The impact of climate change on wind energy resources

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1 Introduction

Climate variability and energy consumption are inextricably linked. Both Europe and North America are investing significantly in increased electricity supply from renewable energy sources. In 2007 the installed capacity of wind energy exceeded 17,000 MW in the USA and 56,500 MW in Europe. In 2007, 31 billion kilowatt-hours of electricity were generated in the US from wind turbines, and the US has a goal of generating 20% of electricity from renewable sources by 2030.

2 Challenges to quantifying historical and possible future wind resources

Although many factors dictate the deployment and success of wind farm developments, identification of optimal sites relies in part on detailed knowledge regarding the local wind climates and hence likely power production over the 20-30 year lifetime of the wind farm. However, establishing the magnitude of the wind resource is critically dependent on:

(i) Assumptions regarding climate stationarity – i.e. that the historical record provides a good analogue of future conditions.
(ii) The availability of long duration, high quality historical wind speed time series.

Both represent significant challenges, and are the focus of this paper.

Because energy density is proportional to the cube of the wind speed, comparatively small changes in the wind speed at turbine hub-height have large consequences for power production and hence for the overall economics of wind projects. This places unprecedented demands for both accuracy and precision on wind speed data and forecasts. However, even in the current generation (ASOS) instrumentation wind speed data are reported in whole knots (i.e. with a resolution of approx. 0.5 ms^{-1}).

Additionally, time series of wind speeds exhibit typically shorter duration than other meteorological parameters and exhibit even larger inhomogeneties. For example, an analysis of 12 stations showed ASOS derived wind speeds were an average of 0.2 m s^{-1} lower than with the prior observing system, with a range of -0.65 m s^{-1} to 0.15 m s^{-1} (McKee et al. 2000), though the higher wind speeds were higher from the ASOS instrumentation.

Even accepting 10-m measurement height is non-ideal for wind farm developers, historically wind speeds were not uniformally measured at 10-m above the ground.

For the reasons articulated above reanalysis data sets are sometimes used to provide a context for shorter in situ observational time series. However, our prior work has shown generally lower mean 10-m wind speeds are observed in the ERA-40 reanalysis products than in the NCEP/NCAR Reanalysis 1 (Pryor et al. 2006a) and as shown herein, near-surface wind speeds from these reanalysis data sets are not consistent in terms of temporal trends.

In terms of explicitly addressing climate non-stationarity, projections of future wind regimes may be made using a variety of tools. Coupled Atmosphere-Ocean General Circulation Models (AOGCM) are critical (and increasingly skillful) tools for assessing future climate states (IPCC, 2007), but operate on spatial scales on the orders of hundreds of kilometers in the horizontal and very low resolution in the vertical. Hence, they are incompatible with the needs for assessing regional and local wind climates and exhibit low skill in reproducing historical wind speeds (Pryor et al., 2006b). Therefore it is necessary to employ downscaling techniques for generation of higher spatial resolution wind climates:

- Physical/dynamical methods, where a Regional Climate Model (RCM) or high resolution or variable resolution atmospheric GCMs are used to produce finer resolution fields (e.g. 10-50 km) in the study region using lateral boundary conditions supplied from AOGCM (Pryor et al., 2005a).

- Statistical/empirical methods, where a transfer function (or functions) is developed that statistically relates the large scale climate parameters generated by the AOGCM to the near-surface parameter of interest (Pryor et al., 2005b).

Or a hybrid combination of these methods.

3 Methods for assessing historical trends

To provide an example of research being undertaken to better address the question; 'has recent evolution of the climate system changed the wind resource?' we focus on the contiguous USA. Wind speed time series from five sources are presented here:

1. Near-surface wind speeds from all land-based sites across the contiguous US that have records from 1973-2005, and had not moved more than 5 km over the study period were obtained and corrected to a nominal measurement height of 10-m using the power law. Only sites where over half of the possible observations are present in every year of record (1973-2005) and in each climatological season of each year are presented resulting in 193 stations being available for analysis. All stations are airports (191) or military installations (2).
2. 10-m U (west-east) and V (south-north) components of the flow were extracted for 1948-2006 from the 4-times daily output of the NCEP-NCAR reanalysis. This data set is referred to as NCEP Reanalysis 1 and it has a spatial resolution of 2.5 × 2.5º.
3. 10-m U and V components of the flow were extracted for 1979-2006 (the data record starts in 1979), from the 4-times daily output of the NCEP-DoE reanalysis. This data set is referred to as NCEP Reanalysis 2. The spatial resolution of these data is approximately 1.9 × 1.9º.
4. 10-m U and V components of the flow were extracted for 1973-2001 (the reanalysis product ends in the middle of 2002) from the 4-times daily output of the ERA-40 reanalysis. The spatial resolution is approximately 2.5 × 2.5º.
5. 10-m wind speeds were extracted from a Regional Climate Model (RCM) simulation conducted as part of the North American Regional Climate Change Assessment Program (NARCCAP). The MM5 model was run at 50 km resolution for 1979-2004 using boundary conditions supplied by NCEP Reanalysis 2.

Wind speed time series exhibit variability on multiple temporal scales. Here we focus on the annual time series and analyze percentiles of the wind speed distribution computed at the annual time scales for trends using linear regression and boot-strapping techniques to determine whether trends are robust to the stochastic effects in the time series. A 90% confidence interval is used to identify significant trends.

Figure 1 depicts temporal trends from the first four data sets over the contiguous USA for 0000 UTC. Of the 193 stations, 150 exhibit declines in the 50th percentile values, 33 stations exhibit no trend, and only 10 stations exhibit increases. 146 stations exhibit declines in the 90th percentile wind speeds, 36 stations exhibit no trend, and 11 stations exhibit increases. The magnitudes of the trends are substantial – upto 1%/year. Similarly large trends are observed in the reanalysis data sets, but over a smaller fraction of the study region. In contrast to the in situ observations, the NCEP-NCAR reanalysis 1 data set generally indicates a tendency towards increased values of the 50th and 90th percentile annual wind speeds during 1973-2005, particularly in the central USA and Midwest. Also in contrast to the station observations, the trends in the NCEP-NCAR reanalysis 1 data set are frequently of larger magnitude in the 90th percentile values. There are differences in both sign and magnitude in trends in the NCEP reanalysis 1 and 2 data sets spatial across the USA. While NCEP reanalysis 1 exhibit most spatially consistent increasing trends over the Midwest, largest positive trends in NCEP reanalysis 2 data are evident over the western USA. Comparable trends in the 50th and 90th percentile wind speeds from ERA-40 are almost evenly divided between increasing, decreasing and no-change over the contiguous USA, and as in the observational data set, some of the percentage trends are slightly larger in the 50th percentile values. While the time windows used differ slightly between the data sets truncation of the NCEP Reanalysis-1 data to reflect the other reanalysis products did not lead to greater homogeneity in trend magnitudes and/or signs.

To further investigate the discrepancies in temporal trends, results from the MM5 simulations conducted using boundary conditions from NCEP-2 were also analyzed.

One example of the results is given in Figure 2, and indicates that as in the observations, the RCM output for this grid cell also indicates declines over the later portion of the C20th and early C21st.

We also examine the wind speed time series using a wind indexing technique in order to quantify both the inter-annual variability in wind indices and temporal trends therein. As shown in Figure 3, according to the NCEP/NCAR data set the early 1970's exhibit low wind speeds and energy low wind indices relative to the 1990's, leading to positive trends for 1973-2005. However, as shown, the trend is positive when the entire NCEP/NCAR reanalysis 1 record is used, in part because the data exhibit maxima in the late 1960's and mid-1980's to date, and minima in the late 1940's and early 1950's and in the early to middle 1970's. These features are not observed in the observational records (see for example Figure 2) or in the shorter time series from the other reanalysis data. The ERA-40 reanalysis wind indices exhibit small (statistically insignificant) declines over 1973-2001, while NCEP reanalysis 2 exhibit small (statistically insignificant) increases over 1979-2005.

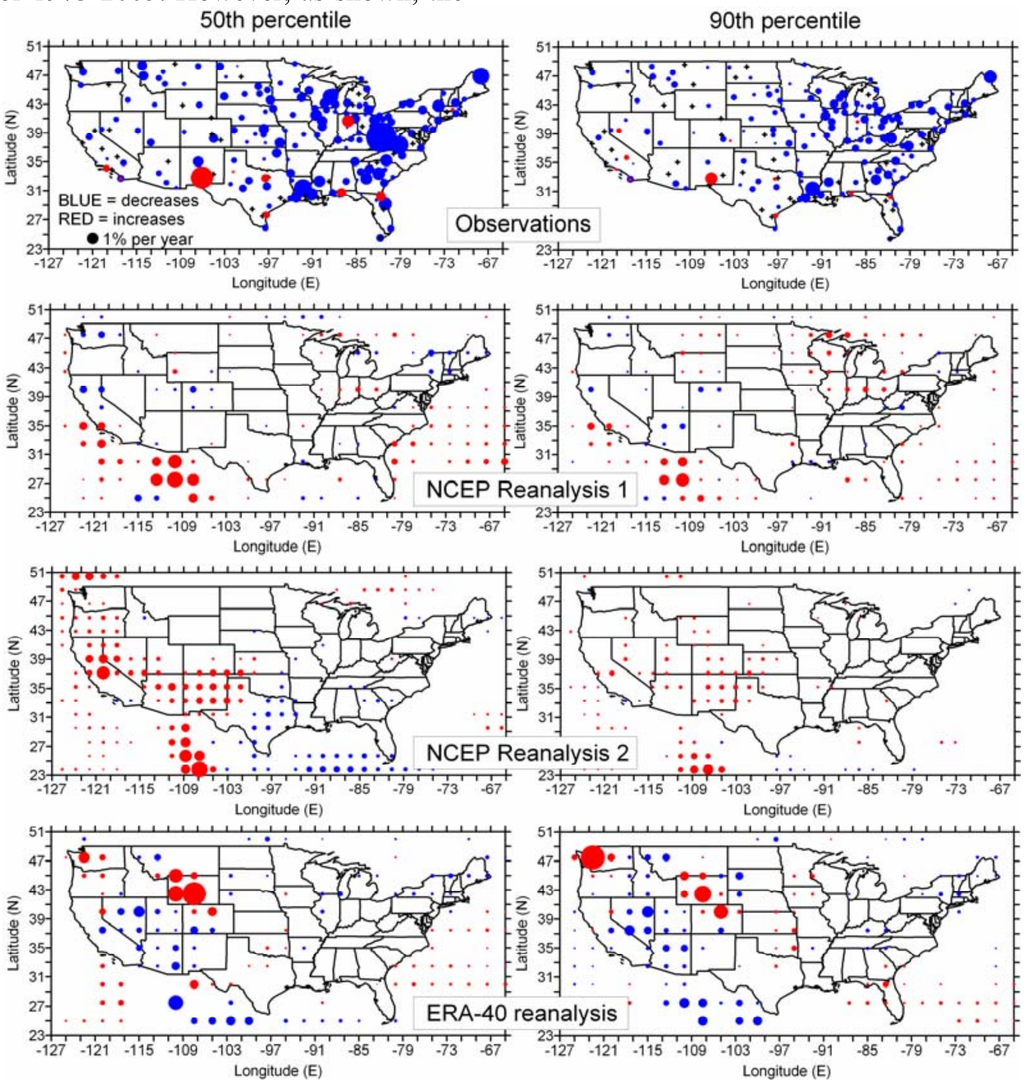

Figure 1: Results of the trend analysis applied to data from 0000 UTC. Top row shows the 50th and 90th percentile wind speeds from the observational station records for 1973-2005, while the next row shows the same information but from the NCEP Reanalysis 1 data set for 1973-2005, the third row shows results for the NCEP Reanalysis 2 data set for 1979-2005, and the bottom row shows results for the ERA-40 data for 1973-2001. In each frame the size of the dot scales linearly with the magnitude of the trend and the color of the dot indicates the sign of the trend. Where the station time series did not indicate a statistically significant trend a + symbol is shown. Where the time series from a reanalysis grid cell did not exhibit a trend no symbol is shown.

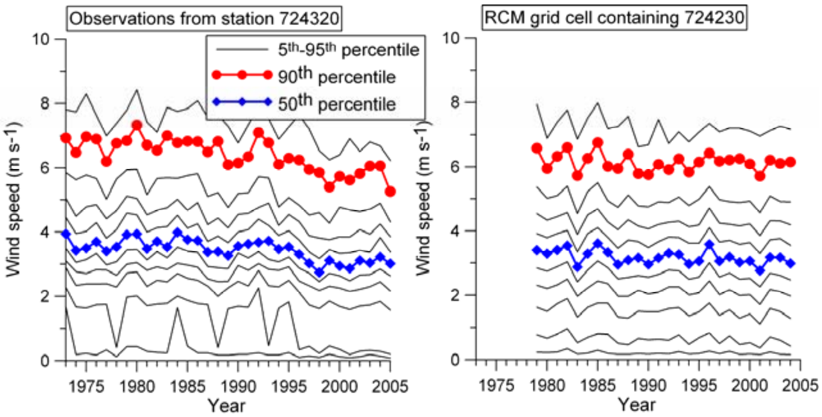

Figure 2: Annual percentiles in observations from 724320 (in southern Indiana) and RCM grid containing this station. Observations/RCM indicate downward trend in 50th percentile (0.7%/year*, 0.4%/year*), and 90th percentile (0.6%/year*, 0.1%/year). *Significant at 90% confidence level.

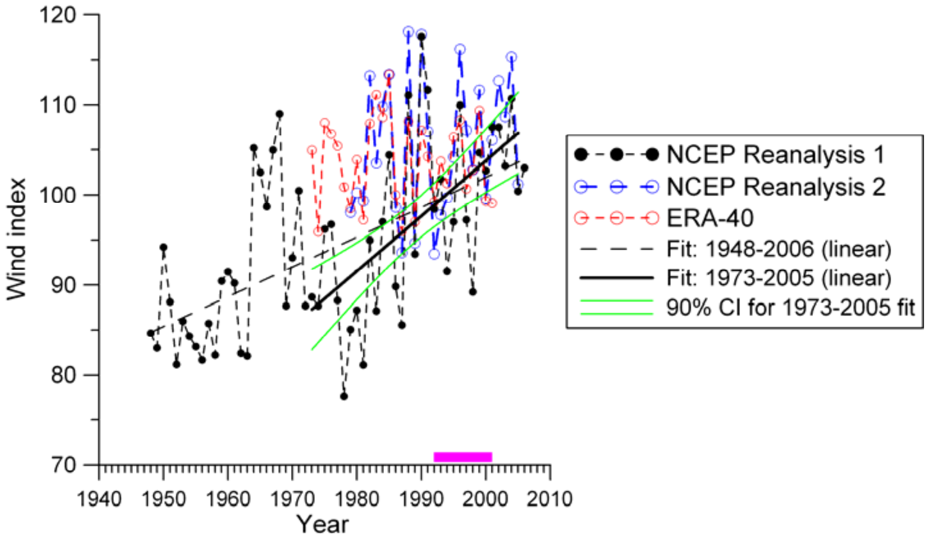

Figure 3: Annual wind indices (WI) for the Midwest (36-50N, 98-80W) from 3 reanalysis data sets computed from wind speed time series (U) with a normalization period of 1992-2001

4 Methods for assessing possible future wind speed regimes

To provide an example of research being undertaken to better address the question; 'will future wind climates and resources differ from those in the past?' we focus on northern Europe. Based on the NCEP/NCAR Reanalysis 1 data set annual mean wind speeds over the Baltic significantly increased over the period 1953–99 with the majority of the increase being associated with increases in the upper quartile of the wind speed distribution and extreme winds (Pryor & Barthelmie 2003). More recent analyses have suggested near-surface wind speeds have subsequently declined relative to the high values observed in the early 1990s (Barthelmie & Pryor 2006).

Dynamical downscaling methods have advantages for generating projections of possible future climate states at the regional level but have not been extensively tested for wind speeds and have a grid-resolution too coarse to allow capture of local wind climates critical to wind farm siting. Hence, both downscaling techniques have been applied.

Application of the Rossby Centre coupled Regional Climate Model (RCM) (RCAO) to northern Europe using boundary conditions derived from ECHAM4/OPYC3 AOGCM and the HadAM3H atmosphere-only GCM generated output that is reasonable and contains realistic features as documented in reanalysis data products during the control period (1961-1990). However, the future projections for wind speeds and energy density for 2071-2100 generated using two IPCC emission scenarios (A2, B2) exhibit contrasting results for the two sets of boundary conditions (Figure 4). This finding implies that the AOGCM used to provide the lateral boundary conditions for RCM simulations appears to play a decisive role in dictating the wind regimes. Indeed the choice of AOGCM is much more critical than the selection of the emission scenario.

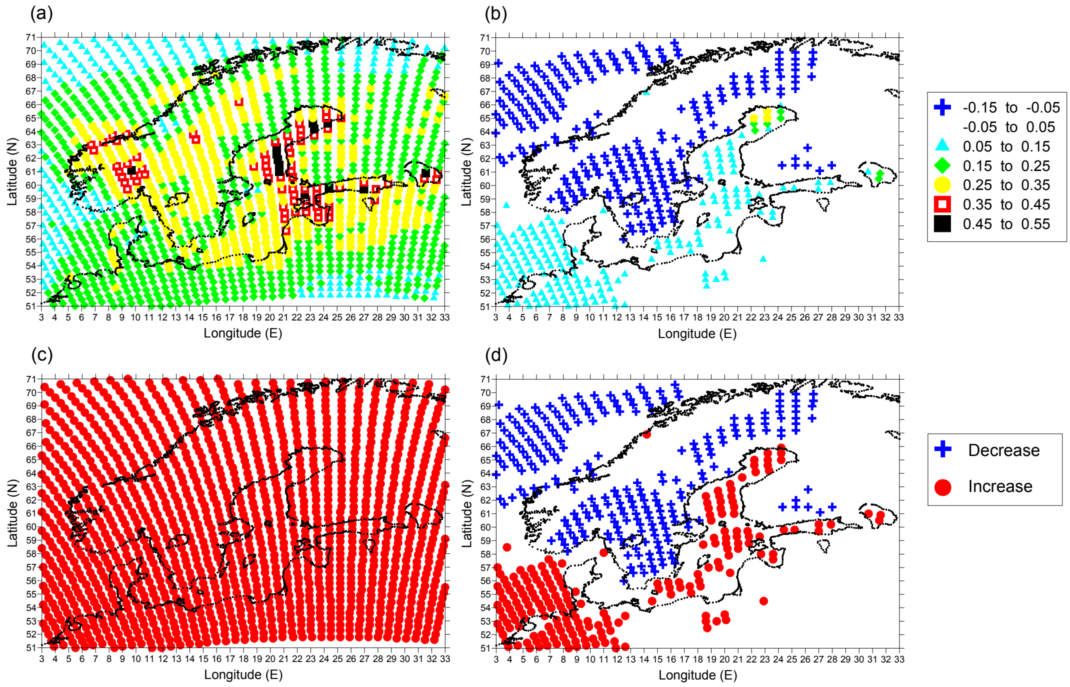

Figure 4: (a) and (b) fractional changes in the wind energy density from 1961-1990 to 2071-2100 from the RCAO simulations using lateral boundary conditions from (a) ECHAM4/OPYC3 and (b) HadAM3H. The changes are shown as a fractional decrease or increase relative to 1961-1990. Hence a value of 0.15 indicates the future period energy density is 15% higher than that during 1961-1990. Frames (c) and (d) show whether the change in energy density in 2071-2100 relative to 1961-1990 is statistically significant at the 95% confidence level. If the future period wind energy density is significantly higher than that during 1961-1990 the grid cell is shown by the red dot. If the wind energy density in the future period is lower than the historical period the grid cell is shown with a plus sign. If neither of these conditions is fulfilled no symbol is shown. Results are for the A2 emission scenario.

Output from ten coupled AOGCMs; BCCR-BCM2.0, BCC-CM1, CGCM3.1, CNRM-CM3, ECHAM5/MPI-OM, GFDL-CM2.0, GISS-ModelE20/Russell, IPSL-CM4, MIROC3.2(medres), and MRI-CGCM2.3.2 for two historical periods (1982-2000 and 1961-1990) and two future time windows (2046-2065 and 2081-2100) (extracted from the A2 emission scenario simulations) were used with our novel empirical downscaling method for 46 stations across northern Europe.

The results indicate good consistency with independent data. At all but one station the downscaled mean wind speed is within ± 5% of the independent observations, and the 90th percentile wind speed is within ± 2.5% of the observed value. The energy density (power in the wind) is an aggregate of the entire probability distribution of wind speeds and hence is more difficult to model, but at all sites the downscaled value is within ± 20% of that calculated from observations. The change of mean wind speed and 90th percentile wind speed between 1961-1990 and the two projection periods (2046-2065 and 2081-2100) from downscaling of the ten GCMs is relatively consistent. The range in percent changes in the mean and 90th percentile wind speed is ≤ 20% for 2046-2065 (Figure 5) and ≤ 35% during 2081-2100 at all stations. As with the changes in downscaled mean and 90th percentile wind speed, the results for energy density at each of the stations tend to span zero with downscaled results from some AOGCMs showing increases and others decreases. It is asserted, therefore, that there is not a consistent signal with regards to an increase or decrease of the mean and 90th percentile wind speed or energy density in either climate projection period relative to 1961-1990. Thus projections for the twenty-first century (C21st) indicate no evidence of substantial evolution relative to the end of the twentieth century (C20th), although there is increased divergence of results from downscaling of different AOGCM towards the end of C21st. Predicted changes in the downscaled mean and 90th percentile wind speeds are small (< ± 15%) and are comparable to the current variability manifest in downscaling from different AOGCMs.

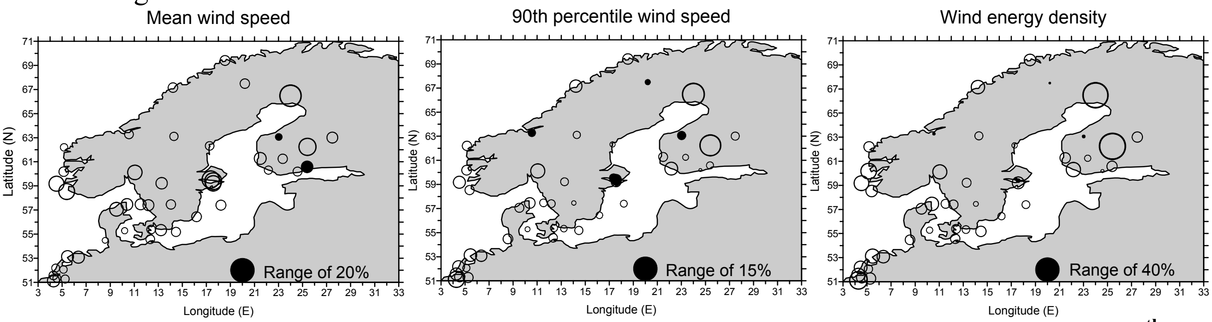

Figure 5: The consistency in the change of downscaled mean wind speed, downscaled 90th percentile wind speed, and energy density at each station from the ten AOGCMs for 2046-2065 relative to the historical period (i.e. ((2046-2065) – (1961-1990))/(2046-2065)). If all the downscaled values indicated declines in the specified parameter the symbol is solid, if the results from the downscaling of different AOGCMs span zero the symbol is an open circle. No stations exhibited consistent increases in downscaled values from each of the ten AOGCMs. The diameter of the symbol used in each frame is linearly related to the data range.

5 Concluding remarks

To return to the questions that motivated this ongoing research:

1. Is the past a good analogue for the future?
   - Likely not, there is evidence that wind climates both over Europe and north America have evolved over the last 30-50 years.
2. Can we accurately characterize the nature of the historical change?
   - Tools are available to conduct this type of analysis and further to assign causality to changes, but data quality issues and discrepancies between data sources merit further attention.
3. Is it possible to develop future projections of wind climates?
   - Yes. AOGCMs are not skillful for wind climates, but both dynamical downscaling and a new probabilistic empirical downscaling tool exhibit skill when applied to wind energy.
4. What are the major sources of uncertainties in projected wind climates?
   - AOGCM lateral boundary conditions and predictor variables used in the empirical downscaling appear to exhibit greater influence on the uncertainties than either stochastic effects within AOGCMs or uncertainties in the emission scenarios used to construct the climate simulations.
5. Are future projections outside the envelope of current variability?
   - For wind speeds over northern Europe, yes, but only towards the end of the C21st.

6 Acknowledgements

Funding for this research was supplied by the National Science Foundation (grant # 0618364), and the Climate and Energy Systems: Risks, potential, adaptation project funded by Nordic Energy Research.

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