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Climatology of the Low-Level Jet at the Southern Great Plains Atmospheric Boundary Layer Experiments Site

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ABSTRACT

A unique dataset obtained with combinations of minisodars and 915-MHz wind profilers at the Atmospheric Boundary Layer Experiments (ABLE) facility in Kansas was used to examine the detailed characteristics of the nocturnal low-level jet (LLJ). In contrast to instruments used in earlier studies, the ABLE instruments provide hourly, high-resolution vertical profiles of wind velocity from just above the surface to approximately 2 km above ground level (AGL). Furthermore, the 6-yr span of the dataset allowed the examination of interannual variability in jet properties with improved statistical reliability. It was found that LLJs occurred during 63% of the nighttime periods sampled. Although most of the observed jets were southerly, a substantial fraction (28%) was northerly. Wind maxima occurred most frequently at 200–400 m AGL, though some jets were found as low as 50 m, and the strongest jets tended to occur above 300 m. Comparison of LLJ heights at three locations within the ABLE domain and at one location outside the domain suggests that the jet is equipotential rather than terrain following. The occurrence of southerly LLJ varied annually in a way that suggests a connection between the tendency for jet formation and the large-scale circulation patterns associated with El Niño and La Niña, as well as with the Pacific decadal oscillation. Frequent and strong southerly jets that transport moisture downstream do not necessarily lead to more precipitation locally, however.

1. Introduction

Nocturnal wind maxima are often observed in the lowest kilometer above the surface in the southern Great Plains of North America. In addition to playing a strong role in generating shear and turbulence below the wind maxima and thereby controlling the nighttime vertical fluxes in the boundary layer, these low-level jets (LLJ) are very efficient in transporting heat energy, moisture, and air pollutants along the surface, where the magnitudes of these scalars tend to be large relative to their values in the free troposphere. Most prior research has focused on the southerly flow associated with the jet, because it serves as a “conveyor belt” moving warm, moist air from the Gulf of Mexico into the continental interior. Recent studies (Higgins et al. 1997; Helfand and Schubert 1995) have estimated that transport by jets accounts for almost 1/3 of the moisture flux into the continental United States. Further, the strong nocturnal phase of the jet is believed to promote nighttime convection by inducing uplifting due to convergence along the nose of the jet (Zhong et al. 1996). Therefore, variations in jet strength and frequency in the southern Great Plains can be expected to have major effects on continental-scale water budgets. Bonner (1968) presented a comprehensive summary of several theories developed to explain the LLJ; only the key points are repeated here. Beginning with the
work of Blackadar (1957), most of the early explanations for jet formation attempted to account for the common occurrence of the LLJ in the Great Plains and its association with stable boundary layer conditions typically found at night. Blackadar suggested that the nocturnal nature of the jet was due to the rapid decay of the surface mixed layer after sundown and the subsequent concentration of momentum transferred from the synoptic flow to the near-surface flow. This mechanism is enhanced by the temperature gradient along the sloping terrain of the Great Plains resulting from surface radiative heating/cooling (McNider and Pielke 1981) and is supported by evidence from individual cases (e.g., Zhong et al. 1996). In addition, typical soil moisture variation across the Great Plains might also enhance LLJ strength, as simulated by McCorkle (1988) and Fast and McCorkle (1990). Holton (1967) showed that the southerly tendency of the jet and its common occurrence in the Great Plains were due to variations in the pressure gradient caused by alternating differential heating and cooling of the west-to-east-sloping terrain from the Rocky Mountains to the Mississippi Valley. Later, Uccellini (1980) proposed that propagation of an upper-level jet from the Rocky Mountains toward the Great Plains is responsible for the leeside cyclogenesis that produces the pressure gradient needed for development of a southerly jet.

More recent work (Arritt et al. 1997; Mo et al. 1997) highlighted the apparent connection between the LLJ and occurrences of severe and anomalous weather in the Great Plains. Kaplan et al. (2000) presented both observational and numerical model results indicating the structure of the LLJ in Dallas–Fort Worth, Texas. Berry and Rasmussen (1999) further suggested that understanding how jet behavior is influenced by large-scale flow patterns should help to reveal the role of large-scale climate variations in regulating regional and continental-scale water budgets. More detailed descriptions of LLJ characteristics, especially over longer time periods, are necessary to amplify and test these hypotheses. Our goals in this study were to use long-term, detailed observations of the near-surface wind profiles at three locations in the southern Great Plains to understand both the physical mechanisms responsible for the jet and the climatological relationship between the characteristics of the jet and larger-scale flow patterns. We describe important earlier descriptive work in section 2. Our approach and a description of the observation site and data are in section 3. We present the results of our detailed analysis in section 4. Section 5 provides a summary and discussion.

2. Previous work

The first observational studies of LLJ were based on analyses of wind profiles measured by a pilot balloon (pibal) network established between Amarillo, Texas, and Little Rock, Arkansas, in the spring of 1961 (Hoecker 1963). The analyses showed that high pressure cells east of the Great Plains produced low-level southerly jet systems over the western plains. Jet speed maxima occurred at 300–800 m above ground level (AGL), at elevations that were not correlated with the height of the inversion. For climatological studies, Bonner (1968) used twice-daily rawinsonde observations at 47 stations in North America, collected in January 1959–December 1960, and found that the jet occurred most frequently in the central plains, particularly Kansas and Oklahoma, where 30% of all soundings showed a jet. Because their data lacked sufficient temporal and vertical resolution and because the sounding times (0000 and 1200 UTC) were not optimal for sampling LLJ, the 30% value probably underestimated the actual frequency of occurrence. Furthermore, the limited duration of the dataset offered no information about interannual variations in jet properties.

The inherent temporal sampling limitations of a pibal network or a standard rawinsonde network can be overcome by the greater sampling frequency of radar wind profilers, which typically generate hourly profiles. Mitchell et al. (1995) used a 404-MHz radar wind profiler network in their study of Great Plains jet characteristics during the warm seasons (April–September) of 1991 and 1992. The authors used the wind profiler data to explore associations between synoptic weather patterns and spatial and temporal variations in LLJs. Although the wind profilers offered adequate temporal sampling, the vertical resolution of the 404-MHz system, approximately 250 m, is fairly coarse. Averaging wind velocity over this broad interval will tend to underestimate the peak wind speed of jets, with the amount of error depending on the wind speed gradient above and below the height of the speed maximum. Another problem with the 404-MHz system is that the lowest useful data come from 750 m AGL (with the lowest data being returned from 500 m AGL); this limitation could prevent identification of jets with maximum wind speeds at lower altitudes. Mitchell et al. (1995) concluded that their comparison of LLJ altitudes across stations was inconclusive, both because the vertical resolution was poor and because the lack of data near the surface likely resulted in overestimates of jet altitude.

The U.S. Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) Program be-
gan making regular, high-vertical-resolution (~10 m) rawinsonde soundings at its southern Great Plains (SGP) site in May of 1992 (Stokes and Schwartz 1994). The daily frequency of soundings has varied with experimental requirements since the SGP site became operational, with sounding intervals ranging from 6 h (regularly) to 3 h [during intensive operational periods (IOP)]. Whiteman et al. (1997) took advantage of a series of IOPs with enhanced soundings in April 1994–April 1996 to study the LLJ climatological characteristics at the SGP site. Their study confirmed that earlier work had underestimated the magnitude of the jet velocity and overestimated the height of the wind maximum. These researchers also pointed out that earlier studies had used an identification criterion that failed to separate the “classical” southerly jets from the less frequent northerly jets. However, because the IOPs were of limited duration (approximately 1 month) and were conducted irregularly, the number of soundings obtained during the 2-yr period varied not only with time of day but also with month. The fewest soundings were available at 0800 UTC, the time when Whiteman et al. (1997) found the southerly jets to be strongest, and during June, one of the months during which the jets were most frequent.

Both the Bonner (1968) and Whiteman et al. (1997) studies were brief for climatological analysis. Furthermore, each was limited by either the vertical or temporal resolution of the data. In this study, we attempted to overcome these limitations by using a long-duration (6 yr) series of hourly, high-vertical-resolution wind profiles obtained by combining measurements made with collocated minisodars and boundary layer (915 MHz) wind profilers. This study uses data from the Atmospheric Boundary Layer Experiments (ABLE) facility in southern Kansas, one of the regions where LLJ occurrences were found to be most frequent by Bonner (1968) and where the role of jet in transporting atmospheric quantities is most significant (e.g., Roads et al. 1994). Although our data within the ABLE facility are limited spatially, we focus on using these detailed, long-term datasets both to provide a climatological description of the LLJ and to examine variations in jet occurrence and properties at three temporal scales—annual, seasonal, and diurnal.

3. Observation site and data

The ABLE site is located within the Walnut River Watershed (WRW) in south-central Kansas, east of Wichita. The watershed (Fig. 1) has an area of about 5000 km² and is divided by the Walnut River into

Fig. 1. Topography of the Walnut River Watershed and locations of ABLE sites with 915-MHz radar wind profilers and minisodars at Beaumont (BE), Whitewater (WH), and Oxford (OX).
rangeland to the east and cultivated land to the west. Intensive field campaigns conducted in the WRW include the Cooperative Atmosphere–Surface Exchange Study (CASES) field campaigns in 1997 (LeMone et al. 2000) and 1999 (Poulos et al. 2002) and the International H₂O Observing Period in 2002 (Weckwerth et al. 2004). In addition to hosting intensive field studies, ABLE served as the base for a multiyear, interdisciplinary study of meteorological and hydrological processes, the DOE project “Water Cycle Observations, Analysis, and Modeling” (more details about ABLE were available online at http://www.atmos.anl.gov/ABLE at the time of writing).

Intended as a long-term, open-access observatory for studies of atmospheric boundary layer processes, ABLE was built around the long-term deployment of 915-MHz radar wind profilers, minisodars, and surface meteorological stations by Argonne National Laboratory (Coulter et al. 1999). ABLE’s three permanent remote sensing sites are arranged in a triangle approximately 60 km on a side (Fig. 1); each site includes colocated radars and sodars. The site at Beaumont, Kansas, located on a ridge at the eastern edge of the ABLE domain, is the highest of the three [478 m above mean sea level (MSL)]. From Beaumont, the surface elevation falls sharply to the east. The Whitewater, Kansas, site (416 m MSL) is at the northwest vertex of the triangular array, and the southernmost site is at Oxford, Kansas (360-m elevation), in the lower part of the Walnut River valley.

Boundary layer radar wind profilers (Eklund et al. 1988) transmit a radar signal at 915 MHz and receive backscattered energy resulting from refractive index fluctuations (caused primarily by moisture fluctuations but also by temperature fluctuations) that move with the mean wind. Wind velocity is determined by measuring the Doppler-shifted frequency of the backscatter from one vertical beam and four offset beams. Sampling in the vertical direction and in tilted planes enables calculation of the three components of motion. An interval of 6 min is required for one scan sequence, and multiple scans are averaged to create hourly averages of winds that are considered to be reliable to within 1 m s⁻¹ (Coulter et al. 1999). The 915-MHz radar wind profiler provides wind profiles 1) from (nominal) 150 m to 2 km, with a range gate (vertical resolution) of 60 m, when operated in low-power mode and 2) from 200 m to 5 km, with a range gate of 200 m, when operated in high-power mode.

The three 915-MHz wind profilers at ABLE are colocated with minisodars, which provide high-resolution wind profiles between the surface and the lowest level of the profiler (Coulter et al. 1999). Sodars rely on the transmission of sound, and thus the sodar signal is directly dependent on the temperature and wind structure of the atmosphere. Minisodars have a range gate of 5 m and are designed to collect data at 10–200 m AGL. Minisodar wind velocity estimates are made hourly for compatibility with the radar profiler data. At levels at which minisodar data and radar data coincide, values are averaged. The combined hourly profiles thus have vertical resolutions of approximately 5 m from the surface to 200 m AGL and 60 m from 200 m AGL to 2 km AGL. Although additional 915-MHz systems are deployed outside the ABLE domain by the ARM Program, no minisodars are collocated with them, and thus the lower-level wind profiles are less reliable. Coulter et al. (1999) found that more than 50% of sodar data can be retrieved above 150 m and that the quality of sodar data is even better at night, because shear improves the signal structure under nocturnal LLJ conditions. When the sodar data and radar data do not totally overlap, LLJs with peaks occurring between the maximum sodar signal height and the second radar range gate cannot be determined, and some accuracy in LLJ position is lost.

The combined radar–sodar sites have been in operation at ABLE since late 1996. In contrast to other wind profilers, such as the 404-MHz wind profilers, the 915-MHz system has considerably smaller beamwidth and pulse volume. As a result, problems with signal contamination caused by migrating birds are much less significant in 915-MHz measurements, though they are still present (Wilczak et al. 1995; Pekour and Coulter 1999). We examined each hourly profile to verify the quality of the data. Although this process was time-consuming, we found it useful for detecting abrupt changes in speed or direction that occasionally occur at some levels because of bird contamination or other interferences. When the wind speed and direction showed signs of contamination, the data at these levels were skipped, and the rest of the profile data were used for LLJ detection. If a wind profile could not be visualized clearly because of suspected contamination at multiple levels, the profile at this hour was discarded.

The lower-level wind profiles sampled by the minisodar, which are not affected much by bird contamination, become a valuable tool for estimating true lower-level wind profiles and for identifying contamination in radar wind profiles made near the overlap altitude of the two systems. Although bird contamination has largely been eliminated from our data, residual bias in the analysis is still possible. Nevertheless, given the large number of profiles in our study, the effect would be small.

Bonner (1968) presented a classification system for
LLJs that is based on the maximum wind speed and wind shear (called falloff) in the lower atmosphere, up to a height of 3 km. In this scheme, each occurrence of a jet is assigned to a category designated LLJ-\(n\), where \(n\) ranges from 1 to 3; larger numbers indicate larger wind speeds and greater falloff. To characterize the falloff, Bonner used the difference in wind speed between the wind speed maximum (the height of which was used to define the height of the jet) and the minimum wind speed found above the height of the jet. In the absence of a clearly defined minimum wind speed above the height of the jet, Bonner used the wind speed at 3 km as the minimum in estimating the difference.

Whiteman et al. (1997) followed this basic scheme but added another jet classification, LLJ-0, because the better spatial and temporal resolution of their data allowed them to detect instances of a distinctive jet that did not meet Bonner’s LLJ-1 criterion, usually when the maximum wind speeds were lower. We used a modified version of the Whiteman et al. scheme in our analysis. The major difference between the two schemes is that we defined the upper limit of the jet extent as 2 km rather than 3 km. We chose this height because the vertical resolution of the 915-MHz data changes at 2 km as the radar shifts to high-power mode. The altitude of the LLJ is almost always below 2 km (Whiteman et al. 1997), and we believe that this change causes little difference either in our interpretations or in comparison of our results with those of others. We do note, however, that because Bonner’s (1968) classification scheme is cumulative (so that, e.g., all LLJ-2 and LLJ-3 jets also qualify as LLJ-1 jets), changing the upper limit of the analysis to 2 km from 3 km may result in smaller falloff values and a tendency to assign a given jet to a weaker classification (with a lower number). Neither Bonner nor Whiteman et al. reported when the falloff calculation was based on the wind speed at 3 km, so we cannot estimate the magnitude of this tendency.

After we analyzed the LLJs from wind profiles at all three ABLE sites, we found that more than 10% of the data points were missing at both Oxford and Whitewater, because minisodars and 915-MHz wind profilers there were removed intermittently for other experiments during our 6-yr period. Instruments at the Beaumont site were permanent, and data there were missing only occasionally because of instrument failures and power outages. Furthermore, weaker LLJs can be detected more easily at Beaumont than at either Oxford or Whitewater, because wind speeds tend to be larger at Beaumont, a finding consistent with reports of Banta et al. (2002). Thus, we used the Beaumont dataset as the basis for our detailed study. Contamination resulting from bird migration affected a fraction of the profiles and caused us to discard some data. In total, however, we discarded only 115 complete nights of the 2191 spanning the 6-yr period, plus an additional 92 h of the total 22836 h sampled (11 h, or 0200–1200 UTC, during each of the 2076 nights for which we had data). The discarded data amounted to about 5% of the total 6-yr record. The data gaps were distributed randomly throughout the record (see section 4). We believe that the edited dataset is suitable for describing long-term (interannual) LLJ climatological characteristics.

We restricted our analysis to data collected at night, defined here as 0200–1200 UTC [corresponding to 2000–0600 central standard time (CST; local time)]. The times indicate the beginning of the radar sampling interval, and we include the endpoints of the time range. Low-level jets are less likely to occur during the day than at night (Whiteman et al. 1997), because turbulence in the unstable daytime boundary layer tends to mix faster-moving air with slower-moving air at adjacent levels, resulting in a vertically uniform wind profile near the surface, especially during the warm season. For each night, we examined the hourly profiles and classified each hour as either non-LLJ or LLJ-\(n\), using the four Whiteman et al. (1997) LLJ categories. For each jet occurrence hour we recorded the maximum and minimum wind speeds in the profile, as well as the wind direction and height at these points. Following Whiteman et al., we also divided the jets into southerly (maximum wind from 90° to 270°) or northerly (maximum wind from either 0° to 90° or 270° to 360°) categories. Many nights had jet occurrences in multiple hours. For nights with jet occurrence, we chose the jet with the highest wind speed within the highest LLJ class to characterize that night’s jet condition. By using the hourly and nightly data in this way, we were able to generate a temporal characterization of the jet over continuous hourly intervals. This representation supplements the Whiteman et al. (1997) descriptions, which were based on fractions of the discrete number of soundings used in their analysis.

We use a simplified general terminology in the subsequent discussion. We refer to jets in categories LLJ-0 and LLJ-1 as “weaker” jets. We use the term “stronger” to describe jets in the LLJ-2 and LLJ-3 categories. Our references to jets falling into a particular category describe jets that fall into only a single category and into no other. That is, although the Bonner (1968) and Whiteman et al. (1997) classifications are inherently cumulative, our classification is not. We preferred to use exclusive classes rather than inclusive classes; the two schemes are equivalent in the sense that one can be derived from the other simply by addition or subtraction. Following previous work, we attributed a speed
and direction to a jet occurrence by using the maximum wind velocity in the profile; the altitude of the wind maximum defines the height of the jet “nose.” We also divided the year into warm (April–September) and cold (rest of the year) seasons, according to Bonner (1968).

4. Climatology of low-level jet characteristics

Because our dataset is longer than the datasets used by previous investigators and has improved spatial and temporal resolution, our focus here is on climatological characterization (i.e., nocturnal, seasonal, and annual variations in the jet) and on a detailed description of the physical characteristics of speed, direction, and height. We summarize in Table 1 our basic observations of nocturnal jet occurrences by type, season, and direction. In the sections below, we first describe the frequency of occurrence and other general characteristics of the jet and then consider the relationships between the jets and larger-scale phenomena.

a. General description of the low-level jet

Because the intensity of LLJ varies temporally, sampling is an important issue. Increasing the temporal and spatial resolution of the observations should improve the accuracy of the statistics describing the occurrence of the jet and, depending on the time and space scales of the phenomenon, increase the estimated frequency of occurrence. The overall LLJ occurrence that we observed, 67% (1396 of 2076 nights), is somewhat higher than the approximately 55% occurrence in the night-time soundings (0200–1100 UTC) studied by Whiteman et al. (1997). We found that jets of class LLJ-1 and above occurred during almost 53% of the nights, as opposed to Whiteman et al.’s finding of approximately 43%. In general, our data show higher frequency of occurrence for all LLJ classes than did the data studied by Whiteman et al.

Our continuous record of hourly observations enabled us to determine both the number of hours for which the LLJ was present and which direction predominated. We found that most LLJ hours and nights were southerly. Of 8299 total LLJ hours, 6453 h, or 78%, were southerly, and of the 1396 total LLJ nights, 999 nights, or 72%, were southerly. Among the four LLJ categories, LLJ-1 occurred most frequently for both the northerly and southerly jets. Of the 2191 total calendar nights in the 6-yr period, weaker LLJs occurred on 744 nights (34%) and stronger LLJs occurred on 652 nights (30%). Considering southerly and northerly jet occurrences in warm and cold seasons separately, we found that, on average, the southerly jet lasts longer during the warm season (about 6.7 h per night) than during the cold season (about 6 h per night). This longer jet duration, despite the shorter nighttime period in the warm season, may be the result of favorable atmospheric flow patterns in the warm season (discussed below in section 4c). The duration of the northerly jet is shorter, at about 4.7 h per night in the warm season and 4.6 h per night in the cold season.

The general distribution of speed and direction for the strongest LLJ each night is illustrated in Fig. 2 with polar plots. For both seasons, the dominant direction (with stronger jet speed) was from the southwest. In the warm season, the second preferred direction (with weaker jet speed) was from the northeast. For the cold season, the second preferred direction ranged from north (0°) to east (90°), with lesser contributions from the northwest. Moreover, average wind speeds for both northerly (15 m s\(^{-1}\)) and southerly (18 m s\(^{-1}\)) jets were weaker in the warm season than in the cold season (northerly 16 m s\(^{-1}\) and southerly 20 m s\(^{-1}\)). For the nightly dataset, which includes only the strongest jet occurring each night, the distribution patterns of speed and direction are similar to those found by Whiteman et al. (1997), whose dataset included all of the available jet soundings (both day and night) in a 2-yr period. In addition, we found that the northerly jet has weaker wind speeds than the southerly jet, by 3 and 4 m s\(^{-1}\) in the warm and cold seasons, respectively. The northerly jet is generated mostly by frontal passage, because a

### Table 1. Criteria for LLJ categories and LLJ occurrence in 1997–2002 (0200–1200 UTC) at the ABLE Beaumont site.

<table>
<thead>
<tr>
<th>Category</th>
<th>Category definition (m s(^{-1}))</th>
<th>Warm season</th>
<th>Cold season</th>
<th>All seasons</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(V_{\text{max}})</td>
<td>(\Delta V_{\text{max}})</td>
<td>Southerly</td>
<td>Northerly</td>
</tr>
<tr>
<td>0</td>
<td>10</td>
<td>5</td>
<td>997/82</td>
<td>303/41</td>
</tr>
<tr>
<td>1</td>
<td>12</td>
<td>6</td>
<td>1638/217</td>
<td>328/76</td>
</tr>
<tr>
<td>2</td>
<td>16</td>
<td>8</td>
<td>967/180</td>
<td>100/31</td>
</tr>
<tr>
<td>3</td>
<td>20</td>
<td>10</td>
<td>569/139</td>
<td>35/15</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>4171/618</td>
<td>766/163</td>
</tr>
</tbody>
</table>
lower-level strong northerly wind behind a cold front is usually overlain by southerly wind aloft. This phenomenon is discussed with synoptic patterns in section 4b.

To explore the reasons for the dominant LLJ direction, we compared daily weather maps produced at 0700 eastern standard time (EST) with radar–sodar wind profiles. For the southerly jet, we found that the wind near the surface was not predominantly from southwest; in fact, the jet usually was southerly at the surface, as is common in the warm sector of a cyclone or to the west of a subtropical high, but it veered with height by about 30°–50° km⁻¹, depending on the strength of wind. Because friction is small in a stable nocturnal boundary layer, an Ekman spiral is not the explanation; hence, veering wind with height indicates warm-air advection. Inertial oscillations also cause winds to veer with time (Lundquist 2000), by about 20°–30° in the warm season and 10°–20° in the cold season over the 11 nocturnal hours (0200–1200 UTC), as is discussed in section 4d. Thus, 1) warm-air advection resulting from the southerly flow with favorable synoptic patterns and 2) inertial oscillation resulting from the stable nocturnal boundary are believed to cause the dominant southwesterly jet. The nocturnal baroclinicity over terrain sloping from west to east, which favors southerly flow, is stronger in the cold season than in the warm season and is believed to cause the higher jet speed in the cold season.

Although the maximum wind of the LLJ can occur at any height, it tends to occur at particular levels (Fig. 3). Stronger jets generally occurred at higher altitudes than weaker jets, consistent with findings of Banta et al. (2002). The most common altitudes are about 350 m AGL for the stronger southerly jets and 250 m AGL for the weaker ones. The stronger northerly jets tend to occur somewhat higher, at 350 and 450 m AGL, and the maximum frequency of the weaker northerly jets is at 250 m AGL. The overall results indicate that LLJs occur predominantly below 500 m AGL.

Comparison of the vertical distribution of maximum jet winds in our 6-yr dataset (Fig. 3) and in the 2-yr rawinsonde analysis (Fig. 5 in Whiteman et al. 1997) indicated similar locations for maximum winds (300–400 m AGL) but different shapes for the distributions. Where our distribution has a gradual increase to the peak occurrence level and then a rapid decrease with height above 500 m AGL, the Whiteman et al. distribution shows a quick increase to the peak level and a gradual decrease with height above. For example, the LLJ occurrence of Whiteman et al. is much smaller below 100 m AGL than at 500–600 m AGL. One possible explanation for their higher LLJ peak is that Whiteman et al. used rawinsonde data that are not reliable below 100 m AGL, and the coarser vertical resolution in their sounding data may have missed weaker jets occurring at the lower levels. Our minisodar wind profiles began near the surface (10 m) and went to 200 m at approximately 5-m intervals, and our 915-MHz wind profiler measurements in low-power mode continued at 60-m intervals above 200 m.

The second possible explanation for the higher LLJ peak in the Whiteman et al. (1997) study is the lower elevation of their site. For a dataset of 102 hourly nocturnal profiles during October from radar–sodar at the

**Fig. 2.** Polar plots of distributions of the strongest LLJ speed and direction in the 6-yr nightly dataset during the (a) warm and (b) cold seasons at the Beaumont site. The criterion for minimum LLJ wind speed is 10 m s⁻¹.
ABLE sites in CASES-99, Banta et al. (2002) found that jets occurred closest to the surface at the Beaumont site, which is at the highest elevation. These authors suggested that the height of the LLJ could be at a constant altitude above mean sea level. To investigate this possibility, we compared the jet heights at the three ABLE sites in our 6-yr dataset. The nightly average heights of the strongest jets among the three sites are plotted in Fig. 4 with site elevations. The results show that the mean height of the LLJ (AGL) increases as the terrain elevation decreases, especially when we added the independent readings of Whiteman et al. (1997) for the lowest-elevation site (the SGP central facility, more than 100 km southwest of the ABLE area). As the result, the mean jet elevations above sea level do not follow the terrain but are approximately parallel to sea level, confirming the finding of Banta et al. (2002).

Comparison of jet wind speed in the 6-yr nighttime data among the three ABLE sites showed that the Beaumont site (highest elevation) on average experiences the strongest wind speed, and the Oxford site (lowest elevation) experiences the weakest. The difference increases as the jet becomes stronger. Stronger jet winds at higher elevations can be explained by continuity as the wind accelerates over a ridge.

b. Interannual variation

As compared with the previous LLJ climatological study that used data for a 2-yr period, our 6-yr continuous wind profiler observations not only improved statistical significance but also allowed us to examine interannual variations in nocturnal LLJ occurrences (Table 2). The results show that, in 1997–2002, southerly LLJ nights occurred less frequently in 1997–99 (with a minimum in 1998) and more frequently in 2000–02 (with a maximum in 2000); in contrast, the northerly LLJ night occurrences show little interannual variation. Further, the hours of southerly LLJ occurrence in the warm season of each year reveal an interannual variation trend similar to that for the southerly LLJ nighttime data, with fewer jet hours in 1997–99 and more in 2000–02 (Table 2). This trend is not clear in the cold
season. Furthermore, nights with stronger southerly LLJ occurrences are fewer before 1999 than after.

The role of southerly LLJ in transporting moisture to the Great Plains is well known, and one would expect precipitation within the WRW to show interannual variation similar to that of the southerly jet. Within the WRW, daily 24-h cumulative, 4-km-resolution radar-observed precipitation during 1997–2002 was obtained from the National Weather Service’s Arkansas–Red River Forecast Center. Annual total precipitation within the WRW and annual mean streamflow at the outlet of the WRW are presented in Table 2 for comparison with LLJ frequency. The data show that the years with greater amounts of precipitation and streamflow in southern Kansas have fewer southerly LLJ occurrences and vice versa.

To explain the seemingly contradictory relationship between LLJ and precipitation, we examined daily weather maps for possible causes of interannual variation in LLJ occurrence that might explain the hydrological components, adopting the synoptic classification scheme of Mitchell et al. (1995), which is based on the idealized model of an extratropical cyclone system. Table 3 shows that within a warm sector (class 1) or near and west of a subtropical high (class 5) chances for southerly jet occurrence are greater (82.8% and 82.7%, respectively, for all southerly categories and 57.2% and 43.6%, respectively, for stronger southerly categories), because the prevailing flow pattern is southerly. In contrast, under a polar high (class 4), even though that condition is present 40% of the time, chances of southerly jet occurrence are only 28.7% for all southerly categories and 10.3% for stronger southerly categories. Behind a cold front (class 3), a southerly LLJ is unlikely to occur (20.0%) but the chance for a northerly LLJ is substantial (44.2%).

Because the southerly LLJs, especially the stronger ones, are most likely to occur in classes 1 and 5, one would suspect these two classes to appear less frequently in southern Kansas before 2000 but more frequently in and after 2000. Examination of the synoptic-class occurrence in each year (Table 4) confirms that classes 1 and 5 did occur less frequently before 2000; however, class 3, which does not favor southerly jet, occurred more frequently before 2000. If synoptic patterns favoring southerly flow, such as classes 1 and 5, occur less and patterns favoring northerly flow, such as class 3, occur more, then the number of southerly jet

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**Table 2.** Interannual variations in the numbers of southerly and northerly LLJ occurrences during warm and cold seasons at the ABLE Beaumont site.

<table>
<thead>
<tr>
<th>Year</th>
<th>Southerly (nights)</th>
<th>Northerly (nights)</th>
<th>Southerly LLJ duration (h)</th>
<th>Stronger southerly LLJ (nights)</th>
<th>Annual mean precipitation at the WRW (mm)</th>
<th>Annual mean streamflow* (ft³ s⁻¹)</th>
<th>Missing data (days/hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1997</td>
<td>156</td>
<td>85</td>
<td>515</td>
<td>78</td>
<td>931</td>
<td>1250</td>
<td>20/15</td>
</tr>
<tr>
<td>1998</td>
<td>133</td>
<td>63</td>
<td>508</td>
<td>74</td>
<td>1056</td>
<td>2028</td>
<td>7/11</td>
</tr>
<tr>
<td>1999</td>
<td>155</td>
<td>57</td>
<td>614</td>
<td>91</td>
<td>1111</td>
<td>1905</td>
<td>45/28</td>
</tr>
<tr>
<td>2000</td>
<td>191</td>
<td>66</td>
<td>871</td>
<td>103</td>
<td>939</td>
<td>913</td>
<td>13/12</td>
</tr>
<tr>
<td>2001</td>
<td>185</td>
<td>63</td>
<td>852</td>
<td>93</td>
<td>850</td>
<td>856</td>
<td>7/13</td>
</tr>
<tr>
<td>2002</td>
<td>179</td>
<td>63</td>
<td>811</td>
<td>93</td>
<td>908</td>
<td>709</td>
<td>23/13</td>
</tr>
</tbody>
</table>

* Annual mean streamflow (1 ft³ = 0.028 m³) for the calendar year is from the Walnut River Watershed at Winfield, KS (information was available online at http://nwis.waterdata.usgs.gov/tutorial/historical_streamflow.html).

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**Table 3.** Synoptic-class occurrence frequency in a 6-yr period at Wichita, KS, with chance of occurrence for all LLJ categories and stronger LLJ categories, southerly and northerly.

<table>
<thead>
<tr>
<th>Synoptic class (Mitchell et al. 1995)</th>
<th>1) Warm sector</th>
<th>2) Ahead of warm front</th>
<th>3) Behind cold front</th>
<th>4) Under polar high with light wind</th>
<th>5) Near and west of subtropical ridge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class occurrence frequency (%)</td>
<td>19.6</td>
<td>12.2</td>
<td>19.0</td>
<td>40</td>
<td>9.2</td>
</tr>
<tr>
<td>Chance of occurrence (%):</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All southerly categories (LLJ-0–3-s)</td>
<td>82.8</td>
<td>53.6</td>
<td>20.0</td>
<td>28.7</td>
<td>82.7</td>
</tr>
<tr>
<td>Stronger southerly categories (LLJ-2–3-s)</td>
<td>57.2</td>
<td>26.2</td>
<td>9.4</td>
<td>10.3</td>
<td>43.6</td>
</tr>
<tr>
<td>All northerly categories (LLJ-0–3-n)</td>
<td>3.3</td>
<td>11.2</td>
<td>44.2</td>
<td>19.1</td>
<td>1.0</td>
</tr>
<tr>
<td>Stronger northerly categories (LLJ-2–3-n)</td>
<td>1.6</td>
<td>2.2</td>
<td>18.5</td>
<td>3.2</td>
<td>1.0</td>
</tr>
</tbody>
</table>
occurrences should be reduced. Thus, less frequent southerly jet occurrence before 2000 is probably associated with a reduced occurrence of favorable synoptic conditions in southern Kansas.

Although southerly LLJ plays an important role in transporting moisture from the Gulf of Mexico, precipitation in the midlatitudes is associated more strongly with the passage of frontal systems. If the frontal system lies farther north and does not sweep through southern Kansas often, moisture transported by the frequent LLJ will flow over the southern Great Plains rather than converging and precipitating there, even though the synoptic condition is favorable for a southerly jet. In contrast, if the frontal system sweeps across southern Kansas frequently, more precipitation may fall, even though this condition is unfavorable for frequent southerly jet. This may explain the observation (Table 2) that fewer southerly jet occurrences in 1998 did not reduce annual precipitation or streamflow at the WRW. Instead, the frequent passage of frontal systems actually increased these quantities. In summary, interannual variation in LLJ occurrence is determined by changes in the locations of large-scale synoptic patterns; frequent and strong southerly jets that transport moisture downstream do not necessarily lead to more precipitation locally, but large-scale precipitation can be influenced by LLJ strength and frequency, as in the case of a 1993 Midwest flood (Mo et al. 1997).

It is of interest that 1998 and 2000 correspond to El Niño and La Niña episodes, respectively, as well as to warm and cold phases of the Pacific decadal oscillation (PDO) (Barnett et al. 1999; Mantua et al. 1997; Trenberth and Hurrell 1994), respectively. The PDO-associated change in locations of cold and warm water masses alters the path of the upper-level jet stream. Meanwhile, the location of atmospheric warm sectors and subtropical highs can shift in response to the long-wave pattern of which the jet stream is an indicator. The warm phase of the PDO (before 1999) acted with El Niño to steer the jet stream southward over the western United States, and the cool PDO phase (since 1999) has acted with La Niña to steer the jet stream farther north (Zhang et al. 1997). The jet stream is tied to frontal systems and delivers storms across the United States; thus, its southward position (as in 1998) favors frequent frontal passages and more precipitation in the southern Great Plains. The northward position of the jet stream (after 1999) placed frontal activity with precipitation farther north, leaving the southern Great Plains largely exposed to the warm sector and the strengthened subtropical high, as well as favoring frequent southerly LLJ formation. Further evidence of the relationship between jet stream position and rainfall can be found during the 1992–93 El Niño (also during the warm phase of the PDO), when the North American jet lay south of its climatological location and unusually enhanced storm activity preceded the 1993 floods (Mo et al. 1997). Thus, interannual variations in jet occurrence might result from large-scale coherent climate variations and should be studied further through dynamic modeling.

c. Seasonal variation

As Fig. 5 shows, LLJ occurrence varies monthly. The occurrence of nights with a southerly jet (Fig. 5a) increased gradually from cold season to warm season for both weaker and stronger LLJs, with their sum being highest in July. The correlation coefficient of seasonal frequencies between weaker LLJ and stronger LLJ (0.70, with a confidence level \( \alpha = 0.05 \)) indicates that weaker LLJ and stronger LLJ have similar seasonal variations. In comparison, both weaker and stronger northerly LLJs (Fig. 5b) occurred much less frequently than southerly LLJs and showed an increasing trend from warm season to cold season, with a correlation coefficient of 0.63 (confidence level \( \alpha = 0.05 \)). This trend was related to increased cold air invasion, but even in the cold season stronger northerly LLJ nights occurred much less frequently than weaker ones.

Hourly and nightly data show that both LLJ speed and altitude vary monthly. Figure 6 illustrates the seasonal variations of the jet speed and altitude (AGL) for the 6-yr hourly dataset. Both the speed and altitude of the southerly jet vary seasonally, with stronger speeds and higher altitudes in the cold season and weaker speeds and lower altitudes in the warm season (correlation coefficient of 0.71 with confidence level \( \alpha = 0.05 \)). Seasonal variations of LLJ in individual years are expected to deviate from the 6-yr climatological results. For example, although July, August, and September have the weakest LLJ speed and the lowest peak altitude in the 6-yr climatological data (Fig. 6), this temporal pattern was delayed 1 month in 1999, when the lowest speed and altitude occurred in August. September
ber, and October (data not shown). Thus, the CASES-99 analysis of LLJ for October 1999 by Banta et al. (2002) indicated weaker LLJ speed and lower LLJ altitude than for October of the other years.

Changes in southerly LLJ altitude with season may be a reason for changes in jet speed. In the cold season, the southerly jet is likely to occur at higher altitudes (Fig. 6), where nocturnal winds will oscillate around a stronger wind to yield a stronger jet speed. Another reason for the reduced mean jet speed in the warm season, especially July–September, is the more frequent occurrences of weaker southerly jets in these months than in other months (Fig. 5). In comparison, the speed and altitude of northerly jets (Fig. 6) do not vary greatly with season, and northerly jet speed is much less than southerly jet speed, with the largest difference between the two occurring in the cold season.

d. Nocturnal variation

The continuous hourly wind profile dataset allowed us to examine nocturnal variations in LLJ characteristics. Although the hours of northerly jet occurrence showed no regular trend (data not shown), a clear nocturnal variation in hours of southerly jet occurrence (Fig. 7) during the warm season does indicate a gradual increase in stronger LLJ occurrence after sunset, reaching a plateau after 0500 UTC (1100 CST) and decreasing gradually after about 1000 UTC (0400 CST). In the cold season, characteristics of the stronger southerly LLJ are similar to those in the warm season, except for a shorter duration at the plateau. In contrast, no trends are obvious in nocturnal variations in the weaker southerly LLJ occurrence during either season (Fig. 7). This result is similar to findings of Whiteman et al. (1997) and Mitchell et al. (1995). According to the inertial oscillation theory (Stull 1988), the strongest jet speed should occur 7.3 h after sunset at Beaumont (37.6°N). This explains the plateau in hours of stronger LLJ occurrence at about 0500–1000 UTC.

Averaging the wind components of southerly LLJ over our 6-yr period and plotting the results on a hodograph for each nocturnal hour masked large standard deviations of 7.7–9.0 m s\(^{-1}\) for the zonal component and 5.4–6.2 m s\(^{-1}\) for the meridional component. Nevertheless, the southerly LLJ demonstrates veering
with time similar to that expected from inertial oscillation, with clear clockwise rotation of the wind (Fig. 8). Although stronger nocturnal LLJs were predominantly southwesterly, weaker LLJs were frequently southeastern (Fig. 2). The large daily variations in LLJ intensity and direction explain the larger standard deviation in the zonal component and the large daily variations in LLJ intensity. In the 6-yr average, the southerly jet speed is strongest at 0700–1000 UTC, in general agreement with inertial oscillation theory (Stull 1988). The northerly jet did not show obvious rotation (data not shown).

5. Summary and conclusions

In the southern Great Plains, the nocturnal LLJ occurs most frequently in Kansas and Oklahoma, according to Bonner (1968). A combination of minisodars and 915-MHz wind profilers at the ABLE facility in southern Kansas provided a unique hourly dataset that revealed detailed LLJ characteristics. Analysis of the nocturnal (0200–1200 UTC) wind data for 1997–2002 indicated a 63% rate of occurrence of LLJs, of which 72% are southerly. The southerly jet lasts longest in the warm season, despite its shorter nighttime period, and the northerly jet has the shortest duration in the cold season. The two preferred directions identified for the LLJ are (first) southwest, with stronger jet speed, and (second) northeast, with weaker jet speed. Four factors explain the predominance of the southwesterly LLJ direction: 1) distinctive synoptic flow patterns with high pressure systems in the east that favor southerly flow, in contrast to frontal passages that induce northerly jet; 2) baroclinic conditions that favor southerly jet development; 3) clockwise wind rotation with height resulting from southerly (warm air) advection; and 4) clockwise southerly wind rotation with time resulting from inertial oscillation. Northerly LLJ seems to be associated with frontal passages. Average jet speed in the cold season is stronger, 20 versus 16 m s\(^{-1}\), for southerly versus northerly LLJ; corresponding warm-season southerly and northerly speeds are 18 and 15 m s\(^{-1}\), respectively. The stronger LLJ is most likely to occur at a higher level (300–400 m AGL) than the weaker jet (200–300 m AGL). A comparison of the altitude of the LLJ maximum wind among the three ABLE sites, plus results of Whiteman et al. (1997) for a fourth site, showed that the mean LLJ altitude was roughly equipotential rather than parallel to the terrain elevation. The jet speed was faster where elevation was higher.

The frequency of southerly LLJ occurrence demon-
stratified large interannual variability, with fewer jets in 1997–99 but more in 2000–02. This result might indicate influences of a large-scale circulation pattern shift associated with the PDO. El Niño and La Niña variations are overlaid on the longer-scale PDO patterns; their effects can be enhanced or diminished in different phases of the PDO. El Niño in 1998 coincided with the warm phase of the PDO, possibly amplifying its strength and impact greatly. The coincidence of these two effects apparently steered the upper-level jet stream southward, caused the withdrawal of subtropical highs, and pushed frontal passages south. During 1998, the southerly jet occurred less frequently in terms of numbers of both hours and nights; 1998 was also a very wet year, according to the annual streamflow in the WRW. The increased number of southerly jets since 2000 may be the result of a phase alteration in the PDO after 1999. During the cool phase of the PDO, the upper-level jet stream was steered farther north, especially in 2000, in coincidence with a La Niña episode, and the southerly jet occurred most often.

In contrast to the northerly LLJ, the southerly LLJ had a clear seasonal variability with peak occurrences in July, though both the mean altitude and mean speed decreased in July–September. Occurrence of the southerly LLJ also demonstrated clear nocturnal variability, increasing after sunset and reaching a plateau at 0500 UTC and then gradually decreasing after 0800 UTC. The nocturnal wind vector demonstrated a tendency to veer or rotate clockwise, even for the hourly averaged 6-yr dataset, with the strongest wind speed at 0700–1000 UTC. This observation, in general, agrees with the inertial theory. The results of this study will be helpful in studying wind power potential in the southern Great Plains.

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