

The Most Extreme Precipitation Events over the Eastern United States from 1950 to 1996: Considerations of Scale

CHARLES E. KONRAD II

Department of Geography, University of North Carolina at Chapel Hill, Chapel Hill, North Carolina

(Manuscript received 9 October 2000, in final form 13 February 2001)

ABSTRACT

The intensity or magnitude of a given heavy precipitation event is typically associated with the greatest point precipitation total. The scale or size of the heavy precipitation region, however, is important because it affects the scale of the flooding potential (e.g., local- vs regional-scale basins). In this study, a heavy-rain climatological description is constructed that identifies all precipitation events for the period of 1950–96 and estimates the heaviest mean 2-day precipitation totals over a range of spatial scales (i.e., circular regions from 2500 to 500 000 km²). Ranks of the most extreme precipitation events are provided for four regions of the study area for each of the 10 spatial scales. To develop the dataset, daily precipitation totals from the cooperative observer network are spatially interpolated onto a finescale (10 km by 10 km) grid over the eastern two-thirds of the United States. An automated algorithm is developed 1) to identify regions displaying the greatest mean 2-day precipitation totals over each spatial scale and 2) to link nearby regions of different scales together to form precipitation events. Precipitation events with regional recurrence intervals of approximately 1 yr or greater at each spatial scale are examined and compared across four subregions. The geographical and seasonal distributions of these events are provided. The extreme events are also tied to the occurrence of tropical cyclones and 500-hPa cyclones. Secular trends are identified in the frequency of extreme events over the different spatial scales.

1. Introduction

According to the National Climatic Data Center (NCDC), the heaviest 24-h precipitation event in the United States occurred in Alvin, Texas, in July 1979, where a point total of 43 in. of precipitation was recorded. There probably have been other more extreme, localized events that have occurred between the stations in the gauge network. In recent years, for example, Doppler radar estimates have provided precipitation amounts on a much finer scale, thus revealing events that otherwise would have escaped detection (Legates 2000). Excessive point precipitation totals, by themselves, provide little information regarding the potential for flooding. It is the timing and spatial distribution of precipitation within a stream basin that are the key factors in determining whether flooding will be observed (Hirschboeck et al. 2000). A vivid example of the influence of these factors is provided by the Mississippi River Valley floods of 1993, when excessive precipitation amounts over a broad spectrum of spatial and temporal scales produced flooding across a wide range of basin sizes (Kunkel 1996).

Reports of extreme precipitation events often high-

light the heaviest point precipitation amount recorded. Furthermore, various climatological treatments of extreme precipitation (e.g., Konrad 1997; Giordano and Fritsch 1991; Winkler 1988) have identified the greatest point precipitation total as a variable for determining whether a given event is “heavy” or “extreme.” The extreme rainfall associated with Hurricane Floyd over eastern North Carolina provides an example. Point totals of up to 480 mm (i.e., 19 in.) were commonly reported in this event (NCDC 1999), and these point totals were associated with catastrophic river flooding that followed the event. The extremeness of the flooding, however, can be tied to rivers at or above flood stage immediately prior to Floyd (i.e., from Tropical Storm Dennis 11 days earlier) and the large region in which extreme precipitation was observed during Floyd. Doppler radar estimates suggest that 48-h precipitation totals exceeded 400 mm over a 20 000 km² region. The return interval for such an event at this scale over North Carolina or the United States as a whole is unknown. Although various case studies (e.g., Hales 1978; Elsner et al. 1989) have provided isohyetal maps that depict the spatial distribution of precipitation, few works have estimated (e.g., Schwartz et al. 1990; Kane et al. 1987; Heideman and Fritsch 1988; Angel and Huff 1998; Junker et al. 1999) maximum mean precipitation totals over a given area.

During the last decade, numerous high-magnitude

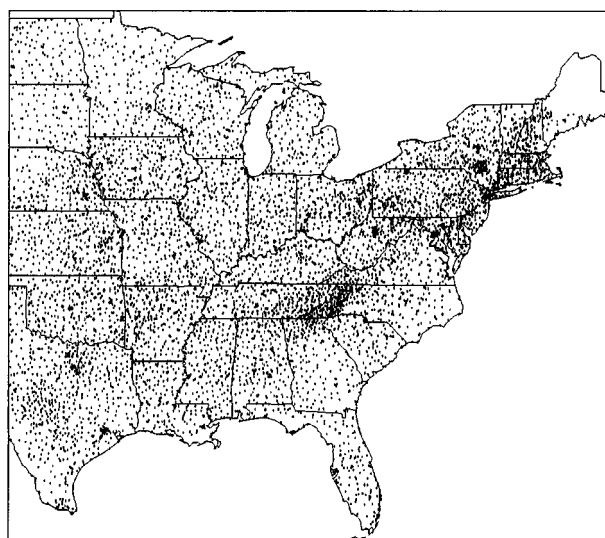
Corresponding author address: Charles E. Konrad II, Dept. of Geography, University of North Carolina at Chapel Hill, Chapel Hill, NC 27599-3220.
E-mail: cek@email.unc.edu

floods (e.g., Shadyside, Ohio, 1991; central South Carolina, 1990; northern Illinois, 1996) have resulted from an increased frequency of heavy precipitation events over the eastern United States (Karl and Knight 1998). It is unclear, however, if the increases in the frequency of extreme precipitation events has occurred across all spatial scales. Other works (e.g., Gleason and Easterling 2000) have examined trends in the total volume of precipitation events, but these studies do not discriminate the spatial scales of the events. Not only are the frequencies of events at different scales unknown, it not clear what types of atmospheric circulations (i.e., tropical vs wave cyclone, mesoscale convective system, etc.) are responsible for changes in the frequencies of precipitation events over different scales. An understanding of the mechanisms behind the frequency changes is needed, especially in the development of future climate scenarios.

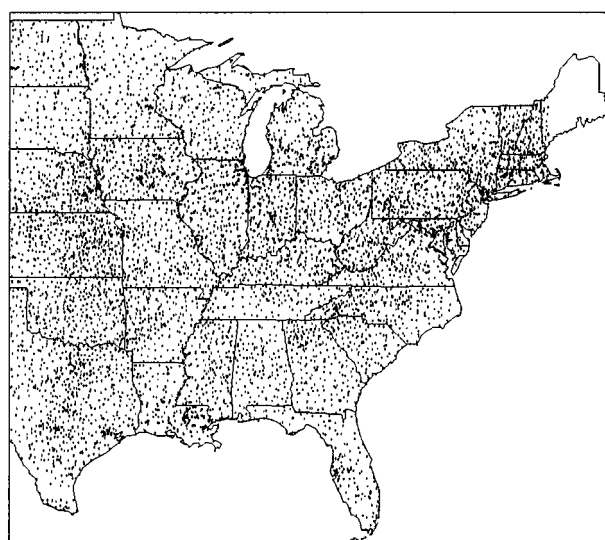
In this study, precipitation events are identified over a 47-yr period across the eastern two-thirds of the United States and are ranked according to the greatest mean 2-day precipitation totals observed over 10 spatial scales from 2500 to 500 000 km². Well-known historical events (e.g., Tropical Storm Agnes in the mid-Atlantic states in 1972) as well as notable recent events (e.g., Tropical Storm Alberto in south Georgia in 1994) are ranked according to the greatest mean precipitation observed over the 10 spatial scales. The most extreme precipitation events are described and compared over each spatial scale and across four subregions within the eastern United States. The climatological characteristics of the events are identified along with the secular trends in their frequencies over the different spatial scales.

2. Methodology

In deriving areal estimates of daily precipitation amounts, a dense network of rain gauges is desirable, especially during the warm season when the spatial variability of daily precipitation is the greatest. Doppler radar precipitation estimates may be used to estimate areal precipitation means over a region, and the accuracy of these estimates is very high when adjustment factors or gauge corrections are applied (Legates 2000). Radar-based estimates unfortunately are only available for recent years, a time period that is not long enough to construct a heavy precipitation climatological description. In this study, daily precipitation amounts from the Cooperative Observer Network were used, accessed from the *Cooperative Summary of the Day* CD-ROMs (NCDC 1997). This network (Fig. 1) provides the best spatial coverage of gauges over the 47-yr study period, although regional differences exist in the density of stations (e.g., southern Appalachian region in North Carolina vs northern Minnesota). In addition, there has been a secular decrease in the station density during the study period. (e.g., cf. Figs. 1a and 1b). The network contained 8280 stations within the study region in 1950; by 1996



(a)



(b)

FIG. 1. The locations of cooperative observer stations situated in the eastern United States during (a) 1950 and (b) 1996.

there were 7527 stations, which represents nearly a 10% decrease. This secular decrease in station density may have at least a slight negative impact on the estimations of areal precipitation during the latter years of the study period. Most of the 24-h precipitation totals were recorded near 0700 or 1900 LST, although primary reporting stations (e.g., National Weather Service) provided measurements near midnight. Unfortunately, no information was available on the recording times for a given station; thus, it was not possible to establish a standard 24-h time frame for estimating areal precipitation totals across a given network of stations.

The objective of this study is to capture areal pre-

precipitation totals for extreme events. Because precipitation events vary greatly in their diurnal timing and duration, there is no single time period that is best for capturing a precipitation event. Most extreme events are relatively short lived, with durations on the order of hours as opposed to days (e.g., Giordano and Fritsch 1991). Because cooperative stations have varying 24-h measurement periods, it is problematic to estimate event totals over an area. If a 2-day precipitation total is used, events whose duration is 24 h or less can be captured over a given region, but, in some cases, the precipitation from an adjacent event will add to the calculated event total and produce a positive bias. As an example, if two mesoscale convective systems pass over a given region during a 2-day period, some stations will provide precipitation totals for both events whereas other stations will capture only one event or one event and part of the other event. In this study, 2-day precipitation totals over the network were collected to ensure the capture of extreme events with durations of 24 h or less. However, it should be recognized that this approach yielded precipitation overestimates in an unknown number of cases.

Two-day precipitation totals from all stations in the cooperative network within the eastern two-thirds of the United States (Fig. 1) were interpolated onto a 279 by 263 grid containing a 10 km \times 10 km grid spacing. This effort was carried out daily, thus providing temporally overlapping, 2-day precipitation totals for each day of the 47-yr period. Because of the voluminous amount of daily data, the computationally efficient method of Thiessen polygons was used to interpolate the precipitation amounts. The Thiessen polygon method of extrapolation exhibits some shortcomings, including the high weighting of isolated stations; also, stations situated along the Atlantic and Gulf of Mexico coastlines are weighted more strongly as their values are extrapolated beyond the coastline. However, extrapolations were not carried out in pixels beyond a radius of 28 km from any station. Precipitation amounts were not defined in the pixels beyond the extrapolation zone. These pixels were restricted to small regions in which the cooperative observer network was relatively sparse (e.g., Fig. 1). In addition, precipitation pixels were not defined over large bodies of water (e.g., Great Lakes, Atlantic Ocean, and Gulf of Mexico) beyond a 28-km extrapolation zone off of the coastline.

The next step in the analysis was to identify regions containing the greatest mean precipitation totals across each of the 10 scales. An automated routine was applied to the daily gridded precipitation fields to identify mean precipitation maxima in space and time (e.g., over 2-day periods) for each day of the study period. Daily precipitation regions were defined by determining regional maxima in the mean 2-day precipitation totals over circular areas of 10 sizes or scales ranging from 2500 to 500 000 km² (Table 1). A moving or floating window approach was applied such that the circular areas at each scale were moved across the study domain

TABLE 1. Precipitation scales considered in this study.

Designation	Circular area (km ²)	Radius (km)
1 (large scale)	500 000	399
2	400 000	357
3	300 000	309
4	200 000	252
5 (medium scale)	100 000	178
6	50 000	126
7	25 000	89
8	10 000	56
9	5000	40
10 (small scale)	2500	28

(i.e., each area centroid moved systematically, pixel by pixel). Precipitation regions were not considered in the sample at a given scale if more than 20% of the pixels were undefined with respect to precipitation amounts. This restriction was imposed to prevent the construction of precipitation regions that extended beyond the study region into areas where precipitation data were unavailable. The restriction mostly affected large-scale events (i.e., scale 4 or less) whose centroids occurred near the borders of the study area. Also, the restriction precluded the identification of large-scale precipitation regions over large peninsular regions of the study area, including Florida and New England. To develop an independent sample of precipitation regions at a given scale, the centroids of these regions on a given day had to be at least 1000 km apart; otherwise the region with the lesser mean precipitation amount was not placed in the sample. Given the computational time required for carrying out this procedure (i.e., calculations at 73 377 pixels over 17 162 days), the moving windows routine was centered only on the population of pixels registering a 2-day precipitation total of at least 2.54 cm.

Precipitation events were formed by linking together daily precipitation regions across the 10 spatial scales that occurred within 1000 km of each other and within a 2-day time period (Fig. 2). If two precipitation regions at a given scale overlapped spatially within a 2-day time frame (i.e., centroids less than 1000 km apart), the region with the lesser mean totals was eliminated from consideration. Using this approach, most precipitation events made links to a precipitation region defined over each of the 10 spatial scales of this study. Precipitation events were therefore associated with regions containing the greatest mean precipitation totals over each scale of the study (Fig. 3). Events centered in peninsular areas as defined by the study area (e.g., Florida, New England) did not make links to precipitation regions over the larger scales.

The spatial pattern of precipitation in many events is complex, because the shapes of the areas of heaviest precipitation vary across scales (e.g., Fig. 3). An examination of several extreme events revealed that precipitation regions were generally elliptical at the larger scales and nearly circular at the smallest scales. The circular pattern over the smallest scales is at least par-

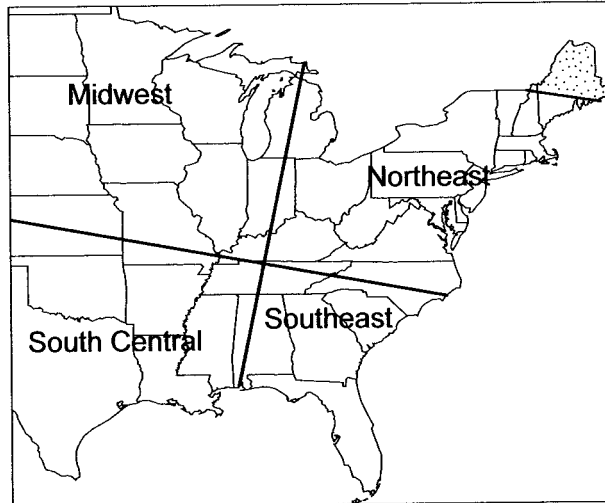


FIG. 2. The eastern United States as defined in this study. The dark lines indicate boundaries between each of the four subregions.

tially the result of the use of Thiessen polygons in the extrapolation of precipitation. The circular precipitation regions defined in this study do not capture elongated or elliptical precipitation regions effectively, and the precipitation amounts in these elongated regions are going to be underestimated. This is especially evident in the large-scale precipitation pattern associated with Hurricane Opal (e.g., Fig. 3), for which the circular regions encompass some areas in which little precipitation is observed (e.g., southeastern Georgia). The circular precipitation regions defined in this study therefore provide a conservative measure of the mean maximum precipitation, at least over the larger spatial scales. Other shapes, including ellipses and rectangles, could always be generated for a given event to maximize the areal precipitation totals, but without a common shape it would be problematic to compare the precipitation totals of different events.

Many of the most extreme events occurred in the southern portion of the study region. To eliminate this regional bias, the study area was broken down into four subregions: midwest, northeast, southeast, and south-

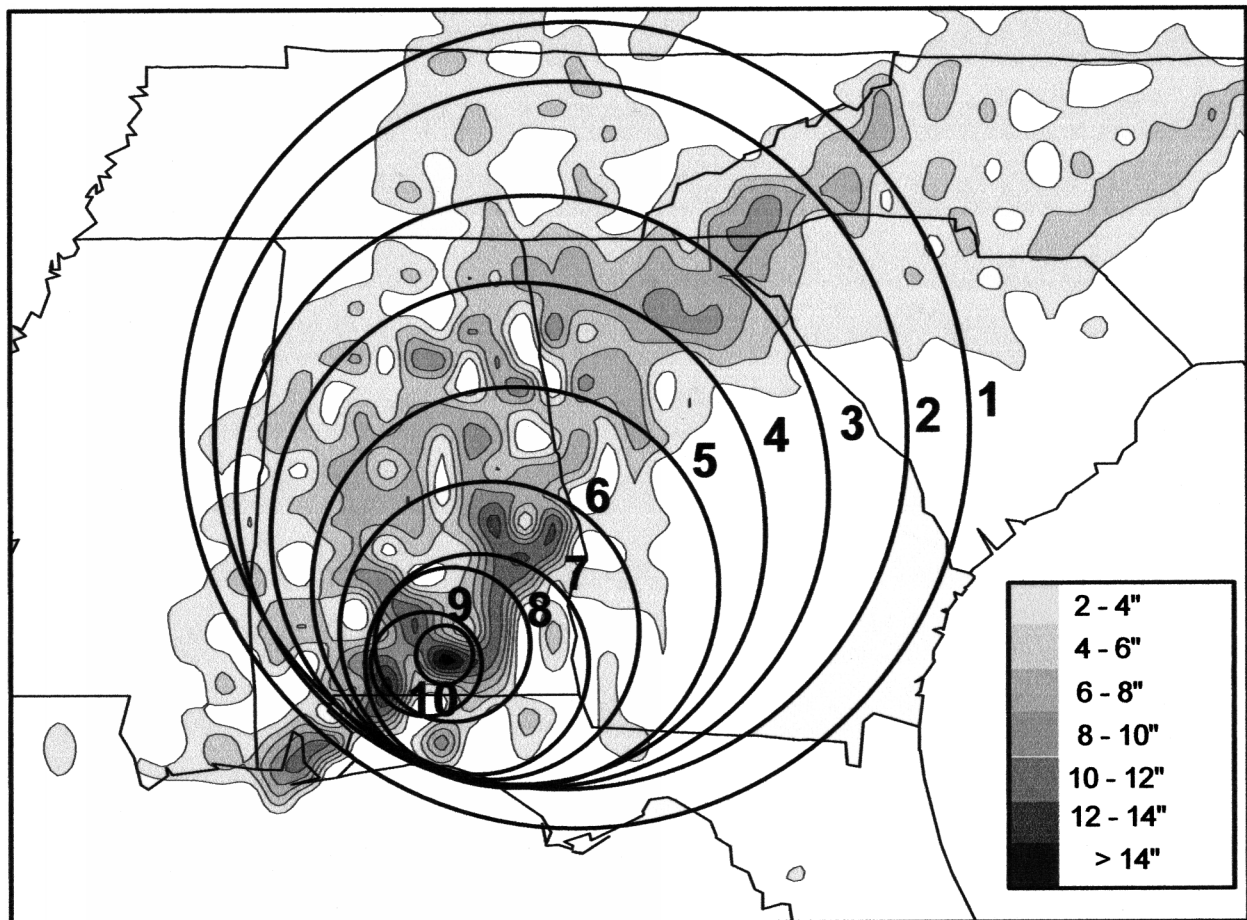


FIG. 3. Two-day precipitation totals associated with Hurricane Opal. The circles circumscribe regions in which the heaviest mean precipitation totals were identified over each of the 10 scales.

TABLE 2. The heaviest precipitation events by scale for each region during the period of 1950–96. Two-day precipitation totals are given for scales in which the event qualifies as the heaviest. Dashed lines indicate that the event has a ranking that exceeds 47. Boldface values represent precipitation totals that are greatest over the entire eastern United States; rm. refers to the remnants of a tropical system (TS). Cyclone and wave refer to the nearest upstream 500-hPa feature.

	Region	Type	Precipitation amounts over each scale (cm)										
			1	2	3	4	5	6	7	8	9	10	
			Midwest										
17 Oct 1968	N KS	Cyclone	8.3	—	—	—	—	—	—	—	—	—	—
12 Oct 1973	KS	Cyclone	—	8.6	9.0	—	—	—	—	—	—	—	—
14 Sep 1961	NW MO	TS Carla	—	—	—	11.0	—	—	—	—	—	—	—
11 Sep 1986	MI	Wave	—	—	—	—	13.4	16.8	—	—	—	—	—
12 Jul 1951	KS	Wave	—	—	—	—	—	—	16.9	—	—	—	—
12 Sep 1972	SW IA	Wave	—	—	—	—	—	—	—	21.5	—	—	—
20 Jul 1965	W MO	Wave	—	—	—	—	—	—	—	—	29.7	41.5	—
			Northeast										
23 Jun 1972	SE PA	TS Agnes	7.6	9.1	12.0	13.8	17.1	19.7	—	—	—	—	—
19 Sep 1955	NE NC	TS Ione	—	—	—	—	—	—	—	—	34.1	—	—
30 Jun 1962	NE NC	Cyclone	—	—	—	—	—	—	22.2	31.1	—	—	44.0
			Southeast										
5 Oct 1995	AL–W GA	TS Opal, front	11.0	12.6	14.7	16.9	20.7	—	28.3	—	—	—	—
17 Mar 1990	SE AL	Wave	—	—	—	—	—	25.9	—	—	—	—	—
6 Jul 1994	S GA	TS Alberto	—	—	—	—	—	—	—	36.7	—	—	—
14 Nov 1954	S FL	Subtropical wave	—	—	—	—	—	—	—	—	—	47.7	—
7 Sep 1950	N FL	TS Easy	—	—	—	—	—	—	—	—	—	—	62.2
			South-central										
4 Oct 1959	cen. TX	Cyclone	11.7	12.8	13.6	14.3	—	—	—	—	—	—	—
18 Oct 1994	SE TX	Subtropical wave	—	—	—	—	22.3	30.5	39.4	43.9	—	—	—
4 Aug 1978	cen. TX	Rm. TS Amelia	—	—	—	—	—	—	—	—	66.1	—	—
3 Dec 1971	SE TX	Wave	—	—	—	—	—	—	—	—	—	—	82.4

central (Fig. 2), and equal numbers of extreme events were identified from each region. The region boundaries were constrained by the orientation of the precipitation grid (e.g., east-southeasterly from the western to eastern fringes of the study region). The choice of boundaries was made by balancing the need for equally sized regions with the need for regional coherence in the synoptic patterns associated with heavy precipitation. Nevertheless, disparities remained in the size of the regions (e.g., the midwest being very large and the southeast relatively small). Also, the northeast region encompassed some areas to the west of the Appalachians (e.g., Ohio River Valley and eastern Great Lakes) for which the synoptic patterns connected with heavy precipitation are a bit different (e.g., Konrad 1994). Forty-seven of the heaviest precipitation events were identified over each region at each scale and were examined. These events roughly exhibit a regional recurrence interval of 1 yr or greater (i.e., 47 events over 47 yr) at the given scale. Daily surface and 500-hPa height analyses were investigated to identify the synoptic environment associated with each of these events.

3. The heaviest precipitation events

The heaviest precipitation events during the study period were identified over 10 spatial scales for each region (Table 2). Each event was characterized according to circulation features at 500 hPa and the surface. Cyclone and wave refer to the presence of a 500-hPa cy-

clone and wave in the vicinity of the event, respectively. Tropical systems identify events in which an organized tropical system (i.e., tropical storm or hurricane) was associated with the precipitation event. The subtropical wave type refers to events that were tied to a low-level trough rotating northward or northwestward around a large anticyclone (e.g., the Bermuda high).

a. The midwest region

In the midwest region, the heaviest events across the broadest scales occurred in October of 1968 and 1973 over Kansas. They were both associated with a slow-moving, but strong, upper-level cyclone and an associated weak surface cyclone (i.e., less than three closed isobars). Both events occurred in a region upstream of a large high pressure region, which provided a transport of deep Gulf moisture, an ingredient that is often the limiting factor in the production of heavy rainfall in the Great Plains. The heaviest event over scale 4 was produced by the interaction of the remnants of Tropical Storm Carla with a front in September of 1961. The heaviest events over the smaller scales (i.e., scales 5–10) all occurred during the summer and developed within a synoptic pattern dominated by weak dynamics.

b. The northeast and southeast regions

In the northeast and southeast regions, tropical systems were largely responsible for the heaviest rainfall

over the spatial scales investigated in this work. Tropical Storm Agnes (Bosart and Carr 1978) was responsible for the heaviest large-scale precipitation in the northeastern region; it was especially remarkable for producing the heaviest precipitation totals over the six largest spatial scales defined in this study. It caused extreme flooding over both large and small drainage basins, especially the Potomac and Susquehanna River basins in southeastern Pennsylvania and Maryland. In the southeastern region, Hurricane Opal produced the greatest rainfall totals over six out of seven of the largest spatial scales (e.g., see Fig. 3). Hurricane Opal's rainfall totals exceeded those of Tropical Storm Agnes across all scales. Also, it provided the heaviest precipitation totals in the study area over scales 3 and 4. Both Agnes and Opal were exceptionally large as identified by the area circumscribed by the outermost closed isobar. Like Tropical Cyclone Carla in the midwest, the moisture associated with these systems interacted with downstream midlatitude features (e.g., fronts and upper-level dynamics) to enhance the rainfall totals. The precipitation totals associated with Tropical Storm Agnes were also enhanced in some areas by the downstream interactions between the system's moisture, the orography, and an upper-level disturbance (Bosart and Carr 1978). Perhaps the most notable event over the southeast region was Tropical Storm Alberto, a relatively small tropical system that stalled out in southwestern Georgia in July of 1994. The floodwaters from the excessive rainfall inundated a region exceeding the size of Massachusetts and Rhode Island and provided Georgia's worst flooding in modern times (NCDC 1994).

c. The south-central region

Curiously none of the most extreme events in the south-central region were directly associated with the landfall of a tropical cyclone. The south-central region, however, experienced precipitation events that were more extreme than those over the other three regions across all spatial scales with exception of scales 3 and 4. The October 1959 event in central Texas provided the most extreme precipitation across the largest scales. The heaviest precipitation occurred within the cool sector of a weak surface cyclone. Most significant in this event was a persistent deep flow of moisture ahead of a vigorous, slow-moving 500-hPa cyclone. Over the medium to small scales, the October 1994 event over southeast Texas produced the most extreme precipitation totals. This event was associated with the movement of a surface wave northward out of the Gulf of Mexico. This weak feature rotated around a large anticyclone positioned east of the area. Also, a vigorous upper-level system located northwest of the region provided a southerly flow, which acted to moisten a deep layer of the atmosphere. Smith et al. (2000) provide an analysis of the extreme precipitation and flooding in this event. The heaviest precipitation observed over scale 9 for the east-

ern United States was associated with the remnants of Tropical Storm Amelia in the Texas hill country. Precipitation amounts with this event exceeded those associated with Tropical Storm Alberto by nearly 20 cm, this over a scale of 5000 km². Unlike the former tropical systems discussed, the remnants of Amelia merely provided a deep layer of tropical moisture; more significant were the interactions of various mesoscale features (e.g., topography and dry line) in focusing the convection and heavy rainfall over a relatively small area (Caracena and Fritsch 1983). The heaviest precipitation event identified over the smallest scale of the study occurred in southeastern Texas in December of 1971. It produced precipitation amounts nearly 2 times as great as the heaviest events on the same scale over the midwest and northeast regions of the study area. The event was associated with a persistent, moist return flow associated with a strong surface anticyclone to the northeast and an advancing cyclonic wave to the west.

4. Recent extreme precipitation events

Increased frequencies of extreme precipitation in recent years (Karl and Knight 1998) have produced some highly publicized flooding events. To provide a climatological context for these events, it is useful to rank them with respect to their heaviest precipitation totals over different scales. Table 3 identifies the six most extreme precipitation events in each region during the last 10 yr of the study.

a. The midwest region

In the midwest region, several events are noteworthy. The September 1989 event in Iowa and Nebraska was associated a slow-moving, nocturnal, mesoscale convective system (MCS). The synoptic situation associated with the MCS featured moisture and warm advection ahead of a weak surface cyclone (Doswell et al. 1996). The event produced extreme rainfall amounts over scales 3–10 and resulted in widespread flash flooding. The most extreme precipitation amounts were noted over a 25 000 km² region (i.e., scale 7) at which it ranked as the fourth heaviest precipitation event in the midwest. The May 1995 event in Missouri and southern Illinois produced especially heavy precipitation totals over the large and medium scales; also, extreme precipitation totals were noted over most of the smaller scales. The heavy precipitation was tied to a slow-moving disturbance on the synoptic scale. This event coupled with several earlier ones was responsible for significant flooding along the Ohio and Mississippi Rivers (CAC 1995), this only 2 yr after the catastrophic floods of 1993. It should be noted that four extreme precipitation events were observed in the Mississippi and Missouri River drainage basins in connection with the 1993 floods; however, none of these events achieved a high enough ranking to be listed in Table 3. Of interest, only

TABLE 3. Ranks of the most extreme events by region and scale over the last 10 yr of the study period. Dashed lines indicate that the event has a ranking that exceeds 47; rm. refers to the remnants of a tropical system. Cyclone and wave refer to the nearest upstream 500-hPa feature.

Date	Region	Synoptic situation	Precipitation ranks by spatial scale									
			1	2	3	4	5	6	7	8	9	10
Midwest												
24 Mar 1987	KS-NE	Cyclone	6	6	8	19	—	—	—	—	—	—
9 Sep 1989	IA-MO	Wave	—	—	44	30	20	16	9	12	26	34
15 Nov 1993	IL-S IN	Wave	—	—	—	12	—	12	17	21	—	—
18 May 1995	MO-S IL	Wave	4	4	5	7	7	10	10	14	28	—
29 Apr 1996	S IL-S IN	Cyclone	19	15	14	15	10	9	11	11	20	32
19 Jul 1996	N IL	Wave	—	—	—	41	19	11	6	5	2	2
Northeast												
19 Aug 1989	E VA	Cyclone	—	—	—	—	—	—	—	—	43	15
9 Aug 1990	E NC	Cyclone	—	—	—	—	—	—	—	—	4	10
28 Nov 1993	N VA	Cyclone	—	—	14	17	24	30	36	36	—	—
13 Jul 1996	E NC	TS Bertha	—	—	—	—	—	33	32	20	17	5
7 Sep 1996	Cen NC	TS Fran	27	20	9	7	5	5	38	16	14	17
22 Oct 1996	NH-ME	Cyclone	—	—	—	46	29	17	23	13	18	21
Southeast												
17 Mar 1990	S AL-S GA	Wave	2	2	2	2	2	1	2	3	8	12
12 Oct 1990	SC-E GA	Rm. TS Klaus	5	5	4	4	5	7	16	18	23	28
3 Mar 1991	S GA-N FL	Cyclone	16	10	8	7	7	6	9	21	26	—
6 Jul 1994	S GA	TS Alberto	—	—	—	29	9	3	3	1	2	5
27 Aug 1995	W SC	TS Jerry	—	37	14	6	11	21	28	24	32	30
5 Oct 1995	S AL-S GA	TS Opal	1	1	1	1	1	2	1	4	5	11
Southwest												
17 Nov 1987	N LA-S AR	Cyclone	4	3	4	5	4	8	5	6	10	15
3 May 1990	N TX-S OK	Cyclone	8	12	12	12	16	35	47	—	—	—
29 Apr 1991	W MS-E LA	Subtropical Wave	9	8	7	6	6	10	10	25	37	0
22 Dec 1991	South-central TX	Cyclone	10	28	32	18	28	—	—	—	—	—
18 Oct 1994	SE TX-LA	Subtropical Wave	—	—	21	9	1	1	1	1	3	4
10 May 1995	SE LA	Wave	—	—	—	—	—	—	22	10	9	10

one of these events produced extreme precipitation totals over the larger scales. The April 1996 event in southern Indiana and Illinois produced extreme precipitation totals over nearly the same region as the May 1995 floods. It featured a slow-moving 500-hPa cyclone along with a well-developed surface cyclone. Extreme precipitation amounts were identified within the warm sector across all spatial scales, but especially the medium scale. Also the event was responsible for a 24-h rainfall record at Evansville, Indiana (CAC 1996). The July 1996 event in northern Illinois displayed the highest ranking of all events in the midwest during the 10-yr period. It resulted from the training of convective cells within two (MCS)s: one occurring during the afternoon and another following during the nocturnal hours (Angel and Huff 1998). The MCSs occurred near the 500-hPa ridge axis on the cool side of a nearly stationary boundary as a vigorous disturbance by summer standards migrated east-southeastward across the region. The synoptic situation in this event most closely resembled the frontal type event in the Maddox et al. (1979) scheme. The event produced severe street and river flooding across the greater Chicago area (CAC 1996). The precipitation was most extreme across the smallest scales, with a second-place ranking over scales 8 and 9 (i.e., 5000 to 2500 km²). Angel and Huff (1998) estimated the areal 24-h precipitation totals for this event and de-

termined that it was the heaviest event in the twentieth century over areas of 2000–5000 mi² (i.e., roughly scales 8 and 9 in this study) for Illinois. This event also produced a record point precipitation total (430 mm or 16.94 in.) for Illinois.

b. The northeast region

In the northeast region, a small-scale event occurred in 1989 over eastern Virginia in which Williamsburg recorded 274 mm (10.78 in.) of rainfall in a 4-h period (CAC 1989). This event was associated with a weak closed circulation at 500 hPa and surface disturbances migrating along a weak frontal boundary. Hurricanes Bertha and Fran both produced extreme rainfall in eastern and central North Carolina during 1996. Bertha's extreme rainfall was limited to the smaller scales along the coast, but Fran, which penetrated far inland, produced extreme precipitation across all scales investigated in the study. Fran's rainfall was especially prolific over scales of 50 000 to 100 000 km², which resulted in 100–200-yr floods along the Neuse and Tar Rivers (CAC 1996); wet antecedent soil moisture conditions, however, conspired to make the floods worse. The October 1996 event in New England produced extreme precipitation over the medium and small scales. It was associated with a slow-moving, vigorous 500-hPa cy-

clone, which entrained tropical moisture from Hurricane Lilli. This storm was one of a few in New England to be ranked in the sample. Because New England events were pooled with events farther southwest where heavy rain occurs more frequently, relatively few events in the region produced rainfall heavy enough to be ranked. The October 1996 storm, however, provided 24-h rainfall records in both Maine and New Hampshire, and Keim (1998) showed through a recurrence interval analysis that the rainfall totals far exceeded the 100-yr rainfall events and perhaps exceeded the 400-yr event for the area.

c. The southeast region

In the southeast region, four out of the six events were associated with tropical systems. Two of the systems, Tropical Storm Alberto and Hurricane Opal, were ranked number one over various scales and were described earlier. The March 1990 event in southern Georgia and Alabama also received a number-one rank, in this case over a single scale. Most extraordinary for this event was the wide range of scales (i.e., from 500 000 to 25 000 km²) in which the event was ranked highly (i.e., 1 or 2). The resultant widespread flooding was exacerbated by nearly saturated soils associated with antecedent rainfall (CAC 1990). The synoptic situation featured shortwave disturbances migrating along the downstream limb of a vigorous long-wave trough stretching southward into the Gulf of Mexico. The October 1990 event in South Carolina and eastern Georgia produced extreme precipitation totals across all scales, but the most extreme precipitation was observed over large and medium scales. This event was associated with the northward movement of tropical moisture associated with the remnants of Tropical Storm Klaus. The northward moisture trajectory was tied to a strong anticyclone positioned northeast of the region. Most of the precipitation fell within a 1-day period; however, Tropical Storm Marco moved over the same areas less than a day later and provided additional precipitation. Point amounts of precipitation were extreme; Augusta, Georgia, received more rain in a 48-h period than they had gotten over the previous 5 months (CAC 1990). Widespread flooding was reported, but the drought conditions existing prior to the event probably reduced the magnitude of the flooding. Tropical Depression Jerry provided extreme precipitation amounts over all but the largest scales in August of 1995. Severe flash flooding was reported in the Carolinas; however, dry conditions prior to the event decreased the magnitude of the flooding to some extent (CAC 1995). Jerry's relatively slow movement coupled with the orographic uplift along the foothills and southern slopes of the Blue Ridge Mountains acted to enhance heavy rainfall totals.

A significant portion of extreme precipitation events in the northeast and southeast regions has been tied to tropical systems, but there are some tropical cyclones

that did not produce prolific precipitation totals: for example, Hurricanes Hugo and Andrew. Although it produced a large heavy rain shield, Hurricane Hugo moved rapidly inland; thus, the duration of the precipitation was relatively short. Hurricane Andrew also moved relatively fast, and the system was very small. Precipitation amounts were therefore relatively lighter and were limited to the smallest spatial scales. Work in progress indicates that the correlation between tropical cyclone strength and heavy precipitation totals is modest, even across the smallest spatial scales.

d. The south-central region

No tropical cyclones were responsible for extreme precipitation in the south-central region during recent years. Four of the most extreme events were tied to a strong upper-level trough. The remaining two events, while indirectly tied to an approaching upper-level trough, occurred along a surface trough migrating northward out of the Gulf of Mexico. The most notable event of the last 10 yr was the October 1994 event in southeast Texas. It produced the most extreme precipitation in the eastern United States over scales 5–8 and was discussed earlier. The November 1987 event in northern Louisiana and southern Arkansas produced extreme precipitation amounts across all scales of the study. This event was tied to a persistent southerly flow associated with the slow approach of a 500-hPa cyclone. Precipitation was heaviest where the moist flow overran a quasi-stationary surface frontal boundary. Although not as extreme, the May 1990 event farther west in Texas and southern Oklahoma produced extensive floods on the Trinity, Red, and Arkansas Rivers, which were already over their banks prior to the event (NOAA 1990). In this case, a stationary front provided a focusing mechanism for the moisture tracking northward ahead of a vigorous cyclonic disturbance. The April 1991 event featured a surface wave that moved northward out of the Gulf in a scenario similar to the October 1994 event. The extreme precipitation amounts produced severe flooding in Louisiana (CAC 1991). The December 1991 event, although less extreme than the other reported events, produced excessive precipitation amounts over the larger scales and was associated with flooding of historical proportions along the Guadalupe, Brazos, and Colorado Rivers (NOAA 1992). The extreme flooding can be related to the duration of the event, which lasted 3 days beyond the 2-day period of extreme precipitation documented in this work. The May 1995 event was especially noteworthy in producing extreme precipitation amounts over a very short time. New Orleans, for example, received over 8 in. of rainfall in a 2-h period, providing some of the worst flooding the city has ever experienced (CAC 1995).

TABLE 4. Summary statistics for the heaviest 47 precipitation events in each region by scale. All measurements are in centimeters.

Region	Scale									
	1	2	3	4	5	6	7	8	9	10
Midwest										
Mean	4.9	5.4	6.0	7.0	8.6	10.5	12.7	16.2	18.8	22.3
Std dev	0.9	0.9	0.9	1.1	1.2	1.7	2.1	4.3	2.8	4.0
Median	4.7	5.2	5.7	6.6	8.3	9.9	12.1	15.3	18.2	21.1
Northeast										
Mean	4.5	5.0	6.0	7.3	9.7	12.0	14.8	17.9	21.7	24.8
Std dev	0.8	1.0	1.4	1.6	2.0	2.3	3.0	3.7	4.4	5.6
Median	4.2	4.8	5.7	6.8	8.9	11.3	14.3	17.1	20.6	22.8
Southeast										
Mean	6.5	7.3	8.3	9.7	12.3	15.2	18.9	23.7	29.2	36.6
Std dev	1.1	1.2	1.6	1.9	2.5	2.9	3.6	4.6	6.2	8.3
Median	6.3	6.9	8.1	9.0	11.7	13.8	18.2	22.6	27.3	34.1
South-central										
Mean	7.7	8.5	9.6	11.2	14.5	18.4	22.0	28.5	35.7	43.2
Std dev	1.0	1.1	1.2	1.3	2.3	3.6	4.8	5.0	7.8	10.7
Median	7.3	8.1	9.2	10.6	13.6	17.1	20.3	26.9	33.6	40.7

5. Climatological aspects of extreme precipitation events according to scale

To get an idea of the general nature of extreme precipitation across different spatial scales, the heaviest 47 precipitation events over each scale in each region were identified and examined. These events correspond roughly to those that have a regional recurrence interval of 1 yr and greater. In the following sections, the climatological aspects of these events are described.

a. Precipitation amounts

Table 4 presents summary statistics for the heaviest 47 precipitation events in each region. The south-central events exhibited the highest mean precipitation amounts across all scales, and the midwest events displayed the lowest values, except over the largest scales. In the south-central region, mean precipitation amounts over scales 9 and 10 were nearly 2 times greater than those observed in the midwest region. In the southeast region, mean precipitation amounts across the smallest scales were nearly 1.5 times greater than those observed in the northeast region. Over the larger scales (i.e., scales 4–10), mean precipitation amounts for events in the northeast region were slightly greater than those observed in the midwest region.

b. Geographic patterns

Figures 4a–c present the centroid of the 47 heaviest precipitation events in each region for three selected scales. It should be noted that peninsular portions of the study area (e.g., New England and Florida) were too narrow to identify larger-scale precipitation. Therefore, many of the largest scale events in the northeast region were defined over the wider southern portion of the region. The centroids of the largest events were concentrated in the central portions of the study region from

the southern Appalachian Mountains west across the southern Mississippi River Valley. A secondary region of concentration was found in eastern Nebraska. It is curious that no events were identified in the interior of Iowa and Missouri.

Medium-scale events displayed a more uniform pattern of occurrence (Fig. 4b). In the midwestern region, these events displayed an increasing concentration toward the southern boundary, which is not surprising given their closer proximity to the Gulf moisture source. In the northeast region, the medium-scale events occurred in a relatively narrow band extending from southern New York to North Carolina. Nearly all of these events were centered on the east slopes of the Appalachian Mountains (i.e., areas of upslope flow under a moist southerly and southeasterly circulation) or the adjacent Piedmont and Coastal Plains, which are near the Atlantic moisture source. With the exception of portions of Tennessee and Kentucky, no events were identified on the west slopes of the Appalachians or the adjacent plateau. This region often lies in a rain shadow for synoptic situations involving the northward or northwestward transport of Gulf or Atlantic air (Konrad 1994). Although the west slopes of the Appalachians have received their share of extreme precipitation and flooding, this analysis suggests that the extreme events on the southeastern slopes of the mountains are typically heavier than those over northwestern slopes. In the southeast and south-central regions, medium-scale events showed a relatively even distribution, with the exception of the peninsula of Florida, which was too narrow to identify events at this scale. Events in the south-central region were especially concentrated in the Gulf Coastal Plain region from southern Georgia westward across Louisiana.

Small-scale events occurred most frequently along the coastal margins (Fig. 4c). In the midwest, the events were more concentrated in northwestern Missouri and

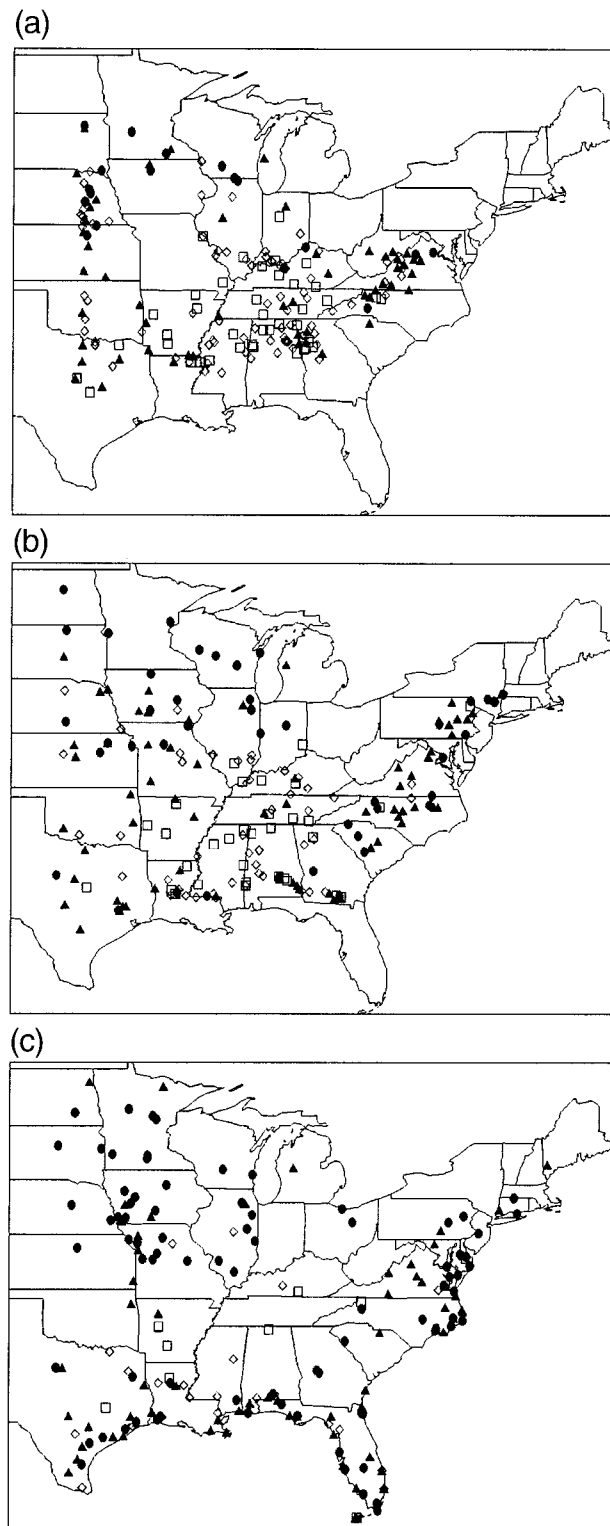


FIG. 4. The geographical centers of extreme precipitation events identified over scales of (a) 500 000, (b) 100 000, and (c) 25 000 km². Squares, diamonds, circles, and triangles indicate events that occurred during the winter (DJF), spring (MAM), summer (JJA), and autumn (SON), respectively.

southwestern Iowa. This region corresponds to an area containing a fair number of flash flood events in the Maddox et al. (1979) sample. In the northeastern region, many of the events were found along coastal portions of Virginia and North Carolina. This pattern was also found in the southern and south-central regions, with events especially concentrated along the Gulf Coast from Florida to Texas.

c. Seasonal patterns

Figure 5 presents the seasonal distribution of the extreme precipitation events for each region. In the midwest, large-scale events occurred most frequently during the late spring and early summer. In the northern portion of the region, most large-scale events occurred during the early summer (Fig. 4). A secondary peak was found during October. All of the winter events were confined to the southeastern portions of the region (e.g., Ohio River Valley). Precipitation events over the medium to small scales showed a midsummer peak, especially over the northern half of the region. This was especially pronounced at the smallest scales (e.g., nearly 60% of the small-scale events were observed during July and August). Many of these events were tied to weak synoptic disturbances, and it is likely that many were associated with mesoscale convective systems.

In the northeastern region, large-scale events showed a more subdued seasonal pattern relative to the midwest, with a major peak observed during autumn and a secondary one in the spring. The large-scale wintertime events were all confined to the southern edge of the region (i.e., North Carolina; Fig. 4). Medium- and local-scale events displayed a pronounced late summer peak. Unlike the midwest, many of these events were related to tropical cyclones. The majority of the fall events occurred on the east slopes of the Appalachians and adjacent Piedmont.

In the southeast, large-scale events showed a very pronounced peak during March. In fact, nearly one-third of these events occurred during this month alone. A slight secondary peak was observed during the autumn and winter months. Medium-scale events also displayed a March peak, although less pronounced. A secondary peak was found during late summer and early autumn and was related to the occurrence of tropical cyclones. Small-scale events occurred most frequently during the late summer and early autumn period in response to tropical cyclones.

In the south-central region, large-scale events occurred with the greatest frequency during the spring and autumn. No events were recorded during the months of June, July, and August. Medium-scale events exhibited a similar pattern, although several summertime events were found. Local-scale events displayed a pronounced peak during September, which can be tied to tropical cyclones.

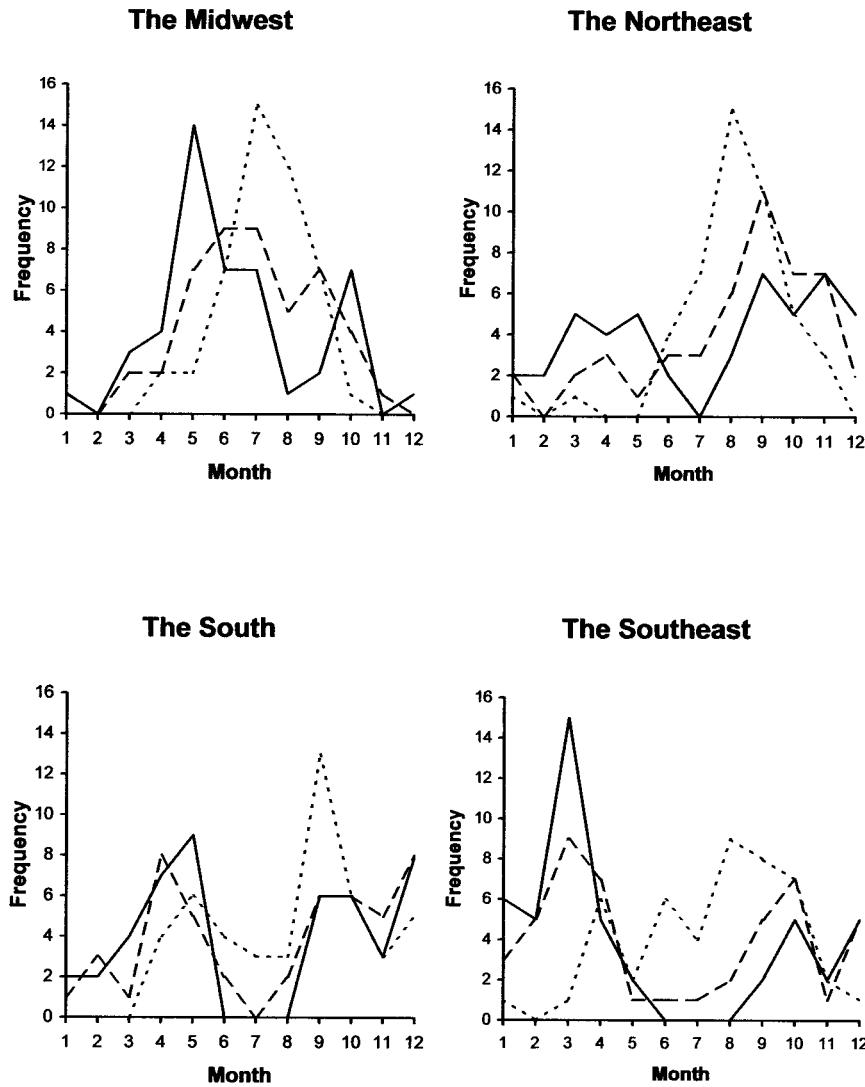


FIG. 5. The seasonal distribution of extreme precipitation events identified over scales of 500 000 (solid), 100 000 (dashed), and 2500 km² (dotted).

d. Tropical systems and 500-hPa cyclones

Many of the most extreme events during the study period (Table 2) and the last 10 yr of the period (Table 3) were connected with tropical systems or 500-hPa cyclones. Therefore, it is useful to examine these connections in the entire sample of extreme events.

Tropical systems were responsible for a significant number of medium- and small-scale events in the northeast and southeast regions (Table 5). This is especially

the case over the smallest scales in the southeast, where 45% of the sample was tied to tropical systems. Only about one-quarter of the south-central events were associated with tropical cyclones. This small fraction does not necessarily imply that relatively fewer tropical events produce heavy rain there relative to the southeast; rather it indicates that other synoptic patterns are more likely to produce the heaviest of the precipitation events.

To investigate the relationships between 500-hPa cyclones and extreme precipitation events, 500-hPa cyclone data were collected from Key and Chan (1999) for the period of 1958–96. The data consisted of position (i.e., latitude and longitude) and strength (minimum 500-hPa height) information for all 500-hPa cyclones identified on twice-daily (0000 and 1200 UTC) analyses. The position information was provided at latitude and longitude intervals of 2.5° and 5.0°, respectively.

TABLE 5. The percentage of extreme precipitation events that is associated with tropical systems.

Scale	Midwest	Northeast	Southeast	South-central
Large	2	15	9	6
Medium	5	35	31	12
Small	2	36	45	26

TABLE 6. The percentage of extreme events that occur within various ranges of the center of 500-hPa cyclone.

Distance (km)	Scale of event		
	Large	Medium	Small
Midwest			
<1500	68	53	15
<1000	58	38	8
<500	34	20	5
East			
<1500	60	58	49
<1000	50	40	39
<500	30	28	29
Southeast			
<1500	48	32	24
<1000	31	17	8
<500	5	10	8
South-central			
<1500	70	48	29
<1000	30	21	22
<500	10	7	15

Algorithms were developed to compute 1) the minimum distance between each extreme event and the nearest 500-hPa cyclone during the 2-day period in which the precipitation was measured, 2) the location of the 500-hPa cyclone relative to the event centroid, 3) the 24-h filling rate of the cyclone, and 4) the speed (i.e., distance traveled over a 24-h period) of the 500-hPa cyclone. Cyclones situated more than 1500 km from an extreme event were not examined.

The sample of 500-hPa cyclones was most strongly associated with large-scale extreme events (Table 6). Nearly three-quarters of the large-scale events in the midwest and south-central regions occurred within 1500 km of a 500-hPa cyclone. The southeast showed the weakest connections; less than one-half of the events were tied to a 500-hPa cyclone. With exception to the southeast, about one-half of the medium-scale events occurred within 1500 km of a 500-hPa cyclone. Small-scale events clearly showed the weakest connections with a 500-hPa cyclone; however, nearly one-third of the small-scale events in the northeast occurred within 500 km of a 500-hPa cyclone. This percentage is nearly 2 times greater than that observed in any other region.

The vast majority of the 500-hPa cyclones were centered northwest of the centroid of heaviest precipitation (Fig. 6). The variability in the cyclone locations was greatest in the south-central events, for which many cyclones were positioned relatively far (i.e., greater than 1000 km) from the heavy rain location. This pattern was evident across all three scales and also showed up to a lesser extent in the southeast region. An examination of synoptic maps for these events reveals that the 500-hPa cyclone played an indirect role in the production of precipitation by providing a persistent southerly to southwesterly flow of moisture over the region of heavy precipitation. Many of the 500-hPa cyclones in the northeast region occurred closer to the location of heaviest precipitation and in a more northerly quadrant rel-

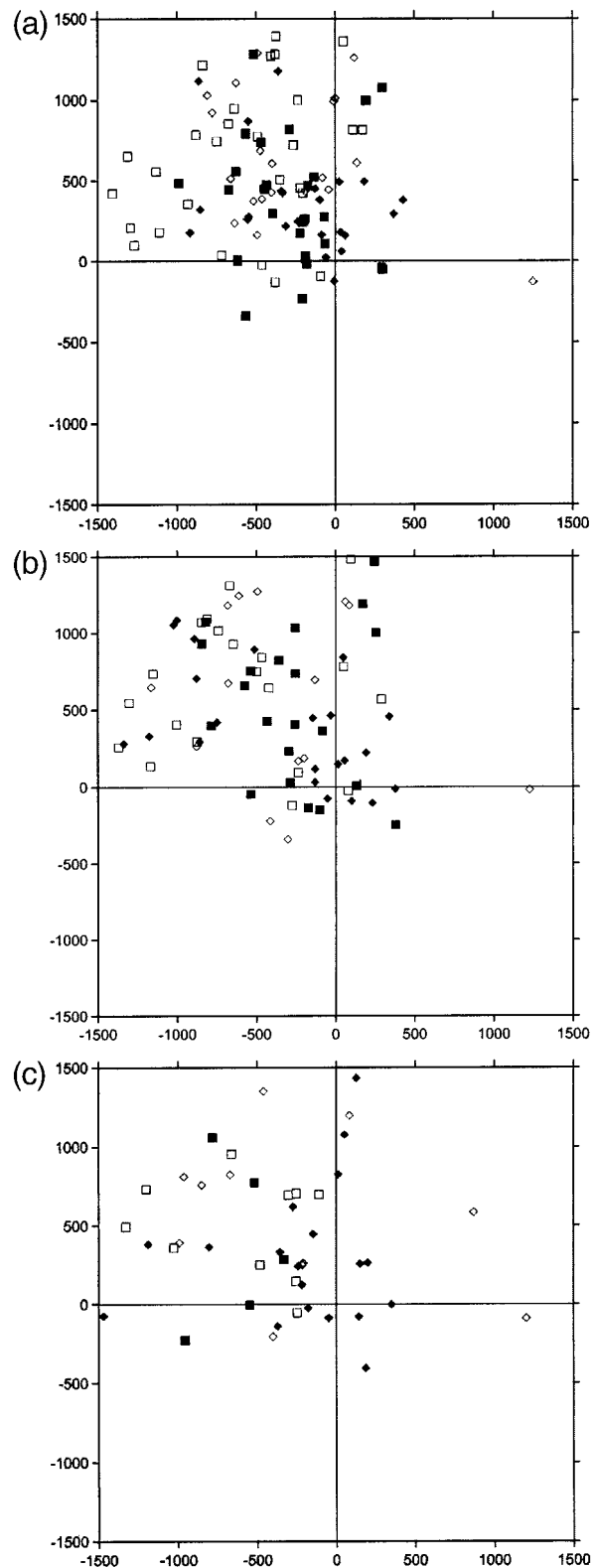


FIG. 6. The location of 500-hPa cyclone centers relative to the location of heaviest precipitation for extreme events defined over the (a) large, (b) medium, and (c) small scales.

TABLE 7. The mean speed, direction of movement, and filling rate of 500-hPa cyclones whose centers occur within 1500 km of extreme precipitation events. Climatology provides mean values of these variables for all 500-hPa cyclones occurring within the region of 30°–50°N and 70°–115°W. Statistically significant differences are bolded.

Season	Speed (km day ⁻¹)	Std dev	Direction	Filling rate (hPa day ⁻¹)	Std dev	<i>n</i>
Large-scale events						
Spring climatology	678	475	S81E	-7.1	54.6	1817
Spring	781	317	N78E	26.7	44.0	22
Autumn climatology	593	341	S85E	0.0	51.2	1227
Autumn	775	310	N84E	22.3	43.3	16
Small-scale events						
Autumn climatology	593	341	S85E	0.0	51.2	1227
Autumn	532	372	S71E	-1.3	40.0	13
Summer climatology	505	324	S66E	-15.8	39.0	498
Summer	281	267	N88E	17.0	33.0	7

ative to the events in the other regions. This was especially evident in the medium- and small-scale events.

The speeds, directions of movement, and filling rates of the 500-hPa cyclones were computed in cases for which position information was available 24 h prior (i.e., two map times earlier). Information was pooled for all regions to develop a robust sample. Means were computed for each season and compared with “climatology,” defined as statistics for the sample of all 500-hPa cyclones in which position information was available over a 24-h time period. Table 7 presents the 500-hPa cyclone statistics for the seasons and scales in which a sample of at least five events was available. The mean speed of the 500-hPa cyclones associated with large-scale spring events was greater than that observed in the spring climatology. In addition, the mean direction of movement was slightly north of east, because the cyclones in the climatology moved east-southeast. Last, the mean filling rate was significantly higher as compared with climatology, which showed a deepening of the mean cyclone. Similar patterns were uncovered for the 500-hPa cyclones associated with large-scale events during autumn, although the directional differences were not statistically significant. A distinctly different pattern emerged in the sample of 500-hPa cyclones associated with the small-scale events. For the fall extreme events, the mean speed of the 500-hPa cyclones was less than that observed in the climatology; also, the direction of movement was more southeasterly relative to climatology. None of the identified differences during autumn was statistically significant, however. Filling rates between the sample and the climatology were similar. The most statistically significant results were found in the summer, when cyclones moved markedly slower and more to the northeast relative to climatology. Also, the summer events displayed a greater filling rate when compared with climatology.

e. Scale issues

Only about one-third of the heavy precipitation and flooding case studies reported in the American Meteorological Society refereed literature were identified as extreme across the spatial scales examined in this study (Table 8). Case studies reported in the literature appear to be biased toward extreme small-scale events, in particular, those that produce flash flooding at the local scale. Some of the more extreme larger-scale events were examined in various government documents (e.g., National Disaster Survey Reports), but these documents do not provide detailed atmospheric analyses. Some of the most well-known events, including the Johnstown, Pennsylvania, flood in 1977 and the floods associated with the remnants of Tropical Storm Camille over central Virginia in 1969, were not ranked in the study, suggesting that the extreme precipitation was confined to scales of less than 2500 km². The Superstorm of 1993 was the only large-scale event tied to a case study analysis (Kocin et al. 1995) that was not ranked. It appears that the most extreme precipitation associated with this event occurred over spatial scales exceeding 500 000 km². In addition, it is likely that precipitation measurements were underestimated because of the strong winds and heavy snows (e.g., Legates and DeLiberty 1993).

It appears that relatively few of the most extreme events at a local or point scale are also extreme over larger scales. Evidence for this idea is gained from an examination of the warm-season events identified as extreme by Giordano and Fritsch (1991) in a study of the mid-Atlantic region. They implicitly defined extreme events at the local scale by the occurrence of at least 19 cm (7.5 in.) of precipitation at a single station in a 12-h period. Of the 47 warm-season events in the Giordano and Fritsch (1991) study that occurred during the time frame of this study (i.e., 1950–86), only 7 (i.e., about 15%) registered as extreme over the spatial scales examined in this study (i.e., 2500 km² and greater). Most significant, none of the Giordano and Fritsch (1991) events was identified as extreme over areas of 50 000 km² and greater.

In comparing cross-scale connections between extreme events across the scales of this study (i.e., 2500–500 000 km²) stronger connections were identified (Table 9). In every region except the southeast, more than 40% of the small-scale events were also extreme over the medium

TABLE 8. Ranks of extreme precipitation events examined in the refereed literature over the spatial scales of 500 000 (scale 1) to 2500 km² (scale 10). Stars indicate unranked events.

Date	Case study	Location	Ranking by spatial scale									
			1	2	3	4	5	6	7	8	9	10
21 Oct 1996	Keim (1998)	Coastal New England	*	*	*	46	*	17	23	13	18	21
27 Jun 1995	Smith et al. (1996) Pontrelli et al. (2000)	Central VA	*	*	*	*	*	*	*	*	*	*
18 Oct 1994	Smith et al. (2000)	Southeast TX	*	*	21	9	1	1	1	1	3	4
6 Jun 1993	Rochette and Moore (1996)	Northern and central MO	*	*	*	*	*	*	*	*	*	*
13 Mar 1993	Kocin et al. (1995)	Eastern United States	*	*	*	*	*	*	*	*	*	*
8 Aug 1992	Funk (1991)	Lower Ohio River Valley	*	*	*	*	*	*	*	*	*	*
9 Jul 1992	Bauer-Messmer et al. (1997)	Great Plains	*	*	*	*	*	*	*	*	*	*
8 Sep 1989	Doswell et al. (1996)	Iowa	*	*	44	30	20	16	9	12	26	34
23 Jul 1987	Schwartz et al. (1990)	Minneapolis, MN	*	*	*	*	*	*	*	*	*	*
6 Aug 1986	Elsner et al. (1989)	Milwaukee, WI	*	*	*	*	*	*	*	*	*	*
24 May 1981	Maddox and Grice (1986)	Austin, TX	*	*	*	*	*	*	*	*	*	*
4 Sep 1979	Gaza and Bosart (1985)	Kansas City, MO	*	*	*	*	*	*	*	*	*	*
18 Sep 1979	Bosart (1984)	Coastal TX	18	25	34	43	20	21	17	33	6	7
1 Aug 1978	Caracena and Fritsch (1983)	TX hill country	*	*	*	*	13	3	3	3	1	2
12 Sep 1977	Hales (1978)	Kansas City, MO	*	31	27	21	13	7	3	4	4	9
19 Jul 1977	Bosart and Sanders (1981)	Johnstown, MO	*	*	*	*	*	*	*	*	*	*
20 Jun 1972	Bosart and Carr (1978)	Wellsville, NY	1	1	1	1	1	1	2	5	9	8
20 Aug 1969	Schwarz (1970)	Central VA	*	*	*	*	*	*	*	*	*	*

scale. With the exception of the northeast, more than 50% of the medium-scale events were defined as extreme over the largest scale of the study. This trend with respect to scale suggests that extreme events defined over the larger scales are more related than those found across the smaller scales, especially scales of less than 2500 km². Relatively few large-scale extreme events were also identified as extreme over a small scale, although in the south-central region the percentage was a bit higher.

6. Secular trends of extreme precipitation events

Figure 7 presents the secular trends in the frequency of extreme precipitation events defined over the three spatial scales. It should be cautioned, however, that the reported trends may be adversely affected by a secular decline in the precision of the areal precipitation estimates during the study period. Between 1952 and 1996, all but the northeast portions of the eastern United States witnessed an increase in the frequency of extremely heavy precipitation over the large, medium, and small spatial scales. In the midwestern region, pronounced secular increases were noted over the large and medium scales. Many of these events, especially those over the largest scales, occurred during the late spring in connection with a 500-hPa cyclone. A marked increase in the frequencies of extreme small-scale events was iden-

tified during the last 9-yr period of the study. This increase was observed primarily during July and August, a time of year in which weak synoptic disturbances frequently produce mesoscale convective systems. In the northeast, decreases in the frequency of extreme events were observed over the large and medium scales, particularly during the last 9-yr period. This parallels a secular decrease in the number of events associated with 500-hPa cyclones. In the southeast, extreme event frequencies increased modestly across all scales. The recent increase (i.e., last 9 yr) in small and medium scale can be tied in part to an increase in the number of landfalling tropical cyclones (e.g., Hurricanes Opal, Bertha, Fran) in the mid-1990s. Marked secular increases in extreme precipitation frequencies were noted over the south-central region (with the exception of large-scale events during the last 9 yr of the study). Nearly one-third of the extreme events over the smallest scales in recent years were tied to 500-hPa cyclones. Unlike in the southeast, most of the extreme precipitation events were not tied to tropical systems.

The general secular trends that are reported here parallel those found by Karl and Knight (1998) for the last half of the twentieth century. Karl and Knight's regional analyses, however, were carried out for a longer time period (i.e., 1910–96), thus preventing the comparison of trends by region. Secular changes in the frequencies of large- and medium-scale events may be tied to changing frequencies in the occurrence of 500-hPa cyclones over some regions. Key and Chan (1999) found statistically significant increases in the frequencies of 500-hPa cyclones over the midlatitudes of North America during the period 1958–97. This matches the period in which large- and medium-scale events associated with 500-hPa cyclones increased over the midwest and south-central regions.

TABLE 9. The percentage of precipitation events that is extreme across both of the indicated spatial scales.

Scale	Midwest	Northeast	Southeast	South-central
Small and medium	41.9	43.5	27.1	47.0
Medium and large	52.4	36.2	55.3	58.8
Small and large	16.7	12.8	10.6	25.5

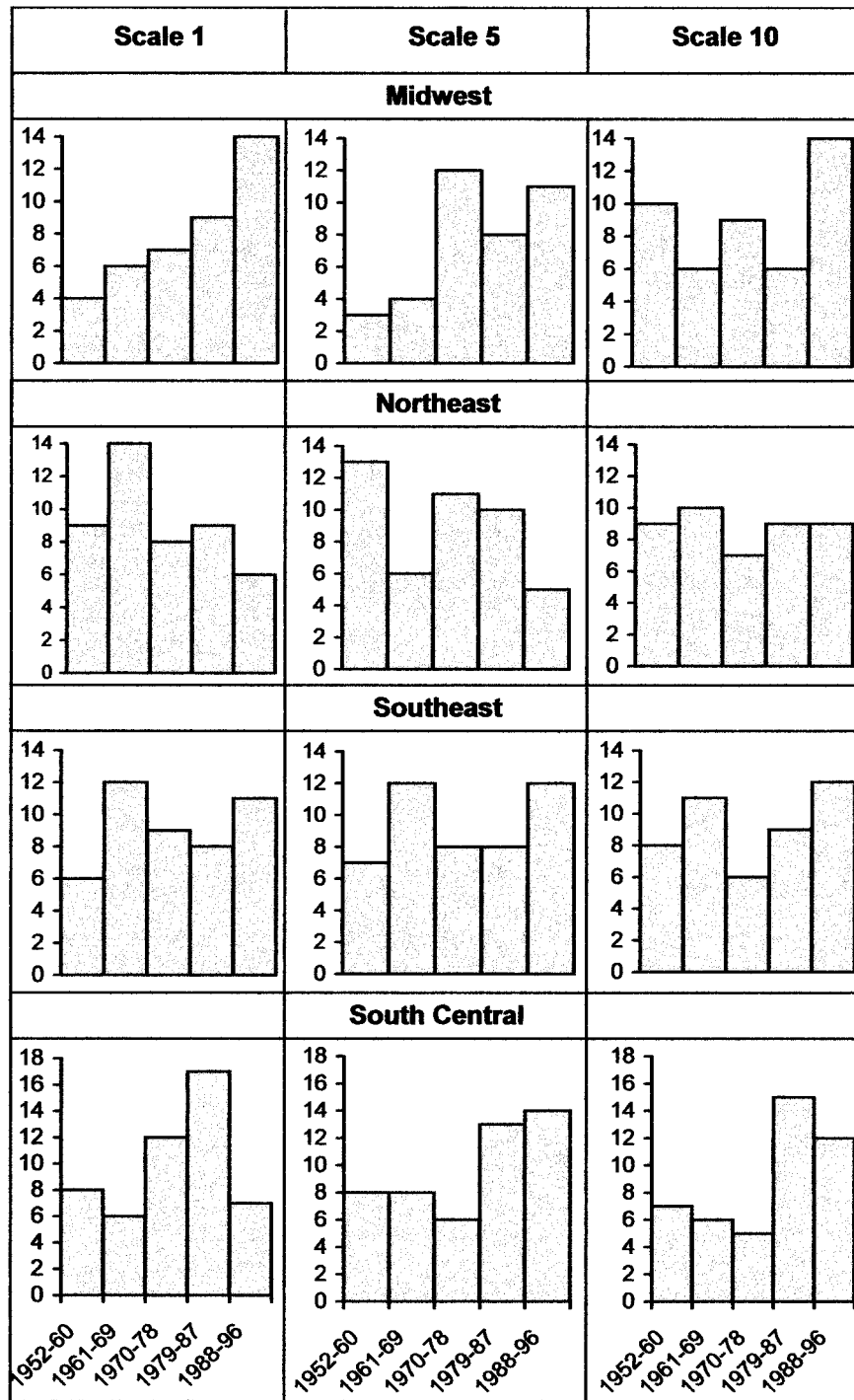


FIG. 7. Secular trends of extreme precipitation events over scales of 500 000 (1), 100 000 (5), and 2500 km² (10).

7. Conclusions

Precipitation events during the period of 1950–96 were ranked according to the heaviest precipitation observed over scales of 2500–500 000 km². Ranks were assigned to the 47 heaviest precipitation events (i.e., regional recurrence interval of 1 yr and greater) at each

scale and across each region. Marked variations were revealed in the seasonal patterns of extreme precipitation over different scales and subregions. Large-scale events occurred most frequently during spring and autumn, especially over the northern half of the study area. Smaller-scale events, on the other hand, exhibited a

strong summer maximum over the midwest, a late summer-to-early autumn maximum over the northeast and southeast, and a relatively even distribution across the south-central region.

Roughly a third or more of the small- and medium-scale events in the southeastern and northeastern regions were connected with tropical systems. These systems were largely responsible for a late summer–early autumn peak in the seasonal distribution of these events. Cyclones at the 500-hPa level were associated with more than one-half of the large-scale events in all subregions of the study area with the exception of the southeast. Relatively few small-scale events were tied to 500-hPa cyclones, except over the northeast, where nearly 50% of the events occurred within 1500 km of a 500-hPa cyclone. Results from a small sample indicated that 500-hPa cyclones that were associated with large-scale events moved faster than those identified in a 500-hPa cyclone climatology. This result is in contrast with the small-scale events, for which the associated 500-hPa cyclone moved more slowly relative to climatology.

Very few of the extreme events identified in this study have been described in the refereed literature, which is biased toward local-scale events (i.e., those occurring on scales of less than 2500 km²). In all but the southeastern region, a relatively high percentage of events (i.e., 40%–50%) were extreme across one-half of the scales (e.g., small to medium or medium to high scale) in this study. However, comparisons between the study sample and the heavy-rain sample from Giordano and Fritsch (1991) suggest that few local-scale (i.e., point scale) extreme events are extreme at scales of 2500 km² and greater, at least during the warm season over the mid-Atlantic region. The relative independence between the two samples suggests that different processes are responsible for local- versus small-scale (i.e., 2500 km²) events.

Work is under way to determine what aspects of the synoptic environments best discriminate extreme precipitation events from ordinary events across different spatial scales. Of particular interest is the connection identified in this work between extremely heavy precipitation and 500-hPa cyclones. Although many of the extreme events in this study were tied to a 500-hPa cyclone, there were many instances in which a 500-hPa cyclone did not produce extremely heavy precipitation. This result suggests that other aspects of the synoptic environment downstream of a 500-hPa cyclone potentially distinguish the extreme precipitation events from the relatively lighter ones. One possibility is the duration of the moisture advection and/or low-level convergence, with extremely heavy precipitation more likely when these features persist or move slowly across a given region. One would expect this to occur if the upstream 500-hPa cyclone moves slowly. The results from a small sample in this work suggest that only smaller-scale events are tied to slow-moving cyclones. However, more work is needed to establish robust connections. Junker

et al. (1999) suggest that the parallel orientation (i.e., superpositioning) of a given lifting field (e.g., low-level convergence) with the mean tropospheric wind vector encourages convective training and heavy rainfall (i.e., convective cells train along the axis of the lifting field). Nearly parallel orientations of the mean tropospheric wind with a frontal boundary (i.e., region of low-level convergence) do occur downstream of 500-hPa cyclones in some heavy rain situations [e.g., synoptic-type event in the Maddox et al. (1979) scheme]. Therefore, it would be interesting to see how frequently this synoptic situation occurs downstream of 500-hPa cyclones and how often heavy precipitation is observed.

The connection identified in this work between tropical systems and small- to medium-scale events suggests an association between tropical systems and extremely heavy precipitation. However, work under way indicates that only about one-half of landfalling tropical systems in the eastern United States produce extreme amounts of precipitation as defined in this study. It appears that various aspects of the tropical system, including its size and speed of movement, are tied to the observed precipitation totals. Also, some of the wettest tropical cyclones mentioned in this study (e.g., Hurricanes Agnes, Opal, and Floyd) interacted with midlatitude troughs, thus suggesting that these interactions may be important in discriminating tropical systems that produce extreme precipitation versus those that do not.

Three out of the four regions identified in this study have experienced a secular increase in the frequency of extreme precipitation events across all scales from the period of 1952–96. Marked increases were noted in large- and medium-scale events over the midwest and south-central regions. Decreases in the frequency of large- and medium-scale events were identified over the northeast region. Recent increases (1979–96) in medium- and local-scale events over the southeast are partially a consequence of the increase in the frequencies of tropical cyclones. In addition, increases in the frequency of El Niño–Southern Oscillation events correlate with these increases over the southeast and south-central regions. The next step is to relate these secular trends to changes in the frequency of “wet” synoptic patterns (i.e., those patterns that are tied to extreme precipitation). Of particular interest are the potential connections between secular increases in large- to medium-scale events identified in this work and increases in the frequency of 500-hPa cyclones identified by Key and Chan (1999).

The areal precipitation estimates calculated in this work have not yet been validated. Precise validations are not possible because ground truth measurements of areal precipitation amounts are not available; however, it would be useful to make some comparisons with the gauge-adjusted radar rainfall estimates that are presently available. In particular, it would be beneficial to compare the estimates across different scales and also under pre-

precipitation situations (e.g., strong winds and warm cloud tops) in which gauge-collected and radar data are biased.

Acknowledgments. This project was funded by NSF Grant BCS-9911315.

REFERENCES

- Angel, J. R., and F. A. Huff, 1998: Hydrometeorological characteristics of the northern Illinois heavy rains of July 17–18, 1996. Preprints, *10th Conf. on Applied Climatology*, Reno, NV, Amer. Meteor. Soc., 277–280.
- Bauer-Messmer, B., J. A. Smith, M. L. Baeck, and W. Zhao, 1997: Heavy rainfall: Contrasting two concurrent Great Plains thunderstorms. *Wea. Forecasting*, **12**, 785–798.
- Bosart, L. F., 1984: The Texas coastal rainstorm of 17–21 September 1979: An example of synoptic–mesoscale interaction. *Mon. Wea. Rev.*, **112**, 1108–1133.
- , and F. H. Carr, 1978: A case study of excessive rainfall centered around Wellsville, New York, 20–21 June 1972. *Mon. Wea. Rev.*, **106**, 348–362.
- , and F. Sanders, 1981: The Johnstown flood of 1977: A long-lived convective system. *J. Atmos. Sci.*, **38**, 1616–1642.
- CAC, 1989: *Weekly Climate Bulletin*. Vol. 89, No. 35, Climate Analysis Center, National Oceanic and Atmospheric Administration, 8 pp.
- , 1990: *Weekly Climate Bulletin*. Vol. 90, No. 42, Climate Analysis Center, National Oceanic and Atmospheric Administration, 11 pp.
- , 1991: *Weekly Climate Bulletin*. Vol. 91, No. 16, Climate Analysis Center, National Oceanic and Atmospheric Administration, 10 pp.
- , 1995: *Weekly Climate Bulletin*. Vol. 95, No. 18, Climate Analysis Center, National Oceanic and Atmospheric Administration, 12 pp.
- , 1996: *Weekly Climate Bulletin*. Vol. 96, No. 15, Climate Analysis Center, National Oceanic and Atmospheric Administration, 9 pp.
- Caracena, F., and J. M. Fritsch, 1983: Focusing mechanisms in the Texas hill country flash floods of 1978. *Mon. Wea. Rev.*, **111**, 2319–2332.
- Doswell, C. A., III, H. E. Brooks, and R. A. Maddox, 1996: Flash flood forecasting: An ingredients-based methodology. *Wea. Forecasting*, **11**, 560–581.
- Elsner, J. B., W. H. Drag, and J. K. Last, 1989: Synoptic weather patterns associated with the Milwaukee, Wisconsin, flash flood of 6 August 1986. *Wea. Forecasting*, **4**, 537–554.
- Funk, T. W., 1991: Forecasting techniques utilized by the Forecast Branch of the National Meteorological Center during a major convective event. *Wea. Forecasting*, **6**, 548–564.
- Gaza, R. S., and L. F. Bosart, 1985: The Kansas City severe weather event of 4 June 1979. *Mon. Wea. Rev.*, **113**, 1300–1320.
- Giordano, L. A., and J. M. Fritsch, 1991: Strong tornadoes and flash-flood producing rainstorms during the warm season in the mid-Atlantic region. *Wea. Forecasting*, **6**, 437–455.
- Gleason, B. E., and D. R. Easterling, 2000: Trends in tropical cyclone precipitation over the eastern United States. Preprints, *12th Conf. on Applied Climatology*, Asheville, NC, Amer. Meteor. Soc., 320–323.
- Hales, J. E., 1978: The Kansas City flash flood of 12 September 1977. *Bull. Amer. Meteor. Soc.*, **59**, 706–710.
- Heideman, K. F., and J. M. Fritsch, 1988: Forcing mechanisms and other characteristics of significant summertime precipitation. *Wea. Forecasting*, **3**, 115–130.
- Hirschboeck, K. K., L. L. Ely, and R. A. Maddox, 2000: Hydroclimatology of meteorologic floods. *Inland Flood Hazards*, E. E. Wohl, Ed., Cambridge University Press, 39–72.
- 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.
- Kane, R. B., C. R. Chelius, and J. M. Fritsch, 1987: Precipitation characteristics of mesoscale weather systems. *J. Climate Appl. Meteor.*, **26**, 1345–1357.
- Karl, T. R., and R. W. Knight, 1998: Secular trends of precipitation amount and frequency in the United States. *Bull. Amer. Meteor. Soc.*, **79**, 231–242.
- Keim, B. D., 1998: Record precipitation totals from the coastal New England rainstorm of 20–21 October 1996. *Bull. Amer. Meteor. Soc.*, **79**, 1061–1068.
- Key, J. R., and A. C. K. Chan, 1999: Multidecadal global and regional trends in 1000 mb and 500 mb cyclone frequencies. *Geophys. Res. Lett.*, **26**, 2053–2056.
- Konrad, C. E., 1994: Moisture trajectories associated with heavy rainfall in the Appalachian region of the United States. *Phys. Geogr.*, **94**, 227–248.
- , 1997: Synoptic-scale features associated with warm season heavy rainfall over the interior southeastern United States. *Wea. Forecasting*, **12**, 557–571.
- Kocin, P. J., P. N. Schumacher, R. F. Morales, and L. W. Uccellini, 1995: Overview of the 12–14 March 1993 superstorm. *Bull. Amer. Meteor. Soc.*, **76**, 165–182.
- Kunkel, K. E., 1996: A hydroclimatological assessment of the rainfall. *The Great Flood of 1993*, S. A. Changnon, Ed., Westview Press, 52–67.
- Legates, D. R., 2000: Real-time calibration of radar precipitation estimates. *Prof. Geogr.*, **52**, 235–258.
- , and T. L. DeLiberty, 1993: Precipitation measurement biases in the United States. *Water Resour. Bull.*, **29**, 855–861.
- Maddox, R. A., and G. K. Grice, 1986: The Austin, Texas, flash flood: An examination from two perspectives—forecasting and research. *Wea. Forecasting*, **1**, 66–74.
- , C. F. Chappell, and L. R. Hoxit, 1979: Synoptic and mesoscale aspects of flash flood events. *Bull. Amer. Meteor. Soc.*, **60**, 115–123.
- NCDC, 1994: 1994 weather in the Southeast: The February ice storm and the July flooding. National Climate Data Center, National Oceanic and Atmospheric Administration, 21 pp.
- , 1997: *Cooperative Summary of the Day CDs*. TD 3200, National Climate Data Center, National Oceanic and Atmospheric Administration, CD-ROM.
- , 1999: *Climate-Watch*. September, National Climate Data Center, National Oceanic and Atmospheric Administration.
- NOAA, 1990: National Disaster Survey Report: Disastrous floods on the Trinity, Red, and Arkansas Rivers: May 1990. National Oceanic and Atmospheric Administration, 11 pp.
- , 1992: National Disaster Survey Report: Disastrous floods on the Trinity, Brazos, Colorado, and Guadalupe Rivers in Texas: December 1991–January 1992. National Oceanic and Atmospheric Administration, 15 pp.
- Pontrelli, M. D., G. Bryan, and J. M. Fritsch, 2000: The Madison County, Virginia, flash flood of 27 June 1995. *Wea. Forecasting*, **14**, 384–404.
- Rochette, S. M., and J. T. Moore, 1996: Initiation of an elevated mesoscale convective system associated with heavy rainfall. *Wea. Forecasting*, **11**, 443–457.
- Schwarz, F. K., 1970: The unprecedented rains associated with the remnants of Hurricane Camille. *Mon. Wea. Rev.*, **98**, 851–859.
- Schwartz, B. E., C. F. Chappell, W. E. Togstad, and X. P. Zong, 1990: The Minneapolis flash flood: Meteorological analysis and operational response. *Wea. Forecasting*, **5**, 3–21.
- Smith, J. A., M. L. Baeck, M. Steiner, and A. J. Miller, 1996: Catastrophic rainfall from an upslope thunderstorm in the central Appalachians: The Rapidan storm of June 27, 1995. *Water Resour. Res.*, **32**, 3099–3113.
- , J. E. Morrison, and P. Sturdevant-Rees, 2000: Catastrophic rainfall and flooding in Texas. *J. Hydrometeor.*, **1**, 5–25.
- Winkler, J. A., 1988: Climatological characteristics of summer-time extreme rainstorms in Minnesota. *Annu. Assoc. Amer. Geogr.*, **78**, 57–73.