RESEARCH ARTICLE

Simulating climate change and its effects on the wind energy resource of Ireland

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ABSTRACT

We consider the impact of climate change on the wind energy resource of Ireland using an ensemble of Regional Climate Model (RCM) simulations. The RCM dynamically downscales the coarse information provided by the Global Climate Models (GCMs) and provides high resolution information, on a subdomain covering Ireland. The RCM used in this work is the Rossby Center's RCM (RCA3).

The RCA3 model is evaluated by performing simulations of the past Irish climate, driven by European Center for Medium-Range Weather Forecasts ERA-40 data, and by comparing the output to observations. Results confirm that the output of the RCA3 model exhibits reasonable and realistic features as documented in the historical wind data record. For the investigation of the influence of the future climate under different climate scenarios, the Max Plank Institute's GCM, European Center Hamburg Model, is used to drive the RCA3 model. Simulations are run for a control period 1961-2000 and future period 2021-2060. The future climate was simulated using the four Intergovernmental Panel on Climate Change emission scenarios A1B, A2, B1 and B2. The results for the downscaled simulations show a substantial overall increase in the energy content of the wind for the future winter months and a decrease during the summer months. The projected changes for summer and winter were found to be statistically significant over most of Ireland. However, the projected changes should be viewed with caution since the climate change signal is of similar magnitude to the variability of the evaluation and control simulations. Copyright © 2011 John Wiley & Sons, Ltd.

1. INTRODUCTION

Greenhouse gas emissions are having a significant effect on the Earth's climate. Globally, an increasing rate of warming has taken place over the last 25 years, and 11 of the 12 warmest years on record occurred in the 1990s and 2000s.[1] Temperatures in Ireland have mirrored this global trend.[2,3] Climate models predict that global temperatures could rise by a further 1–5°C over the next 100 years, depending on the amounts of greenhouse gases (GHGs) emitted and the sensitivity of the climate system. The analysis presented in this paper was undertaken to investigate whether there is evidence that increasing temperatures will lead to changes in the wind climatology of Ireland.

There is considerable interest in renewable energy resources as a means of reducing carbon dioxide emissions to minimize 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 of 6–8 m s^{-1} at 50 m level over land, values that are sufficient to sustain commercial enterprises with current wind turbine technology.

The wind energy potential of the Irish climate has been well documented.[4–6] However, climate change may alter the wind patterns in the future; a reduction in speeds may reduce the commercial returns or pose problems for the continuity of supply; an increase in the frequency of severe winds (e.g., gale/storm gusts) may similarly impact on supply continuity. Conversely, an increase in the mean wind speed may have a positive effect on the available power supply.

The impact of GHGs on climate change can be simulated using Global Climate Models (GCMs). However, long climate simulations using coupled atmosphere-ocean general circulation models are currently feasible only with horizontal resolutions of 50 km or greater. Since the wind energy resource of Ireland exhibits a high degree of spatial heterogeneity, this is inadequate for the simulation of the detail and the pattern of climate change and its effects on the wind resource of Ireland. The Regional Climate Model (RCM) method dynamically downscales the coarse information provided by the global models and provides high resolution information on a subdomain covering Ireland. The computational cost of running the RCM, for a given resolution, is considerably less than a global model. The method of using an RCM to assess the impact of climate change on the wind energy resource has been used before in such studies as Pryor *et al.*[7] Although the present study primarily focuses on the Irish climate, the simulation domain includes the UK. Moreover, the methodology employed in the study is general and may be applied to other geographical regions.

To date, the amount of research on climate change on the wind energy resource of Ireland has been small. Notable international research includes Harrison *et al.*[8] for the UK, Pryor *et al.*[7] and Pryor and Barthelmie[9] for the Nordic and Baltic regions as well as Breslow and Sailor[10] and Sailor *et al.*[11] for the USA. The results for the UK indicate seasonal changes in potential wind production with winter production generally increasing whereas summer production decreasing. For Northern Europe, there is evidence for increased wind energy density[7] in the projected climate change simulations particularly during the wintertime, whereas Pryor and Barthelmie[9] suggests no detectable change in the wind resource or other external conditions that could jeopardize the continued exploitation of wind energy. The results for the USA show an expected overall slight decrease in wind speeds over the next 100 years.

2. OBJECTIVES

The main objective of the research is to evaluate future wind energy resources by simulating the wind climatology of Ireland at high resolution using the method of Regional Climate Modeling.

- To achieve this, we first evaluate the ability of the RCM to accurately simulate the wind climatology. The RCM is evaluated by performing simulations of the past Irish climate and comparing the output with observational data.
- We then simulate the future wind climate for different GHG emission scenarios and determine if (i) future climate projections of the RCM show substantial changes when compared with the past and (ii) whether the changes are significant.

In the concluding section of this paper, we will discuss our results with reference to these objectives.

3. MODELS

3.1. The Rossby Center regional atmospheric model

The Rossby Center regional atmospheric climate model version 3 (RCA3)[12,13] has been developed from the High Resolution Limited Area Model (HIRLAM; see www.hirlam.org). Compared with the numerical weather prediction model HIRLAM, several changes have been made to the radiation scheme, the turbulence scheme and the cloud parameterization. A new land surface scheme has been developed and implemented in RCA3, which is described in detail in Samuelsson *et al.*[14] Within a model grid cell, several tiles with different surface properties such as type of vegetation, roughness length and albedo are considered. For all tiles, water and energy balances are calculated separately, and a weighted average over the grid cell is computed. The land surface scheme also includes soil moisture and runoff parameterizations. Diagnostic variables of temperature and humidity at 2 m and wind at 10 m are calculated using Monin–Obukhov similarity theory as described in Samuelsson *et al.*[14] The RCM model domain used in this study has been set up with a 0.12° (13 km) spherical, rotated latitude/longitude grid. The model domain has 156×166 grid points, and in the vertical, there are 40 unequally spaced levels. The wind fields are output at 3 h intervals. For considering the effect of the North Atlantic Ocean, the model domain includes large parts of the ocean north, west and south of Ireland. There is a large scale jump between the GCM and RCM spatial resolution. However, this model setup has been evaluated extensively, and the results suggest that the model configuration is well able to capture the characteristics of present day climate.[2,3,15] The model domain is presented in Figure 1(a).

3.2. Evaluation of the RCA3 RCM

The RCA3 model was evaluated by performing 40 year simulations of the past Irish climate (1961–2000) and comparing the output with observations. The European Center for Medium-Range Weather Forecasts' ERA-40 global re-analysis data[16] and the Max Planck Institute's European Center Hamburg Model 4 (ECHAM4)[17] and ECHAM5[18] data were used to drive the RCA3 model. The following three simulations were run:
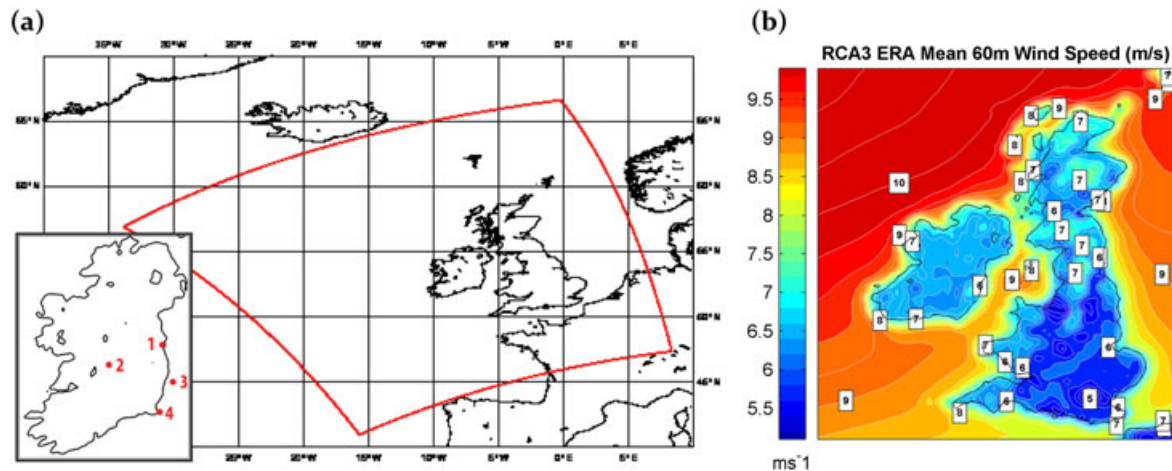
Figure 1. (a) The RCA3 model domain. The subplot shows the locations of specific locations referred to throughout the paper; 1. Dublin Airport synoptic station, 2. Birr synoptic station, 3. Arklow Wind Farm and 4. Rosslare synoptic station. (b) The RCA ERA mean 60 m wind speed [m s^{-1}] 1961–2000.

- ERA-40 Evaluation Simulation 1961–2000 (denoted RCA ERA)
- ECHAM4 Climate Control Simulation 1961–2000 (denoted RCA ECHAM4)
- ECHAM5 Climate Control Simulation 1961–2000 (denoted RCA ECHAM5)

Note that the ERA-40 data are based on the assimilation of actual observations over the integration period. It follows that the RCA ERA simulations should produce a wind field climatology that is close to the observed climate. The ECHAM climate simulations are unconstrained by observations, and therefore, the day-to-day synoptic evolution will not correspond to the observed synoptic sequence. However, the ECHAM and RCA ECHAM simulations should produce a mean climatology that is close to the mean observed climate. The observed winds at Irish synoptic stations are measured at 10 m height. Thus, when comparing model output with observations, the evaluations focus on wind data at 10 m height. Since the typical height of wind turbines is approximately 60 m, all other figures are of 60 m wind data. The 60 m wind speed is interpolated, using the logarithmic wind profile law, from wind speeds at 10 m and the two lowest model levels. The required roughness length is a grid average.

3.3. Future climate projections of the RCA3 Model

For the investigation of the influence of the future climate under different climate scenarios, the Max Plank Institute's GCMs, ECHAM4 and ECHAM5 are used to drive the RCM. As all climate models (regional and global) suffer from systematic errors, we also simulate the past climate (the control runs; RCA ECHAM4 and RCA ECHAM5) using the same RCM and GCM driving data. Differences between the two runs give a measure of the expected change in the Irish climate. The GHG emission scenarios are taken from those developed under the auspices of the Intergovernmental Panel on Climate Change.[19] The following four 40 year future simulations were run:

- RCA3 ECHAM4 B2 GHG emission scenario 2021–2060.
- RCA3 ECHAM5 A1B1 GHG emission scenario 2021–2060.
- RCA3 ECHAM5 A2 GHG emission scenario 2021–2060.
- RCA3 ECHAM5 B1 GHG emission scenario 2021–2060.

4. METHODS

4.1. The Weibull distribution

A number of empirical studies have demonstrated that surface wind speed distributions over both land and sea can be well represented by the two-parameter Weibull distribution[20–22], although it has been noted that the fit is not exact.[23–25]

For each RCM simulation, a Weibull distribution was fitted to the wind speed time series at each grid point on the model domain. The method of Maximum Likelihood Estimates, as recommended for wind speed time series,[20,26] was employed to calculate the Weibull parameters.

The Weibull probability density function (pdf) is given by

$$W(x) = \alpha\beta^{-\alpha}x^{\alpha-1}e^{-\left(\frac{x}{\beta}\right)^{\alpha}} \text{ for } x \in [0, \infty), \ \alpha, \beta > 0 \tag{1}$$

where α is the shape parameter, β is the scale parameter and x is the wind speed.

The mean value is

$$\mu = E(X) = \beta\Gamma\left(1 + \alpha^{-1}\right) \tag{2}$$

where Γ is the gamma function, $\Gamma(\alpha) = \int_0^{\infty} z^{\alpha-1}e^{-z}\,dz$.

Other statistical quantities are given in terms of the parameters.[22]

4.2. The mean winds

The mean wind speed and the mean cubed wind speed were calculated at each grid point per month, per season and per hour (the diurnal cycle). The mean absolute difference metric (MAD) and the root mean square difference metric (RMSD) were used to compare the RCA ECHAM simulations with the RCA ERA simulation. The 'projected percentage change' metric is used to give a measure of expected climate change by comparing the future climate projections with the control simulation. It is defined as follows:

$$D_i = 100 \times \left(\frac{\bar{F}_i - \bar{P}_i}{\bar{P}_i}\right) \tag{3}$$

where i is the grid point, $\bar{P}_i$ and $\bar{F}_i$ are the wind data for the past and future model runs, respectively.

4.3. Statistical analysis

A key purpose for this study is to establish the significance level of any changes of the wind speed in the future projections. Considering that wind speeds are generally not normally distributed, the Wilcoxon rank sum test and the Kolmogorov–Smirnov test[27,28] were applied to the future and past wind speed time series. The null hypothesis states that the past and future winds are from the same continuous distribution. The alternative hypothesis is that they are from different continuous distributions. Small values of the confidence level p cast doubt on the validity of the null hypothesis. If $p < \varphi$, for small φ, this indicates that the null hypothesis is rejected, the alternative hypothesis is accepted and the difference between the future and past wind speeds is statistically significant at the $(100 \times \varphi)\%$ confidence level. The significance tests were applied at each grid point per annum and per season. Since the Wilcoxon rank sum test and the Kolmogorov–Smirnov test gave similar results at the 5% level of significance, only the latter will be presented. It should be noted that whereas the Wilcoxon rank sum test is sensitive to changes in the location of distributions, the Kolmogorov–Smirnov test is sensitive to both changes in location and shape of distributions. Since wind turbines usually work within a certain range of wind speeds (cut-in and cut-out speeds), it is important to investigate the significance of changes in the shape, as well as location (mean and median) of the past and future wind speed distributions.

Three different alternative hypotheses are chosen, depending on the future wind speed projections presented in Figures 6, 7 and 8. The alternative hypotheses are as follows:

- Ha_0: $F_c \neq P_c$. The future and past wind speed cumulative distribution functions (cdfs) are not equal.
- Ha_1: $F_c > P_c$. The future cdf is greater than the past cdf, implying a decrease in the future wind speed.
- Ha_2: $F_c < P_c$. The future cdf is less than the past cdf, implying an increase in the future wind speed.

4.4. Comparison of RCA3 output with observations

When comparing the model output with observed station data, the model data were bilinearly interpolated onto the latitude–longitude station location. Figure 1(a) shows the locations of the synoptic stations referred to throughout this paper. Dublin Airport is located 8.5 km north of Dublin City center. The Irish Sea is approximately 10 km away, between 40 and 150°. The Wicklow mountains lie between 155 and 225°, starting about 18 km south of the airport and extending a further 60 km to the south. The anemometer is well exposed except in the south–southwest direction. Birr station is located in the low-lying plains of the midlands, approximately 1.5 km east–southeast of Birr Town. The anemometer is well exposed in all directions. Rosslare Station is situated on the southeast coast of Ireland within 500 m of the coastline. The observed wind data for Rosslare station was limited to the 36 year period 1961–1996. The anemometer is well exposed in all directions.

5. RESULTS

5.1. Evaluation of the RCA3 models

Figure 1(b) presents the 60 m wind speed averaged over the 40 year integration period (1961–2000) for the RCA ERA simulation. The RCA ECHAM4 and RCA ECHAM5 mean wind speeds (not shown) show qualitatively good agreement in terms of the spatial patterns and magnitude of the wind speed. Comparing the RCA ECHAM4 and RCA ERA simulations for the area shown in Figure 1(b), the difference statistics are $MAD = 0.27$ m s^{-1} and $RMSE = 0.32$ m s^{-1}. Similarly, for the RCA ECHAM5 model, we obtain $MAD = 0.48$ m s^{-1} and $RMSE = 0.53$ m s^{-1}. The difference plots in Figure 2 show a positive bias in the 60 m wind speed over Ireland of between 0 and 0.3 m s^{-1} for the RCA ECHAM4 simulation and between 0 and 0.5 m s^{-1} for the RCA3 ECHAM5 simulation.

The scatter plots in Figure 3 compare RCA ERA 10 m wind speed with observed wind speed at the inland station Birr and the east coast station Dublin Airport. It is noted that the model has a tendency not to capture wind speeds at the more extreme scales. This is particularly evident in the scatter plot for Dublin Airport. The scatter plot evaluations were repeated at a number of stations spanning Ireland.[29] In all cases, the RCA model has a consistent tendency to underestimate the wind speed, typically by about 1.5–2 m s^{-1}. The RMSE ranges from 1.67 to 2.44 m s^{-1}.

We have examined the spatial correlation of the wind speed. The typical scale at which the correlation falls to 0.6 is about 200 km for observed wind speeds. The scales for model simulations are somewhat larger, as the models are unable to capture many small scale features.[29]

Figure 4 shows 10 m wind speed data at Rosslare station (in southeast Ireland) for observed RCA ERA, RCA ECHAM4 and RCA ECHAM5 data for the period 1961–1996. Figure 4(a) shows that the model Weibull distributions compare quite
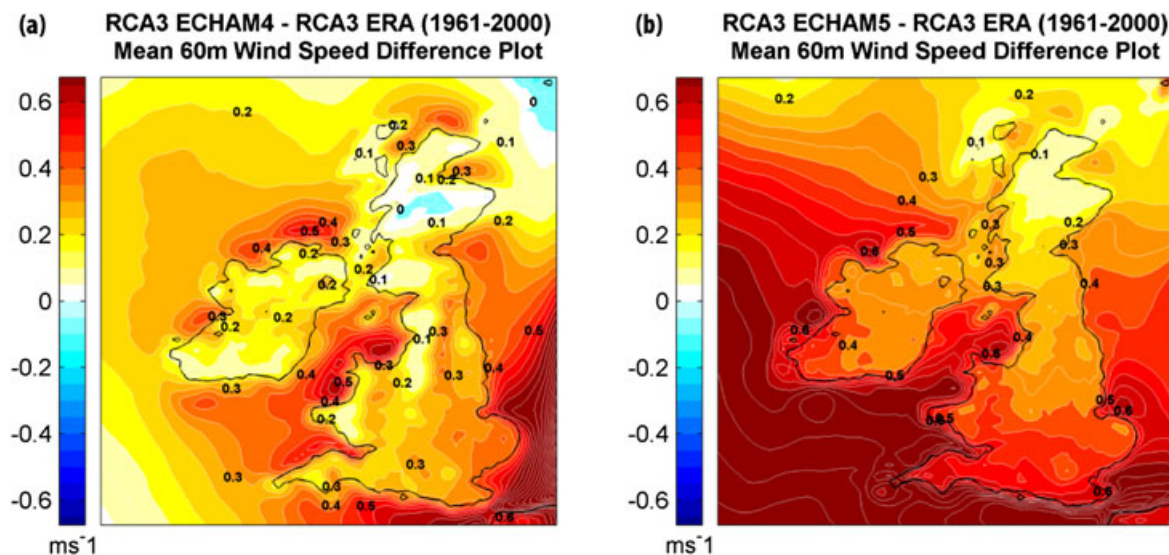

Figure 2. Mean 60 m wind speed difference (1961-2000); (a) RCA ECHAM4 minus RCA ERA and (b) RCA ECHAM5 minus RCA ERA.
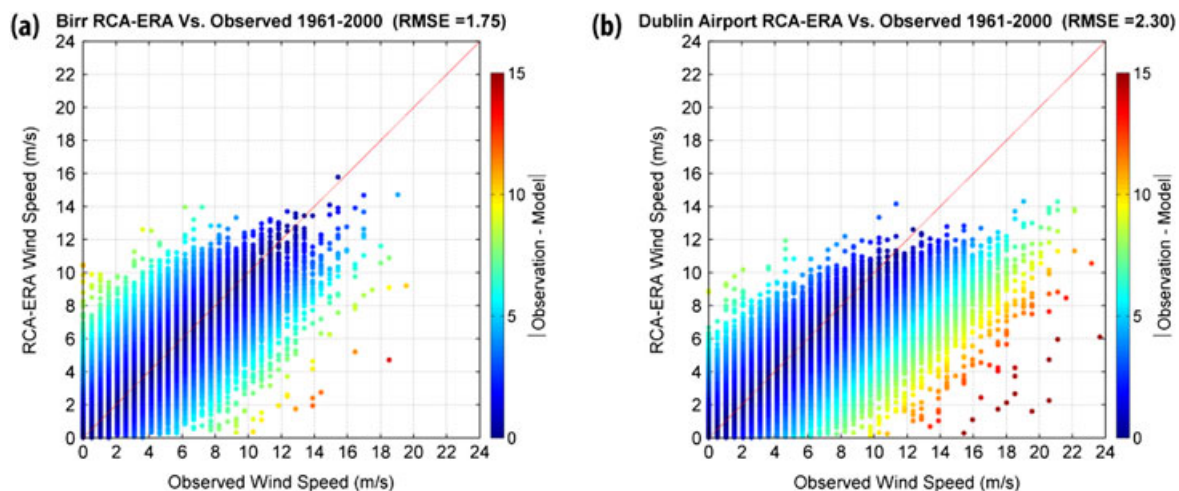
Figure 3. Scatter plot of 3-hourly instantaneous 10 m wind speeds (RCA ERA versus observations) for the period 1961-2000 at the synoptic stations (a) Birr and (b) Dublin Airport.
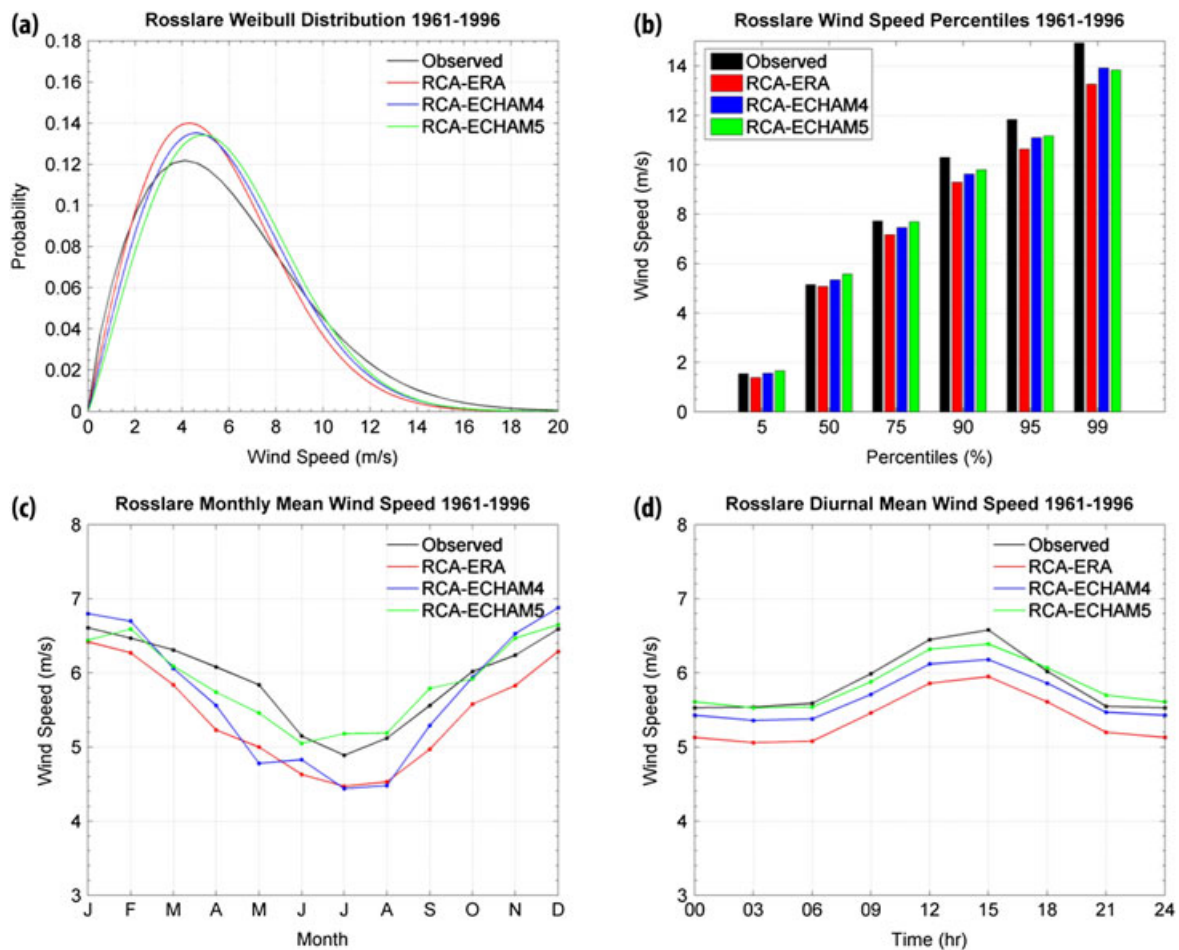

Figure 4. Comparing the observed 10 m winds at Rosslare station with RCA ERA, RCA ECHAM4 and RCA ECHAM5 data for the time period 1961-1996. (a) Weibull distributions (calculated using the fitted Weibull parameters), (b) wind speed percentiles, (c) mean monthly wind speed and (d) diurnal cycle.
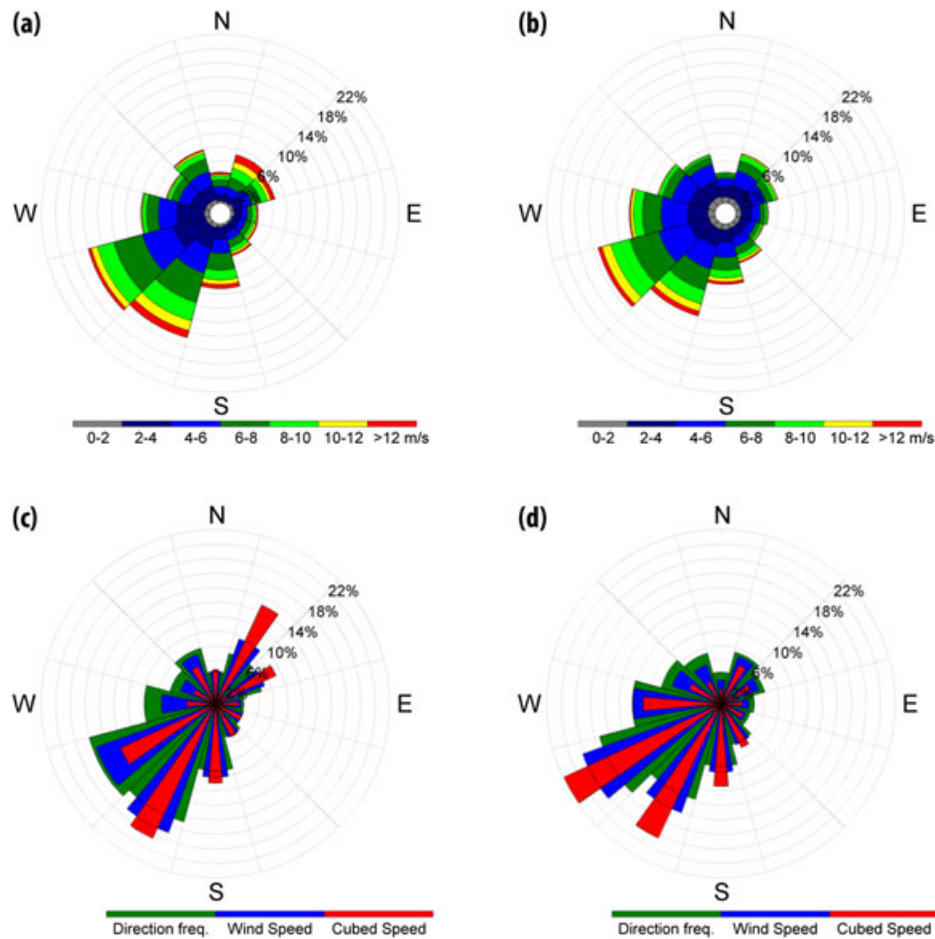
Figure 5. The 10 m wind roses at Rosslare station 1961-1996. (a) Observed, (b) RCA ERA, (c) observed power wind rose and (d) RCA ERA power wind rose. The power wind rose depicts the directional frequency, the contribution of each sector to the total mean wind speed and the contribution of each sector to the cube of the wind speed (or power).

well with the observed distribution. However, the observed distribution shows a slightly higher probability of obtaining higher wind speeds. This is reflected in the wind speed percentiles (Figure 4(b)), the mean monthly wind speed (Figure 4(c)) and the diurnal cycle (Figure 4(d)) where, although we have good agreement, the observed values are generally slightly higher than the model output.

The 10 m wind roses for the period 1961–1996 at Rosslare station are shown in Figure 5 for (a) observed and (b) RCA ERA. Similarly, the power wind roses are depicted in Figure 5(c),(d). We see that RCA ERA wind roses are in good agreement with observations. However, there is a well-known local effect at Rosslare station, where occasionally strong northeast winds are not fully captured by the RCA simulations. The RCA ECHAM4 and RCA ECHAM5 wind roses (not shown) were found to be similar. The evaluations described were repeated for a number of stations covering Ireland, and similar results were obtained.[29]

The RCA3 model shows a consistent tendency to scale down the wind speeds of the global driving data (ERA40 and ECHAM), resulting in a negative bias of approximately 1.5–2 m s^{-1} over Ireland. However, the RCA3 model shows better skill in simulating the detail and the pattern of the wind climate, introduced by the spatial heterogeneity of the Irish landscape.

5.2. Future climate predictions of the RCA RCM

Figure 6 shows the projected percentage change of the 60 m mean wind speed for the four scenario simulations: (a) ECHAM5 A1B, (b) ECHAM5 A2, (c) ECHAM5 B1 and (d) ECHAM4 B2. It is noted that all four scenario simulations show no substantial increase or decrease in mean wind speed over Ireland. In order to investigate the effects of climate
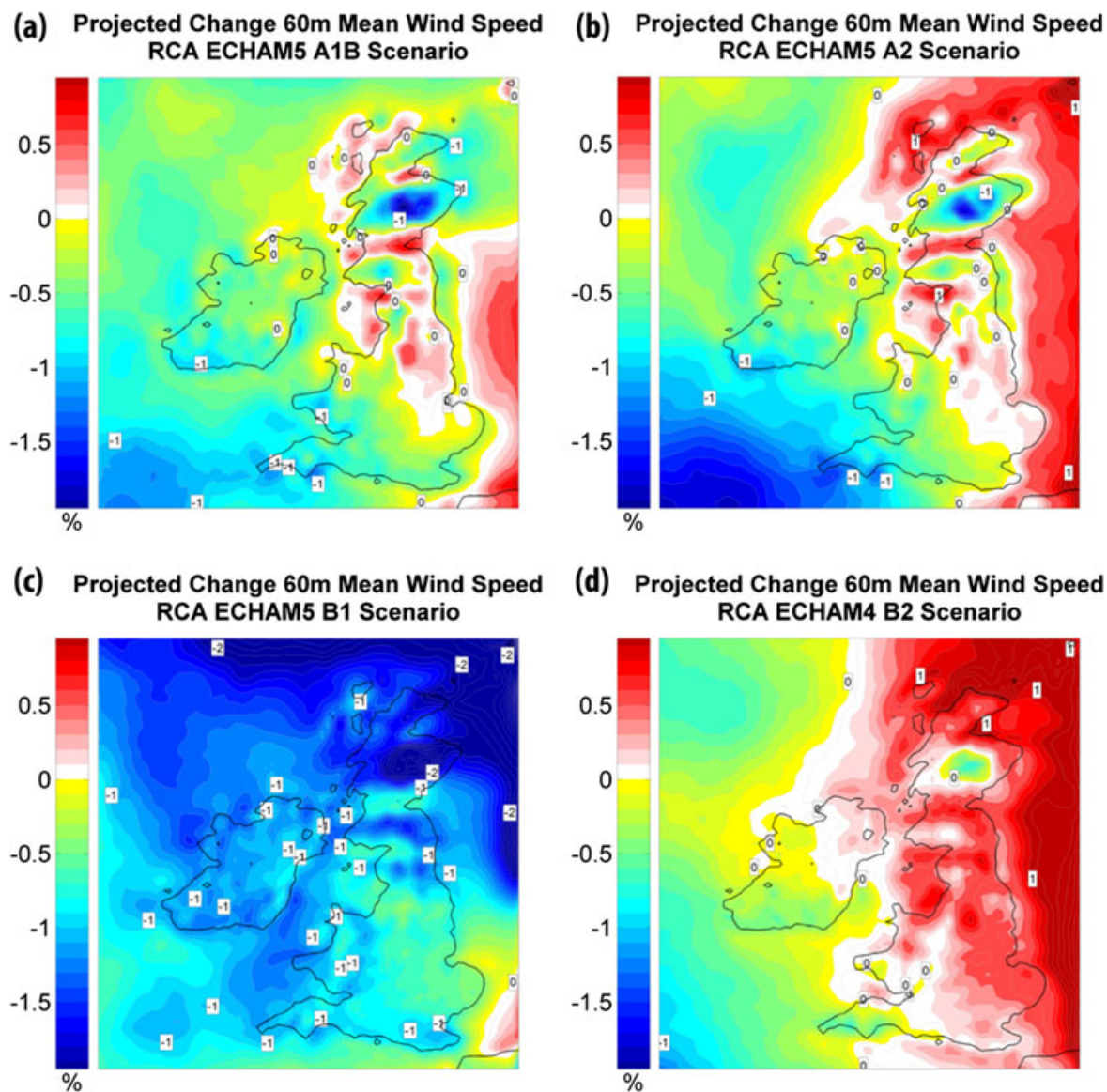
Figure 6. The predicted percentage change of the annual 60 m mean wind speed for the four climate scenario simulations: (a) RCA ECHAM5 A1B, (b) RCA ECHAM5 A2, (c) RCA ECHAM5 B1 and (d) RCA ECHAM4 B2. In each case, the future period 2021-2060 is compared with the control period 1961-2000.

change on the energy content of the wind, the projected change in the 60 m mean cubed wind speed were calculated. Again, small changes (−2 to 2%) were observed in the energy content of the wind for the four GHG scenario simulations (figure not presented).

However, when stratified per season, we do see substantial changes in the mean wind speed, particularly for the winter and summer months. The projections show an expected increase in the winter mean wind speed over Ireland ranging from 1% for the ECHAM5 B1 simulation to 3.5% for the ECHAM5 A1B simulation (not presented). The projected change in the energy content of the wind for the winter months ranges from an increase of 2−4% for the ECHAM5 B1 simulation to an increase of 8−11% for the ECHAM5 A1B simulation (Figure 7). The projections show an expected decrease in the summer mean wind speed over Ireland ranging from 2−3% for the ECHAM5 A2 simulation to 4−5% for the ECHAM4 B2 simulation (not presented). The projected change in the energy content of the wind for the summer months ranges from a decrease of 4−10% for the ECHAM5 A2 simulation to a decrease of 14−16% for the ECHAM4 B2 simulation (Figure 8).

Note that the past and future 60 m mean cubed wind speeds, required for Figures 7 and 8, were calculated using the fitted Weibull parameters.
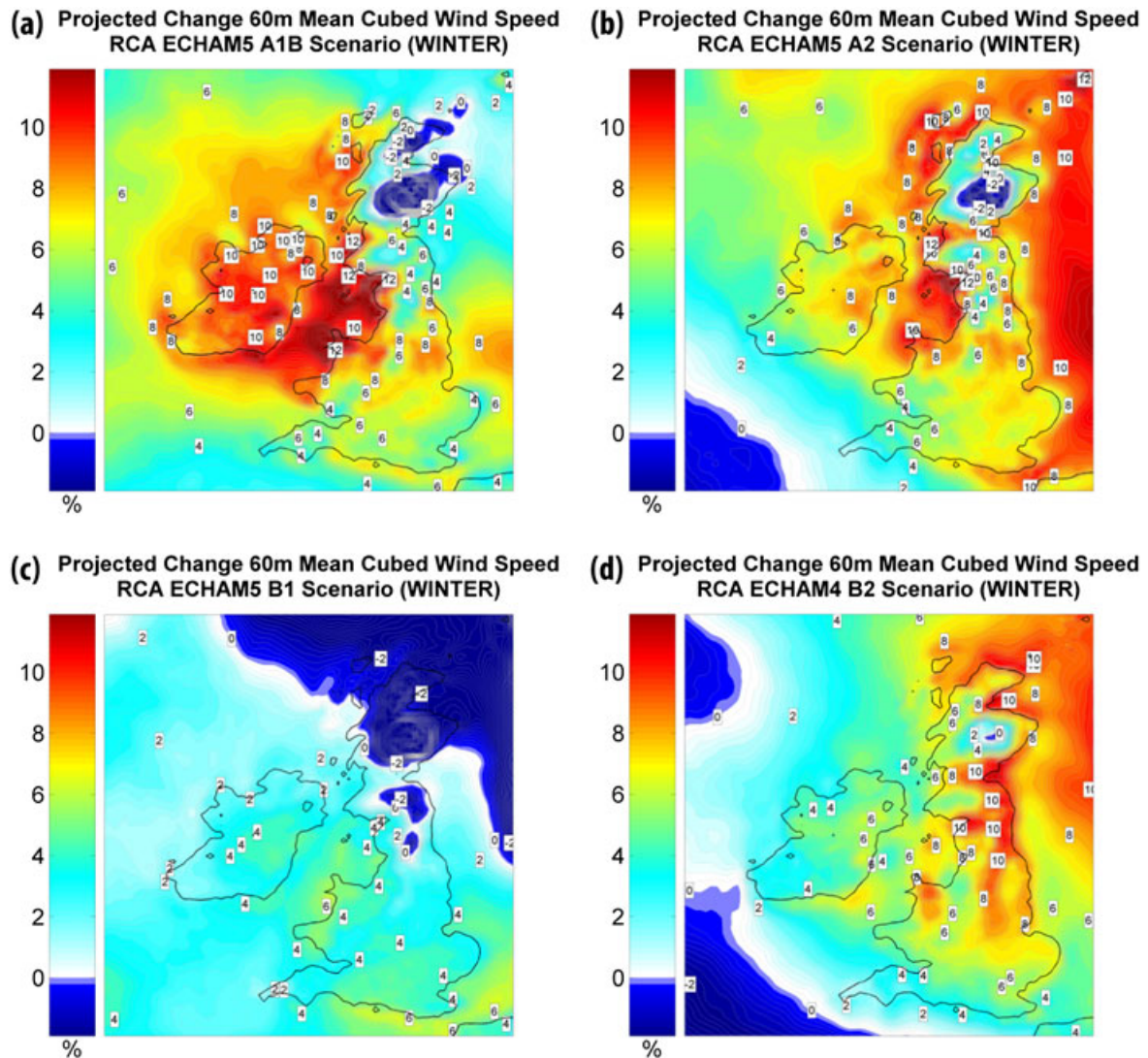
Figure 7. The predicted percentage change of the winter 60 m mean cubed wind speed for the four climate scenario simulations: (a) RCA ECHAM5 A1B, (b) RCA ECHAM5 A2, (c) RCA ECHAM5 B1 and (d) RCA ECHAM4 B2. In each case, the future period 2021-2060 is compared with the control period 1961-2000.

The statistical significance of changes in the 60 m wind speed, for the A2 and B1 GHG scenarios, is presented in Figure 9. Since projections show an increase over Ireland in the mean winter 60 m wind speed, the Ha_2 alternative hypothesis (described in Section 4.3) is tested for the future winter projections. Figure 9(a),(b) shows that the Ha_2 alternative hypothesis is accepted for winter with a high level of significance over most of Ireland for both GHG scenario simulations. Areas in the figures that are shaded white indicate high levels of significance ($p \ll 0.05$). We can conclude that the increase in future winter winds speeds over Ireland is statistically significant. Similarly, we see from Figure 9(c),(d) that the decrease in the summer wind speed is significant over Ireland. Here, the Ha_1 alternative hypothesis is tested. Since the projections in the annual mean wind speed, presented in Figure 6, are between -1 and 0.3% over Ireland, the Ha_0 alternative hypothesis is tested when analysing the statistical significance of changes in the annual wind speed. The past and future annual wind speed distributions were found to be statistically different over the south of Ireland (figures not presented).

In addition to projected changes in the mean wind speed, changes in the variability of the wind speed and the shape of the wind speed pdf are important for energy applications.
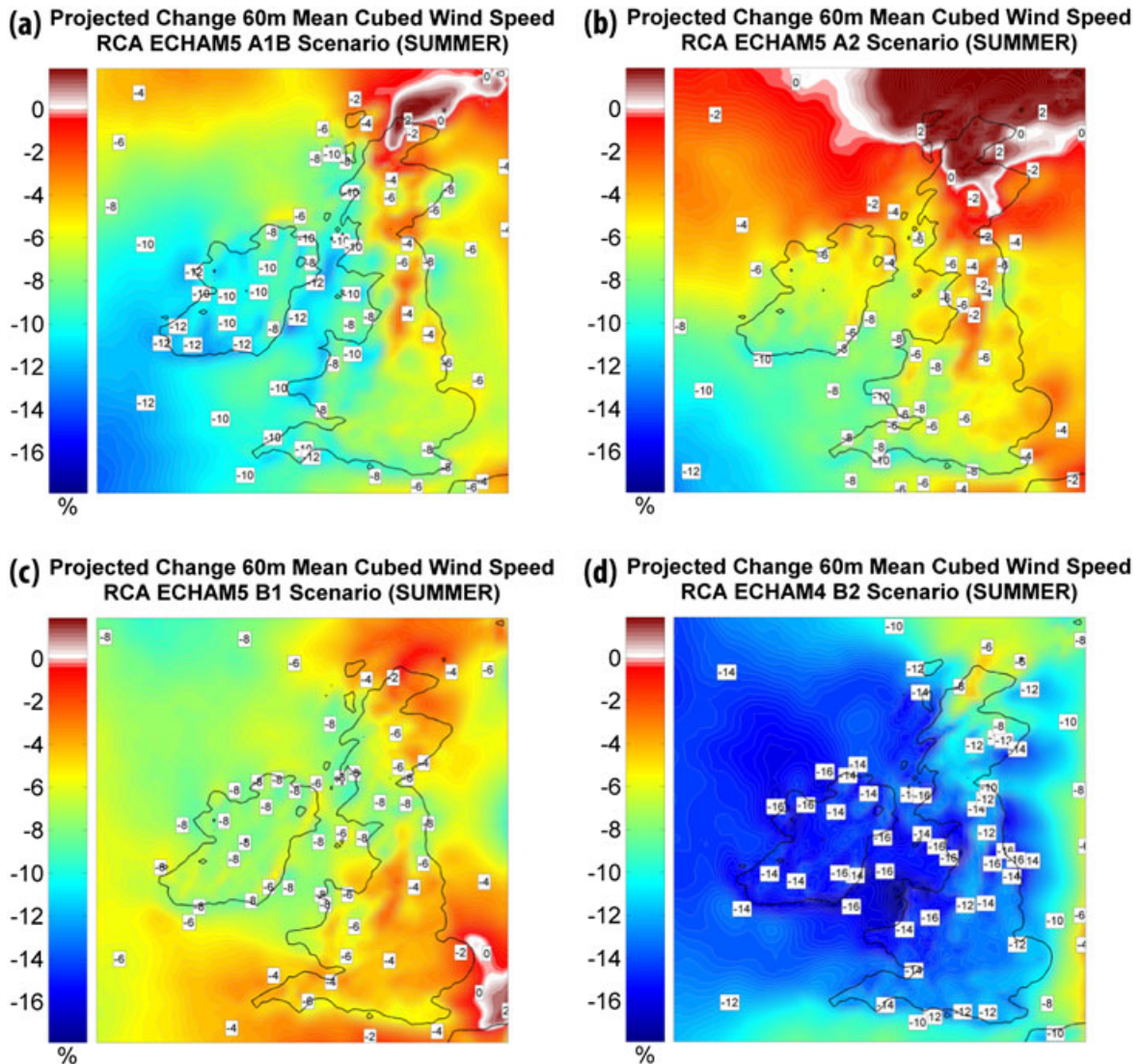
Figure 8. The predicted percentage change of the summer 60 m mean cubed wind speed for the four climate scenario simulations: (a) RCA ECHAM5 A1B, (b) RCA ECHAM5 A2, (c) RCA ECHAM5 B1 and (d) RCA ECHAM4 B2. In each case, the future period 2021-2060 is compared with the control period 1961-2000.

Figure 10 shows the percentage change in the future annual, winter and summer standard deviations of 60 m wind speed for the A1B GHG emission simulation. Similar results were obtained for the A2, B1 and B2 simulations. The maximum increase over Ireland of $\sim 5\%$ occurs during winter for the ECHAM5 A1B experiment and corresponds to an increase of ~ 0.17 m s^{-1}. The maximum decrease over Ireland of $\sim 7\%$ occurs during summer for the ECHAM4 B2 experiment (not shown) and corresponds to a decrease of ~ 0.16 m s^{-1}. Note that the past and future standard deviations, required for Figure 10, were calculated using the fitted Weibull parameters.

The fact that the future winter wind speed projections show an increase in both the mean and the standard deviation suggests that the future winter wind speed distributions are shifted to the right (in the wind pdf) and have a larger spread. This is consistent with Figure 11(a), the past and future (A1B) 60 m winter wind speed distributions at Arklow wind farm. This wind farm is Ireland's largest offshore wind farm and is located approximately 10 km off the east coast (see Figure 1(a)). Figure 11(b) shows the log scale plot, stressing the increase in future high wind speeds during winter. The future summer climate projections show a decrease in both the mean and the standard deviation, suggesting the future summer wind speed distributions are shifted to the left and have a smaller spread. This is consistent with Figure 11(c), the
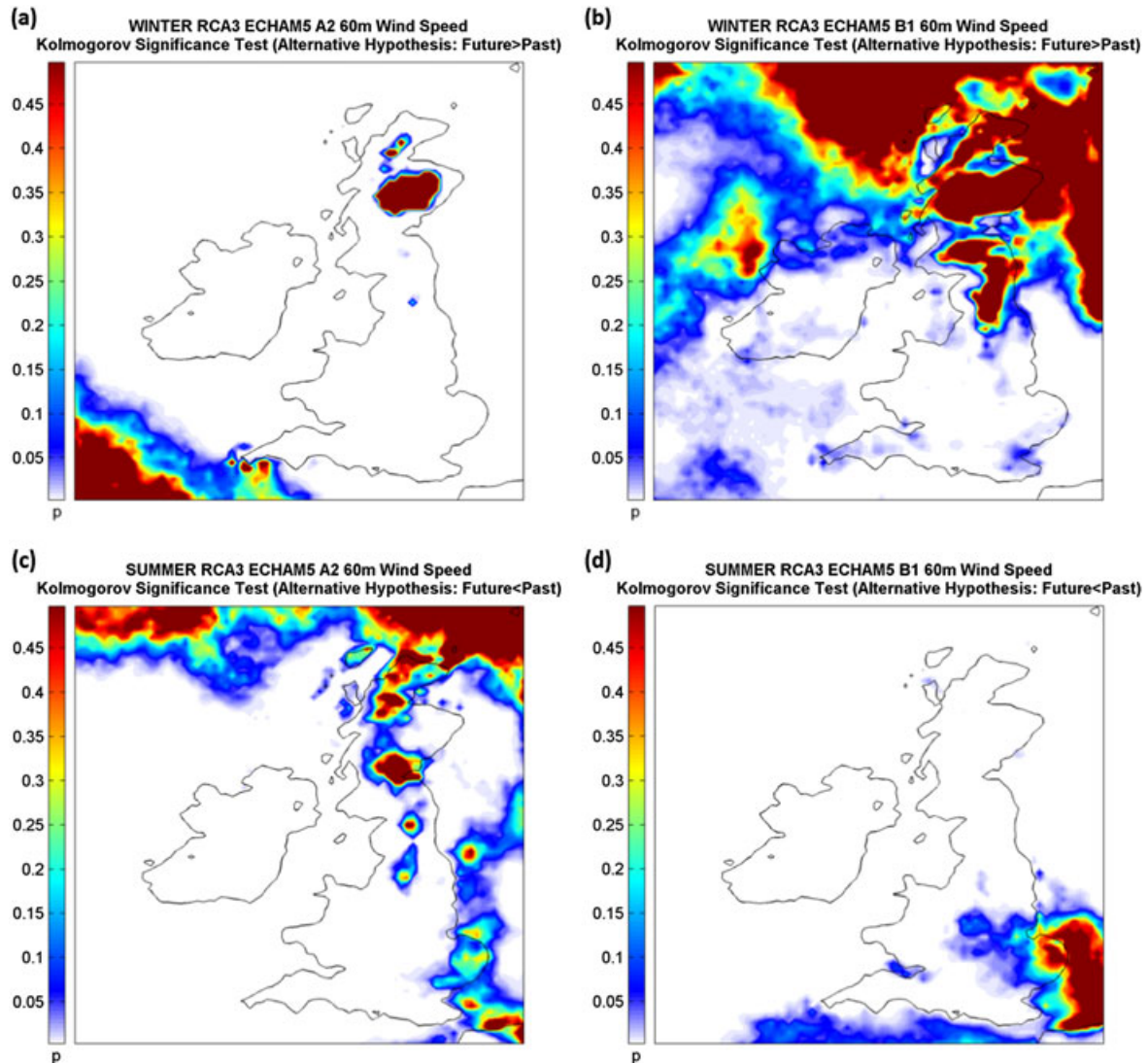
Figure 9. Statistical significance of changes in the future wind speed using the Kolmogorov–Smirnov test. The alternative hypothesis is accepted for small values of *p*. (a) RCA ECHAM5 A2 winter and (b) RCA ECHAM5 B1 winter. For winter, the alternative hypothesis states that the future wind speeds are greater than the past. (c) RCA ECHAM5 A2 summer and (d) RCA ECHAM5 B1 summer. For summer, the alternative hypothesis states that the future wind speeds are less than the past.

past and future (A1B) 60 m summer wind speed distributions at Arklow wind farm. Figure 11(d) shows the log scale plot, stressing the decrease in future high wind speeds during summer. The annual wind speed projections show a small decrease in the mean and an increase in the standard deviation, suggesting a higher probability of both low and high future wind speeds. This is consistent with the annual past and future wind speed distributions at Arklow wind farm (not shown). The analysis described was repeated for the A2, B1 and B2 simulations, and similar results were obtained.

Note that pdfs in Figure 11 were plotted using formula (1) and the fitted Weibull parameters.

To quantify the projected change in extreme wind speeds, the percentage change in the winter 99th percentiles are presented in Figure 12. All four GHG emission scenario experiments show a projected increase of between 0 and 5% in the 99th percentile of wind speed over Ireland. Note that the past and future percentiles, required for Figure 12, were calculated using the fitted Weibull parameters.

Although substantial changes in the wind speed for the future winter and summer months are expected, it is noted that the general wind directions and wind speed spatial correlations do not show any considerable change.[29]
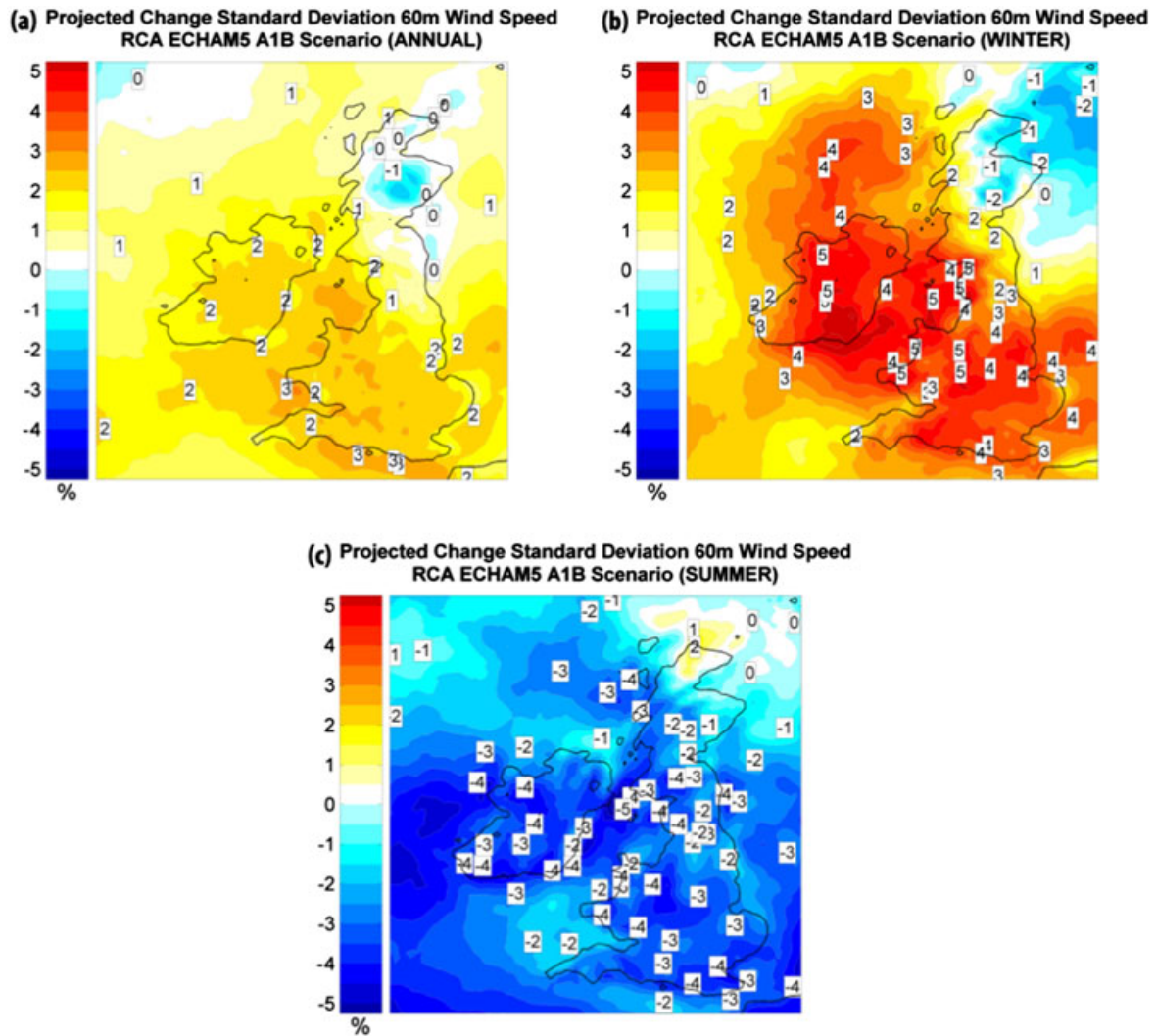
(a) Projected Change Standard Deviation 60m Wind Speed RCA ECHAM5 A1B Scenario (ANNUAL)

(b) Projected Change Standard Deviation 60m Wind Speed RCA ECHAM5 A1B Scenario (WINTER)

(c) Projected Change Standard Deviation 60m Wind Speed RCA ECHAM5 A1B Scenario (SUMMER)

Figure 10. The projected percentage change of the standard deviation of 60 m wind speed for the RCA ECHAM5 A1B simulation: (a) annual, (b) winter and (c) summer. In each case, the future period 2021–2060 is compared with the control period 1961–2000.

6. CONCLUSIONS

We have examined the impact of global climate change on the wind energy resource of Ireland using the method of Regional Climate Modeling. The climate of Ireland was simulated using the Rossby Center's RCM (RCA3).

The results of the analyses are presented below as they pertain to the objectives stated in Section 2.

- *To evaluate the ability of the RCA3 model to accurately simulate the wind climatology of Ireland.*

The RCA3 model was evaluated by performing past simulations of the Irish climate, driven at the lateral boundaries by ERA-40 and ECHAM data, and by comparing the output to observations. Results confirm that the output of the RCA3 model exhibits reasonable and realistic features when compared with the observed wind data record. However, there is evidence of systematic errors in the simulation of the wind fields, such as a tendency for the RCA3 model to scale down the wind speeds of the global driving data (ERA40 and ECHAM), resulting in a negative bias of approximately $1.5-2$ m s^{-1} over Ireland. Some of the errors revealed in the evaluation run may be related to errors in the GCM driving data. Additionally, the RCA3 model shows better skill over the global models in simulating the detail and the pattern of the wind climate, introduced by the spatial heterogeneity of the Irish landscape.
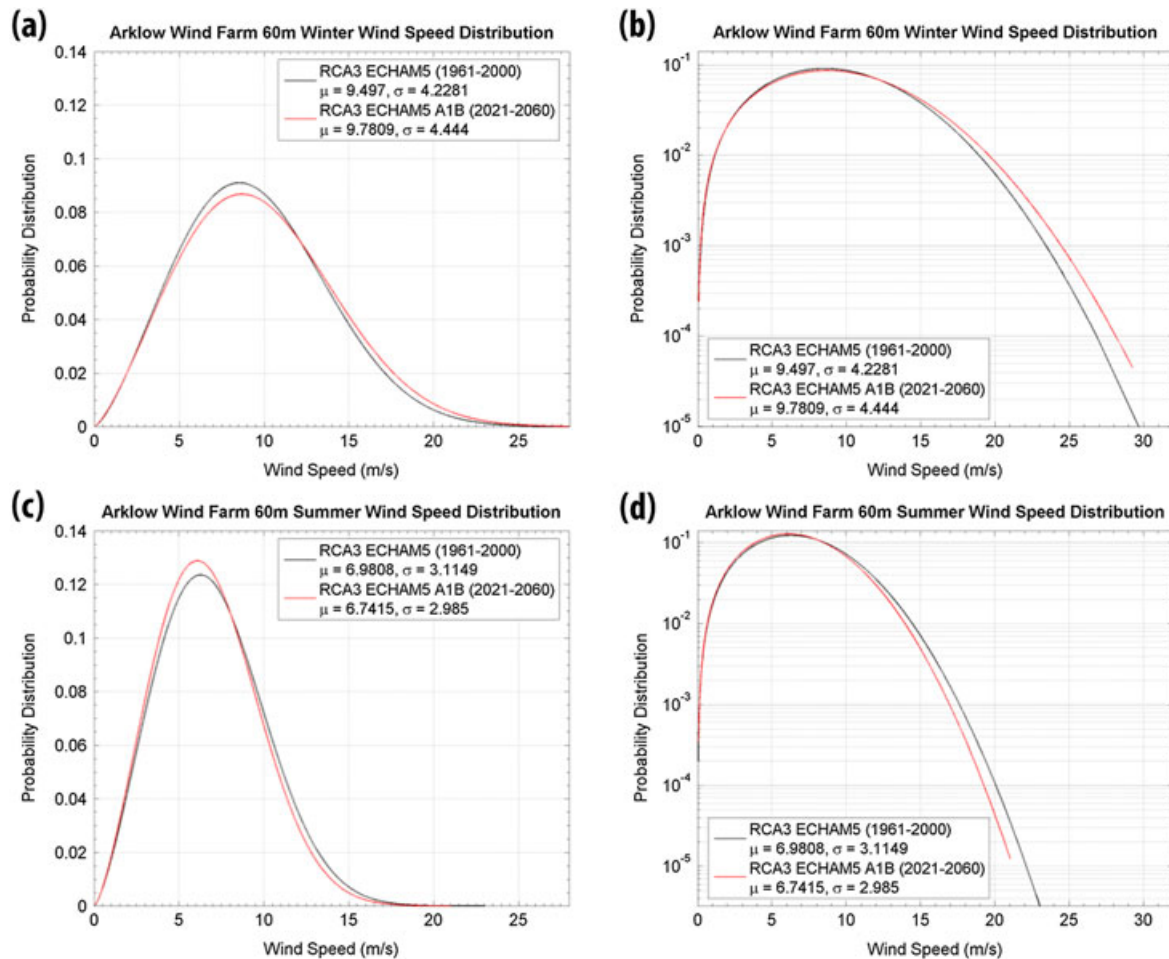
Figure 11. Comparing the RCA ECHAM5 past and future (A1B) 60 m wind speed distributions at Arklow wind farm. (a) Winter distribution, (b) log scale winter distribution, (c) summer distribution and (d) log scale summer distribution.

The evaluation results are consistent with previous studies investigating the ability of the RCA model to accurately simulate wind fields.[2,7] Separate studies, using different RCMs, have also noted an inability of RCMs to accurately simulate high to extreme wind speeds for Northern Europe.[1] For example, most PRUDENCE[30,31] RCMs, although quite realistic over sea, severely underestimate the occurrence of very high wind speeds over land and coastal areas.[32]

- *To simulate the future wind climate for different GHG emission scenarios and to determine if (a) future climate projections of the RCMs show substantial changes when compared with the past and (b) whether the changes are significant.*

Projections for the future Irish climate were generated by downscaling the Max Planck Institute's ECHAM GCM data using the RCA3 model. Simulations were run for the 40 year future period (2021–2060) and a control period (1961–2000). The simulations were run at 13 km resolution using the four GHG emission scenarios A1B, A2, B1 and B2.

Future projections show a marked increase in the amplitude of the annual cycle in wind strength with 4 to 10% more energy available during winter and 5 to 14% less during summer. The projected changes for summer and winter were found to be statistically significant, according to the Kolmogorov–Smirnov test, over most of Ireland. An increase in extreme wind speeds is expected during winter, which may impact on the continuity of supply of wind power. Nevertheless, the simulation results show an expected increase in the frequency of wind speeds in the energetically useful range occurring during the winter months. The future projections of wind direction and spatial correlations did not show any substantial change.

A possible explanation for the inter-annual variability increase in wind speed may be due to a future change in cyclone activity. Most GCMs summarized in IPCC AR4[1] (chapter 10) produce fewer weak but more intense midlatitude cyclones. The increase in intense cyclones over the North Atlantic is found to occur particularly during winter. This projected change
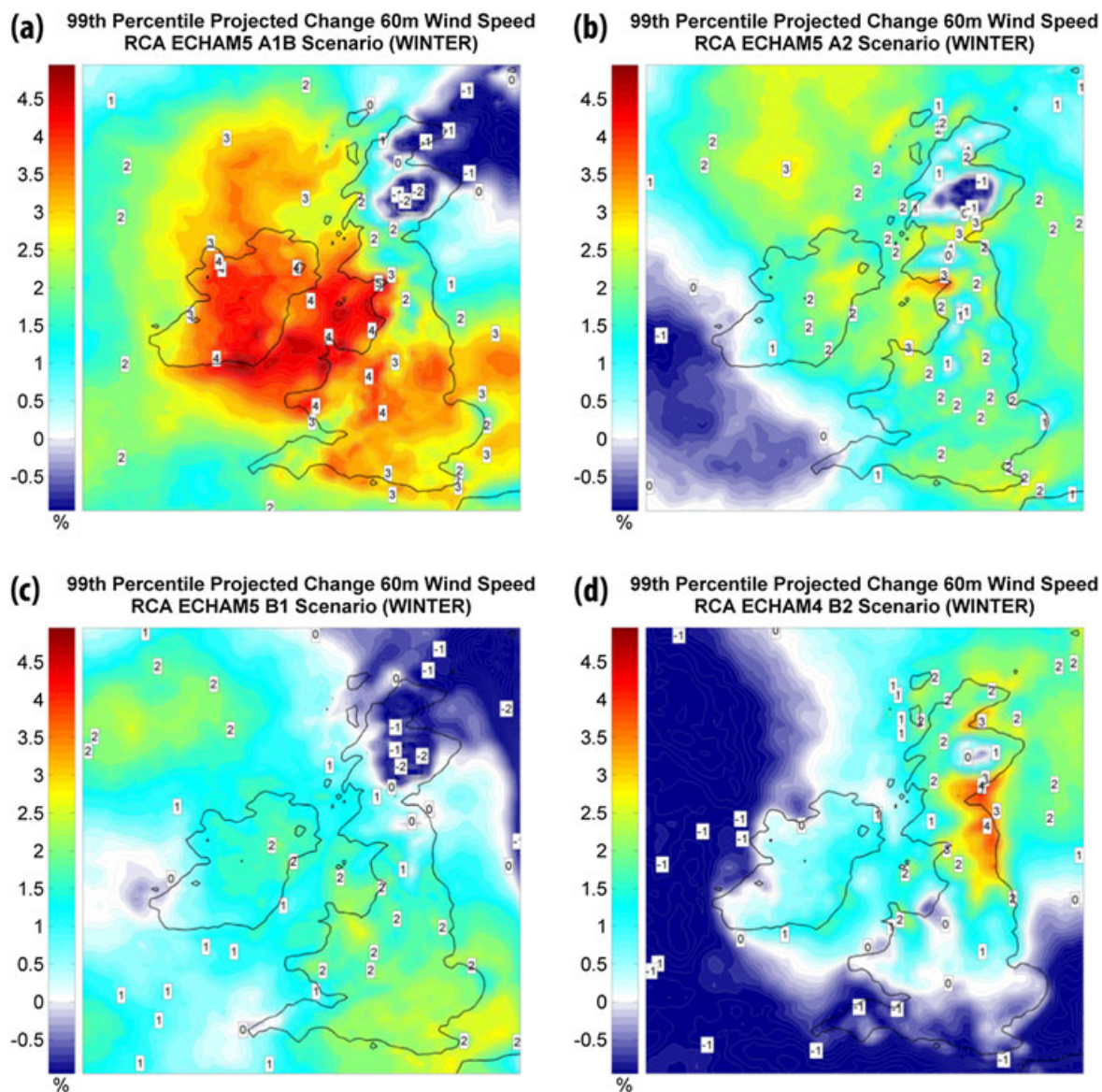
Figure 12. The projected percentage change of the 99th percentile 60 m wind speed for the four climate scenario simulations: (a) RCA ECHAM5 A1B, (b) RCA ECHAM5 A2, (c) RCA ECHAM5 B1 and (d) RCA ECHAM4 B2. In each case, the future period 2021–2060 is compared with the control period 1961–2000.

in cyclone activity is consistent with the wind speed projections presented in the present study of an increase during winter and a decrease during summer. A plausible explanation put forward for the projected changes in cyclone activity[33] is that a decreased meridional temperature gradient and the associated reduced baroclinicity in the future climate could be responsible for the decrease of the total number of extratropical cyclones.[34] The higher moisture supply due to a generally higher SST and the related increase in latent heat fluxes could trigger strong intensity cyclones.[35]

It should be noted that the projections of the mean wind speed (and wind power) outlined in this paper should be viewed with caution since the climate change signal is of similar magnitude to the variability of the evaluation and control simulations. Also, the climate change projections are subject to a degree of uncertainty that limits their utility. Accordingly, future work will focus on employing a multimodel ensemble approach. The ensemble method will use several different RCMs, driven by several GCMs, to simulate regional climate change. This work has already been started; the Climate Limited area Modeling (CLM)-Community's COSMO-CLM RCM[36,37] was employed to simulate the future wind climatology of Ireland for the period 2021–2060 using ECHAM5 A1B and B1 GCM data. To address the issue of RCM uncertainty,

simulations were run using both COSMO-CLM version 3 and version 4 with respective dynamical cores, leapfrog and Runge–Kutta. To address the issue of inherent climate variability, the control and future simulations were repeated using different realizations of the ECHAM5 data to drive the RCMs. Climate variability can then be assessed by comparing the climate change signals with the variability of the control simulations. Preliminary results show that the CLM projections agree with the RCA3 projections in the sense that they show substantial increases in 60 m wind speed over Ireland during winter of 4–5% and decreases during summer of 3–4%. The agreement of the RCA3 and COSMO-CLM simulation results increases our confidence that the future projections are robust.

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