Summertime Low-Level Jets Over the Great Plains

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Introduction

A low-level jet (LLJ) is a wind speed maximum that occurs in the lowest few km of the atmosphere. The frequency of LLJ development over the United States is documented climatologically by Bonner (1968), indicating that the Southern Great Plains Cloud and Atmospheric Radiation Testbed (CART) site of the Atmospheric Radiation Measurement (ARM) Program is situated within the region of maximum LLJ occurrence over the United States. This is fortunate, since LLJs occur world-wide (Figure 1) and yet have not been studied thoroughly. It is also unfortunate because accurately observing LLJs is difficult and anyone using data from the CART site must be aware of the limitations of the observing systems with respect to LLJs.

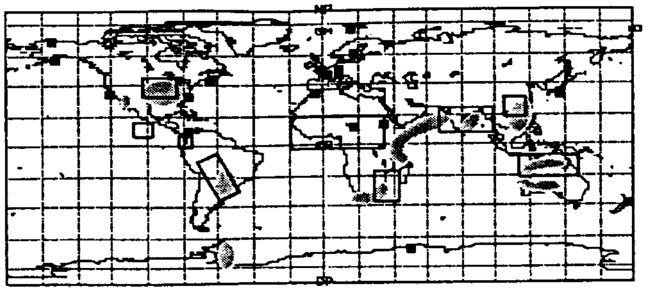

Figure 1. Regions where low-level jets are known or suspected to occur with some regularity (shaded), and where mesoscale convective complexes are known to occur frequently during the summer (open boxes). Squares denote locations where low-level jets have been observed.

Interest in the LLJ continues today because LLJs have been shown to be related to deep convective activity. Means (1954) shows that most of the moisture transported into a region of deep convection is brought in by the LLJ and that over a 2-day period this moisture transport is large enough to produce a region of rainfall covering the entire state of Kansas with up to 7 cm of water. Uccellini and Johnson (1979) compute moisture and sensible heat transports for a different convective event and find that the transports increase by at least a factor of 2 owing to the development of a LLJ. On the larger scale, Rasmussen (1967) shows that the mean water balance for northern North America is determined mainly by low-level flux across the Pacific coast, the Atlantic coast, and the southern United States border. Across the southern border, the low-level eddy flux is strongest during the summer months and accounts for a large portion of the mean annual inflow. In addition, there is a pronounced diurnal flux difference that is a maximum during the summer, with the low-level northward moisture flux larger in the morning than in the early evening. Rasmussen (1967) determined that much of this behavior is due to the diurnal character of the LLJ.

While LLJs are important to horizontal moisture transport, it is clear that this transport is not the entire story. The proper superposition of LLJs with upper-level jets may enhance upward motion throughout much of the troposphere and assist in the development of deep convection (Beebe and Bates 1955). Thunderstorm activity in the central United States, which has a maximum at night (Wallace 1975), has been related to the production of regions of ascending motion associated with LLJs (Pitchford and London 1962). In an examination of 171 squall line events, Porter et al. (1955) find that a LLJ is present in over 75% of the cases. While LLJs by themselves do not cause the development of convective activity, since they generally produce broad regions of ascending motion, they help to produce a favorable thermodynamic environment for deep convection and may be a mechanism for prolonging the lifetimes of regions of convective activity as well (Bonner 1966). This point is a particularly important one to consider when one notes the close correspondence between regions of frequent LLJ occurrence and frequent mesoscale convective complex (MCC) occurrence (Figure 1). The overlap in these regions highlights the importance of LLJs to climate, since MCCs produce widespread cloudiness and alter both the surface energy budget, through changes in soil moisture, and the atmospheric radiation budget, through the production of cirrus clouds.

Observing the Low-Level Jet

Using 404 MHz radar wind profiler data from the NOAA profiler demonstration network, Mitchell et al. (1995) find that the LLJ is most frequent during September, with LLJs occurring less than 15% of the time during June. However, an examination of the ARM 915-MHz wind profiler data and the Weather Surveillance Radar - 1988 Doppler (WSR-88D) velocity-azimuth display (VAD) winds during June 1994 indicates that LLJs with lifetimes of over 10 h occur nearly daily in the central and southern Great Plains. This equates to a frequency of near 35%, nearly 3 times that reported by Mitchell et al. (1995). Further analysis of the data indicates that the 404-MHz wind profilers often under-report wind speeds at the 500-m data level. Since the average height of all LLJs observed with the ARM 915-MHz profiler and the WSR-88Ds is 650 m above ground level (AGL), it is clear that many LLJs have maximum wind speeds below 500 m. How this problem affects the determination of LLJs is illustrated by calculating the average properties of all LLJs with maximum wind speeds of at least 10 m s^{-1} observed separately by the ARM 915-MHz profiler, the WSR-88Ds, and the 404-MHz profilers and displaying the mean height of the LLJ wind maximums (Figure 2). There is a clear dichotomy between the heights calculated from the 404-MHz profilers and the two other systems. The 404-MHz profilers indicate average heights of the maximum wind speed during LLJ events to be 945 m AGL, compared with 650 m AGL for the 915-MHz profiler and the WSR-88Ds. This bias toward jets with higher heights is attributed to the 404-MHz profilers not sampling many of the LLJs that have maximum wind speeds at heights below 500 m AGL. Therefore, during the summertime it is not possible to sample LLJs accurately with 404-MHz profilers, and using these data to calculate fluxes into the ARM site likely will produce underestimations of fluxes (30% or more) on many days.

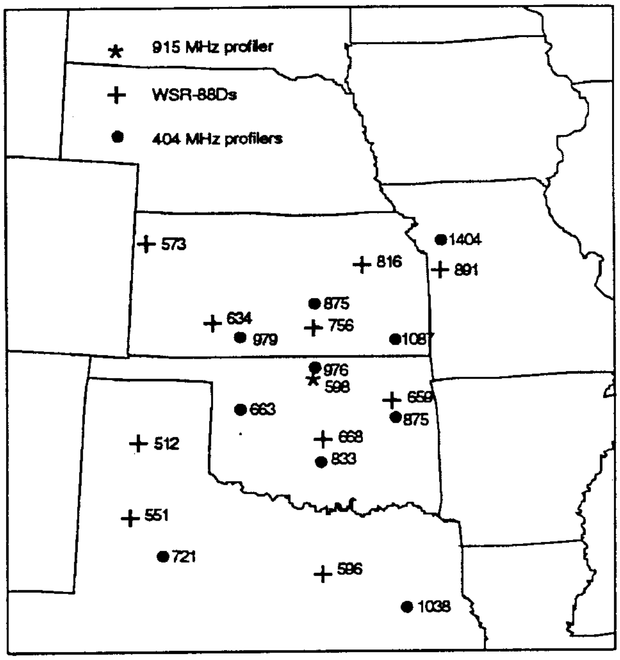

Figure 2. Locations of the ARM 915-MHz profiler (*), the WSR-88Ds (+), and the 404-MHz profilers (solid circles). Numbers indicate the mean height (m) of the level of maximum wind in the sampled LLJs during June 1994 from each of the remote sensing systems.

Data from these three remote sensing systems also are intercompared to evaluate further the utility of these systems to sample the LLJs. The ARM 915-MHz profiler is assumed to provide the best sampling of the low-level winds, since it has better vertical resolution (102 m) than the 404-MHz profilers (250 m) and the WSR-88Ds (304 m). Data from the ARM 915-MHz profiler are compared with the WSR-88D VAD wind data from the Twin Lakes (Oklahoma) radar, located approximately 150 km to the south; the Wichita (Kansas) radar, located approximately 100 km to the north; the 404-MHz profilers located within the ARM CART site at Lamont (Oklahoma); and at a site located to the south (Purcell, Oklahoma). Results indicate that the ARM 915-MHz data agree best with the WSR-88D VAD winds at Twin Lakes and Wichita, and the agreement with the 404-MHz wind profiler data is significantly worse with wind speed differences near 3 m s^{-1} (Table 1). Thus, even though the WSR-88D VAD wind calculations have a coarser vertical resolution, these data are able to capture the increases in low-level wind speeds better than the 404-MHz wind profilers. This strongly suggests that the best method to calculate fluxes into the ARM site is to use a combination of WSR-88D VAD winds for low-level data and 404-MHz profilers for mid- and upper-level data.

Table 1 . Differences in height (Δh), wind direction (Δdir), and wind speed (Δu) of LLJs calculated using data from the ARM 915-MHz profiler (ARM) and the Twin Lakes (TLX88D) and Wichita (ICT88D) WSR-88Ds, and the Lamont (LMN) and Purcell (PUR) 404-MHz profilers. Also shown are the differences between the 404-MHz profilers and the WSR-88Ds.

	Δh	Δdir	Δu
ARM-TLX88D	161	21.2	1.8
ARM-ICT88D	199	18.4	1.6
ARM-LMN	196	26	2.7
ARM-PRC	309	24.7	3.6
LMN-ICT88D	224	25.4	3.3
PRC-TLX88D	132	9.5	2.1

Simulating the Low-Level Jet

Just as important as our ability to observe the LLJ is our ability to simulate LLJ development and evolution. Since the remote sensing of temperature and relative humidity is not possible directly, the LLJ evolution can be used as a proxy for the proper boundary layer structure. Izumi and Barad (1963) show that mixing in the nocturnal boundary layer is closely tied to the LLJ structure when a jet is present, such that the boundary layer vertical temperature profile is influenced greatly by mixing associated with the LLJ. This indicates that if a model can simulate the correct timing, placement, and magnitude of the LLJ, then it is likely (although not certain) that the correct boundary layer structure also is simulated, including the correct horizontal variation of daytime surface sensible and latent heat fluxes that influence LLJ development. This is particularly important, since the nocturnal evolution of the boundary layer, beginning with the transition from a deep to a shallow boundary layer in the late afternoon or early evening, is not as well understood as the daytime evolution of the convective boundary layer. Yet the signal of climate change appears most clearly in the increase of nighttime minimum temperatures over land (Karl et al. 1991). Therefore, one can argue that until the nocturnal boundary layer evolution can be simulated accurately, the utility of regional climate predictions is limited.

Simulations of the first 15 days of June 1994 have been conducted with the Pennsylvania State University - National Center for Atmospheric Research mesoscale model version 4. This is a hydrostatic, sigma coordinate, nested grid model and uses the Kain-Fritsch convective parameterization scheme for the nested grid, a Anthes-Kuo convective parameterization scheme for the coarse grid, a 1.5 order boundary layer closure scheme, a force-restore surface energy budget scheme, and explicit warm and cold cloud microphysics (see Stensrud and Fritsch 1994 for more information). To realistically produce the horizontal inhomogeneities in the surface energy budget, the weekly Crop Moisture Index (CMI) is compared with the Oklahoma Mesonet evapotranspiration measurements from four stations and the modeled heat flux values to tune the model values of moisture availability (M) to match the modeled evapotranspiration amounts to observations. For June 1994, this relationship is

$$M = (CMI + 3.75)/15 \qquad (1)$$

where the CMI values range from -3 to 3. This produces an approximation to the actual distribution of evapotranspiration over the model domain and is a significant improvement over the climatological values of M typically used in model simulations.

Results from the model simulations indicate that the model has difficulty simulating the precise evolution of the LLJ on many days when the jets are relatively weak. Comparisons of the model grid point data with the ARM 915-MHz profiler data indicate that the model typically produces a maximum in the LLJ wind speed that is 312 m below the observed height with a wind speed 4.7 m s^{-1} less than observed. The model results compare best with observations when the LLJs are strongly forced by synoptic features. This indicates that the evolution of the model nocturnal boundary layer is not sufficiently realistic to simulate accurately many weaker LLJ events and that the model likely has difficulty in simulating nocturnal temperatures as well.

Discussion

Numerous studies have documented the importance of LLJs to moisture transport and deep convection, including the indirect effects of convection on surface fluxes and cloudiness, illustrating that the LLJ is a phenomenon of importance to the simulation of climate on global and regional spatial scales and on seasonal time scales. Unfortunately, current routine observing systems typically sample the lower troposphere either at 12-h intervals or at poor vertical resolution below 500 m AGL. These temporal and spatial sampling schemes miss much of the LLJ structure, making it difficult to examine the skill of present numerical weather prediction models to simulate the development and evolution of the LLJ. This previous lack of routine observations of the LLJ enhances the importance of the continuous, long-term record of low-level winds that is being created at the ARM CART site and with the national network of WSR-88Ds. Initial results from mesoscale model simulations suggest that the nocturnal boundary layer is difficult to simulate correctly in synoptically benign situations. Since the nocturnal fluxes can dominate those during the daytime, particularly during the summertime when the LLJ is most frequent, the lack of skill in simulating the nocturnal boundary layer may cause significant errors in numerical simulations. Therefore, even when models are used to fill in the data voids in a four-dimensional data assimilation system, it is important to consider the ability of the model to reproduce LLJs accurately for any investigation where low-level wind information is important.

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