FINAL REPORT:

Collaborative research: Development and evaluation of downscaling techniques for near-surface wind climates (GRS 0618364 (IU) and 0618823 (ISU))

Pryor, Barthelmie, Takle

1 March, 2010

1 Project participants

1.1 People who have worked on the project

- Sara C. Pryor, Professor, Indiana University
- Rebecca J. Barthelmie, Professor, Indiana University
- Duick Young, Ph.D. student, Indiana University
- Taka Kobayashi, Ph.D., Indiana University (degree completed)
- Todd Lindley, Ph.D. candidate, Indiana University
- Jessica Howe, M.S., Indiana University (degree completed)
- Evan Riley, B.S., Indiana University (degree completed)

1.2 Other partners

- Gene Takle, Professor, Iowa State University (Co-Principal Investigator, lead on collaborative project)
- James Corriea, Postdoctoral Fellow, Iowa State University
- Er (Eric) Lu, Postdoctoral Fellow, Iowa State University
- Priyanka Jindal, PhD student, Iowa State University
- Dan Rajeweski, PhD student, Iowa State University
- Adam Deppe, MS student, Iowa State University
- Theresa Anderson, UG student, Iowa State University
- Kristyna Carter, UG student, Iowa State University
- Adam Deppe, UG student, Iowa State University
- Robert Hansen, UG student, Iowa State University
- Rachel Hatteberg, UG student, Iowa State University
- Shannon Rabideau, UG student, Iowa State University
- Aaron Rosenberg, UG student, Iowa State University

1.3 Other collaborators/contacts

- The project is symbiotic and collaborative with the following major national/international research projects:
    - The North American Regional Climate Change Assessment Program (NARCCAP) (www.narccap.ucar.edu). Climate scenarios generated under NARCCAP (at ISU and 5 other laboratories) provide dynamical downscaling

products used in this project to develop regional wind climate projections. Principal link: Takle

- The ENSEMBLES climate modeling initiative (http://www.ensembles-eu.org/) funded by the European Union. RCM output from ENSEMBLES – specifically from the Rossby Centre at SMHI (Sweden) and the Danish Meteorological Institute (Denmark) are being used in this project for calculation of extreme wind speeds – method development and evaluation. Principal link: Pryor
- The Nordic Energy Research Project 'Climate and Energy Systems; Risks, Potential, Adaptation' (www.os.is/ce/). Symbioses are specifically focussed on extreme wind climates, impacts on wind turbine design and siting and assessment of the total climate change impact on wind energy developments. Principal links: Barthelmie and Pryor
- Two other NSF funded projects:
  - GRS #0647868: Collaborative research: Development of 21st century precipitation scenarios using probabilistic downscaling techniques (Schoof and Pryor).
  - Engineering (CBT) #0828655: Quantifying wind farm power losses due to wind turbine wakes (Barthelmie and Pryor).

  And two proposals to federal agencies that are currently under review.
- A study has been launched with MidAmerican Energy Company (MEC) which has 833 100-MW turbines deployed in the state of Iowa. MEC has data from turbines and meteorological towers within the wind farms that they have agreed to share with us to better understand diurnal and seasonal characteristics of wind resources. These data will be a rich complement to standard data available from NCDC. Principal links: Takle and Barthelmie
- On the basis of this research we engaged with a new collaboration with J. Ledolter of the Department of Management Sciences and Department of Statistics and Actuarial Science at the University of Iowa. Principal link: Pryor

- Research undertaken within this project has led to the following symbiotic activities:
  - Pryor was invited to Femern Sund-Bælt: workshop on climate scenarios, held in Ringsted, Denmark in May 2009 to present extreme wind climate analyses conducted within this project. The workshop was developed by the engineering consortium that has been charged with designing and implementing a fixed link between Denmark and Germany. This engineering project (*which has been described as the lunar landing of bridge construction*) has specifically been charged with considering climate change in the design of the bridge (or tunnel) over the 130 year projected lifetime of the structure. Pryor made a presentation describing possible changes in intense and extreme wind speeds and the tools/techniques and uncertainties in making such projections (details of the analyses are given below).
  - Partly on the basis of activities within this project Pryor was asked to be a contributing author for the IPCC report 'Renewable energy's role in climate change mitigation'. Her contributions to the chapter on wind energy focus on climate change impacts on wind energy and possible regional climate impacts of

wind energy. A more comprehensive review of the possible climate change impacts on the wind energy industry developed by Pryor and Barthelmie from the IPCC contribution written by Pryor is entitled 'Climate change impacts on wind energy: A review' and was published by the *Journal of Renewable and Sustainable Energy Reviews.*

- The project is also collaborative with initiatives from the International Atomic Energy Authority (IAEA) e.g. Via the workshop "Vulnerability of energy systems to climate change and extreme events" to be held in Trieste, Italy in April 2010. Pryor is an invited participant who will present a keynote address.
- Barthelmie and Pryor are both active within the American Wind Energy Association. Pryor was an invited presenter and panelist at the AWEA workshop on wind resource estimation, Orlando, Florida in September 2009 to present results of analyses undertaken during this project.
- Pryor initiated the Midwest Assessment Group for Investigations of Climate (MAGIC) – a consortium of 10 Midwest institutions: Indiana University, Michigan State University, Ohio State University, Ball State University, Iowa State University, Illinois State Water Survey (University of Illinois), St Louis University, University of Minnesota, University of Wisconsin. A book describing Regional climate variability, predictability and change in the Midwestern USA, edited by Pryor and deriving from the MAGIC consortium was published by Indiana University Press in June 2009. This 24 chapter volume synthesizing the state-of-the-art regarding knowledge of historical and projected future changes to the physical climate represents a unique contribution to the literature. A follow up workshop, also hosted by Indiana University will be held in October 2010. The workshop is entitled; 'Climate change impacts, vulnerability and adaptation in the Midwest".
- In March 2009, Rebecca Barthelmie received one of the Wind Energy Industries most prestigious awards: The 2009 European Academy of Wind Energy Scientific Award for "her extraordinary efforts and achievements in wind energy research". The award was presented to Rebecca during the closing ceremony of the EWEC 2009 conference in Marseille.
- This NSF wind research grant has served as the basis for launching a multi-dimensional wind speed and wind energy program in the Climate Science Initiative at Iowa State University. The following are exemplars of activities from the IUS group in this context:
    - Collaborations with faculty in the ISU College of Engineering have led to other proposals to DOE, NSF/EPSCoR, and one to NSF/IGERT, currently under development in which Takle is a co-PI, that will develop and launch a cross-disciplinary wind engineering PhD program in the College of Engineering. I also have been asked to serve on the College of Engineering Wind Energy Team which has launched one symposium and has a second scheduled for April 6, 2010.
    - This NSF wind research grant also has led to Takle being granted affiliate scientist status with the Ames Laboratory of US DOE. This, in turn, has

led to the successful DOE proposal (see below) and ongoing development of wind research collaborations within DOE and its other laboratories.

- ISU has developed an affiliation with the Power Systems Energy Research Center in the Iowa State University College of Engineering under which we have secured a 2-year contract with MidAmerican Energy Company, operator of several major wind farms in Iowa. We will use their Iowa meteorological tower data to evaluate wind speed characteristics (vertical profile of wind speed, wind shear at hub height, horizontal variability, diurnal and seasonal variability) as well as ability of mesoscale models to represent these characteristics.
- In a project parallel to the MidAmerican Energy project Takle has secured funding from DOE to develop advanced forecasting systems for Iowa windfarms. Under this project we have engaged two ISU statistics faculty members with interests in spatial statistics and time series to explore dynamic bias corrections and advanced methods of constructing multi-model ensembles for improved 54-hour forecasts of wind speed.
- The ISU team have secured 1-year supplemental funding from the Center for Global and Regional Environmental Research at University of Iowa to perform pilot field studies measuring surface fluxes of momentum, heat, and water vapor over crops in agricultural farms that are co-located with wind farms.
- Through dialog with one of Takle's former PhD students and a former ISU BS student, both now PhD scientists at Los Alamos National Laboratory (LANL), the ISU group is establishing a wind research collaboration through DOE. During a February 2010 visit to LANL by Takle, we developed plans calling for a combined modeling and measurements program under which we will provide mesoscale modeling support to their very high-resolution model for simulation of 3-D, time-dependent turbulence fields within multi-turbine wind-farms. We also will conduct field observations within Iowa wind farms for validation of this combined modeling system. The proposal for the first phase of the supporting measurements has been submitted to DOE.

1.4 Major research and education activities

Activities within this project have focused on the following tasks:

A. Analysis of in situ, reanalysis and RCM output wind speeds in the context of climate non-stationarity:

Detection, quantification and attribution of temporal trends in wind speeds within the historical and contemporary climate provides a critical context for climate change research, and a platform for evaluation of the models being used to estimate possible future wind speed regimes under global climate change scenarios. However, time series of wind speeds from *in situ* measurements are typically highly fractured, and subject to large inhomogeneties. Hence we have conducted a uniquely detailed intercomparison of wind speed trends over the contiguous USA during the end of the twentieth century and early twenty-first century based on two ground-based observational data sets, rawinsonde data, four reanalysis data sets and output from two RCMs. The analysis was formulated in the context of three principal objectives:

- Quantify the magnitude and statistical significance of historical trends in wind speeds and the consistency (or not) of trends derived using different data sets, and to provide a preliminary diagnosis of possible causes of temporal trends.
- Address whether trends in the mean wind climate were associated with changes in the associated variability.
- Quantify inherent (natural) variability and causal mechanisms to climate indices (e.g. teleconnection patterns)

Our results indicate:

- As in prior research across the European continent and Australia there are quantitative differences in mean wind speeds (Figure 1) and trends in wind speed percentiles (Figure 2) between carefully quality controlled observational data, reanalysis data sets and RCM output. Data from two observational data sets exhibit consistently negative trends across the entire contiguous USA during 1973-2000 and 1973-2005. These trends are of largest fractional magnitude over the eastern USA, and particularly the Midwest. The trends in the near-surface observations are not replicated in the rawinsonde data set (Figure 3). The observed temporal trends appear to be reproduced in part by the MM5 RCM nested within the NCEP-2 reanalysis. MM5 also performs relatively well in terms of reproducing the annual mean wind speeds. Negative trends in the *in situ* observations are present in all seasons, and do not appear to be solely related to the introduction of the ASOS firmware. There is no strong evidence of substantial bias in temporal trends with the hour of the day in the observations or the global reanalysis data sets, though the NARR and the RSM simulations exhibit a greater prevalence of positive trends in the western US in the 1200 UTC output.
- There is no clear consensus in the modeled and observational data sets shown in Figure 1 with regards to the presence or absence of links between a change in the annual mean wind speed and inter-annual variability (Figure 4). In all data sources, stations or grid cells that exhibit a statistically significant trend in mean wind speed also tend to exhibit a statistically significant change in the inter-annual variability over the time periods of record. This is particularly the case for output from the two RCMs in which over 90% of grid cells that exhibit a statistically significant trend in annual mean wind speed over the period 1979-2004 also exhibit a significant change in inter-annual variability. In the NCDC-6421 *in situ* data set there is a tendency for stations that exhibit negative trends in the annual mean wind speed

to also exhibit positive trends in the inter-annual variability, however, analyses based on observations from the NCDC DS3505 data set indicate that stations that exhibit significant declines in annual mean wind speed have an almost equal probability of exhibiting increased or decreased inter-annual variability. In the NCEP-1 and NARR data sets there is a tendency for grid-cells that exhibit increases (decreases) in annual mean wind speeds to also exhibit an increase (decrease) in inter-annual variability, though this tendency is by no means uniform. In the NCEP-2 and ERA-40 data sets grid cells characterized by both positive and negative trends in annual mean wind speed exhibit a tendency towards increased inter-annual variability of annual mean wind speed. Output from both RCMs tend to indicate a decline in interannual variability over the simulation.

Thus our analyses, in accord with similar research conducted in Europe and Australia, indicate that in contrast to temperature and precipitation, data sets of wind speed drawn from *in situ* measurements and reanalysis products exhibit substantial discrepancies both in terms of absolute magnitude and the sign of temporal trends over the last 30-50 years. Both RCMs presented herein exhibit some skill in reproducing the mean wind climate across the contiguous USA for the historical period, but MM5 appears to exhibit greater accord with historical trends derived from *in situ* observations. This evaluation thus provides critical insights into the models which will inform our analysis of possible future climate states.

We extended the analyses presented in Pryor et al. (2009) in order to assess the role of 1st-order autocorrelation in the annual wind speed statistics. In this subsequent analysis we showed that treatment of the temporal autocorrelation slightly reduces the number of stations for which linear trends are deemed significant but does not alter the trend magnitudes relative to those presented in Pryor et al. (2009). Analyses conducted accounting for the autocorrelation generate results that indicate 55% of annual 50th percentile wind speed time series, and 45% of 90th percentile annual wind speed time series derived from the NCDC DS3505 data set exhibit significant downward trends over the period 1973-2005 (see Table 1). An interesting feature that is illuminated in this analysis is that as shown in Table 2, nearly half of the annual time series of 10-m wind speeds exhibit significant autocorrelation for lag=1. The higher lag=1 autocorrelation for the median (relative to the 90th percentile values) is attributable to higher variance in the upper percentiles.

We further extended the analysis of the geographic variability in the trends we illuminated in near-surface wind speeds. Using spatially aggregated summaries of trends we showed the median trend (1973-2005) in the 50th percentile wind speed ranges from -0.31 %/yr in the Northeast to -0.09 %/yr in the West. The median trend in the 90th percentile wind speed ranges from -0.25 %/yr in the Midwest to +0.01%/yr in the West. Thus, contrary to the other regions, the median trend in the annual 90th percentile wind speed averaged across all stations in the West is slightly positive (see Figure 5).

Near-surface wind climates at many mid-latitude locations strongly linked to extra-tropical cyclone activity and hence is a function of cyclone frequency, intensity or tracking, which in turn is linked to variability in large-scale climate dynamics and the teleconnection indices which impact regional circulation. These teleconnection indices (which exhibit a high degree of persistence) may thus be invoked as an explanation both for variability and persistence in wind speeds. To examine linkages between annual percentiles of wind speeds from the rawinsonde network and the teleconnection indices we computed regionally averaged p90 anomalies which are conditionally sampled for years in the highest and lowest quartile of each teleconnection index and the results are compared using a t-test applied with the assumption of uneven variance. The results (Figure 6) are physically intuitive and indicate a relatively strong link to the large-scale modes of climate variability. Also in the three northern regions the PNA exerts greatest influence – with a more zonal pattern (negative PNA) being associated with highest wind anomalies, for the west and southeast the SOI exhibits the greatest influence, while in the northeast the NAO is the dominant teleconnection. These dynamical linkages will prove key to understanding inherent variability and may provide a mechanism to differentiate natural climate variability and anthropogenic forcing.

Results from these analyses are published in:

Pryor S.C. and Ledolter J. (2010): Addendum to: Wind speed trends over the contiguous USA. *Journal of Geophysical Research – Atmospheres (in press).*

Pryor S.C., Barthelmie R.J., Young D.T., Takle E.S., Arritt R.W, Flory D., Gutowski Jr W.J., Nunes A., Road J. (2009): Wind speed trends over the contiguous USA. *Journal of Geophysical Research – Atmospheres* **114** D14105 doi:10.1029/2008JD011416.

Pryor S.C. and Barthelmie R.J. (2009): Historical trends in near-surface wind speeds. Chapter 15 in: Understanding climate change: Climate variability, predictability and change in the Midwestern US. Ed. S.C. Pryor, Indiana University Press, p169-183. ISBN: 978-0-253-35344-3.

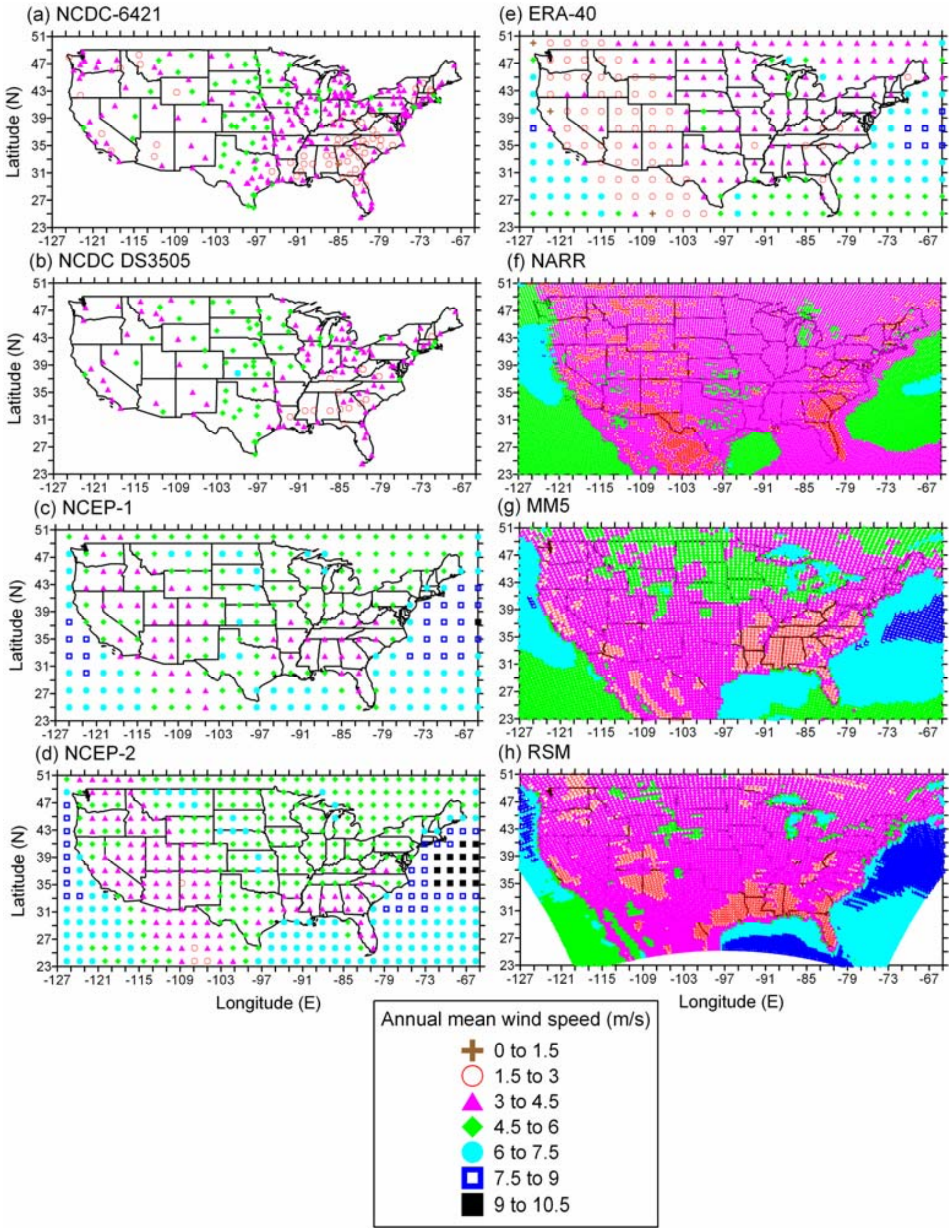


Figure 1. Average of annual mean wind speeds 1979-2000 from; (a) NCDC-6421, (b) NCDC DS3505 (modified as described herein), (c) NCEP-1, (d) NCEP-2, (e) ERA-40, (f) NARR, (g) MM5 and (h) RSM.

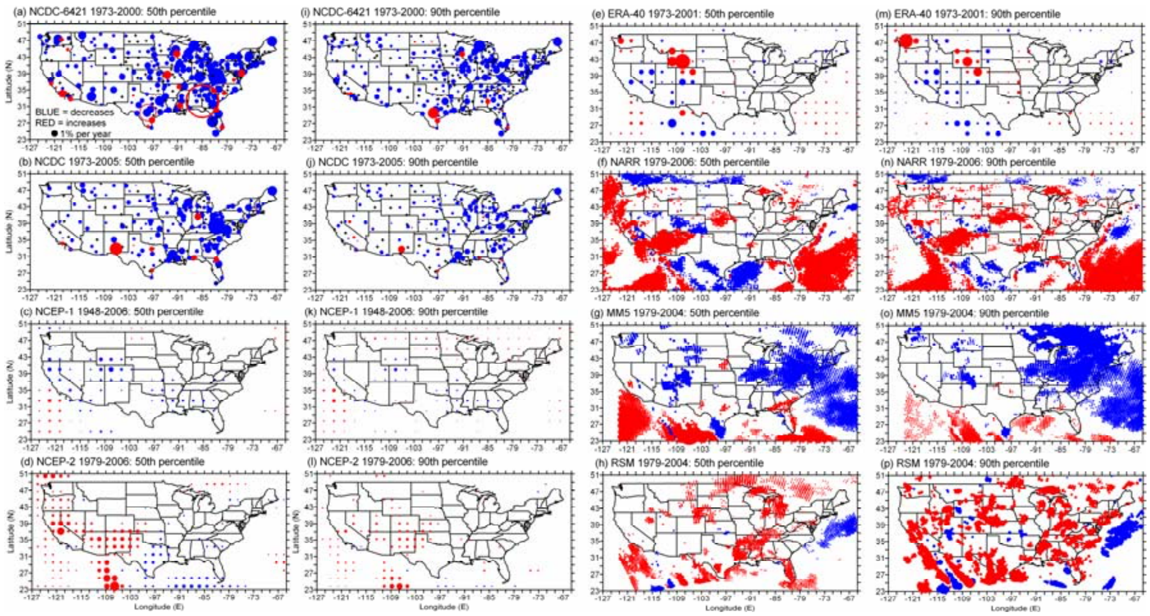


Figure 2: Results of the trend analysis applied to data from 0000 UTC. The individual frames show results for the 50th percentile wind speed from (a) NCDC-6421 (1973-2000), (b) NCDC DS3505 (1973-2005), (c) NCEP-1 (1948-2006), (d) NCEP-2 (1979-2006), (e) ERA-40 (1973-2001), (f) NARR output (1979-2006), (g) MM5 output (1979-2004), (h) RSM output (1979-2004), and the 90th percentile wind speed from (i) NCDC-6421 (1973-2000), (j) NCDC DS3505 (1973-2005), (k) NCEP-1 (1948-2006), (l) NCEP-2 (1979-2006), (m) ERA-40 (1973-2001), (n) NARR (1979-2006), (o) MM5 output (1979-2004), (p) RSM output (1979-2004). 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 (scale as shown in frame (a)). To enhance the legibility of this figure, stations that exhibit a trend in excess of 2%/yr are shown by open circles. Where the station time series did not indicate a statistically significant trend a + symbol is shown. Where time series from a reanalysis or RCM grid cell did not exhibit a trend no symbol is shown.

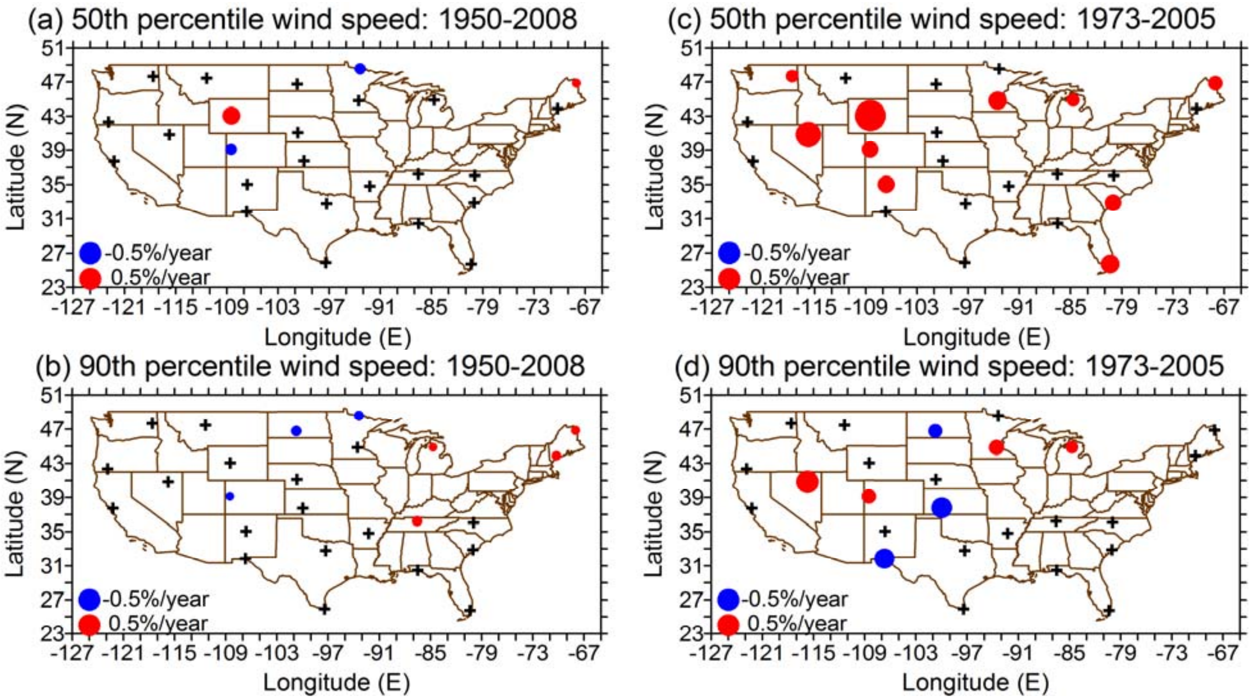


Figure 3. Temporal trends in annual 50th and 90th percentile rawinsonde wind speeds for 1950-2008 (left) and 1973-2005 (right). The data were derived from the 700 hPa level at sites west of -103E, and 850 hPa east of that longitude. As in the analysis of the 10-m wind speeds the regression analysis is undertaken accounting for first-order temporal autocorrelation. Trends significant at 90% confidence level are shown by the blue and red symbols, otherwise the station is denoted by a +. The symbol diameter scales with the square root of the trend magnitude.

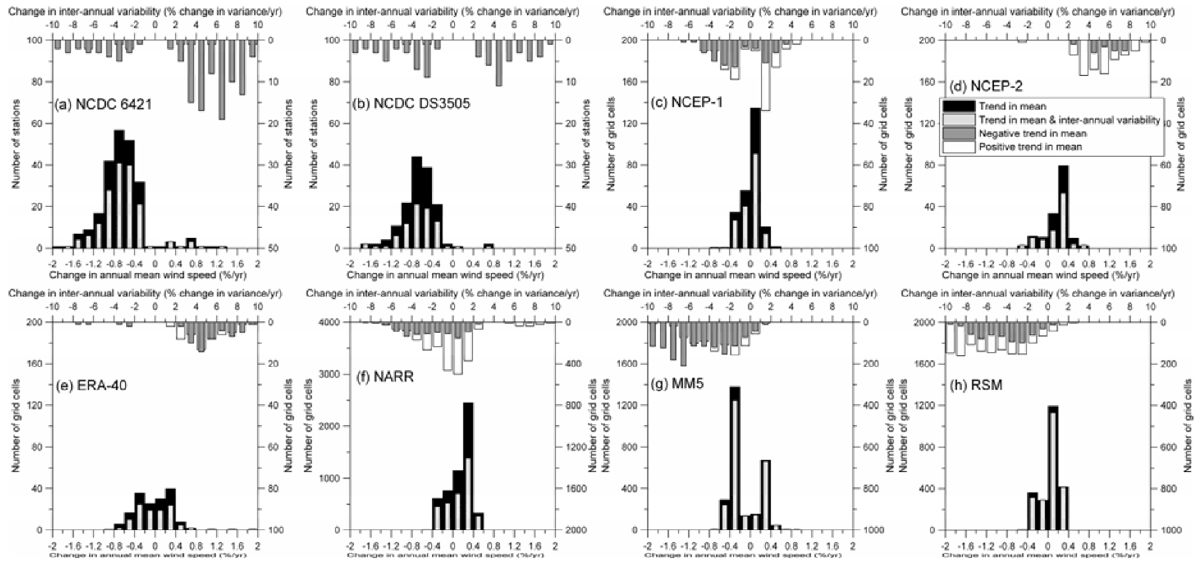


Figure 4: Synthesis of the trend analysis for annual mean wind speed and inter-annual variability. Each frame represents a different data source. In each frame the bottom two sets of bars represent the number of stations or grid cells (left-hand axis) that exhibit; (i) statistically significant change in the annual mean wind speed (shown in the legend as ‘Trend in mean’) and (ii) a statistically significant change in both the annual mean wind speed and inter-annual variability (shown in the legend as ‘Trend in mean and inter-annual variability’). The two top bars show the grid cells or stations (right hand axis) that exhibited a trend in the inter-annual variability of the specified sign and magnitude. This analysis includes only stations or grid cells that exhibited statistically significant changes in the mean wind speed. These data are conditionally sampled based on the sign of the trend in the annual mean wind speed (shown in the legend as ‘negative trend in mean’ or ‘positive trend in mean’). Thus this second analysis (and the results shown by the top bars) illuminates whether a change in the variance (positive or negative) is associated with a given sign of trend in the annual mean.

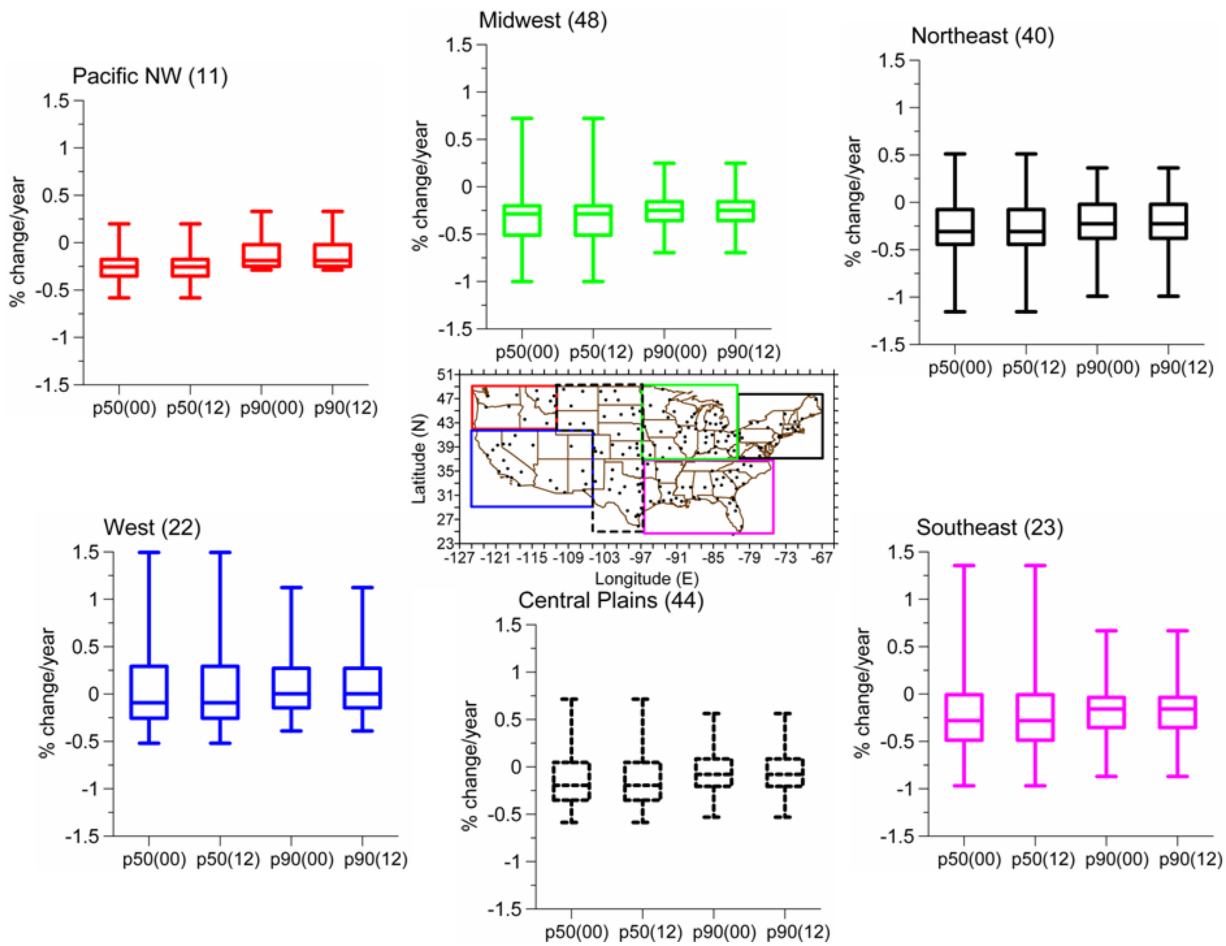


Figure 5. Regional synthesis of temporal trends in the annual median (p50) and 90th percentile (p90) wind speeds from the NCDC DS3505 data set for the 0000 and 1200 ZULU observation times (shown as (00) and (12) in the box-plots). The box-plots are the synthesis of trends computed for all stations within the six regions; Pacific Northwest, West, Central Plains, Midwest, Northeast and Southeast (the numbers in the title of each frame indicate the number of stations in each region). The horizontal bar in the center of the box-plots shows the median value of the annual trend (in %/yr), the upper and lower bars on the box show the 25th and 75th percentile values, while the vertical bars extend from the minimum to the maximum values.

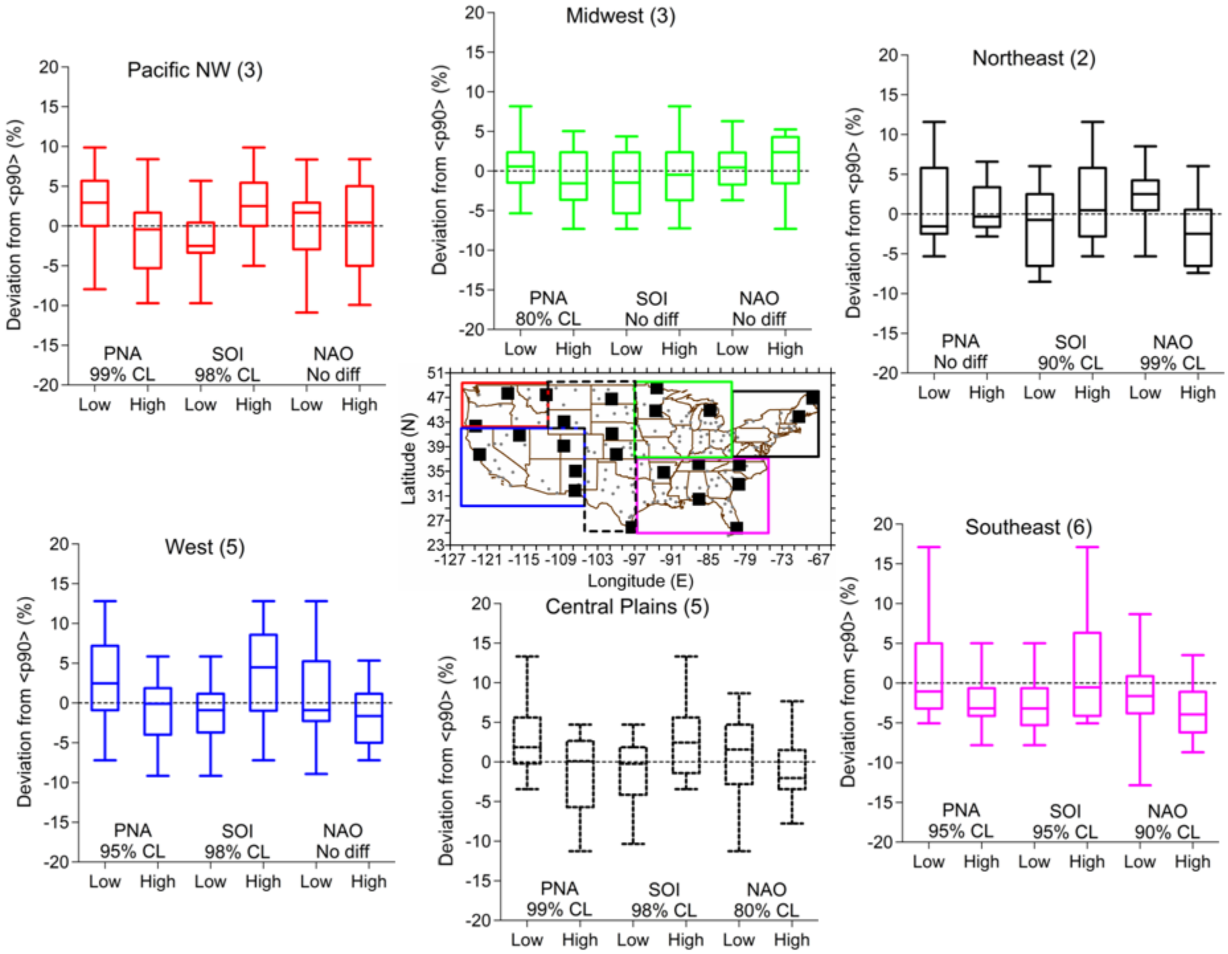


Figure 6. Dependence of regionally averaged annual 90th percentile wind speed anomaly (deviation from the mean p90 computed for 1950-2008) on the phase of three teleconnection indices. The results shown in each frame above the abscissa indicates whether the mean values of p90 anomaly differed for the phase of each teleconnection index (Low v High) according to the t-test and at what confidence level. The numbers reported in the frame titles denoted the number of rawinsonde stations from which data are used. The rawinsonde release locations are shown by the large black squares, while the surface observing stations from which data are presented in Figure 1 are shown by the grey dots.

Table 1: Number of significant trends in the original analysis (Pryor et al., 2009, labeled Original), and in the analysis including autoregressive errors (AR) for the annual 50th and 90th percentile wind speeds (labeled p50 and p90 in the table) (Pryor and Ledolter, 2010). The results are shown as the number of time series co-identified in both analyses as exhibiting significant positive or negative trends, and as the additional numbers that were identified as having significant trends of the specified sign in only one of the analyses. Also shown is the median annual trend magnitude expressed as percentage of the predicted 1972 value and in m s^{-1} from the original analysis (Original) and that conducted including the autoregressive term (AR).

Data set_ observation time	Metric Total sample	Co-identified: Negative	Co-identified: Positive	Additional Negative (Original/ AR)	Additional Positive (Original/ AR)	Median trend (%/yr) Original	Median trend (%/yr) AR	Median trend (m s^{-1}/yr) Original	Median trend (m s^{-1}/yr) AR
NCDC 6421_00	p50 N = 329	166	9	37/1	14/0	-0.44	-0.45	0.019	0.020
NCDC 6421_12	p50 N = 291	169	9	27/1	3/1	-0.58	-0.59	0.019	0.021
NCDC DS3505_00	p50 N = 188	91	16	22/1	4/0	-0.25	-0.25	0.010	0.010
NCDC DS3505_12	p50 N = 168	90	6	21/1	7/0	-0.28	-0.27	0.013	0.012
NCDC 6421_00	p90 N = 329	195	10	33/2	3/1	-0.39	-0.38	0.030	0.030
NCDC 6421_12	p90 N = 291	191	8	20/1	4/0	-0.47	-0.48	0.031	0.032
NCDC DS3505_00	p90 N = 188	84	9	10/0	7/0	-0.16	-0.16	0.012	0.012
NCDC DS3505_12	p90 N = 168	75	5	9/1	3/0	-0.18	-0.17	0.013	0.014

Table 2: Number and proportion of time series from the 10-m in situ data sets that exhibit significant (5% level) positive temporal autocorrelation (AR) for the two data sets, two measurement times (0000 and 1200 ZULU, abbreviated to 00 and 12 in the table), and both the annual 50th and 90th percentile wind speeds.

Data source _ time of observation	# stations	50th percentile		90th percentile	
		Sig. AR (#)	Sig. AR (%)	Sig. AR (#)	Sig. AR (%)
NCDC 6421_00	329	161	48.9	133	40.4
NCDC 6421_12	291	143	49.1	116	39.9
NCDC DS3505_00	188	105	55.9	79	42.0
NCDC DS3505_12	168	94	56.0	65	38.7
OVERALL			503/976 = 51.5		393/976 = 40.3

B. Extreme wind speed climate scenario development.

Unprecedented international efforts being engaged in mitigation of, and adaptation to, climate change. A critical component of these efforts is focused on improved quantification of how changes in global climate have been manifest regionally and how future changes may be manifest at the regional/local scale. As described in our original proposal, one of the major concerns with regard to climate evolution is focused on the possibility of increasing intensity or frequency of extreme events. Thus we proposed 'We will further extend downscaling techniques to include calculation of additional wind speed parameters that may be of particular utility to end-user groups – gusts and extreme wind speeds for pre-specified return periods.' This aspect of the research has been a major focus of our efforts during the current project year.

Our objectives were to:

- Develop and evaluate techniques for providing robust estimates of extreme wind speeds from climate models.
- Quantify potential changes in extreme wind speeds under a variety of climate change scenarios.
- Examine possible projections of intense and extreme wind speeds in the context of inherent variability.
- Quantify major sources of uncertainty in developing climate change projections of intense and extreme wind speeds.

The 2[nd] objective is particularly challenging in the context of much of the USA – because an absolute pre-requisite for analyzing possible changes in intense and extreme wind speeds is that the mechanism by which they are generated must be simulated within our climate models. In northern Europe – these 'wind storms' are likely predominately synoptic scale systems (and possibly polar lows), while in parts of the contiguous USA extreme wind speeds may derive from meso- or micro-scale phenomena. Thus in the first instance, in collaboration with our colleagues from the CES project we have focused on northern Europe.

For wind energy applications we conform to the Wind Turbine design criteria, which define the suitable class of wind turbines based on the 50-year return period wind speed (U_{50yr}). We further determine extreme winds based on the Gumbel distribution so:

$$U_T = \frac{-1}{\alpha}\ln\left[\ln\left(\frac{T}{T-1}\right)\right] + \beta \qquad (1)$$

Where: U_T wind speed for a given return period (T), and α and β are the distribution parameters.

We have applied two approaches to determining the Gumbel distribution parameters:

(a) The method-of-moments applied to simulated time series of annual maximum wind speeds from RCMs:

$$\alpha = \frac{\ln 2}{2b_1 - \overline{U^{\max}}} \qquad (2)$$

$$\beta = \overline{U^{\max}} - \frac{\gamma}{\alpha} \qquad (3)$$

$$b_1 = \frac{1}{n}\sum_{i=1}^{n}\frac{i-1}{n-1}U_i^{\max} \qquad (4)$$

The uncertainty on U_T is given by:

$$\sigma(U_T) = \frac{\pi}{\alpha}\sqrt{\frac{1+1.14k_T+1.10k_T^2}{6n}} \quad (5)$$

Where n is the sample size, the frequency factor (k_T) is:

$$k_T = -\frac{\sqrt{6}}{\pi}\left(\ln\left[\ln\left(\frac{T}{T-1}\right)\right]-\gamma\right) \quad (6)$$

Where γ = Euler's constant (0.577216)

Assuming a Gaussian distribution of U_T, then 95% of all realizations will lie with ±1.96σ of the mean, and thus σ can be used to provide 95% confidence intervals on the estimates of extreme winds with any return period.

(b) A new empirical approach based on the Weibull distribution parameters. This approach is an extension of the probabilistic empirical downscaling approach developed by Pryor et al and reported elsewhere. This empirical downscaling technique develops a probability distribution of wind speeds during a specific time window rather than a time series of wind speeds. Thus the downscaled parameters are the scale (A) and shape (k) of the Weibull distribution:

$$P(U) = 1-\exp\left[-\left(\frac{U}{A}\right)^k\right] \quad (7)$$

This approach is advantageous in the current context because it avoids a focus on mean conditions, underestimation of variance, and difficulties associated with reproducing the time structure of wind speeds.

Downscaled Weibull A and k for each time period, AOGCM and station are used to compute U_{50yr} using eq. (1) and:

$$\alpha = \frac{k}{A}\left((\ln(n))^{1-\frac{1}{k}}\right) \quad (8)$$

$$\beta = A(\ln(n))^{1/k} \quad (9)$$

Where n is the number of independent observations

We have developed an approach to estimate uncertainties on the estimates of U_{50yr} developed from the Weibull fit by propagating uncertainty from the Weibull parameter estimates (derived in our earlier work). In our test case study based on 43 stations and eight-AOGCMs the 95% confidence intervals computed for the 1961-1990 period are within -12% to +10%.

Since this is a new approach to downscaling extreme wind speeds, we have invested considerable effort in method evaluation. For the 8 AOGCMs analyzed and the 43 stations, the range of downscaled U_{50yr} for 1961-1990 lie within ±4% of the mean U_{50yr} and 95% lie within ±2%, so the downscaling results for extreme winds from the Weibull A and k parameters are relatively consistent for the historical period.

Applying these techniques we have derived the following insights:

- In northern Europe there is evidence for a decoupling of tendencies in the body and extremes of the wind speed distribution. There is some evidence that for reasonable climate forcing there may be some small magnitude declines in wind energy resources (though the changes are of lesser magnitude than current inter-annual variability), but particularly in the SW of our study domain an increase in extreme wind speeds. Figure 7 shows an example of probabilistic empirical downscaling approach applied to examine changes in average energy density and 50-year return period wind speed in downscaling of 8 AOGCMs to 43 stations across northern Europe. The results are shown for the ensemble average difference (end of

C21st – end of C20th) for the 8-AOGCMs. We have sought to place this finding in the context of prior analyses. Studies of transitory synoptic-scale systems have not resolved a clear signal in terms of the role that greenhouse gas induced warming has played or might play in changing the frequency/intensity or tracking of these systems in the North Atlantic and northern Europe. Furthermore there is typically some underestimation of AOGCM storm tracks in the Norwegian sea due to the excessively zonal orientation of North Atlantic storm tracks. Nevertheless, research for the entire Northern Hemisphere based on simulations from ECHAM5/MPI-OM1 detected a significant decrease of overall cyclone track density between 35 and 55º N, and a small increase north of that latitude particularly in intense cyclones. This is consistent with the differential trends we have derived.

- We have invested considerable effort in improved understanding of the sources of uncertainty in our projections of wind climates and the consistency of climate change signal from different downscaling approaches. Figure 8 shows an example of the consistency of the climate change signal in U_{50yr} from the probabilistic empirical downscaling and two independent RCMs nested within ECHAM5 simulations of the global climate. In other research we have sought to compare the sensitivity of the downscaling projections to four key parameters:
   i. AOGCM architecture.
   ii. SRES (also referred to as 'Radiative uncertainty'). This uncertainty is due to the fact that any IPCC-SRES is merely one hypothesis of future emissions.
   iii. Stochastic influences within simulations using the same AOGCM. This analysis is based on bootstrap resampling of the time series of the predictors to assess whether the distributions of the relative vorticity and sea-level pressure gradients are influenced by stochastic effects and whether these substantially bias the downscaling of the Weibull parameters at each site.
   iv. Initial conditions. Each AOGCM simulation represents only one realization of possible climate states, thus using multiple runs with a single AOGCM conducted with slightly perturbed initial conditions can be used to assess how uncertainties in initial conditions propagate to alternative climate outcomes.

  Table 3 shows a synthesis of our findings. Naturally, there are other sources of uncertainties such as 'sampling uncertainty' due to the short time periods and integration over a finite number of years. These and other sources of uncertainty are discussed Pryor and Schoof (2010).

- We have invested considerable effort in improved quantification of inherent variability and using internal variability to provide bounds against which we can compare any 'climate change signal'. Figure 9 shows an example of the analyses conducted to examine the relative importance of natural variability v. a climate change signal in dictating 'differences' in U_{50yr} for future time periods relative to the control period 1961-1990. In this analysis, RCM output from every grid cell in the study domain were used to compute U_{50yr} for 1961-1990 and then for each moving window 30 year period (1962-1991,…., 2036-2065… 2071-2100). For each 30-year period and each grid cell we assessed:
   - If the U_{50yr} for the later period was below or above that computed for 1961-1990.
   - If the U_{50yr} for the later period was 1-sigma below or above that computed for 1961-1990.
   - If the U_{50yr} for the later period was 2-sigma below or above that computed for 1961-1990.

  Key findings from these analyses are:

(i) There is a relatively high degree of consistency in the climate change signal in U_{50yr} computed using both dynamically and empirically downscaled wind speeds.

(ii) Out to approximately the middle of the C21st, stochastic variability (multi-decadal, natural variability) appears to dominate a climate change signal. Analyses over northern Europe exhibit some weak evidence for an increase in extreme wind speeds at sites during the middle and end of the C21st relative to 1961-1990 in the southwest of the study domain (northern Germany and Denmark).

(iii) The change in U_{50yr} from the ensemble average probabilistic empirical downscaling approach applied to 8-AOGCMs do not exceed the uncertainty bounds. Uncertainty calculations such as those we have conducted illustrate the challenge of estimating climate change impacts on geophysical extremes, but also provide critical context for interpreting the results of such analyses. It is interesting in this context (as with precipitation?) that there may be an increase in the magnitude of extremes coupled with no change, or even a decline in the central tendency.

Results from these analyses are published in the following manuscripts (one further manuscript is under development):

Pryor S.C. and Schoof J.T. (2010): Importance of the SRES in projections of climate change impacts on near-surface wind regimes *Meteorologische Zeitschrift (in 2nd review).*

Pryor S.C. and Barthelmie R.J. (2010) Climate change impacts on wind energy: A review. *Renewable and Sustainable Energy Reviews* **14** 430-437.

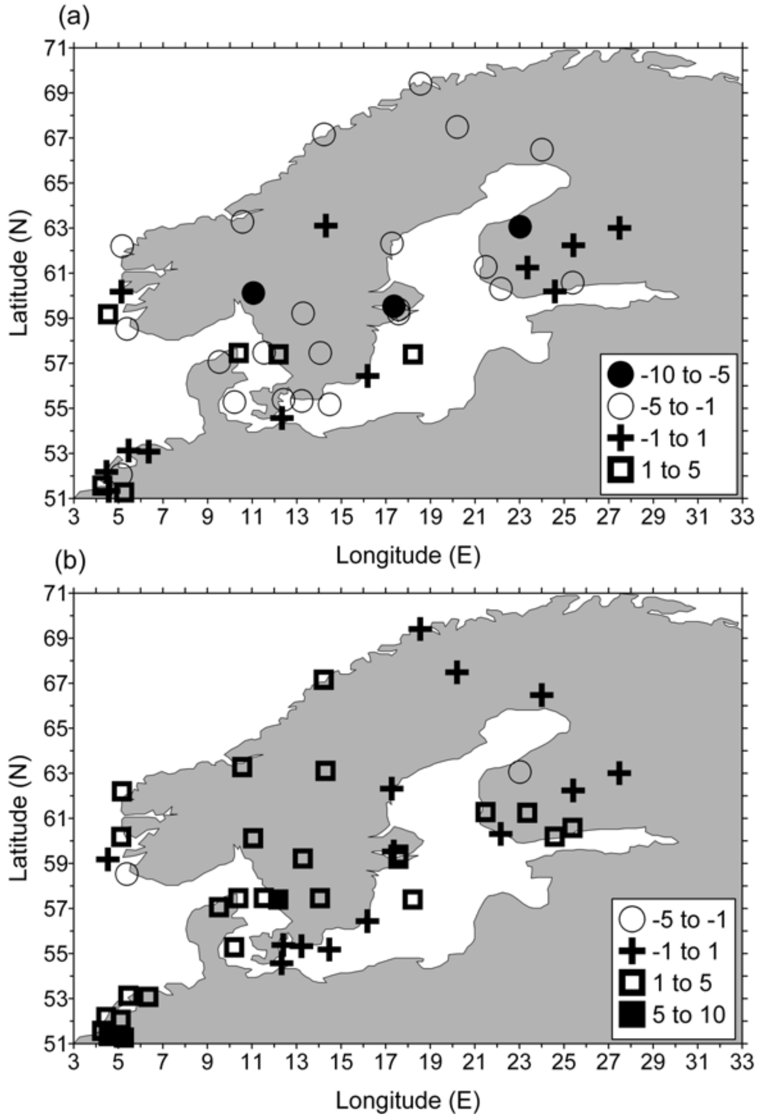
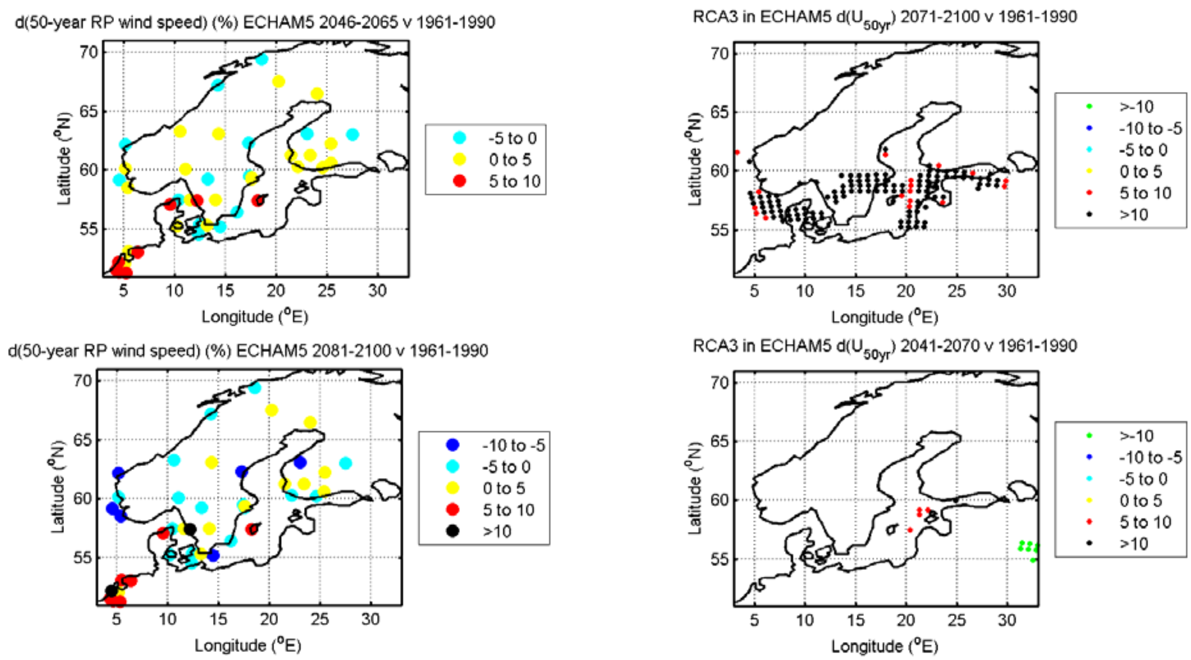


Figure 7. Ensemble average difference in percent of a) energy density and b) 50-year return period wind speed computed using a probabilistic empirical downscaling approach for 43 stations across northern Europe based on output from 8-GCMs (BCCR-BCM2.0, CGCM3.1, CNRM-CM3, ECHAM5/MPI-OM, GFDL-CM2.0, GISS-ModelE20/Russell, IPSL-CM4, and MRI-CGCM2.3.2.). The future time period is 2081-2100, while the historical period in 1961-1990. A positive number indicates a higher value in the later time period.



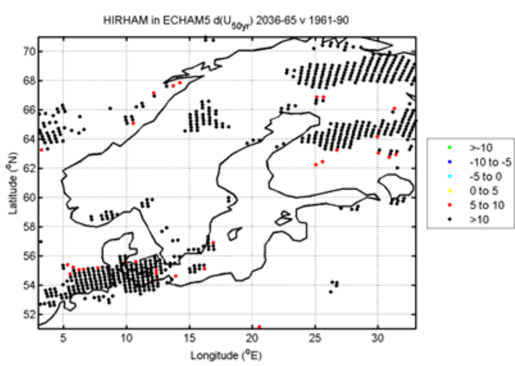


Figure 8. Evaluating the consistency of the climate change signal in extreme wind speed from the probabilistic empirical downscaling and two RCMs. All downscaling is based on output from the ECHAM5 AOGCM. Upper left: Difference in U_{50yr} for 2046-2065 (above) and 2081-2100 (below) relative to 1961-1990 for analyses using the probabilistic empirical downscaling approach. Upper right: Difference in U_{50yr} for 2046-2065 (above) and 2081-2100 (below) relative to 1961-1990. Results from the Rossby Centre 3rd generation RCM. Lower left: Difference in U_{50yr} for 2036-2065 relative to 1961-1990. Results from the DMI 5th generation RCM (HIRHAM). Results are only shown for the RCMs if the future period U50yr estimates lie beyond the 95% confidence intervals computed for the 1961-1990 period.

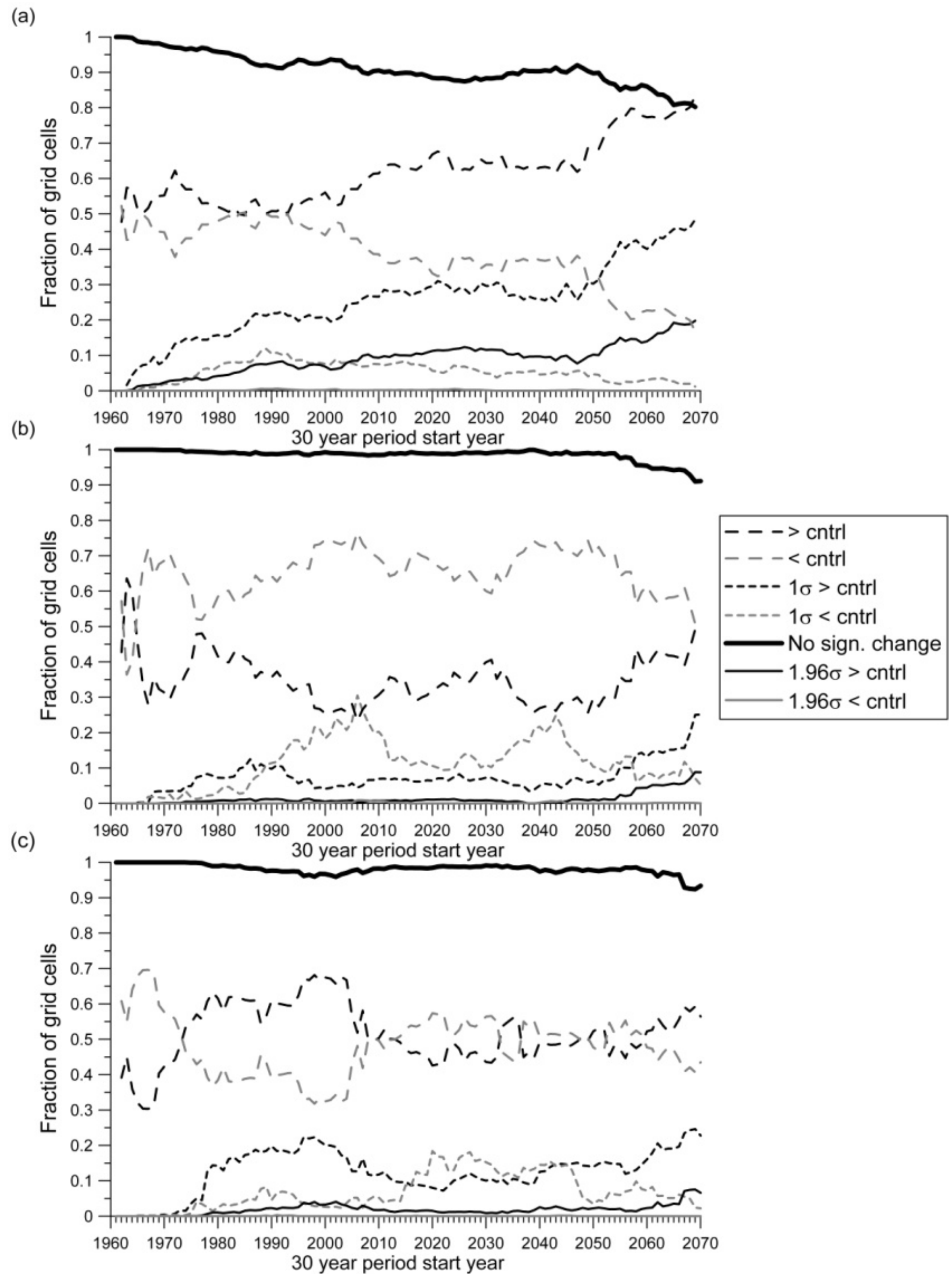


Figure 9: Fraction of the total number of grid cells in the (a) HIRHAM5 simulation of ECHAM5 member#3, (b) RCA3-simulation of ECHAM5 member #1, (c) RCA3- simulation of ECHAM5 member #2 that exhibits a U_{50yr} from a given 30-year period that is (i) above or below the U_{50yr} estimate from 1961-1990 (> cntrl and < cntrl, respectively), (ii) 1-σ above or below the U_{50yr} estimate from 1961-1990 (1σ > cntrl and 1σ < cntrl, respectively), (iii) above or below the 95% confidence intervals on U_{50yr} estimate from 1961-1990 (1.96σ > cntrl and 1.96σ < cntrl, respectively). Also shown is the number of grid cells for which the U_{50yr} from a given 30-year period is within the 95% confidence intervals on the 1961-1990 estimate (No sign. change). All of the AOGCM simulations assume the A1B emission scenario (SRES).

Table 3. Sensitivities of downscaled 90th percentile wind speed derived using the probabilistic approach for 45 stations across northern Europe. The results show the range of differences in the 90th percentile wind speed computed for 2081-2100 versus 1961-1990. Thus if the range is ±X%, the projected period lies within X% of conditions during the historical period. The variation with specific AOGCM member (described herein as run 1 and run 4) is shown in the last row and indicates that two simulations with the same AOGCM differ by upto ±15%.

Parameter	**# AOGCMs**	**SRES**	**Range of estimates**	**Reference**
AOGCM architecture	10	A2	±25%	Pryor et al. (2006b)
Stochastic effects w/in AOGCM	5 (one station, Copenhagen)	A2	95% of realizations w/in ±10%	Pryor et al. (2005b)
SRES	1 (ECHAM5)	A2, A1B, B1, Commit	±15%	Pryor and Schoof (2010)
AOGCM member	1 (ECHAM5)	2 × 20th century	±15%	Pryor and Schoof (2010)

C. Review of the state-of-the-art with regards to possible climate change impacts on wind energy.

Renewable energy sources currently meet approximately 14 % of energy demand world-wide, and are poised to play an even greater role in future energy provision. These technologies provide a key component of efforts to mitigate climate change, and can contribute to the security of energy supply and environmental protection measures. Wind energy, like many of the renewable technologies, is also susceptible to climate change because the ‘fuel’ is related to the global energy balance and resulting atmospheric motion. Hence, as a component of this project we have sought to ‘close the loop’ by asking the question; ‘what impact might global climate change have on the wind energy industry?’

Global climate change may change the geographic distribution and/or the inter- and intra- annual variability of the wind resource, or alter other aspects of the external conditions for wind developments. Results from our extensive review may be summarized as follows: Global and Regional Climate Models do not fully reproduce contemporary wind climates or historical trends, and empirical and dynamical downscaling studies show large model-to-model variability with respect to the climate change signal. Nevertheless from research conducted to date, it appears unlikely that mean wind speeds and energy density will change by more than the current inter-annual variability (i.e. ±15%) over most of Europe and North America during the present century. Some research suggests changes over South America may be of larger magnitude but these estimates are also subject to rather large uncertainty. Other mechanisms by which climate change may influence the wind energy industry are even less well understood. The 50-year return period wind speed, and probability of icing on wind turbines have implications for turbine design, operation and maintenance, but very few studies have considered these parameters. Preliminary studies from northern and central Europe exhibit some evidence for increased magnitude of wind speed extremes, though changes in the occurrence of inherently rare events are difficult to quantify, and the ability of our downscaling models to reproduce intense and extreme wind speeds has yet to be fully evaluated. Sea ice, and particularly drifting sea ice, potentially enhances turbine foundation loading and changes in sea ice and/or permafrost conditions may also influence access for wind farm maintenance. One study conducted in northern Europe found substantial declines in the occurrence of both icing frequency and sea ice extent under reasonable climate change scenarios, both of which are physically consistent with expected changes in thermal regimes, and large magnitude warming in high latitudes. However, caution must be exercised in interpreting these results given recognized limitations of RCMs in simulating humidity particularly close to the freezing point of water. Other meteorological drivers of turbine loading may also be influenced by climate change but are likely to be secondary in comparison to changes in resource magnitude, extremes and icing issues.

Results of this first synthesis activity were published in Pryor and Barthelmie (2010):

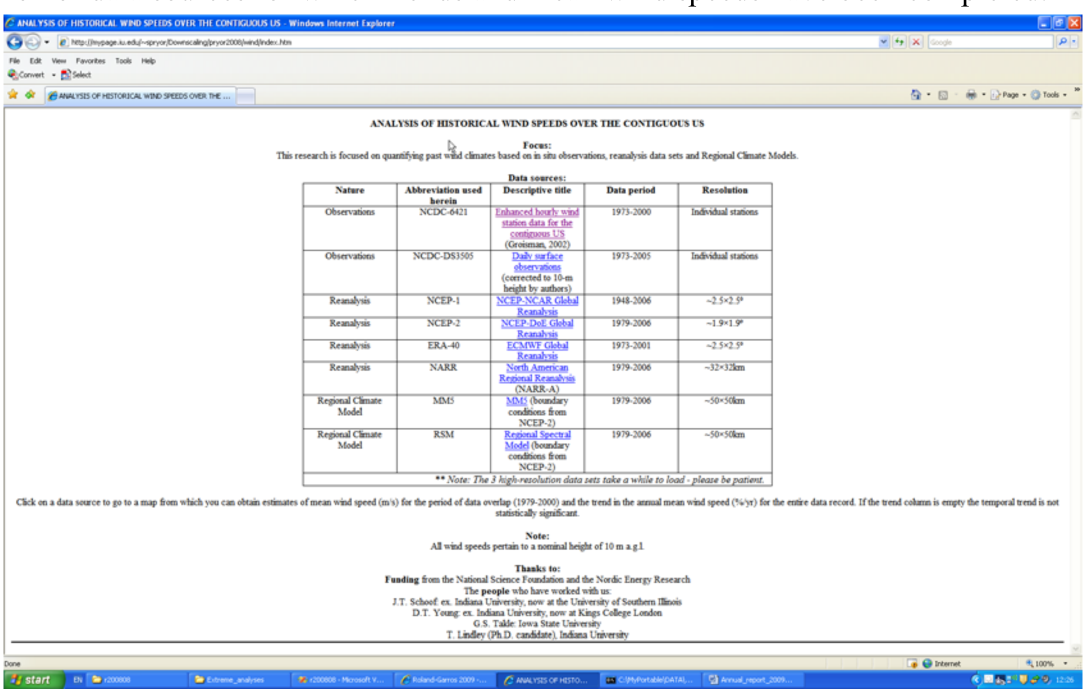
Pryor S.C. and Barthelmie R.J. (2010) Climate change impacts on wind energy: A review. *Renewable and Sustainable Energy Reviews* **14** 430-437.

We have recently extended this analysis to address the key issue of whether our best estimates of possible changes of the extreme conditions key to wind energy installations lie beyond the currently applied wind design and implementation standards. This work will be published in an IAEA volume deriving from the workshop on Vulnerability of energy systems to climate change and extreme events.

D. Dynamical WWW site for distribution/dissemination of project results

The dynamical WWW site has been developed and is continuously updated. It can be accessed at: http://php.indiana.edu/~spryor/Downscaling/overview.htm. We added Google Analytics WWW site tracking and analysis to this site so we can determine site usage.

A key significant addition to the WWW site is a dynamical inter-face of the analyses of wind speed trends over the USA: This aspect of the site is a portal where the user is first shown a tabulation of data sources for which trends and mean wind speeds have been completed:



ANALYSIS OF HISTORICAL WIND SPEEDS OVER THE CONTIGUOUS US

Focus:
This research is focused on quantifying past wind climates based on in situ observations, reanalysis data sets and Regional Climate Models.

Data sources:

Nature	Abbreviation used herein	Descriptive title	Data period	Resolution
Observations	NCDC-6421	Enhanced hourly wind station data for the contiguous US (Groisman, 2002)	1973-2000	Individual stations
Observations	NCDC-DS3505	Daily surface observations (corrected to 10-m height by authors)	1973-2005	Individual stations
Reanalysis	NCEP-1	NCEP-NCAR Global Reanalysis	1948-2006	~2.5×2.5°
Reanalysis	NCEP-2	NCEP-DoE Global Reanalysis	1979-2006	~1.9×1.9°
Reanalysis	ERA-40	ECMWF Global Reanalysis	1973-2001	~2.5×2.5°
Reanalysis	NARR	North American Regional Reanalysis (NARR-A)	1979-2006	~32×32km
Regional Climate Model	MM5	MM5 (boundary conditions from NCEP-2)	1979-2006	~50×50km
Regional Climate Model	RSM	Regional Spectral Model (boundary conditions from NCEP-2)	1979-2006	~50×50km

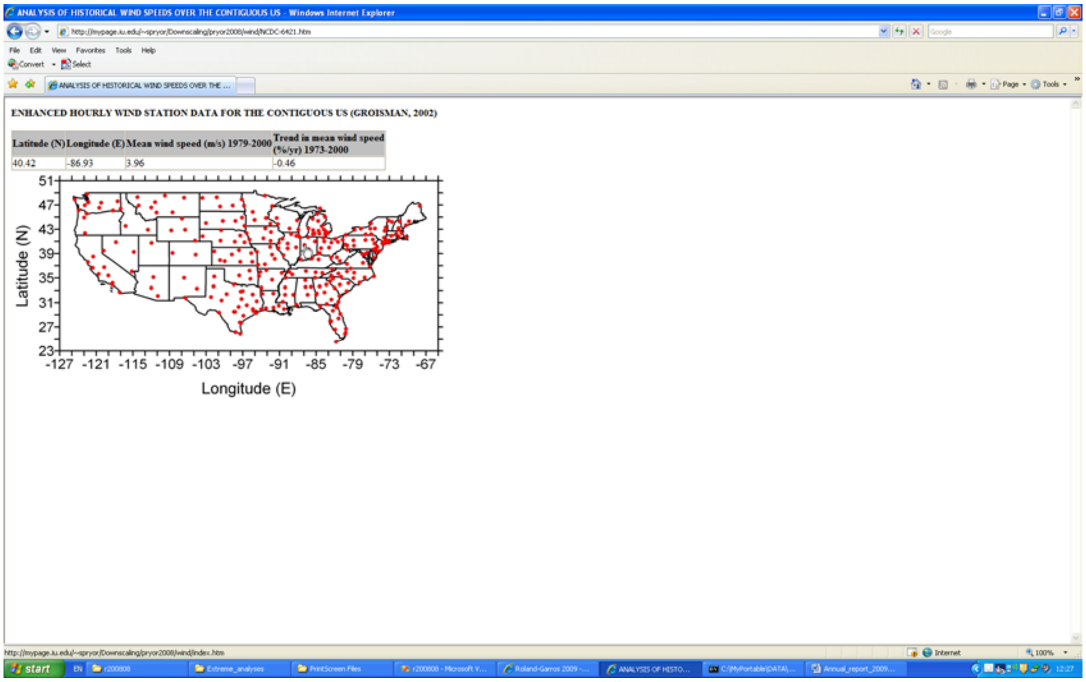
*** Note: The 3 high-resolution data sets take a while to load - please be patient.*

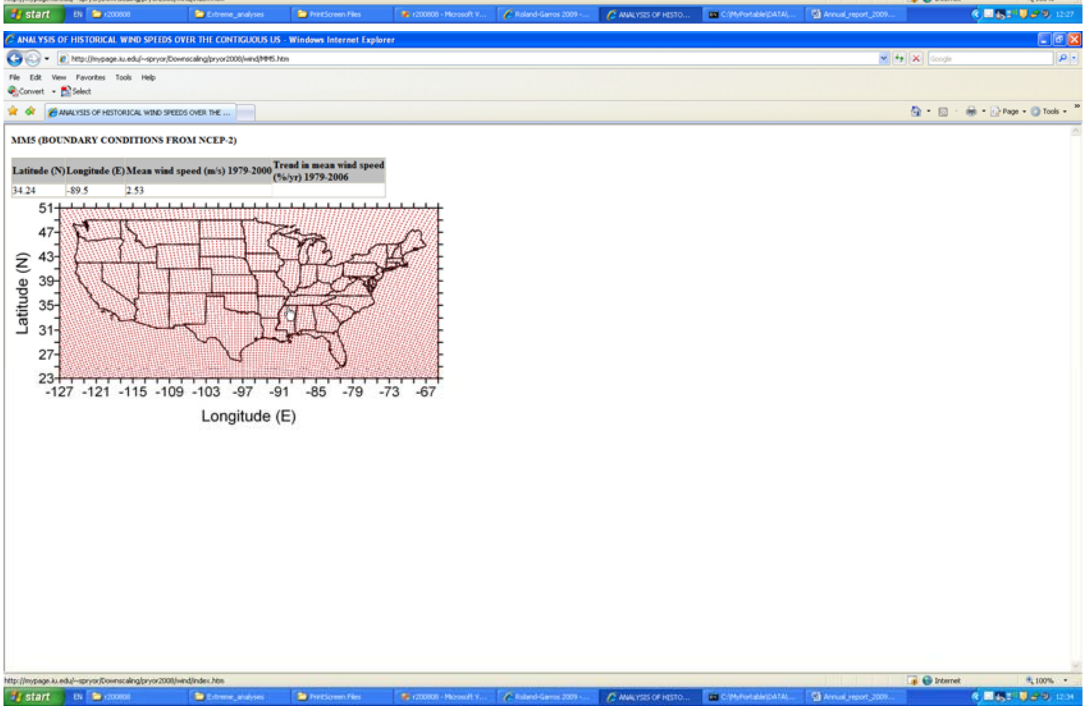
Click on a data source to go to a map from which you can obtain estimates of mean wind speed (m/s) for the period of data overlap (1979-2000) and the trend in the annual mean wind speed (%/yr) for the entire data record. If the trend column is empty the temporal trend is not statistically significant.

Note:
All wind speeds pertain to a nominal height of 10 m a.g.l.

Thanks to:
Funding from the National Science Foundation and the Nordic Energy Research
The **people** who have worked with us:
J.T. Schoof: ex. Indiana University, now at the University of Southern Illinois
D.T. Young: ex. Indiana University, now at Kings College London
G.S. Takle: Iowa State University
T. Lindley (Ph.D. candidate), Indiana University

The user selects the data set of interest by clicking on a data source they are then directed to a map from which they can obtain estimates of mean wind speed (m/s) for the period of data overlap (1979-2000) and the trend in the annual mean wind speed (%/yr) for the entire data record. The results are shown so that a mean wind speed is always reported for every site/grid cell, but if the trend column is empty the temporal trend is not statistically significant, otherwise a trend is shown in %/yr:





1.5 Opportunities for training and development provided

The project provided the following educational/training opportunities:

- Sara Pryor supervised four graduate students working on various aspects of the research:
  - One joined the PhD program in January 2008 and worked on the NARR data.
  - One (who has since completed his PhD) worked largely with data processing and visualization.
  - One had primary responsibility for operationalizing the dynamical WWW site.
  - One completed her M.S. degree and assisted with trend analyses. (thesis title: Analysis of extreme precipitation across the Midwest during the twentieth century)

  She also supervised the undergraduate research of Evan Riley who has subsequently graduated, completed a M.S. degree in renewable energy sources and is now working for a green energy company.
- Rebecca Barthelmie supervised a graduate student who analyzed in situ data to examine wind speed trends and implications for the wind energy industry in Texas and California.
- In part on the basis of activities conducted under this award Barthelmie has led a new initiative at IU for a PhD minor in renewable energy science.
- On the basis of this project Gene Takle and the ISU group, have established an ISU wind research program having three distinct but related dimensions: (1) analysis of regional climate model wind speed and wind speed changes under climate change, (2) field measurements of the interaction of wind farms co-located with agricultural farms, and (3) short-term forecasting of wind speed for more efficient use of wind produced by Iowa wind farms.
- The contacts and collaborations launched by this NSF wind research project have attracted ISU students and faculty to the study of wind and wind energy. The Department of Statistics has established a faculty and graduate student weekly working seminar (now in its second semester) to investigate applications of advanced statistical methods to short-term multi-model ensemble wind speed forecasts.
- Three ISU Freshman Honors students, Aaron Rosenberg, Rob Hanson, and Kristyna Carter, have chosen to work with our ISU wind research team for the spring 2010 semester for their First Year Honors Mentor Program experience. They meet weekly with our graduate students and faculty and each have been assigned a separate meteorological tall tower for data analysis and validation of short-term wind speed forecasts.
- Two senior meteorology majors at ISU have chosen wind projects for their senior theses in 2009. Rachel Hatteberg evaluated the ability of the six regional climate models that have data in the archive of the North American Regional Climate Change Assessment Program to simulated high wind speed events, known as derechoes. She currently is expanding her project from last semester and will present her results at the 2010 Severe Storms Conference. Her experience has prompted her to apply for graduate school at Iowa State.
- Shannon Rabideau's senior thesis, which compared wind speed observations from a tall tower in Iowa with short-term wind speed forecasts made by a weather forecast model, was selected a one of two award winners in this year's thesis competition. Her experience has prompted her to apply for graduate school at Iowa State and elsewhere.

- In addition to the Honors students and senior theses described above, the ISU wind research program will host a DOE research undergraduate student from South Dakota State University during summer 2010. We also have agreed to work with the ISU Program for Women in Science and Engineering to mentor up to two of their high-school students during summer 2010.

1.6 Outreach activities

In addition to typical outreach activities, as described above, a dynamic WWW page for the project has been generated and published. Also the results of this project are highlighted in an edited volume published by Indiana University Press. The PIs have also given numerous colloquia and seminar within academic and industrial contexts featuring research from this project.

2 Publications and products

2.1 Journal publications

In review

Barthelmie R.J., Sempreviva A.M., Pryor S.C. (2010): The influence of humidity fluxes on offshore wind speed profiles. *Annals Geophysicae (in review, submitted June 2009).*

In press

Wang S.-Y., Chen T.-C., and Takle E. S. (2010): Climatology of summer midtropospheric perturbations in the U.S. Northern Plains. Part II: Large-scale effects of terrain boundary layer on genesis. Climate Dynamics, doi: 10.1007/s00382-010-0765-7 (in press).

Pryor S.C. and Ledolter J. (2010): Addendum to: Wind speed trends over the contiguous USA *Journal of Geophysical Research - Atmospheres* **In press**

Published

Pryor S.C. and Barthelmie R.J. (2010): Climate change impacts on wind energy: A review. *Renewable and Sustainable Energy Reviews* **14** 430-437.

*Pryor S.C., Barthelmie R.J., Young D.T., Takle E.S., Arritt R.W, Flory D., Gutowski Jr W.J., Nunes A., Road J. (2009): Wind speed trends over the contiguous USA. *Journal of Geophysical Research – Atmospheres* **114** D14105 doi:10.1029/2008JD011416.

This article has been featured in numerous articles in the popular press including an article in Scientific American: Moyer M. (2009): The way the wind blows, Scientific American October, 27-28.

Pryor S.C., Howe J.A. and Kunkel K.E. (2009): How spatially coherent and statistically robust are temporal changes in extreme precipitation across the contiguous USA. *International Journal of Climatology* **29** 31-45.

Sempreviva A.M., Barthelmie R.J., and Pryor S.C. (2008): Offshore wind resource assessment. *Surveys in Geophysics* **29** 471-497.

Pryor S.C. and Schoof J.T. (2008): Changes in the seasonality of precipitation over the contiguous USA. *Journal of Geophysical Research - Atmospheres* **113**, D21108, doi:10.1029/2008JD010251.

Schoof J.T. and Pryor S.C. (2008): On the proper order of Markov chain model for daily precipitation occurrence in the contiguous United States. *Journal of Applied Meteorology and Climatology* **47**, 2477-2486.

Barthelmie R.J., Murray F. and Pryor S.C. (2008): The economic benefit of short-term forecasting for wind energy in the UK electricity market, *Energy Policy*, **36(5),** 1687-1696. doi:10.1016/j.enpol.2008.01.027

Barthelmie R.J. (2007): Wind energy: Status and trends. *Geography Compass*, 1 (3), 275–301. doi:10.1111/j.1749-8198.2007.00030.x

Barthelmie R.J., Badger J., Pryor S.C., Hasager C., Christiansen M.B. and Jørgensen B.H. (2007): Wind speed gradients in the coastal offshore environment: Issues pertaining to design and development of large offshore wind farms, *Wind Engineering*, **31(6),** 369-382.

Barthelmie R.J., Sempreviva A.M. and Pryor S.C. (2007): The influence of humidity fluxes on offshore wind speed profiles, *e-WindEng* (005). pp. 1-5. ISSN 1901-9181. http://ejournal.windeng.net/9/

2.2 Books

Pryor S.C. (Ed) (2009): Understanding climate change: Climate variability, predictability and change in the Midwestern US. *A 24 chapter volume synthesizing the state-of-the-art regarding knowledge of historical and projected future changes to the physical climate*. Indiana University Press, Bloomington, Indiana, USA, 312pp. ISBN: 978-0-253-35344-3.

Oliver J.E. (2009): Indiana's Weather and Climate. *SP is contributor to the book, and reviewed page proofs of the book after the untimely passing of John Oliver*. Indiana University Press, Bloomington, Indiana, USA, 192pp. ISBN-13: 978-0-253-22056-1.

2.3 Book chapters

In press

Barthelmie R.J. and Pryor S.C. (2010): Meteorology and wind resource assessment. Chapter 1 in: *Wind energy systems. Optimising design and construction for safe and reliable operation*. Eds: J. Dalsgaard Sørensen, J. Nørkær Sørensen. Woodhead Publishing Limited, Cambridge, 37pp.

Published

Pryor S.C. and Takle G.S. (2009): Climate variability, predictability and change: An introduction. Chapter 1 in: *Understanding climate change: Climate variability, predictability and change in the Midwestern US.* Ed. S.C. Pryor, Indiana University Press, p1-18. ISBN: 978-0-253-35344-3.

Pryor S.C. and Barthelmie R.J. (2009): Historical trends in near-surface wind speeds. Chapter 15 in: *Understanding climate change: Climate variability, predictability and change in the Midwestern US.* Ed. S.C. Pryor, Indiana University Press, p169-183. ISBN: 978-0-253-35344-3.

Schoof J.T. and Pryor S.C. (2009): Teleconnection and circulation patterns in the Midwestern United States. Chapter 17 in: *Understanding climate change: Climate variability, predictability and change in the Midwestern US.* Ed. S.C. Pryor, Indiana University Press, p196-206. ISBN: 978-0-253-35344-3.

Takle G.S. and Pryor S.C. (2009): Where is climate science in the Midwest going? Chapter 23 in: *Understanding climate change: Climate variability, predictability and change in the Midwestern US*. Ed. S.C. Pryor, Indiana University Press, p265-276. ISBN: 978-0-253-35344-3.

Pryor S.C. (2009): A tornado climatology of Indiana. Book section in *Indiana's Weather and Climate* John E. Oliver, Indiana University Press ISBN-13: 978-0-253-22056-1

Barthelmie R.J., Pryor S.C. and Frandsen S.T. (2009): Climatological and meteorological aspects of predicting offshore wind energy. Chapter 4 *Offshore Wind Energy* Ed. Twidell and Gaudiosi. Published by Multi-Science Publishing Co, Brentwood, UK. pp. 43-69. ISBN 978-0906522.

2.4 Conference proceedings

<u>2010</u>

Pryor S.C., Barthelmie R.J., Shcoof J.T., Clausen N.E., Kjellstrom E. and Drews M. (2010): Intense and extreme wind speeds over the Nordic countries. Proceedings of the *International meeting on Climate and Energy Systems, 2pp.*

Pryor S.C., Barthelmie R.J., Schoof J.T., Claussen N.E., and Drews M. (2010): Quantifying

possible changes in extreme and intense wind speeds, *Proceedings of the American Wind Energy Conference*, Dallas, May 2010.

Pryor S.C. (2010): Assessing the vulnerability of the wind energy industry to climate extremes. *Special IAEA report on Vulnerability of Energy Systems to Climate Change and Extreme Events.* 32 pp.

Pryor S.C., Barthelmie R.J., Schoof J.T., Claussen N.E., and Drews M. (2010): Changes in extreme and intense wind speeds, *Proceedings of the European Wind Energy Conference*, Warsaw, March 2010

2009

Pryor S., Barthelmie R.J., Clausen N.E., Nielsen N.M., Kjellström E. and Drew M. (2009): Will climate change influence extreme wind speeds? *Proceedings of the Offshore wind and other marine renewable energies in Mediterranean and European Seas conference in Brindisi. p 21-28.*

Pryor S., Barthelmie R.J., Clausen N.E., Nielsen N.M., Kjellström E. and Drew M. (2009): Climate change impacts on extreme wind speeds. *21st Century Challenges in Regional-scale Climate Modelling Workshop. Proceedings of the Regional Climate Models 2009 conference in Lund, p 271-272. Int. Baltex Secretariat. Publication #41. ISSN 1681-6471.*

Clausen N.E., Pryor S.C., Larsén X.G., Hyvönen R., Venäläinen A., Suvilampi E., Kjellström E., Barthelmie R.J. (2009): Are we facing increasing extreme winds in the future? *European Wind Energy Conference and Exhibition 2009, Marseilles, March 2009, 10 pp.*

2008

Pryor S., Leung R., Koracin D., Nakafuji N. (2008): Improved Quantification of Future Changes in the Mean and Variability of Wind Climates/Resources Chapter 14 p86-92 of *U.S. Department of Energy Workshop Report: Research Needs for Wind Resource Characterization Technical Report NREL/TP-500-43521 June 2008. http://www.nrel.gov/docs/fy08osti/43521.pdf*

Leung R., Freedman J., Koracin D., Takle G. and Pryor S. (2008): Improved Quantification and Identify Causes of Historical Change and Variability of Wind Resources Chapter 13 p78-85 of *U.S. Department of Energy Workshop Report: Research Needs for Wind Resource Characterization Technical Report NREL/TP-500-43521 June 2008. http://www.nrel.gov/docs/fy08osti/43521.pdf*

Pryor S.C., Barthelmie R.J., Takle G.S. and Andersen T. (2008): The impact of climate change on wind energy resources. *Proceedings of the World Renewable Energy Congress-X, 6 pp.*

2007

Pryor S.C. (2007): Extreme precipitation over the USA: Did it change during the C20th? *Papers of the Applied Geography Conferences, volume 30, 354-361 (reviewed)*

Barthelmie R.J. and Pryor S.C. (2007): Wind speed trends over the contiguous USA. *Papers of the Applied Geography Conferences, volume 30, 344-353 (reviewed)*

Pryor S.C., Barthelmie R.J. and Riley E.S. (2007): Historical evolution of wind climates in the USA. Proceedings of *Science of making torque from wind, 8 pp, published in the Journal of Physics: Conference Series,* Vol. 75, 012065.

2.5 Presentations

Conference/workshop presentations: (presenter is underlined)

2010

Pryor S.C., Barthelmie R.J., Schoof J.T., Clausen N.E., Kjellstrom E. and Drews M. (2010): Intense and extreme wind speeds over the Nordic countries. *International meeting on Climate and Energy Systems, Oslo, May-June 2010.*

Pryor S.C., Barthelmie R.J., Schoof J.T., Claussen N.E., and Drews M. (2010): Quantifying possible changes in extreme and intense wind speeds, *American Wind Energy Conference*, Dallas, May 2010 (poster).

Pryor S.C. (2010): Assessing the vulnerability of the wind energy industry to climate extremes. *Keynote address at the International Atomic Energy Authority meeting on Vulnerability of Energy Systems to Climate Change and Extreme Events, Trieste, Italy,* April 2010.

Pryor S.C., Barthelmie R.J., Schoof J.T., Claussen N.E., and Drews M. (2010): Changes in extreme and intense wind speeds, *European Wind Energy Conference*, Warsaw, March 2010 (accepted for oral presentation).

2009

Pryor S.C., Barthelmie R.J., Clausen N.E., Nielsen N.M., Kjellström E. and Drew M. (2009): Will climate change influence extreme wind speeds? *Offshore wind and other marine renewable energies in Mediterranean and European Seas conference in Brindisi, Italy, May 2009.*

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Takle E.S., S.C. Pryor, E. Lu, T. Andersen, A. Nunes, and the NARCCAP Team (2009): Characteristics of Wind Speeds over the US from 1982-2004 as Simulated by Regional Climate Models. *AMS Conference on Climate Variability and Change. Phoenix.*

Takle E. S., D. A. Rajewski, M. Segal, R. Elmore, J. Hatfield, J. H. Prueger, and S. E. Taylor, (2009): Interaction of turbine-generated turbulence with agricultural crops: conceptual framework and preliminary results. *Presentation at American Geophysical Union Fall Meeting, San Francisco.*

2008

Pryor S.C., R.J. Barthelmie and G.S. Takle (2008): Trends in wind climates over the contiguous US: Implications for the wind energy resource. *AGU: Fall meeting, San Francisco, December 2008 (invited).*

Takle E.S., Pryor S.C., Barthelmie R.J., Rabideau S., Arritt R.W., Gutowski W.J., Flory D. and the NARCCAP team (2008): Preliminary analysis of wind speed simulations over the US produced by Regional Climate Models. *AGU: Fall meeting, San Francisco, December 2008.*

Pryor S.C., Barthelmie R.J., Takle G.S. and Andersen T. (2008): The impact of climate change on wind energy resources. *World Renewable Energy Congress-X, Glasgow, July 2008 (plenary).*

Pryor S.C. and Barthelmie R.J. (2008): Wind climate of the Midwest. *WIndiana conference ’08,* *Indianapolis, IN, June 2008 (poster).*

Barthelmie R.J., Pryor S.C. and Young D.T. (2008): Use of lidar for wind energy applications. *WIndiana conference '08, Indianapolis, IN, June 2008 (poster).*

Pryor S.C. and Barthelmie R.J. (2008): Long-term trends of wind speeds in the USA. *American Wind Energy Association Conference, Austin, Texas, June 2008.*

Pryor S.C., R.J. Barthelmie and Takle G.S. (2008): Historical trends in wind speeds from observational data, reanalysis output and Regional Climate Model simulations over the continental USA. *EGU General Assembly, Vienna, Apr 2008 (poster).*

2007

Takle E.S., Pryor S.C., Barthelmie R.J., Anderson T.K., Correia J., Flory D., Arritt R.W. and Gutowski W.J. (2007): Trends in US surface winds over the last quarter of the 20C: Observations and model results. *American Geophysical Union, San Francisco, Dec 2007.*

Barthelmie R.J. and Pryor S.C. (2007): Wind speed trends over the contiguous USA. *30th Annual Applied Geography Conference, Indianapolis, USA Oct 2007.*

Pryor S.C. and Barthelmie R.J. (2007): Wind climates over the past 30-years. *Workshop on Midwestern Climate variability, predictability and change. Bloomington, October 2007*

Pryor S.C., Barthelmie R.J. and Riley E.S. (2007): Historical evolution of wind climates in the Midwestern USA. *Science of making torque from wind. Copenhagen, Denmark, Aug. 2007.*

2.6 Other

- Pryor is contributing author to IPCC report: Contributing author to IPCC report: Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN) (Chapter 'Wind Energy') Forthcoming.
- All three PIs (Pryor, Barthelmie and Takle) were contributing authors to a set of research priorities for wind energy R&D developed from the Workshop on Wind Resource Characterization: Research needs for wind energy, sponsored by the Office of Science, Department of Energy and held in Denver Colorado in January 2008.
- Students presentations
    - Hatteberg, Rachel, 2009: Simulation of Extreme Winds by the NARCCAP Models. Iowa State University Senior Thesis. 14 pp (journal style).
    - Hatteberg, Rachel, 2009: Simulation of Extreme Winds by the NARCCAP Models. Iowa State University 15th Annual Undergraduate Atmospheric Science Symposium. (oral presentation)
    - Rabideau, Shannon L., 2009: Analysis of WRF Model Ensemble Forecast Skill for 80 m Winds over Iowa. Iowa State University Senior Thesis. 18 pp (journal style).
    - Rabideau, Shannon L., 2009: Analysis of WRF Model Ensemble Forecast Skill for 80 m Winds over Iowa. Iowa State University 15th Annual Undergraduate Atmospheric Science Symposium. (oral presentation)
    - Rabideau, Shannon, 2009: Analysis of WRF Model Ensemble Forecast Skill for 80m Winds over Iowa. IAWind Symposium, Iowa State University, April (oral and poster)
    - Deppe, Adam, 2009: Improvement of Wind Speed Forecasts Using Ensemble Means. IAWind Symposium, Iowa State University, April (oral and poster)

- Howe, J.A., 2008: Analysis of extreme precipitation across the Midwest during the twentieth century. Indiana University M.S. thesis.
- Andersen, Theresa K., 2007: Climatology of surface wind speeds using a regional climate model. Iowa State University Atmospheric Science Undergraduate Research Symposium. Iowa State University.

3 Contributions

3.1 To geographic research

We have identified a previously unknown discrepancy between in situ data and Reanalysis data sets with respect to the time variance of near-surface wind speeds. Current research is seeking to resolve causation. We have developed and applied new techniques for the quantification of extreme wind speeds under an evolving climate.

3.2 To development of human resources

The project has lead to enhanced educational opportunities for one undergraduate and four graduate students at Indiana University, and seven undergraduates, three graduate students, and two postdoctoral fellows at Iowa State University.

3.3 To development of the physical, institutional, or information resources that form the infrastructure for research and education

- We believe development of the dynamical WWW site will prove to be an exceptional information resource for the geographic community: http://php.indiana.edu/~spryor/Downscaling/overview.htm
- Additionally, we have used the collaborative opportunities afforded by this project (and #0647868) to share teaching materials related to climate change courses. SP has provided all lecture notes, assignments and computer exercises to GT and Justin Schoof (lead on #0647868) in the hopes of stimulating the production of common educational materials drawing the best from each of the three courses that are currently taught at Indiana University, Iowa State University and the University of Southern Illinois.
- This project contributed to research presented in: *Understanding climate change: Climate variability, predictability and change in the Midwestern USA*. The book is a comprehensive assessment of change over last 100 years & projections for C21st with a focus on four 'parameters'; (i) Thermal regimes, (ii) Hydrologic regimes, (iii) Flow regimes (winds and synoptic scale phenomena) (iv) Severe weather. It is a product of the MAGIC consortium (Midwest Assessment Group for Investigations of Climate) and comprises 24 chapters with 33 contributing authors from 13 Midwestern institutions.

3.4 To development of other aspects of public welfare beyond science and engineering, such as commercial technology, the economy, cost-efficient environmental protection, or solutions to social problems.

- We have already received very positive feedback from people who we invited to evaluate the dynamical WWW site developed under this project. We are confident that this site will greatly enhance the availability of our research results and expand the community of researchers who use these results.
- Our article in Journal of Geophysical Research has been featured in numerous articles in the popular press including an article in Scientific American: Moyer M. (2009): The way the wind blows, Scientific American October, 27-28.