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Title:

A high-resolution, multi-model analysis of Irish temperatures for the mid 21st-Century

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Short title: Analysis of Irish Temperatures for 2041-2060

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Running head:

Analysis of Irish Temperatures for 2041-2060

Abstract

There is a paucity of dynamically downscaled climate model output at a high resolution over Ireland, of temperature projections for the mid-21st century. This study aims to address this shortcoming. A preliminary investigation of GCM data and high-resolution RCM data shows that the latter exhibits greater variability over Ireland by reducing the dominance of the surrounding seas on the climate signal. This motivates the subsequent dynamical downscaling and analysis of the temperature output from three high-resolution (4-7km grid size) RCMs over Ireland. The three RCMs, driven by four GCMs from CMIP3 and CMIP5, were run under different SRES and RCP future scenarios. Projections of mean and extreme temperature changes are considered for the mid-century (2041-2060) and assessed relative to the control period of 1981-2000.

Analysis of the RCM data shows that annual mean temperatures are projected to rise to between 0.4°C and 1.8°C above control levels by mid-century. On a seasonal basis, results differ by forcing scenario. Future summers have the largest projected warming under RCP 8.5, where the greatest warming is seen in the southeast of Ireland. The remaining two high emission scenarios (SRESs A1B and A2) project future winters to have the greatest warming, with almost uniform increases of 1.5 - 2°C across the island.

Changes in the bidecadal 5th and 95th percentile values of daily minimum and maximum temperatures, respectively, are also analysed. The greatest change in daily minimum temperature is projected for future winters (indicating fewer cold nights and frost days), a pattern which is consistent across all scenarios/forcings.

An investigation into the distribution of temperature under RCP 8.5 shows a strong summer increase compounded by increased variability, and a winter increase compounded by an increase in skewness.

Key Words: Ireland; regional climate modelling; high resolution; temperature; temperature extremes

Section 1: Introduction

It is a well-documented fact that concentrations of greenhouse gases (GHGs) in the atmosphere have been increasing since the middle of the 19th century (McGuffie *et al.*, 1999). Most of the scientific community and general public alike have accepted the idea that both natural and anthropogenic factors are causing the earth's climate to change (McGuffie and Henderson-Sellers, 2005). The United Nations (UN) has recently declared that the world experienced more unprecedented high-impact climate extremes in the first decade of the 21st century than any previous decade (World Meteorological Organisation, 2013).

In this paper, the projected temperature changes from the output of three high-resolution regional climate models (RCMs) over Ireland, driven by four global climate models (GCMs), under five different possible futures is analysed. This will help to inform policymakers and further the understanding of the potential environmental impacts of climate change at a local scale.

1.1 Overview of Uncertainty

There are many factors that contribute to the uncertainty of climate projections, for which all climate models attempt to account (Fronzek *et al.*, 2012).

Firstly, there is uncertainty due to the natural variability of the climate system (aleatoric uncertainty). A common method which attempts to deal (in part) with this uncertainty typically involves the creation of an ensemble: that is, combining the results of a model run several times with different initial conditions (multiple realisations for one GCM), or from several different models (GCM/RCM pairings), or a combination of both (Déqué *et al.*, 2007). However, this introduces additional uncertainties. Different GCM/RCM pairings may result in different variability, while the timing of natural variability can be different in different GCM realisations.

Secondly, uncertainties arise due to the formulation of the models themselves (epistemic uncertainty). This can be accounted for by using several different models with different parameterisation schemes and dynamical cores, which also results in an ensemble. (Note that accounting for these two uncertainties often leads to further issues because, for example, ensemble members from related climate models will not be statistically independent. However, we do not deal with such issues here.) The relative coarseness of GCMs, with typical grid sizes of the order of one hundred kilometres, leads to related uncertainties in future regional climate. Downscaling the data over the region of interest can reduce this problem. The resulting higher resolution output is more useful for focused climate impact studies. There are two general approaches to downscaling data: statistical and dynamical. Statistical downscaling involves fitting a statistical model to the GCM output to find changes in climate at a local scale. It is quick and inexpensive to perform (Yang *et al.*, 2012). Dynamical downscaling uses RCMs to focus on a particular region (see figure 1) in order to generate projections of future climate at a higher resolution. The GCM outputs are used as boundary conditions to drive the RCM (in contrast to the freely evolving original GCM). The higher resolution allows for a better representation of coastlines, general topography (Chan *et al.*, 2013) and land use. The physically-based RCMs explicitly resolve more smaller-scale transient-dynamical features of atmospheric flow (e.g. squalls) than the coarser GCMs (Wilby and Dawson, 2007).

Thirdly, there is uncertainty concerning the future atmospheric composition, which affects the radiative balance of the earth. In order to account for this uncertainty, the UN Intergovernmental Panel on Climate Change (IPCC) previously recommended using six pre-defined scenarios (Nakicenovic *et al.*, 2000). These scenarios (or storylines) are derived from four families of possible futures, and are referred to as Special Report on Emissions Scenarios (SRES). For its most recent report, AR5 (IPCC, 2013a), the IPCC recommends using four representative concentration pathways (RCPs) in the simulation of future climate projections (Moss *et al.*, 2010). The higher an RCP, the greater its radiative forcing on the climate. No future is treated as more likely or unlikely than another, meaning that all projections are considered as equally plausible futures regardless of the driving scenario or RCP.

(a) (b)

(c) (d)

Figure 1: Different model resolutions over Britain and Ireland are shown above. Successively higher resolutions (from 125km (a) to 50km (b) to 18km (c) to 4km (d)) allow coastlines and topography to be modelled in greater detail, and smaller-scale atmospheric features to be resolved.

Section 2: Previous Studies

2.1 Previous Studies - Changes in mean temperature

The IPCC reports an estimated rise in global mean surface temperatures by the late 21st century of between 0.3 and 4.8°C (IPCC, 2013a). The rise in European mean temperatures is projected to exceed the rise in the global mean. In fact, the median temperature over Ireland for the period 2046-2065 is projected to increase by 1 - 1.5°C in future summers, and by 0.5 - 1.5°C in future winters under RCP 4.5 (IPCC, 2013b).

Heinrich and Gobiet (2012) used 8 RCMs (all approximately of 25km grid size) from the ENSEMBLES project to analyse projected changes in mean temperature over Europe between 1961-1990 and 2021-2050. Examining the multi-model mean change seasonally, they found that warming is projected across all seasons and all areas; these are most pronounced in the north-east of Europe in winter and southern Europe in summer. Temperatures over Britain and Ireland are projected to increase uniformly across all areas and all seasons in that period by approximately 1 - 1.5°C.

Using data resulting from the PRUDENCE project, Déqué *et al.* (2007) compared the results of 25 simulations driven by three GCMs under two different driving scenarios (SRES A2 and B2), in order to estimate the uncertainty in using RCMs for future climate projections over Europe. They investigated the changes projected between 1961-1990 and 2071-2100, while attempting to separate the various sources of uncertainty from each other. They note that the choice of the driving GCM generally introduces more uncertainty than the other sources. They suggest using at least as many GCMs as RCMs in any further studies. However, despite the uncertainties, they concluded that the projected warming evident across Europe is statistically significant (e.g., the lower value of all 99% confidence intervals for projected warming exceeds 1°C).

The ENSEMBLES project (results summarised by van der Linden and Mitchell, 2009) involved downscaling 7 GCMs over Europe by 8 RCMs at a 25km grid size. Under SRES A1B for 2021-2050, projected annual temperature changes over Ireland were found to be in the range of 1 - 1.25°C above the control period of 1961-1990. For the same time-period, winter and summer changes were both projected to lie in the range 1 - 1.5°C.

The Community Climate Change Consortium for Ireland (C4I) downscaled data from 5 GCMs over Ireland and Britain, using all SRES scenarios, achieving a finest grid size of 14km. Looking at seasonal projections for 2021-2060, they found the greatest change in mean temperatures projected for summers and autumns (1.2 - 1.4°C) (McGrath *et al.*, 2008).

Statistical downscaling was used by Fealy and Sweeney (2008) to assess projected temperature changes at several sites in Ireland. They used output from three GCMs under two SRES scenarios (A2 and B2), and found that by the 2050s Irish temperatures are projected to increase by 1.4 - 1.8°C above the control period of 1961-1990. In addition, they found that the greatest warming is projected for future autumns. Mullan *et al.* (2012) also used statistical downscaling, but over Northern Ireland, and achieved similar results.

2.2 Previous Studies - Changes in extreme temperature

A climate model that simulates the observed mean temperature does not necessarily accurately reproduce the distribution of temperature. A change in the distribution of a quantity may not change the mean, but may lead to a change in the number of extreme events (IPCC, 2012). Extreme events are arguably of more importance to people, since they have an abrupt and much larger impact on lives and livelihoods than a gradual change in mean values (Easterling *et al.*, 2000).

The IPCC report that it is now “very likely” that human-induced climate change has contributed “to the observed changes in the frequency and intensity of daily temperature extremes on the global scale” (IPCC, 2013a). This confirms what was already suggested both in IPCC AR4 (2007) and an IPCC Special Report: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (2012). They warn that near-term projections suggest that increases in temperature extremes are likely. In Europe, decadal high-percentile summer temperatures are projected to rise faster than mean temperatures (IPCC, 2013a).

Beniston *et al.* (2007) used the RCM output from the PRUDENCE project to examine how extreme temperature events in Europe are projected to change by the end of the 21st century. They found that an increase in temperature variability in the future implies that the intensity of extreme temperature events (as characterised by having relatively large deviations from the norm) will increase more rapidly than the intensity of more moderate temperatures over the interior of the continent.

In their study over Northern Ireland, Mullan *et al.* (2012) examined the projected changes in extremes of temperature. They used the threshold approach to define percentile values for the control period that depend on each particular location: the thirty-year 90th percentile of maximum temperature to examine changes in hot days and the thirty-year 10th percentile of minimum temperature to examine changes in cold nights. The projected changes in these thresholds at each site was then calculated. Both the hot-day threshold and the cold-night threshold are projected to increase by similar amounts, and show an increasing trend through the 2020s, 2050s and 2080s. There is a large uncertainty range for both changes, though all ranges are non-negative.

2.3 Overview of current study

There is a paucity of data from dynamically downscaled climate models at a high resolution over Ireland, and subsequent analysis of temperature projections for the mid-21st century. Existing studies have focused on larger domains with coarser resolutions (~14km grid size, McGrath *et al.* (2008)), or have instead used statistical downscaling.

In this paper, the outputs of three RCMs driven by four GCMs under different SRESs and RCPs are analysed in relation to projected temperature changes. The final model outputs are at very high grid sizes of 4-7km. Annual and seasonal mean changes are examined, both averaged across the island and analysed spatially. In addition to examining projected mean changes, changes in the behaviour of temperature extremes are analysed. This study also investigates projected changes in the spatially-averaged distribution of temperature over Ireland.

The study methodology is detailed in section 3, including the particular models and the reasons for choosing them, and the domain and time-slices being considered. In section 4, the projections from the various models are presented. In section 5, the results are discussed and assessed in light of previous research. In section 6, an overview of the results is presented. Acknowledgements and References conclude this paper.

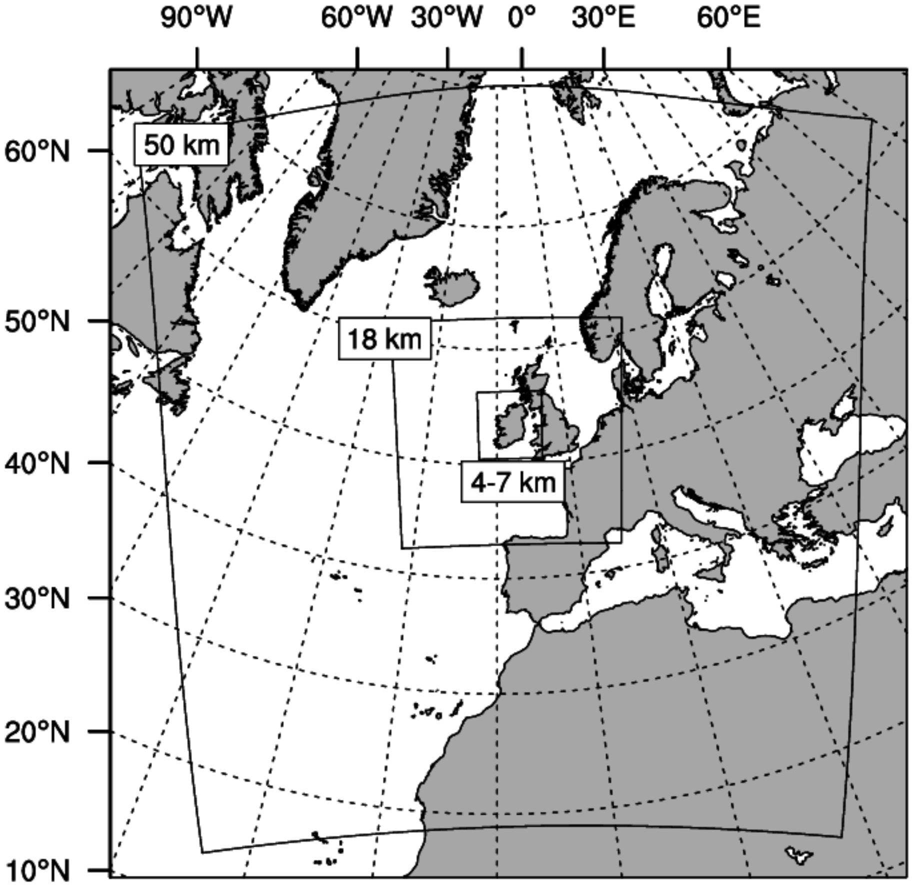

Figure 2: The study domain is shown, with the nest and corresponding grid for each run of the RCMs.

Section 3: Methodology

3.1 Study Domain

The study domain in this paper is shown in figure 2. The RCMs were initially driven by GCM boundary conditions (achieving a ~50km grid size on the domain shown), and were then nested twice in succession (one-way nesting in the case of downscaling using CCLM3 and CCLM4, and two-way nesting using WRF) to achieve the finest resolution (ranging from 4 to 7km grid size). An exception was the downscaling of the ECHAM5 data, which had already been downscaled by the CLM community, and was available at a grid size of 18km (validated by Hollweg *et al.*, 2008). The 50km and 18km domains are large enough to allow changes to synoptic scales. Whereas information may not change further at synoptic scales for the finest grid size, the high-resolution representation of topography and dynamic processes may result in changes to near-surface temperature. Ideally, the domain for the finest grid size would be larger in order to allow the RCM to fully develop small-scale dynamical structures in the interior of the domain, superposed on the coarse-scale information that enters through the lateral boundaries. However, this was not possible due to computational constraints.

3.2 Climate Model Data

An overview of the simulations are included in table 1: each row includes information on a driving GCM, the corresponding RCM used to downscale it, the SRES/RCP used for future simulations, the number of separate realisations, the time-slice simulated, and the finest grid size achieved. Data from two time-slices 1981-2000 (the control) and 2041-2060 were used for analysis of projected temperature changes in the mid-21st century over Ireland. These periods were chosen as these are the longest decadal time periods which were common to all simulations (see table 1).

Table 1:

Details of all simulations used are shown, including the driving GCM; the RCM used to downscale it; the SRES/RCP used for future simulations (including the number of realisations); the time slice simulated; and the finest grid size achieved.

Driving GCM	**RCM**	**Scenario (number of realisations)**	**Time Slice**	**Finest grid size**
ECHAM5	CCLM3	Historical (2)	1961-2000	7km
ECHAM5	CCLM3	SRES A1B (2), SRES B1 (1)	2021-2060	7km
ECHAM5	CCLM4	Historical (2)	1961-2000	7km
ECHAM5	CCLM4	SRES A1B (2)	2021-2060	7km
CGCM3.1	CCLM4	Historical (1)	1961-2000	4km
CGCM3.1	CCLM4	SRES A1B (1), SRES A2 (1)	2021-2060	4km
HadGEM2_ES	CCLM4	Historical (1)	1961-2000	4km
HadGEM2_ES	CCLM4	RCP4.5 (1), RCP8.5 (1)	2021-2060	4km
EC-Earth	CCLM4	Historical (3)	1981-2009	4km
EC-Earth	CCLM4	RCP4.5 (3), RCP8.5 (3)	2021-2060	4km
EC-Earth	WRF	Historical (3)	1981-2009	6km
EC-Earth	WRF	RCP4.5 (3), RCP8.5 (3)	2021-2060	6km

GCMs were chosen from two generations of the Coupled Model Intercomparison Project, CMIP3 and CMIP5. Detailed surveys of all CMIP5 models have been conducted over particular areas in other studies (such as by Van den Hurk *et al.* (2014), who develop a regression technique to use all available CMIP5 projections). However, since the main concern of this study was to investigate the effect of downscaling models at a high resolution, a subset of these had to be selected due to computational constraints. Within CMIP3, CGCM3.1 (Scinocca *et al.*, 2008) was chosen due to its superior ability to capture the spatial and temporal behaviour of the primary modes which drive weather in the Euro-Atlantic region (Casado and Pastor, 2012). ECHAM5 (Roeckner *et al.*, 2003) was chosen due to its previously verified good performance when downscaled at 18 km grid size over Europe by the RCM CLM3 (Hollweg *et al.*, 2008). Within CMIP5, EC-Earth (Hazeleger *et al.*, 2011) and HadGEM2 (Collins *et al.*, 2011) were chosen due to their complementary performance and biases. By comparing 33 models from CMIP5 with the E-OBS dataset over continental Europe for winters and summers separately, Cattiaux *et al.* (2013) found that both EC-Earth and HadGEM2-ES have biases within one standard deviation of the ensemble mean. Moreover, EC-Earth showed a slight warm bias in winter and a slight cold bias in summer, whereas HadGEM2-ES showed the opposite. Consequently, EC-Earth was found to be slightly under-dispersive and HadGEM2-ES over-dispersive. Within the computational constraints of this study and the limitation to two models from CMIP5, these represent a good choice for performance over Europe, with complementary (opposing) biases, while ensuring adequate variability.

After choosing the four models, the individual realisations were selected. These realisations result from running the same GCM with different initial conditions. Since they are all viewed as equally probable, the choice of realisation can often be pragmatic rather than theoretical. For CGCM3.1, the fourth realisation of CGCM3.1 T47 was used. For ECHAM5, realisations 1 and 2 were chosen. For EC-Earth, the three realisations performed by the Irish Meteorological Service (Met. Éireann) were chosen (realisations 1, 13 and 14: r1i1p1, r13i1p1 and r14i1p1). For HadGEM2-ES, r1i1p1 was the chosen realisation.

The output from the four selected GCMs was downscaled using three RCMs: CCLM3, CCLM4 (both Rockel *et al.*, 2008), and WRF (Skamarock *et al.*, 2008). The selected GCM-

RCM pairings were conducted separately for each realisation - e.g., for the pairing EC-Earth-WRF, three separate downscaling computations were run; WRF downscaled EC-Earth realisation r1i1p1; WRF downscaled r13i1p1; and WRF downscaled r14i1p1. There are more GCMs than RCMs used (recommended by Déqué *et al.*, 2007). Due to computational constraints, some (but not all) GCM-RCM combinations or future scenarios/RCPs were simulated.

3.3 Comparison of GCM and RCM Data

In order to justify the computational expense of downscaling an ensemble of GCMs at a high resolution, a preliminary analysis was conducted into the effects of downscaling over Ireland. Two representative cases were considered: a low scenario (SRES B1) and a high scenario (RCP 8.5). For SRES B1, the GCM is ECHAM5 and the RCM is CCLM3. For RCP 8.5, the GCM is EC-Earth (realisation r1i1p1) and the RCM is CCLM4. The RCM data over Ireland ("RCM land") was compared with the corresponding GCM data both over Ireland ("GCM land") and over the Atlantic to the west of Ireland with the same domain size ("GCM sea"). The temperature response was calculated by subtracting the mean state of the historical period from each corresponding future dataset (i.e., the response gives the deviation of each future climate from its historical mean state). Figure 3 illustrates the empirical histogram (achieved by binning the temperature responses) for RCP 8.5. It clearly shows that there is greater variability present in "GCM land" compared to "GCM sea" which is to be expected due to the higher specific heat capacity of the ocean. It also shows that there is greater variability present in "RCM land" compared to "GCM land". This is also to be expected as the higher resolution of the RCM allows for more land-only grid points, thus reducing the moderating effect of the ocean for inland points. This is a clear illustration of one motivation for using high-resolution RCMs: they allow extremes to be captured that are not represented in the lower resolution GCMs. Results for SRES B1 are comparable, showing a similar increase in variability from "GCM sea" to "GCM land" to "RCM land". Further evidence that the high-resolution RCMs reduce the moderating effect of the ocean is seen in table 2, which lists the mean temperature responses of "GCM sea", "GCM land" and "RCM land". For EC-Earth realisation 1 - CCLM4 in scenario RCP 8.5, there is a progressive increase in the response value from "GCM sea" (1.03°C) to "GCM land" (1.20°C) to "RCM land" (1.38°C). More information about how to interpret these values can be gained by including data from other realisations. Realisation 13 shows a larger response than realisation 1, while realisation 14 shows a lower response. The spread for the EC-Earth-CCLM4 response over land is 0.68°C (aleatoric uncertainty), while the mean response is 1.51°C. The equivalent EC-Earth-WRF values are 0.45°C and 1.51°C, respectively.

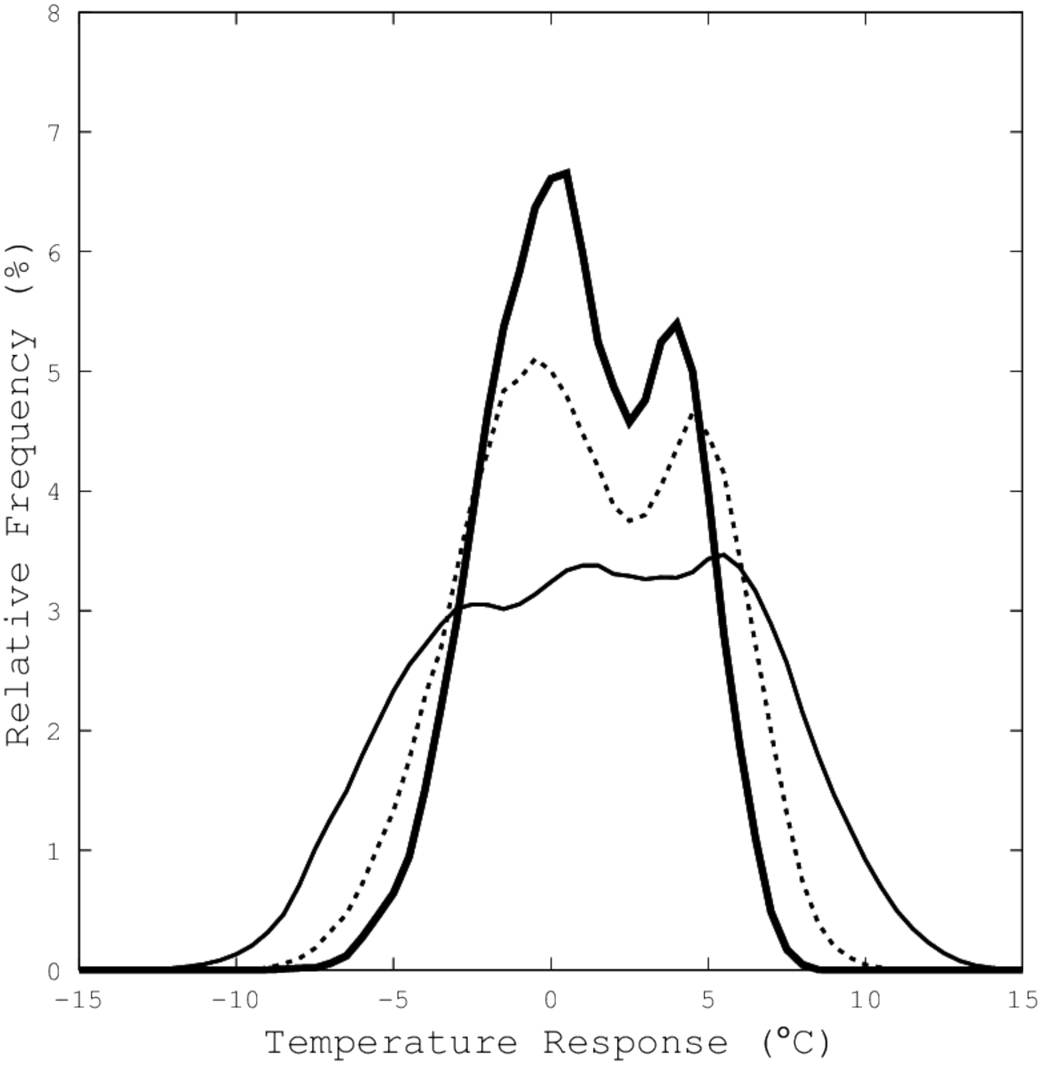

Figure 3: The empirical histograms of temperature responses for EC-Earth over the Atlantic (GCM sea - solid bold line), EC-Earth over Ireland (GCM land - dotted line) and EC-EARTH downscaled over Ireland by CCLM4 (RCM land - solid thin line) are shown, under RCP 8.5.

Table 2:

The results of the analysis of the effect of downscaling on mean two-metre temperature are shown. These include: the particular future scenario in the first column; the GCM and its realisations (if applicable) in the second column; the mean temperature response for the "GCM sea" data in the third column; the mean temperature response for the "GCM land" data in the fourth column; and each RCM and its corresponding mean temperature response ("RCM land") in the fifth column. Responses in **bold** *are those analysed in section 3.3.*

Scenario	GCM	GCM sea response	GCM land response	RCM land response
SRES B1	ECHAM5	**0.26°C**	**0.61°C**	CCLM3: **0.67°C**
RCP 4.5	EC-Earth: (1,13,14)	0.79°C, 1.10°C, 0.90°C	0.93°C, 1.29°C, 1.12°C	CCLM4: 1.06°C, 1.32°C, 1.13°C WRF: 1.13°C, 1.29°C, 1.11°C
SRES A1B	ECHAM5: (1,2)	0.72°C, 0.49°C	1.23°C, 1.06°C	CCLM3: 1.35°C, 1.20°C CCLM4: 1.37°C, 1.20°C
RCP 8.5	EC-Earth: (1,13,14)	**1.03°C**, 1.54°C, 0.82°C	**1.20°C**, 1.77°C, 1.18°C	CCLM4: **1.38°C**, 1.92°C, 1.24°C WRF: 1.38°C, 1.80°C, 1.35°C

These responses of all such pairings are included in table 2, where it can be seen that the response is always greater over land than sea, and that the response is always greater than the aleatoric uncertainty. Responses for SRES B1 also progressively increase (but are of a lower magnitude since it is a low emissions scenario). Both the increased variability and the greater warming evident in the high-resolution RCMs in comparison to the driving GCMs prompted the use of high-resolution dynamical downscaling to investigate both mean and extreme projected temperature changes over Ireland.

3.4 Analysis Methods

In order to analyse temperature changes, responses to the model forcings were calculated as described in the test case comparing GCM driving data and the resulting downscaled RCM data above (section 3.3). That is, the mean of each historical period was subtracted from the corresponding future period of each model *within the same realisation*. This resulted in *temperature responses* for each realisation of a GCM-RCM pair; that is, the difference between future and past. In this way, cold or warm biases of particular models will not skew results, and each response can be meaningfully compared with the other groups.

In order to reduce the GCM-RCM pairings to a more manageable number to ease comparison, the future model data were grouped together by SRES scenario or RCP. This resulted in five groups, hereafter denoted A1B, B1, A2, RCP45, and RCP85.

The data analysis is presented in various ways in section 4. Analysis has been conducted on the mean two-metre temperature (T2m), the daily minimum temperature (Tmn) and the daily maximum temperature (Tmx).

Section 4: Results

Figure 4 shows the time series of annual mean temperature responses for the five groups for 2041-2060. These are calculated using values averaged over Ireland. Dashed lines are lines of regression, calculated by the least-squares algorithm to show the linear trend over the two decades.

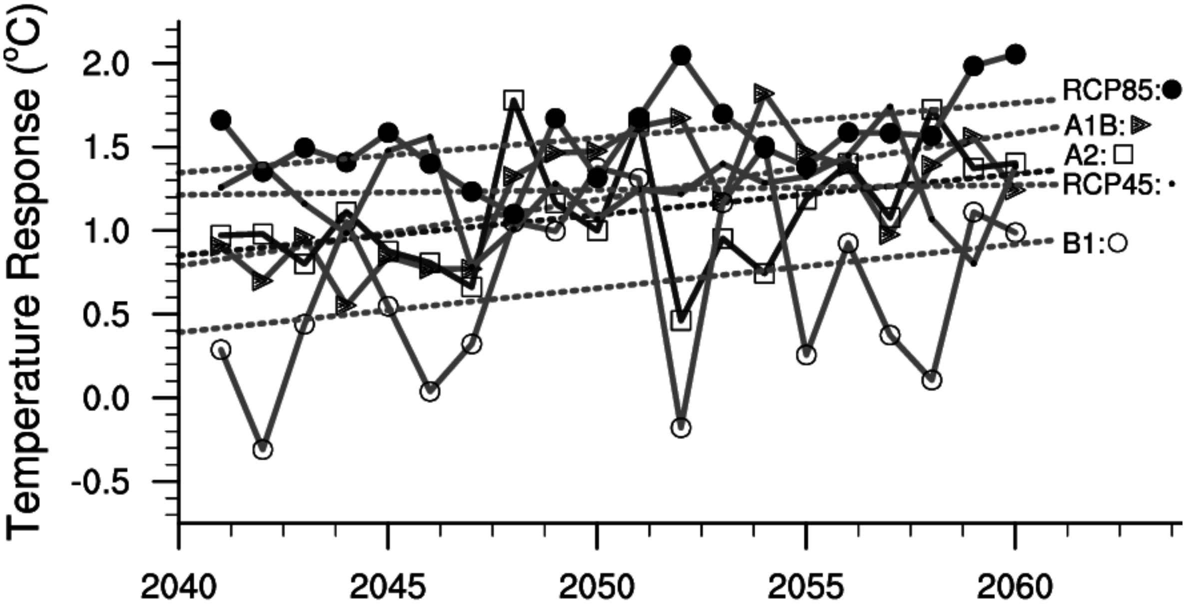

Figure 4: Time series of the annual mean temperature responses for each of the five groups are shown, averaged over Ireland. Dashed lines are lines of regression fitted using the least-squares method.

There is a broad range of values for temperature changes projected across the five groups. Group B1 shows the least warming (its mean response is 0.66°C), and the greatest interannual variability. Its large spread, seen through its annual mean responses ranging from -0.4°C to greater than 1.4°C, is most likely due to it being composed of a single member ensemble. The remaining four groups show greater warming than B1, with A2, A1B and RCP45 having large areas of overlap, and similar twenty-year means (1.1°C, 1.2°C and 1.24°C respectively). RCP85 shows the greatest warming of the groups considered, with a trend line always exceeding the other groups (its mean response is 1.56°C).

Since annual trends can hide or smooth larger seasonal trends, seasonal mean temperature responses have also been examined. Seasonal means from the control period 1981-2000 were calculated for each group, then subtracted from the 20 corresponding seasons in 2041-2060, resulting in seasonal responses for each group (showing their deviation from the mean state of the control period, as explained in section 3.3). The spread of these responses within each group, for each of the four seasons, could then be examined. The box and whisker plots for each group are shown (figure 5) for winter (DJF), spring (MAM), summer (JJA) and autumn (SON). The whisker ends mark the maximum and minimum seasonal values within the 20-year sample, while the box marks the median value (central line) and the first and third quartile values (lower and upper sides respectively).

The seasonal responses in figure 5 again illustrate that there is a lot of uncertainty in future projections, both within each season and within each group. Within summer, for example, temperature responses range from approximately -1°C in one particular year (group B1) to almost 6°C in another (RCP45). The responses below 0°C are indicative of the natural variability inherent in the climate system. A particularly cold spring projected in group A1B, for example, has a seasonal temperature response below -2°C. However, the overall trend of an increase in temperature is evident across all seasons. With the exception of group B1 in spring and summer, all first quartiles across all seasons exceed 0°C, suggesting a definitive upwards shift in temperature across all groups and all seasons, relative to the control period 1981-2000.

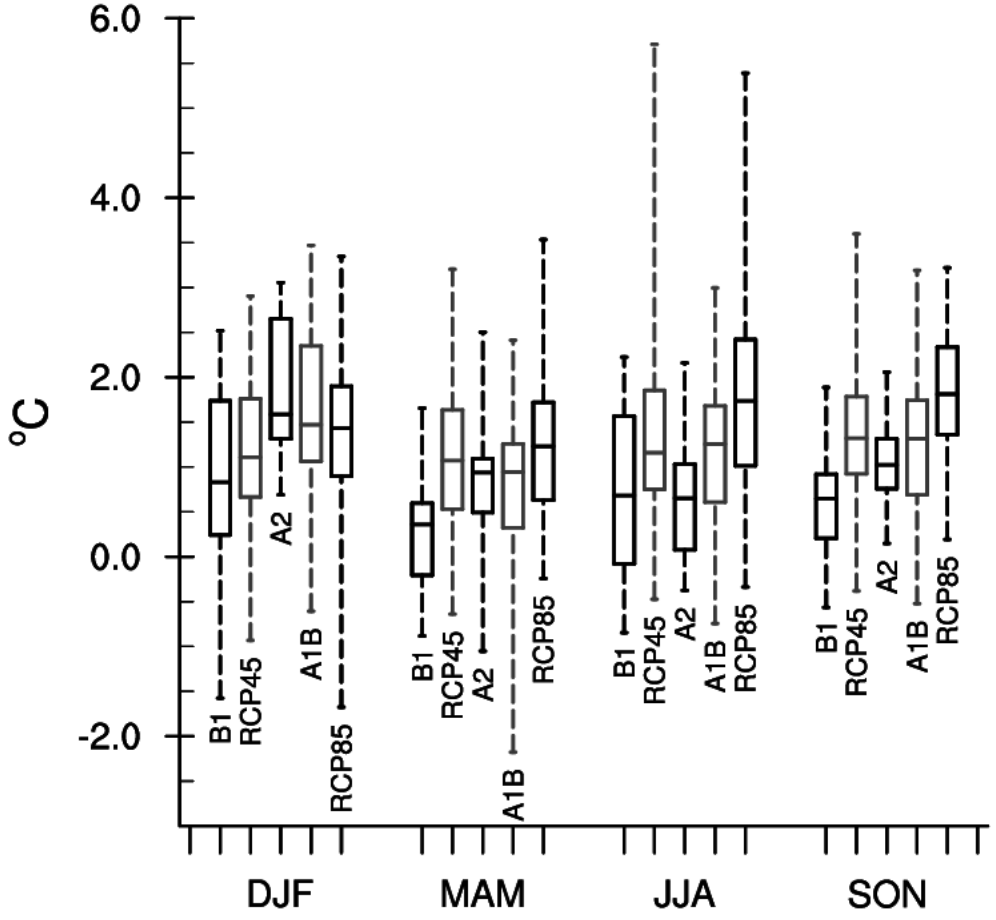

Figure 5: The seasonal T2m responses (winter [DJF], spring [MAM], summer [JJA], and autumn [SON]) are shown for the five groups. The bottom and top whiskers represent the minimum and maximum group values respectively, while the bottom and top of the box represents each group's first and third quartiles respectively, while the middle line represents its median.

There are also clear differences between results across the different groups. Future summers have the largest projected warming in RCP85, whereas winters are projected to warm the most in groups A1B and A2. However, all three agree on autumn as the season with the second-greatest projected warming.

Changes can be spatially dependent, so seasonal responses for each gridpoint over Ireland were calculated for each group. Figure 6 shows the seasonal temperature responses for the group RCP85 (the white areas are an artefact resulting from the regridding process applied to land-sea masks under different projections; only those boxes with sufficient land were included in the final analysis). The single number included on each plot is the value of the response at that particular point, and is included as a visual reference to aid interpretation of the figure.

The greatest change is for future summers, where a uniform warming of between 1.5 and 2°C is projected across the island, with the exception of the southeast. Here, projected warming is greater, in the 2 to 2.5°C range. There is a uniform projected warming in the 1.5 to 2°C range for autumns, while spring is projected to warm the least, with projected temperature increases of between 1 and 1.5°C. In future winters, the greatest warming is projected for the northeast of Ireland, in the range 1.5 to 2°C. There are many possible factors which could have influenced this uneven warming for future summers and winters, such as a change in storm tracks or the North Atlantic Oscillation (NAO) relative to the control period 1981-2000. However, further investigation of these factors is necessary to attribute causation, and is beyond the scope of this study. Moreover, both patterns fail to appear in the other groups. Groups A1B and A2 both project relatively uniform warming across the island within each season. Unlike RCP85 however, the greatest warming is projected for future winters (1.5 to 2°C for both groups, with the exception of the extreme southwest of the country, which has projected warming of 1 to 1.5°C), followed by future autumns (1 to 1.5°C for both groups). This supports the seasonal trends already evidenced from the boxplot analysis of figure 5. Similarly to these two groups, relatively uniform warming is projected in group RCP45. However, the greatest warming for this group is projected for future autumns.

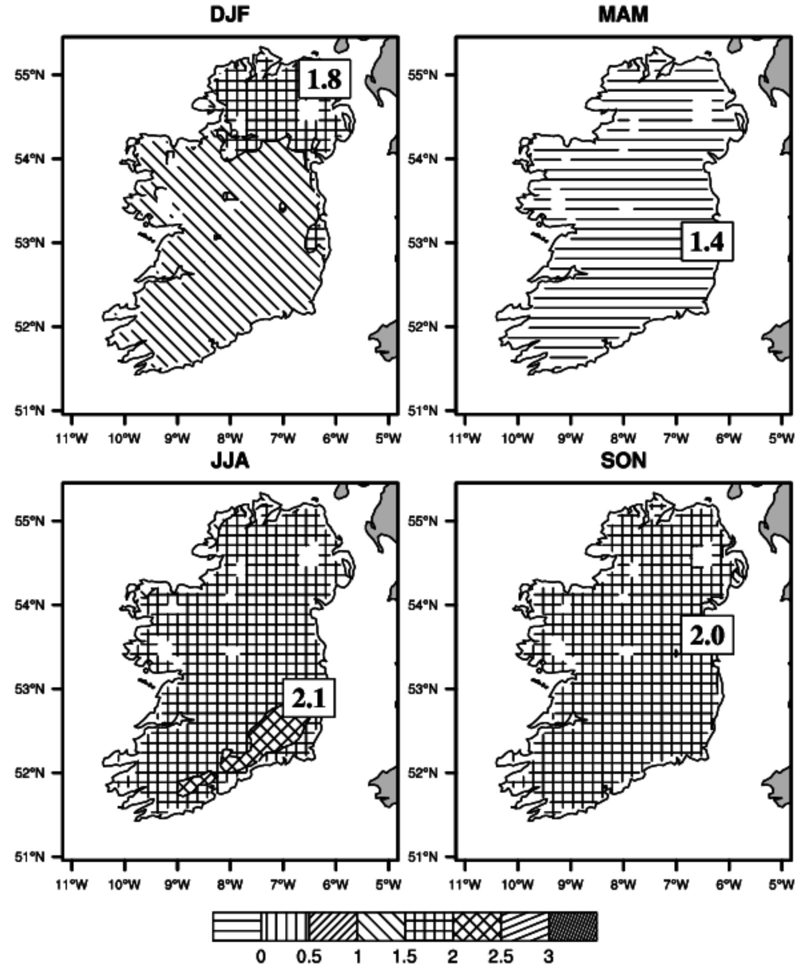

Figure 6: The seasonal T2m responses as calculated at each gridpoint are shown for group RCP85. The number included on each plot is the value of the response at that particular point, and is included as a visual reference to aid interpretation of the figure.

Changes in the extreme values of temperature have also been examined. The IPCC consider *extremely unlikely* events as those which have a less than 5% chance of occurring (IPCC, 2012). Therefore, changes in the 5 percentile value of the daily minimum temperature (hereafter Tmn05) and the 95 percentile value of the daily maximum temperature were examined (hereafter Tmx95). Any changes in these values relate to changes in the number of cold nights and the number of hot days, respectively. Events that are considered *extremely unlikely* to occur in the historical period may occur more or less frequently in the projected futures. Figure 7 shows the RCP85 winter and summer response of Tmn05 and Tmx95 respectively.

There is evidence here (figure 7) of greater warming of the two percentile values considered than for the mean seasonal temperature changes projected in figure 6. Projected changes in the mean temperature do not exceed 2°C, but projected changes in Tmn05 and Tmx95 exceed 2°C across almost the entire island, with many places exceeding 3°C.

For future winters, the projected change in Tmn05 exceeds 1.5°C everywhere, but is considerably greater in the north of the island (2 to 3.5°C). This means that, during the period 2041-2060 under RCP85, the threshold of daily minimum temperature below which only 5% of nights fall is projected to increase by at least 1.5°C and by a much greater amount in the north by mid-century.

Across almost the entire island, Tmx95 is projected to increase by more than 2°C - for most of the south of the country, this increase exceeds 2.5°C. This means that the threshold of daily maximum temperature which is only exceeded by 5% of days is projected to increase by approximately 2.5°C in future summers.

Under all groups, projections for Tmn05 during winter increased by a greater magnitude than those for T2m. In some cases the difference was quite considerable. For example, in group A2 mean winter temperatures are projected to increase uniformly across the island by less than 2°C. However, projections for Tmn05 in the same group exceed 3°C everywhere in future winters, with a maximum increase of 7°C.

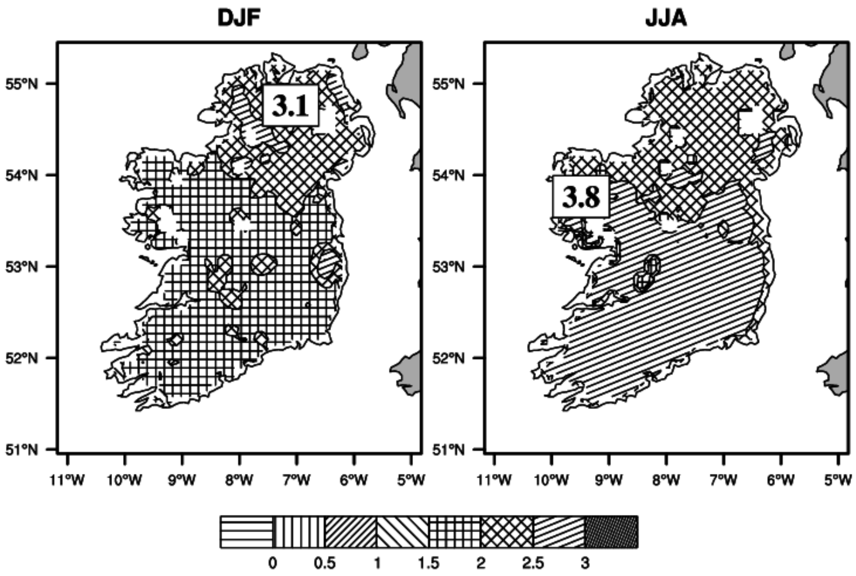

Figure 7: The response for Tmn05 for winter (DJF) and the response for Tmx95 for summer (JJA) are shown above for group RCP85. The number included on each plot as an aid for visual analysis represents the value of the response at that point.

Similarly, the magnitudes of the projections for changes in Tmx95 for future summers exceed the mean changes across all groups. For example, T2m in future summers is projected to increase by 1 to 1.5°C in group RCP45, whereas Tmx95 in future summers is projected to increase by 1.5 to 2°C for the same group across most of Ireland, with projections greater than 2°C in parts of the southwest.

A more comprehensive step in moving from analysing mean values to the examination of extreme events is to consider the *distribution* of a quantity. The distribution of a quantity involving discrete data (as here) can be represented by its empirical density function. Seasonal histograms (hereafter, densities) were calculated by binning responses over all grid points and all group members, and scaling so the area summed to 1, resulting in control and future empirical densities. Group RCP85 has been included, as this was the RCP with the greater projected change. Figure 8 shows the densities of daily temperature responses by season, where the group's control and its respective future are compared. The density of the historical control period is shown as a continuous line with open circles, and the density of projected temperature for the group RCP85 is shown as a dashed line with crosses. *Overlap scores* were calculated which assess the similarity between each group's past and future. This score was obtained by summing the *minimum* value at each bin, across the entire combined range of the two densities (equation (12) in Cha, 2007). By then multiplying by 100, this results in a score between 0 and 100%, with 100% indicating perfect agreement (climate completely unchanged) and 0% indicating no agreement at all (past and future climates have no values in common).

There is evidence in figure 8 of temperature increases across all seasons, as each future density mean is shifted to the right of its historical density mean. In addition to this mean increase, the future density values across the entire range are shifted upwards, strengthening the evidence from all of the previous analysis of increases in both the mean values and the tails of the temperature distribution.

The overlap scores range from 71% in summer (showing the largest increase across the distribution) to 86% in spring (showing the least change between historical and future densities). These reinforce the mean changes suggested by RCP85 in figure 6, which had the greatest increases in summer, and the smallest increases projected for future springs.

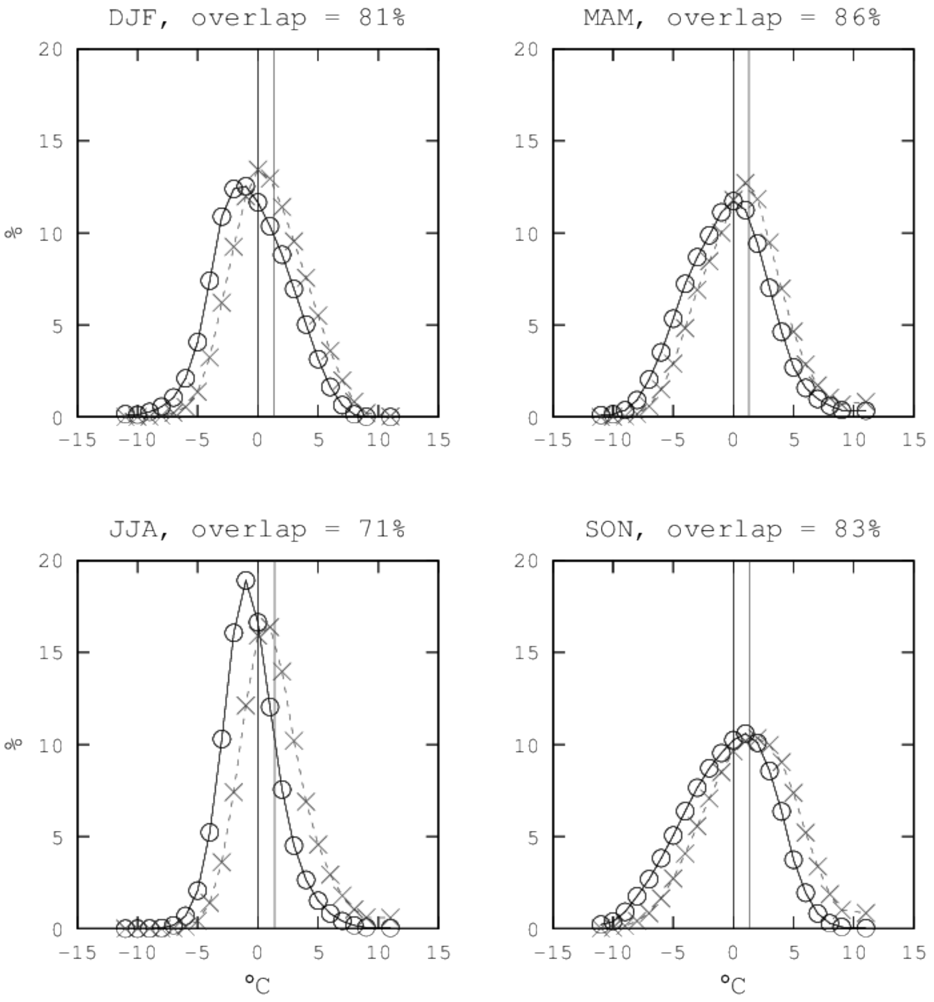

Figure 8: Shown above are seasonal densities for group RCP85 illustrating the distribution of historical model temperature responses (solid line, with open circles) and the future model temperature responses (dotted line, with crosses). A measure of overlap indicates how much the two distributions have changed (DJF (a) = 81%, MAM (b) = 86%, JJA (c) = 71%, SON (d) = 83%). Means are shown as vertical lines for historical (solid line) and future (dotted line) densities.

Section 5: Discussion

Examination of figure 4 reveals a mean temperature increase across all groups, evidenced by positive responses (0.66°C to 1.56°C). Also, the regression lines suggest that temperatures are projected to continue increasing between 2041 and 2060. That is, the regression coefficients (slopes of the lines) are also positive for all groups (0.03°C/decade [RCP45] to 0.4°C/decade [A1B]). However, 95% confidence intervals for the regression coefficients are positive only for groups A1B and RCP85 ((0.16°C/decade, 0.63°C/decade) and (0.02°C/decade, 0.39°C/decade) respectively). The regression line for RCP45 (blue) is quite flat (confidence interval: -0.17°C/decade to 0.23°C/decade), suggesting neither a cooling nor warming trend over the period considered.

The annual results for group A1B (1.2°C response) broadly agree with those of the ENSEMBLES project (van der Linden and Mitchell, 2009) for SRES A1B, which projected annual temperature changes to be in the range of 1 - 1.25°C (though the time-slices are not identical). The seasonal changes are similar in summer (both studies project changes to be in the range 1 - 1.5°C), but the ENSEMBLES winter results (1 - 1.5°C) differ somewhat from this particular study (1.5 - 2°C warming projected across the island).

The results for C4I (McGrath *et al.*, 2008) are averaged across different SRES, but in general their magnitude (1 - 1.4°C across all seasons) is similar to the results observed in figure 5.

Though the time-slices differ slightly, it is worth comparing the results with those obtained at sites over Ireland by Fealy and Sweeney (2008) (see section 2.1). Their projections are for temperature increases of between 1.4 - 1.8°C by the 2050s under SRES A2 and B2. These projections exceed those in figure 4, where the group A2 has a regression line projecting temperature increases of approximately 0.9 to 1.4°C over the 20-year period.

The magnitude of the results for group RCP45 (shown in figure 5) broadly agrees with a study on a larger ensemble analysed in IPCC AR5, which projected the median temperature over Ireland to increase by 1 - 1.5°C in future summers, and by 0.5 - 1.5°C in future winters under RCP 4.5, for the period 2046-2065.

The results illustrated in figure 6 disagree in part with Fealy and Sweeney (2008). They found that the greatest warming was projected for future autumns, in contrast with the analysis above projecting summers (in RCP85) or winters (in A1B and A2) to warm the most. They also note that the inter-GCM range for seasonal change is relatively large, again supporting the idea of using multiple GCMs (as this study does).

Since the mean values of T2m are projected to increase by less than either Tmn05 or Tmx95 for the seasons considered (comparing the relevant seasons in figures 6 and 7), this suggests a change in the variability and/or skewness of the distributions. These statistics were calculated to investigate the source of the changes observed in group RCP85 (figure 8). Summer temperatures show the greatest projected change between future and past, with the lowest agreement score of 71% for this season. Winter has the second lowest agreement between future and past (81%), indicative of the second-greatest projected change. This agrees with the analysis of figures 6 and 7, which shows that Tmn05 in winter and Tmx95 in summer are projected to increase by more than the corresponding changes in T2m. This is in line with the findings of Beniston *et al.* (2007), who concluded that the intensity of extreme temperature events will increase more rapidly than that of moderate temperatures (though their conclusion was for continental Europe; section 2.2). Their conclusion was due to an increase in temperature variability, which is observed in this study in group RCP85 for summer (a 20% increase in standard deviation) and spring (7.6% increase), whereas autumn only shows a 0.1% increase and winter shows a 2.7% decrease. Skewness measures the asymmetry of a distribution, and is also an important statistic to consider. An increase in skewness indicates that either the right tail has become more elongated or the left tail more compressed, or both. A decrease in skewness implies the opposite. Skewness is a dimensionless measure, but the standard deviation of the skewness measure can be used to assess how large the change is. The greatest change in skewness is seen for future springs, where the skewness changed from 0.11 to 0.56, an increase of 0.45. This is much greater than 0.023, the standard deviation of the skewness (this value is the standard deviation of the skewness for all four seasons). The change in mean temperature for future springs is the least of all seasons however, meaning the change in skewness is hidden by the highest similarity score of 86%. Changes in skewness were also positive for winters and autumns, though of a smaller magnitude (from -0.05 to 0.07 for winters, a change of +0.12, and from -0.26 to -0.21 for autumns, a change of +0.05), while the skewness for future summers decreased slightly (from 0.98 to 0.9, a change of -0.08).

In a statistical downscaling of GCM data at specific sites over Ireland, Mullan *et al.* (2012) examine changes in Tmn10 and Tmx90 for the 2050s. It is difficult to compare those results with this study due to their averaging across scenarios and seasons, and choice of a different threshold. Analogous to this study, they found Tmx90 projected to increase more than the mean temperature. In contrast, however, their results for Tmn10 show it projected to change less than the mean temperature.

Section 6: Summary

This study presented results obtained from a high-resolution dynamically-downscaled dataset over Ireland, involving three RCMs and four GCMs. The scale of this study is unique, and has addressed a topic that previously lacked adequate research. Analysis conducted to justify using high-resolution RCM data illustrated the added value of such an approach. Greater variability in the climate signal was captured by the RCMs, which were better able to capture and explicitly resolve more small-scale features that affect the evolution of two-metre temperature. Outputs from our selected ensemble of models and anthropogenic forcing scenarios were then examined. Temperature changes for the mid-21st century have been projected and analysed in detail. A comparison to previous relevant studies was carried out.

Time slices of 1981-2000 (control) and 2041-2060 (anthropogenically-forced future scenarios) were compared in order to determine the nature and magnitude of projected temperature changes. All groups showed an increase in annual mean temperature: this increase was greatest in group RCP85 (1.56°C), with the greatest trend projected in group A1B (0.4°C/decade).

Seasonally, a large spread of temperature responses across groups was evident. However, the warming signal was apparent from each median seasonal temperature exceeding 0.5°C for every group and season (with the exception of B1 in spring). Groups differed in their warmest projected seasons, from winter (A1B, A2) to summer (RCP85).

On a spatial scale, there are discrepancies between the five groups as to which season has the greatest projected warming, and also whether this warming will be uniform or vary across Ireland. As expected, however, the greatest warming is evident from those groups with higher emissions or RCPs: A1B, A2 and RCP85.

Examination of the projected changes in Tmn05 in winter and those of Tmx95 in summer again show differences across the five groups considered. However, a strong pattern of *greater* increases in both of these values when compared to the projected mean changes in T2m is evident across all groups. This is reinforced by examining the densities of seasonal changes.

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