Influence of the Great Plains Low-Level Jet on Summertime Precipitation and Moisture Transport over the Central United States

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ABSTRACT

The influence of the Great Plains low-level jet (LLJ) on summertime precipitation and moisture transport over the central United States is examined in observations and in assimilated datasets recently produced by the NCEP/NCAR and the NASA/DAO. Intercomparisons between the assimilated datasets and comparisons with station observations of precipitation, winds, and specific humidity are used to evaluate the limitations of the assimilated products for studying the diurnal cycle of rainfall and the Great Plains LLJ. The winds from the reanalyses are used to diagnose the impact of the LLJ on observed nocturnal precipitation and moisture transport over a multisummer (JJA 1985–89) period. The impact of the LLJ on the overall moisture budget of the central United States is also examined.

An inspection of the diurnal cycle of precipitation in gridded hourly station observations for 1963–93 reveals a well-defined nocturnal maximum over the Great Plains region during the spring and summer months consistent with earlier observational studies. During summer in excess of 25% more precipitation falls during the nighttime hours than during the daytime hours over a large portion of the Great Plains, with a commensurate decrease in the percentage amount of nocturnal precipitation along the Gulf Coast. Inspection of the nighttime precipitation by month shows that the maximum in precipitation along the Gulf Coast slowly shifts northward from the lower Mississippi Valley to the upper Midwest during the late spring and summer months and then back again during the fall.

Both reanalyses produce a Great Plains LLJ with a structure, diurnal cycle, and frequency of occurrence that compares favorably to hourly wind profiler data. Composites of observed nighttime rainfall during LLJ events show a fundamentally different pattern in the distribution of precipitation compared to nonjet events. Overall, LLJ events are associated with enhanced precipitation over the north central United States and Great Plains and decreased precipitation along the Gulf Coast and East Coast; nonjet events are associated with much weaker anomalies that are generally in the opposite sense. Inspection of the LLJ composites for each month shows a gradual shift of the region of enhanced precipitation from the northern tier of states toward the south and east in a manner consistent with the anomalous moisture transport. LLJ-related precipitation is found to be associated most closely with the strongest, least frequent LLJ events.

The moisture transport in the reanalyses compares favorably to radiosonde data, although significant regional differences exist, particularly along the Gulf Coast during summer. The diurnal cycle of the low-level moisture transport is well resolved in the reanalyses with the largest and most extensive anomalies being those associated with the nocturnal inland flow of the Great Plains LLJ. Examination of the impact of the LLJ on the nighttime moisture transport shows a coherent evolution from May to August with a gradual increase in the anomalous westerly transport over the southeastern United States, consistent with the evolution of the precipitation patterns. The impact of the LLJ on the overall moisture budget during summer is considerable with low-level inflow from the Gulf of Mexico increasing by more than 45%, on average, over nocturnal mean values.

1. Introduction

During spring and summer months, the low-level flow over the Great Plains region of the United States is characterized by the frequent formation of a nocturnal low-level jet (hereafter LLJ). This LLJ, which has often been associated with severe weather events, is well documented in observational studies. Izumi and Barad (1963) discussed the evolution of a LLJ located at Cedar Hill, Texas, during the night of 22–23 February 1961. Hoecker (1963, 1965) used a special pilot balloon network between Amarillo, Texas, and Little Rock, Arkansas, to examine the jet characteristics of three cases during the spring of 1961. He found that the jet maxima occurred between 300 m and 800 m above the ground

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with nighttime speed maxima roughly double the sea level geostrophic speed. The pioneering work of Bonner (1968) described the geographical and diurnal variations of the LLJ over the United States. From two years of radiosonde data he showed that LLJs are most frequent over the Great Plains, that they occur most often from April to September, that they are predominantly a nighttime phenomenon, and that they often have a large horizontal scale extending across much of the region. Recently, Mitchell et al. (1995) used hourly observations from wind profilers during the warm season months of 1991 and 1992 to develop a new climatology of the LLJ.

The relationship between the Great Plains LLJ and deep convection has been recognized for decades and remains a topic of current research. Means (1952) showed that pretrough LLJs are a typical synoptic-scale feature associated with nocturnal thunderstorm activity in the central United States. In a subsequent study, Means (1954) showed that the Kansas City floods in July 1951 were linked to a low-level southerly jet that transported most of the moisture into the area of heavy precipitation. Pitchford and London (1962) used kinematic vertical velocities and percent thunderstorm occurrence for an area centered at Omaha, Nebraska, to show that summer nocturnal thunderstorms are closely related to the production of regions of convergence associated with the LLJ. Hering and Borden (1962) demonstrated quite convincingly that the nocturnal maximum in convective activity over the central United States is related to the occurrence of LLJs. Wallace (1975) further emphasized this relationship in his physical interpretation of the diurnal cycle of precipitation over the central United States. Recently, Augustine and Caracena (1994) examined the relationship between LLJs and the development of nocturnal mesoscale convective systems over the central United States. Recent studies of the 1993 Midwest floods (Bell and Janowiak 1995; Mo et al. 1995) also suggest that the LLJ may have been an important factor in producing excessive rainfall during convective outbreaks.

The location of the Great Plains LLJ in the lowest kilometer and a half of the atmosphere suggests that it is an important component of the atmospheric moisture budget in this region. Benton and Estoque (1954) and Rasmusson (1967) provided clear observational evidence for the key role of the mean jet in bringing Gulf Coast moisture into the continental United States; the latter study also showed a significant diurnal signal in the moisture fluxes. On the other hand, the small vertical extent and diurnal nature of the LLJ have made it difficult to study the detailed nature of the jet and its role in the continental scale moisture budget from observations alone (e.g., Rasmusson 1968).

The current study attempts to extend our knowledge of the influence of the Great Plains LLJ on nocturnal precipitation and moisture transport over the central United States. Following the pioneering work of Wallace (1975), we first examine the diurnal cycle of precipitation over the conterminous United States using a recently compiled multiyear (1963–93) hourly precipitation database (Higgins et al. 1996a). Next we establish the validity of benchmark multiyear (1985–94) reanalyses produced by the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) and the National Aeronautics and Space Administration/Data Assimilation Office (NASA/DAO) (see section 2) as tools for investigating the LLJ. Of particular interest is the quality of the reanalysis winds, which we compare to hourly observations from the Wind Profiler Demonstration Network during the 1994 GCIP Integrated Systems Test. We then explore relationships between the LLJ and nocturnal rainfall by using the reanalysis winds to produce composites of the observed precipitation for LLJ events during the summers of 1985–89. Relationships between LLJ strength and nocturnal precipitation patterns and totals are highlighted. Finally, we quantify the impact of the LLJ on the moisture transport and overall moisture budget of the central United States using the reanalyses.

There have been a number of successful simulations of various aspects of the LLJ using regional boundary layer models (e.g., Astling et al. 1985; Krishna 1968; McCorcle 1988; Paegle and McLawhorn 1983; McNider and Pielke 1981; Fast and McCorcle 1990) and more recently using the Eta model (Berbery et al. 1996), but there have been relatively few studies of the LLJ in global AGCMs. A notable exception is the recent study by Helfand and Schubert (1995), who used a springtime simulation from the Goddard Earth Observing System (GEOS-1) GCM (the same model used for the DAO reanalysis) to show that the diurnal cycle in moisture transport over the continental United States is strongly regulated by the LLJ. They found that the LLJ transported almost one-third of all the moisture that enters the continental United States with most of this influx entering during the nighttime hours. Higgins et al. (1996b) used the DAO and the NCEP/NCAR reanalyses to examine the moisture budget of the central United States during spring, including a preliminary assessment of the impact of the LLJ on the budget.

Section 2 describes the datasets and methodology used in this study. The diurnal cycle of precipitation in the observations is discussed in section 3. The structure, diurnal cycle, and climatology of the LLJ in the observations and in the reanalyses is discussed in section 4. The influence of the LLJ on nighttime precipitation and moisture transport is discussed in sections 5 and 6, respectively. A summary and discussion are given in section 7. A more formal quantitative analysis of moisture budgets for the central United States during summer is discussed in the appendix.

2. Data analysis

The National Centers for Environmental Prediction/National Center for Atmospheric Research and the Data

Assimilation Office at NASA's Goddard Space Flight Center have completed benchmark multiyear reanalyses; as of this date the NCEP (DAO) reanalysis has been completed for the years 1973–95 (1980–93). Documentation of the reanalysis datasets and assimilation systems is found in Kalnay et al. (1996) and Schubert et al. (1993), respectively. The reanalyses are produced with state-of-the-art *fixed* assimilation systems and large input databases (including data available after the operational cutoff time). All reanalysis products, including variables related to the hydrologic cycle, are available to the research community.

The NCEP assimilation system consists of the NCEP Medium Range Forecast (MRF) spectral model and the operational NCEP Spectral Statistical Interpolation (SSI; Parrish and Derber 1992) with the latest improvements (Kalnay et al. 1996). The assimilation was performed at a horizontal resolution of T62 and at a vertical resolution of 28 sigma levels with 7 levels below 850 hPa. The DAO assimilation system consists of the Goddard Earth Observing System (GEOS-1) GCM (Takacs et al. 1994) and an optimal interpolation scheme (Pfaendtner et al. 1995). The assimilation was performed at a horizontal resolution of 2° latitude by 2.5° longitude and at a vertical resolution of 20 sigma levels with four levels below 850 hPa. In this study we utilize the reanalysis winds and specific humidity, which are instantaneous fields available every 6 hours, and several diagnostic fields (e.g., precipitation, evaporation) that are generated by the GCM's physical parameterizations. We rely heavily on the reanalysis winds (which are strongly dependent on the observations, hence the most reliable fields) to identify LLJ events over a multiyear period.

The moisture budget equation used in section 6 is discussed in the appendix; both the NCEP and the DAO moisture budgets include a term for the analysis increments that quantifies the impact of moisture observations on the model forecasts, hence the assimilated data. In the DAO system, the precipitation and evaporation fields were accumulated every 3 hours during the assimilation cycle but have been averaged to four times daily (0000 UTC, 0600 UTC, 1200 UTC, and 1800 UTC). In the NCEP system, the precipitation and evaporation fields are based on a 6-h forecast valid at the initial synoptic time. Moisture transport was computed directly from winds and specific humidity on the respective model sigma levels. For the NCEP analysis, these calculations were performed in the spherical domain to minimize truncation errors. Differences between the reanalyses will serve as our basic measure of uncertainty (especially when independent observations are unavailable).

In order to explore the impact of the LLJ on the diurnal cycle of precipitation, we employ a set of hourly, gridded precipitation analyses over the conterminous United States (Higgins et al. 1996a) that were developed on station observations obtained from the National Weather Service Techniques Development Laboratory. The time domain covers the period 1 January 1963 through 31 December 1993. The analyses were gridded to a horizontal resolution of 2° latitude by 2.5° longitude (Fig. 1a). Because the observations are available only over land, whenever comparisons are made to the reanalysis precipitation it is masked out over the oceans. We note that in this study the term "rainfall" is equivalent to measurable precipitation.

We examine the ability of the reanalyses to capture the vertical and temporal structure of the Great Plains LLJ by comparing the NCEP reanalysis winds to hourly observations from the Wind Profiler Demonstration Network during the 1994 GCIP Integrated Systems Test (Fig. 1b). The wind profilers are Doppler radars that provide wind measurements every 6 min at 250-m vertical increments from 250 m AGL to roughly 19 km. In this paper we use measurements averaged over 1 h that are gridded to a horizontal resolution of 2° lat × 2.5° long (see Fig. 1b); there is no interpolation or extrapolation of wind profiler data in the vertical. A discussion of the quality of the wind profiler data is given in Yarosh and Ropelewski (1994). We note that the NCEP and the DAO do not assimilate wind profiler data.

The moisture fluxes from each reanalysis are validated using radiosonde data (Radiosonde Data of North America 1993). Details concerning the validation upper-air dataset are found in Yarosh and Ropelewski (1996); the data were gridded to a horizontal resolution of 2.5° lat × 5° long. The initial radiosonde data includes both mandatory and significant levels at 0000 UTC and 1200 UTC. Comparisons are made at and below 200 hPa since the number of "good" observations of moisture related quantities above 200 hPa is quite small. To compare vertically integrated moisture fluxes (Fig. 18), the raw station observations are first integrated in the vertical and then gridded. Both the NCEP and the DAO assimilate radiosonde data but the NCEP uses both mandatory and significant level data while the DAO uses only mandatory level data. In addition, both systems have different quality control (prior to data ingest) and different analysis schemes, which makes comparisons to the raw station data important. For consistency, when comparing the mean annual cycle of the moisture budget terms from the reanalyses with the radiosonde data (section 6a, Fig. 16) the reanalyses are restricted to 0000 UTC and 1200 UTC, though this has little effect on the results.

3. The diurnal cycle of precipitation

An inspection of daily mean (1963–93) precipitation rates for each season (Fig. 2) shows centers of maximum rainfall in the Northwest and the Southeast. The northwestern maximum is strongest in winter (DJF) and nearly absent in summer (JJA), while the southeast center persists throughout the year (see also Higgins et al. 1996a). During the summer a maximum in rainfall is also evident over the central Plains resulting from in-

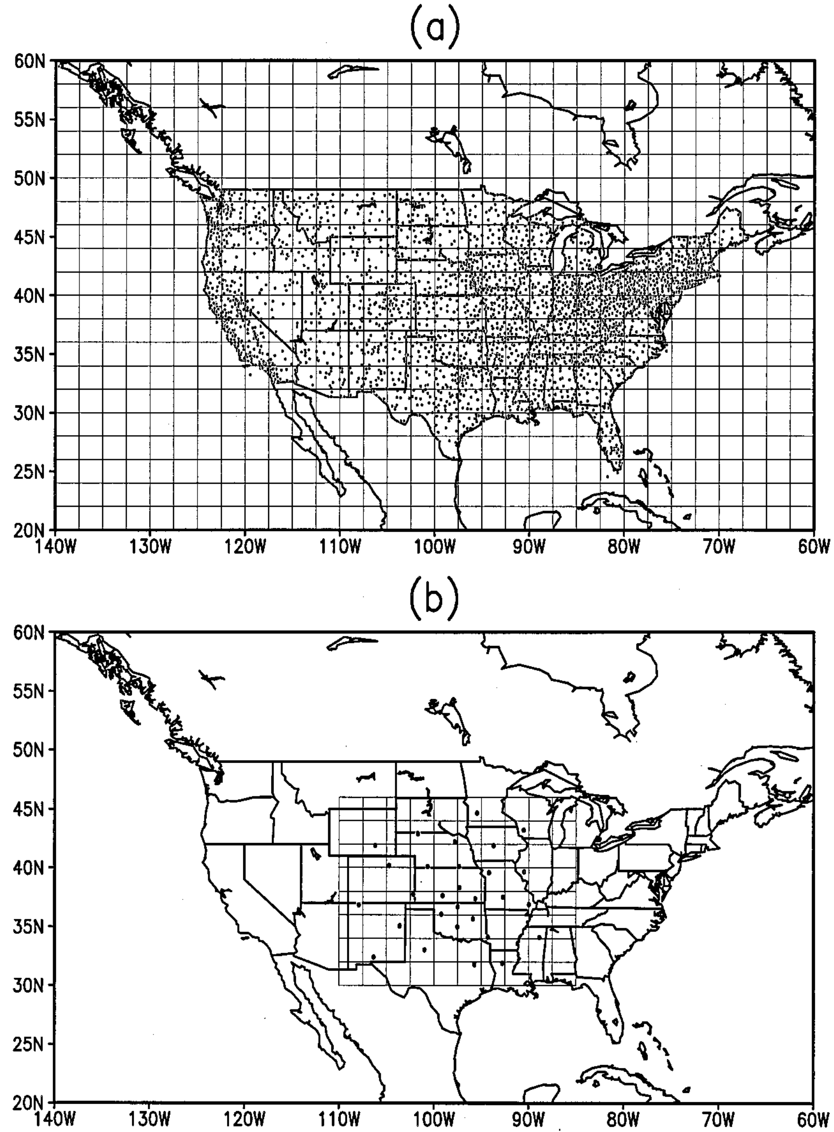

FIG. 1. (a) Typical station distribution for hourly reporting stations in January 1963. Gridlines represent the (33×21) grid to which the station data have been analyzed. (b) Wind Profiler Demonstration Network over the Great Plains during the 1994 GCIP Integrated Systems Test. Gridlines represent the (11×9) grid to which the station data have been analyzed. Note that both gridded datasets have a horizontal resolution of 2.0° lat × 2.5° long.

creased nocturnal convection; in this paper we explore the relationship between this nocturnal precipitation maximum and the Great Plains LLJ. Inspection of the nighttime (0000 UTC to 1200 UTC) rainfall by month (not shown) indicates that the maximum in precipitation along the Gulf Coast slowly shifts northward from the lower Mississippi Valley to the upper Midwest during the late spring and summer months and then back again during the fall. Numerous observational studies (e.g., Pitchford and London 1962) have discussed the importance of convection in the summertime nocturnal precipitation maximum over the Great Plains region.

The seasonal amplification of the diurnal cycle of precipitation is examined in Fig. 3, which shows the seasonal mean nighttime (0000 UTC to 1200 UTC) minus daytime (1200 UTC to 0000 UTC) precipitation difference expressed as a percentage of the mean daily precipitation. Very little difference is observed during DJF. During MAM in excess of 15% more precipitation falls during the nighttime hours than during the daytime hours over the southern Plains states with a commensurate decrease in the percentage amount of nocturnal precipitation over Florida. This pattern is amplified both in magnitude and spatial extent during JJA, when the nighttime rainfall exceeds daytime rainfall by more than 45% in western Nebraska, western Kansas, and eastern

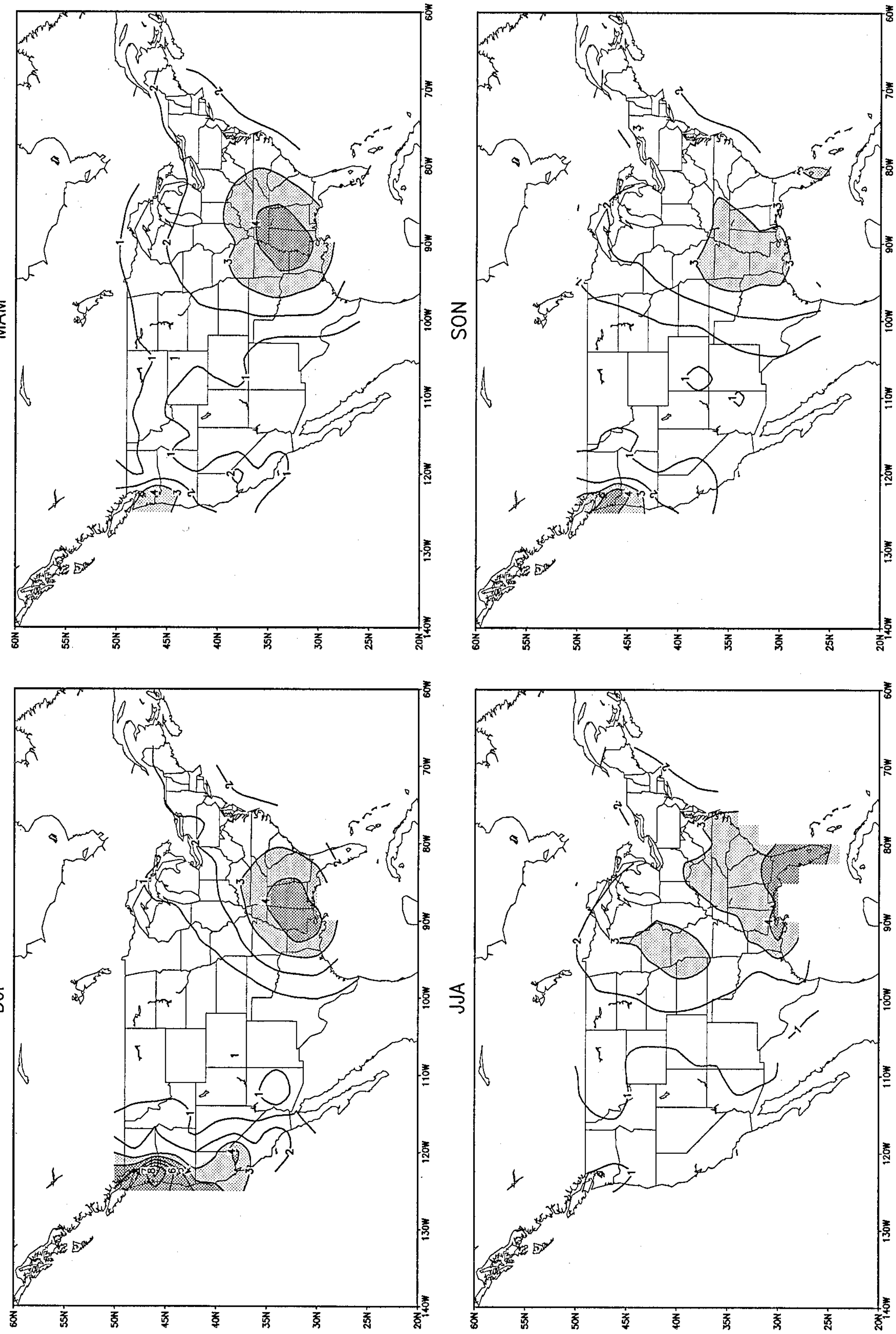

FIG. 2. Mean (1963–93) seasonal precipitation (units: mm day^{-1}) over the conterminous United States. Shading denotes regions with rates exceeding 3 mm day^{-1}.

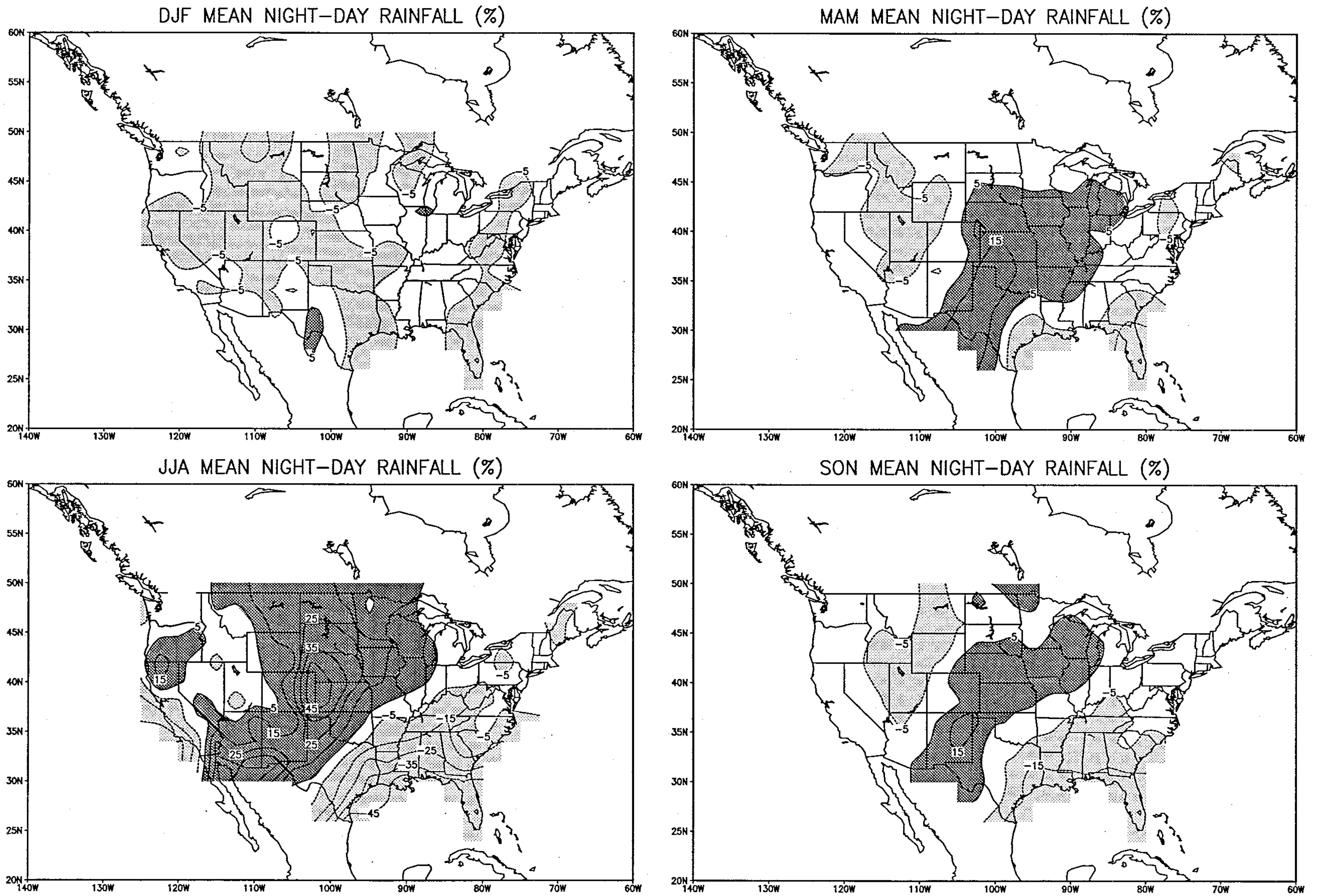

FIG. 3. Mean (1963–93) seasonal precipitation difference between nighttime (0000 UTC to 1200 UTC) accumulation and daytime (1200 UTC to 0000 UTC) accumulation expressed as a percentage of the mean daily precipitation rate.

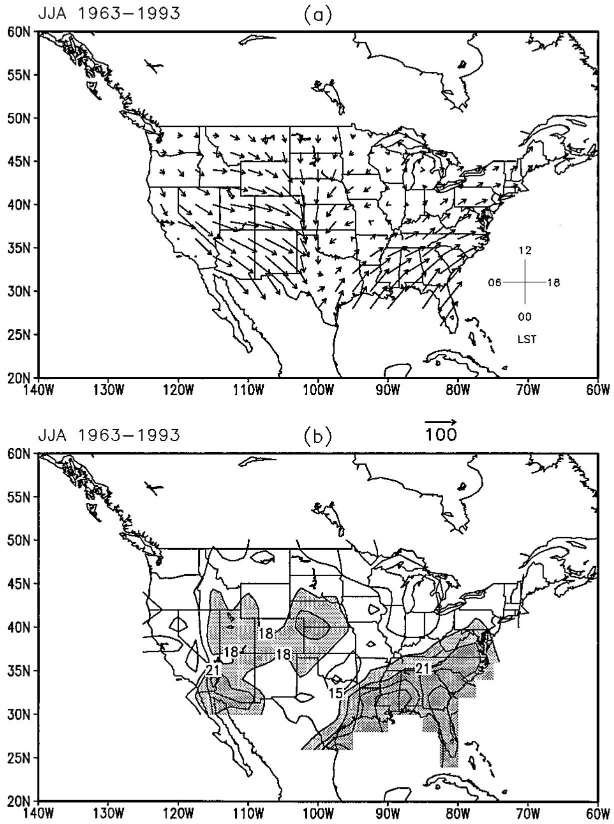

FIG. 4. (a) Normalized amplitude and phase of the diurnal cycle in the total frequency of precipitation during the 1963–93 period for June–August. The direction of the vectors indicates the preferred time of occurrence. The length of the vectors depicts the amplitude in percent (note phase and amplitude legends in lower right of each figure). Since the amplitudes are normalized by the 24-h mean frequency, the normalized amplitudes can exceed 100% in regions where precipitation is strongly suppressed during half of the day (Wallace 1975). (b) Percentage of total daily precipitation amount for JJA that is contributed by precipitation that occurs in the 3-h period centered on the preferred time of occurrence as determined from harmonic analysis.

Colorado. In much of the Southeast during JJA, daytime rainfall exceeds nighttime rainfall by more than 25%. During September–November (SON), daytime rainfall is about 10%–15% higher in the Gulf Coast states compared to nighttime.

The results of a harmonic analysis based on the 31-year mean hourly data indicate large differences in the diurnal cycle of precipitation between the summer and cool seasons; these results are consistent with the study by Wallace (1975). The summer is characterized by an early evening preference over the Rocky Mountains, a near-midnight preference in the Plains, and a midafternoon preference over most of the Southeast and mid-Atlantic states (Fig. 4a). During the cool season (November–March), the amplitude of the diurnal cycle in precipitation is considerably smaller and the phase is also quite different than is observed during the summer season (see Higgins et al. 1996a).

Over portions of the southeastern United States and along the east slopes of the Rockies the late afternoon/early evening maximum in convective activity coincides with the time when the vertical stratification has reached its most unstable values and the boundary layer winds are strongly convergent (Wallace 1975). Simultaneously, there is boundary layer divergence over the Great Plains where late afternoon convection tends to be suppressed. It has been demonstrated by Hering and Borden (1962), Pitchford and London (1962), and many others that the pronounced nocturnal maximum in convective activity over the Great Plains during summer is related to the Great Plains LLJ, which peaks in the late evening/early morning hours over the southern and central Plains states. The percentage of total daily precipitation amount for JJA that is contributed by precipitation that occurs in the 3-h period centered on the preferred time of occurrence is substantial (Fig. 4b), accounting for nearly 20% of mean daily totals in the west-central part of the country and over 20% in much of the South and East (for comparison purposes, note that if the rainfall were equally distributed over the course of the day, then 12.5% of daily total rainfall would be expected over a 3-h period).

Examination of the reanalysis mean daily precipitation rates for the summer season over the conterminous United States [not shown, but see Fig. 1 in Higgins et al. (1996b) for an example during May] indicates that both NCEP and DAO capture the dryness in the west and the wetness in the southeast but overestimate rainfall amounts over the Southeast by almost a factor of 2. Other aspects of the variability of daily mean rainfall and its partitioning by rate are discussed in Higgins et al. (1996a; 1996b). The excessive rainfall produced by the reanalyses is related to the large amplitude of the diurnal cycle inherent in them. The amplitude of the summer mean (1985–89) diurnal cycle of precipitation exceeds observations in both reanalyses by overestimating the daytime rates and underestimating the nighttime rates, particularly over the eastern half of the United States (not shown). In addition, both reanalyses do not capture the observed nocturnal maximum in precipitation over the Plains; a nocturnal signal is evident in both reanalyses once the mean bias is removed (Higgins et al. 1996b).

4. The Great Plains low-level jet

In this section we examine the vertical and temporal structure, frequency of occurrence, and diurnal cycle of the Great Plains LLJ. Comparisons of hourly wind profiler data to the NCEP reanalysis are used to establish the reliability of the reanalysis in capturing the LLJ and in resolving its diurnal cycle. In sections 5 and 6 the winds from the reanalyses are used to diagnose the impact of the LLJ on observed nocturnal precipitation and moisture transport over a multisummer (JJA 1985–89) period. We note that the DAO (which is not available

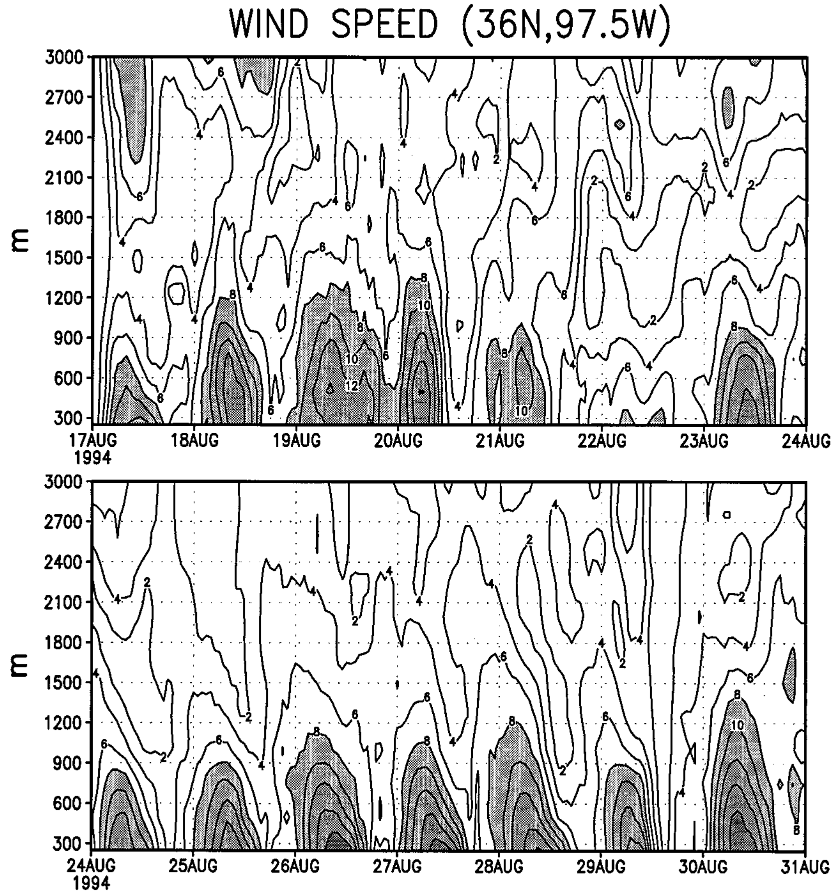

FIG. 5. Vertical profile of the 5-hour running mean (17–31 August 1994) wind speed (units: m s^{-1}) at the grid point (lat,long) = (36°N, 97.5°W) from hourly wind profiler data. Shaded regions denote values exceeding 8 m s^{-1}. Along the abscissa the time coordinate is given in UTC.

for 1994) produces a LLJ with a vertical and temporal structure that compares favorably to observations (Helfand and Schubert 1995; Higgins et al. 1996b).

a. Structure

The Great Plains LLJ is plainly evident in the two-week (17–31 August 1994) time series of wind speed from hourly wind profiler data (Fig. 5) at a grid point (36°N, 97.5°W) near the center of the Wind Profiler Demonstration Network (see Fig. 1b). At this location, it is manifested as a low-level, quasi-regular, nocturnal peak of 10–20 m s^{-1}. It is a fairly shallow feature centered roughly 250–500 m above the earth's surface. The nocturnal winds are primarily from the south. Typically, a wind speed maximum in excess of 10 m s^{-1} (and often in excess of 14 m s^{-1}) develops just above the surface by 0600 UTC in the observations. It persists through the early morning (roughly 1200 UTC) when enhanced surface friction associated with a thermally unstable daytime surface layer quickly retards the boundary-layer winds. By 1800 UTC the boundary-layer winds become well mixed due to thermally driven turbulence and the jet maximum does not redevelop until the following night. We note that the characteristics of the LLJ at the grid point (36°N, 97.5° W) are representative of those at surrounding points.

A comparison of the mean diurnal cycle of the meridional wind component (Fig. 6) between the gridded wind profiler data and the NCEP at the same grid point indicates that both products show a low-level nocturnal maximum around 0600 UTC and a low-level daytime minimum around 1800 UTC (Figs. 6a and 6c). Thus, despite the fact that the NCEP winds are available four times per day (and that radiosonde data is collected twice daily at 0000 UTC and 1200 UTC), the NCEP reanalysis captures the basic elements of the diurnal cycle found in the hourly observations. There is even agreement in features such as the phase reversal of the meridional wind above about 800 hPa. We note, however, that the NCEP meridional wind maximum is located roughly 50 hPa higher than that in the profiler data. The vertical structure of the oscillation in the meridional wind component is better seen by removing the JJA 1994 time mean (Figs. 6b and 6d). Both datasets show the largest anomalies in the lower troposphere,

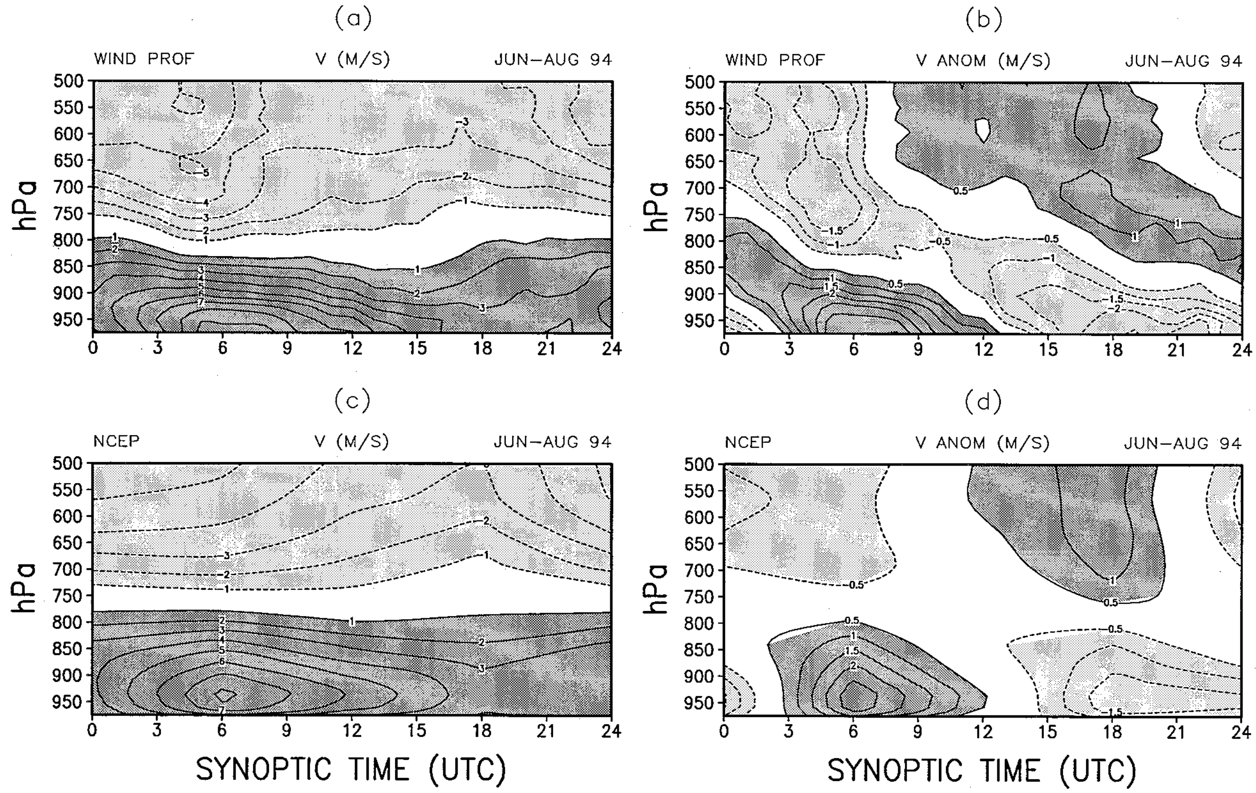

FIG. 6. Vertical profiles at the grid point (lat,long) = (36°N, 97.5°W) of the mean (JJA 1994) diurnal cycle of the meridional wind component (units: m s^{-1}) from (a) wind profiler data and (c) the NCEP reanalysis, and the meridional wind anomalies (departure from the overall JJA 1994 mean) from (b) wind profiler data and (d) the NCEP reanalysis. Pressure levels for the wind profiler observations are approximate assuming a surface pressure of 1000 hPa. In (a) and (c), dark (light) shading denote values greater than 1 m s^{-1} (less than -1 m s^{-1}). In (b) and (d) dark (light) shaded regions denote values greater than 0.5 m s^{-1} (less than -0.5 m s^{-1}).

though the NCEP anomalies are weaker. In the observations, the meridional wind deviations show a sign reversal between the lower and the middle troposphere along a tilted vertical axis. At night the anomalous southerly flow near the surface is accompanied by an anomalous northerly flow near 700 hPa and vice versa during the daytime. The NCEP reanalysis does a reasonable job in capturing this vertical structure and even hints at the vertical tilt.

b. LLJ frequency

Bonner (1968) examined the spatial and temporal characteristics of the Great Plains LLJ using three progressively more stringent criteria to identify the presence of a LLJ from the vertical sounding of wind speed. His criteria 1, 2, and 3 specify that the wind speed profile must have a maximum of at least 12, 16, or 20 m s^{-1}, respectively, within 1.5 km of the ground and that the wind speed must decrease by at least 6, 8, or 10 m s^{-1}, respectively, at the lowest minimum located above the maximum at or below the 3-km level.

The LLJ in both reanalyses exhibits a strong diurnal oscillation primarily over land surfaces. This is illustrated in Fig. 7, which shows the average frequency of occurrence of criterion 1 jets during the nighttime hours (Figs. 7a and 7b) and during the daytime hours (Figs. 7c and 7d), for a five-summer period (JJA 1985–89) from the NCEP and the DAO, respectively. Over portions of the southern Great Plains and northeastern Mexico we find that LLJ events are roughly a factor of 7 (10) times more likely during the nighttime hours in the NCEP (DAO) reanalysis. During the nighttime hours, LLJ frequency maxima are aligned in each case along an axis that runs from the Texas–Mexico border north-northeastward toward the upper Midwest. Nighttime frequencies are considerably higher in the DAO, as was found in Higgins et al. (1996b) for May 1985–89. In general, the pattern of LLJ frequency over the eastern half of the United States is similar to that found in the observations (Bonner 1968; see Fig. 2 in that study).

An additional double maximum of LLJ frequency appears in both reanalyses near the Pacific coasts of California (35°–40°N) and Baja California (25°–30°N). The first jet maximum off the coast of California appears clearly during the day as well as the night, while the second maximum off the coast of Baja California is less clear during the day. This ''Baja jet'' was captured in

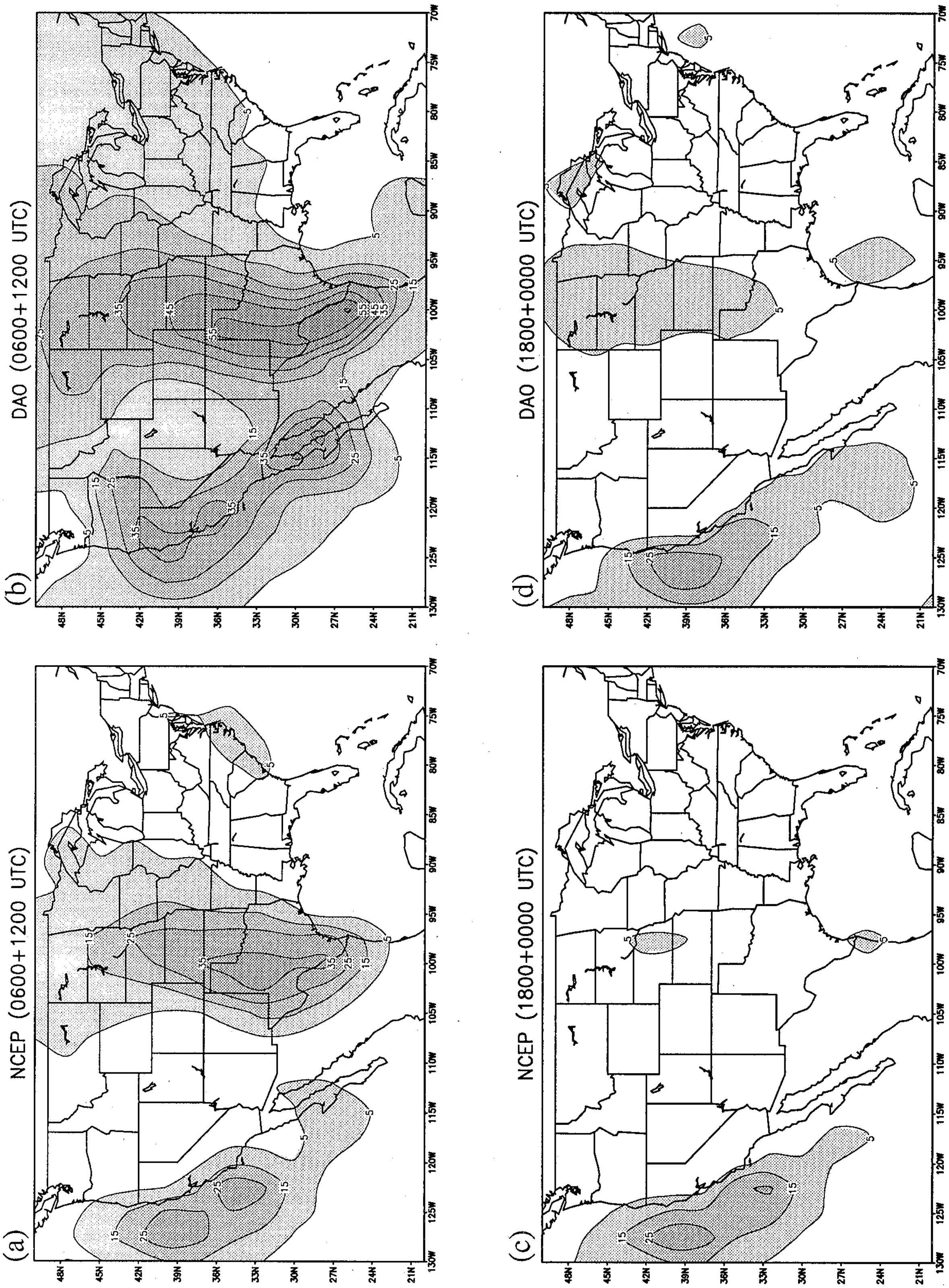

FIG. 7. Percent frequency of criterion 1 jets (Bonner 1968) for JJA 1985–89 during the nighttime (0600 UTC and 1200 UTC combined) in (a) the NCEP reanalysis and (b) the DAO reanalysis and during the daytime (1800 UTC and 0000 UTC combined) in (c) the NCEP reanalysis and (d) the DAO reanalysis.

the springtime simulation of the GEOS-1 GCM discussed in Helfand and Schubert (1995) and has been discussed extensively in a recent modeling study by Burk and Thompson (1996).

Examination of LLJ frequency at the four individual synoptic times (not shown) shows dramatic increases over the southern Great Plains of the United States and northeastern Mexico from a few percent at 0000 UTC in both reanalyses to more than 55% (65%) along the Texas–Mexico border (over northeastern Mexico) at 0600 UTC in the NCEP (DAO) reanalysis. LLJ frequency decreases slightly over most land areas by 1200 UTC and then dramatically by 1800 UTC. In general, the diurnal cycle over the Gulf of Mexico and the Pacific Ocean is much weaker than it is over land surfaces.

c. *Diurnal cycle of the flow over the United States*

The diurnal cycle of the NCEP wind vectors at the $\sigma = 0.98$ level (about 250 m above the surface) in the boundary layer (Fig. 8) is strikingly regular and coherent on the subcontinental scale. Over the Great Plains between 1800 UTC and 0600 UTC there is a considerable southerly acceleration of the low-level winds parallel to the eastern slopes of the Rocky mountains. In northeastern Mexico the low-level acceleration has more of a southeasterly, upslope component. The Baja jet is a feature of an east Pacific anticyclonic gyre that has little variability over the open ocean. However, there is a marked diurnal cycle along the coasts and just inland of California and Baja California where the westerly flow associated with the afternoon seabreeze at 0000 UTC rotates anticyclonically to become northerly flow (northwesterly over Baja California) by early morning and then decelerates due to surface friction by 1800 UTC. We note that similar features are found in the DAO reanalysis.

In the free atmosphere (e.g., $\sigma = 0.85$) the diurnal variability is greatly reduced (not shown). Both the Atlantic and the east Pacific subtropical gyres are still present. The Atlantic gyre shows less northward penetration into the Great Plains or westerly penetration across Mexico than in the boundary layer. The flow across the Rocky Mountains is mainly westerly throughout the day. Overlaying the winds at the four synoptic times, we find clear evidence of anticyclonic rotation and nighttime strengthening of the wind vectors over the southern and western United States and northeastern Mexico in both reanalyses. Overall, the wind vector hodographs are consistent with the idea that the diurnal cycle is an inertial oscillation initiated by an Ekman imbalance due to the sudden decline over land surfaces of daytime turbulence (e.g., Blackadar 1957).

The simultaneous acceleration of the low-level winds around the western edge of the subtropical Atlantic anticyclone and the eastern edge of the subtropical Pacific anticyclone produce significant low-level convergence by 0000 UTC along the eastern slopes of the Rocky Mountains as well as over portions of the Great Basin (Fig. 9). These same accelerations result in divergence along the Pacific Coasts of the United States and Baja California as well as over the northwestern part of the Gulf of Mexico. Considerable weakening of this pattern takes place by 1200 UTC. We note that Fig. 9 shows divergence on the $\sigma = 0.98$ surface, which may be quite different than divergence on pressure surfaces, especially over steeply sloping terrain.

While the diurnal signal is strongest at low levels, there are some regions where it extends into the middle and upper troposphere. Cross sections straddling the Rockies at 30° N of the anomalous (deviations from the time mean) zonal wind (Fig. 10) and meridional wind (Fig. 11), at the four synoptic times, show a phase reversal of the diurnal signal between the lower and middle troposphere in agreement with earlier observational evidence (Hering and Borden 1962) and with results from a 2-month AGCM simulation (Helfand and Schubert 1995). The zonal wind signal at low levels is characterized by anomalous upslope convergence during the late afternoon and evening and anomalous downslope divergence during the rest of the day. The midtropospheric signal shows anomalies in the opposite sense and tends to be much broader in vertical extent. The meridional wind signal in the PBL is dominated by nighttime acceleration and daytime deceleration of the Great Plains LLJ to the east of the Rockies and of the Baja jet to the west. There is a reasonably strong middle-level return flow over the Great Plains LLJ at 0600 UTC, which is in the opposite sense by 1800 UTC. There is an equally impressive return flow over the Baja jet at 0000 UTC, which is in the opposite sense by 1200 UTC.

5. Impact on nighttime precipitation

In this section we examine composites of nighttime precipitation in the observations during late spring and summer Great Plains LLJ events. The focus is on the distribution of precipitation anomalies and on the precipitation amounts that can be expected during the nighttime hours (0600 UTC and 1200 UTC, combined). From Fig. 7 we know that the frequency of occurrence of LLJ events is different in both reanalyses, so composites derived using the Bonner criterion will be constructed from a different set of days. In order to minimize this discrepancy, we apply the Bonner (1968) criterion over a region (25°–30°N, 100°–95°W) rather than at a single grid point and require that at least half of the grid points satisfy the criterion. Note from Fig. 7 that the region chosen encompasses the maximum frequency of occurrence in both reanalyses. Composites of observed precipitation shown here are obtained using the DAO winds (though there is no significant impact on the qualitative nature of the results when the NCEP winds are used).

Recall from section 3 that the nighttime precipitation maximum over the central United States slowly shifts northward during the spring and summer months from

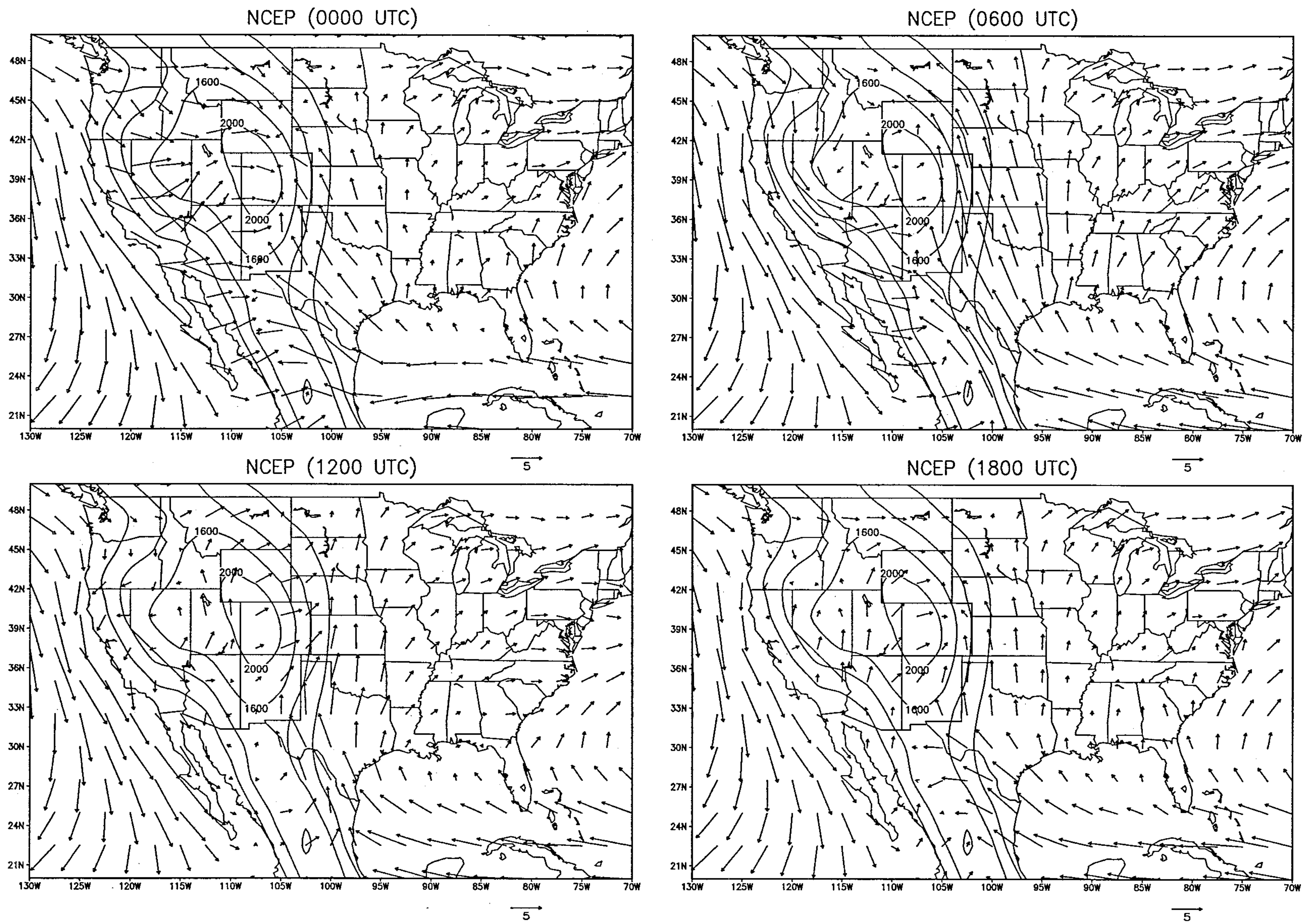

FIG. 8. Wind vectors at the second sigma level (=.98) for JJA 1985–89 at the four synoptic times in the NCEP reanalysis. The standard vector length is 5 m s^{-1}. The contours denote the surface height. The contour interval is 400 m.

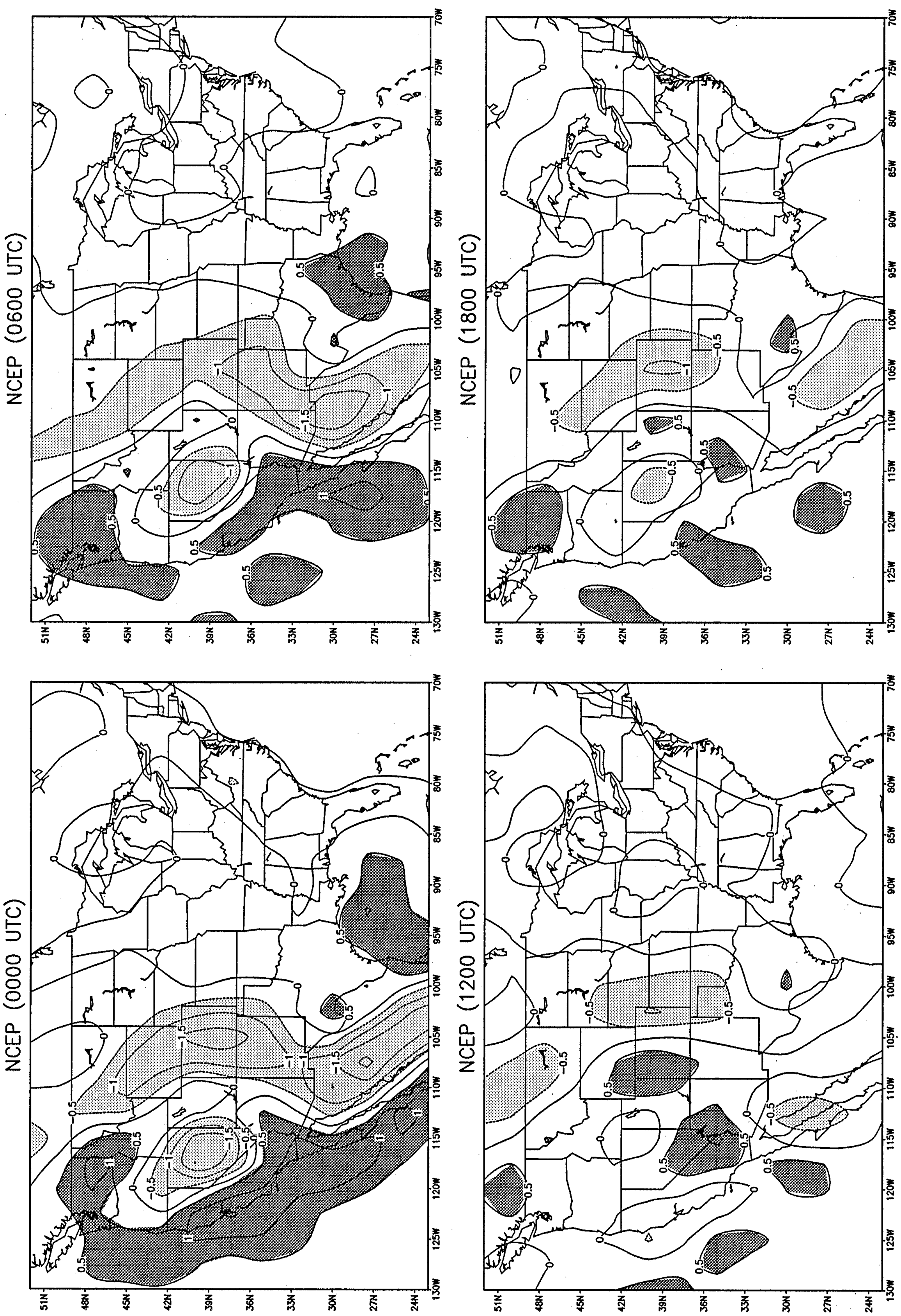

FIG. 9. Divergence (computed on the sigma surface) at the second sigma level (=.98) for JJA 1985–89 at the four synoptic times in the NCEP reanalysis. Units are 10^{-5} s^{-1}. Dark (light) shading denotes values greater than 0.5×10^{-5} s^{-1} (less than -0.5×10^{-5} s^{-1}).

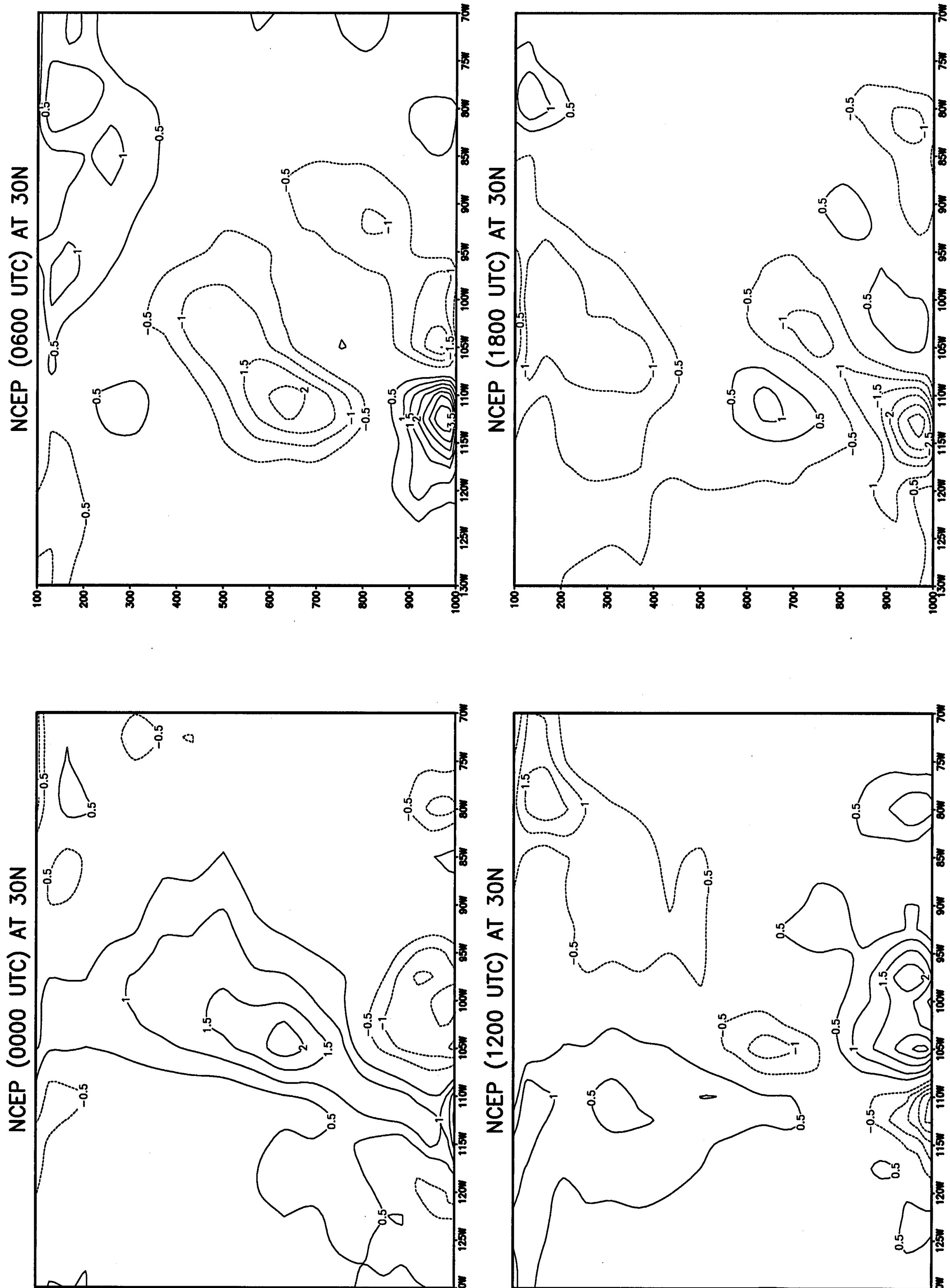

FIG. 10. Zonal (longitude-pressure) cross section of the zonal wind anomalies (deviations from the time mean) at 30°N for JJA 1985–89 at the four synoptic times. Units are m s^{-1}.

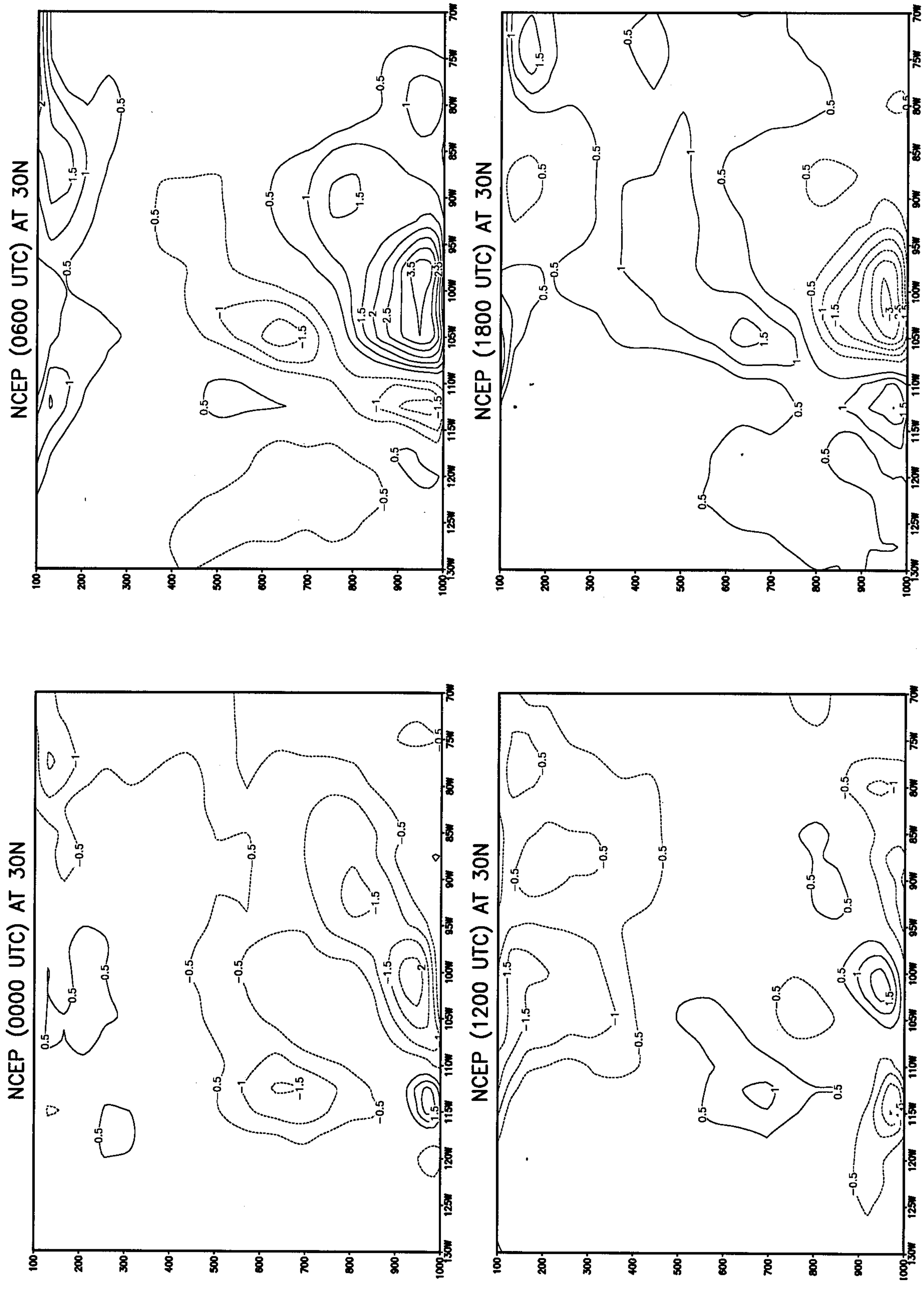

FIG. 11. Same as Fig. 10 except for the meridional wind anomalies.

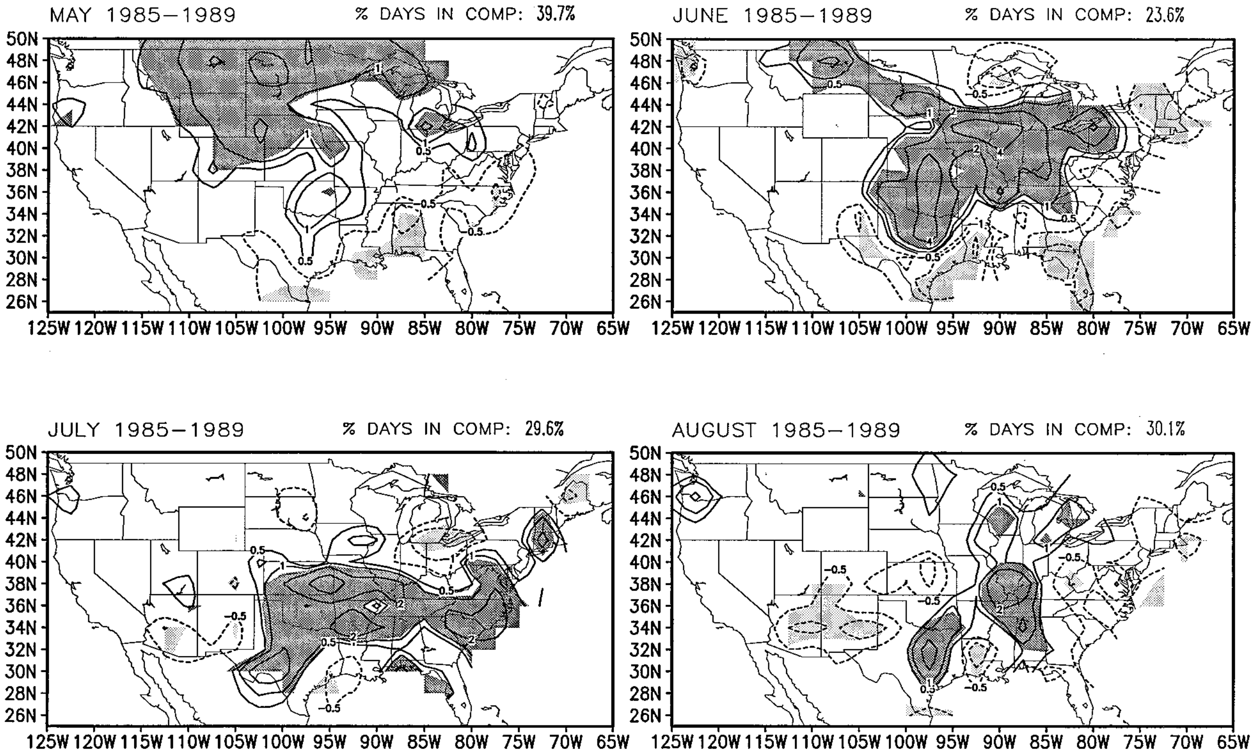

FIG. 12. Observed nocturnal precipitation anomalies (units: mm day^{-1}) expressed as the departure of the nocturnal mean, (0600 UTC + 1200 UTC)/2, for criterion 1 jet events from the nocturnal time mean during May 1985–89, June 1985–89, July 1985–89, and August 1985–89. The percentage of the total possible number of days in each composite is indicated in the upper right corner. The contour intervals are −4, −2, −1, −0.5, 0.5, 1, 2, 4, . . . and dark (light) shading indicates regions where the anomalies are greater than 50% above (below) the nocturnal mean. The units of mm day^{-1} imply the average instantaneous rate of rainfall during only the nighttime hours, not the nocturnal contribution to the daily averaged totals.

the Gulf Coast toward the upper Midwest. To get a sense of the possible impact of the Great Plains LLJ on the strength and location of this maximum, we examine the observed *nighttime* precipitation anomalies, expressed as the departure of the nocturnal mean for criterion 1 jet events from the nocturnal time mean (Fig. 12). Anomalies that are greater than 50% above (below) the nocturnal mean are indicated by dark (light) shading. During May (Fig. 12a) the nocturnal precipitation anomaly pattern shows enhanced precipitation over much of the northern Plains, in a narrow north–south band over the central and southern Plains, and over portions of the Great Lakes region. Precipitation is suppressed along the Gulf Coast and East Coast from Texas to the mid-Atlantic. The distribution of positive precipitation anomalies appears to correlate with the characteristic frontal positions of synoptic-scale systems located over the north central United States (also see the nocturnal moisture flux anomalies in Fig. 20). Numerous authors (e.g., Means 1954; Izumi and Barad 1963; etc.) have used case studies to establish the relationship of upstream low-pressure systems and their characteristic frontal and precipitation patterns with the presence of low-level jets over the Plains. For the nocturnal precipitation anomaly composite in Fig. 12a, we speculate that much of the enhanced precipitation over the northern Plains is light precipitation of relatively long duration while much of that in the north–south band over the central and southern Plains is heavy convective rainfall ahead of cold fronts. The signature of enhanced overrunning precipitation is located to the north and east of warm fronts in the Great Lakes region. The location of LLJ events in the warm sector ahead of upstream low pressure systems is consistent with this interpretation. We note that for nonjet cases (not shown) the nocturnal anomalies are generally much weaker and of opposite sign during May, possibly reflecting the passage of cold fronts to the southeast of the Great Plains.

During June the positive nocturnal anomalies diminish over the northern Plains but increase farther south over the central and southern Plains and over much of the Midwest; these changes in the anomaly pattern from May to June appear to reflect a dramatic decrease in synoptic-scale eddy activity. Comparison to Fig. 20 suggests that this shift in the nocturnal precipitation anomaly pattern toward the south and east is directly related to changes in the anomalous moisture transport, hence the moisture flux convergence associated with the LLJ. Nonjet days in June show suppressed precipitation over the southern Plains and portions of the Midwest but little

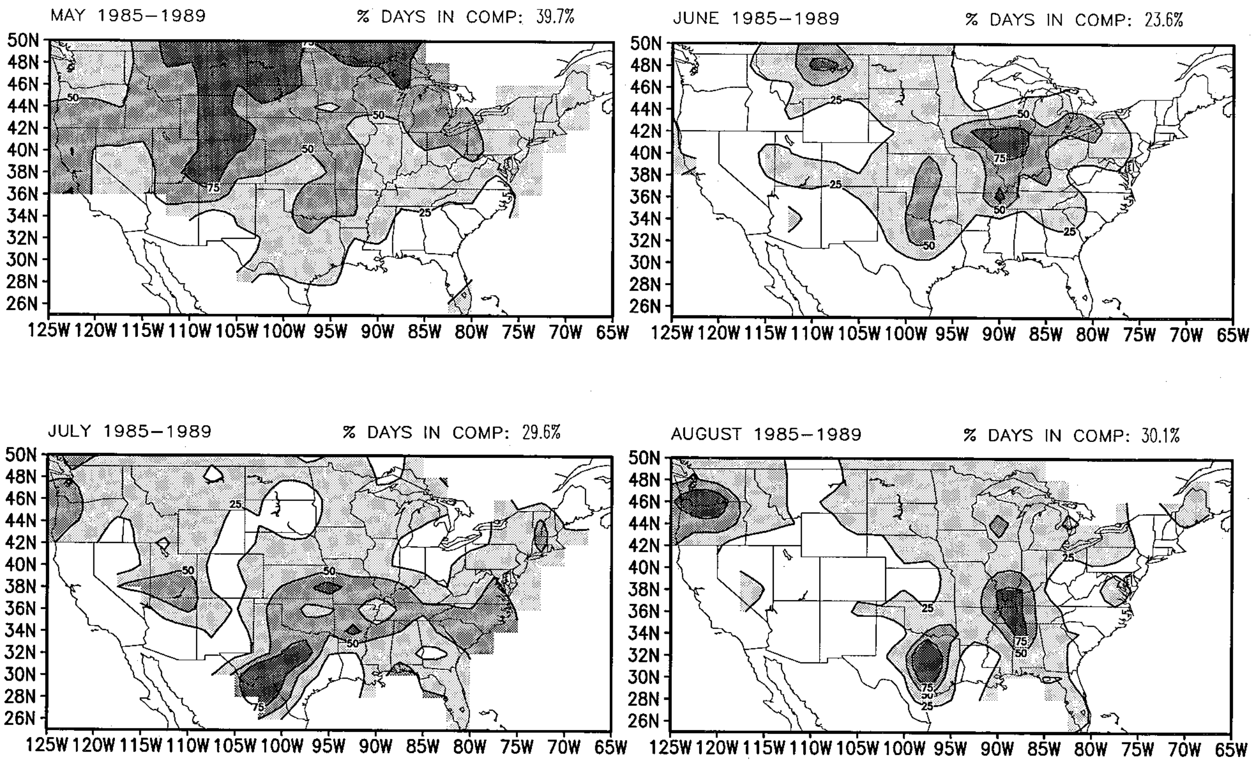

FIG. 13. Observed percentage of total nighttime precipitation for criterion 1 jets during May 1985–89, June 1985–89, July 1985–89, and August 1985–89. The percentage of the total possible number of days in each composite is indicated in the upper right corner. The contour interval is 25% and values exceeding 25% are shaded.

signal elsewhere. In July the region of positive anomalies during LLJ events settles still farther south and takes on a more zonal (east–west) orientation extending from the central Plains to the Carolinas. Again this seems to be consistent with changes in the moisture transport (Fig. 20). In August the positive anomalies during LLJ events decrease over the Plains and Carolinas but increase to some extent over the upper Midwest.

During the late spring and summer months some regions of the United States experience the bulk of nighttime precipitation when the LLJ is active (Fig. 13). During May, the northern tier and intermountain west receive in excess of 75% of total nighttime precipitation when the LLJ is active, despite the fact that jet events occur only 40% of the time. Similar extremes are found over the Midwest and southern Plains during June, over the southern Plains, Tennessee Valley, and Carolinas during July and in isolated regions of the South during August.

An examination of the nocturnal precipitation anomaly patterns for increasing LLJ strength (Fig. 14; results for May–August 1985–89 are combined) shows a similar pattern in each case but with increasing amplitude. Portions of the Midwest and central Plains receive more than 30% of their total nighttime rainfall during the strongest (criteria 2 and 2.5) LLJ events, despite the relative infrequency of these events (Fig. 15). [Note: The criteria 1, 1.5, 2, and 2.5 *labels* used here are consistent with the original labeling in Bonner (1968). Criteria 1, 1.5, 2, and 2.5 specify that the wind speed profile must have a maximum of at least 12, 14, 16, or 18 m s^{-1}, respectively, within 1.5 km of the ground and that the wind speed must decrease by at least 6, 7, 8, or 9 m s^{-1}, respectively, at the lowest minimum located above the maximum at or below the 3-km level. Criteria 1 and 2 jets were considered explicitly in Bonner (1968).]

6. The role of the LLJ in the moisture budget

The Great Plains LLJ is an important source of moisture for the United States east of the Rocky Mountains. In this section we examine the impact of the LLJ on the summertime fluxes of moisture onto the continental United States. To compare and contrast the summer months against the rest of the year, we also examine the seasonal cycle. A formal quantitative intercomparison between the NCEP and the DAO of the overall (JJA 1985–89) moisture budget, for a rectangular region of the central United States (30°–50°N, 105°–85°W), is given in the appendix.

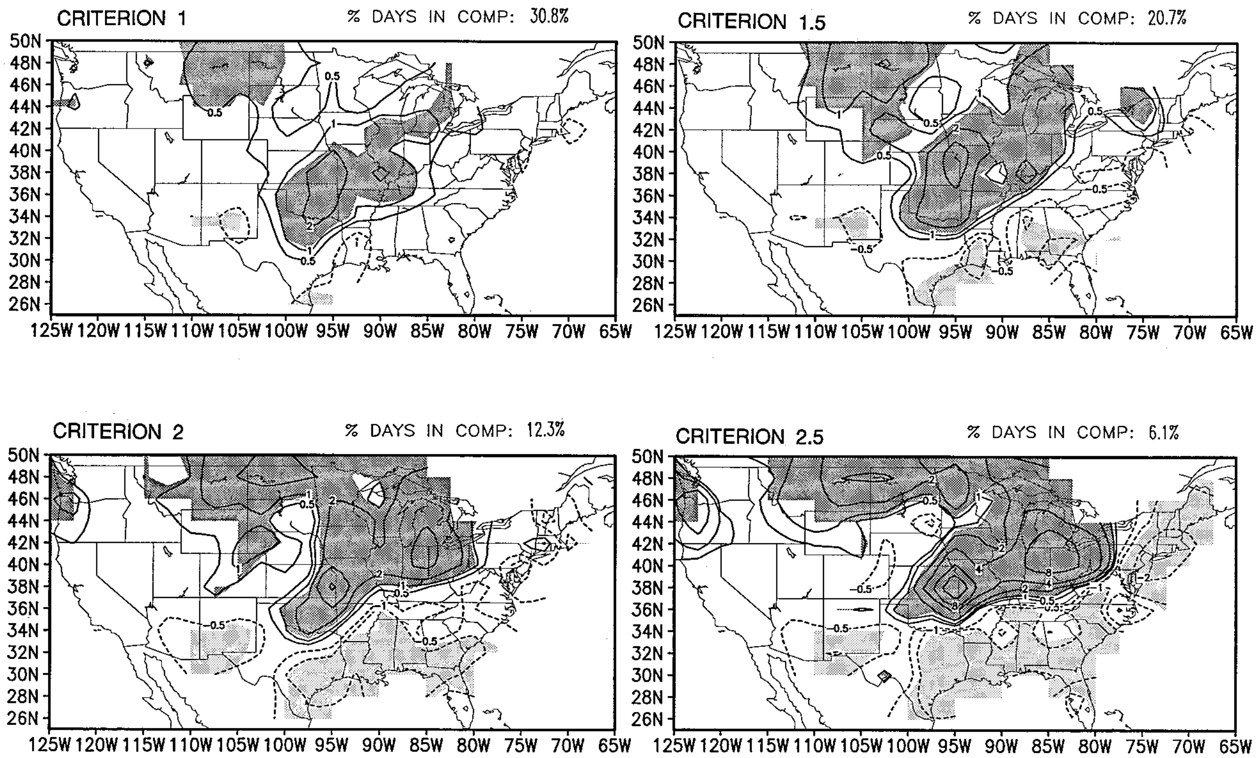

FIG. 14. Observed nocturnal precipitation anomalies (units: mm day^{-1}) during May–August 1985–89 expressed as the departure of the nocturnal mean, (0600 UTC + 1200 UTC)/2, for criteria 1, 1.5, 2, and 2.5 jet events from the nocturnal time mean. The percentage of the total possible number of days in each composite is indicated in the upper right corner. The contour intervals are −4, −2, −1, −0.5, 0.5, 1, 2, 4, 8 . . . and dark (light) shading indicates regions where the anomalies are greater than 50% above (below) the nocturnal mean. [Note: The criteria 1, 1.5, 2, and 2.5 *labels* used here are consistent with the original labeling in Bonner (1968); see the text for details.] The units of mm day^{-1} imply the average instantaneous rate of rainfall during only the nighttime hours, not the nocturnal contribution to the daily averaged totals.

a. Annual cycle

An examination of the mean (1985–89) annual cycle of the vertically integrated moisture budget terms averaged over the central United States (Fig. 16) indicates that the moisture flux convergence from radiosonde data (based on 0000 UTC and 1200 UTC combined) compares well to the reanalyses independent of whether reanalysis data at 0000 UTC and 1200 UTC (shown here) or at all four synoptic times is used. We note that most of the amplitude in the moisture flux convergence curves is due to the 0000 UTC data, especially in the summer months.

The overestimate of the summer precipitation in the reanalyses (when compared to rain gauge data for 0000 UTC and 1200 UTC combined) is clearly evident. Wintertime precipitation is well captured in the reanalyses in this region. Estimates of evaporation derived from observed precipitation and convergence are small during winter, implying a balance between precipitation and moisture flux convergence in the atmosphere. In the observations, evaporation exceeds precipitation slightly during the summer months. Evaporation in the reanalyses appears to be somewhat large throughout the year.

The analysis increments (see the appendix for a brief description) in both reanalyses also have a substantial contribution. The mean contribution of the analysis increments is comparable in magnitude to the convergence term and tends to act in the opposite sense. However, the apparent connection between the increments and convergence suggested by Figs. 16a and 16b may be misleading since a recent diagnostic study of the analysis increments by Schubert and Chang (1996) suggests that the bias is primarily associated with errors in the precipitation and evaporation fields.

b. Daily mean

In this section we examine the fluxes of moisture onto the continental United States in both reanalyses and in observations for the period JJA 1985–89, and present maps of the components of the moisture budget. A quantitative intercomparison of the daily mean (JJA 1985–89) moisture budget in the reanalyses for a rectangular region of the central United States is presented in the appendix. The fluxes are presented as vertical integrals over three different layers to highlight the differences in the transports in the low, middle, and upper levels of the atmosphere.

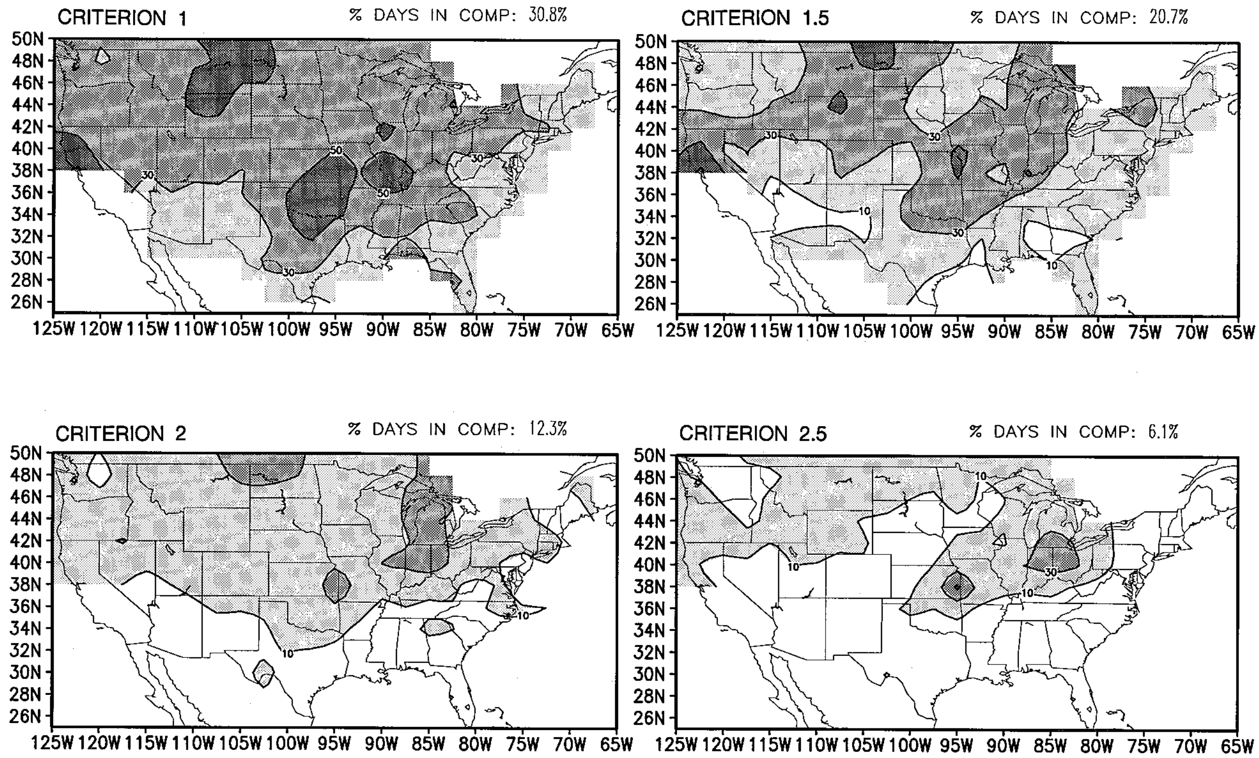

FIG. 15. Observed percentage of total nighttime precipitation during May–August 1985–89 for criteria 1, 1.5, 2, and 2.5 jets. The percentage of the total number of days in each composite is indicated in the upper right corner. The contour interval is 20% and values exceeding 10% are shaded.

The four panels in Fig. 17 show moisture flux in the NCEP vertically integrated over three layers (Figs. 17a–c) and for the full vertical extent of the atmosphere (Fig. 17d). The strongest flux onto the continent occurs at low levels below 850 hPa over the south central United States and northeastern Mexico. Strong southward flux associated with the large-scale circulation of the east Pacific anticyclone occurs off the west coast of the United States and Mexico. Along the West Coast, the low-level flow associated with the Baja jet is primarily parallel to the continent with little influx of moisture. At middle levels, the influx of moisture into the Pacific Northwest and up the Gulf of California is the major source for the western United States and Mexico. Also, there is still considerable influx of moisture from the Gulf of Mexico at middle levels. The strongest outflow is along the East Coast in the lower and middle troposphere.

The patterns of moisture flux in the DAO reanalysis are quite similar to those shown in Fig. 17 but magnitudes differ. Difference maps of the time-mean (JJA 1985–89) vertically integrated moisture flux between each reanalysis product and gridded radiosonde data (see section 2 for a brief description of the data) and between the reanalysis products (Fig. 18) highlight some of the regional differences; the fluxes over water are masked because the number of "good" radiosonde observations is small there. Along the Gulf Coast, the fluxes are underestimated in the DAO reanalysis (Fig. 18a) due to small underestimates of both the precipitable water and the low-level winds (not shown) in this region. On the other hand, the NCEP reanalysis has somewhat stronger low-level winds in this region, which accounts for the better comparison to observations (Fig. 18b) and which suggests that higher vertical resolution in the lower troposphere and/or the use of significant level data (including 925 hPa) in the NCEP system (and not in the DAO system) has a positive impact on the fluxes. The largest differences between the reanalyses (Fig. 18c) are also located over the Great Plains where the southerly transports are locally more than 50% larger in the NCEP reanalysis.

Vertical profiles of the meridional flux at grid points near the center of the Wind Profiler Demonstration Network (not shown; however, see Fig. 6, which shows meridional wind component for NCEP) generally show maxima near (or just above) 950 hPa in reasonable agreement with observations. The maximum value of the observed vertically integrated northward flux onto the continent [about 1400 gm (cm s)$^{-1}$ at 28.0°N, 97.5°W for JJA 1985–89] is generally consistent with the maximum values in the reanalyses [about 1400 gm (cm s)$^{-1}$ at 27.5°N, 97.5°W in the NCEP and 1000 gm (cm s)$^{-1}$ at 28.0°N, 97.5°W in the DAO]. These values

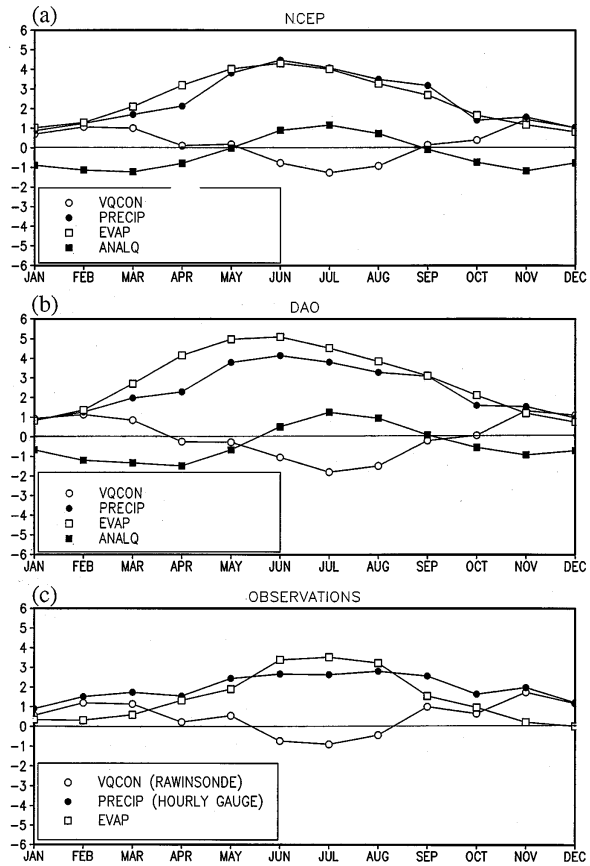

FIG. 16. Mean annual cycle of the vertically integrated moisture budget terms (units: mm day^{-1}) over the central United States (30°–50°N, 105°–85°W) in (a) the NCEP reanalysis, (b) the DAO reanalysis, and (c) the observations.

are considerably smaller than the maximum observed values of vertically integrated moisture inflow presented by Rasmusson (1967) [about 2400 gm (cm s)$^{-1}$ at 28°N, 98°W for July 1962]. The difference may be due in part to interannual variability; Benton and Estoque (1954), for example, show values in this region closer to 1000 gm (cm s)$^{-1}$ for the summer of 1949, and Peixoto and Oort (1983) show long-term averages (1963–73) of about 800 gm (cm s)$^{-1}$ for June through August.

An intercomparison between assimilated datasets of the moisture flux and the area-mean time-mean moisture budget (JJA 1985–89) for the central United States is discussed in the appendix (see Fig. A1); in general, we find that the moisture transports across the various boundaries are in the same direction in both reanalyses but that the NCEP transports are considerably stronger. Spatial maps of the components of the time-mean vertically integrated budget over the continental United States [not shown, but see Figs. 13 and 14 of Higgins et al. (1996b)] show that evaporation exceeds precipitation in the west and that precipitation exceeds evaporation in the southeast in both reanalyses. The analysis increments show the GCM bias and represent a substantial source (sink) of water vapor in the southeast (northwest) in both reanalyses. Our previous comparisons and these results suggest that the increments are consistent with precipitation (evaporation) bias of the AGCM over the southeastern (northwestern) United States. Molod et al. (1996) emphasized that caution must be used in interpreting the analysis increments in the Tropics during the summer months when spurious feedbacks may occur with the convection; similar types of feedbacks may occur in the extratropics as well, though no evidence of this was presented in their paper.

c. Diurnal cycle

During summer, the extent and magnitude of the diurnal cycle of low-level moisture flux over the Great Plains is considerable (Rasmusson 1967; Bonner and Paegle 1970). While the cycle cannot be resolved from twice-daily radiosonde data, it is well resolved with the reanalysis fluxes (Fig. 19), which are available four times daily. The northward moisture flux from the Gulf of Mexico into the Great Plains is clearly evident in each product. The diurnal cycle is most significant east of the Rockies with maximum fluxes at night (0600 UTC) due to the nighttime strengthening of the wind associated with the Great Plains LLJ. Examination of the transports in the lower, middle, and upper troposphere shows that the diurnal cycle is concentrated below 850 hPa over the Great Plains and that there is a significant diurnal cycle at midlevels in the vicinity of Baja California (not shown). Examination of the diurnal cycle of specific humidity and meridional wind separately shows very small changes in the specific humidity but much larger changes in the meridional wind over the Great Plains in agreement with results of Rasmusson (1967) and Berbery et al. (1996).

d. Impact on nighttime transport

In this section we discuss the impact of the LLJ on the nighttime fluxes of moisture over the central United States during the late spring and summer months. We restrict the analysis to the nighttime hours (0600 UTC and 1200 UTC) when the LLJ shows its peak amplitude (Figs. 5 and 6) and peak frequencies (Fig. 7). Anomalies are defined as departures from the nighttime mean (0600 UTC + 1200 UTC)/2 for each month. Results for the NCEP and DAO are similar so only the NCEP is shown.

During the late spring and summer months there is a coherent evolution of the vertically integrated nocturnal moisture flux anomalies when the LLJ is active in the NCEP reanalysis (Fig. 20); from one month to the next these anomalies evolve in a manner consistent with the precipitation anomalies discussed in section 5. During May there is a horizontally confined region of strong excess northward transport to the east of the Rocky Mountains. Over much of the central United States these anomalies represent increases of more than a factor of

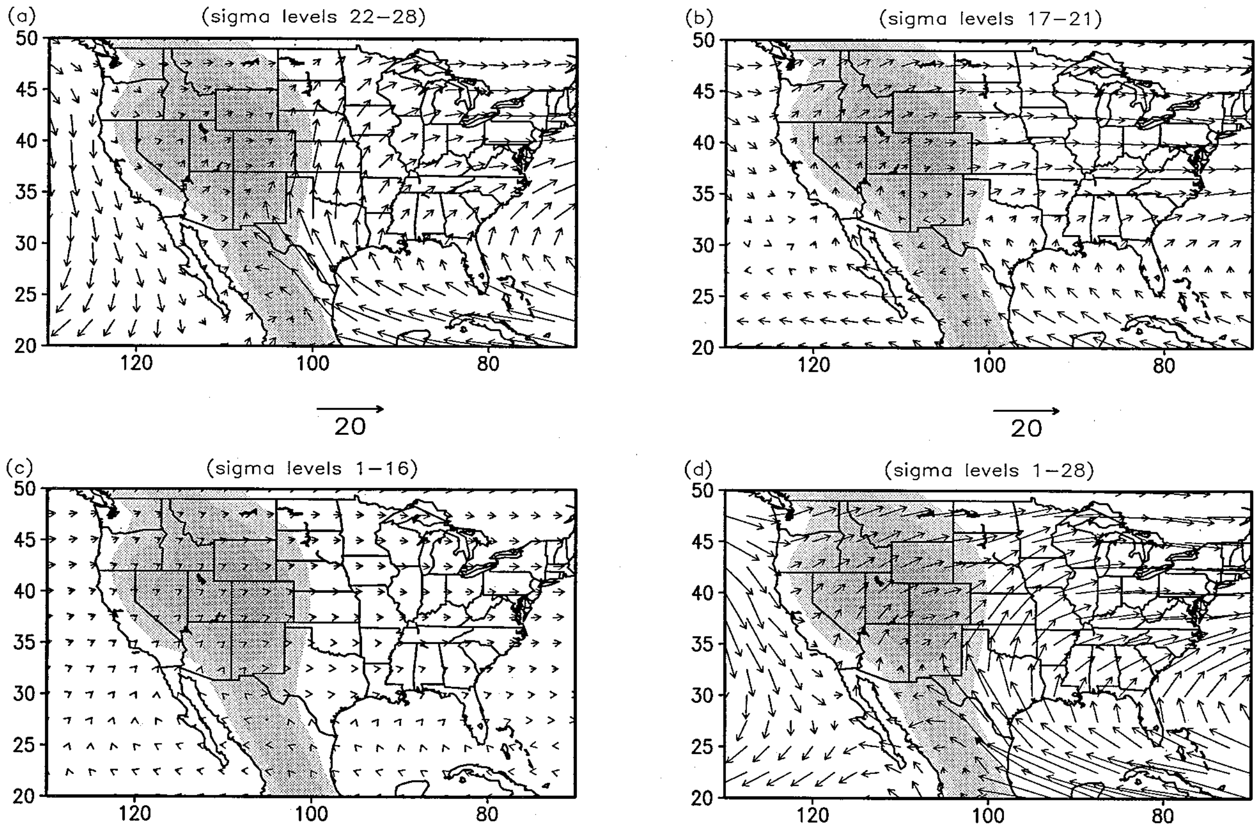

FIG. 17. Time-mean (JJA 1985–89) moisture flux (units: m s^{-1} g kg^{-1}) from the NCEP reanalysis for (a) the bottom 7 sigma levels (approx. 1000–850 hPa); (b) the second 5 sigma levels (approx. 850–550 hPa); (c) the top 16 sigma levels (approx. 550–3 hPa); and (d) the vertical integral (sigma levels 1–28). The shading denotes surface height at 400-m intervals (starting at 800 m). For comparison with Rasmusson (1967), the standard vector length in (d) is approximately 20 $\times$ 10^2 g (cm s)$^{-1}$.

2 in the northward transport (over nocturnal mean values) with the largest increases over the upper Midwest. While the anomalous inflow is shallow (mainly below 850 hPa) near the Gulf Coast, it is relatively deep (up to 550 hPa) over the upper Midwest (not shown). The anomalous northward transports are sandwiched between well-defined synoptic-scale cyclonic (anticyclonic) ''circulation centers'' in the anomalous transport to the northwest (southeast). The upstream cyclonic center appears to be consistent with the largest precipitation anomalies (Fig. 12).

In June the anomalous cyclonic circulation is centered further east with a marked increase in the zonal component of the transport over the Southeast consistent with the shift in the observed precipitation anomalies (see Fig. 12). The anomalous anticyclonic circulation is still quite evident though it has lost its well-defined center. The pattern in July is similar, though the anomalous cyclonic circulation is weaker and the anomalous zonal transports are located farther south and east. The anomalous anticyclonic circulation now appears to be centered to the east over the Atlantic Ocean. In August the anomalous cyclonic circulation reintensifies to the northeast consistent with anomalous precipitation over the upper midwest (see Fig. 12). Thus, from May to August, the anomalous cyclonic/anticyclonic centers of circulation have evolved from an east–west orientation to a north–south one.

Of the two fields that compose the moisture flux vector, it is mostly the velocity (and not the moisture) that changes during criterion 1 jets. That is, nighttime precipitable water anomalies for criterion 1 jets are small compared to nocturnal mean values (no larger than 10%–15% of the mean), indicating that the anomalous nocturnal transports shown in Fig. 20 are mainly due to the winds. Nocturnal evaporation anomalies for criterion 1 jets were also found to be negligible. These increases in the low-level moisture influx from the Gulf of Mexico as well as increases in low-level convergence and precipitation over the central United States are discussed quantitatively in the appendix.

7. Summary and discussion

The Great Plains LLJ has been found to play a fundamental role in the generation of summertime precipitation over the central United States. During the summer season (JJA) a region of maximum rainfall occurs

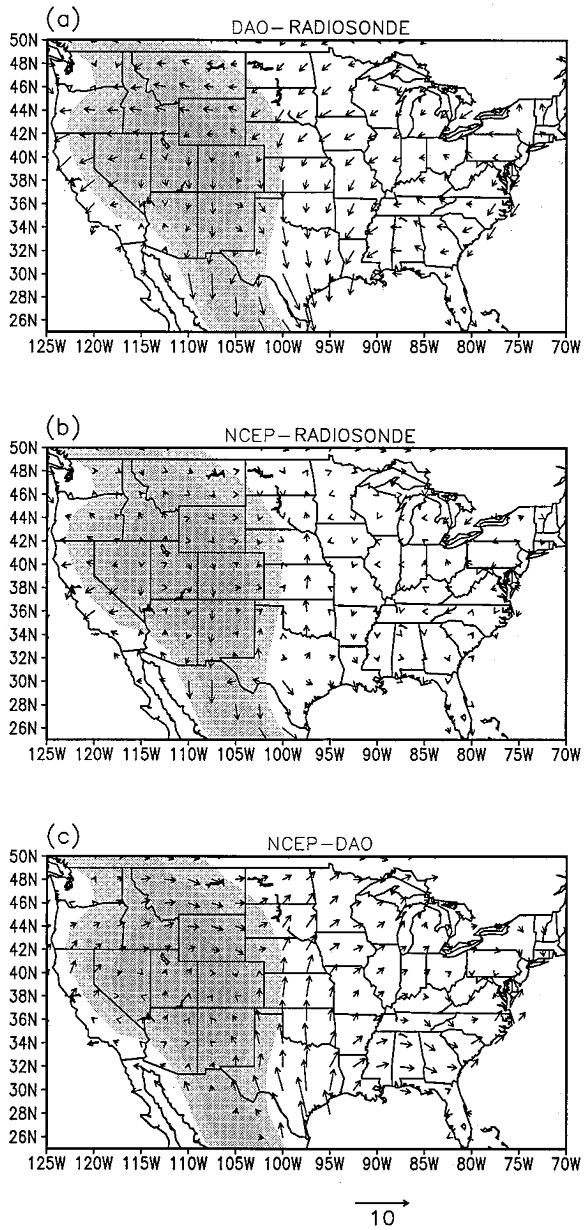

FIG. 18. Time-mean (JJA 1985–89) vertically integrated moisture flux (units: m s^{-1} g kg^{-1}) expressed as the difference between (a) the DAO reanalysis and radiosonde data, (b) the NCEP reanalysis and radiosonde data, and (c) the NCEP and DAO reanalyses. The shading denotes surface height at 400-m intervals.

over the Great Plains in response to the increasing role of nocturnal convective activity that is often linked to LLJ events. During summer in excess of 25% more precipitation falls during the nighttime hours than during the daytime hours over a large portion of the Great Plains with a commensurate decrease in precipitation along the Gulf Coast. The summer season is characterized by a near-midnight preference in the Plains, consistent with the late evening/early morning peak of the LLJ.

Both reanalyses produce a Great Plains LLJ with a vertical and temporal structure that compares favorably to wind observations. Nighttime LLJ frequency maxima are aligned from the Texas–Mexico border north-northeastward toward the upper Midwest, but there are significantly fewer LLJ events in the NCEP throughout the summer season. The diurnal cycle of the low-level flow is quite dramatic and well resolved in both reanalyses because winds are available four times daily. Higher vertical resolution in the NCEP reanalysis below 850 hPa and/or the use of significant level radiosonde data seem to improve the vertical profile of winds considerably when compared to observations. The diurnal variability is strikingly regular in the boundary layer and coherent on a subcontinental scale. In the free atmosphere the diurnal variability is greatly reduced. However, in the vicinity of the southern Plains and northern Mexico the zonal and meridional winds show a coherent phase reversal of the diurnal signal between the lower and middle troposphere in agreement with earlier observational studies.

The LLJ has a considerable impact on the distribution and the intensity of nighttime precipitation over the central United States. LLJ events during May are associated with enhanced nighttime precipitation over the northern Plains, the central and southern Plains, and portions of the Great Lakes region due in part to the interaction of the LLJ with synoptic-scale systems. During the summer months the enhanced precipitation gradually retreats to the south and east in a manner consistent with shifts of the anomalous moisture transport and with the gradual reduction of synoptic-scale activity. All months show suppressed precipitation along the Gulf Coast and East Coast during LLJ events. LLJ-related precipitation seems to be associated most closely with the strongest, least frequent LLJ events. In addition, the rainfall patterns do not appear to be very sensitive to the location of the box where the Bonner criterion is applied as long as it is reasonably close to the maximum in LLJ frequency of occurrence (see Fig. 7).

The strongest influx of moisture onto the continent occurs during the summer months and is from the Gulf of Mexico in the vicinity of the Great Plains LLJ. Unfortunately, this is also where the largest differences in moisture transport between the reanalyses are found. This discrepancy is likely due, in part, to differences in the vertical resolution in the PBL. Also, the DAO does not assimilate significant level radiosonde data (e.g., 925 hPa) while the NCEP does.

Individual terms in the moisture budget over the central United States show fairly good agreement during the summer between the reanalyses. The overestimate of the summer precipitation (when compared to station data) is clearly evident. Evaporation in the reanalyses is larger than estimates from the observations with the largest differences (over the annual cycle) during the late spring and summer. While net precipitation is similar in the daily mean budgets, net evaporation appears

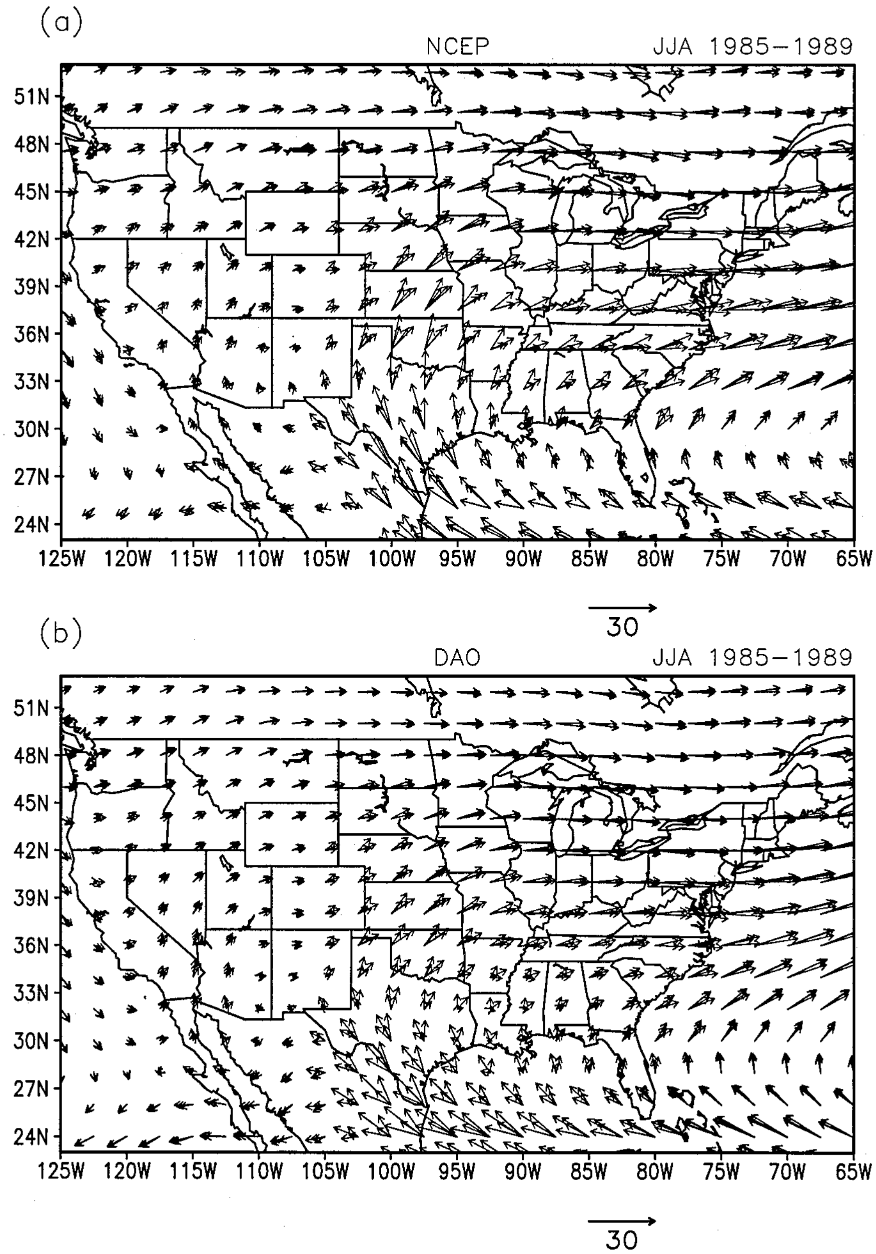

FIG. 19. Mean (JJA 1985–89) diurnal cycle of the vertically integrated water vapor flux (units: m s^{-1} g kg^{-1}) at the four synoptic times (0000 UTC, 0600 UTC, 1200 UTC, and 1800 UTC) in (a) the NCEP reanalysis and (b) the DAO reanalysis.

to be significantly overestimated in the DAO. Offline tests suggest that this is the result of albedos used in the DAO model that are too low. The analysis increments, which are a measure of the model bias, are comparable in magnitude to the convergence term and tend to act in the opposite sense. However, spatial maps show that the increments are a source (sink) of moisture in the southeastern (northwestern) United States, possibly reflecting bias in the precipitation (evaporation). The extent to which such imbalances are related to topography, resolution (space and time truncation errors), and model forecast errors is still an open question.

The diurnal cycle of the low-level moisture transport is well resolved with the largest and most extensive anomalies being those associated with the nocturnal inland flow of the Great Plains LLJ. Examination of the diurnal cycle of specific humidity and meridional wind separately over the Great Plains shows that the diurnal cycle is largely due to winds. The impact of the LLJ on the nighttime moisture transport over the central

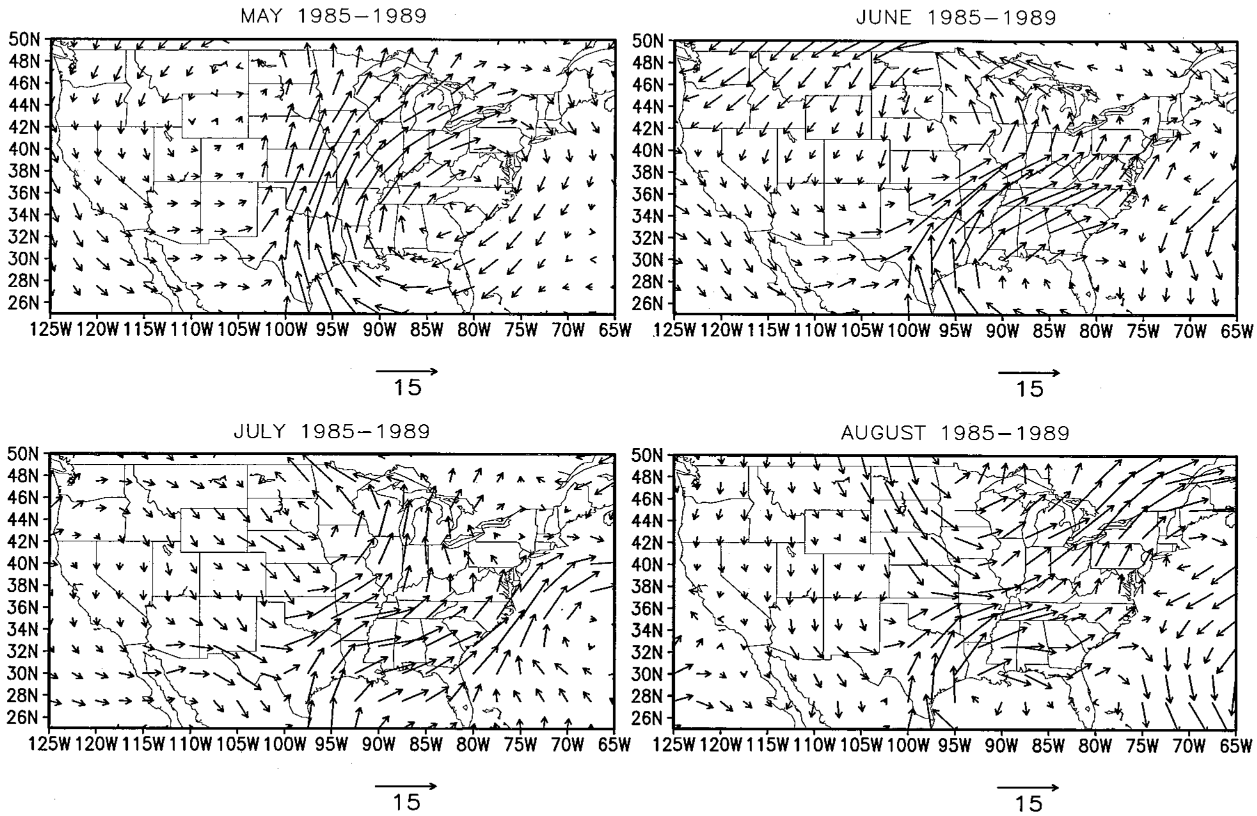

FIG. 20. Vertically integrated nocturnal moisture flux anomalies (units: m s^{-1} g kg^{-1}) expressed as the departure of the nocturnal mean for criterion 1 jet events from the nocturnal time mean in the NCEP reanalysis during May 1985–89, June 1985–89, July 1985–89, and August 1985–89.

United States is dramatic. In particular, there is a coherent evolution of well-defined synoptic-scale cyclonic (anticyclonic) ‘‘circulation centers’’ in the anomalous moisture transport over the central United States from an east–west orientation during May to a north–south orientation during August.

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APPENDIX

Moisture Budget Calculations

We state here the moisture budget equation used in this study. This is followed by an intercomparison between assimilated datasets of the area-averaged moisture budget over the central United States, which is intended to complement and supplement the more qualitative intercomparisons of fields presented in sections 5 and 6.

Trenberth and Guillemot (1995) give a derivation of the vertically integrated budget equation for the total precipitable water in a column [see their Eq. (6)]; this equation may be written as

$$\frac{\partial w}{\partial t} = -\nabla \cdot \mathbf{Q}_v + E - P, \tag{A1}$$

where

$$\mathbf{Q}_v = \int_1^0 q\mathbf{v}\frac{P_{\mathrm{sfc}}}{g}\, d\sigma \tag{A2}$$

and where q is the specific humidity, $\mathbf{v}$ is the horizontal velocity ($= u\mathbf{i}+v\mathbf{j}$), P_{sfc} is the surface pressure, E is the evaporation from the surface, P is the precipitation, and

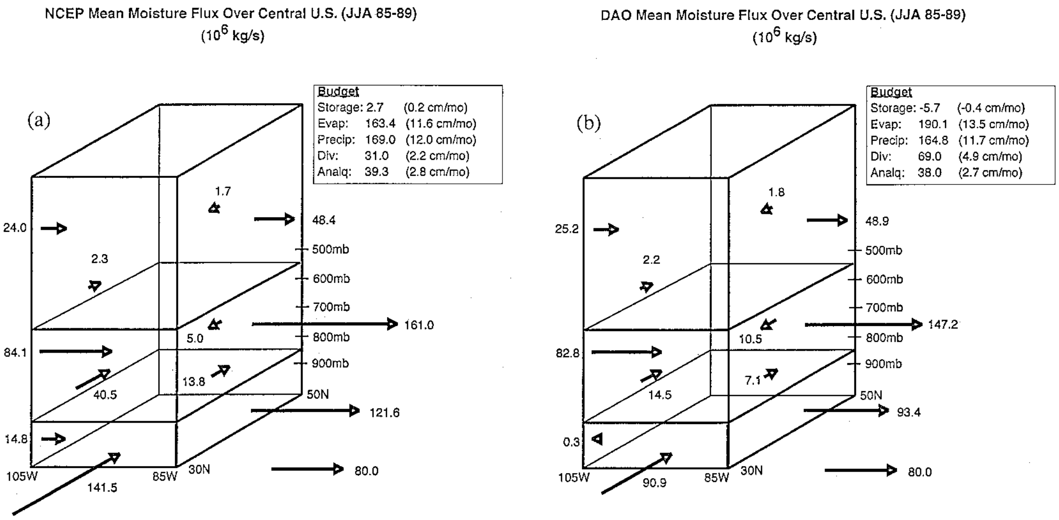

FIG. A1. Time-mean (JJA 1985–89) moisture flux and budget (units: 10^6 kg s^{-1}) over the central U.S. (105°–85°W, 30°–50°N) in (a) the NCEP reanalysis and (b) the DAO reanalysis. The size of this region is 3.77×10^6 km^2.

w is the precipitable water, defined as the vertical mass-weighted integral of the specific humidity. To obtain this equation, the role of liquid water in the atmosphere has been ignored. Over an annual cycle, the change in storage of moisture in the atmosphere is small. Over land, because there is a net runoff in streams, the precipitation must exceed the evaporation, so that $E - P$ should be negative for long term (annual or greater) averages. The first term in (A1) is small for time averages of sufficient length (i.e., seasons) so it is the divergence of the vertically integrated atmospheric moisture flux that determines the net freshwater exchange with the surface.

Equation (A1) describes the atmosphere and is valid regardless of the data source. However, in data assimilation (GCM plus observational analysis scheme) there are inconsistencies between the model and the observations, which arise because we do not have "perfect" observations. The first guess (typically a 6-h forecast started from the previous analysis) is combined with the observations to produce an analysis (e.g., Parrish and Derber 1992). In the case of the moisture budget, this results at each grid point in an analysis increment δw (analysis minus first guess), which quantifies the impact of moisture observations on the model forecasts, hence the assimilated data. This term is added to the right-hand side of (A1) and is included in both the DAO and the NCEP moisture budget computations.

An intercomparison of the moisture flux and the overall moisture budget (JJA 1985–89) for a rectangular region (30°–50°N, 105°–85°W) of the central United States in the DAO and the NCEP reanalyses is shown in Fig. A1. Both reanalyses have a large low-level influx of moisture at the southern boundary but the NCEP inflow is more than 35% larger below 850 hPa. The net inflow from the southern boundary (184×10^6 kg s^{-1} in the NCEP and 108×10^6 kg s^{-1} in the DAO) reflects this low-level difference as well as differences in mid-levels. Another important difference is at the western boundary where the zonal transport below 850 hPa (14.8×10^6 kg s^{-1} in the NCEP and -0.3×10^6 kg s^{-1} in the DAO) are in a different sense; at this boundary transports above 850 hPa agree quite well. Much of the moisture exits through the eastern boundary (331×10^6 kg s^{-1} in the NCEP and 290×10^6 kg s^{-1} in the DAO), where again the NCEP outflow is larger below 550 hPa. There is also appreciable outflow across the northern boundary at low levels but inflow in the middle and upper troposphere. In agreement with the May 1985–89 budget intercomparison of the NCEP and the DAO in Higgins et al. (1996b), we find that the transports across the various boundaries are generally in the same sense in both reanalyses but the NCEP transports are stronger.

The vertically integrated net divergence over the central United States (31×10^6 kg s^{-1} in the NCEP and 69×10^6 kg s^{-1} in the DAO) is in the same sense in both reanalyses but more than a factor of 2 stronger in the DAO. Most of this difference arises below 850 hPa. In the NCEP, the vertically integrated net divergence is composed of net convergence below 850 hPa (20.9×10^6 kg s^{-1}) and net divergence above 850 hPa (51.9×10^6 kg s^{-1}); in the DAO there is net divergence both below 850 hPa (9.9×10^6 kg s^{-1}) and above 850 hPa (59.1×10^6 kg s^{-1}). In the reanalyses, the net column integrated divergence over the central United States compares reasonably well to the observations (see Fig. 3 of Rasmusson 1968) though a bit small in the NCEP. This uncertainty can also be measured by the analysis increments; in both reanalyses the increments act as a net moisture sink but their amplitude is of the same order as the net divergence itself, indicating rather large uncertainties in the assimilated data.

Both the precipitation and the evaporation in the reanalyses are large compared to observations. For this region, the precipitation is 12.0 cm month^{-1} in the NCEP, 11.7 cm month^{-1} in the DAO, and 8.2 cm month^{-1} in the observations. Note that while the net precipitation is quite similar in both budgets, the evaporation is larger in the DAO. This result is consistent with results of Schubert and Chang (1996), who found that the springtime evaporation in the DAO reanalysis is too large over the United States. Rasmusson (1968) reported JJA 1963 precipitation of 8.3 cm mo^{-1} and evaporation of 8.2 cm mo^{-1} (for the central plains and eastern U.S.). Based on his results, the evaporation in both reanalyses appears to be too high.

During LLJ events (0600 UTC and 1200 UTC), both reanalyses show large increases *over nocturnal mean values* in the low-level moisture influx from the Gulf of Mexico as well as considerable increases in low-level convergence and precipitation over the central United States. The low-level moist influx from the Gulf of Mexico increases by 48% (48%) over nocturnal mean values in the NCEP (DAO) to 271 $\times$ 10^6 kg s^{-1} (207 $\times$ 10^6 kg s^{-1}), though the excess inflow is more than 23% stronger in the NCEP reanalysis. The net outflow at the eastern boundary increases by 32% (28%) over nocturnal mean values in the NCEP (DAO) to 460 $\times$ 10^6 kg s^{-1} (385 $\times$ 10^6 kg s^{-1}); most of this increase is below 550 hPa. While evaporation increases only slightly during LLJ events, there are significant increases in precipitation (27% in the NCEP and 31% in the DAO) over nocturnal mean values consistent with the results for the observations in section 5; area mean values during LLJ events are 4.5 cm mo^{-1} and 2.5 cm mo^{-1} in the NCEP (DAO). While the vertical profile of divergence does not change sign during LLJ events (compared to the nocturnal mean), magnitudes vary considerably. Low-level convergence during LLJ events increases by slightly more than a factor of 2 over nocturnal mean values in both reanalyses to -116×10^6 kg s^{-1} in the NCEP and -82×10^6 kg s^{-1} in the DAO. Middle and upper-level divergence increases by factors of 2.5 (0.5) in the NCEP (DAO) to 94 $\times$ 10^6 kg s^{-1} (95 $\times$ 10^6 kg s^{-1}).

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