4.5 LOW-LEVEL JET SCALING OF THE STABLE BOUNDARY LAYER OVER THE UNITED STATES GREAT PLAINS

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Semi-arid conditions in the Great Plains of the United States produce strong surface cooling on clear nights. Under these conditions when the winds are greater than 5 m s^{-1} in the lowest 200 m of the atmosphere, the low-level jet (LLJ) is a recurrent feature of the nighttime stable boundary layer (SBL)(Banta et al. 2002). Here LLJ is taken to mean the vertical layer of the previous afternoon's unstable boundary layer that accelerates in response to the nighttime surface cooling as described by Blackadar (1957). Profiles in this accelerated layer can assume different shapes (Banta et al. 2002, 2006), including the classic "nose" profile, a uniform or "flat" profile, and others as depicted in Fig. 1. This nocturnal wind acceleration produces a layer of strong shear adjacent to the earth's surface (Fig. 2), which generates turbulence. It is this role as a generator of a surface-based turbulent layer—the SBL—that is the subject of this study.

We use data from NOAA/ESRL's High Resolution Doppler Lidar (HRDL; Grund et al. 2001) from field projects at two locations in the U.S. Great Plains, CASES-99 (Poulos et al. 2002) and the Lamar Low-Level Jet Project in September 2003 (Kelley et al. 2004). Mean-wind profiles U(z) and streamwise variance profiles $\sigma_u^2(z)$ were calculated at vertical resolutions of 10 m or less, at time intervals of 10 min or less, from HRDL scan data as described by Banta et al. (2002, 2003, 2006) and Pichugina et al. (2008a).

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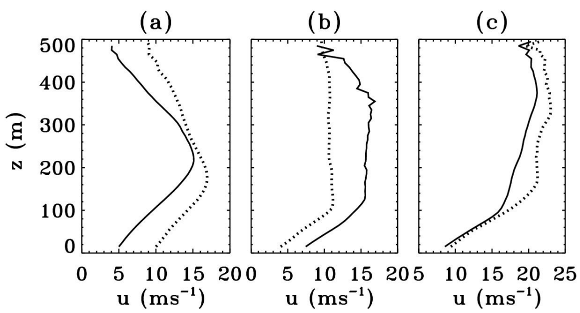

Figure 1. Examples of three types of LLJ profile: a) Type I – two examples of maximum or "nose" type profiles; b) Type II – two uniform or "flat" profiles; and c) Type III – two layered-shear profiles.

Such high-resolution profiles have been used to produce time-height cross sections documenting the nighttime evolution of the LLJ (Fig. 3) and to estimate the depth of the SBL in different ways, as described in a companion paper at this symposium (Pichugina et al. 2008b). Recently

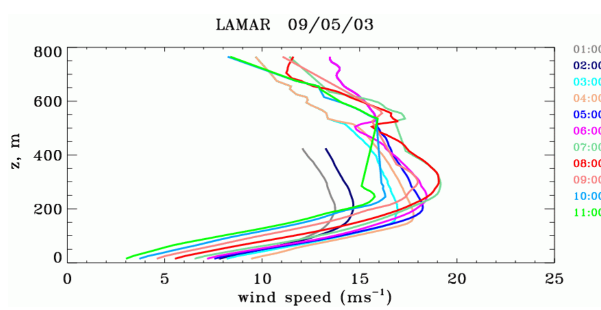

Figure 2. Profiles of hourly averaged mean wind for 15 September 2003

Pichugina et al. (2008a) have shown excellent agreement between lidar-measured mean velocities and those measured by tower-measured sonic anemometers and sodar. They also compared velocity variances calculated from lidar scan data with sonic variances and found high correlation coefficients of 0.9, especially for the strong-LLJ nights.

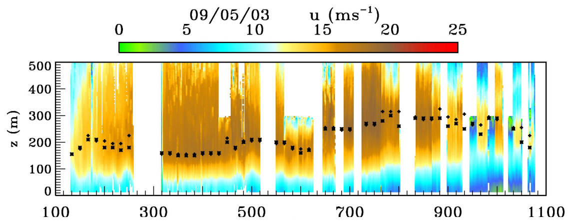

Figure 3. Time-height cross section of horizontal mean wind speed with LLJ heights superimposed for 5 September 2003 at Lamar. Abscissa: UTC hour of the night (local midnight = 0700 UTC), ordinate: height (m AGL).

In this paper we (1) review empirical results supporting LLJ scaling from previous papers and (2) use these results to investigate factors governing the height h of the SBL, which we take as the first minimum above the surface of the turbulent velocity variance profile (Fig. 4, top right). Generalized schemes, designed to represent the full range of stabilities encountered in SBLs, have been described by many authors, including Zilitinkevich and Mironov (1996) and recently Steeneveld et al. (2007). Here we take a new look at expressions derived from bulk-Richardson-number Ri_B formulations (Zilitinkevich and Baklanov 2002).

Empirical results from a previous study using the CASES-99/Lamar-2003 strong-LLJ datasets (Banta et al. 2006) found that composited SBL profiles of mean wind and velocity variance showed properties of a similarity boundary layer when scaled by the speed U_X and height Z_X of the LLJ maximum, this height corresponding to the top of the SBL in general. Scaling mean and turbulent velocities by u_* produced larger scatter and thus inferior results. Other findings

- The height of the minimum in the variance profile h_σ corresponded to Z_X most of the time (see Pichugina et al. 2008b), as illustrated in Fig. 4 (top).

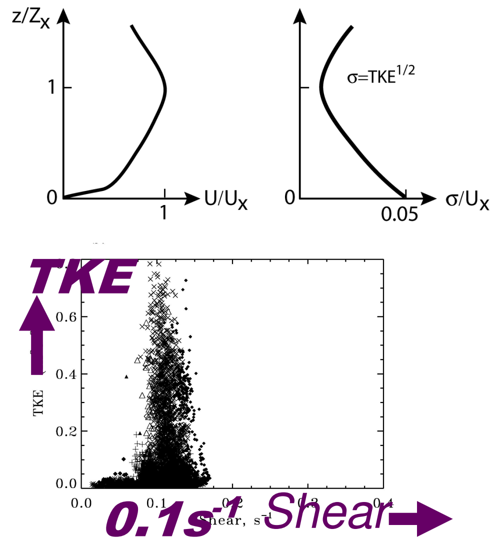

Figure 4. Top: schematic profiles of mean-wind (left) and TKE ^{½} (or streamwise standard deviation)(right) scaled by U_X and Z_X. Bottom: scatter diagram of tower-sonic measured TKE vs. subjet shear, both measured on the CASES-99 tower (Banta et al. 2003).

- σ_{max} , representing the near-surface maximum of σ_u, is approximately 5% of the speed of the LLJ, i.e., σ_{max} ~ 0.05 * U_X (e.g., Fig. 5b).
- The magnitude of the shear below Z_X was found to be equal to, or just less than, 0.1 s^{-1} (Fig. 4, bottom and also see Fig. 2).

Mean U and θ profiles, averaged over 5 min or so, were found to be close to linear with height, in agreement with previous findings (e.g., Wetzel 1982). This becomes an important detail, because the shear, the stratification N^2 (= gdθ/ θdz), and the Richardson numbers Ri become independent of z, and therefore gradient values from different levels, or different values over different intervals for bulk or layer estimates, all become interchangeable (specifically, Ri ≈ Ri_B, for example). An example of one of the composite profiles of U(z) (Fig. 5a) and σ_u(z) (Fig. 5b), shows the traditional shape of the turbulence profile with the maximum at the surface, scaled with Z_X and U_X.

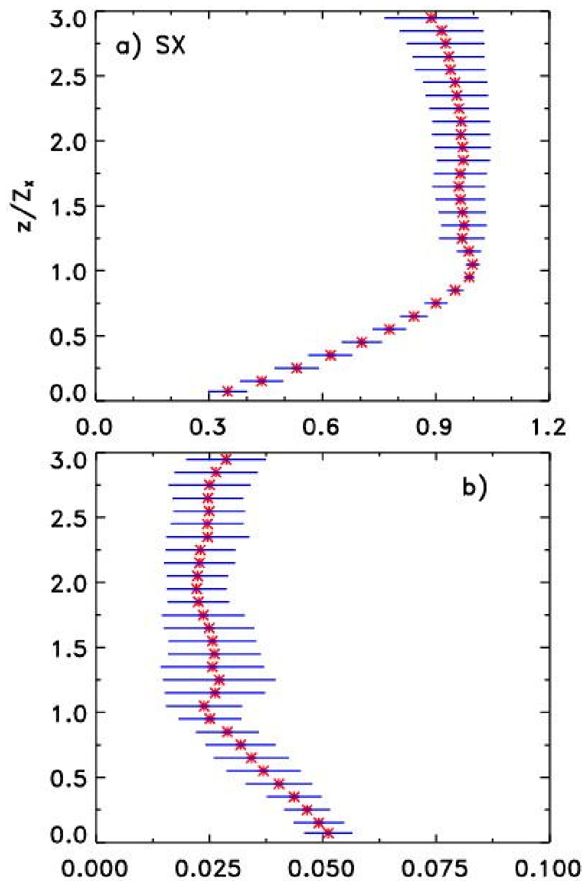

Figure 5. Composite profiles of mean streamwise wind component (left) and streamwise standard deviation (right) for all samples with traditional turbulence structure to the SBL, i.e., maximum at the surface and minimum at the top of the boundary layer, which here corresponds to the LLJ nose (Banta et al. 2006).

An expression for the bulk Richardson number Ri_B across the subjet layer is $Ri_B = (g\Delta\theta/\theta\Delta z)/(U_h^2/h^2)$, where the θ gradient is taken over a layer below the LLJ nose, but we have taken advantage of the linearity of U and θ to estimate the shear in the denominator by using the speed and height of the top of the boundary layer (e.g., Vogelezang and Holtslag 1996). We note that, when the LLJ height is the top of the SBL, as is generally the case for this dataset, this Ri_B is the same as the jet Richardson number (Ri_J) defined in Banta et al. (2003). If we further use the linearity of the profiles to find $N^2 = g\Delta\theta/\theta\Delta z$, we can solve the resulting expression for h to obtain $h = Ri_B^{1/2} U_h/N$, similar to an expression found to be useful by Hanna (1969). This expression assumes that the shear and the stratification within the subjet layer mutually adjust to some 'adjustment Richardson number' Ri_{BA} (after Mahrt, personal communication), but the critical question—that would make this simple equation *very* useful—becomes, what is that value of Ri_{BA}? Unfortunately, the observed values seem to be "all over the place" between 0.1 and 0.25 for the CASES-Lamar datasets, and even worse in the literature, with values ranging from 0.11 to >1 (Zilitinkevich and Baklanov 2002). Inability to specify Ri_{BA} a priori is, of course, a serious drawback to this method.

We now focus on only the strong-LLJ nights with the weakly stable boundary layer (wSBL). Figure 6 shows time series of U_X, Z_X, dU/dz, dθ/dz, Ri_B, and Ri_J for one such night. It can be seen that dU/dz fluctuated about a value of just less than 0.1 s^{-1}, and dθ/dz, near a value of 0.025 K m^{-1}. Despite significant fluctuations in the gradients over 10-20 min, the resulting Ri_B values remained relatively steady all night at just over 0.1. Although the speeds and heights of the LLJs were different from night to night, the gradients and the various Ri values for the other strong-LLJ nights were very similar to this night. Figure 7 shows that for 3½ of the four wSBL Lamar nights, Ri_B was very steady and $Ri_B \approx 0.11$. It thus appears the for wSBL nights a value of Ri_{BA} can be assigned, and that value would be ~0.11, and then very nearly $Ri_{BA}^{1/2} = 1/3$. Using this, the expression for h would be $h = U_h/3N$.

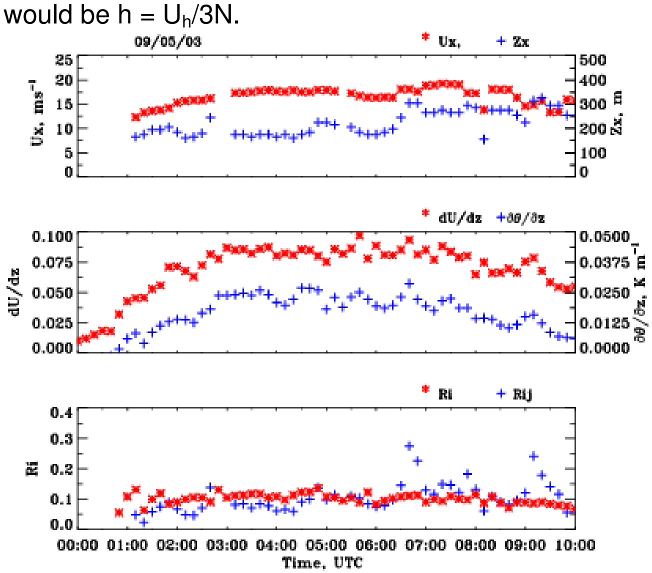

Figure 6. Time series of (top panel) speed U_X (red) and height Z_X (blue) of the LLJ; (middle panel) shear dU/dz (red) and lapse rate dθ/dz (blue) for the layer 54 to 85 m AGL, and (lower panel) Ri_B (red) and Ri_J (blue) for 5 September 2003. As described, U_X and Z_X are equivalent to the wind speed and depth of the top of the SBL U_h and h, for these cases, and $Ri = Ri_B$.

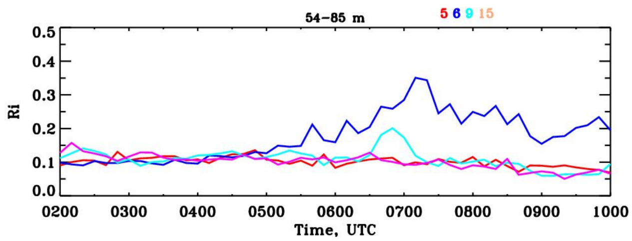

Figure 7. Bulk Ri time series for four nights of Lamar 2003, showing Ri_B ~ 0.1 for 3 ½ of the nights.

We can solve this expression for an estimate of the *shear* across the subjet layer as U_h/h, which would be $U_h/h = 3N$. For $d\theta/dz = 0.025$ K m^{-1}, then $N = 0.03$ s^{-1}, and the result is, $U_h/h = 0.09$ s^{-1}, which is just less than 0.1 s^{-1}, as observed.

A scatter diagram was generated for the four wSBL nights of the Lamar project, using the minimum in the curvature of the U(z) profile, which proved to be a good indicator of the top of the SBL (see Pichugina et al. 2008b), to estimate h. The results are presented in Fig. 8, which shows that this simple relationship has good skill in determining h, with a correlation coefficient of 0.81.

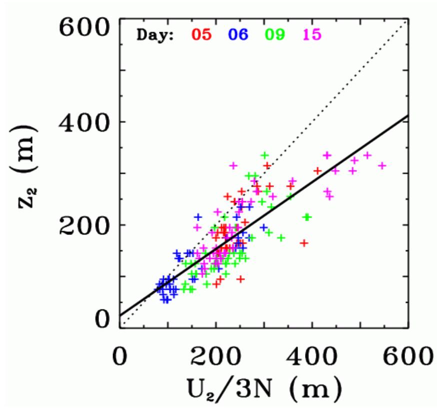

Figure 8. Scatter diagram of height of SBL (ordinate, meters; here indicated as z_2) vs. Ri_{BA}-based expression (abscissa, meters). Correlation coefficient for line of best fit (solid) r=0.81. Colors are for different nights of Lamar experiment in September 2003.

It has been shown that Z_X, corresponding to h, was an effective length scale for profiles of turbulent velocity quantities. It also acts a lid to the turbulence. This is illustrated in the time-height plot in Fig. 9, which shows 1-min vertical profiles of $\sigma_u^2(z)$ rendered in color, superimposed with 10-min-averaged estimates (symbols) of the height of the SBL using four different methods, for the same night as shown in Fig. 3. These methods, described by Pichugina et al. (2008b), can be seen to mostly coincide with each other. Similar cross sections for other nights are given in the Pichugina et al. (2008b) reference in this volume.

The availability of HRDL profile data with high vertical resolution and at frequent time intervals has made it possible to investigate the relationship between mean and turbulent properties of the wSBL and their relationship to the LLJ. The view that wSBL structure and properties are a result of adjustment processes between the stabilizing effects of surface-based cooling and the destabilizing effects of shear, as expressed by the

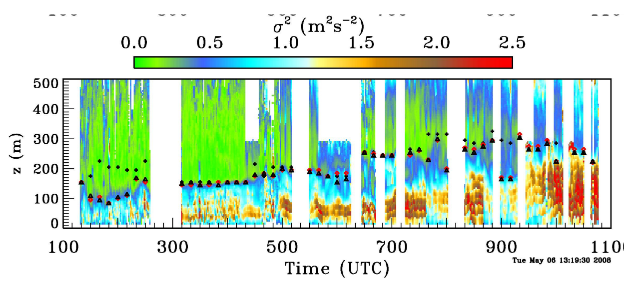

Figure 9. Time-height cross section as in Fig. 3, except of streamwise velocity variance $\sigma_u^2(z)$, which is here equivalent to TKE. SBL top (symbols) forms an upper bound to the layer of surface-based turbulence.

Richardson number, is supported by this analysis. As an example, the shear in the layer between the top of the surface layer and the nose of the LLJ was found to tend to a value of 0.1 s^{-1} or a little less during these experiments. In the wSBLs studied here, the main driver of the boundary layer was the wind speed at the top of the boundary layer, which was most often U_X, the speed of the first low-level jet maximum above the surface. According to the Ri_{BA} analysis presented, when the stratification N does not differ much between nights as often observed, the shear would be the same on each night, and the height of the SBL would be a function of U_X. In addition to its strong relationship to h, U_X also controls the magnitude of the turbulence, since the peak value σ_{max} of the standard deviation σ_u of the streamwise wind component near the surface was found routinely to be ~5% of U_h (or equivalently U_X).

The fact that σ_{max} was proportional to U_X could be explained by larger values of U_X producing stronger shear in the SBL, and more intense turbulence. But shear was not observed to increase as U_X increased; rather, the faster jets were higher and the shear remained about the same (e.g., cf. Fig. 2). An alternative explanation is that as U_X increases, Z_X increases, and the large-eddy size or mixing length λ also increases in the lower part of the SBL, mixing air at greater vertical separations, which would have greater velocity differences (Banta 2008). In other words, $\lambda \sim Z_X$. But this contradicts z-less turbulence concepts and the assumptions of local similarity. Thus, if this interpretation is correct, the present analysis indicates that z-less turbulence and local similarity do not apply to our Great Plains wSBL with strong surface cooling.

The inferences concerning the invariance of the shear and the relationship between h and U_h depend on the constant value of Ri_{BA}, which was found to be ~0.1 for the wSBL. For weaker-wind SBLs, e.g., when $U_h \sim 10$ m s^{-1}, an inspection of Ri_B values shows that they were larger, more like 0.2. Thus, as suggested by Zilitinkevich and Baklanov (2002), the value for Ri_{BA} may vary with stability, large-scale wind speed, or other external conditions.

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