5.6 ANALYSIS OF THE SOUTHERN COLORADO LOW-LEVEL JET BY HIGH RESOLUTION DOPPLER LIDAR DATA. COMPARISON TO THE GREAT PLAINS LLJ CLIMATOLOGIES.

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1. INTRODUCTION

The Great Plains of the western United States (U.S.) has been identified as a region of regular occurrences of the nocturnal low-level jet (LLJ), arising from early-evening accelerations of the late-afternoon mixed-layer flow (Banta et al. 2002). The enhancement of wind speeds over daytime values means that LLJs have a role in transport of water vapor or atmospheric pollutants, for example. Another role of the LLJ is in generating turbulent fluxes, which are produced by the strong shear produced below the jet maximum or 'nose.' In this paper we describe these various roles of the LLJ as they have been studied in other papers, we discuss the published climatologies and the dependence of those climatologies on instrumentation and sampling issues, and then present data taken with Doppler lidar during two field campaigns, over Kansas and Colorado, and describe how these results differ from those previously reported. Intercomparisons between lidar-measured wind speeds and profiles and those measured by tower and sodar will also be presented.

Transport by the LLJ can have important implications to weather, for example, many studies have pointed out the importance of the nocturnal transport of moisture from the Gulf of Mexico to the Great Plains, which can feed summertime precipitation in the region. (Higgins et al., 1997). In previous LLJ climatological studies, variations of LLJ strength and frequency of occurrence were associated with severe weather events such as extreme precipitation (Mitchell et al., 1997), flooding (or drought) years (Song et al., 2005), and thunderstorm activity (Means 1952). Flooding that occurred during July 1951 in Kansas City (Means, 1954), and summer of 1993 (Mo et al., 1995), was connected to anomalously strong southerly LLJs.

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The LLJ has also been shown to be very efficient in transporting urban-generated pollutants away from the urban centers at night (Banta et al., 1998, 2005).

A better understanding of the LLJ is very important for fast-growing wind energy applications; to better estimate wind-resource potential and improve design and management of the new generation wind turbines. The acceleration of the LLJ and production of turbulence and turbulent fluxes in the shear zone below the jet, are not well represented in NWP and climate models, and thus are a source for error in surface-atmosphere interaction processes, lasting over approximately half of the diurnal cycle each day. Detailed observational data for evaluation of the nighttime LLJ are very important for a complete understanding of stable boundary layer processes, including evaluation of the effects of near surface fluxes in the vertical distribution of quantities through a nighttime period, and for the verification and extend of the mesoscale modeling simulations of the LLJ (Zhong et al.,1996).

In previous studies, the estimation of LLJ properties such as the frequency of occurrence, maximum wind speed (U_X), and the height of the maximum (Z_X) was limited by either the vertical or temporal resolution of the data. Rawinsonde and radar-wind-profiler data were often unavailable in the lowest few hundred meters, and a number of LLJ occurrences could be missed from analysis of conventional rawinsonde network data with launch times between 0:00 and 12:00 UTC (Bonner 1968, Mitchell et al. 1995).

The analysis of hourly wind observations from the National Oceanic and Atmospheric Administration (NOAA) Profiler Network (Arritt et al.1997) allowed the study of LLJ climatology during the warm season (April-September) of 1993 over the Great Plains with improved resolution compared with the rawinsonde. But profilers sometimes exhibit biases in the nighttime observations caused by migrating birds, and data were occasionally unavailable due to dry conditions and weak signals or noisy environments such as urban centers.

The results of 6 years of data collected during the Atmospheric Boundary Layer Experiment (ABLE) at the Southern Great Plains site, allowed Song et al. (2004) to estimate the LLJ statistics (such as overall occurrence or occurrence within different classes) with higher accuracy than in previous studies. The analysis was based on hourly wind profiles combined from 5-m range-gate minisodar observations at 10-200 m AGL and observations of the 915 MHZ radar operated in low-power mode with range gate of 60 m at 150-2000 m or in high-power mode with range gate of 200 m at 200-5000 m. But the accuracy of LLJ detection was limited due to occasional occurrences of LLJ maxima in a gap between available sodar and radar measurements.

Over the last decade, the High-Resolution Doppler Lidar (HRDL), 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 ABL because of its temporal and spatial resolution (Grund et al. 2001).

During the 1999 Cooperative Atmosphere-Surface Exchange Study (CASES-99) field campaign HRDL observations were used for the analysis of LLJ characteristics and nighttime evolution over southeastern Kansas (Banta et al., 2002, 2003). Data were obtained from both vertical-slice and conical scans with a range resolution of 30 m, and scan repeat intervals as low as 30 s. The detailed description of the CASES-99 field program can be found in Poulos et al. (2002), the operating parameters of the HRDL were described by Grund et al. (2001) and Wulfmeyer et al. (2000).

The reliability of HRDL measurements was verified against sonic anemometer observations from a 60-m tower, and hourly wind profiles obtained by a 915-MHz wind profiler (Coulter et al, 1999) with range gates of 60 m and minimum available heights of 150 m, along with 5-m range gate minisodar observations from 10 m AGL up to 200 m. A major result of this comprehensive study showed that the greatest frequency of southerly LLJs occurred at a height of 100 m (Banta et al,.2002), which could not be shown by previous climatologies.

Based on the CASES-99 results and the fact that high temporal and spatial resolution of HRDL data from the surface up through several hundred meters AGL permits a much more detailed study of LLJ characteristics than was possible in previous studies of this phenomenon, we used the HRDL data to investigate LLJ properties over the southeastern part of Colorado during 2003 Lamar Low-Level Jet Project (LLLJP-03).The analysis of the HRDL data for a two-week period in September 2003 follows a two year-study of the LLJ at the site by sodar and tower-mounted sonic anemometer measurements (Kelley et al.2004, 2005).

In this paper we highlight the advantages of HRDL for LLJ climatology studies, compare the LLJ properties obtained from the CASES-99 and LLLJP-03 experiments, and test the generality of the Great Plains LLJ climatology for High Plains sites.

We also will draw attention to a difference in the definition of the LLJ in earlier (Bonner, 1968; Mitchell et al., 1995; Arritt et al., 1995) and in more recent (Banta et al., 2002, 2006; Kelly et al., 2004) LLJ-related studies.

Then we will show that most of the jets occur below 500 m with a most probable height of LLJ maxima below 200 m AGL in both experiments. As a result, these jets probably were not included in the previous climatologies. We then present some recent results on the relationships between LLJ properties and the generation of turbulent mixing.

Where applicable, we also evaluate the accuracy of HRDL data by comparing results from the two experiments, or comparing HRDL data against available sodar and sonic anemometer measurements.

2. LAMAR LOW LEVEL JET PROJECT (LLLJP)

During 2001-2003 a coordinated effort between the U.S. Department of Energy (DOE) National Renewable Energy Laboratory (NREL) and General Electric (GE) was made to establish a Lamar Low-Level Jet Program to study the wind and turbulence environment at a site located about 20 miles south of the town Lamar, Colorado. It is situated on a plateau south of the Arkansas River Basin. Locally, the terrain is flat and homogenous, but with more complex elements to the west and north. The site, in the western part of the Great Plains, is characterized by frequent, strong winds during all seasons of the year, has a high wind resource potential to drive wind turbines.

The instrumentation in this campaign included a 120-m tall meteorological tower installed by General Electric Wind Energy (GE Wind) and an acoustic wind profiler operated by the National Renewable Energy Laboratory (NREL). NREL also collected and processed data from sonic anemometers installed at four tower levels.

The National Oceanic and Atmospheric Administration's Earth System Research Laboratory (NOAA/ERSL) joined the program for two weeks in September 2003 and deployed at the site the High Resolution Doppler Lidar (HRDL) to determine mean and turbulent LLJ properties at heights of interest for wind energy. Detailed information on the observational site, instrumentation, and preliminary results can be found at Kelley et al. (2004), Pichugina et al. (2004, 2005), and Banta et al. (2006).

2.1 HRDL measurements

HRDL is a scanning, active remote sensing system that measures range-resolved profiles of Doppler velocity and aerosol backscatter (Grund et al., 2001). The lidar operated with a pulse repetition frequency (PRF) of 200 Hz, typically averaging results from 100 pulses to form range-resolved, line-of-site (LOS) velocity estimates twice per second with a range resolution of 30 m. Detailed descriptions of HRDL operating characteristics can be found in Banta et al. (2002) and Newsom and Banta (2003).

HRDL data were collected for eleven nights from local sunset (0:00 UTC) until prior to sunrise (usually 10:00-11:00 UTC) by performing a variety of different scans (conical, vertical-slice, and staring) to address different scanning objectives. Most of the time HRDL was operated in a vertically-scanning mode (vertical-slice scans) sweeping the atmosphere by varying the elevation angle of the lidar beam with fixed azimuth angle, generally aligned parallel to the mean wind vector. These scans were alternated with short (2-3 min) sequences of conical scans that were performed at several fixed shallow elevations by varying the azimuth angle of the lidar beam over the full range of 0-360^0. Occasionally, during the night HRDL also performed stare scans, when the lidar beam was held fixed parallel to the mean wind. The measurement error was estimated by analyzing fixed-beam scans, and data were quality controlled by removing hard target returns and measurements with low signal-to-noise ratio, as described in Newsom and Banta (2003, 2004).

The vertical structure of the wind field was analyzed by plotting time-height cross sections of wind profiles, determined from vertical-slice scans. The consistency of the results was verified by averaging data over different time intervals and with different vertical steps. An example of such verification is shown in Figure 1, where streamwise velocity profiles for the night of September 15 were averaged over (top) 1-min, and (bottom) over 1-hour.

Both plots demonstrate an increase in the wind speed after local midnight (6:00 UTC) and height of the LLJ maximum (indicated by circles on a bottom panel) also increase.

The accuracy of the mean streamwise velocity was examined by comparing it against wind sped measured by sonic anemometers mounted on a meteorological tower. For this purpose, the lidar streamwise velocities were calculated at the levels of sonic anemometer measurements. As shown in Pichugina et al. (2006) good agreement was found between both instruments. The high correlation in data, with correlation coefficients of 0.87-0.96, was observed for the nights under stable conditions when average wind speed was greater than 15 m s^{-1} most of the time.

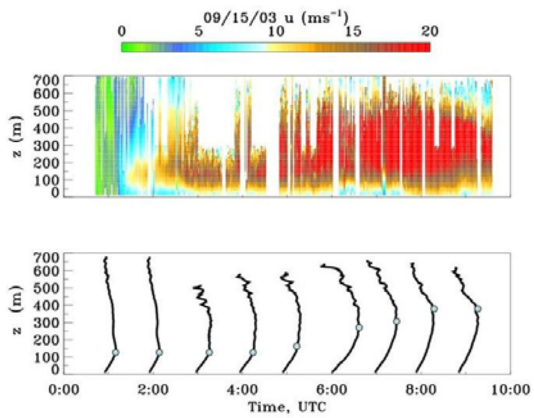

Figure 1. Sample of time-height cross sections of streamwise velocity calculated from HRDL vertical-slice scans during night of September 15; data averaged over (top) 1-min time interval, (bottom) over 1-hour. Velocity profiles were derived from individual vertical-slice scans by sorting the data into 5-m vertical bins. Estimates of the mean and variance were then obtained for each bin. The magnitude range of each wind profile in the bottom panel is 5-20 m s^{-1}.

Lidar measurements were also compared against the Doppler sodar operated at the Lamar site. The sodar provided profiles of the wind speed and direction at 10-min time resolution and 10-m range resolution from 40 m AGL up to 500 m.

An example of 10-min lidar streamwise velocity profiles (blue) and 10-min (red) wind-speed profiles computed from sodar observations, are shown in Figure 2 for every hour and half from 1:30 to 9:30 during the night of September 15. The range of the wind speed within each time interval is 5-20 m s^{-1}. Profiles of all available sodar data (shown by red dots) are overlapped by red pluses that represent sodar data obtained with confidence factor equal or greater than 3 - the full range being 0-5. The confidence factor is calculated from an aggregate of three criteria that are based on the degree of consistency of the individual results from each of the 10 transmitted frequencies, the returned signal strength, and the level of consistency between vertical layers (range gates).

In general, profiles from both instruments show good agreement up to 200-250 m or near the jet nose, when the sodar confidence factor is 3 or more and the wind speed is less than 15 m s^{-1}. Above this height the profiles diverge, with the sodar tending to read stronger velocities than the lidar. Usually the sodar data exhibit low

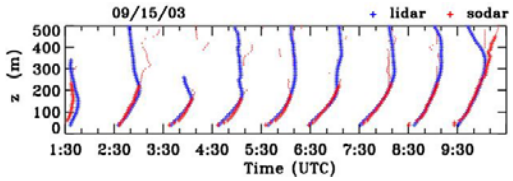

Figure 2. Profiles of 10-min lidar streamwise velocity (blue) and 10-min sodar wind speed profiles (red), for every hour and half from 1:30 to 9:30 during the night of September 15. Red dots show all available sodar data, red pluses are represent sodar data obtained with confidence factor 3 or more.

confidence factor under such conditions, but exceptions occur, for example the last profile taken at 09:30 UTC shows confidence in the sodar data up to 450 m, even though HRDL found significantly lower wind speeds at these levels. In most cases such sudden degradation in the sodar data occurred in the region of the jet "nose" and above. It may be due to the turbulence and thermal structures being significantly different below and within, and above the jet. Typically the temperature inversion extends just above the jet which damps the turbulence, but below, in the strong shear layer, shear-driven instabilities would provide a good signal return as indicated by the high confidence factors. Turbulence, which is a factor in generating the temperature fluctuations that produce the acoustic backscatter signal, has been shown to be often suppressed at- and above the jet nose (Banta et al. 2006).

Another possibility for the poorer performance of the sodar above the jet could be drier air. It was noticed that acoustic signal was weaker in drier air and that the lower layer gradually became more moist (as measured by the tower) during the night. It is possible that the drier air was trapped above the jet increasing the attenuation of the acoustic energy on the way up and back down. The weaker return signals coming from within and above the jet maximum may be highly unsteady, creating multiple spectral peaks in the returned spectrum. To set up the sodar in 2003 NREL engineers followed the manufacturer's recommendations, using multiple frequencies and shorter pulse lengths in order to assess the effectiveness of their new processing software. The higher frequencies would have suffered greater losses due to the increased absorption above the jet if the humidity was below 40% there. Perhaps the sodar processing software employed during Lamar experiment was somehow being biased to the spectral peaks associated with the higher velocities. During August through October 2002, sodar operation at the site sodar was set up for only a single relatively low-frequency and long-period pulse and good profiles were obtained up to 500 m with confidence levels of 4 and 5 almost all of the time (Kelley et al., 2002).

Scatter plots of 10-min, 10-m lidar streamwise velocity and sodar wind speed, obtained for two nights of September 15 (top) and 16 (bottom) are shown in Figure 3. The best fit to the data in each plot is shown as a solid line in the middle, and the upper and lower lines are for ±1 standard deviation. Correlation coefficients of 0.93 and 0.92 for the top and the bottom plots were computed only for sodar measurements with confidence factor of 3 or more as shown in red on both plots. Clearly both instruments show good agreement for both strong (10-22 m s^{-1}) and weaker winds (0-16 m s^{-1}). The corresponding plots for the other nights display similarly good agreement with the best correlation of 0.95 received for the strong winds night of September 5 (not shown). Some of the nights show a lower

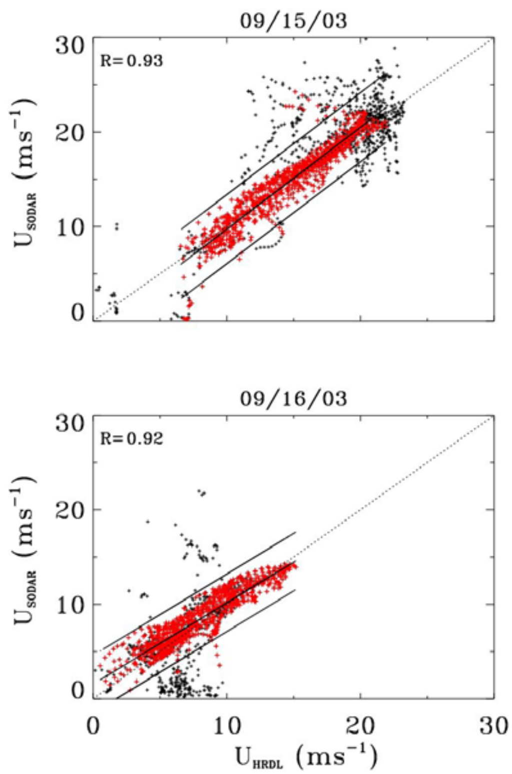

Figure 3. A scatter plots of 10-min, 10-m averaged lidar streamwise velocity and sodar wind speed, obtained for two nights of September 15 (top) and 16(bottom). The middle line in the each plot represents the best-fit linear regression and the upper and lower lines are for ±1 standard deviation. The correlation coefficients (0.93-top and 0.92- bottom) were computed only for sodar measurements with confidence factor of 3 or more, which are shown in red on both plots.

correlation mostly due to shorter synchronized datasets available for the comparison.

3. DEFINITION OF THE LLJ.

A discussion of ambiguities in the usage of term LLJ in the literature and advantages of the LLJ definition using the criteria of Andreas et al.(2000) over the definition used in the previous climatologies, along with examples of wind profiles with and without LLJs present are given in Banta et al. (2002).

Because criteria used in the previous studies of the LLJ climatology “caused us to exclude many jets that we felt obviously belonged in our sample” (Banta et al., 2002), and for consistency with the results obtained from HRDL during CASES-99 experiment, in this study we also use the term LLJ to refer to any wind speed profile that shows a lowest clear maximum below 500 m that forms due to Blackadar (1957) mechanism, and a decrease of speed by at least 1.5 m/s both above and below the maximum.

As mentioned in Banta et al. (2002) wind profiles sometimes exhibit two or more maxima, but in most cases the only lowest one can produce a significant shear that is of interest for turbulence generation.Examples of 10-min wind-speed profiles with one or more maxima occurring during the night of September 15 are shown in Figure 4 to demonstrate the process of choosing a LLJ for the analysis in the present study.

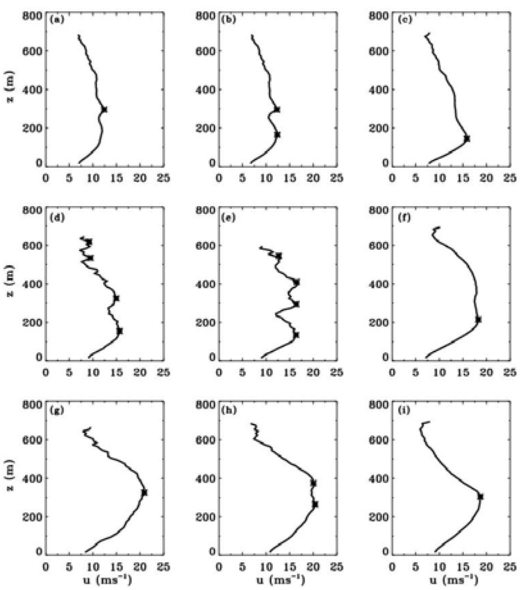

Figure 4 . Sample of the 10-min wind speed profiles with one or more maxima obtained from HRDL vertical-slice scans during the night of September 15. The lowest wind-speed maximum in each case was classified as a LLJ. The second (from the surface) wind-speed maximum in cases (b), (d), (e), and the third wind-speed maximum in case (e) were also classified as LLJs.

The classification of the wind speed profile as a LLJ in this study was based both on the Andreas criteria and magnitude the wind shear produced below the wind-speed maximum. By this classification, 94.5% of 10-min wind-speed profiles for the night of September 15 exhibit only one wind-speed maximum, 25% of profiles show a second maximum, and third and fourth maxima could be defined in 10% and 2% of cases respectively. Such a large number of second and third maxima were observed only for very strong wind nights (>15 m s^{-1}), and the frequency was much lower for the whole dataset from the Lamar experiment. In this study we did not consider the second and higher order maxima in the statistics due to the small shear produced by these maxima, and to be consistent with HRDL results from CASES-99 and analyses of sodar data at the LLLJP site (Kelley, 2004).

3.1 Frequency of LLJ occurrence and distribution of the LLJ characteristics.

Analysis of 10-min wind speed profiles obtained from both conical and vertical-slice scans, employing data processing techniques described by Newsom and Banta (2003) shows that lowest LLJ maxima, defined as mentioned above, were present in 86% of all data collected during the Lamar experiment, and most of these jets were observed below 500 m.

The cumulative frequency of LLJ occurrence defined as a ratio of the number of wind-speed profiles with LLJs present to the total number of measured profiles, is shown in Table 1 for the CASES-99 and Lamar experiments. The comparisons show that during these two experiments conducted in different parts of the Great Plains during different periods of time, there is similarity of LLJ occurrence in the heights above 200 m, and more important, that most of the jets (> 90%) happened below 500 m. A significant difference in the frequency of LLJ occurrence in both sites was found below 150 m, and an even greater difference was observed below 100 m.

The frequency of the LLJ occurrence (%) in the different atmospheric layers.

Below	Cases-99	Lamar-03
50 m	3.1	1.0
100 m	35.0	13.4
150 m	62.4	37.6
200 m	76.8	60.4
300 m	87.45	89.5
500 m	94.7	90.5

The distributions of the frequency of occurrence of the LLJ wind-speed maximum (U_X) and height of the maximum (Z_X) based on HRDL 10-min profiles obtained from 0:00 to 10-12:00 UTC were compared to LLJ characteristics obtained during the CASES-99 experiment. It was shown (Pichugina et al., 2004) that in LLLJP-03 the LLJ heights fell into the 40-400 m range with the largest mode of 100-110 m, and three almost equal modes between 140-200 m, whereas in CASES-99 the single mode was just below 100 m.

The speeds of the jet maxima ranged between 5 and 22 m s^{-1} with the largest modes at 14-15 m s^{-1}, as compared with only one clear mode at 8-9 m s^{-1} in the CASES-99 data. The CASES dataset had few nights when the jet speeds reached 15 m s^{-1}, and none with 20 m s^{-1} jets. If the CASES data had included such high-speed jets, it is likely that the distributions would have been more similar.

Figure 5 shows the distribution of the LLJ heights during the Lamar experiment, where the shaded areas indicate the heights of LLJs with the magnitudes of speed maxima in the interval of between (a) 5-10 m s^{-1}, (b) 10-15 m s^{-1}, (c) 15-20 m s^{-1}, and (d) greater than 20 m s^{-1}. It is clear from these plots that stronger jets were observed at higher elevations. No weak jets with U_X below 5 m s^{-1} were observed during the Lamar experiment. With U_X of 5-10 m s^{-1} (a) most of the jets occurred at 100-120 m; in (b) jet heights were spread almost equally between 100 and 240 m, with a slightly greater mode of 140-160m; jets with speed maxima of 15-20 m s^{-1} in (c)

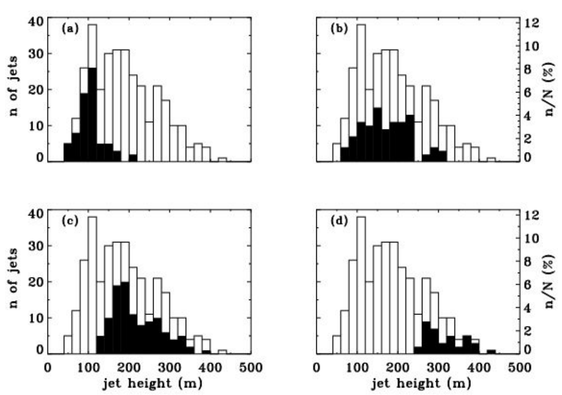

Figure 5. Distribution of the LLJ heights during the Lamar experiment. Shaded areas indicate the heights of LLJs with the magnitudes of speed maxima between (a) 5-10 m s^{-1}, (b) 10-15 m s^{-1}, (c) 15-20 m s^{-1}, and (d) greater than 20 m s^{-1}. In each plot, the distribution for the entire sample is plotted in the background. Percentages of occurrences in each bin are shown along right vertical axis, and total number of occurrences in each bin is indicated along the left vertical axis.

clustered about 180-200 m, and very strong jets (d) were concentrated around 300 m.

The overall distribution of LLJ heights from HRDL measurements is consistent with sodar observations of the lowest LLJs during May-November 2002 at the LLLJP site as described in Kelly et al. (2004).

Histograms of LLJ wind direction computed from HRDL conical scans (a) and from sonic anemometer measurements at four tower levels (b) are shown in Figure 6. Both instruments indicate a very narrow range of prevalent wind directions with a maximum at 170-180^0. The lidar measurements revealed most frequent (about 70%) wind directions of 135-225 degrees.

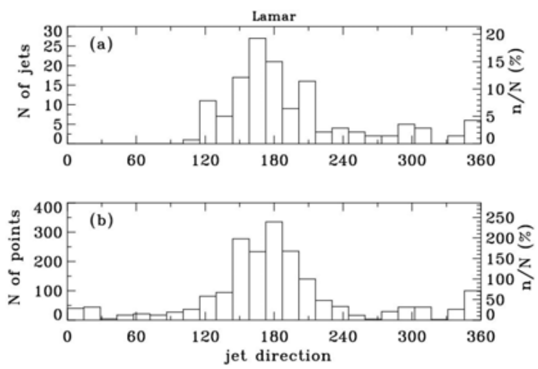

Figure 6. Histograms of jet direction computed from (a) HRDL conical scans and (b) from sonic anemometer measurements at four tower levels for 15-min means. Axis are same as in Figure .

The primary LLJ directions at Lamar are also consistent with prevalent southerly wind directions over the Great Plains found by previous studies (Mitchell et al., 1995, Song et al., 2005), and found from HRDL measurements in Kansas during the Cases-99 experiment and reported by Banta et al. (2002).

3.2 LLJ properties and turbulence

The data of the LLJ speed maximum (U_X) and corresponding height (Z_X) were used to estimate a subjet-layer shear, which was computed as the ratio of the speed to the height of the jet maximum. The shear values determined from the HRDL were compared with the shear computed from sodar data estimated as a ratio of the maximum available speed to the height of this maximum. Sodar data were selected by confidence factor of measurements. Figure 7 represents a time series of U_X (top panel), Z_X (middle) and U_X/Z_X (bottom) determined from HRDL vertical-slice scans (shown in red) and from sodar high confidence measurements (shown in blue) for the night of September 15.

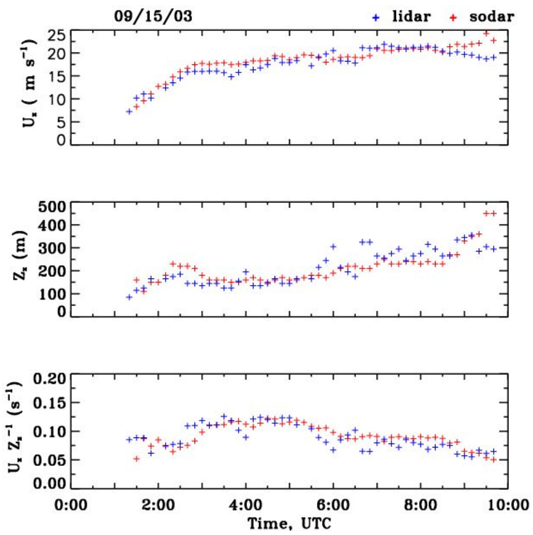

Figure 7. Time-series of the LLJ characteristics determined from HRDL vertical-slice scans (in red) and from sodar measurements with the confidence factor ≥ 3 (shown in blue) for the night of September 15.

Both instruments show an increase of U_X during the first three hours after local sunset (0:00-3:00 UTC) and small fluctuations around 16-17 m s^{-1} over the next five hours. A noticeable difference in the U_X trend happens in the early morning hours (8:00-10:00 UTC), when lidar (sodar) shows a 2-4 m s^{-1} decrease (increase) in jet speed. Lidar data show stronger variations in Z_X than sodar, but both instruments demonstrate a similar tendency of increasing jet height just after local midnight. Z_X was again much more variable both in time and in space than U_X and varied between 100 and 400 m. Both instruments show a very similar tendency in the U_X/Z_X time series, with stronger values before local midnight and a decrease over the next hours. As with the CASES-99 data, the variability in U_X/Z_X was often due to variations in Z_X rather than in U_X.

As shown in Banta et al. (2003) the vertical profile of the mean streamwise velocity component was often nearly linear below the jet maximum (their Figure 2) and the ratio U_X/Z_X could be a reasonable estimate of the shear in the layer below jet "nose". Similar results were produced by streamwise velocity profiles from Lamar-03 averaged over 10-min, or 1-hour. Profiles of mean velocity for each night averaged over 11-hours of observations during (a) Lamar-03, and (b) CASES-99 experiments (Figure 8) also show a roughly linear shear below 200 m.

Shear developed between the surface and the maximum of the LLJ generates turbulence and turbulent fluxes in this layer (Mahrt 1999; Mahrt and Vickers 2002; Banta et al. 2003, 2006).

Based on the analysis of several very strong wind nights from Lamar-03 and CASES-99 experiments Banta et al. (2006, their Figure 8 (a)) showed very strong relation between heights of the LLJ maximum and minimum value of streamwise velocity variance profile with proportionality coefficient close to one.

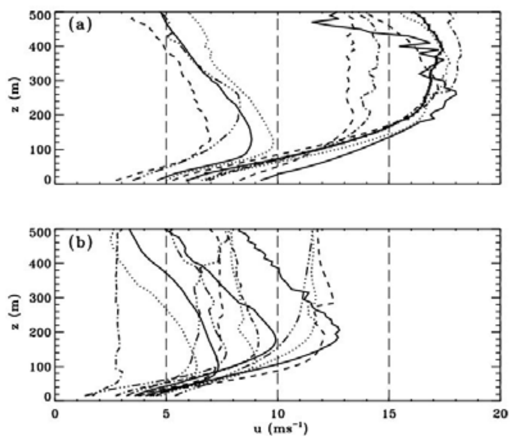

Figure 8 . Profiles of mean streamwise velocity composite for each night of HRDL observations during (a) Lamar-03, and (b) CASES-99 experiments. Different lines in both plots represent different nights; exact dates not important in this context.

Figure 9 illustrates such a relation, where a time-height cross-section of the streamwise velocity variance for the night of September 15 is shown in color, and height of the LLJ wind maximum is shown by plus signs. Vertical profiles of the streamwise velocity variances were shown to be numerically equivalent to turbulence kinetic energy (TKE) for stable conditions (Banta et al. 2006). Velocity variances were computed by averaging over 1-min in time and 10-m vertical intervals. The corresponding velocity profiles were averaged over 10-min in order to get better accuracy in the estimation of the LLJ wind speed maximum and its height. Despite some differences in Z_X and variance time series due to different averaging periods, Figure 9 demonstrates that in most cases the strongest turbulence is below the LLJ maximum.

Regression analysis of the 5-min HRDL streamwise variances and TKE estimated by sonic anemometer data at four tower levels, yielded correlation coefficients better than 0.8 for the most of the nights during the Lamar experiment (Pichugina et al. 2006). It was shown that variance-TKE comparisons are very sensitive to the temporal averaging procedures, but the results in any case were essentially the same, showing proportionality of both variables under stable conditions.

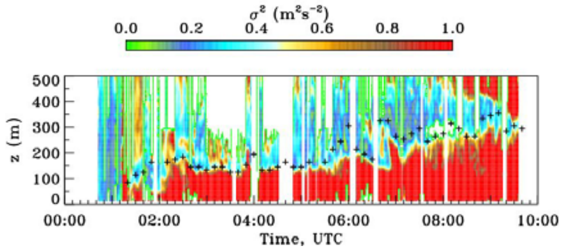

Figure 9. Sample time-height cross sections of the streamwise velocity variance calculated from HRDL vertical-slice scans during night of September 15. Vertical profiles of the streamwise velocity variances were shown to be numerically equivalent to turbulence kinetic energy (TKE) for stable conditions (Banta et al. 2006). The height of the LLJ wind maximum is indicated by plus signs.

4. CONCLUSIONS

Analysis of the HRDL streamwise velocity profiles, obtained from the Cooperative Surface-Atmosphere Exchange study in eastern Kansas in October 1999 (CASES-99) and from a measurement campaign in early September 2003 in the southeastern Colorado, provided an opportunity to test the generality of the Great Plains LLJ climatology against the High Plains site. Intercomparison of the HRDL data with the Doppler sodar observations show good agreement in wind speed between both instruments.

Predominant southerly wind directions and tendency of the strongest jets (U_X > 15 m s^{-1}) to occur around 300 m were found by HRDL measurements from both experiments, and this is consistent with the previous climatologies and two years of sodar observations at the site.

The main difference from the earlier studies of the LLJ climatology is that wind profiles obtained from HRDL shallow vertical-slice scans show that LLJ satisfying the Andreas criteria happened below 500 m, with high frequencies at ~ 100 m. The fine resolution of the HRDL data has allowed us to focus on the first wind speed maximum above the surface produced by nocturnal decoupling of the flow. The first maximum occurred more frequently with a stronger shear than second or third maxima, and it is most likely responsible for the generation of turbulence above the surface.

Detailed studies of LLJ properties, such as these presented above but over longer periods of time are necessary to better understand "both the physical mechanism responsible for jet formation and climatological relations between the characteristics of the jet and larger-scale flow pattern".

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