The Contribution of Mesoscale Convective Weather Systems to the Warm-Season Precipitation in the United States

J. M. FRITSCH, R. J. KANE* AND C. R. CHELIUS

Department of Meteorology, The Pennsylvania State University, University Park, PA 16802

(Manuscript received 18 September 1985, in final form 8 March 1986)

ABSTRACT

The contribution of precipitation from mesoscale convective weather systems to the warm-season (April–September) rainfall in the United States is evaluated. Both Mesoscale Convective Complexes (MCC's) and other large, long-lived mesoscale convective systems that do not quite meet Maddox's criteria for being termed an MCC are included in the evaluation. The distribution and geographical limits of the precipitation from the convective weather systems are constructed for the warm seasons of 1982, a "normal" year, and 1983, a drought year. Precipitation characteristics of the systems are compared for the 2 years to determine how large-scale drought patterns affect their precipitation production.

The frequency, precipitation characteristics and hydrologic ramifications of multiple occurrences, or series, of convective weather systems are presented and discussed. The temporal and spatial characteristics of the accumulated precipitation from a series of convective complexes is investigated and compared to that of Hurricane Alicia.

It is found that mesoscale convective weather systems account for approximately 30% to 70% of the warm-season (April–September) precipitation over much of the region between the Rocky Mountains and the Mississippi River. During the June through August period, their contribution is even larger. Moreover, series of convective weather systems are very likely the most prolific precipitation producer in the United States, rivaling and even exceeding that of hurricanes.

Changes in the large-scale circulation patterns affected the seasonal precipitation from mesoscale convective weather systems by altering the precipitation characteristics of individual systems. In particular, for the drought period of 1983, the frequency of the convective systems remained nearly the same as in the "normal" year (1982); however, the average precipitation area and the average volumetric production significantly decreased. Nevertheless, the rainfall that *was* produced by mesoscale convective weather systems in the drought year accounted for most of the precipitation received during the critical crop growth period.

It is concluded that mesoscale convective weather systems may be a crucial precipitation-producing deterrent to drought and an important mechanism for enhancing midsummer crop growth throughout the midwestern United States. Furthermore, because mesoscale convective weather systems account for such a large fraction of the warm-season precipitation, significant improvements in prediction of such systems would likely translate into significant improvements in quantitative precipitation forecast skill and corresponding improvements in hydrologic forecasts of runoff.

1. Introduction

In a recent study of the warm-season Quantitative Precipitation Forecast (QPF) problem, Heideman and Fritsch (1984) determined that about half of the warm-season precipitation over the United States is produced directly by mesoscale phenomena. In particular, they found that Mesoscale Convective Weather Systems (MCWS's) are a major contributor to the precipitation that falls east of the Rocky Mountains. For the purposes of this paper, MCWS's are long-lived, circularly shaped, convective weather systems (as viewed by satellite) with a Rossby number on the order of 1. Specific criteria for including a convective weather system in the precipitation study are given in section 2. In order to more firmly establish the importance of precipitation from MCWS's and to help define the potential for operationally improving the warm-season QPF, the seasonal and annual contributions of MCWS precipitation over the United States are quantified. The characteristics of MCWS's during a "normal" year and a drought year are compared and the rainfall extremes produced by series of MCWS's propagating over the same region are presented. Section 2 briefly describes the data sources and procedures to obtain the seasonal precipitation from MCWS's. Section 3 presents the results for 1982 and 1983 ("normal" and drought years, respectively), and section 4 documents the precipitation potential from a series of convective complexes. Section 5 briefly summarizes the results and their implications for ameliorating the warm-season QPF problem.

* Present affiliation: National Weather Service Office, Greensboro, NC 27419.

2. Data and procedures

For the two warm seasons (March–September) of 1982 and 1983, 106 MCWS's were identified for inclusion in the precipitation climatology. The set of MCWS's is comprised of 74 MCC's and 32 Mesoscale Convective Systems (MCS's). All the MCC's identified in the annual summaries (Rodgers et al., 1983, 1985) were included in the analysis. The 32 MCS's were MCC-type or MCC-like events which for various reasons, such as insufficient size or duration, did not meet the MCC criteria established by Maddox (1980), but nevertheless manifested many of the characteristics of MCC's. Specifically, each MCS met Maddox's eccentricity (shape) requirements, had a $-32°C$ cold cloud shield of at least 6×10^4 km^2 (compared to 10^5 km^2 required by Maddox) and persisted at this size, or greater, for at least 4 h (Maddox required 6 h). Some systems were slightly smaller than MCC's, but persisted considerably longer than the 6 h criterion. Other systems met all of Maddox's size criteria but for slightly less than the 6 h required in the MCC definition. In view of the arbitrariness in the original definition, and the lack of an accepted "dynamical" definition, it is believed that many MCS's are close enough to what Maddox originally described to warrant investigation. While a dynamical definition of an MCC is not yet available, further relaxation of the MCS criteria previously given would very likely eliminate key dynamical characteristics of the convective weather systems. In particular, the midlevel cyclonic circulation (Maddox, 1983; Smull and Houze, 1985) and the well-defined anticyclonic outflow in the vicinity of the tropopause (Fritsch and Maddox, 1981; Fritsch and Brown, 1982) probably would not appear since the effect of Coriolis force would be considerably less for systems smaller and of shorter duration than the criteria given above for MCS's (see Ooyama, 1982; Frank, 1983; Schubert and Hack, 1982). Thus, the set of MCWS events selected for study includes the bulk of the 1982–83 circular-type convective weather systems that are dynamically representative of the mesoscale (Rossby number of the order 1) while leaving out those smaller and shorter-lived systems more typical of cloud scale and where Coriolis is unimportant. Interestingly, Kane et al. (1985) have shown that, except for size, the *precipitation* characteristics of the 32 MCS's did not exhibit any significant differences from that of MCC's.

Two primary sources of precipitation data were used in the analysis: 24 h precipitation charts obtained from the Heavy Precipitation Branch at the National Meteorological Center and hourly reports from the National Climate Center. There are over 7000 stations that report 24 h amounts and about 700 hourly reporting stations. The precipitation data from all these stations, in combination with satellite and radar data, were used to delineate the amounts and spatial distribution of precipitation for each MCWS event. (See Kane, 1985, and Kane et al., 1986, for a more thorough discussion of the methodology of analysis of each convective event.)

Once individual MCWS precipitation patterns are delineated for an entire convective season, it is possible to perform a summation of all the individual patterns to determine the distribution of *accumulated* rainfall during an entire season. This is accomplished using a single "continental" grid that includes the precipitation from MCWS's anywhere in the contiguous 48 states. Since the grid node spacing of this "continental" grid is 70 km, it sometimes misses the storm maximum by several centimeters. In fact, the actual storm maxima (primary and secondary) are approximately 1 cm greater, on average, than the maxima depicted by the large grid. Therefore, the use of this continental grid results in a *conservative* representation of the precipitation fields.

3. Accumulated MCWS precipitation

a. 1982: The "normal" year

The 1982 convective season seems to have been fairly typical for the midwestern United States. There were no large precipitation anomalies or protracted periods of above-normal temperatures (Wagner, 1983). In such a typical year, the Bermuda high, with its center just off the East Coast of the United States, is the dominant ridge system during the summer. The positioning of the main ridge axis just to the east of the United States coast sets the stage for MCWS production. The ridge frequently intrudes westward, engulfs the eastern half of the country, and provides a persistent, moist, southerly flow from the Gulf of Mexico into the midsection of the nation. Moreover, the upper-level flow is such that short waves frequently propagate from the west and southwestern portions of the United States eastward over the Great Plains. These short-wave disturbances tend to destabilize the environment through vertical motion and differential horizontal temperature advection. They also enhance the northward flow of moisture from the Gulf of Mexico.

Figure 1 shows the geographical limits and distribution of the accumulated warm-season precipitation from 44 MCC's that occurred in 1982. Note that the bulk of the MCC precipitation is confined between the Rockies and the Mississippi River and is mostly south of latitude 45°N. The precipitation amounts taper off gradually to the east, while sharp gradients are apparent in precipitation along the western and southern edges of the overall pattern. The sharp gradient along the western edge reflects the frequent location of the "dryline" near about 100°W longitude. (See Carlson and Ludlum, 1968; Matteson, 1969; Schaefer, 1974.) The reason for the rapid decrease in MCC precipitation near the Gulf Coast is not as obvious as the dryline expla-

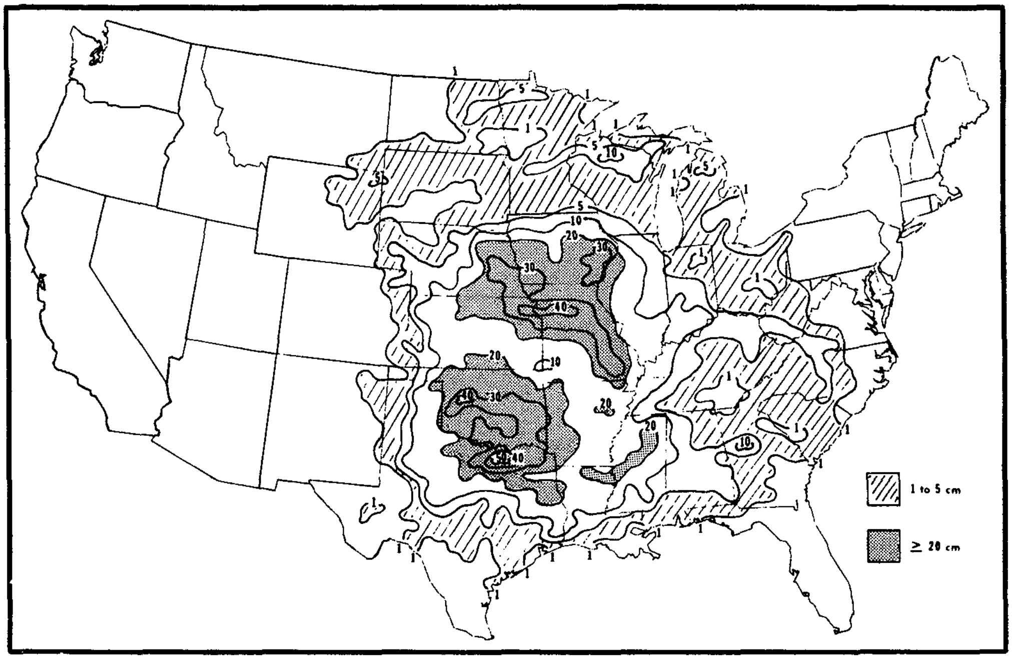

FIG. 1. Accumulated precipitation (cm) from 44 MCC's from the 1982 warm season. Hatched and shaded regions indicate precipitation accumulations of 1 to 5 cm and ≥20 cm, respectively. Note that the outer isohyet is the 1-cm line and that lighter accumulations, especially from the debris of dying MCC's, extend beyond this isohyet.

nation but probably is related to the differential heating between land and water; i.e., everything else being equal, the potential buoyant energy over land would be significantly larger. Although no precipitation is shown in New England southward into the mid-Atlantic States, MCC's have occasionally occurred in this region (e.g., see Bosart and Sanders, 1981). Likewise, MCC's have occasionally occurred over the Great Basin southward to Mexico. However, for the two years investigated in this study, no systems were detected in these regions in the nearly complete satellite data coverage available.

In order to compare the MCC-generated precipitation to the normal *warm-season* amounts, an analysis of the normal precipitation for the 6-month period April–September is provided (Fig. 2a). The normal precipitation for the peak MCC/MCS season, i.e., June, July and August, is also shown (Fig. 2b). A total of 272 stations were used in the analyses. All stations had at least 10-year records, 80% had over 20 years of record and 40% had over 60 years of record. Clearly, after comparing Figs. 1 and 2a, it is evident that in many places MCC's account for a large fraction of the normal warm-season precipitation. In particular, MCC rainfall over parts of Iowa, Nebraska, Kansas, Missouri, Oklahoma and Texas accounted for 30% to 60% of the normal warm-season amounts. Moreover, in some locations (in northeastern Texas for example), MCC's provided 100% of the normal warm-season rainfall. Considering that 70% of the MCC's occurred in June through August, it appears that in 1982, MCC's were a primary source of *summer* rainfall over a wide area of the Midwest. The dominance of MCC-generated rainfall in the Midwest in the warm season seems to be supported by the general rainfall patterns in Figs. 1 and 2. Specifically, the location of the relative precipitation maximum over Arkansas in Fig. 2a, and its shift northwestward to a position over northeastern Kansas and northwestern Missouri in Fig. 2b, roughly corresponds to the location and seasonal movement of the centroid of the MCC pattern for the MCC's that occurred from 1978 through 1983. (See Maddox, 1980; Maddox et al., 1982; Rodgers et al., 1983, 1985.)

Even though MCC's are basically a warm-season phenomenon, it is interesting to estimate their contribution to the average *annual* rainfall. Hershfield (1980), in writing of extreme drought, presents the average annual precipitation for the entire United States. Assuming 1982 to have been an average year for both MCC and annual precipitation, a large section of central Oklahoma received from 20% to 50% of its annual rainfall from *just* MCC's, and it must be remembered that Fig. 1 is a conservative estimate of the accumulated MCC rainfall. These percentages seem typical for many Central Plains states. Moreover, they are similar to findings of other investigators, such as Changnon (1957), in which thunderstorms in Illinois compiled from 37% to 50% of the normal annual precipitation.

Figure 3 shows the accumulated precipitation from both the MCC's and MCS's in 1982. The main effect

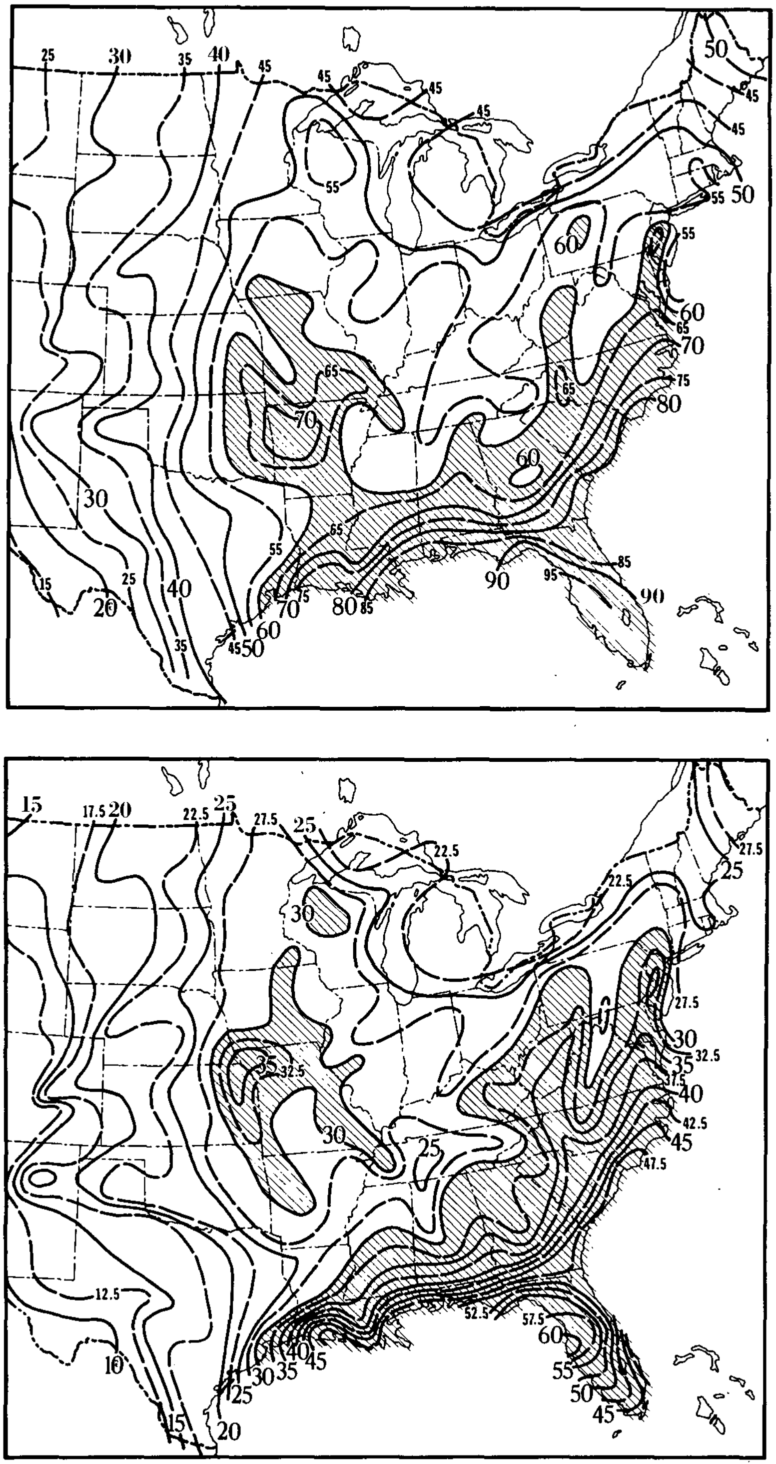

FIG. 2. Geographic distribution of normal precipitation (cm): (a) warm-season precipitation, April–September; (b) summer precipitation, June–August. Hatching indicates amounts greater than 60 cm in (a) and 30 cm in (b).

of adding the MCS precipitation is that the cumulative precipitation area expands and the maxima increase in magnitude. Increases in maxima are particularly evident from Iowa south-southwestward to Texas. Note that MCWS precipitation accounted for 30% to 70% of the average warm-season precipitation in many parts

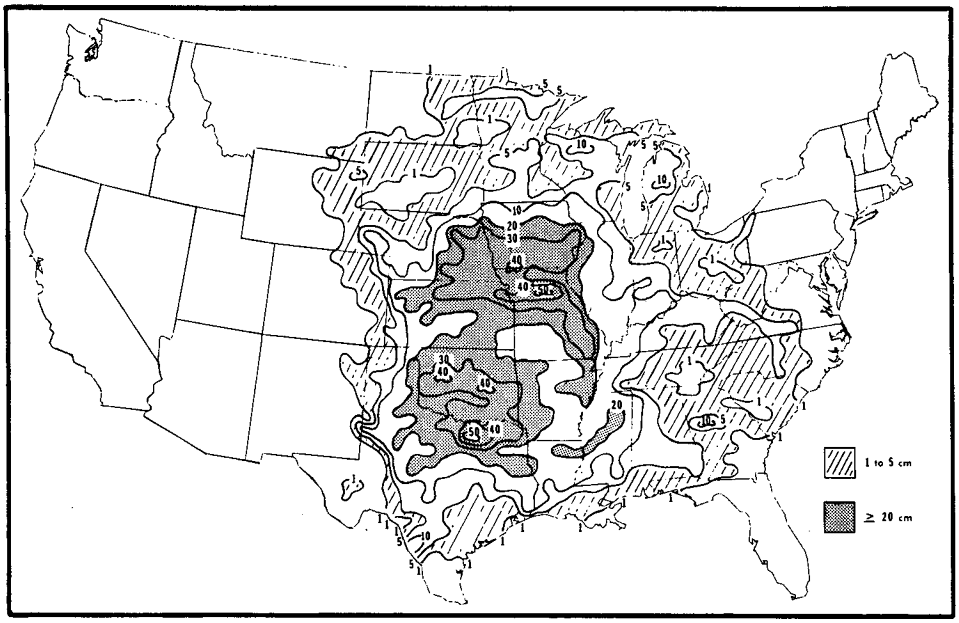

FIG. 3. Same as Fig. 1 except for MCWS's. Total number of MCWS events is comprised of 44 MCC's and 16 MCS's.

of Iowa, Nebraska, Kansas, Missouri, Oklahoma and Texas. Note also that the sharp precipitation gradient stretching from West Texas to Nebraska becomes even more well-defined when the MCS precipitation is included. Apparently, resolution of the dryline is a crucial factor for successful numerical-model prediction of precipitation from MCWS's.

b. *1983: The drought year*

The 1983 convective season was extraordinarily hot and dry, especially during July and August (Wendlend et al., 1984; Ropelewski, 1984). In fact, through a portion of the 1983 season, drought conditions prevailed over much of the Plains states (Ludlum, 1983). It is important to point out that while many parts of the United States are just as likely to exhibit wet conditions as dry conditions when the summer is hot, in the Midwest, precipitation and temperature are inversely correlated during the summer. (See Madden and Williams, 1978.)

Namias (1982), Livezey (1980) and Dickson (1980), among others, have described the weather and circulation patterns associated with the devastating United States heat wave of 1980. They described a large-scale, three-cell anticyclone pattern with one cell centered over the Midwest. This large-scale pattern, typical of North American drought regimes, seemed to materialize in the summer of 1983. By the first week in July, an intense upper-level ridge and its associated surface anticyclone were well entrenched over the *midwestern* United States and the deep northward flow of Gulf moisture was substantially diminished. Once this ridge was established, there were several feedback mechanisms which may have perpetuated its existence. These mechanisms involve surface heating, soil moisture, dust concentrations (Twomey and Squires, 1959) and radiation (Charney, 1975). Based upon historical drought patterns, there is little doubt that in 1983 the existence of the *continental* upper-level anticyclone was a major factor influencing the suppression of precipitation and the subsequent enhancement of surface temperatures throughout the Midwest.

Figures 4 and 5 show the MCC and MCWS precipitation, respectively, for the warm season of 1983. As in 1982, the bulk of the precipitation fell between the Rockies and the Mississippi River. It is also evident that, even in this drought year, MCWS's provided substantial amounts of precipitation to virtually all of the Plains states. In fact, parts of at least ten states received over 25% of their normal warm-season precipitation from MCWS. Moreover, portions of many states received 20% to 40% of their average *annual* precipitation from the MCWS's. On the other hand, comparison of Figs. 1 and 4 or 3 and 5 clearly shows that MCWS precipitation was substantially less in 1983 than in 1982. Furthermore, the sharp peripheral precipitation gradients, clearly evident in 1982, were much weaker and did not extend nearly so far to the north and west in 1983 (compare Figs. 3 and 5); northward of Oklahoma the precipitation gradient breaks down and becomes very chaotic. This rather fractured precipitation gradient and the lack of significant precipitation in the Midwest is probably indicative of the variability in 1983 of the frequency, strength, depth and extent of northward protrusions of moisture. It is important to note

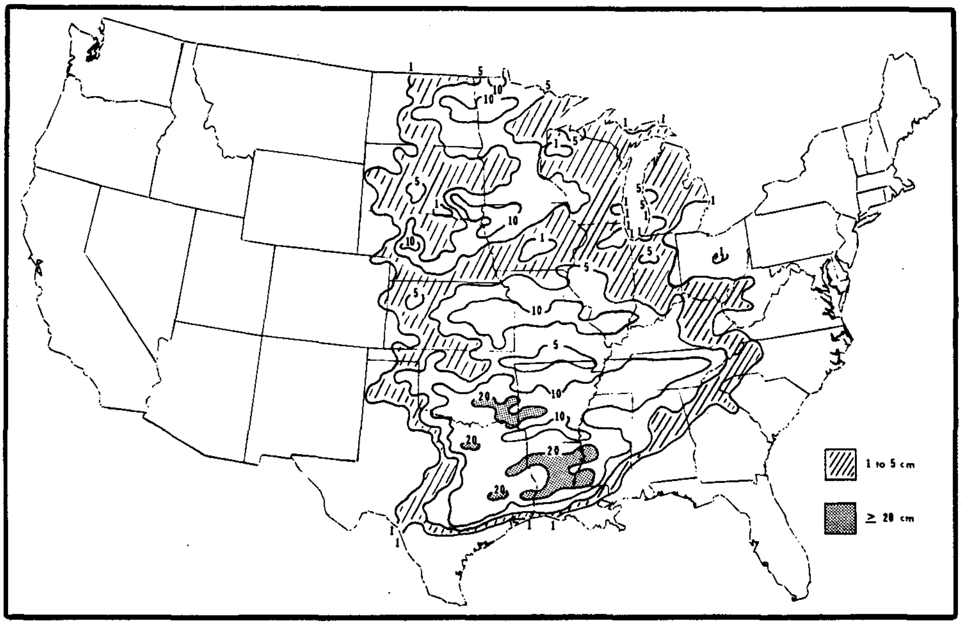

FIG. 4. As in Fig. 1 except for 30 MCC's from the 1983 warm season.

that for 1983, most of the large southern systems that contributed to the strong precipitation gradient over Texas and Oklahoma did so in April and May before the dominance of the continental upper-level anticyclone. It is also interesting that the total MCWS precipitation for *both* years diminishes rapidly along the Gulf Coast in spite of the fact that the moisture source is *from* the Gulf of Mexico. This strongly suggests that, at least for North America, MCWS's are predominantly a land-based phenomenon.

In view of the different large-scale circulation patterns that were set up in 1982 and 1983 (i.e., Bermuda

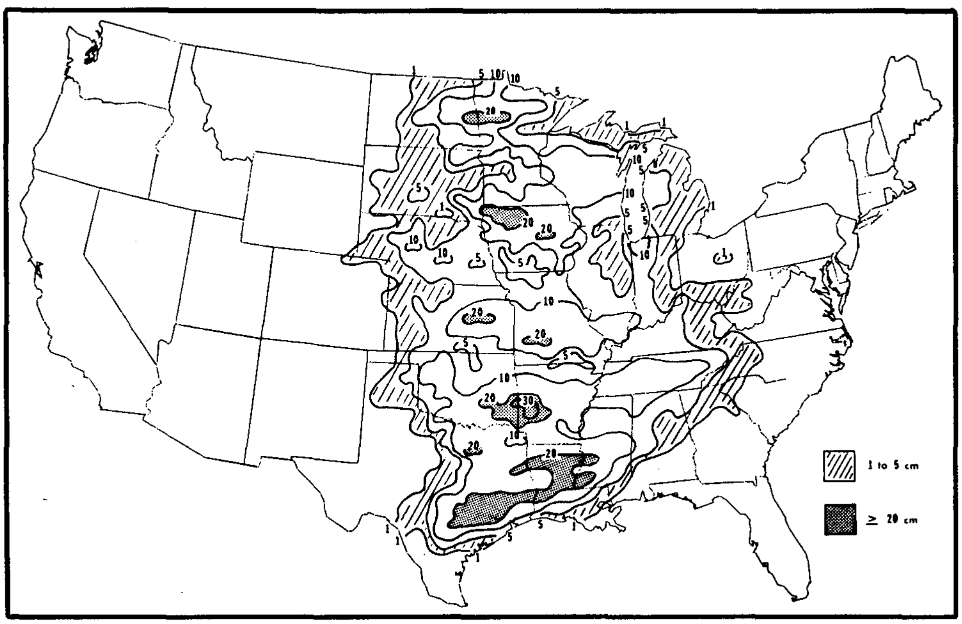

FIG. 5. As in Fig. 1 except for MCWS's from the 1983 warm season. Total number of MCWS events is comprised of 30 MCC's and 16 MCS's.

high vs continental ridge), it seems likely that the number, average size, and precipitation production from MCWS's should also show significant differences. Section 3c highlights some of the differences in MCWS precipitation for the two years and examines how the overall decrease in MCWS precipitation occurred.

c. 1982 versus 1983

Figure 6 shows the difference in total MCWS precipitation between 1982 and 1983. Positive values indicate an excess of precipitation in 1982 and negative values indicate an excess of precipitation in 1983. Obviously, most of the Central Plains states received much more MCWS precipitation in 1982 than in 1983. Moreover, most of the excess rainfall that occurred in 1983 (covering the Tennessee Valley, Louisiana and southeastern Texas) was produced by systems that occurred in April and May.

As mentioned in section 2b, a large-scale continental ridge can hinder the horizontal moisture flux into the central United States and possibly impose limits on the distribution of convective precipitation. More specifically, the dominance of such a ridge may be manifested on the mesoscale as a decrease in both the number of MCWS's and the areal dispersion of the precipitation. This possibility can be examined with the aid of Table 1. It can be seen that not only was the frequency of MCC's and MCS's greater in 1982, but the systems in 1982 produced, on the average, ≥2.54 cm of rain over 30% more area than did the systems in 1983. Furthermore, the average upstream surface mixing ratios in 1982 were 9% higher than those of 1983; the average mixing ratios of just the 1982 MCC's compared to the 1983 MCC's were over 13% higher. Interestingly, though, in July and August, when the 1983 suppression of precipitation peaked in the Midwest, there was approximately the same number of systems in both years. Thus, the large reduction in the area of ≥2.54 cm of precipitation must be due to other factors. One possible explanation is suggested by the data in Table 1. Specifically, in May of 1983 the average latitude of the precipitation pattern centroids is rather far south at 33.8°N. Through June and July the average latitude of the precipitation centroids proceeds northward to a maximum of 43.3°N in August. This northward progression of precipitation centroids with time is also found in 1982 (normal convective year). However, the range is considerably less and there tends to be a reverse progression by August; this reversal does not appear in 1983. Because the Central Plains were dominated by the anticyclone aloft in 1983, favorable dynamics for MCWS formation apparently persisted farther to the north closer to the westerlies. This would explain the northern area of excess 1983 MCWS precipitation (Fig. 6) which was primarily produced by systems in August. The point is, there were fewer MCWS events forming at lower latitudes, and Kane et al. (1985) have shown that MCWS precipitation production in the United States diminishes as latitude and distance from the Gulf of Mexico increase. In this same vein, it can be seen from Table 1 that the average

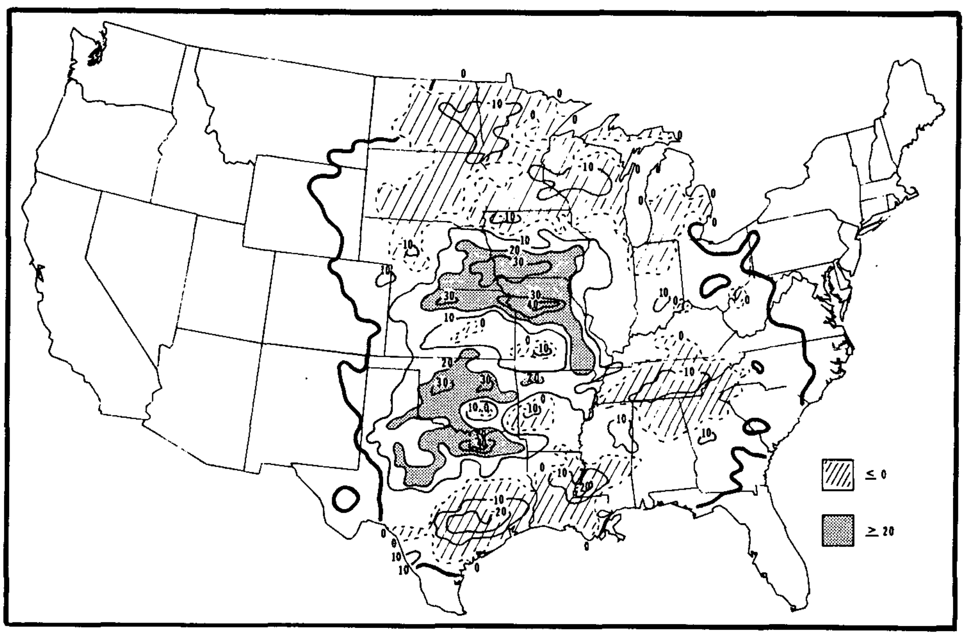

FIG. 6. Difference in MCWS accumulated precipitation (cm): 1982 minus 1983. Negative values (hatched areas) indicate an excess of precipitation in 1983 and positive values indicate an excess of precipitation in 1982. Shaded regions indicate a positive excess of ≥20 cm in 1982.

TABLE 1. Monthly comparison of MCWS characteristics for 1982 and 1983.

Month	Number of events: MCC's	MCS's	(Total) MCWS's	Average area ⩾ 2.54 cm (km²)	Average latitude (°N)	Average mixing ratio (g kg⁻¹)	Average maximum (mm)
				1982			
May	6	4	10	116 000	35.7	14.1	119
June	15	4	19	115 263	37.0	14.8	86
July	7	4	11	89 318	41.8	16.6	116
August	8	4	12	77 917	39.1	15.8	108
				1983			
May	7	0	7	189 643	33.8	14.8	115
June	5	1	6	62 500	40.8	12.5	103
July	6	6	12	54 583	41.9	15.8	106
August	6	6	12	58 542	43.3	15.5	71

area ⩾ 2.54 cm was actually greater in May of 1983 than 1982 but the next 3 months show a much greater areal coverage of precipitation for 1982. Moreover, note that in August of 1982 the average maximum was 52% greater than that of August 1983. This large difference in the distribution characteristics of the respective years is also seen graphically in Figs. 7 and 8. In 1982, a total of 18 systems produced ⩾2.5 cm of rain over at least 160 000 km² (13 of these produced maxima ⩾ 10 cm). In 1983, only five systems produced ⩾2.5 cm of rain over at least 160 000 km². Three of these produced maxima ⩾ 10 cm.)

Further evidence of the difference in precipitation characteristics for the 2 years is apparent from the ratios of the 1982 and 1983 storm frequencies (F), average size (A), average rainfall volume (V) and mean rainfall per unit area (R), i.e.,

$$F_{83}/F_{82} = 0.68,$$

$$\bar{A}_{83}/\bar{A}_{82} = 0.87,$$

$$\bar{V}_{83}/\bar{V}_{82} = 0.82,$$

$$\bar{R}_{83}/\bar{R}_{82} = 0.93.$$

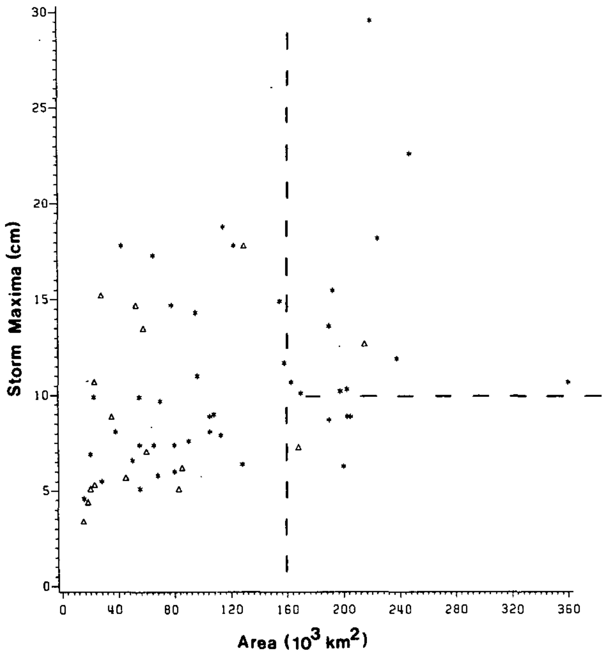

FIG. 7. Storm maximum precipitation (cm) vs the area (10³ km²) covered by ⩾2.5 cm. Stars represent MCC's and triangles represent MCS's. Data set contains 60 MCWS's from 1982. Dashed lines indicate 160 000 km² and 10 cm.

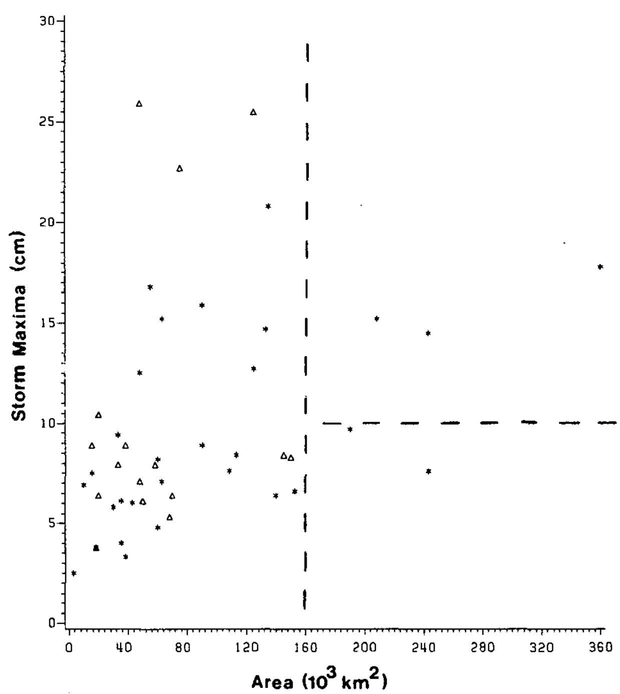

FIG. 8. As in Fig. 7 except for the 46 MCWS's in 1983.

Furthermore, if the same calculations are applied to only those events which occurred in July and August (dominant time of upper-level anticyclone in 1983), the following results are obtained:

$$F_{83}/F_{82} = 1.04,$$

$$\bar{A}_{83}/\bar{A}_{82} = 0.86,$$

$$\bar{V}_{83}/\bar{V}_{82} = 0.72,$$

$$\bar{R}_{83}/\bar{R}_{82} = 0.87.$$

It is apparent from these results that when the *entire* MCC population is considered, the decreases in both the volume of rain per storm and the frequency of storms seem to be the most important factors contributing to the drier than normal conditions throughout the 1983 convective season. Note though, that both the average area and the rain per unit area are less in 1983 than in 1982. When only the convective systems that occurred during July and August are considered, there was actually a slight excess of events (one more) in 1983 while a reduction is shown in everything else. These results suggest that the storm characteristics (volumetric production and, to a lesser extent, size and rain per unit area) contributed more to the drought conditions than the frequency of events, i.e., *in a large-scale drought regime, MCWS's occurred just as often but tended to be smaller and less efficient in producing precipitation.*

4. Series of convective complexes

Under certain synoptic conditions, MCWS's tend to occur in series. Often they develop in succession such that one MCWS completely dissipates prior to the genesis of the next. At other times, however, they occur simultaneously, although usually they are at different stages in their respective life cycles. A group of MCWS's is considered a "series" if the respective precipitation patterns (outer isohyet of 1 mm) of two or more MCWS's coincide by more than 20% and if each subsequent event begins (precipitation starts) 12 h or less following dissipation (precipitation ends) of the previous event.

Probably the most significant aspect of a Series of Convective Complexes (SCC) is its hydrologic ramifications; i.e., the potential for flooding greatly increases with each successive event. The fact that successive storms need not propagate over the same track to induce severe flooding also compounds the problem. This is especially true for the Gulf Coast states where SCC's are more prevalent. The majority of rivers throughout the south central United States flow in a southward direction. Sometimes the second event will propagate slightly to the south of the first MCWS. The next event thus disperses copious amounts of rainfall over an area in which the river tributaries are already flooded or swollen from upstream saturation by the first system. This process can greatly exacerbate the flooding conditions even though some localities do not receive the brunt of the earlier precipitation.

a. *Frequency and characteristics of SCC's*

There were 39 MCWS's, or approximately 37% of the total 106 MCWS events, that fulfilled the above mentioned SCC criteria during 1982 and 1983. These 39 events comprised a total of 16 SCC's. Based on this small sample, Table 2 briefly describes some characteristics of SCC's. It is evident that they occur throughout the warm season, but there is a tendency for the number of series and the number of MCWS's per series to be larger in late spring and early summer. Note also, that as the warm season progresses, both the precipitation maximum and the area tend to decrease. Therefore, by late summer the series loses some of its potential to focus heavy precipitation. It is likely that part of the reason for this decrease in area and intensity is related to the tendency of the series to develop farther north as the summer progresses. Hence, the distance between the MCWS's and their moisture source (Gulf of Mexico) increases. Consequently, as the average latitude (latitude of the centroid of the precipitation pattern) increases through the convective season, both the area and the average maximum decrease. It is also possible that the reduction in MCWS size and precipitation efficiency during July and August 1983 (the drought period) affected the size and intensity of the entire SCC sample. Nevertheless, since both the area and the average maximum in Table 2 are *per single event* and *not* for the entire convective series, even the late summer events can produce an incredible amount of rain in the same catchment or river basin.

b. *Formation and the synoptic environment*

Understanding and forecasting SCC's are complicated by the fact that more than one classification of MCWS (i.e., mesohigh, frontal or synoptic; see Kane et al., 1985) may be involved in their formation. There are 12 synoptic events, 20 frontal events and 7 mesohigh events which comprise the 16 convective series for 1982 and 1983. This indicates that there are several different large-scale regimes conducive to convective series formation. However, for each of these different types of large-scale environments, SCC's occur primarily when the large-scale conditions are evolving very slowly. Mesoscale "short" waves periodically propagate through the large-scale flow and initiate the convection. In addition to the forcing from the short waves, the convection seems to be focused and enhanced by the lifting from overrunning of residual pockets of cool, moist downdraft air from a previous system. This is particularly true for mesohigh events where the outflow boundary effectively takes the place of the synoptic-scale front in providing the lifting to initiate new convection.

TABLE 2. Monthly variation of frequency and physical characteristics of series of convective complexes that occurred in 1982 and 1983.

Month	Number of MCWS's	Number of series	Average area ≥2.54 cm per MCWS (km²)	Average maximum per MCWS (mm)	Average latitude (°N)
April	6	3	184 167	136	34.2
May	12	4	177 292	137	35.7
June	8	3	120 625	104	38.2
July	7	3	66 429	99	41.4
August	4	2	53 125	86	39.5
September	2	1	71 250	110	38.0

Sometimes the large-scale environment *did* change from one MCWS to the next. In one case in particular, moist southerly flow at the surface overran a weak east-west stationary front. Initial convection appeared on the cool side of the frontal system and ran its course as a "frontal" mesoscale convective complex. As the first system dissipated, the stationary front began moving northward as a warm front. Convection ultimately redeveloped as a mesohigh-type event in the warm sector and distributed rainfall over the same general area pelted by the first system.

c. *Series precipitation potential*

Hurricane Alicia was the first and only Atlantic hurricane to make landfall in the United States in 1983. In fact, Alicia was the first hurricane to strike the United States mainland since hurricane Allen in 1980. Alicia was slightly above average in size and intensity upon landfall and also produced average amounts of precipitation for a Gulf Coast hurricane (Savage et al., 1984).

Figure 9 shows the accumulated precipitation pattern produced by Alicia from approximately 1900 GMT 17 August to 1200 GMT 21 August 1983. There are some reports of rainfall totals between 25 and 28 cm primarily over the immediate landfall region. However, the maximum rainfall resolved by the continental grid (see section 2) is approximately 23 cm. The same grid was used to construct Fig. 10. This figure shows the accumulated precipitation from the SCC that produced the Pearl River flood in Mississippi in April 1983. Between 2100 GMT 4 April and 0400 GMT 7 April 1983, three systems developed and propagated over the area shown in Fig. 10. The first two systems were MCC's which displayed large and persistent cold-cloud shields. The third event was an MCS possessing a rather small cold-cloud shield. Nevertheless, this third convective event was a significant rain-producing system, and together these three systems comprised a series of convective complexes that greatly exceeded Alicia in all precipitation-production characteristics. Table 3 quantifies the results that are qualitatively apparent by comparing Figs. 9 and 10. The average rain depth over the storm area of the convective series was 68% higher, the area of ≥1 cm of rain was 31% greater, the SCC produced over twice as much total water and the precipitation was produced in 38% less time than that of Alicia. Note, however, that while Alicia was only an *average* hurricane, the convective series was one of the most intense of the 16 that occurred during 1982 and 1983. On the other hand, Fritsch *et al.* (1981) compared the precipitation from a single large MCC to the precipitation that fell in the 24 h following landfall of Great Hurricane Allen. The large MCC produced double the rainfall generated by Allen! Clearly, the precipitation-production and *frequency* of SCC's make them a strong competitor with the hurricane for this nation's *most prolific precipitation-producing phenomenon.*

5. Summary and concluding remarks

The magnitude and geographic distribution of accumulated precipitation from mesoscale convective weather systems (MCWS's) clearly indicate that these systems, particularly mesoscale convective complexes, contribute a significant fraction of the warm-season precipitation in the midwestern United States. In fact, if the warm season of 1982 is typical of MCWS rainfall, then these systems are *the dominant warm-season, rain-producing weather systems over much of the Midwest.* Specifically, in 1982, they accounted for 30% to 70% of the average warm-season precipitation over many parts of Nebraska, Iowa, Kansas, Missouri, Texas, Oklahoma and Arkansas. This result is especially meaningful in the context of the warm-season quantitative precipitation forecast (QPF) problem. In particular, recent studies have shown that the QPF skill in the warm season lags way behind that of the cool season (e.g., see Fawcett, 1977; Ramage, 1982; Glahn, 1985). If, indeed, most of the warm-season rainfall in much of the midwestern United States is produced by MCWS's, then significant improvements in explicit prediction of such systems would likely translate into significant improvements in the warm-season QPF skill. It is encouraging that several recent numerical modeling studies have shown great promise for explicit prediction of MCWS's and their associated precipitation (e.g., see Fritsch and Chappell, 1980; Chang et al., 1981; Anthes et al., 1982; Perkey and Maddox, 1985; Zhang and Fritsch, 1986). As this modeling capability continues to develop, it is likely that the meteorological

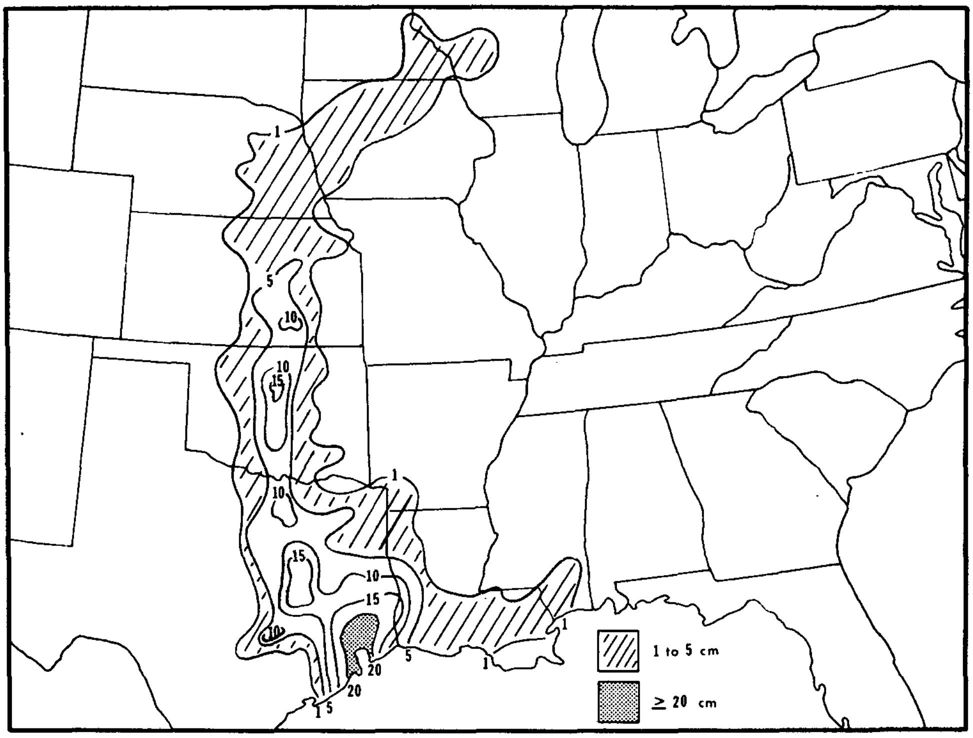

FIG. 9. Accumulated precipitation (cm) from Hurricane Alicia for the period 1900 GMT 17 August to 1200 GMT 21 August 1983. Hatched and shaded areas indicate rainfall accumulations of 1 to 5 cm and ≥20 cm, respectively.

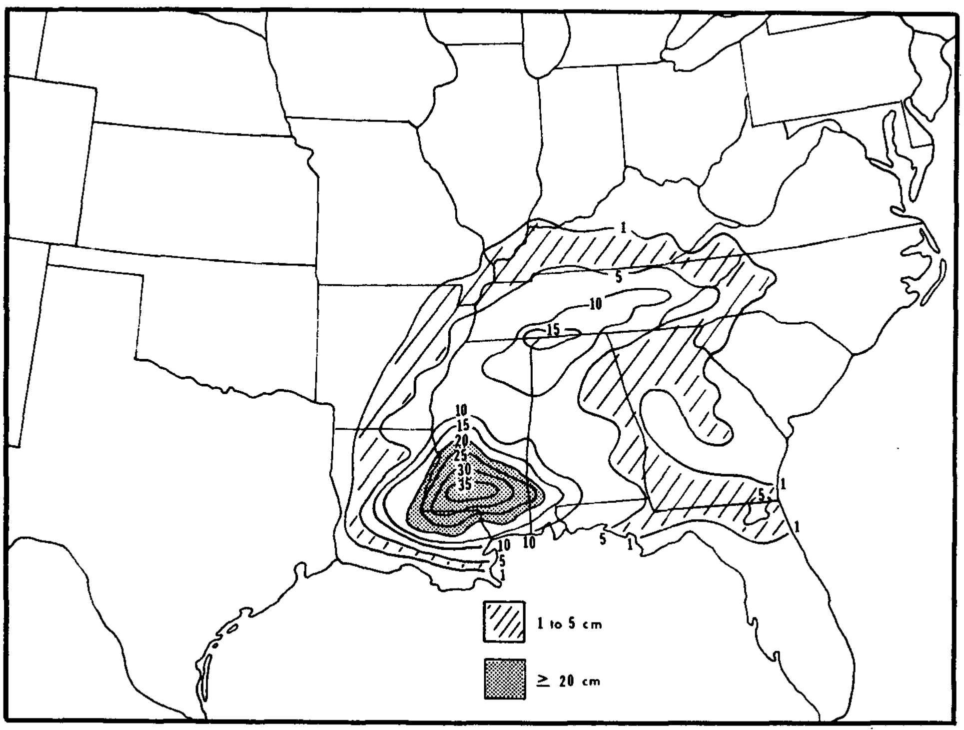

FIG. 10. Accumulated precipitation (cm) produced by SCC from approximately 2100 GMT 4 April to 0400 GMT 7 April 1983. Hatched and shaded areas indicate rainfall accumulations of 1 to 5 cm and ≥20 cm, respectively.

TABLE 3. Precipitation characteristics of Alicia and of a series of convective complexes.

Event	$\bar{P}_G$ (cm)	Average area ⩾ 1 cm (km²)	Total water (m³)	Time (h)
Alicia	4.2	710 500	2.99×10^{10}	89
SCC	6.9	931 000	6.44×10^{10}	55
Ratio:				
SCC/Alicia	1.68	1.31	2.15	0.62

community will be able to provide more of the detailed QPF guidance outlined by Georgakakos and Hudlow (1984) in their discussion of hydrologic forecast needs. Furthermore, since it was also found that series of convective weather systems are very likely the United States' most prolific precipitation producers, rivaling and even exceeding that of a hurricane, there is a certain amount of urgency attached to the current efforts to understand and predict mesoscale convective weather systems.

Based on the differences in MCWS precipitation between 1982 and 1983, it is likely that large-scale atmospheric circulation patterns significantly influence the location and characteristics of mesoscale convective weather systems. During 1982, a "normal" year where the Bermuda high dominated the large-scale summertime circulation, most MCWS's formed between latitude 45°N and the Gulf Coast. During 1983, a drought year where a large-scale ridge set up over the central United States during July and August, most MCWS activity shifted northward away from the moisture source (Gulf of Mexico). Although the frequency of MCWS's was nearly the same for July and August of both years, the average precipitation area of MCWS's during 1983 was only about 86% of that for 1982. Similarly, the average volumetric production of precipitation for 1983 systems was only 72% of that for 1982. Nevertheless, the rainfall that *was* produced by MCWS's during July–August of 1983 comprised most of the precipitation received during the critical crop growth period. This suggests that the MCWS may be a crucial precipitation-producing deterrent to drought and an important mechanism for enhancing midsummer crop growth throughout the midwestern United States.

Finally, it is worth noting that land–sea temperature contrasts and the location of the dryline seem to have a pronounced effect on the production of MCWS precipitation. In both 1982 and 1983, a sharp gradient in precipitation developed along the western edge of the MCWS domain, near the climatological mean position of the dryline, and along the Gulf Coast. The sharp gradient along the Gulf Coast suggests that the generation of potential buoyant energy by heating and deepening of the boundary layer over land may be just as important as the forcing from disturbances that frequently propagate through the Gulf Coast region. Moreover, the differential modification of rain cooled air over land versus that over water would tend to create a thermal boundary inland from the coast. Such a boundary could result in low-level thermal advection with enhanced ascent in the region of minimal static stability. Therefore, numerical prediction of MCWS's will very likely require 1) a sophisticated boundary layer package capable of reproducing the different diurnal cycles of heating and mixing over land and over water, 2) a convective parameterization that includes cooling by moist downdrafts, and 3) accurate resolution of the location of the dryline.

Acknowledgments. The authors express their gratitude to Dr. Gregory Forbes for his critical review of this manuscript and to Jonathan H. Merritt for sharing the results of his work and for his help and input on many aspects of this investigation; to David A. Olson of the National Meteorological Center, Howard Edwards of the National Climatic Center and Dennis M. Rodgers of the National Oceanic and Atmospheric Administration for their help in obtaining data and information used in this project; to Michael Contino of The Pennsylvania State University Computation Center for his assistance in many of the numerical aspects of this study; to Dr. Frederick L. Wernstedt for providing the climatological precipitation data used to construct the normal warm-season precipitation analyses; and to Susan Frandsen for skillfully preparing the manuscript.

This project was conducted under the sponsorship of National Science Foundation Grant ATM-8218208 and NOAA Cooperative Agreement NA82AA-H-00027.

REFERENCES

Anthes, R. A., Y.-H. Kuo, S. G. Benjamin and Y.-F. Li, 1982: The evolution of the mesoscale environment of severe local storms: Preliminary modeling results. *Mon. Wea. Rev.*, **110**, 1187–1213.

Bosart, L. F., and F. Sanders, 1981: The Johnstown flood of July 1977: A long-lived convective storm. *J. Atmos. Sci.*, **36**, 1616–1642.

Carlson, T. N., and F. H. Ludlum, 1968: Conditions for the occurrence of severe storms. *Tellus*, **20**, 203–226.

Chang, C. B., D. J. Perkey and C. W. Kreitzberg, 1981: A numerical case study of the squall line of 6 May 1975. *J. Atmos. Sci.*, **38**, 1601–1615.

Changnon, S. A., 1957: Thunderstorm-precipitation relations in Illinois. *Rep. of Investigation 34,* Illinois State Water Survey, 24 pp.

Charney, J. G., 1975: Dynamics of deserts in the Sahel. *Quart. J. Roy. Meteor. Soc.*, **101**, 193–202.

Dickson, R. R., 1980: Weather and circulation of June 1980—Inception of a heat wave and drought over the central and southern Great Plains. *Mon. Wea. Rev.*, **108**, 1469–1474.

Fawcett, E. B., 1977: Current capabilities in prediction at the National Weather Service's National Meteorological Center. *Bull. Amer. Meteor. Soc.*, **58**, 143–149.

Frank, W. M., 1983: Cumulus parameterization problem. *Mon. Wea. Rev.*, **111**, 1859–1871.

Fritsch, J. M., and C. F. Chappell, 1980: Numerical prediction of convectively driven mesoscale pressure systems. Part II: Mesoscale model. *J. Atmos. Sci.,* **37,** 1734–1762.

——, and R. A. Maddox, 1981: Convectively-driven mesoscale weather systems aloft. Part I: Observation. *J. Appl. Meteor.,* **20,** 9–19.

——, and J. M. Brown, 1982: On the generation of convectively-driven mesohighs aloft. *Mon. Wea. Rev.,* **110,** 1554–1563.

——, R. A. Maddox and A. G. Barnston, 1981: The character of mesoscale convective complex precipitation and its contribution to warm season rainfall in the U.S. *Preprints Fourth Conf. on Hydrometeorology,* Reno, Amer. Meteor. Soc., 94–99.

Georgakakos, K. P., and M. D. Hudlow, 1984: Quantitative precipitation forecast techniques for use in hydrologic forecasting. *Bull. Amer. Meteor. Soc.,* **65,** 1186–1200.

Glahn, H. R., 1985: Yes, precipitation forecasts have improved. *Bull. Amer. Meteor. Soc.,* **66,** 820–830.

Heideman, K. F., and J. M. Fritsch, 1984: A quantitative evaluation of the warm-season QPF problem. *Preprints Tenth Conf. on Weather Forecasting and Analysis,* Clearwater Beach, Amer. Meteor. Soc. 57–64.

Hershfield, M., 1980: Extreme drought. *Biometeorology,* **7,** Part 2, 143–151. [Suppl. to *Int. J. Biometeor.,* **24.**]

Kane, R. J., 1985: The temporal and spatial characteristics of precipitation from mesoscale convective weather systems. M.S. thesis, The Pennsylvania State University, 152 pp.

——, C. R. Chelius and J. M. Fritsch, 1986: The precipitation characteristics of mesoscale convective weather systems. Submitted to *J. Climate Appl. Meteor.*

Livezey, R. E., 1980: Weather and circulation of July 1980—Climax of historic heat wave and drought over the United States. *Mon. Wea. Rev.,* **108,** 1708–1716.

Ludlum, D. M., 1983: Weatherwatch—July 1983. *Weatherwise,* **36,** 262–269.

Madden, D. A., and J. Williams, 1978: The correlation between temperature and precipitation in the United States and Europe. *Mon. Wea. Rev.,* **106,** 142–147.

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

——, 1983: Large-scale meteorological conditions associated with mid-latitude, mesoscale convective complexes. *Mon. Wea. Rev.,* **111,** 1475–1493.

Matteson, G. T., 1969: The West Texas dry front of June 1967. M.S. thesis, University of Oklahoma.

Namias, J., 1982: Anatomy of Great Plains protracted heat waves (especially the 1980 U.S. summer drought). *Mon. Wea. Rev.,* **110,** 824–838.

Ooyama, K. V., 1982: Conceptual evolution of the theory and modeling of the tropical cyclone. *J. Meteor. Soc. Japan,* **60,** 369–379.

Perkey, D. J., and R. A. Maddox, 1985: A numerical investigation of a mesoscale convective system. *Mon. Wea. Rev.,* **113,** 553–566.

Ramage, C. S., 1982: Have precipitation forecasts improved? *Bull. Amer. Meteor. Soc.,* **63,** 739–743.

Rodgers, D. M., K. W. Howard and E. C. Johnston, 1983: Mesoscale convective complexes over the United States during 1982. *Mon. Wea. Rev.,* **111,** 1501–1514.

——, M. J. Magnano and J. H. Arns, 1985: Mesoscale convective complexes over the United States during 1983. *Mon. Wea. Rev.,* **113,** 888–901.

Ropelewski, C. F., 1984: Seasonal climate summary, the climate of summer 1983—A season of contrasts and extremes. *Mon. Wea. Rev.,* **112,** 591–609.

Savage, R. P., J. Baker, J. H. Golden, A. Kareem and B. R. Manning, 1984: *Hurricane Alicia, Galveston and Houston, Texas, August 17–18, 1983.* National Academy Press. [Committee on Natural Disasters, Commission of Engineering and Technical Systems, National Research Council.]

Schaefer, J. T., 1974: A simulative model of dry line motion. *J. Atmos. Sci.,* **31,** 956–964.

Schubert, W. H., and J. J. Hack, 1982: Inertial stability and tropical cyclone development. *J. Atmos. Sci.,* **39,** 1687–1697.

Smull, B. F., and R. A. Houze, Jr., 1985: A mid-latitude squall line with a trailing region of stratiform rain: Radar and satellite observations. *Mon. Wea. Rev.,* **113,** 117–133.

Twomey, S., and P. Squires, 1959: The influence of cloud nucleus population on the microstructure and stability of convective clouds. *Tellus,* **11,** 408–411.

Wagner, A. J., 1983: Seasonal climate summary, the climate of summer 1982—A season with increasingly anomalous circulation over the equatorial Pacific Ocean. *Mon. Wea. Rev.,* **111,** 590–601.

Wendland, W. M., L. D. Bark, D. R. Clark, R. B. Curry, J. W. Enz, K. G. Hubbard, V. Jones, E. L. Kuehnast, W. Lytle, J. Newman, F. V. Nurberger and P. Waite, 1984: A climatic review of summer 1983 in the upper Midwest. *Bull. Amer. Meteor. Soc.,* **65,** 1068–1072.

Zhang, D.-L., and J. M. Fritsch, 1986: Numerical simulation of the meso-β scale structure and evolution of the 1977 Johnstown flood. Part I: Model description and verification. *J. Atmos. Sci.,* **43,** 1913–1943.