Low-Level Jet Climatology from Enhanced Rawinsonde Observations at a Site in the Southern Great Plains

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ABSTRACT

A climatology of the Great Plains low-level jet (LLJ) is developed from 2 yr of research rawinsonde data obtained up to eight times per day at a site in north-central Oklahoma. These data have better height and time resolution than earlier studies, and show that jets are stronger than previously reported and that the heights of maximum wind speed are closer to the ground. LLJs are present in 47% of the warm season soundings and 45% of the cold season soundings. More than 50% of the LLJs have wind maxima below 500 m above ground level (AGL). Because the 404-MHz radar profiler network in the central United States has its first data points at 500 m AGL, it is likely to miss some LLJ events and will have inadequate vertical resolution of LLJ wind structure.

Previous studies have identified LLJs on the basis of a wind speed profile criterion. This criterion fails to separate the classical southerly LLJs from the less frequent northerly jets, which differ in both structure and evolution. Classical southerly jets are more frequent; they occur year round, with the highest frequency in the summer and at night. Southerly LLJ wind speed maxima are most frequently found at 300–600 m AGL, and peak speeds, typically between 15 and 21 m s^{-1}, are attained at 0200 CST. The height of the wind speed maximum varies little during nighttime—a period when surface-based inversions grow in depth but generally remain below the jet. Winds at the nose of the southerly jets exhibit a distinct diurnal clockwise turning in wind direction and an oscillation in speed.

Northerly jets occur year round. They are generally associated with cold air outbreaks and are found in the cold air behind southward-moving cold fronts. In winter, their frequency of occurrence rivals that of the southerly jets. Their occurrence, however, is less dependent on time of day, with a weak daytime maximum. They are more variable in the heights of their wind speed maxima, are associated more frequently with elevated frontal inversions, and do not exhibit a clockwise turning with time. The heights of the jet speed maxima are found to increase with distance behind the surface cold front.

1. Introduction

The Great Plains region of the United States is frequently under the influence of a nocturnal low-level supergeostrophic wind maximum, the low-level jet (LLJ). These recurring boundary layer wind maxima play an important role in transporting moisture from the Gulf of Mexico to the central United States, where it helps to promote thunderstorm development and heavy precipitation (Pitchford and London 1962; Maddox 1983; Augustine and Caracena 1994).

The Great Plains LLJ is well documented through observational studies (Izumi and Barad 1963; Hoecker 1963; Parish et al. 1988; Frisch et al. 1992), theoretical analyses (Blackadar 1957; Wexler 1961; Holton 1967), and numerical modeling (McNider and Pielke 1981; Paegle and McLawhorn 1983; Fast and McCorcle 1990; Zhong et al. 1996). While many studies describe LLJ characteristics for individual cases, few document its climatological behavior. The first LLJ climatology was reported by Bonner (1968) using 2 yr (January 1959 to December 1960) of rawinsonde data summaries from 47 stations across the United States. He found that the LLJ occurred most frequently over the Great Plains, with the maximum frequency of occurrence over Oklahoma and Kansas. He also found significant diurnal and seasonal variations in LLJ frequency—more LLJs appeared in the early morning soundings than in the afternoon soundings, and jets were most frequent in August and September. He noted that the jet wind speeds and the heights of the wind maxima varied greatly from case to case and that the heights of the wind maxima were not strongly correlated with the heights of nocturnal surface inversions.

Bonner's pioneering work is the most complete climatological description of the Great Plains LLJ and has been widely referenced. His primary analyses were based on twice-daily rawinsonde summaries, although some supplementary analyses were performed with

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four-per-day soundings. Reliance on the twice-daily soundings imposes limitations on the climatological analyses. The standard 0000 UTC launch time is too early to observe nocturnal LLJs on many days, and some short-lived LLJs may not persist until the 1200 UTC launch times. The twice-per-day soundings are also inadequate for determining the time variation of the LLJ structure and may fail to observe its maximum state of development. Bonner's climatological analyses were also limited by the relatively coarse vertical resolution of the rawinsonde summaries, which were limited to wind data at the surface, at 150 and 300 m AGL, at 500-m increments from 500 to 3000 m MSL (above mean sea level), and at 1000-m increments above 3000 m MSL. This relatively coarse vertical resolution, especially in the lowest 1500 m of the atmosphere, is likely to affect the resolution of jet height and jet speed, as well as calculations of the associated vertical wind shear.

As radar-derived hourly wind profiles have become available over much of the Great Plains from the National Oceanic and Atmospheric Administration's 404-MHz Wind Profiler Demonstration Network (WPDN), it has become possible to construct new LLJ climatologies. Mitchell et al. (1995) developed a warm-season LLJ climatology using WPDN data from April to September 1991 and 1992. The hourly wind data made it possible to accurately identify LLJ events and to study their diurnal evolution. Although the new climatology has a much-improved time resolution, it suffers from a lack of vertical resolution near the ground. The 404-MHz wind profilers report data at 250-m increments from 500 m AGL to about 19 km AGL, but data at the first range gate are often unreliable. With the lowest useful data point often at 750 m, the profiler may fail to detect the maximum jet speed and yield an incorrect description of the vertical jet structure. In addition, concerns were raised by Wilczak et al. (1995) that the profiler wind data may be contaminated by anomalous radar returns from migrating birds. The bird contamination has since been found to be a serious problem for studies of the nocturnal Great Plains LLJ using profiler data because 1) the birds migrate preferentially at night, 2) they migrate preferentially on nights having strong LLJs, and 3) the jet axis corresponds well with the bird migration path over the Great Plains. Arritt et al. (1997) found a sharp reduction in the availability of good quality wind data after sunset, an increase after sunrise, and a significant reduction in usable data during the spring and the fall seasons, consistent with the signature of contamination by migratory birds.

In this paper, we present climatological analyses of LLJ characteristics for a site in north-central Oklahoma, using special research rawinsonde data having high vertical resolution and enhanced temporal resolution. The analyses focus on the frequency of occurrence, vertical structure, and temporal evolution of the LLJ. To facilitate comparison with earlier climatologies, we adopt an LLJ definition (Bonner 1968) based on a wind speed

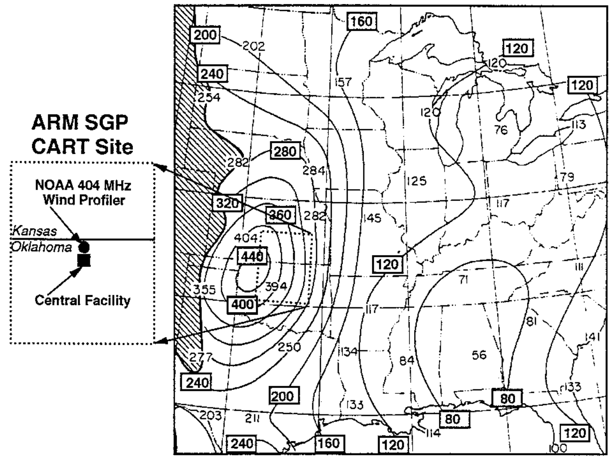

FIG. 1. Geographic distribution of the number of LLJ-1 occurrences from January 1959 to December 1960 for 1800 and 0600 CST combined (from Bonner 1968). The numbers can be converted to frequencies by dividing by the maximum possible number of observations, 1462. The dashed rectangle indicates the boundaries of the ARM SGP CART site, the solid square indicates the CART central facility where rawinsondes are launched, and the solid circle indicates the 404-MHz radar wind profiler at Lamont, Oklahoma.

profile criterion irrespective of wind direction and present results for data stratifications used by previous investigators—for example, for inclusive jet categories, as defined by Bonner (1968), and for the warm season, as defined by Mitchell et al. (1995). Section 2 describes the site characteristics and the data. Section 3 presents the analysis results. Our analyses reveal a significant percentage of northerly LLJs in all seasons, and section 3e is devoted specifically to determining the separate characteristics of the northerly and southerly LLJs. Conclusions are presented in section 4.

2. The site and data

The U.S. Department of Energy's Atmospheric Radiation Measurement program is establishing three research sites around the globe for cloud and radiation research to improve climate models (Stokes and Schwartz 1994). The Southern Great Plains (SGP) Cloud and Radiation Testbed (CART) site in Oklahoma–Kansas is the first of these three sites. The SGP CART site was commissioned in 1992 and many in situ and remote sensing meteorological instruments have been in routine operation at this site since then. This site is ideally suited for LLJ research because, as indicated in Fig. 1, it is located near the axis of maximum LLJ frequency in the southern Great Plains, as identified by Bonner (1968).

Rawinsondes are generally launched five times per day at 0530, 0830, 1130, 1430, and 2330 CST at the SGP CART central facility (36.601°N, 97.487°W, 315 m MSL). There are many intensive observing periods at the site, however, when additional soundings are made at 0230, 1730, and 2030 CST. The standard launch times for the United States rawinsonde network, while nominally given as 0000 and 1200 UTC, are actually at 2315 and 1115 UTC (1715 and 0515 CST) and are thus within 15 min of two of the eight launch times at the central facility. For convenience, sounding times will be referred to as 0200, 0500, 0800, 1100, 1400, 1700, 2000, and 2300 CST.

Wind, temperature, and moisture data from nearly 2 yr of rawinsonde observations (7 April 1994 through 30 March 1996) were analyzed to produce a detailed description of the climatological behavior of the LLJ and its relation to temperature and moisture structure. Unless otherwise noted, all analyses are based on data from this entire period. The number of soundings during the 2-yr period varied with time of day, with 127, 497, 123, 513, 512, 523, 519, and 140 soundings at the observation times of 2000, 2300, 0200, 0500, 0800, 1100, 1400, and 1700 CST, respectively. The numbers also varied by month, with 214, 228, 206, 289, 219, 106, 327, 301, 248, 328, 275, and 213 soundings from January to December, respectively. Because fewer observations are available at 1700, 2000, and 0200 CST and in June, the level of statistical significance is lower for analyses at these times. Although the 24-month period of rawinsonde records is rather short for climatological analyses, it is comparable to Bonner's (1968) and Mitchell et al.'s (1995) periods of record and provides a benchmark for future analyses that can be completed when further data are accumulated. The computed statistics should prove useful as initial indications of LLJ characteristics at this site.

Wind data were obtained at the central facility by tracking Vaisala RS80-15L radiosondes using radio signals intended for Long Range Navigation (LORAN) by ships and aircraft. The LORAN-C cross-chain windfinding technique that was used utilizes two chains of LORAN stations for improved accuracy. The radiosondes have a LORAN-C receiver and an unwinding antenna that is deployed immediately on sonde release. The sonde receives the LORAN signals, modulates them onto the 400-MHz carrier frequency together with the other sonde data, and transmits them to the ground station. At the ground station, the signals are extracted, are fed to a LORAN-C receiver, and are compared with signals generated by an internal reference synchronized with signals transmitted by the two LORAN chains that are used at the site. The rate of change of time differences measured between the reception of the transmitting stations in the chains is used to compute wind speed and direction. Wind data are reported only when time differences can be determined for three or more stations, with wind quality improving as the number of transmitting stations increases from the three-station minimum as the sonde ascends. Our analyses used SGP "raw" wind data, in which no interpolations were performed to obtain missing wind values. The distribution of the heights of the first-reported winds is shown in Fig. 2. The analyses showed that 83%, 96%, and 99% of the first winds were reported at levels below 100, 200, and 300 m AGL, respectively. Examination of individual wind profiles confirms that wind data quality was sufficient to exclude the generation of spurious LLJs at the lowest wind-reporting levels.

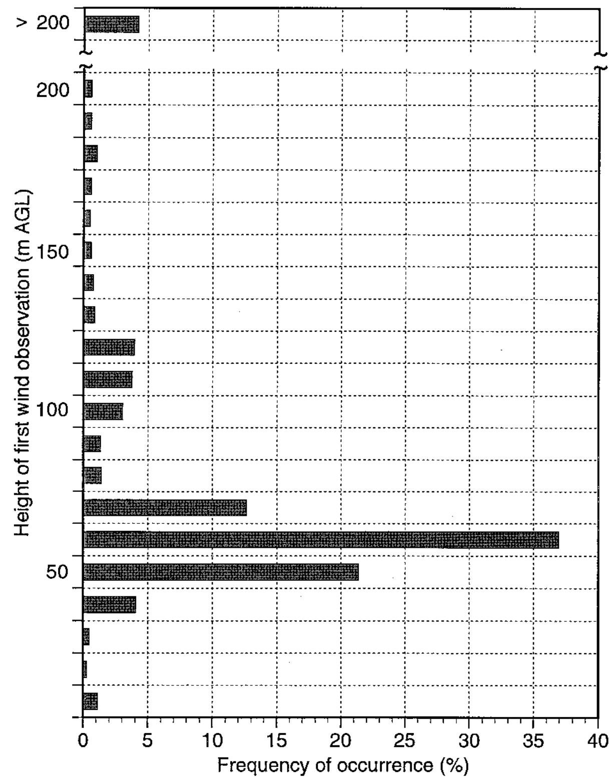

FIG. 2. Frequency distribution of the heights of first-reported wind observation for the 2 yr of rawinsonde soundings at the SGP CART site. Approximately 4% of the heights are between 200 and 3000 m AGL.

The height of the balloon is obtained from the rawinsonde pressure sensor, thereby eliminating the constant rate of rise assumption that, according to Boatman (1974), can result in a relatively large position and hence wind errors. Since the balloon is carried by the wind, the sounding is not, strictly speaking, a vertical profile directly over the site. Our interest is primarily in the first 1500 m of ascent. The balloon typically remains within 5 km of the site during its ascent through this altitude. Because of the homogeneity of the nearby terrain and the broad horizontal homogeneity of the LLJ throughout the Great Plains, this horizontal translation is not expected to affect the climatological results.

3. Low-level jet characteristics

a. Frequency of occurrence

For our climatological analyses, rawinsonde wind soundings from the 2-yr period of record were classified into four LLJ categories. Two criteria are used for the

TABLE 1. Percentage of all rawinsonde soundings exhibiting LLJs during the period of record.

LLJ category	Definition* V_{max} (m s^{-1})	ΔV (m s^{-1})	Warm season	Cold season	All seasons	Bonner (1968)
No jet	—	—	52.9	55.1	54.0	72.0
LLJ-0	≥10	≥5	47.1	44.9	46.0	—
LLJ-1	≥12	≥6	34.4	34.6	34.5	28.0
LLJ-2	≥16	≥8	15.8	20.5	18.1	12.0
LLJ-3	≥20	≥10	6.7	10.7	8.7	4.0

* Here, V_{max} is the maximum wind speed at the nose of the jet, and ΔV is the difference between the jet maximum speed and the minimum speed above the jet maximum height, but below 3 km AGL. Categories 1 through 3 are identical to Bonner's (1968) categories.

classification, and both must be satisfied simultaneously. One specifies the threshold value for maximum wind speed, and another specifies the falloff value from the wind speed maximum upward to the next wind speed minimum at or below the 3000-m level. Jets in the LLJ-0 category have a maximum speed greater than or equal to 10 m s^{-1} in the lowest 3000 m, and the wind speed must decrease by at least 5 m s^{-1} before the 3000-m level is reached. The LLJ-1 through LLJ-3 criteria are defined similarly, except that they use speed criteria of 12, 16, and 20 m s^{-1} and falloff criteria of 6, 8, and 10 m s^{-1}, respectively (Table 1). The LLJ-1 through LLJ-3 criteria are identical to Bonner's (1968) criteria, and the LLJ-0 criterion was added to include distinctive jet wind profiles that were found in many soundings but did not meet Bonner's LLJ-1 criteria. Note that the LLJ categories are inclusive, so that the LLJ-0 category includes

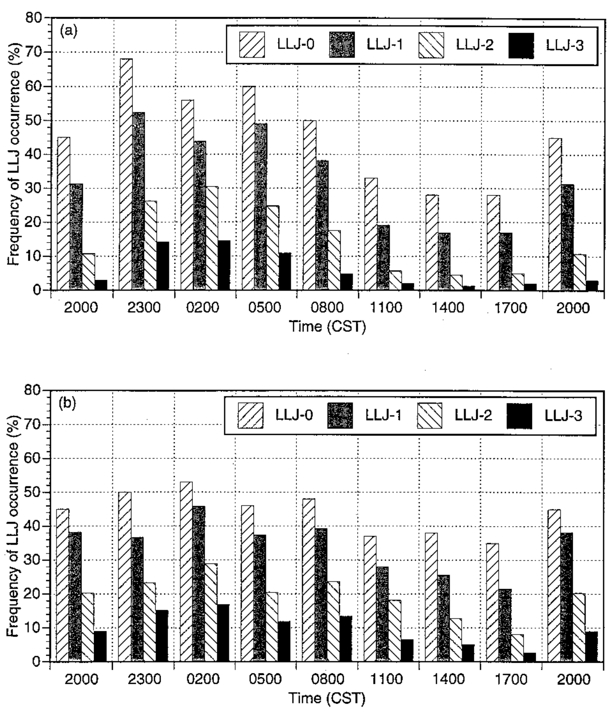

FIG. 3. Diurnal variation of the frequency of LLJ occurrences for (a) warm and (b) cold season soundings for the 2-yr period of record. Separate bars are shown for each of the inclusive LLJ categories.

the stronger jets in categories LLJ-1 through LLJ-3, the LLJ-1 category includes LLJ-2 and LLJ-3 jets, etc., and that the LLJ categories are defined without regard to wind direction. Examples of the categorization scheme include the following: a 16 m s^{-1} jet with a falloff of 6 m s^{-1} would be considered an LLJ-1 (and also an LLJ-0), and a 20 m s^{-1} jet with a falloff of 12 m s^{-1} would be considered an LLJ-3 (and also an LLJ-2, an LLJ-1, and an LLJ-0). In general, stronger jets are associated with larger falloffs.

The nearly 2-yr period of record had 2954 rawinsonde wind soundings, distributed almost equally between the warm (April through September, 1490) and cold (October through March, 1464) seasons. Table 1 provides the frequency distributions for LLJ occurrences and includes, for comparison, Bonner's frequency computations. According to Table 1, LLJs are present in 46% of the soundings, and there is surprisingly little difference in the seasonal frequency of occurrence (44.9% in the cold season and 47.1% in the warm season). Bonner stated that 55% to 60% of all jets in the Great Plains occur during the warm season, but no detailed information is available to make a specific comparison with our site in north-central Oklahoma.

It is interesting to note that while weaker LLJs (LLJ-0 and LLJ-1) occur somewhat more frequently in the warm season, the stronger jets (LLJ-2 and LLJ-3) actually occur more frequently in the cold season. Compared with Bonner's climatology near our location for the corresponding categories, our frequency of LLJ occurrence is only slightly higher in categories 1 and 2, but twice as high as Bonner's for category 3, which suggests that the twice-daily soundings that Bonner used are more likely to miss the strongest jet events.

The diurnal distribution of LLJ frequency (Fig. 3) shows that LLJs are more frequent at night than during the day for both the warm (Fig. 3a) and cold (Fig. 3b) seasons, and that this nocturnal preference is more pronounced in the warm season than in the cold season and for stronger jets than for weaker jets. The strongest jets (LLJ-3) are most frequent between 2300 and 0500 CST, which explains why they are more likely to be missed by the standard rawinsonde soundings at 0500 and 1700 CST.

The wind direction at the height of the jet speed max-

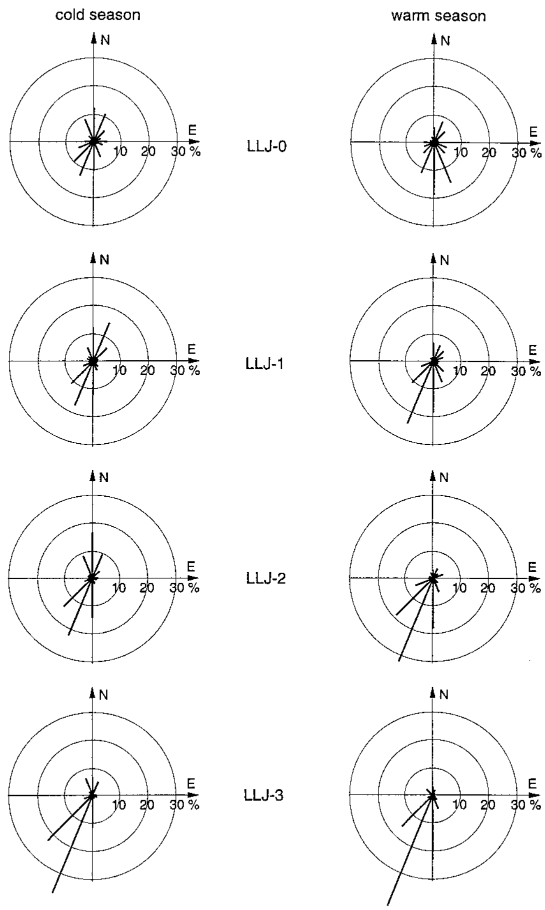

FIG. 4. The frequency of occurrence of wind directions measured at the height of the maximum wind speed for warm and cold season LLJ soundings. Separate plots are shown for each of the inclusive LLJ categories.

imum differs for the warm and cold seasons, as seen in Fig. 4. In the warm season, the weakest jets tend to come from the south and the stronger jets come from the south-southwest. A small percentage of mainly weaker northeast jets is seen in the wind roses. Thus, warm season LLJs are confined predominantly to a rather narrow range of wind directions. In the cold season, however, the frequency roses indicate a bimodality in direction, with a marked secondary maximum in jet directions from the north-northwest to the north-northeast.

b. Vertical structure

The statistics of the distribution of LLJ wind speed maxima are summarized in Table 2. The mean of the jet wind speed maxima for all jet soundings was 17.1 m s^{-1}, while the mean for the LLJ-3 category, the highest speed jets, was 24.2 m s^{-1}. When the jet soundings are segregated by season, the mean and standard deviation of the peak speed distribution are higher for the cold season (18.3 and 5.3 m s^{-1}) than for the warm season (16.0 and 4.8). The median of the distribution of wind speed maxima is lower than the mean in both seasons, showing that the distributions are somewhat skewed.

The height distributions of the jet wind speed maxima are shown in Fig. 5. Using 100-m height intervals, the height of the jet maximum occurs most frequently in the 300–600-m height range, with a peak between 300 and 400 m. Over 57% of LLJs have their wind speed maxima below 500 m, and 83% are below 1000 m. Warm season jets have a more pronounced low-level maximum than cold season jets.

Bonner found that the mean height of the LLJ wind maximum over 22 stations in the Great Plains at 0500 CST was 785 m AGL, with a standard deviation among the individual stations of 127 m. Mitchell et al. (1995) computed an average LLJ height of around 1000 m AGL. The mean (median) height of the wind maximum from our data, however, is 596 (430) m AGL, which is significantly lower than reported in these earlier studies. We believe that the higher vertical resolution of our data (approximately 15 m) accounts for the differences. Bonner's rawinsonde summaries had data at a limited number of heights, as mentioned in section 1, and the vertical resolution depends on the altitude of the particular rawinsonde station. At the central facility (315 m MSL), the rawinsonde summaries would have had only five data points below 1500 m; the heights of these data points, when translated to meters above ground level, are 0, 150, 185, 300, 700, and 1200 m AGL. Mitchell et al.'s (1995) 404-MHz wind profiler data had a resolution of 250 m, beginning at 500 m AGL (or sometimes 750 am AGL, see below).

The climatological mean warm season jet (Fig. 6a) undergoes a significant diurnal variation in the lowest 1 km as compared to the mean profiles for warm season nonjet soundings (Fig. 6b), with the mean jet reaching

TABLE 2. Peak wind speed statistics (m s^{-1}) for all LLJs, warm season LLJs, and cold season LLJs in the period of record.

	All seasons				Cold season				Warm season			
Category	LLJ-0	LLJ-1	LLJ-2	LLJ-3	LLJ-0	LLJ-1	LLJ-2	LLJ-3	LLJ-0	LLJ-1	LLJ-2	LLJ-3
Count	1360	1017	535	257	658	506	300	157	702	511	235	100
Mean	17.1	18.5	21.5	24.2	18.3	19.6	22.1	24.6	16.0	17.5	20.8	23.7
Median	16.1	17.6	20.8	23.4	17.7	19.2	21.5	24.2	14.9	16.3	19.9	22.6
Std dev	5.2	4.8	4.1	3.4	5.3	5.00	4.2	3.4	4.8	4.5	3.9	3.4
Minimum	10	12	16	20	10	12	16	20	10	12	16	20
Maximum	34.9	34.9	34.9	34.9	34.5	34.5	34.5	34.5	34.9	34.9	34.9	34.9

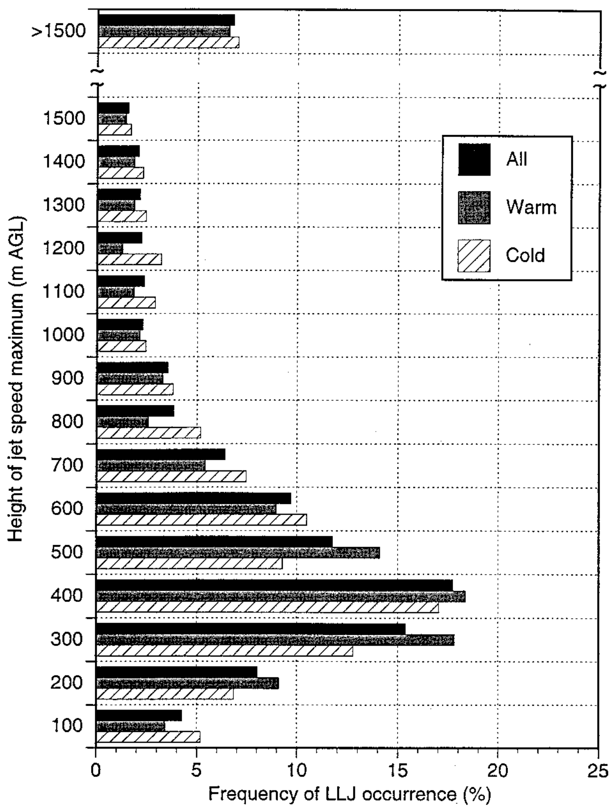

FIG. 5. Frequency of occurrence of the heights of the wind speed maxima in the 2-yr period of record for the warm, cold, and all-season LLJ soundings. The total number of cases of warm, cold, and all-season LLJs were 702, 657, and 1359, respectively. The heights labeled greater than 1500 represent heights between 1500 and 3000 m.

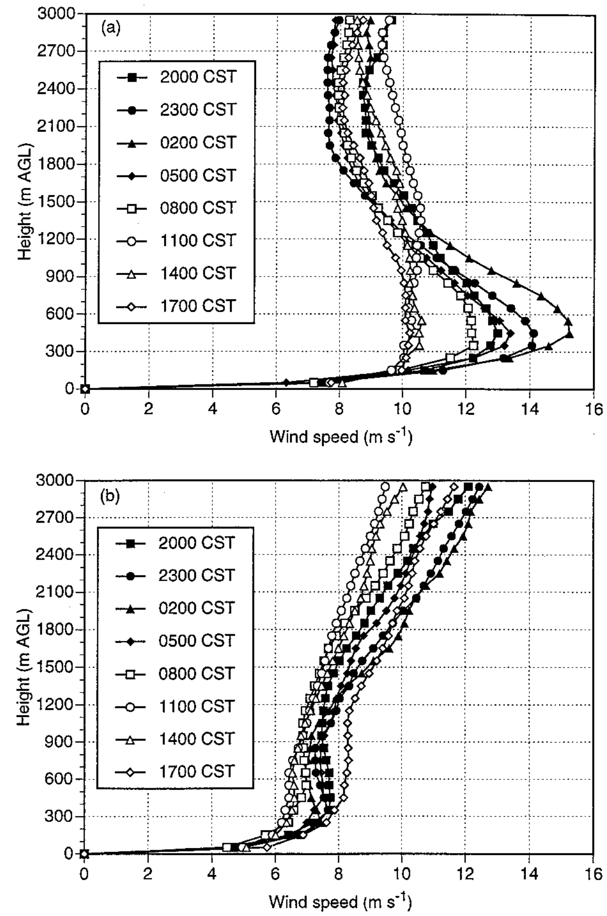

FIG. 6. Diurnal variation of the mean warm season wind profiles as determined from (a) LLJ soundings and (b) non-LLJ soundings.

its maximum strength of about 15 m s^{-1} at 0200 CST. While Fig. 6a illustrates the diurnal variation of the jet profiles well, it is important to recognize that the wind speed maxima are reduced somewhat in these mean profiles because of the effects of averaging individual profiles having differing heights of wind speed maxima. For comparison, Table 2 lists the mean warm season jet, regardless of time of day, as having a mean wind maximum of 16 m s^{-1}.

The fact that 50% of the LLJs have their levels of maximum wind speed below 430 m AGL raises questions regarding the adequacy of the 404-MHz WPDN network of radar wind profilers for observing the vertical structure (see also Stensrud et al. 1990). The 404-MHz profilers have their lowest range gate at 500 m. They report data at 250-m intervals, as averaged over height intervals of 320 m centered on each of the reporting levels. Data from the 500-m range gate is often unreliable, however, so that the first data point is often at 750 m AGL, above the height of most of the jet wind speed maxima.

A 915-MHz radar wind profiler was used to provide wind profile measurements at hourly intervals at the CART central facility, where the rawinsonde soundings were launched. Data from the 915-MHz radar profiler and rawinsonde at the CART central facility can be compared to data from the WPDN 404-MHz wind profiler at Lamont, Oklahoma, about 9 km north of the central facility. This comparison is made in Figs. 7a–c for a 24-h period, which began at 1800 CST on 31 July 1994. This period was chosen to illustrate a well-developed diurnal jet occurring at a time of year when bird migrations are at a minimum (Arritt et al. 1997). On this date, the 915-MHz wind profiler was in continuous operation, but alternating between two operational modes. The low mode reported winds averaged over 102-m height intervals every 100 m beginning at 138 m AGL. The high mode reported winds averaged over 420-m height intervals every 100 m beginning at 320 m AGL. Figures 7a–c show comparisons between rawinsonde vertical wind profiles and profiles obtained at the same time from the 915-MHz low mode, 915-MHz high mode, and the 404-MHz radar profilers, respectively. The low mode of the 915-MHz profiler shows the best agreement with the rawinsonde wind soundings (Fig. 7a). The 915-MHz high mode soundings are highly smoothed compared to the low mode soundings, but

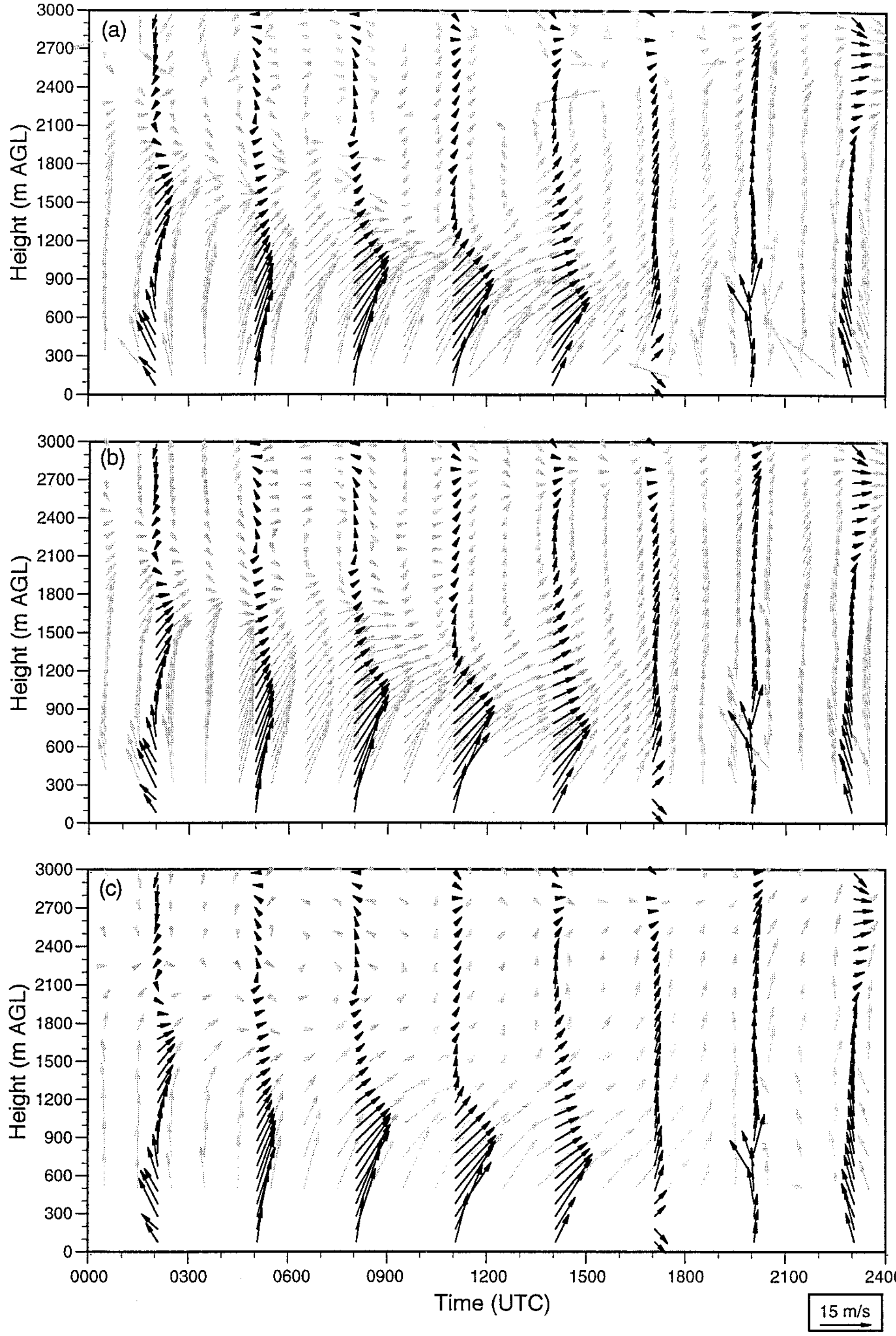

Fig. 7. Comparison of rawinsonde vector wind profiles (dark vectors), averaged over 100-m height intervals, with those measured (gray vectors) by (a) the low mode of the 915-MHz wind profiler, (b) the high mode of the 915-MHz wind profiler, and (c) the 404-MHz wind profiler for a 24-h period starting at 1800 CST 31 July 1994.

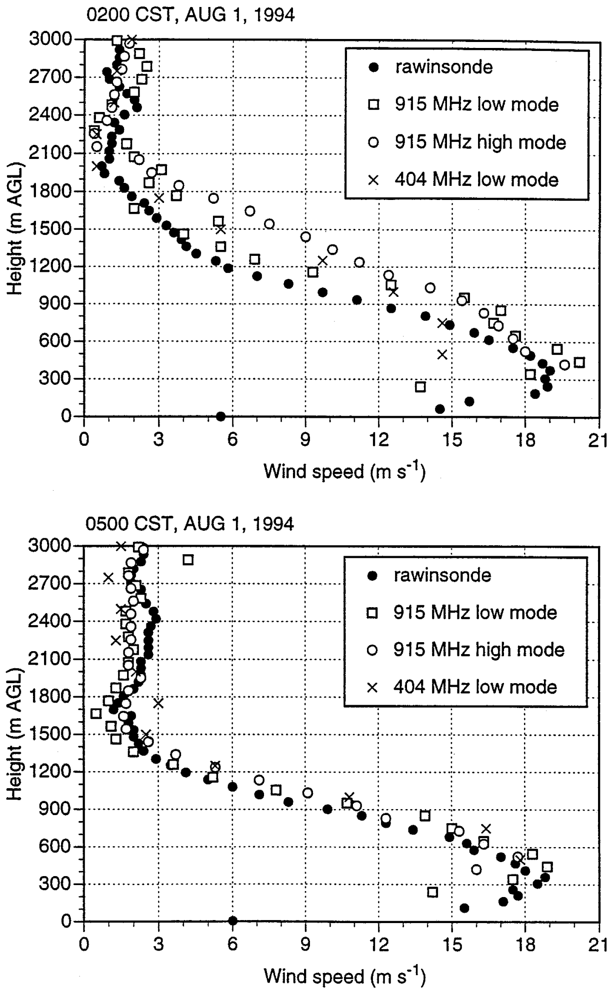

FIG. 8. Vertical profiles of wind speed at 0200 and 0500 CST 1 August 1994.

have fewer missing or obviously erroneous data points (Fig. 7b). The 404-MHz profiler often reports its first wind speed observation at heights that are above the jet wind speed maximum and, therefore, reports a weaker jet (Fig. 7c). This comparison between instruments can be seen more clearly in Fig. 8, where vertical wind speed profiles are plotted for each instrument at 0200 and 0500 CST. There are interesting wind speed differences among the soundings. None of the radar profilers resolves the jet well from the ground to the nose of the jet. Further, the radar profilers report wind speeds that are somewhat higher than observed by the rawinsonde between the level of the jet maximum and the minimum above.

Some differences between radar and rawinsonde wind profiles are expected in individual instances because the rawinsonde profiles are nearly instantaneous snapshots of wind structure, while the radar profiler winds are 1-h averages of winds within fixed atmospheric volumes. Further comparisons between radar profiler and rawinsonde wind soundings over longer periods will be necessary to better document any systematic differences during LLJ events.

c. Temperature inversion and the height of the wind speed maximum

According to Blackadar (1957), the surface temperature inversion that develops after sunset plays a crucial role in LLJ development. Bonner (1968) examined early morning temperature profiles at 60 stations located near the core of the jet for one southerly jet case to investigate the relationship between temperature inversions and LLJ development. Bonner found the level of maximum winds to be above the inversion top at 21 stations, below the inversion top at 16 stations, and at about the same height as the inversion at the remaining 15 stations. The correlation coefficient between the jet maximum height and the inversion top for his case was 0.53, which is significantly different from zero, but only accounts for one-fourth of the variance in jet heights. To investigate this relationship further, we used the 2-yr CART rawinsonde data to compare the heights of the inversion tops for southerly LLJs with the heights of the jet wind speed maxima (Table 3). For this analysis, the inversion top was defined as the height of the temperature maximum between the surface and 3 km AGL; this criterion thus does not distinguish between surface-based and elevated inversions. During nighttime, jet heights were generally found to be above the tops of the nocturnal inversions, although there was great variability from case to case. Further, the height of the jet maximum varied little throughout the night (the median height stayed in the range from 426 to 456 m AGL during the entire time period from 2000 to 0500 CST, while the

TABLE 3. Heights (m) of the southerly jet wind maxima (Z_{LLJ}) and the tops of the nocturnal surface inversion (Z_{INV}) for the period of record.

	Sounding time							
	2000 CST		2300 CST		0200 CST		050 CST	
	Z_{LLJ}	Z_{INV}	Z_{LLJ}	Z_{INV}	Z_{LLJ}	Z_{INV}	Z_{LLJ}	Z_{INV}
Mean	553	275	524	355	500	403	537	514
Median	456	137	440	208	441	312	426	373
Mode	400–500	100–200	300–400	100–200	400–500	200–300	300–400	200–300
No. observations	41		193		52		168	

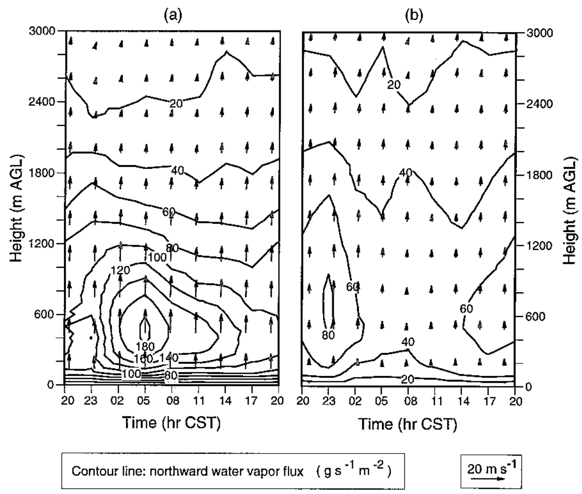

FIG. 9. Diurnal variation of mean horizontal wind vector profiles (arrows) and northward moisture fluxes (contours) as determined from (a) southerly LLJ soundings and (b) southerly wind soundings that did not meet LLJ criteria (right) for the 2-yr period of record. Vectors pointing upward represent horizontal winds from the south, vectors pointing to the right represent winds from the west, etc.

median inversion depth grew from 137 to 373 m AGL). The data therefore do not confirm Blackadar's prediction of a coincident increase in inversion-top height and the height of the jet maximum. A detailed examination of 19 nights of southerly jets in August 1994 occurring under generally weak synoptic flows and exhibiting a night-to-night regularity in structure revealed that the maximum wind levels often increase slightly in height between 1800 and 2300 CST, remain steady between 2300 and 0200 CST, and decrease slightly between 0200 and 0500 CST. We emphasize that this pattern is not pronounced and that there are large variations among individual jet events. A similar pattern was also observed by Mitchell et al. (1995) using the 404-MHz wind profiler network data, although their mean jet height was almost double our values.

d. Moisture flux

The southerly LLJ is known to play an important role in transporting moisture from the Gulf of Mexico northward into the central United States (Rasmusson 1967, 1968; Helfand and Schubert 1995; Berbery et al. 1996). This role was investigated further using the 2-yr high-resolution rawinsonde dataset at the CART central facility. Figure 9 shows the diurnal variation of wind profiles (vectors) and northward moisture transport (contours) for the southerly jet and the southerly nonjet soundings. The strong southerly low-level winds associated with the jet are clearly seen in the jet sounding composite, and the northward moisture flux at low levels, which occurs primarily at night, exceeds 180 g s^{-1} m^{-2}. For comparison, the composite obtained from the nonjet rawinsonde soundings that exhibited southerly winds is also shown. The northward moisture flux for the nonjet events is weak and variable, with a much weaker diurnal signal. An investigation of the humidity differences between the jet and nonjet southerly wind soundings found that the mean specific humidity was 8.27 g kg^{-1} when averaged over all warm season southerly jet soundings from the surface to 3 km, while the mean humidity for the warm season southerly nonjet soundings was 7.92 g kg^{-1}. For the cold season, the mean humidities were 4.05 and 4.06 g kg^{-1} for the southerly jet and southerly nonjet soundings, respectively. Thus, the much larger mean northward moisture fluxes for the jet soundings compared to the nonjet soundings is caused primarily by differences in the northward wind speed components, rather than by differences in the jet and nonjet moisture fields. This conclusion is in agreement with the results of Berbery et al. (1996).

e. The characteristics of northerly and southerly low-level jets

The low-level jet definition is based solely on the vertical profile of wind speed, without regard to wind direction. Our analyses (Fig. 4) indicate that, while jets in the warm season have wind directions predominantly from southeast through southwest, a significant number of jets in the cold season have wind directions from the northwestern through northeastern octants (303.75° through 56.25°). In the cold season, the frequency of these northerly jets approaches that of southerly jets. Bonner's (1968) climatology focused exclusively on the southerly jet, and Mitchell et al.'s (1995) climatology focused only on the warm season when southerly jets are predominant. Thus, no climatological descriptions have yet been made of the northerly jets. In this section, we identify some of the major characteristics of the northerly LLJs and compare these characteristics to those of the southerly LLJs.

While there were 821 southerly LLJs in the period of record (470 in the warm season and 351 in the cold season), there were only 351 northerly LLJs (122 in the warm season and 229 in the cold season). Because of the lower frequency of northerly LLJs, the statistical significance of conclusions regarding the characteristics of the northerly jets is lower than for the southerly jets.

A different diurnal variation pattern is revealed by comparing the frequency of occurrence of the northerly and southerly LLJs at the different rawinsonde sounding times (Fig. 10). The southerly jets show a pronounced diurnal variation in frequency, with the nighttime frequency almost double the daytime frequency. This nocturnal nature of the southerly LLJs has been attributed mainly to diurnal processes occurring in the atmospheric boundary layer, including the inertial oscillation of boundary layer winds after they become decoupled from surface friction at night (Blackadar 1957) and the diurnal oscillation of the horizontal pressure gradient over

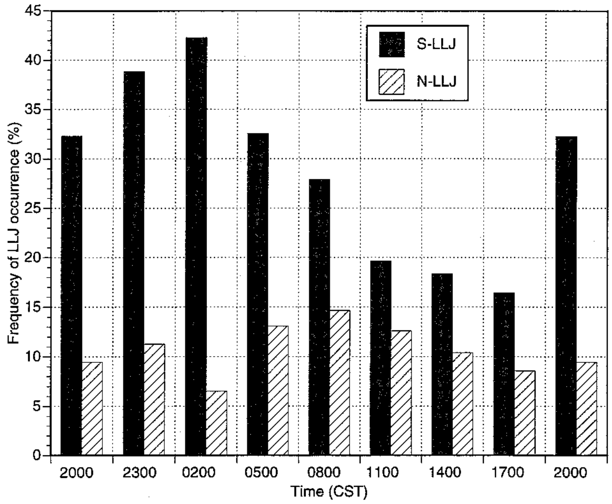

FIG. 10. Diurnal variation of the frequency of occurrence of southerly and northerly LLJs. The frequencies were obtained by dividing the number of northerly and southerly jet soundings at a given hour by the total number of soundings at that hour.

the sloping Great Plains (Holton 1967). The frequency of occurrence of the northerly jets, however, shows only a small diurnal variation, indicating that diurnal boundary layer processes play a less important role in the development of these jets, perhaps because of the relatively more important role of advection in the cold air outbreaks associated with northerly jets, the damped

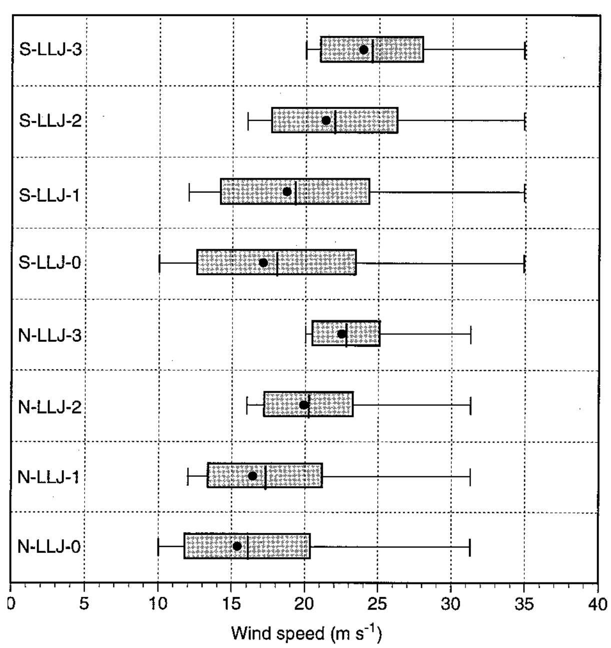

FIG. 11. Distribution of wind speed maxima for the southerly and northerly LLJ categories. Shown for each category are the minimum (left whisker), the maximum (right whisker), the median (dots), the mean, the mean plus one standard deviation, and the mean minus one standard deviation (vertical lines in the shaded box).

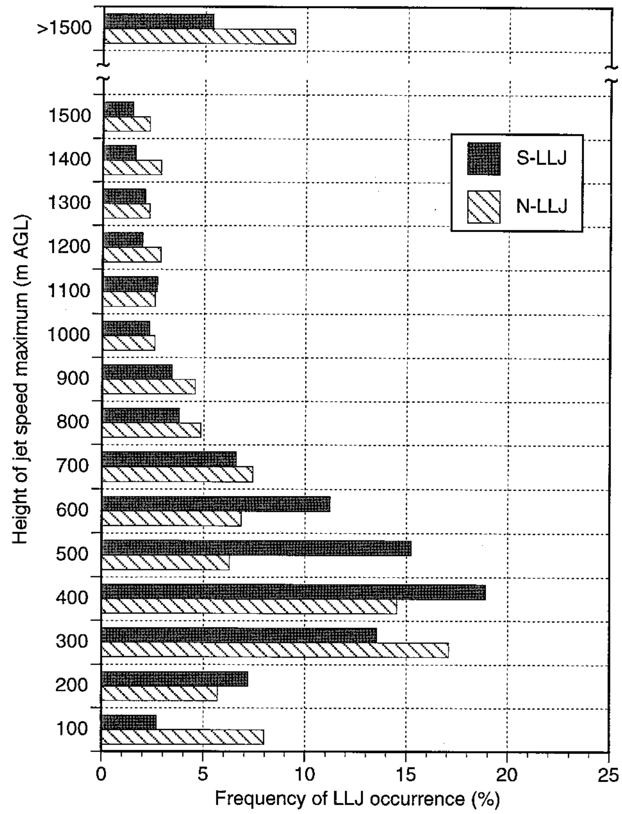

FIG. 12. Frequency distribution of the heights of LLJ wind speed maxima for northerly and southerly LLJs. The southerly and northerly jet frequencies individually add to 100% when summed over all heights. Heights labeled greater than 1500 m represent heights between 1500 and 3000 m.

diurnal cycle in the cold air mass, or the role of postfrontal cloudiness.

The statistics of the distribution of the wind speed maxima for southerly and northerly jets are presented in Fig. 11 using the inclusive LLJ definitions given in section 3a. The mean maximum jet wind speed and its standard deviation were 18.0 and 5.4 m s^{-1} for the southerly jets and 16.1 and 4.3 m s^{-1} for the northerly jets. The medians of the distributions are lower than the means—a situation similar to that for the warm and cold season jets (compare Table 2).

The distributions of the heights of the jet wind speed maxima for northerly and southerly LLJs are presented in Fig. 12. Both southerly and northerly LLJs generally have their peak frequency of the heights of maximum wind speed below 500 m AGL. The heights of the wind speed maxima are more variable for northerly jets than for southerly jets, with relatively more northerly jet maxima found at elevations above 600 m. For comparison, the heights of temperature inversions are shown for northerly and southerly jets in Fig. 13. Inversion heights are generally below 300 m for the southerly jets. The northerly jets have a weaker low-level inversion

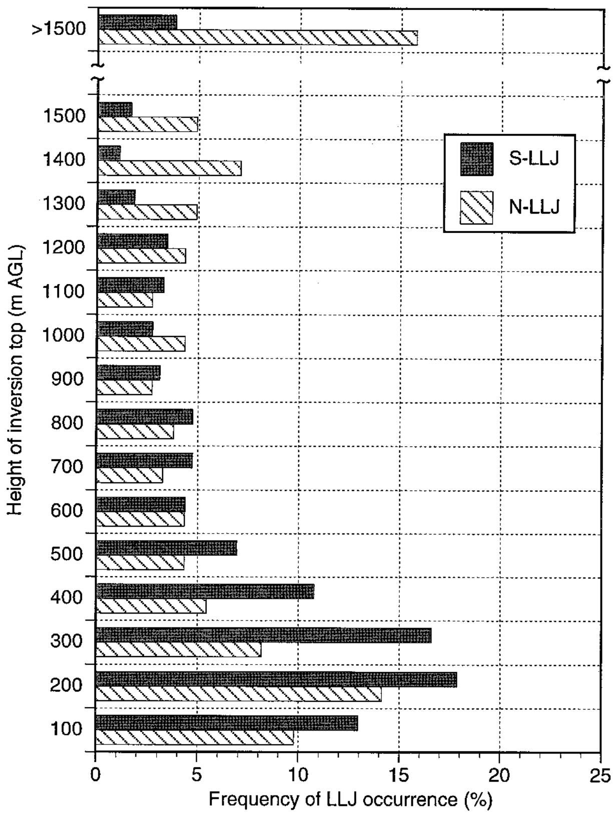

FIG. 13. Frequency distribution of the heights of temperature inversion tops for northerly and southerly LLJs. The southerly and northerly jet frequencies individually add to 100% when summed over all heights. Heights labeled greater than 1500 m represent heights between 1500 and 3000 m.

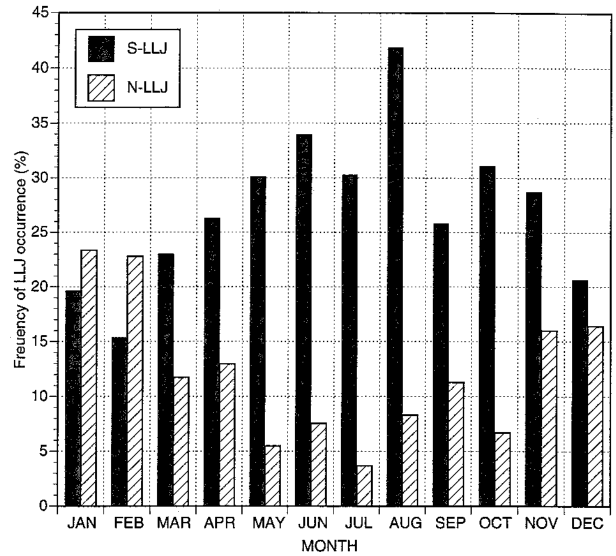

FIG. 15. The monthly distribution of the frequency of occurrence of northerly and southerly LLJs. Frequencies are based on the total number of soundings in each of the months, as stated in section 2.

peak than the southerly jets and have a more frequent association with elevated temperature inversions.

While jet heights remain nearly constant through the course of the night (Table 3), there is a distinct diurnal variation in the speed and direction of the southerly jets (Fig. 14a) that is not a feature of the northerly jets (Fig. 14b). For the southerly jets, the vector mean speed at the height of the jet maximum undergoes an oscillation from 15.5 m s^{-1} at 1700 CST to 19.5 m s^{-1} at 0200 CST. The wind direction at the height of the peak speed turns clockwise with time, attaining its minimum, 184°, at 2000 CST and its maximum, 207°, at 0500 CST. The northerly jets have about the same diurnal speed range as the southerly jet (13.4 to 17.5 m s^{-1}), but the wind directions and speeds do not undergo the regular clockwise turning that is seen with the southerly jets.

The seasonal distribution of the frequency of LLJ occurrence, shown in Fig. 15, reveals a completely opposite pattern for the northerly and southerly LLJs, with the southerly jet occurring more frequently in the warm season and the northerly jet occurring more frequently in the cold season. The frequency of northerly LLJs is below 9% from May to August, emphasizing that it occurs rather infrequently in summer.

Figures 16a–c show surface pressure, temperature,

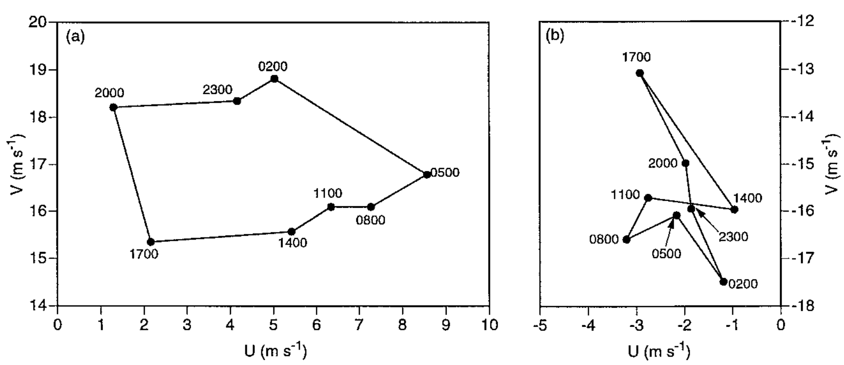

FIG. 14. Diurnal oscillations of wind speed and direction at the maximum jet wind level for (a) southerly and (b) northerly LLJs. The U represents the eastward wind speed component and V the northward component. Indicated times are central standard time.

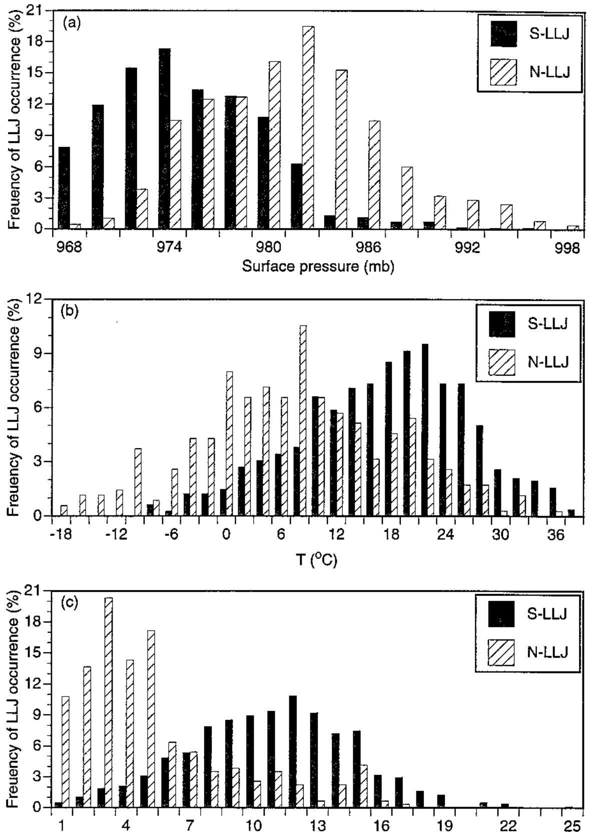

FIG. 16. The frequency of LLJ occurrence as a function of (a) surface pressure, (b) surface temperature, and (c) surface specific humidity for northerly and southerly LLJs.

FIG. 17. Surface frontal positions determined from the 12 UTC daily surface weather maps for selected northerly LLJ soundings observed at the SGP site at the same time of day.

and specific humidity frequency distributions associated with northerly and southerly LLJs, respectively, as measured by a surface meteorological station near the CART central facility. The northerly LLJs are associated with higher surface pressure, lower temperature, and much lower humidity compared to those associated with southerly LLJs, suggesting that the northerly jets are frequently related to the passage of cold fronts in the southern Great Plains. The lower mean temperatures associated with the northerly jets are, no doubt, partly due to the fact that the northerly LLJs have a higher relative frequency of occurrence in winter than the southerly LLJs. To eliminate this seasonal factor, we calculated the differences in surface temperature between each jet sounding and the monthly mean surface temperature at the same hour as the sounding and found that there is an annual average temperature deficit of 2.8°C associated with northerly jets and an excess of 2.2°C associated with southerly jets.

An inspection of synoptic weather maps indicates that approximately 68% of the northerly jets are post cold frontal. Figure 17 shows the frontal positions associated with selected northerly jet cases observed at 1100 CST. The northerly jets frequently occur in the cold air behind a southward-moving cold front. Winds are often strong behind the cold front, and speeds usually drop off above the frontal inversion, where winds often exhibit an abrupt change in direction. Thus, the LLJ wind criteria are often satisfied behind a cold front. Since the rawinsonde sounding times are fixed, but the front can traverse the site at any time of day, the individual northerly jet soundings are made at different distances behind the front. When the height of the maximum northerly jet wind speed is plotted as a function of distance behind the front as determined from the 12 UTC surface weather map (Fig. 18), a near-linear relationship is found between the height of the maximum wind speed and the distance from the front. The strongest northerly jets are often located 150–350 km behind the front. Inspection of temperature and wind soundings on days when the site is located behind cold fronts shows that the elevated temperature inversions seen with northerly jets in Fig. 13a are frontal inversions. The relative maximum in inversion height frequency at 100–200 m AGL (Fig. 13a) probably represents nighttime soundings having shallow surface-based temperature inversions, and the range of inversion heights above this level represents

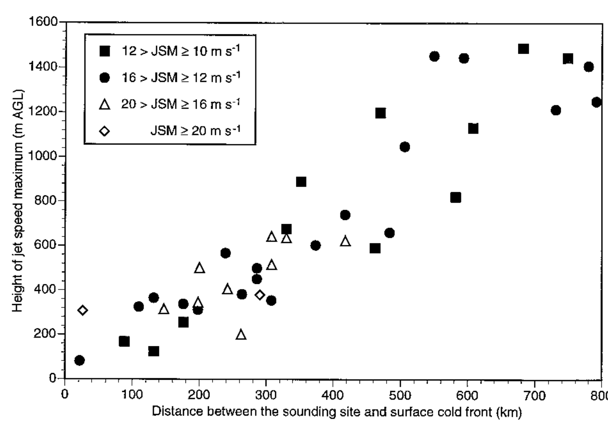

FIG. 18. The height of the jet speed maxima (JSM) for northerly LLJs as a function of distance behind the surface cold front.

the variation in frontal inversion heights with distance behind the surface front.

4. Summary

Analyses of 2 yr of high-resolution research rawinsonde observations from a site in north-central Oklahoma have provided a detailed climatological description of LLJ characteristics at a location near the axis of maximum LLJ occurrence in the southern Great Plains. LLJs are present in 46% of the soundings, and the frequency of occurrence of LLJs is almost the same for the warm and the cold seasons. The height of the jet maximum occurs most frequently in the 300–600-m height range, with a peak between 300 and 400 m. More than 50% of LLJs have their wind speed maxima below 500 m, regardless of the LLJ category. This fact calls into question the ability of the 404-MHz radar wind profiler network, with its lowest range gate at 500 m AGL (often, good data are first available only at 750 m AGL), to adequately sample LLJ events or to describe their vertical structure. The 915-MHz radar wind profilers, however, appear to provide sufficient vertical resolution to adequately resolve most jet characteristics and should prove useful in observing the time evolution of the jets if the known contamination of the radar echoes by migrating birds can be eliminated from the wind data.

While there is considerable variability from case to case, the mean height of the southerly LLJ wind maximum varies little through the night and generally remains above the height of the growing surface-based inversion. The peak speed of the LLJ is generally attained in the 0200 CST sounding. The southerly jet soundings are associated with large northward moisture fluxes as compared to southerly nonjet soundings, and the differences in the values of moisture fluxes and the patterns of diurnal variations are attributed primarily to the differences in the speed of northward wind components, not to the differences in the moisture fields.

Bonner's LLJ criteria, while taking account of the jetlike structure of the low-level winds, do not specify wind direction. The classical LLJ that has been studied by many previous investigators is a low-level jetlike wind profile that occurs with southerly winds. There are, however, a significant number of LLJ events that meet the Bonner wind speed profile criteria, but for which the winds at the level of the jet maximum are from the north. These northerly LLJs occur year around at the site, but are more frequent in the cold season when their frequency approaches that of the southerly LLJs. A comparison of northerly and southerly LLJs shows that the southerly jets have a much higher frequency at nighttime than during daytime, while the northerly jets have only a weak diurnal variation in their frequency of occurrence, with the highest occurrence during daytime. Both the southerly and northerly jets have a diurnal range of maximum speed of about 5 m s^{-1}, and peak speeds are attained at 0200 CST. The average peak speed for the southerly jet is 19.5 m s^{-1}, while the average peak speed for the northerly jet is 17.5 m s^{-1}. The highest frequency of jet maximum heights is in the range from 200 to 600 m AGL for both northerly and southerly jets, but the height of the wind maximum is more variable for the northerly jets. The southerly jets undergo a distinct diurnal clockwise turning in wind direction at the height of maximum speed, while the northerly jets exhibit small and irregular diurnal wind direction shifts. The northerly jets are usually associated with high pressures, low specific humidities, and low temperatures at the surface, and are frequently found below elevated temperature inversions. Inspection of synoptic charts shows that the northerly LLJs frequently occur behind cold fronts that move southward through the latitude of the Oklahoma site. The jets occur in the cold, slightly stable air behind the front. The depth of this cold air and the height of the jet maximum increase with distance behind the front. The variability in temperature inversion height that was noted for the northerly jets represents the variability in height of the frontal inversion with distance behind the surface front.

There are five key differences between our climatological findings and those of previous investigators. First, our climatology shows little difference in the frequency of occurrence of LLJs between the warm and cold seasons. The increased frequency of northerly jets in the cold season counters the decreased frequency of southerly LLJs in that season, and the increased frequency of southerly LLJs in summer counters the decreased frequency of northerly jets in that season. Despite this partial seasonal balancing of the northerly and southerly LLJ frequencies, the high frequency of southerly LLJs in winter is worth emphasizing, as it may prove to be important in future theoretical or modeling work. Second, the highest jet wind speed category has a much higher frequency than expected from earlier climatologies. This result is, no doubt, occasioned by the improved temporal resolution of our wind soundings, as the strongest jets often occur in the middle of the night and are not sampled at the standard rawinsonde sounding times. A related issue worth mentioning is that the averaging process, when made over fixed-height intervals to produce composite jet wind speed profiles (see, e.g., Fig. 6a), produces an estimate of mean jet wind speeds that is invariably too low. When we average the maximum wind speeds, regardless of their heights, we find that the *mean* jet wind speed maximum at 0200 CST is 19.5 m s^{-1}, which is somewhat stronger than is generally realized. Third, the mean height of the LLJ wind speed maximum is much lower than expressed in earlier climatologies. These earlier overestimates of jet heights appear to be caused by poor vertical resolution of wind data. Fourth, the lack of a clear-cut relationship between the near-constant nighttime jet height and the growing height of the surface-based inversion is a feature of the climatology. This result may prove important in the formulation and testing of hypotheses regarding jet formation mechanisms. Finally, the current climatology includes new information on the northerly LLJ. The northerly LLJ is interesting in its own right and has a very different origin and significant differences in characteristics from the classical southerly jet. It is associated with traveling synoptic-scale weather systems, rather than the diurnal boundary layer processes (inertial oscillation and slope-derived baroclinicity) that have been postulated for the southerly jet. The northerly jet, nevertheless, satisfies the Bonner LLJ wind speed profile criteria, and investigators of the classical southerly LLJ will want to remove these jets, using a wind direction criterion, from datasets that are being analyzed for classical jet characteristics.

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