The Life Cycle of Lightning and Severe Weather in a 3–4 June 1985 PRE-STORM Mesoscale Convective System

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ABSTRACT

Cloud-to-ground lightning flash characteristics of a series of four mesoscale convective systems (MCS) that occurred in Oklahoma and Kansas on 3–4 June 1985 during the Oklahoma–Kansas Preliminary Regional Experiment for STORM-Central project are described. A total of 23 490 flashes were detected by the network from all four MCSs; 96% of them lowered negative charge to ground. Because the second MCS (MCS II) spent nearly all of its lifetime within the optimal region of coverage of the lightning and radar networks, trends in ground-flash characteristics could be documented throughout the system's life cycle. Lightning trends were analyzed relative to rainfall parameters based on radar network data and were stratified by the flashes' polarity and locations according to their association with convective and stratiform radar echoes.

Most flashes in the second MCS were negative ground strikes within convective radar echoes. In convective regions the flashes were primarily negative; in stratiform regions the negatives were somewhat more than half the flashes. Positive flashes were much less frequent than negative ground strikes for the entire storm. Positive strikes in stratiform echoes during the last half of the storm exceeded the number of negative flashes, but positive ground strikes were always scarce in convective regions. For the second MCS, time series of flashes were developed for flash density, flash rate per rain volume, and number according to radar echo type. Severe weather tended to occur during the growth and mature stages of the storm and was located on the southern and western sides of the MCS's lightning activity. During the growth stage, smaller elements within the new storm had a somewhat linear organization of frequent negative flashes in convective echoes. During the mature stage, negative flashes were in a large cluster, their rates peaked, and then began to decrease. During the decay stage, negative flash rates rapidly decreased but continued to cluster in convective regions. At most, a few percent of the flashes in convective regions lowered positive charge to ground, and positive flash rates in convective regions followed trends very similar to those of negative flash rates. Positive flash rates in the stratiform region, however, tended to increase until early in the decay stage. In the stratiform region during the decay stage, positive flashes were spread over a much larger area than negative flashes.

1. Introduction

Mesoscale convective systems (MCSs) are prolific producers of lightning flashes. The major features of the distributions of cloud-to-ground lightning (CG) flashes in such storms have been identified in studies by Goodman and MacGorman (1986), Rutledge and MacGorman (1988), and Keighton et al. (1991). The significance of several factors that influence the production of frequent flashes in the stratiform region is also being studied (e.g., Rutledge et al. 1990; Marshall and Rust 1991; Schuur et al. 1991; Hunter et al. 1992).

However, few MCSs have been analyzed in detail over most of their areal extent and life cycle with ground-strike network data. The Oklahoma–Kansas Preliminary Regional Experiment for STORM-Central (PRE-STORM) field program was specifically designed to examine MCSs; four such systems passed over the lightning detection and radar networks in one 24-h period. In addition to temporal and spatial tracking of cloud-to-ground lightning, precipitation volume was calculated with data from the radar network for the entire lifetime of the second MCS (hereafter MCS II). This paper documents cloud-to-ground electrical activity through the life cycle of this MCS and compares flashes in the MCS with rainfall and attendant severe weather, according to whether the lightning activity is associated with convective or stratiform radar echoes.

The number of CG flashes that occurred each hour is large enough to determine meaningful trends in characteristic stages that develop coherently through the storm's history; these trends are often less organized in

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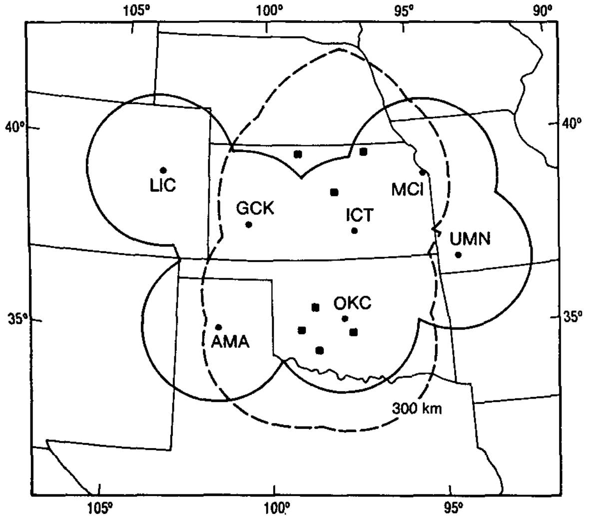

FIG. 1. Analysis area for the four MCSs on 3–5 June 1985. Squares indicate locations of seven DFs detecting CG flashes; dashed line encloses 300-km range from two or more direction finders, where a 65%–80% detection efficiency applies. Circles and three-letter identifiers locate seven NWS digitized radars used in study; circle segments indicate 232-km (125 n mi) range from any radar.

smaller storms. Life cycles of the number and percent of negative and positive CG flashes are shown, as well as of flash density and rain volume per flash. These appear to be the first quantitative data on flash activity related to the convective mode of a large storm through time.

2. Data

The PRE-STORM field program (Cunning 1986) was held during May and June 1985. Figure 1 shows where data were recorded simultaneously from CG lightning sensors and radars.

The CG flashes were detected by a network of four direction finders (DF) in Oklahoma and three in Kansas. The DFs were manufactured by Lightning Location and Protection, Inc. Positions were determined within a 300-km range of two or more DFs using the optimization method of MacGorman and Nielsen (1991). A small number of flashes were missed on the outer edges of the detection network due to attenuation of the signal with range (López et al. 1991a; López et al. 1992). However, MCS II was especially well located with respect to the lightning detection network: flashes started in the southwest portion of the analysis region as the MCS entered the area of network coverage and dissipated in the stratiform region toward the northeast as it left the region of coverage.

Radar data were digitized and recorded at seven National Weather Service (NWS) sites within the region of Fig. 1. Data within 232 km (125 n mi) of each radar were collected with typical elevation angles near 0.5°. For MCS II, the precipitation amount (based on the reflectivity) and area was specified by time and convective mode from these NWS radar data. Areas of convective and stratiform echoes were determined at 30-min intervals. To determine convective mode, anomalous propagation and ground clutter were first removed from the radar data. Subsequently, a somewhat simplified version of the method by Cheng and Houze (1979) was used; Table 1 in Watson et al. (1988) shows its application in a flow chart. With this method, convective echoes were identified as areas with strong and rapidly fluctuating cores, strong reflectivity gradients, and/or echoes with areas less than 1000 km^2 at the radar map time. All remaining echoes were considered stratiform. Rain rates (mm h^{-1}) were calculated from digitized radar data. The Marshall–Palmer relationship of $Z = 200R^{1.6}$ was used; this relationship is considered by the NWS to give reasonable rainfall rates in these types of storms in this region and time of year, as mentioned in Watson et al. (1988). Finally, rain amounts were determined by multiplying the rain rates and areas by the 30-min increments.

Severe weather reports were taken from the monthly publication *Storm Data* produced by the National Oceanic and Atmospheric Administration's (NOAA) National Environmental Satellite Data and Information Service in Asheville, North Carolina, and from the storm log compiled at the National Severe Storms Forecast Center in Kansas City, Missouri.

Life cycles of the MCSs were divided into segments with the method of McAnelly and Cotton (1989). This method follows the satellite-derived stages (using the −52°C contour) of the MCS life cycle, from the first small storms that combined to form MCS II through maturity to dissipation.

3. General features of the 3–4 June 1985 MCSs

On 3–4 June 1985, a series of four MCSs formed in succession in the vicinity of west Texas and moved

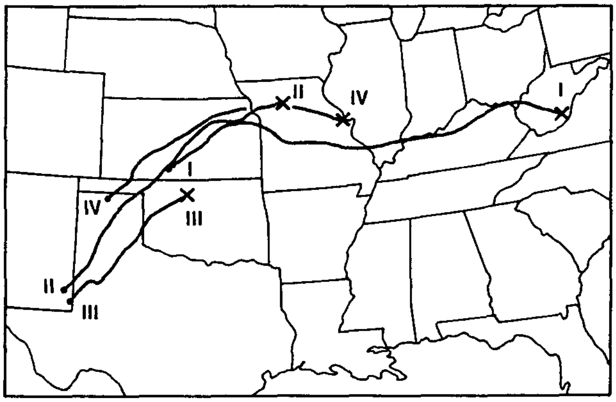

FIG. 2. Tracks of the −52°C centroid of the cloud tops, based on GOES digital satellite infrared imagery for the four PRE-STORM MCSs on 3–5 June 1985. Circles indicate points of origin; crosses indicate points of termination of the areas of −52°C imagery larger than 10 000 km^2.

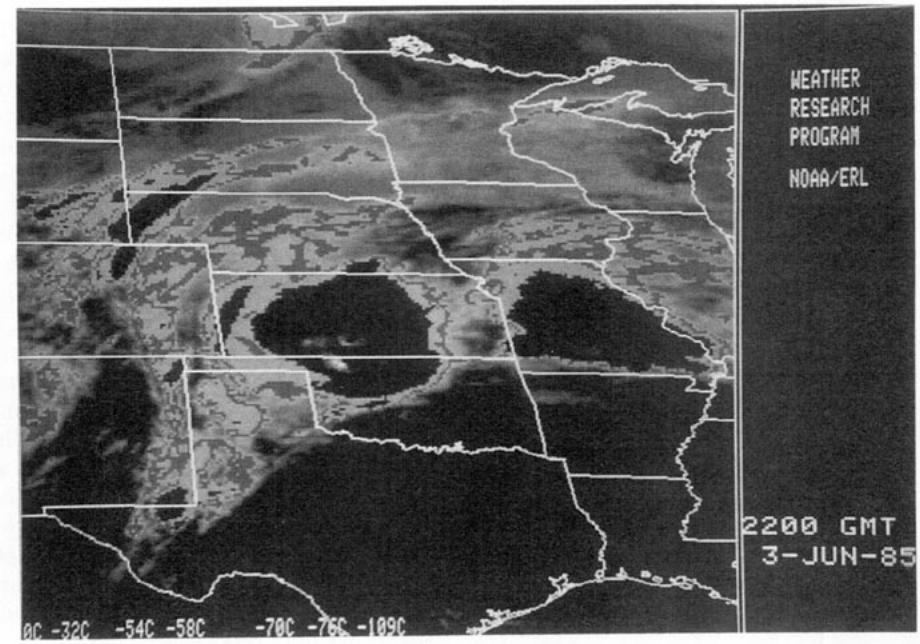

FIG. 3. Infrared satellite imagery at 2200 UTC 3 June 1985. MCS I is in mature-to-dissipating stage east of the PRE-STORM network over Missouri. MCS II is in rapid-growth stage directly over the network. Dark gray encloses area of −54°C; an MB curve is used in this enhancement.

northeast (Fig. 2). Figures 3 and 4 show satellite views of these storms. Three of the systems were approximately the same size; MCS III was the smallest and is shown in Fig. 4 as it started to merge with MCS IV. MCS II had "diverse" internal convective organization (according to Smull and Augustine 1993) during its development stage, whereas the other three had disorganized "chaotic" convection as identified by Blan-

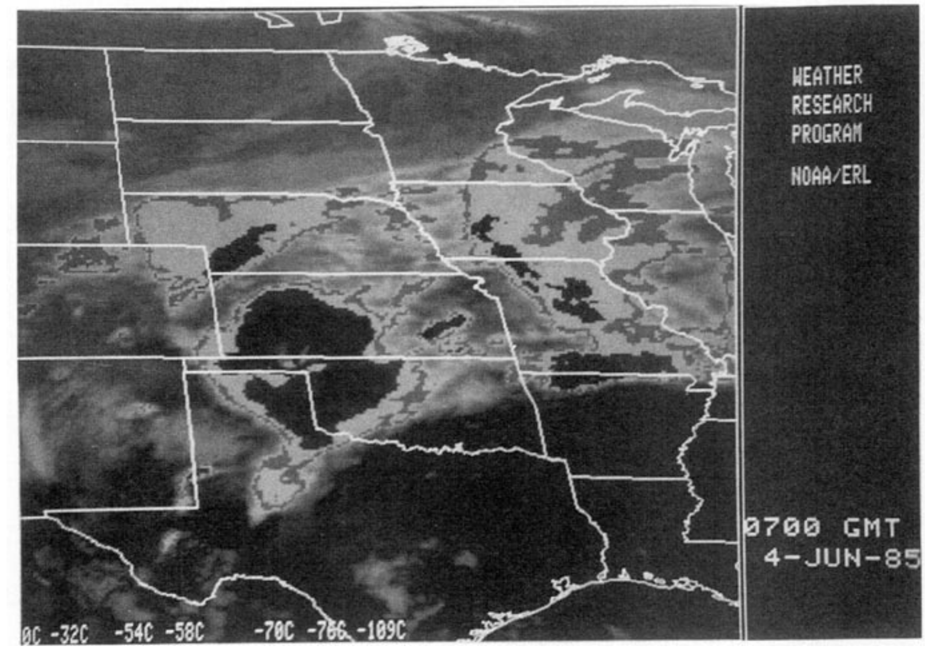

FIG. 4. As in Fig. 3 but for 0700 UTC 4 June 1985. Remnants of MCS II are east of the PRE-STORM network. MCS III is contiguous to and south of MCS IV on the west side of the network. A separate (smaller) MCS is over western Nebraska.

TABLE 1. Meteorological parameters during the four MCSs on 3–4 June 1985 in PRE-STORM area.

MCS	I	II	III	IV	All
Flashes	5635	7011	2178	8666	23 490
Radar rain volume (10^6 m^3)	1986	5449	735	4504	12 674
Severe weather events	0	10	0	2	12

chard (1990). About one-half of the life cycles of MCSs I and III were in the joint lightning-radar analysis area, nearly all of II was in the region, and most of IV was monitored in this area. Data for this study are only for the portion of the storms' evolution within the joint lightning–radar analysis region (Fig. 1). The MCSs had large temporal and areal extents; during the 25 h from 3 June at 1400 UTC to 4 June at 1500 UTC, thunder was heard at three observation stations in the region for 9 h or more, and precipitation was observed at four stations for 9 h or more.

Table 1 provides the numbers of CG flashes in each storm while in the analysis area of Fig. 1. Table 1 also shows the large rainfall volume measured with base-scan information from each radar. Ten of the 12 severe weather events during the four MCSs were in MCS II.

Table 2 shows that most flashes lowered negative charge to ground (negative CG flashes), and no more than 10% of the ground flashes for each MCS lowered positive charge (positive CG flashes). Convective echoes tended to have almost exclusively negative flashes (Table 3), whereas up to one-third of flashes in stratiform regions were positive. For all four MCSs, 13% of the flashes were in stratiform echoes. For comparison, 30% of the rainfall was reported by Cheng and Houze (1979) to fall in stratiform rainfall regions in the tropics; 35% of the precipitation fell in stratiform regions in this storm (next section).

Because MCS II produced frequent flashes, was mostly in the analysis region during its lifetime, and had most of the severe weather reports for the four MCSs, it was chosen for more extensive study. MCS II is also featured in Augustine and Howard (1988), where areal time histories detected by satellite at several temperature thresholds are shown, as are sample radar and satellite views. The same MCS is also the subject of detailed analyses of the precipitation patterns (Leary and Bals 1990) and of the stratiform region (Stumpf et al. 1991; Smull and Augustine 1993).

4. Variations with time for MCS II

The series of four MCSs on 3–4 June in Figs. 3 and 4 formed in succession at approximately 6-h intervals during both day and night. Although MCSs are considered principally nocturnal phenomena, MCS II had 88% of its flashes during the day and 12% at night. The ratio of positive to total flashes was 2% during the day and 6% after sunset.

a. Whole-storm trends

Time series plots of lightning and severe weather in MCS II are shown in Fig. 5. For the entire system, most flashes in convective areas are negative throughout the system's lifetime (top panel). The flash count peaked in the middle of the storm's life cycle at more than 1000 flashes per hour for 3 h. Flashes in the stratiform areas (second panel from top) are much less frequent. Early in the storm, most stratiform-area flashes are negative, but the percentage that lowered positive charge increases to 30%–40% during the mature stage, and increases to approximately 50% during the dissipating stage. Combining information in these upper two panels into the third panel from the top, late in the storm more than 50% are positive in stratiform areas, whereas positive flashes in the convective regions stay below 10% throughout the storm. Orville et al. (1988), Rutledge and MacGorman (1988), and López et al. (1990) also reported a higher ratio of positive CG flashes later in the life cycle of large convective systems. Severe weather reports (bottom panel) tend to occur during the period of rapid growth of the negative flash count and the convective system itself, consistent with trends reported by Maddox et al. (1986) and Cunning (1986).

Additional information about the life cycle of MCS II is indicated by echo area and rain volume (Fig. 6), determined from digitized radar data within the region jointly observed by lightning and radar instrumentation (Fig. 1). Convective and stratiform echo areas are roughly equal during the first half of the system's lifetime (upper panel of Fig. 6). Afterward, stratiform areas grow substantially and become up to an order of magnitude larger than the convective echo areas toward the end of MCS II. These temporal variations in area are similar to those for the MCS during the Severe Environmental Storms and Mesoscale Experiment (SESAME) described by Watson et al. (1988).

Rainfall production (lower panel, Fig. 6) is dominated by convective echoes during the first half of the

TABLE 2. Numbers of flashes and percentages by polarity of the four MCSs.

MCS	I	II	III	IV	All
Flashes (number)	5635	7011	2178	8666	23 490
Negative	5466/97%	6319/90%	2048/94%	8339/96%	22 172/94%
Positive	169/3%	692/10%	130/6%	327/4%	1318/6%

TABLE 3. Distribution of flashes according to convective mode measured by radar echoes.

MCS	I	II	III	IV	All
Convective mode	4918/87%	6007/86%	1950/90%	7469/86%	20 344/87%
Negative	99%	94%	96%	99%	97%
Positive	1%	6%	4%	1%	3%
Stratiform mode	717/13%	1004/14%	228/10%	1197/14%	3146/13%
Negative	82%	66%	81%	80%	76%
Positive	18%	34%	19%	20%	24%

storm. Stratiform precipitation increases more rapidly during the second half of MCS II and eventually surpasses convective rainfall. These trends by convective mode are quite similar to those described in Watson et al. (1988).

Although the emphasis of this study concerning precipitation is on time changes of rain volume related to lightning, and not on absolute amounts of rainfall, some comparisons can be made to other datasets. The total rain volume in MCS II calculated with radar data for this study is 5.4 km^3; the volume was 3.5 km^3 in the convective region and 1.9 km^3 in the stratiform area. This amount is more than the total rain volume of 2.0 km^3 found from raingage data in the monthly NOAA publication *Hourly Precipitation Data* by Zhong and Tollerud (1989) for MCS II. The difference may be due to beam filling and propagation effects of radars, as well as to the continuous nature of radar reflectivity compared to unevenly distributed point values of gauge measurements, which can miss maxima in heavy convective precipitation. Also, the Marshall–Palmer Z–R relation used here may not be appropriate during all portions of the MCS life cycle. In summary, much more

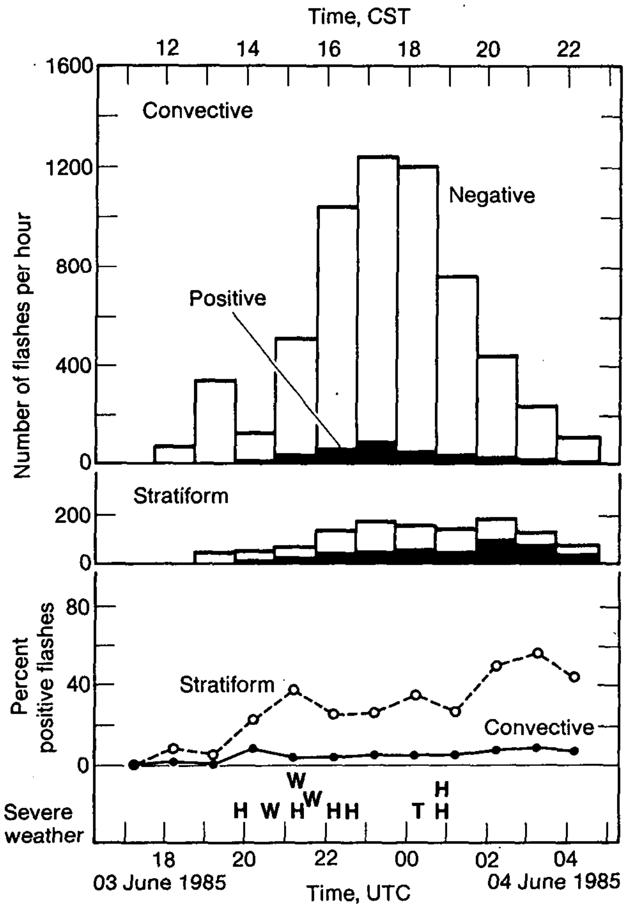

FIG. 5. Time series for MCS II of lightning in convective echoes (top panel), stratiform echoes (second from top), percent positive flashes (third from top), and severe weather parameters (bottom panel). Severe weather events are H—hail, W—wind, and T—tornado.

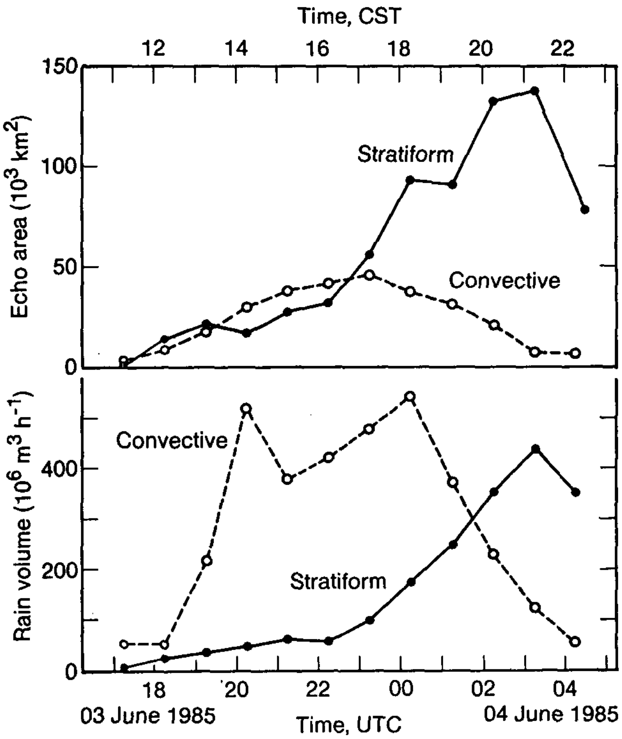

FIG. 6. Time series for MCS II of echo area (10^3 km^2, top panel) and rain volume (10^6 m^3 h^{-1}, bottom panel) in convective and stratiform echoes. Values are averaged over three 30-min intervals; the first hour's values are shown by thinner lines to indicate small sample sizes.

precipitation was produced in convective portions of this MCS than in the stratiform areas, especially during the growth stage.

b. Flashes relative to precipitation

Figure 7 shows areal flash density in the number of flashes per radar echo area above 18 dB*Z* through the storm life cycle. The flash density for the entire storm is three flashes per 100 km^2 of echo for locations that had an echo at any time during the storm's life cycle. There is a much higher frequency of negative flashes per echo area in convective echoes than for either polarity in stratiform areas throughout the life of MCS II. However, although the density is low, the stratiform region is large enough during the mature and decay stages that the total number of flashes in stratiform areas is no longer minimal.

Figure 8 shows CG flashes per rainfall volume. Unlike the areal flash densities in Fig. 7, stratiform and convective regions have roughly equal numbers of negative flashes per rainfall volume for most of the first half of MCS II. Furthermore, during the mature and decay stages, there is a relatively steady amount of negative flashes per rainfall production in convective echoes.

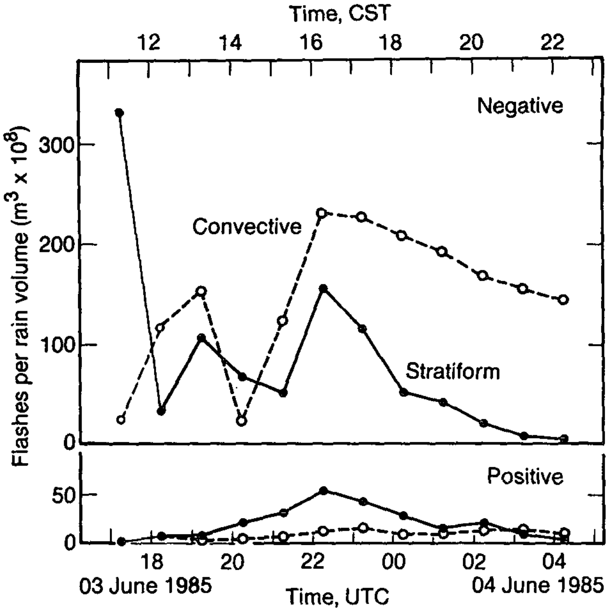

FIG. 8. Time series for MCS II of negative and positive flashes per rain volume (10^8 m^3) in convective and stratiform echoes.

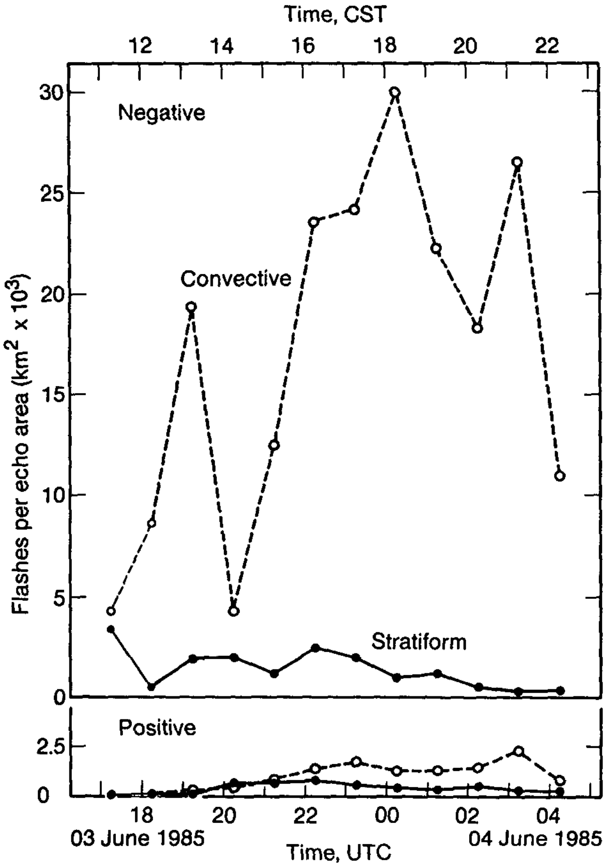

FIG. 7. Time series for MCS II of negative and positive flashes per echo area (10^3 km^2) above 18 dB*Z* in convective and stratiform echoes.

For positive flashes, in contrast, there is a greater frequency of flashes per precipitation volume in stratiform echoes than convective regions. Although in the convective region the number of positive flashes per rainfall volume is much smaller than the number of negative flashes per rain volume, in the stratiform areas the values are sometimes comparable for positive and negative flashes.

The MCS II total-storm value of 1.3 flashes per 10^6 m^3 can be compared with values from other studies. Buechler et al. (1990) found 0.1 flashes per 10^6 m^3 in the largest storm during the Cooperative Huntsville Meteorological Experiment (COHMEX) in the southeast United States, an order of magnitude larger than MCS II. Williams et al. (1992) determined a maximum value of 1 flash per 10^6 m^3 for a day during a continental meteorological regime over northern Australia. López et al. (1991b) calculated up to 1 flash per 10^6 m^3 for 1 h over central Florida. But, there is a variation of two to three orders of magnitude among the individual storms published in these Florida and Australia results. Major variations could depend on types of storms and synoptic situations. Higher variability and lower ratios of flashes per rain volume could also be expected to occur from low-level radar measurements in arid locations, since rainfall evaporation varies from day to day.

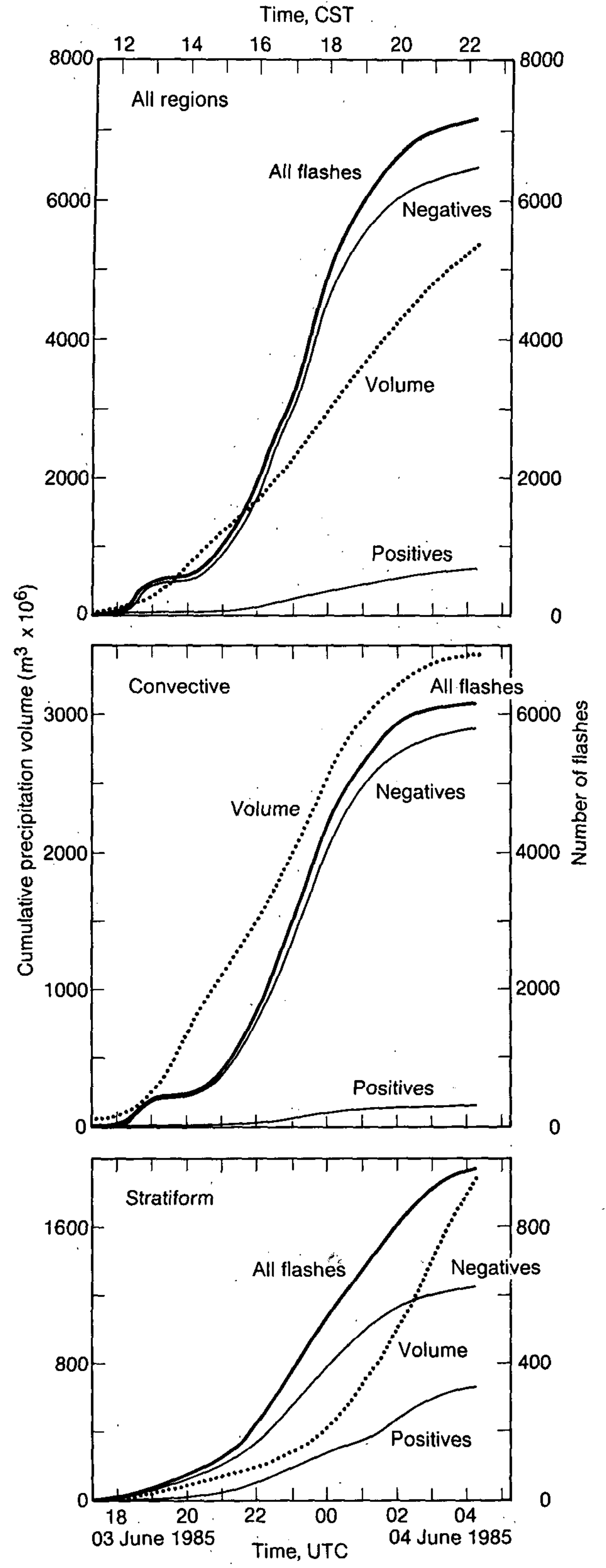

FIG. 9. Cumulative totals for MCS II of precipitation volume (10^6 m^3), and positive and negative flashes for all regions (top panel), in convective (middle panel) and stratiform echoes (lower panel). Note changes in scale between panels.

c. Cumulative variations

The cumulative variability of total storm rain volume and lightning flashes (Fig. 9) was calculated to determine whether lightning trends through the lifetime of MCS II are similar to trends in radar-measured precipitation. As shown in the top panel, rain volume and negative flashes increase similarly through the storm's lifetime, but positive flashes show a much weaker increase with time. In convective echo regions (middle panel), the precipitation and negative-flash curves have nearly identical shapes, but again there is almost no positive flash contribution (note change in volume scale). In stratiform regions (lower panel), the associated rain volume is smaller (note change in scales), and positive flashes have a more significant role.

5. Spatial patterns of flashes and severe weather in MCS II

The left panels of Figs. 10–13 show the number, location, and polarity of flashes, as well as the locations and types of severe weather in convective-echo regions. The right panels show the same flash and severe weather properties in stratiform regions. To contrast the horizontal maps according to the stage of the life cycle of the storm, MCS II was divided into the following stages with the convention used by McAnelly and Cotton (1989):

- Growth: 1700–2230 UTC 3 June.
- Mature: 2300 UTC 3 June–0130 UTC 4 June.
- Decay: 0200–0430 UTC 4 June.

a. Total storm

Figure 10 shows the distribution of CG flashes throughout the life cycle of MCS II in the analysis area. The dominant feature is the large grouping of negative flashes in convective echoes over northern Oklahoma and Kansas. Several locations have 30 or more flashes over an area of 156 km^2. Negative flashes in convective echoes are much more common than negative ground strikes in stratiform regions. Positive flashes are concentrated in the same convective regions as negative flashes and are more widely dispersed in stratiform areas. The 10 cases of severe weather are concentrated along the southern and western sides of the region traversed by the MCS.

The peak density of more than 50 flashes per grid square of 156 km^2 for the whole MCS in Fig. 10 equals about one-third flash per square kilometer. Such a frequency from one storm is a significant portion of the flash density of two to four flashes per square kilometer reported for this region during all of 1989 by Orville (1991). Therefore, the passage of several strong MCSs across the same region can produce a substantial portion of the year's lightning in that location.

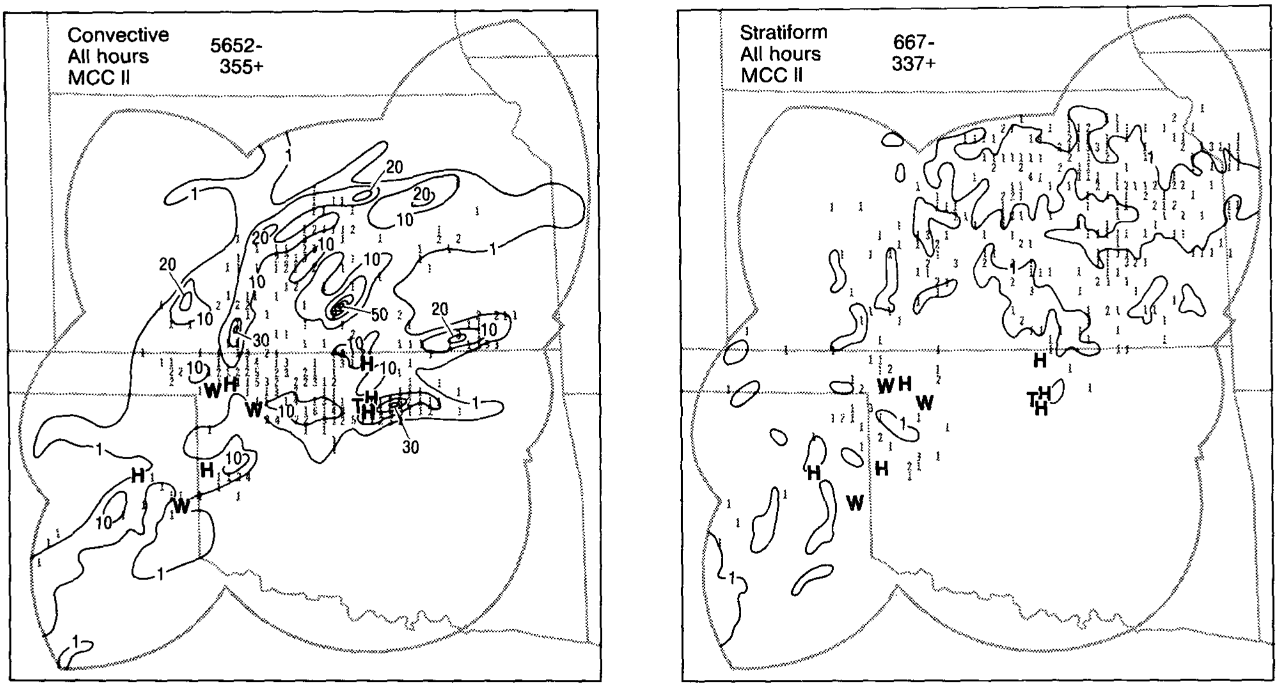

FIG. 10. Horizontal maps of CG lightning flashes during the entire life cycle of MCS II in convective echoes (left panel) and stratiform echoes (right panel). Contours show negative flash density per grid square of 12.5 km × 12.5 km (156 km^2); outermost (minimum) contour is one flash per square kilometer for negative CG flashes. Positive flashes plotted in numbers per grid square. Severe weather events indicated by H—hail, W—wind, and T—tornado.

b. Growth

The storm formed over the Texas Panhandle and then moved into western Oklahoma and Kansas; Fig. 11 shows all flashes during the growth stage. Negative flashes during the growth stage are over a large area. Some negative flashes are in smaller groups in a somewhat linear organization that is similar to the rainfall pattern during an MCS life cycle shown by Fritsch et al. (1981); the original half-hourly lightning maps show clear linear organization. Nearly all CG flashes during the growth stage are negative and occurred in convective echoes; a similar pattern occurred in MCS IV (not shown). Lightning during the formative stage of an MCS over Colorado investigated by López et al. (1990) also showed negative flashes at this stage. The hail report in northern Oklahoma occurred at the end of the growth stage and associates better with flashes in the mature stage (next figure). Otherwise, most severe weather reports are close to peaks in negative flash density in convective regions and are located on the south and west sides of the MCS.

c. Mature

Cloud-to-ground flashes in MCS II (Fig. 12) are clustered in a large group associated with convective echoes over northern Oklahoma to central Kansas. They are very frequent and continue to consist primarily of negative flashes. Stumpf et al. (1991) found the storm to be well organized at this time, containing two primary intersecting convective bands. Both negative and positive flashes are more frequent in stratiform regions than during the growth stage. A few severe weather events are found in northern Oklahoma, again on the south side of the convective area.

d. Decay

A few groups of negative flashes with somewhat linear structure are located in convective regions during the decay stage (Fig. 13). A more widespread region of stratiform flashes of both polarities was over eastern Kansas. There were no severe weather reports during the decay stage.

6. Summary and conclusions

This observational study analyzed cloud-to-ground lightning characteristics in four MCSs. Coverage by the lightning mapping system encompassed enough of the life cycle of one of the MCSs (MCS II) that it was possible to examine lightning trends during the system's evolution.

The life cycle of MCS II showed rapid growth in the number of flashes until the peak frequency was reached a few hours after storm initiation. As the storm matured, the fraction of positive flashes increased. As the

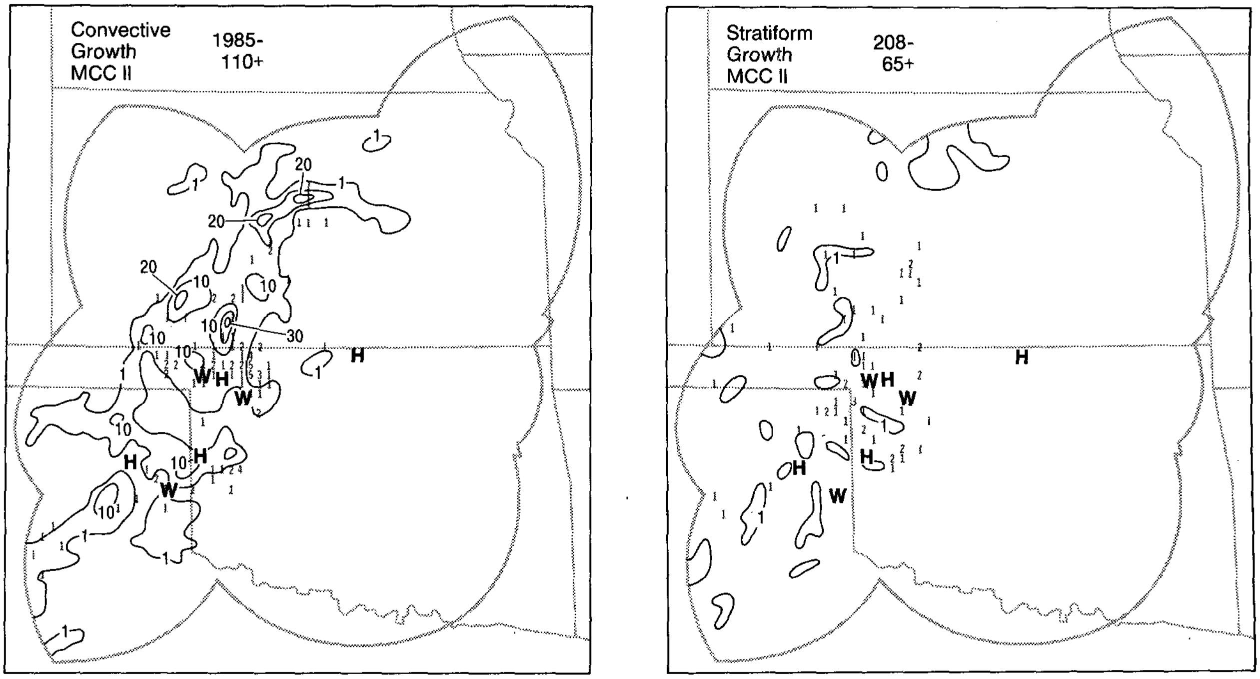

FIG. 11. Same as Fig. 10 but for growth stage from 1700 to 2230 UTC 3 June.

storm reached the decay phase, negative flashes decreased rapidly and positive ground strikes exceeded 60% in stratiform echo areas.

There were more flashes per convective echo area throughout the lifetime of the storm than per stratiform echo area, and more negative than positive flashes per echo area. Flashes per rain volume were largest for negative flashes, especially in convective regions.

The maps of flashes also showed differences in organization according to the stage of the life cycle of

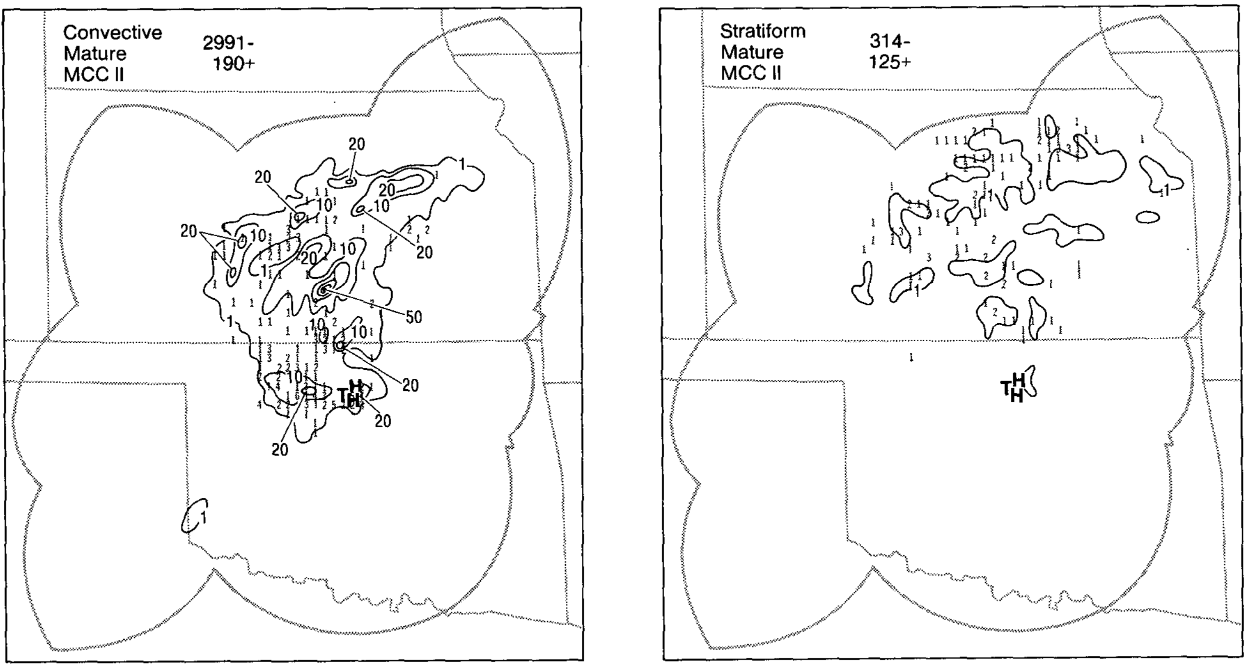

FIG. 12. Same as Fig. 10 but for mature stage from 2300 UTC 3 June to 0130 UTC 4 June.

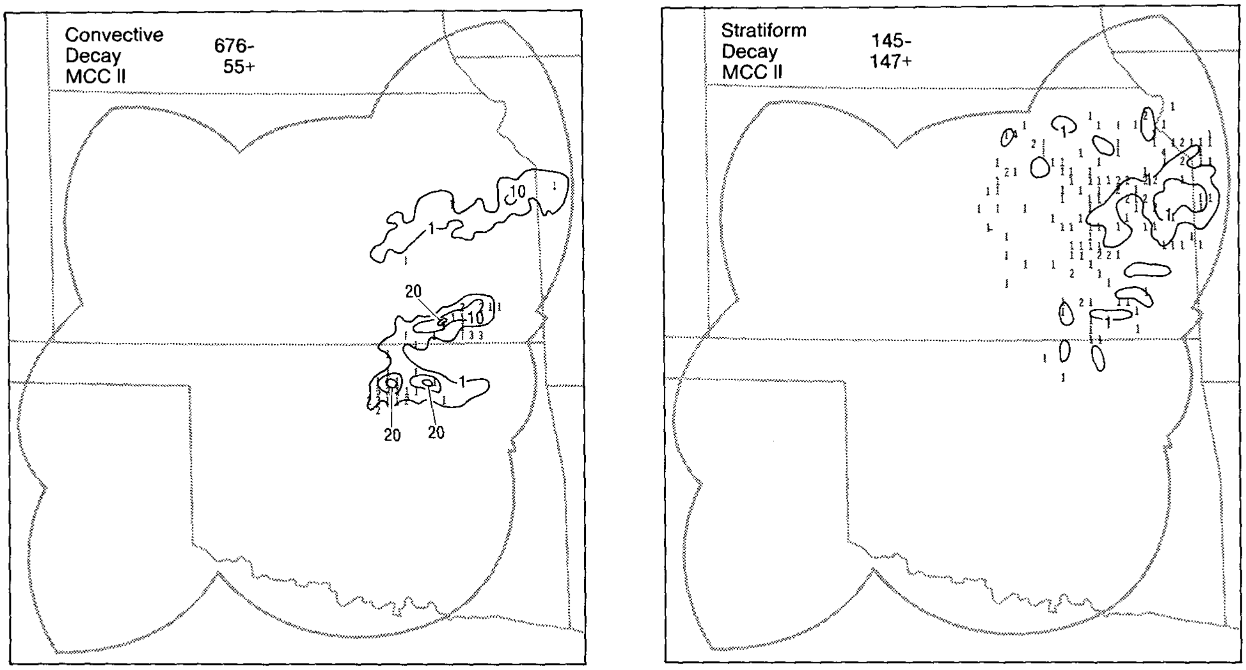

FIG. 13. Same as Fig. 10 but for decay stage from 0200 to 0430 UTC 4 June.

the storm. During the *growth* stage, the large new storm area had negative flashes in smaller elements of convective echoes arranged in a somewhat linear organization; severe weather tended to occur on the south and west sides near the groups of negative flashes associated with convective echoes. During the *mature* stage, flashes were tightly grouped on a large scale, and more positive flashes occurred; some severe weather occurred on the south side of the flash concentration. During the *decay* stage, there continued to be more negative than positive flashes; positive cloud-to-ground flashes were associated most often with stratiform echoes and were spread over a wider area than the negative flashes.

It is plausible that lightning data are valuable for diagnosis of the temporal and spatial variability of large convective systems. This diagnostic value is particularly important when lightning mapping systems can provide data in real time on the embedded convection for whole MCSs that span the coverage of several radars. For CG flashes to be most useful as a diagnostic tool, however, further documentation of their behavior in MCSs is needed to develop the requisite descriptive models. This documentation should include radar data, satellite imagery of MCSs, CG lightning data, and in situ electric field measurements. The installation of nationwide lightning-strike mapping networks in recent years has made possible more complete documentation of the interesting ground-flash trends in MCSs, as shown in this study, than has been available to date.

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