Characteristics of Sprite-Producing Positive Cloud-to-Ground Lightning during the 19 July 2000 STEPS Mesoscale Convective Systems

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ABSTRACT

During the summer of 2000, the Severe Thunderstorm Electrification and Precipitation Study (STEPS) program deployed a three-dimensional Lightning Mapping Array (LMA) near Goodland, Kansas. Video confirmation of sprites triggered by lightning within storms traversing the LMA domain were coordinated with extremely low frequency (ELF) transient measurements in Rhode Island and North Carolina. Two techniques of estimating changes in vertical charge moment (M_q) yielded averages of ~800 and ~950 C km for 13 sprite-parent positive polarity cloud-to-ground strokes (+CGs). Analyses of the LMA's very high frequency (VHF) lightning emissions within the two mesoscale convective systems (MCSs) show that +CGs did not produce sprites until the centroid of the maximum density of lightning radiation emissions dropped from the upper part of the storm (7–11.5 km AGL) to much lower altitudes (2–5 km AGL). The average height of charge removal (Z_q) from 15 sprite-parent +CGs during the late mature phase of one MCS was 4.1 km AGL. Thus, the total charges lowered by sprite-parent +CGs were on the order of 200 C. The regional 0°C isotherm was located at about 4.0 km AGL. This suggests a possible linkage between sprite-parent CGs and melting-layer/brightband charge production mechanisms in MCS stratiform precipitation regions. These cases are supportive of the conceptual MCS sprite-production models previously proposed by two of the authors (Lyons and Williams).

1. Introduction

Since their serendipitous discovery during tests of a low-light television (LLTV) camera in Minnesota during the summer of 1989 (Franz et al. 1990), it has become clear that mesospheric sprites occur worldwide. Observations have been reported above Japan (Fukunishi et al. 1999), Australia (Hardman et al. 2000), Europe (Neubert et al. 2001), near China (Su et al. 2002), and, most recently, Brazil (R. Holzworth 2002, personal communication). The first ground-based campaign intentionally searching for sprites with LLTVs was conducted at the Yucca Ridge Field Station (YRFS) near Fort Collins, beginning on 7 July 1993. That first night, 248 events were recorded above a large mesoscale convective system (MCS) in Kansas (Lyons 1994). Subsequent annual airborne (Sentman et al. 1995) and ground campaigns have confirmed over 8000 sprites over the U.S. High Plains, suggesting that the meteorological conditions prevalent on summer nights in this region may be among the most conducive to sprites in the world (Lyons et al. 2000).

Initial studies of High Plains MCSs noted that sprites were uniquely associated with positive polarity cloud-to-ground strokes (+CGs) occurring during the MCS's mature-to-late stages, often after +CGs had been occurring for several hours (Lyons and Williams 1993; Boccippio et al. 1995; Lyons 1994, 1996). Sprites tend to cluster over portions of the expanding stratiform precipitation region once the MCS attains a radar-echo size of ~20 000 km² (as defined by reflectivity values >~10

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dBZ). Sprites have occasionally been observed above smaller storms covering 2500–7500 km^2 (Stanley 2000), but such occurrences appear to be much more the exception than the rule. Often convective storms generate many +CGs but produce no sprites, and in those that do, the ratio of +CGs that produce sprites is often <1:100 and rarely rises to 1:5, even in the most prolific systems. National Lightning Detection Network (NLDN) +CG peak currents have been investigated as a possible predictor for sprites (Lyons 1996). While the sprite-parent +CG (SP+CG) peak currents often average ~50% higher than other +CGs in the storm, sprites also occur with peak currents smaller than 20 kA. Thus, +CG peak current does not appear to be a robust predictor of sprite potential (Huang et al. 1999).

Several theories have been advanced to explain sprite formation (Rowland 1998). One proposes runaway electron avalanches within the strong, downward-directed mesospheric electric field induced by tropospheric lightning lowering positive charge to ground, which requires a +CG (Roussel-Dupre and Gurevich 1996). The second theory, conventional dielectric breakdown, has recently become the more favored mechanism (Boccippio et al. 1995; Pasko et al. 2001; Cummer et al. 1998; Huang et al. 1999; Williams 2001). In this process, sprites are triggered by the rapid removal of large amounts of charge from a laterally extensive charged layer, which in turn stresses the mesosphere to dielectric breakdown. The breakdown occurs when mesospheric quasi-static electric fields that exceed a certain threshold value are generated by a highly atypical CG stroke. The mesospheric field is essentially linearly proportional to the lightning's charge moment change (M_q), defined as the product of the amount of charge lowered (Q) and the height from which it is lowered (Z_q), a concept dating back to Wilson (1925). In the low-density air of the middle atmosphere, the imposed electric field exceeds the dielectric strength and initiates a conventional breakdown process. Using high-speed LLTV imagers, Stanley et al. (1999) confirmed that most sprites initiate within very small volumes around 75-km altitude and then propagate (sometimes first) downward and upward as corona streamers at velocities in excess of 10^7 m s^{-1}. Williams (1998, 2001) and Huang et al. (1999) computed that for conventional dielectric breakdown to occur at this altitude, M_q values on the order of ~750 C km are required. The threshold M_q values are thought to be much larger for conventional breakdown than for the runaway avalanche mechanism (Huang et al. 1999). Such M_q values are much more than an order of magnitude larger than found in ''ordinary'' negative lightning (Uman 1987). But evidence is accumulating that such events do occur. For instance, Cummer and Stanley (1999) provided evidence for M_q values up to 1100 C km as sprite optical emissions reached their peak, typically 2–11 ms after the SP+CG return stroke.

There is nothing inherent in the conventional breakdown hypothesis that favors positive polarity lightning strokes. Only a very small subset of CGs appear capable of transporting the large amounts of charge to earth required for sprites. This is likely due, in part, to unusually large and long-lasting continuing currents. The current presumption is that +CGs are far more likely than negative polarity cloud-to-ground strokes (−CGs) to possess the required characteristics. Continuing currents of 10 kA persisting for 5 ms were reported in +CGs by Brook et al. (1982). Cummer and Fullekrug (2001) similarly provide evidence for unusually large +CG continuing currents, perhaps several tens of kiloamps, lasting for tens of milliseconds. It is noted that there are only two documented cases (over Mexico) of negative CGs producing sprites, and that their M_q values were exceptionally large: ~1500 C km (Barrington-Leigh et al. 1999). Over the U.S. High Plains, in 7 yr of monitoring, no −CG has been confirmed as the parent of a sprite. We also note, however, that large peak current negative CGs (>75 kA) occur more frequently over the High Plains than their positive counterparts (Lyons et al. 1998). Video monitoring reveals that these −CGs are also often associated with long-lasting (>100 ms) continuing currents. These discharges presumably can tap into large areas of negative space charge within MCS stratiform regions with magnitudes comparable to the positive space charge layers (Stolzenburg et al. 2001). Based upon studies conducted largely in other geographic regions, it is generally presumed that the initial charge lowered to ground in −CGs (perhaps 10 C) is substantially smaller than in positives and, more important, the continuing currents are very small, generally <0.5 kA (Uman 1987; Koshak and Krider 1989). Whether these parameters are typical of High Plains −CGs is unknown.

Our working hypothesis is that, at least for High Plains MCSs, the most common sprite parents are positive flashes associated with horizontally extensive, low-altitude, positive charge layers that transfer extremely large amounts of charge to ground, both in the initial return stroke and in the continuing current (Lyons 1996). Williams (1998, 2001) proposed that the SP+CG lightning charge transfers of a few hundred coulombs were drawn from the 4–6 km AGL height range, which is close to the average summer melting layer altitude in the region. [Note that all altitudes are above ground level (AGL).] Such large values of Q were required for consistency with theories for sprite optical intensities and to account for extremely low frequency (ELF) Schumann resonance transient signal strengths. That the horizontal component of lightning in large storms can be of mesoscale dimensions (~100 km) has been known for decades (Ligda 1956). The complex electrical structure of MCS stratiform regions has been extensively studied (Stolzenburg et al. 2001; Marshall et al. 2001). MCSs are accompanied by laterally extensive regions of stratiform precipitation, often associated with weak vertical motions (tens of centimeters per second) and radar bright bands just beneath the 0°C isotherm. The type B electrical sounding of Marshall and Rust (1993) is representative of MCS stratiform regions in which the dominant positive charge reservoir coincides with the melting layer. MCS stratiform regions are characterized by several laminae of alternately positive and negative space charge, some less than 1000 m thick. Both charge advection from the convective core and in situ generation appear to play major roles, with the latter predominating (Schuur and Rutledge 2000b). Positive charge densities up to 5 nC m^{-3} have been measured in MCS stratiform regions (Schuur and Rutledge 2000a). Integration of typical charge densities of both polarities over the large stratiform laminae can yield thousands of coulombs. Whether melting processes in the bright band are a significant source of positive charge remains a more problematic issue (Shepherd et al. 1996; Marshall et al. 1996; Schuur and Rutledge 2000a). But it appears that the extended laminae of positive space charge at or near the melting layer (~4 km in High Plains MCSs) are in some storms associated with horizontally extensive (>50–150 km) lightning discharge channels (spider lightning). The dendritic spider lightning channels can access massive quantities of charge that are then brought to ground by the +CG return stroke and the subsequent intense and long-lasting continuing currents (Mazur et al. 1998; Marshall et al. 1996, 2001). A survey of 17 published sprite-modeling papers between 1995 and 2000 found that 75% postulated that the positive charge was lowered from a height of at least 10 km, while 3 papers suggested 15 km or higher. Such Z_q altitudes were elected in part to attain the desired large charge moments. If, however, the charge is removed from the lower portion of the stratiform region (~5 km), the required charge transfers increase to even larger values: 100–200 C.

This paper presents initial analyses of coordinated remote sensing measurements taken during the summer of 2000 Severe Thunderstorm Electrification and Precipitation Study (STEPS). Resources include LLTV sprite video, stroke data from the NLDN (Cummins et al. 1998), the New Mexico Institute of Mining and Technology's three-dimensional Lightning Mapping Array (LMA; Krehbiel et al. 2000), and ELF receivers at several locales monitoring the associated radio frequency (RF) transients to provide estimates of M_q. Our focus will be on SP+CGs within two moderately sized MCSs (10-dBZ radar-echo areas <50 000 km^2) traversing the LMA on 19 July 2000. These STEPS observations allow us to test current conceptual models for sprite-producing lightning and storms (Lyons 1996; Williams 1998, 2001). The LMA provides estimates of the area over which charge is removed by the SP+CG and, more important, the altitude of Z_q, which, along with the estimated M_q value, allows retrieval of the charge lowered to ground.

2. Sprite studies during STEPS

STEPS was a multiagency effort deploying a variety of in situ and remote sensing systems to investigate the coevolving microphysical, dynamical, and electrical nature of High Plains convective storms, especially those producing large numbers of +CGs. Operations were conducted from mid-May through July 2000. The centerpiece of the experiment was the LMA (Krehbiel et al. 2000), with a nominal 250-km range, centered at 39.5°N, 102.0°W (northwest of Goodland, Kansas). Our specific task was to quantify the characteristics of the +CGs that created sprites, as well as to explore the convective storm regimes that gave rise to these unusual lightning discharges. The STEPS domain was located on the western edge of a band of climatologically elevated +CG flash densities over the northern High Plains (Orville and Huffines 2001). This roughly coincides with the region in which high percentages of all flashes exhibit positive polarity, mean positive peak currents are above average (Orville and Huffines 2001; Zajac and Rutledge 2001), and large peak current (>75 kA) +CGs are frequent (Lyons et al. 1998). During summer, orogenic convective systems frequently advect eastward into the High Plains during the afternoon and evening, followed by upscale development into large MCSs, which often persist through the night as they travel farther eastward.

YRFS, located about 275 km to the northwest of the LMA centroid, was at an ideal range for LLTV monitoring of sprites and other transient luminous events (TLEs) above STEPS nocturnal storms. LLTV intensifiers included a red sensitive GEN II Xybion ISS-255 and an ultrablue extended GEN III ITT NQ 6010. Video streams were GPS time stamped, resolving individual 16.7-ms integrated video fields. Very low frequency (VLF) audio (1–10 kHz) was recorded on the tape audio tracks. In addition to NLDN stroke level files, we archived Next-Generation Weather Radar (NEXRAD) single-site and regional-radar mosaics, Geostationary Operational Environmental Satellite (GOES) infrared images, and upper-air data from Internet sources.

The three-dimensional LMA deployed during STEPS, described in detail by Krehbiel et al. (2000), detects very high frequency (VHF) radiation (60–66 MHz) bursts emitted by processes within the lightning discharge. Using multiple remote locations, GPS technology measures the arrival time of the radiation independently at each receiver. The best-case locational accuracy of 50–100 m occurs within the network. Locational errors increase with distance, as locations become two-dimensional at large distances. Radio signal propagation is primarily line of sight, causing the minimum detectable source altitude to increase with range. While emissions can be received for distances greater than 200–250 km, they are confined to the upper portion of the storm. The LMA horizon is ~4 km at 200-km range, but it is below 2 km within 100 km. In general, the best candidates for studying complex 3D discharges are <150 km from the LMA centroid.

During STEPS, predictions were issued via e-mail messages at 2200 UTC for sprite potentials within 750–

1000 km of YRFS for the upcoming night. During actual sprite conditions, hourly nowcast e-mail messages alerted several teams of ELF researchers to obtain correlated measurements. A total of 1237 TLEs (90% sprites) were observed using LLTVs on 22 nights during STEPS. More important, 161 sprites on 13 nights occurred within 300 km of the center of the LMA: 62 closer than 200 km and 39 within 150 km. Figure 1a shows the locations of YRFS, the LMA coverage, and the SP+CGs confirmed by the NLDN, while Fig. 1b shows their range distribution from the centroid of the LMA.

3. Meteorological and NLDN analyses

At 0000 UTC 19 July 2000, conditions were favorable for the development of vigorous nocturnal convection over the Colorado High Plains and farther eastward into Kansas. Surface dewpoints were generally >15°C, providing for areas of relatively high convective available potential energy (CAPE) values above 3000 J kg^{-1}. Weak, low-level southerly flow was capped by stronger (>20 m s^{-1}) westerly winds above 500 hPa. We note that at 0000 UTC 19 July 2000, the 0°C isotherm level at Dodge City, Kansas (to the south of the MCSs), was at 4.3 km, and was 3.8 km at North Platte, Nebraska (to the north of the MCSs).

Rather typically, convection initiated early the prior afternoon above the Colorado Front Range and several systems moved eastward into the near-surface moisture supply. Initially many of the storms displayed supercell characteristics. As sunset approached (~0300 UTC), some of these cells began evolving upscale into larger MCSs in eastern Colorado, and two of these subsequently traversed the LMA domain. The first, MCS 1, crossed the Colorado–Kansas border around 0100 UTC (1800 LST). It grew rapidly and reached its mature stage around 0300 UTC. The LLTV cameras were activated at 0300 UTC to monitor for sprites above MCS 1. Considerable debris cloudiness made sprite detection rather problematic during the first hour. Several VLF audio signatures characteristic of sprites were noted, however. As the debris clouds overhead cleared, moderately bright, ''carrot-type'' sprites were optically confirmed at 0348 and 0356 UTC. Though radar indicated that this system was increasing in size at 0400 UTC, by that time a rapid warming of the cloud-top temperatures in the GOES infrared imagery was underway, indicating that the storm was losing vigor. No further sprites were detected from this system.

MCS 2 produced the majority (15) of the 17 sprites as it followed a path just slightly to the south of the first MCS. This MCS likewise initiated as afternoon supercell severe thunderstorms producing hail up to 4.5-cm diameter developed over eastern Colorado. These cells then rapidly evolved upscale into an MCS by 0430 UTC as they crossed into Kansas. Neither MCS was exceptional in size or intensity for nocturnal convective storms in Kansas. These modest MCSs produced far fewer sprites, for instance, than the massive mesoscale convective complex of 18 August 1999, which produced over 120 sprites (Lyons et al. 2000).

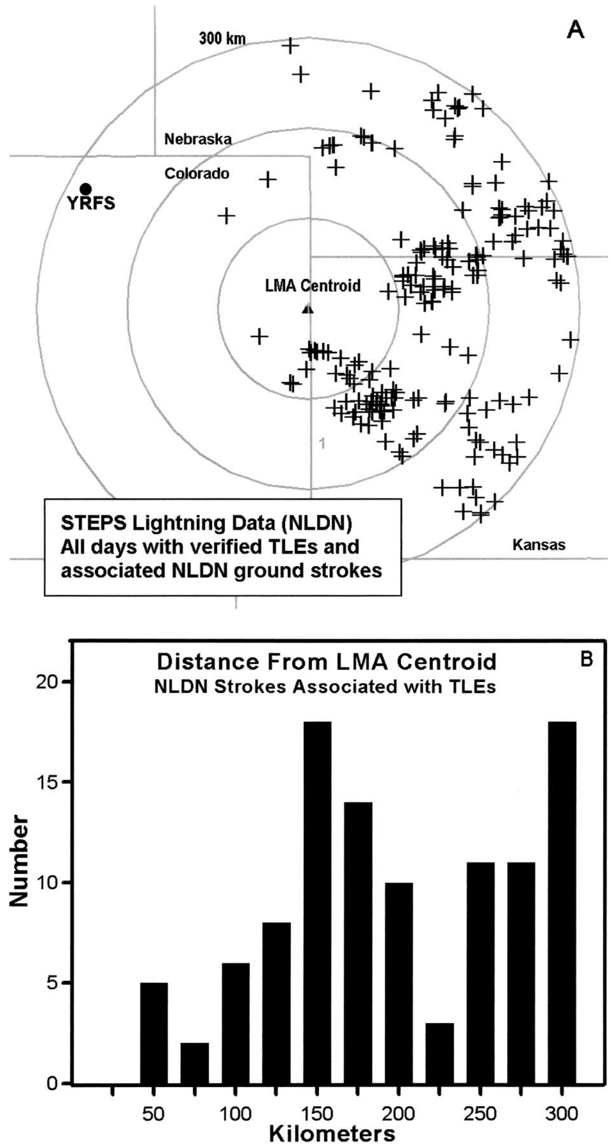
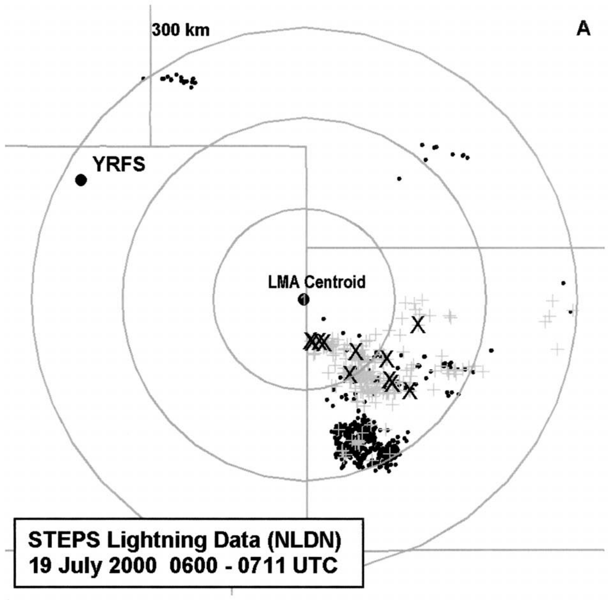
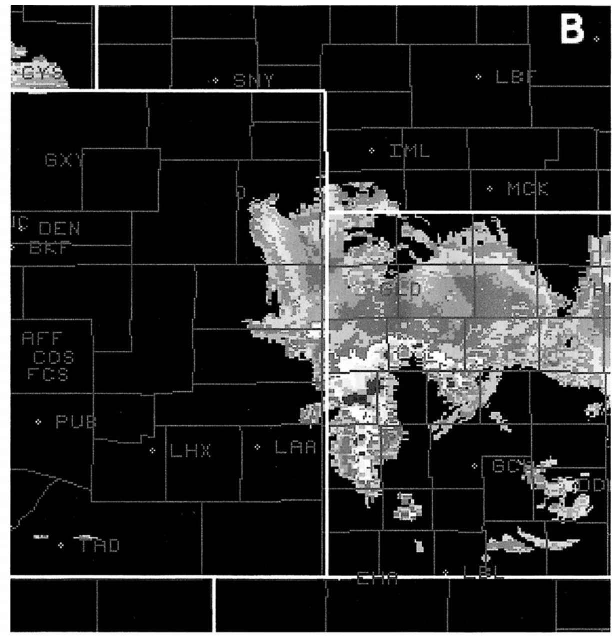


FIG. 1. (a) NLDN-determined locations of SP+CGs observed during the STEPS campaign and (b) their distribution as a function of range (km) from the centroid of the LMA. LLTV cameras monitored sprites optically from their location at YRFS.

The MCS 2 sprites occurred between 0551 and 0711 UTC. As shown in Fig. 2a, within MCS 2 the patterns of cloud-to-ground strike locations exhibited a distinct bipolar separation of positive and negatives flashes. The −CGs clustered around the convective core, while most +CGs, along with the sprite parents, were found in the large stratiform precipitation region to the north. Most of the SP+CGs were associated with base radar reflectivities of <35 dB*Z* (Fig. 2b). The SP+CGs clustered about 50–100 km north of the area of the coldest (highest) cloud tops (Fig. 2c).





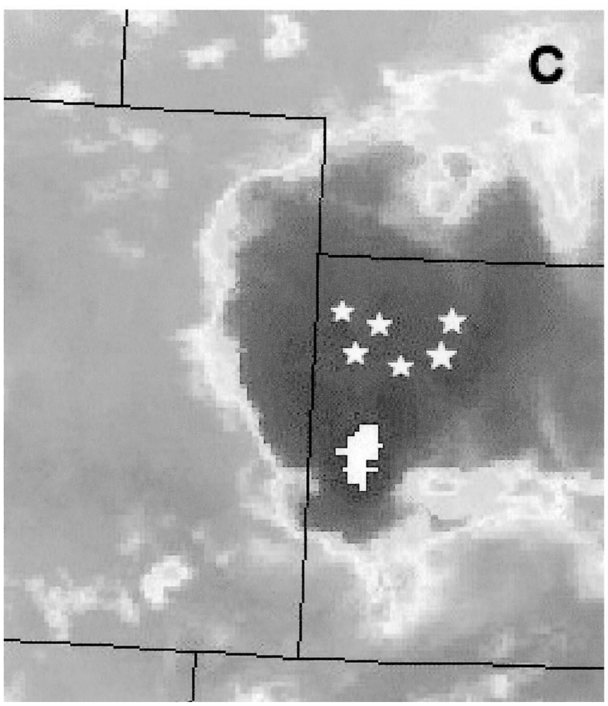


FIG. 2. (a) Location of −CGs (black dots), +CGs (gray crosses), and SP+CGs (black Xs) during the 71-min period of max sprite production from MCS 2; (b) base radar reflectivity at 0615 UTC, with lightest colors surrounding the highest values; and (c) GOES infrared image at 0630 UTC 19 Jul 2000. Stars indicate approximate location of selected SP+CGs. The coldest cloud-top pixels are shown in white.

Table 1 summarizes the data for sprites, their parent lightning, and LMA-derived parameters. The average sprite illumination duration was 59 ms (17–119 ms). The estimated minimum time delays between the SP+CG and the optical sprite onset ranged from 4 to 130 ms, with an average of 45 ms. The SP+CGs occurred from 44 to 186 km of the LMA centroid, with an average of 96 km.

NLDN lightning-stroke characteristics for these MCSs were consistent with previously studied, sprite-producing MCSs (Lyons 1996). Figure 3a shows hourly totals of average peak current values of negative and positive lightning strokes, along with those for SP+CGs, while Fig. 3b plots the number of −CGs, +CGs, and SP+CGs. These statistics are summed for both MCSs, though after 0500 UTC they were dominated by the stronger MCS 2. During the period of active sprite monitoring (0300–0711 UTC), 4319 strokes were detected, of which 23% were positives. The −CG peak averaged 22 kA, while the +CGs were consistently

TABLE 1. Summary of information for 17 sprite events from two MCSs on 19 Jul 2000 over the STEPS domain. Left to right, the NLDN stroke time of the parent lightning, its polarity, and its peak current; the start time of the first video field showing an image of the sprite, the video duration of the spite, the minimum lag time between the parent CG and the sprite initiation; the azimuth and range (km) from YRFS of the +CG, and the range from the LMA centroid; the charge moment change (M_q) computed from the Duke and MIT ELF systems; the area covered by the sprite-parent lightning, and the mean altitude from which the charge was drawn (Z_q), as determined by the LMA.

NLDN CG time, polarity, and peak current		Sprite video		CG − TLE	From YRFS		From LMA	Charge moment M_q ($C \cdot$km)		LMA data		
Time (UTC)	kA	Start time of 1st video field	Event duration (ms)	start (ms)	Azimuth (degree)	Range (km)	range (km)	Duke	MIT	Area (km^2)	Z_q (km)	TLE description
MCS 1												
0348.54.042	+50	0348.54.057	51	>12	112	437	163	>568	786	—	—	1 bright carrot
0356.10.196	+48	0356.10.205	67	>9	112	460	186	>406	816	—	—	Small carrot
MCS 2												
0551.23.241	+98	0551.23.293	51	>52	125	305	44	—	1094	1155	4.5	Small carrot
0556.06.820	+68	0556.06.885	85	>65	122	355	140	—	—	1102	5.0	Carrot, c-sprite
0557.29.429	+85	0557.29.417	85	>6	125	309	48	>702	1165	1332	5.0	2 small c-sprites
0558.00.461	+62	0558.00.495	51	>34	122	337	66	—	752	1496	5.0	1 dim c-sprite
0559.30.339	+32	0559.30.469	51	>130	124	359	91	—	—	2408	4.5	Small carrot
0600.15.261	+30	0600.15.364	67	>103	124	309	47	—	525	1144	4.5	2 dim carrots
Nondetect	n/a	0600.55.138	51	—	—	—	—	—	—	558	4.5	Dim c-sprite
0604.22.558	+45	0604.22.595	119	>37	121	357	82	—	—	2408	4.0	1 carrot
0610.41.470	+53	0610.41.581	33	>111	123	322	53	—	1762	1892	3.5	1 small carrot
0611.15.888	+61	0611.15.906	100	>18	125	366	98	>358	493	560	5.0	1 dim c-sprite
0615.44.075	+38	0615.44.154	67	>79	123	317	50	—	376	912	4.0	1 dim carrot
0622.10.921	+73	0622.10.969	51	>48	124	310	49	—	826	486	4.0	1 small carrot
0650.38.821	+127	0650.38.808	33	<4	122	410	135	1655	1776	800	3.5	Bright c-sprites
0652.31.821	+104	0652.31.811	17	<7	122	405	131	<829	1083	880	3.0	6 c-sprites
0711.39.763	+111	0711.39.755	33	<9	121	431	156	1042	986	2450	2.0	Halo, 4 carrots
Range	30–127		17–119	4–130				358–1655	376–1776	558–2450	2–5	
Average	+68		59	45				794	957	1306	4.1	

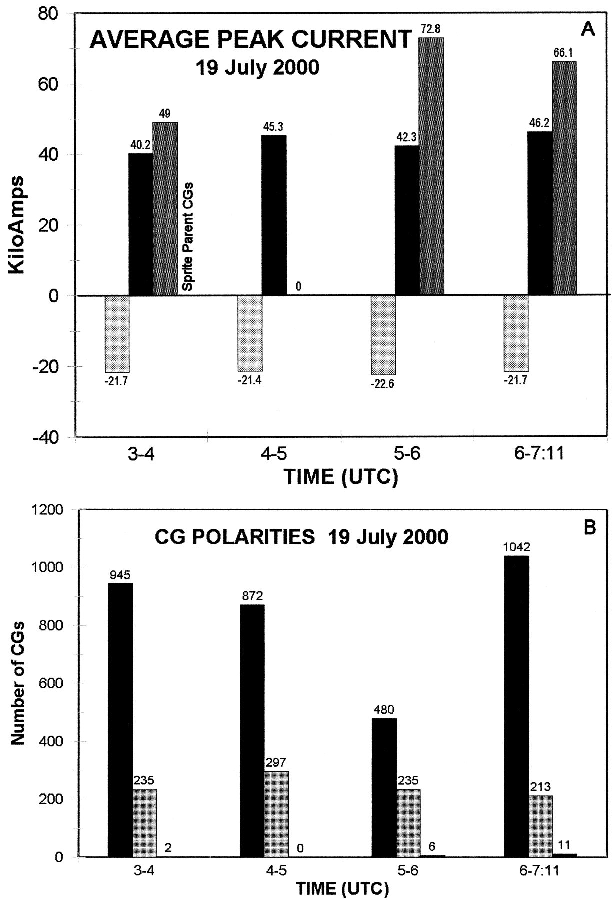


FIG. 3. (a) Hourly average peak currents (kA) for NLDN-detected strokes from both MCSs, for −CGs, +CGs (black), and SP+CGs (gray). (b) Number of NLDN-detected −CGs (black), +CGs (stippled), and SP+CGs during the sprite observation period 0300–0711 UTC 19 Jul 2000.

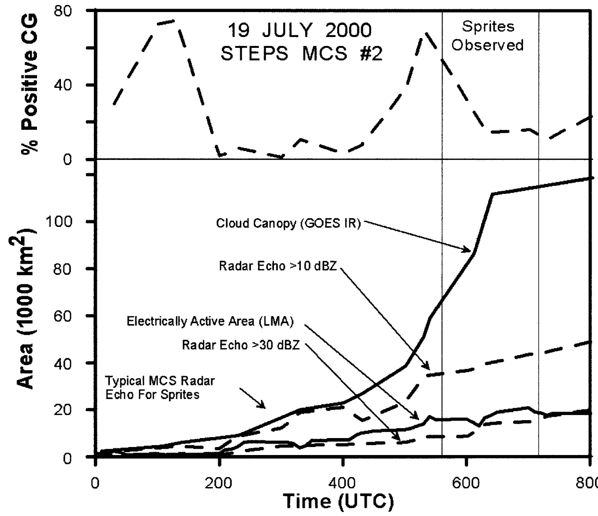


FIG. 4. History of key parameters for MCS 2 on 19 Jul 2000. The percentage of strokes with positive polarity detected by the NLDN is shown on top. Also shown are the area covered by VHF electrical emissions detected by the LMA, the area of base radar reflectivities >10 and >30 dB*Z*, and the area of the cloud canopy on the *GOES-8* infrared imagery. The period during which 15 sprites were detected from 0551 to 0711 UTC is indicated.

twice as large (44 kA). Of the 17 observed sprites, 16 were associated with NLDN-detected SP+CGs (a 94% detection rate). The lone nondetected event was associated with an extremely dim sprite. Three sprites were accompanied by two-stroke +CG flashes. The tendency of some sprites to have multistroke positive parents was previously noted by Lyons (1996). The peak currents for the SP+CGs averaged 68 kA, 55% larger than the average for other +CGs in the storms. The range in SP+CG peak currents, however, was substantial, from 30 to 127 kA, again suggesting this metric may not be especially predictive of sprites.

The evolution of MCS 2 is portrayed in Fig. 4, covering the period from 0000 to 0800 UTC. Before sunset, the storm was small, supercellular in nature, and exhibited high percentages (up to 70%) of +CGs, many associated with high-reflectivity convective cores. Figure 4 also shows the size of the cloud canopy, the size of the detectable precipitation region (>10 dB*Z*), the area of heavier, mostly convective precipitation (>30 dB*Z*), and the area of VHF electrical emissions observed by the LMA. After sunset, the storm grew steadily in size and exhibited a second period of high percentages of +CGs around 0500 UTC. Operational experience at YRFS has documented that sprites tend to occur once the MCS develops considerable stratiform precipitation regions as the >10 dB*Z* region grows larger than 15 000–20 000 km^2. The period of sprite activity for MCS 2 commenced as the radar-echo area reached 34 000 km^2. Interestingly, this was a period of declining numbers and percentages of CGs with positive polarity. This suggests that it is not the absolute number of +CGs but specific qualitative characteristics of some +CGs that enhances the probability of sprite production in a storm.

4. ELF determinations of charge moment changes (M_q)

STEPS provided an opportunity to coordinate remotely sensed ELF transients at several locations worldwide originating from the SP+CGs of YRFS's optically confirmed sprites. Boccippio et al. (1995) first linked LLTV-detected sprites at YRFS with distinctive ELF Schumann resonance transients (*Q* bursts) associated with SP+CGs. Several geolocation techniques for SP+CGs during STEPS included single-station direction finding from the Tohoku University receiver at Syowa Station, Antarctica (16.8 Mm), which resulted in great circle propagation paths approaching the SP+CGs, with an average error of 240 km for the STEPS sprites on 4 July 2000 (Sato et al. 2003). Price et al. (2002) demonstrated the effectiveness of a hybrid ELF/VLF range- and direction-finding system for SP+CGs from the same storm. A high detection efficiency, low false alarm rate, and an average locational error of 184 km were noted at a range of 11 Mm. Moreover, two ELF installations, one at Duke University (Hu et al. 2002), Durham, North Carolina, at a range of 2.0 Mm, and the other operated in Rhode Island by the Massachusetts Institute of Technology (MIT; Huang et al. 1999), at a range of 2.7 Mm, were capable of determining the charge moment changes associated with SP+CGs. The 19 July STEPS storms permitted the first comparisons, for specific SP+CGs, of results from two ELF receivers (though using slightly differing analysis techniques).

The Duke technique, applied in the upper ELF band, is described in Cummer and Inan (2000). The 50 Hz–5 kHz signal was sampled at 25 kHz, with GPS time stamping. The system is capable of monitoring M_q on a submillisecond scale for the first 10–20 ms of the event, and if the exact time of sprite onset is known, it also determines the value of charge moment change associated with sprite initiation. Hu et al. (2002) detected ELF transients from 881 sprite SP+CGs from 17 STEPS intensive periods. For a subset of the events, it was possible by using LLTV images to determine the lightning M_q for sprite initiation occurring within ~6 ms of the SP+CG return stroke. While an M_q value as low as 120 C km was noted, most events were much larger. It was estimated that +CG charge moment changes had to reach 600 C km to have a 10% probability of sprites, whereas M_q values >1000 C km produced sprites 90% of the time.

The MIT technique for analysis of ELF transients in the Schumann resonance band has been described in considerable detail by Huang et al. (1999). The approach estimates the charge moment change for the entire lightning discharge, based on the assumption that the time for the lightning charge transfer is short in comparison to the time required for the signal to propagate around the earth. By definition, this approach overestimates the M_q value responsible for the initiation of the sprite. A detailed study of a major sprite storm (24 July 1996) suggested a minimum M_q of ~300 C km for sprite production (Huang et al. 1999), later revised to ~750 C km after adjusting the assumed altitude of sprite initiation from 55–60 to 75 km.

As detailed in Table 1, of the 17 sprites detected in the 19 July MCSs, charge moment changes were computed using both methods for seven SP+CGs. Values of M_q were provided by the MIT method for six additional SP+CG events. Values of M_q for four sprites, among the dimmer events during this storm, were not retrieved by either method. The Duke method showed a range from 358 to 1655 C km, with an average of 794 C km. The MIT method produced a range from 376 to 1776 C km, with an average of 957 C km, which, as expected, was larger (by 21%). Six of the seven MIT-determined charge moments were larger than the Duke estimate. The reason for fewer Duke results is not that the transients were not detected but that sprite initiation

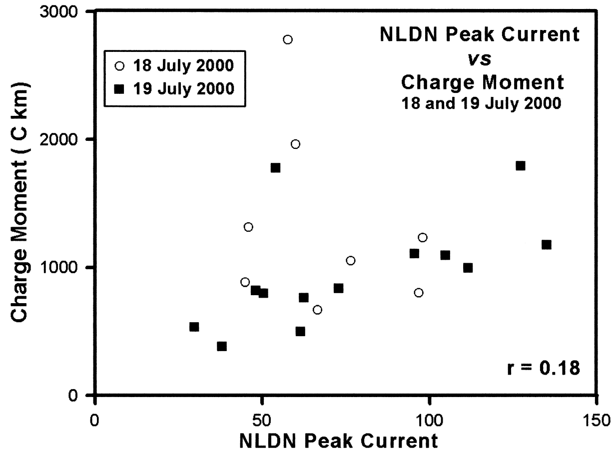


FIG. 5. NLDN peak current vs charge moment change computed by the MIT technique for SP+CGs for MCSs near the LMA on 18–19 Jul 2000. The computed value of R is 0.18.

after the SP+CG was substantially longer than the 20-ms interval for which the technique is optimal.

Thus, these MCSs produced SP+CGs M_q values comparable with the analyses of the overall STEPS dataset. A similar analysis was conducted from an MCS occurring on the prior night. For eight sprites, the Duke method computed an average M_q of ~850 C km, and MIT averaged ~1350 C km, again larger as expected. A plot of the MIT M_q values versus the SP+CG peak currents for both nights is shown in Fig. 5. While there is a weak positive correlation, the computed R value is a modest 0.18.

While very large M_q values accompany SP+CGs, it is not clear that there exists a single, invariant threshold value for sprite production. The reasons for this are several. The charge moment change itself can have a variety of time histories, as some events are far more impulsive than others. There are likely fluctuations in the mesospheric medium, including the local neutral density and conductivity profiles (perhaps partially influenced by storm-generated, vertically propagating gravity waves). There is evidence that a previously occurring sprite in the same volume of space alters subsequent events (Stenbaek-Nielsen et al. 2000). The role of meteoric dust may also have to be considered (Zabotin and Wright 2001).

5. Results from the LMA

The LMA's VHF emissions integrated over time (typically 10 min) to reveal 3D volumetric displays of the density of the lightning radiation events. (One can retrieve the time-integrated displays for STEPS case studies from the online archive at http://zeus.nmt.edu/~steps). LMA data can also be processed to reconstruct the paths of individual lightning discharges. The VHF emissions were used to map specific individual SP+CGs discharges for the 15 sprites detected in MCS 2.

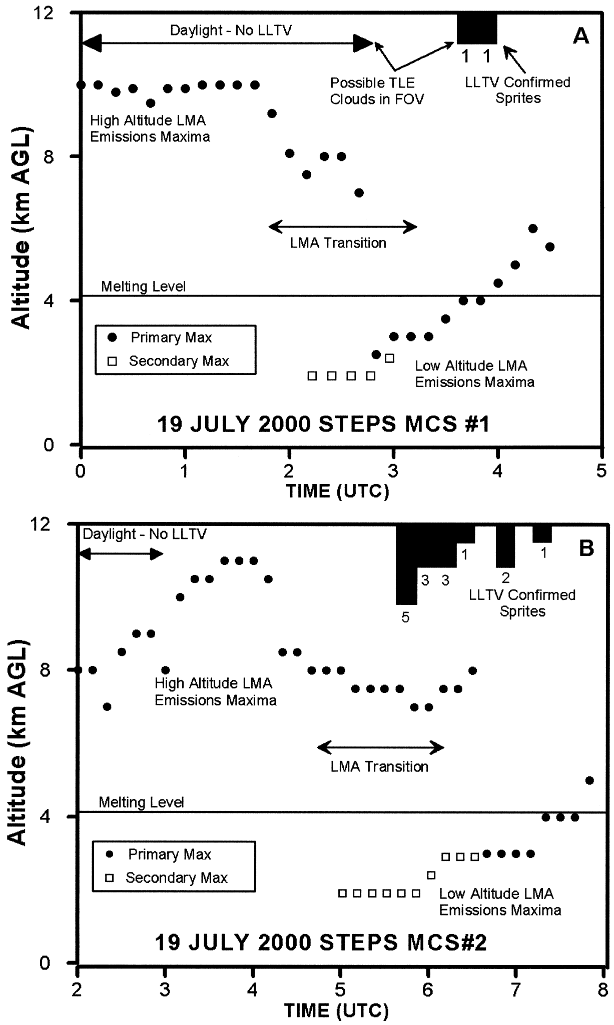


FIG. 6. (a) History of the altitude of the centroid of max VHF emissions detected by the LMA for MCS 1 on 19 Jul 2000 as it moved through the STEPS domain. The occurrence of sprites is indicated at the upper right. (b) The same as (a), but for MCS 2.

Time–height histories, at 10-min resolution, of the altitude of the maximum occurrence of VHF lightning radiation sources for both MCSs are shown in Figs. 6a and 6b. For MCS 1, during the period exhibiting active growth through 0200 UTC, the centroid of maximum VHF lightning emissions remained within the upper portion of the storm, near 10 km. As the storm entered its late mature phase around 0200 UTC, there was a gradual lowering of the upper-level activity. Coincident with this behavior, a secondary emissions maximum formed around 2–3 km. After 0315 UTC, this low-altitude maximum became the primary VHF emissions region. Though rising slowly in altitude thereafter, it remained below 6 km. The two sprites from MCS 1 occurred after the lower activity center became dominant.

Figure 6b shows the same analysis for MCS 2 between 0200 and 0800 UTC. Between 0200 and 0500 UTC, the centroid of lightning radiation sources remained in the upper portion of the storm, above 7 km, and sometimes as high as 11 km. After 0500 UTC, this activity center descended, and a secondary activity center emerged, again below 3 km. Around 0545–0615 UTC, after the onset of strong emissions at lower levels, some +CGs began to produce sprites. Thus, in both MCSs, the onset of sprites followed the transition from high-altitude maxima of lightning radiation sources to much lower heights.

For the 15 sprites generated by MCS 2, we prepared detailed plan and vertical cross-sectional displays of the VHF emissions during the lifetimes of the SP+CGs, including the pre- and post-return-stroke intracloud events. Though the visual analysis of these plots was subjective, it was clear that in all cases the VHF activity was confined to the lower portion of the storm. The results are summarized in Table 1. The estimated altitude from which the majority of the charge appeared to have been lowered to ground varied between 2 and 5 km, with a mean Z_q of 4.1 km. The maximum horizontal linear extent of the entire SP+CG lightning event was typically 20–40 km. Using the smallest rectangle enclosing the region from which the charge was apparently being drawn produced areas from ~500 to ~2500 km^2, with a mean of ~1300 km^2 (assuming the VHF emissions detected the entire spatial extent of the intracloud discharge). These values are comparable to those found by Stanley (2000) for a Florida sprite-producing MCS. The SP+CG LMA emissions for this MCS clearly occurred within the lower portion of the storm. Perhaps not coincidentally, the average Z_q altitude is generally aligned with the height of the melting layer. We note, though, that during the later phases of the storm, Z_q was located below the melting layer. These SP+CGs and their associated low-level spider lightning horizontal channels would appear consistent with the nature of the parent lightning events for MCSs proposed by Boccippio et al. (1995), Lyons (1996), Williams (1998, 2001), and Marshall et al. (2001).

6. Conclusions

Sprites became associated with +CGs during the late mature stages of two moderate-sized High Plains MCSs, as stratiform precipitation regions expanded beyond ~30 000 km^2. These SP+CGs were confined to the stratiform precipitation region where radar reflectivities were generally <35 dB*Z*, in accordance with a conceptual meteorological model for High Plains storms (Lyons 1996; Lyons et al. 2000). Throughout the 0300–0711 UTC observation period, only 1 out of every 58 +CGs produced LLTV-detectable sprites. This ratio varied considerably with time and storm structure, however. The average peak current of the SP+CGs was 55% higher than the storm +CG average, but there was a very wide range in values. Two ELF transient analysis techniques for determining M_q were applied. The Duke method, which retrieves M_q values primarily during the first 20 ms after the return stroke, produced an average value of 794 C km. The MIT method, which estimates total M_q values from the entire stroke, averaged 957 C km, which was, not unexpectedly, larger by ~20%. These M_q values are substantially larger than those believed to be associated with ''normal'' lightning flashes (Koshak and Krider 1989). There was only a weak positive correlation between SP+CG M_q values and NLDN peak current. This weak correlation is understandable if the initial portion of the lightning return stroke is only weakly connected with any subsequent continuing current.

LMA analyses of 15 SP+CGs discharges revealed that the layer from which the charge was lowered to ground varied between 2.0 and 5.0 km, with an average Z_q of 4.1 km. This is much lower than several previous Z_q observations (6–8 km) in Florida storms (Stanley 2000). The Z_q values in MCS 2 were also substantially smaller than the 7- or 10-km values used in recent theoretical sprite models (Pasko et al. 2001). The melting levels (0°C isotherm) for the nearest upper-air stations were 3.8 and 4.3 km. In this case, at least, a strong argument can be made that the positive charge layer generating SP+CGs may be associated with melting-layer/brightband processes. We note, however, that Marshall et al. (2001) documented +CG events that were plausible sprite-parent candidates occurring in layers a few kilometers above the melting layer. The considerable storm-to-storm differences in charge layer structures in various MCSs discussed by Stolzenburg et al. (2001) might provide a clue as to why some MCSs meeting all criteria for sprites sometimes fail to produce any.

Though the MCSs were not unusually large, the SP+CG horizontal discharge lengths were several tens of kilometers and drew from an average area of ~1300 km^2. For both MCSs it was noted that the centroid of VHF lightning emissions measured by the LMA remained at 7–11 km during the developing and early mature phases of the storms. As the centroid of peak VHF lightning emissions became established in the lower part of the storm (below 5–6 km), some +CGs began producing sprites. These results support the conceptual model of the likely range of altitudes of the positive charge reservoir for SP+CGs proposed by Williams (1998, 2001). Clearly many more storms will have to be investigated, but a working hypothesis has now been presented. Future case studies will determine if the LMA-derived temporal and spatial patterns of lightning emission activity provide a robust signature of an MCS about to enter its sprite-production stage.

It appears that large M_q values are a necessary condition for sprites. Yet it is not clear if they represent a sufficient condition. We have not yet determined if there were other large +CG charge moment changes that failed to produce sprites, or, for that matter, if any −CGs with large M_q values were present. We also know little about the climatological distribution of charge moment changes for strokes of either polarity for the High Plains general lightning population. While the results for these MCSs are consistent with past High Plains case studies, we note that other storm types have produced sprites (snow squalls, late-stage supercells, etc.), and the present results may or may not be transferable.

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