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Kevin J. Lawless
Northern States Power Company, Minneapolis

Katherine Klink
University of Minnesota

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Climatology and Interannual Variability of Wind Speeds In and Around Minnesota†

Kevin J. Lawless‡ and Katherine Klink

Abstract

Wind is receiving renewed attention as an energy resource. Unfortunately, many wind energy assessments are based on records that may not be representative of the long-term wind resource. To better evaluate wind energy potential in and around Minnesota, we analyze wind speeds from 1961 to 1990 for seven stations in the region at a height of about 6.1 m above ground level. We used hourly and three-hourly speed observations to develop a 30-year time series of mean monthly wind speeds, their maxima and minima, and the diurnal wind speed range. Simple linear regression was used to evaluate long-term trends in each variable. Wind speeds across the state show meaningful intrannual and interannual variability for each of the seven stations and for the seven-station (regional) average. The diurnal wind speed range (DWR) also exhibits marked variability, with distinct periods of increased and decreased DWR separated by abrupt transitions. The observed variability of wind speed over the 30-year period underscores the necessity of recognizing this variability when making investment decisions for wind energy generation.

Introduction

Wind power continues to attract attention as a potential source of widespread, relatively inexpensive, electric power generation. A large region of significant wind energy exists in the north-central United States, including Minnesota. About 20,000 megawatts of potential wind power capacity have been identified in southwestern Minnesota alone, with much larger quantities available in North Dakota (DPS, 1996). The ability to successfully tap this energy resource requires understanding of wind's long-term variability and consistency, or lack thereof, on a broad geographic scale.

Investments in renewable energy must be considered in relation to known long-term fluctuations of their energy source. For example, hydropower investments are routinely analyzed against long-term hydrologic factors and their frequency of occurrence. Many wind power assessments, in contrast, have relied on fairly short time series of ten or fewer years. For example, D.G. Baker (1983) provided a detailed wind speed and direction climatology of Minnesota based on 10 years of record at eight stations; R.W. Baker (1985) used a six-year wind speed record to assess interannual variations of wind generator output in the Pacific Northwest; and Labraga (1994) used only one year of data to estimate the frequency distribution of extreme wind speeds in the Pampa del Castillo region of Argentina. One exception is the study by Shein and Robeson (1995), who analyzed wind power potential at Fargo, ND, Des Moines, IA, and St. Louis, MO, using a 30-year wind record.

The use of short-duration records for wind climatology and energy assessment may largely be due to the lack of availability of longer-period wind records in a digital form. Additional information on the variability of wind would be useful in estimating wind energy potential over long-term investment horizons. The objectives of our study are to briefly describe the climatology of wind speed and the diurnal wind speed range in Minnesota and the surrounding region, and to elucidate their longer-term temporal variations.

Data and Methods

Wind records from seven weather stations are used for our study: Duluth, International Falls, Minneapolis-St. Paul, and Rochester, MN; Eau Claire, WI; Fargo, ND; and Sioux Falls, SD (Figure 1 and Table 1). Wind speeds at each station were taken from the SAMSON database (NREL 1993), which spans the period 1961-1990. To be able to compare wind records across sites, wind speeds were adjusted to a common, 6.1 m (20-foot) measurement height using the 1/7 power law (Peterson and Hennessey 1978). The distance above ground level (6.1 m) was chosen as the standard because this height is near the most common measurement height at these stations (Table 1). Wind speeds at Eau Claire were left unchanged after 1978 because anemometer height is unknown after this date.

† Contribution from Northern States Power Company, 414 Nicollet Mall, Minneapolis, MN 55401 and the Department of Geography 414 Social Sciences Building, 267 19th Ave S. University of Minnesota, Minneapolis, MN. 55455

‡ Corresponding Author

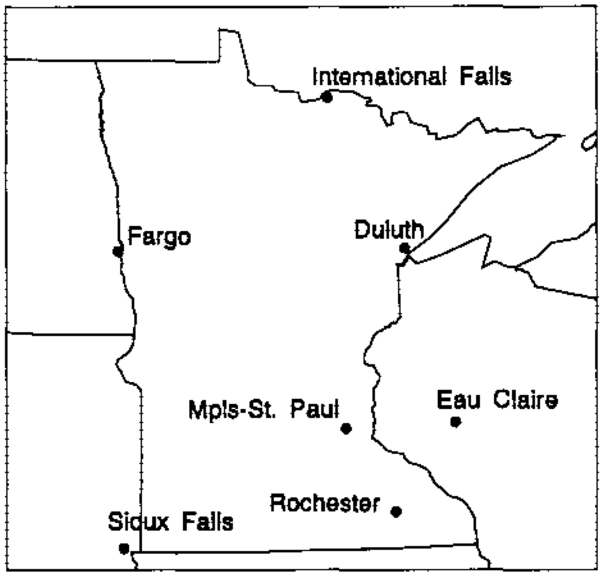

Figure 1. Locations of wind data stations.

Daily maximum, minimum, and average wind speeds were based on hourly or three-hourly observations for each day of the 30 years of record. Missing observations accounted for less than 0.001% of the record at each station. Daily data were used to compute a monthly average for each of the three variables for each month within the period. Thirty-year climatological averages in turn were based on the monthly values. Time series of the monthly diurnal wind speed range (DWR) were computed as the difference between the mean monthly maximum and mean monthly minimum wind speeds. To assess interannual variability in the DWR, the time series for each station and for the seven-station (regional) average were smoothed by applying a twelve-month moving average, centered in the sixth month. Simple linear regression was used to identify long-term trends in the time series of maximum and minimum winds, and in the DWR. To evaluate possible relationships between the DWR and the diurnal temperature range (DTR), we also computed the 30-year time series of mean monthly DTR (using the same procedures as for the DWR) for each station and for the regional average.

Results

Mean Wind Speeds and Diurnal Wind Speed Range (DWR)

Mean annual wind speeds at the seven stations are shown in Table 2. Rochester is the windiest station, with a mean wind speed of 5.6 m s^{-1}. The least windy stations on average are International Falls and Eau Claire, both having mean annual wind speeds of 3.9 m s^{-1}. Rochester has the greatest wind speeds of all seven stations in 11 of 12 months and itís April mean speed of 9.4 m s^{-1} is the fastest monthly mean for any station. The greater wind speeds at Rochester are not unexpected because this weather reporting station is located on a ridge 91 m (300 feet) above the city (NOAA 1993).

Wind speeds in Minnesota fluctuate over the year, reaching their greatest values in April and their smallest values in July or August. This pattern is consistent with that found by D.G. Baker (1983). The

Table 1. Locations and elevations of weather stations and relative heights of measurement.

Station	State	Latitude N	Longitude W	Elevation	Anemometer Height	Date
		° ′	° ′	m	m	Mo-day-yr
Duluth	MN	46 49	92 10	432	16.1	4 11 1959
					6.4	6 22 1961
Eau Claire	WI	44 52	91 28	273	7.9	1 1 1960
					8.5	7 17 1961
					Unknown	1 1 1979
Fargo	ND	46 54	96 48	274	26.2	1 1 1953
					8.5	5 1 1963
International Falls	MN	48 34	93 22	361	7.0	9 16 1953
					10.4	10 1 1963
					6.1	8 26 1965
Minneapolis-St. Paul	MN	44 52	93 13	255	6.4	9 19 1958
					10.0	10 17 1981
Rochester	MN	43 55	92 30	402	9.1	9 26 1960
Sioux Falls	SD	43 34	96 43	435	16.8	4 17 1956
					5.2	11 26 1961
					9.1	7 18 1984

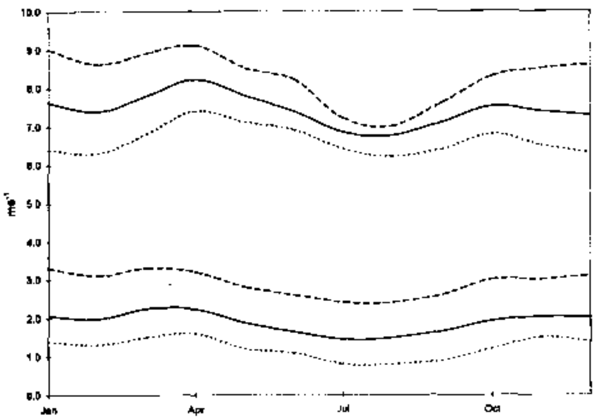

Figure 2. Seasonality of the regional-average (solid line) monthly maximum and minimum wind speeds. Also shown are the monthly maxima and minima for Rochester (large dashes) and Eau Claire (small dashes), the two stations with the fastest and slowest mean wind speeds, respectively. Data are monthly means for 1961 to 1990.

annual variation in mean monthly wind speed ranges from 1.7 m s^{-1} at Rochester to 1 m s^{-1} at International Falls. Mean monthly maximum wind speeds exhibit greater variability over the annual cycle than do minimum wind speeds (Figure 2).

The mean annual diurnal wind speed range (DWR) shows considerable variation among the seven stations (Table 3). Sioux Falls and Fargo have the largest mean annual DWR and between them have seven of the largest monthly values. The largest DWR occurs in April (six stations) or May (one), in conjunction with the peak in maximum wind speeds. The maximum DWR is 16 to 28% larger than the minimum, which occurs in December (four stations), August (two), or July (one).

Interannual Variations of the DWR

Over the period 1961 to 1990, the regional-average mean monthly DWR undergoes five periods of positive and negative anomalies (Figure 3): (1) early 1960s; (2) mid-1960s through early 1970s; (3) mid-1970s; (4) late 1970s through early 1980s; and (5) early 1980s through 1990. Periods 1, 3, and 5 are times of enhanced DWR while periods 2 and 4 show reduced DWR. The first four periods are separated by abrupt transitions, the most distinct of which occurs over a 14-month period between June 1964 and August 1965, when the DWR decreases by 1.58 m s^{-1} (a 29% change relative to the 30-year mean). Another abrupt transition occurs between July 1972 and July 1974, when the DWR increases by 0.98 m s^{-1} (18% change). The third transition, a decrease of 0.79 m s^{-1} (14% change), occurs over 13 months between May 1977 and June 1978. The transition between Periods 4 and 5 is very gradual, with a 0.96 m s^{-1} (17%) change occurring over 10 years.

Many of the individual stations exhibit the same DWR anomaly patterns that appear in the regional-average time series. Period 1 appears distinctly in six of seven station records while Period 2 appears in all seven. Most of the stations also are distinguished by the abrupt transition between Periods 1 and 2. Transitions between anomaly periods are not coincident with changes in wind measurement heights (Table 1). Correlations between the individual stations and the 30-year regional-average show that Rochester, Minneapolis-St. Paul, and Duluth contribute the most to the regional-average trend (Table 4).

Table 2. Mean annual average, maximum and minimum wind speeds for 1961 through 1990.

Station	Velocity†		
	Mean Annual	Maximal	Minimal
	m s^{-1}		
Duluth	4.7 ± 0.60	7.2 ± 0.79	2.1 ± 0.63
Eau Claire	3.9 ± 0.59	6.6 ± 0.77	1.2 ± 0.55
Fargo	4.9 ± 0.63	7.9 ± 0.89	2.0 ± 0.54
International Falls	3.9 ± 0.52	6.6 ± 0.68	1.4 ± 0.55
Minneapolis-St. Paul	4.5 ± 0.52	7.3 ± 0.73	1.7 ± 0.51
Rochester	5.6 ± 0.72	8.3 ± 1.01	2.9 ± 0.52
Sioux Falls	5.0 ± 0.71	8.0 ± 0.89	2.0 ± 0.70
Regional Average	4.6 ± 0.83	7.4 ± 1.03	1.9 ± 0.77

† A velocity of 1 mile per hour = 0.447 m s^{-1}. Values represent means ± standard deviations.

Table 3. Mean annual, maximal, and minimal diurnal wind speed ranges (DWR) and month of occurrence during 1961-1990.

Station	Velocity		
	Mean Annual	Maximal	Minimal
	m s^{-1}		
Duluth	5.2	5.7 (April)	4.8 (Dec.)
Eau Claire	5.4	5.9 (April)	4.9 (Dec.)
Fargo	5.9	6.1 (April)	5.5 (July)
International Falls	5.2	5.6 (May)	4.7 (Dec.)
Minneapolis-St. Paul	5.7	6.2 (April)	5.3 (Dec.)
Rochester	5.4	5.9 (April)	4.6 (Aug)
Sioux Falls	6.0	6.8 (April)	5.6 (Aug)
Regional Average	5.5	6.0	5.3

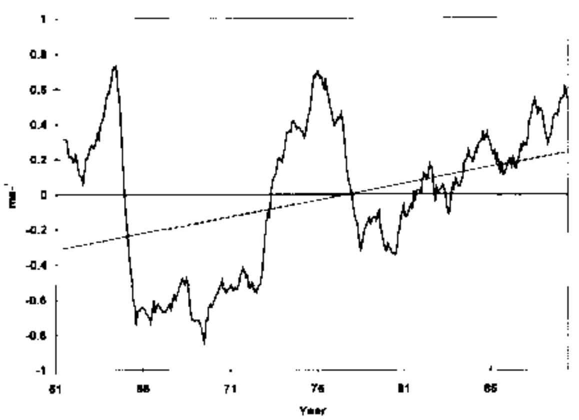

Figure 3. Regional average diurnal wind speed range (DWR) anomalies (1961-1990 baseline) (solid line) and the DWR trend (dashed line) over the 30-year period. The data have been smoothed using a 12-month moving average.

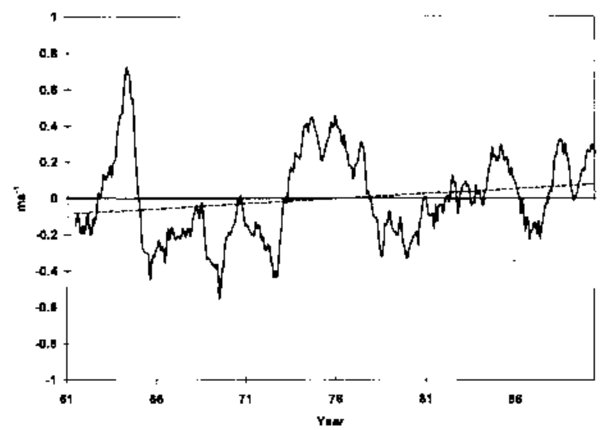

Figure 4. Regional-average monthly maximum wind speed anomalies (1961-1990 baseline) (solid line) and the trend in the monthly maxima (dashed line) over the 30-year period. The data have been smoothed using a 12-month moving average.

Table 4. Pearson correlation between individual stations and the regional-average time series of diurnal wind range.

Station	Correlation Coefficient
Duluth	0.80
Eau Claire	0.70
Fargo	0.65
International Falls	0.75
Minneapolis-St. Paul	0.80
Rochester	0.92
Sioux Falls	0.69

The regional-average DWR time series shows a positive trend over the 1961 to 1990 period, of 0.019 m s^{-1} yr^{-1} (Fig. 3). Positive trends also occur in five of the seven individual station records, though the record at Eau Claire has a negative trend and that for International Falls shows no clear trend (Table 5). Using the same 30-year period, Shein and Robeson (1995) identified positive trends in the January and July DWRs at Fargo, ND, Des Moines, IA, and St. Louis, MO; they found that the increase in DWR resulted primarily from increasing maximum wind speeds. Our regional-average time series of monthly maximum wind speeds also exhibits an upward trend (0.0056 m s^{-1} yr^{-1}, Fig. 4). More significant for our region, however, is the trend in monthly minimum wind speeds, which decreased by 0.014 m s^{-1} yr^{-1} over the period (Fig. 5). This trend is 2.5 times larger than the trend in maximum speeds, and it accounts for about 70% of the trend in the DWR.

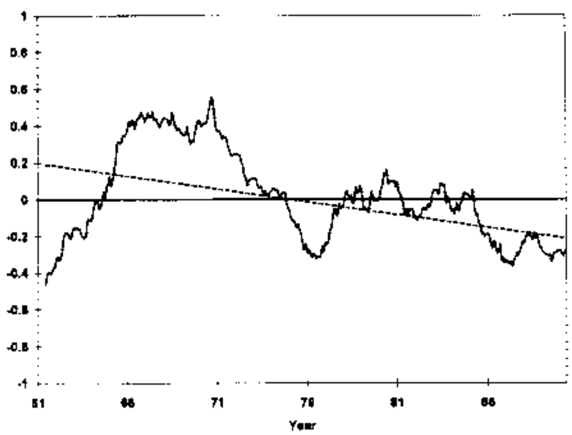

Figure 5. Regional-average monthly minimum wind speed anomalies (1961-1990 baseline) (solid line) and the trend in the monthly minima (dashed line) over the 30-year period. The data have been smoothed using a 12-month moving average.

Table 5. Trends in diurnal wind range.

Station	Change in Velocity†
	cm s^{-1} yr^{-1}
Duluth	23
Eau Claire	-14
Fargo	41
International Falls	- 3.2
Minneapolis-St. Paul	21
Rochester	28
Sioux Falls	40
Average	19

† A velocity of 1 mile per hour = 44.7 cm s^{-1}

Because wind speed is, in part, a function of air temperature, it is possible that trends in maximum and minimum wind speeds, and thus the DWR, are related to observed trends in maximum and minimum air temperatures (Karl et al. 1991). Shein and Robeson (1995) suggested that increasing daytime temperatures were a possible cause of the increasing DWR at the three stations they studied. For our sites, the regional-average DTR increased by 0.0064° C yr^{-1} from 1961 to 1990. Three of the individual station records also showed positive DTR trends: Duluth (0.019° C yr).

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Another possible temperature-related mechanism for changes in the DWR is related to the development of urban heat islands. In a study of wind speed trends in Phoenix, AZ, Balling and Cerveney (1987) reported that wind speeds generally, and minimum speeds in particular (which they assumed to occur at 5:00 a.m. local time), showed a positive trend over their 38-year observation period. Balling and Cerveney related the increase in minimum wind speeds to the development of a well-defined urban heat island at Phoenix. The data for our region, however, suggest that any existing heat-island effects are not large enough to overcome an apparent regional trend toward decreasing minimum speeds. Even at Minneapolis-St. Paul, which is expected to have the strongest heat island, minimum wind speeds exhibit a decreasing trend over the study period of about 0.006 m s^{-1} yr^{-1}.

Wind speed variability may also be related to large-scale changes in atmospheric circulation patterns. For example, Davis and Benkovic (1992) documented a significant expansion of the January circumpolar vortex over eastern North America after 1965. Our study shows an abrupt decrease in the DWR at about the same time (Figure 3), which is related primarily to a sharp decrease in the maximum wind speed (Figure 4). Davis and Benkovic showed that expansion of the vortex produced a change from a zonal (east-west) to a more meridional (north-south) flow, increasing the frequency of Arctic air masses moving southward into eastern North America and possibly changing the frequency and intensity of cyclones and anticyclones passing over the upper Midwest.

Summary

Wind speeds vary over diurnal, annual, and inter-annual time scales. Wind speeds at seven sites in and around Minnesota peak in April and typically reach their minima in mid-summer. Mean monthly wind speeds at these sites average 4.6 m s^{-1}, with individual stations varying by up to 20% from the regional average. The annual range of mean monthly speed varies at individual sites by 1.0 to 1.7 m s^{-1}. Mean monthly maximum wind speeds vary by up to 2.0 m s^{-1}, while mean minimum speeds vary across the annual cycle by less than 1.0 m s^{-1} at each station.

The regional-average mean annual DWR is 5.4 m s^{-1}, with individual sites varying by up to 8% from this value. The DWR has varied markedly between 1961 and 1990, with distinct anomaly periods separated by abrupt shifts occurring over one to two years. The

DWR shows a slight increasing trend over the 30-year period and is related more strongly to decreasing minimum wind speeds than to increasing maxima. The causes of interannual fluctuations and trends in the DWR at these seven stations need further investigation, although long-term trends in maximum and minimum temperatures, the development of urban heat islands, and hemispheric changes in the large-scale circulation are some of the possible mechanisms.

The viability of wind energy investments in the north-central United States depends upon both improved turbine performance and the long-term availability and consistency of wind conditions sufficient to operate wind energy conversion systems. With regard to wind power, our findings have several implications:

- Interannual wind speed fluctuations are nontrivial and investment decisions based on short-term monitoring programs may be more risky than anticipated.
- Large, abrupt shifts in monthly average wind speeds and the DWR show that, for any given month, wind energy production may fluctuate substantially from one year to the next.
- A moderate degree of spatial coherency in wind speeds and the DWR occurs across the seven stations in our study. Therefore, it is reasonable to expect that other wind generation sites within Minnesota will experience interannual fluctuations in wind speed (and thus wind power) similar to the variability observed at these stations.
- Investors in wind energy conversion systems should develop long-term historical information on wind speed and DWR fluctuations and trends in order to more accurately assess the wind energy resource.

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