Cloud-to-Ground Lightning in Linear Mesoscale Convective Systems

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ABSTRACT

Recently, three distinct archetypes for midlatitude linear mesoscale convective systems (MCSs) have been identified: those comprising convective lines with trailing stratiform precipitation (TS), leading stratiform precipitation (LS), and parallel stratiform precipitation (PS). While cloud-to-ground (CG) lightning in TS MCSs has received a great deal of study in recent years, linear MCSs exhibiting leading or parallel stratiform precipitation have received comparatively little attention. This paper documents the arrangement and frequency of CG lightning for four LS and four PS MCSs that occurred during May 1996 and May 1997. On average, the LS cases bore some similarity to previously studied TS MCSs; they produced predominantly positive CG lightning (+CG) early in their lifetimes (concomitant with convective precipitation) and late in their lifetimes (concomitant with stratiform precipitation). In contrast with previously published results for MCSs in general, the LS MCSs in the present study overall had relatively low negative CG (−CG) flash densities, yielding higher percentages of +CGs than other MCS archetypes. While the PS systems had higher average flash densities than the LS systems, they did not exhibit prolonged +CG modes early in their lifetimes, and they produced a lower overall fraction of +CGs. Notably, the presence of line-parallel flow may render a somewhat unique electrical character in PS systems. In particular, the PS MCSs in this study exhibited enhanced CG lightning in the vicinity of decaying convective cells that were embedded within their stratiform precipitation regions.

1. Introduction

Recently, Parker and Johnson (2000, hereafter PJ00) identified three modes of organization in mesoscale convective systems (MCSs) by using national radar data from May 1996 and May 1997: those comprising convective lines with trailing stratiform[1] precipitation (TS, Fig. 1a), leading stratiform precipitation (LS, Fig. 1b), and parallel stratiform precipitation (PS, Fig. 1c). Mazur and Rust (1983) were probably the first authors to investigate the cloud-to-ground (CG) lightning structure of a TS MCS. Thereafter, increasing effort was directed to documenting and understanding the electrical behavior of TS MCSs (e.g., Rutledge and MacGorman 1988, hereafter RM88; Engholm et al. 1990; Rutledge et al. 1990, hereafter RLM90; Keighton et al. 1991; Schuur et al. 1991; Marshall and Rust 1993; Rutledge et al. 1993; Nielsen et al. 1994; Rutledge and Petersen 1994; Stolzenburg et al. 1994; Bateman et al. 1995; Marshall et al. 1996). RM88 found that a TS MCS on 10–11 June 1985 during the Preliminary Regional Experiment for Stormscale Operational and Research Meteorology produced numerous positive CG flashes (+CGs), often in its region of stratiform precipitation. Other studies (e.g, RLM90; Morgenstern 1991) have also discovered that +CGs can frequently occur near convective cells in TS MCSs, particularly during the early part of their lifetimes. RM88 noted a horizontal bipole in the 10–11 June lightning pattern, comprising predominantly negative CG flashes (−CGs) in and near the convective line and predominantly positive CG flashes in the trailing stratiform rain region, much as had been observed in ''mesoscale storm systems'' by Orville et al. (1988). Similar bipole patterns were also documented in MCSs by Hill (1988), Engholm et al. (1990), RLM90, Schuur et al. (1991), Hunter et al. (1992), Nielsen et al. (1994), and MacGorman and Morgenstern (1998). RM88 suggested that either rearward advection of charged particles from the convective line or in situ generation of charge might explain the occurrence of +CGs within the stratiform precipitation. Additional evidence led Engholm et al. (1990), RLM90, Rutledge and Petersen (1994), and Nielsen et al. (1994) to suggest that localized charging in the trailing stratiform region was probably more significant than advection of charged particles from the nearby convective line. Recently, Schuur and

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[1] Although some authors (e.g., Doswell et al. 1996) have pointed out that secondary ''stratiform'' precipitation in MCSs may not always be purely stratiform in nature, we have retained the term due to its widespread usage in the published literature.

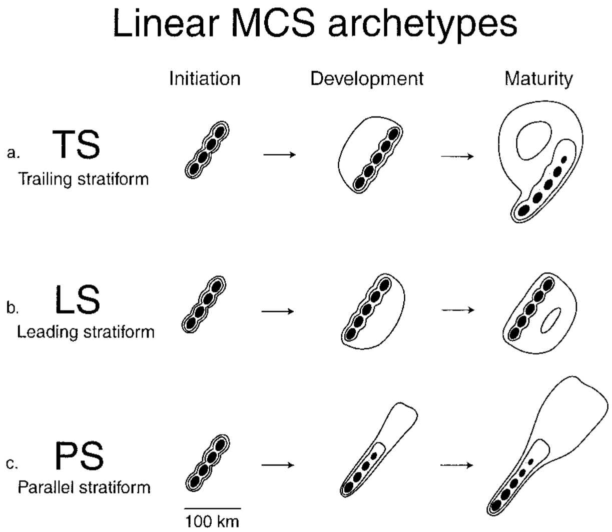

FIG. 1. Schematic reflectivity drawing of idealized life cycles for three linear MCS archetypes (from Parker and Johnson 2000): (a) leading line trailing stratiform (TS), (b) convective line with leading stratiform (LS), (c) convective line with parallel stratiform (PS). Approximate time interval between phases: for TS 3–4 h; for LS 2–3 h; for PS 2–3 h. Levels of shading roughly correspond to 20, 40, and 50 dB*Z*.

Rutledge (2000) used a two-dimensional model of a TS MCS to conclude that advection of charge from the convective line can account for the three uppermost charge layers (of a five-layer charge model; e.g., Schuur et al. 1991) in the stratiform region, while in situ production can account for the lowest two charge layers. Reports of occasionally conflicting surface corona point measurements beneath MCSs' stratiform clouds (e.g., the foul weather field observed beneath +CG producing stratiform regions by Engholm et al. 1990), as well as visual observations of *spider lightning* in MCSs (e.g., Marshall et al. 1989), have led to yet a third hypothesis (as discussed by Hunter et al. 1992) that +CGs in trailing stratiform regions may result from lightning channels that propagate great distances horizontally, striking the ground far from their initiation points.

Since the benchmark work of Houze et al. (1990), MCSs with convective lines and trailing stratiform precipitation (Fig. 1a) have been generally recognized as very common. Extending that study, PJ00 discovered that approximately 20% of the observed linear (i.e., possessing a convective line) MCSs in the central United States during May 1996 and May 1997 had LS precipitation, and approximately 20% had PS precipitation. Given that sizeable numbers of non-TS linear MCSs exist, it is important to establish the degree to which TS MCSs are unique mesoscale dynamical entities. Our present results indirectly address this problem by comparing LS and PS MCSs to TS MCSs in terms of their CG lightning flash density and arrangement. In addition, because they have received relatively little study to this point, the LS and PS archetypes represent a novel population of MCSs with which to test current (or propose new) hypotheses for charging and lightning production in MCS stratiform regions. We believe that this study of CG lightning in distinctly non-TS MCSs can shed light on previous results concerning TS case studies and populations.

2. Data and methods utilized

In this study we analyzed four examples, chosen for their archetypal reflectivity structures, of both the LS and PS linear MCS modes. After investigating all eight cases and compiling statistics for the LS and PS classes, we chose one system that exemplified each group's lightning behavior. These examples are presented in section 3 along with the overall group characteristics and statistics. The LS MCSs that we studied occurred on 18 May 1996, and on 7, 8, and 18 May 1997; the PS MCSs that we studied occurred on 24 and 26 May 1996, and on 1 and 23 May 1997.

For this study we utilized the same 2 km $\times$ 2 km, 15-min national radar base scan composite data as were used by PJ00. We chose the national radar composites for their reasonable temporal and spatial resolution along with their ability to provide a general overview of regional radar returns. As the position, movement, and horizontal extent of MCSs often preclude complete sampling by one radar site, the composited data provided an advantageous depiction of storms in their entirety. In section 3, we present the details of both an LS MCS and a PS MCS whose lightning behaviors were archetypal; for additional insight into these two exemplary systems, we also obtained and investigated the full-volume Level II radar data from nearby operational Doppler radars (WSR-88Ds).

All of the lightning data in this study are from the National Lightning Detection Network (NLDN), which is operated by Global Atmospherics, Inc., Tucson, Arizona. Cummins et al. (1998) recently described the characteristics of the network's sensors and the latest improvements thereto. The NLDN data comprise the polarity, amplitude, and multiplicity of detected lightning flashes, which are uniquely described by time and latitude–longitude coordinates. For the cases in our study, the network had an expected detection efficiency of 80%–90% and a location accuracy of approximately 0.5 km (Cummins et al. 1998; Idone et al. 1998a,b). In accordance with the results of Cummins et al. (1998), we rejected positive flashes with peak currents less than 10 kA since such small-magnitude +CG observations may result from intracloud flashes rather than CG lightning. Approximately 5% of the positive NLDN CG observations in our study were discarded for this reason; therefore, while our gross statistics are not changed much by the filtering, we do have increased confidence that the positive flashes included in our study were indeed CGs. In order to plot CG data atop radar imagery, we horizontally translated the NLDN CG flashes by

TABLE 1. Lifetime-averaged orientation, motion vector, and layer-mean ground-relative wind vectors for the 26 May 1996 and 7 May 1997 MCSs (discussed in detail in the text). Orientation is the average azimuthal direction toward which a convective line's tangent points (0° ≤ orientation ≤ 180°). Vectors are expressed in terms of speeds (all units are m s^{-1}) and directions (degrees azimuth, representing the direction from which the vector originates). Mean wind vectors were computed for layers 0–1, 1–2, 2–4, 4–7, and 7–10 km AGL.

Date	MCS type	Orien-tation	Motion		0–1 km		1–2 km		2–4 km		4–7 km		7–10 km	
			spd	dir	spd	dir	spd	dir	spd	dir	spd	dir	spd	dir
7 May 97	LS	165°	6	260°	11.3	184°	8.3	199°	11.3	240°	16.3	286°	30.7	285°
26 May 96	PS	40°	9	245°	16.7	167°	17.5	210°	20.8	223°	23.3	228°	41.3	235°

using each MCS's motion vector, thereby depicting storm-relative CG locations for a 30-min period centered on the time of the plotted radar data. We computed flash densities at half-hour intervals, using the area covered by radar echoes with reflectivities ≥10 dB*Z* in the composite reflectivity plots to normalize an MCS's flash count.

Because other studies of lightning in MCSs have used various filtering techniques that differed from ours, we have performed a brief study of four TS systems for comparison. These cases, which occurred on 11 May 1996 and 8, 23, and 24 May 1997, were subjected to the same method of analysis as were the LS and PS MCSs in our study, and thereby represent a fair basis for comparison. We refer to this population of four TS systems throughout sections 3 and 4, even though we do not present their details (which are very similar to those of TS MCSs documented elsewhere within the established literature).

3. Observations of cloud-to-ground lightning in LS and PS MCSs

a. A typical LS MCS

An LS MCS from 7 May 1997 had CG lightning behavior typifying that of the LS cases in our study. An overview of the kinematic properties of the MCS and its environment are given in Tables 1 and 2. Early in its lifetime (0615 UTC), the 7 May MCS comprised a line of convective cells preceded by a small, developing region of stratiform rainfall (Fig. 2a). The reflectivity cores along the convective line of the 7 May LS MCS were not extraordinarily deep [echo tops generally below 9 km above ground level (AGL), 40-dB*Z* echoes generally below 7.5 km AGL], nor were they exceptionally strong (generally <55 dB*Z*). The CG lightning during the development phase was located entirely within and downshear of the convective cores, and was predominantly positive. This behavior has been called the *convective* +CG mode by Morgenstern (1991). Beginning around 0700 UTC, the 7 May MCS showed evidence of a developing radar bright band in its leading stratiform precipitation (not shown). By 0945 UTC, the LS region extended approximately 100 km in advance of the convective line (Fig. 2b), and the MCS was producing predominantly −CGs in and near its convective cores (apart from the line's center, where +CGs continued to occur approximately 10 km downshear of the reflectivity cores). By 1045 UTC, as the leading rain region reached its maximum extent, the 7 May 1997 MCS had a readily apparent horizontal bipole structure (Fig. 2c). While −CGs still outnumbered +CGs by nearly an order of magnitude, most of the 31 observed +CGs occurred ahead of the convective line, while −CGs were closely related to the convective cores. At 1245 UTC, as the MCS decayed, the horizontal bipole was still evident despite the decrease in overall number of CG flashes (Fig. 2d). Throughout the later part of its lifetime, numerous +CGs occurred 10–20 km downshear of the convective line, yielding horizontal bipoles of a quasi-convective scale; in addition, smaller groups of +CGs also occurred in the stratiform region [Morgenstern (1991) called this the *stratiform/dissipating* +CG mode], with characteristic bipole lengths of approximately 75–115 km. An areally extensive radar bright band was evident throughout the MCS's demise. In animating radar–CG composites of the 7 May 1997 MCS at 30-min intervals, we observed that +CGs in

TABLE 2. Lifetime-averaged layer-mean storm-relative line-parallel and line-perpendicular winds for the 26 May 1996 and 7 May 1997 MCSs (discussed in detail in the text) as well as for the mean LS, PS, and TS MCSs (each group average represents four cases). All units are m s^{-1}. Rear-to-front line-perpendicular flows are positive signed, while front-to-rear flows are negative signed. With respect to the MCS's motion vector, right-to-left line-parallel flows are positive signed, while left-to-right line-parallel flows are negative signed. Mean wind vectors were computed for the same layers as in Table 1.

MCS or group	0–1 km		1–2 km		2–4 km		4–7 km		7–10 km	
	line—∥	line—⊥	line—∥	line—⊥	line—∥	line—⊥	line—∥	line—⊥	line—∥	line—⊥
7 May 97 LS	11.9	−2.3	7.7	−1.3	3.8	4.7	−7.4	7.7	−14.2	20.4
26 May 96 PS	1.8	−17.2	9.3	−7.0	12.6	−2.7	14.9	−0.5	31.7	6.7
Average LS	3.7	−8.7	4.4	−5.9	3.7	−2.1	0.8	−0.1	0.2	8.8
Average PS	3.3	−14.4	4.5	−10.2	10.6	−6.0	13.6	−5.8	20.1	−2.7
Average TS	−0.1	−16.6	0.0	−13.1	3.3	−5.3	4.5	−6.0	9.6	−5.6

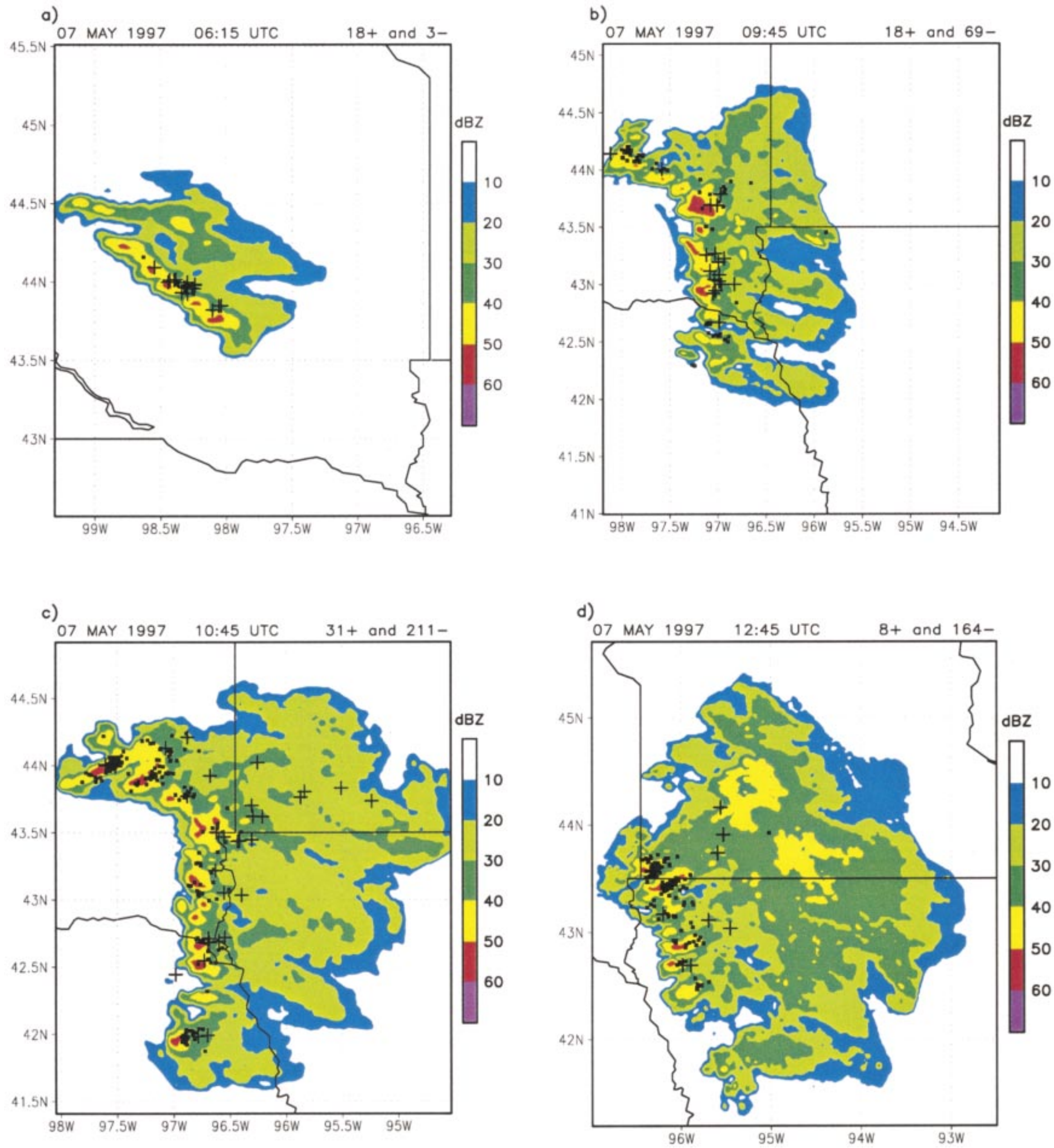

FIG. 2. Low-level composite reflectivity (shaded) and cloud-to-ground lightning map for an LS MCS on 7 May 1997. (a) At 0615, (b) at 0945, (c) at 1045, and (d) at 1245 UTC. Location and polarity of NLDN CG strokes are indicated by + for positive flashes and ● for negative flashes. Lightning data are from a 30-min period centered on the time of the radar image and are translated according to the MCS's motion vector. Note that the horizontal scale varies among subfigures.

the stratiform rain region tended to congregate within and near plumes of enhanced reflectivity therein. This relationship is weakly evident in Figs. 2c and 2d.

The 7 May MCS had a relatively low flash density throughout its lifetime, averaging just over 3×10^{-3} h^{-1} km^{-2}, and only peaking momentarily above 5×10^{-3} h^{-1} km^{-2} (Fig. 3). Such low flash densities were common among the LS MCSs, which averaged 7.9×10^{-3} h^{-1} km^{-2} (Fig. 4a). By comparison, the average flash density among the four TS MCSs that we studied was 1.8×10^{-2} h^{-1} km^{-2}, which is similar to values that we have inferred from the results of Goodman and MacGorman (1986, who studied an MCC) and Holle et al. (1994, who studied MCSs with ''diverse'' and ''chaotic'' organization). As well, the 7 May case produced >50% +CGs during the first half of its lifetime (Fig. 3), which was true for three of the four LS MCSs that we studied (Fig. 4b). The early +CG flashes occurred

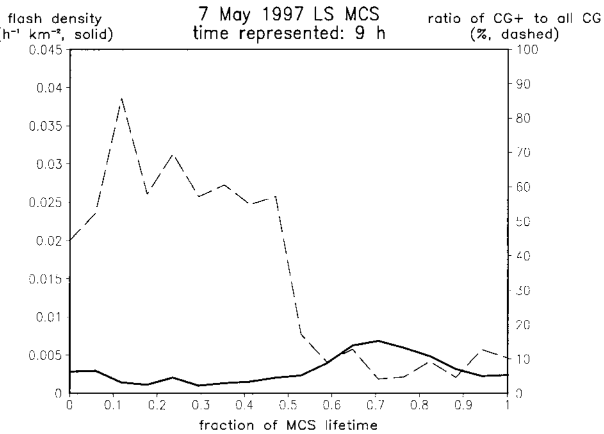

FIG. 3. Lightning behavior for 7 May 1997 LS MCS: flash density (h^{-1} km^{-2}, heavy solid curve, left-hand ordinate axis) and positive CG fraction (%, light dashed curve, right-hand ordinate axis). Abscissa values are time normalized by the MCS's 9-h lifetime, where ''lifetime'' is defined as in Parker and Johnson (2000).

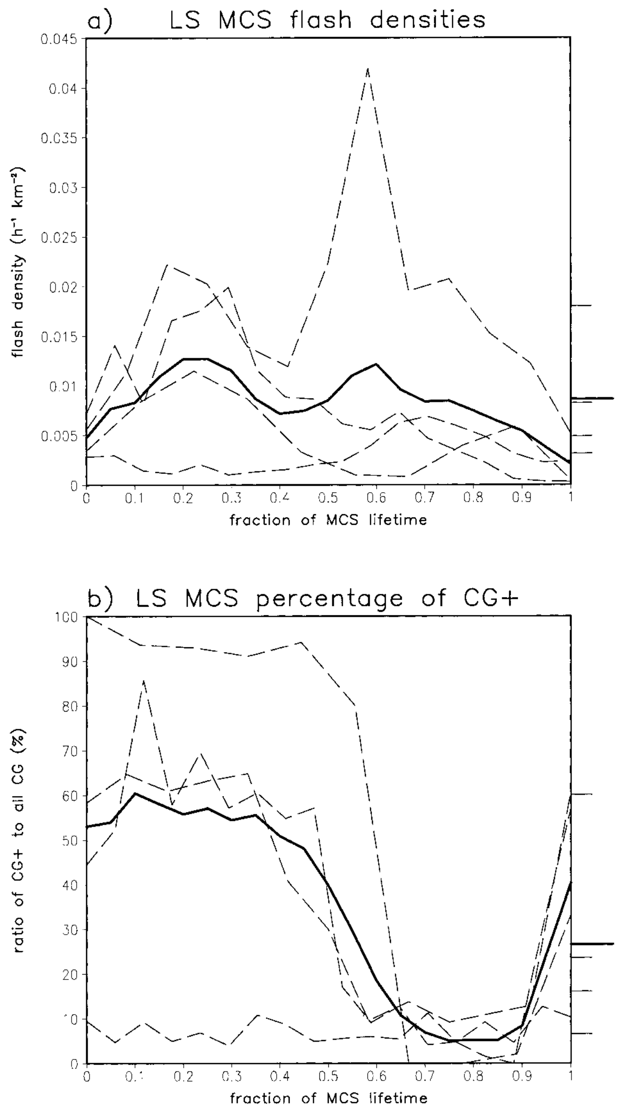

FIG. 4. Composite lightning behavior for four LS MCSs in this study: (a) flash density (h^{-1} km^{-2}), (b) positive CG fraction (%). Thin dashed curves: values for each of four systems. Heavy solid curve: average for all four systems. Hash marks on the right-hand axis denote lifetime values for each system and the four systems' average. Abscissa values are time normalized by each MCS's lifetime (average duration: 7.5 h), where ''lifetime'' is defined as in Parker and Johnson (2000).

mainly in and near the LS MCSs' convective lines, consistent with the observations of RLM90, Morgenstern (1991), and Nielsen et al. (1994). In addition to its +CG convective mode, the 7 May system also showed a propensity to produce +CGs in its leading stratiform rain region, a trait that yielded a horizontal bipole CG structure during its later stages. The other three LS systems also exhibited horizontal bipole patterns of CGs to some extent, although relatively few overall flashes occurred late in the lifetime of the 18 May 1996 MCS. Notably, while the bipole length for the LS systems' *stratiform* +CGs was most frequently between 60 and 80 km in length, numerous other +CGs were observed in closer proximity to their convective lines. In addition, whereas the 7 May MCS did not produce greater than 15% +CGs late in its lifetime, the other three LS systems exhibited maxima between 30% and 60% during the last tenth of their lives (Fig. 4b), when the precipitation was predominantly stratiform. The presence of numerous +CGs in the stratiform region of some LS MCSs suggests that they may also be producers of mesospheric sprites (cf. Boccippio et al. 1995).

The combination of early convective production and later stratiform production of +CGs rendered relatively high proportions of +CGs in the LS MCSs. The 7 May 1997 case produced 16.1% +CGs during its lifetime, as compared to an LS group average of 26.6% (the other cases produced 60.1%, 23.6%, and 6.6%). While the sample size is small (and the average is heavily influenced by the 60.1% +CG fraction of the 18 May 1996 MCS), the LS average +CG fraction is about twice that of the four TS MCSs that we studied (which produced, on average, 13.0% +CGs), and is substantially larger than generally accepted values for thunderstorm and MCS lightning such as those reported by Toracinta et al. (1996) and MacGorman and Morgenstern (1998). Indeed, in their study of 25 MCSs, MacGorman and Morgenstern (1998) found only two systems that produced greater than 16.1% +CGs (percentage coincidentally identical to that of the 7 May MCS), while Toracinta et al. (1996) found that only two of nine Texas MCSs produced 16.5% or greater +CGs. It is unclear to what degree these past studies included TS, LS, and PS MCSs, although most of the examples shown by Toracinta et al. (1996) appear to have TS structure. The 10–11 June 1985 TS MCS studied by RM88 produced approximately 10% +CGs overall whereas a subregion of the 10–11 June TS MCS, which had a significant

+CG convective mode and was studied by Nielsen et al. (1994), produced approximately 15%–20% +CGs over the course of its lifetime. The peak LS MCS +CG flash densities were approximately 1.4×10^{-2} h^{-1} km^{-2}, a modest value compared to the high-density +CG storms documented by Stolzenburg (1994), although her study focused only on convective-scale storms. In the context of prior studies, rather, LS MCSs appear to produce somewhat depressed amounts of −CGs. We discuss possible reasons for this in section 4.

Finally, PJ00 pointed out that some LS MCSs are fed by inflow from behind their convective lines. In the present study, two of the four LS systems (7 and 18 May 1997) received such rear inflow, while two (18 May 1996 and 8 May 1997) were fed by front-to-rear inflow, as documented in the average profiles presented by PJ00. These differences notwithstanding, the lightning behavior and meteorology of each LS MCS in the present study bear much greater qualitative and quantitative similarity to those of other LS systems than of non-LS systems.

b. A typical PS MCS

A PS MCS from 26 May 1996 had CG lightning behavior typifying that of the PS cases in our study. An overview of the kinematic properties of the MCS and its environment are given in Tables 1 and 2. During its organizing phase (0315 UTC), the 26 May MCS consisted of an elongated band of high radar reflectivity surrounded by a narrow area of weaker echo (Fig. 5a). The reflectivity cores along the convective line of the 26 May PS MCS were quite deep (echo tops near 14 km AGL, 40-dB*Z* echoes near 13 km AGL), and generally exhibited maximum reflectivities near 60 dB*Z*. Even during its very early stages, CG flashes associated with the MCS were predominantly negative, although during one half-hour period the percentage of +CGs did approach 50% (Fig. 6). By 0645 UTC, a quasi-linear group of convective cells extended approximately 200 km from southwest to northeast, with a large region of line-parallel stratiform rainfall to its northeast (Fig. 5b). The MCS continued to produce predominantly −CG flashes at this time. Notably, decaying (as assessed from animated radar data) deep convective cells, which had been advected along the line, were embedded within the broader plume of stratiform precipitation, a common characteristic of the PS mode (cf. Fig. 7 of PJ00). These weak cores extended upward to as high as 8 km AGL (well above the freezing level) yet generally had maximum reflectivities of less than 55 dB*Z*. In and near a decaying convective core within the stratiform rain, numerous −CGs were observed, while in the surrounding stratiform rain, CG flashes were predominantly positive. This general behavior continued through the mature phase of the 26 May PS MCS (Fig. 5c), as the convective cores amalgamated into a contiguous line. As it dissipated (1215 UTC, Fig. 5d) the MCS exhibited a sharp decline in −CGs, especially along and within the diminishing convective line. While +CGs also decreased during this phase, the MCS's fraction of +CGs (compared to total CGs) was at its largest during this time period (Fig. 6).

The 26 May MCS had an average flash density of 2.2×10^{-2} h^{-1} km^{-2} (Fig. 6), which was close to the PS average of 1.8×10^{-2} h^{-1} km^{-2} (Fig. 7a). These values are nearly the same as those for the TS MCSs that we studied and are similar to those inferred from Goodman and MacGorman (1986) and Holle et al. (1994) for other non-PS MCSs (as detailed above). Each of the four PS cases exhibited flash densities in excess of 3.5×10^{-2} h^{-1} km^{-2} over at least one half-hour period (Fig. 7a). The 26 May 1996 system also typified the other PS MCSs in that its fraction of +CGs was relatively modest throughout its lifetime, averaging 12.9% (Fig. 6), as compared to a PS group average of 12.4% (Fig. 7b). This percentage is about half that of the four LS systems and is close to that for the group of TS MCSs that we studied (13.0%). Notably, +CG flash densities in the four PS MCSs were comparable to those in the four LS MCSs that we studied; however, their −CG flash densities were nearly twice those of the LS systems. The 26 May case exhibited a brief maximum in +CG fraction early in its lifetime, a mode that existed in two of the four PS MCSs, although in both cases this +CG convective mode was much shorter lived than in the LS examples. As well, the 26 May MCS produced increasingly positive CGs during the last quarter of its lifetime (Fig. 6), a stratiform/decaying +CG mode that occurred in three of the four PS cases that we studied (Fig. 7b). Nevertheless, as in the other three PS MCSs, no simple MCS-scale horizontal CG bipole pattern was evident in the 26 May 1996 case, despite the occurrence of +CGs in the stratiform region (at distances of 40–50 km from any convective cell). As exemplified by the 26 May system, three of the four PS MCSs produced numerous −CGs within and immediately surrounding decaying convective cores that were embedded within their PS precipitation. Such behavior apparently precludes the production of a simple horizontal bipole pattern, as has been observed in other MCS archetypes, but it may give rise to more complicated patterns comprising several localized convective-scale bipoles (with length scales of 10–20 km), as in Figs. 5c and 5d.

4. Synthesis of results

The lightning behavior of LS MCSs in this study was something like that observed for TS MCSs in previous studies. In particular, three of four LS cases exhibited a +CG convective mode [as was documented in TS MCSs by RLM90 and Nielsen et al. (1994)]; indeed, when compared to the convective +CG modes in four TS systems that we studied, the LS systems produced much higher percentages of +CGs, and for a longer period of time. Later in their lives, we observed LS

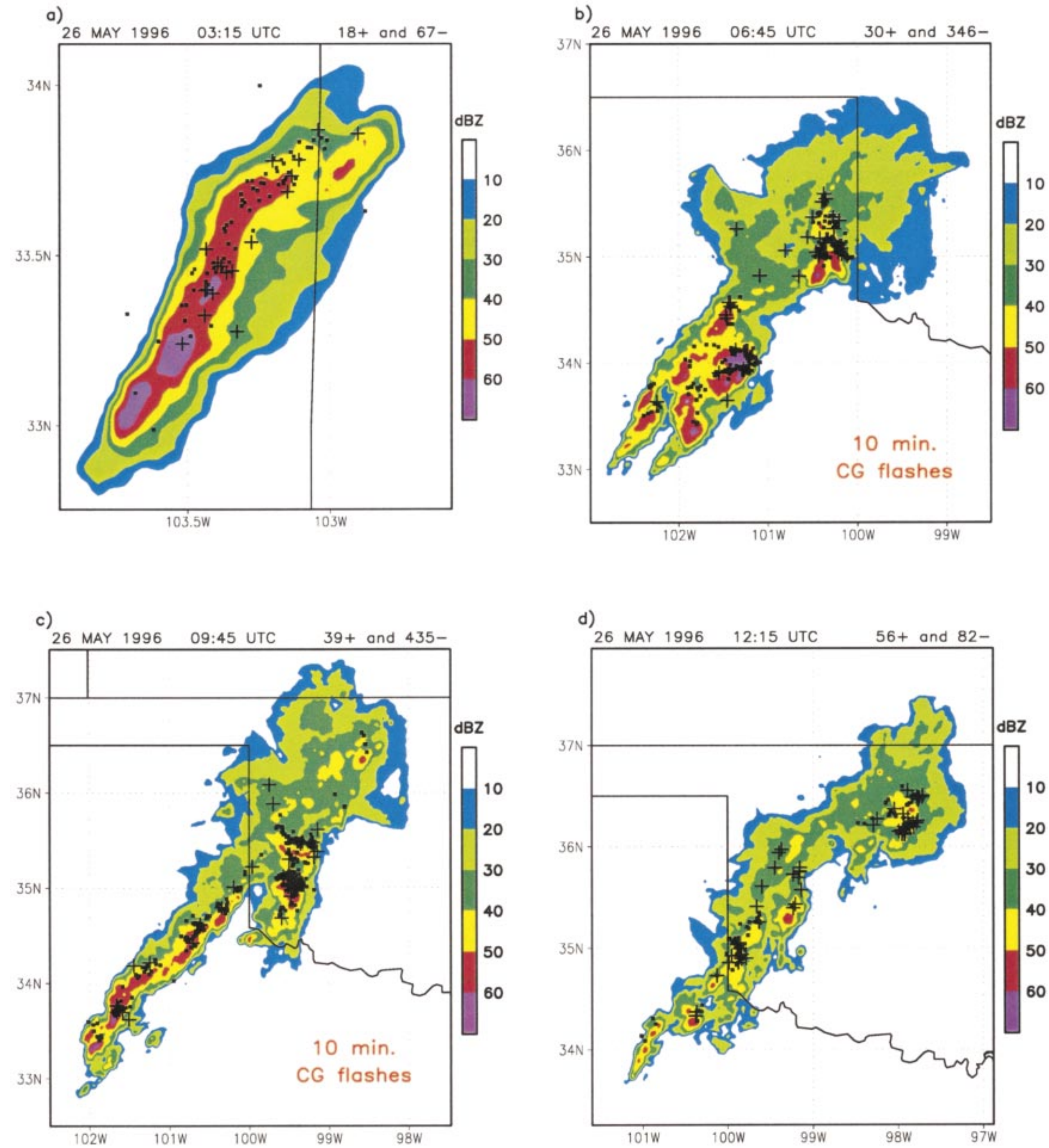

FIG. 5. Same as Fig. 2 except for a PS MCS on 26 May 1996 (a) at 0315, (b) at 0645, (c) at 0945, and (d) at 1215 UTC. In (b) and (c), only 10 min (as compared to 30 min) of NLDN data are plotted to lessen the clutter that is due to the high flash densities depicted. Note that the horizontal scale varies among panels.

MCSs to produce horizontal bipole patterns of CG lightning (as are frequently observed in TS MCSs; e.g., RM88; Engholm et al. 1990; RLM90; Schuur et al. 1991), with −CGs in and near their convective lines and +CGs in their stratiform precipitation regions. Our current lack of charge profiles in LS MCSs allows us only to speculate about possible similarities in the charging and lightning production of LS and TS systems. Marshall and Rust (1993) have documented four- and five-layer charge structures in TS MCSs. Schuur and Rutledge (2000) suggested that a combination of advection of charge from the convective line and local generation of charge in the stratiform region may explain such complicated charge structures. It is unclear to what degree these processes occur in LS MCSs.

We note that CG activity decreased markedly in one LS MCS (from 18 May 1997, not presented) as its stratiform region became separated from its convective line by an increasing distance. As well, comparatively many of the +CGs in LS MCSs were within 40 km of their

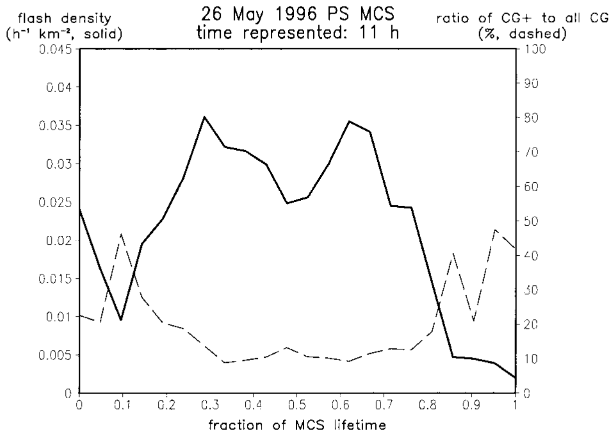

FIG. 6. Same as Fig. 3 except for 26 May 1996 PS MCS. Abscissa values are time normalized by the MCS's 11-h life cycle.

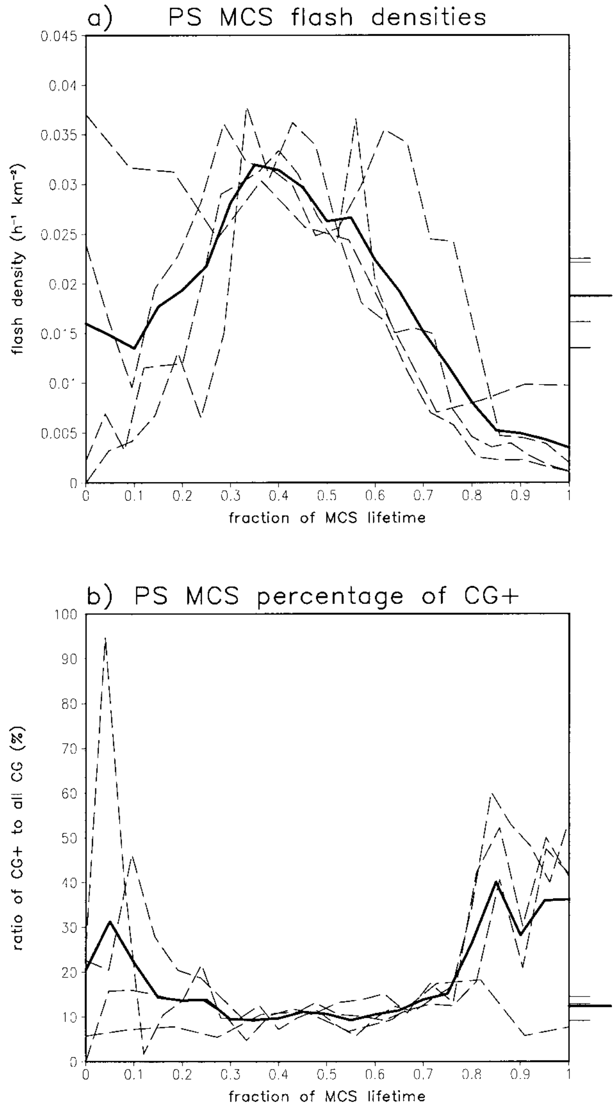

FIG. 7. Same as Fig. 4 except for four PS MCSs in this study (average duration: 10.25 h).

convective lines, as opposed to comparatively fewer that occurred far into the stratiform region (i.e., at distances approaching 100 km, as we observed in the TS systems). This evidence suggests the importance of convective lines to the production of +CG lightning in LS MCSs' stratiform precipitation (whether via charge advection or horizontally propagating flashes). In addition, PJ00 pointed out that many LS and PS MCSs are relatively shorter lived than their TS counterparts; in the present study LS MCSs had average lifetimes of 7.5 h, PS MCSs 10.25 h, and TS MCSs 13.25 h. Insofar as it takes time for the development of an MCS's stratiform region and the mesoscale updraft therein, the comparatively fewer +CGs at great distances from LS and PS (as opposed to TS) MCSs' convective lines might be anticipated. In keeping with this interpretation, the stratiform regions of LS and PS MCSs had somewhat smaller average areal extents than their TS counterparts (≈45 000 km^2 and ≈40 000 km^2 vs ≈55 000 km^2, respectively). Nevertheless, in the stratiform region of the 7 May 1997 LS MCS (whose lifetime was 9 h, cf. section 3a), reflectivities of 25 dB*Z* extended several kilometers above the 0°C level and a radar bright band was present, observations that Rutledge and Petersen (1994) argued to be consistent with in situ charge separation.

While LS and TS MCSs can apparently produce significant early (convective) +CG modes, the PS cases in this study generally produced fewer +CGs during their initial stages. RLM90 discussed the possibility that early +CGs in TS MCSs may be caused by a tilted dipole, owing to horizontal displacement of upper-level positive charge (cf. Fig. 8a). The upper-tropospheric storm-relative flow for LS MCSs in this study was, on average, directed from rear to front (Table 2), suggesting that an upper-level positive charge center might be advected forward from an LS convective line (cf. Fig. 8a). Indeed, many of the +CGs in LS MCSs occurred downshear of their convective cells at distances of less than 15 km, locations that are broadly consistent with tilted convective dipoles. The storm-relative wind profiles for four TS MCSs that we studied (Table 2) were consistent with a rearward displacement of upper-level positive charge. However, the PS MCSs in this study had strong line-parallel flow aloft (Table 2), indicating that an upper-level positive charge center would likely be advected along PS convective lines. The convective lines of PS MCSs often resemble almost completely contiguous regions of echoes ≥50 dB*Z* (generally, cell spacings were 10 km or less). It may be that in PS MCSs, upper-tropospheric line-parallel advection of upper-level positive charge is less amenable to +CGs because the positive charge is displaced over negative charge farther along the line and is not exposed to the ground via unshielding (Fig. 8b).

MacGorman and Burgess (1994) and Carey and Rut-

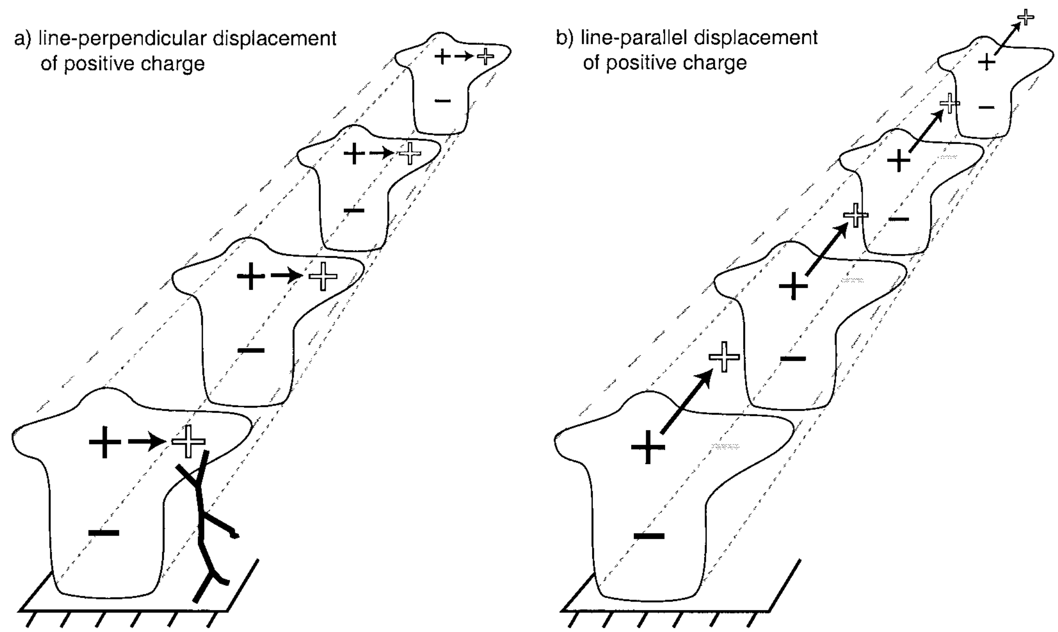

FIG. 8. Schematic illustration of hypothesized displacements of upper-level positive charge region during early stages of an MCS. (a) For line-perpendicular storm-relative flow (quasi-LS or TS), with possible +CG due to dipole tilting shown; (b) for line-parallel storm-relative flow (quasi-PS), with hypothetical linear lower-level negative charge region indicated.

ledge (1998) discussed the possibility that an enhanced lower positive charge center, associated with large amounts of graupel within severe hailstorms, could account for an increase in the fraction of +CG flashes. For the LS systems in our study, there does appear to be a correlation between the density of surface reports (see NCDC 1996, 1997) of large hail (i.e., diameter ≥ 4 cm) and the percentage of +CGs. However, the hail reports are fairly sparse (on average, only two large hail reports per LS system) and the maximum reflectivities in LS MCSs are not exceptionally large (generally ≤55 d*BZ*). As mentioned in section 3, the LS systems in our study apparently had lower than average −CG flash densities. In the LS MCS for which we had full-volume radar data, the convective cells were not exceptionally deep, such that we do not immediately infer the existence of a relatively high proportion of intracloud flashes. PJ00 discussed the possibility that preline precipitation could diminish the buoyancy of inflow that passes through it; perhaps this process decreases the convective vigor and associated charge separation within LS MCSs, leading to comparatively lower flash densities. It is also possible that, as suggested by Carey and Rutledge (1998), the presence of an enhanced lower positive charge center in hailstorms both inhibits −CG and increases the tendency for intracloud lightning. However, some PS systems whose densities of associated hail reports (see NCDC 1996, 1997) were comparable to or higher than their LS counterparts produced lower fractions of +CGs (although the use of surface reports is an admittedly crude way to estimate the production of hail by storms).

We also observed that CG activity tended to occur in regions of enhanced reflectivity in the eight MCSs that we studied, similar to the findings of RM88 and Rutledge and Petersen (1994). More interestingly, decaying (generally, more than 30 min after their time of deepest reflectivity development) embedded convective cells within the stratiform regions of PS MCSs appeared to serve as foci for CG lightning. PJ00 noted that PS MCSs often possess decaying convective cells in their stratiform regions. The role of such convective cells in electrification within the stratiform region is not entirely clear at this time, particularly because we were unable to investigate the vertical or horizontal charge structure of the MCSs in this study. It is likely, nevertheless, that decaying cells within PS precipitation regions may continue to separate charge locally, and therefore serve as ''hot spots'' for CGs in their general vicinity. Indeed, many of these weak embedded convective cells extended vertically into the mixed-phase region. Straightforward mesoscale horizontal bipole CG patterns were not observed in the PS MCSs of this study, in part owing to the numerous −CGs produced by old convective cores in their stratiform regions.

5. Indicated future work

In general, the sources of lightning in MCSs' regions of stratiform precipitation have not been satisfactorily explained, although the electrical behavior of TS MCSs is indeed well documented. Based upon our investigation of four LS cases, we hypothesize that lightning production in LS MCSs is qualitatively similar to that in TS MCSs. Both MCS types are commonly observed to produce early convective +CG modes and later stratiform/dissipating +CG modes, with horizontal bipole structures. Only with detailed measurements of the temporal and spatial evolution of charge (such as have been made for TS MCSs), along with collocated kinematic measurements, can the similarity of LS to TS MCSs be fairly evaluated. Further explanation of the apparently low −CG flash densities in LS MCSs would also be of interest. As well, Boccippio et al. (1995) discussed the common occurrence of mesospheric sprites above +CG flashes within MCSs' stratiform regions: given our observations, sprite researchers may be particularly interested in LS MCSs.

In addition, PS MCSs may have a unique contribution from active yet decaying convective cells within their stratiform regions. Again, only finescale observations of charge distribution can determine the extent and manner in which such convective entities affect the overall electrical structure in plumes of PS precipitation. We also observed that if PS MCSs produced a convective +CG mode, it was briefer and of more modest amplitude than those of LS MCSs. While the tilted dipole and enhanced lower charge region hypotheses provide plausible explanations for these observations, relating the electrical behavior of LS and PS MCSs to their dynamics will require a better knowledge of their internal and external flow fields as well as their possibly unique thermodynamics and cloud microphysics. The incorporation of data from new tools such as mesoscale lightning mappers (cf. Krehbiel et al. 2000) could also delineate the origins of +CG flashes in MCSs, and thereby help in inferring the relevant processes in MCSs' +CG production. Finally, given the small sample size, additional work is needed to determine how well the four LS and four PS MCSs in our study represent their respective MCS populations.

6. Summary

We investigated the relationship of cloud-to-ground (CG) lightning to radar reflectivity for eight linear mesoscale convective systems (MCSs), four of which had leading stratiform (LS) structure and four of which had parallel stratiform (PS) structure. Our main findings include the following.

- The LS MCSs had some qualitative similarities to trailing stratiform (TS) MCSs in their CG behavior, and typically exhibited an early positive CG (+CG) convective mode and a later stratiform/dissipating +CG mode with a horizontal bipole structure.
- Negative CG (−CG) flash densities in the LS MCSs were significantly lower than those suggested by previous studies of MCSs, rendering a higher than average fraction of +CGs. Three of four LS systems produced predominantly positive CG lightning over the first half of their lifetimes.
- The PS MCSs were generally unique in that during their early stages they produced a relatively smaller fraction of +CGs than LS and TS MCSs, and that during their mature and decaying phases they tended not to exhibit a simple mesoscale horizontal bipole structure in CG flash polarity.
- In PS MCSs, decaying convective cells are often observed within the line-parallel stratiform region, where they may play some role in charging and lightning production.

Because LS and PS MCSs have received relatively little study, we commend further investigation of their temporal and spatial charge structures. Such work will help to evaluate some of the current hypotheses for charging in MCSs' stratiform regions, and will contribute to the presently scant literature on the LS and PS archetypes.

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