4.6 CLIMATOLOGICAL AND RADAR-INDICATED CHARACTERISTICS OF UNITED STATES EXTREME RAINFALL EVENTS

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1. INTRODUCTION

The atmospheric conditions in which extreme rain-producing storms are likely to occur in the United States have been studied and documented in the literature over the years (e.g., Maddox et al. 1979, Doswell et al. 1996, Davis 2001). The wide variety of storm types that have produced flash floods in the past have also been mentioned, but no radar-based analysis of the organizational structures of these storms has been completed. This study aims to determine the types of storms most often responsible for producing extreme rainfall totals, and to examine how these structures vary in time and space. Knowledge of when and where such events may occur and how they might appear in meteorological observations would likely aid those responsible for forecasting them.

The area east of the Rocky Mountains, excluding Florida, will be the focus of this work. Because part of the motivation for this study is to determine the types of mesoscale convective systems (MCSs) that produce extreme rainfall totals, we have chosen the region most likely to be affected by these systems.

2. CLIMATOLOGICAL CHARACTERISTICS

The first challenge in researching flash floods and extreme rainstorms is that they have no widely accepted definitions. One could create equally justifiable classifications of flash floods based on rainfall amounts, the magnitude of flooding, or the amount of damage and injury caused. In this study, the concern is primarily with the meteorology and less so with hydrology; thus meteorological data will be used. Two primary datasets are available for precipitation observations in the continental U.S.: the National Weather Service (NWS) 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 features on more appropriate timescales. However, since we hope to pinpoint a large number of events and neglect as few as possible, the NWS dataset will be used in this study because it has far superior spatial resolution. (Brooks and Stensrud 2000 have created a climatology of heavy rain events using the hourly observations.)

2.1 *Characteristics with a fixed threshold*

Bradley and Smith (1994) defined an "extreme rainstorm" in Oklahoma as an event with a daily rainfall accumulation of 125 mm (approx. 5 in) or more at one or more gauge. This threshold can be used over the entire area of interest to gain an understanding of how frequent such storms are in different regions. In Fig. 1, the monthly frequency distribution of 125 mm $(24\ h)^{-1}$ rainfall events from 1999-2001 is presented. A three-year period was chosen to partially eliminate biases from any one year, and this particular period was chosen because data were readily available. The regions used are the same as those in Karl and Knight (1998). Accumulations of this magnitude are relatively frequent in the southern part of the country and can occur in any month of the year. In the north, however, 125 mm events are less frequent and are mostly confined to the warm season.

2.2 *Characteristics with a spatially varying threshold*

To examine the storm structures that cause extreme rainfall totals in different parts of the United States, it is necessary to use a definition of "extreme" that suits a particular area. As shown in the previous subsection, accumulations of 125 mm $(24\ h)^{-1}$ in the south are relatively common, while such events are probably too rare in the northeast to draw any meaningful conclusions about them. Thus, a 24-h rainfall threshold was selected for each state that approximately balances the number of events per year in each state and each region. The cases selected using these thresholds (Fig. 2) provide an adequately large sample size, though not so large that the events can no longer be considered "extreme." They range from a maximum threshold of 175 mm $(24\ h)^{-1}$ along the Gulf Coast to a minimum of 100 mm in some of the Plains and northeastern states. While this definition of an extreme rainfall event does not consider the extent of the flash flooding that resulted from a particular storm (or whether flooding occurred at all), it offers an objective method for selecting cases that is based on meteorological data, rather than hydrological or land-use factors.

After eliminating bad data, there were 193 extreme rainfall events from 1999-2001 in the area of interest. The monthly frequency distribution of these events (Fig. 3) very closely resembles the distribution for flash flood events presented by Maddox et al. (1979, hereafter MCH79). For the part of the nation considered in this study, extreme rainfall events are most common in the summer months of June, July, and August, though they can occur in every month of the year. In the northern, Plains, and Ohio/Mississippi Valley regions, there are strong summertime maxima. In the northeast, the maximum occurs in August and September, while in the

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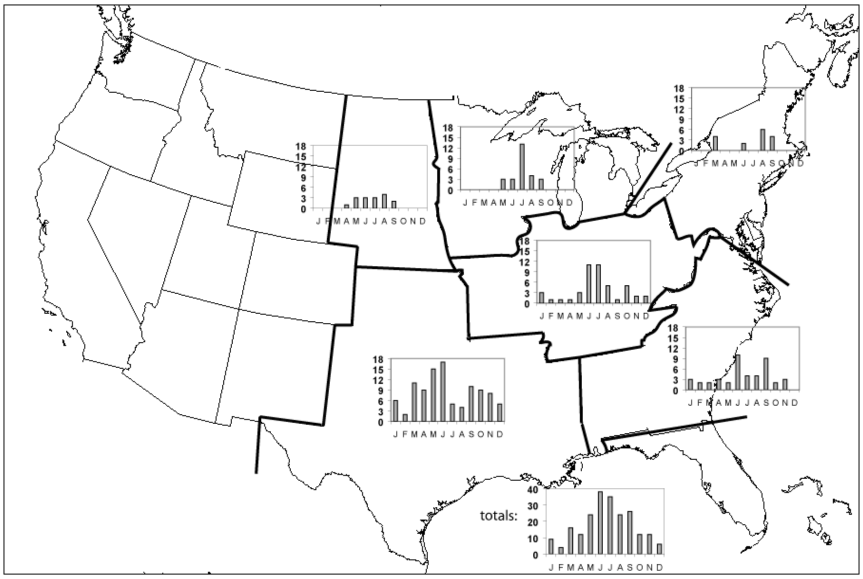

Figure 1. Monthly frequency distribution of 125 mm (24 h)$^{-1}$ events from 1999-2001 by region. The total distribution is shown at the bottom. Ordinates are scaled equally for the regional graphs, and range from 0 to 18 events.

south and southeast there are relative minima in July and August with maxima on either side.

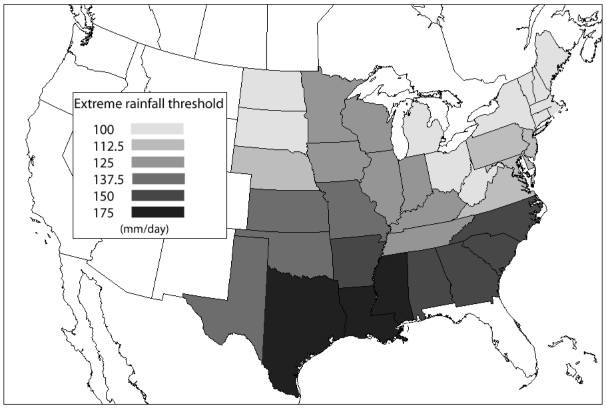

Figure 2. Thresholds used to define extreme rain events for this study, in mm (24 h)$^{-1}$. Thresholds were selected to approximately balance the number of extreme rain events in each state.

3. RADAR ANALYSIS

National composite radar reflectivity data were used to examine the structure and evolution of each extreme rainfall event. The data used have 2-km horizontal resolution and 15-min temporal resolution. An animation of each event's life cycle was created, and then each event was classified into one of the following categories based on its reflectivity pattern and the information obtained from synoptic weather analyses: MCS (using the definition presented in Parker and Johnson 2000, i.e., greater than 100 km in extent and 3 h in duration), synoptic (directly related to a synoptic weather system, such as an extratropical cyclone), isolated (smaller in extent than an MCS, such as a small multicell system or a supercell), tropical (associated with a tropical cyclone or its remnants), or sea-breeze front (associated with the sea-breeze front in coastal areas).

The results of this analysis show what might have been inferred from the monthly distributions. In the regions where extreme rainfall events occur exclusively during the summer (i.e., the Plains and northern regions), most are associated with MCSs, while those regions where many events occur in spring and autumn (i.e., the south and southeast) have a higher proportion of synoptically-forced systems. The distribution of storm type by month (Fig. 4) bears this out: MCS-related extreme rain events typically only occur in the months of March to October, with a July maximum, while synoptic events are more evenly distributed throughout the year with a July minimum.

In total, just over half of the events were associated with MCSs; such cases are not, however, associated with the “typical” passage of a summertime MCS. A common linear MCS with a region of trailing stratiform precipitation and motion perpendicular to the convective line will not produce locally extreme rainfall (Fig. 5). However, when the system motion has a large component parallel to the line, extended periods of high rainfall rate are possible.

4. EXTREME RAIN-PRODUCING MCS TYPES

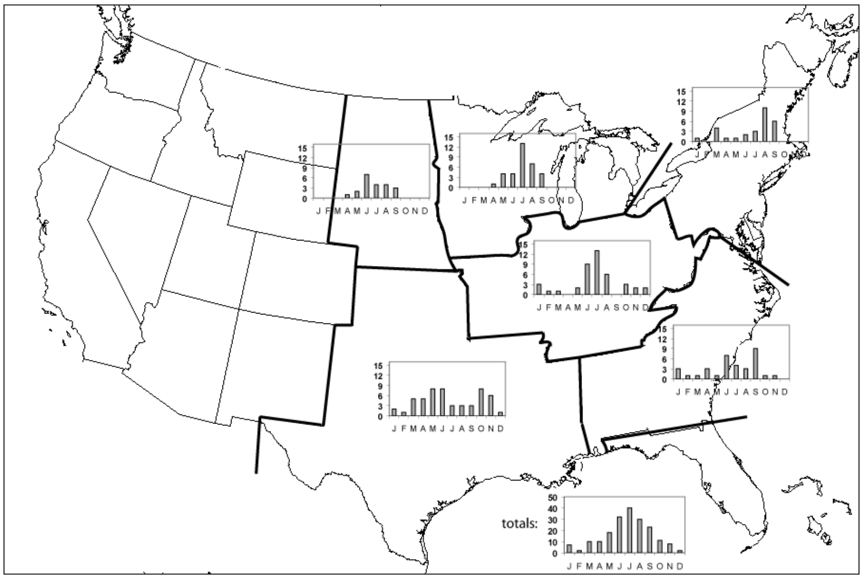

***Figure 3.** As in Fig. 1, except for extreme rain events as defined in the text. Ordinates range from 0 to 15 events for the regional graphs.*

The MCSs that produced extreme rainfall had varied organizational structures as observed in the composite radar reflectivity data. Some were caused by linear MCSs with the structures examined by Parker and Johnson (2000), namely those with trailing stratiform (TS) and leading stratiform (LS). A few 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. Others 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 systems were typically not organized into convective lines, and were deemed "disorganized MCSs," though this is not a completely accurate name--a certain degree of organization exists in all such systems. Two particular patterns, however, appeared most frequently (Table 1).

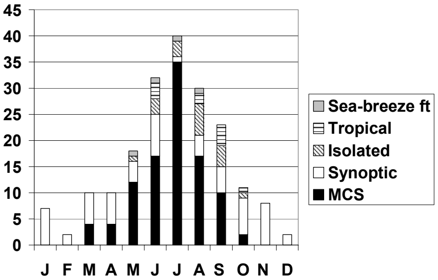

***Figure 4.** Monthly frequency distribution of all extreme rain events, separated by storm type.*

The first, "type A," is a linear MCS with cell motion approximately parallel to the convective line. As these systems develop, an area of stratiform precipitation forms adjacent to the convective line and moves in approximately the same direction. The second pattern, "type B," is a backbuilding or quasi-stationary line of convection with a region of stratiform precipitation downstream and approximately parallel to the line. (These systems would be classified as PS using the taxonomy of Parker and Johnson 2000). In this pattern, convective cells repeatedly form upstream and "train" over a particular area. An example of the instantaneous radar reflectivity structure from each type is shown in Fig. 6, and a generalized schematic drawing of each type and its motion characteristics is presented in Fig. 7. The system described by Chappell (1986, his Fig. 13.11) is another example of a type B MCS. Both patterns are organized such that multiple convective cells can pass over a given area, which is conducive to high rainfall rates over an extended period of time (see Fig. 5 and caption).

5. CORRESPONDING SYNOPTIC AND MESOSCALE CONDITIONS

5.1 *Type A MCSs*

Preliminary analysis of the synoptic and mesoscale atmospheric conditions associated with type A extreme rain-producing MCSs shows a pattern almost identical to the "frontal" flash flood type described by MCH79. These systems typically form on the cool side of a synoptic-scale stationary boundary (most often to the north of an east/west-oriented boundary.) Strong low-level winds flow approximately perpendicular to the boundary, and the cloud-level winds are relatively weak and have a large component parallel to the boundary.

Convective cells form near the boundary and are advected downstream by the mean flow, creating a reflectivity structure such as is shown in Figs. 6a and 7a. The reason that the region of stratiform precipitation develops and moves as it does needs to be examined further.

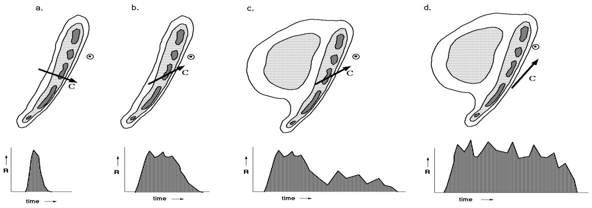

Figure 5. *Schematic illustrating how different types of convective systems with different motions affect the rainfall rate (R) at a point (indicated by a circled dot) as a function of time. C indicates the motion of the line, and the total rainfall experienced at the point is the shaded area under the R vs time graphs. (From Doswell et al. 1996)*

5.2 *Type B MCSs*

For type B systems, the setting seems somewhat less clear, though there are many similarities to the type A scenario. Several of these systems also formed along large-scale stationary boundaries, though others developed along more subtle outflow boundaries and convergence lines. For these MCSs, the low-level winds tend to be at a smaller angle to the boundary than in the type A systems, while the upper-levels winds are again approximately parallel to the boundary and the developing line of convective cells. In these cases, cells often form repeatedly in the same area, intensify, and dissipate as they move downstream. It is likely that the most unstable air remains upstream, which results in continued upstream formation but a short lifetime for each individual cell. While only base-scan reflectivity composites have been analyzed here, the evolution of type B systems seems to concur with the conceptual model for quasi-stationary convection presented by Doswell et al. (1996, their Fig. 7).

Storm Type	Number	Percentage of all MCSs
Type A	33	32.67%
Type B	29	28.71%
TS	12	11.88%
LS	6	5.94%
Mult. MCS	6	5.94%
Disorg. MCS	15	14.85%
total	101	100.00%

Table 1. *Frequency of occurrence of each MCS type during the period of study. Both the number of events and the percentage of all MCSs are given for each type. A description of the MCS types is given in the text.*

5.3 *Discussion*

This early look at the atmospheric conditions associated with extreme rain-producing MCSs appears to agree with other conceptual models for flash flood and extreme rainstorm formation, such as those in MCH79 and more recent work by Junker et al. (1999) and Davis (2001), among others. However, the two most frequently observed MCS types occur in the cool sector; many of the studies to analyze and classify MCSs have focused on warm-sector systems (e.g., Houze et al. 1990, Parker and Johnson 2000, etc). This may provide a further challenge to understanding such storms. A more detailed analysis of the atmospheric observations will be undertaken for comparison with the studies mentioned above and other investigations of MCSs and extreme rainstorms. This will hopefully yield a better understanding of the conditions associated with each type of system mentioned in this study, and how these conditions lead to the organizational structures we have observed.

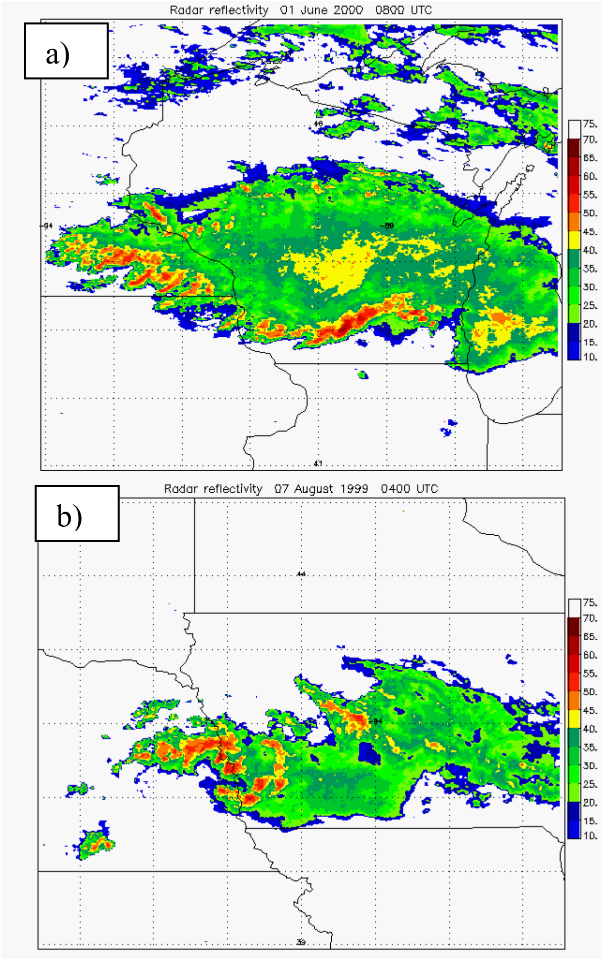

Figure 6. *Examples of instantaneous radar reflectivity (dBz) for the extreme rain-producing MCS types described in this paper. (a) Type A system, 0800 UTC 1 June 2000, (b) Type B system, 0400 UTC 7 August 1999.*

6. CONCLUSIONS

Several characteristics of extreme rainstorms were presented in this study. First, the spatial and temporal distributions of various rainfall events using both a fixed and a spatially varying threshold were presented. The spatially varying threshold was used to define “extreme rain events” for the purpose of this study, and each such event from a three-year period was observed using national composite radar reflectivity data. Each event was classified by its storm type, and it was found that just over half of the cases were associated with mesoscale convective systems.

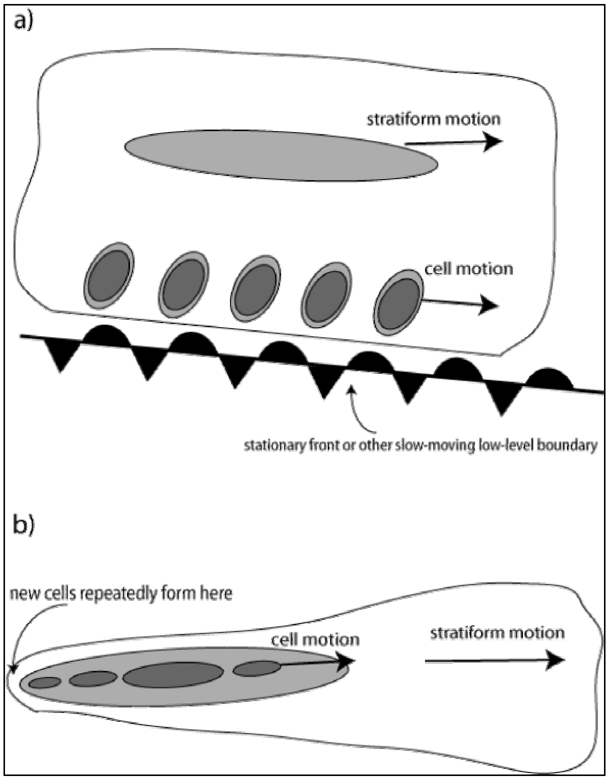

Figure 7. *Schematic diagrams of radar reflectivity and motion characteristics for the type A and type B extreme rain-producing MCSs. Most type A systems were observed to occur on the cool side of a stationary boundary, hence such a boundary is added to the diagram.*

Of the MCS-related cases, two reflectivity patterns were most frequently observed. Each type has a line of convective cells that is capable of producing large rainfall totals over a given area. Preliminary analysis of the atmospheric conditions in the vicinity of these systems shows agreement with previous studies of flash flood-producing storms, and these results may provide further insight into how such potentially damaging weather systems form and evolve.

7. ACKNOWLEDGEMENTS

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