
108	ERA40-SD	0.69	0.10	3.96	0.76	0.54
	ERA40-DD	0.45	-0.64	5.84	0.70	0.49
1529	ERA40-SD	0.61	0.14	3.67	0.74	0.59
	ERA40-DD	0.39	-0.64	5.30	0.68	0.54
1712	ERA40-SD	0.68	0.01	4.41	0.74	0.53
	ERA40-DD	0.42	-0.28	6.10	0.69	0.50
184	ERA40-SD	0.68	0.07	6.29	0.77	0.69
	ERA40-DD	0.47	0.97	8.05	0.77	0.70
1923	ERA40-SD	0.65	-0.27	4.62	0.70	0.53
	ERA40-DD	0.41	-1.14	6.73	0.73	0.56
2704	ERA40-SD	0.76	0.29	7.59	0.75	0.62
	ERA40-DD	0.49	1.04	10.31	0.74	0.64
2727	ERA40-SD	0.69	-0.28	3.75	0.76	0.64
	ERA40-DD	0.49	-0.67	5.47	0.72	0.58
3237	ERA40-SD	0.67	-0.22	3.60	0.75	0.63
	ERA40-DD	0.44	-0.70	5.42	0.71	0.59
5012	ERA40-SD	0.72	0.28	5.48	0.74	0.55
	ERA40-DD	0.42	0.14	7.69	0.73	0.57
518	ERA40-SD	0.67	-0.05	3.23	0.75	0.59
	ERA40-DD	0.42	-0.79	5.08	0.69	0.53

Figure 4 Intercomparison of ERA-40 (left) and ECHAM5 (right) 850 hPa vertical velocity. Mean (top) and vertical velocity mean and standard deviation (bottom) values over the integration area are shown for the period 1980-1989.

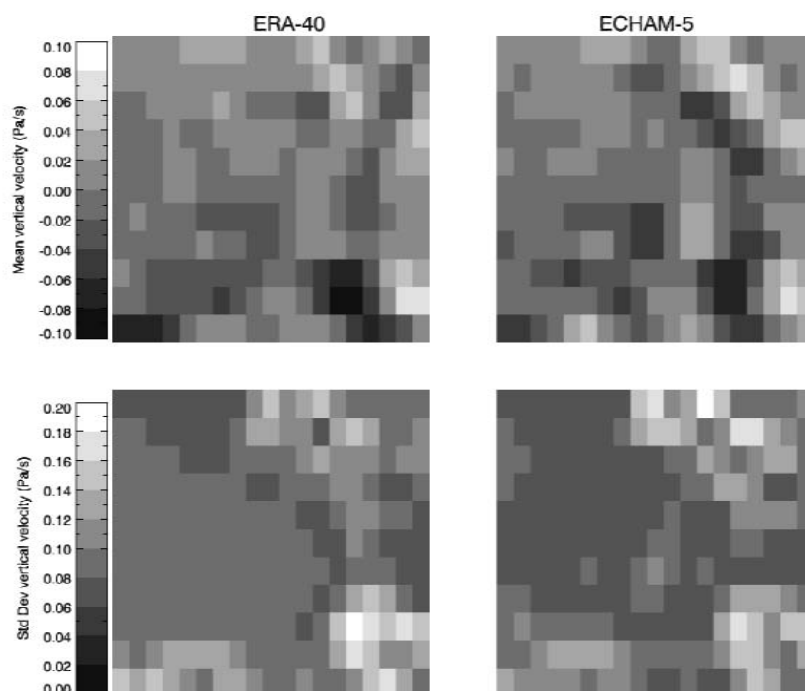


Figure 5 Winter (DJF), spring (MAM), summer (JJA), autumn (SON) and annual (ANN) mean rainfall intensity per rain day for 3 models: ERA40-DD (*), ERA40-SD (o), and EC5-SD (Δ).

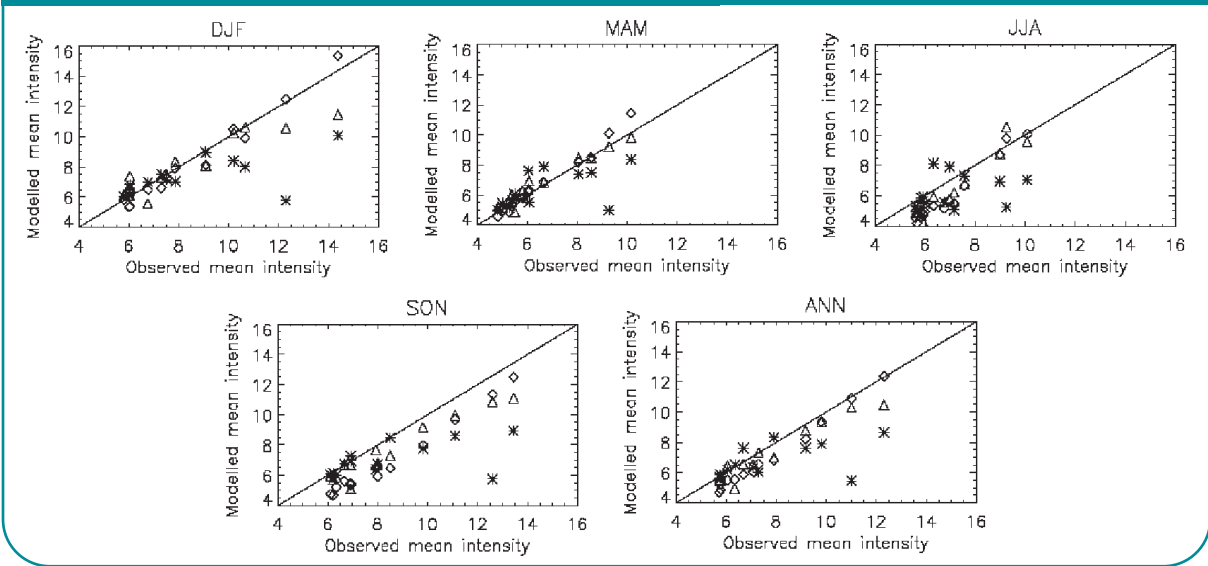


Figure 6 As for Figure 5, but for percentage of rain days.

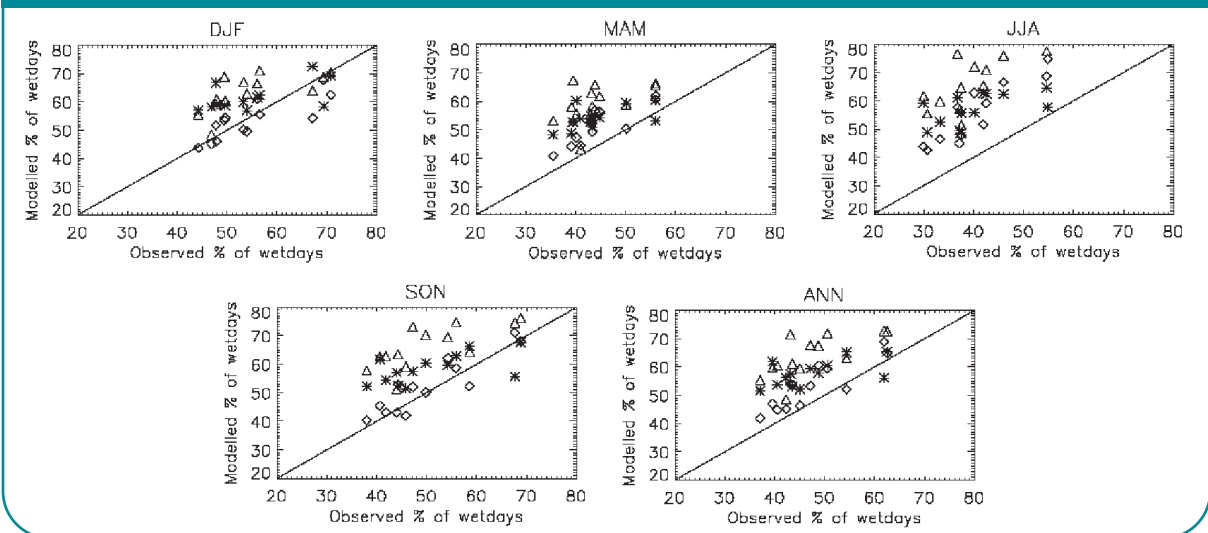


Figure 7 As for Figure 5, but for 70th percentile rainfall amounts.

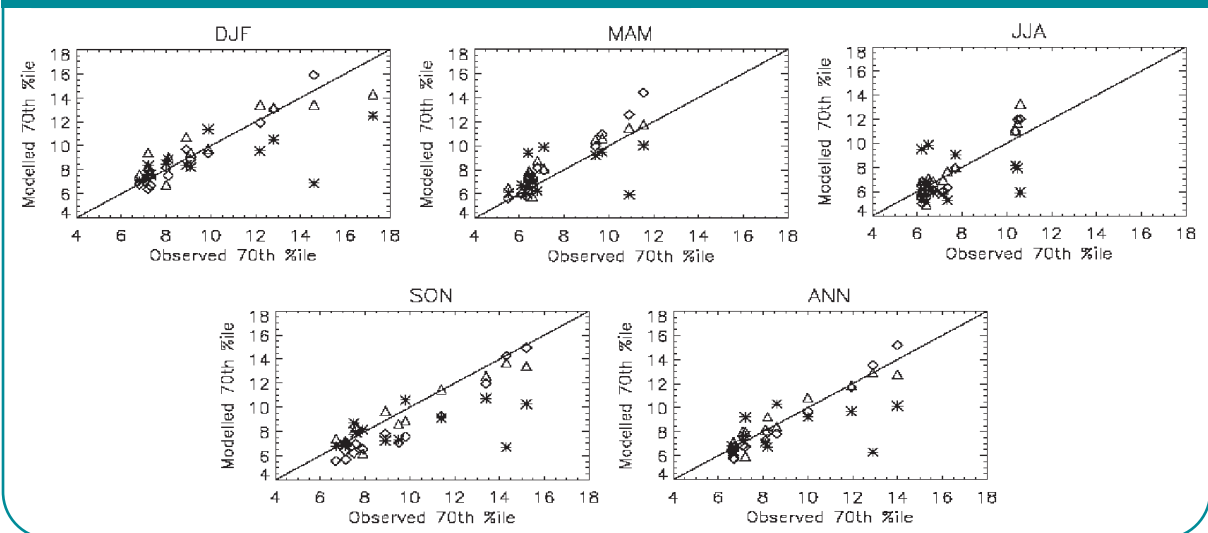
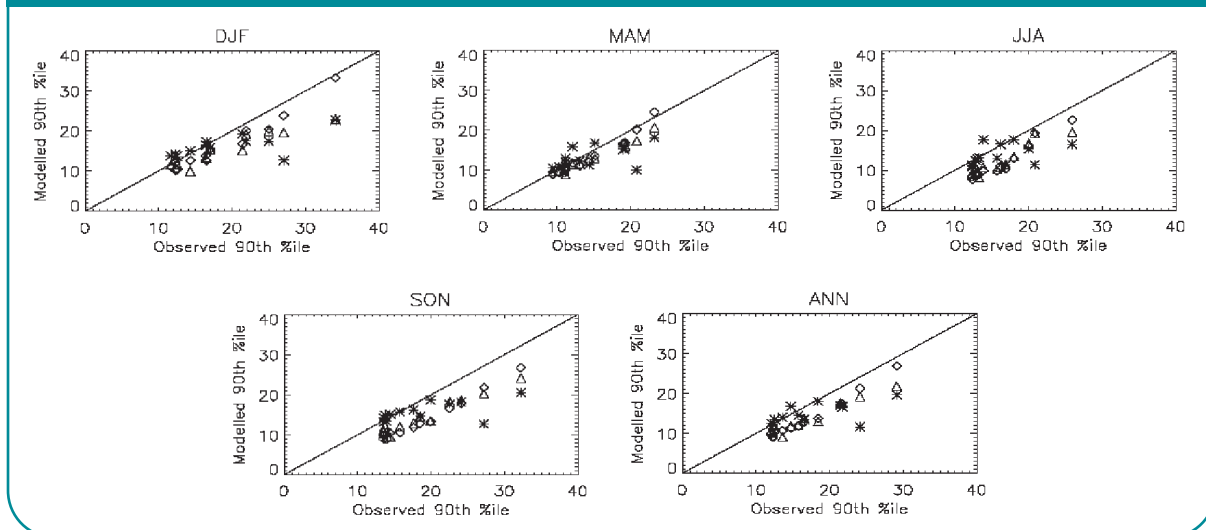


Figure 8 As for Figure 5, but for 90th percentile rainfall amounts.



All models tend to overestimate the number of rain days and perform better in winter and autumn than spring and summer. The ERA40-SD is consistently closer to the observed compared to the ERA40-DD, but the ECHAM5-SD has the worst performance in this respect. This is likely due to the biases in the large-scale air indices mentioned above, as stronger, more cyclonic and more frequent southwesterly flows in the GCM will result in more frequent rainfall events. The tendency for the DD model is to overestimate the stations with fewer rain days than those with more frequent rain days.

Standard deviations, on the other hand are consistently underestimated by all the models, particularly for stations with higher variance. The DD model performs better here, with very good comparisons with the observations for low variance stations, but again underestimating the higher variance stations. Both the ERA40 and the ECHAM5 forced SD underestimate standard deviations for all stations, but do so more consistently than the DD. This difference is highlighted in Table 4, which shows the mean annual modeled/observed ratio of each metric averaged across all stations and the correlation between the modeled and observed annual mean of each metric over all stations.

Table 4: Comparison of statistics of observed rainfall with modeled. The modeled/observed quantity is the average over 20 years over all stations. The correlation is between the annual averages of the modeled and observed, across stations.

Model	Metric	No raindays	Mean intensity	70th pc	90th pc	Std dev
ERA40-DD	Mod/obs	0.91	1.24	0.94	0.90	0.87
	Correlation	0.53	0.57	0.45	0.60	0.66
ERA40-SD	Mod/obs	0.90	1.13	0.95	0.80	0.67
	Correlation	0.99	0.87	0.99	0.99	0.99
EC5-SD	Mod/obs	0.94	1.37	1.02	0.80	0.64
	Correlation	0.97	0.69	0.96	0.97	0.96

For the measures of heavy rainfall, the 70th percentile amount is modeled very well by the SD models for most seasons and for the annual amounts. The more extreme 90th percentile values are underestimated for almost all stations and seasons, however, but the station correlations are still good and better than the DD model.

For 2061-2100, frequency of rain days is increased by up to 10% for most stations compared to 1961-2000, apart from some along the south coast and in the northeast. Changes in mean intensity, on the other hand are less spatially coherent. More stations may experience drier conditions, on average, but the stations with larger rainfall returns show increases. Most stations show very little difference between the A1B and A2 scenarios.

JJA and SON show the largest increases relative to the 20th century, particularly for those stations with the highest returns and variance. The number of wet days shows a larger seasonal signal, with most stations showing an increasing frequency of rainfall in DJF and SON, little change in spring and a tendency to reduced frequencies in summer. These differences tend to cancel out in the annual mean. The 70th and 90th percentile amounts show a tendency to increase in the annual means, mostly driven by increases in extreme JJA and SON values. To summarise: the statistical modelling approach, applied to two scenarios from one GCM, predicts that future rainfall will be more frequent in winter and autumn, and less so in summer. Both the mean intensity and extreme values will increase in both summer and autumn, however, which will offset the reduction in summer rainfall frequency.

5 Discussion and conclusions

The aim of this study was to develop a statistical downscaling technique for precipitation, to evaluate the method against dynamical downscaling, and to use the method to predict future Irish rainfall. Multiple linear regression was used to define statistical relationships between the observed rainfall and large-scale mass, moisture and temperature fields, which were weighted towards heavy rainfall events. Sets of valid predictor fields and regression coefficients were determined for different large-scale flow directions for each rainfall station.

The predictor selection process chose the 850 hPa vertical velocity as the first predictor of rainfall in 64% of cases. While not a prognostic model variable, it is calculated from dynamic model variables, which GCMs can model well. Combined with vorticity and relative humidity, it makes for a very robust predictor set for rainfall.

Daily rainfall time series generated by the statistical downscaling model, and by dynamical downscaling using a 25km resolution RCM, both forced with ERA40 reanalysis data, were compared with observations over a 20 year validation period. The statistical model performed better at station level for both occurrence and intensity metrics. This is expected as each set of regressions are weighted towards the statistics of rainfall experienced at a point location given a particular set of large-scale conditions.

Comparison of the two methods showed that the statistical downscaling model performs better at station level for all metrics except for the standard deviation of the rainfall intensity. Seasonally, summer rainfall poses the most difficult scenario for all models; predictive ability is best for autumn/winter rainfall. When forced by the GCM fields, the statistical downscaling model predicts more frequent but less intense rainfall. This is partly due to the GCM overestimating the frequency of moist southwesterly flows over the region.

The developed statistical downscaling method has been applied to the ECHAM5 future (2061-2100) data (A1B and A2 scenarios). Compared to the reference period 1961-2000, the annual mean intensity changes are small for all stations although in summer and autumn mean intensity increases can be seen for the wetter stations. Decreases in rain day frequency in summer for the drier stations and increases in autumn and winter for the wetter stations are predicted. In the annual average, changes offset each other. One of the more important predictor fields selected by the multiple linear regression used in this study was vorticity. An investigation of changes in large-scale vorticity, calculated from the MSLP fields shows that both the A1B and A2 scenarios have a significant trend towards larger values, particularly pronounced in summer months. This is almost certainly the driver of the increased summer rainfall intensity in these scenarios. This index is highly correlated with rainfall (Conway and Jones, 1998) and is a dynamical quantity and therefore well-represented by GCMs. While increases in the absolute value of the vorticity field is plausible in climate change scenarios, the question remains whether these changes are realistic or whether the statistical model is too sensitive to such changes.

Future work should include the application of the suggested SD method to more GCMs to reduce the uncertainty in the predictions.



9 Wind Energy Resources in Ireland: possible impacts of climate change

There is considerable interest in renewable energy resources as a means of mitigating the impacts of climate change. 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 m/s at 50 m level over land, values that are sufficient to sustain commercial enterprises with current wind turbine technology. However, climate change is likely to alter the wind patterns in the future; a reduction in speeds may reduce the commercial returns or pose problems in the continuity of supply; an increase in the frequency of severe winds (e.g. gale/storm gusts) may similarly impact on supply continuity.

In this preliminary study the impacts of climate change on wind speeds are examined from a wind energy perspective. Using a regional climate modelling approach a small ensemble of wind predictions are produced at 60 m level for Ireland. The simulation datasets suggest an increase in available wind power in future winter months (2021-2061 relative to 1961-2000) and a decrease in the summer months. The magnitude of the change is about 10%.

Experiments with the COSMO regional climate model show that increasing the horizontal resolution of the downscaling grid has a positive impact on the quality of the winds; local effects, such as the distortion of the airflow by surface features, are better resolved.

1 Introduction

The wind energy potential of the Irish climate has been well documented. The work by ESBI International with TrueWind Solutions (SEI, 2003) led to the production of a Wind Atlas for Ireland specifically aimed at the wind energy community. Based on a wind mapping system (MesoMap) the methodology involved observational weather data and a numerical weather model (MASS) that downscaled reanalysis data to produce wind information at 50, 75 and 100 m level on a 1 km grid over Ireland (the modelling went as fine as 0.2 km).

In principle, this work could be extended to account for climate change by downscaling AOGCM future scenario data. However, running models at such high resolution is a substantial task. The objective of this study is to quantify the change and to evaluate the ability of dynamical downscaling to describe near surface winds at a local level.

2 The current climate

Met Éireann's observational network provides detailed (i.e. hourly frequency) observations of the wind flow at 10 m level. However, the data are of limited use in wind energy applications where turbine heights are typically in the range 50-100 m. Upper-air soundings at two locations in Ireland do provide some wind information at the higher levels but the data are not regularly available for a specific height. Fortunately, Numerical Weather Prediction models provide a method for extracting the relevant information; all available observational data (satellite and surface based) are assimilated by a model that produces a physically consistent three-dimensional picture (analysis) of the atmosphere. Analyses are available for Ireland through the ERA-40 reanalysis project but the resolution of the archive data is relatively coarse (~125 km) – too coarse to pick up the influence of small surface features. A regional climate model is therefore used to map the information onto a finer grid.

The RCA3 regional climate model was used to downscale ERA-40 reanalysis data on a 13 km grid (31 vertical levels) covering Ireland for the period 1961-2000. This downscaling approach also has the advantage that wind information can be delivered by the model for arbitrary heights above the surface. For convenience, this study will focus on winds at 60 m height, although this figure is probably on the low side for modern wind turbines. While the ERA-40 data are

based on actual observations, climate model simulations are also available, unconstrained by observations, that provide a description of the current and future climate; the global datasets, with a much coarser resolution compared with the ERA-40 data, can also be downscaled for comparison.

Figure 1 Mean 60m wind speed [m/s] 1961-2000 produced by downscaling global model atmospheric data using the RCA3 regional climate model. In (a) the global data (ERA-40) are based on the assimilation of actual observations over the period i.e. are a measure of the “true” wind field. For (b) and (c), climate model simulation data are used (ECHAM4 and ECHAM5 respectively). These are not linked to observations but nevertheless produce an average wind field that is close to (a), confirming the ability of the climate models to capture the essential details of today's climate.

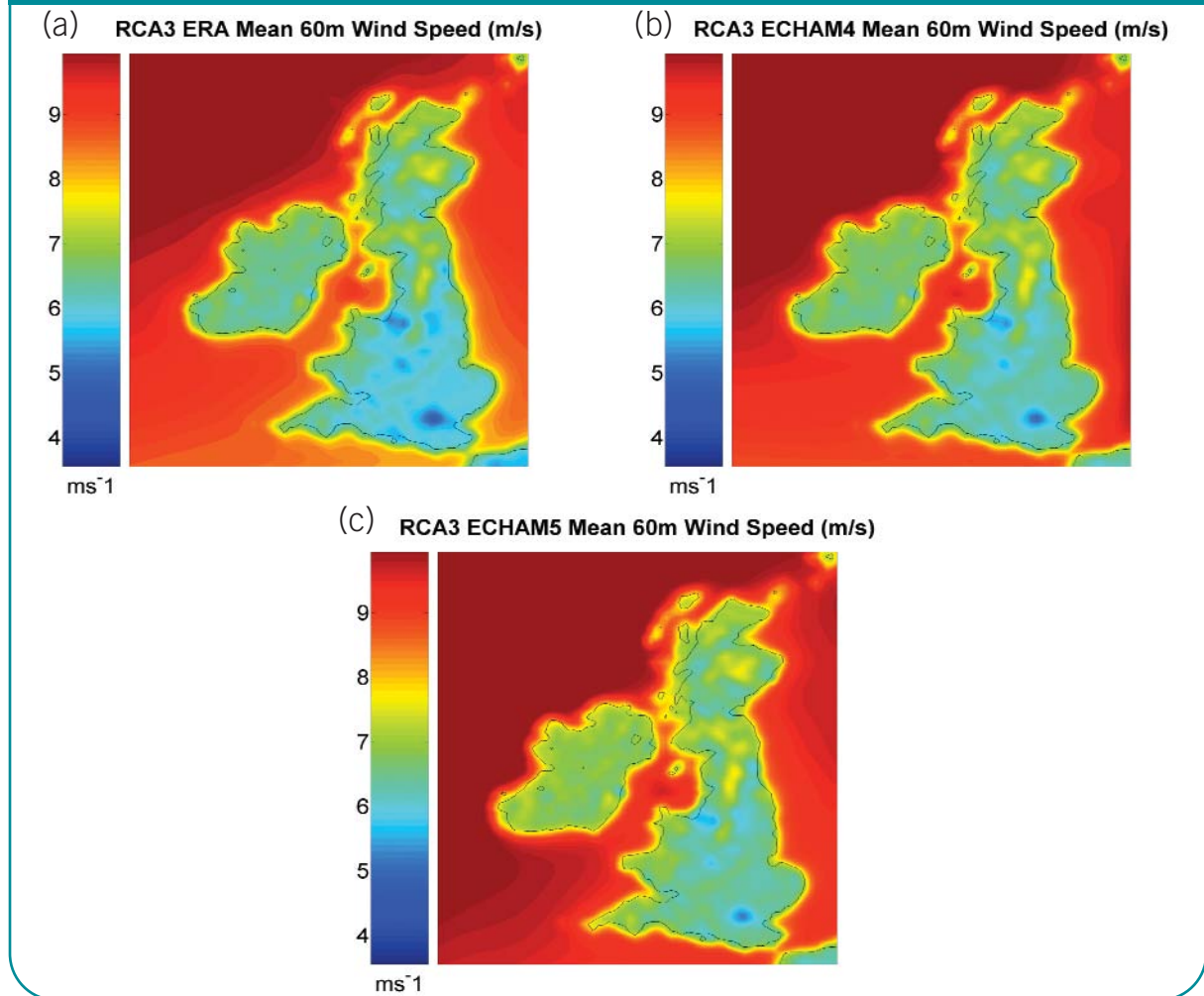


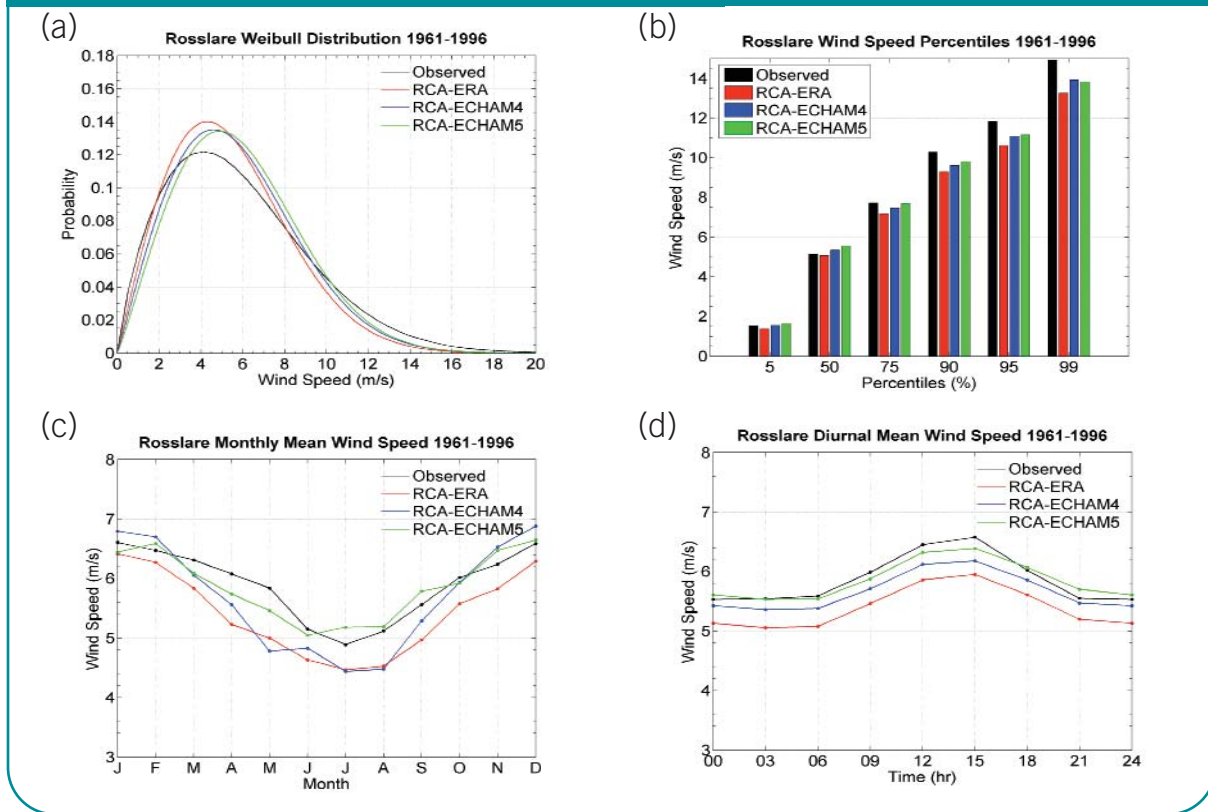
Figure 1 shows the downscaled 60 m winds averaged over the period 1961-2000 for ERA-40 and for two climate model simulations (ECHAM4 and ECHAM5). The performance of RCA3 has been comprehensively analysed (see Mc Grath et al, 2004) but the wind verification focused on the 10 m level due to a lack of observations at higher levels in the boundary layer. In spite of the improved horizontal resolution of the output wind fields the data are still too coarse for wind energy applications. Nevertheless, it is instructive to compare the observed 10 m winds at Met Éireann’s synoptic stations against the downscaled 10 m values. A typical comparison is shown in Figure 2. Note that while the agreement is reasonable, there are systematic differences between the observed and simulated winds, some which are probably related to the lack of resolution; this issue is returned to in section 4.

3 Future simulations

The power available for extraction from the winds is proportional to the cube of the wind speed³. The cube of the speed will therefore be used as a surrogate for the available power. Figure 3 shows the relative changes in the power between

3 More correctly, it is proportional to ρV^3 where ρ is the air density, V the wind speed.

Figure 2 Performance of the regional climate model: wind data at 10 m level from the models listed in Figure 1, compared against the observed winds at Rosslare (1961-1996). Wind speeds in many cases can be accurately described with a Weibull distribution; in (a) the fits for the observations and downscaled data are shown, with a similar percentile analysis in (b). The seasonal and diurnal variation of the speeds are shown in (c) and (d). Agreement in all cases is reasonable, but not perfect as local winds are often influenced by surface features that are too small to be resolved by the model resolution (13 km) used here.



the current (1961-2000) and future (2021-2060) climate, based on downscaled ECHAM5 and ECHAM4 simulations for different greenhouse gas emission scenarios. The changes are relatively small but when stratified by season (Figure 4) larger differences emerge: winter increases – as much 8-11% in the case of ECHAM5 A1B simulation; and summer decreases – as much as 14-16% for the ECHAM4 B2 simulation. The results can also be categorised for a wind speed range to reflect the cut-in and cut-out speeds of a turbine (typically 4 and 25 m/s, respectively). The results (not shown) indicate a decrease in the probability of useful wind speeds occurring during the summer months.

In spite of the changes in the speed, the average wind directions do not change significantly in the simulations (see Figure 5 for Arklow wind farm).

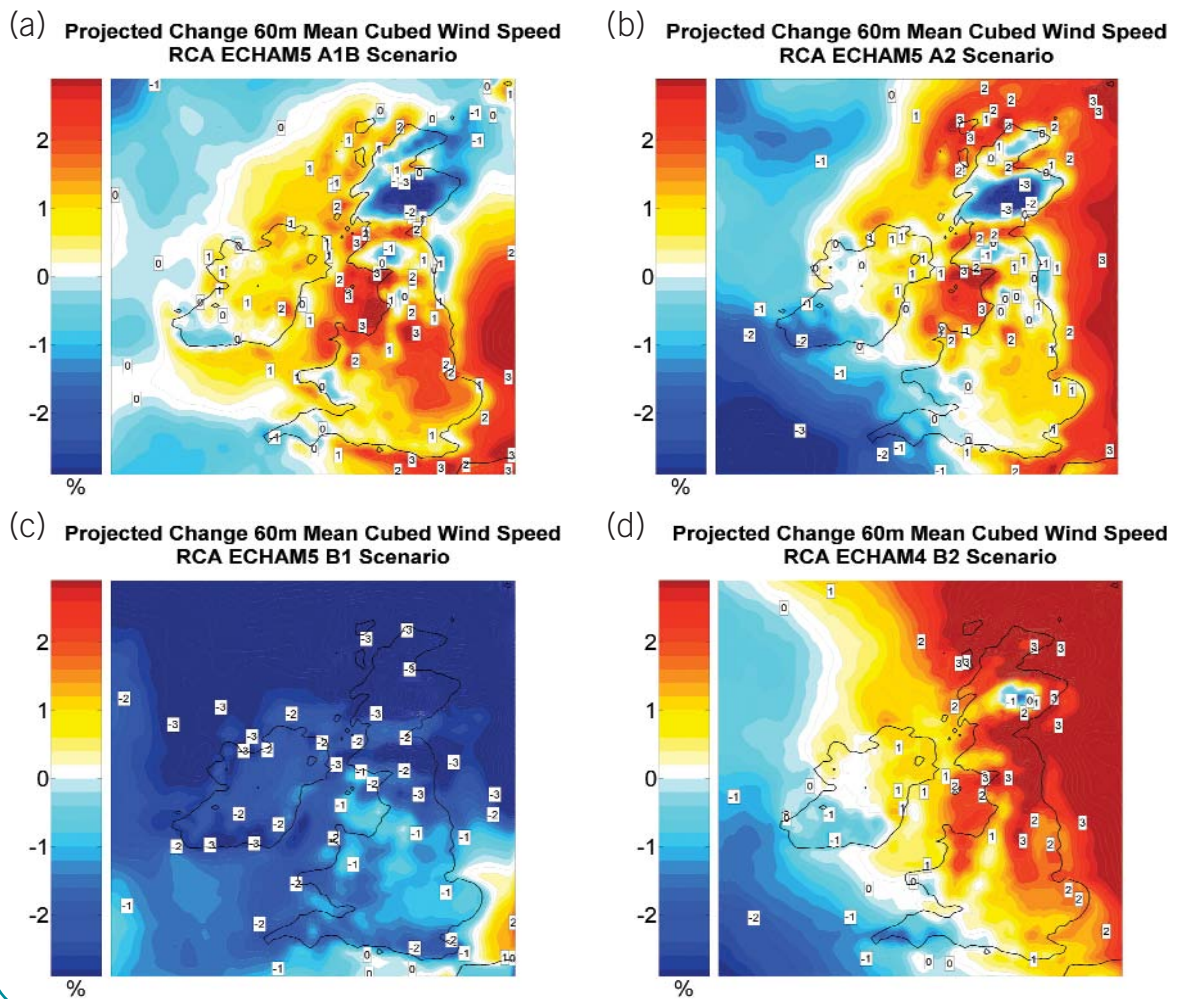
4 High resolution downscaling

Increasing the horizontal resolution of the downscaling should in principle increase the quality of the output winds, particularly near the surface where the local elevation features can have a marked influence on the wind flow pattern. To investigate this feature the climate version of the Lokal-COSMO model⁴ was used to simulate the current climate. The model was run on a 7 km horizontal grid with 45 vertical levels. ERA40 reanalysis data were used for the downscaling, with hourly output fields. In addition, the model was configured to run simulations on an internal area at a 2.8 km horizontal resolution i.e. a one-way nesting procedure. Two years of simulations were run (2005-2006).

The impact of the increase in resolution is highlighted in Figure 6, which shows the validation of the winds at 10 m height averaged over 12 stations. The COSMO model produces a better fit to the observations compared with ECMWF and RCA3 (not shown). The COSMO 2.8 km simulations do not show significant improvements over the 7 km simulations, but in individual cases the increased resolution does have a positive impact.

4 A nonhydrostatic regional climate model.

Figure 3 Projected change in wind power (2021-2060 relative to 1961-2000): % change in the mean annual cubed wind speed at 60 m level for 4 climate simulations. The changes for Ireland are relatively small (typically 0-2%).



A good example of the benefits of high resolution is shown in the wind rose for Casement Aerodrome (Figure 7). The observed wind rose shows few southerly winds due to the influence of the Wicklow Mountains. The COSMO simulations, particularly on the 2.8 km grid, provide the most accurate simulations.

5 Conclusions

The impact of climate change on the near surface winds over Ireland has been evaluated by downscaling AOGCM data using regional climate models. The results from a small ensemble of simulation datasets suggest an increase in available wind power in future winter months (2021-2061 relative to 1961-2000) and a decrease in the summer months. The magnitude of the change is about 10%. However, these results should be treated with caution in view of the uncertainty in future greenhouse gas emissions, the reliability of the AOGCM simulations and the relatively coarse grid (~13 km horizontal grid) used for the dynamical downscaling. There are other issues of relevance to wind energy use. The frequency of spells of weather with light winds, for example, needs to be investigated.

Experiments with the COSMO regional climate model show that increasing the horizontal resolution of the downscaling grid has a positive impact on the quality of the winds; local effects, such as the distortion of the airflow by surface features, are better resolved. This approach is obviously justified in mapping the current wind climate but for the future climate it may be prohibitively expensive; the uncertainty in climate projections will require an ensemble approach, substantially increasing the computational cost. The use of very high resolutions (1-3 km) may be difficult to justify in the light of the basic uncertainty in the raw data.

It is intended to follow up this study with the production of a wind atlas for the future climate, guided by the above results.

Figure 4 As for Figure 3 with mean data stratified into summer and winter seasons.

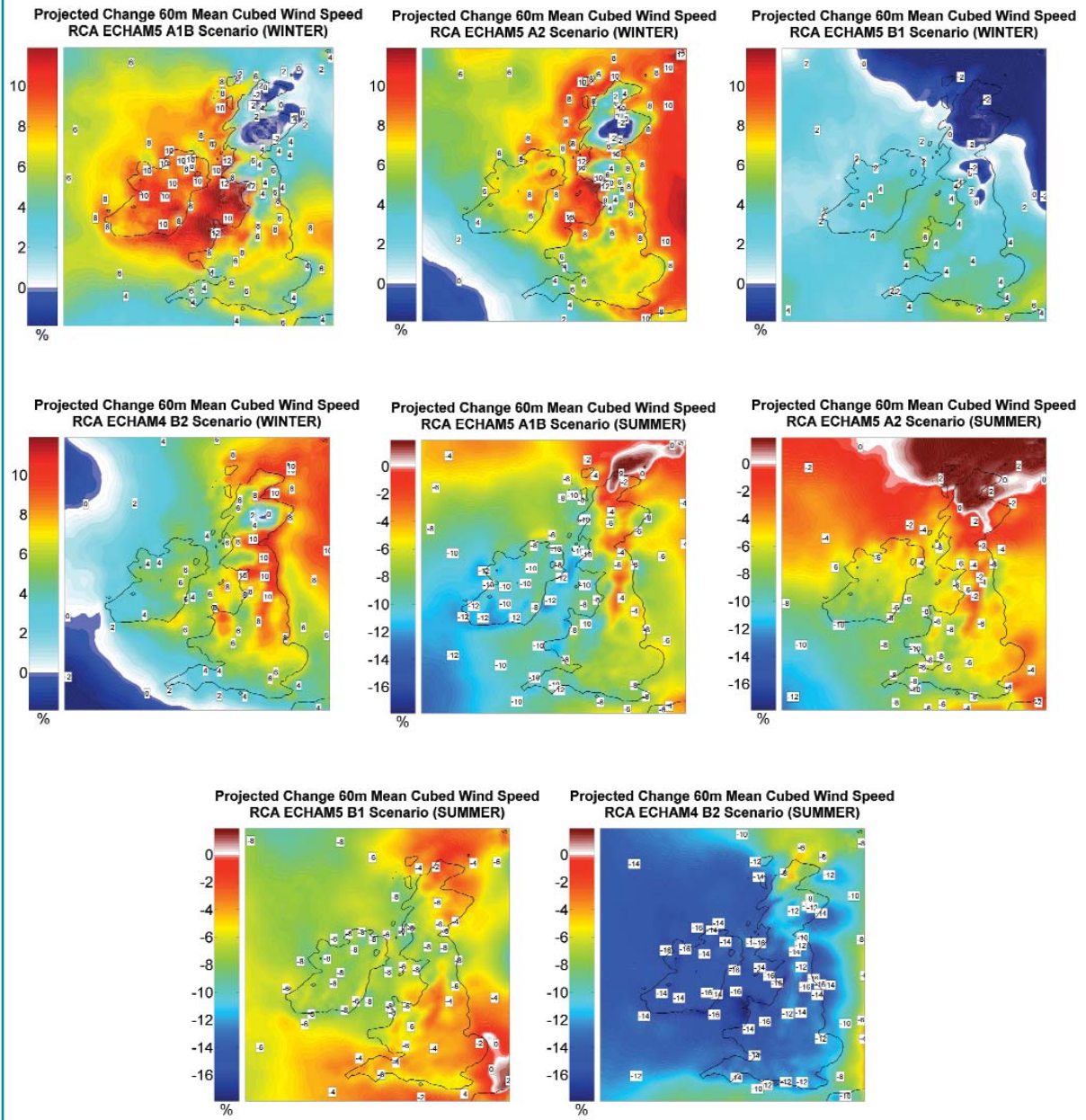


Figure 5 The 60m winter wind rose for downscaled ECHAM5 data at Arklow wind farm: (a) 1961-2000; (b) 2021-2060 (A2 scenario).

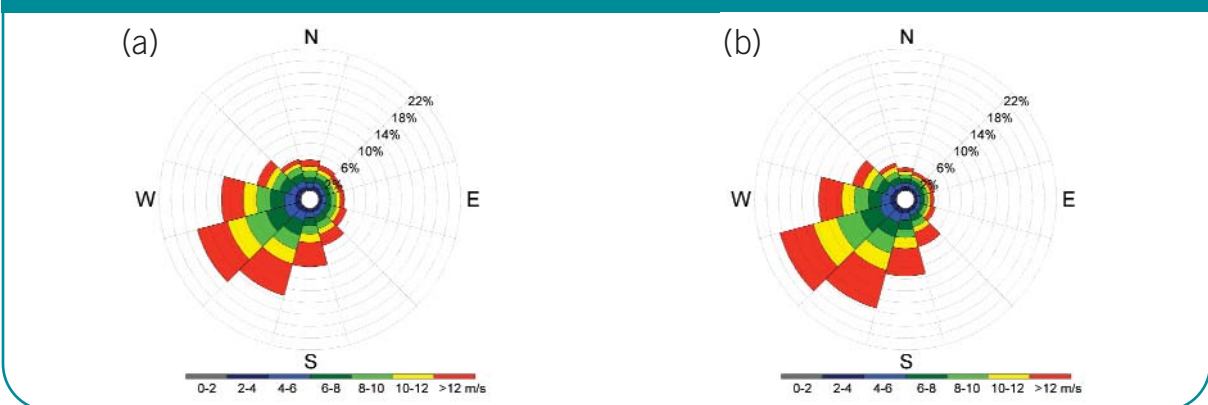


Figure 6 Mean observed 10m winds at 12 Irish stations compared against ECMWF analysis data, COSMO 7 km data and COSMO 2.8 km data for the period 2005-2006. (a) shows the Weibull distributions, (b) the wind speed percentiles, (c) the mean monthly wind speeds and (d) the diurnal cycle.

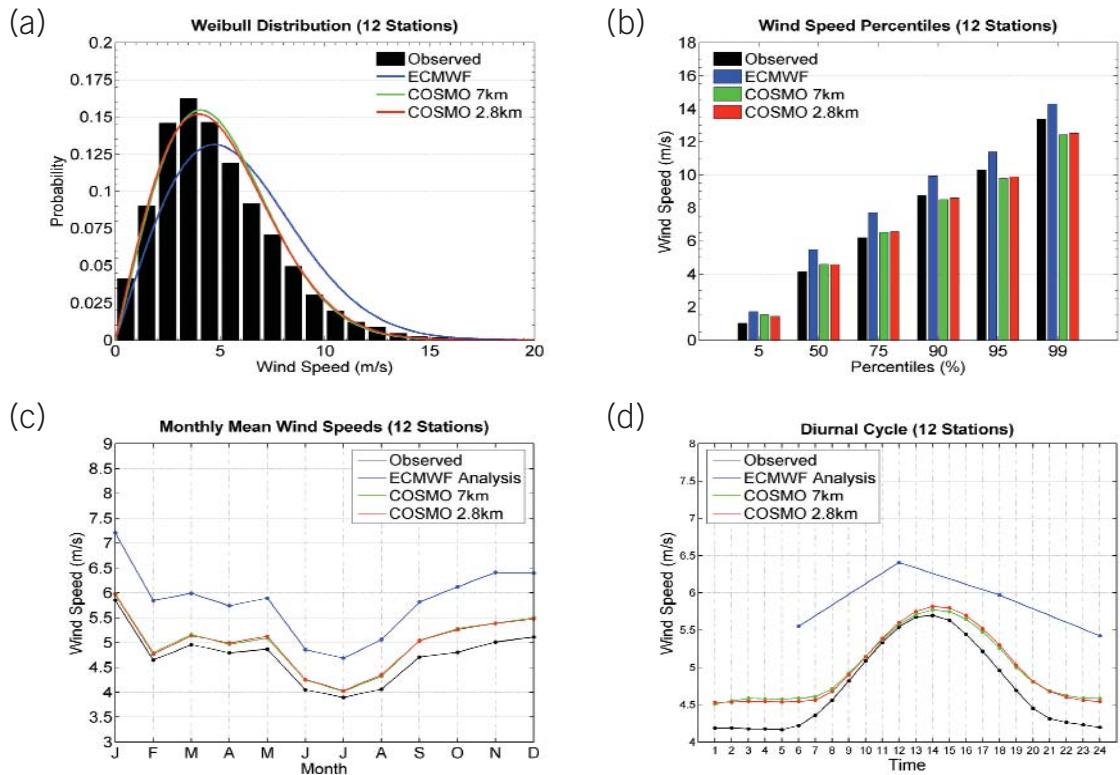
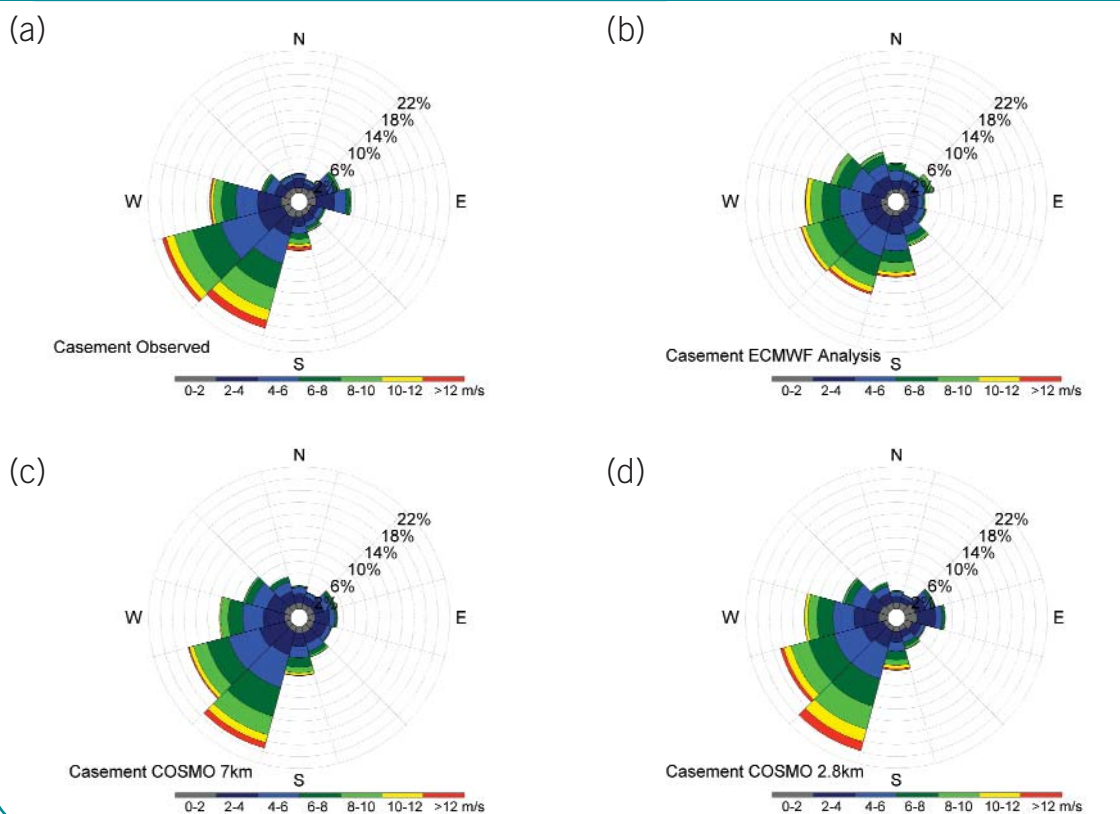


Figure 7 10m Wind Roses at Casement Aerodrome 2005-2006 for (a) Observed, (b) ECMWF ERA-40 reanalysis data, (c) COSMO 7 km downscaled ERA-40 data and (d) COSMO 2.8 km downscaled ERA-40 data.





10 Very High resolution Downscaling

As part of its commitment to the ENSEMBLES project, C4I agreed to investigate whether the use of very high resolutions might yield more accurate climate simulations, particularly for precipitation. The approach is scientifically plausible as a finer representation of land elevations and coastlines should yield a more accurate description of the flow patterns and surface forcing. As the existing RCA3 regional climate model is tuned to synoptic scales it is not an appropriate tool for very high resolution (e.g. 5 km) modelling. The Pennsylvania State University / National Center for Atmospheric Research mesoscale model (known as MM5) was chosen instead; it is a limited-area, nonhydrostatic, model designed to simulate or predict mesoscale atmospheric circulation. A 'community' model, it is widely used within the meteorological community. MM5 is similar to RCA3, but computationally more expensive to run. As ENSEMBLES was also interested in the use of a wide range of regional climate models, C4I agreed to test the MM5 model over the reference European area used by this project and the results are reported here; its performance is similar to RCA3 which was also run over the same area.

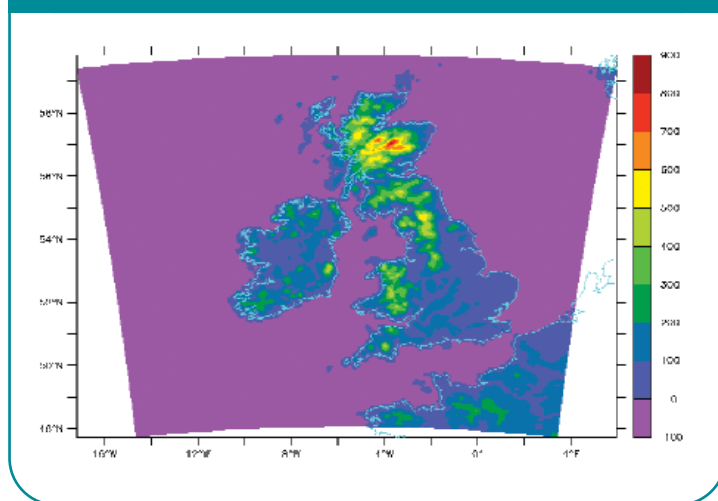
The results for the 5 km resolution experiments were a little disappointing, making it difficult to justify the very heavy computational cost. It is possible that the 3-year simulation was too short to properly evaluate the benefits of very high resolution.

This note formed part of a report to ENSEMBLES.

Introduction

Test simulations with MM5 have been carried out on the common ENSEMBLES domain (25 km horizontal resolution) for 1961-1970, and on a smaller domain (Figure 1) with a 5 km horizontal resolution for 1961-1963. In both cases the model was driven with ERA-40 reanalysis data. The 25 km resolution run has been carried out with the aim of providing the ENSEMBLES community with another RCM ensemble member. With the high resolution run the aim has been to investigate whether this approach has any advantage over statistical downscaling methods which, computationally, are far cheaper to perform. Statistical downscaling of the 25 km resolution simulation is possible for Ireland and the UK, since gridded observation data of 2 m temperature and precipitation are available from the UK Climate Impacts Programme (UKCIP) in a horizontal resolution as fine as 5 km.

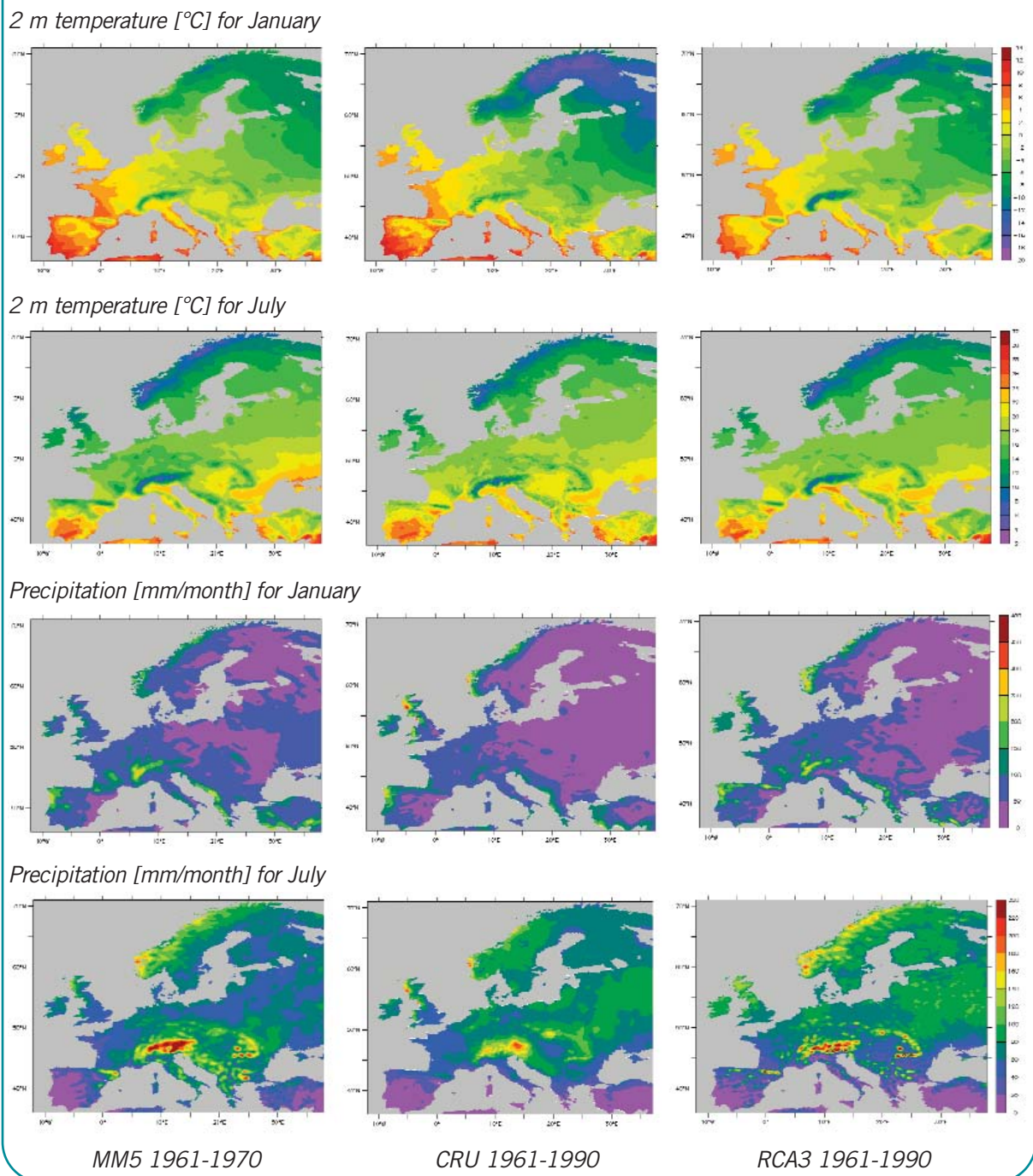
Figure 1 Orography of the 5 km resolution simulation domain [m].



1 Evaluation of the 25 km RCA3 and MM5 simulations

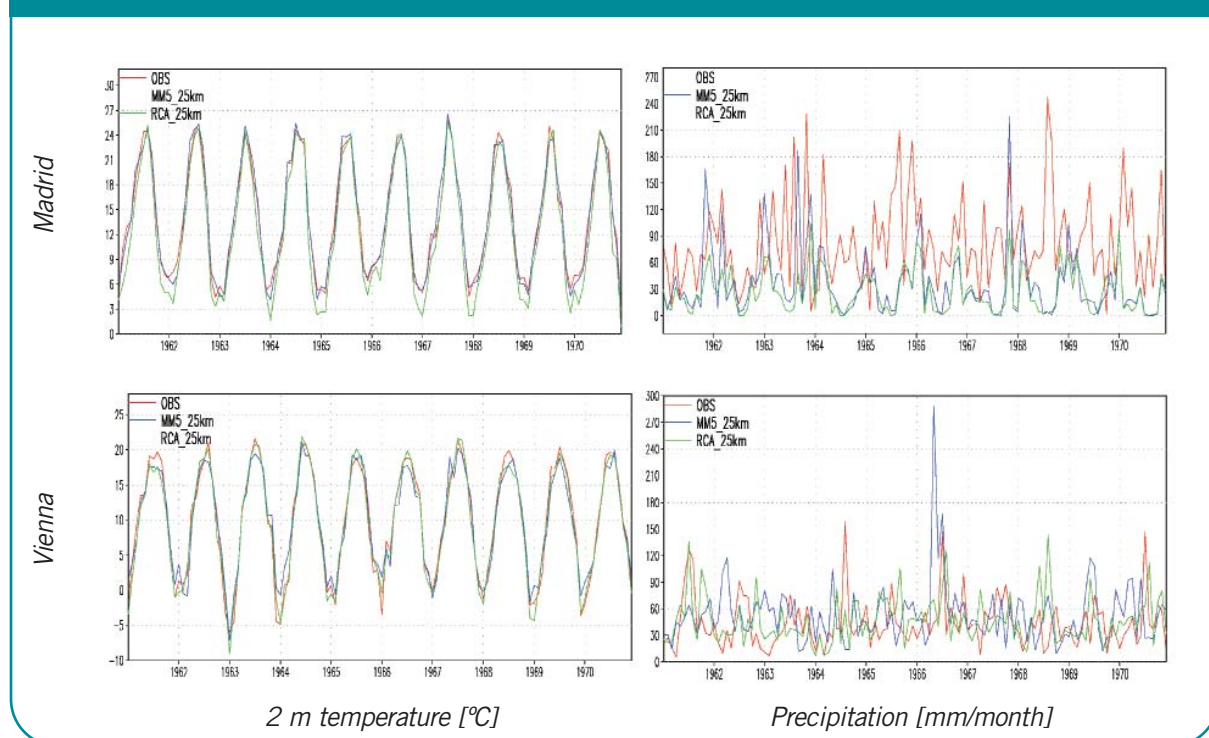
Results from the reanalysis-driven 25 km RCA3 and MM5 simulations have been compared to gridded observation data from the Climate Research Unit (CRU). In MM5 a choice of parameterisations is available. The following set has been chosen after a series of tests: mixed-phase cloud microphysics after Reisner, Kain-Fritsch with shallow convection, MRF planetary boundary layer scheme, RRTM longwave radiation scheme and Noah land-surface scheme. The comparison can only be seen as a preliminary assessment of the quality of the MM5 simulation, since the simulation has been carried out for the limited time period of 1961-1970, whereas the CRU observation data are available as climatological means for 1961-1990. The outputs from the RCA3 simulation, which were delivered to DMI in October 2006, are available for the whole CRU observation period of 1961-1990 and can be directly compared to these data. Figure 2 shows climatological monthly means of 2 m temperature and precipitation for the RCA3 and MM5 simulations as well as the CRU observation data.

Figure 2 2 m temperature and precipitation as simulated by RCA3 and MM5 compared with gridded observation data from CRU.



Both MM5 and RCA3 show too warm winter temperatures over Scandinavia. The over-prediction is as strong as 6°C for the MM5 simulation and around 4°C for the RCA3 simulation. For other regions and other seasons, the temperature is reasonably well represented. MM5 seems to over-predict the precipitation in winter over Eastern Europe. In summer the RCA3 simulated precipitation distribution is quite noisy. In this respect the MM5 model seems to be slightly better. Figure 3 shows time series of 2 m temperature and precipitation at two selected stations from both model simulations and from observations from the European Climate Assessment & Dataset (ECA&D) project for the overlapping time period 1961-1970. The quality of the results is station dependent, possibly because of some local effects. Based on the spatial distribution and the time series results, RCA3 and MM5 seem to simulate the present day climate with similar quality when driven by ERA-40 reanalysis data. Thus MM5 could well be used to create another ensemble member.

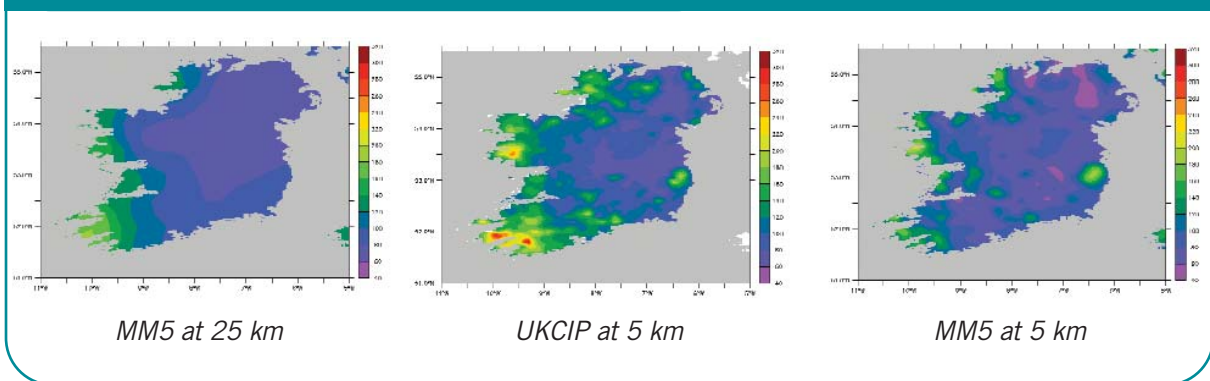
Figure 3 *Figure 3. Time series of monthly mean values of 2 m temperature and monthly sums of precipitation in Madrid and Vienna as simulated by RCA3 and MM5 and according to observation data from ECA&D.*



2 Evaluation of the 5 km MM5 simulation

Figure 4 shows the simulated mean (1961-1963) monthly precipitation over Ireland, from the 25 km and the 5 km resolution MM5 runs compared to the gridded UKCIP observation data for January. In the 25 km resolution run the main features of the spatial precipitation distribution pattern are captured: less precipitation over the east and the midlands and more over the mountainous areas in the southwest, west and northwest. However, due to a poor representation of the orography in the 25 km resolution run, the more intense precipitation over small scale mountains is not captured. Even over the Wicklow Mountains (horizontal extent of about 100 km) in the east/southeast of the country, the precipitation is no more intense than in the surrounding region according to the 25 km resolution run. In addition, a slight under-prediction of the precipitation in most areas should be noted. The 5 km resolution run shows much more detail in the precipitation distribution. But, unfortunately, the general under-prediction is more pronounced than in the 25 km resolution run. Thus, the high computational cost does not seem to be justified unless some further effort is put into the development of more suitable parameterisations. In a 5 km resolution the application of a convection parameterisation scheme is questionable, since some of the convective processes are resolved at this resolution. But results without the application of the convection scheme are not promising either, probably because only some of the convective processes are resolved. It might be difficult to achieve a good realisation in a 5 km resolution for this reason.

Figure 4 Mean monthly precipitation [mm/month] for January (1961-1963) as simulated by MM5 at 25 and 5 km resolution and according to gridded observation data from UKCIP.



3 Summary and conclusions

An additional regional climate model, MM5, has been set up on the common European ENSEMBLES domain with a 25 km horizontal resolution and has been run for 10 years driven by ERA-40 reanalysis data and compared to the RCA3 simulation results and to observation data. Results suggest that the MM5 and RCA3 simulations are comparable in quality. MM5 could be used to create an additional ensemble member for the ENSEMBLES community. However, it has been suggested that the GCM/RCM matrix⁵ is only sparsely filled at this stage and that instead of adding another RCM it would be more desirable to fill the gaps in the matrix. However, the non-hydrostatic formulation of the MM5 model opens up the possibility of simulations with horizontal resolutions finer than 10 km.

The MM5 model has been run on a model domain covering Ireland and the UK with a 5 km horizontal resolution for 3 years. The results are not very promising – possibly due to partly resolved and partly unresolved convective processes in such an intermediate grid resolution. Even though more orography-induced details of the spatial precipitation distribution are captured compared to the 25 km resolution simulation, the precipitation is generally under-predicted. As a result, extreme precipitation events are also strongly under-predicted in the 5 km resolution simulation – more so than in the 25 km resolution simulation. The high computational cost of a 5 km resolution simulation does not seem to be justified according to our investigation, unless more work is undertaken to make the parameterisations suitable for this resolution.

5 ENSEMBLES devised a spreadsheet matrix, listing desirable downscaling simulations (global model and regional model pairings).



11 Influence of climate change on ozone concentrations and UV-B radiation in Ireland

Overexposure to the ultraviolet radiation from the sun has negative health consequences and may trigger skin cancers. High level atmospheric ozone acts as a filter to reduce the intensity of the rays reaching the surface. However, the use of chlorofluorocarbons (CFC) in the industrial era has led to a reduction in the ozone concentrations, reducing the effectiveness of this filter. While CFCs are now stabilising or decreasing, thanks to the Montreal Protocol in 1989, the effects of climate change may upset this recovery.

This study, using AOGCM data, links ozone concentrations with stratospheric circulation and temperature patterns. It suggests that, as a consequence of climate change in the stratosphere, the recovery in the atmospheric ozone might be slower than anticipated from a reduction in CFC emissions. While in the long term the concentrations will recover, the risk of skin cancer in Ireland will not necessarily decrease. Social factors may also play a role. A warmer Irish climate (with drier summers) is likely to increase outdoor leisure activities and potentially increase the exposure to damaging UV-B.

1 Introduction

Without the stratospheric ozone layer, intense ultraviolet (UV) radiation from the sun would reach the surface, with destructive biological consequences. The most damaging component, UV-C, is completely removed by high level atmospheric ozone, while UV-B is partially blocked and UV-A is virtually unaffected. In this study, the focus is on the UV-B which is associated with sunburn and implicated in the incidence of skin cancers. It is also of interest because the intensity of the radiation reaching the Earth's surface is sensitive to the atmospheric ozone concentration, and therefore may be affected by climate change.

Global ozone concentrations declined at a rate of 6% per decade from 1980 to 2000 due to the anthropogenic release of chlorofluorocarbon (CFC) with a consequent increase in the UV-B radiation (Meehl et al., 2007). According to Böhm (1993) every 1% decrease in ozone leads to a 1.3 % increase in UV-B radiation. Following the international treaty designed to protect the ozone layer (Montreal Protocol) in 1989, emissions of CFC have declined in recent years and ozone concentrations are predicted to recover at a rate of 1 to 2% per decade from 2000 to 2020. However, there is uncertainty in the prediction – 2006 witnessed a record low concentration over Antarctica.

Ozone concentrations are also affected both by the atmospheric circulation and temperatures in the lower and middle stratosphere (Austin et al., 1994; Pitari et al., 2002). This meteorological dependence is used here to assess the impact of climate change, focusing on summer months when UV exposure in the population is greatest due to increased outdoor activity.

2 Relating atmospheric ozone to the weather

Austin et al. (1994) developed a linear, multiple regression model to predict UK ozone concentrations for a few days ahead using geopotential height and temperature values as predictors:

$$\Omega = a * g_{250} + b * T_{150} + c * T_{30} + d$$

where Ω is the total ozone column in Dobson units (DU), g_{250} the 1000-250 hPa thickness field in m, T_{150} the temperature at 150 hPa in K, T_{30} the temperature at 30 hPa in K and a , b , c and d the regression coefficients (seasonally dependent).

Table 1 shows the values for June, July and August from Austin et al. (1994), their Table 2a:

For g_{250} and t_{30} the regression coefficients (a and c) are negative. Therefore an increase in these parameters leads to a decrease in total column ozone. In contrast, an increase in t_{150} leads to an increase in total column ozone. To assess circulation and temperature induced ozone concentration changes in a future climate, the regression model was applied to mean values of the predictors in the ECHAM5-A1B global climate simulation for 2021-2060 and to the control simulation for 1961-2000. Values for June, July and August from the ECHAM5 simulations were extracted for Dublin and regression equations applied for each month separately. The assessment is generally valid for the whole country.

Month	a	b	c	d
June	-0.113	1.85	-2.62	1691
July	-0.097	1.82	-2.90	1573
August	-0.038	1.71	-0.33	408

Table 2 shows extracted predictor values for June, July and August 1961-2000 and 2021-2060 and predicted total ozone column values.

Month	g_{250} [m]	t_{150} [K]	t_{30} [K]	Ω [DU]
June 1961-2000	10280	219.4	222.8	352
June 2021-2060	10440	216.3	221.4	331
July 1961-2000	10550	214.7	224.2	290
July 2021-2060	10460	217.4	222.2	310
August 1961-2000	10500	214.6	222.8	302
August 2021-2060	10640	213.1	220.5	295

Whereas t_{30} decreases in all months from the control to the scenario period, g_{250} and t_{150} show contrasting changes for the different months. A decrease in t_{30} alone would lead to an increase in total column ozone, but the increase in g_{250} and the decrease in t_{150} in June and August overwhelm this signal leading to an overall decrease in total column ozone. Only in July do the simulated changes in all three predictors lead to an increase in ozone concentration. Averaged over all summer months, 315 DU are simulated for the control and 312 DU for the scenario period. Even though there are considerable month to month differences, this averaged decrease of 1% is similar to the globally averaged circulation induced ozone reduction simulated by Pitari et al. (2002): 0.8% by 2030 compared to 2000.

The results suggest that the recovery in the atmospheric ozone might be slower than anticipated from a reduction in CFC emissions; circulation changes in a future climate may have a significant impact. While in the long term the concentrations will recover, the risk of skin cancer in Ireland will not necessarily decrease; social factors may also play a role. A warmer Irish climate (with drier summers) is likely to increase outdoor leisure activities and potentially increase the exposure to damaging UV-B.



12 Influence of climate change on heating and cooling energy demand in Ireland

The influence of climate change on heating and cooling energy demand in Ireland is investigated using a small ensemble of regional climate simulation datasets, driven by the ERA-40 reanalysis data, and by the global climate model ECHAM5-OM1 assuming three different greenhouse gas emissions scenarios. Simple relationships between commonly used temperature based indices and heating/cooling energy demand have been used. It has been shown previously that these relationships are highly correlated even though other parameters such as wind speed, sunniness and cost of energy also influence consumption.

Results suggest that heating energy demand has already slightly decreased in the south of the country, for the time period 1981-2000 compared to 1961-1980. The difference might not be a robust signal because of the relatively short averaging time period of 20 years and the model uncertainty, which is in the same order as the simulated changes. However, a clear trend of decreasing heating energy demand is predicted for the rest of this century using longer averaging periods of 40 years. Whereas air conditioning is not an issue in Ireland's current climate, a weak demand might develop towards the end of this century in the southeast of the country in summer.

1 Introduction

Climate change mitigation policies that attempt to reduce the dependence on fossil fuel resources require realistic forecasts of future energy demand. On the industrial and transport side, the future requirements are difficult to predict as demand is driven largely by economic and social factors. However, domestic heating (and cooling) requirements are known to be strongly linked with the climate, and therefore more amenable to analysis and forecasting. The relationship has been studied mainly using observations (Heim et al., 2003; Valor et al., 2001; Kadioglu and Sen, 1999; Lough et al., 1983; Le Comte and Warren, 1981; Warren and Leduc, 1981; Quayle and Diaz, 1980). As expected, a strong link between temperature and heating/cooling energy demand can be found. Kharin and Zwiers (2000) have investigated changes in future heating/cooling energy demand from an ensemble of coarse resolution AOGCM simulations. Other applications include forecasting the heating/cooling energy demand for several months ahead (Lehman and Warren, 1994). The prediction of heating/cooling energy demand has important economic value (Davis, 2001; Valor et al., 2001) as energy production can be planned in advance.

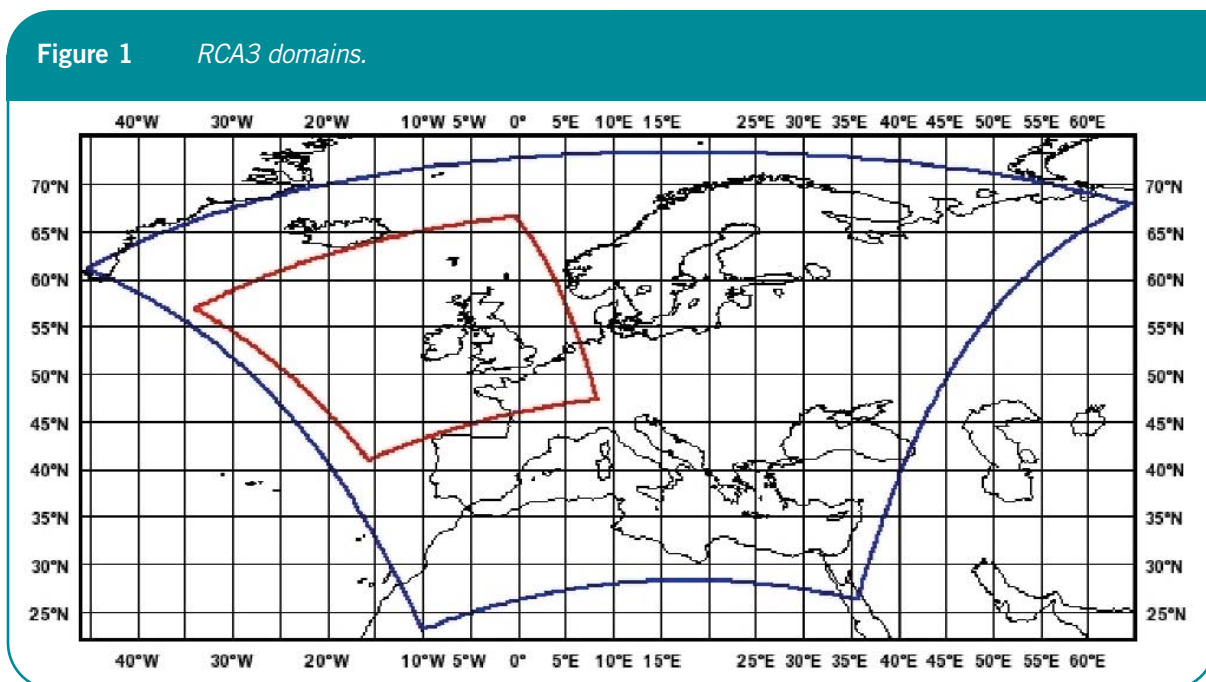
In 2006, thermal energy usage in Ireland accounted for 34% of the Total Primary Energy Requirement (Howley et al., 2007); a high fraction of this is associated with space and water heating. A changing climate is not the only factor that will affect this energy demand; population change, improvements in building insulation standards and changing social attitudes will also play a part. However, it is important to quantify the contribution from climate change. Therefore, our study investigates changes in heating/cooling degree days using high-resolution regional climate model simulations.

2 Experiment setup

Instead of only using one single model simulation of the future climate, we use a small ensemble of model simulations generated with the Rossby Centre regional Atmospheric climate model version 3 (RCA3) (Kjellström et al., 2005; Jones et al., 2004). This allows us to obtain an estimate of the uncertainty in our prediction. Two different model domains (Figure 1) and three different emissions scenarios from the Special Report on Emissions Scenarios (SRES) (Nakicenovic et al., 2000) have been used to include both the uncertainty stemming from internal variability in the

regional climate model and from the future development of greenhouse gas emissions: globalisation with an emphasis on environmental sustainability (B1), globalisation combined with strong economic growth (A1B) and regional development with emphasis on economic growth (A2). RCA3 uses a rotated latitude/longitude grid. Simulations on the small model domain have been run at a resolution of 0.12° (~14 km) for the three emissions scenarios (in the following called B1-S, A1B-S and A2-S) and on the large model domain at 0.22° (~25 km) for only the A2 scenario (in the following called A2-L). All simulations have been evaluated for 2021-2060, the A2-S simulation in addition for 2061-2100. For the present day climate, RCA3 has been driven by the ERA-40 reanalysis dataset (Uppala et al., 2005) and by the output of the global climate model ECHAM5-OM1 (Roeckner et al., 2003) on both model domains for 1961-2000 (in the following called ERA-S, ERA-L, ECH-S and ECH-L). The ERA-40 driven RCA3 simulations are expected to be closer to observations than the ECHAM5-OM1 driven ones since the ERA-40 data are based on observations. Since heating and cooling degree days are temperature driven, it is important to know how well the simulated temperature compares against observation data; this is discussed in the next section.

Figure 1 *RCA3 domains.*

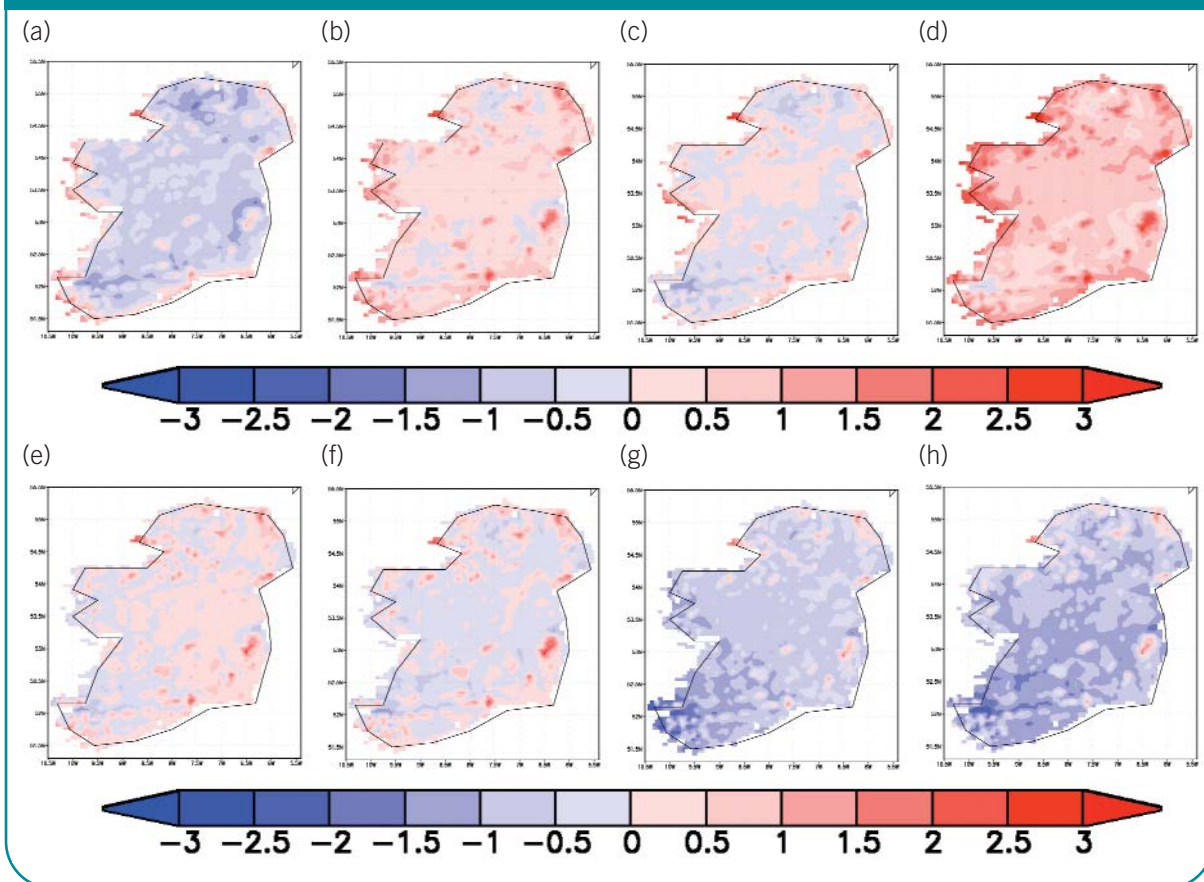


3 Evaluation of simulated temperatures against observations

Figure 2 shows temperature biases for the four different present day simulations for winter and summer, averaged over the 40 year period. As a reference, gridded observation data from UKCIP (Perry and Hollis, 2005) have been used. For most regions, the bias is below 1°C. Exceptions are mainly over the mountainous regions for which the orographic details are smoothed due to the limited horizontal resolution in our simulations. Area averages over Ireland (Table 1) show biases below 1°C for all seasons and all simulations. In autumn and winter both the driving data (ECHAM5 versus ERA-40) and the model domain affect the bias. In spring and summer the bias is dependent on the driving data (ECHAM5 versus ERA-40) while the model domain does not seem to play an important role. Here the ECHAM5 driven simulations show a cold bias which comes close to 1°C averaged over the whole area and exceeds 1°C especially in some southwestern areas. This seems to be due to a too cold sea surface temperature off the southern and western coasts. Only for spring and summer is the temperature bias lower and generally very close to zero for the ERA-40 driven

Table 1: Area average of the temperature bias in different RCA3 simulations averaged over seasons and all months for 1961-2000 for ERA-40 driven simulations on small domain (ERA-S) and large domain (ERA-L) and for ECHAM5 driven simulations on small domain (ECH-S) and large domain (ECH-L)..				
	ERA-S	ERA-L	ECH-S	ECH-L
DJF	-0.38	0.40	0.04	0.92
MAM	0.22	0.30	0.49	0.60
JJA	0.10	-0.05	-0.68	-0.87
SON	-0.22	0.24	-0.31	0.19
All months	-0.07	0.22	-0.12	0.21

Figure 2 Temperature bias (°C) in different RCA3 simulations averaged over the winter months (December, January, February) of 1961-2000 for ERA-40 driven simulations on (a) small domain (ERA-S) and (b) large domain (ERA-L) and for ECHAM5 driven simulations on (c) small domain (ECH-S) and (d) large domain (ECH-L). (e) to (h) same as (a) to (d) but for summer months (June, July, August).



simulations as opposed to the ECHAM5 driven simulations; in autumn and winter, seasons with large heating degree day values, the quality of the ERA-40 and ECHAM5 driven simulations is comparable except for the ECH-L simulation in winter.

4 Calculation of heating and cooling degree days

For each day, the heating and cooling degree days are calculated using the following formulae:

$$\text{HDD} = \text{MAX}(18 - (T_{\text{max}} - T_{\text{min}})/2, 0) \quad (1)$$

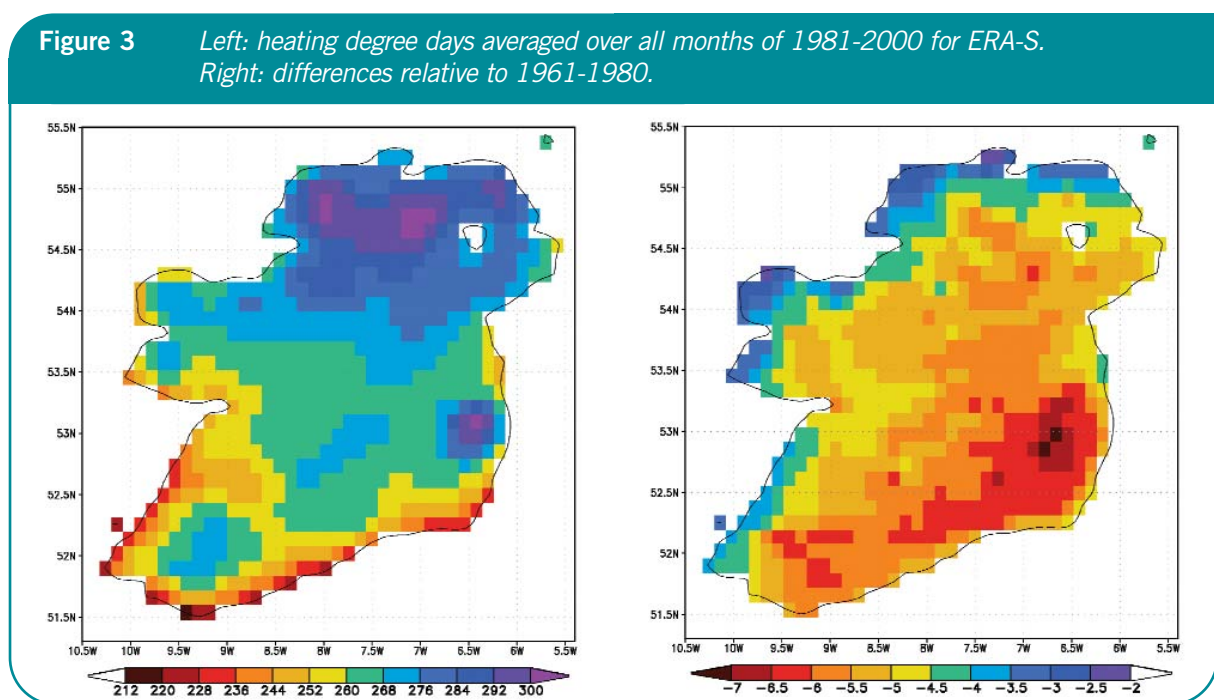
$$\text{CDD} = \text{MAX}((T_{\text{max}} - T_{\text{min}})/2 - 18, 0) \quad (2)$$

with HDD being the heating degree days, CDD the cooling degree days, T_{max} the daily maximum temperature in °C and T_{min} the daily minimum temperature in °C. HDD and CDD are quantitative indices reflecting the demand for energy to heat or cool houses. For example, a day with an average temperature (average between T_{max} and T_{min}) of 4 °C would result in 14 HDD. These formulae are widely used (e.g. Davis, 2001; Kharin and Zwiers, 2000), although T_{max} and T_{min} are given in °F in the United States and 65°F is used as the reference value in this case (e.g. Lehman and Warren, 1994; Le Comte and Warren, 1981; Thom, 1954), resulting in higher HDD and CDD values than for °C.

For each month, a sum of the daily heating and cooling degree days is calculated. Very high correlations between heating/cooling degree days and energy consumption are found (Quayle and Diaz, 1981) even though other meteorological parameters such as wind speed, sunniness and economic factors such as the cost of energy also influence consumption.

5 Recent trends in heating and cooling degree days in Ireland

In this section heating and cooling degree days are compared between 1961-1980 and 1981-2000. Figure 3(a) shows heating degree days averaged over all months of 1981-2000 according to the ERA-S simulation. The other three simulations (not shown) differ by up to 15 heating degree days per month from the shown simulation. These differences can be interpreted as uncertainty in our simulations. For 1981-2000 a small decrease in heating degree days is simulated compared to 1961-1980 (Figure 3(b)). The decrease is most pronounced in the southeast of the country but with 7 heating degree days per month (about 3%) still below the uncertainty of 15 heating degree days. Slightly larger decreases of up to 10 heating degree days in the south of the country (about 4%) – which are still below the uncertainty – are simulated according to the ECHAM5 driven simulations while the ERA-40 driven simulation on the large model domain lies somewhat in between (not shown). When investigating seasonal averages of heating degree days for 1981-2000 the uncertainty is larger than for the annual mean: there are differences of up to 50 heating degree days between the four simulations. In addition, the changes from 1961-1980 to 1981-2000 are quite different between the four simulations for some seasons. For autumn and winter some of the simulations show increases in heating degree days in some regions. For the other seasons all simulations show decreases over the whole island. The two compared time periods of 20 years each seem to be too short to detect robust signals which are free from decadal variability.



In the summer months the average number of cooling degree days per month stays below 5 for 1981-2000 and below 4 for 1961-1980 according to all four simulations, with the highest values occurring in the midlands (not shown).

6 Predicted future trends in heating and cooling degree days in Ireland

Figure 4 shows heating degree days for the two present day simulations on the small domain averaged over winter and summer months of 1961-2000. In winter generally 350 to 450 heating degree days per month are simulated with the larger values in the northeast and the smaller values in southern and western coastal areas. The simulations on the large model domain show smaller winter values compared to the ones on the small model domain (Table 2). The maximum difference in the area average and therefore the uncertainty of the simulations is 43 heating degree days or 10%. As expected, the differences in the simulations can be explained by the different temperature biases shown in Figure 2 and Table 1. Since the bias appears to be smallest in the ECH-S simulation in winter, it can be expected that the simulated heating degree days are closest to reality for this simulation and season. In summer generally 100 to 150 heating degree days are simulated. According to the ERA-40 driven simulations smaller values are simulated in southern coastal areas whereas the ECHAM5 driven simulations show larger values in mountainous areas. Averaged over the whole island 121 to 149 heating degree days are simulated dependent on the simulation;

the uncertainty therefore is 28 heating degree days or 24%. Again the differences can be explained by the different temperature biases. In this case the calculated heating degree days from the ERA-40 driven simulations are expected to be closest to reality. In the spring and autumn months generally 250 to 300 heating degree days are simulated with slightly higher values in some mountainous areas in spring and slightly lower values in coastal areas in autumn (not shown). The differences, and therefore the uncertainty in the simulations, are smaller than for winter and summer. For spring the uncertainty is 11 heating degree days or 4% and for autumn 14 heating degree days or 5% (Table 2). As expected, the uncertainty in the annual mean is much smaller, partly due to compensating errors: 9 heating degree days or 3%.

Figure 4 Top: Heating degree days averaged over the winter months of 1961-2000 according to ERA-S (left) and ECH-S (right). Bottom: corresponding results for summer months.

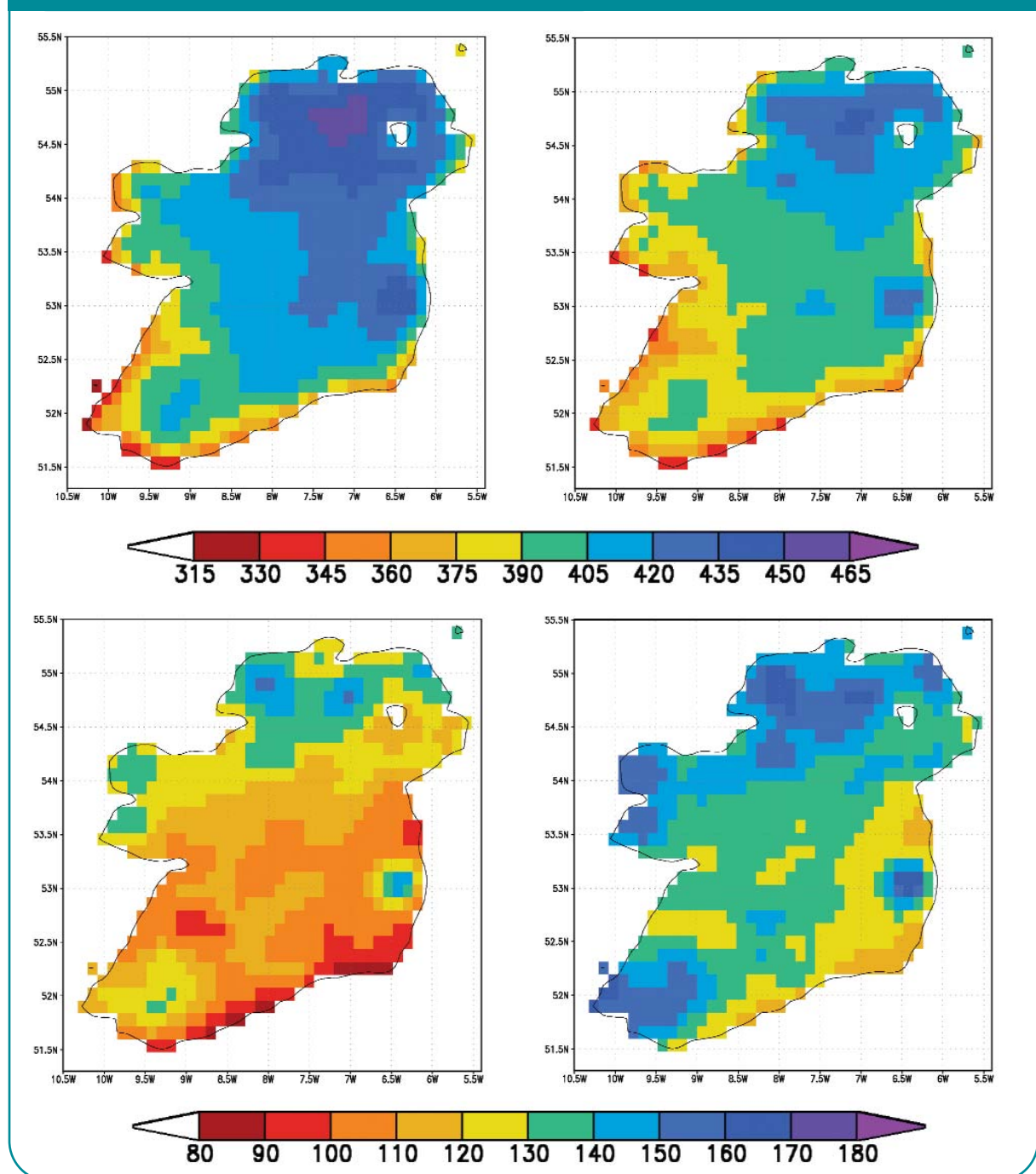
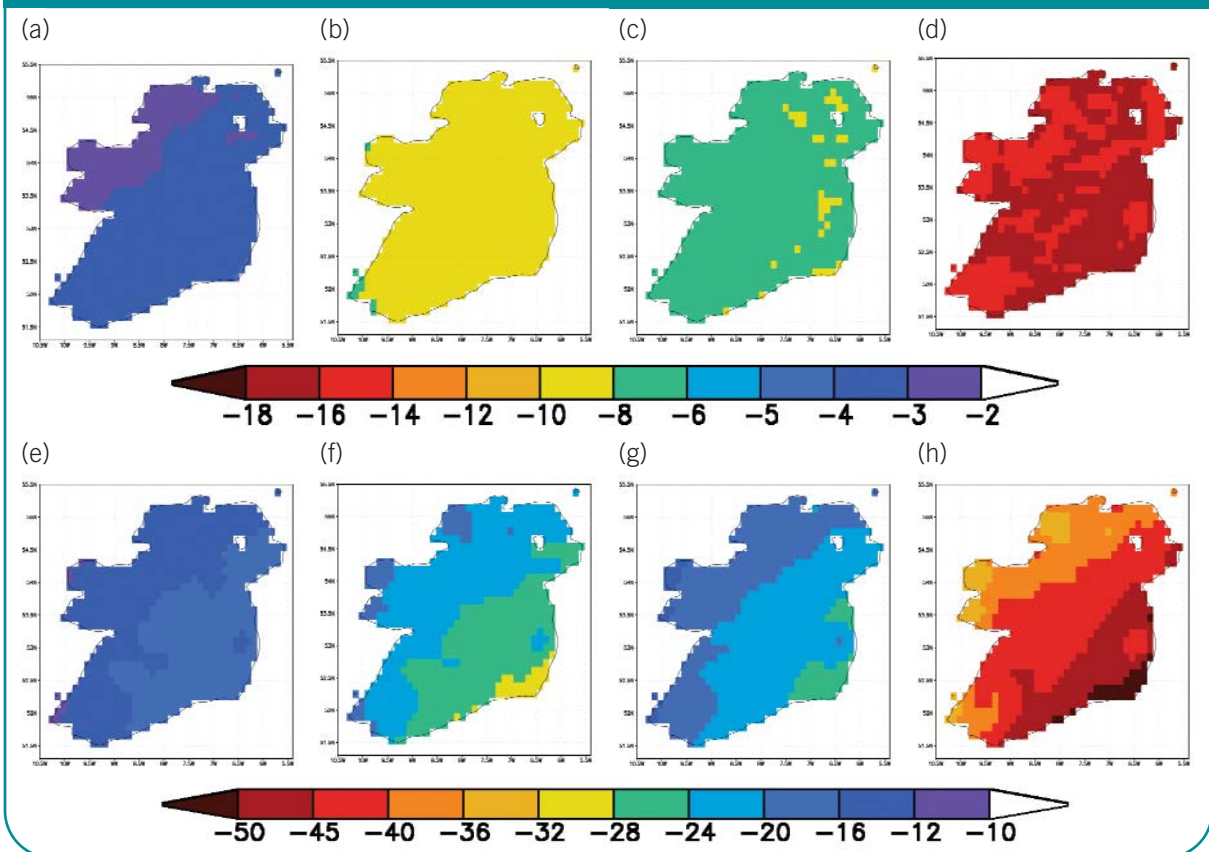


Table 2: Area average of heating degree days in different RCA3 simulations averaged over seasons and all months for 1961-2000 for ERA-S, ERA-L, ECH-S and ECH-L. The uncertainty is determined from the maximum difference between the simulations.

	ERA-S	ERA-L	ECH-S	ECH-L	Uncertainty
DJF	425.3	399.0	409.3	382.4	42.9 (10%)
MAM	302.1	301.8	291.0	291.5	11.1 (4%)
JJA	120.6	126.0	141.0	149.0	28.4 (24%)
SON	265.9	252.4	266.2	253.3	13.8 (5%)
All months	278.5	269.8	276.9	269.1	9.4 (3%)

Figure 5 shows relative changes in % for four different scenario simulations for 2021-2060 and 2061-2100 compared to the control period of 1961-2000; Table 3 shows these relative changes for all five different scenario simulations averaged over the whole area. It should be noted that changes have been calculated relative to the respective control simulations (B1-S, A1B-S and A2-S to ECH-S and A2-L to ECH-L) following the “delta approach” generally applied to climate simulations (Tebaldi and Knutti, 2007). The hypothesis is that a similar bias would occur in future climate simulations compared to the control simulations; in interpreting changes rather than absolute values the bias becomes irrelevant. In winter and spring (only winter data are shown in Figure 5) very homogeneous changes in heating degree days can be seen over Ireland. According to both A2 scenario simulations 5-8% reduction in heating degree days is simulated for 2021-2060 compared to 1961-2000 (only A2-S shown in Figure 5). This reduction increases to 14-18% in winter and 16-20% in spring for 2061-2100 compared to the same control period. For the A1B-S simulation a reduction of 8-10% is simulated for 2021-2060 and for the B1-S simulation 3-4%. In summer larger relative changes are simulated, especially in the southeast of the country, although absolute changes are comparable since in this season less heating is required: up to 30% according to the A2 and A1B scenarios and

Figure 5 Changes in heating degree days in % averaged over the winter months of 2021-2060 compared to 1961-2000 according to (a) B1-S, (b) A1B-S and (c) A2-S. (d) same as (c) but averaged over the winter months of 2061-2100. (e) to (h) same as (a) to (d) but for the summer months.



up to 20% according to the B1 scenario. Averaged over the whole island, decreases are between 16% for the B1-S simulation and 23% for the A1B simulation. For 2061-2100 the decrease amounts to over 50% in some regions and averages to 42%. In autumn (not shown) the changes are more homogeneous similar to winter and spring but slightly larger: the A1B-S simulation shows decreases by 12-16% for 2021-2060, the B1-S simulation 5-8% and A2-S and A2-L simulations 8-10%. For 2061-2100 the A2-S simulation shows a decrease of 22-30%. The simulated changes are larger than the uncertainty (Table 2) for spring and autumn of 2021-2060 and for all seasons of 2061-2100. If averaged over all months of the year all simulated changes are larger than the small uncertainty of 3%. It is worth noting that the delta approach seems to work well if comparing the changes according to A2-S and A2-L simulations. Even though absolute values differ by up to 7% between ECH-S and ECH-L control simulations (Table 2: 409 versus 382 heating degree days in winter), the maximum differences in the simulated changes between A2-S and A2-L simulations are well below 3% (Table 3: -18.5% versus -20.8% change in heating degree days in summer). This means that our error estimates defined by the maximum differences in present day climate simulations might be unnecessarily high. They could be reduced if more pairs of simulations using the same emissions scenario would be available; then the maximum differences in simulated changes could be used as an error estimate. Nevertheless even with these high error estimates many of the simulated changes are clearly higher than the uncertainty. Furthermore, because of the long averaging periods of 40 years the decadal variability is filtered out making the results robust.

Table 3: Area average of heating degree days in different RCA3 simulations averaged over seasons and all months for 2021-2060 for B1-S, A1B-S, A2-L and A2-S and for 2061-2100 for A2-S. In brackets changes in % compared to the respective control simulation (ECH-S or ECH-L) are given.

	2021-2060				2061-2100
	B1-S	A1B-S	A2-L	A2-S	A2-S
DJF	394.8 (-3.5%)	372.1 (-9.1%)	353.7 (-7.5%)	376.1 (-8.1%)	341.4 (-16.6%)
MAM	278.8 (-4.2%)	265.0 (-8.9%)	274.3 (-5.9%)	271.4 (-6.7%)	237.1 (-18.5%)
JJA	118.7 (-15.8%)	108.2 (-23.3%)	121.5 (-18.5%)	111.7 (-20.8%)	81.5 (-42.2%)
SON	249.2 (-6.4%)	229.4 (-13.8%)	229.6 (-9.4%)	242.4 (-8.9%)	198.2 (-25.5%)
All months	260.4 (-6.0%)	243.7 (-12.0%)	244.8 (-9.0%)	250.4 (-9.6%)	214.6 (-22.5%)

Most seasons do not exhibit any cooling energy demand. In summer up to 4 cooling degree days per month are simulated in the midlands averaged over 1961-2000 (not shown). This value increases to 6 according to the weak B1 scenario and to 8 according to the A1B and A2 scenarios for 2021-2060. For 2061-2100 up to 14 cooling degree days are simulated in the southeast.

7 Summary and conclusions

In this study the influence of climate change on heating and cooling energy demand in Ireland has been studied using a small ensemble of regional climate model (RCM) simulations. For the present day climate the RCM has been driven by ERA-40 reanalysis data and ECHAM5 global climate model (GCM) data. For future climate GCM data with contrasting emissions scenarios have been used. Furthermore the RCM domain and resolution have been changed to include the uncertainty stemming from the internal variability of the RCM. The results of simulations using two moderately strong emissions scenarios (A1B and A2) suggest major savings in winter and spring heating energy of 5-10% for the period 2021-2060 and 14-20% for 2061-2100 compared to the control period 1961-2000. For summer and autumn, relative changes are even larger although changes in absolute values are comparable. Averaged over all available simulations (A1B and A2 emissions scenarios), over all months and over the whole of Ireland, a $10\pm 3\%$ decrease in heating degree days is predicted for 2021-2060 and a $22\pm 3\%$ decrease for 2061-2100 compared to 1961-2000. The reductions in heating degree days are smaller for the weak B1 emissions scenario ($6\pm 3\%$ averaged over all months and over Ireland), but this scenario (globalisation with an emphasis on environmental sustainability) seems to be unlikely considering the current economic development.

The increase in summer cooling degree days, from a low value in the current climate, may intensify a weak demand for air conditioning towards the end of this century. However, the main influence of a warming climate will be reflected in a decrease in energy requirements for commercial and domestic heating in Ireland.



13 Carrying forward the Work of C4I

“The Government is committed to sustaining and developing a climate-modelling framework within Met Éireann, building on the C4I project, with links to national and international research in this area, to ensure that Ireland has an advanced capability for prediction of future climate conditions.” National Climate Change Strategy 2007-2012.

A considerable amount of expertise has been developed through this project, building on Met Éireann’s extensive knowledge in meteorological science: detailed understanding of climate processes; development of complex models in software; use of high performance computing (HPC) facilities to run climate simulations; managing large (terabyte-sized) datasets. Additionally, the project has developed strong international links with other climate-related projects: ENSEMBLES, EC-EARTH. The first phase of C4I ended in December 2007; other initiatives will build on the project and benefit from the foundations it has laid in climate modelling.

Met Éireann, in collaboration with the UCD Meteorology and Climate Centre and the Irish Centre for High-End Computing (ICHEC), will continue the modelling work and continue to support ENSEMBLES and EC-EARTH. Also, several fellowships under the EPA Science, Technology, Research & Innovation for the Environment (STRIVE) Programme will pursue strands of work touched on by C4I: the impact of the Atlantic Ocean on the Irish climate; impacts of climate change on plant/crop growth; impacts of climate change on trans-boundary air pollution. Met Éireann and its partners will play a major role in supervising these fellowships.

Issues to be addressed in future work

Uncertainty

The uncertainty in climate predictions, particularly for regional precipitation, remains a key issue for applications. For example, even with 8 ensemble simulations the only robust signal that can be inferred from the future precipitation data relates to seasonal differences; spatial differences across Ireland are still elusive in terms of accuracy. This is partly due to deficiencies in the global models and partly to the random nature of local precipitation. The limited extent of climate simulations and the possible masking of anthropogenically-driven trends by natural variability are also relevant issues. Future work will attempt to reduce this uncertainty by extending the ensemble size (through ENSEMBLES partnership) and by developing and running a new Earth System Model (through EC-EARTH partnership). A judicious use of statistical and dynamical downscaling applied to existing and future model outputs should provide sharper estimates of regional differences. The same issues are relevant for weather extremes.

Ensembles

The ENSEMBLES project will run to 2009 and will deliver about 16 ensemble simulations for the future climate based on a variety of global and regional models. Combined with the C4I simulations, and supplemented with statistical downscaling, these should provide a definitive resource for evaluating regional climate change over Ireland.

Applications

The impacts of climate change need to be assessed in the following areas:

- ▶ Transport: occurrence of fog at airports and ice on roads; frequencies of gales/storms disrupting marine activities.
- ▶ Agriculture/Forestry: crop growth and harvesting; plant/animal diseases.
- ▶ Marine: fishing (including rivers, lakes).
- ▶ Energy: future requirements; renewables (e.g. wind, wave, tide).
- ▶ Health: cold/heat stress; diseases.
- ▶ Flooding: coastal, river catchment.

Ideally, applications require probability distributions of the future climate elements. These should be delivered by the ensemble approach. Most of the applications (storm surges, waves, river catchment flooding) reported on in this document have been run using a single climate simulation as a driver to investigate climate change impacts. These need to be extended using a multi-simulation approach.

An ensemble approach will be essential for the estimation of the frequency of occurrence of extreme weather events (e.g. return periods).

Scientific issues

According to the IPCC Fourth Assessment Report (IPCC, 2007) the Atlantic meridional overturning circulation is likely to weaken and Arctic sea ice cover continue to decline in the coming decades. The impacts for Ireland will be investigated using the global and regional models to assess the sensitivity of the climate system to these changes.

Building capacity in climate research

In recognition of the urgency of addressing climate change, biodiversity loss and adverse health impacts, which are priority concerns at national level, UCD has established the UCD Earth Institute. This institute brings together the natural sciences, engineering and technology, the human sciences and public policy to undertake high-quality multi-disciplinary research to address environmental challenges.

The Government is committed to sustaining and developing a climate-modelling framework within Met Éireann, building on the C4I project, with links to national and international research in this area, to ensure that Ireland has an advanced capability for prediction of future climate conditions.

The link between UCD and Met Éireann has been extremely valuable in advancing collaboration in research (e.g. modelling future climate) and in graduate education (e.g. the UCD MSc programme in Meteorology, which is an integral part of the training for meteorologists at Met Éireann). A climate change research programme will be an important component of the UCD Earth Institute. Met Éireann and UCD plan to build further on our links and advance our collaboration on research, specifically in the area of climate modelling.



14 Scientific Output and access to key results

Most of the key results from the project can be accessed on the C4I website (<http://www.c4i.ie>); it provides a wealth of detailed information on the climate simulation outputs (e.g. time series and maps of weather elements for individual simulations). The work of the project has also been advertised through several media interviews. In February 2007, C4I gave a summary presentation to the Oireachtas Joint Committee on Environment and Local Government, debating 'Climate Change in Ireland'.

1 Publications (Peer-reviewed journals)

Dunne, S., Lynch, P., McGrath, R., Semmler, T., Wang, S., Hanafin, J. and P. Nolan, 2008: The impacts of climate change on hydrology in Ireland. *Journal of Hydrology*, DOI:10.1016/j.hydrol.2008.03.025.

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ISBN 0-9521232-5-5



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