

Atmospheric Circulation Effects on Wind Speed Variability at Turbine Height

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ABSTRACT

Mean monthly wind speed at 70 m above ground level is investigated for 11 sites in Minnesota for the period 1995–2003. Wind speeds at these sites show significant spatial and temporal coherence, with prolonged periods of above- and below-normal values that can persist for as long as 12 months. Monthly variation in wind speed primarily is determined by the north–south pressure gradient, which captures between 22% and 47% of the variability (depending on the site). Regression on wind speed residuals (pressure gradient effects removed) shows that an additional 6%–15% of the variation can be related to the Arctic Oscillation (AO) and Niño-3.4 sea surface temperature (SST) anomalies. Wind speeds showed little correspondence with variation in the Pacific–North American (PNA) circulation index. The effect of the strong El Niño of 1997/98 on the wind speed time series was investigated by recomputing the regression equations with this period excluded. The north–south pressure gradient remains the primary determinant of mean monthly 70-m wind speeds, but with 1997/98 removed the influence of the AO increases at nearly all stations while the importance of the Niño-3.4 SSTs generally decreases. Relationships with the PNA remain small. These results suggest that long-term patterns of low-frequency wind speed (and thus wind power) variability can be estimated using large-scale circulation features as represented by large-scale climatic datasets and by climate-change models.

1. Introduction

Wind power generation has increased significantly within the United States, but a number of difficulties, both real and perceived, limit the willingness of power companies to integrate significant amounts of wind power into their energy generation matrix. One of these difficulties is wind speed variability. Of primary importance for power companies is the ability to satisfy electrical needs with the most reliable and efficient mix of generation sources (e.g., Parsons et al. 2004; Saylor 2005; Zavadil and Ahlstrom 2005). Power companies must provide electricity on demand, and when winds fail, production from other sources must be available to make up the difference.

The mean seasonal and diurnal variability of wind is well known (Elliott et al. 1986; Klink 1999; Archer and Jacobson 2003; Nørgård et al. 2004), and wind speed reliably can be forecast for hours to days in advance

(Watson et al. 1994; Landberg et al. 2003; Torres et al. 2005; Westrick et al. 2005). One aspect of wind variability that we know little about, however, is how and why wind speeds vary from one year to the next. Information on this kind of low-frequency variability is important for anticipating long-term power (as well as revenue) generation from wind turbines (D. Moon and R. Miller 2005, unpublished manuscript; Westrick et al. 2005).

The goal of this research is to determine the extent to which mean monthly wind speeds at a typical wind turbine height are related to variability in selected large-scale atmospheric circulation features. If such relationships can be demonstrated, it may be possible to use existing climatological datasets, atmospheric circulation index time series, and climate-change models to estimate the historical and future low-frequency variability of wind power at a given site (Sailor et al. 2000; Segal et al. 2001; Pryor et al. 2005).

2. Wind data

Nine years (1995–2003) of wind speed measurements at 11 70-m wind-monitoring sites in Minnesota (Fig. 1) are used to identify spatial and temporal patterns in

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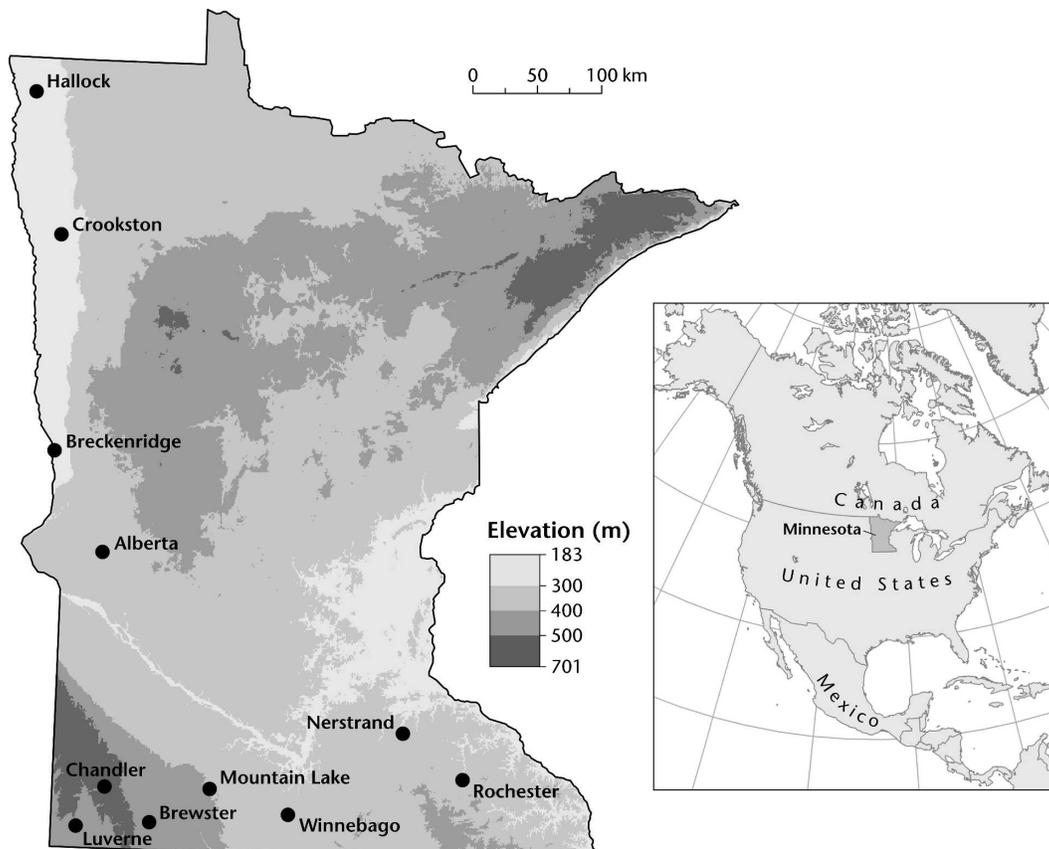


FIG. 1. Location of the 70-m wind stations in Minnesota.

wind speeds measured at the height of a typical wind turbine. Although the period of record is short relative to typical climatological analyses (30 yr of data or more), it is comparable to record lengths used for wind energy analysis (often around 10 yr; e.g., Petersen et al. 1998). These data also are useful because they are not extrapolated from surface and/or radiosonde measurements. The Minnesota monitoring sites represent a unique opportunity to directly observe wind speed variability at a typical wind turbine hub height and to contribute to the development of turbine-level wind climatological descriptions (e.g., Schwartz and Elliott 2005).

The Minnesota Department of Commerce (DoC) has instrumented approximately 50 wind-monitoring towers within the state (Minnesota Department of Commerce 2002, 2004). A total of 12 active stations with 70-m data are available from the DoC database, with hourly records that begin in 1995 or 1996. Each wind-monitoring site has two standard, three-cup (NRG Systems, Inc.) anemometers on two sides of the tower at 30, 50, and 70 m. At each level, one anemometer is on the northwest side of the tower and the other is on the southeast side (prevailing winds are north-northwest in

winter and south-southeast in summer). Vanes monitor wind direction at 30 and 70 m and typically are mounted on the west side of the tower. A datalogger records mean hourly values of wind speed, wind direction, and air temperature (measured at 50 m). Minnesota DoC personnel examine data from each tower every 1 to 2 weeks, and anomalous data are flagged for quality checks and for possible sensor malfunction (J. Sheehy 2002, personal communication). Wind speed measurements are checked by the DoC for consistency between the paired anemometers at each location on the tower. Wind instruments typically are not recalibrated once deployed, but examination of the paired readings allows the DoC to determine when it is necessary to repair, replace, or recalibrate the instruments (R. Artig 2003, personal communication). Hourly wind speeds provided by the DoC were recorded as the higher of the two measured wind speeds under the assumption that the lower speed is affected by tower shading (Minnesota Department of Commerce 2004). Minnesota DoC personnel used wind speeds, air temperature, and site elevation to derive time series of hourly wind power density (a function of the cube of

TABLE 1. Seventy-meter wind stations used in this study.

Station	Location	Elev above MSL (m)	Mean monthly wind speed at 70 m (m s^{-1})	Record begins	No. of missing months (1995–2003)
Hallock	48.76°N, 96.93°W	250	6.91	Jun 1995	11
Crookston	47.76°N, 96.67°W	264	6.70	Jun 1995	14
Breckenridge	46.26°N, 96.53°W	292	7.07	May 1996	19
Alberta	45.58°N, 96.05°W	338	7.03	Feb 1995	6
Chandler	43.89°N, 95.93°W	555	8.49	May 1996	23
Luverne	43.71°N, 96.07°W	472	7.19	Jul 1995	17
Brewster	43.73°N, 95.36°W	427	7.46	Aug 1995	10
Mountain Lake	44.04°N, 94.85°W	366	7.32	Jul 1995	20
Winnebago	43.70°N, 94.03°W	343	7.36	Jul 1995	11
Nerstrand	44.35°N, 93.04°W	365	6.99	Jul 1995	14
Rochester	43.97°N, 92.42°W	364	6.36	Oct 1996	22

wind speed) using standard wind power formulas (e.g., Gipe 1995).

In addition to the DoC quality-control procedures, the data at each station also were checked for inconsistencies in wind speed measurements. Near-zero 70-m wind speeds were flagged if they were inconsistent with simultaneous values of speed at 30 and 50 m, as were long time periods of zero wind speed that were preceded and/or followed by records flagged as “missing” by the DoC. One of the active 70-m stations (Clarks Grove) was excluded because more than 40% of the record was missing or was suspect based on these quality checks. Hourly records at the remaining 11 stations were used to compute the mean wind speed for each month at each site (Table 1). Monthly means were computed only when missing data composed fewer than 25% of the hourly observations for that month.

The 70-m wind towers are located exclusively within the “high wind power” areas of Minnesota as identified in Elliott et al. (1986). The towers are located in agricultural areas outside of towns and cities (Land Management Information Center 2006). Primary crop types are wheat, soybeans, and sugar beets in northwestern Minnesota and corn, soybeans, and hay in southern Minnesota (Minnesota Agricultural Statistics Service 2006). The Hallock, Crookston, and Breckenridge sites are within the lake bed of glacial Lake Agassiz and have very little topographic variation; topography around the Alberta site near the southern end of the lake bed is somewhat more variable. The Chandler, Luverne, Brewster, and Mountain Lake sites are in areas of more rugged topography (by Minnesota standards) with some of the highest elevations in the state near or on the Buffalo Ridge/Coteau des Prairies landform. The tower at Winnebago is in an area of smoothly varying topography and atop the highest point within about 150 km². The Nerstrand and Rochester sites are in areas of highly dissected moraines and glacial till.

Topographic maps for the areas surrounding each tower site can be found in Minnesota Department of Commerce (2002).

Although the anemometers are 70 m above the ground, seasonal variation in surface roughness still may influence the measured wind speed. The roughness effect can be approximated by the wind shear exponent α , which often is used to describe vertical wind profiles:

$$u_2 = u_1 \left(\frac{z_2}{z_1} \right)^\alpha,$$

where u_1 and u_2 are the wind speeds at heights z_1 and z_2 (e.g., Petersen et al. 1998). The average wind shear at these sites (computed between 50 and 70 m) is highest in the summer and autumn (0.271 and 0.277, respectively), lowest in the winter (0.224), and intermediate in spring (0.243) (Minnesota Department of Commerce 2002). This variation is consistent with the increase in roughness one would expect as snow melts from cultivated fields and crops begin to grow. These changes in α , however, produce only about a 2% change in 70-m wind speed; thus, seasonal changes in surface roughness are assumed to be negligible for this analysis.

On average in Minnesota, wind speed follows a distinct seasonal cycle. Most stations experience their fastest winds in February and April, with a secondary maximum in October or November (Fig. 2). Minimum wind speeds occur in July and August. This seasonality reflects the variation of the north–south temperature (pressure) gradient in the Northern Hemisphere, as well as the seasonal migration of the polar jet stream. Wind speed variability as measured by the mean absolute deviation (calculated from hourly values) usually is highest in the spring and again in late autumn/early winter and is lowest in the summer. This pattern of variability also is reflected in shape parameter k of the Weibull density function (a commonly used function

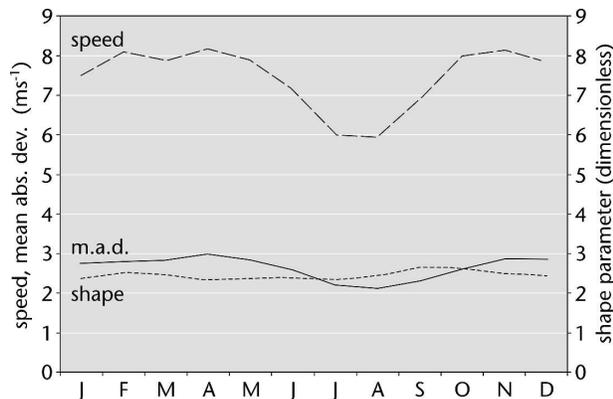


FIG. 2. Typical seasonal cycle of mean monthly wind speed and wind speed variability (based on hourly data from 1995 to 2003) as given by the mean absolute deviation (mad) and the Weibull shape parameter (k). These data are for the Brewster site in southwestern Minnesota.

for describing wind speeds; e.g., Frost and Aspliden 1994), which for all stations is largest (indicating a narrower wind speed distribution and thus smaller variability) in the late summer or early autumn.

3. Measures of the large-scale circulation

a. North–south pressure gradient

Wind speeds largely are governed by the pressure gradient, defined here using the mean monthly north–south gradient of 500-hPa heights along 95°W, which roughly bisects the state of Minnesota. The 500-hPa heights are used because this height is well above the level of local and upstream (e.g., west of Minnesota) surface effects, and the north–south gradient is used because this is the typical orientation of the largest height differences over Minnesota at monthly time scales (lower heights are to the north). The gradient is computed from the transect of 500-hPa heights as given by the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis (Kalnay et al. 1996) for each month

from 1995 to 2003 and from 25° to 65°N (approximately 20° south and 20° north, respectively, of the latitude of the Minnesota wind sites) along 95°W. The difference between the highest and lowest 500-hPa heights along this transect (termed $\max \Delta Z_{500}$; Table 2 and Fig. 3a) is used to characterize the strength of the upper-level pressure gradient. As defined, $\max \Delta Z_{500}$ represents the mean north–south height (pressure) gradient rather than the effects of topography, roughness, or other aspects of local or upstream surface heterogeneity.

b. Atmospheric circulation indexes

The North Atlantic Oscillation (NAO) and the Pacific–North American (PNA) pattern are two long-recognized midlatitude circulation modes. Thompson and Wallace (1998, 2001), among others, have described the NAO as a regional manifestation of the larger Arctic Oscillation (AO). The AO is used in this research because it is based on hemispheric pressure patterns rather than pressures in a particular region (the North Atlantic Ocean) and because several authors have demonstrated a relationship between the AO and midlatitude climate (e.g., Thompson and Wallace 1998, 2000, 2001; Shindell et al. 1999; Higgins et al. 2000; Thompson et al. 2000; Rauthe and Paeth 2004). Variation in the PNA also has been shown to have important regional climate impacts (e.g., Rodionov 1994; Angel and Isard 1998; Huntington et al. 2004). Many of these studies have investigated only the winter/cold seasons because it is during this time of year that the indexes are most strongly correlated with the surface climate.

The El Niño–Southern Oscillation (ENSO) is a tropical phenomenon with global impacts. The Niño-3.4 sea surface temperature (SST) anomalies (referred to here as the Niño-3.4 index) are used to characterize ENSO because the central Pacific Ocean is the primary area of importance in affecting midlatitude circulation (Graham and Barnett 1995; Trenberth 1997). The effects of ENSO within the United States are well documented (e.g., Gershunov 1998; Assel et al. 2000; Huntington et

TABLE 2. Circulation indexes used in this study. Dataset title is given in parentheses.

Index	Source
$\max \Delta Z_{500}$ (25°–65°N, along 95°W)	http://www.cdc.noaa.gov/cgi-bin/DataMenus.pl?stat=mon.ltm&dataset=NCEP (“NCEP individual monthly means”)
AO	http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/ao_index.html (“Monthly mean AO index since January 1950”)
PNA	ftp://ftp.prd.ncep.noaa.gov/pub/cpc/wd52dg/data/indices/tele_index.nh (“Table archive of indexes dating back to 1950”)
Niño-3.4 (SST anomaly)	http://www.cpc.ncep.noaa.gov/data/indices/sstoi.indices [“Sea surface temperature (SST): Monthly”]

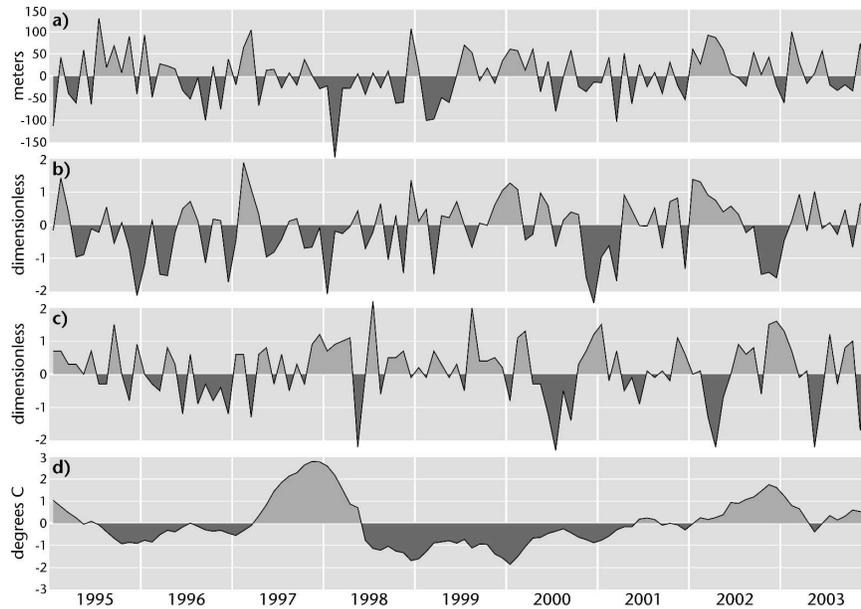


FIG. 3. (a) Mean monthly north-south pressure gradient ($\max \Delta Z_{500}$, anomalies computed from the 1995–2003 base period) and monthly (b) AO, (c) PNA, and (d) Niño-3.4 indexes. Sources are listed in Table 2.

al. 2004), although ENSO's impact on midcontinent climate is less clear, particularly outside of the winter-cold season. Monthly values of the AO, PNA, and Niño-3.4 indexes were obtained from the National Oceanic and Atmospheric Administration Climate Prediction Center (Table 2 and Figs. 3b–d).

4. Analysis

a. Comparison across sites

Mean monthly 70-m wind speeds are highly correlated across the 11 sites (Fig. 4) despite differences in the geographic settings of the stations (Fig. 1). This high spatial correlation is larger than that observed between 10-m wind speed measurements in the north-central United States (including Minnesota) reported by Robeson and Shein (1997) and also is higher than the spatial correlation for 80-m wind speeds in northern Europe (transformed from 10-m speeds derived from reanalysis data) reported by Giebel (2000). For the Minnesota tall-tower data, the higher spatial coherence at 70 m may be due to reduced surface roughness effects (as compared with 10 m) and the relatively small topographic variation in Minnesota, as evidenced by the similarity of the 50- to 70-m wind shear exponents across these sites (Minnesota Department of Commerce 2002). Another factor appears to be the choice of averaging period; Robeson and Shein (1997) show that

the spatial coherence for mean monthly wind speeds is higher than that for mean annual wind speeds, which have a weaker spatial correlation (see also Giebel 2000). One also cannot rule out that the high correlation observed here may be a fortunate coincidence; Robeson and Shein (1997) used 30 yr of record and Giebel (2000) analyzed data for a 34-yr period, as compared with the 9 yr (1995–2003) used here. Longer time series are needed to confirm whether the small distance decay of between-station correlation in Minnesota is an artifact of this time period (1995–2003) or whether it is representative of wind speeds measured at elevations substantially higher than 10 m above the ground. Tall-

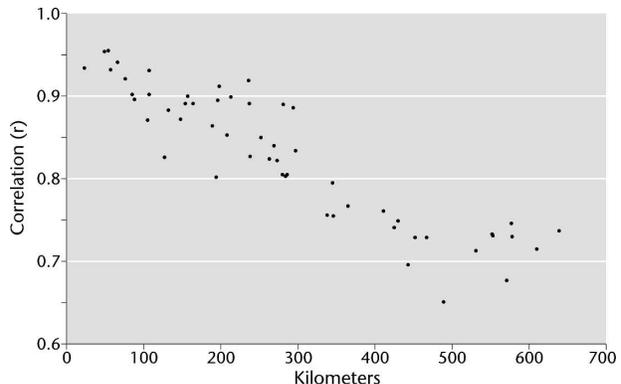


FIG. 4. Between-station correlation at the 70-m stations for mean monthly wind speed.

tower wind speed measurements from other regions, including those with more topographic heterogeneity than exists in Minnesota, would help to clarify these results.

Wind speed anomalies (Fig. 5) show a high degree of spatial and temporal coherence, as expected from the high correlation between stations. Anomalies for each site were computed by subtracting the 1995–2003 monthly mean from the observed mean for the same month. Because each station has some months missing from the record (Table 1), the long-term means often are computed from fewer than 9 yr of observation. Over 90% of the 132 station–month pairs are based on a minimum of 7 yr of record, with the shortest records occurring at Chandler in January and February (5 and 4 yr of record, respectively).

A striking feature of the anomaly series (Fig. 5) is the occurrence of extended periods of above- and below-normal mean monthly wind speed that can persist for as long as 12 months. These periods are approximately synchronous across the stations, indicating that low wind power at one site is less likely to be compensated by higher power generation at another site in the region. This result has important implications for the potential for geographic dispersion of wind turbines to smooth out long-term, low-frequency (as opposed to short-term, high-frequency) variations in wind-derived power generation (e.g., Milligan and Artig 1998; Nana-hara et al. 2004; Nørgård et al. 2004).

The sizeable spatial coherence among the stations suggests that much of the month-to-month variability in wind speed is governed by large-scale pressure and circulation patterns. Scatterplots and correlation statistics (not shown, but see section 4b) indicate that speed is most strongly related to $\max \Delta Z_{500}$. Correlations between speed and the AO and Niño-3.4 indexes are somewhat smaller than for $\max \Delta Z_{500}$, and correlation with the PNA index appears to be the weakest of the indexes used here.

b. Regression analysis

Atmospheric dynamics dictate that mean monthly wind speed at the Minnesota tall-tower sites will increase with stronger 500-hPa height (pressure) gradients. We also may expect that increased wind speed would be associated with positive values of the AO index and negative values of the PNA and Niño-3.4 indexes. A positive AO reflects an enhanced westerly flow in mid- to high latitudes, which should lead to increased wind speeds in Minnesota (cf. Thompson and Wallace 2001). Angel and Isard (1998) showed that cyclones in the Great Lakes region are more frequent when the PNA index is negative, which should lead to

faster mean wind speeds because of the higher probability of strong winds that often occur with cyclone passages. Rodionov and Assel (2001) show that, in the United States, El Niño winters have weaker upper-level westerlies, and Enloe et al. (2004) show that peak winds in the United States generally are stronger during La Niña (cold events) and weaker during El Niño. Consequently, we would expect that wind speeds in Minnesota would be stronger during neutral or cold events (average to negative Niño-3.4 SST anomalies) and weaker during warm events (positive SST anomalies).

Multiple linear regression is used to quantify the relationships between wind speed, $\max \Delta Z_{500}$, and the AO, PNA, and Niño-3.4 indexes. Nonlinear regression also was investigated but with less satisfactory results than for linear regression.

Based on the ENSO teleconnection literature (e.g., Diaz et al. 2001) and on comparison of Figs. 3 and 5, the regression analysis uses Niño-3.4 SST anomalies from 5 months prior to the month of observed wind speed, rather than concurrent values. Using a 5-month lead also is consistent with the results of Enloe et al. (2004) who compared monthly peak wind gusts with a 5-month running mean of SST. Concurrent values of $\max \Delta Z_{500}$, AO, and PNA are used in the regression equations because there is little evidence for significant lagged relationships based either on atmospheric dynamics, the teleconnection literature (e.g., Angel and Isard 1998; Thompson and Wallace 2001; Rauthe and Paeth 2004), or on comparison of Figs. 3 and 5. The predictor variables $\max \Delta Z_{500}$, AO, PNA, and Niño 3.4 are only weakly correlated among themselves (variance inflation factors are less than 1.5), indicating that these quantities reflect nearly independent patterns of (statistical) variability over the time period analyzed here (1995–2003).

The 500-hPa height gradient has the single greatest effect on wind speed at these sites. Between 22% and 47% of the variation in mean monthly wind speed can be described by changes in $\max \Delta Z_{500}$ alone (Table 3). To more closely examine the relationships between wind speed and the AO, PNA, and Niño-3.4 indexes, the pressure gradient effect was removed by first regressing mean monthly wind speed against $\max \Delta Z_{500}$ and then examining the relationship between the monthly residuals and the AO, PNA, and Niño-3.4 indexes. The regression against $\max \Delta Z_{500}$ also reduces the influence of the slightly weaker north–south pressure gradient during 1995–2003 (as compared with the NCEP–NCAR reanalysis climatological values), thus making the residuals more comparable to the long-term climatological values on which the AO, PNA, and Niño-3.4 indexes are based. The Jarque–Bera and

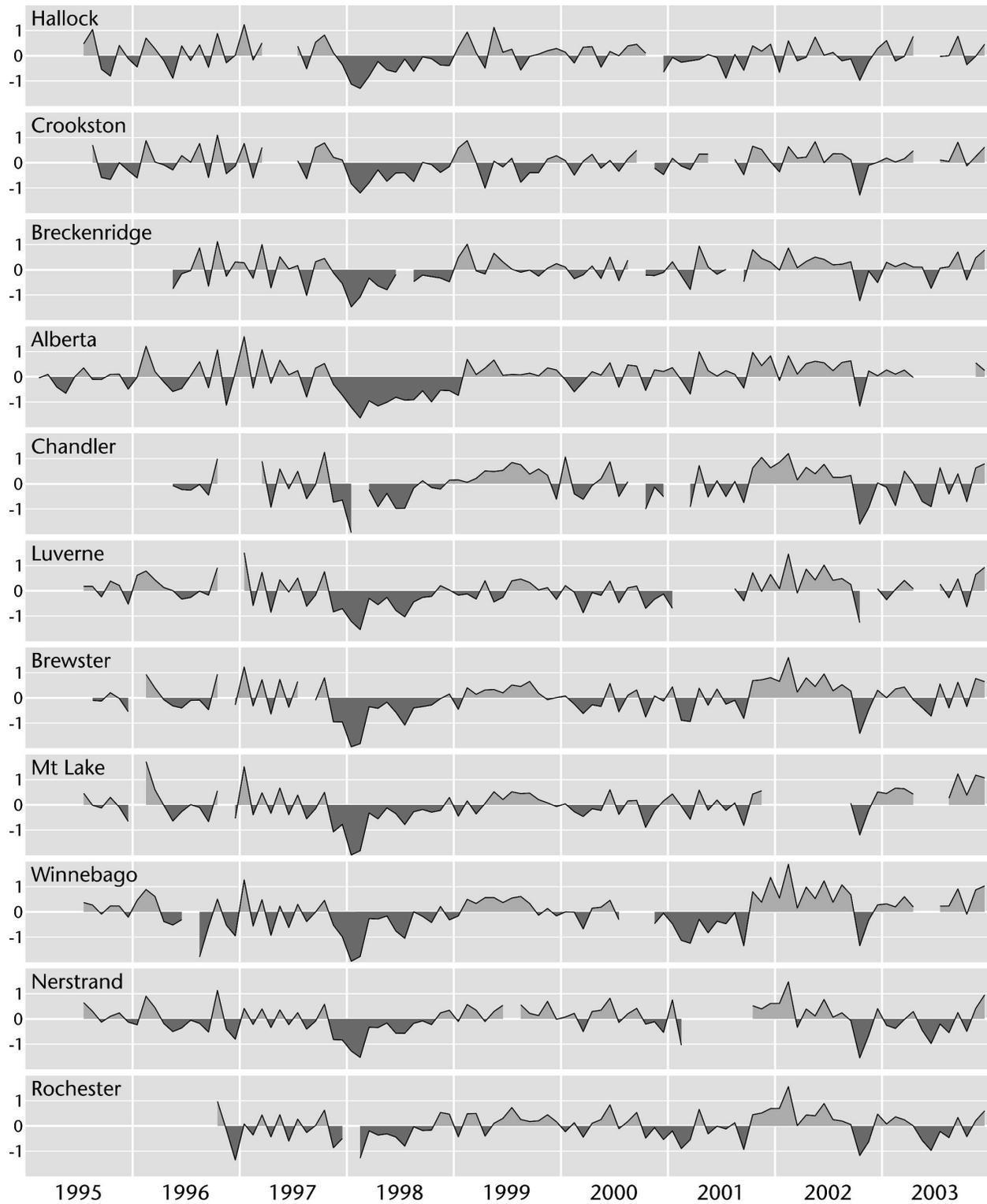


FIG. 5. Monthly wind speed anomalies (m s^{-1}) at the 11 70-m wind-monitoring sites. Anomalies are computed from monthly means derived from the 1995–2003 base period.

TABLE 3. Least squares regression coefficient b and model r^2 for mean monthly wind speed regressed against $\max \Delta Z_{500}$. Probabilities that the regression coefficients is zero are less than 0.0001 for all sites. In columns 2 and 3, coefficients are computed from all available data; in columns 4 and 5, coefficients are computed from the data excluding 1997/98.

Station	All available data (1995–2003)		Data for 1997/98 removed	
	b	r^2	b	r^2
Hallock	0.002 20	0.224	0.002 12	0.221
Crookston	0.002 77	0.267	0.002 10	0.251
Breckenridge	0.002 66	0.279	0.002 85	0.339
Alberta	0.003 65	0.386	0.003 38	0.404
Chandler	0.004 06	0.348	0.004 07	0.394
Luverne	0.003 14	0.278	0.003 06	0.294
Brewster	0.004 16	0.395	0.004 34	0.457
Mountain Lake	0.004 82	0.469	0.004 96	0.528
Winnebago	0.004 43	0.384	0.004 45	0.398
Nerstrand	0.003 15	0.340	0.003 08	0.339
Rochester	0.002 51	0.238	0.002 32	0.208

Lilliefors tests show that, for the majority of stations, the residuals are symmetrically distributed around zero and are approximately normally distributed ($p < 0.10$; Fig. 6a). Exceptions to normality (Chandler “fails” the Jarque–Bera but not the Lilliefors test, and Breckenridge fails the Lilliefors but not the Jarque–Bera test) occur primarily because of a small number of outliers. Autocorrelation statistics and scatterplots (Fig. 6b) show that autocorrelation in the residuals is small.

Regression coefficients and statistics for mean monthly wind speed residuals are shown in Table 4. Seven of the 11 sites have regression coefficients for the Niño-3.4 index (5-month lead) that are different from zero ($p < 0.10$) and five sites show a meaningful correspondence with the AO ($p < 0.10$), but only Luverne

shows a strong relationship between the wind speed residuals and the PNA index ($p < 0.10$). Each coefficient has the sign hypothesized based on atmospheric dynamics: wind speeds in Minnesota are stronger when ENSO is in its cold (or at least “not warm”) phase (negative SST anomalies); when the AO is positive (stronger westerlies); and when the PNA is negative (more zonal flow). Between 6% and 15% of the variance in the monthly wind speed residuals can be described by changes in the AO and Niño-3.4 indexes and to a lesser extent by variations in the PNA index. The weak relationships between the residuals and the PNA may be related to Rodionov and Assel’s (2001, p. 1519) assertion that the PNA cannot “unambiguously characterize the flow pattern over North America,” despite its status as a leading circulation mode.

The tall-tower wind speed series are only 9 yr long and include one of the strongest El Niño events on record (Bell and Halpert 1998; Bell et al. 1999). To investigate the effect of this unusual event on the statistical results, the 1997–98 data were removed and the regression equations for mean monthly wind speed and the wind speed residuals were reevaluated. The variance in mean monthly wind speed that is captured by $\max \Delta Z_{500}$ generally increases when this strong El Niño event is removed from the record (Table 3), as does the relationship between wind speed residuals and the AO (Table 5). The Niño-3.4 index (5-month lead) remains important for only one station and again the coefficients for the PNA are small. These results reaffirm that the north–south pressure gradient is the dominant factor affecting 70-m wind speeds and suggest that in the absence of strong ENSO forcing the AO is an important contributor to low-frequency wind speed variability.

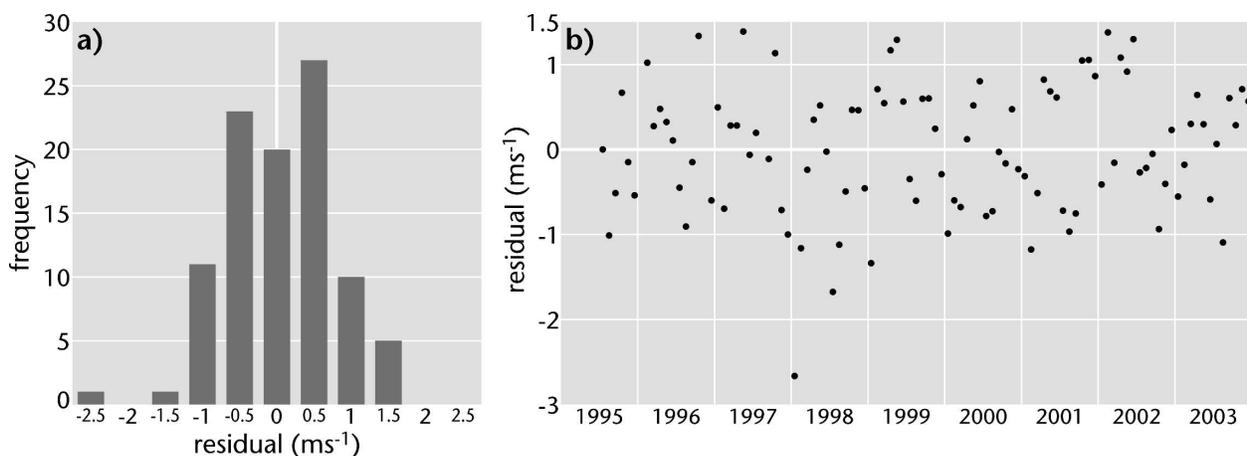


FIG. 6. Example (a) histogram and (b) time series of wind speed residuals obtained from regression equations using all available data and coefficients listed in Table 3. These data are for the Brewster site in southwestern Minnesota.

TABLE 4. Standardized coefficients and total model r^2 for mean monthly wind speed residuals (obtained from regression equations using all available data and coefficients listed in Table 3) regressed against the circulation indexes used in this paper. Values in parentheses are the probabilities that each coefficient is zero. Coefficients with $p < 0.10$ are in boldface.

Station	AO	PNA	Niño-3.4 (5-month lead)	Model r^2
Hallock	0.072 (0.280)	-0.062 (0.363)	-0.106 (0.106)	0.072
Crookston	0.112 (0.073)	-0.054 (0.394)	-0.057 (0.346)	0.077
Breckenridge	0.133 (0.063)	-0.053 (0.452)	-0.099 (0.144)	0.098
Alberta	0.041 (0.548)	-0.043 (0.536)	- 0.220 (0.002)	0.125
Chandler	0.180 (0.050)	-0.030 (0.741)	- 0.219 (0.013)	0.147
Luverne	0.050 (0.546)	- 0.145 (0.086)	-0.128 (0.113)	0.093
Brewster	0.113 (0.156)	-0.067 (0.406)	- 0.168 (0.029)	0.101
Mountain Lake	0.078 (0.344)	0.000 (0.996)	- 0.151 (0.065)	0.060
Winnebago	0.138 (0.123)	0.009 (0.918)	- 0.146 (0.095)	0.063
Nerstrand	0.132 (0.053)	0.021 (0.753)	- 0.213 (0.001)	0.154
Rochester	0.159 (0.032)	-0.016 (0.826)	- 0.141 (0.045)	0.121

Although many coefficients in Tables 4 and 5 are not statistically significant ($p < 0.10$), excluding “nonsignificant” variables and recomputing the regression equations does not alter the sign or the relative magnitude of the coefficients of “significant” variables. At nearly all stations the r^2 value changes little when coefficients with $p > 0.10$ are excluded from the regression equation (exceptions occur at stations where a coefficient’s p value is just over 0.10). The purpose of this paper is to explore to what degree interannual and month-to-month variability in mean monthly wind speed can be related to large-scale circulation variability as represented by max ΔZ_{500} and the AO, PNA, and Niño-3.4 indexes. Full statistical results that include nonsignificant variables provide some indication of the strength of these relationships. This work does not seek to determine the “best” predictive equation for wind speed, which likely would require the investigation of a number of additional variables not considered here.

5. Discussion

Two of the most prominent and spatially coherent features of the mean monthly wind speed time series (Fig. 5) are the periods of below-average values from

late 1997 through most of 1998 and above-average values from late 2001 through mid-2002. Low speed during 1997/98 is coincident with small 500-hPa gradients over Minnesota, negative AO and positive PNA indexes, and a strong warming in the central Pacific (positive Niño-3.4 SST anomalies, 5-month lead; Fig. 3). The combination of these features contributed to unusually low monthly wind speeds that were greater than one standard deviation from the mean. Over this same period, the Minnesota Department of Commerce’s wind power calculations show a 12%–27% decrease in mean monthly wind power (depending on the station). Above-average monthly wind speeds from late 2001 through mid-2002 coincide with generally stronger 500-hPa gradients and a positive AO, although the Niño-3.4 index (5-month lead) shows neutral to weak warming and the PNA index exhibits both positive and negative values. Mean monthly wind power is between 2% and 16% higher during this period, a much smaller deviation than for 1997/98 when all four circulation features should have had reinforcing effects on mean monthly wind speed.

A number of researchers have investigated how greenhouse gas-induced climate change could alter

TABLE 5. Same as in Table 4 but with data for 1997/98 excluded.

Station	AO	PNA	Niño-3.4 (5-month lead)	Model r^2
Hallock	0.098 (0.189)	-0.041 (0.590)	-0.039 (0.597)	0.045
Crookston	0.154 (0.023)	-0.053 (0.439)	0.054 (0.415)	0.101
Breckenridge	0.163 (0.040)	-0.051 (0.515)	-0.026 (0.728)	0.098
Alberta	0.096 (0.195)	-0.014 (0.855)	-0.057 (0.438)	0.040
Chandler	0.200 (0.045)	-0.001 (0.990)	-0.141 (0.136)	0.114
Luverne	0.112 (0.229)	-0.113 (0.234)	-0.027 (0.765)	0.069
Brewster	0.171 (0.050)	-0.002 (0.986)	-0.058 (0.474)	0.069
Mountain Lake	0.156 (0.086)	0.050 (0.581)	0.008 (0.927)	0.049
Winnebago	0.237 (0.020)	0.071 (0.486)	-0.044 (0.656)	0.080
Nerstrand	0.206 (0.009)	0.081 (0.297)	- 0.173 (0.021)	0.168
Rochester	0.295 (0.001)	0.048 (0.561)	-0.103 (0.190)	0.213

equator-to-pole temperature gradients and the frequency and/or intensity of preferred circulation modes such as the AO, PNA, and ENSO (e.g., Corti et al. 1999; Cubash et al. 2001; Gillett et al. 2002; Rauthe et al. 2004; Collins et al. 2005). Enhanced high-latitude warming (as compared with mid- and low latitudes; e.g., Cubash et al. 2001) would result in a weaker north-south pressure gradient, which should significantly reduce wind speed and wind power (cf. Sailor et al. 2000; Segal et al. 2001; Pryor et al. 2005). Results described by Rauthe et al. (2004) suggest that the AO may strengthen under future climate change, which could increase wind speed (and wind power) in Minnesota and possibly mitigate some of the effects of a weakened north-south pressure gradient. There is more model uncertainty regarding changes in the PNA and in ENSO. Rauthe et al. (2004) found considerable variability among model estimates of future changes in the Aleutian low (one component of the PNA), and in some cases changes in the Aleutian low partly counteract the increase in the AO. Collins et al. (2005) found no strong modeling evidence for changes in the frequency of either El Niño or La Niña events under future climate change, although they note that the models tested had variable levels of skill in representing ENSO events in their control climates.

6. Summary and conclusions

Tall-tower wind-monitoring sites across western and southern Minnesota show a high degree of spatial correlation, with periods of above- and below-average mean monthly wind speeds that can persist for many months. These long-lived, anomalous periods are approximately contemporaneous across the stations and are related to large-scale patterns of the Northern Hemisphere circulation as represented by the north-south gradient of 500-hPa heights and to a lesser extent by the AO and Niño-3.4 SST indexes. There was little correspondence between monthly wind speed and the PNA index.

The relationship demonstrated here between mean monthly 70-m wind speeds in Minnesota and the large-scale circulation suggests that it is possible to make probabilistic forecasts of the low-frequency variability of above- and below-average wind speed (and thus wind power) from months-ahead forecast models, particularly forecasts of 500-hPa heights. It also may be possible to use reanalysis datasets and past values of atmospheric circulation indexes to estimate how wind speed has varied in the past at sites where long-term data are unavailable and to use climate model projections to estimate how wind power at these sites may vary in the future.

As wind power becomes a larger component of the energy generation matrix, it increasingly is important to understand the factors that govern wind speed variability over a variety of space and time scales. The Minnesota data show that prolonged and spatially coherent periods of above- or below-normal monthly wind speed (and thus wind power) may occur most predictably when the dominant “modes” of atmospheric circulation have reinforcing effects on speed (e.g., 1997/98, 2001/02). These results also suggest that the large-scale circulation can affect wind speed in all seasons, a useful complement to the extensive climatological literature that focuses primarily on connections with the cold-season climate.

The spatial coherence of periods of above- and below-normal wind speed in Minnesota (approximate area of 225 000 km²) also suggest that, while dispersing turbines over very large regions can smooth out high-frequency variations in wind power production (e.g., Milligan and Artig 1998; Giebel 2000; Archer and Jacobson 2003; Nørgård et al. 2004), such dispersion may not be sufficient to mitigate low-frequency variability. The Minnesota tall-tower data cover a smaller area than is considered in some of the above studies (e.g., northern Europe), however, and it is unclear whether this high spatial coherence is unique to Minnesota. The relationships between mean monthly wind speed and the large-scale circulation described in this paper need additional evaluation with longer and more geographically extensive datasets in order to validate (or refute) these conclusions, particularly because circulation changes may have different impacts in different parts of the globe (Diaz et al. 2001; Rauthe and Paeth 2004). Seasonal analyses would further enhance our understanding of the relationships between turbine-level winds and the large-scale circulation.

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