P8.6 CLOUD-TO-GROUND LIGHTNING CHARACTERISTICS OF DERECHO-PRODUCING CONVECTIVE SYSTEMS IN THE CENTRAL AND SOUTHERN GREAT PLAINS

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1. INTRODUCTION

The scientific literature is voluminous with respect to the cloud-to-ground (CG) lightning and electrical characteristics of mesoscale convective systems (MCSs). MacGorman and Morgenstern (1998) define an MCS as a long-lived storm system that amalgamates from a group of smaller storms through interactions with the local environment. One of the more common types of MCS is the squall line, which is composed of a narrow, linear region of strong convection with (oftentimes) a region of shallow, stratiform precipitation located downshear (relative to inflow) of the convective line.

Rutledge and MacGorman (1988), among others, noted a distinct horizontal pattern of CG lightning in squall lines whereby most of the positive CG (+CG) lightning occurred in the stratiform precipitation while most of the negative CG (–CG) lightning occurred within the convective line (i.e. bipole). Observations of 25 MCSs across the Great Plains by MacGorman and Morgenstern (1998) revealed that the average +CG lightning fraction was <7% with only two storms exhibiting >20% +CG lightning. Further, 18 of the 25 storms exhibited total CG lightning densities >10,000. Later studies suggest that these figures are not consistent among all MCSs. For instance, Parker et al. (2001) noted that the fraction of +CG lightning and the total CG lightning density in linear MCSs may vary according to the extent and orientation of stratiform precipitation.

One class of MCS that has received comparatively little attention in the published literature with respect to its CG lightning and electrical structure is the bow echo. In a bow echo one or multiple parts of the squall line segment accelerate, creating a bulge, or wave, in the convective line. Marshall and Rust (1993) reported that the electrical structure of bow echoes is composed of four main charge regions with the predominant polarity alternating with altitude. Murray and Orville (1999) studied a bow echo event across Kansas and Oklahoma and noted a total CG flash density of >50,000 and an average +CG lightning fraction of 42% during its 26-hr lifetime.

A common feature of the bow echo is the production of damaging, straight-line winds (Przybylinski 1995). These straight-line winds can extend over hundreds of km and last for many hours. If certain criteria are met (see Ashley and Mote 2005), such an event is classified as a derecho. We are aware of only one study where the CG lightning characteristics of a derecho-producing convective system (DPCS) have been investigated (the bow echo studied by Murray and Orville did not meet the length requirement for derecho classification). Price and Murphy (2002) determined the trends in CG lightning associated with the DPCS of 4 July 1999 over Minnesota and noted a simultaneous decrease in total CG lightning and increase in the fraction of +CG lightning during the time of the derecho. In fact, during the most intense phase of the derecho, the fraction of +CG lightning reached 97%. A predominance (i.e. >50%) of +CG lightning associated with severe weather, namely tornadoes and large hail, has been observed most frequently across the Great Plains and Upper Midwest (e.g. Carey et al. 2003), although there is much storm-to-storm variability (e.g. Perez et al. 1997). It is unclear whether the results of Price and Murphy (2002) are representative of DPCSs or whether CG lightning data can be used to identify storm-relative features of bow echoes/DPCSs, or forecast their genesis and decay.

The objective of this study is to investigate the CG lightning characteristics associated with a sample of warm-season DPCSs across the central and southern Great Plains. Specifically, we determine the relationships between CG lightning location, polarity, storm structure, and severe wind by analyzing both CG lightning data and the corresponding radar images at different stages of each DPCS. Overall trends in CG lightning density and polarity are also examined, as well as the spatial relationships between CG lightning polarity and narrow swaths of extreme winds embedded in a high-end DPCS.

2. DATA AND METHODS

Three data sources were utilized in this research: 1) a unified derecho dataset for the contiguous U.S. (1986-2003) compiled by Ashley and Mote (2005); 2) CG lightning data from the National Lightning Detection Network (NLDN); and 3) low-level (0.5°) base reflectivity radar scans from individual sites in the WSR-88D network.

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Seven DPCSs occurring during the warm season months (May-September) of 1995-2001 across the central and southern Great Plains were analyzed (Table 1). The study region was chosen based on climatological studies which show that the Great Plains is a favored region for DPCSs during the warm season (Ashley and Mote 2005, cf. their Figure 2). The NLDN data were restricted to a 700,000 km² area within the study region centered roughly on Oklahoma City, OK. This restriction limited us to seven DPCSs so as to capture both early and decaying convection.

The production of CG lightning across the U.S. is monitored and recorded by Vaisala, Inc., which operates the NLDN. The ground-based sensors that comprise the NLDN record the location, date, time, and peak current of each CG flash, while a central processor at Vaisala calculates the polarity and multiplicity of each CG flash. Upgrades to the NLDN in the mid-1990s resulted in a detection efficiency over the central U.S. of 80-90%, a locational accuracy of 0.5 km, and a temporal accuracy of ~1 s (Cummins et al. 1998). Cummins et al. (1998) also demonstrated that +CG lightning observations with a peak current <10 kA are actually strong intra-cloud discharges and should be removed from analysis. This routine eliminated 5% of the flashes recorded in the NLDN dataset used in this study.

Low-level, short-range (230 km) base reflectivity scans from individual sites in the WSR-88D network were used to produce CG lightning-radar overlays at six stages of each DPCS: 1) early convection; 2) derecho-genesis; 3) maximum DPCS; 4) initial derecho decay; 5) derecho decay; and 6) decaying convection. From these overlays, relationships between storm structure, severe wind, and CG lightning can be discerned. For brevity, we present the results from the 22 August 1997 DPCS. This event also serves as a suitable archetype for the other six DPCSs studied. CG flashes within either a 10-min or 6-min window centered on the time of the radar image were plotted to reduce the clustering effect of high-density CG lightning periods (e.g. numerous –CG flashes in the convective line may obscure the few +CG flashes occurring nearby). CG lightning-radar overlays were created using the GRLevel3 software package.

3. CG FLASH TENDENCIES IN DPCS

3.1 Overall CG characteristics

Mean CG lightning characteristics for the seven DPCSs are presented in Table 1. Of these events, one was classified as low-end, four were classified as mid-end, and two were classified as high-end (see Coniglio and Stensrud 2004 for definitions). The mean duration was >11 hr Although decaying convection continued for an additional 1-4 hr following derecho decay, the associated CG activity associated with many of the events was largely outside the boundaries of the NLDN dataset and was not included in the mean CG flash rates presented in Table 1. The mean 1-min CG flash rate among these events was approximately 53 flashes, although there was much variability among the different derecho types. Mid-end derechos (50-73 CG flashes min^{-1}) exhibited an average of 28% more CG flashes min^{-1} than the two high-end derechos and 122% more than the low-end derecho. The mean percent +CG lightning among all events was 21% with two events (one low-end and one high-end) exhibiting >30% +CG lightning.

Table 1. Mean CG lightning characteristics for each DPCS event. “Dur” refers to the event duration (from the first CG flash to the last wind report; hr^{-1}). “MFR” is the mean total CG flash rate (flashes min^{-1}). “MPR” is the mean +CG flash rate (flashes min^{-1}). “MPP” is the mean percent +CG lightning.

Event	Type	Dur	MFR	MPR	MPP
9-10 Jun 1998	Low	7.5	27.2	6.8	34.3
7-8 May 1995	Mid	10.0	60.1	9.9	22.5
22 Aug 1997	Mid	12.0	73.2	7.2	18.0
1 Jul 1999	Mid	11.5	62.0	7.0	15.7
22 Jul 2000	Mid	11.0	50.1	4.3	15.3
24 Jul 1995	High	11.0	50.5	5.4	11.6
27-28 May 2001	High	15.5	45.8	11.4	32.7
Average		**11.2**	**52.7**	**7.4**	**21.4**

3.2 CG flash rates

Temporal trends in the frequency of CG lightning associated with each DPCS are presented in Figure 1 and are standardized according to the duration (Table 1) of each event (see Parker et al. 2001). The period between 0.0 and 0.1 on the abscissa represents early convection (i.e. the period before derecho-genesis) while 1.0 corresponds to the time of the last wind report (i.e. derecho decay).

When averaged among all seven DPCSs, the 1-min CG flash rate exhibited an increase from 18 flashes to 55 flashes following derecho-genesis. The CG flash rate remained relatively constant before decreasing slightly approximately halfway through the mean DPCS lifetime. Inspection of the wind reports and radar imagery revealed that six of the seven DPCSs exhibited maximum intensity between one third and two thirds of their lifetimes. The CG flash rate then increased again to a maximum value of 84 flashes approximately three-quarters through the mean DPCS lifetime. From this point to derecho decay the 1-min CG flash rate decreased from its maximum value to 30 flashes. It is inferred from subsequent radar images of decaying convection that the CG flash rate likely continued decreasing at a near exponential rate.

Inspection of the 1-min CG flash rates for each DPCS revealed much variability among event types. Two of the DPCSs (one high-end and one low-end) exhibited decreasing CG flash rates following the period of maximum derecho intensity and maximum CG flash density (i.e. the maximum derecho intensity occurred *after* the maximum CG flash rate). Three of the DPCSs (one high-end and two mid-end) exhibited increasing CG flash rates during the period of maximum derecho intensity. In these cases the DPCS reached maximum intensity *before* the maximum CG flash rate. In a mid-end DPCS, the maximum derecho intensity occurred early in its lifetime (between 0.1-0.2) well before the CG flash rate was maximized. In another mid-end DPCS, the derecho reached maximum intensity during a lull in CG lightning approximately halfway through its lifetime. This trend in suppressed CG lightning around the time of maximum derecho intensity was also observed in the 4 July 1999 DPCS over Minnesota (Price and Murphy 2002).

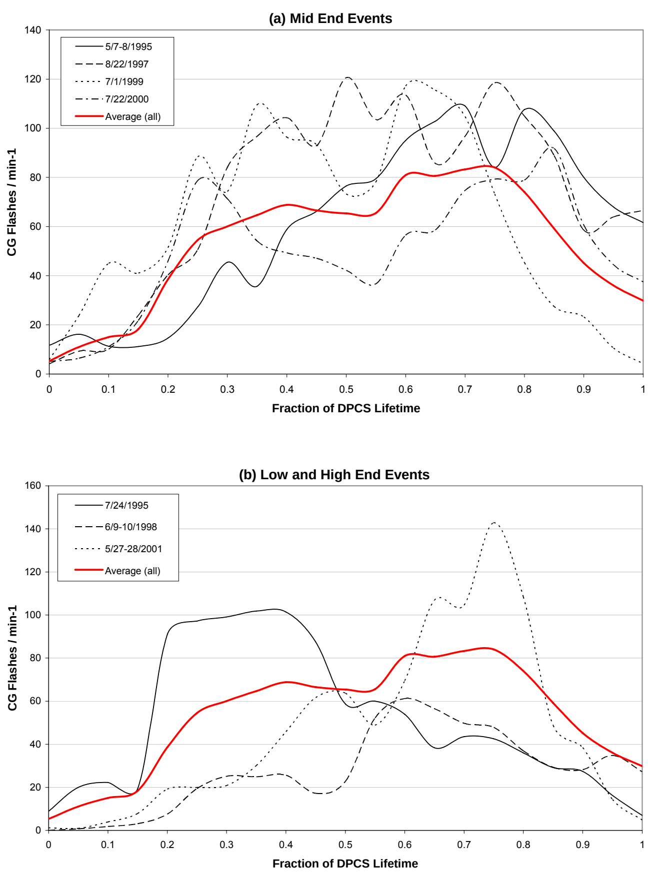

Figure 1. Trends in the 1-min CG flash rate for (a) four mid-end derechos, (b) one low- and two high-end derechos, and the average among all seven DPCSs [solid red line in (a) and (b)].

3.3 Percent +CG lightning

Figure 2 reveals the trends in the percentage of +CG lightning throughout the lifetime of each DPCS. Mid-end events exhibited >50% +CG lightning during the first tenth of their lifetimes. This value decreased to approximately 20% a quarter of the way through their lifetimes before leveling-off between 8-13%. In two of the cases the percent +CG lightning increased again to >20% just prior to derecho decay. The percentage of +CG lightning during high-end and low-end events was quite variable. One high-end event exhibited only 10% +CG lightning over three quarters of its lifetime while the other high-end event exhibited >50% over half its lifetime (the CG lightning polarity associated with this event is examined in detail in Section 5). The anomalously-high percentage of +CG lightning in the low-end DPCS is likely due to the ingestion of smoke advected into the central U.S. from persistent wildfires in Central America during the spring and summer of 1998 (Murray et al. 2000). An anomalously high percentage of +CG lightning in the 1998 bow echo event studied by Murray and Orville (1999) was also attributed to modifications in cloud microphysics associated with the ingestion of smoke and pollution from the fires. The percentage of +CG lightning in the low-end DPCS reached >70% shortly before maximum derecho intensity and decreased to <20% following this period. A connection between the trends in the percent +CG lightning and derecho intensity is not as apparent in the other six DPCSs.

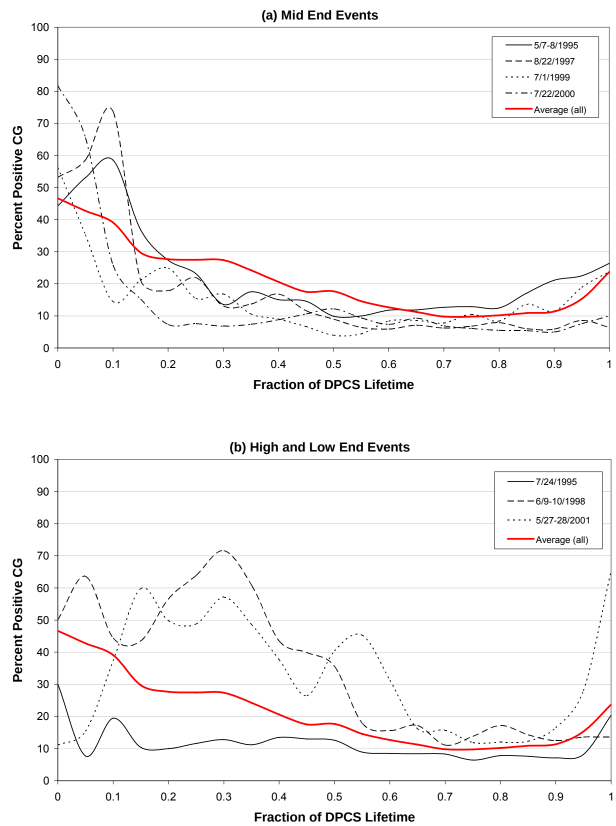

Figure 2. Same as Figure 1, but for trends in the percent +CG lightning.

4. CG LIGHTNING AND STORM STRUCTURE: 22 AUGUST 1997 DPCS

The DPCS of 22 August 1997 began as a classic supercell complex with high reflectivity factors (>65 dBZ) (Figure 3)[1]. Strong convection was also taking place downshear of the supercell. The percent +CG lightning was 79% at this stage. These patterns are qualitatively similar to the early convective period in linear MCSs described by Parker et al. (2001).

The radar-lightning image in Figure 4 corresponds to the time of derecho-genesis. The convective core expanded in size and exhibited an increase in CG lightning density. The percent +CG lightning was 57% and was located mostly downshear of the main convective center (where the initial wind reports were located) in an area of strong reflectivity. Conversely, the developing cells to the south and east were producing predominantly –CG lightning.

The stage of maximum derecho intensity exhibited both bow echo (Figure 5) and squall line (Figure 6) reflectivity and velocity signatures. The radar-lightning image in Figure 5 corresponds to a period of 65-70 kt. wind reports along the apex of the bow. The distinctive horizontal bipole pattern described earlier (Rutledge and MacGorman 1988) is clearly evident with a few –CG flashes occurring in regions of enhanced reflectivity within the stratiform region. Some unique features of the bow echo lightning pattern are the enhanced density of +CG flashes along and to the northeast of the apex and the preponderance of +CG lightning at the western tail of the system.

Approximately 4-hr later the DPCS, which was still producing winds >60 kt. along its leading edge, transitioned into a squall line with a large region of trailing stratiform precipitation and a horizontal bipole pattern. In this DPCS there was not an appreciable difference in CG lightning density or percent +CG lightning between the bow echo and squall line stages, although in two other events the bow echo stage exhibited nearly twice the number of CG flashes than the squall line stage. In each case, rear-inflow notches (e.g. Figure 5) were clearly evident in the radar imagery, suggesting that any relationship between kinematic features of bow echoes and cloud electrification is not a simple one.

The radar-lightning image in Figure 6 corresponds to the period of initial derecho decay; only five wind reports were recorded over the next 1.5-hr leading to derecho decay. The DPCS still exhibited a contiguous convective line, although the strength of the convection had weakened considerably (reflectivity ≤50 dBZ). As such, the CG flash density decreased markedly within the convective line, although a horizontal bipole pattern was still evident. The percentage of +CG lightning did not exhibit much change from when the derecho was at maximum intensity, even though the total CG flash density decreased. This suggests that the +CG flashes occurring in the stratiform region may have originated in the convective line (Shafer et al. 2000). A horizontal bipole pattern was still observed as the derecho ended (Figure 7).

The 22 August 1997 DPCS was one of the few for which we had NLDN data during decaying convection (i.e. following derecho decay). Approximately 1-hr after derecho decay, the radar imagery continued to reveal a weak convective line with an areally-extensive region of stratiform precipitation (Figure 8). Oddly, no +CG flashes were recorded by the NLDN in the vicinity of the radar echoes during this time. Radar-lightning images examined shortly after derecho decay revealed a dissipating +CG lightning mode similar to the one shown by Parker et al. (2001) for linear MCSs.

5. CG LIGHTNING POLARITY AND EXTREME DAMAGING WIND: 27-28 MAY 2001 DPCS

Recent research has demonstrated that narrow swaths of extreme damaging wind (XDW), with peak gusts ≥80 kt. and observed damage >F1 in intensity, are sometimes embedded within the widespread wind corridor of DPCSs (Miller et al. 2002). Although the damage gradient associated with XDW is very tight, such high-intensity winds can last as long as 10-20 min Three main convective elements have been tied to XDW: MCS with embedded supercells, non-supercell MCS (e.g. progressive or serial types), and "hybrid" MCS with a mesovortex. At present, these convective elements are only distinguishable from otherwise ordinary DPCSs using full-volume radar (Miller et. al. 2002). The deployment of mesonet stations (Figure 9) and more detailed post-storm damage surveys can reveal the footprint of XDW, but cannot be used to detect the *development* of XDW for pin-point nowcasting purposes. The applicability of real-time NLDN polarity data to identify XDW corridors is explored in this sub-section using the Memorial Day Weekend 2001 DPCS with embedded supercells (aka "The People Chaser Derecho").

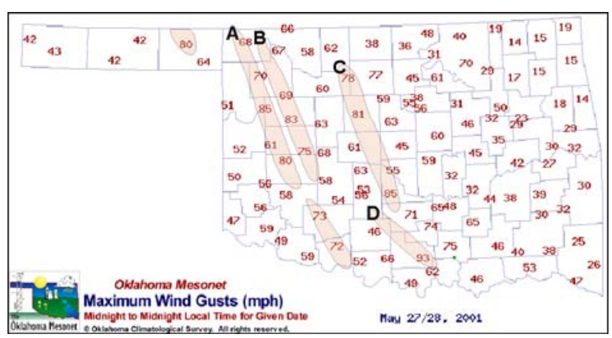

Figure 9. Maximum wind gusts recorded across the OK Mesonet during the passage of the 27-28 May 2001 DPCS. Narrow swaths of XDW (see text) are shaded in light red. Figure adopted from Miller et al. (2002).

[1] Due to space limitations, the reader is referred to the website of the first author to view Figures 3-8: http://www.unc.edu/~fuhrman1

The Memorial Day Weekend DPCS began as a cluster of high-precipitation (HP) supercells in western Kansas during the mid-afternoon of 27 May 2001. Conditions across the central Plains were favorable for tornadic supercell development and storm chasers positioned themselves in southwest Kansas for the clearest and safest views of the storms. Although a few tornadoes were reported early in the DPCSs lifetime, few anticipated that the cluster of supercells would organize into a convective line. Due to the juxtaposition of the supercells, the rear-flank downdrafts merged to form an exceedingly strong and fast-moving gust front that propagated to the south and east in the direction of the storm chasers. As the storm chasers raced south to outrun the gust front (hence the name “The People Chaser”), some of the most breathtaking photographs of supercell structure and dynamics in the lore of storm chasing were captured.

As the DPCS moved through Oklahoma, stations within the Oklahoma Climatological Survey Mesonet recorded wind gusts generally <50 kt in the eastern half of the state, while wind gusts >50 kt and XDW were primarily observed west of Oklahoma City (Figure 9). Miller et al. (2002) attributed the regions of XDW to HP supercells embedded in the convective line of the DPCS. Examination of the 5-min +CG flash rate as the DPCS was propagating through Oklahoma revealed a near absence of +CG lightning in the zone of non-XDW, while numerous +CG flashes occurred in the zone of XDW associated with the HP supercells (Figure 10). Interestingly, this pattern was observed for >2-hr period (0211-0428 UTC 28 May 2001) while XDW winds were occurring in western Oklahoma.

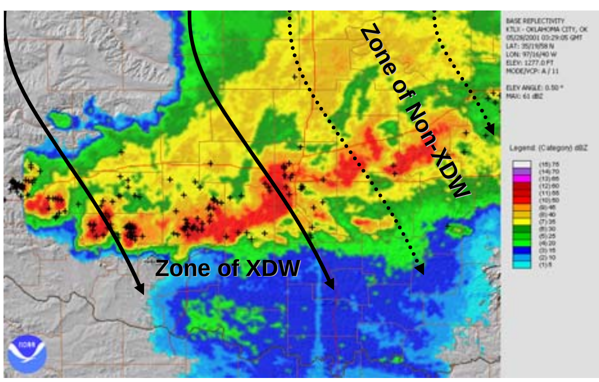

Figure 10. Low-level base reflectivity and +CG lightning overlay for 0329 UTC 28 May 2001. Arrows demarcate the zones of XDW and non-XDW as inferred from Figure 9. +CG flashes are from a 10-min period centered on the time of the radar image.

Radar-lightning images from earlier in the DPCS’s lifetime (i.e. near the Kansas-Oklahoma border) did not reveal a geographical preference for +CG flashes within the leading line of HP supercells. Only after XDWs commenced did a +CG lightning-wind corridor relationship become evident, as reflected in Figure 10. A geographical preference for the location of –CG flashes was not inferred during this DPCS. It is important to note that full-volume radar scans indicated HP supercell structure in both the XDW and non-XDW zones, yet the occurrence of +CG lightning was noted almost exclusively within the XDW zone. By combining real-time NLDN polarity data and full-volume radar scans, it is possible in at least some cases to identify zones of XDW in DPCS with embedded supercells.

6. DISCUSSION AND CONCLUSIONS

Data from the NLDN were used in conjunction with a unified derecho database to determine the characteristics of CG lightning associated with a sample of warm-season DPCSs across the central and southern Great Plains. Low-level base reflectivity images were also used in conjunction with the NLDN data, as well as with storm reports and Oklahoma Mesonet observations of severe and damaging wind, to determine the horizontal patterns of storm electrification at different stages of DPCS structure and intensity.

Perhaps one of the more revealing aspects of this research is the high CG flash densities associated with DPCSs compared to other convective systems examined in the literature. The mean 1-min CG flash rate associated with the seven DPCSs was nearly three times higher than the mean rate of the 25 MCSs inferred from MacGorman and Morgenstern (1998) and as much as four times higher than the mean rate of a small MCC sample inferred from Goodman and MacGorman (1986), who suggested that MCCs were at the “high end” of the CG rates associated with MCSs. Interestingly, the *maximum* 1-min CG flash rate identified in the present work was more than twice that found in the bow echo event from Murray and Orville (1999). Recall that this event, while having produced a 96 kt wind gust, did not meet the length requirement for derecho classification. Future research should examine the contribution of storm-relative dynamic features to the electrification of both derecho and non-derecho bow echo MCSs.

Six of the seven DPCSs examined in this study had a +CG lightning fraction that was higher than the values for trailing stratiform MCSs identified by MacGorman and Morgenstern (1998), yet was comparable to the values for linear MCSs identified by Parker et al. (2001). Further, the trends in the +CG lightning fraction throughout most of the DPCSs were qualitatively similar to those identified by Parker et al. (2001). The apparent connection between an anomalously high +CG lightning fraction and derecho intensity suggested by Price and Murphy (2002) may be unique to the northern Great Lakes region, where the frequency of +CG-dominant severe storms is maximized (Carey et al. 2003). Recent research (Carey and Buffalo 2006) has demonstrated that the region of +CG-dominated storms extends into western Kansas where four of the seven DPCSs originated. While Carey and Buffalo (2006) contend that the +CG lightning anomaly in this region is due to unique features of the mesoscale environment, we believe that an unknown portion of this anomaly may be attributed to the genesis of long-lived MCSs that exhibit an early +CG convective mode as described by Parker et al. (2001).

Similar to the linear MCSs described by Parker et al. (2001), a horizontal bipole pattern was clearly evident during the bow echo stage of the 22 August 1997 DPCS. It was also observed in other DPCSs that the bow echo stage produced nearly twice as many CG flashes than the squall line stage. One of the more revealing features of the bow echo-lightning structure was the preponderance of +CG flashes near the apex of the bow and along the tails of the convective line (in most cases, along the western or southern tail). A similar pattern was noted by Marshall and Rust (1993). These observations beg the question: how do the storm-relative features unique to bow echo MCSs (e.g. rear-inflow jet, mesovortices) contribute to storm electrification? Additionally, the relationship between the peak in the CG flash rate and the intensity of the derecho winds warrants further investigation.

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