Distribution of Mesoscale Convective Complex Rainfall in the United States

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ABSTRACT

Several annual mesoscale convective complex (MCC) summaries have been compiled since Maddox strictly defined their criteria in 1980. These previous studies have largely been independent of each other and therefore have not established the extended spatial and temporal patterns associated with these large, quasi-circular, and, typically, severe convective systems. This deficiency is primarily due to the difficulty of archiving enough satellite imagery to accurately record each MCC based on Maddox's criteria. Consequently, this study utilizes results from each of the MCC summaries compiled between 1978 and 1999 for the United States in order to develop a more complete climatology, or description of long-term means and interannual variation, of these storms. Within the 22-yr period, MCC summaries were compiled for a total of 15 yr. These 15 yr of MCC data are employed to establish estimated tracks for all MCCs documented and, thereafter, are utilized to determine MCC populations on a monthly, seasonal, annual, and multiyear basis. Subsequent to developing an extended climatology of MCCs, the study ascertains the spatial and temporal patterns of MCC rainfall and determines the precipitation contributions made by MCCs over the central and eastern United States. Results indicate that during the warm season, significant portions of the Great Plains receive, on average, between 8% and 18% of their total precipitation from MCC rainfall. However, there is large yearly and even monthly variability in the location and frequency of MCC events that leads to highly variable precipitation contributions.

1. Introduction

For several decades, researchers have shown that mesoscale convective systems (MCSs) produce a substantial quantity of the precipitation during the growing season over the Midwest and the Great Plains (Maddox et al. 1979; Fritsch et al. 1986; Tollerud and Collander 1993). Furthermore, it has been observed that annual variation in the number of MCSs and the relative concentration of these events has an impact on the total annual rainfall over these regions that, in turn, produces conditions ranging from drought episodes to flooding events (Fritsch et al. 1986; Kunkel et al. 1994; Anderson and Arritt 1998, 2001).

Characteristically, an MCS is an assemblage of thunderstorms, organized on a larger scale than its individual building blocks (i.e., storm cells), in which the individual convective storms within the system act in concert to generate flows and features that facilitate the organized system. For this study, the focus is exclusively on a particular type of large, long-lived MCS that exhibits a quasi-circular cloud shield: the mesoscale convective complex (MCC). MCCs are strictly defined by Maddox (1980) and classified according to cloud-top characteristics observed in infrared (IR) satellite images. MCC criteria include critical cloud-top temperatures of −32° and −52°C that must meet specific spatial and temporal requirements (Table 1). Since MCC precipitation impacts large portions of the United States, it would be beneficial to understand MCC precipitation characteristics and the patterns associated with these significant convective systems.

A number of past studies have investigated the spatial and temporal distribution of MCCs over the United States for specific years (Table 2) to provide a record of their occurrences. In general, these summaries conclude that MCC activity in the United States is primarily located between the Rocky and the Appalachian Mountains, with development normally during the afternoon and early evening (Augustine and Howard 1988). About 35 MCCs affect the United States annually (Anderson and Arritt 1998), with a maximum of 59 in 1985 (Augustine and Howard 1988) and a minimum of 23 in 1981 (Maddox et al. 1982). Furthermore, Anderson and Arritt (1998) established that within the period of March through September, the peak frequency of MCCs occurs in July. Tollerud et al. (1987) and Tollerud and Rodgers (1991) conclude that MCCs follow a clearly defined diurnal cycle that includes a strong tendency for first storms to appear in midafternoon, for the anvil to reach

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TABLE 1. Mesoscale convective complex criteria as defined by Maddox (1980).

Mesoscale convective complex definition* (physical characteristics based upon analyses of enhanced IR satellite imagery)		
Size	A	Continuous cold cloud shield with IR temperature ≤−32°C must have an area ≥100 000 km^2
	B	Interior cold cloud region with IR temperature ≤−52°C must have an area ≥50 000 km^2
Initiate		Size definitions A and B are first satisfied
Duration		Size definitions A and B must be met for a period of ≥6 h
Maximum extent		Continuous cold cloud shield (IR temperature ≥−32°C) reaches maximum size
Shape		Minor axis/major axis ≥0.7 at time of maximum extent
Terminate		Size definitions A and B no longer satisfied

* Some criteria have been modified by authors [e.g., Anderson and Arritt (1998, 2001) remove the −32°C areal criteria in their definition in order to simplify their cloud-top documentation procedure].

MCC initiation size criteria shortly before local midnight, and for the MCC to achieve maximum areal extent in the very early morning.

Past MCC climatologies illustrate specific impacts of MCC activity on the precipitation patterns across the United States. For example, Fritsch et al. (1986) conclude that smaller storm precipitation totals and anomalous northward tracks (due to subtropical high position) may have more of an impact on drought conditions over the Midwest than does the overall frequency of MCC events during specific years (e.g., during 1983). Anderson and Arritt (1998) conclude that higher frequencies of large, long-lived MCSs and MCCs, and the subsequent concentration of storm occurrences across the Midwest, seem to be associated with positive precipitation anomaly patterns. Conversely, negative precipitation anomalies tend to occur in areas reporting fewer MCSs and MCCs during the years 1997–98. For example, during 1985, more MCCs were recorded than have ever been documented in any annual MCC summary. Despite the record number of MCCs that occurred, no regional flooding was observed in 1985 because the storms were dispersed across a large region. This finding supports Anderson and Arritt's (1998) argument that concentrated occurrences of MCCs and storm precipitation efficiencies are more important than overall MCC frequency with respect to regional flooding.

MCC precipitation characteristics have been examined (e.g., Kane 1985; Kane et al. 1987; McAnelly and Cotton 1989; Tollerud and Collander 1993) to determine the spatial and temporal distribution of rainfall across the United States due to MCC activity. Kane (1985) and Kane et al. (1987) found that greater precipitation rates occur just after system initiation until soon after maturation and that, on average, MCCs produce a rain depth of 16.1 mm over 510 000 km^2. Moreover, the heaviest rainfall normally is generated 50–100 km equatorward of the anvil-cloud-shield track (McAnelly and Cotton 1989). Tollerud and Collander (1993) established that MCCs contribute to precipitation frequencies beyond a rate suggested by their number and are generally dominated by higher rainfall rates than non-MCC rainfall events. However, Kane (1985) suggests that during an abnormally dry year (i.e., 1983), precipitation due to convective weather systems and MCCs contributes only a small percentage of the total warm-season rainfall. Kane (1985) recognized that MCCs might be the dominant precipitation-producing instrument for the deterrence of drought and for the assurance of normal soil moisture levels across the Midwest. Likewise, Fritsch et al. (1986) discovered that during 1982, large convective weather systems were the dominant warm-season, rain-producing weather systems over much of the Central Plains and Midwest. These systems accounted

TABLE 2. Previous annual MCC surveys.

Year	Author(s)
1978	Bartels et al. 1984; Tollerud and Collander 1993
1979	Bartels et al. 1984; Tollerud and Collander 1993
1980	Bartels et al. 1984; Tollerud and Collander 1993
1981	Bartels et al. 1984; Maddox et al. 1982; Tollerud and Collander 1993
1982	Bartels et al. 1984; Rodgers et al. 1983; Tollerud and Collander 1993
1983	Bartels et al. 1984; Rodgers et al. 1985; Tollerud and Collander 1993
1984	Tollerud and Collander 1993
1985	Augustine and Howard 1988; Tollerud and Collander 1993
1986	Augustine and Howard 1991; Tollerud and Collander 1993
1987	Augustine and Howard 1991; Tollerud and Collander 1993
1992	Anderson and Arritt 1998
1993	Anderson and Arritt 1998
1997	Anderson and Arritt 2001
1998	Anderson and Arritt 2001
1999	C. J. Anderson 2001, personal communication

for 30%–70% of the average warm-season precipitation over the region.

Kane (1985) illustrated that MCCs are essential to Iowa's corn-growing season because of the crop's dependence on July and August precipitation. Kane (1985) concluded that regardless of the small MCC total rainfall during 1983, it did compose most of the rainfall received by the state during the critical corn-yield period. Therefore, MCC precipitation is important to growing seasons in the Midwest during ''normal'' precipitation years and essential when soil moisture is limited.

Previous literature has defined some of the unknowns in annual MCC spatial and temporal distributions and helped in clarifying MCC precipitation characteristics and impacts. Despite these findings, a full climatological examination of the role that MCC rainfall plays in the ''normal'' precipitation patterns across the United States has yet to be accomplished. Preceding studies have been limited by either spatial [e.g., Tollerud and Collander's (1993) two-state examination] or temporal [e.g., Kane et al.'s (1987) 2-yr climatology] considerations. In addition, previous studies raise important questions: What is the monthly, seasonal, and annual variability of MCC precipitation in the United States? How much of the variability in warm-season precipitation is due to MCCs? In order to answer the aforementioned fundamental climatological questions, this study tabulates and compares MCC events across the United States for the years 1978–87, along with 1992–93 and 1997–99.

2. Research methodology

Constructing an accurate MCC climatology can be a difficult task even if data are continually gathered as each event occurs. Attempting to reconstruct past climatologies based on archived satellite data is difficult because of the sparse availability of historical satellite imagery, especially prior to the 1990s. Therefore, many studies include only a few years at a time (e.g., Augustine and Howard 1988, 1991; Anderson and Arritt 1998, 2001) or are limited in their spatial scope (e.g., Tollerud and Collander 1993). To create an MCC climatology of reasonable extent, years must be spent collecting and archiving data, or results from past climate studies must be used. This study employs the latter method.

To determine the annual precipitation produced by MCCs in the central and eastern United States, this study analyzes 15 yr of data (Table 2) from existing MCC summaries. The first significant MCC summary, covering 6 yr (1978–83), was produced by Bartels et al. (1984). Other MCC studies (i.e., annual and/or biannual summaries) have been presented by Maddox et al. (1982), Rodgers et al. (1983, 1985), Augustine and Howard (1988, 1991), Tollerud and Collander (1993), and Anderson and Arritt (1998, 2001). Nevertheless, there are still 7 yr between 1978 and 1999 in which MCCs have not been documented. This project utilizes MCC characteristics from the aforementioned studies to ascertain the spatial and temporal patterns of MCC rainfall and determine the precipitation contributions made by MCCs over the central and eastern United States.

a. Data

This project employs data that describe each MCC track documented by past MCC climatological studies. Such track data primarily include time, size, and locations of each MCC. Each track in our composite database includes the year, date, and times corresponding to three critical stages (i.e., initiation, maximum extent, and termination) of a typical MCC life cycle. Initiation is considered to be the time when the size criteria outlined by Maddox (1980) is first met, while termination is when the MCC no longer meets the Maddox size criteria (Table 1). In addition, portions of the composited database include information on ''first storms.'' First storms are the initial convective cells that later conglomerate to form an MCC. Because the first-storm statistics are incomplete, these data were not employed in our analyses. Information about the size of each event, typically noted in kilometers squared (km^2), is most commonly documented at the maximum extent only, and it normally includes a value for the extent of the $-32°$ and the $-52°C$ cloud shields. Location data for each MCC include latitude and longitude values that indicate the position of the anvil centroid during the three critical stages of the MCC life cycle. All data of past MCC track summaries mentioned above were obtained via the cited articles and/or by personal communication with the authors.

In addition to the MCC track data included in this study, precipitation data are used to determine the extent to which MCCs contribute to annual, seasonal, and monthly precipitation totals. Past studies have used 24-h precipitation charts from the Heavy Precipitation Branch of the former National Meteorological Center (Kane 1985; Fritsch et al. 1986; Kane et al. 1987) and hourly precipitation totals from the National Climatic Data Center (NCDC) (McAnelly and Cotton 1989; Tollerud and Collander 1993).

This project utilizes a database of hourly precipitation observations from a network of first-order and cooperative stations—NCDC's Hourly Precipitation Dataset TD-3240 (HPD; Hammer and Steurer 2000). Groisman and Legates (1994) and Brooks and Stensrud (2000) have discussed a number of the sources of error in the dataset, which include the following: gauges tend to underestimate true precipitation (especially in winter), there is no objective way to determine whether isolated large precipitation totals are the result of ''bad'' data, and these data are inadequate for use in areal-mean calculations in mountainous areas. We believe that most of the error sources discussed in Groisman and Legates (1994) and Brooks and Stensrud (2000) will not greatly affect our results. First, rather than use raw precipitation totals, we examine the fraction of precipitation produced by MCCs (i.e., both the MCC and non-MCC precipitation will experience gauge undercatch). Moreover, spatial averaging of precipitation data reduces the impact of anomalous precipitation observations at individual stations. Finally, MCC precipitation largely occurs on the more level terrain *between* the Rocky and Appalachian Mountains, removing concerns about areal averaging over rough terrain.

Additionally, 8-km, 15-min radar reflectivity data for the years 1997–99 were obtained from the National Aeronautics and Space Administration (NASA) Marshall Space Flight Center's Global Hydrology Resource Center (GHRC) to ensure that the defined MCC cloud shield areas are large enough to include sufficient MCC-related precipitation.

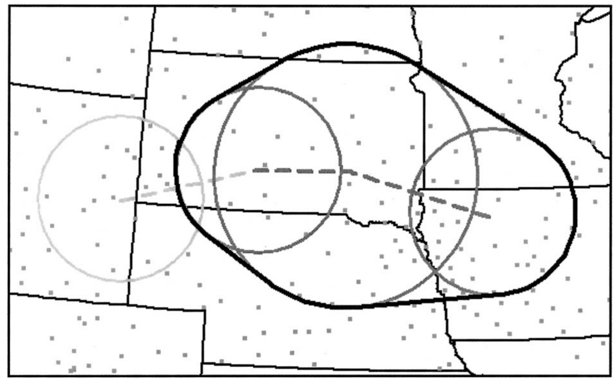

FIG. 1. Schematic depiction of the procedure that was used to determine MCC-related precipitation observations across the Central and Northern Plains during the 4 Jun 1982 MCC. The large circles are representative of the MCC's −32°C anvil at four critical times during the MCC's lifetime, including the initial storm cells (westernmost, light-gray circle), initiation of MCC (i.e., MCC size criteria met), MCC maximum (i.e., when extent of −32°C cloud reaches maximum size), and termination (i.e., when MCC size criteria are no longer met). HPD stations with precipitation data used in this study are indicated by the gray dots. All observations positioned within the black outline representing the anvil path are included in the event's precipitation totals (after Tollerud and Collander 1993).

b. Cloud-track technique and MCC precipitation

Upon obtaining all of the necessary data, the first task was to determine the tracks (including size and location based on average speed) of each MCC. Hourly location data are used to interpolate the tracks of each event. Given the exact time and location of each initiation, maximum extent, and termination, it was possible to find an average storm vector. In addition, it was assumed that the MCC expands at a linear rate from initiation to maximum extent and contracts at a linear rate from maximum extent to termination. Results from McAnelly and Cotton (1989) support this assumption of a linear increase/decrease of the −32° and −52°C cloud shields. Each MCC is also presumed to be circular based primarily on criteria set forth by Maddox (1980). This method yields a track with an approximate anvil centroid, areal extent, and motion at any given hour during the entire MCC life cycle (Fig. 1).

After each event track is delineated, precipitation data are used to quantify the amount of rainfall associated with each MCC event. At any given observation time, recorded precipitation that lies beneath the area of the −32°C cloud shield is included in that event's precipitation totals. Consequently, based on the MCC definition in Table 1, both the initiation and termination points of each MCC are represented by a −32°C anvil of 100 000 km^2. Between initiation and termination, the MCC is assumed to expand to the mature −32°C anvil size and subsequently contract to the predefined termination size. The size of the mature −32°C anvil (i.e., when the storm has reached a life cycle −32°C cloud shield maximum) will depend upon each individual storm in the dataset. However, only data prior to 1992 include the maximum areas of the −32°C cloud shields. Therefore, an average ratio of the maximum −52° and −32°C cloud shields was used to estimate the maximum −32°C clouds shields for years 1992–93 and 1997–99. A ratio of 1.31 of the maximum −32° to −52°C shield was derived by taking the average ratio of maximum −32° to −52°C radii over the period 1978–87.

This cloud-track method has some limitations when trying to estimate MCC tracks and/or rainfall contributions because of data restraints and/or availability. First, an MCC's movement can be quite variable over its lifetime, especially when using cloud centroids to track the system. The cloud centroids may be sensitive to cell development and can shift even when the complex itself is not propagating (e.g., in the case of decreasing convective intensity). Second, there are some MCC cases in the database that form from a merger of two convective systems. In such cases the actual cloud centroid's path may be quite nonlinear. Third, most, if not all, events may be characterized by noncircular cloud shields, which may allow for some MCC rainfall to fall outside of the −32°C cloud shield. Finally, McAnelly and Cotton (1989) conclude that throughout the MCC life cycle, the heaviest rainfall tends to be displaced 50–100 km south of the cloud shield centroids, while the stratiform pattern tends to be more MCC-centered. This asymmetry in the heavy rainfall during the evolution of the MCC may produce some underestimation in precipitation contributions from some MCCs. These limitations in the cloud-track technique utilized in the study will be assessed in the following subsection.

c. Cloud-track technique tests

To determine how much the aforementioned cloud-track technique underestimates MCC-produced precipitation, we examined all MCCs from 1997 to 1999 for rainfall associated with the MCCs that fell outside the −32°C cloud shield. We limited our test to this period

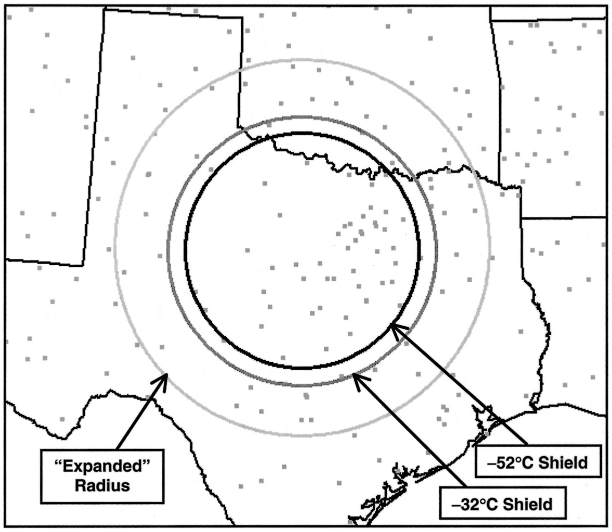

FIG. 2. Schematic depiction of the different radii utilized in testing the MCC cloud-track technique. The radius of the −32°C cloud shield, the radius of the −52°C cloud shield, and the expanded radius (1.4 times the −32°C cloud shield radius) are based on the averages for the 527 events in the database. HPD stations with precipitation data used in this study are indicated by the gray dots.

because we were able to obtain 8-km, 15-min resolution radar imagery for these events. The radar data were examined for each of the 109 MCC events that occurred during this 3-yr period. We subjectively categorized each event based on how isolated the MCC event was from any other precipitation-producing mechanism. We identified 28 isolated events to examine how much precipitation should have been attributed to MCCs but was excluded by our methodology. Only isolated events were employed because in most cases it was impossible to determine where MCC precipitation begins and ends with nonisolated cases. Many MCCs straddle boundaries that focus convergence, which tend to initiate a series of convection along the periphery of the MCC. We believe that most of this precipitation on the flanks of the MCC would be considered to be outside the influence of the MCC and would therefore not directly manipulate the MCC's organization.

After identifying the 28 isolated events, we calculated the amount of precipitation that occurred between the radius of the −32°C cloud shield and a second, larger radius. This second radius (hereafter ''expanded radius'') was 1.4 times the radius of the −32°C cloud shield. The 1.4 multiplier was chosen because a visual examination of radar imagery for the isolated events indicates that the areas included within this expanded radius would clearly contain any precipitation resulting from the MCC (Fig. 2).

After determining the expanded radii for the 28 isolated events in 1997–99, we calculated the amount precipitation under the −32°C cloud shield versus that which fell within the expanded radius. Of the 10 660 hourly observations at stations *outside* the −32°C cloud shield but within the expanded radius, 96.2% of reports indicated no precipitation. Only 0.3% of the reports taken between the −32° cloud shield and the expanded radius recorded 1.27 cm (0.5 in.) or more precipitation. Most precipitation associated with the MCCs falls under the −32°C cloud shield. Additionally, we interpolated the precipitation data onto a 1° latitude by 1° longitude grid in order to spatially weight the observations. Using the gridded precipitation data, we found that the region within the −32°C anvil captured 86.6% of the precipitation found within the expanded radius.

Further, we examined the average fraction of precipitation captured by the −32°C cloud shield versus the expanded radius on the 1° × 1° grid. For those nineteen 1° × 1° cells that average move than 2.54 cm (1 in.) of total precipitation per MCC, the −32°C cloud shield captured less than 95% of the precipitation in only three cells. In 14 of the 19 grid cells, the −32°C cloud shield captured all of the precipitation found within the expanded radii for the 28 isolated events in 1997–99. Finally, we examined the differences in precipitation captured by the −32°C cloud shield and the expanded radius during the life cycle of the MCC. At initiation, 85% of the total precipitation was contained by the −32°C cloud shield. At the maturation point, the total precipitation contained by the −32°C cloud shield was 93%. Finally, at termination, 80% of the precipitation was contained by the −32°C cloud shield. Again, in the region with the greatest MCC precipitation (greater than 2.54 cm per MCC on average), the −32°C shield captured 95% or more of the precipitation in at least three-fourths of the 1° × 1° cells. Overall, the cloud-track method utilized in this study appears to account for nearly all of the MCC precipitation and, despite some limitations, appears to be a reasonable method for estimating the fraction of precipitation attributed to MCCs.

d. MCC precipitation

Total precipitation values for each MCC were tabulated for each year and compared with the overall precipitation for that year and for each warm season (for this study, the warm season consists of May–June–July–August). MCC precipitation values were also aggregated by each month for the entire period. Additionally, the percentages of precipitation due to MCCs for several temporal periods were calculated. These percentages were obtained by summing the total amount of MCC precipitation during the period and dividing that total by the sum of all precipitation. Finally, the variance in the total precipitation ascribed to MCC variance was determined. The study region was defined by the total extent of MCC events; that is, states without MCC events during the study period were not included in the project.

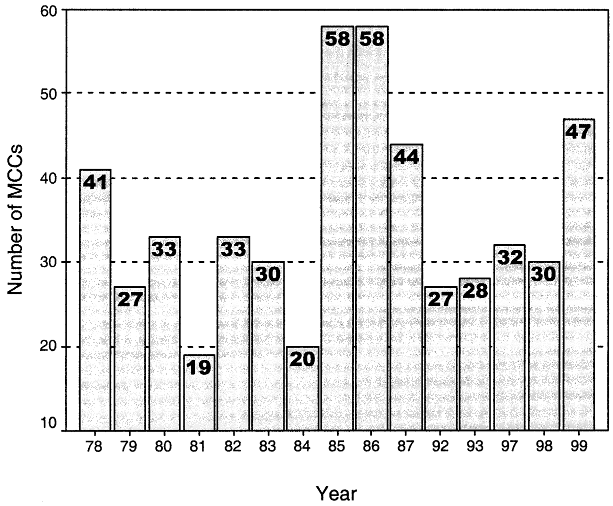

FIG. 3. MCC tabulations of the number of MCCs per year for 15 yr.

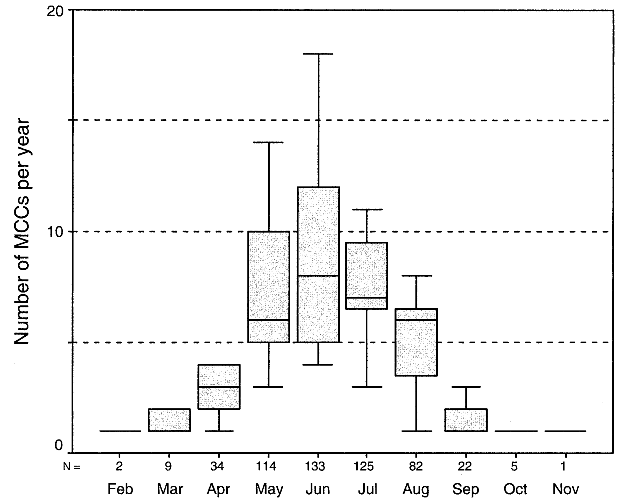

FIG. 4. Box-and-whisker plot of the number of MCCs per year as derived from the 15-yr dataset. The box-and-whisker plots show the median (thick line), interquartile range (shaded), and outliers (i.e., the 10th and 90th percentile as whiskers) for the indicated months. Additionally, the total number of MCCs per month for all 15 yr investigated is indicated along the *x* axis.

3. Results

Developing a climatology of MCCs has been restricted in the past by incorporating data for only a few years and/or by limiting the spatial extent of the analysis. The large spatial and temporal component of this study will allow for a clearer examination and comprehension of the MCC climatology of the central and eastern United States.

a. Temporal analysis of MCC events

Great interannual variability is apparent in yearly MCC frequency, with a peak of MCC activity in 1985 and 1986, when 58 events occurred each year (Fig. 3). The years 1978, 1987, and 1999 were all above the average of 35.1 events, with 41, 44, and 47, respectively. The only years with notably fewer events were 1981 and 1984, with 19 and 20 events, respectively.

Tollerud and Rodgers (1991) suggest that some of the variability is produced by changes in the processing of satellite imagery. Prior to 1985, most analyses of infrared satellite imagery were performed manually; since then, the methods used to measure MCC size using satellite imagery have been substantially automated (Augustine 1985; Tollerud and Rodgers 1991). Furthermore, it is also possible that satellite imagery may not have always been available during the early years of the study period. Some cases may have been missed altogether. Tollerud and Rodgers (1991) suggest that there may be a 10%–15% undercount [relative to the new automated system and criteria introduced by Augustine (1985)] in the years occurring before 1985. For this analysis, the tabulations made during the 15 yr in which MCC summaries are available have been uncritically accepted. In all, 538 events are documented during the 15 yr. However, 11 of these events were removed from our dataset because of missing data fields (e.g., missing initiation location and/or time). Thus, this study encompasses 527 events over 15 yr—an average of over 35 MCCs per year.

MCCs are definitive warm-season events (Fig. 4), with a maximum number of events occurring during May, June, July, and August. More than 86% of the events documented in the 15-yr study occurred during this 4-month period. This indicates that high instability, which is at a maximum during the summer months because of greater heat and humidity in the lower troposphere, is the key factor in generating more of these large convective systems. Undoubtedly, transition-season months have lower energies available for the generation of MCCs and therefore, are less frequented by the systems. In addition to less thermal energies for MCCs, transition seasons have more frequent cyclone activity, which implies more linear forcing for convection and less capping to confine convective development to a particular region (as is typically the case during the warm season). Monthly, MCCs tend to peak in June, with an average of nearly 9 MCC events occurring per year during this month. However, when looking at June on an interannual basis, MCCs vary from 4 events in 1984 to 18 events in 1985, leading to further indication that MCC frequency can vary greatly interannually. July has the second greatest frequency of MCCs with more than eight events annually, while May is frequented by more than seven events on average.

When examining the average size of the maximum −52°C MCC anvil by month (Fig. 5), the spring transition season is clearly different than that of the later warm-season period. For example, April has an average −52°C cloud-anvil size of nearly 220 000 km^2, which is significantly larger than the average August cloud-

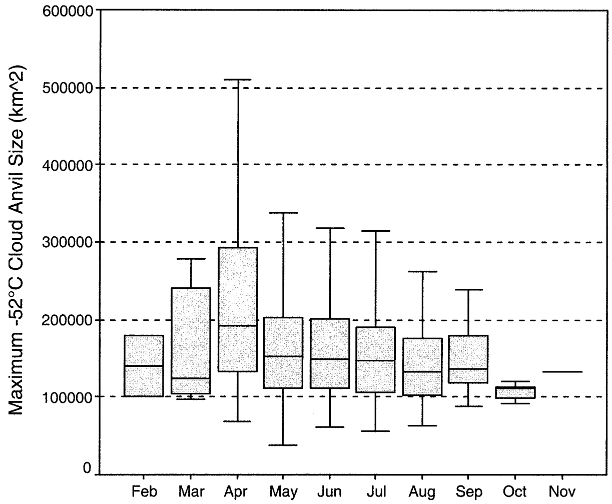

FIG. 5. Box-and-whisker plot of the maximum −52°C anvil-cloud size for each month derived from the 15-yr MCC dataset. See Fig. 4 for details on box-and-whisker plot.

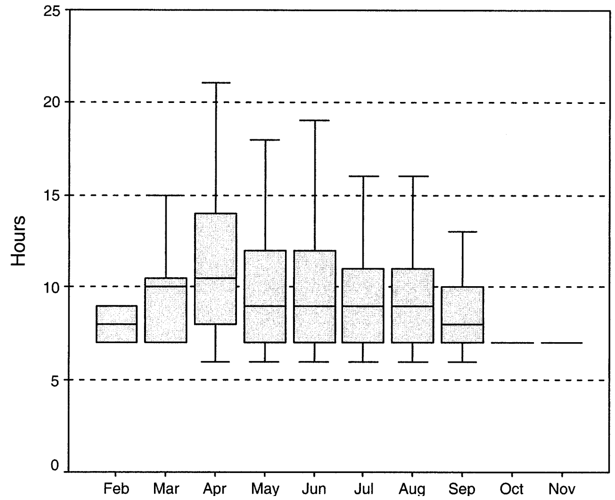

FIG. 6. As in Fig. 5, except for the duration of MCCs derived for each month from the 15-yr MCC dataset.

anvil size of around 140 000 km^2. In addition, MCCs that occur in April persist, on average, 2–5 h longer than any other month (Fig. 6). Tollerud and Rogers (1991) found the same discernable size and duration patterns when they examined 10 yr of MCC data. They hypothesized that differing dynamical mechanisms may cause the large differences in the sizes of these events. In general, April and May MCCs tend to develop in regions of stronger forcing from vigorous springtime synoptic-scale circulations. Moreover, Tollerud and Rodgers (1991) suggest that April and May MCCs have a tendency to be in closer proximity to the Gulf of Mexico, which might provide them with an easier and more dependable access to low-level moisture, which, in turn, may induce larger cloud-anvil shields. These two factors may cause springtime MCCs to be larger in size and longer in duration than those in the later part of the warm season.

As established by Tollerud et al. (1987) and Tollerud and Rodgers (1991), MCCs have a distinct diurnal pattern of development and evolution (Fig. 7). Convection typically reaches MCC criteria between 0000 and 0200 UTC. Thereafter, the MCC continually grows until reaching maximum anvil extent around 0600 UTC. Subsequently, the MCC begins a lengthy decay until, on average, the system falls below MCC criteria around 1300 UTC.

b. Analysis of MCC precipitation

One of the primary goals of this research is to determine the amount that MCCs contribute to precipitation totals in the central and eastern United States. Because MCCs are predominantly warm-season phenomena, their numbers (or lack thereof) can have large impacts on the growing season throughout the central and eastern two-thirds of the United States. Thus, to determine the overall effect of MCCs and their precipitation patterns, a detailed process was used to estimate the precipitation amounts and the percentages of total rainfall attributed to MCCs in the United States during the 15-yr period.

A point kriging technique was utilized to interpolate and plot maps indicating the distribution of MCC precipitation fractions. Kriging is a geostatistical gridding method that attempts to express statistical trends in irregularly spaced data. This method optimizes the interpolation procedure on the basis of the statistical nature of the surface (DeMers 2000). For thorough discussions of kriging, see Cressie (1990, 1991) and DeMers (2000). The kriging routine interpolates the station data utilized in this study onto a 40-km resolution grid that covers the conterminous United States. After the initial inter-

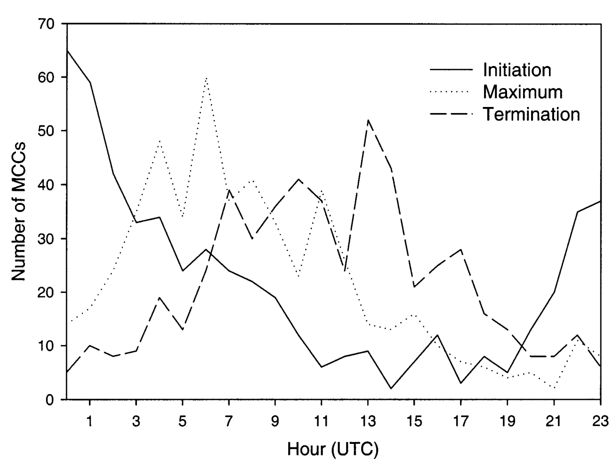

FIG. 7. Number of MCCs that reached initiation, maximum, and termination criteria by time of day, as derived from the 15-yr MCC dataset.

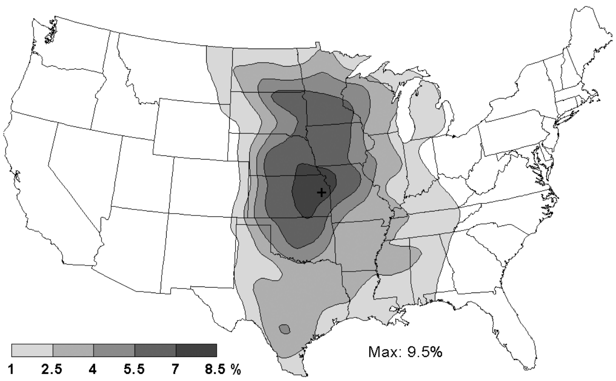

FIG. 8. Spatial distribution of the average percentage of total annual precipitation due to MCC rainfall.

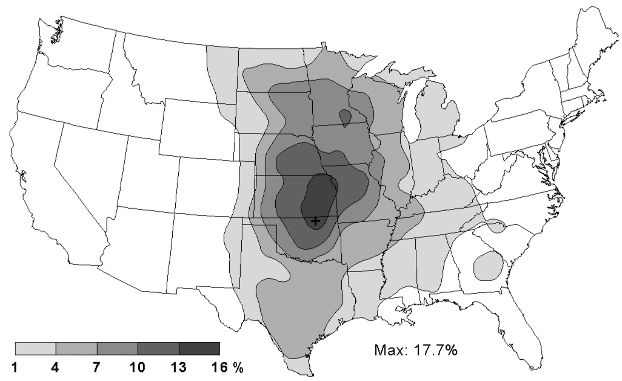

FIG. 9. Spatial distribution of the average percentage of total warm-season (May–Jun–Jul–Aug) precipitation due to MCC rainfall.

polation, the output grid is ingested into an average matrix smoothing procedure in order to remove undesired ‘‘noise’’ and/or small-scale variability that might be present in the original grid. As with many objective analysis schemes, this interpolation technique smoothes some maximum values and, thus, there may be some underestimation of these extreme values in the plots. For this reason, maximum values are indicated on maps of MCC precipitation percentages.

1) Annual analysis

When looking at the total annual rainfall percentages generated by all 527 events over 15 yr tabulated for this study (Fig. 8), the percentages appear rather low. A broad region stretching from central Minnesota to the Texas–Oklahoma border, on average, receives 5%–10% of its precipitation from MCCs. However, these percentages can be deceiving when not taking into account the extreme variability that MCC precipitation percentages engender on a monthly, seasonal, and annual basis. In fact, when considering only the warm-season precipitation percentages (Fig. 9), the region outlined above nearly doubles its MCC precipitation percentages to between 8% and 18%. In any given year, MCCs can account for a much larger fraction of total precipitation.

2) Monthly analysis

Examining warm-season percentages on a monthly basis averaged over the 15 yr (Fig. 10) reveals interesting spatial patterns. For the month of May, Oklahoma, southeastern Kansas, western Missouri, Arkansas, western Tennessee, and much of eastern Texas have MCC precipitation percentages over 10%. Several locations in Texas, Oklahoma, and Kansas receive over 20% of their May rainfall from MCCs. Between May and June, there is a rapid poleward shift in the larger percentages. During June, the highest percentages are located over the middle and lower Missouri Valley, with some locations reporting over 20% of their monthly precipitation totals from MCC contributions. July has an extensive region where greater than 10% of precipitation is from MCCs, including much of the Central and Northern Plains. Furthermore, significant portions of Nebraska, Kansas, and Iowa receive between 15% and 25% of their July rainfall from MCCs. MCCs contribute from 10% to 28% of August precipitation totals throughout much of the Central Plains and portions of the Northern Plains.

In an investigation of 2 yr of convective system precipitation contributions in Iowa, Kane (1985) discovered that mesoscale convective weather systems, including but not limited to MCCs, might have been the most important precipitation-producing mechanism for the deterrence of drought and the maintenance of normal moisture levels throughout the midwestern United States. Kane’s research indicates that in years of average precipitation, convective system precipitation is rather important to the corn crop of the Midwest, but when moisture is at a premium, convective system precipitation becomes critical to corn production. In addition, Kane (1985) suggests that the corn yield is most dependent upon the precipitation received during July and August. Clearly, removing 15%–28% (average MCC precipitation percentage contributions during July and August) of a locale’s precipitation could have significant effects on agriculture.

3) Spatial analysis

Examining MCC precipitation contributions on a yearly basis (Fig. 11) displays the large amount of spatial variability associated with MCCs during the warm season. For all 15 yr, at least some portion of the middle Missouri Valley and the Central Plains have significant MCC contributions (generally, between 15% and 60%) to precipitation totals. However, on a yearly basis, there is no dominant region or precipitation pattern. The fraction of precipitation from MCCs across the Northern and Southern Plains, as well as the Mississippi and Ohio Valleys, vary even more than the Central Plains, with

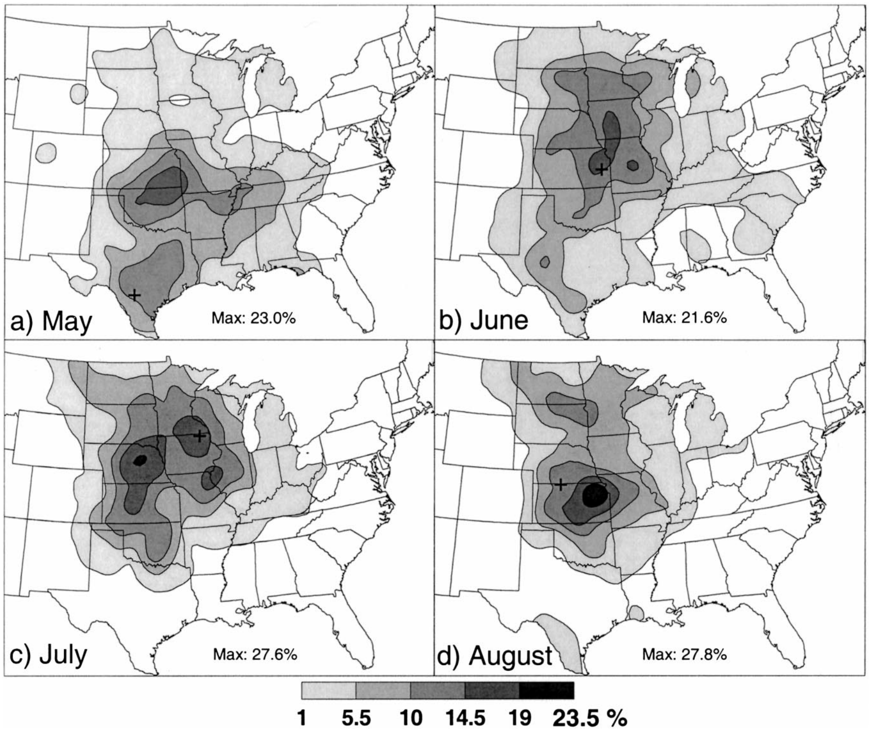

FIG. 10. Spatial distribution of average percentage of total monthly precipitation due to MCC rainfall during the warm-season months of (a) May, (b) Jun, (c) Jul, and (d) Aug.

some years receiving a substantial portion of their precipitation from MCCs (e.g., 1983), while other years receive only a small percentage (e.g., 1992).

Over the 15-yr period, a number of years show noteworthy MCC precipitation contribution patterns. For example, during 1985, MCC precipitation supplied a high percentage of the total warm-season precipitation in the Central Plains and the lower Missouri Valley. In 1986, MCCs were an especially important contributor of rainfall for the region extending from South Dakota, Minnesota, and Wisconsin down to Oklahoma and Arkansas. Although to a lesser degree, 1998 is also a year during which MCCs provided significant rainfall in the Central and Southern Plains. In contrast, during 1981, MCCs accounted for very little of the rainfall in the central or eastern United States.

Additionally, for the years 1979 and 1984, a large portion of the Southern Plains remained relatively void of any considerable MCC contributions to its total precipitation, and, during 1992, they contributed to less than 5% of the precipitation totals within the upper Mississippi Valley region. In 1993, MCC percentages over Oklahoma and the lower Mississippi Valley remained low despite the fact that this region has a propensity to receive a large percentage of its precipitation from MCCs over the remainder of the 15 yr. Lastly, there are a number of years where MCC precipitation tended to be an inefficient supplier to the precipitation totals in the lower Mississippi Valley, particularly, 1980, 1987, 1992, 1993, 1997, and 1998.

It is interesting to compare these findings (see Fig. 11) with results from Fritsch et al. (1986), who determined the warm-season MCC precipitation contributions for both 1982 and 1983. Their precipitation estimates for 1982 are greater than those obtained in our study. However, when calculating percentages, Fritsch et al. (1986) specified a warm-season from April through September, whereas we restricted our warm season to a 4-month period. Fritsch et al. (1986) also utilized a different approach for delineating MCC precipitation. For instance, their methodology included precipitation that fell between initial storm cells and MCC initiation (cf. Fig. 1), precipitation from all clusters that merged into the MCC, and all rainfall that was judged via radar summaries and satellite imagery to be within the MCC precipitation pattern. [See Kane (1985), Fritsch et al. (1986), and Kane et al. (1987) for a more thorough discussion of the methodology utilized to quantify MCC precipitation.] Additionally, there is a discrepancy in the number of MCCs during 1982 obtained by the Fritsch et al. (1986) study and the number of MCCs we obtained from E. I. Tollerud (2001, personal communication). Thus, one should use caution when drawing comparisons between Fritsch et al.'s (1986) precipitation percentages and our results.

The spatial variation of MCC precipitation fractions

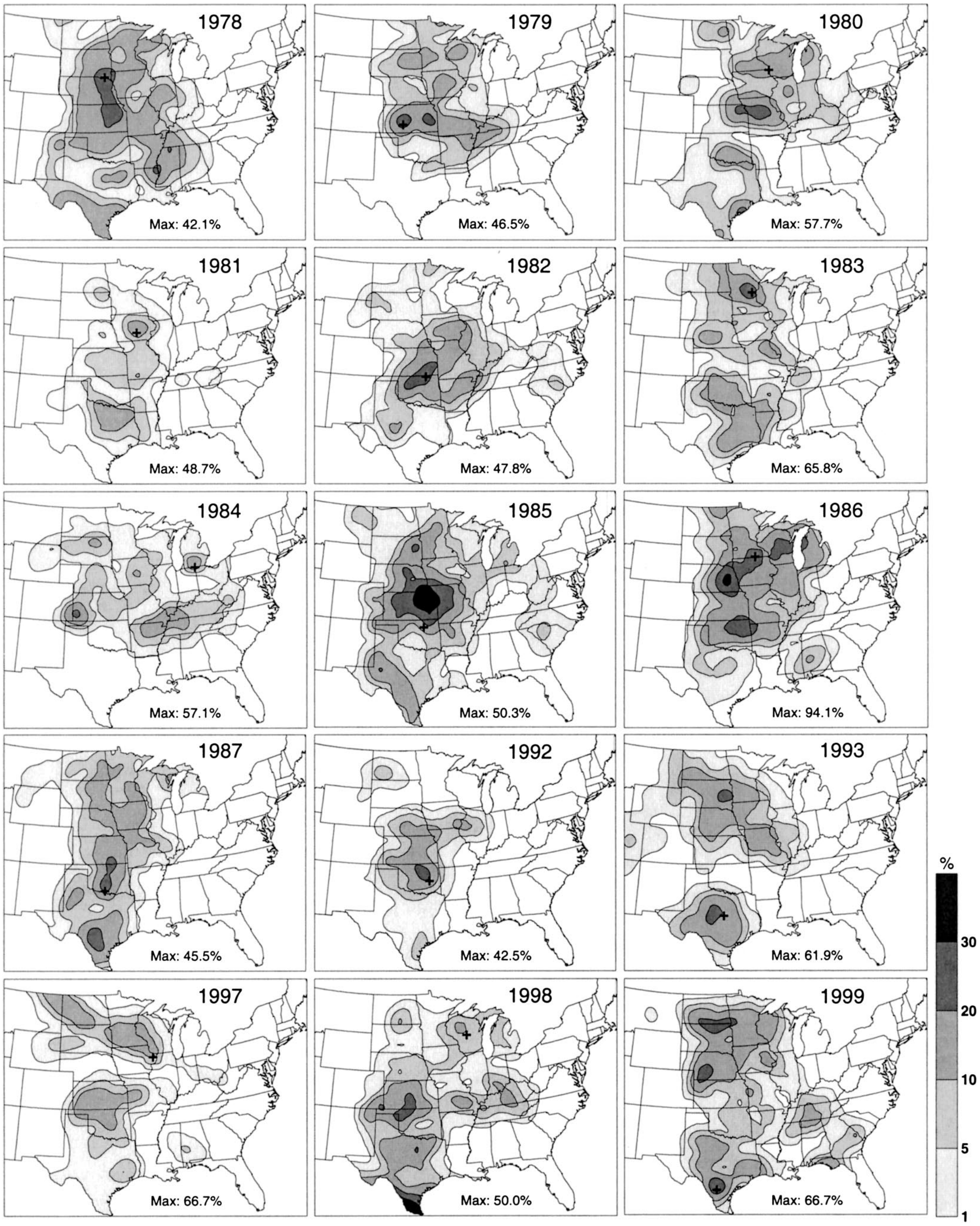

FIG. 11. Spatial distribution of percentage of total warm-season (May–Jun–Jul–Aug) precipitation due to MCC rainfall for each year.

over time also portrays years during which a given region receives a larger portion of precipitation in a year because of MCCs than during ensuing years. For example, throughout the 15 yr, the southeastern states of Mississippi, Alabama, and Georgia generally received little to no MCC contribution to their total precipitation except during the years 1978, 1986, and 1999. In addition, North and South Carolina received a significantly higher percentage of MCC precipitation during the years 1982 and 1985.

In summary, the spatial distribution of significant warm-season MCC precipitation contributions from 1978 to 1999 tended to migrate within the area bounded by the Rocky and Appalachian Mountains. The fraction of total precipitation due to MCCs for any given region within the study area fluctuated from year to year, re-

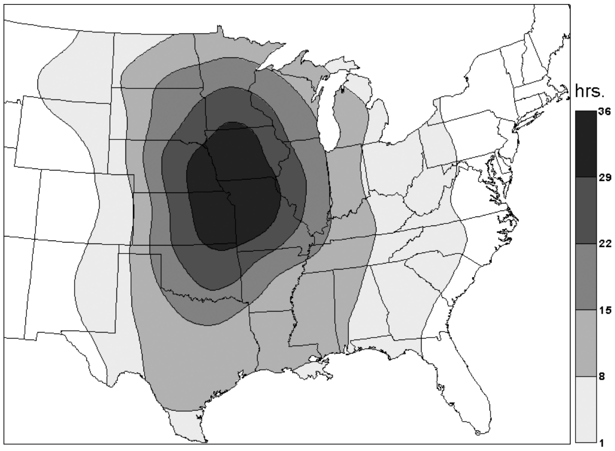

FIG. 12. Spatial distribution of the average number of hours of MCC −32°C cloud shield coverage during a single year.

sulting in no obvious generalizations. Despite this lack of an obvious predictable climatological pattern, MCC precipitation does contribute considerably to the year-to-year variations of precipitation over the central United States.

c. MCC anvil hours

Point location data tend to be a poor representation of the spatial and temporal distribution of MCCs. Therefore, calculating the number of hours MCC anvils are atop stations for various categories (e.g., study period, seasonal, and monthly totals) better illustrates MCC distributions along with MCC migration patterns. This work sought to determine significant spatial and temporal patterns associated with MCCs in the United States over the 15-yr study period. For this purpose, MCC anvil hours were based upon the −32°C anvil size by interpolating each track, which was assumed to be linear, into an area that was outlined by the −32°C anvil. The areas were interpolated onto a 7.5-min grid using a kriging procedure. This allows for a calculation of the average number of hours the −32°C anvil from an MCC was over a given location. Subsequently, the unit utilized in this study, MCC anvil hours, was determined according to how many hours a location was under the −32°C interpolated anvil through a specific time period (e.g., month, season, year).

During an average year (Fig. 12), MCCs are most likely to occur in the lower Missouri Valley where this region has, on average, around 36 MCC anvil hours per year. An axis of greater than 8 MCC anvil hours stretches from southern Texas to the Canadian border and from the High Plains eastward toward the Ohio and Tennessee Valleys, indicating that MCCs are primarily a Great Plains phenomenon.

When examining the 15 yr of MCC frequencies (Fig. 13), the most noticeable tendency is for annual MCC anvil-hour maxima to frequent the intersecting borders of Missouri, Iowa, Nebraska, and Kansas. There is considerable interannual variability in the location of the maxima. Maxima are most prevalent in the Central and Northern Plains and adjoining upper Midwest and central Mississippi Valley.

An examination of monthly MCC tracks (not shown) and anvil-hour totals (Fig. 14) for the 15-yr period reveals high variability in the spatial distribution of the events. During the month of February, only two events occurred with tracks situated in Texas and the other in the southeast region of the United States. Nine MCCs occurred in March and cover an area extending from central Mississippi to southern Minnesota and from western Oklahoma to the Canadian border. In March, the highest number of MCC anvil hours is positioned primarily over southwest Missouri, parts of southeast Kansas, northeast Oklahoma, and northwest Arkansas. In April, the anvil hours increase by 4.5 times the March values, while the maximum anvil-hour core is positioned over central Mississippi and western Alabama. The coverage area of the 34 MCCs during this month extends primarily from the Gulf of Mexico to the Upper Peninsula of Michigan and from central Texas to Lake Ontario.

The most significant number of MCCs occurs during the warm season of May, June, July and August. In May, the number of MCCs increases significantly from 34 in April to 114 during May and the events are widespread across the Great Plains and Mississippi River Valley of the United States. The maximum anvil-hour core shifts northwestward into southeast Kansas, northeast Oklahoma, northwest Arkansas, and southwest Missouri. Another maximum MCC anvil-hour core, slightly smaller in coverage area, is located in southern Texas. MCC anvil-hour maximums continue to increase through June. The anvil-hour maximum core shifts slightly northeastward into Missouri and, likewise, the broad area of MCC distributions generally migrate in the same direction. MCCs become more frequent in the upper Midwest and Northern Plains as they diminish around the Gulf of Mexico with some MCCs situated east of the Appalachian Mountains. During the month of June, MCCs reached their highest total of 133 events and, subsequently, July marks the initial decline, with the MCC totals dropping to 125 events during the month. The MCC anvil-hour maximum becomes most concentrated over northern Iowa and southern Minnesota. MCCs become less frequent in the southern and eastern regions of the United States and occur more often in the Northern Plains and upper Midwest regions. During August, the total number of MCCs drops significantly to 82. Accordingly, MCC anvil hours also decrease during this month. The area with the highest anvil hours shifts south-southwestward into the northeast corner of Kansas, and the width of the coverage area decreases, whereas the latitudinal coverage area generally remains the same.

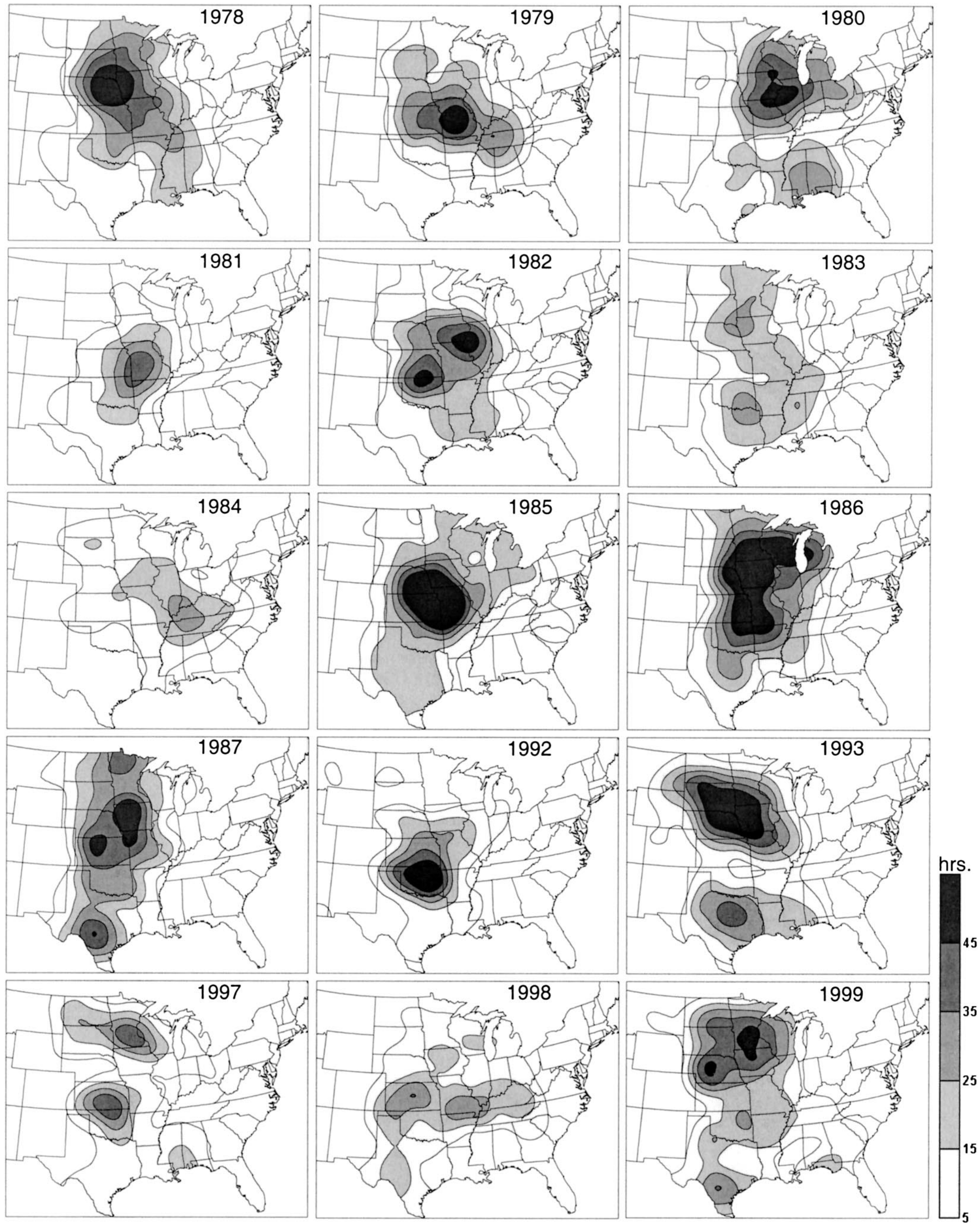

FIG. 13. Spatial distribution of the total number of hours of MCC −32°C cloud shield coverage for each year.

The month of September shows a significant decline in both MCC anvil hours and totals. Both the MCC anvil-hour totals and the total number of MCCs decrease significantly in September. The anvil-hour core is located over northern Illinois, southern Lake Michigan, and northwest Indiana, while an additional smaller core with nearly the same MCC anvil-hour values is noticeable over northern Wisconsin. During October and November, there is no significant location of maximum MCC density because of the rarity of events during these months. In October, only five MCCs occurred with anvil-hour maximums distributed over the southern Great Plains and northern High Plains. Only one event, centered over the southern Mississippi Valley, occurred over the entire study period for the month of November. Lastly, December and January have no recorded MCCs during the period of study.

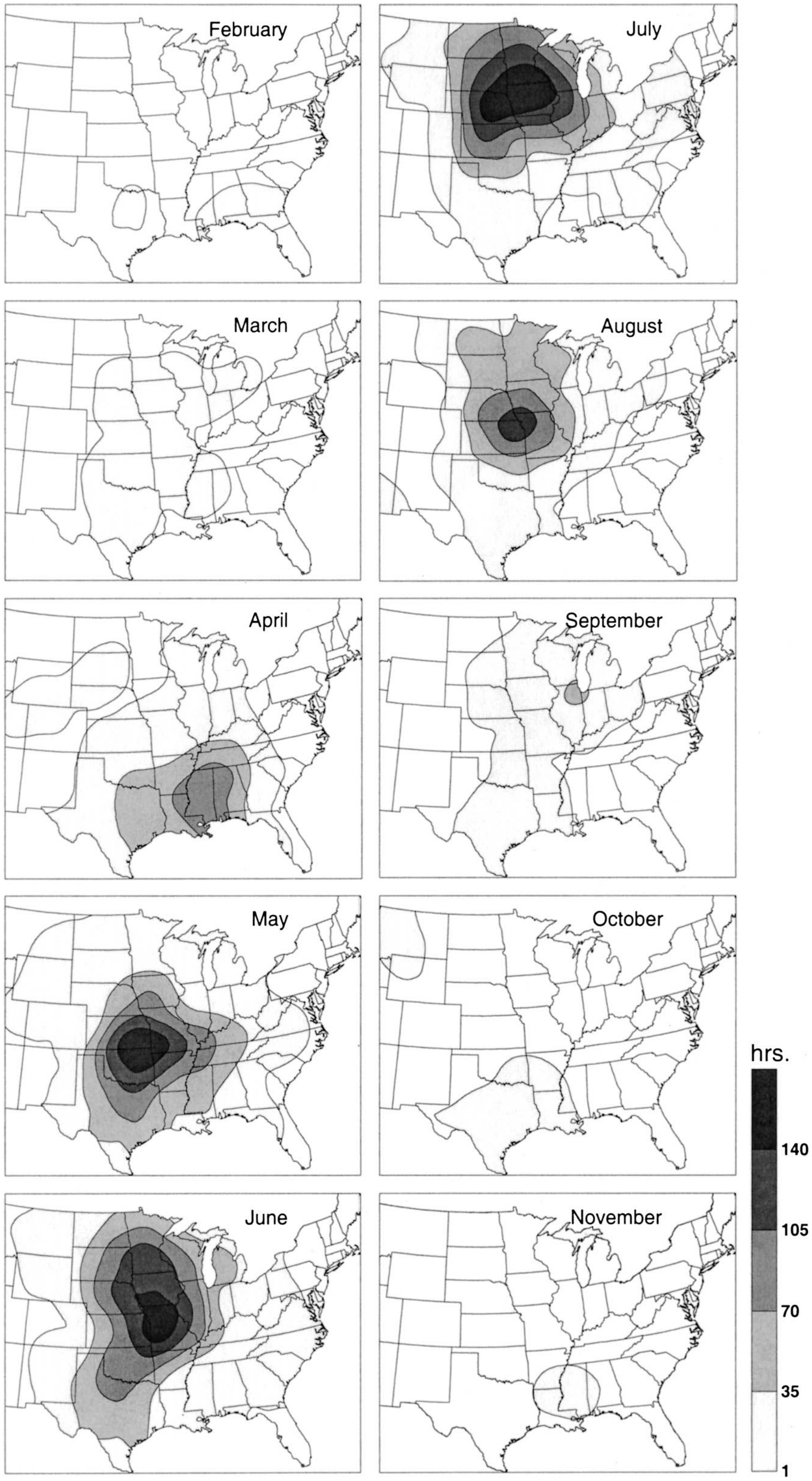

FIG. 14. Spatial distribution of the total number of hours over 15 yr of −32°C cloud shield coverage for each month.

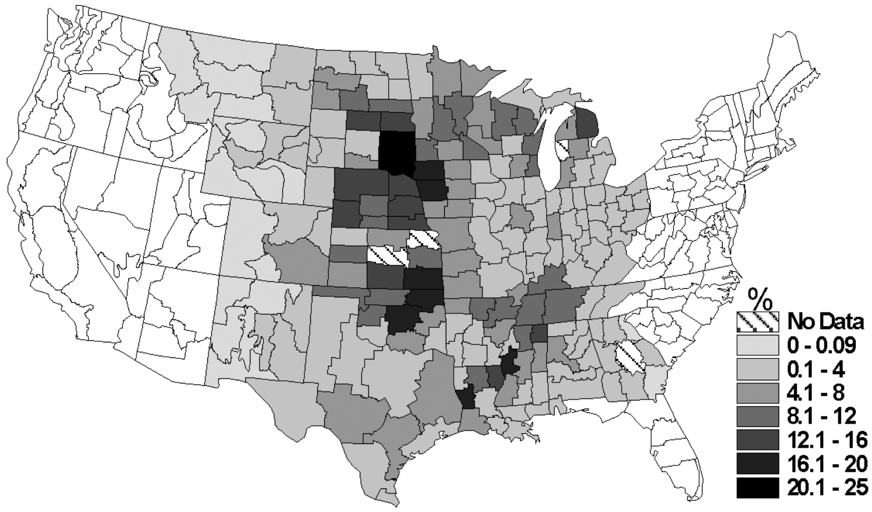

FIG. 15. Spatial distribution of variance in total warm-season precipitation attributed to MCC precipitation variance (shown in percentage). White-filled climate divisions were not analyzed.

d. MCC precipitation variance

In order to determine the spatial distribution of the interannual variance in total precipitation that is explained by variation in MCC precipitation, we calculated [Var (*A*)/Var (*B*)], where *A* is MCC precipitation and *B* is total precipitation. For a given climate division, *A* and *B* represent the sum of the observation points that fall within that climate division. The use of climate divisions may provide a basis of comparison for climatological studies of drought, which are often conducted with climate division data. The analysis covers the 15-yr period consisting only of states located east of the Rocky Mountains and west of the Appalachian Mountains for the warm-season months. This area is selected upon the assumption that MCC occurrences generally are confined to the region between the Rocky and Appalachian Mountains. Because of several missing years of climate data, which results in either extremely high or low ratios, four climate divisions are excluded from the analysis, including one in Georgia, two in Kansas, and one in Michigan. In addition, the ratio is not computed for climate divisions receiving no MCC precipitation over the period of study.

To determine the variance in total precipitation ascribed to MCC variance in this fashion, the MCC and non-MCC precipitation should not be correlated. Therefore, the coefficient of determination value (r^2) was evaluated for 10 selected climate divisions having MCC precipitation during all years. For these climate divisions, the correlation coefficients were not found to be statistically significant at the 90% confidence interval.

The ratios of the variance in MCC precipitation to variance in total precipitation are plotted to display the spatial distribution of the percentage of total precipitation variance credited to MCCs (Fig. 15). The highest fraction of MCC variance to variance of total precipitation extends from South Dakota to northern Oklahoma, with percentages ranging from 12% to 25%. There exists a second concentration of moderately high values (8%–20%) relative to the surrounding climate divisions in regions of Arkansas, Kentucky, Louisiana, Mississippi, and Tennessee. Consequently, even though the southern Mississippi Valley is not in the main corridor of MCCs (Fig. 12), the variability in total precipitation due to MCCs appears to be larger than in other regions with more frequent MCC occurrence. These results reveal that the variation in MCC precipitation that explains the year-to-year variance in total precipitation is at most 25%, occurring in the central plains of the United States.

4. Summary and conclusions

Past investigations of MCC precipitation in the central and eastern United States have been limited in either their spatial or temporal scope. This study utilized existing MCC track data from other investigations to better represent and understand the climatology of MCCs. Rainfall from MCCs was quantified for 15 yr between 1978 and 1999, allowing for a more thorough understanding of MCC rainfall contributions to monthly, seasonal, and yearly precipitation totals over the central and eastern United States.

The frequency of MCC events and percentages of total rainfall contributed by MCCs varies greatly on a year-to-year and even month-to-month basis. In general, locations throughout the Great Plains receive between 8% and 18% of their warm-season precipitation from MCCs. However, MCCs can account for a much larger fraction of total precipitation. In any given year, some location within the central United States receives at least 40% of its warm-season precipitation because of MCC rainfall. On average, precipitation contributions, anvil hours, and event numbers from MCCs peak during June and July across the middle and lower Missouri and upper and middle Mississippi River Valleys. Significant warm-season MCC precipitation contributions may be found from the Gulf of Mexico to the Canadian border.

Further study could examine how MCC precipitation may play a role in intensifying or alleviating periods of flooding or drought. It is expected that MCC precipitation will, in general, contribute to excess rainfall, which may act to alleviate dry periods and/or produce flooding episodes. On the other hand, the lack of MCC precipitation will result in enhancing drought conditions. Furthermore, it could be determined whether or not extreme values of precipitation due to MCCs, if any, show a different effect on the magnitudes of wet or dry spells. Additionally, it is theorized that large-scale changes in the atmospheric circulation may influence convective rainfall distribution across the central United States. From the analysis shown in this paper, it is clear that there is a large degree of yearly and even monthly variability in the location and frequency of MCC events. For these reasons, the authors suggest further investigation into how the year-to-year distribution of MCCs across the central United States is related to persistent, large-scale circulation anomalies. Augustine and Howard (1988, 1991), Kunkel et al. (1994), and Anderson and Arritt (1998, 2001), among others, have examined some of the large-scale circulations and anomalies associated with MCCs and MCSs. However, none of these studies investigated timescales longer than 1–2 yr. With the 15-yr dataset gathered here, a multitude of MCC aspects can be studied in more detail. Hopefully, this initial study and assembly of data will allow for such research to flourish.

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REFERENCES

Anderson, C. J., and R. W. Arritt, 1998: Mesoscale convective complexes and persistent elongated convective systems over the United States during 1992 and 1993. *Mon. Wea. Rev.,* **126,** 578–599.

——, and ——, 2001: Mesoscale convective systems over the United States during the 1997–98 El Niño. *Mon. Wea. Rev.,* **129,** 2443–2457.

Augustine, J. A., 1985: An automated method for the documentation of cloud-top characteristics of mesoscale convective system. NOAA Tech. Memo. ERL ESG-10, Boulder, CO, 121 pp. [Available from NOAA/FSL, 325 Broadway, Boulder, CO 80303.]

——, and K. W. Howard, 1988: Mesoscale convective complexes over the United States during 1985. *Mon. Wea. Rev.,* **116,** 685–701.

——, and ——, 1991: Mesoscale convective complexes over the United States during 1986 and 1987. *Mon. Wea. Rev.,* **119,** 1575–1589.

Bartels, D. L., J. M. Skradski, and R. D. Menard, 1984: Mesoscale convective systems: A satellite data-based climatology. NOAA Tech. Memo. ERL ESG 8, Boulder, CO, 63 pp.

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

Cressie, N. A. C., 1990: The origins of kriging. *Math. Geol.,* **22,** 239–252.

——, 1991: *Statistics for Spatial Data.* John Wiley and Sons, 900 pp.

DeMers, M., 2000: *Fundamentals of Geographic Information Systems.* 2d ed. John Wiley and Sons, 498 pp.

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

Groisman, P. Ya, and D. R. Legates, 1994: The accuracy of United States precipitation data. *Bull. Amer. Meteor. Soc.,* **75,** 215–227.

Hammer, G., and P. Steurer, 2000: Data documentation for data set 3240 (DSI 3240) hourly precipitation data. Tech. Doc. TD-3240, National Climatic Data Center, Asheville, NC, 19 pp. [Available online at ftp://ftp.ncdc.noaa.gov/pub/data/documentlibrary/tddoc/td3240.doc.]

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, 1987: Precipitation characteristics of mesoscale convective weather systems. *J. Appl. Meteor.,* **26,** 1345–1357.

Kunkel, K. E., S. A. Chagnon, and J. R. Angel, 1994: Climatic aspects of the 1993 upper Mississippi River basin flood. *Bull. Amer. Meteor. Soc.,* **75,** 811–822.

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

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

——, D. M. Rodgers, and K. W. Howard, 1982: Mesoscale convective complexes over the United States during 1981—Annual summary. *Mon. Wea. Rev.,* **110,** 1501–1514.

McAnelly, R. L., and W. R. Cotton, 1989: The precipitation life cycle of mesoscale convective complexes over the central United States. *Mon. Wea. Rev.,* **117,** 784–808.

Rodgers, D. M., K. W. Howard, and E. C. Johnston, 1983: Mesoscale convective complexes over the United States during 1982. *Mon. Wea. Rev.,* **111,** 2363–2369.

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

Tollerud, E. I., and D. M. Rodgers, 1991: The seasonal and diurnal cycle of mesoscale convection and precipitation in the central United States: Interpreting a 10-year satellite-based climatology of mesoscale convective complexes. Preprints, *Seventh Conf. on Applied Climatology,* Salt Lake City, UT, Amer. Meteor. Soc., 63–70.

——, and R. S. Collander, 1993: Mesoscale convective systems and extreme rainfall in the central United States. *Extreme Hydrological Events: Precipitation, Floods and Droughts,* Z. W. Kundzewicz et al., Eds., IAHS Publ. 213, 11–19.

——, D. Rodgers, and K. Brown, 1987: Seasonal, diurnal, and geographic variations in the characteristics of heavy-rain-producing mesoscale convective complexes: A synthesis of eight years of MCC summaries. Preprints, *11th Conf. on Weather Modification.* Edmonton, AB, Canada, Amer. Meteor. Soc., 143–146.