4.10 LOW-LEVEL JET PROPERTIES AND TURBULENCE BELOW THE JET DURING THE LAMAR LOW-LEVEL JET PROJECT

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The magnitude of the turbulence kinetic energy (TKE) in the stable boundary layer (SBL) below the nocturnal low-level jet (LLJ) was shown to be related to the properties (speed and height) of the LLJ using CASES-99 data in southeastern Kansas during October 1999 (Banta et al. 2003). This relationship is potentially important for determining near-surface fluxes in the SBL and is also important for applications such as wind energy, where one issue is the premature failure of turbine hardware as a result of significant bursts of turbulence (Kelley et al. 2004; NREL report). An uncertainty in the CASES-99 results is how general they are—do they apply to other locations and other seasons?

To address this problem in addition to other wind-energy issues, a late-summer field project was organized at a High Plains location near the town of Lamar in southeastern Colorado (Kelley et al. 2004; Pichugina et al. 2004: this symposium). Instrumentation included a 120-m tower instrumented at four levels, a 3-component Doppler sodar, and ETL's High-Resolution Doppler lidar (HRDL). Data were analyzed in a manner similar to that described in Banta et al. (2002, 2003). LLJ properties were somewhat different for this early-September period, with the LLJs significantly stronger and higher than during the October CASES-99 project (Pichugina et al. 2004).

During CASES-99 most LLJs were ~10 m s^{-1} and only three nights had jets of 15 m/s or stronger. During the stronger-jet cases of Lamar, at least five nights exhibited LLJs of 15 m/s or more, providing an opportunity to further investigate the low-stability, high-wind (low Richardson-number Ri) regime, and to see whether the sensitivity of turbulence in the subjet layer to decreasing Ri_J found in CASES-99 also applied to the Lamar cases.

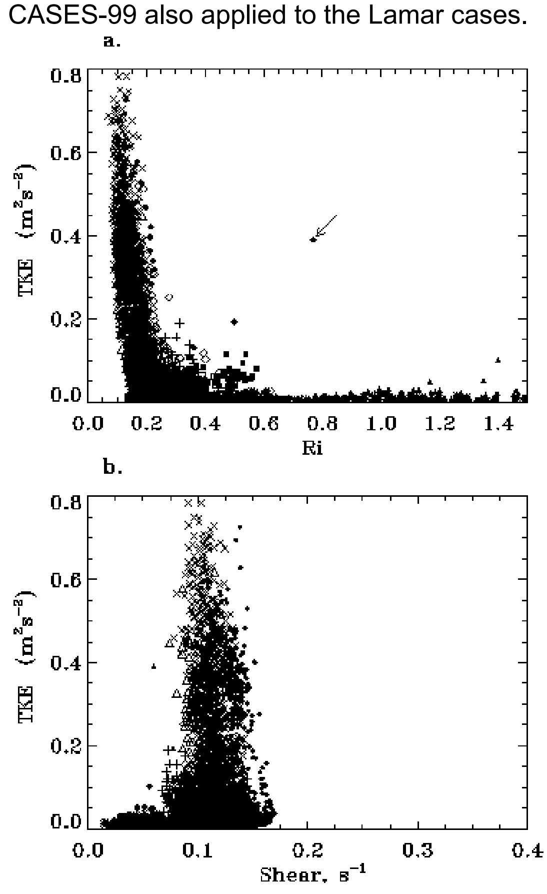

Figure 1: Scatter diagram of gradient (bulk) Ri vs. TKE (top, $m^2 s^{-2}$) and tower-measured shear (s^{-1}) vs; TKE (bottom) for a sample of 10 nights during the CASES-99 experiment. The shear in the lower panel and in between the 5- and 55-m levels on the tower (from Banta et al. 2003).

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CASES-99 results are given in Fig. 1, which shows the dependence of TKE on bulk Ri and bulk shear measured between the top and bottom of the 60-m tower. TKE was small for Ri greater than ~0.3 and became larger with decreased Ri below that value. The shear tended to cluster around a value of just over 0.1 for TKE > 0.1 $m^2\ s^{-2}$. A plot using the speed U_X and height Z_X of the jet maximum to estimate the shear gave similar results with somewhat more scatter.

Lamar data were analyzed in the same way as in the CASES-99 studies. The top panel of Fig. 2 shows LLJ properties U_X and Z_X calculated from HRDL vertical-slice scan data, analyzed as described in Pichugina et al. (2004) and averaged over 15-min intervals for a night when the jet reached speeds of ~20 m s^{-1}.

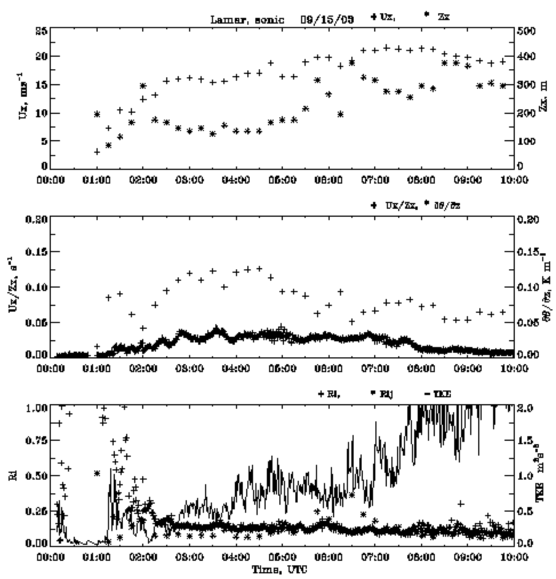

Figure 2: Time series of LLJ quantities for the night of 15 September 2003, averaged over 15-min intervals and plotted against hour UTC. Top: LLJ speed U_X (m s^{-1}) and height Z_X (m) determined form HRDL vertical-slice-scan data. Middle: LLJ shear U_X/Z_X (s^{-1}) calculated from the quantities in the top panel and stability *dθ/dz* (K m^{-1}) between the 54- and 116-m tower levels. Bottom: Ri and Ri_J plotted along with TKE ($m^2\ s^{-2}$), averaged over the 54 and 116-m levels for 15-min time intervals. Sunset was about an hour before 0000 UTC, and midnight, ~0500 UTC.

The middle panel shows the jet-estimated shear U_X/Z_X and the stability *dθ/dz* calculated from the 54 and 116-m levels on the 120-m tower. The jet Richardson number Ri_J (in which the shear is estimated from the jet properties) and the bulk Ri (where the shear is estimated from mean U at the top and bottom levels of the tower) are shown in the bottom panel of Fig. 2 along with the TKE averaged at the 54- and 116-m levels over 15-min intervals. Both Ri values were less than 0.2, and TKE was greater than 1.0 $m^2\ s^{-2}$, for much of the night.

Plots of tower TKE vs. tower shear and bulk Ri are shown in Fig. 3 for the high, high-moderate, and low-moderate category nights (Pichugina et al. 2004) of the Lamar project, and Fig. 4 shows a composite of all the nights. The nights with the lower-speed jets overall exhibited large Ri and relatively smaller values of TKE, whereas the highest-speed nights have small Ri values mostly < 0.5, and the higher values of the TKE. The intermediate cases show both types of behavior.

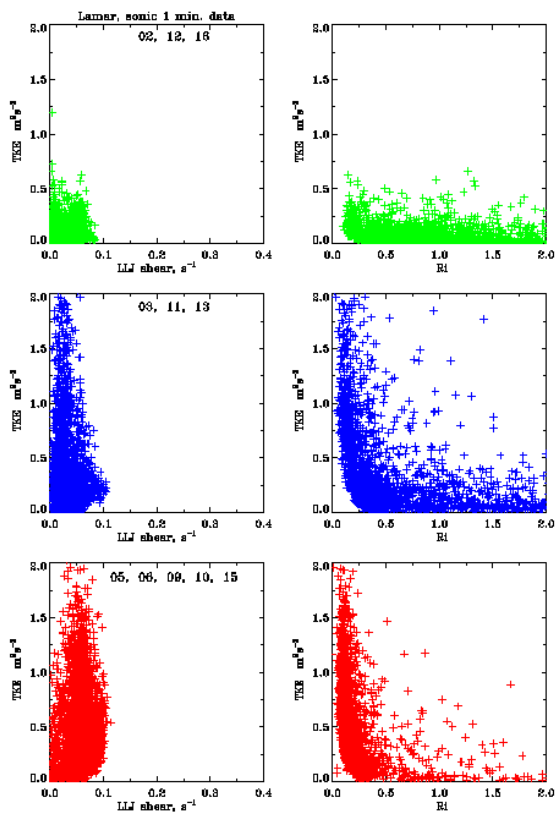

Figure 3: TKE ($m^2\ s^{-2}$) plotted as a function of bulk shear (54 to 116 m tower levels, left panels) and Ri (right panels) for low-moderate LLJ nights (top), high-moderate LLJ nights (middle) and high jet-speed nights (bottom).

The results also agree with the overall dependence of TKE on Ri found during CASES-99 (Fig. 1). The composited results indicate a boundary curve marking minimum values of TKE that correspond to values of Ri below 0.25. Smaller values of TKE prevail for higher values of Ri, especially for Ri > 0.5.

These preliminary analyses of the data thus reinforce the dependence of TKE on a jet or bulk Ri that was noted in the CASES-99 findings. The CASES result that the shear tended to cluster around a value of just over 0.1 was less evident in the Lamar data. The highest values of TKE occurred primarily in the low Ri_J regime, which has been classified as the "moderately-stable boundary layer" regime by Mahrt (1999). In this regime the shear is supposed to be strong enough to maintain continuous turbulence in the surface layer, with the implication that Monin-Obukhov scaling applies.

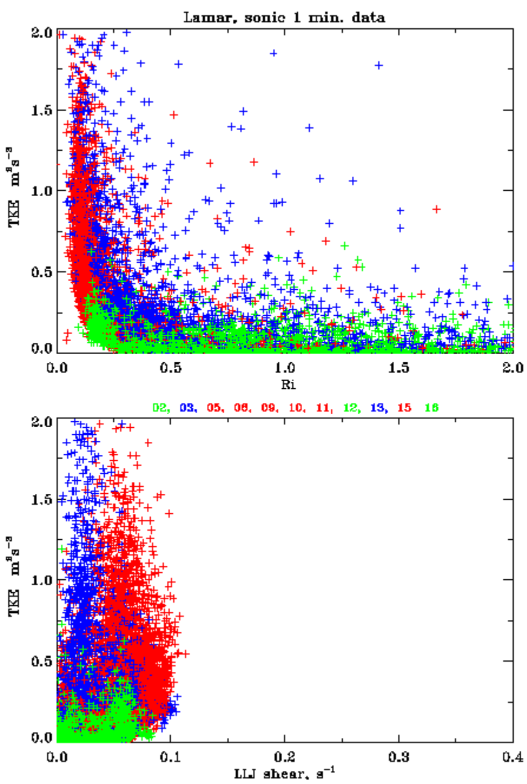

Figure 4: TKE (m^2 s^{-2}) vs. shear (top), and TKE vs. Ri (bottom) composited from the data in Fig. 3.

As is discussed in Kelley et al. (2004) it has been found that wind turbines experience high levels of turbulent loading when the gradient Ri calculated over the rotor disk layer is between 0.0 and + 0.1, with the largest response often seen with Ri values in the vicinity of +0.01 to +0.02. The plots of Figure 3 seem to demonstrate this, with the high values of TKE observed in both the high-moderate (Cases 03, 11, and 13) and high (Cases 05, 06, 09, 10, and 15) wind categories. Thus we would expect to see some form of a significant structural response in operating wind turbines exposed to these conditions.

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