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Will climate change impact on wind power development in the UK?

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Abstract Partly in response to concerns about anthropogenic climate change, renewable energy production is growing rapidly in the United Kingdom (UK). The wind power industry takes advantage of the country having some of the highest mean wind speeds in Europe. Future climate change, however, has the potential to alter the characteristics of the UK wind climate. Small changes in mean wind speed could produce much greater changes in wind energy output as the power generated is related to the cube of wind speed. This paper aims to use a simple method to provide insight into projected future UK wind climate and how this might differ from current patterns. A discussion of the scale of the projected impacts on the wind energy industry follows.

Keywords *Climate change impacts; Wind power Energy; Electricity system; geostrophic wind*

1 Introduction

Climate change represents one of the greatest scientific, socio-economic and political challenges in the coming century. The consensus reached by the majority of scientific experts is that anthropogenic emissions of carbon dioxide (CO_2) and other greenhouse gases will cause global warming on a scale beyond that which would have been expected under natural variability; moreover, this has the potential to provoke change all around the globe, with temperatures thought likely to increase by between 1 and 6.4˚C by 2099, depending on the emissions scenario (IPCC SPM, 2007).

One particularly obvious need arising as a result of climate change is the necessity of restructuring the way in which energy is produced, transported and used. It is widely understood that CO_2 emissions from fossil fuel-based electricity generation are contributing to potential future temperature increases. As such, alternative renewable sources are developing rapidly, and in the United Kingdom (UK), wind power is a particularly strong contender. Troen and Petersen (1989) show that the UK has some of the highest mean wind speeds in Europe, and wind power developers are keen to exploit this. Currently in the UK, renewables meet around 5% of electricity demand (DECC, 2009d) with wind, biomass and hydro the most common renewable energy sources. Wave and tidal power, whilst much discussed, are still very much in the development phase and solar PV contributes only a tiny amount. The European Renewables Directive obliges the UK to meet 15% of its energy demand with renewable resources by 2020; the latest UK government assessment suggests up to 30% of electricity could come from renewables by this time (DECC 2009d). The majority of this increase is currently expected to be met by massive expansion of both onshore and offshore wind power.

As a renewable power source, wind is governed ultimately by the climate which is projected to undergo significant change in the coming century. This is a striking caveat to bear in mind when considering renewable energy in the context of climate change. As amounts of renewable generation increase with the aim of reducing carbon dioxide emissions and slowing the rate of climate change, it is possible that in a changing climate, renewable energy resources will themselves be vulnerable to change. Any difference in the inward or outward flux of solar energy has the potential to alter circulation patterns, and thus, wind climate – with possible consequences for the wind energy resource.

2 Modelling wind climate

2.1 Wind climate

The wind climate of the UK follows a strongly seasonal pattern, with the highest mean wind speeds occurring in the winter months of December and January and the lowest in the summer months of June and July. The daily variations follow a diurnal pattern with speeds tending to be lower at night time than during the day. There is a reasonably large variation in the mean wind speeds in different regions of the UK, with the coasts and northern areas experiencing typically higher speeds than elsewhere. An important influence for the wind climate is a fairly permanent low pressure to the north west of the British Isles (the ‘Icelandic Low’), and a high pressure to the south west (the ‘Azores High’). These pressure centres move and vary in intensity, but are normally present in all seasons (Barry and Chorley, 1998) and their variation is recorded in an index known as the North Atlantic Oscillation (NAO). The effect of this dominant pressure pattern is felt as a prevailing south-westerly to westerly wind direction over the UK.

Understanding the wind climate at a specific site is key to successful energy generation from wind turbines. The surrounding topography and surface features strongly characterise the site’s wind climate, influencing wind speeds and direction up to between 500 and 1000m above the surface. As such, the output of a turbine with an 80 to 100m hub height is dependent on having favourable local conditions as well as on the larger-scale wind climate. Typical methods for carrying out wind resource analyses for individual sites include: (a) using measurements taken directly at the intended wind power development site, normally over the period of at least one year; (b) taking measured data from the site over a shorter period and extending these by correlating it statistically with longer-term data obtained from a nearby site; (c) using very high resolution mesoscale models to develop representative wind climates for small gridded areas, with individual grid cells between 1 and 5km square; and (d) applying wind flow models such as the Wind Analysis and Application Program (WA^{S}P) to relate longer-term measured time series from one site to another nearby site.

Climate information for specific sites is not always desired, for instance, if the interest is broader, such as an understanding of the overall wind climate of the UK. Instead, this might be analysed through the use of mesoscale or regional climate models, at resolutions of hundreds down to perhaps tens of kilometres (km) or less, providing gridded output; for example, Burch *et al.* (1992). Mesoscale models cannot account for surface features at a site level, but do take into consideration the general characteristics of an area, such as its average elevation and surface roughness, employing more detail as the resolution increases. Another source of gridded wind climate data is the reanalysis products (e.g., NCEP-NCAR (Kalnay *et al.* 1996), ERA40 (Uppala *et al.* 2005)). These are datasets derived from numerical weather prediction models which take actual measurements as input, and output homogeneous gridded data, at resolutions of 1 to 2° latitude and longitude.

2.2 Compatibility with climate change analysis

For the purposes of analysing wind climate near to the surface at individual points, a large-scale model such as a General Circulation Model (GCM) is not suitable. The resolution of the best current models is around 2° of latitude and longitude, whilst the topography – which has a strong influence on surface wind climate – varies on significantly smaller scales. In parts of the UK such as northern Scotland, where the terrain is very mountainous, important surface features change on scales as small as hundreds of metres. It is impossible to model the wind climate successfully in these regions without having a spatial resolution at a similar scale and so it would be unwise to directly use the surface wind output of a GCM to carry out wind climate analysis at a site.

The second issue with using GCMs for wind climate analysis relates to the use of time series generated from the model. The models are created such that over, say, a 30 year time period, the derived climate output from the model should be representative of the actual climate over that period. The time series is not necessarily authentic in terms of sequences of events. Thus, only the average values and statistics of variability over the 30 year period would be expected to be directly useful. From the point of view of understanding future wind climate, this implies that, for example, the twelve monthly mean values of wind speed or the frequency distributions ought to be useful but the value of mean wind speed on a particular date is not.

2.3 Existing climate change work

Most existing studies looking at climate change effects on wind speeds employ some form of downscaling to the GCM output in order to enhance the quality of the wind climate results, either by the use of Regional Climate Models (RCMs) – dynamic downscaling – or statistical-empirical methods. Results are available in the literature from several studies on wind power using both empirical and dynamic downscaling of climate models. As yet, the only published study on climate change and wind speeds in the UK is Harrison *et al.* (2008), which analysed the surface wind changes modelled by an RCM as part of the UK Climate Impacts Programme 2002 (UKCIP02) – based on the Hadley Centre HadRM3. They found that the general tendency as determined by this model was for future UK mean wind speeds to increase in winter and decrease in summer. There were some exceptions to this, particularly in the north west of the country, where the tendencies appeared to be in the opposite direction.

Pryor and Barthelmie (2005a) carried out a detailed investigation using RCM simulations to predict wind energy availability over Scandinavia and the Baltic states using RCM output from the Rossby Centre in Sweden. Using wind energy density as the measure, i.e. the power available from the wind per square metre, the authors conclude that there is a sufficiently significant increase indicated by the model in wind energy density between 1961-90 and the 2080s, and also some evidence to suggest that the increases are more substantial in winter. However, “the uncertainty of these prognoses remains high”. The same authors also conducted work using empirical downscaling methods. Pryor *et al*. (2005b) find a negative trend in wind speeds across the Baltic States using statistical downscaling of a GCM, with most locations showing a decrease in the 2071-2100 period in energy density, 90th percentile wind speed (as a proxy for extreme winds) and mean wind speed. In comparing the parts of the two studies that concern the same driving GCM, it was found that the RCM-predicted wind speeds tend to be lower than those from empirical downscaling. In terms of the future predictions, however, they show a general increase in mean wind speeds in contrast to the decrease predicted by the empirical method. Pryor *et al.* (2005c) describe an extension of the empirical downscaling method using multiple GCMs: the general findings are that “there is no significant difference between conditions during 2046-2065 and 1961-90 based on the ensemble of the model results” but that the period 2071-2100 shows a slight decrease in mean wind speeds, 90th percentile wind speeds and energy density consistent with their initial empirical downscaling study.

Two studies covering the US again give a varying pattern of results. As was found for the Baltic region, using different GCMs seems to result in very different answers. For example, Breslow and Sailor (2002) used the output of two GCMs: the Hadley Centre model suggested insignificant changes in mean wind speed over much of the US, whilst the Canadian Climate Center model showed a reduction of 10-15%. The authors speculate that this could result in a reduction of wind power generation of 30-40%. Segal *et al.* (2001) undertook a study into wind power in the US under future atmospheric conditions with increased CO_2 using an RCM driven by the Hadley Centre GCM. From the results of the future predictions, they conclude that over most of the US, wind power would decrease by 0-30% on a seasonal basis, with a few small areas seeing increases of the same magnitude. Annually, the changes were shown to be around ±10%. The authors note that due to the sensitivity of the results to the particular GCM used to drive the model, the outcomes should be considered ‘exploratory’. A more recent study by Sailor *et al.* (2008) used a statistical downscaling technique to analyse climate change impacts on wind speeds at five locations in the north west US using four GCMs. The study found that the most significant change was likely to be in spring and summer months. The authors calculated that speeds may reduce by 5-10%, causing a potential fall in energy output of around 40% or slightly more in some cases. Broadly speaking, the results from the different GCMs agreed in terms of the direction of future changes, but there were a few exceptions to this, particularly at one of the chosen locations.

It is clear from these studies that the outcome is very model-dependent, that is, the skill of the entire model – including the downscaling – is clearly paramount in obtaining a reasonable result. In order to understand whether climate models could be indicating broad changes in UK wind climate over the coming century, the primary concerns are the regional climate, its spatial variability and temporal tendencies rather than site-specific wind climates; and the time-scales considered could be anything from 20 to 100 years. It may be interesting in light of this to consider using large-scale climate variability as a proxy for near-surface wind climate, thus avoiding the involvement of apparently lower quality GCM surface wind results.

3 Using GCM geostrophic wind as a proxy indicator

Atmosphere Ocean GCMs (AOGCMs) have been shown to be better at describing historical climate characteristics on a macro scale, perhaps at hundreds of kilometres, rather than those climate factors with smaller scales, such as surface winds (Wilby *et al.*, 2004). Pressure fields, which vary on typically larger scales, have been used to generate downscaled higher resolution surface wind climate from AOGCMs in a number of studies (e.g. Pryor *et al.*, 2005b; Sailor *et al.*, 2000). As such, pressure patterns are known to be very closely related to wind climate, and it may be more helpful to investigate their variation rather than relying on the GCM's interpretation of the surface winds. Geostrophic wind is a wind field derived from pressure gradients and is representative of frictionless balanced air flow. It was reasoned that deriving the theoretical geostrophic winds from the pressure gradient information may give more useful information than pressure fields alone as it allows obvious analysis of both wind speed and direction changes.

3.1 Calculating geostrophic wind from gridded data

Using gridded mean sea-level pressure (MSLP) data, the components of geostrophic wind in the x (westerly) and y (southerly) direction can be found by considering the geostrophic wind equation in directional form, such that:

$$u_g = -\frac{1}{f\rho}\cdot\frac{\partial p}{\partial y} \tag{1}$$

$$v_g = +\frac{1}{f\rho}\cdot\frac{\partial p}{\partial x} \tag{2}$$

where u_g is the westerly (eastward) and v_g the southerly (northward) geostrophic wind; $\frac{\partial p}{\partial y}$ and $\frac{\partial p}{\partial x}$ are, respectively, the MSLP gradients in the y direction (northward) and x direction (eastward) (McQueen and Watson, 2006; Gordon *et al.*, 1998). f is the Coriolis parameter which varies with latitude, according to

$$f = 2\omega\sin\phi \tag{3}$$

where ω is the angular velocity of the earth and ϕ is the latitude. For simplicity, this work assumes a constant f of 1.114×10^{-4} s^{-1} for a latitude of 50˚N. The results will thus be marginally underestimated for the northern half of the country but any bias will be identical for all datasets.

3.2 Results for historical control period

Before using geostrophic winds as a proxy for surface wind climate, it is of benefit to investigate whether a GCM, in this case the ECHAM5 GCM from the Max Planck Institute for Meteorology, can reproduce the geostrophic wind climate with reasonable accuracy for an historical control period. The model has a relatively high resolution at 1.865˚ latitude by 1.875˚ longitude. Data from the model is available at daily time steps from the World Climate Research Program's (WCRP's) Coupled Model Inter-comparison Project phase 3 (CMIP3) multi-model dataset via the Intergovernmental Panel on Climate Change (IPCC) data distribution centre; this study employs the *Climate of the 20th Century experiment (20c3m), Run 1* (IPCC Data Distribution Centre, 2005a).

The process of determining the skill of ECHAM5 in reproducing historical geostrophic wind fields for the UK requires comparison of the GCM output with climate records for a typical 30-year period, often taken in the IPCC assessments to be 1961-90. Rather than use data from the irregular network of UK Met Office observation stations directly for the comparisons, reanalysis data was deemed more suitable. The ERA40 reanalysis dataset (European Centre for Medium Range Weather Forecasting, 2006) was used in Pryor *et al.* (2005a) at a resolution of 2.5˚ latitude and longitude. The alternative NCEP-NCAR reanalysis (Kalnay *et al.*, 1996), was used in Pryor *et al.* (2005b) also at a resolution of 2.5˚ latitude and longitude, and in Watson *et al.* (2001); the latter demonstrated a good degree of similarity between the NCEP-NCAR reanalysis and observed geostrophic wind data from radiosondes. As the ERA40 data is now available at a higher resolution of 1˚ latitude and longitude it has been chosen for this study.

For an area approximately 43 to 66˚ north in latitude and 23˚ west to 24˚ east in longitude, shown in Fig. 1a, the reanalysis pressure data at 1˚ resolution was interpolated using cubic splines (via a standard Matlab function) to the lower resolution GCM grid. The pressure gradients at each point in the grid for both the GCM and reanalysis datasets were then calculated over distances equivalent to one grid box either side in the north-south direction and ±2 grid boxes in the east-west direction, which keeps the spacing a little more similar in both directions in terms of metric measurements (In the UK region one degree of latitude is approximately 111km while one degree of longitude is approximately 70km). From the pressure gradients, the u and v geostrophic wind vectors were calculated as per equations (1) and (2).

The resultant mean wind speed averaged over the immediate UK region (Fig. 1b) was calculated for the GCM and ERA40 data for each month over the thirty-year period. Fig. 2 shows that the ERA40 values match to within an average of 6% for the autumn and winter months, and an average of 11% for the spring and summer months. The month with the greatest difference was August, and that with the least difference was January. One plausible explanation for the better results in winter months is that the average wind climate tends to be more strongly influenced in winter by the very large-scale forcings, such as the NAO, and these tend to be better-represented by the GCM than the smaller, more local influences (Schoof and Pryor, 2006) which dominate in summer months when the NAO is weaker.

With the exception of January and March, the GCM values are all greater than those from the reanalysis data. A possible explanation for this, given in Demuzere *et al.* (2008), is that ECHAM5 tends to underestimate the MSLP to the north of the British Isles and overestimate it in the Mediterranean Sea area - leading to a larger north-south pressure gradient, which results in a higher magnitude of westerly geostrophic flow.

Taylor diagrams (Taylor, 2001) have been used in the IPCC third assessment report (McAvaney *et al.*, 2001) as a convenient method for visualisation of several statistics used to determine modelling success. They can be used with model output and/or observations and allows quick analysis of how well two datasets correspond with each other. In a follow-up tutorial Taylor (2005) describes how three statistical measures of correspondence between two spatial or time series datasets – correlation coefficient, root mean square difference and standard deviation – can be calculated and the results displayed in a Taylor diagram. The radial axis represents the correlation coefficient; the distance from the reference to the corresponding field point indicates the pattern root mean square error; and the standard deviation is read from the x- and y-axes. Pryor *et al.* (2005b) used this method in their comparison of monthly mean pressure gradients and vorticity from several GCMs; a similar approach has been adopted here.

Spatial average fields for each of the twelve months were generated for both the ERA40 and ECHAM5 datasets by averaging daily data for each month over the thirty-year period. Fig. 3 compares them using Taylor diagrams for each monthly field individually. It was shown that when the area under consideration was larger (Fig. 3a), the spatial patterns were more highly correlated, with correlation coefficients between 0.82 and 0.96. July and November were the months with the lowest correlation coefficient and the months of September, October and May had the highest. The standard deviation is similar to that calculated from the reanalysis data for some months in this region, with normalised standard deviations for July to September, November and December close to a value of 1. June has the lowest value, at 0.58, and April has a value slightly higher than one, 1.10. For the smaller region directly over the UK (Fig. 3b), the patterns were not so well correlated in some months, with correlation coefficients dropping to less than 0.4 in the months of July and November. This can be explained intuitively as since the pressure pattern varies on large scales, reducing the region of comparison increases the possibility that the patterns are different. August and April also stand out for the smaller region, as both have normalised standard deviations of 1.10 and 2.26 - suggesting ECHAM5 models higher variability within the region in these months than in ERA40.

Taking the mean resultant geostrophic wind speed, Fig. 4 shows the worst performing months (a) July and (b) August, in terms of percentage difference relative to ERA40. Both months show areas where ECHAM5 has significantly over-estimated wind speeds over northern Scotland by up to 30%. The results for the remaining months show that for winter, ECHAM5 typically produces geostrophic wind speeds within ±10% of ERA40 values. The tendency in most months is towards over-prediction in the immediate onshore UK region, with January and March predominantly under-predicted, as was manifest in the spatial average statistics.

In terms of regionality, the GCM appears to show closer correspondence to ERA40 in the Midlands and South than the North. To explore this further, Fig. 5a shows the locations of grid cells chosen representing Scotland (‘Scot’), north eastern England (‘NE Eng’) and southern England (‘S Eng’). The monthly percentage differences between the ECHAM5 and ERA40 results for each location are shown in Fig. 5b, with percentage differences ranging from -8% in NE Eng in March to 29% in Scotland in August. An explanation might perhaps be that the northerly areas are more sensitive to the location of cyclones in the north Atlantic region, whilst the midlands and south may be less affected by their precise location.

To include direction in the analysis, the mean monthly field of the geostrophic wind vectors for the 1961-90 period was calculated from the daily averages for each month. For most months of the year, the GCM fields look broadly similar in both magnitude and direction to those from the ERA40 reanalysis dataset. Two months with particularly obvious differences were March and April, as shown in Fig. 6. There is clearly a difference in the underlying pressure pattern in the cases of March and April. It can be seen from analysis of the MSLP fields in Fig. 7 that the low pressure area present in both datasets in the north west of the domain extends further south in the ECHAM5 model. The high pressure area in the south of the region is confined to eastern points in the ECHAM5 grid. The resulting pressure pattern creates a local anticlockwise curvature of the geostrophic wind vectors in ECHAM5 which is not evident in the ERA40 data. A map of the March pressure field for the larger region shows this more clearly: the difference in the location of the low pressure centre causes the variation in wind vectors over the UK.

Fig. 8 shows wind roses drawn for the three grid cells described above. They show a consistent difference in the annual pattern described by the ERA40 data and that from ECHAM5. In all three locations the GCM shows a prevailing westerly, a strong tendency to winds from the south-westerly quadrant, a slightly smaller amount from the north-westerly directions and very small amounts of consistently low wind speeds from the easterly directions. The ERA40 results show a peak also from the westerly direction, but a lower density of north- and south-westerlies, and instead, a larger frequency of easterlies – some of which, particularly from the north east, have high wind speeds. Easterly winds over the UK tend to result from a high pressure over Scandinavia. This changes the eastward track of the depressions that typically travel over the north of the country and for this reason is known as ‘blocking’. The easterly winds tend to bring very cold air to the region (Barry and Chorley, 1998). It may be that the GCM does not capture the Scandinavian high pressure blocking effects sufficiently

In general, the geostrophic wind speeds as manifest in the GCM tend to be higher than those from the reanalysis data, and in most months, are less variable both temporally and spatially. The tendency towards higher wind speeds is likely a result of an overestimation in the north-south pressure gradient, whilst the reduced variability could be the consequence of low spatial resolution, or the inability of the model to represent extreme features of the climate.

There is evidence to suggest from the analysis presented here that the summer wind climate is not captured satisfactorily, particularly within the smaller UK region of interest. The winter season would appear, however, to be more successfully represented. This implies more successful modelling of the pressure patterns in these months and is confirmed by Demuzere *et al.* (2008), in which the authors carried out a comparison of the ECHAM5 GCM with the ERA40 reanalysis mean sea-level pressure. They used a slightly longer control period (1961-2000), a larger spatial domain of 27.5˚W-27.5˚E, 15-85˚N; and they chose the 2.5˚x2.5˚ reanalysis resolution rather than the higher 1˚x1˚ resolution used here. Their main finding with regard to the skill of the GCM was that, for the area in question, only the October-April season was adequately represented with respect to the ERA40 reanalysis; the model output for the summer months did not show good similarity with this baseline.

3.3 Future projections

The analysis carried out has shown that for the area 48˚ to 61˚ north and 12˚ west to 3˚ east in particular, the ECHAM5 GCM replicates some of the main features of the mean monthly geostrophic wind climate as defined by the ERA40 reanalysis for the period 1961-90. There are differences, however, some of which appear to stem from a mismatch in location and strength of mean monthly pressure fields. Bearing this in mind, the future geostrophic wind climate for the period 2081-2100 was derived from pressure data extracted from *SRES A2 experiment (sresa2), Run 1* of the ECHAM5 GCM (IPCC Data Distribution Centre, 2005b) to see if any changes were discernable.

In general, the changes projected by the GCM for geostrophic winds in 2081-2100 are smaller than the difference between the GCM 1961-90 hindcast and the ERA40 data for the same period. Pryor *et al.* (2005a) used this to suggest that further analysis of the climate model data was needed, with the clear suggestion that it is not an accurate enough representation of current climate. Fig. 9 shows that patterns throughout most of the grid cells suggest a strengthening of the seasonal pattern of wind speeds in the UK, with decreases of around 1% to 5% in the spring and summer months and increases of 2% to 4% in the autumn and winter months (with the exception of December which shows a small percentage decrease). This is reasonably consistent with what was shown using the change factor method with an RCM in Harrison *et al.* (2008). It is worth noting that this RCM was unrelated to the GCM used here, and so a correspondence of results is interesting.

Specific areas within the UK show larger changes, particularly in the southern UK in the summer months – where a decrease in wind speeds of over 10% is projected – and in northern areas in the spring and autumn months. The two months with areas of largest potential change are July and August (Fig 10 a and b), which both show areas in the south of the domain as having up to 16% decreases in mean geostrophic wind speed. These months also showed notably high differences between ECHAM5 and ERA40 data for the control period, however. Winter tends to show smaller and more consistent changes over the whole UK.

Taking the results for some individual locations as in section 2, it is clear that the effects in some areas of the country are more severe than others. The percentage differences in monthly mean geostrophic wind speed are shown in Fig. 12 for the three ECHAM5 grid squares representing some UK regions. The differences manifest in the southern England grid cell are generally of greater magnitude than in the other two locations. On average, the changes are predominantly negative in the S Eng and NE Eng cells, with the May-August period showing the largest decreases. The Scottish grid cell tends to show smaller changes in the mean speed over all months except September, where it appears to increase by 12%. For Scotland, positive changes outweigh the negative, with September-November experiencing the greatest increase in mean speeds.

Analysis of the wind vectors shows those months with the most deviation from the baseline climate are May and November (Fig. 12). For May, there is clearly a change in the mean pressure field such that the cyclone turning the wind anticlockwise in the north west of the region is no longer as strong or there is a change in its location. In November, the wind appears to be turning more anticlockwise in this region and increasing in speed, suggesting the presence of stronger or more north-westerly located cyclones.

The data at the three locations was processed into wind roses using the control period and future GCM data to highlight any changes in prevailing direction or wind strengths in any particular direction. From Fig. 13, there appears only to be very slight changes in the overall annual pattern of wind directions, consistent with the country-wide results presented above. Interestingly, however, an additional small frequency of higher speed winds – between 40 and 45 m/s – appears in the plots for NE Eng and Scot that is not present in the 1961-90 rose. In both cases, this is only present in the sector 255-265˚.

4 Impacts on wind energy

There are two clear issues with using the analysis presented here to consider potential changes in wind energy output: Firstly, the work considers geostrophic wind, i.e. the theoretical frictionless wind that in practice is only likely to exist above the planetary boundary layer, far above the height of a wind turbine; secondly, the resolution of the wind data is low and will not necessarily be representative of the true wind climate experienced at any individual location. Adopting the ‘change factor’ approach of the IPCC (Wilby *et al.*, 2004) would suggest considering the projected anomalies alone - or applied to a more reliable baseline climate - and not the baseline data (1961-90) given by the GCM. Bearing this in mind, it is feasible to use the changes to the geostrophic wind climate as projected by the GCM to ascertain a potential range of impacts on wind climate closer to the surface, and hence the energy outputs from wind turbines in a very general, UK-wide sense.

Geostrophic wind is related to wind speeds at any height, z, within the boundary layer via two relationships: the geostrophic drag law (5) and the logarithmic wind profile (6):

$$G = \frac{u^*}{\kappa}\sqrt{\left(\ln\left(\frac{u^*}{f \cdot z_0}\right) - A\right)^2 + B^2} \tag{5}$$

$$U(z) = \frac{u^*}{\kappa}\ln\left(\frac{z}{z_0}\right) \tag{6}$$

where G is the geostrophic wind speed, u^* is the friction velocity; κ is the von Karmann constant with a value of 0.4; z_0 is the surface roughness; and A and B are dimensionless constants. The parameters A and B within the drag law equation are often empirically derived, and may vary by site. Here they are given values of 4.5 and 1.8 respectively, following the work of Troen & Petersen (1989).

Examining some sample values of wind at turbine height and the corresponding calculated geostrophic winds shows that except at very low speeds, the relationship is pseudo-linear. Using this reasoning implies that for a given percentage change in mean geostrophic wind speed, the corresponding percentage change in mean surface wind speed will be the same. For the three grid cells identified, the ERA40 10m wind for 1961-90 has been taken as the current baseline and has then been adjusted for the future by applying the relevant percentage change in geostrophic wind speed. This has been done for each of the twelve months of the year and the wind speeds then extrapolated to 80m hub height using a 1/7th power law (Manwell, 2002).

Expected wind energy yield can be calculated using a combination of the actual wind speed frequency distribution at a site at turbine height and a wind turbine power curve

(Manwell, 2002). Most commonly, the characteristic distribution for sites in Europe is the two-parameter Weibull. The scale parameter of the Weibull distribution is closely related to the mean wind speed whilst the shape parameter typically varies from 1 to 3, depending on the individual location. Without site-specific wind speeds in this case, it seems misleading to use site-specific distribution parameters so instead the more general case of the Weibull distribution with a shape parameter equal to 2 (i.e., a Rayleigh distribution) will be assumed. The power curve applied is the Vestas V90 3MW (Vestas, 2004).

Compared to the percentage changes in wind speeds, the changes in energy output are proportionately greater, as might be expected given the relationship between the quantities. All three locations show a tendency for energy output to decrease in the spring and summer months; the most pronounced effects are seen in the southern England region where the August energy output decreases by over 40%. The Scottish region shows an increase in energy output in autumn; the value for September rises by almost 40%. The three locations display evidence of increases in energy output in winter, with the southern England cell more affected than the others: the maximum change is 17% in December.

5 Discussion

Along with Harrison *et al.* (2008), this work represents part of the first detailed assessment of future wind climate for the UK and its implications for the growing wind power fleet. It shows that the ECHAM5 GCM produces a largely correct – if not perfect – representation of the large scale wind climate over the UK and provides an analysis of the potential changes in wind speeds that are simulated to occur towards the end of the century, and the possible consequences for wind energy production. Its primary limitation is its reliance on a single GCM, although other work suggests it is fairly representative; further work will employ additional GCMs to confirm the findings.

Whilst the analysis of energy output based on the GCM projections is very much an estimation, averaged over the whole region on an annual basis, the changes seem unlikely to be large enough to impact on the overall viability of wind farms. Seasonally, however, there are variations that could affect wind farm operation and the electricity system as a whole, particularly with regards to electricity prices. The electricity prices in the UK are dynamic and have a strong relationship to demand for electricity and gas. Prices tend to be higher at times of peak demand, and currently that means the winter months, when ambient temperatures are lowest and daylight is at its minimum. An increase in winter mean wind speeds would tend to increase revenue for wind generators during this period. The potential shortfall in summer revenue due to reduced wind speeds would probably be relatively less than the winter gain, due to the lower sales price during this period, creating an overall positive situation for the wind operators.

However, some other factors must be accounted for in considering these scenarios: firstly, the implications of changes in wind generation capacity at peak times for fossil-fuel generators are not clear, and this could further affect prices; secondly, with ambient temperatures projected to rise, it is possible that the current winter peak in demand could become smaller, or at some point could even move to a summer peak as demand for space cooling grows; thirdly, the current UK system of financial support for renewable generators contains a certain degree of variability, and the system itself may also be subject to alteration. In addition to these factors, there have been some fairly major fluctuations in oil prices in recent years, resulting from political and economic instabilities, and these directly affected gas and electricity prices in the UK. If oil - and natural gas - reserves are indeed in decline, it might be expected that the price would tend to increase further in the coming decades. This would put generators of renewable power in a much more competitive position. Without a dynamic market model, it is not possible to arrive at firm conclusions about the seasonal pricing effects, but the possibilities certainly merit further investigation.

In terms of electricity network management, one point that requires detailed research is the potential increase in winter wind speeds and how that might impact on the ability of network operators to manage large power flows. This is especially important regarding the distribution network where much of the onshore wind power is connected. Curtailing generation from wind farms is sometimes part of distribution network management strategy. It is an expensive option, as the operators will still require payment for ‘non-produced’ electricity; and so an increase in the potential for this situation to occur may require a different management method.

In terms of changes in the optimum geographical locations for wind farms, these results suggest little in the way of perceptible change. Troen and Petersen (1989) shows that current mean wind speeds are higher in the northern half of the UK; this is already reflected in the higher installed capacity of wind generation in Scotland compared to England (BWEA, 2009). The analysis of mean geostrophic wind speeds over the whole UK area using the GCM showed similar annual patterns for the future period as for the control period, and so it is likely that the north-south differences will persist.

The analysis is necessarily broad brush using relatively simple measures of monthly mean wind speeds. Although the daily time series simulated by the GCM is used to generate the monthly values, the time series itself has not been used directly due to the mismatch with measured climate. However, the authors anticipate that there may be merit in taking a closer look at whether useful information is contained within the time series that may shed light on the nature of future changes and their true impact. An aspect of particular interest is in the patterns of high and low wind speeds as the phasing and combinations of these are potentially important as inherently greater reliance is placed on wind power as penetration increases. Further work is planned on this.

6 Conclusion

The analysis carried out here demonstrates that whilst there is no evidence in this particular climate model of a definite change signal with regards to the mean wind climate, there are suggestions of possible smaller effects which merit further investigation and modelling. The impacts of such changes will be dependent on the scenario in which they occur, such as particular demand patterns for example, or the total amount of renewable generation in the system.

Under all scenarios of future climate change, it will be the combination and interaction of the changes in both energy supply and demand that the industry will, directly or indirectly, be burdened with. It is important that there be a full understanding of how the interaction will occur before mitigating strategies can be developed and deployed. There is a danger that the risk could be over- or underestimated if the individual effects are considered in isolation from each other.

The major limitation of this work is its reliance on one run from a single climate model, the ECHAM5 GCM. It is important to recognise that there are a large number of alternative models and these may produce different and potentially disparate results. The analysis does not consider variability in any detail, or the possibility of changes in extreme wind conditions; these factors may obligate adaptation in the future, and so it is important to understand the potential scenarios of future change in these factors.

Figures

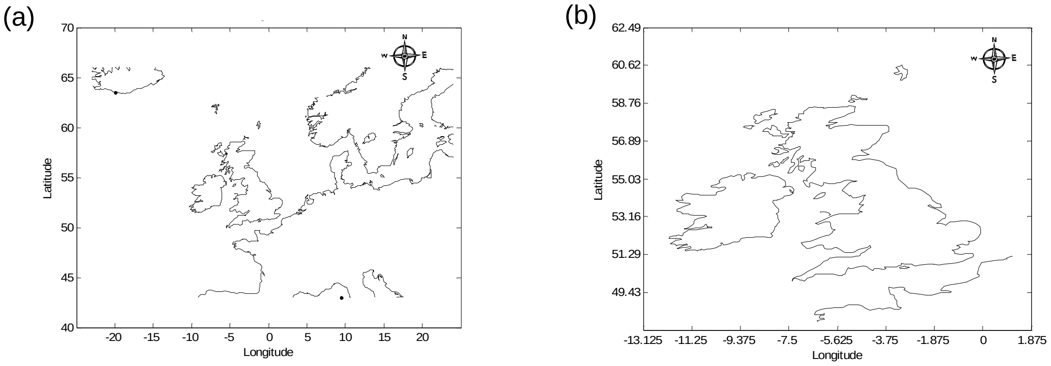

Fig. 1 Regions of interest selected

(a) Large region, 43 to 66˚ N, -23 to 24˚ E; (b) Small region, 48˚ to 61˚ N, -12˚ to 3˚ E

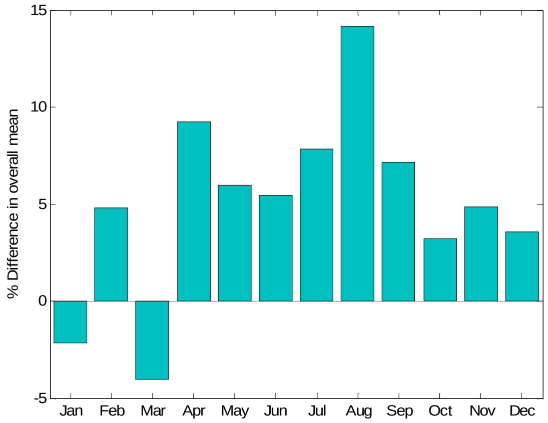

Fig. 2 Comparison of ERA40 and ECHAM5 spatial average monthly means 1961-90 – percentage difference in regional monthly mean wind speed

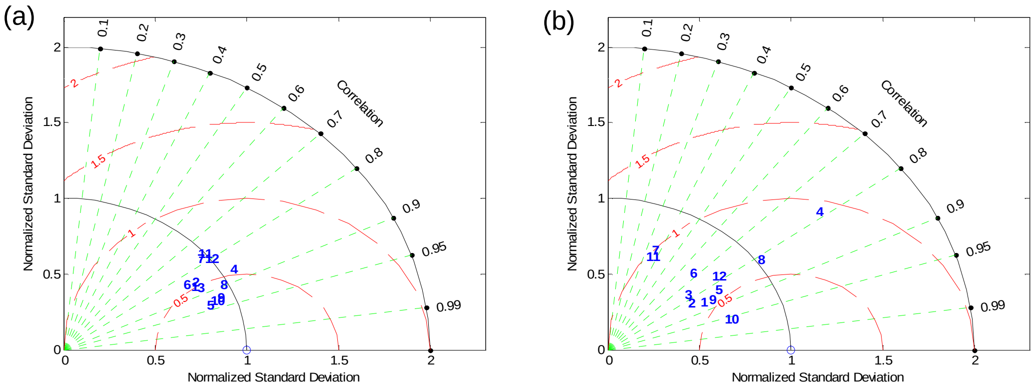

Fig. 3 Taylor Diagrams for ECHAM5 vs. ERA40 geostrophic wind 1961-90

(a) Larger spatial domain; (b) Smaller spatial domain

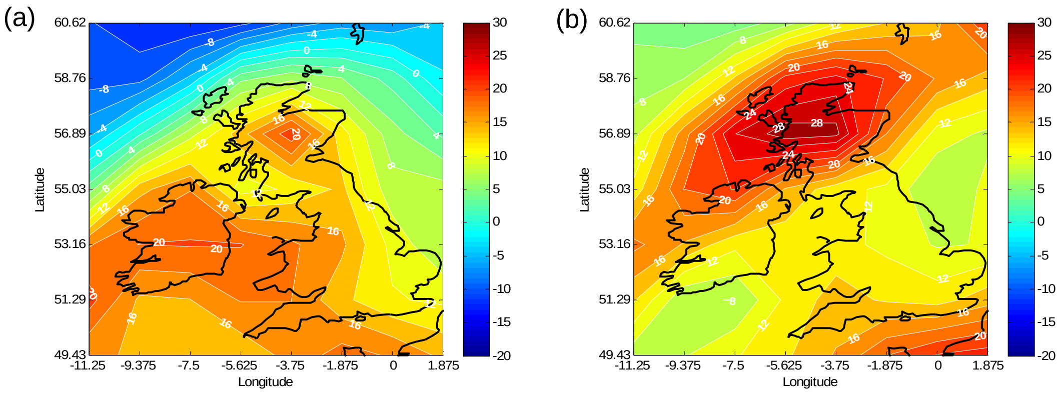

Fig. 4 Monthly mean percentage differences ECHAM5 vs. ERA40 1961-90

(a) July; (b) August

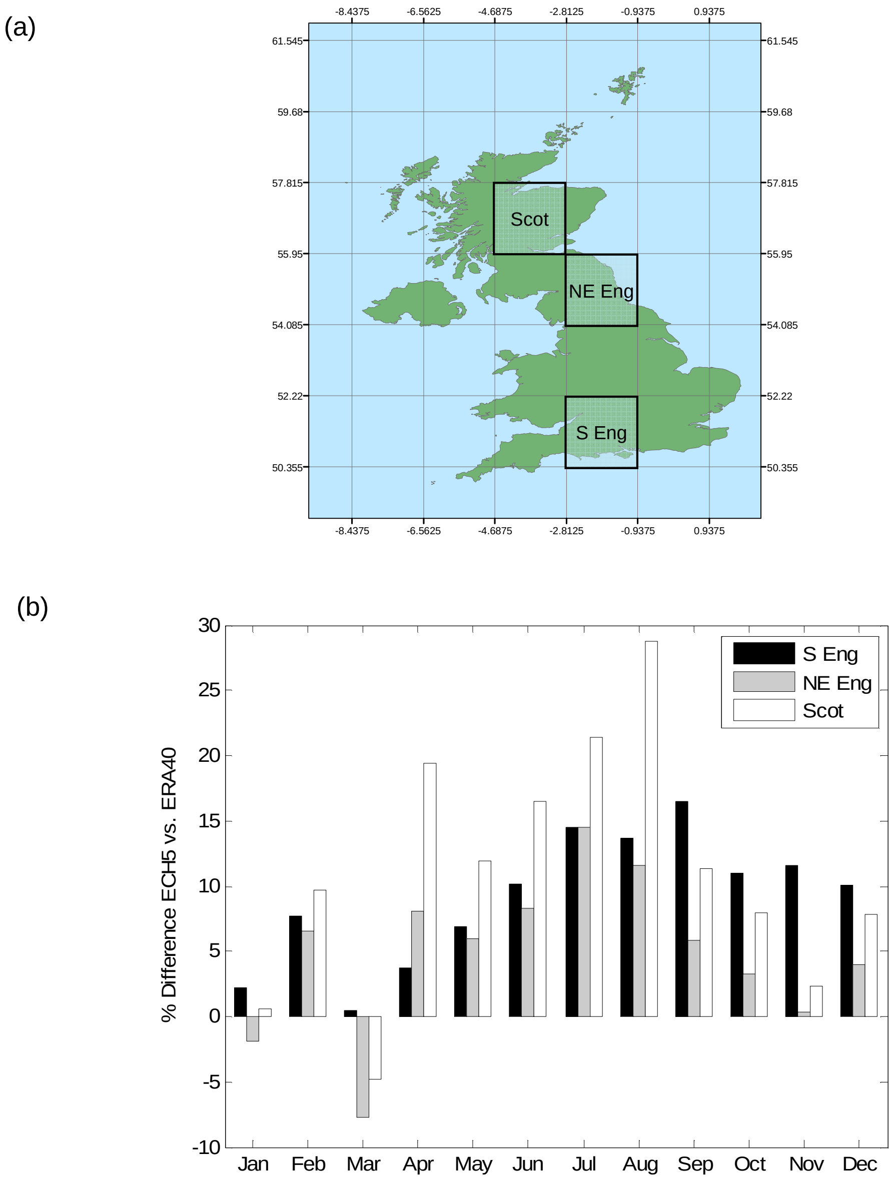

Fig. 5 (a) Locations chosen for further analysis; (b) % Differences in ECHAM5 vs. ERA40 1961-90 monthly mean geostrophic wind speeds for three locations in the UK area

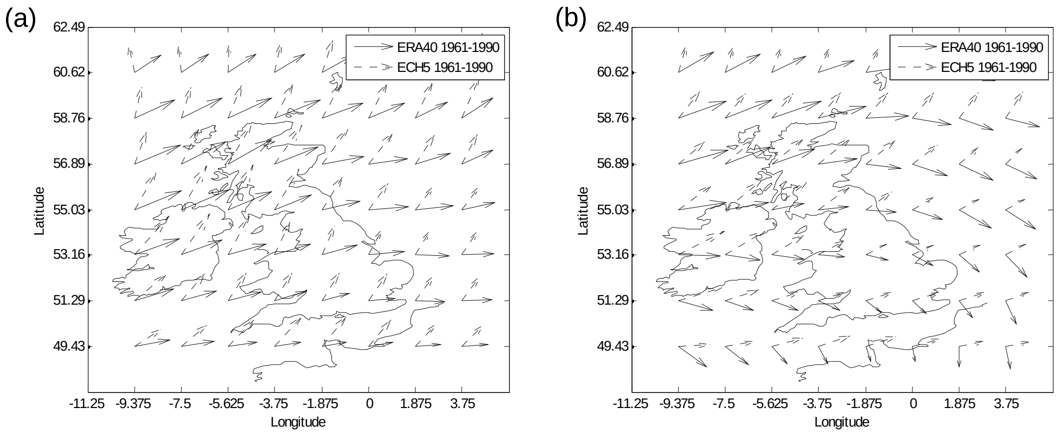

Fig. 6 Geostrophic wind vectors ERA40 and ECHAM5 1961-90

(a) March; (b) April

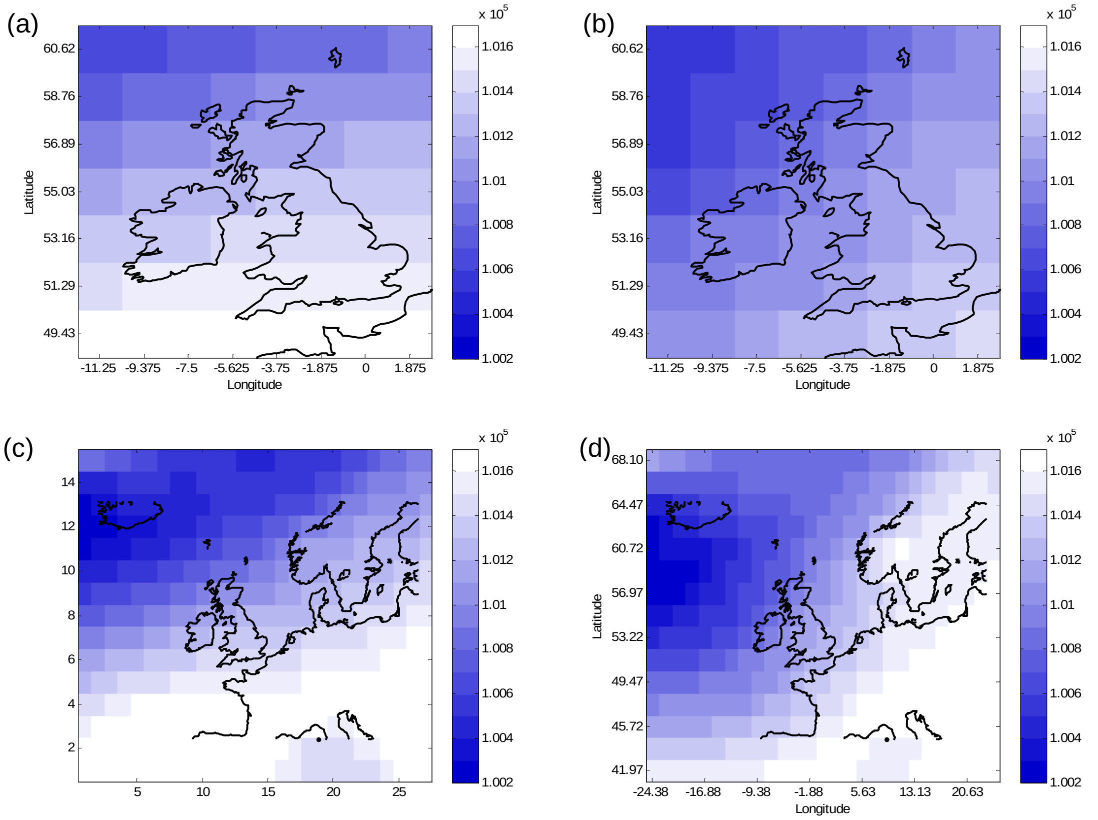

Fig. 7 Monthly mean pressure patterns from ERA40 and ECHAM5 (Pa)

UK region (a) ERA40 March; (b) ECHAM5 March; larger region (c) ERA40 March; (d) ECHAM5 March

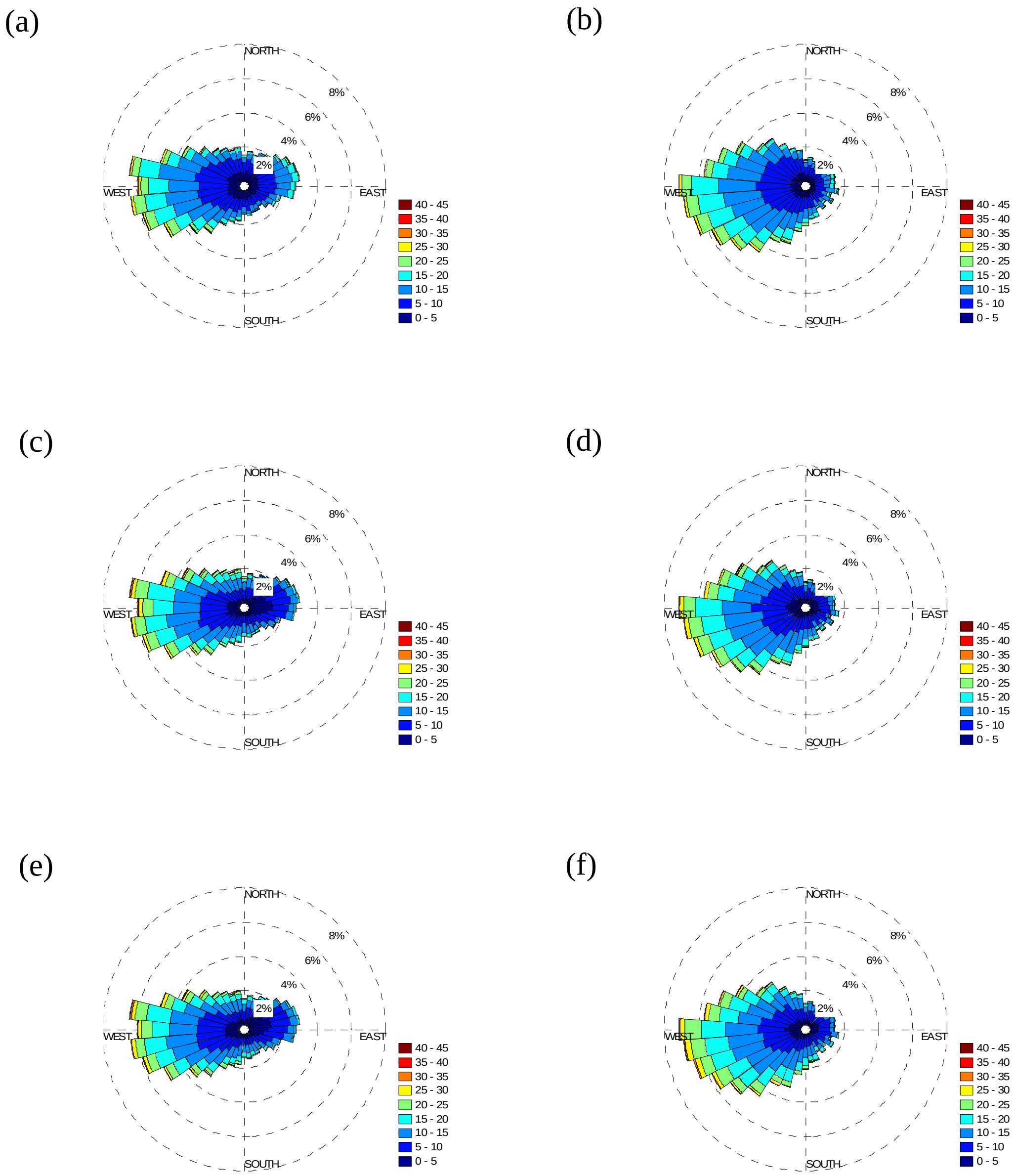

Fig. 8 S Eng (a) ERA40 and (b) ECHAM5; NE Eng (c) ERA40 and (d) ECHAM5; Scot (e) ERA40 and (f) ECHAM5

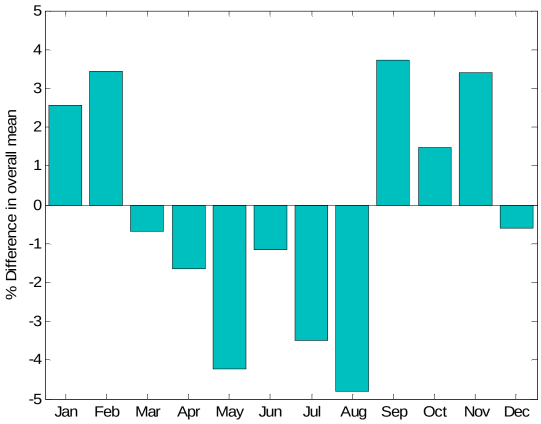

Fig. 9 Comparison of ECHAM5 spatial average monthly means 1961-90 and 2081-2100

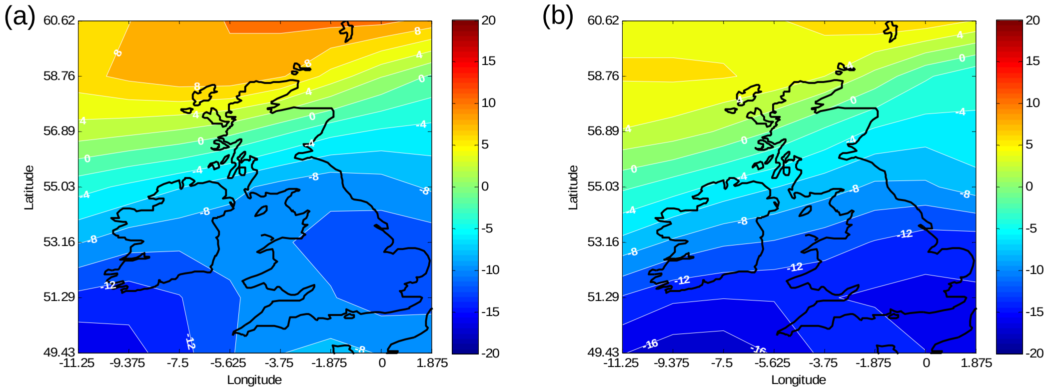

Fig. 10 Future percentage differences in monthly mean wind speeds from ECHAM5 for 2081-2100 vs. 1961-90

(a) July; (b) August

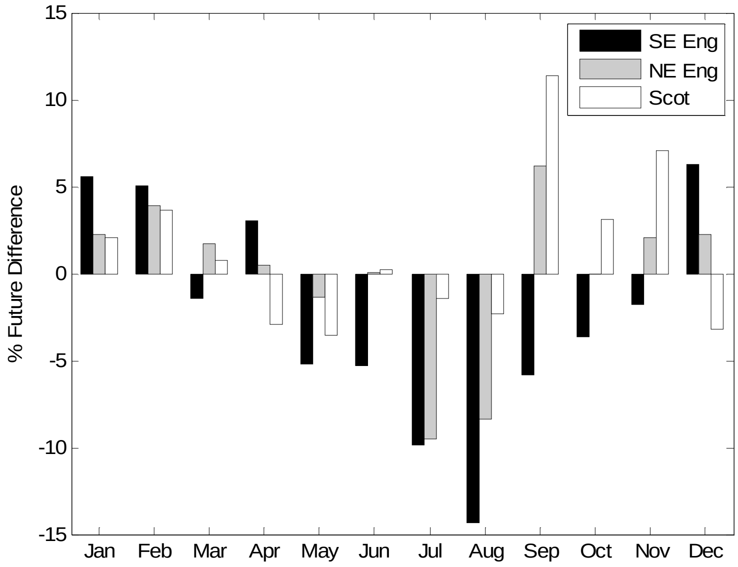

Fig. 11 % Differences in 2081-2100 vs. 1961-90 monthly mean geostrophic wind speeds calculated using ECHAM5 data for three locations in the UK area

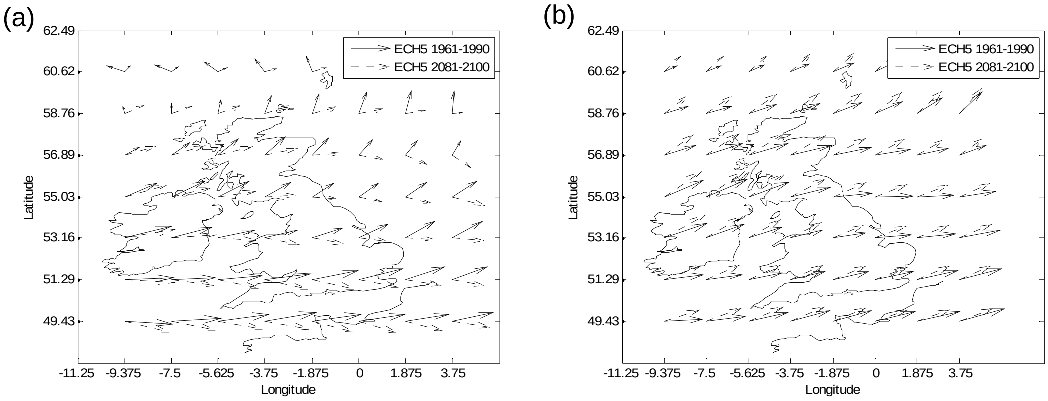

Fig. 12 Geostrophic wind vectors ECHAM5 1961-90 and 2081-2100

(a) May; (b) November

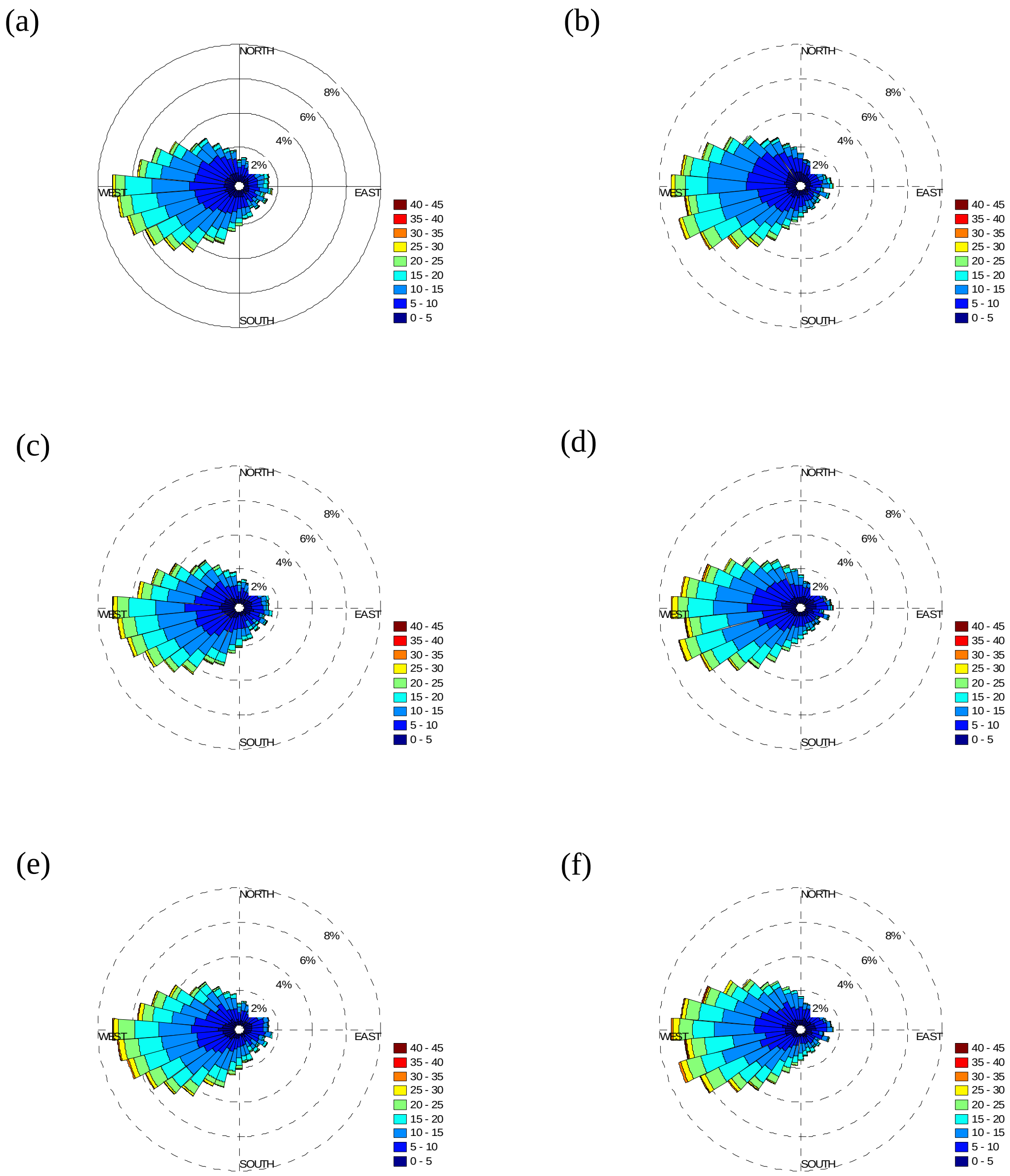

Fig. 13 S Eng (a) 1961-90 and (b) 2081-2100; NE Eng (c) 1961-90 and (d) 2081-2100; Scot (e) 1961-90 and (f) 2081-2100

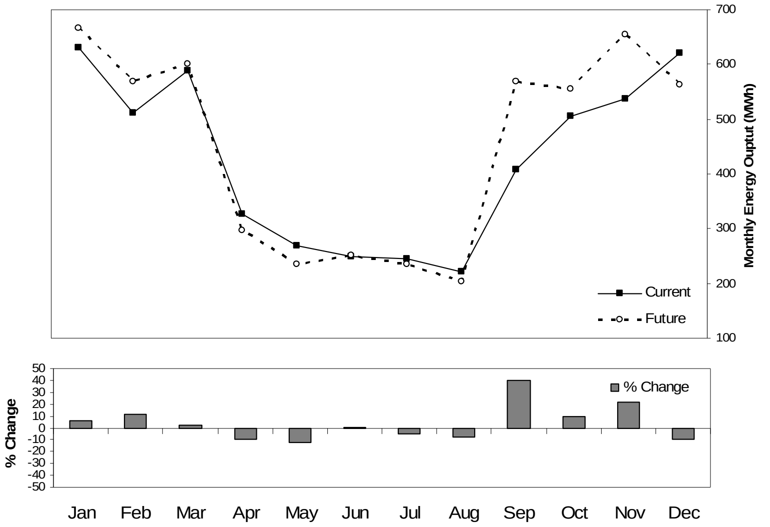

Fig. 14 Percentage change in monthly energy output change for 'Scot' grid cell

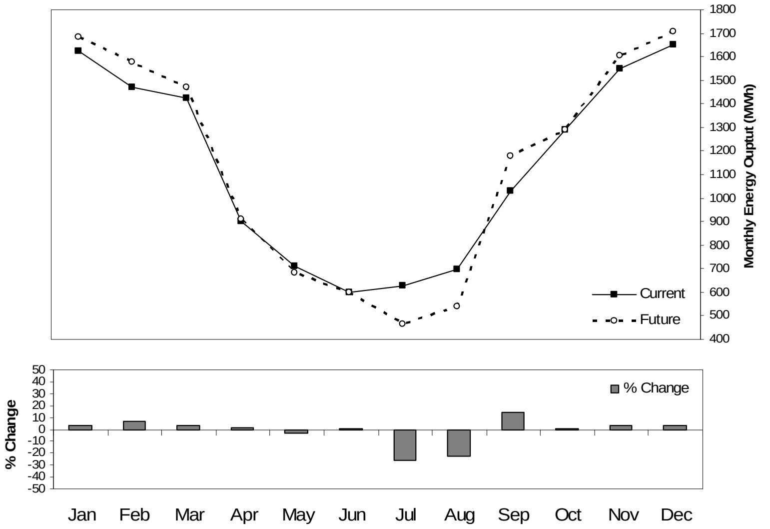

Fig. 15 Percentage change in monthly energy output change for 'NE Eng' grid cell

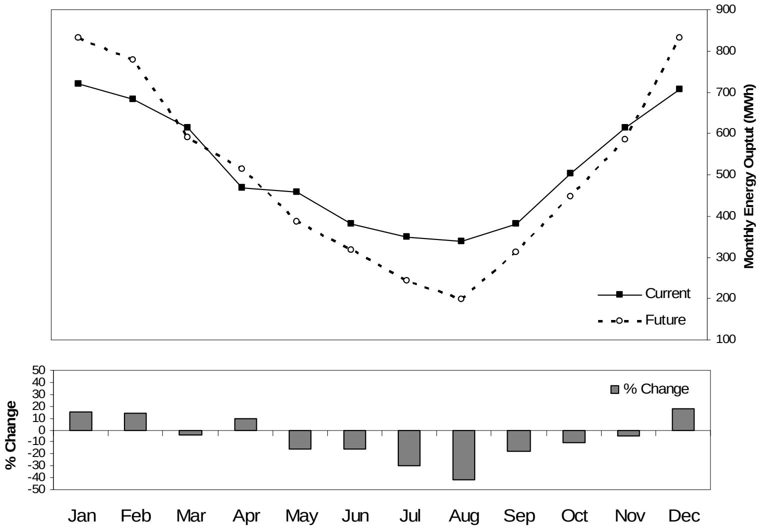

Fig. 16 Percentage change in monthly energy output change for 'S Eng' grid cell

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