Characteristics of 50–200-m Winds and Temperatures Derived from an Iowa Tall-Tower Network

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Abstract
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Disciplines
Agronomy and Crop Sciences | Atmospheric Sciences | Geology

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Characteristics of 50–200-m Winds and Temperatures Derived from an Iowa Tall-Tower Network

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(Manuscript received 15 November 2013, in final form 25 July 2014)

ABSTRACT

Limitations in skill of wind speed forecasts lead to conservative bids of wind-plant production in the day-ahead energy market and usually to an underutilization of wind resources. Improvements are needed in understanding wind characteristics in the turbine-rotor layer (40–120 m) for developing refined forecast models. The seasonal and diurnal behavior of wind speed, wind direction, and temperature were analyzed from data taken on five tall meteorological towers across Iowa. Several significant high-shear events, which would have the potential to cause problems by inducing substantial stress on the infrastructure of the wind turbine, were observed, with vertical shear up to 15 m s$^{-1}$ accompanied by $30^\circ$ of directional shear between 50 and 200 m. These events exhibited supergeostrophic wind speeds by 50% through the night followed by a collapse of shear through midday, indicating the influence of an inertial oscillation.

1. Introduction

In 2012, Iowa generated nearly 25% of its electrical power from wind (Iowa Wind Energy Association 2013). The Iowa electrical utility with the largest wind-power capacity has commitments for 39% of its generation capacity to be supplied by wind plants by 2015. Limitations in skill of 54-h forecasts of wind speed lead to conservative bids of wind-plant production in the day-ahead energy market and usually to an underutilization of wind resources. The consequences of this limitation are exacerbated as wind contributes an increasing share of total electrical-energy production.

Iowa has a strong nocturnal low-level jet (LLJ) that produces high wind shear in the lowest 300 m. This condition is not well represented by current boundary layer parameterizations in weather forecast models (Deppe et al. 2013). A better understanding of basic characteristics of wind speed and direction in the rotor layer (40–120 m) is needed to improve boundary layer parameterizations for wind-power forecasts.

The first wind-energy resource characterization for Iowa was reported by McKibben and Davidson (1933) and was based on a study conducted between 1925 and 1931 of 66 wind electric plants. Wind speed data reported from the U.S. Weather Bureau showed a spring (March, April, or May, depending on the year) maximum and an August minimum. A yearlong study was conducted on a single 1-kW turbine with two 5-ft blades on a 100-ft tower (1 ft $\approx$ 0.3 m). This machine produced maximum monthly energy of 140 kWh in March and a minimum of 14 kWh in August.

The earliest known analyses of climatological data on wind and temperature derived from multiple heights above the standard 10-m level are the wind-energy reports of Takle and Brown (1976) and Takle et al. (1978). These studies analyzed 10-min-average wind speed and temperature data from 2, 4, 8, 16, and 32 m on a 32-m tower in Ames, Iowa, summarized seasonal and diurnal characteristics, and provided frequency distributions for all levels.

Two tall-tower studies in states adjoining Iowa also provide context for our study. Redburn (2007) analyzed 8 months of wind observations from tall towers in northwestern Missouri and found that current wind-resource maps gave a good indication of the wind resource despite underestimating observational wind speeds. Klink (2007) reported observations from a network of eleven 70-m towers across Minnesota. She
found spatially consistent periods in above- and below-
average monthly-mean wind speed associated with
large-scale atmospheric phenomena but did not report
information on vertical profiles or diurnal characteristics
of wind and temperature.

The LLJ is known to affect vertical wind shear and
turbulence within the rotor layer, but data have not been
available for Iowa to quantify this effect. We provide
a preliminary analysis of wind speed, wind direction,
wind shear, and temperature within the rotor layer from
data acquired from five 200-m meteorological towers
across Iowa.

2. Data

We analyzed wind speed, wind direction, and tem-
perature data from five tall towers in Iowa. The data
were acquired from the Iowa Energy Center on
CD-ROM. These data were collected at towers located
in Quimby, Palmer, Mason City, Altoona, and Home-
stead (Fig. 1). Each tower had instrumentation at 50,
100, 150, and 200 m that collected data over the period
December 2006–January 2009, except Palmer, which did
not have measurements at 200 m. Each level of the
tower initially had a Met One Instruments, Inc., model
50.5 heated sonic anemometer, an NRG Systems Co.
(now Renewable NRG Systems) model Max 40 three-
cup anemometer and a model 200P wind vane, and
a Campbell Scientific, Inc., model 109 temperature
probe. By the second quarter of 2007, all of the heated
sonic anemometers had failed and were replaced with
NRG Systems model IceFree III cup anemometers
and vanes. An icing event in late 2007 damaged the
instruments at 150 and 200 m in Quimby. These
instruments were not replaced (AWS Truepower 2010).
Automated Surface Observing Systems (ASOS) and
Automated Weather Observing Systems (AWOS)
within 50 km of all tall towers were used to estimate 2-m
temperature, 10-m wind speed, and 10-m wind direction
at the tall towers. ASOS/AWOS data were also used to
determine density. The data have been quality con-
trolled by inserting "NA" values for missing times; for
values such as −999, −990, and so on that indicate an
error; and for occurrences of sudden zero values be-
tween values at least three units larger. Time is given in
local standard time, and the data interval is 10 min.
These data were collected as part of the Iowa Energy
Center wind resource assessment projects and were
available for download from its Internet site (http://
www.iowaenergycenter.org/).

The terrain at the five tall towers varies: the Quimby
tower is in a hilly, rural area with a small river to the
southeast; the Palmer tower is in a flat, rural area with
a lake 10 km to the northeast; the Mason City tower is in
a flat, rural area with a creek to the southeast with the
Mason City urban area to the southwest; the Altoona
tower is surrounded by suburban housing on all sides but
the southeast in a flat area; the Homestead tower is in
a hilly, rural area with the Iowa River just to the north.

3. Wind speed and direction

a. Seasonality

Seasonal and diurnal variations of wind speed and
direction for all four levels on the Homestead tower are
given in Fig. 2. Times at which data were missing at one
or more levels were excluded to eliminate potential bias
(e.g., from icing events for which winds with a northerly
component might dominate). The fraction of winds
eliminated at each level by this procedure was fairly
uniform across all directions and never exceeded 2.3%.

From near-surface wind observations in Iowa, we
generally expect winds to be stronger during the day
and weaker at night and to increase with height. Takle and
Brown (1976) found that 32-m winds were highest
in spring (March–May) and lowest in summer [June–
August (JJA)], which is consistent with the observations
from 50 years earlier as reported by McKibben and
Davidson (1933). From the tall-tower data (Fig. 2), wind
roses show seasonal and diurnal patterns similar to
surface stations, with the notable exception that the
upper levels have strongest winds at night rather than
the daytime as occurs at the surface. Throughout the
data period at all locations, upper levels (150 and 200 m)
have their diurnal maximum wind speeds at night
whereas the lower levels (50 and 100 m) have diurnal
maxima during daytime hours as was also observed by
Takle and Brown (1976). The tall-tower seasonal pat-
terns generally agree with surface data that show
FIG. 2. Daytime and nighttime wind roses at 200, 150, 100, and 50 m at the Homestead tower and the nearest 10-m ASOS site (Cedar Rapids, at the bottom of the figure) separated by season (the labels in parentheses correspond to the first letters of the three appropriate corresponding Northern Hemisphere months).
a summer minimum, but they differ in having a winter (December–February) speed maximum rather than a spring maximum.

A gradual veering of the prevailing winds with increasing elevation can be seen at most sites in all seasons. In addition, perhaps the most notable anomaly is the relatively high frequency of very strong winds with a southerly component at 200 m during the winter, especially at night when 10-m winds from the south are rare and weak. Northwest flow dominates in winter at all levels, but the strongest winds aloft occur with southerly flow. These strong south winds occur when large cyclones exist in the western United States, allowing development of southerly LLJs across the plains.

Data on seasonal wind speed and direction differences give a consensus of a summer (JJA) minimum wind speed difference between all tower levels (Fig. 3). All seasons showed very little (0–1 m s\(^{-1}\)) vertical wind speed difference between 50 and 200 m during the day (0800–1800 LST) with the greatest wind speed difference occurring between 50 and 100 m at night (1800–0800 LST). Vertical wind direction difference exhibited similar behavior, with peak differences between 1800 and 0800 LST.

b. High shear

Throughout the tall-tower network dataset, there were several high- and moderate-shear cases that occurred at night. For the layer between 50 and 200 m we define a high-shear event as a wind speed difference of 15 m s\(^{-1}\) or greater (shear value of more than 0.100 s\(^{-1}\)) and a moderate-shear event as a 10–15 m s\(^{-1}\) difference (shear values of 0.067–0.100 s\(^{-1}\)). These events last approximately 18 h before the shear between the levels collapses. In Homestead, four of these events took place from 3 to 7 October 2007 (Fig. 4). This period was characterized by clear skies and weak pressure gradients from the surface to 500 hPa.

The wind-energy industry frequently uses a power-law relationship to describe wind shear, in which the wind speed \(u_2\) at height \(z_2\) is related to the wind speed \(u_1\) at height \(z_1\) by

\[
\frac{u_2}{u_1} = \left( \frac{z_2}{z_1} \right)^\alpha
\]

(1)

and the wind power-law exponent \(\alpha\) is typically considered to be a value near \(\frac{1}{7} = 0.143\). In Fig. 5 we summarize the diurnal variation of the power-law exponent over the layer occupied by the typical utility-scale wind turbine (50–150 m) for all five sites and all seasons. Data from all towers agree very well with diurnal and seasonal patterns of \(\alpha\) from the 32-m tower in Ames (Takle and Brown 1976); note, however, that the commonly used value of \(\alpha = 0.143\) is a poor estimate of the power-law exponent in Iowa. Case studies performed by Kelley et al. (2004) found that there can be “challenging flow conditions” for turbine operations within the rotor layer when the mean hub wind speed is between 8 and 13 m s\(^{-1}\), the layer is critically stable \([0 < Ri < 0.25, \text{ where } Ri \text{ is Richardson number (see section 4 for definition)}]\), and the power-law exponent is larger than 0.2. By using the Kelley et al. (2004) criteria for what constitutes challenging flow conditions, we find that the Iowa sites experienced such conditions approximately 25% of the time (37% for Altoona, 26% for Homestead, 26% for Mason City, 22% for Palmer, and 22% for Quimby).
During high- and moderate-speed shear events, there is also directional shear between 50 and 200 m for the same duration, with veering (clockwise rotation with height) of up to 50°. Careful examination of the wind speed time traces during high-shear periods reveals occasional speed fluctuations of order 1 m s\(^{-1}\) and periods of order 1 h or less that correlate with height. In some cases a concurrent signature in the wind direction trace is visible and sometimes also in the 200-m temperature trace. These may indicate passage of gravity waves in the stable medium of the nocturnal boundary layer that are similar to those observed by Sun et al. (2004).

We computed the surface geostrophic wind at the Homestead tower by estimating the pressure gradient using a finite-difference scheme in which the pressure was determined with the Barnes objective analysis scheme (Barnes 1964) at points that are located 80 km away in all cardinal directions from the tall tower. The elevation at these four points differs from the elevation at the tower by no more than 80 m so that this method introduces minimal error. Density in the calculation was determined using temperature interpolated from nearby ASOS/AWOS stations (within 50 km of the tower) and the Barnes-scheme interpolated value of pressure. The following equation was used for geostrophic wind:

$$V_g = (u_g^2 + v_g^2)^{1/2}, \quad (2)$$

where

$$u_g = -\frac{1}{f \rho} \frac{dp}{dy} \quad \text{and} \quad v_g = \frac{1}{f \rho} \frac{dp}{dx} \quad \text{and} \quad (3)$$

![Fig. 4. Wind speed, wind direction, temperature, and Ri at Homestead from 3 to 7 Oct 2007.](image1)

![Fig. 5. Diurnal variation of 50–150-m power-law exponent annually and by season at each tall tower: Altoona (solid lines), Homestead (dashed lines), Mason City (dotted lines), Quimby (dot-dashed lines), and Palmer (long-dashed lines). Each station uses the same colors that are indicated in the legend for the seasons.](image2)
\[ f = 2\Omega \sin \phi, \]  
(4)

with \( \mathbf{v}_g \) defined as the geostrophic wind vector with components \( u_g \) and \( v_g \). In these equations, \( p \) is pressure, \( \rho \) is air density, and \( f \) is the Coriolis parameter, with \( \Omega \) being constant at \( 7.292 \times 10^{-5} \text{ s}^{-1} \) and \( \phi \) being the latitude. We discovered that during high-shear events 200-m winds are supergeostrophic by up to 50% and veered from the geostrophic in direction by up to 30° toward high pressure. These results are similar to the findings of Sun et al. (2013) in which near-surface wind blew toward high pressure 50% of the time. After morning heating, the winds collapse to subgeostrophic levels. The changes in speed and direction of the wind relative to the geostrophic wind are consistent with an inertial oscillation, which continues throughout the high-shear period, suggesting that this process has a role in sustaining these events.

4. Temperature

Absolute temperature differences between 50 and 200 m were observed to be about 2°C most of the time, with little to no temperature differences around 1200 LST, maximum positive temperature differences (warmer at 50 m than at 200 m) around 1800 LST, and maximum negative temperature differences (cooler at 50 m than at 200 m) occurring around 0600 LST, matching the trend of 2-m temperatures. Throughout the data period, temperature inversions were noted most nights. During high-shear events, the inversions were large, with 50–200-m temperature differences reaching near 5°C. In Fig. 4 the nocturnal temperature inversion establishes at almost exactly 1800 LST on the last three days, although a little later on the first day. This is 14–17 min after sunset on these days at this location. The inversion collapses at ~0730 LST (15 min after sunrise) the last two mornings but approximately 1.5 h later (1.83 h after sunrise) the first two mornings. The shear in wind speed starts to increase approximately 2 h before the onset of the inversion.

The Richardson number was calculated between each layer as

\[ \text{Ri} = \frac{g}{T_v} \left[ \frac{d \theta}{dz} \right]^2, \]  
(5)

where

\[ \frac{d \theta}{dz} = \frac{dT}{dz} + \Gamma_d. \]  
(6)

Here \( g \) is gravity and is held constant at 9.81 m s\(^{-2}\), \( T_v \) is virtual temperature and is held constant at 294 K, \( \theta \) is the potential temperature, \( T \) is the temperature, \( z \) is the height, \( \Gamma_d \) is the dry adiabatic lapse rate with a value of \(-9.8 \text{ K km}^{-1}\), and \( V \) is the wind speed. During these events, \( \text{Ri} \) followed the expected trend of being negative during the day and positive at night. Careful examination of changes in the wind profile with changes in \( \text{Ri} \), using 50- and 150-m levels to represent \( \text{Ri} \) across the layers occupied by wind turbine blades (Fig. 6), reveals abrupt changes in wind shear with small absolute values of \( \text{Ri} \), likely due to turbulent mixing that leads to a reduced vertical temperature gradient and a wind shear increase with decreasing \( \text{Ri} \). In fact, we considered the strong and abrupt response of the wind shear to seemingly small changes in \( \text{Ri} \) (e.g., temperature gradient) to be remarkable and a strong incentive to refine the details of temperature forecast models for the lowest 300 m.

5. Conclusions

Improvements in understanding characteristics of wind and temperature in the lowest 200 m of the atmosphere will provide opportunities for improving weather forecast models designed to simulate wind speeds in the vicinity of wind farms. Periods of high wind resource in Iowa frequently are accompanied by temperature inversion and strong wind shear that both are difficult to forecast and may lead to structural damage to blades and other wind turbine components. We found wind shear events with mean wind of \(-15 \text{ m s}^{-1}\) and wind shear of \(0.100 \text{ s}^{-1}\) to occur in clear conditions with \( \text{Ri} \) near 0.2 and temperature inversions from 50 to 200 m of near 5°C. The data we have provided may be good case studies for developing simulation models that are needed to more accurately forecast periods of high wind resource but also periods of high potential damage to wind turbine components. Work in progress seeks deeper understanding of these high-shear events along with ramp events and their spatial consistency across Iowa.
Acknowledgments. The authors acknowledge the Iowa Energy Center for providing wind and temperature data obtained during performance of its “Tall Tower Investigation of Midwest Wind Patterns” project that was funded, in part, with a grant from the U.S. Department of Energy for the State Energy Program. Partial support was provided by the National Science Foundation under the State of Iowa EPSCoR Grant 1101284.

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