Cloud-to-Ground Lightning Activity in Mesoscale Convective Complexes

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(Manuscript received 25 November 1985, in final form 8 May 1986)

ABSTRACT

A study of cloud-to-ground lightning activity attending an important subclass of mesoscale convective weather systems called the mesoscale convective complex shows that groun discharge flash rates in excess of 1000 h^{-1} can be sustained on average for more than nine consecutive hours with peak rates of nearly 2700 h^{-1}. Peak rates, averaged over 5 minute intervals, of 60 min^{-1} are not uncommon and average 42 min^{-1} for the MCCs analyzed. These rates are comparable to the highest observed rates within other mesoscale storm systems, four times those observed in severe or multicell storms in Florida, and greater than 20 times the rates previously observed in isolated thunderstorms. Peak ground strike densities for individual cells within the MCC of 0.09 strikes km^{-2} min^{-1} are comparable to the observed values of Florida storms. However, a single MCC can produce one-fourth of the mean annual lightning strikes to ground at any site it passes over during the most intense phase of its life cycle. Lightning damage occurs with half of the MCCs and is most frequent between the development and mature phases (the most electrically active period) of the MCC life cycle. The most active period is also characterized by the greatest average number of discrete strokes (3–4 component strokes per flash) and largest fraction of multiple stroke discharges, while the fewest multiple stroke discharges occur during the first hour of MCC development. The lightning activity appears to be independent of the size of the total storm system cloud shield at maximum extent and MCC life-cycle duration. The peak flashing rates can vary by a factor of two or more in basically similar, convectively unstable, synoptic environments.

1. Introduction

Mesoscale convective systems (MCS) are of great scientific interest to meteorologists because they are responsible for much of the beneficial precipitation and most of the severe weather (heavy rains, flash floods, high winds, hail, tornadoes, and lightning) that occur in the United States in the spring and summer months (Maddox, 1980). MCSs can be described as meso-α scale weather systems (Orlanski, 1975) having horizontal length scales of 250–2500 km and time scales in excess of a few hours, and including significant convection during some part of their life cycle. Some examples of MCSs include squall lines, tropical cyclones, hurricanes, cloud clusters, and the large mesoscale convective complexes (MCC) discussed in this paper. Squall lines, active thunderstorm cells organized in lines or bands that usually persist for 3–5 h, may also be imbedded within the much larger MCC. These weather systems can be further classified according to their physical characteristics, organization (linear or circular), and geographical occurrence (tropics or midlatitudes).

The definition of the MCC in Table 1 is based on the circular appearance, duration, and size of the weather system cloud shield in GOES infrared satellite images. The temperature and duration criteria are used to guarantee that active storms are embedded within a persistent cloud complex producing widespread precipitation. The MCC cloud shield is more than two orders of magnitude greater than the cloud shield extent of an individual thunderstorm cell. The cold cloud shield of the mature MCC also suggests a more concentrated area of meso-α scale vertical motion in the middle and upper troposphere than is suggested by the chaotic cloud shield structure of cloud clusters (Maddox, 1980). In addition, the size and shape criteria serve to separate the MCC weather system from classical prefrontal squall lines and large, long-lived single cell thunderstorms or supercells. However, the organized precipitation patterns of many MCCs suggest some similarity with the spatial distribution of the deep convective cells and stratiform rain areas in squall lines (Zipser, 1982). The internal structures of these long-lived MCSs and the role of convection in their formation and persistence is considered so fundamental for understanding the behavior of the atmosphere that the research goals of a proposed major national field program are focused toward the study of MCSs (the National STORM Program, 1984).

Many of the measurements of lightning activity in MCSs have been made with radio frequency (rf) di-

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TABLE 1. Mesoscale convective complex (MCC) definition (based upon analyses of enhanced IR satellite imagery).

Size	A—Cloud shield with continuously low IR temperature $\leq -32°C$ must have an area $\geq 100\,000$ km^2 B—Interior cold cloud region with temperature $\leq -52°C$ must have an area $\geq 50\,000$ km^2
Initiate	Size definitions A and B are first satisfied
Duration	Size definitions A and B must be met for a period ≥ 6 h
Maximum extent	Contiguous cold cloud shield IR temperature $\leq -32°C$ reaches maximum size
Shape	Eccentricity (minor axis/major axis) ≥ 0.7 at time of maximum extent
Terminate	Size definitions A and B no longer satisfied

rection finding systems. Johnson et al. (1980) and Johnson and Goodman (1984) used 2 MHz radio interferometers with an effective range of 2000 km to observe the evolution of lightning activity associated with hurricanes in the Gulf of Mexico and midlatitude severe thunderstorms. They show peak electrical activity associated with hurricanes Bob (July 1979) and Alicia (August 1983) occurring in conjunction with their minimum barometric pressure and maximum sustained wind speed. In addition, sferics rates from Hurricane Alicia exceeded 1000 h^{-1} for at least 5 consecutive hours beginning 1 h prior to landfall. Johnson et al. (1980) also present a few limited snapshots of lightning activity in midlatitude MCCs, but they do not provide any characterization of lightning activity throughout the MCC life cycle. Instead, their study concentrates only on correlations between severe weather occurrence and the detection of rf emissions produced by lightning discharges.

More recent remote sensing studies of only the cloud-to-ground lightning in MCSs, based on data from a network of lightning detection and location systems, suggest that the spatial density and frequency of these discharges are closely related to the intensity and organization of the individual thunderstorms embedded within the MCS (Goodman, 1983; Goodman et al., 1984). Thunderstorm cells obscured from satellite detection by cirrus overcast are also readily identifiable with the lightning data. Indeed, significant lightning damage occurs with about half of the MCCs in the central United States (see Rodgers et al., 1985).

Lightning may very well play an important, yet undocumented, role in the MCS life cycle. In this paper we present an analysis of lightning discharges to ground in the framework of the MCC life cycle to improve our understanding of the relationships between the physics and life cycle of convective storm systems and their environment.

2. Instrumentation and data

The lightning discharge data are acquired by a commercially available lightning detection and location system manufactured by Lightning Location and Protection, Inc. The system referred to in this paper is owned and operated by the National Severe Storms Laboratory (NSSL) located in Norman, Oklahoma. Four magnetic field direction finders (DF) using crossed loop antennas and waveform signal processing determine the angle of arrival and polarity of the cloud-to-ground lightning signal source (Krider et al., 1976). The detection efficiency of this network, based on a few case studies, has been determined to be 70% for lightning flashes within 350 km (Mach et al., 1986). Random errors on the order of one degree at each of the DF sites (having approximately 100 km baselines) produce triangulation errors on the order of 20–30 km at the outer edge of the network (Fig. 1). Systematic errors in azimuth measurements (also referred to as site errors) are not uncommon with magnetic direction-finding techniques. These errors have been removed from the data using a redundant data technique described by Mach et al. (1986).

Potential data sets were identified from all possible 1981–83 MCCs that might have been sampled during at least one of their four major life-cycle phases by the NSSL lightning network. The four periods (see Table 1) are 1) first storm development (F), 2) initiation (I), 3) maximum extent (M), and 4) termination (T). One in five MCCs that occurred in the United States between 1981 and 1983 passed through the NSSL network. However, only 5 of 14 MCCs occurring in 1982–83 spent their entire life cycle within the 70% detection efficiency region. Incomplete data result because of a seasonal (spring only) operational period in 1981, data gaps during tape changes, and miscellaneous hardware problems. Lightning activity in only 10 MCCs could be ultimately analyzed in detail because of data availability and quality. The tracks of the MCC centroids are depicted in Fig. 2.

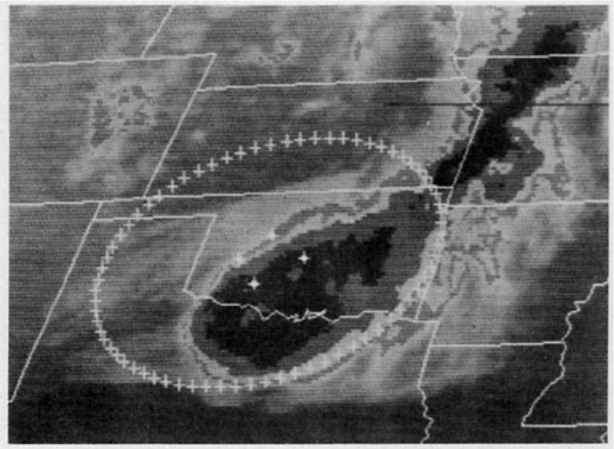

FIG. 1. NSSL lightning network shown in a satellite projection with the infrared image of the 13–14 June 1983 MCC during its mature phase (maximum cloud shield extent). The four direction finders and the 350 km range ring are denoted by crosses.

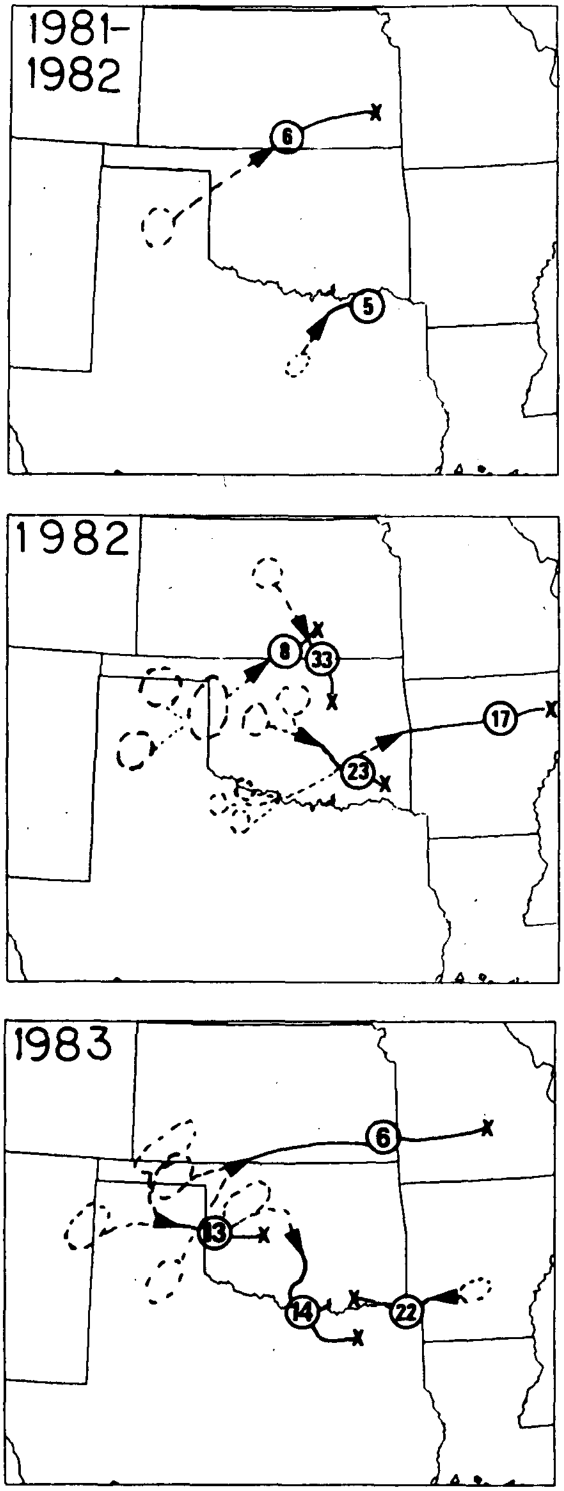

FIG. 2. Tracks of the centroid of the infrared cloud shield of 1981, 1982, and 1983 MCCs. Dashed areas and lines indicate regions and movements of initial thunderstorm developments; arrows indicate positions where systems reach MCC "initiate" proportions; circles show positions of systems at "maximum extent"; crosses locate systems' positions where they decay below "terminate" size criteria (refer to Maddox, 1980). Numbers in circles correspond to case numbers shown in Tables 2 and 3.

3. Results and discussion

Table 2 presents a summary of the 10 MCCs that moved through the NSSL lightning network. Following the convention of Merritt and Fritsch (1984) for characterizing the MCC environment, 8 of the 10 cases represent synoptic MCCs where the major features are 1) a major 500 mb trough located to the W or NW of a closed low at 500 mb, 2) a slow moving or quasi-stationary synoptic scale cold front oriented SSW–NNE, 3) occurrence to the east of a front in a conditionally unstable environment, 4) diffluence at 200 mb and sometimes at 300 mb, 5) a polar and/or subtropical jet at 300–200 mb, and 6) strong low-level moist southerly flow enhanced by an approaching short-wave trough. The two August cases (MCCs 33, 22) are both mesohigh MCCs characterized by 1) initial storm formation ahead of a cold front or triggered by a mesoboundary that is difficult to detect in synoptic surface analyses, but is often visible in satellite imagery; 2) location near the mean ridge with weak mid- to upper level tropospheric winds; 3) a slow moving mesoscale cold front produced by thunderstorm outflow; 4) moderate to strong moist southerly low level flow often associated with a diurnal low level jet and sometimes associated with an approaching short wave trough; and 5) development of the MCC on the cool side of the mesoscale cold front.

Significant weather reports are from the NOAA publication *Storm Data* and are abbreviated in Table 2 as follows: tornadoes (T), large hail (H), high wind (W), lightning damage (L), heavy rain (R), flash flooding (F), number of people killed (K), and number injured (I). Five of these MCCs are associated with lightning damage reports and all produce severe weather.

The average storm duration varies from 11 to 19.5 h with a mean duration of 14.3 h. This average is within about 1 h of the average duration of the 90 MCCs that occurred in 1981–83 (Rodgers et al., 1985). The average cloud-top area at maximum extent of the MCCs studied is within about 10% of typical maximum areal extents for the 1981–83 MCCs. Thus, our data subset exhibits fairly typical satellite-derived temporal and spatial characteristics for central United States MCCs.

A summary of lightning discharges to ground is given in Table 3. The life-cycle data collection periods in column 2 identify those phases of the MCC when its centroid is located within 350 km of the center of the network. Because of the detection efficiency and errors inherent with sampling these large weather systems (i.e., a cloud shield with infrared temperatures colder than −32°C covering an area greater than 100 000 km^2), when the MCC centroid is within 350 km we assume the lightning detection efficiency is the same in each case. Beyond this range we believe the number of flashes detected and located is seriously undersampled. Note that in only three of the ten cases did the entire MCC life cycle take place within this region.

TABLE 2. Mesoscale convective complex summary.

			Time (GMT)/Date					Cloud-top area at maximum extent $\times 10^3$ km^2		
Year	Case	Date	First storms	Initiate	Maximum extent	Terminate	Duration (h)	$\leqslant -32°C$	$\leqslant -52°C$	Significant weather events
1981	5	8–9 May	2015/08	0115/09	0445/09	1015/09	14.0	267	160	T, H, W
1982	6	11–12 May	1920/11	0600/12	0915/12	1315/12	17.75	210	189	T, H, W, R, F, 3K, 59I
	8	16–17 May	2000/16	0030/17	0430/17	0730/17	11.5	435	242	T, H, W, F
	17	15–16 Jun	1730/15*	0130/16	0530/16	0800/16	14.5	321	193	H, W, L, F
	23	6–7 Jul	2215/06	0530/07	1100/07	1300/07	14.75	279	172	L, F
	33	29–30 Aug	2130/29	0330/30	0600/30	0930/30	12.0	169	74	T, H, W, L, R, F
1983	6′	13–14 May	1800/13	2200/13	0630/14	1000/14	16.0	637	226	T, H, W, L, R, 2K, 11I
	13	11 Jun	0100/11	0530/11	0900/11	1200/11	11.0	165	98	T, H, R, F
	14	13–14 Jun	2030/13	0130/14	0600/14	1600/14	19.5	173	137	T, H, W, L, R, F
	22	12–13 Aug	2000/12	2330/12	0245/13	0800/13	12.0	180	101	W, 1I
		Mean					14.3	284	160	

* Subsequent analysis of the GOES satellite imagery shows that the onset of first storms ($T < -32°C$) occurs 2 h earlier than the time reported by Rogers et al. (1985).

The flashes (or flash rate per hour) occurring at the time of each life cycle phase (column 3) are analyzed on the basis of hourly totals beginning at the top of the hour. For example, for the first storms present at 2015 GMT 8 May 1981 the corresponding flash rate is given as 160 flashes per hour over the time interval 2000–2100 GMT. On average, the hourly flash rate is seven times greater during the MCC initiate phase than during the first storms phase. The peak ground strike density at initiate, however, is more than 40 times the maximum strike density at first storms. The initiate phase is characterized by a rapid growth of the MCC cloud shield in response to the intensification and merger of the embedded convective elements (Maddox, 1980). The great increase in lightning rates between first storms and initiate may be due to a combination of the vigorous vertical motions in severe storms (43% of the severe weather reports occur by the onset of the initiate phase in these ten cases) and the convective scale interactions which enhance the existing low-level convergence and create new boundaries of convergence within the MCC (Maddox, 1980). The enhanced mass convergence is likely to enhance updraft intensities and thus increase the rate of charge separation. The generally lower flash rates at termination are consistent with the dissipation stage of the MCC when the intense convection ceases to develop (Maddox, 1980). Discharge rates may still be high at termination, however, when an active squall line is present (e.g., case 17).

In column 4 we have computed the time rate of change (dL/dt) or trend of flash rates during each lifecycle phase. The time rate of change represents the difference in flash rate between the following and current hour. In virtually every case the flash rates are rapidly increasing during the first storm phase. This trend is often true at the initiate phase as well. By maximum extent the rates are beginning to decrease as the convective precipitation regions are replaced by widespread stratiform precipitation.

Column 5 gives flash accumulations from the time of first storms through the initiate, maximum extent, and termination phase of the MCC life cycle and the percent of the total accumulation for each phase. The total number of ground discharges observed during the MCC life cycle range from 12 000 to 33 000 with an average of 22 316 discharges per MCC. On average, almost one-third of the total flashes occur by initiation and three-fourths by maximum extent. However, the percentages vary from a low of 12% through initiation (case 6′) to a high of 97% through maximum extent (case 23). While only 5.2% of the 134 severe weather reports associated with case 6′ occur between the first storm and MCC initiate phases; all of the severe weather reports for case 23 occur by maximum extent. If we assume the active convective region of the MCC at maximum extent is that area delineated by cloud-top temperatures colder than −52°C, then the strike density of the MCC at maximum extent is on the order of 2×10^{-4} strikes km^{-2} min^{-1}. For those MCCs that produce lightning damage (Table 2), the damage occurs 4–13 h after the first storms with most reports (14 of 17 documented events) between the initiate and maximum extent phases, coinciding with the time when squall lines and most severe weather events are observed.

In columns 6 and 7 we show the peak hourly flash rate and the time it occurs relative to the four phases of the MCC life cycle. The average peak rate is 2679

TABLE 3. Ground discharge summary.

Case	Life-cycle data collection periods	Flashes at time of F	I	M	T	dL/dt (CG/min) at time of F	I	M	T	Flash accumulations (% of total) $\sum_F^I$	$\sum_F^M$	$\sum_F^T$	Peak hourly rate/time	Time (h) of peak relative to F	I	M	T
5	M, T	160	2530	3161	1540	−0.03	7.1	−15.3	−10.3	5375 (19.8)	14565 (53.7)	27146	3161/0400	7.75	2.75	−0.75	−6.25
6	F, I, M	498	—	—	—	3.2	—	—	—	—	—	—	—	—	—	—	—
8	F, I, M, T	599	—	1238	—	—	—	−1.5	—	—	—	—	2023/2300	—	—	—	—
17	F, I	202	2585	1706	539	3.7	−2.6	−2.7	−2.5	18611 (65.0)	25818 (91.0)	28492	3299/2200	4.5	−3.5	−7.5	−10.0
23	F, I, M, T	623	1464	404	186	3.5	2.7	−0.8	−0.3	9371 (54.1)	16817 (97.1)	17313	1830/0400	5.75	−1.5	−7.0	−9.0
33	I, M, T	185	3085	2599	728	2.3	0.1	−1.9	−1.3	9941 (42.6)	18528 (79.4)	23322	3110/0500	7.5	1.5	−1.0	−4.5
6′	F, I	56	865	938	472	1.1	−3.0	−5.4	0.03	2425 (11.9)	17926 (88.1)	20359	2944/0400	10.0	6.0	−2.5	−6.0
13	I, M, T	93	2066	2055	266	—	5.5	−8.7	−0.8	4725 (27.7)	15375 (90.2)	17042	3028/0600	5.0	0.5	−3.0	−6.0
14	F, I, M, T	225	2001	1843	293	3.8	1.0	6.5	−0.9	7891 (24.0)	19057 (58.0)	32832	2852/0900	12.5	7.5	3.0	−7.0
22	M, T	104	786	1626	66	2.7	5.8	0.8	0.6	1965 (16.3)	6939 (57.7)	12022	1864/0100	5.0	1.5	−1.75	−7.0
Averages		275	1923	1730	582	2.5	2.1	−3.2	−1.9	7538 (32.7)	16878 (76.9)	22316	2679/0320	7.3	1.8	−2.6	−7.0

* Data begins at 0138 GMT.

"—" indicates missing or incomplete data.

discharges to ground per hour with four cases having rates in excess of 3000 h^{-1} (50 min^{-1}). The maximum 5 min MCC ground discharge rates during peak activity approach 60 min^{-1} (cases 17, 5, 33, 13). On average, the peak rate occurs more than 7 h after the first storms, 2.6 h prior to maximum cloud shield extent, and 7 h prior to termination. Our peak flash rate occurs at approximately the same time as the minimum cloud-top temperature is observed by McAnelly and Cotton (1985) in their study of MCC life cycles. Maximum reported echo tops for our cases range from 15.5 to 21.3 km.

The most active electrical period (±2 h of the peak ground discharge rate) is also characterized by the greatest average number of discrete strokes (3–4 component strokes to ground) per flash and largest fraction of multiple stroke discharges, while the first hour of MCC storm development contains a greater fraction of single stroke discharges (Fig. 3). On 13 June 1983 (case 14), for example, the average number of strokes per flash increases from 1.55 ± 0.92 strokes per flash at first storms to 3.96 ± 2.74 strokes per flash at the time of the peak flashing rate and decreases to 2.42 ± 1.83 strokes per flash at termination. However, less than 5% of all flashes during storm initiation on 13 June produce more than three component strokes per flash. This percentage increases to 62% of all flashes by maximum extent and then decreases to 35% at termination. Krehbiel (1981) suggests that single stroke discharges occur more often in the developing stages of individual storm cells when the charge distributions in the clouds may be relatively simple compared to the mature and dissipating stages of storms when the multiple stroke discharges to ground tend to be dominant. Brook and Kitagawa (1960) also suggest that the durations of individual flashes may be tied to the intensity or discharge rate of a storm. Since a flash with a greater number of component strokes will have a longer flash duration (Kitagawa and Kobayashi, 1958), the flash durations should also be the greatest during the most intense phase of the MCC life cycle. Livingston and Krider (1978) find their ground flash durations in Florida storms only show a small dependence on the total discharge rate, but their period of maximum flashing rate does produce the longest durations.

A comparison of the peak flashing rate in MCCs (ground discharges only) to other types of storm systems listed in Table 4 shows that the highest total rates (cloud plus ground discharges) occur in both the midlatitudes and subtropics. The MCC produces maximum ground discharge rates of 54 min^{-1} averaged over 1 h or 60 min^{-1} averaged over only a 5 minute interval. The ratio of ground discharges in MCCs to the Florida storm clusters (Peckham and Uman, 1984) is approximately 4:1. This Florida study used an earlier version of the instrumentation used in our present study. We do not believe meaningful contrasts can be made between MCCs and Kinzer's (1974) squall line results

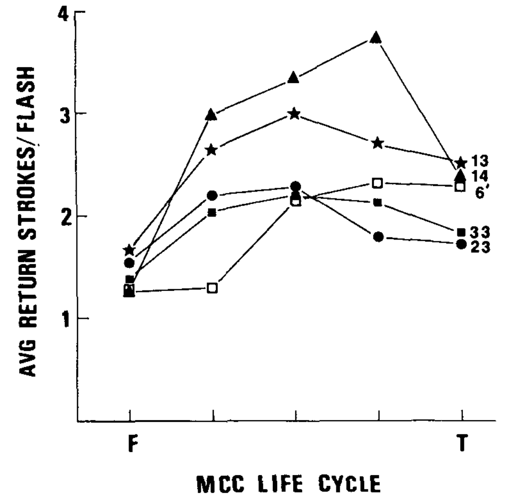

FIG. 3. The average number of strokes per flash are shown as a function of the MCC life cycle for five of the cases listed in Table 3. The three intermediate points between F and T represent the values at I, M and peak, where the peak can occur before I, between I and M, or after M.

because three of our cases (13, 14, 17) show radar and satellite images that are more suggestive of classical squall lines than of MCCs.

Comparisons with the other studies in Table 4 require that we know the fraction of ground and cloud discharges in MCCs. Livingston and Krider (1978) observe that the percentage of ground discharges during the active periods of large and small storms range from 42% to 52% of the total, and about 20% during the latter part of the storm life cycle. Other investigators report the percentage of ground discharges can be from 2% in a squall line (Rust et al., 1985) to 79% (Norinder and Knudsen, 1961) of the total lightning activity. Using these values we conservatively estimate that the ratio of the total flashing rate of MCCs to Florida storms is in excess of 20:1. If we assume the 2% value of Rust et al. (1985) is a lower limit for the percentage of ground discharges in a mesoscale weather system (i.e., a squall line), then the peak rate in MCCs could be as high as 3000 min^{-1} (60 min^{-1} divided by 0.02) or an astounding 395 times the average maximum total flash rate given by Piepgrass et al. (1982) and 25 times the maximum value in Table 4 reported by Mackerras (1963). However, this estimate assumes maximum ground discharge rates are coincident with maximum cloud flashing rates. Based on a limited study of isolated storms in New Mexico, Brook and Kitagawa (1960) suggest the cloud and ground discharge rates are related such that the maximum flashing rates of both types of discharges are not necessarily coincident in time.

A comparison between the average flashing rate of MCCs and other storm systems can be obtained by dividing the total number of ground discharges between first storms and terminate (column 5 of Table 3) by the duration of the MCC. These values range from a low of 8.5 min^{-1} for case 7 to a high of 32.7 min^{-1} for case 17, with an average of 24.4 min^{-1} per MCC. In comparison, Brook and Kitagawa (1960) report an average flashing rate of 2 min^{-1} in New Mexico. Piepgrass et al. (1982) report a range of 0.2–12.5 min^{-1} with an average of 2.4 total flashes per minute per storm. Since almost half of their lightning activity occurs as ground discharges, the ratio of ground strikes produced by MCCs to the New Mexico and Florida storms is again about 20:1.

Figure 4 shows an example of the spatial distribution of the lightning and heavy precipitation (>12 mm per site) for the most electrically active MCC we studied. This case (number 14) produced 32 832 discharges over a 19.5 h period. There is a general agreement of the overall shape and centroid maxima between heavy precipitation and lightning strike density. The peak strike density accumulated over the entire MCC life-

TABLE 4. Maximum lightning discharge rates of selected storm systems.

Maximum rate	Location	Storm type	Investigators
30 min^{-1} (1800/60 min)	New England	Hailstorms	Shackford (1960)
120 min^{-1}	Subtropics	—	Mackerras (1963)
70 min^{-1}	Great Plains	Hailstorms	Blevins and Maurwitz (1968)
23 min^{-1}	Northwest United States	—	Fuquay and Baughman (1969)
67 min^{-1} (1000/15 min)	—	—	Israel (1973)
25 min^{-1} (5594/225 min)[a]	Oklahoma	Squall line	Kinzer (1974)
26 min^{-1}	Florida	Tornado	Livingston and Krider (1978)
7.6 min^{-1} (5 min average)[b]	Florida	Isolated storms/clusters	Piepgrass et al. (1982)
3.7–14 min^{-1} (5 min average)[a]	Florida	Isolated storms/clusters	Peckham et al. (1984)
53 min^{-1} (3150/60 min)	Gulf of Mexico	Hurricane Alicia	Johnson and Goodman (1984)
45 min^{-1} (1 h average)[a] 54 min^{-1} (1 h maximum)[a] 60 min^{-1} (5 min maximum)[a]	Oklahoma	MCC	Present study

[a] Ground discharges only.
[b] Range from 0.6–30 min^{-1}.

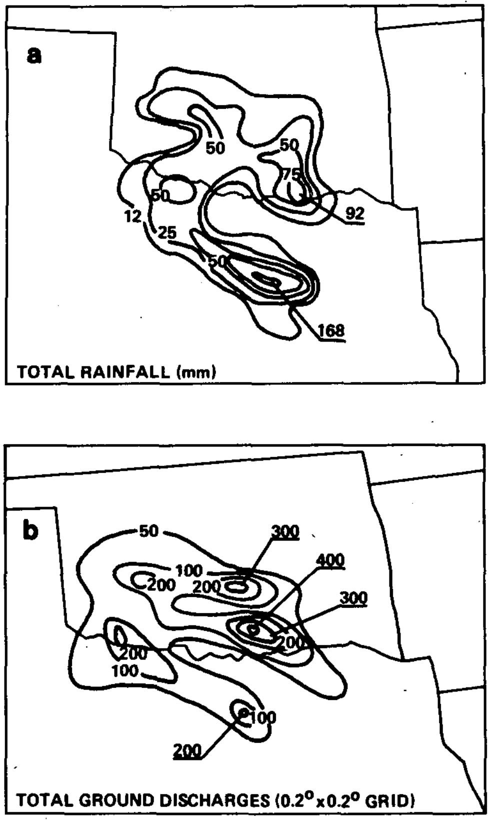

FIG. 4. Total precipitation (mm) and lightning discharges to ground between first storms and termination of the June 1983 MCC (case 14). (Rainfall data courtesy of R. Kane.)

cycle is 426 flashes to ground within a 0.2 × 0.2 area, which is equivalent to about 0.7 discharges km^{-2}. The peak strike density for a single storm is about 0.09 strikes $\mathrm{km}^{-2}\ \mathrm{min}^{-1}$ and occurs 3 h after maximum extent along the MCC centroid track shown in Fig. 2. This peak strike density is on the order of the maximum strike density reported by Peckham et al. (1984).

To illustrate the significance of the lightning rates produced by MCCs consider the following. The peak strike density at maximum extent for case 14 is 254 discharges in 1 h within a 625 km^2 area where the detection efficiency is 70%. During this same hour there are 3.33 ± 2.57 component strokes per flash on average. Therefore, the strike density at maximum extent is 0.03 strikes $\mathrm{km}^{-2}\ \mathrm{min}^{-1}$ or 1.93 strikes km^{-2}. Compare this value with the 30-year mean strike density derived by MacGorman et al. (1984) from a combination of lightning location network data and thunderstorm duration records. They estimate a mean annual strike density for any site within the state of Oklahoma of less than 8 strikes km^{-2}. Thus, this MCC produced at least 24% of the mean annual strike density for any site located beneath the MCC centroid at maximum extent.

Figure 5 shows individual flash rate histograms and a composite life cycle of the lightning activity. Even the two incomplete cases show the rapid rise to peak that is common to these MCCs. The increasing flash rates to peak also occur in conjunction with the most rapid expansion of the anvil cloud shield area colder than −52°C. The typical time lag between the peak flashing rate and maximum cloud shield extent is only 2–3 h, but can be as great as 7 h (case 23, for example). Note, too, that the average ground discharge rate decreases to only 65% of the peak value by maximum extent and continues decreasing rapidly through MCC termination. However, even at termination the MCC flashing rate (10 min^{-1}) is comparable to the maximum flashing rate of the Florida storm clusters described in Table 4.

The composite lightning life cycle in Fig. 6 reflects an observed exponential increase from first storms to peak followed by an exponential decrease to termination (at which time the number of discharges is 20% of the total number at peak, on average). The exponential relations which best fit the hourly averaged data are of the form

$$N = 0.93\, e^{0.18t}, \quad t_{\text{first storms}} \leq t < t_{\text{peak}} \qquad (1)$$

$$N = 1.15\, e^{-0.26t}, \quad t_{\text{peak}} \leq t < t_{\text{termination}} \qquad (2)$$

where N is the fraction of discharges to ground in a given hour occurring at a time, t, relative to the magnitude and occurrence of the peak. Relations (1) and (2) have correlation coefficients of 0.92 and 0.98, respectively. Evidence of exponential flashing rates can also be inferred from storms analyzed by Brook and Kitagawa (1960) and Piepgrass et al. (1982). The rate of increase and decrease of the lightning attending the whole weather system (i.e., the histogram structure) and the average number of strokes per flash may be useful as a supplement to conventional meteorological observations in diagnosing and predicting MCC intensification, duration, and demise.

Another significant feature of the MCC life cycle is the number of consecutive hours with the flash rates exceeding 1000 h^{-1} (Table 5). These high rates are sustained on average for over nine consecutive hours and do not depend on the size or duration of the MCC as defined in Table 1. For example, the 13–14 June 1983 MCC exists for 19.5 h and has 15 consecutive hours with flash rates greater than 1000 h^{-1}, and yet no hours with rates greater than 3000 h^{-1}. However, one of the shortest lived MCCs (15–16 June 1982) with a lifetime of only 12.5 h has 12 consecutive hours with rates greater than 1000 h^{-1}, and the maximum peak flash rate of all 10 cases.

4. Conclusions

A comprehensive study has been undertaken to examine the evolution of lightning discharges to ground attending the convective storms in mesoscale convec-

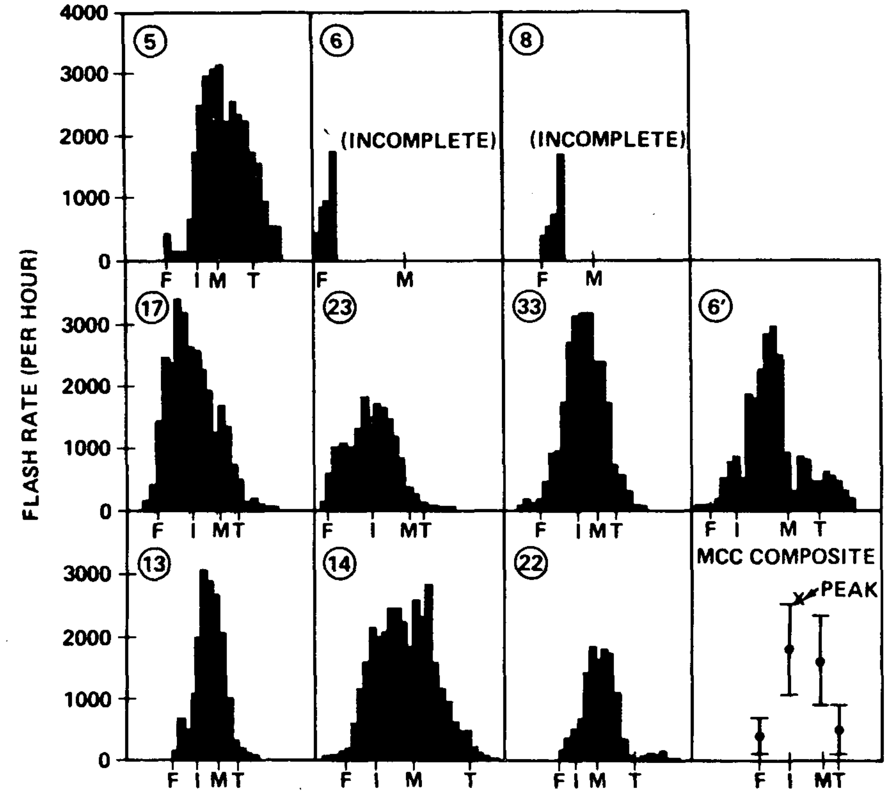

FIG. 5. Ground discharge histograms and MCC composite. The four life-cycle phases are identified as first storms (F), initiate (I), maximum extent (M), and terminate (T). The composite is plotted with respect to the time and magnitude (± one standard deviation) of the average peak flash rate.

tive systems. The peak flash rates occur on average 1.8 h after initiation, 2.6 h prior to maximum cloud shield extent, and over 7 h prior to the termination phase of the MCC life cycle. The total cloud-to-ground lightning activity and maximum flashing rate do not appear to be directly related to either the size of the cloud shield or total duration of the MCC. However, increasing flash rates occur in conjunction with the rapid expansion of the anvil cloud shield area colder than −52°C. The typical MCC produces cloud-to-ground lightning flash rates in excess of 1000 h^{-1} for nine consecutive hours and thus probably represents one of the most prolific lightning-producing weather systems in the United States. Peak ground discharge rates of 60 min^{-1} are not uncommon and average 42 min^{-1} for the MCCs analyzed. These peak rates are comparable to the peak rates produced by other large mesoscale convective systems. The life-cycle average flash rate from first

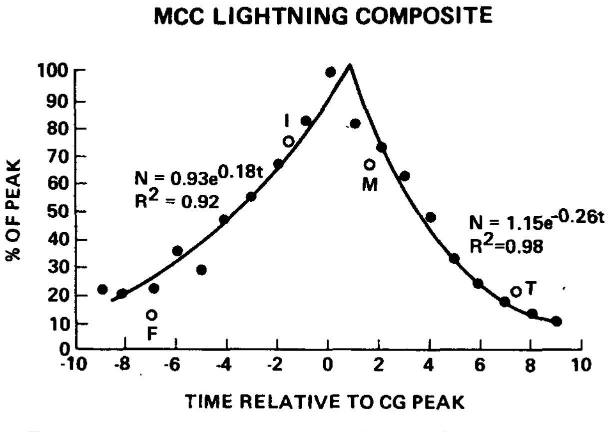

FIG. 6. The average hourly ground discharge flash rates are normalized to the average peak flash rate of the MCCs listed in Table 3 and are shown relative to the time of occurrence of the peak. N represents the percentage of the peak rate at a given hour and R^2 is the correlation coefficient for each of the exponential curves. The open circles denote the time and magnitude of the lightning rates for each of the MCC life-cycle phases F, I, M, T.

TABLE 5. Consecutive hours with high rates.

Case	$\geq 1000\ h^{-1}$	$\geq 2000\ h^{-1}$	$\geq 3000\ h^{-1}$
5	11	8	2
17	12	7	2
23	11	0	0
33	8	6	3
6′	6	4	0
13	7	5	1
14	15	6	0
22	6	0	0

storms through termination is 24.4 $\min^{-1}$ per MCC. The ratio of ground discharges in MCCs to Florida storms is 4:1 for severe or multicell storms and in excess of 20:1 for isolated thunderstorms. Peak strike densities for individual storms embedded within the MCC of 0.09 strikes $\mathrm{km}^{-2}\,\min^{-1}$ are comparable to the observed values of Florida storms. Yet, a single MCC event can produce one-fourth of the mean annual strike density for any site passed over during the most intense phase of its life cycle. An important implication of this result is that a given location may end up well above or below its mean annual strike density as a result of an MCC passing directly overhead or circumventing the station when the MCC is most intense. Multiple stroke discharges are less common during the first hour of MCC storm development than during the most intense phase of the MCC life cycle when the charge distributions in the storms are more likely to be complex. Lightning damage occurs with half of the MCCs and is most frequent between the initiate and maximum extent lifecycle phases. The exponential increase and decrease of discharge rates and the variations in the average number of discrete strokes per flash correlate well with the intensification and decay of the MCC evolving through its life cycle. In addition, very different lightning activity life cycles may occur with apparently similar synoptic environments. Both the synoptic and mesohigh MCCs are capable of producing sustained high flashing rates.

Acknowledgments. This document was prepared during work sponsored by the Universities Space Research Association under NASA Contract NAS8-34748 and Government Order H-39299B. We would like to acknowledge Dennis Buechler and Doug Mach for their programming assistance. Reference herein to any specific commercial products, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement, recommendation, or favoring by the United States Government or USRA.

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