4.6 APPLICATION OF HIGH RESOLUTION DOPPLER LIDAR DATA FOR WIND ENERGY ASSESSMENT.

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1. INTRODUCTION

The formation of a Low-Level Jet (LLJ) in the stable mixed layer during nighttime is very important to wind-energy operations. LLJs occur frequently at the site to the south of Lamar, Colorado, in the southeastern corner of the state, particularly during the period of April - September (Kelley et al. 2004)

Based on measurements over southeastern Kansas during CASES-99 (Banta et al. 2002, 2003), shear generated below a nocturnal LLJ may have an important role in regulating near-surface turbulence and fluxes in the stable boundary layer. The atmospheric waves and turbulence produced by shear can cause strong vibration in turbine rotors. It has been suggested that these vibrations can contribute to premature failures in large wind turbines (Kelly et al. 2004), which, of course, would be a considerable disadvantage for wind-energy applications.

To obtain detailed information about LLJ characteristics and the turbulence environment in which large General Electric (GE) wind turbine rotors were being installed, an intensive field-measurement campaign was carried out in early September 2003 at this site. Instrumentation included a 120-m tower instrumented at 4 levels and a 3-component Doppler sodar, which were in operation for two summers, and ETL's high resolution Doppler lidar (HRDL), which was deployed from September 1 through 16. Approximately 120 hours of HRDL data were collected at nighttime from local sunset (0:00 UTC) until sunrise (10:00-11:00 UTC) for eleven nights.

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2. OBJECTIVES

The main objectives of the study include the following:

- Investigate wind-speed and turbulence conditions within the atmospheric layer occupied by turbine rotor and up to 200 m.
- Examine the role of the LLJ in generating shear below the jet speed maximum and the distribution of the shear exponent.
- Determine the ability of a HRDL for wind resource assessment up to heights of 200 m above ground level.

3. LLJ CHARACTERISTICS

In this study we use the term LLJ to refer to any wind speed profile that shows a first clear maximum below 500 m and a decrease of speed by at least 1.5 ms^{-1} both above and below the maximum (Andreas et. al. 1997). The ability of HDRL to study the LLJ shown by Grund et al. (2001) and Banta et al. (2002), and the importance of the LLJ for wind energy applications was also mentioned by Banta et al. (2002).

Analysis of 15-min wind speed profiles derived from both conical and vertical-slice scans, employing data processing techniques, (Newsom and Banta, 2003), shows that LLJ structure was present in 86% of all data collected during the experiment.

To determine the role of the LLJ for wind energy applications, we calculated LLJ characteristics within the atmospheric layer of 45-115 m occupied by GE wind turbine rotors. Since the wind turbines projected for the future will extend to higher elevation, we also included in our search the layer of 45-200 m., as well as the layer between surface and 500 m.

The distributions of frequency of occurrence of jet speed U_X (top) and jet direction D_X (bottom) are presented in Figure 1, where different atmospheric layers are indicated by different colors. All jets observed (94.5%), were within the layer between the surface and 500 m (entire layer of jet occurrence), and with a largest speed mode in a range of 9-11 ms^{-1} and a second noticeable mode of 18-19 ms^{-1}. Nearly 56% of all jet maxima happened between 45-200 m and only 23%

happened in a layer of turbine height with a maximum speed mode of 10-11 ms^{-1}.

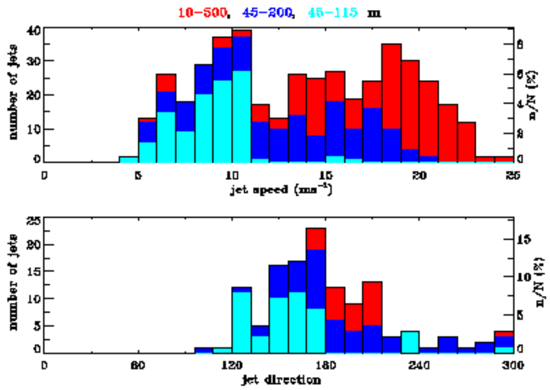

Figure 1. Histograms of jet speed Ux (top) and jet direction Dx (bottom) for 15-min means derived from both conical and vertical-slice scans. Percentages of occurrences in each bin are shown along left vertical axis, and total number of occurrences in each bin is indicated along the right vertical axis. The atmospheric layers of 10-500, 45-200, and 45-115 m are indicated by different colors.

The histogram of LLJ wind direction indicates a very narrow range of prevalent wind directions (160-180) with a maximum of 170 degrees over the LLJ layer. Similar results were found at the Lamar site in September 2002 as described by Kelly et al. (2004). The sonic anemometer data revealed most frequent wind directions of 160-200 degrees. The primary LLJ directions at Lamar are also consistent with prevalent southerly wind directions over Great Plains found by Banta et al. (2002) during the Cases-99 experiment.

3.1 Inertial oscillations

The high resolution of lidar data allows the analysis of the spatial structure of wind and its evolution through the night in great detail. The mean wind speed and direction, calculated from conical scans and averaged over 15-min time intervals, are presented in Figure 2 (a). Figure 2 (b) shows the mean winds and directions calculated from sonic anemometer data at tower levels of 54, 67, 85 and 116 m, and linearly extrapolated from those levels up to 200 m. CASES-99 results (Banta et al. 2002) and preliminary analysis of Lamar data indicate that the wind-speed profile is often close to linear trough much of the layer below the LLJ maximum. The arrows indicate the direction of wind flow, and the color indicates wind speed magnitude from 0 (green) to 20 ms^{-1} (red). Both instruments show approximately 6 hours (from 3:00 till 9:00 UTC) of very strong wind above the level of turbine top, and noticeable veering of wind direction from south to southwest.

Profiles of the jet speed (a) and direction (b), averaged over 1-hour time intervals, are shown in Figure 3. This example clearly demonstrates an increase of jet speed through the night, with the maximum about nine hours after local sunset (8:00 - 9:00 UTC), and clockwise turning of wind.

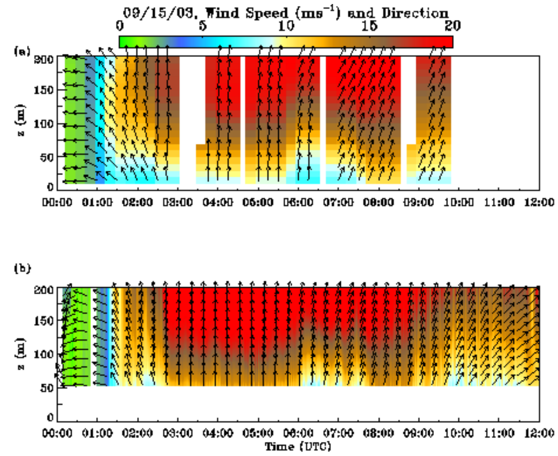

Figure 2. The mean winds and directions, calculated from 15-min means of HRDL conical scans (a), and the mean winds and directions, calculated from sonic anemometer data at tower levels of 54, 67, 85 and 116

A diurnal clockwise turning in wind direction and an oscillation in speed with a period very close to period of inertial oscillations (18.4 h) calculated at the latitude of the Lamar site was also mentioned by Kelly et al. (2004).

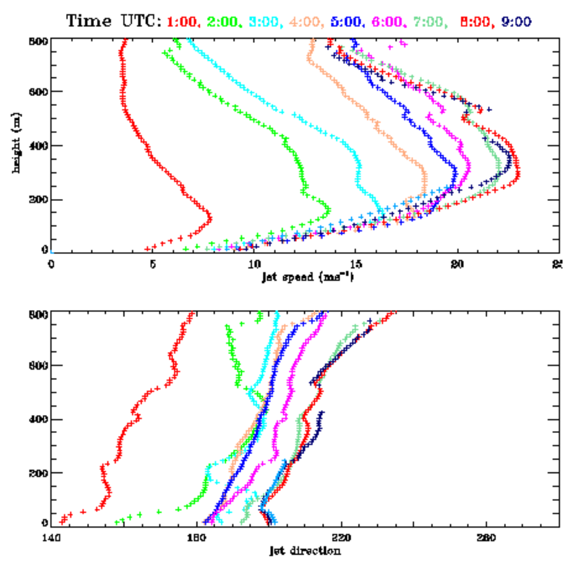

Figure 3. Profiles of 1-hour mean (a) wind speeds and (b) wind directions derived form conical scans on 09/15.

3.2 Importance of wind speed

The vertical structure of the wind field can be analyzed in terms of a time-height cross section of wind profiles, determined from vertical-slice scan data (Banta et al. 2002) and shown in Figure 4 for the sample night of September 15.

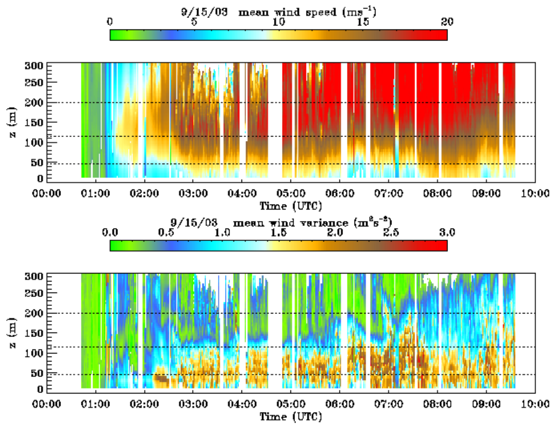

Figure 4. Sample time-height cross sections of mean wind speed (top panel) and variance of the radial wind component (bottom panel) calculated from HRDL vertical-slice scans during night of September 15.

Each vertical line represents a profile of wind speed or variance averaged in 10-m vertical bins. Dotted lines indicate the top (115 m) and bottom (45 m) of a turbine rotor up to the 200 m level. Figure 4 demonstrates an increase in wind speed from bottom to the top of the turbine and a decrease in wind-speed variance.

For further analysis, we used the HRDL velocity data to determine how wind speeds were distributed as a function of height over height intervals that would affect wind turbine operations. Histograms of the mean wind speed, wind-speed standard deviation, and turbulence intensity (TI=σ/U(z)) at the height of 45, 80, 115, and 200 m, combined for eleven nights, are shown in Figure 5 (a)-(c), respectively. Distributions of variables in each histogram interval have been slightly displaced, in order to show four histograms together. It shows that for the entire data set mean wind speed shifted from a largest mode of 8-10 ms^{-1} toward stronger wind speeds of 14-16 ms^{-1} as height increases. The largest mode in speed variance distributions decreased with height from a mode of 1.2-1.4 m^2s^2 at the lowest level to a mode of 0.6-0.8 m^2s^2 at the highest level, supporting the idea that the flow tends to be smoother at higher levels of the nocturnal boundary layer.

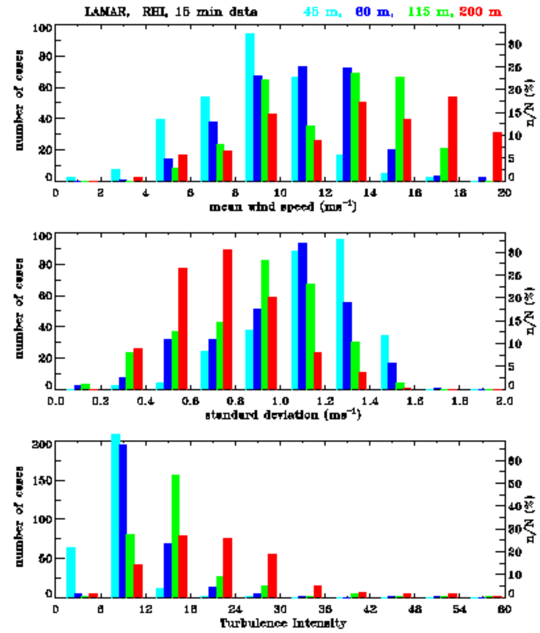

Figure 5. Histograms of the mean wind speed, wind speed standard deviation, and turbulence intensity at the height of 45, 80, 115, and 200 m combined for the eleven nights of September 2003 during a HRDL measurements from 0:00 till 10:00 UTC.

To investigate turbulence magnitude that can be produced by strong winds, we plotted wind speed standard deviation at the 45-, 80-, 115-, and 200-m as a function of mean wind speed at those heights (Figure 6.) Best linear fits for each elevation are indicated by solid lines of different color. Also, this figure shows plots of two turbulence levels "A' and "B", defined by International Electrotechnical Commission (IEC, 1998).

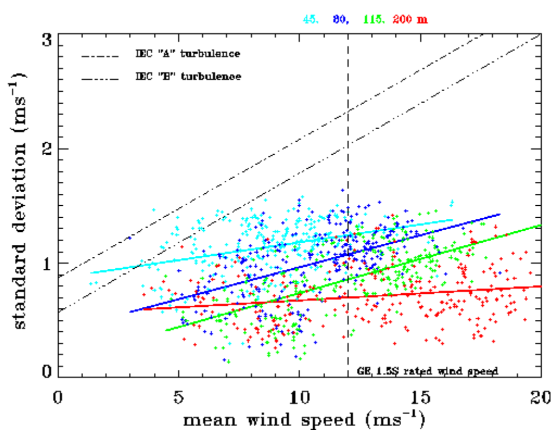

Figure 6. Wind speed standard deviation at the heights of 45-, 80-, 115-, and 200-m as a function of mean wind speed at those heights. Two dotted lines are indicate the turbulence levels "A' and "B" Data were averaged over 15-min time interval.

As shown in the Figure 6, turbulence at all heights are much lower than IEC specifications and exceed level "B" at 45-m height with wind speeds less than 2.5 ms^{-1} These results suggest that turbine operations would not have been affected by the turbulence conditions observed during the experiment

3.3 Vertical shear

Besides providing strong winds for wind energy production, LLJ can create intense vertical shear within the layer occupied by a turbine rotor. The magnitudes of the shears between two atmospheric layers in terms of the shear exponent could be calculated as:

$$\alpha = \ln(U_2/U_1)/\ln(z_2/z_1)$$

where U_1 and U_2 are the mean wind speeds at the heights z_1 and z_2, respectively.

The IEC Standard (IEC,1998) defines the Normal Wind Profile (NWP) as having a shear exponent of 0.2 and rated wind speed for turbine operations near 12 ms^{-1}.

Distribution of the shear exponent between layers of 45-115 and 45-200 m, based on 15-min means of wind speed for entire period of HRDL observations (Figure 7, a-b), indicate a dominant mode of 0.40-0.45 within the turbine layer and broader distribution within the layer 45-200 m with relatively even modes of 0.10-0.15, 0.20-0.25, and 0.3. The results are slightly different from those that were obtained at the Lamar site in September 2002 as described by Kelly et al. (2004).

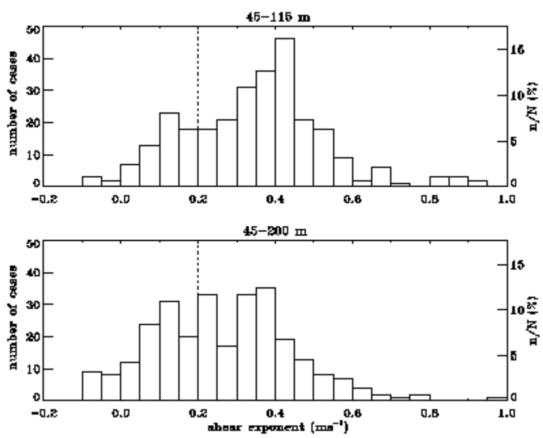

Figure 7 Distribution of the shear exponent between layers of 45-115 and 45-200 m, based on 15-min means of wind speed derived from vertical slice scans for the entire period of HRDL observations.

The shear exponent calculated between 52 and 113 m by cup anemometer data, showed a maximum peak at 0.2 and a slight secondary maximum at about 0.4. The differences may be due to the fact that eleven nights are not the best representation of an entire month of September 2003 or that the averaging of lidar data in 10-m vertical bins might increase the shear exponent.

Profiles of the wind-shear exponent, calculated using a 10-m height increment and averaged over a 1-hour time interval during the evening (top panel) and early morning (bottom panel) hours of September 15, are shown in Figure 8, where the extent of turbine rotors and 200 m are indicated by the dashed lines. The maximum of the shear exponent varies with time and height and reaches the maximum peak near local midnight (5:00-6:00 UTC) at the level close to the half of turbine height.

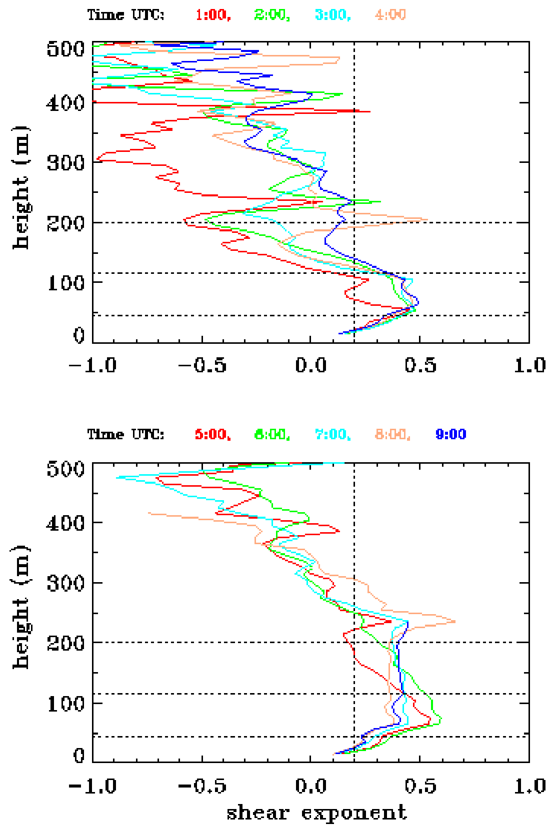

Figure 8. Profiles of wind shear exponent, averaged over 1-hour time interval, during the evening (top panel) and early morning (bottom panel) hours of September 15.

3.4 Jet Richardson number estimates

To investigate how often the flow can become turbulent, we calculated a dynamic stability and Richardson number (Ri) by 1-min means of sonic anemometer data between 54 and 116 m tower levels presented in Figure 9 (a) and (b). Also shown in Figure (b), is a bulk jet Richardson number (Rij), where the shear in the denominator is estimated from the speed and height of the jet (Banta et al. 2003). Almost 6 hours during the night of

September 15, both Ri and Rij remained in the critical range (0 < Ri < 0.25) and static stability oscillated between 0.025 and 0.040 K/m.

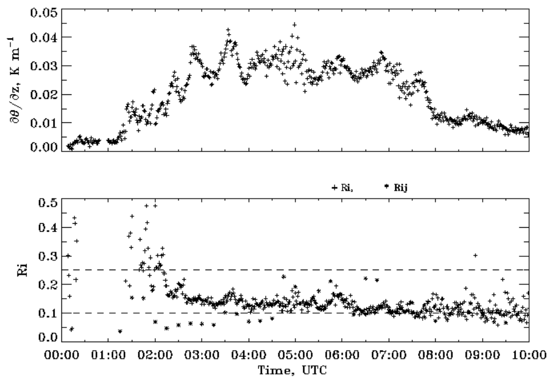

Figure 9. A dynamic stability and gradient Richardson number (Ri), calculated by 1-min means of sonic anemometer data between 54 and 116 m tower levels, and a bulk jet Richardson number (Rij), calculated by 15-min means of LLJ shear for the night of September 15

The distribution of Ri (a) and Rij (b) for the set of eleven nights presented in Figure 10 indicates a similar picture. Both instruments show the most frequent occurrence of Richardson number within the critical range, with largest peak of 0.10-0.15 and 0.05-0.1 for Ri and Rij, respectively.

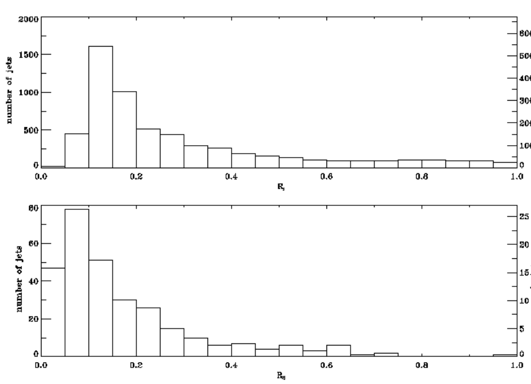

Figure 10. The distribution of gradient Richardson number (Ri), calculated by 1-min means of sonic anemometer data between 54 and 116 m tower levels (top), and a bulk jet Richardson number (Rij), calculated by 15-min means of LLJ shear for the set of eleven nights (bottom).

4. CONCLUSIONS

- Nocturnal Low-level jets occur frequently at the Lamar site with a prevalent jet direction of 160-180 degrees.
- Histograms of the mean wind speed show a shift of the largest peak toward stronger wind speeds with height increase and a smoother wind flow at higher levels of the nocturnal boundary layer.
- The observed mean turbulence level (wind speed standard deviations) at heights of 45, 80, 115 and 200 m remained below both IEC "A" and "B" specifications.
- The distribution of the shear exponent over the rotor layer (45-115 m) and the 45-200 m layer exceeds the IEC standard of 0.2 in most cases (53%).
- In most cases, both Richardson number (Ri) and jet bulk Richardson number (Rij) remained within a critical range 0-0.25 for the entire data set.

5. REFERENCES

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