Historical evolution of wind climates in the USA

S.C. Pryor[1], R.J. Barthelmie[2,1] and E.S. Riley[1]

[1]Atmospheric Science Program, Department of Geography, Indiana University, Bloomington, IN 47405, USA.

[2] Institute of Energy Systems, School of Engineering and Electronics, University of Edinburgh, Edinburgh, EH9 1UQ, SCOTLAND, UK

spryor@indiana.edu

Abstract. Near-surface wind speeds over the contiguous USA generally declined between 1973 and 2005. These trends are statistically robust and are not demonstrably the result of changing anemometer technology. The trends are regionally coherent – with sites in the eastern USA generally indicating declining wind speeds, while in the western states approximately equal numbers of stations exhibit positive and negative trends and a large number exhibit trends that are not statistically significant. The trends are not monotonic and at over half of sites studied embedded within the data period of 1973-2005 are periods of reverse trends. Nevertheless, the start of the data period is characterized by higher energy density than the end at the majority of stations analysed.

1. Introduction

1.1. Motivation

Identification of optimal sites for development of wind farms relies on detailed knowledge regarding the local wind climates and hence likely power production. In the context of wind energy applications, where wind farms have typical lifetimes of the order of 30 years, the question that is often asked is 'What is a normal wind year?', or alternatively stated, 'Over the lifetime of the wind farm what is the average expected energy production?' This question can be extended to: 'Will non-stationarities in the global climate system cause the definition or magnitude of a normal wind year to evolve on time scales of relevance to wind energy developments?' [1] These questions provide the motivation for the current research.

1.2. Wind energy development in the USA

The US is investing in renewable energy resources to meet national and international goals related to reducing greenhouse gas/pollutant emissions and to improve the diversity of energy portfolios and security of supply. During 2005 approximately 2500 MW of wind energy came online in the US, while in 2006 2700 MW was added to the existing capacity of approximately 10000 MW. Although almost half of the installed capacity is installed in Texas and California, here we focus primarily on the Midwestern USA due to the relatively high penetration of wind energy developments, particularly in the west of the region. Total installed capacity in these states exceeded 2000 MW (Figure 1).

1.3. Research objectives

The objectives of this research are as follows:

(i) To identify and quantify the presence of any temporal trends in wind speeds across the contiguous USA, and particularly in the Midwest, during 1973-2005.

(ii) To determine if the trends are the result of changing measurement technologies (e.g. introduction of different anemometers), local effects (e.g. local land use changes), or are the product of climate variability/change.

(iii) To determine if the trends are robust to stochastic effects within the time series.

(iv) To quantify the degree to which any changes in the wind climate have relevance for wind energy developments.

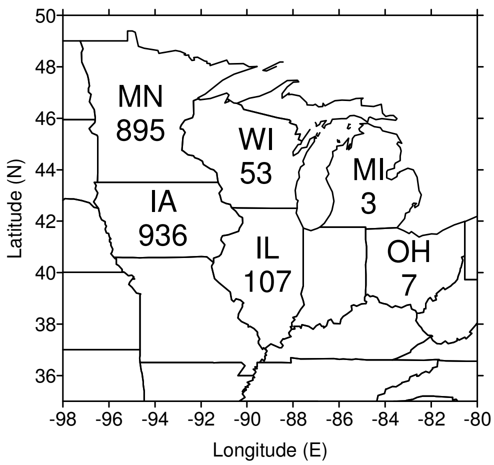

Figure 1. Installed wind energy capacity (MW) in the Midwestern USA as of December 31, 2006. Data from the American Wind Energy Association (http://www.awea.org/projects/).

2. Analysis

2.1. Data set

Hourly wind speed data analyzed herein are derived from the data archive held by the National Climate Data Center (NCDC). In addition to the raw time series of wind speeds during 1973-2005, comprehensive station histories were also obtained and used to correct the time series to a standard height of 10 m a.g.l. and exclude stations that have undergone significant relocations.

2.2. Pre-processing of the wind time series

All valid data that had NCDC data quality codes of 5 assigned (which means they passed all NCDC data quality control procedures) were selected for sites where the station histories (including anemometer height) were available and indicated the station had not moved more than 5 km over the study period. Not all wind speed data were collected at 10-m above the ground and several anemometer heights changed during the study period. Additionally, the wind speed data were truncated to the nearest knot when stored and so the following pre-processing steps were undertaken:

(i) Data were corrected to a common measurement height of 10 m based on the recorded anemometer heights and the power law wind profile and an exponent of 1/7.

(ii) Log-normally distributed random numbers were added to the time series to 'recover' the variability lost by the data truncation.

Although the data records are nominally hourly, at least in the initial part of the study period at many sites the data were actually recorded at 3-hourly intervals or only during daylight hours. Accordingly here we focus on observations from 0000 UTC and 1200 UTC. In order to obtain robust, representative time series we consider only sites where over 500 observations are present in every year of record (1973-2005) and more than 50 valid observations are available in each climatological season of each year. These data selection criteria leave 157 sites for analysis across the entire contiguous USA (Figure 2), a significant fraction of which are within the Midwestern states.

2.3. Methodology used to detect temporal trends in historical wind speeds.

The observed wind speed time series from each site were used to:

(i) Compute the 5th to 95th percentile wind speeds and energy density at each site over the entire data record (Figure 2).

(ii) Compute the annual 5th to 95th percentile wind speed at each site. These annual time series of the various wind speed percentiles were then subject to linear trend analysis based on application of ordinary least-squares regression (OLSR). In this analysis the trend is assumed to be statistically significant if the trend term (slope) in the regression of annual Xth percentile wind speed against the year of observation is different from zero at the 90% confidence level.

(iii) Compute trends using robust linear regression and boot-strapping techniques to determine if trends indicated in (ii) are robust to the stochastic effects in the time series. In brief, this involves bootstrap resampling of the residuals from the linear regression analysis of annual Xth percentile wind speed on year. These residuals are randomly selected using a bootstrapping technique and added onto the linear fit line from the trend analysis and the trend is re-estimated [2]. This procedure is repeated 1000 times to generate 1000 plausible trends for each station. If a zero trend falls within the middle 900 values in an ordered sequence of the distribution of 1000 realizations the trend is not significant at the 90% confidence level.

(iv) Compute 5-year running means of the annual percentiles and determine the year in which the largest change in the percentiles was observed. Such changes can then be considered in terms of identification of possible shifts due to introduction of new measurement technologies or protocols. Major discontinuities in measurement technique for near-surface wind speeds occurred in 1964, and with the introduction of Automated Surface Observing System (ASOS) which commenced in the early 1990s.

(v) Compute the Weibull parameters and associated energy density for the entire time series and also for the beginning and end of the record to determine if they differ. The Weibull distribution is fit using the Moments II approach which fits the distribution based on the 1st and 3rd moments and has been demonstrated to be both robust and accurate [3].

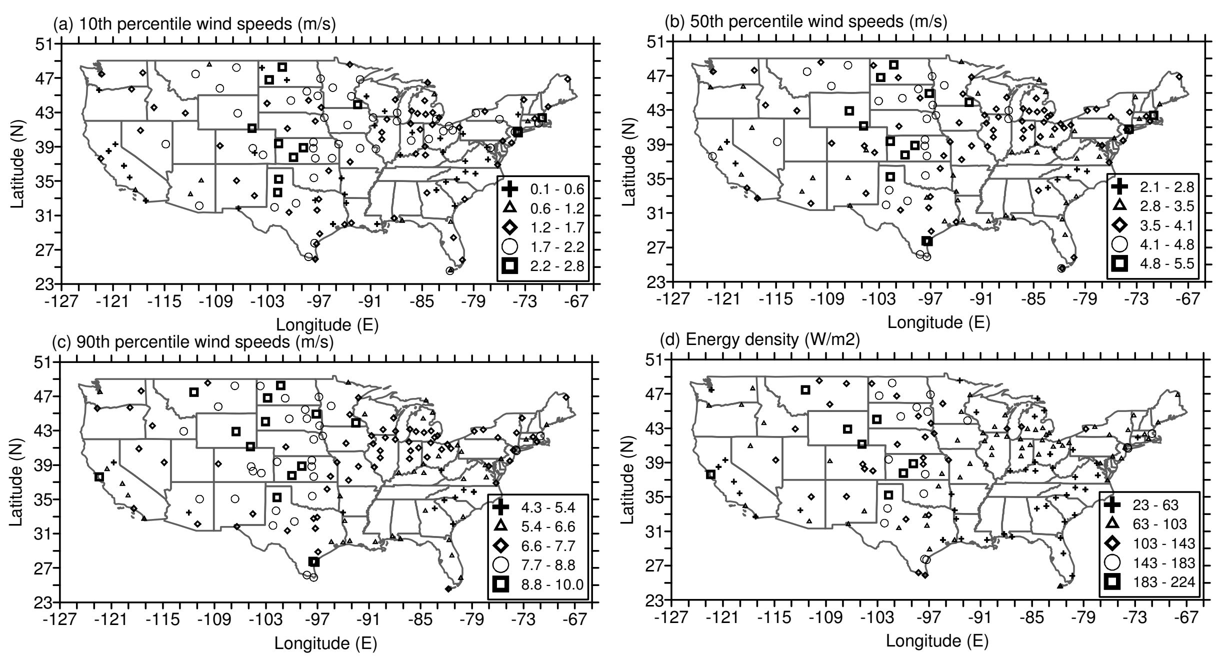

Figure 2. The (a) 10th, (b) 50th and (c) 90th percentile wind speeds (at 10 m a.g.l.) at each site along with (d) the energy density computed using data from 1973-2005.

Naturally individual sites may not be representative of the regional wind climate, but in general highest wind speeds and energy density are observed in a north-south swath extending from North Dakota/Montana to Texas (Figure 2). Highest energy densities in these regions are up to 200 W/m^2 at 10 m a.g.l.. Ninetieth percentile wind speeds in this region generally exceed 7.7 m/s. The spatial patterns and magnitudes of wind speeds and energy density show agreement with the wind resource atlas published in 1986 by the U.S. Department of Energy [4].

3. Results

3.1. Trends in wind speed percentiles: Results from application of ordinary least squares regression
Given the lower percentiles contribute relatively little to the energy density, here we focus on analysis of the 50th and 90th percentile wind speeds. The overwhelming majority of stations that exhibit statistically significant linear trends in the median and 90th percentile wind speeds, exhibit declining values over the study period (Figure 3). Of the 157 stations that pass the data selection criteria articulated above, 118 exhibit statistically significant negative trends in the annual 50th percentile wind speeds, and 105 exhibit statistically significant negative trends in 90th percentile wind speeds. Only 17 and 19 stations, respectively exhibited significant increases. Significant declines in wind speed percentiles tend to be geographically clustered in the eastern USA. Perhaps somewhat surprisingly at many sites the relative trends are larger for the 50th percentile wind speeds than the 90th percentile.

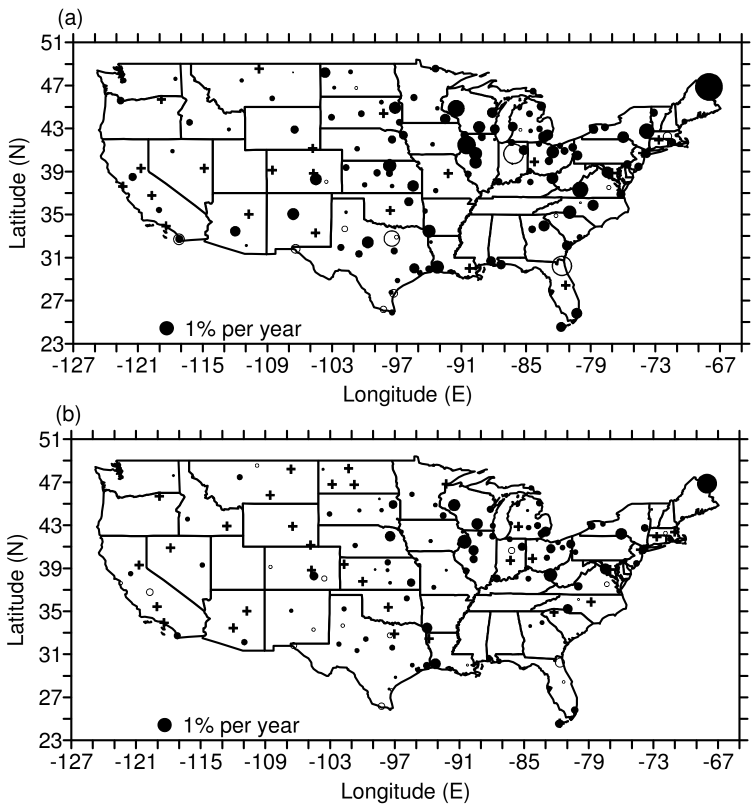

Figure 3. Linear trends in the annual 50th and 90th percentile wind speeds at each site derived using OLSR and presented as a percent change per year. If the site is denoted by an open circle the trend is significant and positive (indicating increased values through time). If the site is denoted by a filled circle the trend is significant and negative. If the station is denoted by a + then the trend is not significant at the 90% confidence level. The trends depicted are computed using data from 1973-2005 and the percentiles are computed at the annual time scale.

3.2. Trends in wind speed percentiles: How robust are the trends?

Results from application of the robust trend analysis method indicate linear trends derived using OLSR are generally robust to stochastic effects in the percentiles computed at the annual time scale (Figure 4). Of the 157 stations, data series from 111 exhibit statistically significant negative trends in the 50th percentile wind speed, and 13 exhibit significant positive trends. Similar statistics for the 90th percentile wind speed are 97 stations exhibit negative trends and 14 positive trends.

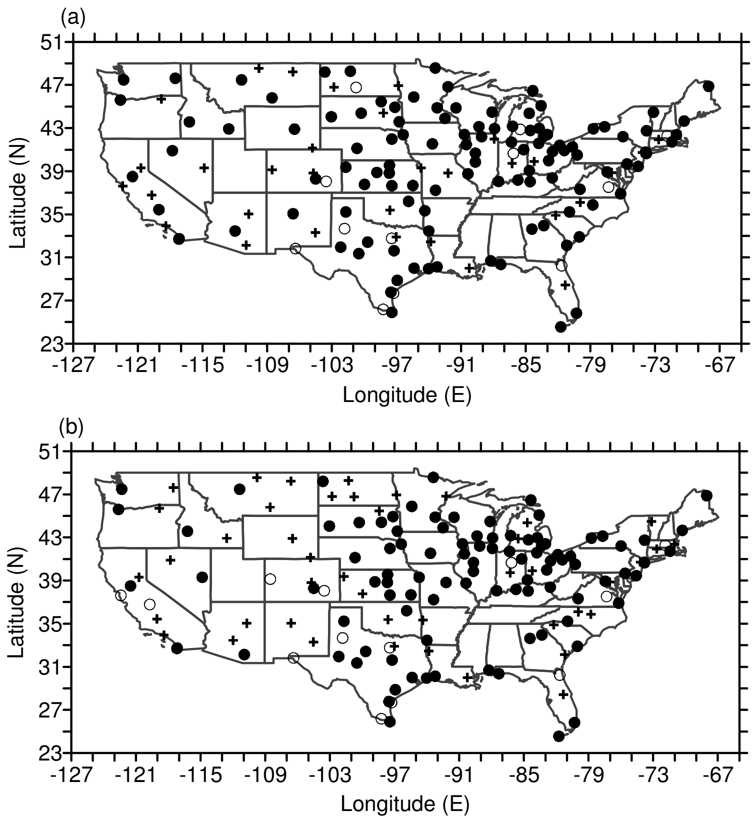

Figure 4. Linear trends in the annual 50th and 90th percentile wind speeds at each site as determined using the robust trend analysis methodology. If the site is denoted by an open circle the trend is significant and positive (indicating increased values through time). If the site is denoted by a filled circle the trend is significant and negative. If the station is denoted by a + then the trend is not significant. The trends depicted are computed using wind speed percentiles computed at the annual time scale from 1973-2005.

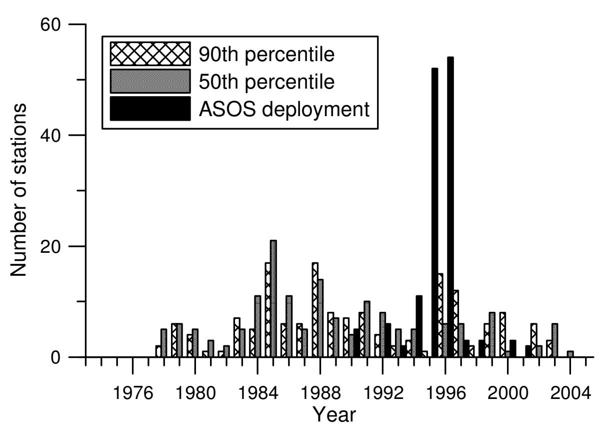

Figure 5. Year in which the largest change in a 5-year running mean of the annual 50th and 90th percentiles occurs. Also shown is the year in which ASOS systems were deployed.

Introduction of ASOS systems does not appear to have resulted in significant perturbations in the time series as manifest as inflection points in the time series of the annual percentiles (Figure 5). This result lends some credence to assertions that the temporal trends identified herein are not solely the result of instrumentation changes but may reflect climate variability or change.

Regardless of their source, temporal trends in wind speeds need not be monotonic. Analysis of short-term (decadal or longer) parts of the data series indicates that embedded within the longer records there are many examples of reverse sign trends (i.e. trends that are both statistically significant and of opposing sign to those computed using the entire data series). Short-term reverse trends are observed in the 50th percentile wind speed at a total of 79 stations in the data set of 157 sites. Sixty-one stations that overall exhibit declining trends, also have statistically significant positive trends over a component of the time series of greater or equal to one decade in duration. Eighteen have overall increases but sub-components of the time series exhibit significant decreasing trends. Similar statistics for the 90th percentile wind speeds are 37 reverse trends are observed at sites with overall negative trends, and 12 are observed at sites that overall exhibit a tendency towards increased wind speeds (Figure 6).

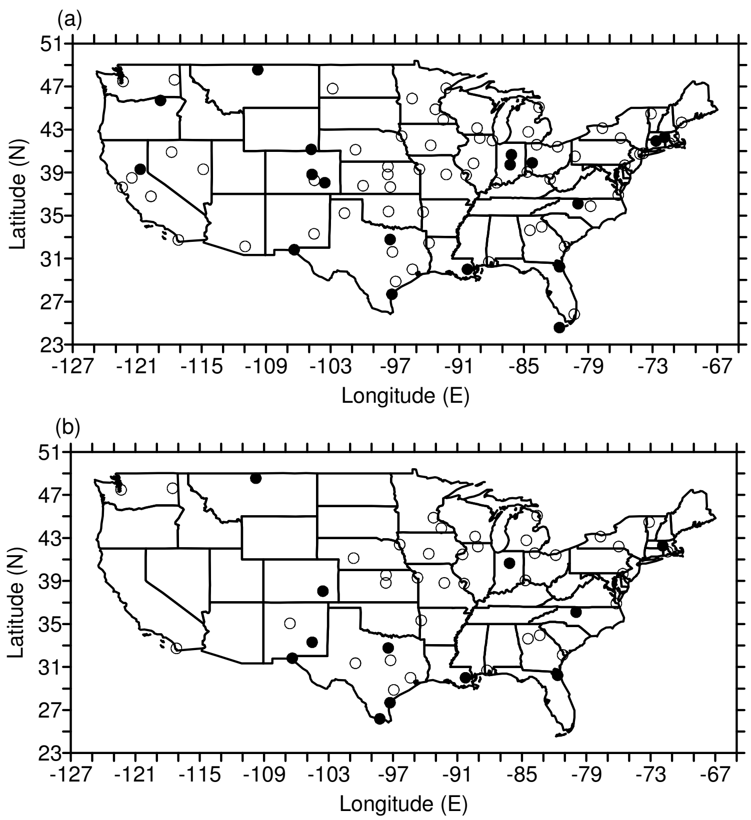

Figure 6. Analyses of trend reversals. If the long term trend in (a) the 50th percentile or (b) 90th percentile wind speed is negative but a short term trend (10 years or more) is statistically significant and positive, the circle is open. If the long term trend in (a) the 50th percentile or (b) 90th percentile wind speed is positive but a short term trend (10 years or more) is statistically significant and negative, the circle is closed. If no reverse trends that are statistically significant are found at a site no symbol is shown.

3.3. Do the temporal trends have relevance for wind energy development?

In contrast to much of Europe, electricity demand in the USA generally exhibits two maxima of almost equal magnitude – one in summer (JJA) and one in winter (DJF) (Figure 7).

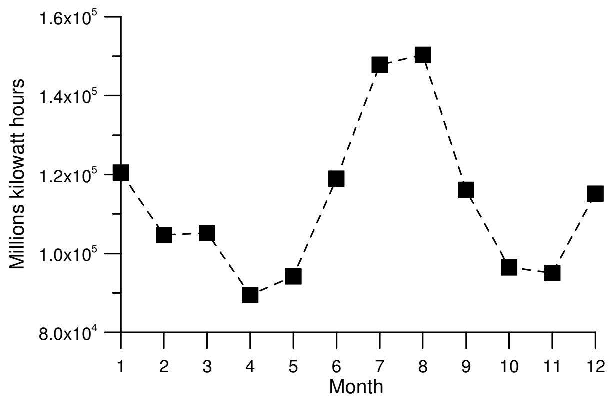

Figure 7. US electricity sales during 2006. Data from http://www.eia.doe.gov/cneaf/electricity/epm.

One metric of how closely the wind power potential couples seasonally to that demand is shown in Figure 8 which depicts the season in which the highest fraction of observations exceeds the 90th percentile wind speed computed over the entire data set. As shown, generally the highest proportion of large magnitude wind speeds are observed during winter in the eastern USA (including the Midwest), indicating coupling between one metric of potential wind production and demand at the seasonal timescale, while sites in the western USA exhibit a spring maximum in the frequency of wind speeds above the 90th percentile value.

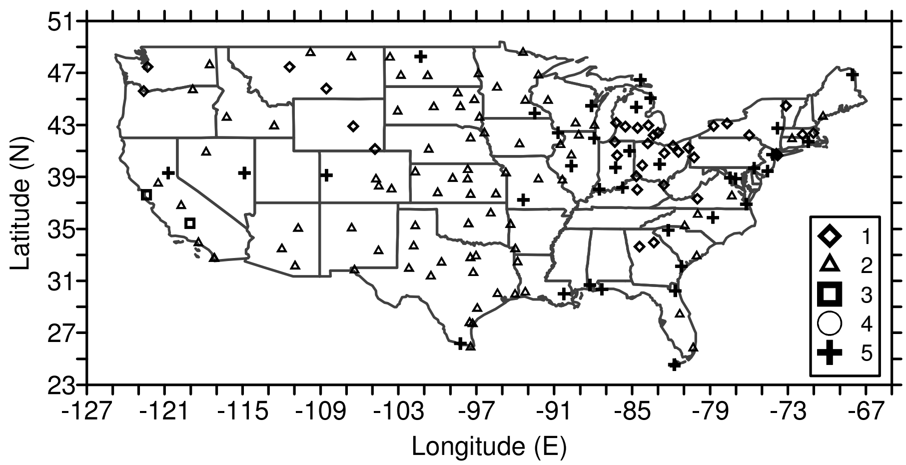

Figure 8. Seasonality in the contribution of a given season to the values in excess of the 90th percentile computed at each site. A value of 1 indicates the winter season dominates, 2 = spring, 3 = summer, 4 = autumn and 5 indicates two or more seasons exhibit almost equal contributions.

The decline in wind speeds across much of the contiguous USA between 1973 and 2005 is manifest as lower average wind energy density at the end of the record (1991-2005, inclusive), than at the beginning (between 1973-1987) (Figure 9). In the Midwest, and particularly the state of Illinois, some sites indicate energy densities that are over 30% lower in the last 15 years of the data record than at the beginning.

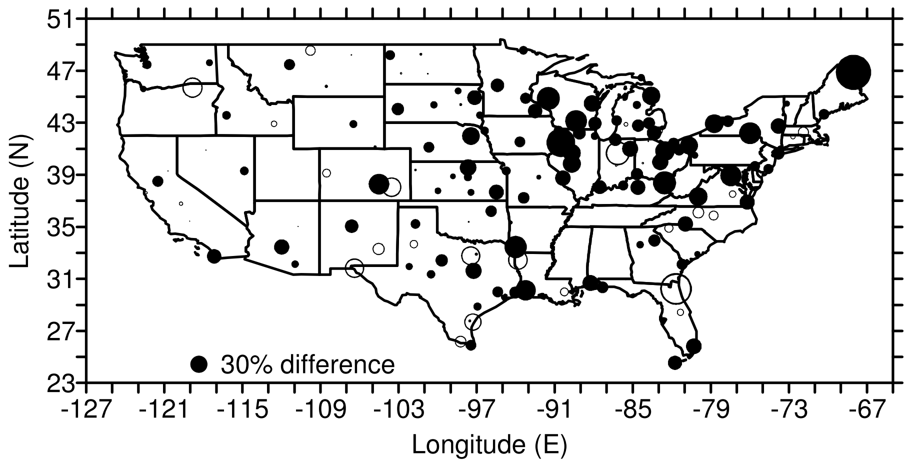

Figure 9. Percent difference in energy density computed using data from 1973-1987 and 1991-2005. If the site is denoted by an open circle the energy density is higher in the latter period, if the site is denoted by a filled circle the energy density is lower in the latter period.

4. Summary

Measured wind speed time series from the National Climate Data Centre archive are analyzed to evaluate whether there are temporal trends present in the data and whether those trends are due to instrumentation changes undertaken principally during the 1990's or to physical causes. Finding no evidence for the former implies that trends in the site wind speeds are synoptically driven, particularly given their regional coherence. In much of the USA, particularly the eastern states, there has been a negative trend in wind speeds over the past thirty years. While there are generally also sub-periods (decades or longer) with increasing wind speeds, the negative trend is robust. The negative trends in wind speeds are manifest in lower energy density at the end of the data period (1991 to 2005, inclusive) than at the beginning (1973-1987). There is also a strong regional grouping in the seasonality of highest wind speeds – with a winter maximum over the eastern US and spring/summer dominating in the western US. These regional variations have implications for the integration of increasing amounts of wind energy into the electricity grid. At this point it is not possible to assert whether the decline in wind speeds over the eastern USA over the period 1973 to 2005 will be continued in the future of whether it is part of a multi-decadal cycle of variability. Nevertheless, given the magnitude of the trends further research is warranted.

5. Acknowledgments

Support from NSF Geography & Regional Science (grant # 0618364) and Nordic Energy Research project Climate and Energy Systems; Risks, Potential, Adaptation is gratefully acknowledged.

References

1. Pryor, S.C., J.T. Schoof, and R.J. Barthelmie, *Climate change impacts on wind speeds and wind energy density in northern Europe: Results from empirical downscaling of multiple AOGCMs.* Climate Research, 2005. **29**: p. 183-198.
2. Kiktev, D., et al., *Comparison of modeled and observed trends in indices of daily climate extremes.* Journal of Climate, 2003. **16**: p. 3560-3571.
3. Pryor, S.C., et al., *Can satellite sampling of offshore wind speeds realistically represent wind speed distributions? Part II: Quantifying uncertainties associated with sampling strategy and distribution fitting methods.* Journal of Applied Meteorology, 2004. **43**: p. 739-750.
4. Elliott, D.L., et al., *Wind Energy Resource Atlas of the United States*, Available from AWEA, Washington DC 20002). http://rredc.nrel.gov/wind/pubs/atlas/. 1986, Solar Technical Information Program. U.S. Department of Energy: Washington, D.C. 210pp.