Nocturnal Low-Level-Jet-Dominated Atmospheric Boundary Layer Observed by a Doppler Lidar over Oklahoma City during JU2003

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(Manuscript received 31 August 2005, in final form 21 August 2006)

ABSTRACT

Boundary layer wind data observed by a Doppler lidar and sonic anemometers during the mornings of three intensive observational periods (IOP2, IOP3, and IOP7) of the Joint Urban 2003 (JU2003) field experiment are analyzed to extract the mean and turbulent characteristics of airflow over Oklahoma City, Oklahoma. A strong nocturnal low-level jet (LLJ) dominated the flow in the boundary layer over the measurement domain from midnight to the morning hours. Lidar scans through the LLJ taken after sunrise indicate that the LLJ elevation shows a gradual increase of 25–100 m over the urban area relative to that over the upstream suburban area. The mean wind speed beneath the jet over the urban area is about 10%–15% slower than that over the suburban area. Sonic anemometer observations combined with Doppler lidar observations in the urban and suburban areas are also analyzed to investigate the boundary layer turbulence production in the LLJ-dominated atmospheric boundary layer. The turbulence kinetic energy was higher over the urban domain mainly because of the shear production of building surfaces and building wakes. Direct transport of turbulent momentum flux from the LLJ to the urban street level was very small because of the relatively high elevation of the jet. However, since the LLJ dominated the mean wind in the boundary layer, the turbulence kinetic energy in the urban domain is correlated directly with the LLJ maximum speed and inversely with its height. The results indicate that the jet Richardson number is a reasonably good indicator for turbulent kinetic energy over the urban domain in the LLJ-dominated atmospheric boundary layer.

1. Introduction

One of the characteristics of lower-troposphere winds over the Great Plains of the central United States is the low-level jet (LLJ). The LLJ is a thin stream of fast-moving air, usually more than 10 m s\(^{-1}\), elevated about 200–500 m above the ground (Hoecker 1963; Bonner 1968). The LLJ can appear in the daytime as a result of baroclinic forcing over sloping terrain (Holton 1967) or because of the dynamical pressure differences caused by localized convection (Bowen 1996). Because of its low altitude and greater wind speed than the air above and below, the LLJ has a great impact on the development of severe weather (Frisch et al. 1992; Zhong et al. 1996). It serves as a major moisture transport mechanism and initiates shear instabilities for storm development. The most frequently occurring LLJs develop during the night and are referred to as the nocturnal LLJ (Blackadar 1957). The nocturnal LLJ is formed when the wind becomes decoupled from the surface due to the development of a stable surface layer and the air above the stable layer accelerates along the pressure gradient. In addition, the Coriolis force in-
roduces an inertial oscillation that produces a greater speed than the geostrophic wind (Blackadar 1957). The nocturnal LLJ has a great influence on the underlying boundary layer and shear-generated turbulence (Sun et al. 2004; Banta et al. 2003; Mahrt 1998, 1999; Nappo 1991). During the Joint Urban 2003 (JU2003) experiment, the nocturnal LLJ was observed during 9 of the 10 intensive observation periods (IOPs; De Wekker et al. 2004). The LLJ and its associated wave motions have been observed in many other investigations in the Great Plains of the United States. Using a Doppler lidar in the Cooperative Atmosphere–Surface Exchange Study 1999 (CASES-99), Banta et al. (2002), Newsom and Banta (2003), and Blumen et al. (2001) recently showed that nocturnal LLJs were often at or below 100 m above ground level. As shown in the continuous observations by the radar wind profilers (De Wekker et al. 2004), the LLJs start to develop right after sunset and strengthen with time afterward.

Atmospheric boundary layer flows over an urban domain are not only influenced by the larger-scale weather systems such as LLJs passing over the region, but are also highly modified by the roughness elements and thermal properties of the city. Higher roughness in the urban area interacts with the flow above and produces greater turbulence in the wakes and strong shear regions near building surfaces. The large percentage of asphalt, concrete, and other man-made materials creates heterogeneous nonpermeable surfaces with different heat capacities and radiative properties. Thermal property and surface moisture contrasts between the urban area and the surrounding countryside can produce substantial temperature differences, resulting in an urban heat island effect. This effect was noted several decades ago (Bornstein 1968; Oke 1976) and continues to be a topic of research. Due to the interaction of high roughness and thermally generated turbulence, the urban atmospheric boundary layer is complex and difficult to study. Many observational studies have focused on intraurban surface fluxes using standard micrometeorological towers. Very few observations have been made above the building height. Most published urban boundary layer (UBL) field studies have concentrated on convective conditions (Jackson 1978; Ching 1985; Godowitch 1986; Rotach 1995; Roth and Oke 1995; Westcott 1989). Uno et al. (1988) have reported some turbulence observation results within the nocturnal UBL. Roth (2000) has given an extensive review of observational studies of atmospheric turbulence over cities. The results are mostly from high-density urban areas with relatively short buildings. In recent years, there have been some developments on the urban atmospheric boundary layer parameterization in mesoscale numerical weather prediction models (Taha 1999; Brown 2001; Martilli et al. 2002; Dupont et al. 2004). Observational data are a necessity for further improving urban parameterization schemes.

Because of the difficulty of obtaining turbulence and wind observations at higher altitude over urban areas, there are, to our knowledge, no reported lidar observations on the LLJ interaction with the urban environment. The recent development of scanning Doppler lidar technologies enables us to observe this type of flow and its interaction with the underlying UBL. Combined with in situ measurements from towers in urban and suburban domains, the strong shear of the LLJ, its turbulence structure, and its influence on the turbulence production and transport in urban and suburban areas can be studied.

The objective of this paper is to analyze the boundary layer wind structure within the LLJ-dominated boundary layer. We seek to characterize the following aspects of the turbulent atmosphere boundary layer over Oklahoma City, Oklahoma: 1) urban effects on the strength and height of the LLJ, 2) the general pattern of the wind speed distribution in urban and suburban areas for nocturnal LLJ-dominated boundary layer flow, and 3) the influence of the nocturnal LLJ on the turbulence production in urban and suburban areas.

2. Instrumentation and observation sites

The Joint Urban 2003 (JU2003) project, a cooperative undertaking to study turbulent transport and diffusion in urban atmospheric boundary layers, was conducted in Oklahoma City (OKC) in late June through the end of July of 2003 (Allwine et al. 2004). Two Doppler lidars, one operated by the Army Research Laboratory (ARL) and the other by Arizona State University (ASU), and a large number of sonic anemometers, sodars, and radar wind profilers were deployed to monitor the wind field during tracer release experiments. A large amount of lidar data has been collected for various wind conditions. Figure 1 shows a map and an aerial photograph of OKC and the surrounding areas. The locations of the ARL lidar, tower 1 (T1), and tower 5 (T5) are marked in the map and aerial photograph. Two radar wind profilers from the Pacific Northwest National Laboratory (PNNL) and Argonne National Laboratory (ANL) are also shown in the figure. Data collected from these instruments at the various locations shown are used for this study.

The Doppler lidars deployed in this experiment are WindTracer Systems, products of Coherent Technologies, Inc., in Lafayette, Colorado. The systems are designed specifically for atmospheric boundary layer ob-
reservation and research (Frehlich et al. 1994, 1998; Grund et al. 2001). The laser system is operated at a wavelength of 2025 nm with a 2.5-mJ laser pulse energy. The lidar pulse repetition frequency (PRF) is 500 Hz, with 100-pulse averaging, which yields products at 5 Hz. The gate range varied from 66 to 71 m depending upon the dataset. The laser pulse width is 300 ns. The system measures range-gate-resolved backscatter intensity and the Doppler radial velocity. The location of the ARL lidar is shown in Fig. 1, where the lidar is located at the top of a two-story parking garage [global position system (GPS) coordinates: 35°28.385′N, 97°30.266′W, 381 m above the mean sea level]. The ASU lidar data are not used in our analysis since the scanning setup was not coordinated for the objective of this paper. The ARL lidar scanning area covers various morphological types, from the OKC central business district (CBD) to urban–industrial, residential–suburban, and rural areas.

Oklahoma City is located in fairly flat terrain with the elevation variation of less than 10 m. Burian et al. (2003) have reported a detailed morphological analysis of Oklahoma City. They found that the CBD area has 39 buildings with heights greater than 25 m. The tallest building is the Bank One Tower with a height of 150 m. Building heights in the CBD area have fairly large variation. The average building height in the CBD area is 19.4 m. Burian et al. (2003) also computed several morphological parameters using methods proposed by Grimmond and Oke (1999). The frontal area index, defined as the total area of buildings projected into the plane normal to the approaching wind direction divided by the horizontal projected plan area of the study site, ranges from 0.3 to 0.4 from the four cardinal directions. The complete aspect ratio, defined as the ratio of the surface area of buildings to the horizontal projected plane area, is 1.5–12 in the CBD area. The areas surrounding the CBD, about 6 km to the south and 8 km to north, are categorized as the urban and suburban areas with one–two-story buildings. Morphologically derived displacement heights are 13 and 2.5 m for the CBD and the urban area, respectively. We will use two ARL sonic anemometer towers: towers 1 and 5. Tower 1 is located in a suburban area 5 km southwest of CBD and tower 5 (T5 in Fig. 1) is located in an urban area about 1 km west of CBD. Figure 2 shows the location and immediate surroundings of these two towers. The area around tower 1 is relatively open and there are no houses or trees within a distance of 50 m. Tower 5 is located in a small open area and is surrounded by two-story buildings in all directions except for a vacant lot with a few mature trees to the north.

3. Data and analysis

The data presented in this paper were collected with the ARL lidar during IOP2, IOP3, and IOP7. We also used PNNL and ANL radar wind profiler data as a verification of the lidar data (De Wekker et al. 2004). The time periods for the selected data are listed in Table 1. IOP2 and IOP3 were designed for daytime trace gas releases. The lidar data collection was initiated in the morning around 1300 UTC (0800 local time). We choose data from these time periods to analyze the LLJ and its interaction with the urban environment because the scanning directions were approximately parallel to the wind directions. IOP7 was designed for nighttime trace gas release. IOP7 lidar data collection started right after local midnight (0600 UTC), after complete formation of the LLJ. We choose the entire night of IOP7 to analyze the development of the stable boundary layer, as well as the development of the LLJ. The scanning types for the ARL lidar in-
include a complete conical velocity–azimuth display (VAD; Browning and Wexler 1968), a range–height indicator (RHI), and a plan position indicator (PPI). A PPI scan is a constant-elevation angle scan, and a RHI scan is a constant-azimuth angle scan. The VAD is a method of retrieving an average wind profile from a constant-elevation angle scan. The VAD scan is used to observe the average wind profile given the assumption of horizontal uniform wind distribution. After the VAD scan obtains the mean wind direction, the RHI scan cuts through a vertical plane into the mean wind direction so that the vertical wind profiles in the scanning plane can be retrieved. The horizontal wind speed \( U \) is retrieved by doing transformation of the radial wind velocity \( V_r \) from the RHI scan parallel to the mean wind direction: \( U = V_r / \cos \theta \), where \( \theta \) is the laser beam elevation angle.

These three IOPs were chosen because the mean wind direction was approximately parallel to the vertical RHI scan slices. The RHI scans in IOP2 and IOP3 were from 0° to 45° elevation angles, and a scan took 24 s to complete. The lidar scanner was programmed such that seven RHI scan slides were taken every hour after the VAD and PPI scans. During IOP7, the RHI scan was from 0° to 15° elevation angles and it took only 6 s to complete each scan. The sonic anemometer data from ARL tower 1 (suburban) and tower 5 (urban) were chosen to analyze the turbulence near the surface in what has been called the roughness sublayer (Roth 2000). Both towers had two R. M. Young sonic anemometers (model 81000) at 5- and 10-m heights. The sonic anemometer data were quality controlled using a package developed by Vickers and Mahrt (1997).

### a. The mean atmospheric conditions

Figure 3 shows the temperature conditions for the time periods analyzed. The mean potential temperature profiles were obtained from radiosonde observations by PNNL and ANL (De Wekker et al. 2004). The potential temperature profiles obtained at the PNNL and ANL sites are fairly similar, although near the ground the potential temperature difference was about 1 K in both IOP2 and IOP3. This is probably because the PNNL radiosondes were released about 7–20 min later than those of ANL. The morning soundings from IOP2 and IOP3 showed a well-developed mixed layer below 400 m with temperature-capping inversions above. The IOP7 sounding was during the early morning. The LLJ is much lower in this case and the temperature profile is characterized by a strong inversion throughout the boundary layer. The mean wind profiles of speed and direction retrieved from the lidar VAD scans are shown in Fig. 4. Both IOP2 and IOP3 showed a strong LLJ at 1400 UTC. IOP3 has an LLJ of 18 m s\(^{-1}\), while the LLJ during IOP2 was weaker, about 12 m s\(^{-1}\). The LLJ completely disappeared at 1600 UTC for both cases. We did not have a VAD scan available for the IOP7 case, so the mean wind direction was determined by

| Table 1. List of radar wind profiler (PNNL and ANL) and lidar data used for wind profile retrieval. |
|---------|----------------|-|-----------------|----------|
| IOP | Date | Radar profiler times (UTC) | Lidar times (UTC) | RHI scans |
| | | Start | End | Start | End | Azimuth (°) | Elev (m) |
| 2 | 2 Jul 2003 | 1330 | 1400 | 1344 | 1348 | 238 | 0–45 |
| 3 | 7 Jul 2003 | 1300 | 1330 | 1316 | 1321 | 201 | 0–45 |
| 7 | 19 Jul 2003 | 0800 | 0830 | 0810 | 0815 | 223 | 0–15 |
using the tower sonic anemometer data. Figure 4 indicates that the LLJ was washed out by the underlying convective boundary layer development. The depth of the LLJ layer decreased at almost a constant rate until it was completely wiped out by convective boundary layer development.

Mean wind directions in the analyzed time periods are $238^\circ$ for IOP2 and $201^\circ$ for IOP3, very close to the RHI scanning directions (Table 1). The IOP7 data were analyzed throughout the nighttime period, but only the section of data from 0810 to 0815 UTC is used to retrieve the average wind profiles; the wind direction was about $223^\circ$. Generally speaking, the wind directions started southerly or southeasterly and gradually rotated clockwise to southwest and south for IOP2–IOP9 (De Wekker et al. 2004; Lundquist and Mirocha 2006). Banta et al. (2003) also showed a similar mean wind rotation as the LLJ developed in their CASES-99 dataset. However, the LLJs in CASES-99 were generally much lower in altitudes than those observed in JU2003. The lidar scanning directions for IOP2 and IOP7 went through the CBD while for IOP3 it only cut through the outskirts of the CBD (see Fig. 1).

b. Low-level jets and their interaction with the urban environment

An advantage of scanning Doppler lidar data is that it can be used to continuously display the spatial structure of the wind field along a line of sight. Figure 5 displays an example of a RHI scan and its location over the city taken during IOP2. The negative sign of the radial velocity indicates that the wind is blowing toward the lidar beam (i.e., from the southwest). The LLJ is the most significant feature in this image and appears to elevate gradually as it approaches and passes over the urban area. The boundary layer wind over the CBD area (approximately from range $-1.6$ to $-1$ km) is much slower and more turbulent than that in the suburban areas. The CBD wake area, located downwind from $-1$ to $-0.5$ km, has an even slower wind speed and a higher LLJ elevation above the surface.

1) Comparison of radar wind profiler and lidar observations

The radar wind profiler data from the PNNL and ANL sites (see Fig. 1) are plotted to independently substantiate the lidar observations. The data were
taken approximately every half hour for the two radar wind profilers. The lidar data shown were obtained at the same time as the radar wind profilers and fell into the interval of two radar wind profiles scanned each half hour. Therefore, we use data from the average of two consecutive wind profiler readings, taken approximately about 15 min earlier and later, for this study. These two radar wind profilers were both located in the

FIG. 5. The Bank One Tower lee wake (side vortex) captured by an ARL lidar in an IOP2 RHI scan. The underlying location and the scanning laser beam are shown in the aerial photograph (courtesy of the U.S. Geological Survey). The yellow–orange arrow lines point from the locations at the aerial photograph to the lidar range location. Urban, CBD, and CBD wake areas are also depicted.
urban to suburban areas: the PNNL radar was in the upwind area ~2 km south of CBD while the ANL radar was in a downwind area ~5 km north of the CBD for prevalent south and southwest wind directions. The profiler data were downloaded from the JU2003 data server maintained by personnel at the Dugway Proving Ground and were processed by colleagues at PNNL and ANL using the National Center for Atmospheric Research’s Improved Moment Algorithm (De Wekker et al. 2004; Morse et al. 2002). Fairly persistent south-west wind conditions within a half hour (Fig. 4; also see De Wekker et al. 2004; Lundquist and Mirocha 2006) during these IOPs allowed us make a valid comparison. Figure 6 shows the averaged wind profiles over the urban area obtained from the lidar and from the half-hour average of the PNNL and the ANL radar wind profilers. The lidar wind profile is an average in the urban area upwind of the CBD. The lidar data and the data from the two radar wind profiler measurements agree reasonably well given the fact that the scanning times and areas were not exactly matched. The differences among them are slightly larger in the case of IOP2. The lidar data are closer to the data from the PNNL radar since the spatial average of the lidar data was taken near the PNNL site. The LLJ nose height at the PNNL is also in better agreement with the lidar data, which shows that the LLJ is at a lower altitude upwind of the CBD. Wind directions during IOP2, IOP3, and IOP7 from the radar wind profilers showed some variations from the near surface to the LLJ levels. The

Fig. 6. Comparison of PNNL and ANL radar wind profiler data with (left) the averaged lidar-retrieved wind speed and (right) wind direction in the urban area (the location of the urban area is shown in Fig. 7) during (top) IOP2, (middle) IOP3, and (bottom) IOP7 in the time sections as shown in the legend. The lidar scanning directions are 238° (IOP2), 201° (IOP3), and 223° (IOP7).
maximum variation is about 20°. If this is translated into the uncertainty in the RHI-scan-retrieved wind profiles, the maximum error in the RHI wind speed profile retrieval is about 6%. In the following analysis, we concentrate on the RHI-retrieved wind profile analysis to demonstrate the spatial variation of the LLJ due to the underlying morphological differences.

2) Lidar Scans of the LLJ Spatial Structure

To derive the general pattern of LLJ flow over the OKC area, many frames of the RHI scans are averaged. Figure 7 shows the average of seven RHI scan frames from selected time periods for IOP2, IOP3, and IOP7. Unfortunately, the RHI scans during nighttime IOPs (from IOP6 to IOP10) all had a maximum elevation angle of 15°, so we were unable to derive the LLJ elevation near the lidar site in the CBD wake area for IOP7. We do have the data upwind urban locations and CBD areas in the IOP7 data. There were some common characteristics among these three cases. The LLJ elevation shows a gradual increase over the urban area compared to that over the upstream suburban area. The step-like structure evident at far distance from the lidar is due to the lidar beam cone. The beam cone has a larger volume farther away from the laser source and therefore has coarser resolution. The LLJ was about 25–100 m higher over the urban area than over the suburban area. The mean wind speed below the height of the jet over the urban area is about 10%–15% less than that over suburban area. This is probably due to internal urban boundary layer development and the urban heat island effect (Bornstein 1968; Bornstein and Johnson 1977; Oke 1987). The urban heat island buildup is due to the slower-moving and warmer air in the urban area. An internal urban boundary layer will develop in the area due to the higher roughness and warmer temperature in the urban area. The internal urban boundary layer pushes the LLJ higher than in suburban and rural areas. In the CASES-99 experiment (Banta et al. 2002), the heights of the LLJ showed very little difference over several locations having less than 50-m surface elevation differences. The most probable cause for the difference between JU2003 and CASES-99 is the urban internal boundary layer development.

The profiles in Fig. 8 are the area averages from the seven RHI scans depending on the underlying urban characteristics. The CBD area is located from 1 to 2 km away from the ARL lidar. The urban area is located approximately from 2 to 2.5 km away from the ARL lidar. The suburban area is located approximately from 2.5 to 5 km away from the ARL lidar. Distances greater than 5 km from the lidar in the view direction are the rural area. The urban wake area at the lee side of the

![Figure 7](image_url)

**Fig. 7.** Averaged streamwise wind (U) spatial distribution along the mean streamline from ARL lidar RHI scans at different IOPs: (top) 2, (middle) 3, and (bottom) 7. Each frame is an average of seven frames of RHI scans over about 4 min. The CBD area is located from 1 to 2 km from the ARL lidar. The urban area is located approximately from 2 to 2.5 km from the ARL lidar. The suburban area is located approximately from 2.5 to 5 km from the ARL lidar. Distances of more than 5 km from the lidar represent rural areas.
CBD showed a significant slowdown compared with the suburban and rural areas in all three cases. The urban lee wake is a combined effect of taller individual buildings and building clusters in the CBD area. Some of the Doppler lidar data scan images captured the reversal of flow from the tallest building, the Bank One Tower. The horizontal extent of the lee vortex (Fig. 4) had a length scale slightly less than twice the building height. In addition, the area beyond the lee vortex also had a large area of slower flow. The lee wakes from many individual buildings created CBD wake areas, which had much slower wind speeds than did the surrounding areas. Using a dual-Doppler lidar retrieval method, Calhoun et al. (2006) also found that there was a deceleration of the wind speed as it approached the CBD area for cases in IOP4 in JU2003. The LLJ in IOP4 was significantly higher (around 800 m) than those during IOP2, IOP3, and IOP7, and the wind direction was more variable at different heights.

c. Low-level jets and their turbulence production

The LLJ was a dominant feature in the nocturnal and morning atmospheric boundary layer flow in OKC. The turbulence production in OKC was not only related to the surface characteristics, but also influenced by the LLJ above. It is more reasonable to use the mixing height as the boundary layer height in an urban area at night. The point where the turbulent kinetic energy has a large decrease is considered to be the boundary layer height due to the larger roughness in the urban area. The roughness sublayer is the most significant part of urban boundary layer. The boundary layer defined by the temperature inversion is not adequate to capture this layer as well as the mixing height does at night. It appears that the mixing height is right under the LLJ jet nose in the JU2003 data. It is difficult to separate the turbulence production due to the urban effects from that due to the strong shear of the LLJ. One way (Mahrt and Vickers 2002; Banta et al. 2002) to assess the LLJ’s effect on the turbulence production is to examine the turbulent kinetic energy [TKE = \( \frac{1}{2} (u'^2 + v'^2 + w'^2) \)]. Mahrt and Vickers (2002) point out that when the turbulence is predominantly produced by upper-level shears rather than by the surface roughness, the turbulent kinetic energy will increase with height and the vertical turbulent flux of TKE [defined as TKE flux = \( \overline{u' w'} + \overline{v' w'} + \overline{w' w'} \)] will be directed downward. The overbar denotes the time average of the sonic-anemometer-observed turbulence values.

Figure 9 displays time series of TKE and TKE vertical flux throughout the entire night of IOP7 at urban (T5) and suburban (T1) tower sites. TKE and TKE...
fluxes are computed from deviations from 5-min means. Vickers and Mahrt (2003) indicate that an averaging time of 5 min is probably adequate for neutral and stable boundary layer conditions. The LLJ heights and the LLJ speeds shown for these locations were derived from the lidar RHI scans at ranges approximately above the urban and suburban sonic tower sites. The $U_x$ is defined as the maximum LLJ wind speed and $Z_x$ is the corresponding height where the $U_x$ is located. The potential temperature gradient ($\frac{d\theta}{dz}$) is derived using the radiosonde data averaged up to the maximum LLJ level. The $Z_x$ varied about 200 m from 0400 to 1200 UTC, with the lowest values at from 0500 to 0900 UTC. The LLJ was strongest when it was at its lowest altitude. This is different from the reported CASES-99 LLJ strength, which generally increased with height (Banta et al. 2002). The potential temperature gradient had its largest increase from 0400 to 0500 UTC and had gradual growth after 0500 UTC. The TKE at both the urban and suburban sites decreased from 0400 to 1200 UTC. The fluctuations of TKE appeared to be loosely correlated to $U_x$ and inversely correlated to the potential temperature gradient. The TKE was much greater during 0400–0500 UTC when the LLJ was not well developed. The vertical TKE fluxes between the urban and suburban sites had a much larger discrepancy. The TKE flux at the suburban site had small negative values (downward flux) indicating that the turbulence at 10 m at the suburban site was perhaps transported from upper-elevation wind. The TKE flux at the urban site had larger negative values. One plausible explanation is that the LLJ altitude was too high to transport a large amount of turbulence flux to the 10-m level at the suburban site. The shear by the buildings dominated the TKE production that was transported downward to the 10-m level at the urban site.

The TKE observed at the sonic anemometer towers (at 10 m) during IOP7 is related to several parameters, including the shear of the LLJ and the potential temperature gradient. Banta et al. (2003) have proposed a bulk scaling parameter, defined as the jet Richardson number, $R_{ij} = \frac{(g/\theta)(\Delta\theta/\Delta z)(U_x/Z_x)^2}{\theta}$, to correlate to the TKE, where the $U_x$ and $Z_x$ are the maximum LLJ speed and its height. The advantage of this parameter over the traditional gradient Richardson number is that it uses the dominant flow feature—the bulk shear of the LLJ rather than local shear. Since LLJ maximum speed and height are easier to observe and to simulate in some mesoscale models, the $R_{ij}$ would be a readily available parameter to relate the TKE underneath the LLJ. Figure 10 is a scatter diagram for TKE computed...
from the sonic anemometer at 10-m height in the urban site versus Ri. The TKE had an inverse relationship in the stable boundary layer over the urban domain. The TKE reaches a constant of about 0.2 m$^2$s$^{-2}$ at Ri = 0.25. This relation is similar to the results reported by Banta et al. (2003) for CASES-99, but the TKE is twice as large in the urban domain.

### 4. Discussion and conclusions

The observational data from the Doppler wind lidar and sonic anemometers show the basic structure of the nocturnal boundary layer and the LLJ of the area around the CBD over Oklahoma City during JU2003. The higher roughness and distinctly different thermal properties caused a more elevated LLJ in the urban than that in the suburban domain. Lidar scans through the LLJ taken after sunrise reveal that the LLJ elevation shows a gradual increase over the urban area compared to over the upstream suburban area upstream, indicating a development of the internal boundary layer due to an enhanced roughness and thermal property change over the city. The LLJ is about 25–100 m higher over the urban area than over the suburban area. The mean wind speed below the height of the jet over the urban area is about 10%–15% slower than that over the suburban area. While the TKE production at the LLJ height was probably not transported to the near surface (10 m), the TKE due to the local production does positively correlate with the LLJ shear. The results indicated that the Ri proposed by Banta et al. (2003) should be a reasonably good indicator for stable boundary layer TKE parameterization over the urban-dominated LLJ.

The investigation of the LLJ and the associated nocturnal boundary layer remains an important research topic. It is an extremely difficult subject and there are many other aspects to analyze. The results from this analysis can be applied in urban boundary parameterizations of mesoscale models (Taha 1999; Brown 2000; Martilli et al. 2002; Dupont et al. 2004). The results can also be readily applied in transport and diffusion models over an urban environment for characterizing the mean and turbulent boundary layer flow. We have begun to use the results to improve our diagnostic wind model (Wang et al. 2005) parameterization over the urban environment.

**Acknowledgments.** We acknowledge the contributions of the JU2003 organizers and participants. We thank the Pacific Northwest National Laboratory and Argonne National Laboratory for providing radar wind profiler data and radiosonde data. Special thanks are given to our colleagues Young Yee, Edward Creggan, Jimmy Yarbrough, Scott Elliot, Giap Huynh, James Cogan, Edward Measure, Edward Vidal, Gail Vaucher, Manny Bustillos, and David Quintis. We also thank Walter Bach for useful discussions on the data analysis.

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