Spatial and Temporal Characteristics of Extreme Rainstorms over the Central United States

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1. Introduction

Many aspects of extreme rainstorms have been studied. Some are case studies of individual events, and focusing on their meteorological aspects (e.g., Changnon and Kunkel 1999; Petersen et al. 1999) or their impacts (e.g., Angel and Huff 1999; Changnon 1999). Some are climatologies (e.g., Changnon and Vogel 1981; Kunkel et al. 1993; Brooks and Stensrud 2000), developed for a region to illustrate the general characteristics of certain events. In this study, we identify a series of extreme rainstorms that produced the largest rainfall within two days between 1950 and 2000, and use this storm catalog to illustrate the spatial and temporal characteristics of extremes over the central United States. The study area is focused on sixteen states, including Arkansas, Illinois, Indiana, Iowa, Kansas, Kentucky, Michigan, Minnesota, Missouri, Nebraska, North Dakota, Ohio, Oklahoma, South Dakota, Tennessee, and Wisconsin, in the central United States. This region is selected because it is a relatively homogeneous region in terms of storm meteorology and topography. Also, we choose to focus on two-day rainfall extremes, since heavy rainfall in this region is mainly produced by convectively-driven storms with typical durations of less than two days. In addition, this type of storm is frequently associated with costly flash flooding.

2. Storm Catalog Development

The data used to identify extreme rainstorms are the *Daily Precipitation Data of the Cooperative Summary of the Day (SOD), Record of Climatological Observation (TD3200)*, from the National Climatic Data Center (NCDC). This data set was utilized because it has a high density network covering the region of interest. The storm list was constructed by sorting the two-day accumulations of each date and station from all rainfall data of the sixteen states.

As with any large observational data set, data quality control is a major concern. Similar to the findings by Brooks and Stensrud (2000) for the *Hourly Precipitation Data* published by the NCDC, some errors are easily detected, such as an extreme value at a single station with no other precipitation recorded in the neighborhood; some errors are less obvious, such as an large value (e.g., 12 in) surrounding by relatively small rainfalls (e.g., 2-4 in). In these cases, some are real events, and some are bad data (due to a typo or missed reports). Suspicious storms were carefully inspected using supplementary information such as hourly precipitation from the same or near-by gages, reports from *Storm Data* published by the National Weather Service (NWS), and near-by U.S. Geological Survey (USGS) streamflow data. Several storms were removed after the inspections. The final storm catalog contains 57 storms and is listed in Table 1.

For each storm in the catalog, a storm database was created by collecting rainfall data of all stations for the storm dates on the list. Then, the two-day rainfall accumulation map was generated for each storm to view the spatial distribution of rainfall. The *Daily Weather Maps for the United States*, published by the NWS, were also collected for all events. Due to the lack of maps for some dates, especially for storms occurred before 1961, the *6-Hourly National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis Data Composites* were used as a substitute to provide surface and upper-air information. In addition, the information reported in *Storm Data* were gathered to provide some details for the storms.

3. Storm Classification

Maddox et al. (1979) identified three basic meteorological patterns from 120 flash floods in the central and eastern United States and classified them as synoptic, frontal, and mesohigh events. A synoptic event is associated with a relatively intense synoptic scale cyclone or frontal system (usually a eastward-moving quasi-stationary cold front). The moisture is lifted up by the approaching surface front and rains at the warm, moist side. The rain area usually is parallel to the front

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Table 1: Storm catalog.

Rank	Date	Rainfall Center	Rainfall (mm)	Storm Type
1	3-4 Dec. 1982	Danville, AR	544.8	S
2	19-20 Jul. 1965	Edgerton, MO	496.8	F
3	13-14 Oct. 1981	Tishomingo, OK	457.7	M
4	18-19 Jul. 1996	Aurora, IL	432.8	F
5	24-25 Sep. 1993	Girard, KS	402.3	F
6	30 Sep.-1 Oct. 1986	Kansas, OK	401.6	M
7	10-11 Oct. 1973	Enid, OK	398.3	S
8	10-11 May 1950	Purcell, OK	395.0	F
9	4-5 Nov. 1994	Deer, AR	392.7	S
10	2-3 Jul. 1958	Audubon, IA	364.0	M
11	13-14 Sep. 1978	Beedeville, AR	354.8	M
12	25-26 Apr. 1958	El Dorado, AR	351.5	F
13	20-21 May 1990	Hot Springs, AR	348.2	M
14	14-15 Jun. 1998	Atlantic, IA	348.0	F
15	28-29 Mar. 1977	Charleston, MO	343.9	S
16	19-20 May 1955	Comanche, OK	339.1	M
17	26-27 Jul. 1969	Parks, AR	337.3	M
18	9-10 Dec. 1971	Bear Mountain, OK	335.5	S
19	9-10 Jul. 1950	York, NE	335.3	M
20	8-9 Oct. 1990	Horatio, AR	333.0	M
21	10-11 Sep. 1986	Big Rapids, MI	332.2	S
22	15-16 May 1957	Hennessey, OK	332.0	F
23	17-18 Jun. 1996	Port Washington, WI	332.0	F
24	26-27 May 1991	Savannah, TN	331.2	M
25	2-3 Oct. 1959	Maramec, OK	331.0	F
26	2-3 Jul. 1976	Longton, KS	331.0	F
27	30-31 Oct. 1972	Hee Mountain, OK	330.2	F
28	25-26 Oct. 1991	Tuskahoma, OK	328.2	M
29	27-28 May 1987	Walters, OK	325.6	M
30	30 Sep.-1 Oct. 1954	Sobol, OK	322.8	M
31	8-9 Oct. 1970	Sulphur, OK	320.6	S
32	17-18 Sep. 1972	Bonnerdale, AR	319.5	M
33	10-11 Apr. 1994	Nevada, MO	319.5	F
34	14-15 Sep. 1998	Fort Scott, KS	317.5	T
35	7-8 Jun. 1974	El Dorado, AR	316.7	M
36	22-23 Dec. 1990	Winchester, TN	311.4	S
37	13-14 Jul. 1998	Lawrenceburg, TN	311.4	M
38	20-21 Oct. 1983	Shawnee, OK	311.2	F
39	7-8 May 2000	Union, MO	310.1	M
40	30-31 Aug. 1962	Ida Grove, IA	306.1	F
41	16-17 Jul. 1996	Castana, IA	305.3	F
42	14-15 Jun. 1957	St Louis, IL	305.1	F
43	12-13 Aug. 1957	Damascus, AR	304.8	M
44	1-2 Mar. 1997	Williamstown, KY	304.8	S
45	11-12 Sep. 1972	Harlan, IA	303.5	M
46	21-22 Jul. 1972	Isle, MN	302.3	F
47	13-14 May 1968	Langley, AR	302.0	F
48	4-5 Apr. 1997	Magnolia, AR	300.2	S
49	24-25 Jul. 1960	Checotah, OK	299.2	M
50	18-19 Feb. 1991	Hamburg, AR	299.2	S
51	2-3 Oct. 1986	Osceola, MO	298.7	S
52	8-9 Aug. 1995	Piqua, OH	297.2	F
53	28-29 Sep. 1980	Nathan, AR	295.9	F
54	6-7 Aug. 1998	Sheboygan, WI	295.9	F
55	27-28 Jun. 1986	El Dorado, AR	292.1	T
56	31 Aug.-1 Sep. 1982	Dover, TN	289.1	M
57	17-18 Jul. 1968	Dumont, IA	286.5	M

* S: synoptic events; F: frontal events; M: mesohigh events; T: tropical events.

and sometimes spreads over several states. A frontal event is associated with a slow northward-moving (or stationary) warm front. The warm, moist air rises up at the frontal boundary and rains at the cool side of the front. A mesohigh event is a smaller scale feature and related to a nearly stationary thunderstorm outflow boundary that had been generated by prior convective activity. The rain area is usually circular in shape and is located on the cool side of the boundary.

Since the classification by Maddox et al. is based on rainfall generation mechanism, several studies (e.g., Bradley and Smith 1994; Bauer-Messmer et al. 1997; Konrad 2001) adopted their approach to classify rainstorms. We also employed Maddox's classification scheme to identify the dominate lifting mechanism for extreme rainstorms in the central United States. The results are shown in Table 1. Two storms do not fit into Maddox's classification scheme. The 14-15 September 1998 and 27-28 June 1986 storms were generated by a tropical depression or a landfall hurricane, which were excluded in the analysis by Maddox et al. (1979). These storms are classified as tropical events in Table 1.

A summary of the classification results is listed in Table 2(a). Among the 57 events, the majority are mesohigh (22 events, 39%) or frontal events (21 events, 37%). There are significantly fewer synoptic events (12 events, 21%). Tropical events are the least common (2 events, 3%). The rank of the types of events is similar to the results from Maddox et al. (1979) for flash floods, listed in Table 2(b) for comparison. However, extreme rainstorms have a higher percentage of frontal events than flash floods. In fact, the percentage of frontal events is close to the percentage of mesohigh events for extreme rainstorms. This result suggests that mesoscale forcing is crucial for generating extreme rainstorms in the central United States.

Table 2: Classification summary of (a) extreme rainstorms and (b) flash floods from Maddox et al. (1979).

	(a) Extreme Rainstorms		(b) Flash Floods	
Storm Type	No. of Storms	Percentage	No. of Storms	Percentage
Synoptic	12	21%	30	25%
Frontal	21	37%	38	32%
Mesohigh	22	39%	52	43%
Tropical	2	3%	—	—

4. Top Three Extreme Rainstorms

In this section, the top three storms in the catalog are shown as examples to illustrate some characteristics of extreme rainstorms. Figure 1 shows the storm total rainfall map of the top-ranked event in the catalog. This storm rained over a large area extending from north-

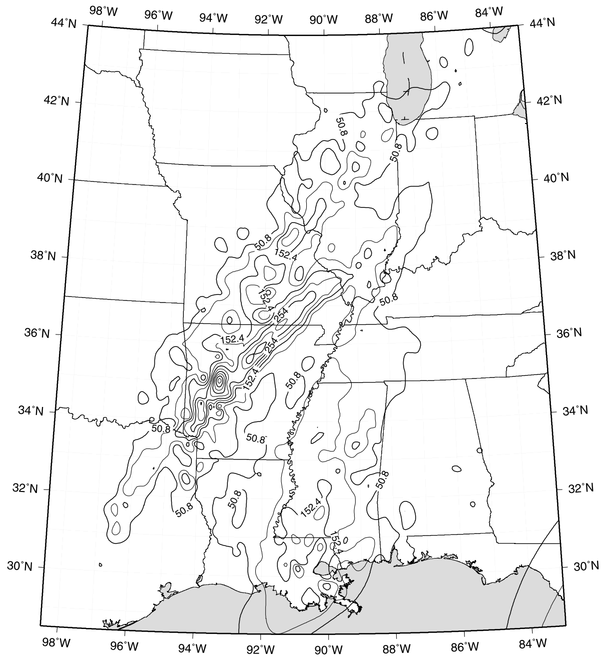

Figure 1: Storm total rainfall map of the Danville, AR storm of 3-4 December 1982 — the first-ranked event in the storm catalog.

eastern Texas to Illinois and Michigan. The heaviest rain fell mostly in Arkansas, with a maximum of 545 mm at Danville, AR. From the *Daily Weather Maps* (not shown), a cold front appeared over the Rocky Mountain area on 1 December and moved eastward. On 2 December, the cold front approached the storm region and slowed down its speed. East of the front, abundant Gulf moisture was fed into the storm area by a strong low-level jet. The storm was initiated by the cold front passing by and lifting up the moisture on the warm side of the front. The axis of the elongated rain area is parallel to the cold front, which is typical for a synoptic event. Also, a strong upper-level jet was observed at 500 mb. Several tornados were reported in *Storm Data*. The damage was estimated to be $3 million for the state of Arkansas. Based on above analysis, this storm was classified as a synoptic event.

Figure 2 shows the storm total rainfall map of the second-ranked event. This storm produced an elongated rain area oriented from northwestern Missouri to eastern Nebraska. The two-day accumulation (19 to 20 July) had a maximum of 497 mm at Edgerton, MO. The heaviest rain fell mostly on 20 July. From the *Daily Weather Maps* (not shown), a warm front extending from western Kansas to southern Missouri was present south of the storm region on 19 July and moved northward. The air was moist at both sides of the front, but warmer south of the front. The storm was initiated by the warm front moving through the region, and rain occurred at the cool side of the front. At 500 mb, a ridge was observed near the rain area with a surface high in the south, resembling a typical upper-level environment for a frontal event. Based on all these features, this storm was classified as

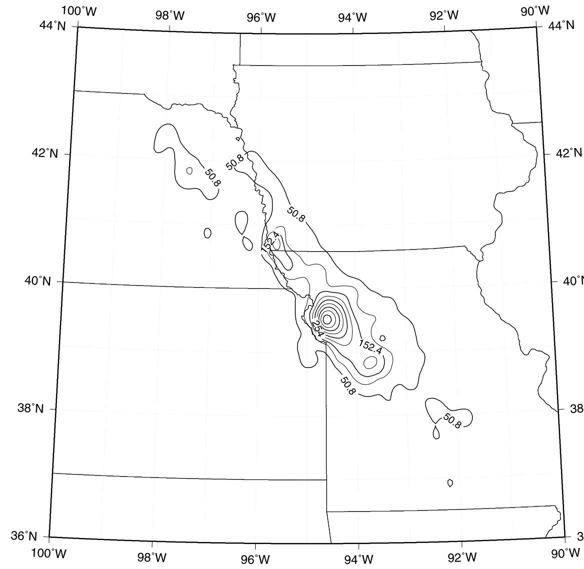

Figure 2: Storm total rainfall map of the Edgerton, MO storm of 19-20 July 1965 — the second-ranked event in the storm catalog.

a frontal event.

Figure 3 shows the storm total rainfall map of the third-ranked event. This storm also produced an elongated rain area extending from Texas to Iowa. The heaviest rain mostly fell in Texas and Oklahoma. The maximum occurred at the Texas-Oklahoma boundary with an amount of 458 mm at Tishomingo, OK. On 13 October, several features were observed from the *Daily Weather Maps* (not shown). A slow-moving cold front appeared west of the storm region. A quasi-stationary warm front was located south of the region. A ridge was present at 500 mb over Oklahoma. In addition, rain occurred the day before over Oklahoma and Kansas. Several tornados were reported in Texas and Oklahoma in *Storm Data*. The damage was estimated to be $25 million for the state of Texas.

This storm does not match a prototype of events. Some aspects, the appearance of the quasi-stationary warm front, the elongated rain area ahead of the surface cold front, and the comparison of the surface low to the rain area, resemble a synoptic event. However, there was no strong short wave moving through the region. Instead, there was only weak dynamic forcing at upper levels. Some features, for example, the 500-mb ridge near the rain area, resemble a typical upper-level environment for a mesohigh event. Likewise, the rain area was away from the cold front, which is more typical for a mesohigh than a synoptic event. In addition, the surface wind within the rain area did not point to the cold front, indicating there were some boundary outflow within the rain area. All these elements indicate that this event is more likely a mesohigh event than a synoptic event. However, the location of the surface high was away from the outflow boundary, which makes it less favorable for a mesohigh event. From above analysis, this storm was given a pri-

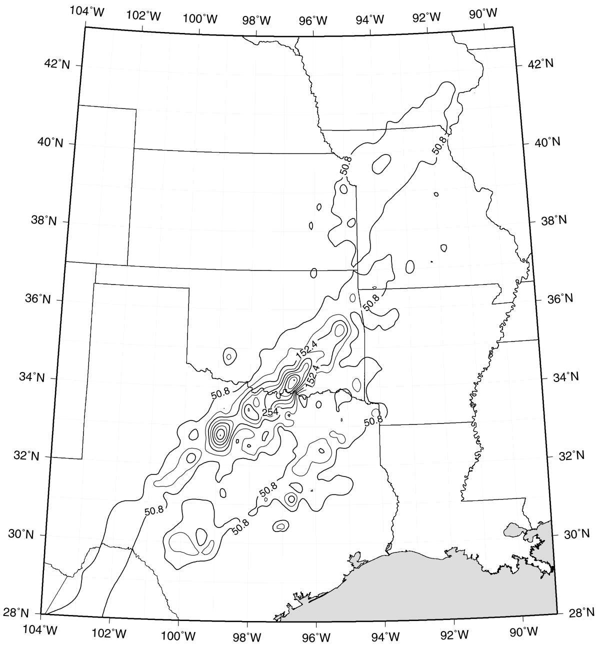

Figure 3: Storm total rainfall map of the Tishomingo, OK storm of 13-14 October 1981 — the third-ranked event in the storm catalog.

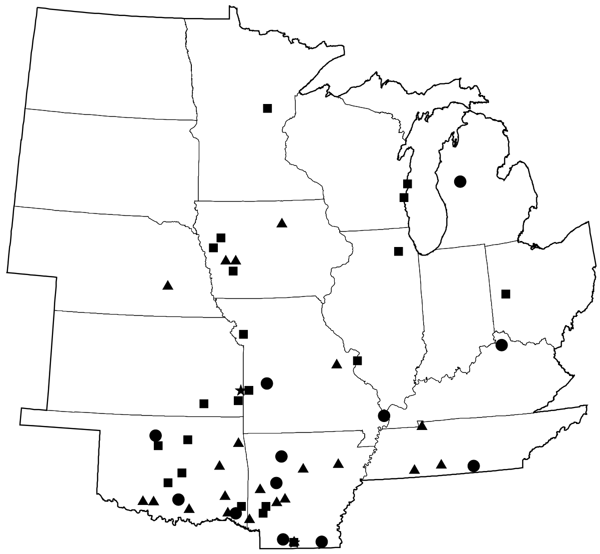

Figure 4: Spatial distribution of the storm centers of fifty-seven extreme rainstorms over the central United States for all seasons. Circles represent synoptic events, squares represent frontal events, triangles represent mesohigh events, and stars represent tropical events.

mary classification as a mesohigh event because of the weak upper-air trough and the distance between the rain area and the front, and a secondary classification as a synoptic event.

5. Spatial Characteristics

To illustrate the spatial characteristics of extreme rainstorms over the central United States, Figure 4 shows the location of the storm centers for all 57 events, along with their classification based on the scheme by Maddox et al. (1979). The catalog contains only those storms producing more than 285 mm of rain within two days. Given a single rainfall threshold for the entire region, it is not surprising to see that many of these storms are near its southern boundary. Another cluster of storms is located near the boundary of Nebraska, Iowa, Missouri, and Kansas, while the remainder are widely scattered throughout the rest of the region. No extreme rainstorm is observed in North Dakota and South Dakota.

Fritsch et al. (1986) analyzed the geographic distribution of warm-season precipitation (April to September), and showed that large amounts of rainfall occur along the Gulf coast, with a separate heavy rain area over Arkansas. Similar results are observed from the *Annual Mean Maximum Daily Precipitation Map* published in the *Climate Atlas of the Contiguous United States* by the NCDC. Generally, the closer to the Gulf, the larger the rainfall. Since plentiful moisture supply is one of the main ingredients needed to produce extreme rainstorms, it is not surprising that more extreme rainstorms occurred in the south than in the north because of its proximity to the Gulf moisture. One interesting thing to point out is that twelve storms in the catalog are located in the heavy rain area over Arkansas that appears in both Fritsch et al. (1986) and the *Annual Mean Maximum Daily Precipitation Map*.

Fritsch et al. (1986) further analyzed the accumulated precipitation patterns from mesoscale convective systems (MCSs) for the 1982 and 1983 warm seasons, and concluded that MCSs account for a large fraction of the warm-season precipitation for the region between the Rocky Mountains and the Mississippi River. Therefore, we compare the storm location map to the accumulated precipitation patterns from 44 mesoscale convective complexes (MCCs) for the 1982 warm season in Fritsch et al. (1986). Very interestingly, the two clusters of extreme rainstorms in our analysis are located in the two largest rainfall accumulation areas in their analysis. Ashley et al. (2003) analyzed the spatial distribution of the average percentage of total annual precipitation due to MCC rainfall based on a 15-year survey, and showed that a high percentage of total annual MCC precipitation is located near the boundary of Nebraska, Iowa, Missouri, and Kansas (over one of the cluster area in our analysis), where MCCs are most active (Tollerud and Collander 1993). Moreover, Tollerud and Collander (1993) investigated the contribution of MCC rainfall to different rainfall categories, and concluded that MCCs contribute a large portion of precipitation to the high and extreme rainfall categories. These results support the observations by Maddox et al. (1979) and Maddox et al. (1980) for flash floods and Foufoula-Georgiou and Wilson (1990) for the midwest region, and suggest that MCCs may be a main mechanism for generating extreme rainstorms in the central United States.

One common feature observed from the extreme rainstorms during the classification process is the appearance of low-level jets, responsible for transporting moisture from the Gulf of Mexico to the storm regions. Thus, the low-level jet plays an important role in the occurrence of extremes in the central United States. A key feature that has been identified and related to summertime precipitation and moisture transport over the central United States is the Great Plains low-level jet. The climatology and variations of the Great Plains low-level jet have been well studied (Bonner 1968; Chen 1993; Helfand and Schubert 1995; Mitchell et al. 1995; Higgins et al. 1997). Comparing the jet core location map in Bonner (1968) with the extreme rainstorm locations, 53% of the events are located within the axis of the Great Plains low-level jet, extending from Oklahoma to Wisconsin, in Bonner's analysis. Moreover, the location of the clustering storms near the boundary of Nebraska, Iowa, Missouri, and Kansas is very close to the climatological location of the jet cores. This result, combined with our previous analysis, suggests that the Great Plains low-level jet may contribute to the clustering extreme rainstorms near the boundary of Nebraska, Iowa, Missouri, and Kansas.

The lack of extreme rainstorms in North Dakota and South Dakota may be due to the cooler climate, higher elevation, and lower atmospheric moisture and conditional instability in this area. The climatology of the cooler, drier environment results in fewer convective storms, and they are less likely to be large rain producers when they do occur.

Foufoula-Georgiou and Wilson (1990) analyzed the spatial distribution of the storm centers of 77 storms in midwest region using the storm data collected by the U.S. Army Corps of Engineers for the period of 1891 to 1951. This storm catalog was used in the development of the generalized probable maximum precipitation estimates for the United States east of the 105th meridian (Schreiner and Riedel 1978). Similar to our results, no extreme rainstorm is observed in North Dakota and South Dakota, and a majority of the storms occurred in Missouri and Iowa for the midwest region defined by Foufoula-Georgiou and Wilson (1990). However, in their analysis, storms are more widely spread than those in our analysis. The difference is caused by the storm selection criteria. In contrast to the large-accumulation (more than 285 mm), short-duration (less than two days) storms used in our analysis, their storms have rainfall accumulations more than 229 mm (9 in) and durations up to 186 hours. Foufoula-Georgiou and Wilson (1990) further classified their storms based on rainfall maximum and duration, and found that storms with rainfall maximum between 229 mm (9 in) and 268 mm (10.5 in) are distributed more uniformly in space for the midwest region. The spatial distribution of storm centers shows similar clustering to our result for the storms with depth larger than 330 mm (13 in).

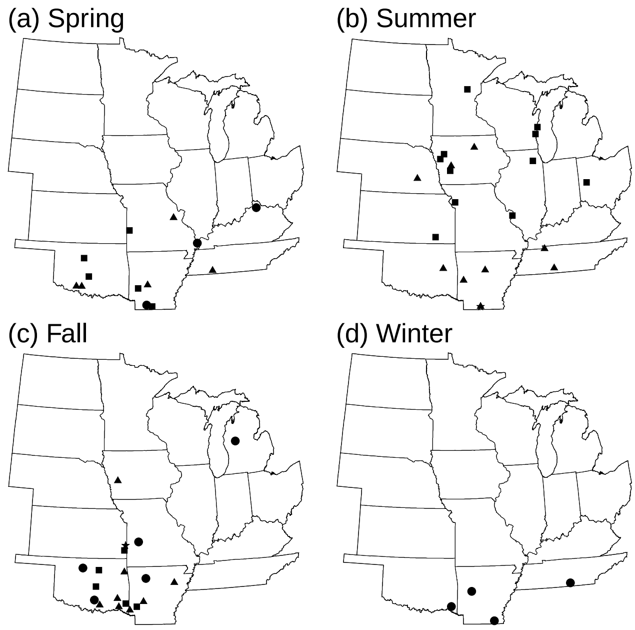

Figure 5: Spatial distributions of the storm centers of the fifty-seven extreme rainstorms over the central United States for (a) spring, (b) summer, (c) fall, and (d) winter. Circles represent synoptic events, squares represent frontal events, triangles represent mesohigh events, and stars represents tropical events.

To further illustrate the seasonal variation of the spatial distribution of extreme rainstorms, Figure 5 shows the locations of the storm centers for the four seasons. In spring, more than half of the extreme rainstorms occurred in Arkansas and Oklahoma. No extreme rainstorm occurred in the northern states (e.g., Minnesota, Wisconsin, and Michigan). In summer, extreme rainstorms are widely spread in the Great Plains. This is the only season when more than half of the storms occurred north of the 40°N latitude, and interestingly, most of them are frontal events. In fall, the occurrence of extreme rainstorms seems to be clustered in the south. In fact, 75% of the storms occurred in Arkansas and Oklahoma. Only two storms occurred north of the 40°N latitude (in Iowa and Michigan). Four extreme rainstorms occurred in winter. All of them are synoptic events and located south of the 36°N latitude.

This seasonal variation shows similarity to the analysis by Maddox et al. (1986), who displayed the spatial distribution of the tracks of MCCs progressing from April to July. In April (springtime), MCCs occurred more often in the south. As time progresses into June and July (summertime), more MCCs track through the north. Our previous analysis pointed out that MCCs may be responsible for producing extreme rainstorms in the central United States. The matching of the seasonal variation of the tracks of MCCs with the occurrence of extreme rainstorms reinforces this hypothesis.

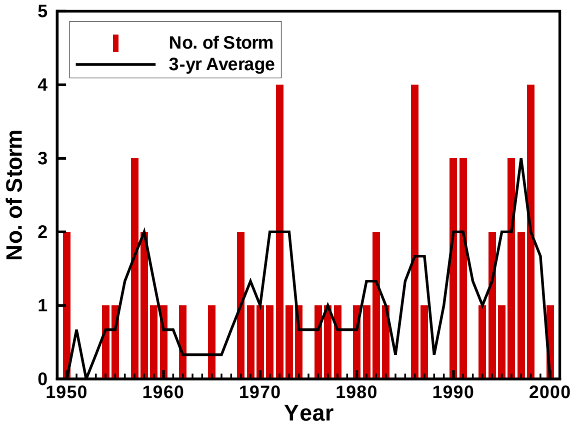

Figure 6: Chronological distribution of the fifty-seven extreme rainstorms over the central United States. The number of storms for each year is shown by the bar. The solid line represents a three-year moving average. The three-year average is positioned in the middle year of the three-year period.

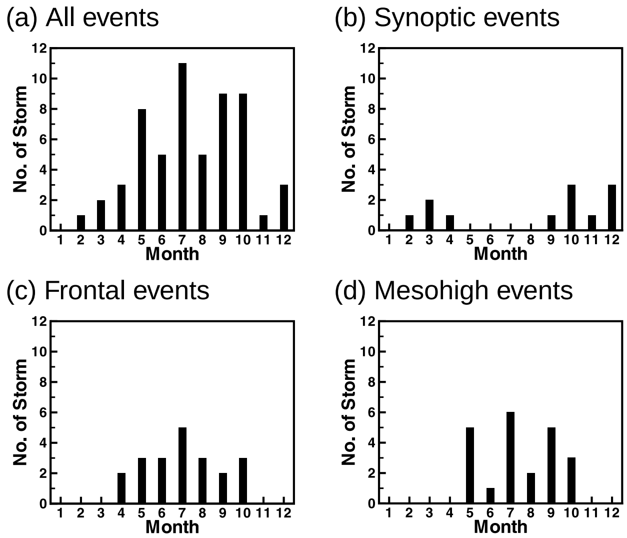

Figure 7: Monthly distributions of extreme rainstorms for (a) all events, (b) synoptic events, (c) frontal events, and (d) mesohigh events.

6. Temporal Characteristics

To illustrate the temporal characteristics of extreme rainstorms over the central United States, Figure 6 shows the chronological distribution of the 57 storms in the catalog. With an average of 1.14 storms per year (57 storms in 50 years), it is not surprising to see that most years had only one or two extreme rainstorms. 1972, 1986, and 1998 were years when an unusually large number of extreme rainstorms (4) occurred. Two periods, 1951 to 1956 and 1961 to 1967, had low occurrence of extremes (only two storms occurred within a five-year and six-year period).

The time distribution of the extremes is not uniform. The occurrence of extremes increases over the 50-year period. In fact, half of the extreme rainstorms occurred in the last twenty years (from 1981 to 2000), and one third of the extreme rainstorms occurred in the last eleven years (from 1990 to 2000). This feature can be clearly seen from the three-year moving average. Similar results have been observed by Karl and Knight (1998), Kunkel et al. (1999), and Groisman et al. (2001), who all stated that heavy and extreme precipitation occurred more frequently in the late 20th century. Several studies (e.g., Cubasch et al. 2001; Yonetani and Gordon 2001; Zwiers and Kharin 1998) suggested that anthropogenic forcing of the climate systems, due to increasing greenhouse gas concentrations, results in an increase of heavy precipitation. However, Kunkel et al. (1999) showed that the frequency of extreme precipitation events in the central United States was almost as high in the early 1900s, before anthropogenic forcing was significant, as in the 1980s and 1990s. Therefore, the causes (global warming, natural climate variation, or random sampling) for the increasing occurrence of extreme precipitation are still in debate.

Figure 7 shows the monthly distributions for all 57 extreme rainstorms and storms classified by Maddox storm type. For all storms, a seasonal variation is observed. More than 80% of the extreme rainstorms occurred between May and October. The occurrence of extremes has a minimum in January and a maximum in July. Similar to the analysis by Maddox et al. (1979) for flash floods (151 events), a majority of the events occurred between May and October, and July has the highest occurrence in a year. However, extreme rainstorms occur more often in late spring (May) and early fall (September and October) than flash floods. Bradley and Smith (1994) studied the occurrence of extreme rains in the southern plains of United States for a 43-year period (from 1948 to 1990), and concluded that the high occurrence of extremes during late spring and early fall is due to a combination of strong dynamic forcing and high moisture and instability in this region. They did not observe a peak occurrence in July. Similarly, our results also show a spring/fall peak in the southern plains (Figure 5). The July peak in our analysis is due to a shift in the occurrence of extremes to the north during the summer.

Of the different types of events, synoptic events (Figure 7(b)) occurred in all seasons except summer. The monthly distribution of synoptic events is more uniform than others, but with higher occurrence in fall and early winter. This result is similar to the result in Maddox et al. (1979) for flash floods (30 events). Both synoptic extreme rainstorm and flash flood events tend to be uniformly distributed throughout the year with no event occurred in January. However, Maddox et al. (1979) observed a small occurrence of synoptic flash flood events in summertime. The difference may be caused by the small sample size (12 events) in our analysis.

In contrast, frontal events (Figure 7(c)) mostly occurred from late spring to early fall. A large number (5) is also observed in July. No event is observed in winter. Similarly, most frontal flash flood events (38 events) occurred in summer and fall (Maddox et al. 1979). Both frontal extreme rainstorm and flash flood events peak in July. However, extreme rainstorms seem to occur more frequently in spring than flash floods.

Similar to frontal events, mesohigh events only occurred in the warm season (Figure 7(d)). Unlike the analysis by Maddox et al. (1979), where a bell-shape distribution was observed for mesohigh flash flood events (52 events) from January to December, mesohigh extreme rainstorms occurred irregularly throughout the year with a large number occurred in May, July, and September.

7. Summary and Conclusions

A storm catalog was created to illustrate the spatial and temporal characteristics of extremes over the central United States. The catalog contains 57 extreme rainstorms that produced more than 285 mm of rainfall within two days from 1950 to 2000. The storms were classified on the basis of pre-storm conditions using Maddox's classification scheme for flash floods (Maddox et al. 1979). The majority of the events are mesohigh and frontal events, suggesting that mesoscale forcing is crucial for generating extremes in the central United States. In addition, the low-level jet plays an important role transporting moisture from the Gulf of Mexico to the storm region. Abundant moisture supply accompanied with a proper lifting mechanism creates a suitable environment for extreme rainstorms.

The distribution of extreme rainstorms is not uniform in space. Two clusters were observed. One is located in the region of Arkansas and Oklahoma, and the other is located near the boundary of Nebraska, Iowa, Missouri, and Kansas. Further analysis found that the two clusters of extreme rainstorms are located within the two largest rainfall accumulation areas produced by MCCs in the 1982 warm season (Fritsch et al. 1986). Moreover, the seasonal variation of the spatial distribution of storm centers is consistent with the seasonal movement of MCC tracks observed by Maddox et al. (1986). These results support the observations by others (Maddox et al. 1979, 1980; Foufoula-Georgiou and Wilson 1990), and suggest that MCCs may be a dominate mesoscale system for generating extreme rainstorms in the central United States. In addition, the clustering of the extremes and the large percentage of total annual MCC rainfall near the boundary of Nebraska, Iowa, Missouri, and Kansas may be related to the Great Plains low-level jet.

Extreme rainstorms occurred more frequently in the last 20 years, which is consistent with the findings by others (Karl and Knight 1998; Kunkel et al. 1999; Groisman et al. 2001). The occurrence of the extremes depends on season and storm type. Extreme rainstorms occurred more frequently in mid-summer, early fall, and late spring. Synoptic events occurred mostly in the cool season (from October to March), in contrast to frontal events in the warm season (from April to September). The monthly distributions of synoptic and frontal types extreme rainstorms are similar to those observed by Maddox et al. (1979) for flash floods. However, the monthly distribution of mesohigh extreme rainstorms shows distinct characteristics.

Acknowledgements This research was funded by the National Science Foundation (NSF) under grant CMS-9702715.

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