The Great Plains Low-Level Jet during the Warm Season of 1993

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ABSTRACT

Hourly wind profiler observations from the NOAA Profiler Network were used to develop a climatology of the low-level jet (LLJ) over the Great Plains of the central United States from April to September of 1993. The peak precipitation episode of the 1993 flood was associated with a sustained period of high incidence of strong low-level jets (over 20 m s^{-1}). Consistent with previous studies, strong low-level jets were found to be promoted in the warm sector of an extratropical cyclone. Comparison of datasets formulated using velocity variance thresholds with unthresholded data similar to the operational hourly data suggests that the profiler observations often were contaminated by radar returns from migrating birds, especially during the months of April and May.

The strong low-level jets during the peak precipitation episode of the 1993 flood over the upper Mississippi River basin were associated with a high-amplitude upper-level wave pattern over and upstream of the continental United States. Separating the composite 850-mb wind for strong low-level jets into geostrophic and ageostrophic components showed that the magnitudes of the ageostrophic component and the anomalous geostrophic component were comparable.

1. Introduction

The nocturnal low-level jet (LLJ) is an important contributor to the continental-scale flux of water vapor over the Great Plains of North America (Rasmusson 1967; Helfand and Schubert 1995). In addition, moisture convergence associated with the LLJ has long been known to be conducive to summer rainfall over the central United States (e.g., Means 1952; Pitchford and London 1962). It follows that flood (or drought) years for this region may be associated with an increase (or decrease) in the frequency and strength of the LLJ. Previous investigators have indeed noted that anomalously strong southerly low-level flow over the Great Plains was a major contributor to the widespread flooding that occurred during the summer of 1993 (e.g., Bell and Janowiak 1995; Mo et al. 1995). While several modeling studies have investigated the LLJ during the 1993 floods using numerical simulations (e.g., Helfand and Schubert 1995; Paegle et al. 1996; Giorgi et al. 1996), it is desirable to have an observational evaluation of the LLJ to corroborate and extend the model results. Such an evaluation is difficult because the LLJ has a pronounced diurnally varying nature so that its strength and frequency of occurrence are maximized at times between the nominal 0000 and 1200 UTC launch times of the conventional rawinsonde network (Bonner 1968; Mitchell et al. 1995, hereafter MAL95). It is therefore useful to evaluate the occurrence of the LLJ using a data source with improved time resolution compared with the rawinsondes.

To this end, we have performed a climatological analysis of the LLJ during the warm season (1 April–30 September) of 1993 over the Great Plains using hourly wind observations from the National Oceanic and Atmospheric Administration (NOAA) Profiler Network. Our analysis for 1993 follows a similar analysis for the LLJ in the warm seasons of 1991–92 (Mitchell et al. 1995). We begin with a summary of the geographical distribution and frequency of occurrence of the LLJ and then examine the relationship of the LLJ to the surface synoptic patterns as well as the upper-level height and wind fields. We also evaluate the extent of data contamination by returns from migratory birds based on an

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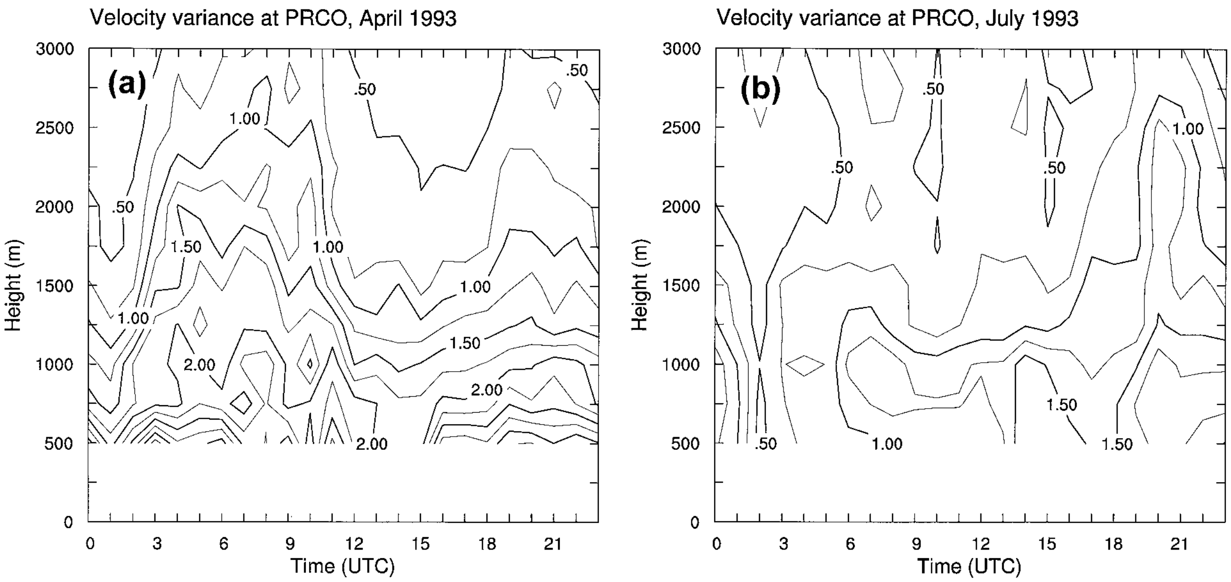


FIG. 1. Monthly averages of hourly velocity variances at Purcell, Oklahoma (station identifier PRCO), for (a) April and (b) July 1993. The contour interval is 0.25 $m^2 s^{-2}$.

approach suggested by Wilczak et al. (1995) and discuss the implications of this contamination for detection of the LLJ using microwave wind profilers.

2. Data processing and analysis methods

a. Wind profiler data

The NOAA Profiler Network (NPN, formerly known as the Wind Profiler Demonstration Network) includes a network of clear-air Doppler wind profiling radars operating at approximately 404 MHz. These profilers provide wind measurements every 6 min at 250-m increments for heights usually extending from 500 m above ground level (AGL) to the lower stratosphere. The 6-min cycle is made up of 1-min measurements for each of six beams (one vertical and two oblique beams, with low and high modes for each). Although the 6-min data can be used directly, the most common practice, and the one used in this paper, is to combine the 6-min data to obtain hourly averages. This averaging is used to obtain more reliable observations and to eliminate higher-frequency fluctuations such as those resulting from gravity wave propagation. For additional details of the operational wind profilers see Weber et al. (1993) and references cited therein.

Concern has been raised that the profiler data may be contaminated by returns from migratory birds (passerines). We have reanalyzed the 1993 profiler data in an attempt to identify and possibly reduce this contamination. Wilczak et al. (1995) have proposed that contamination of the 404-MHz profiler data by passerines can be reduced by rejecting observations in which the velocity variance σ_v^2 exceeds a given threshold. The choice of threshold is subjective; that is, a stringent threshold may be effective in eliminating contaminated data but reject a large amount of good data, while a less restrictive threshold will yield a more complete dataset with a greater likelihood that contaminated data will be included. The thresholding is complicated further in that the contamination may be correlated with the phenomenon we are attempting to detect. This is because the birds ordinarily migrate at night, and there is evidence that they take advantage of favorable winds. The extent of this correlation is unknown because we do not have independent measurements of the migration and the LLJ. We might also expect that the LLJ itself could be associated with relatively high values of velocity variance, owing to shear production of turbulence kinetic energy. [The relationship of the LLJ to boundary layer turbulence was one of the motivations for the classic work of Blackadar (1957).] Thus the attempt to remove the contamination will itself create an unknown bias in the data. For this reason we have evaluated LLJ statistics using three different datasets as described below.

We calculated statistics and histograms of the velocity variance for several profiler sites as a function of level and time of day in order to gain further insight into its typical values as well as the spatial and temporal distribution. We found that there was substantial variability of the velocity variance both in space (with height and from station to station) and in time (diurnal and seasonal). An example of the temporal variability is given in Fig. 1, where we show monthly average time–height cross sections of the velocity variance in April and July at Purcell, Oklahoma. The velocity variances are noticeably larger in April than in July. The velocity variance in April is largest at low levels, with broad maxima during the night and at midday. The latter may be a result of daytime convective turbulence, while the former is consistent with the nocturnal migration of passerines during the spring. The velocity variances in July are usually lower for a given time and elevation, and tend to be largest in the daytime boundary layer.

Based on our examination of the velocity variances, we have evaluated three different hourly datasets produced by consensus averaging of the 6-min measurements. We applied the thresholding to the 6-min data rather than the hourly data in an attempt to minimize data loss. That is, by thresholding the 6-min data, we retained the possibility of constructing an hourly consensus average if a sufficient number of 6-min subperiods during the hour survived the thresholding procedure. The three datasets were constructed according to the following velocity variance thresholds.

1) Dataset 0: No thresholding of velocity variance.
2) Dataset 1: Apply thresholding to the 6-min data as recommended by Wilczak et al. (1995); that is, reject data with σ_v^2 exceeding 1.8 m^2 s^{-2}. Large velocity variances can be produced by precipitation as well as birds; accordingly, we suspend the thresholding if the downward vertical velocity exceeds 0.7 m s^{-1} (indicative of precipitation, in which the birds do not usually migrate).
3) Dataset 2: Same as dataset 1 but increase the σ_v^2 threshold to 3 m^2 s^{-2} at levels of 1000 m and below, and 2.2 m^2 s^{-2} aloft. The intent here is to discard only the more obviously contaminated data and to allow for higher velocity variances induced by boundary layer turbulence.

The 6-min observations passing each threshold were then combined into hourly averages. Additional quality control procedures such as the median filter and shear check were performed identically for all three datasets using standard procedures (Weber et al. 1993). Dataset 0 corresponds essentially to the procedures used to obtain the hourly values available from the NPN. We rederived the hourly data for dataset 0 rather than using the archived hourly data to ensure that the same quality control methodologies were used for all three datasets. This gives more confidence that any differences between the datasets can be attributed to the thresholding. We found that our dataset 0 agreed closely with the archived hourly values from the NPN, in that over 98% of the paired hourly values from these two datasets agreed within a vector difference of 1 m s^{-1}.

Aside from contamination by migratory birds, the other main limitation of the profiler data for detecting the LLJ is that the lowest range gate of the 404-MHz profilers is at 500 m AGL (Stensrud et al. 1990). Furthermore, the 500-m level is fairly often missing, so that in those cases, the lowest usable level will be even higher. Whiteman et al. (1997) performed an analysis for the CART-ARM (Cloud and Radiation Testbed–Atmospheric Radiation Measurements) site (in north-central Oklahoma) using high-resolution rawinsonde data and found that the height of maximum winds in the LLJ was typically 300–600 m AGL. This height is consistent with earlier results from pibal observations discussed by Hoecker (1963). These results suggest that in many cases the lowest range gate of the 404-MHz profilers will be above the height of maximum winds, leading to underestimates of the strength of the LLJ. Some occurrences of the LLJ may even be missed altogether if the jet maximum is below 500 m and the vertical gradient of the wind speed is sharp. Although the analysis by Whiteman et al. (1997) was performed for only one site, it is clear that the incidence of strong LLJs is likely to be greater than reported in the present paper and that strong LLJs are especially likely to be underreported. The reader should keep this limitation in mind when interpreting the results shown here.

b. Station selection and normalization criteria

As discussed in MAL95, when evaluating the frequency of LLJ occurrence, it is necessary to consider that all of the stations do not operate simultaneously and continuously. We accounted for this in a similar manner to MAL95, that is, by specifying that each station included in the analysis had to operate for at least some minimum period and by normalizing the frequency of occurrence of the LLJ by a measure of the data availability. When specifying the minimum operating period and normalization criteria, we considered the number of usable profiles rather than the number of hours that the profiler was in operation as was used in MAL95. We defined a "usable profile" as containing at least three valid observations at 1500 m or below and at least four valid observations in the layer from 1750 to 3000 m. The minimum operating period for a station to be included in the analysis was specified as 1800 usable profiles for the warm season of 1993 (1 April–30 September) out of a possible maximum of 4392 profiles. The stations meeting this requirement are the ones shown in Fig. 2 (see Table 1 for the names of the profiler stations corresponding to each identifier). The normalized frequency of the LLJ was defined as the ratio of the number of observations of the LLJ during some period (e.g., daily or monthly) to the number of usable profiles during the same period. The normalized frequency can be calculated for individual stations or by summing both the LLJ observations and usable profiles over all stations or some group of stations.

c. Data availability

We defined the data availability as the ratio of the number of usable profiles to the maximum possible number of usable profiles. Data availability summed over all stations was about 75%–80% for dataset 0 (Fig 3). For the thresholded datasets there was a noticeable diurnal variation in the data availability, with the lowest data availability occurring during the night. (Local sun-

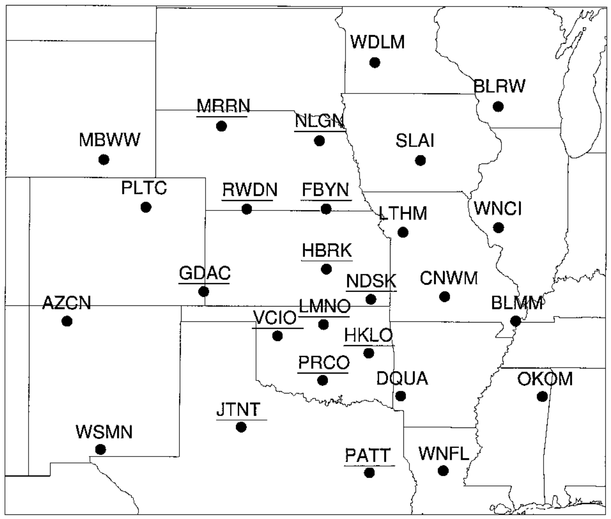


FIG. 2. Locations of the wind profiler sites used in the analysis. All stations meet the minimum requirement of 1800 usable profiles for the warm season of 1993. (The site is centered under the identifier; see Table 1 for station names corresponding to each identifier.) The underlined station identifiers indicate the stations used to compute the LLJ daily average frequency.

TABLE 1. Stations included in the wind profiler data analysis.

AZCN	Aztec, NM
BLMM	Bloomfield, MO
BLRW	Blue River, WI
CNWM	Conway, MO
DQUA	DeQueen, AR
FBYN	Fairbury, NE
GDAC	Granada, CO
HBRK	Hillsboro, KS
HKLO	Haskell, OK
JTNT	Jayton, TX
LMNO	Lamont, OK
LTHM	Lathrop, MO
MBWW	Medicine Bow, WY
MRRN	Merriman, NE
NDSK	Neodesha, KS
NLGN	Neligh, NE
OKOM	Okolona, MS
PATT	Palestine, TX
PLTC	Platteville, CO
PRCO	Purcell, OK
RWDN	McCook (Red Willow Dam), NE
SLAI	Slater, IA
VCIO	Vici, OK
WDLM	Wood Lake, MN
WNCI	Winchester, IL
WNFL	Winfield, LA
WSMN	White Sands Missile Range, NM

set is around 0000 UTC at the equinoxes and 0200–0300 UTC in midsummer.) There was a sharp reduction in data availability for datasets 1 and 2 shortly after sunset and an increase in data availability after sunrise, consistent with the nocturnal migration of passerines. Daytime values of data availability for datasets 1 and 2 were about 2%–5% and 5%–10% lower, respectively, than for dataset 0. This may have been the result of vigorous convective turbulence that produced velocity variances sufficiently large to exceed the specified thresholds, or to some background level of contamination. There was also a slight decrease in data availability at night for dataset 0, suggesting that the nocturnal decrease in data availability may have been attributable in part to weaker turbulence and hence less well-developed refractive-index structures to provide returns to the profiler.

d. Low-level jet classification and spatial analysis

We defined the LLJ using the criteria first proposed by Bonner (1968). This facilitates the interpretation of our results in the context of other studies that have also used Bonner's (1968) criteria. We classified the LLJ into three criteria based on the maximum wind speed in the lowest 3000 m: criterion 1 requires a speed of at least 12 m s^{-1}, criterion 2 at least 16 m s^{-1}, and criterion 3 at least 20 m s^{-1}. The LLJ definition requires that these speeds represent local maxima in the wind speed profile and that the speed must decrease by a given amount above this level so that a well-defined jetlike profile exists (see Bonner 1968 and MAL95 for details). As a supplement to the LLJ evaluations, we have defined a "southerly wind event" (SWE) as the occurrence of wind with direction between 120° and 240° in the lowest 3000 m that meets one or more of the wind speed criteria but does necessarily constitute the local maximum that defines a low-level jet. (A southerly wind event can qualify as an LLJ if the SWE contains the local maximum in the wind speed profile required by Bonner's criteria.) Our analysis departs from Bonner's LLJ definition in that we interpret the speed criteria as non-overlapping unless stated otherwise; that is, criterion 1 corresponds to maximum wind speeds of 12 m $s^{-1} \leq V_{max} < 16$ m s^{-1}, criterion 2 corresponds to 16 m $s^{-1} \leq V_{max} < 20$ m s^{-1}, and criterion 3 corresponds to $V_{max} \geq 20$ m s^{-1}. Our intent in interpreting the criteria as

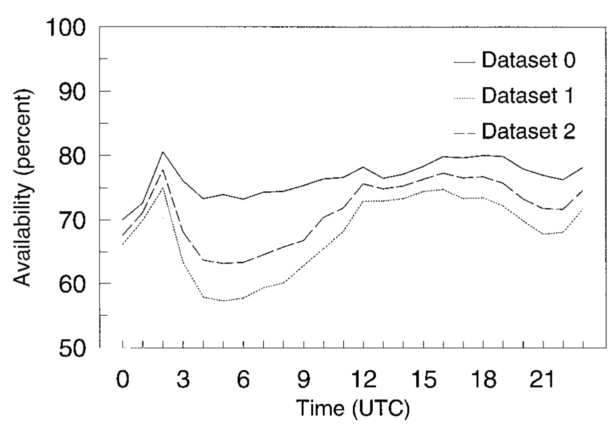
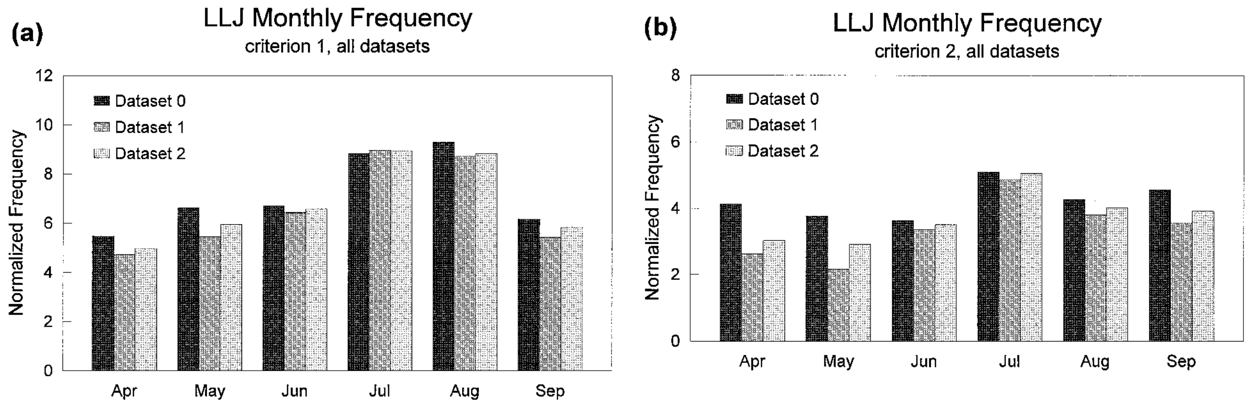


FIG. 3. Data availability for each dataset as a function of time of day summed over all stations and all days in the warm season of 1993 (1 April–30 September).



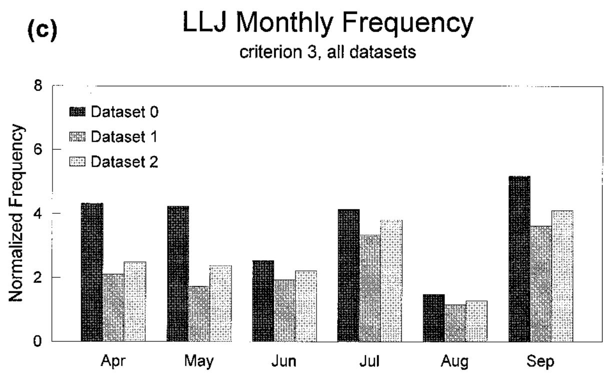


FIG. 4. Monthly normalized frequencies of LLJ occurrence (in percent) using each of the three datasets: (a) criterion 1, (b) criterion 2, and (c) criterion 3.

nonoverlapping is to make a closer examination of the distinctions between strong and weak LLJs (e.g., the analysis for criterion 1 will not also include LLJs satisfying criteria 2 and 3).

Finally, we mention that the contour plots shown here were produced by objective analysis of the profiler observations onto a 0.5° latitude–longitude grid. The analysis used a single pass of the Barnes method with parameters chosen such that the response function was equal to e^{-1} for a wavelength twice the mean separation of adjacent profiler sites (about 4°). In such an implementation, the Barnes scheme is primarily a smoother that damps out the small-scale features while maintaining the larger-scale trends. This could also be done by careful subjective analysis, but we have preferred to use a well-known objective scheme so that the reader can recognize the degree of smoothing in the analyses without requiring extensive explanation of the analysis criteria [see Barnes (1994) for detailed discussion of the objective analysis scheme].

3. Temporal and spatial distribution of the low-level jet

a. Temporal variability of LLJ frequency

We defined the monthly domain-average normalized frequency of the LLJ as the number of hourly observations of the LLJ in a given month summed over all stations in our domain, as a fraction of the total number of usable profiles in the domain during the same month (Fig. 4). The results showed that the frequency of the weaker LLJs (criterion 1) tended to increase through the warm season and then decreased in September. The thresholded data indicated peak frequencies for criterion 3 during July (when the heaviest precipitation occurred during the 1993 flood) and in September [consistent with LLJ climatologies for previous years as presented by Bonner (1968) and MAL95]. The unthresholded data showed no obvious seasonal trend, except for a lull in criterion 3 LLJs during August. The small differences between the datasets for criterion 1 LLJs imply that the weaker LLJs were not often contaminated by returns from passerines (assuming that the differing frequencies of LLJ occurrence in the thresholded and unthresholded data correspond to a rough indicator of the severity of contamination). In contrast, the frequencies of criteria 2 and 3 LLJs differed noticeably between the datasets during April and May. The contamination in those two months was sufficient to cause about a factor-of-2 decrease in the normalized frequency of criterion 3, when the most stringent velocity variance threshold was applied (dataset 1). The frequencies of LLJ occurrence during June, July, and August were relatively insensitive to the thresholding for all three LLJ criteria, which suggests that the observations during those months were not often contaminated by migratory birds.

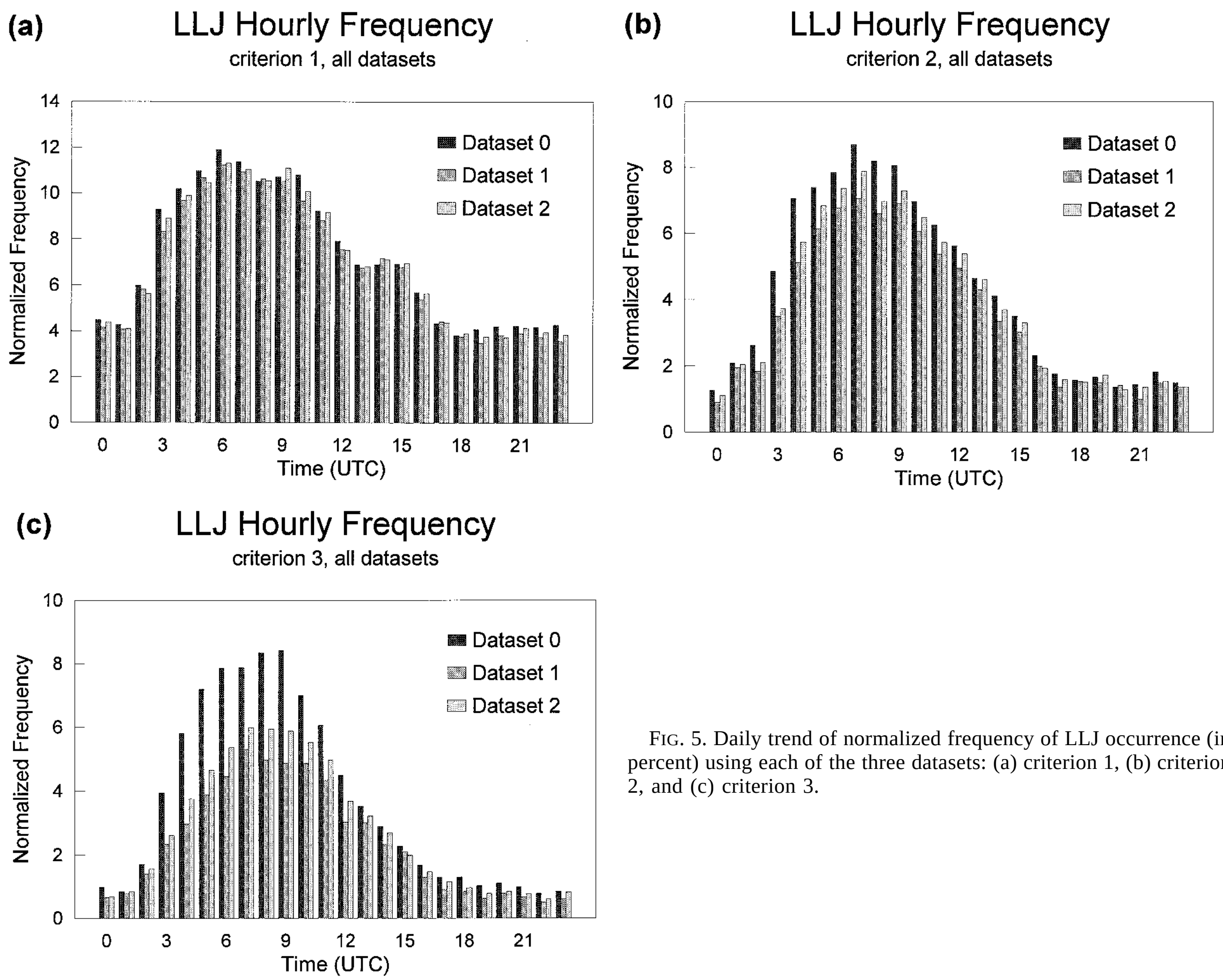


FIG. 5. Daily trend of normalized frequency of LLJ occurrence (in percent) using each of the three datasets: (a) criterion 1, (b) criterion 2, and (c) criterion 3.

Diurnal variability in the frequency of occurrence of the LLJ was greater for the stronger LLJs than for the weaker ones (Fig. 5), consistent with the results obtained for LLJs in 1991 and 1992 as given by MAL95. One difference from MAL95 is that the weaker LLJs (criterion 1) show more diurnal variability in the present results. As with the monthly frequencies, we found that the weaker LLJ criteria showed little difference between the three datasets but that the criterion 3 LLJs showed large differences between the thresholded and unthresholded data. The differences were most pronounced from 0300 to 1100 UTC, consistent with the tendency for passerines to migrate mostly at night. Even allowing for the contamination, it is clear that the diurnal variability in the frequency of LLJs was greater for the stronger criteria than for the weaker ones.

A more detailed representation of the LLJ seasonal variability is provided by the daily average frequency of the LLJ. We define the daily average frequency as the number of hourly observations of the LLJ on a given day as a percentage of the number of usable profiles on that day, averaged over a subset of the stations in our domain (see underlined identifiers in Fig. 2). The subset was subjectively chosen to include stations mostly over the Great Plains that did not have lengthy gaps in their data record that would distort the seasonal trends of the statistics. We present the daily average frequency as a 3-day running mean, which smooths out the day-to-day variability that can obscure trends (Fig. 6). In order to provide a rough evaluation of the correspondence of the LLJ with heavy regional precipitation, we have used the gridded hourly precipitation dataset developed by Higgins et al. (1996) to compute the average daily precipitation for the region bounded by latitudes 37°–47°N and longitudes 99°–89°W (Fig. 7). This region was specified so as to mostly overlap the greater upper Mississippi River basin defined in the analysis of the 1993 flood by Kunkel et al. (1994). Since our focus is on convective precipitation, we rejected all hourly intensities less than 2.5 mm h^{-1} [see McAnelly and Cotton (1989) for discussion on the use of precipitation intensity thresholding to distinguish between convective and stratiform precipitation].

One of the most striking features of the trend in daily

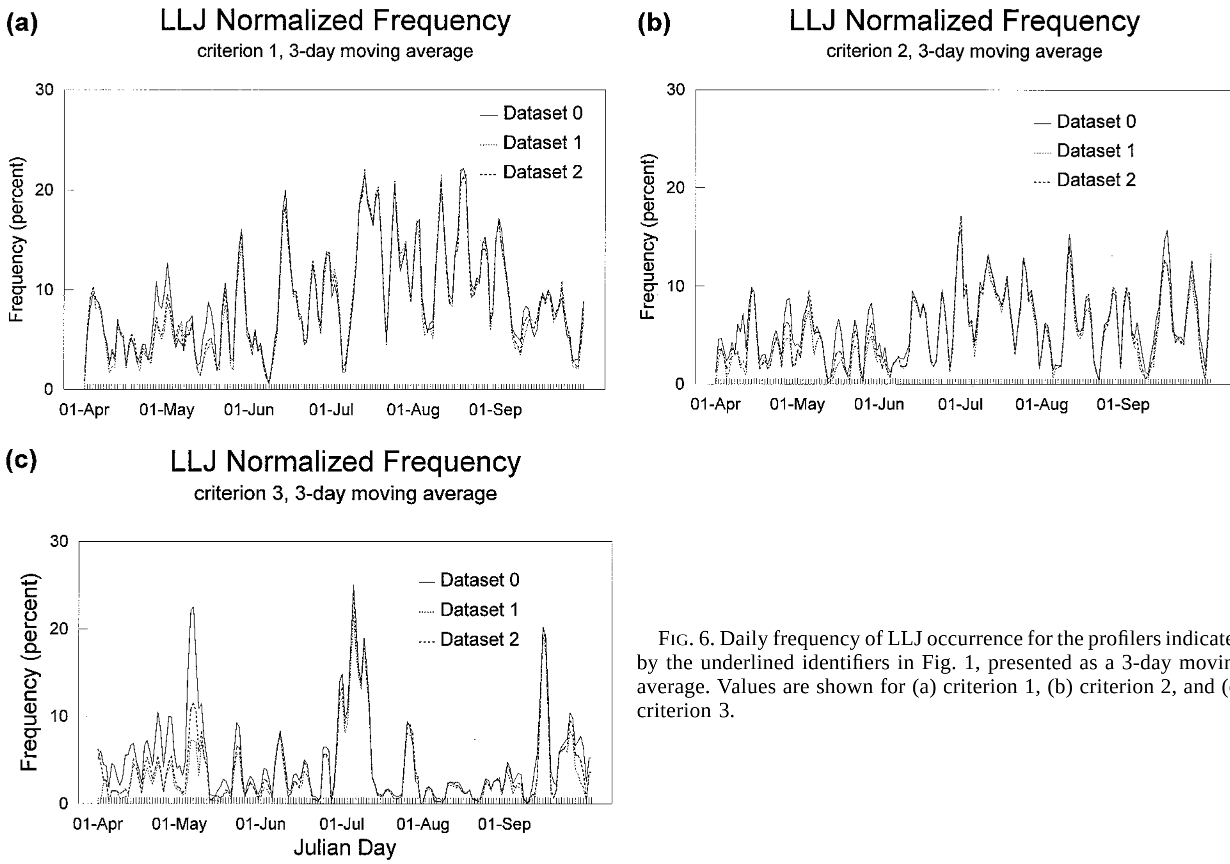


FIG. 6. Daily frequency of LLJ occurrence for the profilers indicated by the underlined identifiers in Fig. 1, presented as a 3-day moving average. Values are shown for (a) criterion 1, (b) criterion 2, and (c) criterion 3.

average frequency of the LLJ is a broad peak in the incidence of criterion 3 LLJs (Fig. 6c) during late June and early July. This peak in criterion 3 LLJs is seen to coincide with the peak rainfall for the 1993 flood over the upper Mississippi River basin (Fig. 7). (Notice also that the heavy precipitation episodes in early May and mid- to late September corresponded with high incidence of criterion 3 LLJs.) In contrast, the frequencies for criteria 1 and 2 LLJs (Figs. 6a,b) were not noticeably greater during the peak of the flood than at other times in the summer. This implies that the most severe precipitation episode of the 1993 flood was associated with an increased frequency of the *strongest* LLJs rather than an increase in the general incidence of LLJs. Later we will give special attention to the circumstances that promoted the strong LLJs during this period.

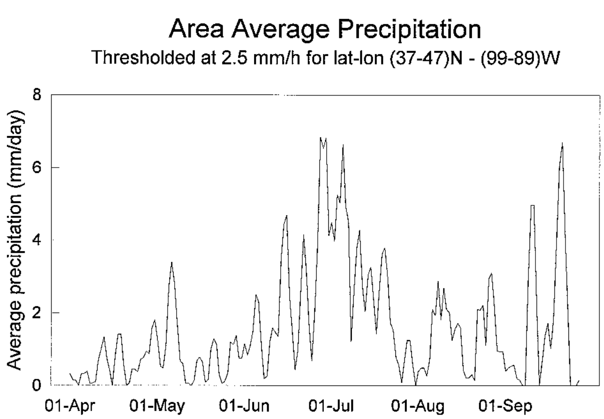


FIG. 7. Daily area-averaged precipitation over the greater upper Mississippi River basin expressed as a 3-day moving average. Hourly amounts were thresholded at 2.5 mm in order to focus on convective precipitation (see text).

The differences in the LLJ daily average frequency for the three datasets have some possible implications with regard to contamination of the data by passerines. In the early part of the warm season, through about the first week of June, there were substantial differences between the three datasets, especially for the criterion 3 LLJs. This was most noticeable on 5 May, when the (unsmoothed) normalized frequency of criterion 3 was 32% for dataset 0 (no thresholding) but only 7% for dataset 1 (the most stringent thresholding). Later in the season the results from the three datasets were nearly identical until mid-September, when the differences increased somewhat but still were less than in spring. These trends are consistent with the seasonal character of the migration of passerines (i.e., the data tended to be contaminated during the northward migration in spring and again during the southward migration in the fall). Thus, it appears that profiler observations of criterion 3 LLJs in April and May often are contaminated by returns from passerines, suggesting that profiler indications of strong LLJs during this time of the year be interpreted cautiously. For the criterion 1 LLJs, the contamination was limited to a fairly brief period (most of the month of May) and even during this period the contamination was less severe than for the criterion 3 LLJs.

We have two subtly different hypotheses regarding the tendency for the stronger LLJs to be more contaminated than the weaker ones. First, the birds tend to fly with, rather than against, the wind, so that the speed errors owing to bird contamination will usually be positive. This causes either a spurious report of an LLJ or classification of the LLJ at a higher criterion than the actual wind speed, leading to an overestimate of the incidence of strong LLJs. Second, the birds are adept at utilizing favorable wind conditions for their migrations (see Wilczak et al. 1995 and references cited therein), so strong LLJs will tend to be contaminated because the birds fly in them. In the latter case, a strong LLJ may in fact occur but the presence of birds causes the measurement to be rejected, leading to an underestimate of the incidence of strong LLJs. Thus while the unthresholded data almost certainly overestimate the incidence of strong LLJs, there is a possibility that the thresholding causes an underestimate.

Reviewing the differences in the LLJ frequency for the three datasets, we infer that the velocity variance thresholding apparently is useful in identifying data that are contaminated by returns from passerines. Contamination was indicated during periods in which the birds most often migrate (spring, autumn, and the nighttime). At times when the birds do not usually migrate, the results for the three datasets differed little, implying that the velocity variance thresholding did not often reject uncontaminated observations. We cannot, however, establish the true frequency of the LLJ for the reasons discussed previously. As discussed in section 2 the choice of threshold is problematic. Here we attempt a compromise and use dataset 2 in the remainder of this analysis, except where indicated otherwise.

b. LLJ direction

We evaluated the LLJ direction using both directional wind roses (Fig. 8) and the persistence of the wind (Fig. 9). The directional wind roses were plotted as the fraction of the number of LLJ hours at a given station that were from each directional octant. The persistence (Panofsky and Brier 1956) P indicates the degree of consistency of the vector wind in a set of observations of the wind (in our case, hourly observations of a given criterion of LLJ). Persistence is formally defined as the ratio of the magnitude of the resultant mean vector to the mean wind speed; $P = (\overline{u}^2 + \overline{v}^2)^{1/2}/\overline{(u^2 + v^2)^{1/2}}$. For a constant wind speed the persistence equals unity if the wind is always from the same direction (i.e., the velocity vector is always the same) and decreases toward zero as the wind direction becomes more variable. (The persistence also decreases as the wind speed becomes more variable. However, recall that we have classified the LLJ occurrences into limited ranges of wind speed, reducing the effect of wind speed variations on the persistence.)

Results for dataset 2 show that while the direction of the LLJ was predominately from the south to southwest at stations in the central and southern Great Plains, elsewhere the tendency for the LLJ to be from the south was less consistent (Fig. 8). Stations in the northern Great Plains tended to have a moderate fraction of their LLJ observations directed from the north, while a few stations close to the Rocky Mountains had LLJs that were often from the west. These geographical differences are also reflected in the persistence (Fig. 9), which shows a fairly regular decrease from south to north. The implication is that the southerly LLJs tend to be generated most often in the southern part of the region and vary in their northward penetration into the Great Plains. Conversely, cold-air outbreaks that can produce northerly LLJs often affect the stations in the northern part of the region but seldom reach the southern stations. Therefore the more northern stations tend to have a bimodal distribution of LLJ directions (Fig. 8) that corresponds to a relatively low persistence (Fig. 9).

c. Spatial variability

The seasonal normalized frequency of the LLJ is defined here as the number of hourly profiles that contained an LLJ at a particular station in proportion to the total number of usable hourly profiles for that station, summed over the entire warm season of 1993. The spatial distribution of LLJ seasonal normalized frequency (Fig. 10) was broadly similar to that found by MAL95 for LLJs during the warm seasons of 1991–92. The frequencies for criterion 1 were essentially the same for all three datasets. For criteria 2 and 3 the geographic distributions were similar for all of the datasets, although for criterion 3 the frequencies were increased by a factor of about 1.2 for dataset 0 (not shown) compared to the thresholded datasets. The maximum frequencies for criteria 2 and 3 were located slightly to the north of the maximum for criterion 1 (essentially, the maximum shifted from the Jayton, Texas, profiler to the Vici, Oklahoma, profiler). MAL95 noted that this northward displacement for the stronger criteria may simply reflect the Lagrangian nature of fluid dynamics; that is, forces act on a moving parcel, so that the LLJ strengthens as it propagates northward.

4. Southerly wind events

As in MAL95, we have performed a separate analysis of strong southerly winds that do not necessarily contain the local maximum in the wind speed profile that is specified in Bonner's (1968) definition of the LLJ. We

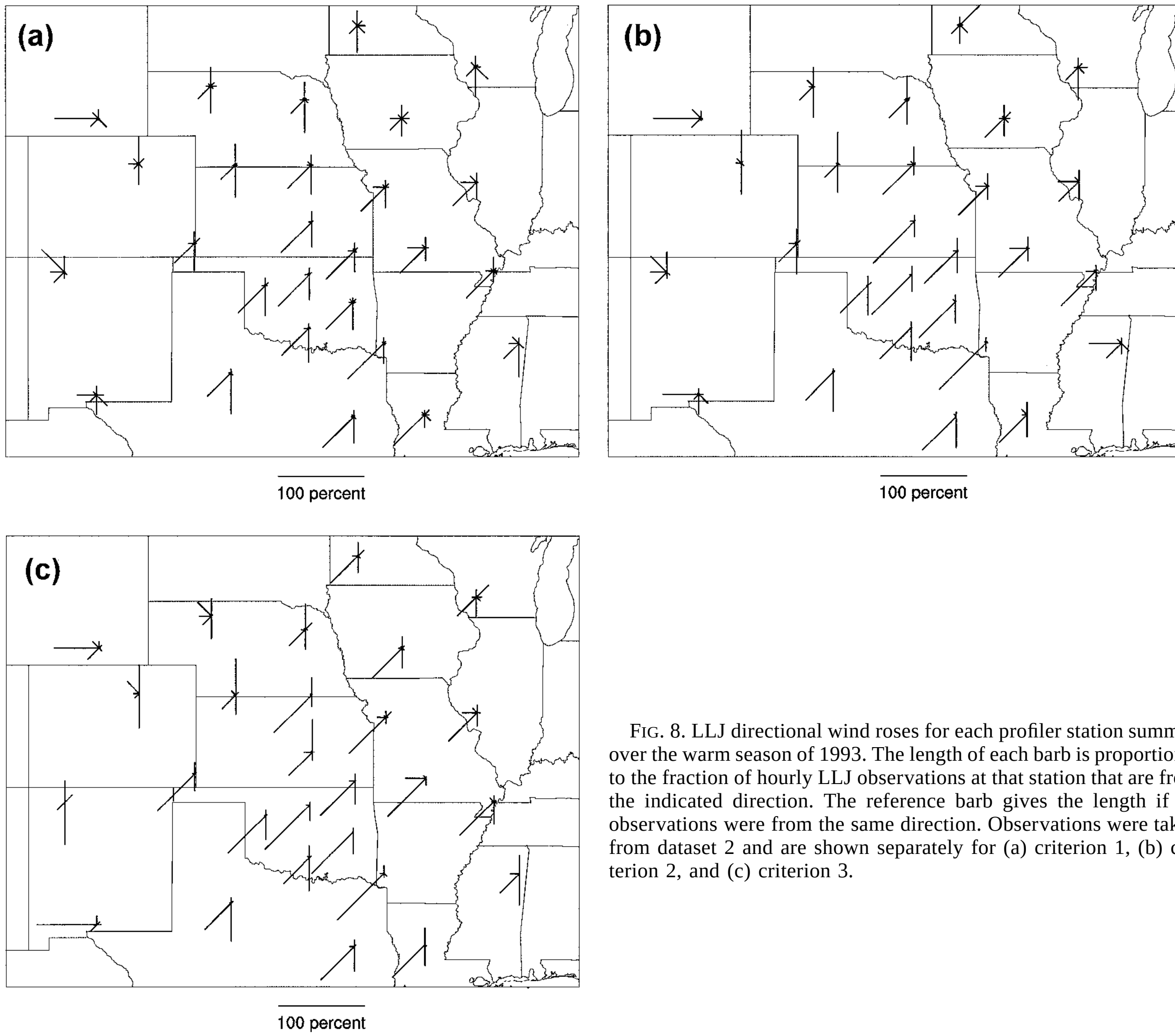


FIG. 8. LLJ directional wind roses for each profiler station summed over the warm season of 1993. The length of each barb is proportional to the fraction of hourly LLJ observations at that station that are from the indicated direction. The reference barb gives the length if all observations were from the same direction. Observations were taken from dataset 2 and are shown separately for (a) criterion 1, (b) criterion 2, and (c) criterion 3.

refer to these cases as SWEs. Note that an SWE can qualify as a (southerly) LLJ if the SWE contains the requisite local maximum in the vertical profile of the wind speed. Thus we can also focus on southerly LLJs (as compared with LLJs in general) by considering the SWEs that contain the local maximum in the wind speed profile that defines the LLJ. In the following discussion those SWEs that do not qualify as LLJs will be referred to as ''non-LLJ SWEs,'' while those that do will be called ''SLLJs,'' that is, southerly low-level jets.

In most months the ratio of SLLJs to all SWEs ranged from about 30% to 50% (Fig. 11). This compares to a fraction of slightly over 50% for 1992, as reported in MAL95. We propose two reasons for the lower proportion of SLLJs in the present study: (i) the thresholding reduces the number of reported SLLJs (MAL95 did not use thresholded data) and (ii) the anomalously strong synoptic southerly flow is likely to have produced an increased incidence of non-LLJ SWEs. There was a pronounced lull in the incidence of criterion 3 SWEs (both SLLJs and non-LLJ SWEs) during the month of August, which corresponded with a retreat of the upper-level jet from its anomalous position over the United States to its climatologically normal location to the north (Mo et al. 1995).

It is notable that the diurnal variability in the frequency of occurrence of strong southerly LLJs was greater than for all strong LLJs considered without regard to direction (Fig. 12). Specifically, the afternoon frequency of criterion 3 SLLJs was very low and was much lower than the afternoon frequency for the total population of criterion 3 LLJs (cf. Fig. 5c to Fig. 12c). In contrast to the LLJs, the diurnal variability of the non-LLJ SWEs was greater for the weaker criteria than for the stronger ones (a similar trend was found by MAL95). The diurnal variability for criterion 1 was out of phase between the SLLJs and non-LLJ SWEs, such that when the two were summed the normalized

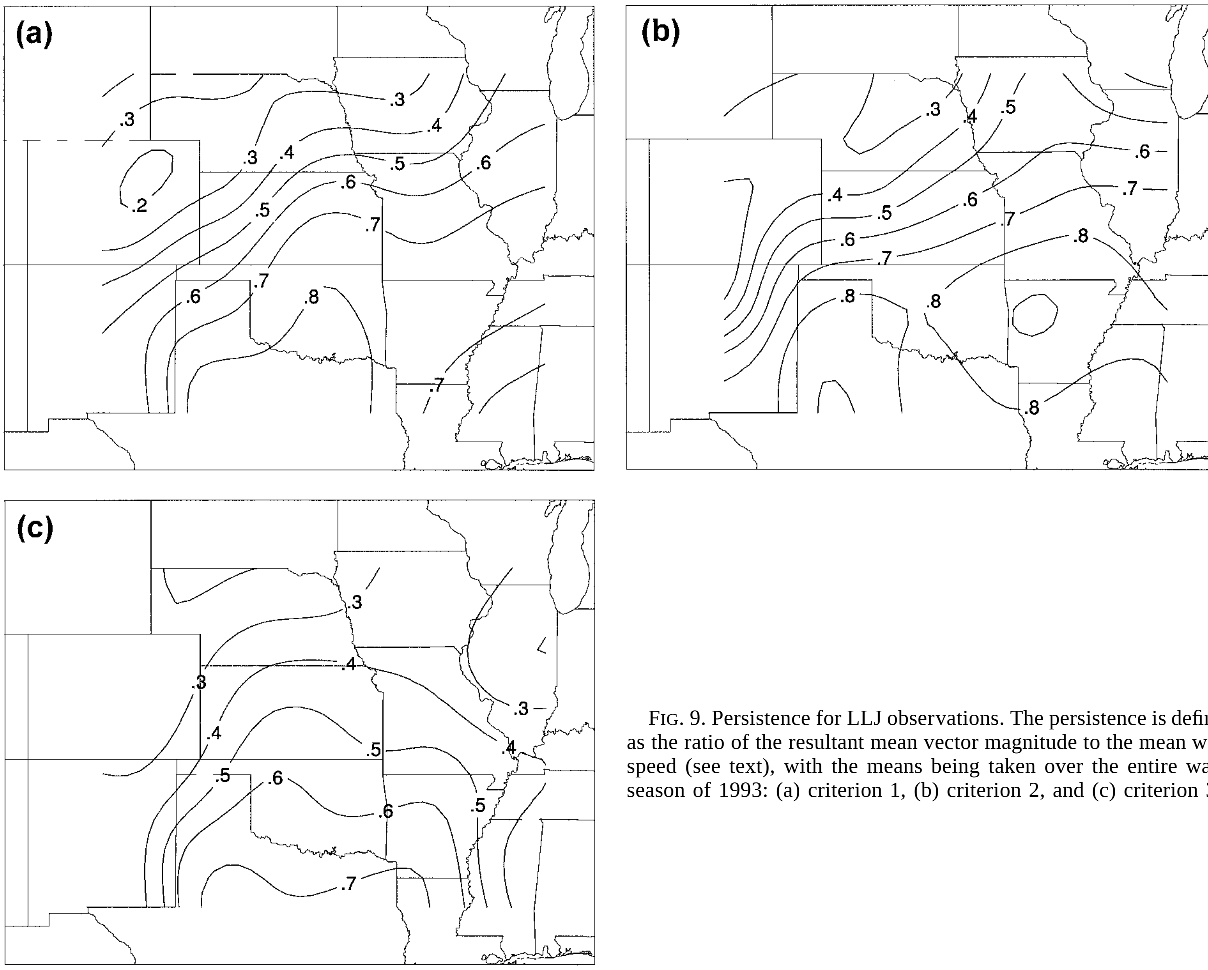


FIG. 9. Persistence for LLJ observations. The persistence is defined as the ratio of the resultant mean vector magnitude to the mean wind speed (see text), with the means being taken over the entire warm season of 1993: (a) criterion 1, (b) criterion 2, and (c) criterion 3.

frequency varied relatively little throughout the day. The strong SWEs (criteria 2 and 3) showed diurnal variability that was attributable primarily to the nocturnal maximum in the occurrence of SLLJs.

The diurnal and seasonal trends for the frequency of non-LLJ SWEs exhibited little difference between the three datasets even during the nighttime hours (not shown). This suggests that the non-LLJ SWEs were less susceptible to contamination than the LLJs. The reasons for this are unclear (later we will offer some tentative hypotheses). The criterion 3 southerly LLJs were very heavily contaminated during April and May, even more so than the criterion 3 LLJs in general. In those months there was about a factor-of-3 difference in the incidence of SLLJs between the thresholded and unthresholded data. Once again we find that the velocity variance thresholding gives results that are consistent with the expected signal resulting from contamination of the profiler observations by returns from passerines, since the birds migrate *from the south* during the springtime.

5. Relation of low-level jets to the large-scale environment

a. Synoptic classification

We performed a synoptic classification of hourly LLJ observations using the same procedure as in MAL95, in which the classification was done independently by two of the authors (here MJM and CAC) with disagreements being arbitrated by a third (KML). The classification was done in this way to minimize biases attributable to a particular individual's subjective interpretation of the synoptic pattern. The classification was based on an idealized model of an extratropical cyclone, with the synoptic classes defined as 1) warm sector, 2) ahead of a warm front, 3) behind a cold front, 4) polar high, and 5) subtropical ridge. We also accounted for unclassifiable observations. For further details of the methodology and descriptions of the synoptic categories, see Pielke et al. (1991) and MAL95.

Consistent with MAL95 and earlier studies (e.g., Uccellini 1980), we found that the relation to the synoptic environment was most noticeable for strong LLJs

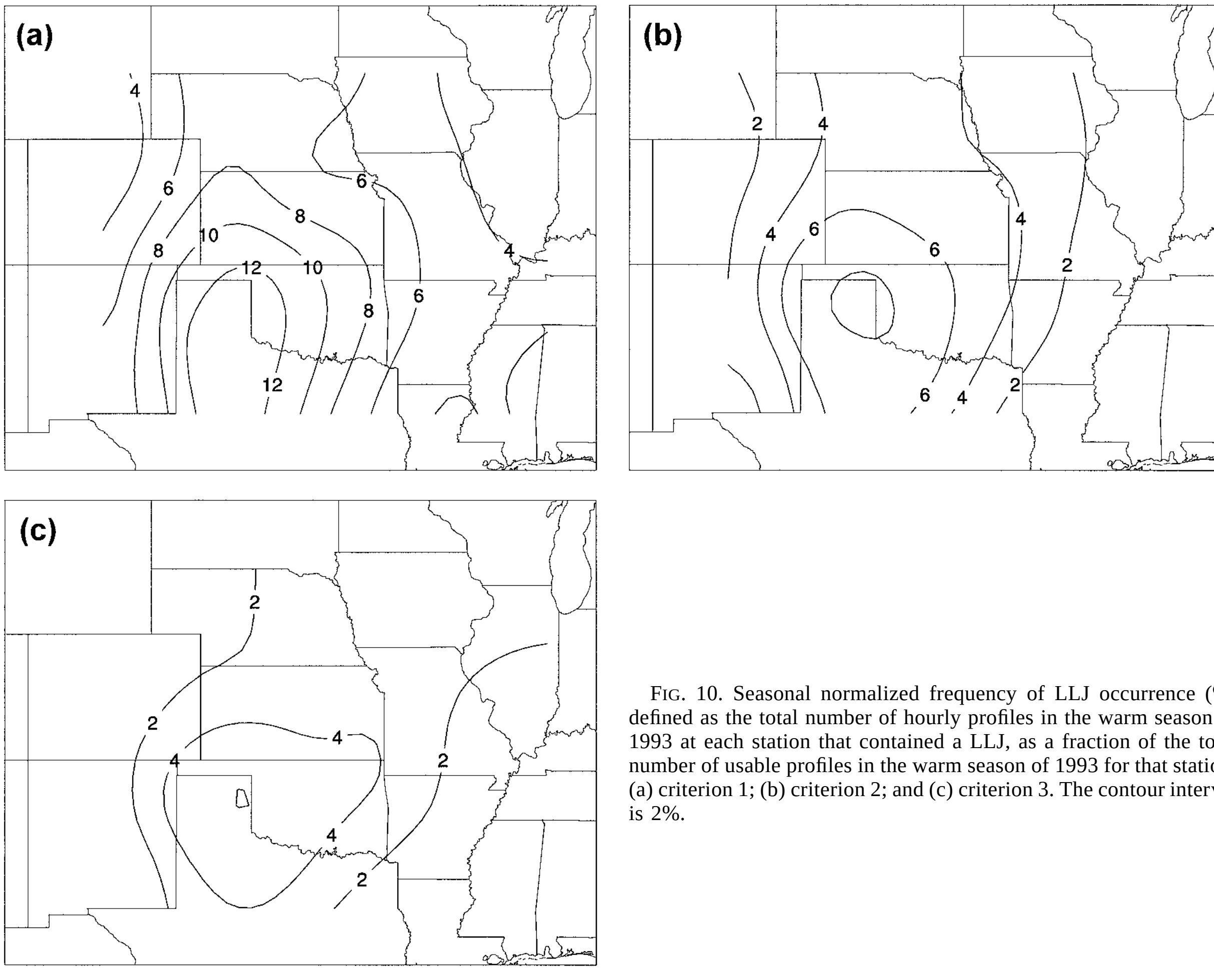


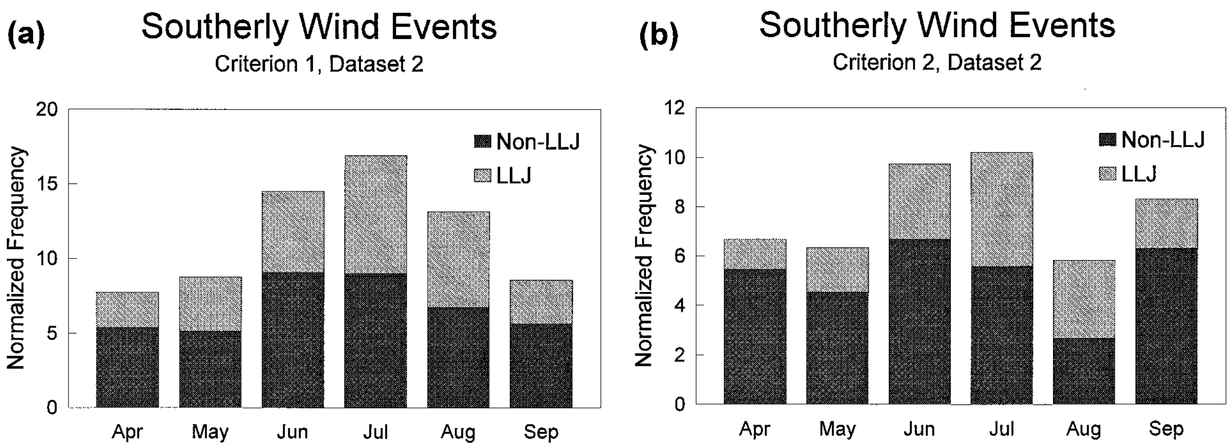
FIG. 10. Seasonal normalized frequency of LLJ occurrence (%) defined as the total number of hourly profiles in the warm season of 1993 at each station that contained a LLJ, as a fraction of the total number of usable profiles in the warm season of 1993 for that station: (a) criterion 1; (b) criterion 2; and (c) criterion 3. The contour interval is 2%.

(Fig. 13) and, in particular, that strong LLJs were promoted in the warm sector of an extratropical cyclone (our synoptic class 1). Analysis of the incidence of the different synoptic classes (Fig. 14) indicates that during June–July 1993 there was a moderate increase in the frequency of class 1, so that the anomalously high frequency of occurrence of LLJs during the midsummer of 1993 can be explained in part by a more conducive synoptic pattern. Earlier we noted that the seasonal trend of criterion 1 and 2 LLJs disagreed with previous studies, in that they did not show a peak frequency in September. This discrepancy appears to be explained in part by a less conducive synoptic pattern than previous years, since September 1993 did not show the increase in occurrence of synoptic class 1 that occurred in September 1992.

b. Upper-level height and flow fields

Previous investigators have proposed that the LLJ is related to specific features in the upper-level flow field. Uccellini and Johnson (1979) found that the LLJ could be promoted by coupling with an upper-level jet streak, while Chen and Kpaeyeh (1993) found that the LLJ was associated with a developing baroclinic wave in the lee of the Rocky Mountains. Both of these studies were performed before the availability of the hourly data from the profiler network. Thus, it is appropriate to investigate the relationships of the LLJ to the mid- and upper-level height and wind fields when the LLJ is defined using profiler observations. Here we focus on the criterion 3 LLJs because of their strong association with the peak precipitation of the 1993 flood.

We derived composite upper-level height and wind fields using Global Data Assimilation System (GDAS) analyses on a 2.5° by 2.5° latitude–longitude grid. During 1993 the GDAS used the T80 resolution Medium-Range Forecast model to provide background or ''first-guess'' fields [see Kalnay et al. (1990) for a concise summary of the GDAS methodology]. We composited these fields first for the entire period 1 June–31 August 1993 (hereafter JJA, for June–July–August) and then composited for days with high incidence of criterion 3 LLJs. The specific days were 29–30 June, 3–9 July, and 14 July, which corresponded essentially to the period of peak precipitation over the upper Missis-



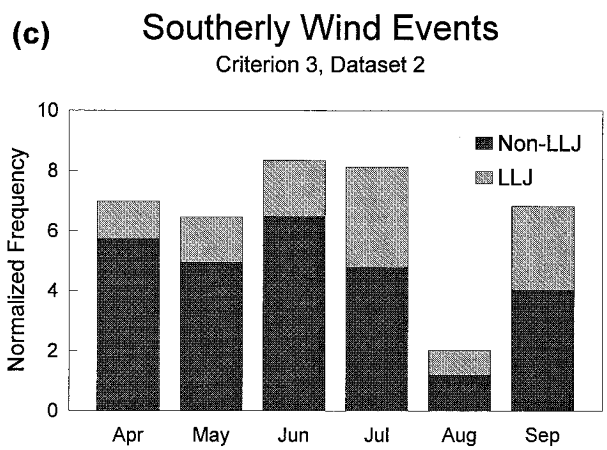


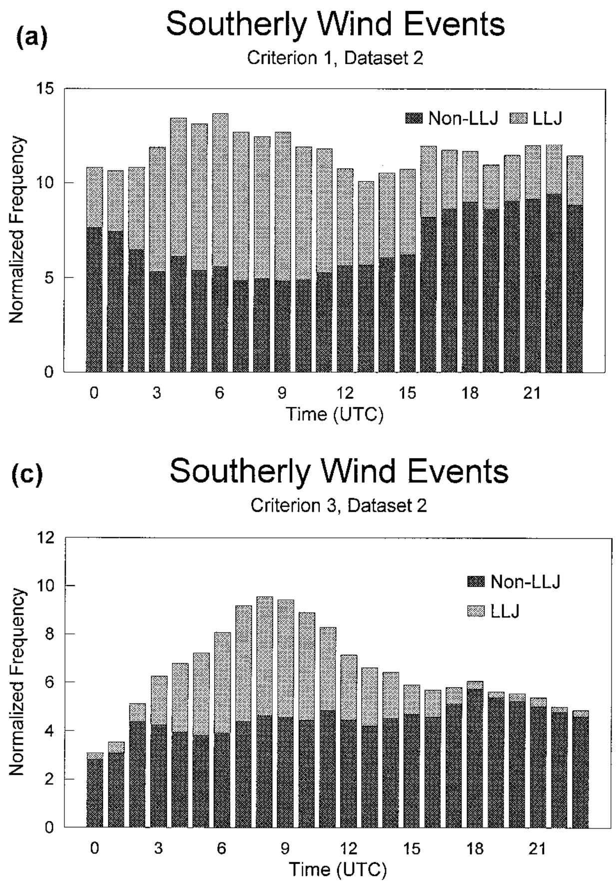
FIG. 11. Monthly normalized frequency of occurrence (%) of southerly wind events (SWEs) satisfying (a) criterion 1, (b) criterion 2, and (c) criterion 3. The total height of each bar is the sum of events that included the low-level local maximum of wind speed required for the low-level jet definition (lighter portion of the bar) and those that did not (darker portion).

sippi River basin during the 1993 flood (see Fig. 7 and the related discussion). In defining the LLJ occurrences, we used only stations over the Great Plains indicated by the underlined station identifiers in Fig. 2. Except as noted, the composites are for the 0000 UTC analysis on each day. (Diurnal variability of the height and wind fields was small above 850 mb.)

The 500-mb height field for LLJ days showed noticeable anomalies as compared to the JJA composite (Fig. 15). There was an anomalous trough over the western United States and Canada and an anomalous ridge over the eastern Pacific Ocean. Similar but more intense height anomalies occurred at 200 mb (not shown). The mid- and upper-level height patterns closely resembled the ‘‘flood look-alike’’ composites presented by Mo et al. (1995), reinforcing the link between strong low-level jets and extreme precipitation episodes as found by previous investigators (e.g., Means 1952; Pitchford and London 1962). The upper-level anomalies (along with the synoptic climatology discussed previously) are also consistent with Uccellini’s (1980) finding that the LLJ was associated with leeside troughing and cyclogenesis in the lee of the Rocky Mountains. The trough anomaly at 850 mb extended farther south over the Great Plains than at the upper levels (Fig. 16). The 850-mb height anomaly field implies an increase in the southerly to southwesterly geostrophic wind at 850 mb, consistent with the LLJ incidence during this period. The magnitude of the anomaly in the 850-mb geostrophic wind corresponding to this height anomaly was about 8 m s^{-1} over the southern Great Plains (Fig. 17).

We turn now to the analysis of the composite wind fields at 850 mb, which is the level in the GDAS archive closest to the height of the LLJ maximum winds. The composite 850-mb winds for the days with high incidence of criterion 3 LLJs were stronger and more westerly over the central United States at 1200 UTC than at 0000 UTC (Fig. 18). We can gain some insight into the nature of the LLJ by separating the 850-mb winds into geostrophic (Fig. 19a) and ageostrophic (Figs. 19b,c) components. This was done by computing the geostrophic wind from the composite 850-mb height field for the aforementioned days with criterion 3 LLJ occurrences and then subtracting this geostrophic wind from the composite wind field to obtain the ageostrophic wind. (The 850-mb geostrophic wind at 1200 UTC was nearly the same as at 0000 UTC, except in a small region over the Rocky Mountains, and is not shown here.)

The 850-mb ageostrophic winds for the criterion 3 LLJ cases showed an easterly component of about 5–7



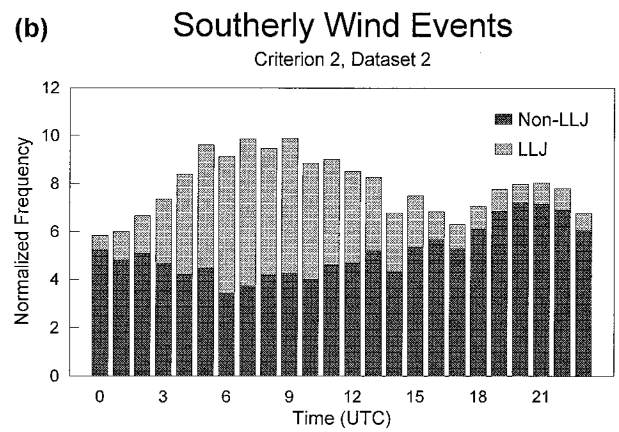


FIG. 12. Hourly normalized frequency of occurrence (%) of SWES satisfying (a) criterion 1, (b) criterion 2, and (c) criterion 3. The total height of each bar is the sum of events that included the low-level local maximum of wind speed required for the low-level jet definition (lighter portion of the bar) and those that did not (darker portion).

m s^{-1} at 0000 UTC, that is, near sunset before the LLJ developed (Fig. 19b). Note that this ageostrophic component apparently was not solely a result of frictional retardation of the geostrophic wind, because the direction is too easterly. The ageostrophic component resembles the ageostrophic vector attributed by Uccellini (1980) to the isallobaric wind (see especially his Fig. 4 and related discussion). The ageostrophic component may also include some contribution from regional-scale upslope winds. By 1200 UTC (i.e., around sunrise, toward the end of the LLJ events) the ageostrophic component over the Great Plains had maintained close to its earlier magnitude but had veered to a southerly to southwesterly direction (Fig. 19c). This directional change corresponds to an inertial oscillation through a period of 6–8 h, which is slightly shorter than the time from local sunset to 1200 UTC (about 9 h).

The inertial oscillation of the ageostrophic vector is

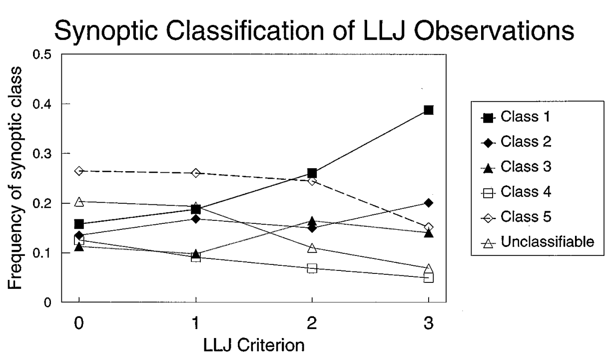


FIG. 13. Proportion of low-level jets associated with a particular synoptic class (normalized by the frequency of occurrence for each class) summed over all profiler stations for the warm season of 1993. The synoptic classes are (1) warm sector, (2) ahead of a warm front, (3) behind a cold front, (4) polar high, and (5) subtropical ridge.

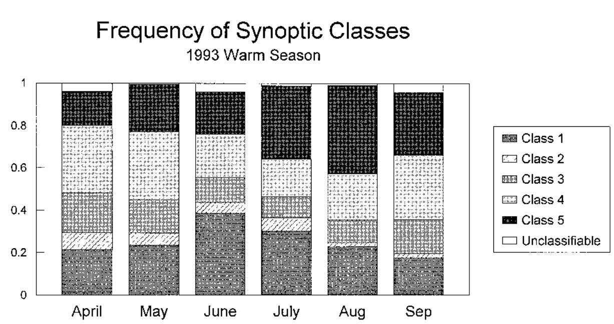


FIG. 14. Frequencies of synoptic classes by month for 1993 summed over all stations. The classes are (1) warm sector, (2) ahead of a warm front, (3) behind a cold front, (4) polar high, and (5) subtropical ridge.

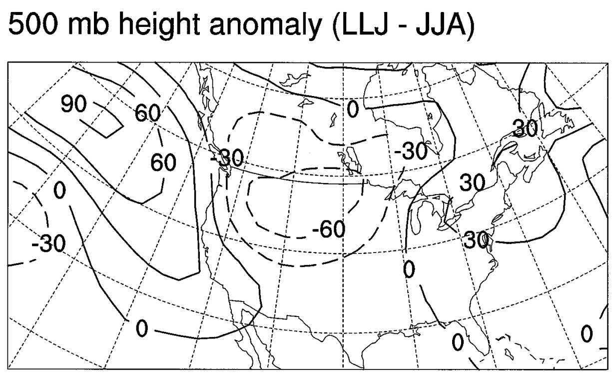


FIG. 15. Composite 500-mb height anomaly field (geopotential meters) at 0000 UTC constructed by subtracting the composite heights for the period 1 June–31 August 1993 from the composite for a subset of the days in the same period having a high incidence of criterion 3 LLJs. The contour interval is 30 m. Solid contours indicate positive anomalies; dashed, negative.

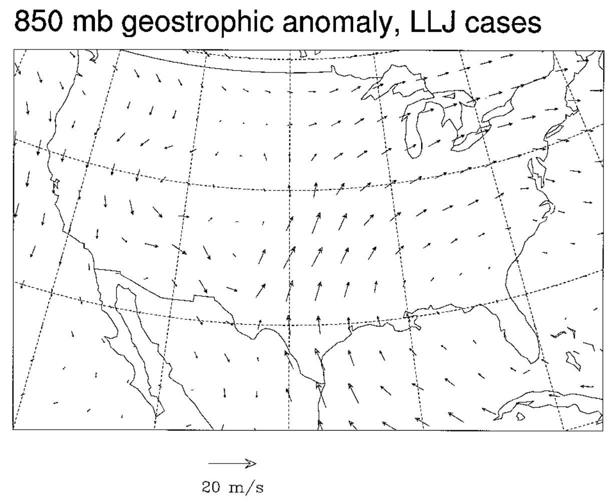


FIG. 17. Composite 850-mb geostrophic wind anomaly corresponding to the 850-mb height anomaly shown in Fig. 16c. The magnitude of the reference vector is 20 m s^{-1}.

generally consistent with the mechanism proposed by Blackadar (1957), with the main difference being that the ageostrophic component apparently is not produced solely by daytime frictional retardation of the geostrophic wind. Such a modification of Blackadar's (1957) mechanism could partly explain the observed relation between the LLJ and the regional terrain gradient. The pure inertial oscillation makes no explicit consideration of terrain slope and, thus, at first glance would not necessarily explain the relation of the LLJ to the sloping terrain of the Great Plains. If we recognize that an ageostrophic vector can be generated not just by daytime eddy friction, but also by the isallobaric wind resulting from leeside troughing and by thermally forced daytime upslope flows, then the latter two processes provide physical linkages to the sloping terrain. The relation of the ageostrophic vector (and hence the LLJ) to the terrain gradient may also be explained in part by the effect of the terrain on the *time-mean* pressure gradient (i.e., the geostrophic wind rather than the isallobaric wind); for

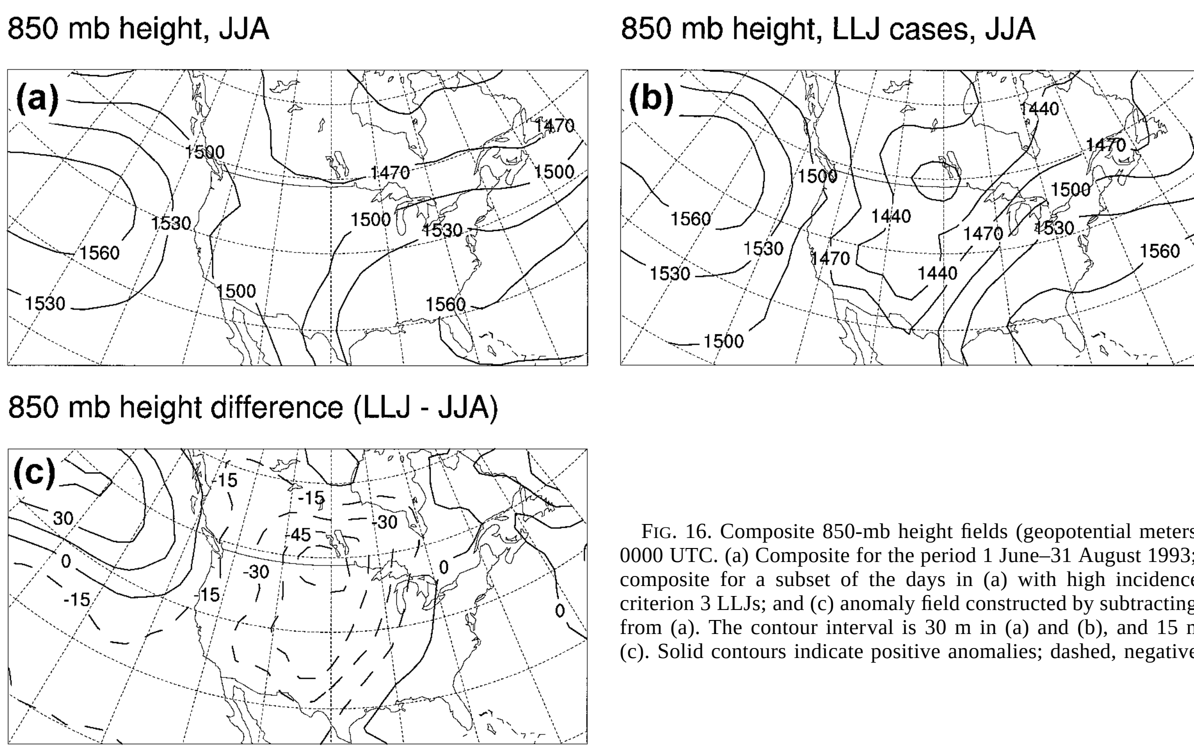


FIG. 16. Composite 850-mb height fields (geopotential meters) at 0000 UTC. (a) Composite for the period 1 June–31 August 1993; (b) composite for a subset of the days in (a) with high incidence of criterion 3 LLJs; and (c) anomaly field constructed by subtracting (b) from (a). The contour interval is 30 m in (a) and (b), and 15 m in (c). Solid contours indicate positive anomalies; dashed, negative.

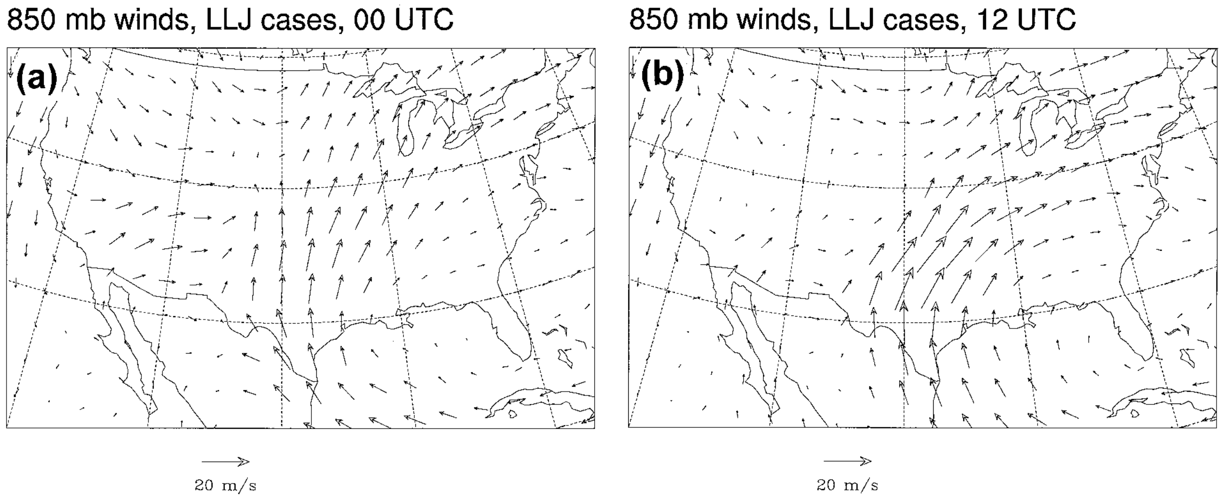
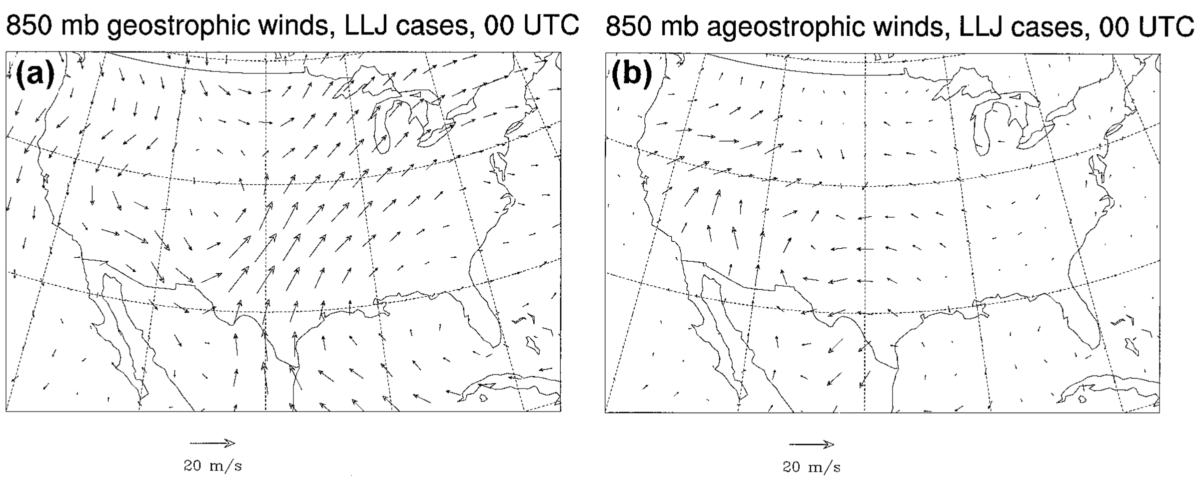


FIG. 18. Composite 850-mb winds for days with high incidence of criterion 3 LLJs: (a) at 0000 UTC and (b) at 1200 UTC. The magnitude of the reference vector is 20 m s^{-1}



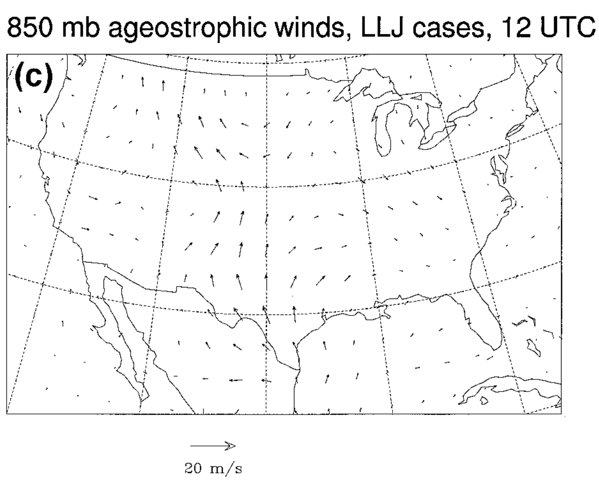


FIG. 19. Decomposition of 850-mb winds for days with high incidence of criterion 3 LLJs into geostrophic and ageostrophic components: (a) geostrophic wind computed from the composite height field shown in Fig. 16b; (b) ageostrophic wind component at 0000 UTC; and (c) ageostrophic wind component at 1200 UTC. The magnitude of the reference vector is 20 m s^{-1}.

example, a persistent leeside trough may provide a stronger southerly geostrophic flow on which friction acts to initiate a stronger ageostrophic component.

Another noteworthy feature is the convergence shown by the ageostrophic part of the flow. The convergence of the ageostrophic flow over the Great Plains around 40°N (Fig. 19c) is in close agreement with the marked spatial concentration of mesoscale convective complexes near this latitude during 1993 (Anderson and Arritt 1996). This result implies that if the effect of the LLJ on mesoscale convection and the hydrologic cycle is to be satisfactorily predicted, it is essential that the details of the LLJ dynamics be properly included. In particular, it is necessary that the relative contributions of the geostrophic and ageostrophic components be correctly represented, since the latter determines the convergence. One might interpret this as a requirement that the forecasted LLJ be right for the right reasons and not just approximately correct in the final result.

6. Summary

Analysis of average LLJ direction and speed for the warm season of 1993 showed that the LLJ in the Great Plains was primarily out of the south or southwest at stations in the central and southern Great Plains, with more variable direction for stations to the north and west. The frequency of LLJ occurrence was greatest in midsummer, which contrasts with previous studies showing peak occurrence in late summer (Bonner 1968; Mitchell et al. 1995). This midsummer incidence of LLJs was shown to be related at least in part to anomalies in the surface synoptic pattern and the upper-level wave regime. A broad peak in the frequency of occurrence of strong (criterion 3) LLJs corresponded to the maximum precipitation episode of the 1993 flood during late June and early July, whereas the occurrence of weaker LLJs did not show any obvious difference in this period as compared to other parts of the warm season. These results suggest that the relationship between the LLJ and extreme precipitation depends primarily on the incidence of *strong* LLJs rather than the incidence of LLJs in general.

Results for the LLJ climatology using data to which velocity variance thresholding was applied sometimes differed substantially from those obtained for unthresholded data that corresponded essentially to the operational procedures that were used until recently. (On 15 August 1996 the National Weather Service implemented a quality control procedure intended to identify profiler observations contaminated by migrating birds.) We cannot conclusively state that the differences between the datasets are attributable to contamination by migrating birds, because we do not have independent observations of the winds and the migrations. Nevertheless, the differences between the datasets were consistent with the expected characteristics of such contamination: the contamination was strongest during the springtime, at night, and for southerly LLJs. Observations during June, July, and August showed little evidence of contamination. Until the extent of the contamination is better understood, we recommend that observations of strong southerly LLJs in the springtime using the operational 404-MHz profilers be viewed with caution. We recommend specifically that historical profiler data not be inserted into four-dimensional data assimilation schemes or used to compute hydrologic budgets without careful assessment of the extent of the contamination, especially during the periods when the data are most likely to be contaminated.

An unexpected result was that LLJs were more contaminated than strong southerly winds that did not qualify as LLJs. Although the reasons for this are unclear, we offer two hypotheses for further study. First, it may be that the birds migrate preferentially when there is a well-defined level of maximum winds (as when an LLJ is present); in this regard, Wilczak et al. (1995) pointed out that the birds are adept at locating the most favorable winds. Second, there may be some factor affecting migration that in turn is correlated with the LLJ, such as precipitation or cloud cover. Interdisciplinary research among meteorologists, ornithologists, and remote sensing specialists would be required to address these hypotheses.

The composite mid- and upper-level height fields for LLJ events showed strong anomalies from the seasonal means. These anomalies were part of a large-scale wave pattern that extended upstream at least to the central Pacific. This suggests that the LLJ provides a *scale interaction mechanism* that couples the regional meteorology and hydrologic cycle over the Great Plains to the large-scale circulation patterns. Separating the composite 850-mb wind into its geostrophic and ageostrophic components also showed the importance of the ageostrophic wind in producing strong LLJs. The magnitudes of the ageostrophic wind and the anomalous geostrophic wind associated with the strong LLJs were comparable (about 5–7 and 8 m s^{-1}, respectively). The need to correctly represent both the anomalous geostrophic wind and the ageostrophic wind may pose a challenge for the prediction of the LLJ using numerical models and, in particular, is crucial if the linkage of the LLJ to regional precipitation is to be properly represented.

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