Quasi-Stationary, Extreme-Rain-Producing Convective Systems Associated with Midlevel Cyclonic Circulations

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(Manuscript received 11 June 2008, in final form 13 October 2008)

ABSTRACT

This study identifies and examines the common characteristics of several nocturnal midlatitude mesoscale convective systems (MCSs) that developed near mesoscale convective vortices (MCVs) or cutoff lows. All of these MCSs were organized into convective clusters or lines that exhibited back-building behavior, remained nearly stationary for 6–12 h, and produced locally excessive rainfall (greater than 200 mm in 12 h) that led to substantial flash flooding. Examination of individual events and composite analysis reveals that the MCSs formed in thermodynamic environments characterized by very high relative humidity at low levels, moderate convective available potential energy (CAPE), and very little convective inhibition (CIN). In each case, the presence of a strong low-level jet (LLJ) and weak midlevel winds led to a pronounced reversal of the wind shear vector with height. Most of the MCSs formed without any front or preexisting surface boundary in the vicinity, though weak boundaries were apparent in two of the cases. Lifting and destabilization associated with the interaction between the LLJ and the midlevel circulation assisted in initiating and maintaining the slow-moving MCSs. Based on the cases analyzed in this study and past events described in the literature, a conceptual model of the important processes that lead to extreme rainfall near midlevel circulations is presented.

1. Introduction

The prediction of warm-season precipitation, and in particular heavy rain events that can result in damaging flash flooding, remains one of the greatest challenges in operational forecasting (e.g., Fritsch and Carbone 2004). In the warm season in the United States, most heavy rainfall events are associated with mesoscale convective systems (MCSs; Schumacher and Johnson 2005, 2006). Most of these MCSs occur in “weakly forced” synoptic-scale environments, and a variety of mechanisms can initiate, organize, and maintain them. These forcings include surface fronts (e.g., Sanders 2000), con-ceptively generated outflow boundaries (e.g., Maddox et al. 1979), and orographic lifting (e.g., Pontrelli et al. 1999). However, in some cases, quasi-stationary MCSs develop when there are no apparent surface boundaries present prior to the initiation of convection (e.g., Schumacher and Johnson 2008, hereafter SJ08). These systems can provide a particular challenge to forecasters, because there is no obvious focusing mechanism for the forecaster to key in on. Regardless of the forcing, important factors for the production of extreme local rainfall by MCSs include slow system motion and the organization of deep convection such that “echo training” can occur (Chappell 1986; Doswell et al. 1996).

In some of the cases where preexisting surface boundaries are absent, another prominent forcing mechanism is at work: the midlevel mesoscale convective vortex (MCV; Bartels and Maddox 1991). A number of papers (Bosart and Sanders 1981; Zhang and Fritsch 1987; Fritsch et al. 1994; Trier and Davis 2002; SJ08) have investigated individual cases of flash-flood-producing
rainfall occurring in conjunction with an MCV. Nielsen-Gammon et al. (2005) examined another event in which a convectively reinforced midlevel PV anomaly that originated from a cutoff low contributed to the development of heavy rainfall. The work of Raymond and Jiang (1990) and Trier et al. (2000a) helped to elucidate why MCVs, which typically outlive the MCSs that spawned them, are often responsible for generating new convection on subsequent days. Raymond and Jiang showed that a midlevel vortex in a vertically sheared environment lifts air on its downshear side, and Trier et al. demonstrated that these motions also help to destabilize the environment by lifting moist and conditionally unstable air to saturation. When the direction of the shear vector opposes the direction of the (usually weak) ambient flow, as was the case in the events studied by Fritsch et al. (1994), Trier and Davis (2002), and SJ08, the resulting convection tends to develop near the location of the vortex center and to move slowly.

The synoptic and mesoscale environments in which MCVs typically develop have been well documented (e.g., Bartels and Maddox 1991; Trier et al. 2000b), as have the characteristics of MCVs that go on to initiate subsequent convection (Trier et al. 2000b). However, motivated by the commonalities between some of the previously studied events, as well as by several recent events of note, we will attempt herein to synthesize the characteristics of that subset of MCVs and other midlevel circulations that assist in initiating extreme-rain-producing convection. In Schumacher and Johnson (2005), extreme rain events were defined as those exceeding the 50-yr recurrence interval for 24-h rainfall, but the events considered in the present study generally produced rainfall amounts that far surpassed that threshold. The results to be presented will establish that there are several characteristics common to such extreme rain events associated with midlevel vortices, including the presence of a low-level jet (LLJ).

Additionally, the idealized findings of Raymond and Jiang (1990) and Trier et al. (2000a) do not address another important component of extreme local rainfall production: the organization of the convective system. The organization is crucial in determining whether the MCS will produce smaller rainfall amounts over a large area or extremely large rainfall amounts over a local area that can lead to a flash flood threat. The MCSs to be discussed herein were all organized similarly to the "back-building/quasi-stationary" pattern of organization discussed by Schumacher and Johnson (2005). This pattern consists of a line or cluster of deep convection in which new convective cells form upstream of their predecessors [i.e., the motion of convective cells opposes the motion from propagation; Corfidi (2003)]. However, as will be shown, these events occurred in environments with high relative humidity (RH) that were not conducive to the production of strong convectively generated cold pools. Such cold pools (i.e., density currents) are typically the cause for linear organization in MCSs (e.g., Rotunno et al. 1988; Parker and Johnson 2004), but the fast propagation speeds of MCSs driven by the progressive parts of strong cold pools make them less favorable for large rainfall amounts over a localized area. As such, understanding the mechanisms that lead to linear organization and slow system motion is an important research area. This study, along with a companion manuscript showing the results of idealized numerical simulations (Schumacher 2009, hereafter S09), will demonstrate some of the key processes responsible for initiating, organizing, and maintaining extreme-rain-producing convective systems.

2. Data and methods
   a. Identification of events

Six extreme rainfall events associated with midlevel circulations will be the focus of this study, and they were identified in several ways. They may not span the full range of variability of events of this type, but they were identified by the authors as having many similarities such that some patterns began to emerge. Other similar events have likely occurred in the past, but it is unclear how frequently they occur. Some details about the events are shown in Table 1. Two of the cases have been described previously in the literature [27–28 May 1998, Trier and Davis (2002); 6–7 May 2000, SJ08]. Two (5–6 May and 3–4 June 2000) were part of the authors’ investigation of extreme rain events in Schumacher and Johnson (2005). And two were very recent events (18 June and 20 August 2007), which occurred during the anomalously wet summer of 2007 in the southern plains of the United States. All six events have several similarities:

- gauge-observed rainfall accumulation greater than 200 mm (7.9 in.) in less than 12 h;
- the heavy rainfall was produced by organized convective systems, all of which fit the back-building/quasi-stationary pattern described by Schumacher and Johnson (2005) for at least a portion of their lifetime cycles;
- the presence of a preexisting midlevel circulation near where the convective system developed; and
- significant flash flooding resulting from the rainfall.

These events have much more in common, which will be demonstrated in section 3.
b. Data sources and analysis methods

Observations and analyses from several sources will be shown in the following section. Among these datasets will be the following:

- rain gauge observations from both the National Weather Service (NWS) Cooperative Observer Program (COOP) high-resolution 24-h gauge network and from the hourly precipitation dataset (HPD);
- Rapid Update Cycle (RUC; Benjamin et al. 2004) hourly analyses, which have horizontal grid spacings of approximately 40 km and have been interpolated to pressure levels with 25-hPa spacings between 1000 and 100 hPa;
- level 2 and 3 base radar reflectivity data from Weather Surveillance Radar-1988 Doppler (WSR-88D);
- National Centers for Environmental Prediction (NCEP) operational model precipitation forecasts from the Eta/North American Mesoscale (NAM) model on a grid with 40-km horizontal grid spacing;
- NCEP gridded rainfall observations, including the stage IV multisensor product and gauge observations analyzed on a 4-km horizontal grid;
- representative radiosonde observations, when available (the soundings taken at the 0000 and 1200 UTC observing times are often not representative of the environment between observations, especially in cases such as these where a nocturnal LLJ is present; also, the combination of the sparse radiosonde network and the localized nature of the convective systems makes it difficult to find truly representative soundings); and
- storm reports from the National Climatic Data Center’s online storm events database (information online at http://www4.ncdc.noaa.gov/cgi-win/wwcgi.dll?wwEvent~Storms).

To show the important features in these events, data from individual events will be presented, as will the results of a composite analysis on the RUC analyses. Though the RUC analyses are not without problems, they have been shown to be relatively accurate in capturing the thermodynamic environment near convection (Thompson et al. 2003) as well as MCV circulations (Davis et al. 2002). To perform the composite analysis, hourly precipitation observations were used to identify the location and time of the heaviest rainfall observed in each event. Then, a $41 \times 41$ grid point domain (approximately $1640 \text{ km} \times 1640 \text{ km}$) centered at the RUC grid point nearest the heaviest rainfall location was created for each event, and these grids were averaged to create the composites shown in section 3. Composite grids for the hour of heaviest rainfall, as well as 12 and 6 h prior to and 6 h after the heaviest rainfall, were created. This composite technique was generally the same as that used in Schumacher and Johnson (2005), except that the domain used in this study is larger, and there was no need to rotate any of the grids because the convective systems were all oriented generally west to east (section 3).

3. Description of the extreme rain events

In this section, a very brief overview of each event is presented. For each event, an upper-level synoptic analysis at 0000 UTC (typically 2–4 h before convection initiation) and a radar image at the time of peak rainfall will be shown, along with any other notable details as applicable. This will set the stage for the composite analysis in the next section. (Maps showing the distribution of rainfall in these events will be shown later in section 6; readers interested in these data may wish to look ahead to Fig. 15 while examining the other data from each case.)

a. 27–28 May 1998

A thorough investigation of the 27–28 May 1998 MCS was presented in Trier and Davis (2002) and Davis and Trier (2002); we include it in this study because it fits the pattern of MCV-related extreme rain events and because it has been well documented in the literature. In this event, a strong MCV developed within the stratiform region of an MCS in central Texas early on 27 May 1998. This vortex drifted eastward through the day on 27 May, and by 0000 UTC\(^1\) 28 May it was located over northeastern Texas (Fig. 1a). Around this time, new convection initiated near the vortex, and it eventually organized into a back-building, quasi-stationary MCS (Fig. 1b). [This was the MCS labeled “S2” by Trier and

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\(^{1}\) For all of these cases, 0000 UTC corresponds to 1900 local daylight time.
FIG. 1. Observations of each of the six extreme rain events. (left) Absolute vorticity averaged over the 700–500-hPa layer (10^{-5} m s^{-1}), shaded every 2 × 10^{-5} m s^{-1} for values above 12 × 10^{-5} m s^{-1}), 600-hPa heights (thick lines contoured every 30 m), and winds (vectors, m s^{-1}, with vector length scale indicated at the bottom) from the RUC analysis. (right) Base radar reflectivity (dBZ), surface observations (conventional; temperatures and dewpoints in °C), and objective analysis of pressure corrected to sea level (contoured every 1 hPa). Dates, times, and radar sites shown are (a) 0000 UTC 28 May 1998; (b) Shreveport, LA, radar at 0956 UTC and surface observations at 1000 UTC 28 May 1998; (c) 0000 UTC 6 May 2000; (d) Tulsa, OK, radar at 0859 UTC and surface observations at 0900 UTC 6 May 2000; (e) 0000 UTC 7 May 2000; and (f) St. Louis, MO, radar at 0659 UTC and surface observations at 0700 UTC 7 May 2000; (g) 0000 UTC 4 Jun 2000; (h) Dallas–Fort Worth, TX, radar at 0759 UTC and surface observations at 0800 UTC 4 Jun 2000; (i) 0000 UTC 18 Jun 2007; (j) Dallas–Fort Worth radar at 1056 UTC and surface observations at 1100 UTC 18 June 2007; (k) 0000 UTC 20 Aug 2007; and (l) Springfield, MO, radar at 0959 UTC and surface observations at 1000 UTC 20 August 2007. In (g), the vorticity field is averaged over the 750–550-hPa layer and heights and winds are at 650 hPa. The locations of the maps in the right column are shown by the dotted rectangles in the maps in the left column.
Fig. 1. (Continued)
Davis (2002).] Trier and Davis (2002) noted the presence of a weak near-surface baroclinic zone to the south of the vortex that may have provided additional forcing for the initiation of the MCS. This MCS produced very heavy rainfall in extreme northeastern Texas and southwestern Arkansas, with a maximum report of 262 mm (10.30 in) at Nashville, Arkansas. Many homes, businesses, and roads in the Texarkana area were flooded, resulting in $1.9 million in damage. In animations of the radar reflectivity (not shown), the strong cyclonic circulation of the MCV was evident in the stratiform precipitation region. At the surface (Fig. 1b), a weak low pressure center was located just to the west of the convective line, and an associated mesoscale cyclonic circulation surrounded the MCS. This convective system in turn assisted in reintensifying the vortex, which went on to spawn additional convection on subsequent days.

b. 5–6 May 2000

The 5–6 May 2000 heavy-rain-producing MCS occurred in conjunction with a strong MCV that had existed for several days prior to this event. It began as a cutoff low within a large-scale blocking pattern over the southern plains, and was responsible for initiating convection each afternoon and evening, which then reinforced the vortex’s circulation (see Fig. 2 of SJ08 for a figure showing the MCV’s evolution.) By 0000 UTC 6 May 2000, the MCV was located over northeast Oklahoma (Fig. 1c), and it proceeded to assist in the initiation of convection in that area. Surface observations (Fig. 1d) showed nearly saturated conditions and 5–10 m s$^{-1}$ southeasterly flow. As the convection developed, it was scattered at first but then organized into several lines and clusters (Fig. 1d) that produced rainfall amounts exceeding 200 mm and flash flooding in several areas of northeast Oklahoma. The flooding caused over $9M in damage and one fatality. The evolution of the MCS’s organization was complex, with aspects of it resembling the leading stratiform (LS) and trailing stratiform (TS) types of Parker and Johnson (2000), as well as the training line/adjoining stratiform (TL/AS) and back-building/quasi-stationary (BB) patterns described by Schumacher and Johnson (2005) at different stages of its life cycle.

c. 6–7 May 2000

After contributing to heavy rainfall and flash flooding in Oklahoma on the night of 5 May and the morning of 6 May, the MCV reintensified and moved eastward to central Missouri by the evening of 6 May. At 0000 UTC 7 May, the vortex was centered over Missouri (Fig. 1e) and again contributed to the initiation of deep convection around 0300 UTC. This convection organized into a west-to-east-oriented cluster of convection that remained nearly stationary through 1200 UTC (Fig. 1f). Over 300 mm of rain fell in this 9-h period in east-central Missouri, which led to devastating flooding in the towns of Washington and Union, Missouri. The flash flooding caused two fatalities and over $100M in damage. Associated with the development of the MCS was the appearance of a surface mesolow and pressure trough upstream of the deep convection (Fig. 1f). This and other processes involved in this quasi-stationary MCS were described in detail in SJ08 and Glass et al. (2001).
Fig. 3. RUC analyses of equivalent potential temperature ($\theta_e$, K, shaded), winds, and isotachs (m s$^{-1}$) for each of the six events at the time of peak rainfall, which are the same times shown in the right column of Fig. 1. Panel (b) shows these fields at the 850-hPa level; all other panels show the 900-hPa level. The location of the maximum midlevel vorticity is also noted with an “X” in each panel. The shading scale for $\theta_e$ is shown to the right of each map and varies from panel to panel.
d. 3–4 June 2000

Similar to the events of 5–7 May 2000, the synoptic pattern leading up to the 3–4 June 2000 event involved a midlevel low that moved slowly eastward, helped to initiate convection each day, and was subsequently intensified by that convection. This low moved from Mexico into west Texas on 1 June 2000 (not shown) and slowly drifted northeast such that it was located over north Texas as a positively tilted trough at 0000 UTC 4 June 2000 (Fig. 1g). Unlike the previously discussed cases, the midlevel circulation was not an MCV per se, in that it was not entirely formed via convective processes, and it had much weaker vorticity compared with those events. Nonetheless, deep convection initiated within the circulation around 0000 UTC 4 June, and organized within a few hours to an extreme-rain-producing back-building MCS. By 0800 UTC (Fig. 1h), the convective line was located just to the south of the Dallas–Fort Worth, Texas, metroplex. Surface observations revealed moist conditions with a developing pressure trough oriented from southwest to northeast, which may have also played a role in the initiation and organization of deep convection. Winds were southerly to the south of the trough, and they switched to southeasterly and easterly on the north side of the trough. A mesolow was present to the south of the convective line, but it is unclear whether this feature was convectively generated. The quasi-stationary convective line produced heavy rain over parts of north Texas, with a maximum rainfall total of 281 mm (11.08 in) at Cresson, just to the southwest of Fort Worth. Four people were killed and over 100 homes were damaged in the resulting flooding (USA Today 2000).

e. 18 June 2007

The 18 June 2007 extreme-rain-producing MCS also occurred in association with a convectively reinforced cutoff low over the southern Great Plains. This low cut off from the main branch of upper-level flow on 13 June 2007 over the Rocky Mountains, and slowly moved toward the southeast over the next several days. By 0000 UTC 18 June, the circulation was a hybrid between the synoptic cutoff low and an MCV located over north Texas and southern Oklahoma (Fig. 1i). The surface flow was southerly with no discernible boundaries prior to convection initiation at around 0400 UTC. After this time, scattered convection developed over north Texas, and it organized into a quasi-stationary convective system.

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2 Media reports are cited where the NCDC storm reports are incomplete or unavailable.
over the next few hours. This convective system was much smaller than those previously discussed (Fig. 1j), with the convective line throughout most of its life cycle being shorter than the 100-km threshold for MCSs proposed by Parker and Johnson (2000). Nonetheless, the convective line was responsible for localized extreme rainfall, with a maximum rainfall amount of 203 mm (7.99 in) at Gainesville, Texas. This area had received well-above-normal rainfall in the months leading up to this event, and as a result the cities of Gainesville and Sherman suffered substantial flooding. Six fatalities, over 500 flooded homes, and over $75 million in damage were reported in this event.

f. 20 August 2007

The origin of the midlevel circulation in the 20 August 2007 case was different from those previously discussed: it was the remnants of Tropical Storm Erin, which made landfall in south Texas on 16 August, turned northward, and then traversed eastward across Oklahoma and Missouri. The remnant surface low and associated convection intensified while over Oklahoma on 19 August and produced heavy rainfall in parts of Oklahoma on that day. Later, the surface low dissipated and the circulation was primarily confined to midlevels with a structure similar to an MCV. At 0000 UTC 20 August 2007, the vortex was located over southwestern Missouri (Fig. 1k), and deep convection initiated in that region around 0600 UTC. Again, no surface boundaries were apparent prior to the convection. By 1000 UTC (Fig. 1l), a weak pressure trough was present to the west of the deep convection, but analyses at other times did not show this feature. A weak north–south temperature gradient also existed at this time, partially due to the

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**Fig. 5.** Composite of 600-hPa absolute vorticity ($\times 10^{-5}$ s$^{-1}$, shaded every $2 \times 10^{-5}$ s$^{-1}$ for values above $12 \times 10^{-5}$ s$^{-1}$), 900-hPa winds (short barb, 2.5 m s$^{-1}$; long barb, 5 m s$^{-1}$), and isotachs (thick contours every 3 m s$^{-1}$ beginning at 9 m s$^{-1}$) for the six extreme rain events at (a) 12 h prior to peak rainfall, (b) 6 h prior to peak rainfall, (c) peak rainfall time, and (d) 6 h after peak rainfall.
presence of a cold dome beneath the vortex and warm advection from the south. The convection organized into a west-to-east-oriented back-building MCS (Fig. 11) that remained nearly stationary through approximately 1500 UTC. This MCS produced a maximum of 266 mm (10.5 in.) of rain in the town of Miller, Missouri. The resulting flood caused one fatality and over $18 million worth of damage, primarily to roads.

4. Similarities among the cases

Several prominent similarities emerged among the six aforementioned extreme rain events:

- All of the events were nocturnal, with the heaviest rain generally falling between 0700 and 1100 UTC (0200 and 0600 local time). The average amount of time between the onset of heavy rainfall and the dissipation of the extreme-rain-producing MCS was 12 h, though the majority of the rainfall generally fell in a period shorter than 12 h.
- The extreme rainfall was highly localized.
- In four of the convective systems, no fronts or other preexisting surface boundaries were present. Two of the events occurred near weak surface boundaries. In at least three of the cases, a surface mesolow was observed on the upstream side of the convective system.

In the interest of space, additional synoptic and mesoscale conditions associated with the individual events have not been shown. Furthermore, as discussed previously, radiosonde observations that are truly representative of the environment were not always available. However, three soundings deemed reasonably representative are shown in Fig. 2. These observed soundings and investigations of RUC analyses for each case reveal several additional similarities:

- Each convective system developed in association with an LLJ and relatively weak midlevel flow. As a result, the wind shear vector reversed direction sharply with height; this shear reversal is illustrated by a “hairpin” shape in a wind hodograph (Fig. 2).
- The lower troposphere exhibited high values of precipitable water and RH in the region of convective development.
- According to the soundings as well as RUC analyses of convective inhibition, the area beneath the midlevel circulation had been destabilized relative to surrounding areas.

The position and strength of the LLJ in relation to the midlevel vortex in each case are shown in Fig. 3. The maximum wind speeds within the LLJ varied from case to case, from approximately 12 m s$^{-1}$ in the 27–28 May 1998 (Fig. 3a) and 3–4 June 2000 (Fig. 3d) cases to over 24 m s$^{-1}$ in the 5–6 and 6–7 May 2000 events (Fig. 3b–c). Although there was case-to-case variability in LLJ strength, each convective system developed near the terminus of an LLJ, and, in particular, near where the LLJ was approaching the location of the preexisting mesoscale circulation. Figure 3 also illustrates that the LLJ in each case appears to be associated with the transport of air with high equivalent potential temperature ($\theta_e$) toward the heavy rainfall region. These and other features will be illustrated in the following section using composite analysis.
5. Composite analysis of synoptic and mesoscale conditions

The composite of the six events, calculated as described in section 2, shows a midlevel cyclonic vorticity maximum and height minimum located slightly to the north of the location of the heaviest rainfall (Fig. 4). The primary kinematic features responsible for the development of deep convection are this circulation and a nocturnally enhanced LLJ. In the hours leading up to the extreme rainfall, the circulation moved eastward and interacted with increasing southerly low-level winds (Figs. 5a and 5b). By the time of the heavy rainfall, the nose of the LLJ with wind speeds exceeding 15 m s\(^{-1}\) was almost directly below the vortex (Fig. 5c), and both of these features were very near the extreme rainfall location. In the 6 h following the heaviest rainfall, the composite LLJ weakened as morning arrived, while the vortex intensified somewhat, reflecting the latent-heating effects of the convective system (Fig. 5d). This evolution of the LLJ and the midlevel vortex was common to all of the individual events as well, and the positions of the LLJ and midlevel vorticity in the composite are representative of those observed in the individual cases (cf. Fig. 3).

The observed hodographs previously shown in Fig. 2 had a hairpin shape, and the composite analysis of vertical wind shear shows a similar pattern. With northwesterly midlevel winds above the strong south-southwesterly LLJ, convection developing in this area would be interacting with vertical shear that changed directions sharply with height (Fig. 6). This shear structure is characteristic of strong, nocturnally enhanced LLJs (e.g., McNider and Pielke 1981; Whiteman...
et al. 1997). Corfidi et al. (1996) showed that the combination of an LLJ and weak midlevel flow is generally favorable for back-building convection.

The vertical structure of the composite vorticity maximum shows a deep, generally upright circulation (Fig. 7). In the 12 h prior to the heaviest rainfall, the composite vortex was maximized at approximately 500 hPa, with cyclonic vorticity extending through a deep layer (Figs. 7a and 7b). Twelve hours prior to the peak rainfall, there was a cold, moist dome of air beneath the circulation, with a well-mixed boundary layer away from the circulation where skies were generally clear (Fig. 7a). After this time, nocturnal radiational cooling led to the stabilization of the boundary layer outside of the circulation, and this in turn decreased the temperature gradient associated with the cold dome. Moist advection associated with the LLJ as well as radiational cooling increased the ambient low-level RH near the vortex. By the peak rainfall time (Fig. 7c), the surface temperature gradient associated with the daytime cold dome had weakened considerably, and a large area with RH > 90% was in place. Six hours after the peak rainfall time, the cyclonic circulation had intensified considerably at midlevels and had weakened aloft (Fig. 7d), consistent with the diabatic redistribution of potential vorticity described by Haynes and McIntyre (1987). The evolution of the vertical structure of the circulation shown in the composite is generally consistent with the RUC analyses in all of the individual cases.

Isentropic lifting resulting from the vortex’s interaction with vertical wind shear can also be inferred from Figs. 7 and 8. Determining a single direction for the ambient shear (i.e., the shear the entire vortex is experiencing, as opposed to that affecting the convection on smaller scales) is not straightforward when the shear vector is turning sharply with height, and therefore determining the “downshear” and “upshear” directions is also difficult (e.g., Knievel and Johnson 2002). In the composite, low-level (between approximately 950–700 hPa) air was generally approaching the vortex from the south-southwest (i.e., from the left in Figs. 7 and 8a) and was rising along upward-sloping isentropes. There was also an area of downward motion on the north side of the vortex (Fig. 8b). This couplet of ascent and descent is consistent with the findings of Raymond and Jiang (1990) and Trier and Davis (2007) for a vortex in northerly midlevel shear. In addition to the lifting on the southwest side of the vortex, there was additional forcing for ascent provided by convergence at the nose of the strengthening LLJ (Figs. 5, 8b, and 9). Leading up to the heavy rainfall time, there was a persistent convergence maximum between around 950 and 800 hPa, which increased in magnitude with time as the LLJ strengthened (Figs. 9a–c). At the peak rainfall time, the composite shows a large area of ascent (part of which may be a reflection of deep convection in the RUC analyses) near the vortex center above a broad convergence maximum, with a maximum of divergence in the upper troposphere (Fig. 9c). This ascent continues for several hours after the peak rainfall (Fig. 9d). The combined lifting from the vortex in shear and from low-level convergence was also contributing to the aforementioned increase in low-level RH (e.g., Trier et al. 2000a). These factors made the region near the center of the circulation increasingly favorable for the
development of the deep convection that was observed in the individual cases. The nearly saturated conditions also prevent the development of strong cold pools with deep convective activity. The effect on convection of this lifting, the strong reversal of shear with height, and the very moist environment are examined in idealized simulations in S09.

As discussed above, vertical cross sections reveal minimal surface temperature gradients leading up to the time of peak rainfall, and composites of surface virtual potential temperature $\theta_v$ bear this out (Fig. 10). Six hours prior to the heaviest rainfall, the daytime cold dome is still apparent near the location of the midlevel circulation, but there are no additional thermal boundaries (Fig. 10a). By the time of peak rainfall there is a localized temperature gradient near the heavy rainfall location, which is located near a weak pressure trough and wind shift (Fig. 10b). This composite boundary is consistent with the observation of mesolows in some of the individual cases (Figs. 1b, 1f, and 1h), and with the weak preexisting boundaries observed in two of the other cases (Figs. 1a and 1d). Nonetheless, the temperature gradient across it is relatively weak, and its scale is quite small.

At the level of the LLJ, there were no notable features in this area 6 h prior to the peak rainfall (Fig. 11a). However, by the peak rainfall time (Fig. 11b) there is a band of strong $\theta_e$ advection, which is indicative of destabilization and has been cited as an important factor in previous studies of heavy rain events (e.g., Junker et al. 1999; Moore et al. 2003; Schumacher and Johnson 2005). The LLJ is also responsible for transporting additional moisture toward the region where heavy rainfall would occur (not shown). The differences between Fig. 11a and Fig. 11b emphasize the important changes that take place in the 6 h leading up to the heavy rainfall, most of which are attributable to the nocturnal enhancement of the LLJ.
The evolution of the thermodynamic structure near the circulation (Fig. 12) illustrates the effects of the destabilization caused by a vortex in shear. In the afternoon prior to the heavy rainfall (Fig. 12a), the most-unstable convective available potential energy (MUCAPE) near the circulation is relatively limited (<1000 J kg\(^{-1}\)), and there is nonzero convective inhibition (CIN). However, as the evening progresses, the CIN beneath the vorticity maximum decreases considerably, with all of the CIN eroded by the time of peak rainfall (Figs. 12b and 12c). Though these values may reflect some effect of the representation of deep convection in the RUC analyses used to make this composite, the minimum in CIN beneath the circulation is quite striking and is consistent with the findings of Trier et al. (2000a). At the same time, the MUCAPE has increased to over 1500 J kg\(^{-1}\) in this region, as a result of vortex-related destabilization (Trier et al. 2000a) and positive \(\theta_e\) advection by the LLJ (Fig. 10b). These processes have created a relatively small region that is very favorable for deep moist convection. By 6 h after the peak rainfall time, a minimum in CIN under the vortex remains, though the values have increased somewhat, and there are smaller values of CAPE in this region at this time (Fig. 12d).

Based on an examination of these six cases, past case studies in the literature (e.g., Fritsch et al. 1994; SJ08), and the composite analysis shown above, the primary synoptic and mesoscale conditions and processes that lead to extreme-rain-producing MCSs near midlevel circulations are summarized in Fig. 13. Figure 13a illustrates the location of a convective system in relation...
to the LLJ and the midlevel circulation in a “plan view,” and Fig. 13b shows a southwest-to-northeast section through the convection and the vortex. Representative isentropes show upglide on the southwest side of the circulation and the development of deep convection in that region. Also of note in this cross section are the large region of nearly saturated air and the lack of a surface cold pool beneath the deep convection. A thorough analysis of the low-level thermal structure leading to the organization of convection is beyond the scope of this study, but is considered in the case study of SJ08 and the idealized numerical experiments in S09. The results of those studies suggest that a low-level gravity wave, instead of a cold pool, may often be an organizing mechanism in quasi-stationary MCSs.

The thermodynamic environment and wind profile in which the extreme-rain-producing convective systems occur are summarized in the composite sounding shown in Fig. 14. This sounding was calculated by averaging the RUC conditions at the grid point and analysis time nearest the heaviest rainfall for the six events. The composite sounding has similar characteristics to the three observed soundings in Fig. 2, and is also similar to the immediate inflow sounding shown in the simulation of SJ08 (their Fig. 16b). It also bears resemblance to the flash-flood sounding discussed by Davis (2001, his Fig. 12). Composite of MUCAPE (thick contours every 500 J kg\(^{-1}\) above 1000 J kg\(^{-1}\)) and most unstable convective inhibition (MUCIN; shaded as shown) for the six extreme rain events at (a) 12 h prior to peak rainfall, (b) 6 h prior to peak rainfall, (c) peak rainfall time, and (d) 6 h after peak rainfall. In the RUC analyses, the MUCAPE is the CAPE of the parcel with the largest buoyancy in the lowest 300 hPa of the model atmosphere; the MUCIN is the CIN for that same parcel.

3 To create the composite sounding, pressure level temperature, relative humidity, and zonal and meridional wind components from the RUC analyses were simply averaged together. Since there was relatively little variation in elevation at the locations of the six events, this method provided reasonable results, and the composite sounding compares favorably to the observed soundings and to the composite CAPE and CIN.
Fig. 13. Schematic diagrams showing important processes in the development and maintenance of extreme-rain-producing convective systems associated with midlevel circulations. (a) Plan view. A schematic representation of the radar reflectivity structure of an MCS is shown in color, in relation to the location of a midlevel vorticity maximum (dark gray shading and curved arrows). The thick dashed curve indicates the flow in the upper troposphere (e.g., 250 hPa). Thick black arrows show the location of an LLJ, and the light gray shading shows the location of high-$\theta_e$ air at low levels (e.g., 925–800 hPa). (b) Southwest-to-northeast cross section. Representative isentropes (every 5 K) are shown by the thin black lines; the wind profile (including LLJ) is shown by the vectors on the left. A reference vector and length scale are shown at the bottom. Green shading indicates areas with relative humidity > 90%; gray shading indicates high values of absolute cyclonic vorticity. The thick dashed arrow shows air approaching the circulation from the southwest, which is undergoing isentropic upglide and destabilization.
The composite sounding is nearly saturated over a layer approximately 100 hPa deep, has relatively high RH throughout the column, and has precipitable water of 49 mm (1.92 in.). The high RH inhibits the development of strong storm-generated cold pools, and also contributes to very efficient precipitation processes (e.g., Market et al. 2003). For parcels lifted from near the surface there is substantial CIN, but elevated parcels have CAPE exceeding 1000 J kg\(^{-1}\) and no CIN. The hairpin hodograph is also evident, with a 15 m s\(^{-1}\) LLJ.

6. Quantitative precipitation forecasts from operational models

To illustrate the overall precipitation structure and distribution in these events and to emphasize the challenges in predicting such events, quantitative precipitation forecasts (QPFs) from operational numerical weather prediction models and observed precipitation analyses for each case are shown in Fig. 15. The forecasts shown are from the NCEP Eta/NAM model. This model had changes in grid spacing in 1998, 2000, and 2001 (Kain et al. 2008), but the forecasts shown in the left column in Fig. 15 have all been represented on the same grid, with 40-km horizontal grid spacing. All of these forecasts use parameterized, rather than explicitly predicted, deep convection.

Perhaps the most apparent result shown in Fig. 15 is that the operational models were unable to predict the magnitude of the extreme rainfall in any of the six cases. However, given the relatively coarse resolution of the model and the localized nature of the heavy rainfall in these cases, some of the underprediction can be attributed simply to the inability of the coarser grid to represent such small-scale variability. In some of the cases (e.g., 6–7 May 2000 and 18 June 2007; Figs. 15e,f and 15i,j), the model forecasts succeeded in predicting rainfall maxima in approximately the correct location. However, in others (such as 5–6 May and 3–4 June 2000; Figs. 15c,d and 15g,h), the model QPFs provided no
suggestion that heavy rain would occur in the location where it did.

Despite questionable guidance from numerical models, operational forecasters have shown awareness of the potential for heavy rainfall in these situations. For example, prior to the Gainesville flash flood on 18 June 2007, the National Weather Service forecast office in Fort Worth issued a particularly precise flash flood watch (and subsequent warnings) based on their analysis of the midlevel circulation interacting with a low-level jet and leading to focused isentropic ascent over north Texas. 4

A more complete verification study of heavy rainfall in association with midlevel circulations is beyond the scope of this study but is suggested for future research. This research could include coarsening the grid on which the observations are analyzed (shown on the right-hand side of Fig. 15) to obtain a more equitable comparison with the model forecasts, and an analysis of commonly used metrics for precipitation verification. In at least some cases (e.g., Davis and Trier 2002; SJ08), higher-resolution model configurations with explicitly predicted convection have been able to provide better forecasts and/or simulations of these types of extreme rain events, but it is unclear whether this would be consistently true for all such events. An examination of the predictability of the types of extreme rain events considered herein is another possible avenue for future work.

7. Summary and conclusions

In this study, six extreme rain events that were associated with MCVs or other midlevel circulations were

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**FIG. 15.** Comparison between 24-h quantitative precipitation forecasts from operational models and 24-h observed precipitation analyses for the six cases. (a), (c), (e), (g), (i), (k) The 0–24-h accumulated precipitation forecasts from the NCEP Eta/NAM, initialized at 1200 UTC the day before the extreme rainfall occurred. [For example, the forecast shown in (a) was initialized at 1200 UTC 27 May 1998; the extreme rainfall generally occurred between 0000 and 1200 UTC 28 May 1998.] (right) The gridded precipitation analyses for the same 24-h period. (b), (d), (f), (h) Use the NCEP gauge-only precipitation analysis, and (j), (l) use the NCEP stage IV analysis. Each panel shows an area of $10^5$ latitude $\times 6^5$ longitude. Precipitation values are in mm and are shaded as shown. The maximum values shown may vary from those given in Table 1 because of the use of different datasets.

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4The area forecast discussion from the Fort Worth Weather Forecast Office at 1935 UTC 17 June mentioned these features specifically, and a flash flood watch was issued at 2050 UTC 17 June for areas along and east of a line from Gainesville to Meridian to Waco.
discussed, and composite analysis was performed to identify the characteristics of the environments in which they formed. In each of the six events, deep convection was organized into back-building lines or clusters that remained nearly stationary. These convective systems occurred in the overnight hours, produced locally excessive rainfall, and led to flash flooding.

Examination of the individual events and composite analysis of RUC data showed that the six events were similar in many ways. The primary conclusions of this investigation are as follows:

- In each case, a strong LLJ interacted with a midlevel vorticity maximum, which provided the lifting and destabilization required to initiate and maintain deep convection.
- The presence of the LLJ and generally weak midlevel winds led to a strong reversal of the vertical wind shear with height. This type of wind profile appears as a “hairpin” shape in a wind hodograph.
- The thermodynamic environment near the deep convection was characterized by very high relative humidity at low levels, moderate convective available potential energy (CAPE), and very little convective inhibition (CIN).
- A brief analysis of operational model QPFs showed that model forecasts vary considerably for these events; in some cases, the model predicted rainfall in the correct place (though the amount was underpredicted); in other cases, model guidance provided no hint that heavy rain might occur.

In addition to the idealized simulations presented in the companion study (S09) that examine the meso- and storm-scale processes in these types of MCSs, the results of this work offer several possibilities for future research. First, it would be helpful to have a more general idea of how often such events occur, based on more objective methods for case selection so that the results presented in this study could be further generalized. Similarly, an analysis of how often the MCV–LLJ combination occurs but heavy rainfall does not result would provide additional information that could aid in forecasting such events (or nonevents). A more detailed analysis of surface observations could lend insights into the development of surface low pressure centers that were observed in at least three of the events. Finally, a set of idealized simulations could be designed to determine if there exists a configuration of the interaction between the LLJ and the midlevel circulation that is “optimal” for persistent, slow-moving deep convection.

Acknowledgments. The authors thank John Nielsen-Gammon, Wes Junker, and an anonymous referee for thorough reviews and suggestions that helped to significantly improve the manuscript. WSR-88D and precipitation gauge data were provided by the National Climatic Data Center, RUC analyses were provided by the Atmospheric Radiation Measurement (ARM) Program, and gridded precipitation data and model forecasts were provided by the National Center for Atmospheric Research. This research was supported by National Science Foundation Grant ATM-0500061.

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