Organization and Environmental Properties of Extreme-Rain-Producing Mesoscale Convective Systems

RUSS S. SCHUMACHER AND RICHARD H. JOHNSON

Department of Atmospheric Science, Colorado State University, Fort Collins, Colorado

(Manuscript received 7 April 2004, in final form 13 September 2004)

ABSTRACT

This study examines the radar-indicated structures and other features of extreme rain events in the United States over a 3-yr period. A rainfall event is defined as "extreme" when the 24-h precipitation total at one or more stations surpasses the 50-yr recurrence interval amount for that location. This definition yields 116 such cases from 1999 to 2001 in the area east of the Rocky Mountains, excluding Florida. Two-kilometer national composite radar reflectivity data are then used to examine the structure and evolution of each extreme rain event. Sixty-five percent of the total number of events are associated with mesoscale convective systems (MCSs). While a wide variety of organizational structures (as indicated by radar reflectivity data) are seen among the MCS cases, two patterns of organization are observed most frequently. The first type has a line, often oriented east–west, with "training" convective elements. It also has a region of adjoining stratiform rain that is displaced to the north of the line. The second type has a back-building or quasi-stationary area of convection that produces a region of stratiform rain downstream. Surface observations and composite analysis of Rapid Update Cycle Version 2 (RUC-2) model data reveal that training line/adjoining stratiform (TL/AS) systems typically form in a very moist, unstable environment on the cool side of a preexisting slow-moving surface boundary. On the other hand, back-building/quasi-stationary (BB) MCSs are more dependent on mesoscale and storm-scale processes, particularly lifting provided by storm-generated cold pools, than on preexisting synoptic boundaries.

1. Introduction

Flash flooding, defined as flooding that occurs within 6 h of its causative rainfall, is responsible for more fatalities in the United States each year than any other convective storm-related phenomenon, including tornadoes, hurricanes, and lightning [the National Oceanic and Atmospheric Administration (NOAA 2004a)]. This flooding usually occurs when a large amount of rain falls at a given location in a relatively short period of time. For such extreme rainfall to occur, certain atmospheric ingredients must be in place, regardless of location. Doswell et al. (1996, hereafter DBM96) note that the total precipitation at any point is directly proportional to the rate and duration of rainfall. The precipitation rate depends on the available moisture in the air, vertical motion, and precipitation efficiency, while the rainfall duration is related to the size and speed of the system as well as within-storm variations in rainfall intensity.

The synoptic and mesoscale atmospheric conditions most often responsible for bringing these ingredients together have been well documented in the literature. Maddox et al. (1979, hereafter MCH79) examined 151 flash flood events and determined that one of four patterns described each event: synoptic, frontal, mesohigh, or western. Glass et al. (1995), Junker et al. (1999), and Moore et al. (2003) used composite analysis to further elucidate the synoptic and mesoscale conditions associated with extreme precipitation, especially in Midwest events resulting from mesoscale convective systems (MCSs). These papers emphasized the importance of strong low-level winds (often in the form of a low-level jet) advecting warm, moist air into the region where the heavy rain falls. In addition, they found that extreme rainfall can be tied to the orientation of fronts and outflow boundaries, and that it often occurs in or near regions of low-level positive equivalent potential temperature (θ_e) advection and moisture convergence.

Large local rainfall totals often occur when deep convective cells (which typically produce large rainfall rates) are organized such that they move repeatedly over a given area, a process commonly called "echo training" (DBM96; Davis 2001). When the motion of the convective system is slow, the duration is increased even further. Since MCSs are quite common in the central part of the United States (e.g., Maddox 1980; Fritsch et al. 1986; Carbone et al. 2002), but extreme precipitation events are rare, it is obvious that the size, organization, and motion characteristics of MCSs are

Corresponding author address: Russ Schumacher, Department of Atmospheric Science, Colorado State University, Fort Collins, CO 80523.
E-mail: rschumac@atmos.colostate.edu

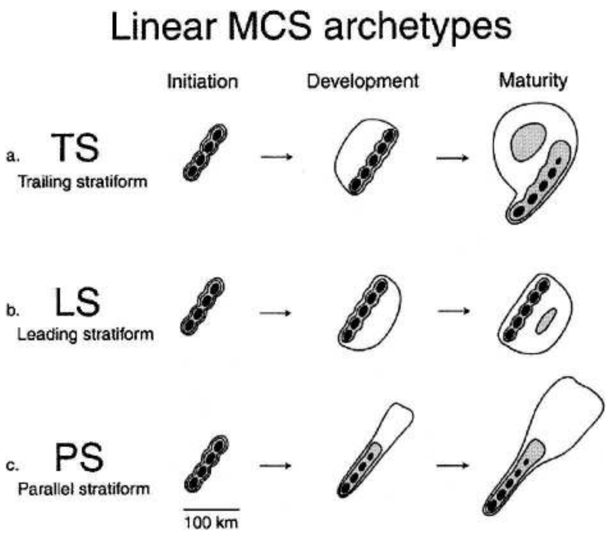


FIG. 1. Schematic reflectivity drawing of idealized life cycles for three linear MCS archetypes: (a) TS, (b) LS, and (c) PS. Approximate time intervals between phases: for TS 3–4 h; for LS 2–3 h; for PS 2–3 h. Levels of shading roughly correspond to 20, 40, and 50 dB*Z*. From Parker and Johnson (2000).

the key factors that determine whether they produce heavy rainfall.

DBM96 state that "virtually all flash floods are produced by MCSs," at least in terms of characteristics that can be observed by satellite. They also speculate that a radar depiction of flash-flood-producing MCSs "would probably show a linear organization in many cases." It is clear that MCSs are important producers of extreme rainfall, though these particular assertions have not been thoroughly tested in the literature.

In addition to MCSs, high-precipitation supercells have been observed to produce flash floods (Moore et al. 1995; Smith et al. 2001). Others have shown that extreme precipitation can result from both strongly and weakly forced synoptic systems (MCH79; Heideman and Fritsch 1988; Bradley and Smith 1994), from tropical storms and hurricanes (Davis 2001), and from terrain-forced convection (Petersen et al. 1999; Pontrelli et al. 1999).

Houze et al. (1990) found that linear MCSs are more likely to produce flash flooding than nonlinear ones in Oklahoma. Parker and Johnson (2000, 2004) identified and described the governing dynamics of three modes of linear MCSs that are common in the central plains—those with trailing stratiform (TS) precipitation, those with leading stratiform (LS), and those with parallel stratiform (PS; Fig. 1). They found that LS MCSs typically move more slowly than the other modes, and thus may be more conducive to extreme rainfall and flash flooding.

In this study, a Weather Surveillance Radar-1988 Doppler (WSR-88D)-based analysis of a large sample of extreme rain events over the eastern two-thirds of the United States is undertaken to document the types of weather systems responsible for extreme precipitation and determine their convective organization. Detailed climatological aspects of these events, such as their monthly and diurnal distributions, have also been analyzed and will be presented in a forthcoming paper.

In section 2, the data and methods used in the study are presented. Rain gauge data from a 3-yr period are then used to select extreme rain events across the United States. Composite radar reflectivity data are analyzed to observe the type of weather system responsible for the extreme rainfall in each case. This analysis shows that over 65% of the events are associated with MCSs, and two patterns of convective organization are most frequently observed. These patterns are described in section 3, and the synoptic and mesoscale conditions in which they typically occur are presented in section 4.

2. Data and methods

a. Selection of cases

Two sets of rain gauge data are readily available for use in selecting appropriate cases: observations from the National Weather Service (NWS) cooperative high-resolution 24-h network, and the hourly precipitation dataset (HPD). The benefit of the HPD for this type of study is that it can resolve the characteristics of convective rainfall on short time scales. However, since it would be advantageous to pinpoint a large number of events and neglect as few as possible, the NWS dataset will be used for case selection because it has far superior spatial resolution. To quantify the difference in spatial resolution, in the month of May 2001 the NWS network had 7923 active stations in the United States, while the HPD had 2707. [See Brooks and Stensrud (2000) for a climatology of heavy rain events using the hourly observations.] The region of study will be the part of the country east of the Rocky Mountains, excluding Florida. This region has generally good data coverage and is presumably where most MCS-related extreme rain events occur.

The objective in selecting cases for this study was to find a sample of events large enough that conclusions or generalizations about them may be meaningful, while ensuring that the events are truly significant for their location. To accomplish this, events were deemed "extreme rain events" when one or more gauges reported a 24-h rainfall total greater than the 50-yr recurrence interval amount (Hershfield 1961) for that location (Fig. 2). While these data may be outdated, at the time of the submission of this manuscript they still represent the current valid NWS data for rainfall frequency in the area of study (NOAA 2004b). In addition, we have chosen to use meteorological data for selecting cases and to focus on the meteorological aspects of these events, without regard for the hydrology of whether they caused flash flooding.

This threshold was applied over a 3-yr period (1999–

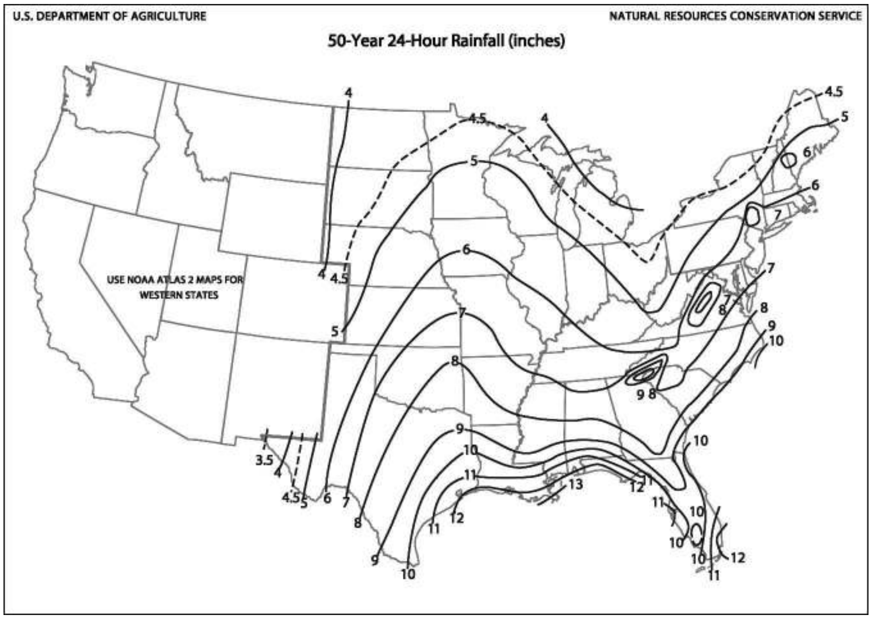


Fig. 2. Fifty-year frequency for 24-h rainfall (in.) in the United States. Adapted from Hershfield (1961); figure courtesy of the Natural Resources Conservation Service of the U.S. Department of Agriculture.

2001), and after eliminating bad rainfall data, it yielded 116 extreme rain events. Rainfall data were eliminated when there were no radar echoes in the area during the 24-h reporting period, or when radar and rain gauge data did not seem to match and no other documentation could be found to confirm that a large amount of rain actually fell in that area. For the purpose of this study, an "event" refers to a weather system that produces one or more rainfall observations over the given threshold. This typically represents all or part of the 24-h period in which the rainfall was reported. However, a single event can include multiple 24-h periods if the same weather system is responsible for the precipitation (e.g., a tropical cyclone that produces heavy rainfall over several states in a 2- or 3-day period).

b. *National composite radar reflectivity data*

Each extreme rain event's life cycle was observed using composite radar reflectivity data from the WSI Corporation NOWrad product. Data from the WSR-88Ds are used to generate this dataset, which has pixel resolution of 2 km $\times$ 2 km and temporal resolution of 15 min.

Each event was then classified as either an MCS, a synoptic system, or a tropical system, based on the radar observations. Convective systems (those with reflectivity greater than 40 dBZ) with areal extents greater than 100 km and with durations between 3 and 24 h were classified as MCSs, consistent with the criteria of Orlanski (1975) and Parker and Johnson (2000). Events characterized by the strong large-scale ascent commonly associated with synoptic-scale features (i.e., extratropical cyclones) and/or lasting longer than 24 h were classified as synoptic. Thus, long prefrontal squall lines and other convective systems that persisted for longer than 24 h were classified as synoptic systems rather than MCSs, though mesoscale aspects (and sometimes even individual MCSs) clearly played an important role in the heavy rainfall. The key distinction, when classification was difficult, was between systems that were clearly strongly forced on the synoptic scale and those that were not. Events were classified as tropical if they were the direct result of a tropical cyclone or its remnants. Synoptic and MCS events were then arranged into subclassifications based on their organizational structures and system evolutions, which will be discussed in section 3. Additionally, the times of peak rainfall at the location(s) reporting extreme rainfall totals were noted, using the radar reflectivity and cross-checking with hourly precipitation data where available.

c. *RUC analysis data*

To determine the synoptic and mesoscale atmospheric conditions in which the different types of extreme-rain-producing storms occur, composite analysis of 0-h Rapid Update Cycle Version 2 (RUC-2; Benjamin et al. 2004) model analyses was used. For the 1999–2001 time period, hourly RUC-2 analyses with horizontal grid spacing of 40 km are available. The composite analysis was performed using a 31 $\times$ 31 grid-point domain (approximately 1240 km $\times$ 1240 km) cen-

TABLE 1. Weather systems responsible for extreme rain events in the eastern two-thirds of the United States, excluding Florida. Numbers in parentheses represent the percentage of all extreme rain events associated with that storm type.

System	Total
MCS	76 (65.5%)
Synoptic	31 (26.7%)
Tropical	9 (7.8%)
Total	116 (100%)

tered at the grid point nearest the location of highest reported total rainfall. While most of the events that will be described herein were oriented approximately west–east, a few were oriented closer to north–south. For these few events, the composite domain was rotated 90° so that, for example, a north–south-oriented front would appear as a west–east-oriented front when averaged. The variables from the peak rainfall time (as described above) were averaged to create the composite maps shown in section 4.

While many atmospheric variables are included in the RUC-2 analyses, a few fields need to be calculated. To calculate θ_e on a constant pressure surface, the method of Bolton (1980) was used. Standard finite-difference methods were used to calculate the advection or divergence of certain variables. In the composite analysis, advection and convergence fields were calculated for each case, and then averaged (rather than calculated from the composite values of the wind and other variables).

3. Extreme-rain-producing storm types

As explained in the previous section, national composite radar data were used to classify each extreme rain event as synoptic, MCS, or tropical. In this sample of 116 extreme rain events, there were no cases that had a time or length scale shorter than that of an MCS. This analysis shows that over 65% of all extreme rain events considered were associated with MCSs, and that just over 25%were caused by synoptic weather systems (Table 1). These results help support the speculation of DBM96 and others that most extreme rain events and flash floods are caused by MCSs. Furthermore, several patterns of storm structure and organization were observed within these broad categories and will be discussed in greater detail below.

a. Tropical systems

While the overall percentage of tropical events was relatively low, there were two events that led to the most widespread and destructive flooding of the entire sample: Hurricane Floyd (1999) along the east coast, and Tropical Storm Allison (2001) in the Gulf Coast states. So while there may be relatively few extreme rain events associated with tropical cyclones, the potential for damage and injury is much greater when they do occur.

TABLE 2. Number of extreme rain events associated with the subclassifications of synoptic systems and MCSs.

Synoptic systems	Events	% of synoptic	% of all events
Convective	28	90.3%	24.1%
Nonconvective	3	9.7%	2.6%
Total	31	100%	26.7%
MCSs	**Events**	**% of MCSs**	**% of all events**
Training Line/Adjoining Strat. (TL/AS)	24	31.6%	20.7%
Backbuilding/Quasi-stationary (BB)	15	19.7%	12.9%
Trailing Stratiform (TS)	13	17.1%	11.2%
Other MCS	12	15.8%	10.3%
Parallel Stratiform (PS)	7	9.2%	6.0%
Multiple MCSs	3	3.9%	2.6%
Leading Stratiform (LS)	2	2.6%	1.7%
Total	76	100%	65.5%

b. Synoptic systems

While a thorough investigation of the precipitation features of extratropical cyclones and other synoptic systems that produce extreme precipitation is beyond the scope of this study, a description of some of the basic structures of these systems (as observed by radar) is warranted. Of the 31 extreme rain events classified as "synoptic," 28 (90%) were caused by deep convection that had strong synoptic forcing and was organized on the synoptic scale. These events often resulted in several states (Table 2). Some of these events were caused by long-lived, slow-moving squall lines, while others were associated with the repeated passage of convective systems for more than 24 h. The remaining three events were characterized not by widespread convection but by long-duration stratiform (i.e., radar reflectivity <40–45 dBZ) rain. Embedded convective rainfall sometimes contributed to the extreme rainfall totals in these events, but the persistent stratiform precipitation provided nearly all of the rainfall. Most of the convective synoptic events occurred in the warm sector of an extratropical cyclone ahead of a synoptic-scale cold front, while the nonconvective events occurred in the cool sector north of the warm front or the "wrap around" region to the north and west of the surface low pressure center.

c. Extreme-rain-producing MCSs

As previously discussed, one of the main purposes of this study is to determine how many extreme rain events are caused by MCSs and what types of MCSs are most often responsible for producing extreme rainfall.

After observing the radar data for all of the extreme-rain-producing MCSs, it was found that, as with all convective systems, their structures and evolutions were quite varied. However, several patterns of convective organization repeatedly emerged, which are summarized in Table 2.

When classifying the organizational structures of these MCSs, the main concern was the character of the system *during the time period when it was producing the extreme rainfall.* It is well documented that MCSs often transition between different modes of convective organization over the course of their lifetimes (e.g., Parker and Johnson 2000), and while other MCS classification studies have focused on the dominant organizational mode of the MCS (or the longest-lasting pattern), this study aims to determine the organization characteristics that make certain MCSs capable of producing abnormally large amounts of rain. If a system had a given structure for 3 or 4 h during which the extreme rainfall occurred, then persisted for 8 h more with a different organization (without extreme rain production), its structure would be classified as the former. Additionally, the evolution of the system (as seen from animating the radar images) is key to classifying and understanding these systems. As discussed in the introduction, it is not only the organization but also the motion of the system that determines whether a large amount of rain will fall at a given location.

Before describing the most common patterns of convective organization, some description can be made of the extreme-rain-producing MCSs that fit previously published MCS classification schemes. Many of the extreme rain events were caused by linear MCSs with the structures identified by Parker and Johnson (2000; Fig. 1), namely the TS, PS, and LS archetypes, which represented 17.1%, 9.2%, and 2.6%, respectively, of the MCS population (Table 2). The extreme-rain-producing TS MCSs usually had anomalous motion characteristics (rather than the more common line-perpendicular motion) that allowed them to produce extreme rainfall totals. For instance, some had bowed segments that allowed for periods where cell motion was parallel to the convective line. Similarly, PS MCSs are organized so that, given cell motion parallel to the line, a "training" line of convection will develop (Fig. 1). A few (3.9% of the MCS cases) were the result of multiple distinct systems (usually two) in the same 24-h period, where neither MCS alone would have produced enough rainfall to achieve the extreme rainfall threshold, but the combination of them did. Several (15.8% of the MCS cases) were associated with a convective system that met the definition of an MCS but did not conform to other MCS classifications in the literature. These were deemed "other MCSs." In these systems, the echo training or other behavior leading to the extreme rainfall often appeared to be fortuitous rather than well organized.

The two most frequently observed patterns, however, do not exactly fit any of the MCS archetypes appearing in the literature. The patterns have been classified and named in a manner consistent with the archetypes for linear MCSs presented by Parker and Johnson (2000) to minimize confusion over acronyms and abbreviations, and so that they can be compared and contrasted with systems fitting those archetypes.

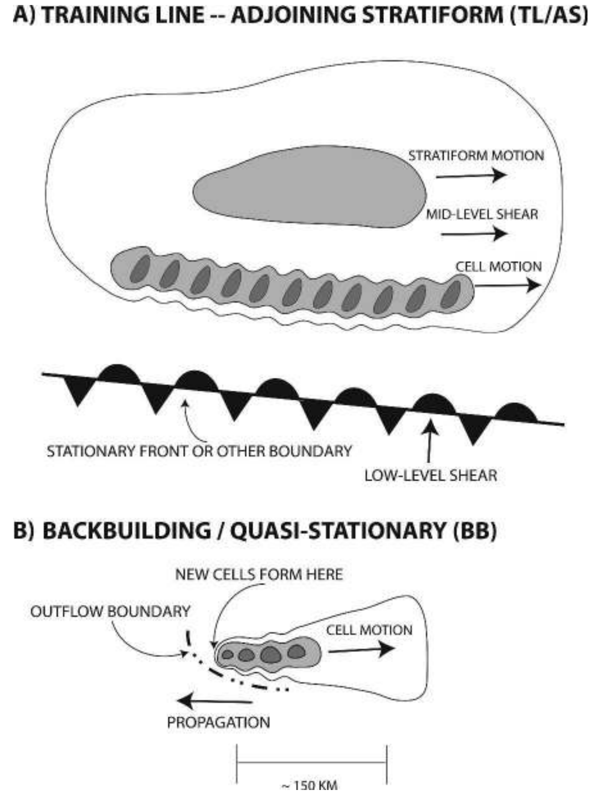


FIG. 3. Schematic diagram of the radar-observed features of the (a) TL/AS and (b) BB patterns of extreme-rain-producing MCSs. Contours (and shading) represent approximate radar reflectivity values of 20, 40, and 50 dB*Z*. In (a), the low-level and midlevel shear arrows refer to the shear in the surface-to-925-hPa and 925–500-hPa layers, respectively, as discussed in section 4. The dash–dot line in (b) represents an outflow boundary; such boundaries were observed in many of the BB MCS cases. The length scale at the bottom is approximate and can vary substantially, especially for BB systems, depending on the number of mature convective cells present at a given time.

The first, which will be termed "training line, adjoining stratiform," and abbreviated "TL/AS," is a linear MCS with cell motion approximately parallel to the convective line (Fig. 3a). These accounted for 31.6% of the MCS cases (Table 2). As the cells move in a line-parallel direction, there is very little motion in the line-perpendicular direction, which distinguishes them from the TS and LS archetypes. This combination of motion characteristics leads to prolonged heavy convective rainfall at locations along the line of convective cells (i.e., a training line). The convective elements within the line are often slightly canted with respect to the line-perpendicular direction, a characteristic that was

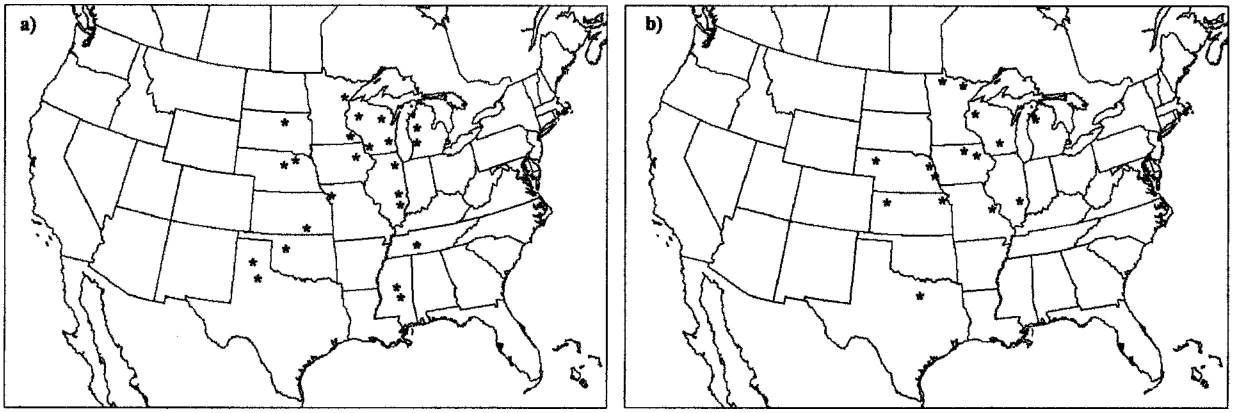


FIG. 4. Approximate locations of highest rainfall totals for (a) TL/AS and (b) BB MCS extreme rain events analyzed in this study.

also observed in MCSs by Houze et al. (1990) and Pettet and Johnson (2003) but has not been thoroughly explained.

As these MCSs develop, an area of stratiform precipitation typically forms adjacent to the convective line and moves in approximately the same direction as the line. TL/AS MCSs almost always form on the cool side of and approximately parallel to a slow-moving boundary, such as a warm front, stationary front, or remnant outflow boundary. The stratiform precipitation forms farther toward the cool side of this boundary. The overall structure of these MCSs is influenced by the directions of the low- and midlevel wind shears, which are typically at large angles to one another. This will be discussed in greater detail in the next section. The tendency for TL/AS systems to form in environments with largely line-parallel midlevel shear further differentiates them from the TS and LS archetypes, which Parker and Johnson (2000, 2004) have shown to occur in situations with strong line-perpendicular shear.

The second most common extreme-rain-producing MCS pattern is characterized by a line or cluster of quasi-stationary or back-building convection and will be abbreviated "BB" (Fig. 3b). BB MCSs, representing 20.0% of the MCS cases (Table 2), occur when convective cells repeatedly form upstream of their predecessors and pass over a particular area, leading to large local rainfall totals. Decaying cells move downstream and are replaced by cells reaching their mature stage, behavior that sometimes appears in radar data as an unmoving area of high reflectivity. This slow system motion can be explained by a "cancellation" or near-cancellation of the cell motion and propagation vectors, as described by Chappell (1986). BB MCSs tend to cover a smaller area than their TL/AS counterparts, but their potential for producing exceptionally high point rainfall totals is greater. The rainfall characteristics of each type will be discussed in a forthcoming paper on the climatological characteristics of these systems.

In some cases, a region of stratiform precipitation will develop downstream (similar to the PS archetype), but in others there is very little stratiform rain. Some BB systems form on the cool side of a preexisting boundary, which is sometimes a front but more frequently an outflow boundary left behind by previous convection. Others appear (in the datasets used for this study) to form without a discernible boundary nearby and are maintained by their own storm-generated outflow boundaries/cold pools. The environmental conditions associated with these MCSs will be discussed in more detail in section 4. While some of the features described above vary from case to case, the radar signatures of persistent back-building or quasi-stationary convection are common to all MCSs classified as "BB."

Of course, not all of the MCSs classified as "TL/AS" or "BB" (or as any other storm type, for that matter) correspond perfectly to the conceptual models shown in Fig. 3, and they sometimes take on different patterns through their lifetimes. For instance, several of the TL/AS MCSs transitioned into the TS mode after producing the locally heavy rain. When classifying leading-line, trailing-stratiform MCSs, Houze et al. (1990) noted whether each system was strongly, moderately, weakly, or not classifiable into this archetype. While these particular distinctions have not been made in the classification of extreme-rain-producing MCSs in this study, the reason for making such a distinction has not been ignored. As mentioned above, the key factor in making classification decisions was the structure of the system at the time when the heavy rain was occurring. If the organizational structure of an MCS at and around this time did not closely resemble the TL/AS, BB, or any of the other classifications, it was put into the "other MCS" category.

The approximate locations of the TL/AS and BB extreme rain events identified in this study are shown in Fig. 4. These maps show that both TL/AS and BB events were fairly well distributed throughout the central part of the country (where MCSs in general are more common), while events farther east were rare. (Most extreme rain events in the eastern United States were associated with synoptic or tropical systems.)

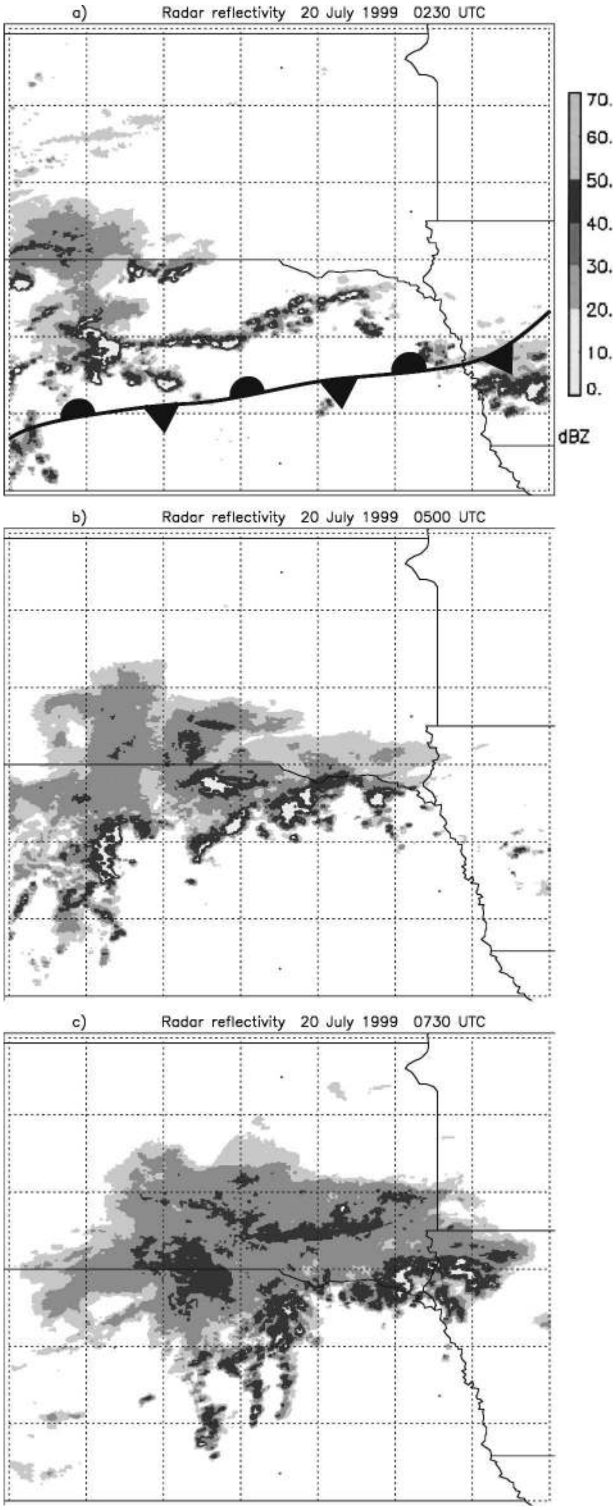


FIG. 5. Composite radar reflectivity (dBZ) from the TL/AS MCS extreme rain event at (a) 0230, (b) 0500, and (c) 0730 UTC 20 Jul 1999. Map boundary is the same for all panels. Position of stationary front is shown in (a).

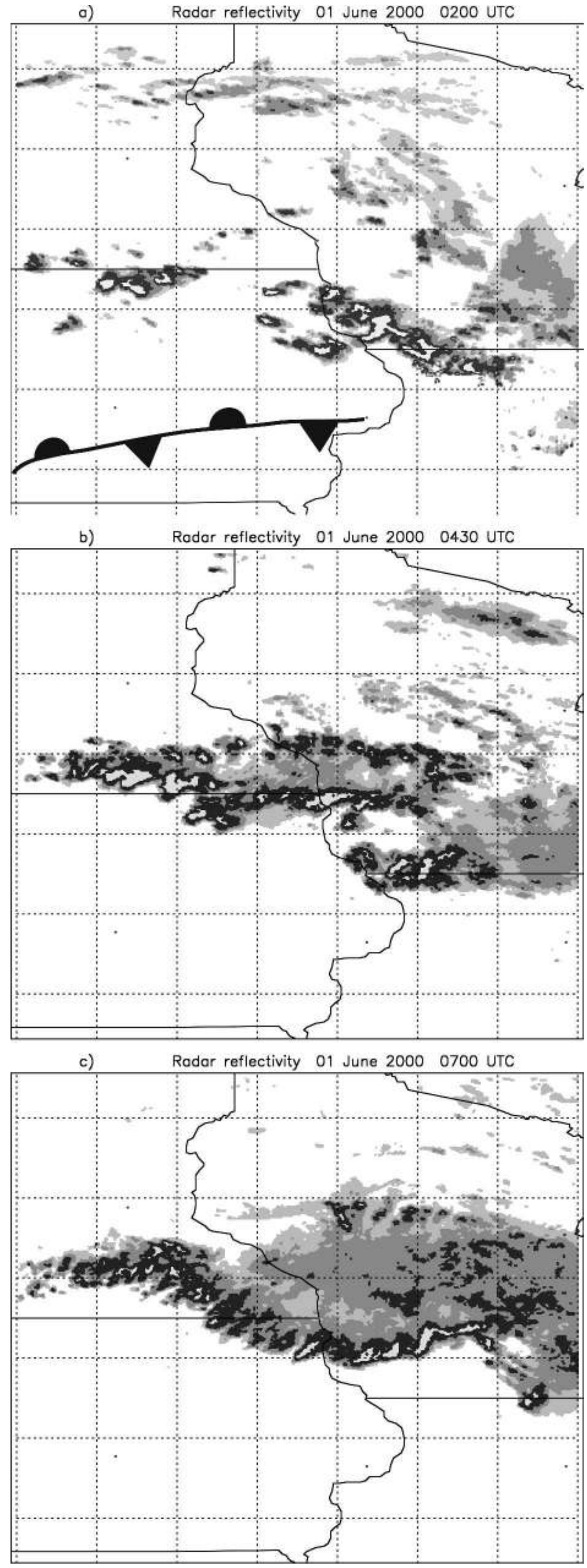


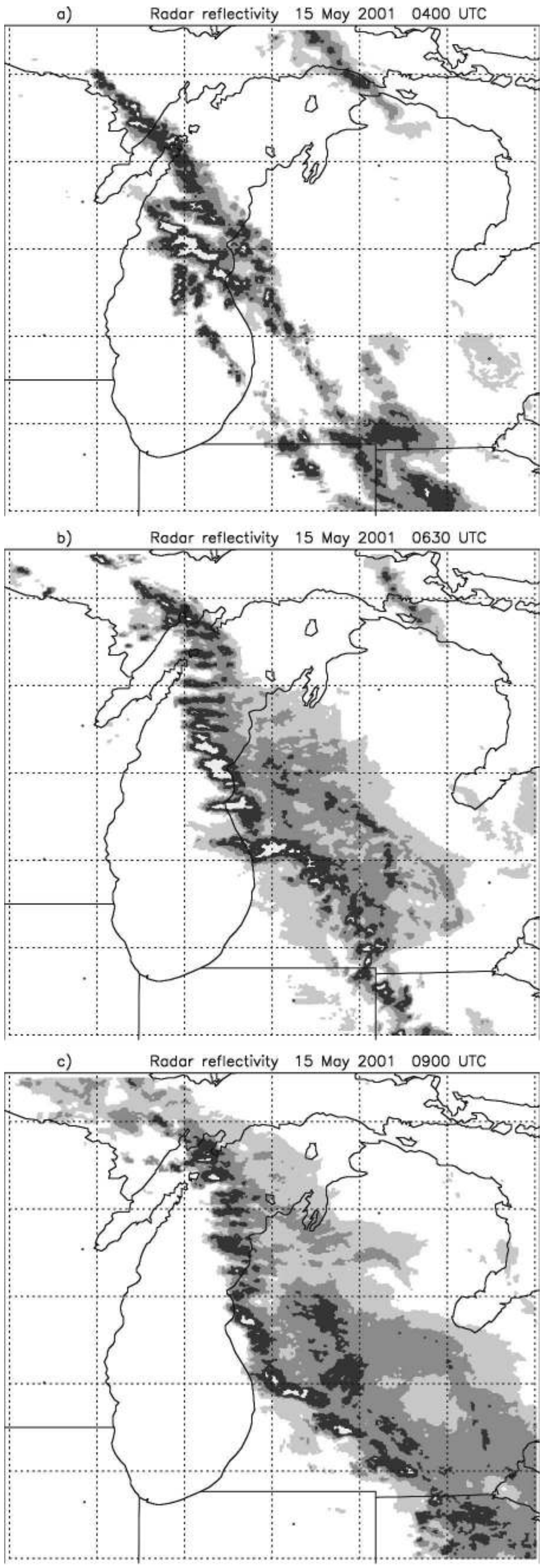
FIG. 6. As in Fig. 5, except for (a) 0200, (b) 0430, and (c) 0700 UTC 1 Jun 2000. Reflectivity scale is the same as in Fig. 5.

Back-building or quasi-stationary events were less prevalent in the south than were TL/AS events in this 3-yr period.

Radar data from examples of three TL/AS MCSs are shown in Figs. 5–7 . In each case, an area of convection began to form that eventually organized into a quasi-linear system with a region of stratiform precipitation moving in approximately the same direction as the convective cells, with the position of the line itself remaining nearly stationary. The stations reporting extreme rainfall totals were along the convective line and were therefore in an area conducive to echo training.

The 19–20 July 1999 MCS formed to the north of a stationary front that extended approximately from west to east across Nebraska. A line of convection, oriented parallel to the front, developed around 0200 UTC and intensified through 0500 UTC (Fig. 5b). By 0500 UTC, an area of stratiform precipitation had also formed to the north and west of the convective line. The convective and stratiform precipitation continued to parallel the front as it moved to the east-northeast, producing "training" behavior in northeast Nebraska. This resulted in up to 142 mm (5.58 in.) of rainfall and many reports of flash flooding in that area. One interesting aspect of this MCS, though unrelated to the extreme rainfall, is the development of convection perpendicular to the existing convective line, as seen in Fig. 5c. These bands developed briefly and then weakened while the TL/AS structure continued to progress east-northeastward. These structures are similar to those described by Smull and Augustine (1993).

The 31 May–1 June 2000 system (Fig. 6) produced six reports of extreme rainfall in Minnesota, Wisconsin, and Iowa, with an unofficial report of 184 mm (7.25 in.) in 3 h at Victory, Wisconsin. Flash floods that followed the rainfall caused over $10 million in property damage, and several counties in Minnesota and Wisconsin were declared federal disaster areas. This MCS formed well to the north of a surface stationary front, along a band of strong low-level positive θ_e advection (not shown). Deep convection began to form around 0200 UTC (Fig. 6a) with two areas having the greatest development, one in extreme northeast Iowa/southwest Wisconsin and one farther west along the Minnesota/Iowa border. The cells moved to the east and more convection developed to fill in the line, setting up a training effect all across this area. By 0700 UTC (Fig. 6c), a large area of stratiform rain was in place to the north of the line. Around 1000 UTC (not shown), after most of the heavy rain production was over, the eastern part of the MCS took on a north–south orientation and moved quickly to the east with a TS structure. This scenario was similar



←

FIG. 7. As in Fig. 5, except for (a) 0400, (b) 0630, and (c) 0900 UTC 15 May 2001. Surface stationary front is to the west of the map boundary for this case.

to the concurrent downwind- and upwind-propagating MCS examples shown by Corfidi (2003).

On 15 May 2001, a low pressure center was located in western Minnesota, with a stationary front extending southeast through western Wisconsin. The TL/AS MCS that produced the extreme rainfall in this event occurred in western Michigan, several hundred kilometers ahead of the surface front. Surface temperatures in Wisconsin and western Michigan were mainly in the 50°F range, indicating that the convection likely needed to be elevated well above the sloping frontal surface to release the instability required for the intense storms that formed. Convection initiated along a line parallel to the front and moved south-southeastward, training across extreme western Michigan and producing up to 118 mm (4.65 in.) of rain in 24 h, which is nearly a 100-yr event for the area. Resultant flash flooding caused well over $1 million in damage to property and crops.

Three BB MCSs are shown in Figs. 8–10 . In the 6–7 May 2000 case (Fig. 8), a small area of quasi-stationary convection produced a remarkable amount of rain over several counties just to the southwest of the St. Louis, Missouri, metropolitan area. Three stations reported 24-h rainfall totals over the extreme rainfall threshold, including the highest 24-h total of all nontropical events in the entire population (309 mm, or 12.15 in., at Union, Missouri). Nearly all of the creeks in the area flooded as a result of the rainfall, and this flash flooding caused two fatalities and over $100 million in property damage. The convection developed upstream of weak precipitation associated with a mesoscale convective vortex, and remained quasi-stationary for almost 6 h. There were no surface boundaries preceding the deep convection, but a weak, slow-moving outflow boundary generated by this system provided a focus for the continued development. For a more complete analysis of the mesoscale and storm-scale features of this event, see Glass et al. (2001).

The 19–20 June 2001 BB event formed upstream of a decaying convective system. At 1830 UTC (Fig. 9a), a cluster of intense convection had developed behind this earlier convection that had weakened. As the stationary front located across northeast Kansas began to move southward as a cold front, new cells formed upstream along the previous system's outflow boundary (positioned based on surface observations), which further strengthened the boundary and provided the focus for continued development in this area. More cells formed upstream and moved eastward, resulting in an area of quasi-stationary convection for several hours. One station reported 209 mm (8.25 in.) of rain from this system, and there were unofficial reports of over 250 mm (9.8 in.).

While the 25–26 July 1999 system barely reached MCS dimensions, it persisted for well over 3 h as a back-building area of heavy rainfall. Isolated convection developed along a surface pressure trough in northwest Kansas around 2100 UTC 25 July (Fig. 10a) and continued to intensify through 0000 UTC (Fig. 10c), with the entire system actually moving slightly *westward* over this 3-h period. Eventually this particular convective cluster weakened and merged with other storms in the area to form a larger but not especially well organized MCS. The system caused flash flooding in the small town of Quinter, Kansas, which reported a 24-h rainfall total of 176 mm (6.92 in.). Yet another example of an extreme-rain-producing BB MCS can be found in Chappell (1986, his Fig. 13.11).

4. Environmental conditions associated with TL/AS and BB MCSs

One way to better understand the processes at work in the extreme-rain-producing MCS patterns introduced in section 3 is to observe the prevailing atmospheric conditions before and during these events. Here, data from observations and hourly RUC-2 model analyses will be used to demonstrate the conditions associated with TL/AS and BB extreme rain events. The analyses presented in this section will be compared with the findings of past studies and will attempt to show, for example, the conditions in which a TL/AS MCS is likely to form.

Certainly, some aspects of the composite maps presented in this section should be approached with caution. The RUC-2 analyses, as with any model output, are highly dependent on the quality of the data ingested, as well as of the model itself. (For a discussion of the quality of RUC-2 analysis data compared with observed data, see Thompson et al. 2003.) Since the conditions have been averaged over many cases, the fields will often be smoother than those observed for any one case by itself. In the following discussion, references to "surface" fields are in actuality the lowest level represented in the model (2 m for temperature, dewpoint, etc., and 10 m for winds.) Since the environments in which the more established MCS types (i.e., TS, LS, PS, etc.) are fairly well known, the discussion to follow will focus on the two most common extreme-rain-producing MCS types presented above, TL/AS and BB.

a. *Training line/adjoining stratiform MCSs*

1) Surface

Many of the prevailing features at the surface during TL/AS MCSs can be observed using standard surface observations and the analyses performed by the National Centers for Environmental Prediction (NCEP). The NCEP analyses show that 17 out of 24 (over 70%) of the extreme-rain-producing TL/AS MCSs in this sample occurred during surface conditions consistent with MCH79's "frontal" pattern (Table 3). In other words, they formed on the cool side of a synoptic-scale

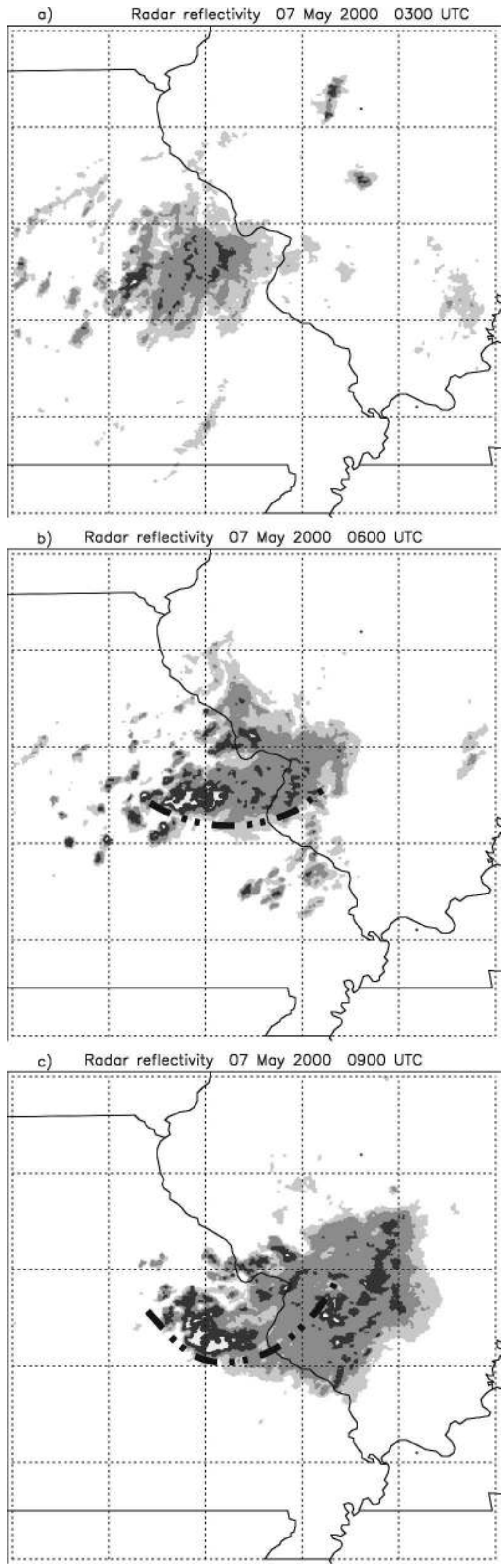


FIG. 8. As in Fig. 5, except for BB MCS extreme rain event at (a) 0300, (b) 0600, and (c) 0900 UTC 7 May 2000. Dash–dot lines in (b) and (c) indicate position of outflow boundary.

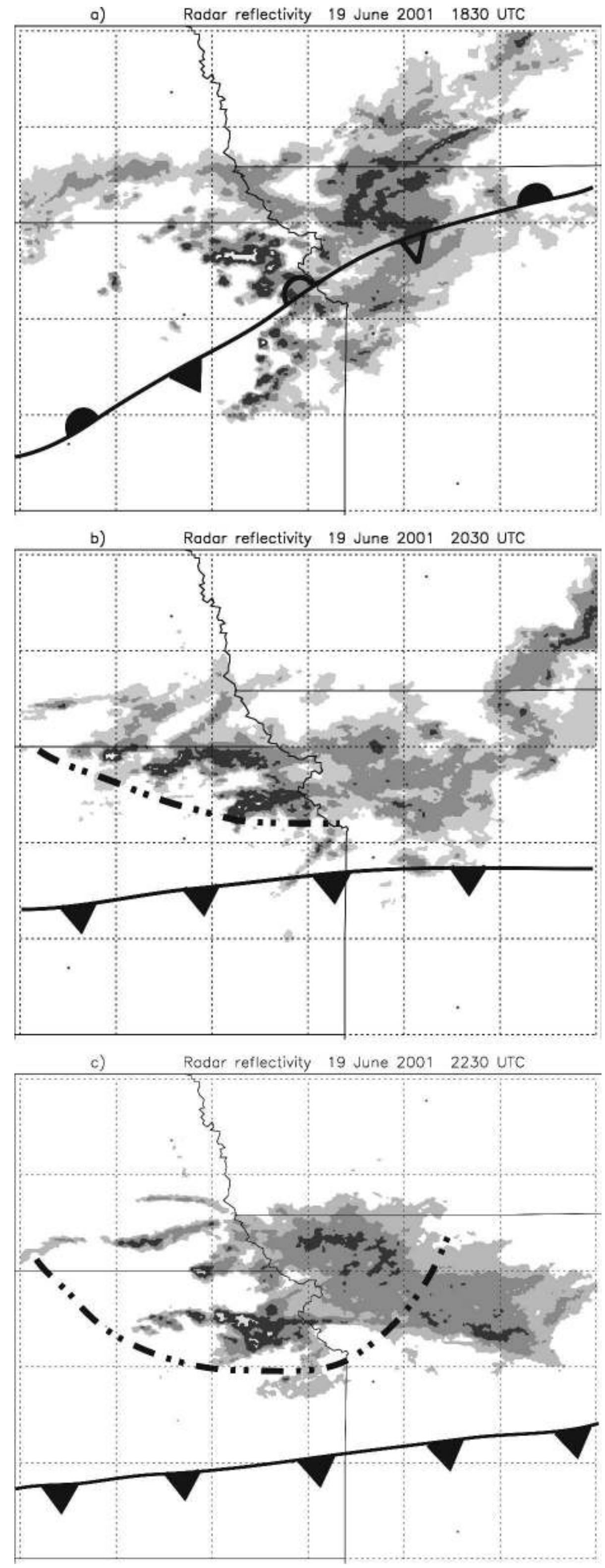
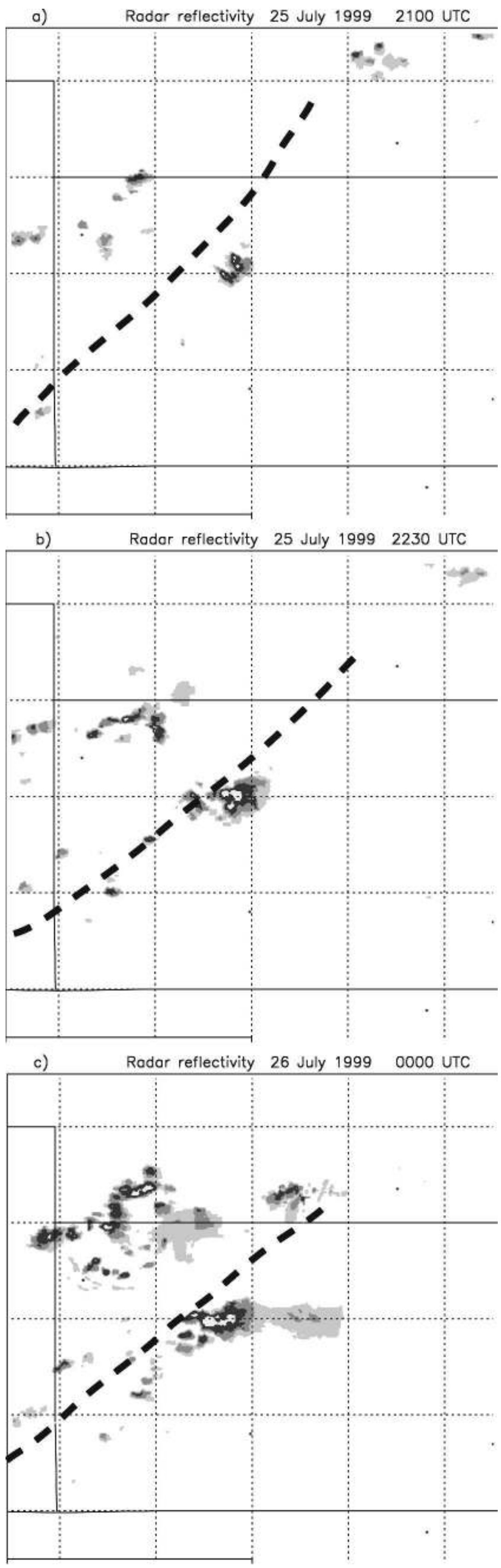


FIG. 9. As in Fig. 5, except for BB MCS extreme rain event at (a) 1830, (b) 2030, and (c) 2230 UTC 19 Jun 2001. The extreme rainfall totals were associated with the area of quasi-stationary convection in northeastern Kansas. Location of the front and outflow boundary (dash–dot line) is shown in (a)–(c).



warm front or stationary front. Others formed on the cool side of a long, preexisting outflow boundary, which can be conducive to similar linear development. A few TL/AS MCSs formed where no boundaries were analyzed on the NCEP charts.

Consistent with the observations, the RUC-2 composite maps for the 24 TL/AS cases also show the presence of a boundary to the south of the extreme rainfall location (Fig. 11). There is a tight north-to-south gradient in θ_e, as well as a shift from southerly winds south of the extreme rainfall center to weak winds from the east and southeast to the north of the center.

2) Upper levels

A north-to-south vertical cross section through the extreme rainfall center shows higher-θ_e air being lifted over the boundary, indicating that the convection in TL/AS MCSs is typically elevated (Fig. 12). This composite cross section is very similar to the schematic shown by Moore et al. (2003, their Fig. 14) for heavy-rain-producing, elevated MCSs. The region of high θ_e (and the associated convective instability illustrated by the decrease in θ_e with height) coincides with a maximum in low-level convergence. Corfidi (2003) suggests that such regions where maxima in instability and convergence coincide are the most favorable for new cell development. There is also an upper-level divergence maximum just to the north of the heavy rainfall center, consistent with the northward shift of the precipitation pattern. The values of relative humidity (RH; with respect to water) are high throughout the troposphere, which creates a favorable environment for heavy rainfall by inhibiting the entrainment of dry air into the updrafts. The composite precipitable water (PW; not shown) also shows a strong increase from approximately 35 mm to over 40 mm during the 12-h period preceding the peak rainfall. Furthermore, the composite appears to reflect the convective/stratiform structure of the TL/AS pattern, with the axis of highest RH "tilting" to the north with height.

The composite winds for TL/AS MCSs show veering winds at low levels, and an approximately unidirectional profile at mid- and upper levels (Fig. 13). While the boundary near the surface clearly determines the initial orientation of the convective line in TL/AS MCSs, the wind shear associated with this profile influences their structure and evolution.

The midlevel (925–500-hPa) wind shear vector has a large component parallel to the convective line (Fig. 14). This result may be related to the fact that TL/AS MCSs typically occur in regions of strong baroclinicity.

←

FIG. 10. As in Fig. 5, except for BB MCS extreme rain event at (a) 2100 UTC 25 Jul 1999, (b) 2230 UTC 25 Jul 1999, and (c) 0000 UTC 26 Jul 1999. Dashed lines denote a surface pressure trough.

TABLE 3. Boundaries associated with each extreme-rain-producing MCS type, as determined from NCEP surface analyses. The distinction is made between events where there was a preexisting outflow boundary in the analyses, and those where an outflow boundary was analyzed later, presumably as a result of the extreme-rain-producing convection. "TROF" represents systems that formed along surface pressure troughs. Events with no boundaries in the NCEP analyses were classified as undetermined, though more detailed analyses may show boundaries to be present in these cases.

	Fronts			Outflows			
MCS type	Stationary	Warm	Cold	Preexisting	Not preexisting	TROF	Undetermined
TL/AS	12	5	0	4	0	0	3
BB	3	1	0	3	4	1	3
TS	4	0	7	0	0	1	1
LS	1	0	0	0	0	1	0
PS	3	1	0	0	2	1	0
Total	23	7	7	7	6	4	7

Assuming approximate thermal wind balance, it could be expected that the shear would be largely boundary parallel (and subsequently line parallel). The direction of both the low- and midlevel shear may also help to explain the development of the adjoining stratiform region. While the shear above 925 hPa is approximately parallel to the convective line, the shear from the surface to 925 hPa (the approximate depth of the cool air beneath the frontal surface, and where thermal wind balance is not valid) has a large component *perpendicular* to the line (Fig. 14). In the theory of Rotunno et al. (1988), this scenario would favor updrafts that lean over the cold pool/frontal surface. Such leaning updrafts could contribute to the movement of hydrometeors aloft that end up as stratiform precipitation farther to the cool side of the boundary. Fritsch and Forbes (2001, their Fig. 9.18) showed a similar situation with a low-level jet impinging on a front, where the horizontal vorticity associated with the shear and the front are in the same direction. Additionally, the line-parallel shear at midlevels can also create an asymmetric region of adjoining stratiform rain, similar to the MCSs described by Hilgendorf and Johnson (1998). Such asymmetric features are seen in Figs. 6 and 7. While the convection itself in these systems certainly modifies its environment (which may or may not be reflected in the RUC-2 analyses), these results provide a starting point for explaining the organization of the convective and stratiform regions of extreme-rain-producing TL/AS MCSs.

The vertical wind profile to the south of the rainfall center (i.e., in the inflow region; Fig. 13b) shows a maximum in wind speed near 850 hPa, consistent with the presence of a low-level jet (LLJ). This wind maximum is also evident in the wind field to the south and west of the center in Fig. 15. The important role that the LLJ

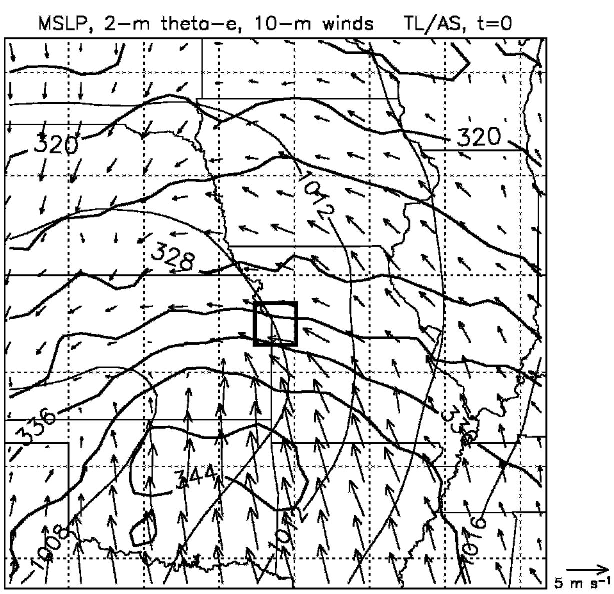


FIG. 11. Composite of 2-m equivalent potential temperature (thick contours every 4 K), 10-m winds, and mean sea level pressure (thin contours every 4 hPa) for TL/AS MCS extreme rain events at the peak rainfall time. Maximum wind vector is shown in the lower right. For visual reference, the composite has been projected onto a map of the central United States, centered near Kansas City, MO. The square at the center of the figure indicates the approximate location of the highest rainfall report.

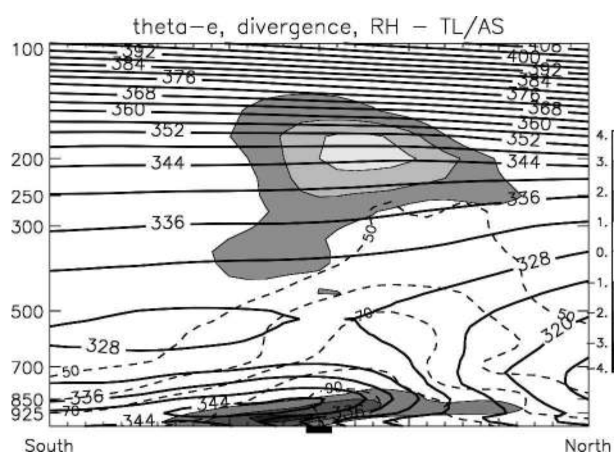


FIG. 12. Composite north–south vertical cross section of equivalent potential temperature (K; thick lines), horizontal divergence (shaded contours), and relative humidity (percent; with respect to water; dashed lines) through the grid center. Composite is for TL/AS MCS extreme rain events at the peak rainfall time. Divergence contour interval is 1×10^{-5} s^{-1}; scale is at right. Extreme rainfall location is denoted by the black rectangle below the horizontal axis.

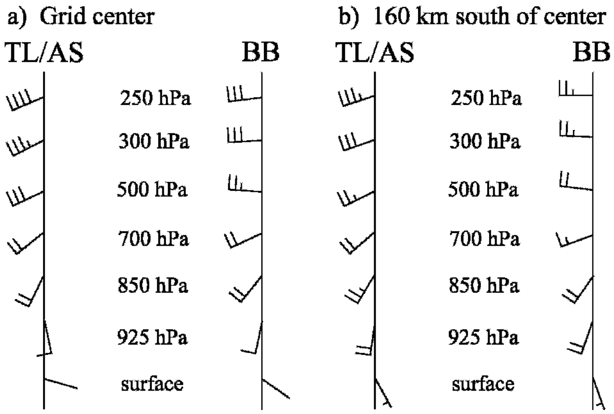


FIG. 13. Composite wind profile at (a) the grid center and (b) four grid points (~160 km) south of the center for TL/AS and BB MCS extreme rain events at the peak rainfall time. Wind barbs are plotted conventionally in kt. Recall that the grid has been rotated for some cases, so 160 km south of the center may physically represent a distance east or west of the center, but still reflects the inflowing air.

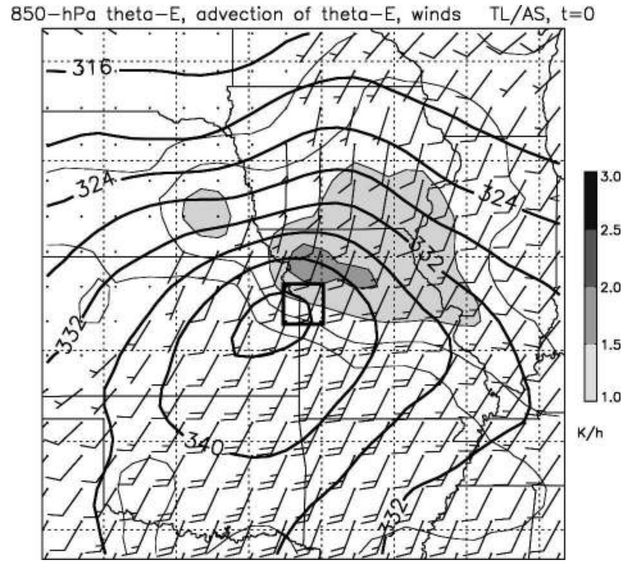


FIG. 15. Composite of 850-hPa equivalent potential temperature (K; thick lines), equivalent potential temperature advection (thin gray lines) 7, and winds (kt; conventional plotting) at the peak rainfall time for TL/AS MCS extreme rain events. Advection contour interval is 0.5 K h^{-1}, and values greater than 1.0 K h^{-1} are shaded. Map projection is the same as in Fig. 11.

plays in heavy rainfall events has been well documented by past investigators. Another feature in the TL/AS composites that is consistent with previous findings (e.g., Glass et al. 1995; Junker et al. 1999) is a maximum of θ_e advection to the north and northeast of the heavy rainfall location (Fig. 15).

b. BB MCSs

1) SURFACE

While it was shown that most TL/AS MCSs form on the cool side of well-defined fronts or outflow boundaries, the surface patterns in which BB-type MCSs occur are less clear (Table 3). These results show that BB MCSs can occur in a variety of surface weather patterns, including those without any well-defined features. There are concerns with classifying events in this manner, because the NCEP analyses often do not include mesoscale features such as subtle convergence lines. For instance, NCEP did not analyze an outflow boundary in any of the events shown in Figs. 8–10, though they were evident in two of the cases upon closer examination of surface data. Since there must be *some* "trigger" that initiates the convection in these cases, what Table 3 effectively illustrates is that the initiation and maintenance of BB MCSs often occurs on the mesoscale and storm scale. As such, the BB type of extreme-rain-producing MCS is likely even less predictable than the TL/AS type.

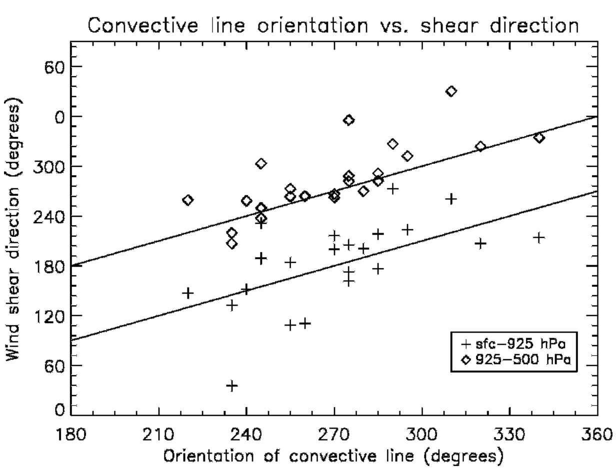


FIG. 14. Relationship between the convective line orientation and the direction of the low- and midlevel wind shear for TL/AS MCSs. Shear is calculated at the RUC-2 grid point nearest the highest rainfall. A line or shear vector pointed from west to east is shown with a direction of 270°. The lines $y = x$ (i.e., shear parallel to the convective line) and $y = x - 90$ (i.e., shear perpendicular to the convective line) are also shown for reference.

The surface composite fields for the 15 BB MCSs are, to first order, quite similar to those for the TL/AS MCS extreme rain events (Fig. 16). The expanse of the wind shift, however, is substantially smaller in the BB composites. In the TL/AS composites, nearly the entire domain displays the shift from southerly to easterly winds across the temperature gradient, while here the shift is only apparent in the vicinity of the centerpoint. Similarly, there is again a sharp gradient in θ_e, but the tightest part of the gradient only exists near the centerpoint, while it occurs over a larger west-to-east area in the TL/AS composites. These characteristics in the thermal and wind fields near the surface suggest that any boundaries that help to focus the convection in BB events may be smaller-scale features (i.e., outflow boundaries) than those associated with TL/AS MCSs.

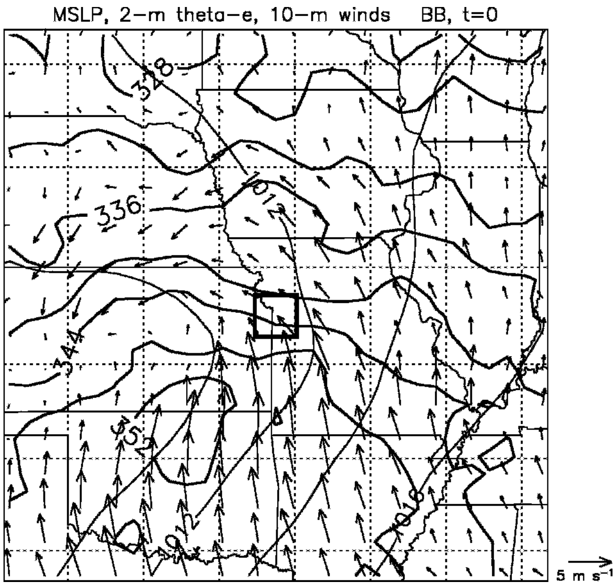


FIG. 16. As in Fig. 11, except for BB MCS extreme rain events.

As shown above, such outflow boundaries were apparent in surface observations (and in the RUC data) for the several of the individual cases, but they do not appear especially clearly in the composites.

2) Upper levels

The north-to-south vertical cross section (Fig. 17a) is also similar to the TL/AS cross section, showing a region of high-θ_e air being lifted over a sloping boundary near the surface. A cross section taken from west to east (Fig. 17b) shows that the maximum low-level convergence is located to the west of the grid center. This is consistent with the upstream convective development that these systems typically exhibit. Rather than being displaced to the north of the maximum rainfall, the upper-level divergence maximum is directly above the center point in the BB composite. If much of the RUC-2's upper-level divergence is a result of convective outflow, this suggests that the updrafts in BB MCSs may be more upright, instead of tilting to the north over the front/cold pool as TL/AS systems do. Furthermore, the axis of highest RH does not "tilt" to the north as it did in the TL/AS; instead, the east–west cross section reveals that it tilts to the east, consistent with the area of stratiform precipitation that is often observed downstream of the convection. Values of PW for BB MCSs are somewhat higher than for TL/AS systems, averaging over 45 mm near the center point and also showing a strong increase in the hours preceding the MCS (not shown).

The composite wind fields for BB events are also very similar to those for TL/AS MCSs, with slightly weaker upper-level winds (Fig. 13). There does not appear to be a strong relationship between the direction of the wind shear and the orientation of the convection for these systems, most likely because BB MCSs are typically small in size and because they do not form along strong fronts as often as TL/AS MCSs. There is once again strong positive θ_e advection associated with a low-level jet, though the maximum is at a slightly lower level (not shown).

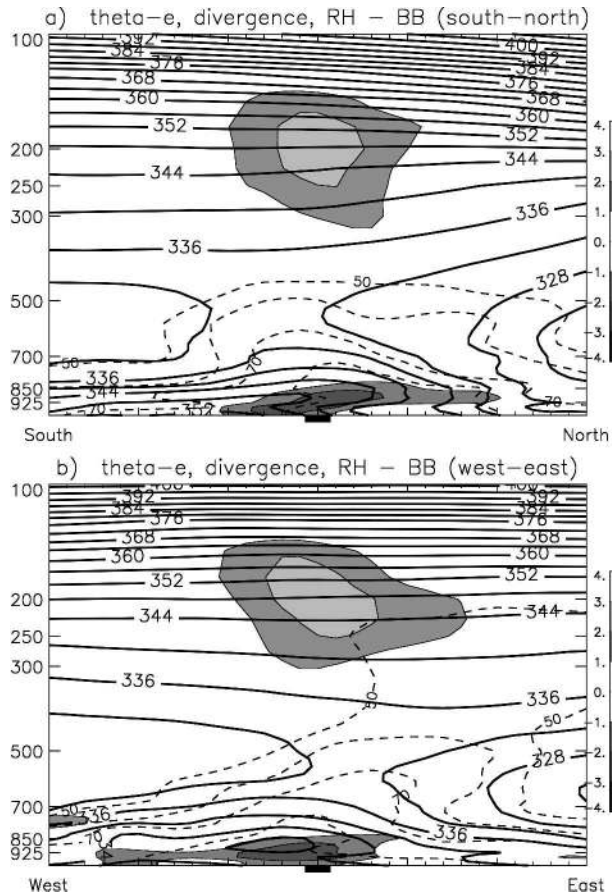


FIG. 17. As in Fig. 12, except for BB MCS extreme rain events: (a) north–south cross section and (b) west–east cross section through the composite grid center.

c. Synthesis

The information presented above shows that the environments in which TL/AS and BB MCSs typically develop are generally quite similar. The key differences appear to be in the low-level features that are present for each type of system. Extreme-rain-producing TL/AS MCSs are most likely to form on the cool side of a well-defined, synoptic-to-meso-α-scale boundary, which is usually a front. The cells within the convective line that develops do not necessarily move slowly, but a "training" process sets up, whereby deep convective cells repeatedly pass over the areas along the line. Back-building or quasi-stationary systems, on the other hand, are less dependent on preexisting large-scale boundaries. They often initiate along mesoscale boundaries (preexisting outflow boundaries, pressure troughs, etc.) and then appear to be maintained by storm-generated outflows, resulting in areas of back-building or quasi-stationary convection. This behavior is well illustrated by DBM96 (their Fig. 7).

As mentioned above and shown in Table 3, the conditions conducive to heavy rainfall that have been discovered in the past (and confirmed in this study) are capable of producing a variety of MCS types. However, perhaps one conclusion that can be reached from this work is that when an MCS takes on the TL/AS or BB organizational pattern (and maintains it for several hours), it may be somewhat more likely to produce extreme rainfall amounts than another MCS forming in the same conditions. This type of information may be helpful from an operational standpoint as well, as a forecaster could be on alert for these patterns of organization, while keeping in mind that heavy rain can come from many different types of storms.

5. Conclusions

Using rain gauge observations from the part of the United States east of the Rocky Mountains (excluding Florida) in 1999–2001, it was found that 116 events exceeded the 50-yr recurrence interval amount for 24-h precipitation accumulation. National composite radar reflectivity data were used to make a quantitative determination about what types of weather systems are most often responsible for producing the extreme rainfall totals in such events. The radar analysis showed that over 65% of all extreme rain events were associated with MCSs, and 27% resulted from synoptic weather systems. Since this analysis showed that MCSs produce many of the extreme rainfall events in the area of study, the radar data from each MCS event were analyzed further to determine the most common modes of convective organization.

Not surprisingly, there was great variability in the radar-indicated structures of extreme-rain-producing MCSs. Many of these systems corresponded to previously established patterns for MCS organization, and many others were not organized into discernible patterns. However, two previously unidentified patterns of convective organization were observed most frequently. The first is a convective line, often oriented east–west, with "training" convective elements (TL/AS; Fig. 3a). This MCS type also has a region of adjoining stratiform rain that is displaced to the north of the line. The second pattern is a back-building or quasi-stationary area of convection that produces a region of stratiform rain downstream (BB; Fig. 3b).

Surface observations and composite analysis of RUC-2 model analyses were then utilized to determine the atmospheric conditions in which TL/AS and BB MCSs typically form and to compare these results to previous findings on the environments of extreme precipitation systems. The composite analysis showed that extreme-rain-producing TL/AS MCSs usually form in conditions described by the "frontal" flash flood type of Maddox et al. (1979) and others. In this pattern, the convective line forms on the cool side of and parallel to a preexisting slow-moving synoptic boundary. The convective line is also oriented approximately parallel to the midlevel shear vector, which is consistent (from a thermal wind perspective) with the temperature gradient across the front. The conditions in place for BB MCSs were similar, but not as well defined, and they show that these systems are more dependent on mesoscale and storm-scale processes and forcings (such as outflow boundaries) than on larger-scale features.

Several ideas for future work are suggested by these results. In addition to the climatological characteristics of extreme rain events that will be presented in a forthcoming paper, more detailed observations of extreme-rain-producing MCSs would lead to a better understanding of how they operate. Higher-resolution radar data, dual-Doppler techniques, and observations of flash floods from various field campaigns would be beneficial, as would numerical simulations of these systems. Finally, while the composite analysis utilized herein is helpful for determining the environments in which extreme-rain-producing MCSs develop, the question of how often such conditions exist without MCS (or extreme-rain-producing MCS) formation remains unanswered.

Acknowledgments. The WSI NOWrad data were obtained from the Global Hydrology Resource Center (GHRC) at the Global Hydrology and Climate Center, Huntsville, Alabama. RUC-2 analyses were obtained from the Atmospheric Radiation Measurement Program (ARM) archive. Precipitation data were provided by the National Climatic Data Center. Information about damage and flash flooding resulting from the events described was obtained from NOAA's *Storm Data* publication. The authors thank Prof. Matthew Parker for his insights into the issues of classifying MCSs, and Prof. Jorge Ramirez for helpful suggestions. Thanks also go to Richard Taft and Brian McNoldy for assistance in creating some of the figures, and to two anonymous reviewers for their suggestions that helped to improve the manuscript. This research was supported by National Science Foundation Grant ATM-0071371, and the first author was partially supported by a one-year American Meteorological Society Graduate Fellowship.

REFERENCES

Benjamin, S. G., and Coauthors, 2004: An hourly assimilation–forecast cycle: The RUC. *Mon. Wea. Rev.,* **132,** 495–518.

Bolton, D., 1980: The computation of equivalent potential temperature. *Mon. Wea. Rev.,* **108,** 1046–1053.

Bradley, A. A., and J. A. Smith, 1994: The hydrometeorological environment of extreme rainstorms in the southern plains of the United States. *J. Appl. Meteor.,* **33,** 1418–1431.

Brooks, H. E., and D. J. Stensrud, 2000: Climatology of heavy rain events in the United States from hourly precipitation observations. *Mon. Wea. Rev.,* **128,** 1194–1201.

Carbone, R. E., J. D. Tuttle, D. A. Ahijevych, and S. B. Trier, 2002: Inferences of predictability associated with warm season precipitation episodes. *J. Atmos. Sci.,* **59,** 2033–2056.

Chappell, C. F., 1986: Quasi-stationary convective events. *Mesoscale Meteorology and Forecasting,* P. S. Ray, Ed. Amer. Meteor. Soc., 289–309.

Corfidi, S. F., 2003: Cold pools and MCS propagation: Forecasting the motion of downwind-developing MCSs. *Wea. Forecasting,* **18,** 997–1017.

Davis, R. S., 2001: Flash flood forecast and detection methods. *Severe Convective Storms, Meteor. Monogr.,* No. 50, Amer. Meteor. Soc., 481–525.

Doswell, C. A., III, H. E. Brooks, and R. A. Maddox, 1996: Flash flood forecasting: An ingredients-based methodology. *Wea. Forecasting,* **11,** 560–581.

Fritsch, J. M., and G. S. Forbes, 2001: Mesoscale convective systems. *Severe Convective Storms, Meteor. Monogr.,* No. 50, Amer. Meteor. Soc., 323–357.

——, R. J. Kane, and C. R. Chelius, 1986: The contribution of mesoscale convective weather systems to the warm-season precipitation in the United States. *J. Appl. Meteor.,* **25,** 1333–1345.

Glass, F. H., D. L. Ferry, J. T. Moore, and S. M. Nolan, 1995: Characteristics of heavy convective rainfall events across the mid-Mississippi valley during the warm season: Meteorological conditions and a conceptual model. Preprints, *14th Conf. on Weather Analysis and Forecasting,* Dallas, TX, Amer. Meteor. Soc., 34–41.

——, J. P. Gagan, and J. T. Moore, 2001: The extreme east-central Missouri flash flood of 6–7 May 2000. Preprints, *Symp. on Precipitation Extremes: Prediction, Impacts, and Responses,* Albuquerque, NM, Amer. Meteor. Soc., 174–179.

Heideman, K. F., and J. M. Fritsch, 1988: Forcing mechanisms and other characteristics of significant summertime precipitation. *Wea. Forecasting,* **3,** 115–130.

Hershfield, D. M., 1961: Rainfall frequency atlas of the United States. U.S. Weather Bureau Technical Paper 40, 115 pp.

Hilgendorf, E. R., and R. H. Johnson, 1998: A study of the evolution of mesoscale convective systems using WSR-88D data. *Wea. Forecasting,* **13,** 437–452.

Houze, R. A., Jr., B. F. Smull, and P. Dodge, 1990: Mesoscale organization of springtime rainstorms in Oklahoma. *Mon. Wea. Rev.,* **118,** 613–654.

Junker, N. W., R. S. Schneider, and S. L. Fauver, 1999: A study of heavy rainfall events during the Great Midwest Flood of 1993. *Wea. Forecasting,* **14,** 701–712.

Maddox, R. A., 1980: Mesoscale convective complexes. *Bull. Amer. Meteor. Soc.,* **61,** 1374–1387.

——, C. F. Chappell, and L. R. Hoxit, 1979: Synoptic and meso-α scale aspects of flash flood events. *Bull. Amer. Meteor. Soc.,* **60,** 115–123.

Moore, J. T., S. M. Nolan, F. H. Glass, D. L. Ferry, and S. M. Rochette, 1995: Flash flood-producing high-precipitation supercells in Missouri. Preprints, *14th Conf. on Weather Analysis and Forecasting,* Dallas, TX, Amer. Meteor. Soc., (J4) 7–12.

——, F. H. Glass, C. E. Graves, S. M. Rochette, and M. J. Singer, 2003: The environment of warm-season elevated thunderstorms associated with heavy rainfall over the central United States. *Wea. Forecasting,* **18,** 861–878.

NOAA, cited 2004a: Natural hazard statistics. [Available online at http://www.nws.noaa.gov/om/hazstats.shtml.]

——, cited 2004b: Precipitation frequency. [Available online at http://www.nws.noaa.gov/ohd/hdsc/studies/prcpfreq.html.]

Orlanski, I., 1975: A rational subdivision of scales for atmospheric processes. *Bull. Amer. Meteor. Soc.,* **56,** 527–530.

Parker, M. D., and R. H. Johnson, 2000: Organizational modes of midlatitude mesoscale convective systems. *Mon. Wea. Rev.,* **128,** 3413–3436.

——, and ——, 2004: Structures and dynamics of quasi-2D mesoscale convective systems. *J. Atmos. Sci.,* **61,** 545–567.

Petersen, W. A., and Coauthors, 1999: Mesoscale and radar observations of the Fort Collins flash flood of 28 July 1997. *Bull. Amer. Meteor. Soc.,* **80,** 191–216.

Pettet, C. R., and R. H. Johnson, 2003: Airflow and precipitation structure of two leading stratiform mesoscale convective systems determined from operational datasets. *Wea. Forecasting,* **18,** 685–699.

Pontrelli, M. D., G. Bryan, and J. M. Fritsch, 1999: The Madison County, Virginia, flash flood of 27 June 1995. *Wea. Forecasting,* **14,** 384–404.

Rotunno, R., J. B. Klemp, and M. L. Weisman, 1988: A theory for strong, long-lived squall lines. *J. Atmos. Sci.,* **45,** 463–485.

Smith, J. A., M. L. Baeck, Y. Zhang, and C. A. Doswell, 2001: Extreme rainfall and flooding from supercell thunderstorms. *J. Hydrometeor.,* **2,** 469–489.

Smull, B. F., and J. A. Augustine, 1993: Multiscale analysis of a mature mesoscale convective complex. *Mon. Wea. Rev.,* **121,** 103–132.

Thompson, R. L., R. Edwards, J. A. Hart, K. L. Elmore, and P. Markowski, 2003: Close proximity soundings within supercell environments obtained from the Rapid Update Cycle. *Wea. Forecasting,* **18,** 1243–1261.