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Doppler lidar measurements of the Great Plains low-level jet: Applications to wind energy

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Abstract. The southerly low-level jet (LLJ) of the Great Plains of the United States is a recurrent flow feature of the nighttime boundary layer of the region, which has been identified as a region of high potential for wind energy. The acceleration of the LLJ after sunset produces an enhancement of the wind speed over daytime values, and provides a dependable resource for wind energy. On the negative side, occasional bursts of strong turbulence may be generated that can be of just the right frequency to excite strong oscillatory response in the turbine rotors, thereby accelerating the fatigue of the rotor parts. High resolution Doppler lidar has been used in two studies of the LLJ over the U.S. Great Plains. In this paper we show the usefulness of this remote sensing tool in documenting the mean and turbulent vertical structure, and the evolution of these vertical structures through entire nights. This leads to implications about potential usefulness of Doppler lidar in monitoring mean winds and turbulence in real time to aid in turbine operations.

One of the major wind-energy resource regions in the United States (U.S.) is the Great Plains, extending in a north-south band through the central part of the country, just to the east of the Rocky Mountains. During the warm season when winds in the well mixed daytime boundary layer (BL) can often be 5 m s^{-1} or less, a significant contributor to the wind resource is the nocturnal low-level jet (LLJ). The acceleration of the LLJ after sunset, a dynamic response in the lower BL to surface cooling (Blackadar 1957), can result in significant accelerations of the wind speed at the height of wind-turbine rotors (figure 1). The evolution of the mean wind profile after sunset is therefore an important forecast for wind energy applications, and interaction between LLJ-induced winds and the landscape below is important for wind-

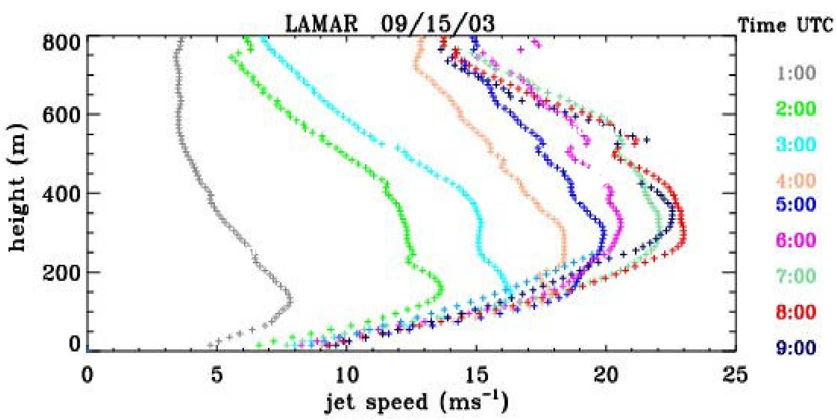

Figure 1: Hourly profiles of mean wind speed showing LLJ evolution after sunset on 15 Sept 2003 (Pichugina et al. 2005).

farm siting. On the other hand, turbulence and wave activity in the strongly sheared wind layer below the LLJ can adversely affect turbine performance by producing vibrations in the rotor blades, limiting the lifetimes of turbine hardware (Kelley et al. 2004).

Two field projects in the past decade have studied mean and turbulent properties of the LLJ over the Great Plains in detail, the Cooperative Atmosphere-Surface Exchange Study campaign in October 1999 (CASES-99; Poulos et al. 2002) and the Lamar Low-Level Jet Project of September 2003 (LLLJP-03; Kelley et al. 2004; Pichugina et al. 2004. 2006). In addition to meteorological towers instrumented with sonic anemometers, both projects featured the High-Resolution Doppler Lidar (HRDL) developed by the National Oceanic and Atmospheric Administration's Earth System Research Laboratory (NOAA/ESRL), in collaboration with the National Center for Atmospheric Research (NCAR), and with initial funding by the U.S. Army Research Office (ARO). HRDL is well suited to studying the LLJ and the accompanying stable boundary layer (SBL), because of its 30-m range resolution, ~10-20 cm s^{-1} velocity precision, narrow beam, and scanning capability. Analysis of scan data involving low elevation angles can provide profiles with vertical resolutions down to a meter or less. Elevation scans aligned with the mean wind, which provide a vertical slice of data through the atmosphere, have been analyzed by binning the velocity data in the vertical (e.g., figure 2) and calculating means and turbulent variances for each bin (Banta et al. 2002, 2006; Pichugina et al. 2008). This procedure provides vertical profiles of the mean wind speed U(z) and streamwise variance $\sigma_u^2(z)$ for each scan, generally repeated every 20-30 s.

An example of how vertical profiles of the mean horizontal wind derived from such scans can be used to document the evolution of the LLJ is shown in figure 1. These hourly profiles show a nascent LLJ at sunset (~0100 UTC) developing into a 23 m s^{-1} jet by midnight local time (0700 UTC). Accelerations at the level of the turbine rotors (up to heights of 150 m in the near future) were not well reflected at the surface, illustrating limitations of near-surface data in evaluating the wind resource. Availability of such data at 20-30 s intervals allows time-height cross sections, such as figure 3, to be generated for each night, to illustrate variations in mean winds that can occur over periods of a few minutes or more in the SBL. Velocity profile data can be further analyzed to determine the height, speed, and direction of the LLJ maximum or nose as a function of time (figure 4) for each night (e.g., Banta et al. 2002).

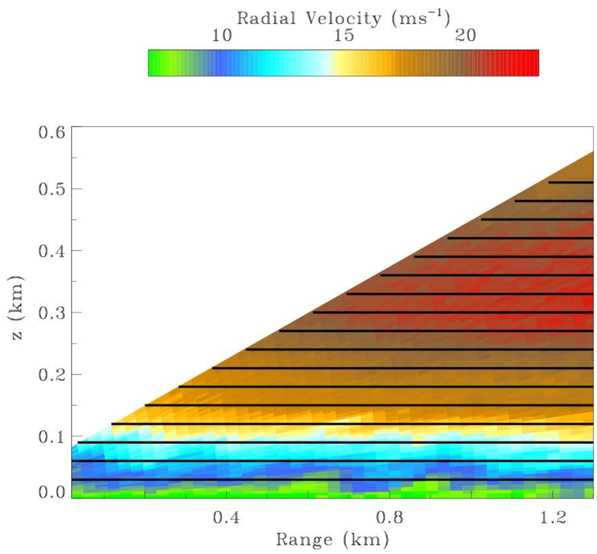

Figure 2: Sample vertical-slice scan showing binning procedure (Banta et al. 2006).

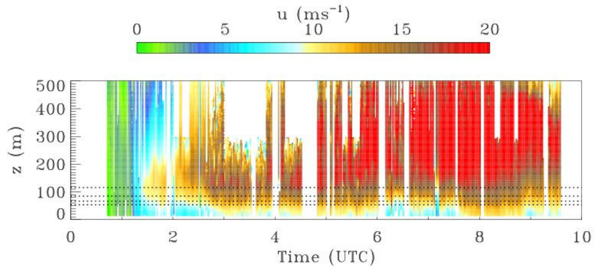

Figure 3: Time-height cross section of streamwise velocity for 15 September 2003. Abscissa is time (UTC), with sunset at 0100 UTC and midnight local time at 0700 UTC. Ordinate is height in meters (up to 500 m), and velocity scale on color bar is in m s^{-1}, from 0 to 20 m s^{-1} (Pichugina et al. 2005, 2007).

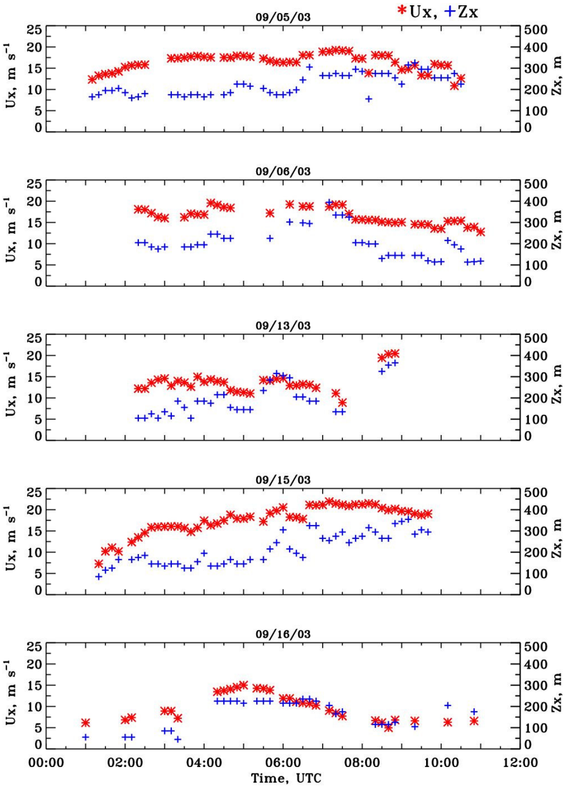

Figure 4: LLJ speed (red, scale at left from 0 to 25 m s^{-1}, and height (blue, scale at right from 0 to 500 m) vs. hour UTC for 5 nights of LLLJP.

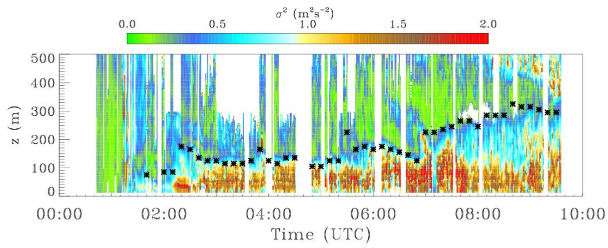

Figure 5: Time-height cross section of streamwise velocity variance for 15 September 2003. Abscissa is time (UTC), with sunset at 0100 UTC and midnight local time at 0700 UTC. Ordinate is height in meters (up to 500 m), and velocity scale on color bar is in m^2 s^{-2}, running from 0 to 2.0 m^2 s^{-2} (Pichugina et al. 2005, 2007).

Turbulent fluctuations—also of significance to wind-energy applications—are generated in the strong shear layer between the surface and the LLJ nose. The intensity and temporal variability of the turbulence is illustrated by time-height cross sections of the streamwise variance. Figure 5 shows the evolution of turbulence in the subjet layer with temporal variations of minutes or more. Higher-frequency fluctuations also occur, as revealed by individual HRDL vertical-slice scans (figure 6). Although strictly turbulent fluctuations tend to be random in time, the fluctuations in Fig. 6 are periodic shear-instability waves that have been analyzed in detail by Newsom and Banta (2002). Waves such as these or other types appearing in the atmosphere have the potential to produce significant fatigue or damage to rotors and turbine hardware, if the frequency is in resonance with the natural frequency of the rotor blades (Kelley et al. 2004).

The ability to adjust the rotors in real time to avoid these disturbances would seem to be advantageous for extended hardware lifetimes. Since numerical weather prediction (NWP) models are not useful for prediction of these kinds of disturbance in any sort of useful way for this application, the alternative would be to detect these bursts in real time upwind of the turbines. Figure 7 shows examples of using HRDL in staring mode at low elevation angles to detect oncoming turbulence. In these examples, the elevation angle was 10º, chosen to show the turbulence structure up to the height of the LLJ. Turbulence is detected at hub height 600 m upstream, providing 1 min of lead time for a 10 m s^{-1} flow speed.

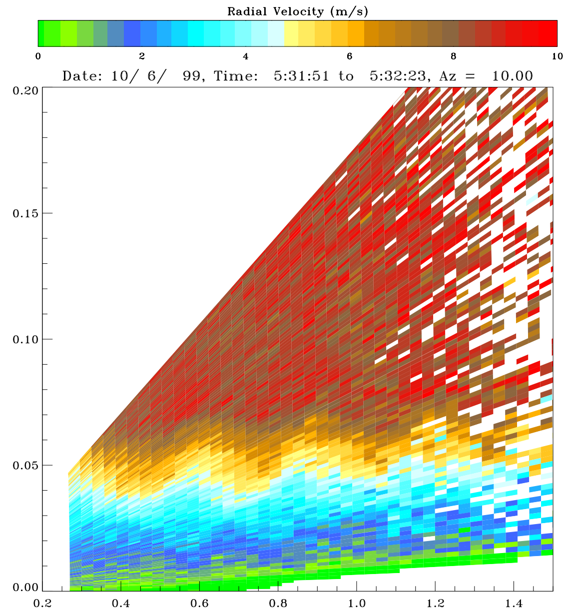

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Figure 6: Shear-instability waves observed on 6 Oct 1999 (Newsom and Banta 2003).

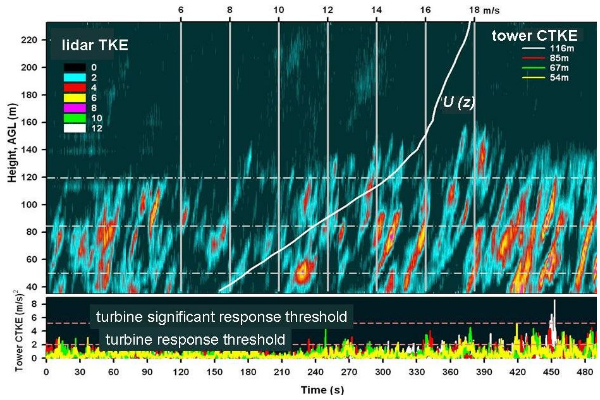

Figure 7: Sample range-time plot of streamwise velocity variance calculated from HRDL in staring mode at 10° elevation angle for the night of 9 Sept 2003, 0729-0739 UTC, where range has been scaled to match the height of the beam. Bottom strip: corresponding tower measured coherent TKE. Abscissa for both plots given in seconds.

Because of the poor representation of stable mixing processes in NWP models, such mesoscale models, even those optimized for research purposes, have not demonstrated quantitative skill in predicting LLJ properties including speed, shear, height, turbulence properties, and their temporal evolution. An important aspect of SBL research, therefore, is to produce better model physics so that such predictions can be more accurate for forecasting, siting, and other planning activities, and to produce accurate case studies for model evaluation.

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