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5.5 LIDAR MEASUREMENTS OF EXTREME INFLOW EVENTS FOR WIND ENERGY OPERATIONS

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1. INTRODUCTION

Extreme events such as wind gusts, rapid wind direction changes, or passage of energetic atmospheric fronts impose critical loads on wind turbines. Scanning lidar measurements of line-of-site (LOS) wind speed, with high resolution in time and space, can provide detailed information about the spatial and temporal structure of atmospheric events considered extreme or anomalous for the wind energy operations.

Better knowledge of long-term wind conditions at wind-farm sites and accurate estimates of wind characteristics (speed, direction, turbulence) at the heights of modern turbine rotors, along with improved turbine engineering and technology, will accelerate the deployment of wind energy systems.

At present, there is a need for data that adequately describe the atmospheric boundary layer structure up to 150-200 m, where some modern wind turbines reside. Tall meteorological towers used in wind-energy studies may reach 120-160 m. Installation of such towers and instrumentation by several cup or sonic anemometers takes time, and they are expensive to deploy. Extrapolation of near-surface wind measurements to higher altitudes is often not very accurate and does not reliably reflect the true vertical structure of the wind field. In contrast, data from operational wind-profiler and scanning radars do not extend low enough to span the turbine heights. Therefore remote sensing instruments such lidars appear to be a good alternative for wind-energy needs: they can provide continuous measurements at turbine heights and are easy to install.

The High-Resolution Doppler Lidar (HRDL), a scanning system designed and developed at the National Oceanic and Atmospheric Administration (NOAA) Earth System Research Laboratory (ESRL), has been highly effective in the study of dynamic processes in the atmospheric boundary layer (ABL) because of its temporal and spatial resolution (Grund et al., 2001).

This paper discusses the results of HRDL measurements of the mean wind and turbulence characteristics of the flow for several nights from the Lamar Low-Level Jet Program (LLLJP) in southeastern Colorado in September 2003.

As a part of an ongoing effort to extract quantities of interest for wind-power meteorology, lidar data obtained in 2003 is examined in this paper to characterize rapid wind speed and wind direction change associated with a cold front passage, occurred during the night of September 13.

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2. MEASUREMENTS

Southeastern Colorado is characterized by frequent, strong winds during all seasons of the year, and thus has a high wind resource potential to drive wind turbines. In 2004, 108 wind turbines were installed at the Colorado Green Wind Farm about 20 miles south of the town of Lamar. Each turbine produces 1.5 megawatts of electricity for a potential combined power of 166 MW. These turbines have 70-m diameter wind rotors and a hub height of 80 m AGL. To understand the impact of turbulence in the wind field on these turbines requires a knowledge of the wind and turbulence profiles up to about 115 m and higher for some modern turbines.

Two years prior to the wind-farm development, a study of the wind and turbulence environment was conducted by collaborative efforts between the U.S. Department of Energy (DOE), National Renewable Energy Laboratory (NREL), and General Electric (GE) using data from an acoustic wind profiler (sodar) and sonic anemometers installed at four levels of a 120-m tall meteorological tower.

NOAA/ ESRL joined the program for the first half of September 2003 and deployed HRDL to the site to determine mean and turbulent wind structure, at heights of interest for wind energy. Detailed information on the observational site, instrumentation, processing techniques, and inter-comparison of data measured by different instruments can be found in Kelley et al. (2004, 2007), Pichugina et al. (2008).

3. DATA ANALYSIS

The flexibility of lidar to perform conical, vertical-slice or fixed-beam measurements, allows investigation of a variety of boundary-layer characteristics and wind-field structure from different points of view, for example as mean wind and turbulent profiles, time series, or as images of individual scans to reveal flow features at turbine height and above the range of tower measurements.

During the period of the HRDL observations at the Lamar site, the observed wind speeds ranged from 5 m s^{-1} to 25 m s^{-1} with the highest probability of 17-18 m s^{-1} in the distribution histogram (Pichugina et al., 2004). Several nights were characterized by strong (>15 m s^{-1}) low-level jet (LLJ) winds from late evening (1-2 UTC) up to early morning (~10 UTC). Occasionally there were periods of moderate (10-15 m s-1) and calm (<10 m s^{-1}) winds. Only one night (12 September), was characterized by very calm winds, as described below in the paper. Hub-height wind speeds were, in most cases, 15-25 m s^{-1}, which is much stronger than nominal “rated” wind speeds (11-12 m s^{-1}) for modern multi-megawatt turbine operations according to International Electro-technical Committee (IEC) specifications.

To demonstrate the evolution of wind and turbulence from night to night, Figure 1 shows time-height cross sections of (top) mean horizontal wind and (bottom) wind variance for the sequence of four nights (September 12, 13, 15, and 16). Vertical dotted lines in both panels separate each night.

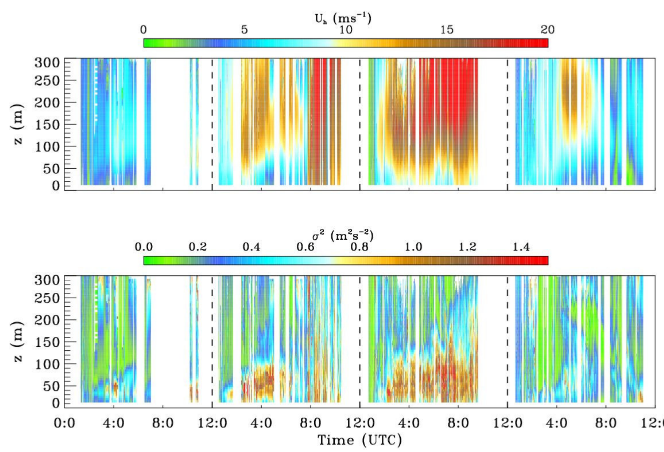

Figure 1. Time-height cross sections of (a) mean horizontal wind and (b) variance calculated from HRDL measurements during four nights in September 2003. Each vertical line represents a vertical profile of the UH derived from individual vertical-slice scans by averaging data over 1 min and within 5-m vertical bins.

This figure illustrates significant differences in the magnitude of wind and turbulence for these nights. The magnitude of the turbulence can be estimated by HRDL-measured values of the horizontal (streamwise) velocity variance, which was shown to be numerically equivalent to turbulence kinetic energy (TKE) for stable conditions (Banta et al. 2006; Pichugina et al. 2008).

On the first night (September 12) the winds were weak (less than 5-7 m s^{-1}) and low turbulence was observed all night up to 300 m, except for a very short period of the time around 4:00 UTC, when turbulence increased to 0.6 m^2 s^{-2} at ~50 m AGL.

During the next night (September 13), a cold front passed through the observational site, resulting in a rapid change of wind speed and wind direction. Hub-height winds increased from 10 to 25 m s^{-1} and direction changed more than 120° as shown in Figure 2. Strong shear developed between the surface and the height of maximum in the wind profile generating strong turbulence in this layer (Mahrt and Vickers 2002; Banta et al. 2003, 2006), which increased to ~1.5 m^2 s^{-2}. The height of the LLJ maximum extended from ~100 m to ~200-250 m resulting in increased boundary layer heights (Banta et al., 2006).

No lidar measurements were made on the night of September 14 due to heavy rain, however sonic anemometer data show very high winds and turbulence all the night long.

During the night of September 15 the LLJ wind speed was greater than 15 m s^{-1} with strong turbulent variances of 1.2-2.0 m^2 s^{-2} most of the time.

LLJ winds and turbulence were less intense on September 16. The wind speed was between 5 and 10 m s^{-1} with a short period (~4:40-6:30 UTC) of stronger (~12 m s^{-1}) winds at 100-300 m. Turbulent variances were less than 0.6 m^2 s^{-2}.

These contrasting nights, identified as "low-wind", "high-moderate-wind", "high-wind", and "low-moderate-wind" nights according to the classification in Banta et al. (2002), were selected to illustrate different boundary layer conditions that can be a big challenge for numerical model simulations of wind and turbulence at turbine heights.

4. EXTREME EVENT

Rapid changes in wind speed cannot be followed by the wind turbine, thus might not contribute to power production. Modern turbines are designed so that the turbine yaw should be locked with a disk-brake after the wind speed surpasses a predetermined cut-out limit. However, there are some examples worldwide when the yaws still were moved when the wind speed exceed 25 m s^{-1}. As a result, turbines suffered larger wind load than they were designed to take.

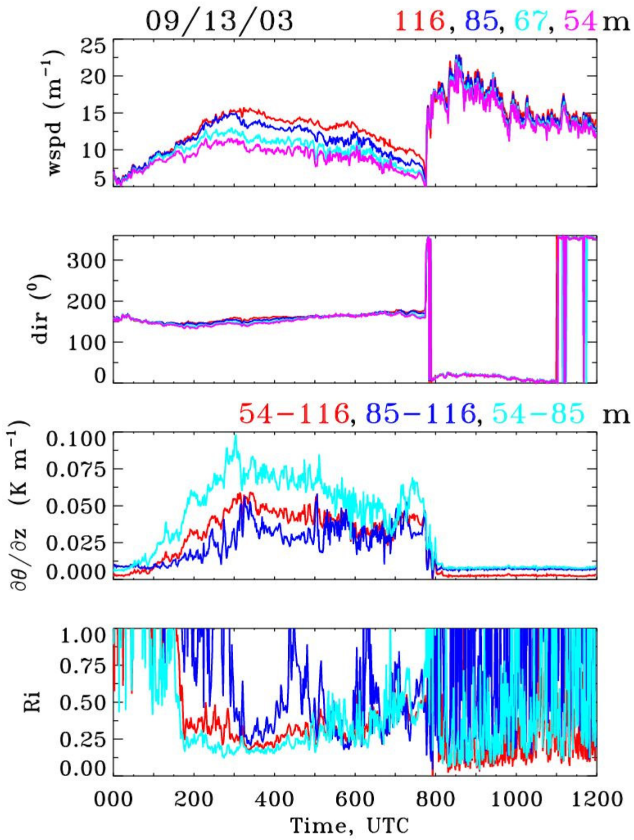

Figure 2. Sonic anemometer measured change in (from top to bottom) wind speed, wind direction, stability, and Richardson number during the night of September 13. Data averaged over 1 min. Different colors indicate data at four tower levels of 54, 67, 85, and 116 m. Passage of a rapidly moving cold front is evident just before 0800 UTC.

Figure 2 (top panel) illustrates abrupt wind speed changes from 5 m s^{-1} to 18 m s^{-1}

recorded by sonic anemometers at four tower levels during the frontal passage on September 13. Data, shown in the Figure, were averaged over 1 min to better demonstrate nighttime evolution of (from top to bottom) wind speed, wind direction, stability, and Richardson number (Ri). Data averaged over 1 sec (not presented here) show correlated abrupt changes in these time-series during the event for the duration of the time less than 10 sec. Such a big change of a wind speed (more than 10 m s^{-1}) over a small period of time is defined as a gust. Levels of wind speed and direction are shown by different colors corresponding to the legend on the top panel, while layers for which stability and Rib were computed are represented by the colors as in the legend on the third panel.

Figure 3 demonstrates similar results from HRDL vertical-slice (top) and conical (bottom) LOS velocity measurements. The top panel of the Figure shows averaged over 1 min time-height cross sections of mean horizontal wind for the night of September 13 to demonstrate the abrupt wind change at ~ 0800 UTC in finer detail than in Figure 1.

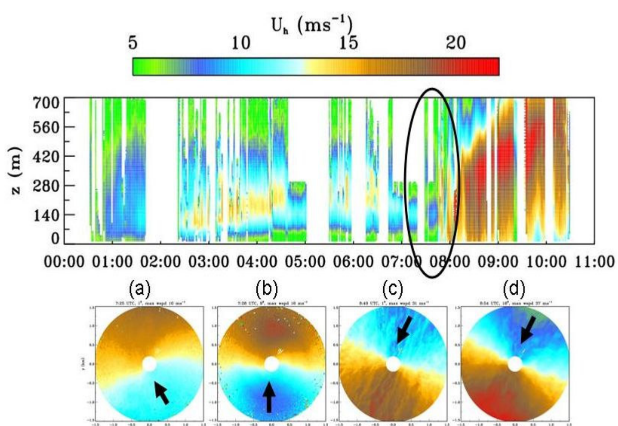

Figure 3. Time-height cross sections of (top) mean horizontal wind computed from HRDL vertical-slice scans and (bottom) conical scans. Two scans (a and b) were obtained before the event at ~ 0800 UTC, and two scans (c and d) were obtained after the event. Arrows show the wind direction

The lower panel of the Figure shows LOS wind speed measurements made while performing conical scans (0-360° in azimuth and at fixed shallow elevation angles between 2 and 16°. The panel illustrates two scans obtained before the event: (a) 0725 UTC, elevation angle of 1°, and maximum wind speed of 10 m s^{-1}; (b) 0728 UTC, elevation angle of 9°, and maximum wind speed of 16 m s^{-1}. The next two scans were obtained after the event: (c) 0840 UTC, elevation angle of 1°, and maximum wind speed of 30 m s $^{-1}$; and (d) 0854 UTC, elevation angle of 16°, and maximum wind speed of 37 m s $^{-1}$. The prevalent wind direction, indicated in (a)-(d) by arrows, changed ~120 degrees during the event.

5. CONCLUSIONS

- Accurate estimates of the dynamics and nighttime evolution of wind and turbulent quantities through remote sensing measurements provide a better understanding of atmosphere-turbine interactions under nighttime stable conditions and offer wind-farm developers needed information for decision-making important to the success of wind energy.
- Continuous lidar measurements may be an efficient alternative to measurements from tall-tower instrumentation, which may not be tall enough to provide a reasonable picture of the wind field at the required heights.
- Lidar measurements, with high resolution in time and space, can also provide detailed information on atmospheric events considered extreme or anomalous for wind energy operations.

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REFERENCES

Banta, R.M., Y.L. Pichugina, and W.A. Brewer, 2006: Turbulent velocity-variance profiles in the stable boundary layer generated by a nocturnal low-level jet. *J. Atmos. Sci.*, **6**2, 2700-2719.

Banta, R.M, Y.L. Pichugina, and R.K. Newsom, 2003: Relationship between low-level jet properties and turbulence kinetic energy in the nocturnal stable boundary layer. *J. Atmos. Sci.*, **60,** 2549-2555.

Banta, R.M., R.K. Newsom, J.K. Lundquist, Y.L. Pichugina, R.L. Coulter, and L. Mahrt 2002: Nocturnal low-level jet characteristics over Kansas during CASES-99. *Bound.-Layer Meteor.*, **105**, 221-252.

Grund, C. J., R. M. Banta, J. L. George, J. N. Howell, M. J. Post, R. A. Richter, A. M. Weickmann, 2001: High-resolution Doppler lidar for boundary layer and cloud research. J. *Atmos. Oceanic Technol.*, **18**, 376-393.

Kelley, N.D., B.J. Jonkman, G.N. Scott, Y. L. Pichugina, 2007: Comparing Pulsed Doppler LIDAR with SODAR and Direct Measurements for Wind Assesement. *NREL/CP-500-41792*, Golden, CO: National Renewable Energy Laboratory

Mahrt, L., and D. Vickers, 2002: Contrasting vertical structure of nocturnal bounady layers. *Bound.-Layer Meteor.*, **105**, 351-363.

Pichugina, Y.L., R.M. Banta, N.D., W.A. Brewer, N.D. Kelley, R.K. Newsom, and S.C. Tucker, 2008: Horizontal-velocity and variance measurements in the stable boundary layer using Doppler lidar: Sensitivity to averaging procedures, *J. Atmos. Ocean. Technol.*, **24**, 1307-1327.

Pichugina, Y.L., R.M. Banta N. D. Kelley, 2007: Analysis of the southern Colorado Low-Level jet by high resolution Doppler Lidar data. Comparison to the Great Plains LLJ climatologies. 3^{d} Symposium on Lidar Atmospheric Applications, San Antonio, TX