

## Corridors of Warm Season Precipitation in the Central United States

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### ABSTRACT

During the warm season in the central United States there often exists a corridor of precipitation where a succession of mesoscale convective systems (MCSs) follow similar paths lasting several days. The total cumulative rainfall within a corridor can be substantial while precipitation at nearby regions may be below normal. Understanding the nature of the corridors and the environmental factors important for their formation thus has important implications for quantitative precipitation forecasting and hydrological studies. In this study a U.S. national composite radar dataset and model-analyzed fields are used for the 1998–2002 warm seasons (July–August) to understand the properties of corridors and what environmental factors are important for determining when and where they develop. The analysis is restricted to a relatively narrow longitudinal band in the central United States ( $95^{\circ}$ – $100^{\circ}$ W), a region where convection often intensifies and becomes highly organized. It is found that  $\sim 68\%$  of MCSs were members of a series and that corridors typically persist for 2–7 days with an extreme case lasting 13 days. Cumulative radar-derived maximum rainfall ranges from 8 to 50 cm, underscoring the fact that corridors can experience excessive rainfall. Combining radar with Rapid Update Cycle model kinematic and thermodynamic fields, 5-yr composites are presented and stratified according to the environmental conditions. While the corridors show the expected association with areas of enhanced CAPE and relatively strong northwesterly/westerly shear, the strongest association is with the northern terminus region of the nocturnal low-level jet (LLJ). Furthermore, the relative intensity of the rainfall is positively correlated with the strength of the LLJ. The LLJ is thought to play a role through enhanced convergence and lifting, moisture transport, and frontogenesis. In the five years analyzed, the large-scale environment varied considerably, but the role of the LLJ in the formation of corridors remained persistent.

### 1. Introduction

During the warm season in the central United States there often exists a well-defined corridor<sup>1</sup> of precipitation events where a series of convective systems following similar paths occur over a period of several days.

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<sup>1</sup> Here a corridor is defined as a series of two or more separate MCSs with each subsequent MCS occurring within one calendar day and overlapping by  $\sim 25\%$  or more with the previous MCS. A corridor may remain nearly stationary for several days or it may drift slowly N–S while maintaining the overlap criteria. The percentage of overlap is determined from radar-derived rainfall.

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For example, in a study based upon severe weather reports for 1962–77, Johns (1982) found that 72% of severe weather outbreaks occurred in a series lasting several days. Most series involved two or three events, but a few were composed of eight or more separate outbreaks. In a 15-yr climatological study of derechos (large-scale convectively induced wind storms), Bentley and Sparks (2003) showed that more than half occurred in groups lasting several days. Ashley et al. (2005) found similar results when using a larger derecho dataset and more conservative criteria for delineating derecho groupings. Approximately 62% of derechos were members of a series, with most series involving two or three derecho events ( $\sim 24\%$  of series contained four or more events). Using precipitation data for the warm season of 1982 and 1983, Fritsch et al. (1986) noted that mesoscale convective complexes (MCCs) accounted for much of the warm season precipitation in the central United States and, under synoptic conditions that were evolving very slowly, often occurred in

a series with one mesoscale convective system (MCS) dissipating before the generation of the next. Trier and Parsons (1993) investigated one of a series of four MCCs that developed in succession and followed similar paths over a 2-day period in 1985. They found that the interactions between the nocturnal low-level jet (LLJ) and a quasi-stationary front were important for the development of the MCCs. Other studies that have noted MCCs occurring within a series include Smull and Augustine (1993) and Fortune et al. (1992). In a radar-based climatological study, Carbone et al. (2002) found a high frequency of long-lived coherent rainfall episodes and noted a tendency for precipitation to occur in preferred latitude bands having a slow north-south oscillation over several days.

The focus of this study is precipitation corridors that become established in the central United States between 95° and 100°W longitude. It has been well documented that thunderstorm activity in this region reaches a maximum during the night (Wallace 1975). The nocturnal maximum is a combination of convection that initiates over the higher terrain to the west (Rocky Mountains) and propagates into the region and that which develops in situ. A number of studies have shown that the eastern slopes of the Rocky Mountains during the afternoon hours are a preferred initiation region for MCSs affecting the central United States (Maddox 1980; Cotton et al. 1983; Wetzell et al. 1983; Augustine and Caracena 1994; McAnelly and Cotton 1986; Hane et al. 2003). Provided that the environmental conditions are favorable, these systems can intensify and last well into the evening and early morning hours. Evans and Doswell (2001) used proximity soundings to examine the environment ahead of derechos and found that in conditions of strong synoptic forcing long-lived convection can occur in weak CAPE environments. Under weak synoptic conditions, much higher values of CAPE are needed to sustain convection. Other studies, however, have emphasized the importance of convection developing in situ due to forcing by fronts, troughs, LLJs, and drylines (Maddox et al. 1986; Augustine and Howard 1988, 1991; Rodgers et al. 1983, 1985). The LLJ in particular is thought to be a major contributor to the forcing and maintenance of nocturnal convection in the central United States (Maddox and Grice 1983; Pitchford and London 1962; Augustine and Caracena 1994; Hering and Bordon 1962; Arritt et al. 1997; Stensrud 1996) through the transport of moisture from the Gulf of Mexico (Means 1952; Helfand and Schubert 1995; Higgins et al. 1997) and convergence at the northern terminus of the LLJ (Maddox and Grice 1983; Augustine and Caracena 1994).

When a corridor persists in nearly the same location

for several days, the cumulative rainfall can be substantial while nearby regions may be below normal. Understanding the nature and synoptic conditions favorable for setting up a corridor thus has important implications in quantitative precipitation forecasts (QPFs) and hydrological studies. In this study a U.S. national composited radar dataset and model analysis fields are used for the 1998–2002 warm seasons<sup>2</sup> to describe some of the important properties of the corridors (such as their preferred locations, the day-to-day drift, persistence, etc.) and determine what large-scale environmental conditions have the most influence on the timing and locations of the corridors. In the process a number of analysis techniques will be developed to reduce five seasons of radar and model data to a few simple but informative displays.

## 2. Data sources

The primary data used in this study are the WSI Corporation National Operational Weather Radar (NOWrad) national composite radar reflectivity and the Rapid Update Cycle (RUC-2) model analysis. While products such as NOWrad are inadequate for some research purposes, it is the only practical means for access to the complete Weather Surveillance Radar-1988 Doppler (WSR-88D) network data at high spatial and temporal resolutions. The precise algorithm for creating the composite is information proprietary to WSI Corporation, but is commonly described as the maximum value of radar reflectivity as measured by any WSR-88D at any height in a vertical column. The properties of the product include an  $\sim 2$  km latitude-longitude grid with 15-min temporal resolution and 16 levels of reflectivity at 5-dBZ intervals. The reflectivity values are first converted to a rainfall rate ( $\text{mm h}^{-1}$ ) using a standard  $Z$ - $R$  relationship ( $Z = 300R^{1.6}$ ). It is well known that reflectivity-rainfall rate relationships applied locally are subject to errors of factors of 2 or more. Although the errors are expected to be reduced in climatological applications (such as that being done here), the averaged rainfall rates shown in the next two sections should be viewed in relative terms to indicate regions of enhanced or reduced rainfall.

To reduce the dataset to a more manageable size the rainfall estimates are averaged over a  $0.2^\circ$  latitude  $\times$   $0.2^\circ$  longitude grid and saved as a Custom Editing and Display of Reduced Information in Cartesian space (CEDRIC) disk file (Mohr et al. 1986), thereby reducing the volume of data by about 100.

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<sup>2</sup> The warm season is defined here as July–August, the time when synoptic-scale transients are weakest.

RUC-2, developed by the National Oceanic and Atmospheric Administration/Forecast Systems Laboratory, is a regional modeling and data assimilation system that cycles in new data (profile, surface observations, Aircraft Communications Addressing and Report System, rawinsondes, and winds derived from satellite cloud motions) and is initialized every hour (Benjamin et al. 2004a,b). RUC-2 provides data with a 40-km horizontal grid spacing on a Lambert conformal projection. The data were interpolated from the RUC  $\sigma$ - $\theta$  vertical coordinate system to constant pressure surfaces spaced 25 hPa apart. While there are limitations to the assimilation process, the RUC-2 analyses provide a good representation of the atmosphere in a convenient format. Details of the assimilation process can be found in Devenyi and Benjamin (2003).

### 3. Properties of corridors

Because of the large amounts of data being processed in this study (July and August for five years for a total of 310 days), the data are analyzed and presented in reduced dimension format where data are averaged in one dimension (latitude, longitude, or time) and presented in the remaining two dimensions. This is similar to the procedure used by Carbone et al. (2002) and Tuttle and Carbone (2004). An example of this process and the impetus for this study are illustrated in Fig. 1. The figure shows radar-derived rainfall in a time-latitude format for a 10-day period in July 1998. The data were averaged in the longitudinal direction (along constant latitude slabs) in three different bands—one centered over the continental divide ( $105^{\circ}$ – $110^{\circ}$ W longitude), the second over the western high plains, and the third over the central plains ( $95^{\circ}$ – $100^{\circ}$ W). Over the elevated terrain convection develops on a daily basis around 0000 UTC (unless otherwise stated all time are UTC) often extending from Mexico to the Canadian border (Fig. 1a), but apparently only a small fraction is long-lived and is able to propagate into the central United States,<sup>3</sup> arriving some 8–10 h later (Fig. 1c). In Fig. 1c the rainfall is confined to a relatively narrow latitudinal corridor  $\sim 3^{\circ}$ – $4^{\circ}$  wide and shows a slow N–S oscillation with time. The averaged rainfall typically reaches a peak intensity around 0800–1000 UTC. It is clear that in conditions such as that shown in Fig. 1c, the cumulative precipitation over the duration of the corridor would be substantial. Indeed for the 10-day period shown, parts of eastern Kansas and Missouri re-

ceived 40–50 cm of total rainfall while areas to the north and south were below normal. How much cumulative rainfall an area receives is dependent upon a number of factors including the persistence of a corridor, how much it drifts with time, and the intensity and propagation speeds of individual MCSs comprising a corridor. It is also important to know the spatial extent of the corridor. Is it confined to a relatively narrow band as in Fig. 1c or are there times when it is more spread out, and why?

Addressing these questions objectively is challenging. Consider first a series of time–latitude plots of rainfall for the 1998–2002 warm seasons in the  $95^{\circ}$ – $100^{\circ}$ W longitude band. In this band, convection often intensifies and becomes highly organized, and the LLJ likely plays an important role. For each 24-h period starting at 0000 UTC, the centroid of all-rain events enclosed by the  $1.0 \text{ mm h}^{-1}$  contour is found. To be counted as a centroid the number of data points within the contour must exceed 75, which corresponds to a convective system having a latitudinal extent of about  $2^{\circ}$  (10 data points at  $0.2^{\circ}$  spatial resolution) and lasting 2 h (8 data points at 15-min temporal resolution). These criteria will eliminate the small, short-lived ordinary thunderstorm, but keep everything else of significance. In many situations only one centroid per day will meet the criteria, but occasionally the rainfall may be more widespread and more than one centroid is found (e.g., 30 July in Fig. 1c). Once all of the centroids have been found, statistics can be generated for the 5-yr dataset. The analysis is restricted to a relatively narrow band because the topographic and geographic features that affect weather and climate in North America vary widely across the continent. By focusing the analysis to a narrow longitudinal band, the important environmental factors responsible can more easily be determined. As the band is moved eastward or westward other factors would be expected to come into play.

Figure 2a shows the latitudinal distribution of the centroids. A well-defined maximum is seen between  $38^{\circ}$  and  $43^{\circ}$ N with nearly 50% of convective events occurring in this band. This is consistent with climatological data of warm season precipitation showing a tongue of higher total rainfall extending westward across Kansas and Nebraska (e.g., <http://lwf.ncdc.noaa.gov/oa/climate/normals/assessments.html>).

Figure 2b shows the number of centroids that were found for each day. A majority (52%) of the days had a single rainfall centroid indicative of convection being confined to a single latitude band. About 23% of days had more than one centroid, while 25% did not have a measurable event using the criteria described above.

One of the key factors controlling the cumulative

<sup>3</sup> Although not shown here, the propagation of convection from the higher terrain to the central plains is evident in time–longitude plots.

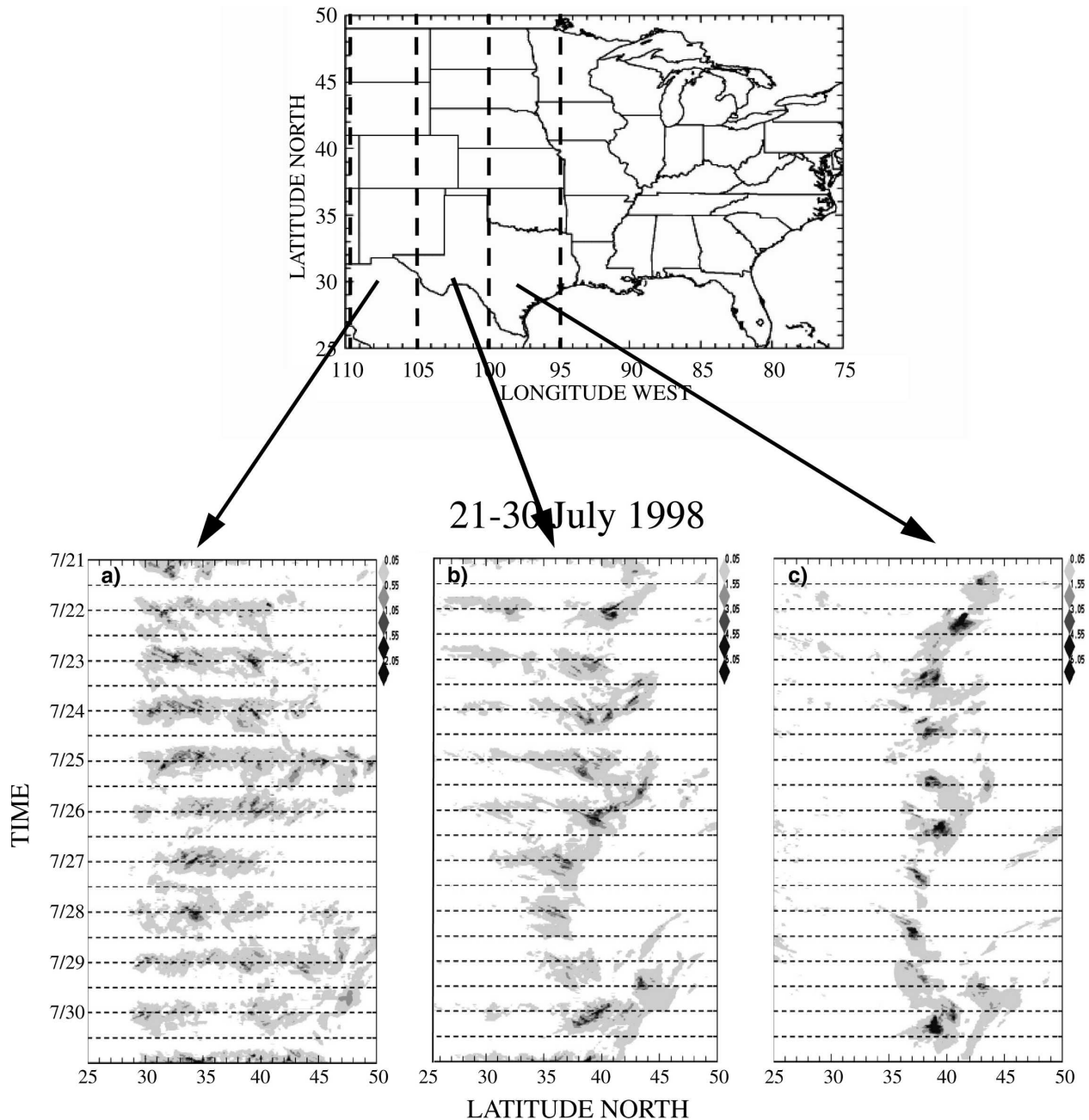


FIG. 1. Time-lat (Hovmöller) plots of radar-derived rainfall rate ( $\text{mm h}^{-1}$ ) averaged over (a)  $110^{\circ}$ – $105^{\circ}$ W, (b)  $105^{\circ}$ – $100^{\circ}$ W, and (c)  $100^{\circ}$ – $95^{\circ}$ W bands for 21–30 Jul 1998.

precipitation is the N–S movement of a corridor from one day to the next. If a corridor shows little day-to-day movement, then the cumulative precipitation would be expected to be larger. The distribution of daily N–S centroid movement is shown in Fig. 2c. A large percentage (42%) of the centroids had a day-to-day drift between  $-2^{\circ}$  to  $1^{\circ}$  latitude with the distribution skewed toward negative values; that is, there is a tendency for a corridor to drift southward. There is a secondary peak

at the larger drift value of  $7^{\circ}$ – $8^{\circ}$ . These represent significant rapid changes in the synoptic conditions, perhaps a traveling low pressure system or the development of a new front.

As noted in past studies, corridors of precipitation may persist for several days (Johns 1982; Bentley and Sparks 2003; Trier and Parsons 1993; Carbone et al. 2002). Using Fig. 2c as a basis, a corridor is defined here as being a series of events in which the day-to-day

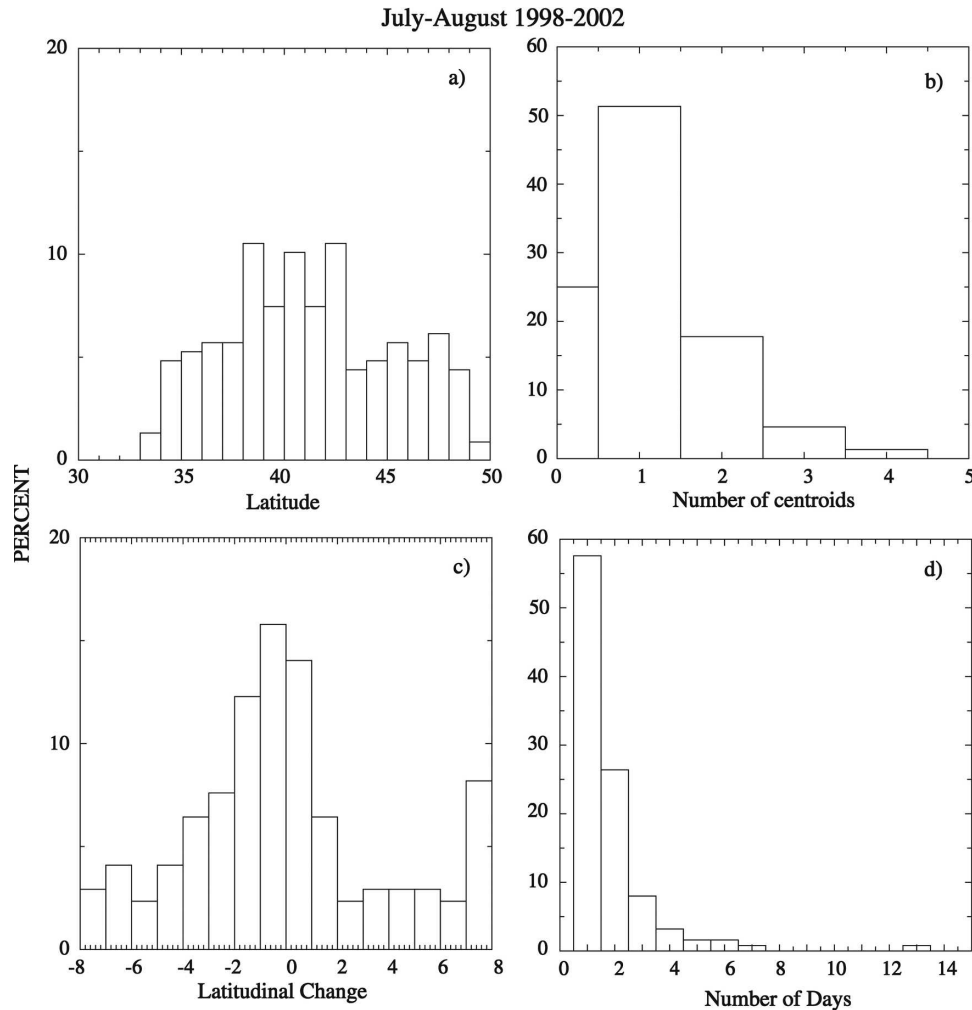


FIG. 2. Histograms of (a) latitudinal distribution of precipitation centroids, (b) number of centroids per day, (c) day-to-day latitudinal drift of centroid, and (d) number of days per corridor.

change of latitude is no more than  $\pm 3^\circ$ . This value is chosen somewhat arbitrarily, but should be small enough such that, in order to be considered a member of a series, an MCS from one day should at least partially overlap ( $\sim 25\%$  or more) that of the previous day. A N-S movement of  $3^\circ$  in one day corresponds to  $\sim 4 \text{ m s}^{-1}$ . Figure 2d shows the number of days comprising each corridor. Many (57%) of the “events” lasted only one day, consisting of a single convective event, and do not meet the criteria of a corridor as defined here. The remaining true corridors typically persist 2–7 days with one extreme case lasting 13 days (19–31 July 1998; Fig. 1). Of all the convective events found, 68% were a member of a corridor consisting of two or more days (not shown). These percentages are similar to that found by Johns (1982) and Bentley and Sparks (2003).

#### 4. Large-scale environment of corridors

Given that 68% of convective events were found to be a member of a corridor, what are the important environmental factors that determine where a corridor might be located? To investigate this, radar data are compared with various fields from the RUC analyses including winds at the 300-, 600-, and 900-hPa levels, low-level wind shear (computed between the 900- and 600-hPa levels), and computed CAPE and 900-hPa convergence. CAPE is computed assuming a parcel ascent from 900 hPa.

Figure 3 shows an example of radar rainfall overlaid on the meridional wind component (averaged in the  $95^\circ$ – $100^\circ\text{W}$  longitude band) at 900 hPa ( $V_{900}$ ), which is near the level of maximum LLJ. The meridional wind reaches a peak around 0900 UTC nearly every day and



21-30 July 1998

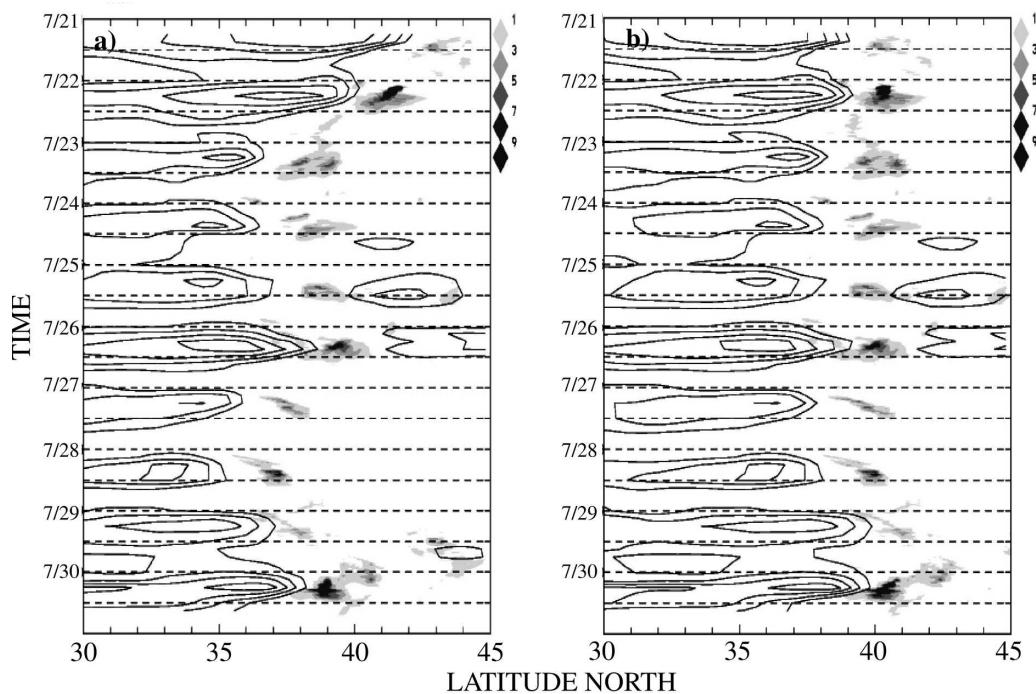


FIG. 3. Time-lat plots of radar rainfall rate (gray shading) and 900-hPa meridional wind (contours) for (a) unshifted data and (b) data shifted to 40°N using the centroid of the radar data as a reference. Contours of meridional wind start at 6 m s<sup>-1</sup> and are incremented by 2.0 m s<sup>-1</sup>.

the relationship between the convection and the LLJ is readily visible with the convection located near the northern terminus of the LLJ. The interest here is to construct 5-yr averages. Since the location of the corridor shifts north-south with time, taking an average of Fig. 3a would smear out the signal in the latitudinal direction. To reduce the smearing, the latitudes of the centroids of the radar data are used as a reference to shift the radar and RUC data by the appropriate amount to bring the data to 40°N as shown in Fig. 3b. Each centroid has an associated time and latitude coordinate. At times between adjacent pairs of centroids, a linear interpolation of the centroid latitudes is done to find the locations at intermediate times. Once this is done the data are averaged for each time of day and composited in time-latitude, time-longitude, and longitude-latitude formats. In addition composites are stratified according to a number of environmental conditions such as strength of LLJ and low-level shear. Shifting the data to a common grid allows for the 5-yr-averaged RUC data to be shown with respect to the averaged radar echoes. Note that for days that had more than one centroid, the southernmost centroid was used as the reference point. The 40° latitude (Kansas-Nebraska border) was chosen as the origin since this is

near the latitude having the highest frequency of convection (Fig. 2a).

The intent here is to gain an understanding of the large-scale environmental factors that have the greatest influence on the intensity and distribution of precipitation. During the compositing process small-scale transient features will be lost. The temporal standard deviation of the RUC fields is calculated to assess the variability that goes into the composites. When appropriate, the one-sided Student's *t* test (Wilks 1995) is also used to determine the significance of the composited signals.

Figures 4 and 5 show a 5-yr average (of all days) of radar and RUC data in a time-latitude (except Fig. 4d, which is in time-longitude format) and latitude-longitude formats, respectively. In Fig. 4a, the rainfall shows a peak centered at 0800 UTC, indicating that on average the rainfall is locked to the diurnal cycle and has a nocturnal maximum. This can be seen as well in the time-longitude plot (Fig. 4d) as a streak originating near 105°W and 0000 UTC (over the higher terrain) and propagating eastward reaching the central plains in the early morning hours. Some fraction of the precipitation in the central plains also develops locally in the evening, probably in response to the LLJ. Not surpris-

July–August 1998–2002

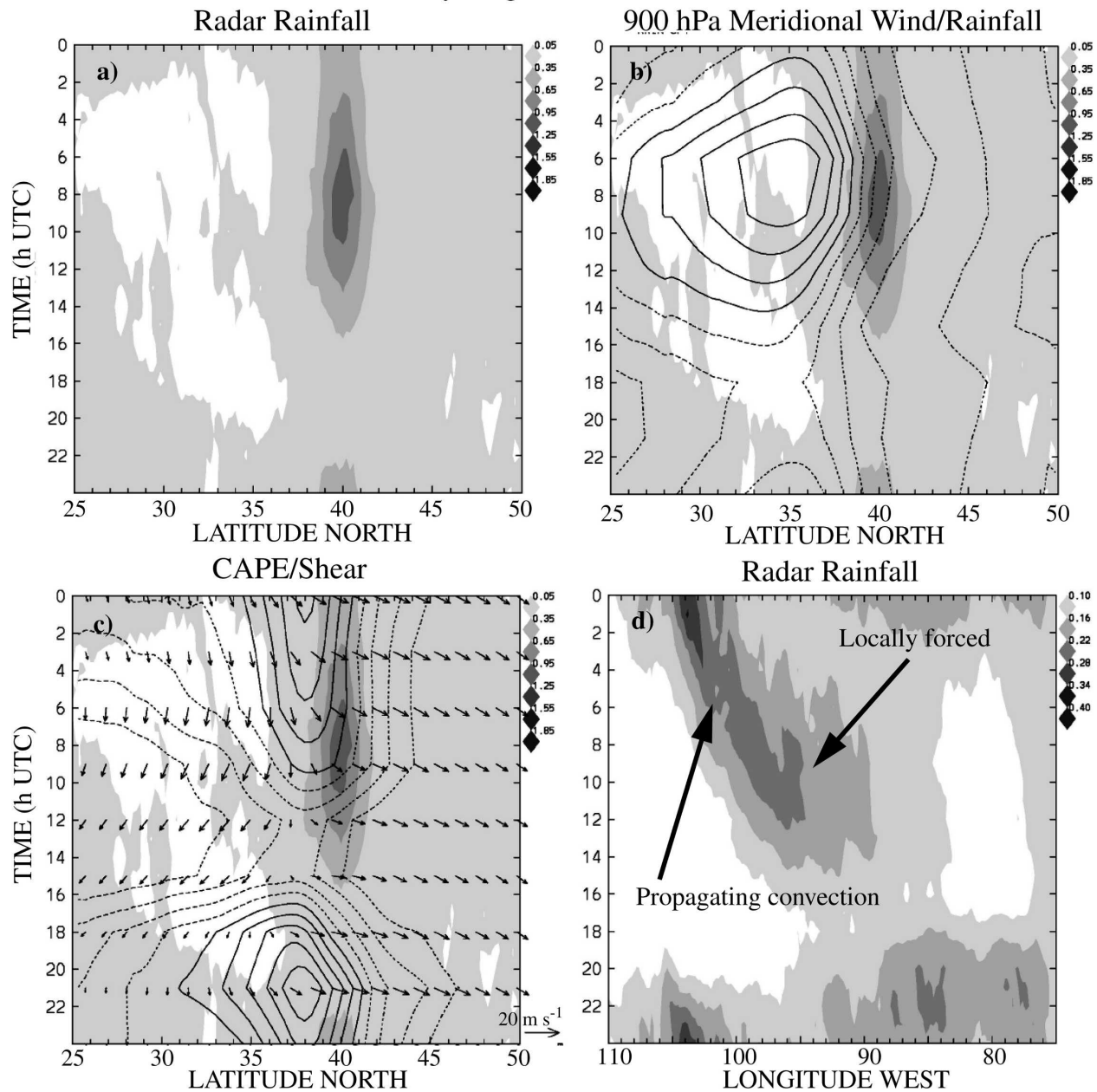


FIG. 4. Diurnally averaged (a) radar-derived rainfall rate ( $\text{mm h}^{-1}$ ), (b) 900-hPa meridional wind (contours) and radar rainfall (gray shading), (c) CAPE (contours), shear (between 600 and 900 hPa) and radar rainfall in time–lat format over the lon band shown in Figs. 1b and 1d), and radar rainfall in time–lon format averaged between  $33^{\circ}$  and  $48^{\circ}\text{N}$ . For the shear vectors in (c) north is taken as directed toward the top of the page in the usual sense. Contours of meridional wind start at  $0 \text{ m s}^{-1}$  and are incremented by  $1.0 \text{ m s}^{-1}$  with contours of  $6 \text{ m s}^{-1}$  and greater shown as solid. Contours of CAPE start at  $400 \text{ J kg}^{-1}$  and are incremented by  $100 \text{ J kg}^{-1}$  with contours of  $800 \text{ J kg}^{-1}$  and greater shown as solid.

ingly the rainfall maximum is located near a relatively narrow band of enhanced CAPE values and relatively strong westerly–northwesterly shear (Fig. 4c). The rainfall is just to the north of the transition from northerly shear to a more westerly component in a region favor-

ing eastward-propagating convection. Most notable is the location of the precipitation near the exit region of the LLJ ( $V_{900}$ ; Fig. 4b). It is well known that the LLJ often plays an important role in the development and maintenance of convection in the central plains (Means

## July–August 1998–2002

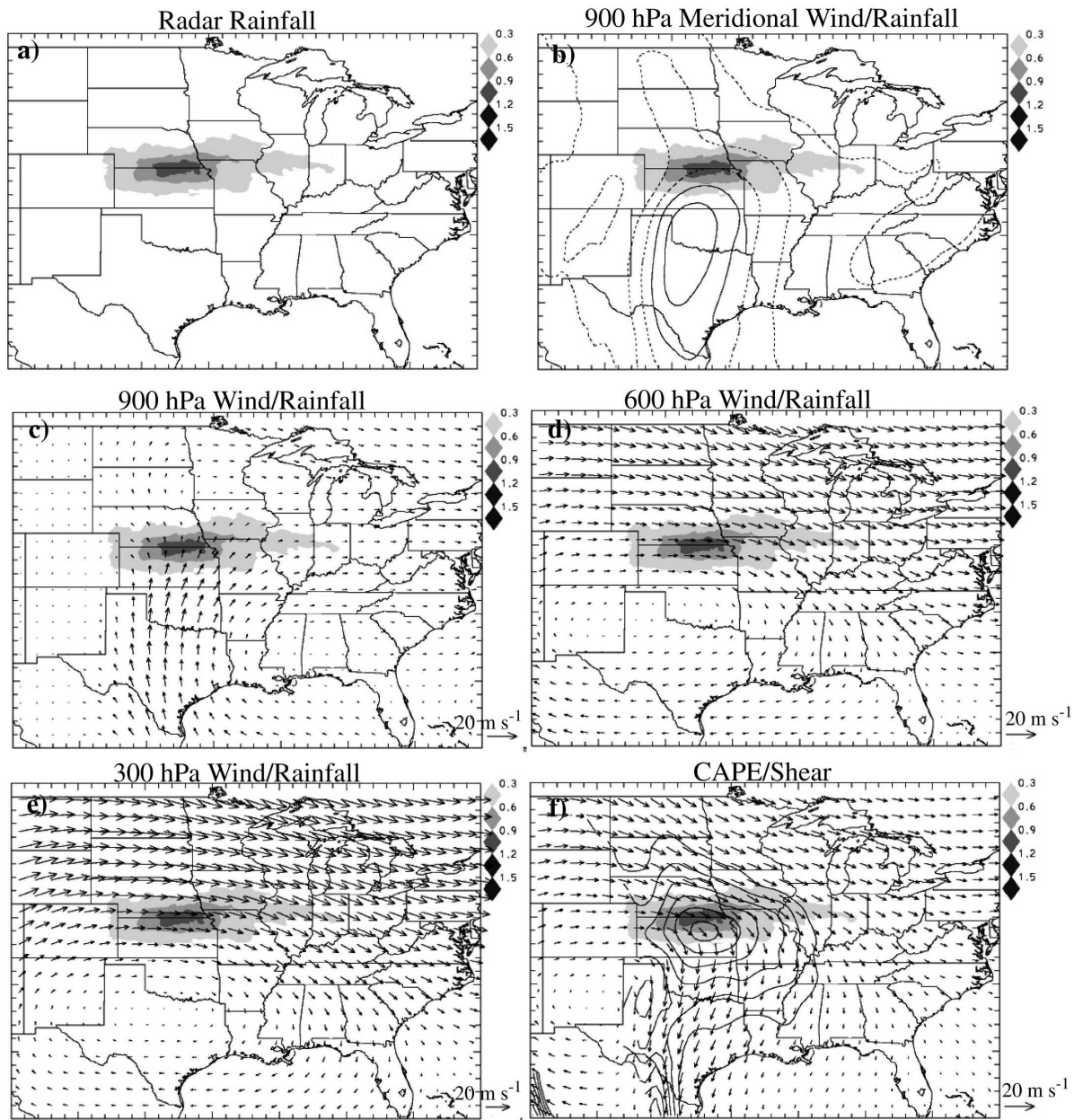


FIG. 5. Averaged (310 days for times between 0300 and 1200 UTC) lat–lon plots of (a) radar-derived rainfall rates ( $\text{mm h}^{-1}$ ), (b) 900-hPa meridional wind (contours)–radar rainfall (gray shading), (c) 900-hPa winds–radar rainfall, (d) 600-hPa winds–radar rainfall, (e) 300-hPa winds–radar rainfall, and (f) CAPE–shear–radar rainfall for July–August 1998–2002. Contours of meridional wind start at  $0 \text{ m s}^{-1}$  and are incremented by  $2.0 \text{ m s}^{-1}$  with contours of  $6 \text{ m s}^{-1}$  and greater shown as solid. Contours of CAPE start at  $400 \text{ J kg}^{-1}$  and are incremented by  $100 \text{ J kg}^{-1}$ .

1952; Augustine and Caracena 1994). It is encouraging to see such a strong relationship to the LLJ in a 5-yr-averaged dataset. Traditionally the LLJ has been viewed as advecting moist unstable air into the central plains during the evening hours and in enhanced convergence (as shown in Fig. 6) at the northern terminus. The terminus of the LLJ may also play a role in fron-

togenesis when preexisting temperature gradients exist (Augustine and Caracena 1994). The recent work of Trier et al. (2006) offers a somewhat different interpretation in which lifting and differential temperature advection also play key roles. Together these mechanisms create a favorable environment for the maintenance of convection propagating into the area and in the initia-



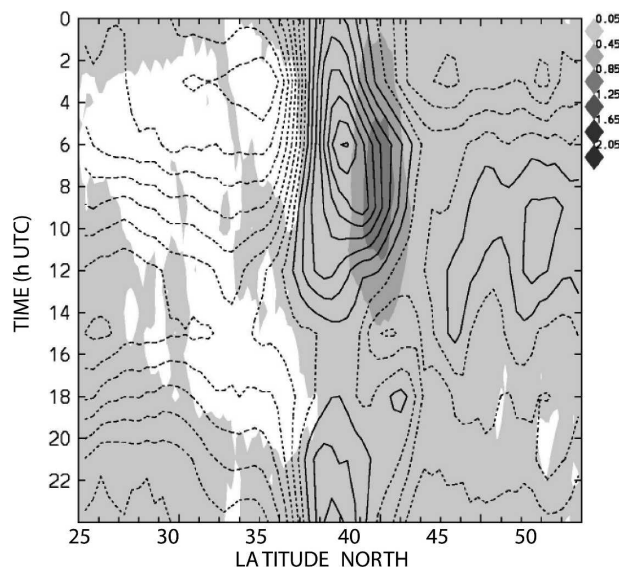


FIG. 6. Diurnally averaged July–August 1998–2002 900-hPa convergence (contours) ( $10^{-5} \text{ s}^{-1}$ ) and radar-derived rainfall rate (gray shading). Contours of convergence start at  $-1.0 \text{ s}^{-1}$  and are incremented by  $1.0 \text{ s}^{-1}$  with contours of 0.0 and greater shown as solid.

tion of new convection locally. To the south of the LLJ core, the flow is divergent, acting to suppress convection (Fig. 6).

The longitude–latitude plots (Fig. 5) represent a 5-yr average of data between 0300 and 1200 UTC, the time period of maximum LLJ. Again, the relationship between the convection and LLJ, CAPE and shear is clearly seen in Figs. 5b, 5c, and 5f with the convection just north of the LLJ and corridor of maximum 900-hPa CAPE. At the upper levels the flow is dominated by an anticyclone centered over Texas. The convection is situated at the top of the anticyclone in a region of strong gradients of the westerly flow (Figs. 5d and 5e). The northerly shear to the south of the convection is due to the strong southerly winds of the LLJ at the low levels and weak winds at 600 hPa. The reader should recall that since the data are shifted to  $40^\circ\text{N}$ , the position of the radar and RUC features on the map background are in a relative sense. However, since the highest frequency of convection occurs around  $40^\circ\text{N}$ , the features are presented fairly close to their absolute location.

We note (not shown) that the temporal standard deviation of  $V_{900}$  is greatest north of the precipitation (despite the weaker winds), being  $\sim 7.5 \text{ m s}^{-1}$  compared to  $\sim 5.0 \text{ m s}^{-1}$  in the LLJ core. This implies that the LLJ is a persistent feature. The other fields (upper-level winds, CAPE, etc.) have standard deviations that are generally about 50% of the mean value. The one no-

table exception is the low-level moisture field (mixing ratio) in the LLJ where the temporal variability is less than 20% of the mean.

Since the LLJ jet appears to play an important role in the location and timing of the convection, the sensitivity of rainfall to the strength of the LLJ is investigated. A  $6^\circ$ -wide region south of the rainfall maximum is selected ( $32^\circ$ – $38^\circ\text{N}$ ) and within that region the number of data values of  $V_{900}$  greater than or less than some threshold are summed for each day. For days to be counted as having weak or nonexistent LLJs, it is required that 96% of  $V_{900}$  values be less than  $5 \text{ m s}^{-1}$ . For days having strong LLJs, it is required that 20% of  $V_{900}$  values be greater than  $12 \text{ m s}^{-1}$ . For the 310 days analyzed, 32 and 45 days met the criteria for weak and strong LLJs, respectively.

Figures 7 and 8 show the summary plots for weak LLJs. Convection for these days is much reduced (Figs. 7a,d and 8a) and there is little evidence of propagating convection. CAPE values are also much lower than in the 5-yr average. The upper-level flow is northwesterly (Fig. 8e) with the anticyclone shifted well to the west over Utah and Arizona. Some insight into synoptic-scale differences can be obtained by examining maps of geopotential height anomalies. The 900- and 300-hPa height anomalies<sup>4</sup> show strongly positive values (ridging) in the west and negative values (troughing) in the east, resulting in northeasterly geostrophic flow in the central plains. The large-scale environmental flow thus opposes the formation of the LLJ. In this dry northwesterly flow regime with the surface high located in the west it is not surprising that convection and the formation of the LLJ were suppressed. Other studies have noted that under conditions of a polar high, the formation of a LLJ is suppressed (Bonner 1968; Mitchell et al. 1995; Arritt et al. 1997).

Conditions for days that had strong LLJs are shown in Figs. 9 and 10. Some notable features (compared to the 5-yr average) are the significantly larger values of CAPE (50% larger), increased rainfall, stronger westerlies in the upper levels, and a well-defined 300-hPa jet entrance near the western edge of the precipitation. In particular, note the strong negative 900-hPa height anomalies in the lee of the Rocky Mountains and positive anomaly in the southeast (strong southwesterly geostrophic flow). This is the opposite of the suppressed LLJ cases. Another important feature is that a

<sup>4</sup> The height anomalies are computed with respect to the 5-yr mean. Statistical significance of the anomaly fields are assessed using a one-sided Student's  $t$  test. Generally contour levels above (below) 5 m ( $-5$  m) are significant at a confidence level of 95%. This holds true for all subsequent height anomaly plots.

## July-August 1998-2002 32 days

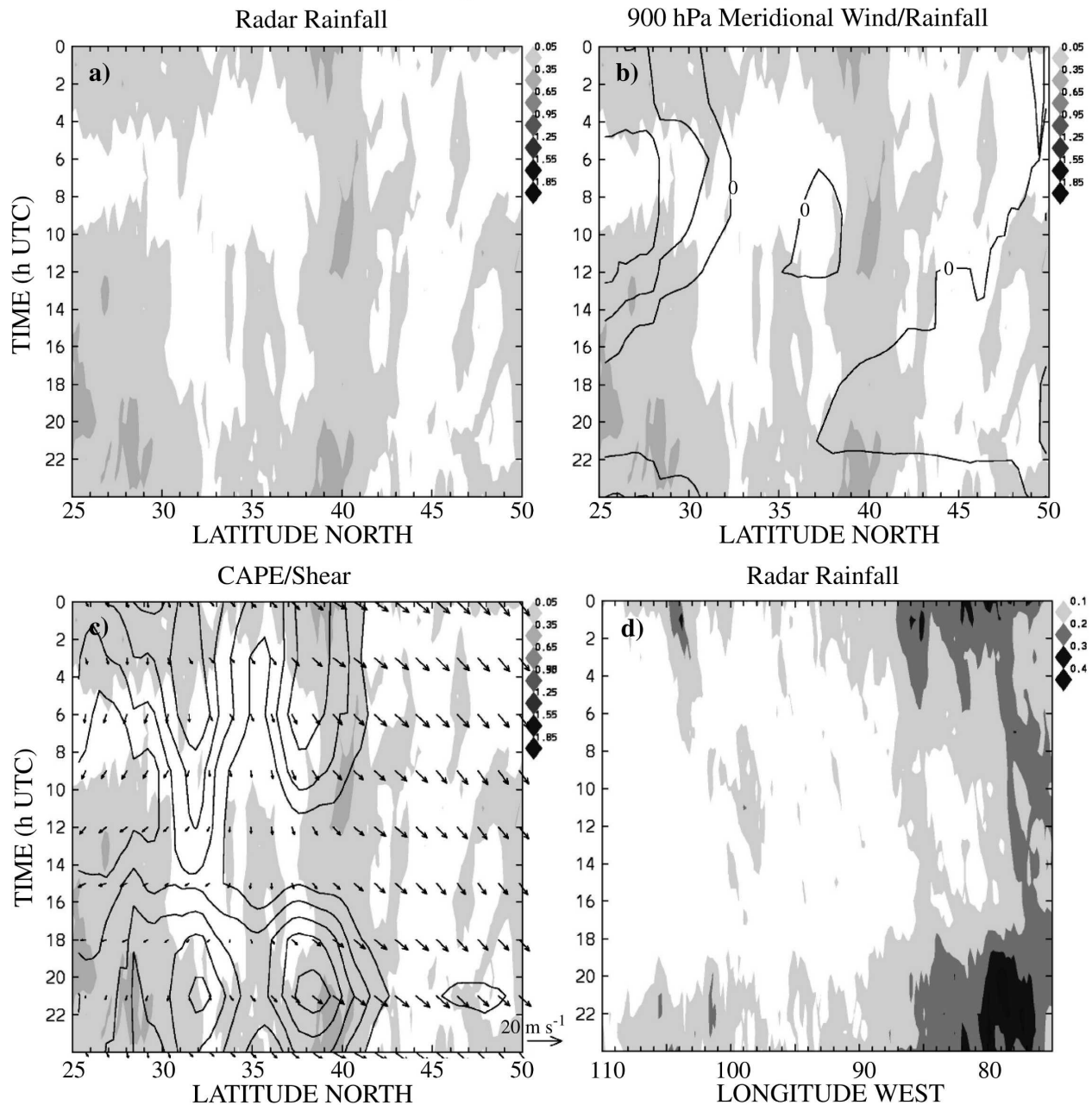


FIG. 7. Same as Fig. 4 but for days with LLJ < 5 m s<sup>-1</sup>. Contours of meridional wind start at 0 m s<sup>-1</sup> and are incremented by 1.0 m s<sup>-1</sup>. Contours of CAPE start at 400 J kg<sup>-1</sup> and are incremented by 100 J kg<sup>-1</sup>.

greater percentage of convection develops in situ (~25% more than the 5-yr climatology) as opposed to propagating into the region from the west. During the warm season of 1993 severe flooding occurred over the central plains and the upper Mississippi River basin. Arritt et al. (1997) attributed the enhanced precipitation to an increased frequency of the strongest LLJs rather than an increase in the general incidence of

LLJs. Their findings are consistent with the results here; that is, increased strength of the LLJ leads to enhanced rainfall.

The strength of the wind shear in the lowest 2.5–5.0 km is also known to be a factor in the maintenance convection (Weisman et al. 1988; Thorpe et al. 1982; Xue 2000; Coniglio and Stensrud 2001). Figures 11 and 12 show averaged conditions for days with weak wind

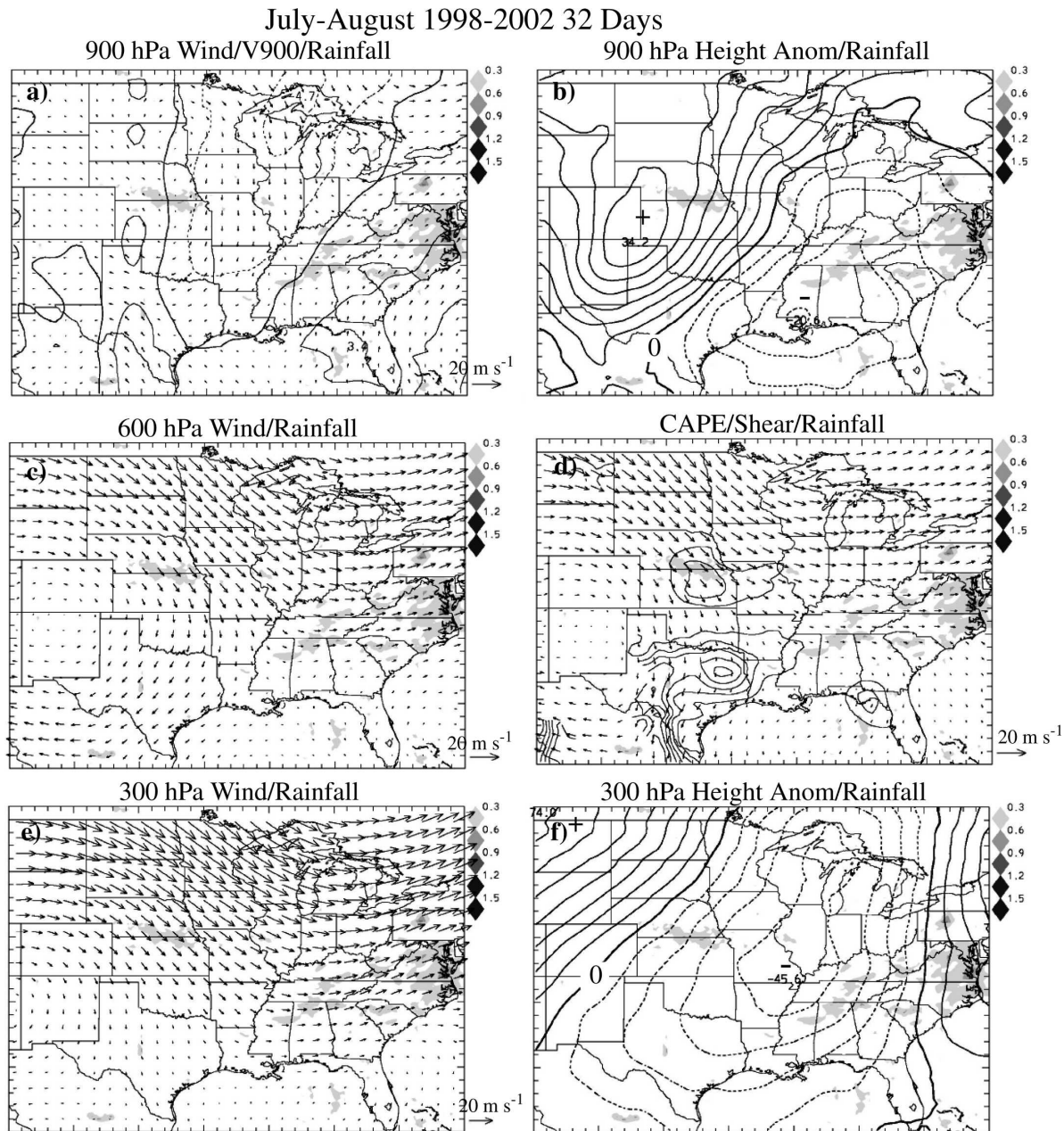


FIG. 8. Five-year composite for days with LLJ < 5 m s<sup>-1</sup> of (a) 900-hPa wind (vectors), meridional 900-hPa wind (contours), radar-derived rainfall (gray shading), (b) 900-hPa height anomalies-radar rainfall, (c) 600-hPa wind-radar rainfall, (d) CAPE-shear-radar rainfall, (e) 300-hPa wind-radar rainfall, and (f) 300-hPa height anomalies-radar rainfall. Contours of meridional wind are incremented by 2.0 m s<sup>-1</sup> with contours greater than or equal to (less than) 0 m s<sup>-1</sup> shown as solid (dashed). Height anomaly contours are solid (dashed) for positive (negative) values with the 0 m contour shown as boldface solid. Contour increments for 900- and 300-hPa height anomalies are 5 and 10 m, respectively. Contours of CAPE start at 400 J kg<sup>-1</sup> and are incremented by 100 J kg<sup>-1</sup>.

shear (94% of shear values < 10 m s<sup>-1</sup> between 38° and 42°N). The differences between the low-shear days and the average are dramatic. There is an almost complete lack of any long-lived propagating organized convection (Fig. 11d), the LLJ is quite weak, and the winds in the vicinity of the convection are weak at all levels. The

height anomalies (Figs. 12b and 12f) show lower heights in the south and higher values in the north, the net result being weaker gradients (weaker winds). The convection that does form occurs near or shortly after the time of maximum solar heating, that is, between 2200 and 0200 UTC (1700 to 2100 local time) as opposed to



## July-August 1998-2002 45 Days

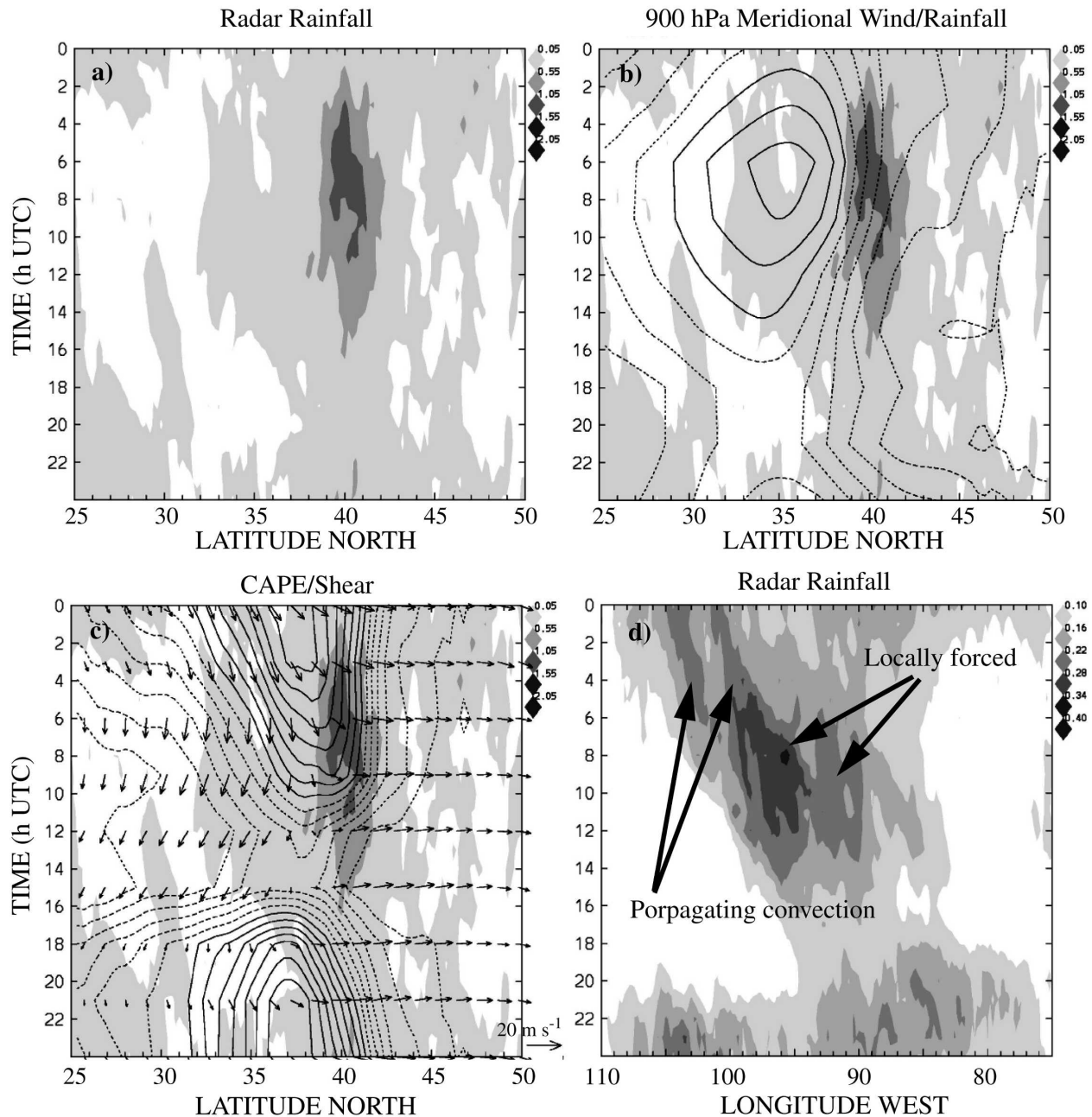


FIG. 9. Same as Fig. 4 but for days with  $LLJ > 12 \text{ m s}^{-1}$ . Contours of meridional wind start at  $0 \text{ m s}^{-1}$  and are incremented by  $2.0 \text{ m s}^{-1}$  with contours of  $12 \text{ m s}^{-1}$  and greater shown as solid. Contours of CAPE start at  $400 \text{ J kg}^{-1}$  and are incremented by  $100 \text{ J kg}^{-1}$  with contours of  $1000 \text{ J kg}^{-1}$  and greater shown as solid.

being nocturnal. Somewhat surprising is that the CAPE values are only slightly less than the 5-yr average. Thus while there is sufficient moisture and instability to promote fairly intense convection (rainfall intensity is similar to average; cf. Fig. 11a to Fig. 4a), the convection is tied to the solar heating maximum, is short-lived, and does not propagate.

As mentioned earlier, 77% of days had one convection centroid or fewer. The remaining days had two to four centroids. Obviously, knowing the conditions when convection will be more widespread is an important forecast issue. The conditions for multiple centroid days are shown in Fig. 13. The rainfall pattern (Fig. 13a) now shows two bands of maximum rainfall. The pri-



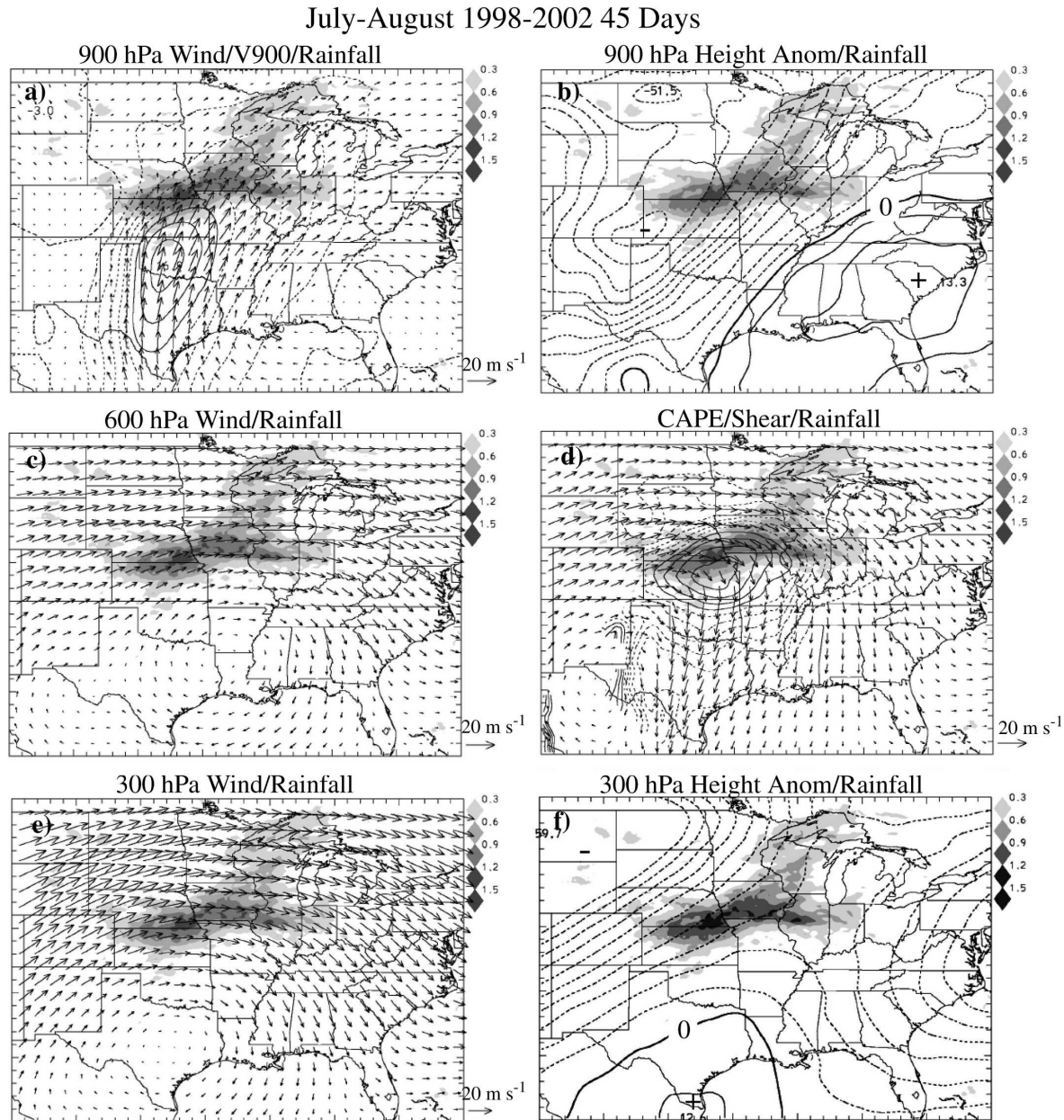


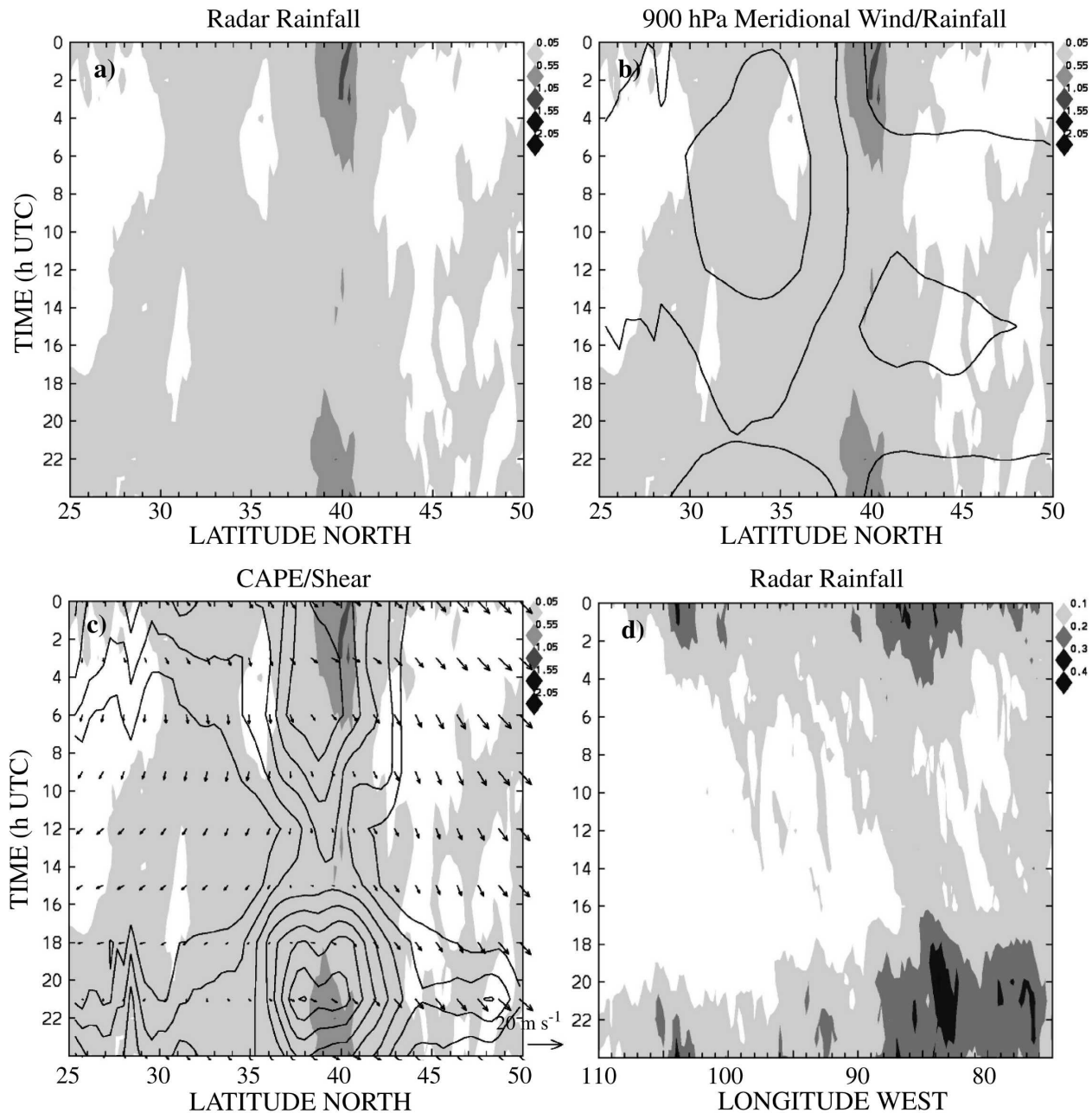
FIG. 10. Same as Fig. 8 but for days with LLJ  $> 12 \text{ m s}^{-1}$  and contours of meridional wind greater than or equal to  $12 \text{ m s}^{-1}$  are shown as solid. Contours of CAPE are incremented by  $100 \text{ J kg}^{-1}$  with contours of  $1000 \text{ J kg}^{-1}$  and greater shown as solid.

mary maximum is located along the Kansas–Nebraska border with a secondary maximum  $\sim 800 \text{ km}$  to the north in North Dakota (again, positions of data on map are in a relative sense). At the upper levels the synoptic flow pattern is similar to the 5-yr mean and the LLJ is of comparable magnitude. The main difference can be seen in the 900-hPa height anomaly (Fig. 13b). The southeast surface high has elongated and expanded northward into the Great Lakes region (as evident by positive height anomalies in that region) while the west-

ern part of the northern plains has negative anomalies. This pattern results in relatively strong southerly flow reaching as far north as the Canadian border. A northern extension of higher CAPE values is associated with the southerly flow. Even under these conditions, however, the primary precipitation maximum is still located just north of the LLJ. The secondary rainfall maximum is just north of a weak secondary LLJ.

It is instructive to briefly compare the multiple centroid composites to those of strong LLJs (Fig. 10). In

## July-August 1998-2002 34 Days

FIG. 11. Same as Fig. 8 but for days with low-level shear  $< 10 \text{ m s}^{-1}$ .

both cases strong low-level southerly/southwesterly flow is present as far north as the Canadian border and precipitation is more widespread in the north-south direction. The main difference in the strong LLJ precipitation pattern (other than the increased intensity) is the location of the secondary rainfall maximum shifted well to the east in Wisconsin. The 900-hPa height anomaly (Fig. 10a) of the strong LLJ days is dominated by a

strong, tilted (SW-NE) lee trough in the west. Thus the core of strong southwesterlies extends diagonally from Oklahoma-Kansas to Wisconsin causing an eastward shift in the secondary rainfall maximum. For the multiple centroid days, the western trough is much weaker and is accompanied by enhanced ridging over the Great Lakes region.

Consider now the long-lived corridors, here defined



## July-August 1998-2002 34 Days

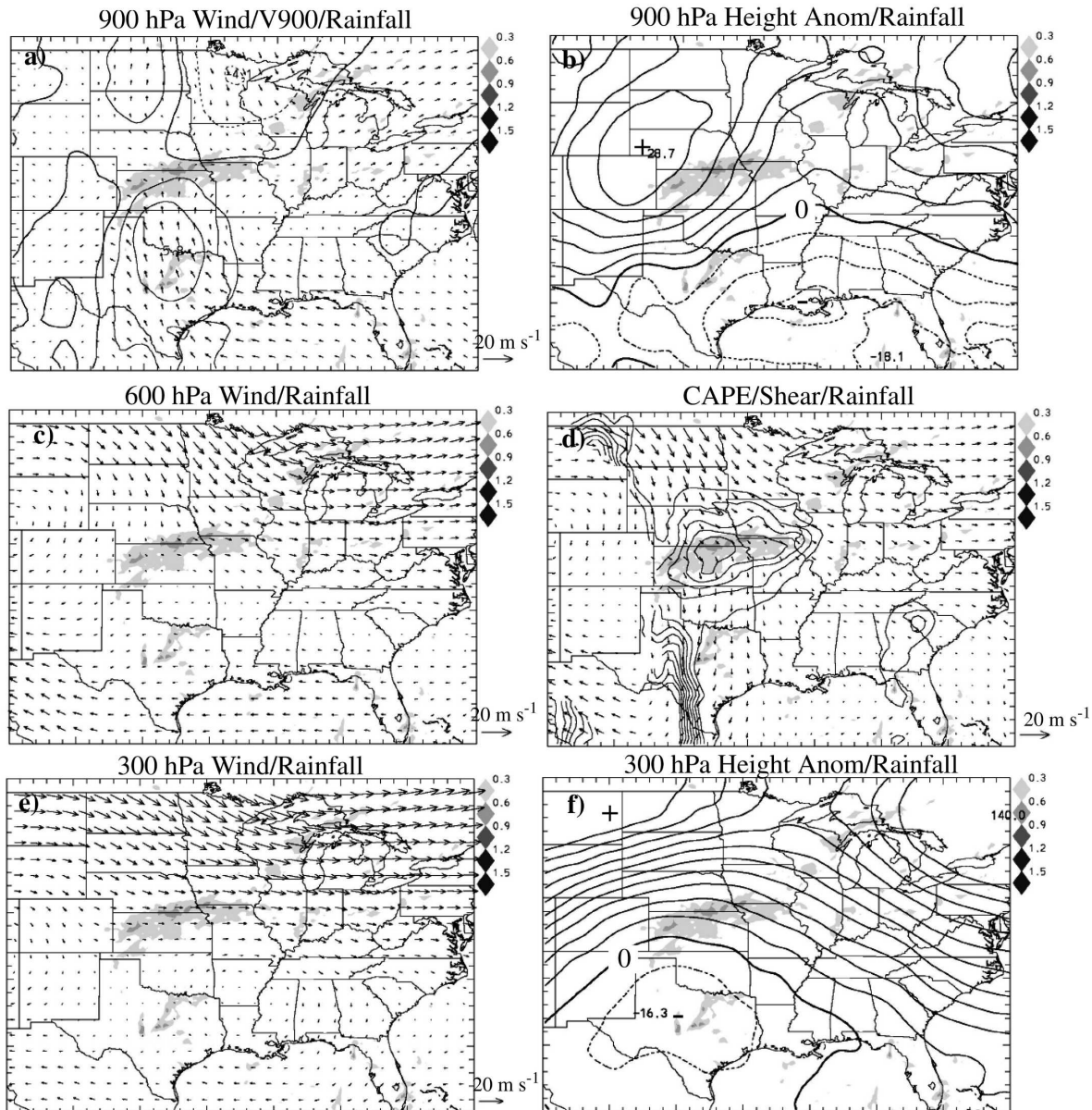


FIG. 12. Same as Fig. 5 but for days with low-level shear  $< 10 \text{ m s}^{-1}$ . Contour intervals same as Fig. 7.

as lasting four days or more. During the 5-yr period, a total of nine long-lived corridors occurred. Several synoptic-scale and mesoscale differences are evident between these long-lived events and more transient corridors. First, as compared with corridors during times of an enhanced LLJ, the composite LLJ in the long-lived corridors is weaker. Precipitation is strongly confined to a narrow latitudinal band oriented nearly east-west with virtually no precipitation more than 300 km north or south of the corridor axis (Fig. 14a).

At 900 hPa, anomalously high heights are evident to the north of long-lived corridors, implying an east-west stationary front located slightly to the south of the corridor axis. Note that the absence of convection poleward of the corridor in the long-lived cases is consistent with broad-scale subsidence and anticyclone formation. At 300 hPa, the composite of long-lived cases reveals a northwest-southeast elongated region of anomalously high heights straddling the corridor axis. An enhanced equatorward height gradient is found farther north, as-

July–August 1998–2002

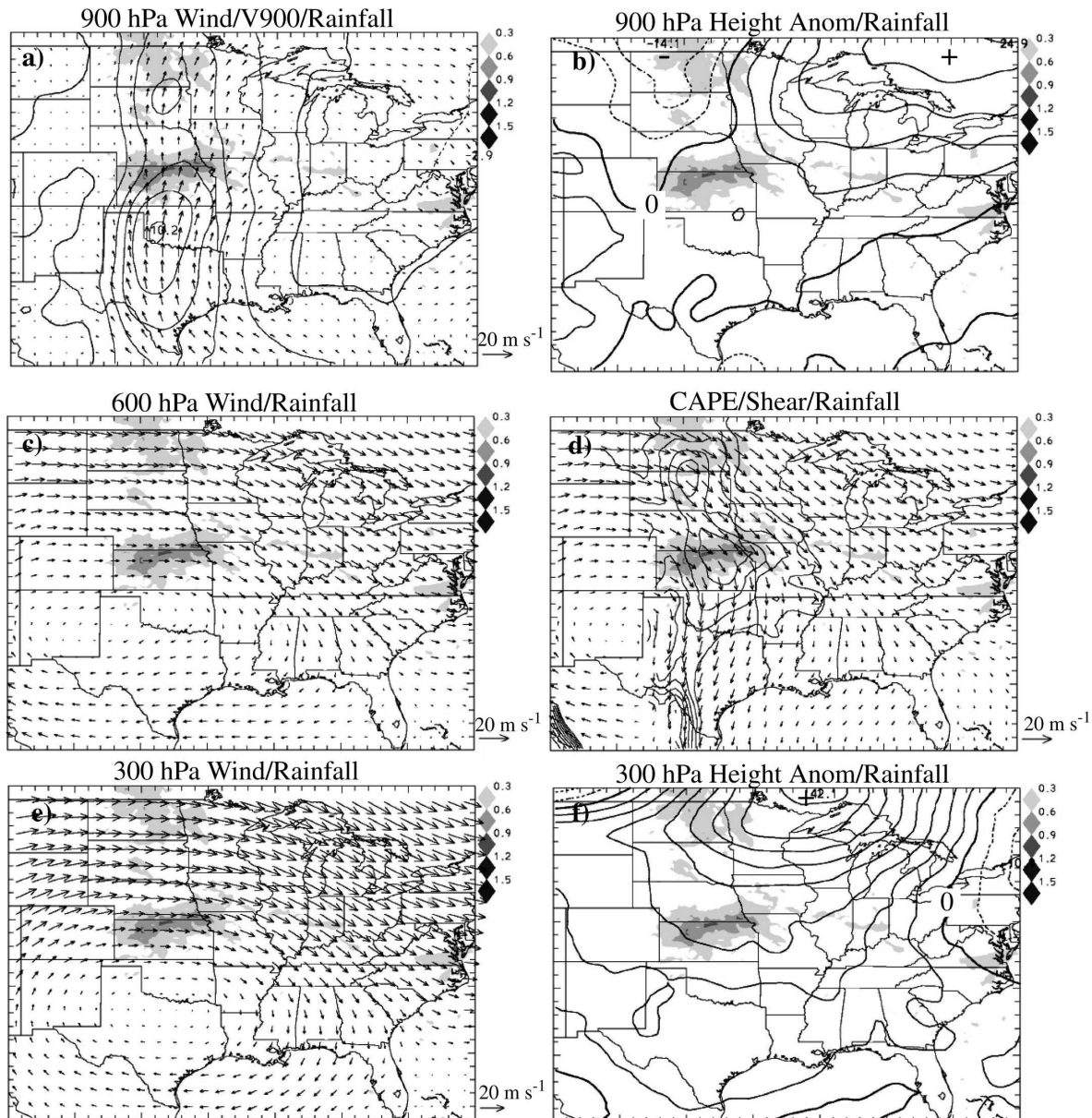


FIG. 13. Same as Fig. 8 but for days with more than one rainfall centroid.

sociated with anomalously strong west-northwesterly flow. The full wind fields at 300 hPa (Fig. 14e) show confluent deformation poleward of the corridor axis, consistent with anticyclonic tendencies in the lower troposphere. The corridor axis is slightly poleward relative to the 300-hPa anticyclone. In this position, it is possible that the organized convection reinforces the anomalously high heights through systematic divergence aloft. This divergence would create anticyclonic tendencies and also advect the tropopause poleward, creating an

enhanced jet at the terminus of the outflow. This process was originally detailed in Maddox et al. (1981). The enhanced jet would maintain confluence in the upper troposphere tending to reinforce anticyclonic tendencies in the lower troposphere poleward of the corridor. The possibility that long-lived corridors are self-sustaining is thus raised, but this hypothesis cannot be addressed using observations alone.

In the earlier analysis, the nocturnal low-level jet appears paramount in the organization of rainfall within



## July-August 1998-2002

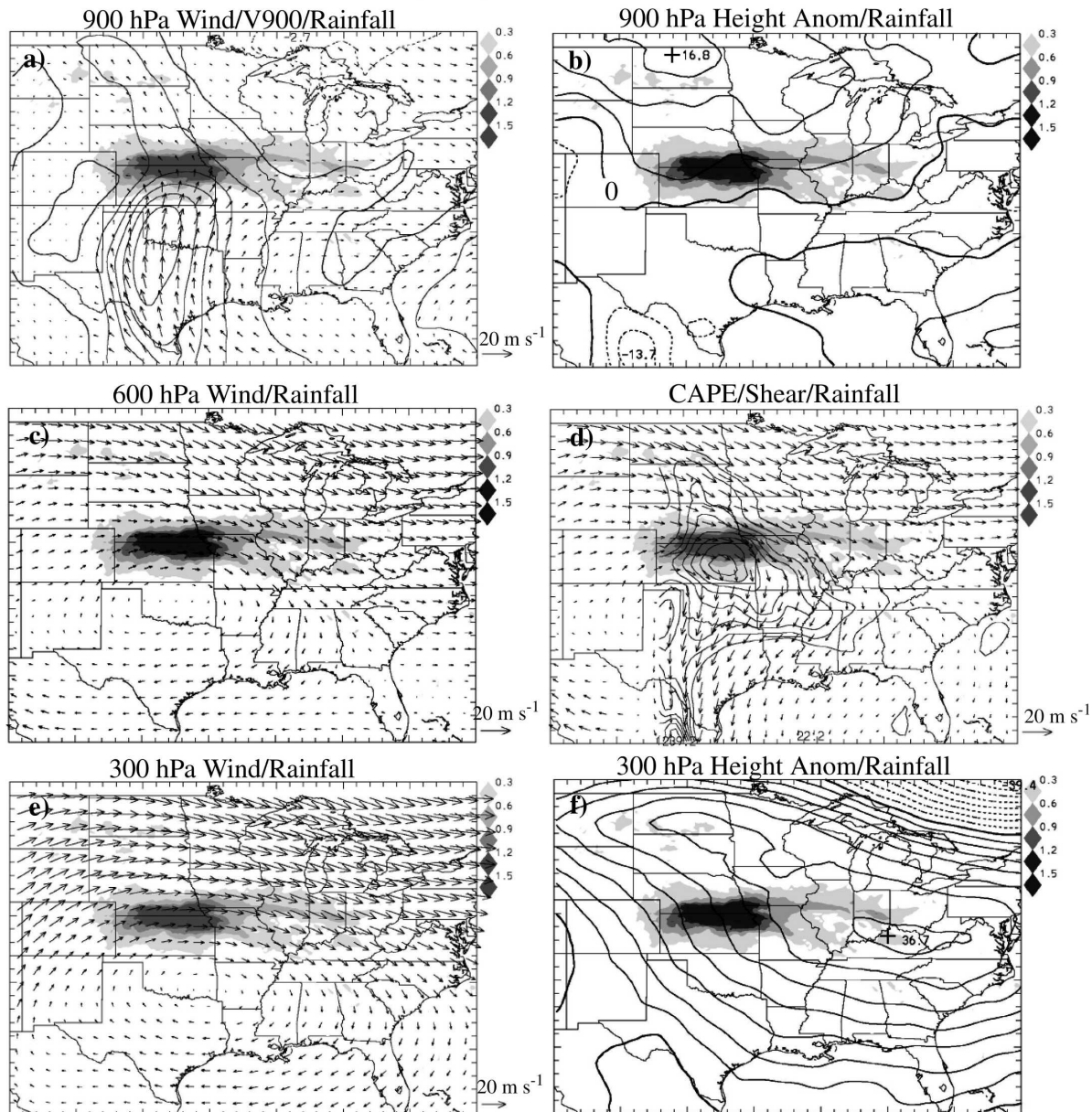


FIG. 14. Same as Fig. 8 but for persistent corridors lasting four or more days.

corridors. However, the association by itself does not speak to the mechanism. The traditional view on the role of the jet is one of transport of warm, moist air over a weak frontal boundary, such that conditional instability is rapidly generated and convection is forced (e.g., Maddox 1983; Trier and Parsons 1993; etc.). However, Augustine and Caracena (1994) point out the frontogenetic properties of the environment prior to the passage of nocturnal MCSs. In their study, the terminus of the low-level jet is identified with convergence and enhancement of a preexisting frontogenetical circulation.

Apparently not fully appreciated is that the terminus of lower-tropospheric southerly flow (whether a jet confined vertically or not) represents deformation that, with a preexisting temperature gradient, can be strongly frontogenetical. The associated upward motion is highly localized to the warm side of the frontal zone. Convection is maximized slightly poleward of this ascent, consistent with the inferred maximum upward displacement of poleward-moving air parcels. Furthermore, there is the question of origin of the water vapor that augments the potential instability on which the

convection builds. A vertical cross section from 25° to 50°N in corridor-relative space indicate that the greatest water vapor mixing ratios are clearly within the frontal zone prior to convection (Fig. 15a). The composite cross section at 0000 UTC suggests that water vapor is being vertically advected by the transverse frontal circulation. To the south, a relative minimum of water vapor exists on pressure surfaces below 850 hPa. The maximum  $\theta_e$  (not shown) is also found within the frontal zone, and this location is consistent with the meridionally confined maximum in CAPE (Fig. 4). As night progresses, the low-level jet strengthens and there is a slight increase of water vapor between 200 and 600 km south of the rainfall corridor (Fig. 15b) but not within the rainfall corridor. Data within the corridor at 0900 are difficult to compare with data at 0000 UTC because of the influence of organized convection itself, and uncertainty about how this influence is represented in the RUC-2 analyses.

In a study of a single corridor, 3–10 July 2003, Trier et al. (2006) performed composite and trajectory diagnostics of the environment preceding convection based on finescale numerical simulations. They found structures remarkably similar to the 5-yr composite structures shown here. From one night to the next, the strength of the front would vary, and so varied the relative importance of vertical transport of water vapor within the frontal zone (strong fronts) and horizontal transport of water vapor in the low-level jet (weak fronts). The upward moisture transport offset the drying effects of vertical mixing in the daytime boundary layer, resulting in a maximum in  $\theta_e$  and CAPE within the frontal zone.

## 5. Discussion

Previous climatological studies of derechos and severe weather outbreaks have documented a tendency for those events to occur in a series spanning several days. The focus of this study was to use a 5-yr national composite radar dataset to document this same tendency in convection of all scale sizes ranging from large MCCs down to the fairly ordinary MCS of around 100 km in size and lasting 5–6 h. The study was limited to the months of July and August, the time period of weakest synoptic-scale forcing, and to the central United States (specifically 95°–100°W), an area where convection often intensifies and becomes highly organized. The radar data were combined with RUC-2 model analysis to understand what large-scale environmental factors control the location and timing of corridors. Understanding the nature of precipitation corridors has important implications in QPF. If a corridor

persists for several days with little movement, the cumulative rainfall in the corridor can be substantial while nearby regions may experience below-normal rainfall. Corridors lasting two to seven days were found to be typical, with one extreme case lasting 13 days. Cumulative rainfall (estimated from the radar measurements) in the corridors ranged from 8 to 50 cm with a modal value of 15 cm. In this study it was found that 68% of all convective events were members of a corridor.

Combining radar with RUC model analyses, plots showing 5-yr averages for the months of July and August were presented. While the corridor of convection showed the expected association with the area of enhanced CAPE and relatively strong northwesterly-westerly shear, the strongest association was to the exit region of the LLJ. At the northern terminus of the LLJ convergence and lifting is enhanced, particularly when there is a preexisting frontal boundary. The deformation flow at the terminus of the LLJ can also be strongly frontogenetic and can lead to enhanced vertical motions. The nocturnal maximum in convection in the central plains is a combination of convection propagating into the region from the eastern slopes of the Rockies and that forced locally by the LLJ. As the strength of the LLJ increases, a greater percentage of the convection is locally forced and the rainfall increases. Strong (weak) LLJs are associated with negative (positive) 900-hPa height anomalies in the lee of the Rocky Mountains and positive (negative) anomalies in the southeast. The results also showed a strong sensitivity to the strength of the low-level wind shear. For days that had low shear ( $<10 \text{ m s}^{-1}$ ) the number of long-lived propagating convective events was much reduced and the convection that did develop was locally forced near the time of solar heating maximum and was short-lived.

The analyses here were limited to the months of July and August, the period when synoptic-scale disturbances are usually weak. No attempt was made to restrict the analysis to days with weak forcing. Thus it is inevitable that a few days of strong forcing were included in the analysis. Nevertheless the corridor of convection is strongly tied to the exit region of the LLJ. The lack of propagating convection south of the corridor is for several reasons. The low-level flow south of the LLJ is strongly divergent (implying subsidence); hence convection is suppressed. Second, the shear vector is northerly and not conducive for eastward-propagating convection. Finally the steering flow at the midlevels is generally weak, making it difficult for convection to advect eastward. North of the corridor, the air tends to be cooler and dryer and is generally less favorable for the development and maintenance of con-

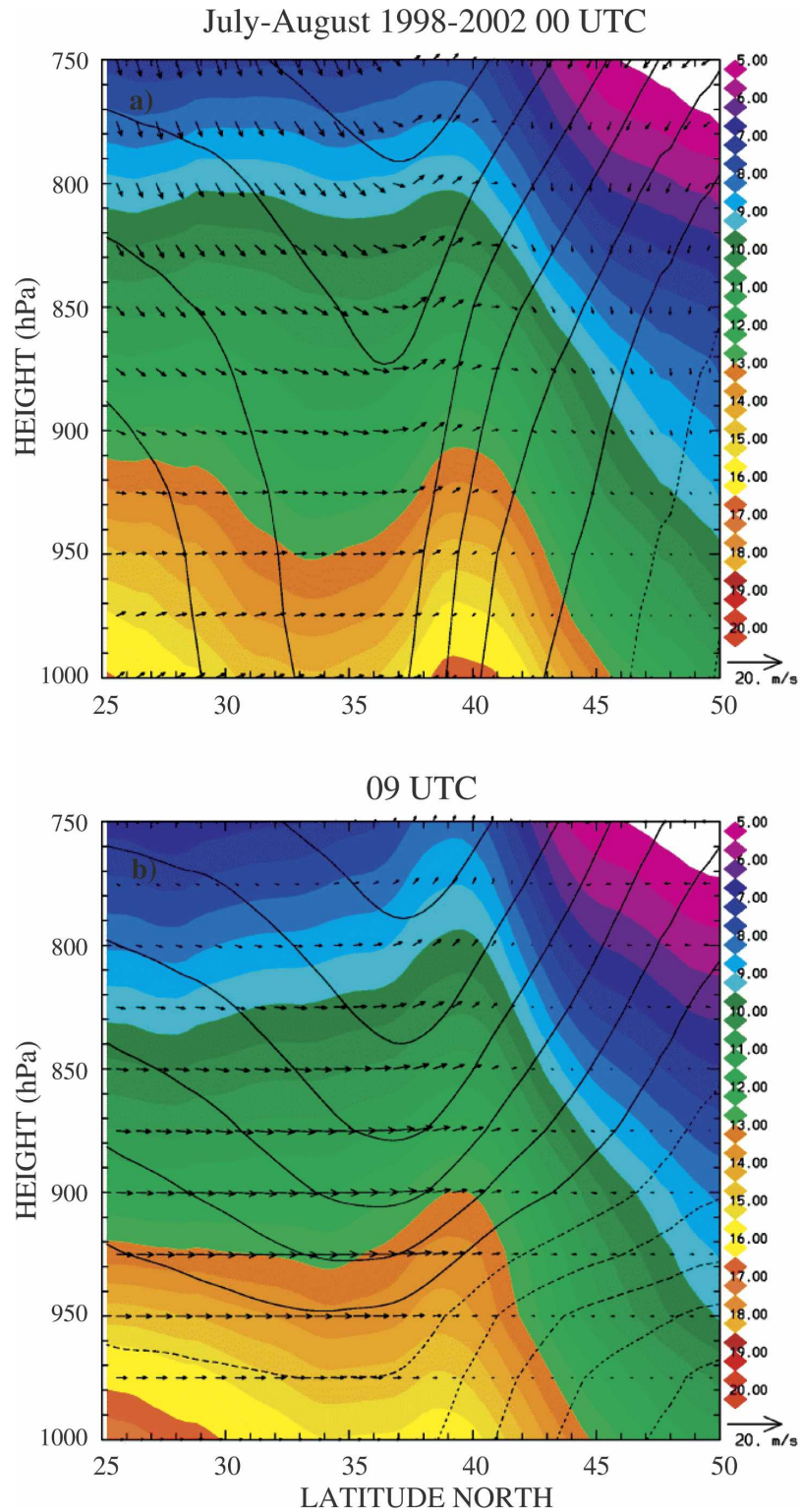


FIG. 15. Five-year averaged height-latitude sections of mixing ratio (color),  $v$  and  $w$  winds (vectors), and  $\theta$  (contours) for (a) 0000 and (b) 0900 UTC. Contours of  $\theta$  of  $300^\circ$  and colder are dashed; contours warmer than  $300^\circ$  are solid. Contour interval is  $2.0^\circ$ .



vection. Thus on average there is a relatively narrow corridor favorable for the development of long-lived propagating convection.

Of the days that had measurable convection, approximately two-thirds had only one centroid; that is, convection was not very widespread north–south. The exceptions (remaining one-third of convective days) to this are those situations when strong southerly low-level flow is present farther north in the central plains. This was due to a northward expansion of the subtropical southeastern U.S. high and lee troughing east of the Rocky Mountains. Under these conditions convection is more widespread with a secondary maximum of rainfall located several hundred kilometers north of the primary. However, even in these cases, the primary rainfall maximum is located near the northern terminus of the LLJ.

Of paramount importance to the QPF problem is the persistent corridor lasting several days. Persistent corridors were found to be associated with an east–west stationary front just to the south and a surface high pressure several hundred kilometers to the north. Convection was found to travel along and just to the north of the stationary front.

In this study the concentration was on the 95°–100°W longitude band. Because of the widely varying topography of the United States it is expected that different environmental factors will come into play in different regions. Future work will include doing the same analysis in a succession of 5° wide bands from the Rocky Mountains to the East Coast. Even a cursory look at Fig. 1 reveals that very different mechanisms are operating in the three bands between 110° and 95°W. By doing the analysis in different bands, it is expected that a more complete understanding of what environmental factors are important in each region will be obtained.

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