ENSO's Effect on the Wind Energy Production Of South Dakota

Bret Harper

Academic Affiliation, Fall 2005: Graduate Student, University of California at Berkeley

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Science Research Mentor: Robert Harriss
Writing and Communication Mentor: David Gochis

ABSTRACT

An aging infrastructure, environmental concerns, and growing demand threaten to undermine the reliability and long-term sustainability of the current fossil fuel electricity supply and transmission system. It is widely agreed that renewable energy sources will become increasingly important in the evolution to a next-generation electric grid. In this study we investigated the use and value of climate information in determining the location and performance of wind power turbines in the Northern Great Plains of the United States. Fifty years of hourly wind speed data were used to evaluate the possible influence of seasonal and interannual climate variability on wind power production at four locations in South Dakota. The El Nino Southern Oscillation (ENSO) is a documented source of climate variability in the Northern Great Plains. Our results documented a dominant El Nino/La Nina influence on the probability of lull in wind speeds, with the stronger influence in the eastern half of the state. Information on wind speed lulls is important to the wind energy industry because these are periods when no energy is being produced All of the locations also showed a slight decrease in power production potential during El Nino events. Our preliminary results confirmed that information on climate variability and change can be of significant use and value to future wind power planning, siting, and performance.

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1. Introduction

a. Background and Motivation

The design and implementation of a next-generation electricity supply system is essential to America's economy and security (Geller 2003). An aging infrastructure, environmental concerns, and growing demand threaten to undermine the reliability and long-term sustainability of the current electricity supply and transmission system. There are numerous competing visions and potential pathways for the design of a next-generation system; the fuel supply options range from nuclear to clean coal, to renewable resources such as wind, solar, and biomass. Options for the infrastructure range from highly distributed local generation to an enhanced centralized system similar to the current electric grid.

An electric utility must provide a reliable and continuous source of electricity to its customers. Due to wind energy's intermittent nature, it has been restricted to supplementing a small portion of the total U.S. energy demand, today only 0.4% (EIA 2005). Nevertheless, wind energy has lately demonstrated environmental and economic benefits as an energy resource and is growing in significance as a component of the US electric supply system (IEA 2005). As wind energy continues to capture a larger percentage of the U.S. energy market, the forecasting and understanding of wind characteristics in time and space must also become more reliable in order for the wind industry be effective and competitive.

In this investigation, we examine the consequences of temporal and spatial variations in the wind resource of the Northern Great Plains for electricity supply planning and design. Wind resource variability and limited capabilities for onsite energy storage currently present significant challenges to large-scale applications in a traditional electricity grid. The research questions we address here are:

(1) Are there systematic characteristics in the long-term climatology of the wind resource that are relevant to power system planning and operations?
(2) Does the EL Nino Southern Oscillation (ENSO) have an effect on inter-annual variations in wind characteristics in the Northern Great Plains?
(3) Could improved climate observations and data and information be a valuable asset to future electric grid arrangement and operations?

b. Estimating Wind Power

The worldwide use of wind turbine generators continues to increase in utility-scale applications, and issues related to the site specific dependability and economics of these intermittent resources are crucial to utility planning. Although modern wind turbines have long lifetimes, the site planning data used to estimate potential energy production is often based on only 12 months of data (Bergen 2005). This limited understanding of wind climatology could cause energy production potential to be inaccurate if the single year measured happens to have stronger or weaker than long-term winds.

Accurate wind climatology is important to the wind energy industry because the power generated by a wind turbine rotor is:

$$P = 0.5 * \rho * A * V^3 \quad (1)$$

Where:
P = power in watts
ρ = air density (about 1.225 kg/m^3 at sea level)
A = rotor swept area, exposed to the wind (m^2)
V = wind speed in meter/sec

Therefore, the power in a free flowing stream of wind is directly related to the cube of the wind speed[1]. If wind speed measurements used for locating turbines are limited or inaccurate, the resulting power over the lifetime of the wind farm will likely differ from the expected performance goals. There are obviously financial and grid management consequences if a site does not produce as much energy as expected.

c. Is El Nino a Source of Variability in Winds of the Northern Great Plains?

The El Nino Southern Oscillation (ENSO) is a known source of climate variability in the Northern Great Plains *(*Nash 2002). This study explores the potential role of El Nino as a source of seasonal to inter-annual variability in the winds at four sites. Our study sites were selected on the basis of identified influences of El Nino on precipitation and temperature. Enloe et al. (2004) have previously documented ENSO impacts on extreme winds over the U.S. These authors, however, did not have sufficient data to draw any conclusions about the impacts of ENSO on wind energy generation. Our study focused on the influence of ENSO on high or low wind frequencies.

d. The Northern Great Plains study region

The Northern Great Plains ranks first among regions in wind energy potential, as the source of 58% of the United States' onshore wind resources (AWEA, 1991). More than one-fifth of America's possible wind resource is located in North and South Dakota[2]. Therefore, the Northern Great Plains area is ideally positioned to become a national center in the design and prototyping of integrated renewable energy systems because of its excellent wind resource.

The process for determining ENSO months for the period 1950 – 2000 is described in section 2 while the wind speed data set is described in section 3. Various

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[1] In practice, P is roughly proportional the square of the wind speed. Each turbine also has a threshold below/above which P = 0. Practice is limited my the mechanical limitations of the turbine rather than physics of converting wind energy into electricity.

[2] The remaining 38% of the United States onshore wind resource is located in Minnesota, Iowa, Nebraska, Wyoming, and Montana.

methods of identifying a signal between the ENSO cycle and wind speed are explained in section 4, including whether there are any trends in the parameters. Section 5 consists of a discussion.

2. Data

Hourly wind speed data were obtained from the TD6421 Enhanced Hourly Wind Station Data for the Contiguous United States dataset developed by the National Climatic Data Center. The wind speed data is taken at the original anemometer height in m sec^{-1} x 10 (NCDC 2001). The data represent observations from four airport anemometers located at Huron Regional Airport (44.38, -98.22), Pierre Municipal Airport (44.38, -100.28), Ellsworth Air Force Base (44.15, -103.10), and Rapid City Airport (44.05, -103.07). These sites were selected to examine wind characteristics along an east-west transect across South Dakota. All four of the stations have some missing data (Table 1), but are relatively complete in their record. The data before 1957 and after 1998 from the Ellsworth station was not used in our analysis due to step functions identified in the data that may indicate a change in the station surroundings or the physical movement of the station. The station at Rapid City did not have data available before November 1950. Our study was constrained by the ENSO index data we used, which spanned the period from January 1950 – December 1999 (Trenberth 1997). Altogether 1,745,850 hours of wind speed data were analyzed.

Table 1.

Station Location	Completeness	Dates Used
Ellsworth AFB	99.3%	1 January 1957 – 29 December 1998
Huron RA	89.0%	1 January 1950 – 31 December 1999
Pierre MA	89.0%	1 January 1950 – 31 December 1999
Rapid City Airport	77.5%	1 November 1950 – 31 December 1999

The classification of ENSO events followed in the present study is defined by the National Oceanic and Atmospheric Administration's (NOAA) Multivariate ENSO Index (MEI). The MEI Sea Surface Temperature (SST) index defines phases of ENSO based on the main observed variables over the tropical Pacific. These surface marine observations have been collected and published in the Comprehensive Ocean-Atmosphere Data Set (COADS) for many years. The MEI can be understood as a weighted average of the main ENSO features contained in the following six variables: sea-level pressure, the east-west and north-south components of the surface wind, SST, surface air temperature, and total amount of cloudiness (NOAA-CIRES 2005). Extremes in ENSO typically develop during summer, climax in the fall, and subside the following spring. The periods of ENSO events used in this study are summarized in Table 2.

TABLE 2.
Listings of El Nino and La Nina events after 1950 as defined by SST's in the Nino 3.4 region and exceeding ± 0.4^0C threshold. The starting and ending month of each is given with the duration in months.

El Nino events			La Nina events		
Begin	End	Duration	Begin	End	Duration
Aug-51	Feb-52	7	Mar-50	Feb-51	12
Mar-53	Nov-53	9	Jun-54	Mar-56	22
Apr-57	Jan-58	15	May-56	Nov-56	7
Jun-63	Feb-64	9	May-64	Jan-65	9
May-65	Jun-66	14	Jul-70	Jan-72	19
Sep-68	Mar-70	19	Jun-73	Jun-74	13
Apr-72	Mar-73	12	Sep-74	Apr-76	20
Aug-76	Mar-77	8	Sep-84	Jun-85	10
Jul-77	Jan-78	7	May-88	Jun-89	14
Oct-79	Apr-80	7	Sep-95	Mar-96	7
Apr-82	Jul-83	16	Jul-98	Dec-99	18
Aug-86	Feb-88	19			
Mar-91	Jul-92	17			
Feb-93	Sep-93	8			
Jun-94	Mar-95	10			
Apr-97	Apr-98	13			

3. Methodology

The main tool used to analyze the data set was the R Project for Statistical Computing. R is a language and environment for statistical computing and graphics. It is a GNU project which is similar to the S language and environment which was developed at Bell Laboratories by John Chambers and colleagues. R can be considered as a different implementation of commercially available S language. There are some important differences, but much code written for S runs unaltered under R.

The first step in our methodology involved checking for a qualitative relationship between ENSO and wind speeds. This was done by quickly boxploting all of the data for a particular month to spot long term trends over the last half century[3]. Since we were primarily interested in the effect of ENSO we plotted all of the Novembers because El Nino tends to peak in November and may therefore be reasonably guessed to have the biggest effect during this month. By superimposing the MEI index on the plot of statistical data for every November we were quickly able to identify possible relationships between the ENSO phase and the resulting median wind speed. Since an association did appear to exist we next performed a more quantitative analysis.

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[3] A boxplot is a graph summarizing the distribution of a set of data values. The upper and lower ends of the center box indicate the 75th and 25th percentiles of the data; the center box indicates the median. Suspected outliers appear in a boxplot as individual points o outside the box. The o outlier values are known as outside values.

The quantitative analysis involved classifying each hour of data according to ENSO phase (Table 2). For the 49 yr of data, from 1 January 1950 to 31 December 1999, there are 16 warm phases, 27 neutral phases, and 11 cold phases. After categorizing each hour according to ENSO phase, boxplots were constructed for the combined El Nino, La Nina, and neutral data. We also produced annual and daily trends using boxplots to display the median wind speed and inner-quartile range for each station. This showed us the distribution of the normal seasonal and diurnal wind speed cycles. We were then able to divide the data along the three phases of ENSO and made the same plots for each phase on both the hourly and monthly time scales. Any differences between the cold, neutral, and warm phase plots could be related to ENSO. ENSO, however, is an inter-annual climate factor and has been shown to have most of its effects on time scales smaller than one year.

In order to assess the importance of our findings to the wind energy industry, we next converted our results from wind speed to power using a power curve for a typical utility scale turbine. Utility scale turbines have a hub height of around 80 m and therefore typically experience higher wind speeds than those at the height where weather data are recorded. An approach commonly used to extrapolate 10 m wind speed data to 80 m is the power-law relation (Elliott et al. 1986; Arya 1988) [available at rredc.nrel.gov/wind/pubs/atlas],

$$V(z) = V_R\left(\tfrac{z}{z_R}\right)^{\alpha} \qquad (2)$$

where V(z) is wind speed at elevation z above the topographical surface (80 m in this case, i.e., V(80))), V_R is wind speed at the reference elevation z_R (10 m above the topographical surface in the rest of this paper), and α (typically 1/7) is the friction coefficient (Archer and Jacobson 2003).

Once the wind speed was corrected we used a power curve for a typical utility scale turbine to calculate the power produced from the 80 m wind speed. This is because of the earlier mentioned non-linearity of wind power production. In this study we used a power curve for the NORDEX N60 1.3-MW turbine approximated by a 4th order equation:

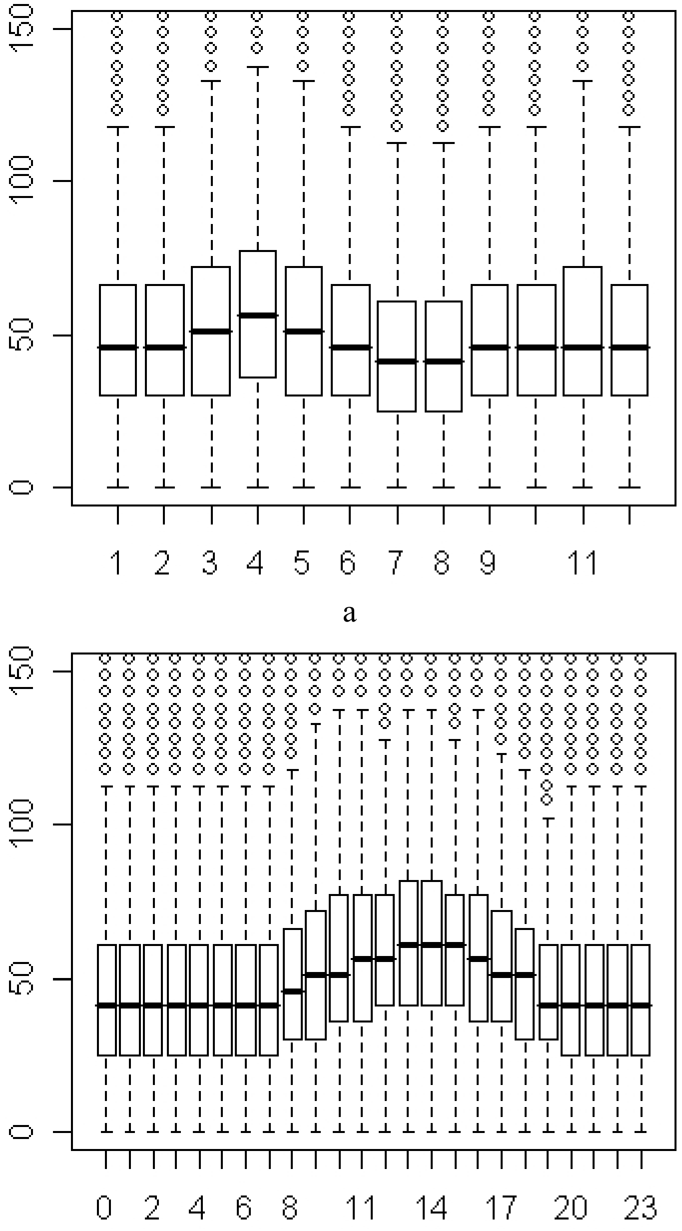
$$P = 0.0649s^4 - 3.8773s^3 + 74.418s^2 - 429.14s + 785.06 \qquad (3)$$

where P is the power in kW and s is the speed of the wind between 4 m s^{-1} and 26 m s^{-1} because most utility scale turbines only produce power within this range. After estimating power production from the wind speed data, we constructed plots similar to those previously discussed to compare both ENSO phases against the neutral phase. We plotted the mean power production to most easily observe the differences between phases.

Finally, we also looked at how many low wind events occurred during each ENSO and neutral phase. A low wind event was defined as one that goes under a threshold of 4 m/sec^{-1} (8.95 mph), at a height of 10 m. This wind speed corresponds to a wind speed of 5.4 m s^{-1} at 80 m, which produces a nominal power output of 81.2 kW. The probability of a low wind event occurring for any specified hour was calculated and plotted by month and phase.

4. Results

For the four sites analyzed during this study, the largest variations in wind speed occurred on both an annual and diurnal cycle. The most reliable high winds normally occur in April, whereas average wind speeds are the lowest in July (Figure 1a). The strongest daily winds typically peak during the warmest part of the day (1 – 3 pm), while the weakest winds are characteristically consistent during the coldest part of the day (8 pm – 7 am) (Figure 1b). These cycles are the dominant source of variability in wind speeds. ENSO's effect, however, does have some discernable signals that should be considered in wind power planning.



a

b

Figure 1: Boxplots summarizing the typical median wind speed and variability for a) the annual and b) daily time scales at Huron station. The other stations showed a similar cycle.

a. La Nina impacts

The qualitative analysis using data from November immediately suggested that a relationship with La Ninas were associated with more frequent occurrence of higher median wind speeds (Figure 2). A more detailed analysis indicated that over most of the year and the majority of the state, La Nina is also associated with a lower probability of a low wind event (Figure 3). The strongest, most persistent signals for low wind conditions associated with La Nina occurs in our eastern South Dakota stations (Huron and Pierre). The Rapid City site in western South Dakota exhibits a cold phase signal during the period from April through June. However, at the Ellsworth station the effect of La Nina is not as evident.

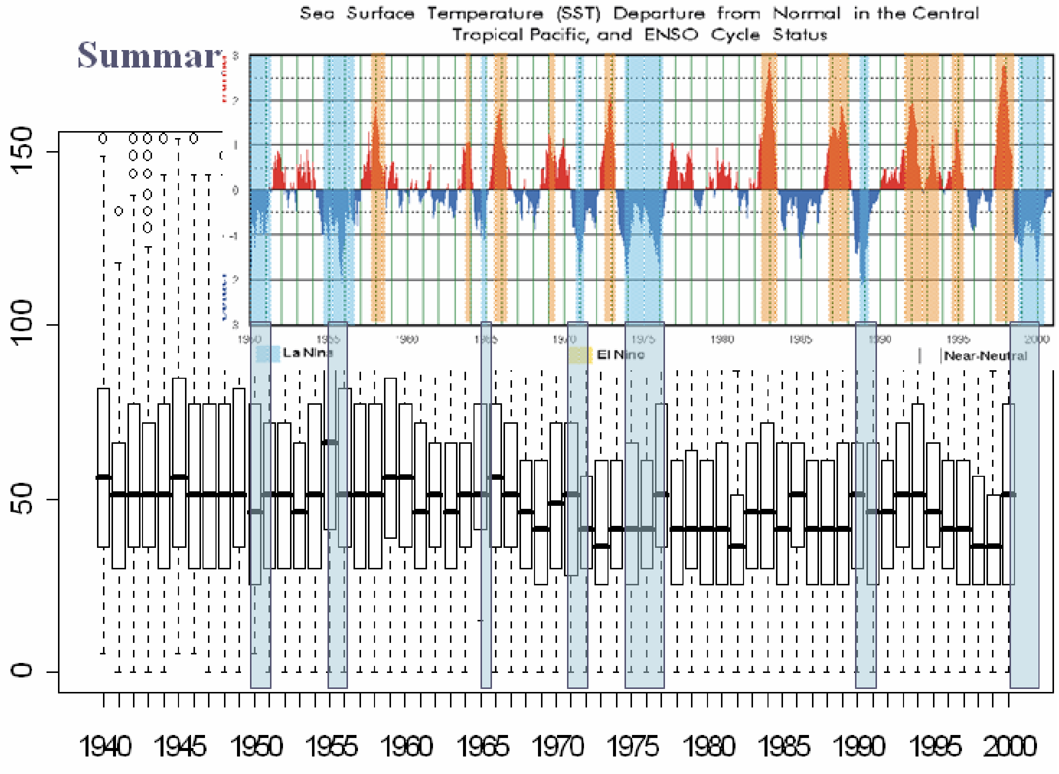


Figure 2: Qualitative analysis of consecutive Novembers wind speeds at Huron station. Note the high median wind speeds during La Nina conditions.

The observed statistical differences associated with La Nina are characterized by larger magnitude differences in the monthly probability of low wind events than are observed during El Nino, particularly during the summer months. During an average, neutral August, Huron experiences an hourly median wind speed of 4.1 m s^{-1}, compared to a La Nina August median wind speed in Huron of 4.6 m s^{-1}, a 10.9% difference.

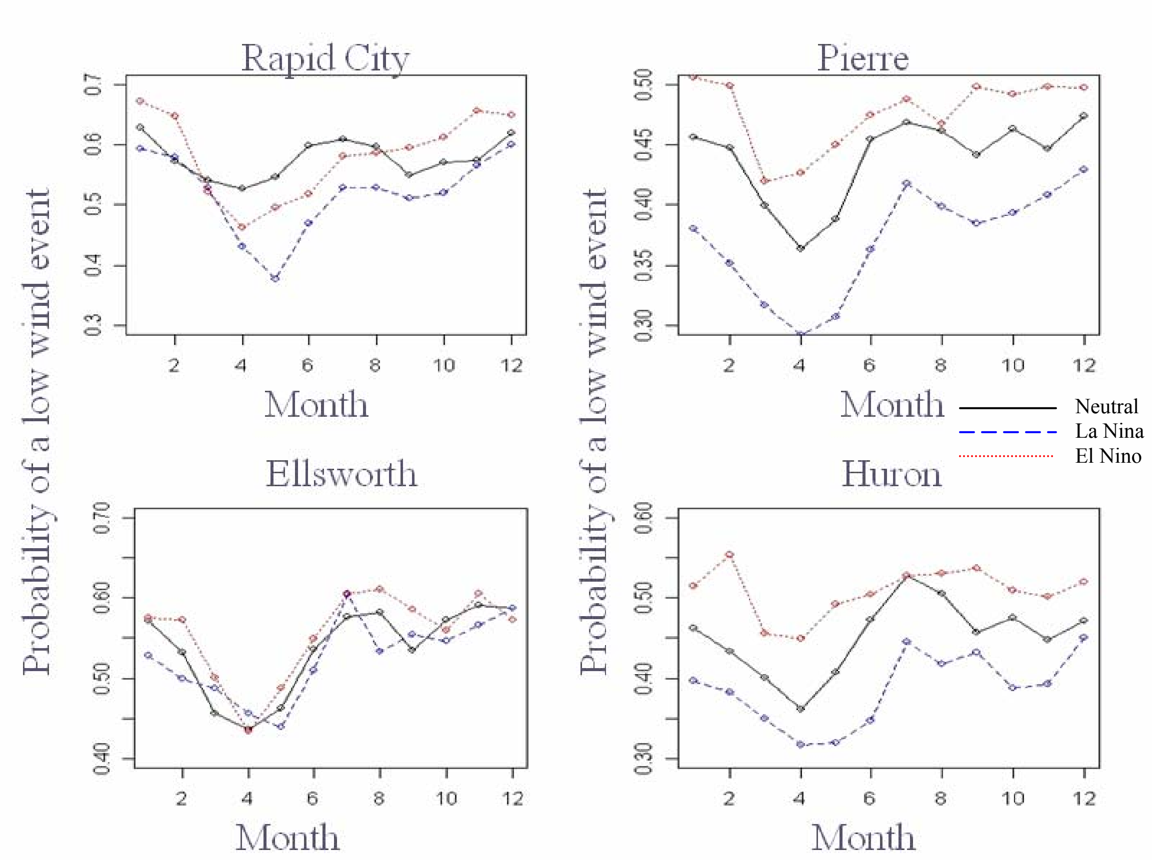


Figure 3: The probability of a low wind event per month separated by ENSO phase for each to the four stations. The solid black line indicates the neutral phase, the dashed blue line represents the La Nina phase, the dotted red line shows the El Nino phase.

b. El Nino impact

The observed patterns in wind speeds associated with El Nino are not always as definitive as those observed during the La Nina. In eastern South Dakota, El Nino periods are associated with a higher probability of low wind events than neutral or La Nina periods (Figure 3). As in La Nina, this general effect is persistent throughout all seasons, with the exception of the July-August summer, when there is decrease in the effect. Significant differences in the probability of low wind events are not observed in western South Dakota, there is a general reduction in wind power over the entire state of South Dakota during El Nino, on daily time scale (Figure 4).

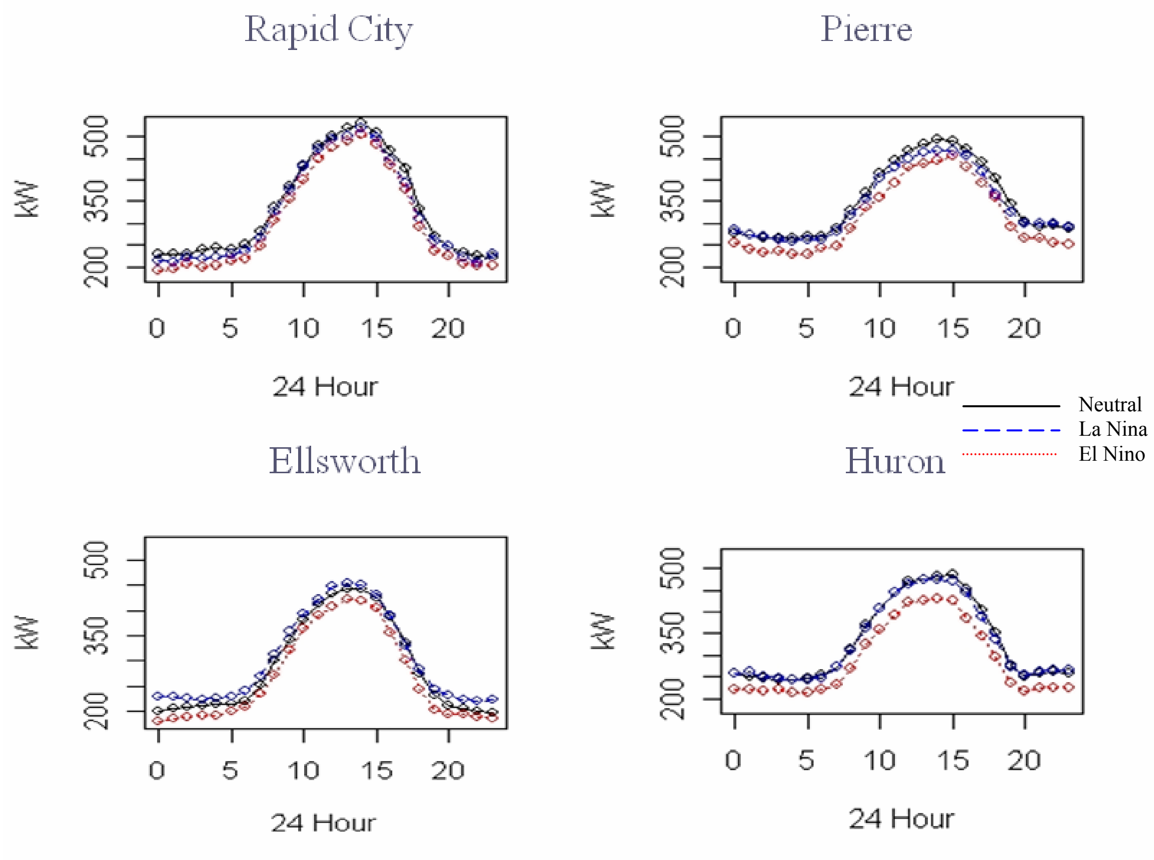


Figure 4: Wind power production per hour separated by ENSO phase for each of the four stations. The solid black line indicates the neutral phase, the dashed blue line represents the La Nina phase, the dotted red line shows the El Nino phase.

One persistent El Nino signal, though weak, is observed in the monthly plots of wind power production (Figure 5). From the beginning of the year (January) through the peak (April), a general weak reduction in the monthly mean peak wind power spans most of the state.

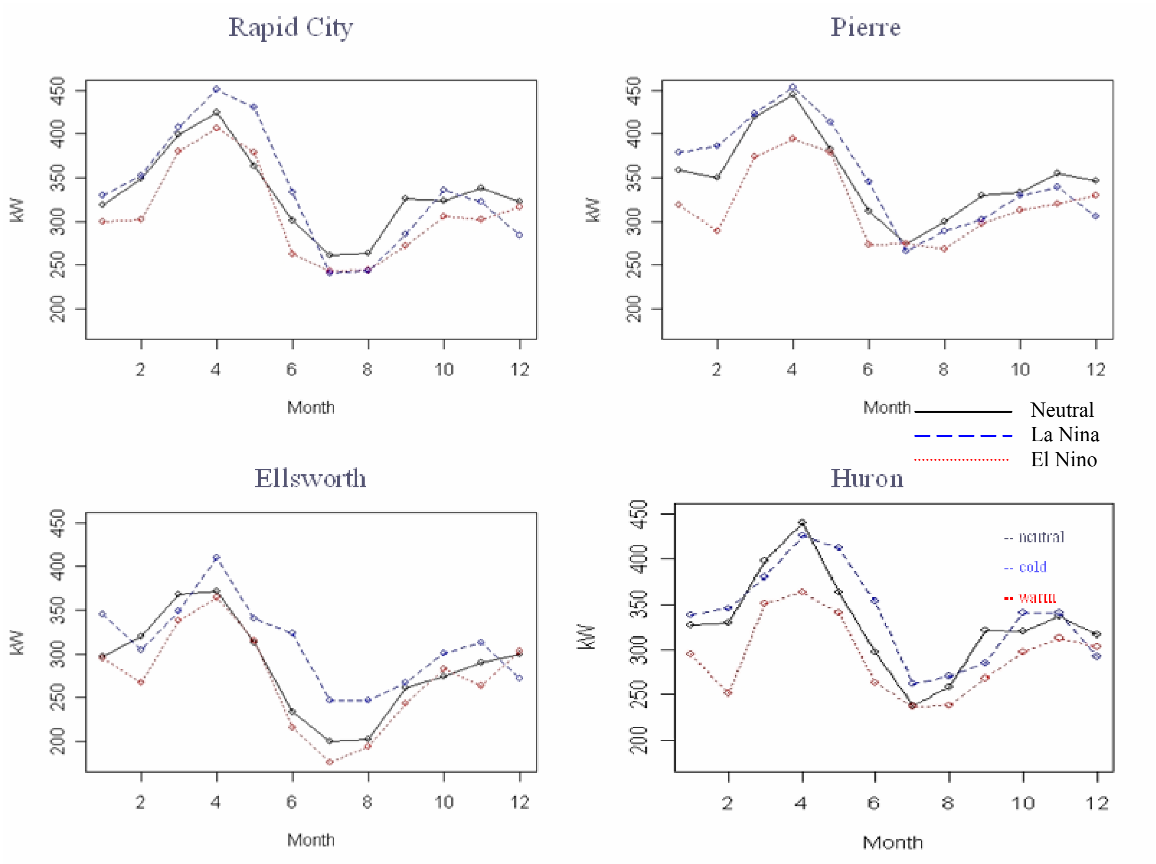


Figure 5: Mean wind power production per month separated by ENSO phase for all four stations. The solid black line indicates the neutral phase, the dashed blue line represents the La Nina phase, the dotted red line shows the El Nino phase.

5. Discussion

The annual and diurnal wind cycles on the Northern Great Plains are well known to the wind industry. Although ENSO's effect on wind speed is smaller in magnitude, it remains an important consideration because of the exponential relation ship between wind speed and power. This means that the potential power is very sensitive to wind speeds. If a wind prospector were to overestimate a wind resource by 10% the expected energy output could be off by as much as 25%.

The apparent ENSO signal in the eastern half of the state may not have been as evident in the western half for a number of reasons. First, because of the limited number of stations used in this study, it is difficult to discern whether the discrepancy is a local effect or indicative of the entire region. The Ellsworth and Rapid City stations are only about 15 miles apart, so they may be subject to the same geographical effects. Rapid City and Ellsworth are located at the base of the only mountains in the state, the Black Hills (7,242 ft). The Black Hills could be modifying local and regional winds. The data from the Ellsworth station also showed suspicious step functions in wind speed statistics in 1957 and 1998. This often indicates either the environment around the weather station changed or the station was physically moved to a new location. Wind measurements are very responsive to the roughness of the surface upwind of an anemometer. No documentation of such an occurrence could be found.

a. Testing the significance of ENSO impacts on wind speeds

In addition to the importance of accurate wind speed measurements, it is also useful to consider that the ENSO index is a continuum rather a discrete 3 phase index. This sometimes causes El Nino phases of different intensity to behave very differently from each other (Philander 2004). This study used a threshold of ± 0.4°C as the distinction between the three phases of ENSO. While it appears a relationship exists between ENSO and wind, it is important to understand the significance of the results presented here. A randomization of the ENSO phases was performed to explore the importance of the results. When these random ENSO events were plotted in same way as before, we found they did not produce the separation observed in some of the results. Although a more thorough analysis is necessary to determine the appropriate confidence intervals, we believe that the results are reflective of a real effect.

6. Conclusions

The wind power resource in South Dakota was variable at inter-annual time scales, in part at least, due to forcing associated with ENSO conditions. Shifts in the distribution of wind speed were identified in association with the El Nino and La Nina phases of ENSO. Monthly mean wind speeds, were also found to generally decrease during the El Nino phase. Other systematic characteristics in the long-term climatology of the wind resource that are relevant to power system planning and operations were found. Significant shifts occurred in the probability of a low wind event in eastern South Dakota. La Nina noticeably decreased the probability of a low wind event while El Nino increased it. Improved climate observations, data, and information could be a valuable asset to future electric grid arrangement and operations. Physical mechanisms connecting wind speeds in South Dakota to ENSO may be related to a storms direction and/or frequency; however, this connection must await further analysis.

Table 3: A summary table of El Nino and La Nina's impacts on wind in the Northern Great Plains.

ENSO condition	Impacts on Wind Power in Eastern South Dakota
El Nino	• Higher probability of low wind events • General decrease in monthly mean wind speeds
La Nina	• Lower probability of a low wind event • Higher mean wind speeds

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