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LIGHTNING, SUPERCELLS AND SPRITES

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1. INTRODUCTION

The serendipitous discovery of red sprites by the late Prof. Jack Winckler, while testing a low-light television camera (LLTV) for a sounding rocket mission in 1989, changed forever our view of the middle atmosphere (Franz et al. 1990). Once thought to be dynamically and electrically quiescent, the stratosphere and mesosphere are increasingly understood to be regions of intense gravity waves (much generated by tropospheric convection) and a growing variety of lightning-related electrical discharges and intense transient electric fields (Lyons and Armstrong 2004). The discovery of literal cloud-to-stratosphere electrical discharges from intense thunderstorm tops, including blue jets, giant jets and true upward lightning (Lyons et al. 2004a) continues to engender the need for intensive investigations of this region. However, the relative scarcity and apparently random nature of cloud top discharge events makes them difficulty to study in a systematic manner. Red sprites, by contrast, are increasingly well understood and predictable. During the summer of 2000, a major field program, the Severe Thunderstorm, Electrification and Precipitation Study (STEPS) was conducted on the U.S. High Plains. While its focus was on supercell convection, especially low-precipitation events, the experimental design also allowed for detailed investigations of mesoscale convective systems (MCSs). Sprites are known to frequently occur in association with positive cloud-to-ground (+CG) strokes in MCSs (Lyons 1996), although even in the most productive storms rarely do more than 1 in 5 +CGs trigger a sprite. Theoretical research into red sprite production has seen the proposal and disposal of a number of theories. At the current time, sprites are generally agreed to be the result of conventional dielectric breakdown at approximately 70-75 km height, the result of a strong transient electrical field resulting from the removal to ground of large amounts of electrical charge in a CG flash (Pasko et al. 1996). Though this theory is not polarity dependant, the vast majority of sprite parent CGs are positive (SP+CGs), with only two documented –CG events on record (Barrington Leigh et al. 1999). While the peak current of SP+CGs is typically 50% larger than the other +CGs in the same storm (Lyons et al. 2003b; Lyons 1996), the peak current by itself is not a good predictor of sprite formation.

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As initially suggested by C.T. R. Wilson (1925), the key metric is the charge moment change:

$$\Delta M_q(t) = Z_q \times Q(t) \qquad (1)$$

defined as the product of Z_q, the mean altitude (AGL) from which the charge is lowered to ground, and the amount of charge lowered. [Note this second term is most appropriately considered as a function of time.]

Huang et al. (1999) and Williams (2001) refined Wilson's original theory and proposed, based upon initial measurements gleaned from Schumann resonance ELF transient analyses (Boccippio et al. 1995), that for such breakdown to occur, ΔM_q values would need to be on the order of 500 to 1000 C km. These values are many times larger than what have been believed to be the "normal" values for ΔM_q (Rakov and Uman 2003). The STEPS program provided ideal circumstances to delve into the characteristics of MCS SP+CGs strokes. The key question to be addressed: What is different about those +CGs which trigger sprites? Where in these storms, and during what phase of their life cycle, do these unusual discharges occur?

But STEPS also allowed us to address a companion question. Ten years of experience with LLTV sprite monitoring at FMA's Yucca Ridge Field Station (YRFS) has shown sprites to be relatively rare within supercells, though this convective regime is often accompanied by large peak current +CGs (Stolzenburg 1994; Rust and MacGorman 1998). This paper investigates the characteristics of supercell lightning from the viewpoint of their potential to generate sprites. It applies ELF-based remote sensing methods for the characterization of lightning charge moment changes based upon the concepts proposed by Cummer and Inan (1999). The investigation of sprites has, in fact, lead us to develop new methods to quantify and describe a family of unexpectedly large tropospheric lightning events. Charge moment change is an important new metric which is now being found to vary temporally and spatially within storms and between different convective regimes (Cummer and Lyons 2004a).

2. STEPS 2000

The STEPS program was conducted on the High Plains of eastern Colorado, western Kansas and southwest Nebraska from 22 May through 10 August 2000. The observational program was designed for coordinated measurements of the dynamical, microphysical and electrical processes within several classes of severe storms, especially those producing positive CGs. Lang et al. (2004) provide a complete description of the field program resources and some initial results. Most relevant to our efforts was that STEPS deployed an operational 3-D Lightning Mapping Array (LMA), which provided information on intracloud discharges to ranges approaching 150-200 km (for 3-D mapping) and 300 km (for 2-D mapping) (Thomas et al. 2004). Centered near Goodland, KS, the LMA domain was ideally situated to allow for monitoring sprites and other transient luminous events using a suite of LLTVs and photometers deployed some 275 km to the northwest at YRFS. During the campaign, over 1200 TLEs were documented, with approximately 150 within the prime coverage area of the LMA. [Additional information can be obtained from www.FMA-Research.com]. Coincident with the optical monitoring, ELF transients were recorded by both MIT (Earle Williams) and Duke University (Steve Cummer) for the purpose of extracting ΔM_q values for the CGs occurring within the storms of interest. This represented the first large scale effort to determine not only lightning polarity and peak current within these storms, but also ΔM_q, and for events within the LMA, Z_q and the computed charge (Q) lowered to ground. It also allowed for further testing the hypothesis of Lyons (1996) that SP+CGs tended to be largely confined to portions of the stratiform precipitation region of MCSs, generally in areas with reflectivities <35-40 dBZ once this region had attained a size of >1-2x10^4 km^2. In addition, Williams (1998) had proposed that the SP+CGs were most likely associated with charge removal (Z_q) from the lower stratiform charge layers, in the 0 to -10 C region. This contrasts sharply with the numerous theoretical modeling papers of sprite energetics which postulate Z_q values between 10 and 20 km, in part to allow for generation of sufficiently large ΔM_q to trigger mesospheric breakdown.

3. SPRITES AND MESOSCALE CONVECTIVE SYSTEMS

To maximize the likelihood of imaging sprites in the LLTVs at YRFS, a decade of experience has suggested training the cameras above MCS and MCC stratiform regions (Lyons et al. 2000). Figure1 shows the distribution of +CGs and SP+CGs (boxes) above the MCC of 18 August 1999. During STEPS, the Duke ELF system obtained the ΔM_q values for a large number of SP+CGs. For those events with CG-to-sprite onset time delays on < ~6-10 ms, very little correlation between peak current and ΔM_q could be found (Fig. 2). This is consistent with the notion that for sprites with time delays greater than several milliseconds after the SP+CG, much of the charge transfer occurs after the initial return stroke (as measured by the NLDN), and is accomplished by continuing currents of considerable magnitude (likely fed by the extensive dendritic patterns of spider lightning spreading outward into the large laminae of positive charge found in the MCS stratiform region). Most interesting, a probability distribution of ΔM_q threshold values suggested there was a 10% chance of a sprite for +CGs of 600 C km, increasing to 90% for values of 1000 C km or larger (Hu et al. 2001).

Two modest size MCSs passed through the LMA domain on 19 July 2000. Two techniques of estimating changes in vertical charge moment (ΔM_q) yielded averages of ~800 C km (Duke) and ~950 C km (MIT) for 13 sprite-parent +CGs. Analyses of the LMA's VHF lightning emissions within the two mesoscale convective systems (MCS) show +CGs did not produce sprites until the mature phase of the storm when the stratiform region grew to >3x10^4 km^2. Moreover, the centroid of the maximum density of VHF lightning radiation emissions dropped from the upper part of the storm (7-11.5 km AGL) to much lower altitudes (2 - 5 km AGL) (Fig. 3). The average height of charge removal (Z_q) from the 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 (maximum 345 C). The average area from which charge was removed was ~1300 km^2. These cases are supportive of the conceptual MCS sprite production models previously proposed by Lyons (1996) and Williams (1998).

4. THE 29-30 JUNE 2000 SUPERCELL

Supercells, which were a major focus of STEPS, tend to occur during daylight hours when LLTV monitoring for TLEs is not feasible. After sunset on 29-30 June 2000, a large MCS produced 18 sprites over central Kansas (Fig. 4). The average peak current was 42 kA, with the mean ΔM_q being 1086 C km. All SP+CGs occurred in the lower reflectivity, stratiform region at a considerable distance from the MCS's convective cores. Unfortunately, this MCS was beyond the range of the LMA. One might speculate, however, that the initial in-cloud breakdown may have begun near the convective core, and propagated rearwards into the stratiform charge layers, initiating one or more +CGs which triggered sprites. Such discharge structures have been noted by Lang et al. (2004) and Mark Stanley (2000, personal communication). However, during the prior afternoon, as this MCS was developing, a compact supercell formed within the same air mass in northwestern Kansas, within the LMA domain (Fig. 5). This much-investigated tornadic supercell is described in Lang et al. (2004). The path of this right-turning supercell is evident in Fig. 5, as is the dominant positive polarity (91%) of the CGs, whose peak currents averaged 46 kA.

The Duke ΔM_q retrieval technique, with the sensitivity available at that time (it has since been markedly improved), was able to determine charge moment changes for most of the storm's CGs (Fig. 6a). No individual +CG had an ΔM_q >600 C km, consistent with the sparsity of sprites in most supercells. LMA data for these CGs was processed by CSU (courtesy Kyle Wiens) which allowed us to plot the typical Z_q values for such events (Fig. 6b). With values typically around 7 km AGL, most Q values for the supercell were 50 C and less, large but not exceptional (Fig. 6c). A plot of ΔM_q versus NLDN peak currents for CGs of both polarities is shown in Fig. 7. There appears to be a modest correlation between the two, suggesting that the ΔM_q values were produced by rather impulsive CGs, with much of the charge lowered during the return stroke. Moreover, while the –CG sample is small, with few values reaching even 50 C km, this suggests part of the sprite "polarity paradox" may be explained by systematic differences between the ΔM_q distributions of +CGs and –CGs.

5. THE 25 JUNE 2000 SUPERCELL.

In spite of supercells often exhibiting extremely high intracloud (IC) flash rates and numerous +CGs, they rarely produce many TLEs. The one exception appears to be during their decaying stage when significant stratiform debris clouds develop. On 25 June 2000, a supercell with nearly continuous IC discharges and 80% positive CGs passed through the LMA during nighttime (Fig. 8). It was monitored by several LLTV cameras and was thought to have produced no sprites – until the very last two +CGs of the storm. The "end-of-storm" sprites occurred over the low reflectivity portion of the decaying storm which had reached a size of ~10,000 km^2 (Fig. 8). ULF observations in California (Martin Fuellekrug, personal communication) showed the parent +CGs produced a classic Q-burst. Duke computed the charge moment changes for these last two +CGs, and both exceeded 1300 C km, well above the likely sprite threshold. Yet this storm had been producing high peak current +CGs for several hours (Fig. 9). Just before sunset, electric field soundings (Rust and MacGorman 2002) confirmed an apparent "inverted polarity" structure in this cell. We also note a sharp cessation of +CG events for about one hour, during which the low rate of negative CGs continued. The "end-of-storm" sprites were not totally unexpected. The most likely explanation is that the smaller supercell dimensions during its mature stage constrained the development of the horizontally extensive dendritic structures necessary to support the extensive continuing currents required to produce the requisite large ΔM_q values.

The Duke ELF transient analysis system then retrieved the ΔM_q (6-10 ms duration) for a majority of +CGs between 0300 UTC (the onset of LLTV monitoring) and the end of the storm (0530 UTC) (Fig. 10). The very high values of the "end-of-storm" sprites are evident. But also shown are three ΔM_q events >600 C km that occurred during the active period of the storm. A recheck of the LLTV tapes indeed found three sprites associated with these +CGs, and albeit dim and easily overlooked, did provide evidence of mesospheric electrical breakdown.

The plot of the LMA's VHF returns (Fig. 11) show electrical activity consistently reaching 11 to 14 km until the storm's demise began shortly after 0500 UTC. The centroid of maximum VHF returns remained near 8 km AGL until it dramatically lowered after 0500 UTC. Reminiscent of the pattern found for the MCS (Fig. 3), the two "end-of-storm" sprites occurred during this collapsing phase. The earlier three sprites are another matter. They occurred during a period of presumably strong updrafts and overall high storm electrical activity, when prior experience suggests sprites were most uncommon.

Figure 12 summarizes the storm's electrical structure for the second of the "end-of-storm" sprites. The LMA shows the horizontal IC discharge to extend laterally some 50 km. The peak current was a robust +109 kA, and the ΔM_q was an impressive 1396 C km. The LMA indicated Z_q to be approximately 5 km, resulting in a computed 280 C charge lowered to ground. The discharge area was ~1200 km^2, and assuming that (1) most of the charge was removed from a layer 1000 m in depth, and (2) that 25% of the charge was removed by the event, this implies an initial charge density on the order of 1.0 nC/m^3. Most interestingly, a slow antenna electric field measurement made close to the parent +CG by Mark Stanley (now of Los Alamos National Lab), suggested a significant continuing current after the return stroke, as high as 11 kA in the period 5-10 ms after the return stroke.

By contrast, one of the mid-storm events is shown in Fig. 13. The cell was smaller (7500 km^2) at this time, and the total discharge was also smaller, only about 20 km in horizontal dimension, covering only 160 km^2. The NLDN peak current was +155 kA and the ΔM_q estimated at 1327 C km. Estimating the charge was removed from a layer about 1500 m deep centered at 4 km, and also assuming 25% charge depletion, the initial charge density in the volume was closer to 5-6 nC/m^3. This is a value larger than those typical of MCS stratiform positive charge laminae (Schuur and Rutledge 2000). The slow antenna electric field showed far less evidence of significant continuing current after the return stroke.

We would suggest that the final two "end-of-storm" sprites occurred within a cloud structure more reminiscent of an MCS stratiform region. By contrast, the unexpected sprites during the intense stage of the supercell may be considered exceptions which prove the rule. Charge generation may have been so vigorous that the charge lowered primarily during the return strokes was sufficient to initiate breakdown with relatively little contribution required from subsequent continuing currents.

Thus, based upon our understanding of supercell evolution, it does seem reasonable to expect that SP+CGs would most likely occur near the end of the storm. In rare cases, during the mature storm phase, sufficiently large charge may be lowered in some very impulsive return strokes to initiate a sprite, and perhaps an elve as well.

6. THE 23 JUNE 2003 BAMEX SUPERCELL

During the summer of 2003, the Bow Echo and MCV Experiment (BAMEX) was conducted in the central U.S. (Davis et al. 2004). As the project domain was quite far east of YRFS, LLTV monitoring for sprites was not undertaken. Though the focus of the program was large MCSs and associated phenomena, on the evening of 22-23 June 2003, two highly unusual supercellular systems developed in south central Nebraska. The more southerly one, called the Superior, NE supercell (or the southern cell in our Fig, 15) contained the largest (~9 km diameter) and most intense (118 m s^{-1}) velocity differential ever documented (Wakimoto et al. 2004). To its north, the Aurora, NE cell produced the largest documented hailstone in the U.S. at 0005 UTC, measuring 17.8 cm in diameter and 47.6 cm in circumference. We are engaged in a detailed analysis of the lightning characteristics of these supercells, and some initial results are discussed here.

The climatology of giant hail (>4 inch diameter) shows a broad region of the central U.S. stretching from Texas to the Dakotas (Polston, 1996). The northern portion of the large hail belt is also associated with storms which have a high percentage of CGs with positive polarity, higher than average peak currents and numerous large peak current (>75 kA) positive events (Lyons et al, 1998). Since the initial linkage of +CGs and severe weather (Rust and MacGorman 1981), relationships between +CG lightning and hail have been sought (MacGorman and Reap 1989). As summarized in MacGorman and Rust (1998), the relationship has proven complex and elusive. Some supercell storms experience periods of almost exclusive positive polarity (Rust et al. 1985), as also seen in our studies. Curran and Rust (1991) describe low-precipitation supercells dominated by positives until splitting, after which they became negative. Supercells dominated by positives tend to have low precipitation supercell characteristics. Supercells changing polarity, often in association with tornadic development, have also been documented (Seimon 1993). Stolzenburg (1994) reports on supercells that remained primarily positive while producing large hail. This, however, appears not be the case of the Aurora and Superior storms. Low rates of CGs, though with very high IC rates, were documented in the STERAO-A supercells of 10 and 12 July 1996 (Lange et al. 2000). More recently, Soula et al. (2004) report on hail producing storms in France in which CG rates appear lower than for rain-only convective storms. Some of their cases, while producing high percentages of +CGs, were also associated with negative CGs which had low peak currents and multiplicity.

The Aurora cell remained distinct from the developing MCS between 2245 and 0100 UTC. During that time it produced 1462 CGs, of which 17% were positive. The average peak current for positives was 28 kA, but for negatives was only 9 kA. However, the lightning characteristics of this system underwent considerable temporal evolution. During the first half hour of this supercell's life cycle, the percent positive approached 50%, with average +CG peak currents of 56 kA (while the negatives were only 8 kA). Then things changed. Figure 16 shows a plot of NLDN peak currents. Note that at the time of the impact of the giant hail stone, only a few, low peak current +CGs were recorded.

Using an improved ELF transient analysis system more sensitive than available for STEPS, Duke University analyzed the signature for CGs in the Aurora cell. For this study, the impulse ΔM_q was extracted, that is, the charge moment change in the first 2 milliseconds resulting from the return stroke and only a small portion of any continuing current which might have been present (Cummer and Lyons 2004b). For the given noise conditions and range to the target, the estimated minimum detectable impulse ΔM_q was ~5 C km. Table 1 shows the analysis of both NLDN polarity and peak current and ELF impulse ΔM_q values for three time periods: 2325-2335 UTC (during the initial rapid growth of the storm), 2355-0005 UTC (while the giant hail was descending) and 0025-0035 UTC (as the storm matured and grew in size). Of the 327 total strokes in these three time periods, only 21 had impulse ΔM_q values > ~ 5 C km, and of these, 19 were from +CGs.

Table 1. Electrical characteristics of the Aurora, NE hailstorm, 22-23 June 2003, during BAMEX.

	2325-2335	2355-0005	0025-0035
Total CG	47	143	137
Total Pos	27	7	25
% Pos	57	5	18
Avg kA Pos	54.9	17.1	18.3
Max kA Pos	191.9	36.5	80.4
# Pos with CMC	15	1	4
% Pos with CMC	56	14	16
Avg Pos CMC	68.9	36.5	98.7
Max Pos CMC	200	36.5	123.9
Total Neg	20	136	112
% Neg	43	95	82
Avg kA Neg	-9.5	-9.1	-10.2
Min kA Neg	-25.9	-27.4	-21.6
# Neg with CMC	0	0	2
% Neg with CMC	0	0	1.8
Avg Neg CMC	0	0	8.6
Min Neg CMC	0	0	11.7

The storm was initially dominated by +CGs with relatively large peak currents (55 kA), but the number and peak current of +CGs fell rapidly during and after the giant hail phase. During the peak growth stage, the largest impulse ΔM_q was only 200 C km, not especially large when compared to the other supercells evaluated in this paper. Most striking is the persistence of low peak currents in the negative CGS (9-10 kA), with the largest only being 27 kA. While supercells rarely produce impulse charge moment values large enough to trigger sprites (>300-600 C km) (Cummer and Lyons 2004b), the intense BAMEX supercell was characterized by (1) relatively low total flash rates, (2) low percentages of +CGs during the period of maximum hail fall, (3) very small peak currents for strokes of both polarities but especially the negatives, and (4) low impulse charge moment changes, the vast majority being <5 C km. This suggests charge lowered to ground by individual strokes was typically on the order of only ~1 C (Note: Most continuing current contributions, if any, are not retrieved by this technique). Unfortunately, no information is currently available on IC/CG ratios. During the mature phase of the storm, the extremely high surface dewpoints (21 C), small dewpoint depressions (~8 C) and large CAPE values (~3000 J kg^{-1}) for these storm environments support recent contentions by Williams (2004) that positive CGs in convective cores are less likely to be found in storms with low cloud bases. This does not explain, however, the burst of +CGs early in the storm's growth period. Many aspects of this storm's electrical behavior merit considerable further attention. The Superior supercell also appears to have shown a similar evolution in its electrical structure and will likewise be further investigated.

7. DISCUSION AND CONCLUSIONS.

Based upon sprite studies in MCSs, a working hypothesis was proposed that +CGs would typically induce sprites when they occurred within large (>10,000 km^2) horizontal pools of positive charge in the stratiform precipitation region, often near the melting layer (Lyons, 1996; Williams 1998). The observation that sprites rarely occur during the active phase of High Plains supercells, even though they produce copious numbers of high peak current +CGs, appears consistent with this notion. The occasional "end-of-storm" sprites that occur when the supercell is developing MCS-like stratiform region characteristics, is likewise consistent.

The three sprites during the active stage of the 25 June 2000 STEPS supercell would appear to be a rare exception to the rule. In this case, the impulse charge moment changes in return strokes associated with very high charge densities in the storm's convective cores were sufficient to trigger mesospheric breakdown. More typically, ΔM_q values in the cores of such storms are insufficient to initiate sprites, presumably due to the lack of a horizontally extensive pool of positive charge from which to draw.

Sprites do occur in other types of convective systems, including squall lines, winter snow squalls, tropical cyclones and orographic storms. This begs the larger question as to what processes are active in such storms to produce CGs with the requisite large ΔM_q?

Our emerging capability to routinely monitor storms using ELF transient analysis to estimate charge moment change (and by extension, the charge lowered to ground if Z_q is available or estimated), provides additional metrics by which the electrical activity of convective storms can be characterized (Cummer and Lyons, 2004a,b). The behavior of the Aurora, NE supercell, while producing record-setting hail, illustrates how complex and variable is the electrical nature of even one class of deep convection.

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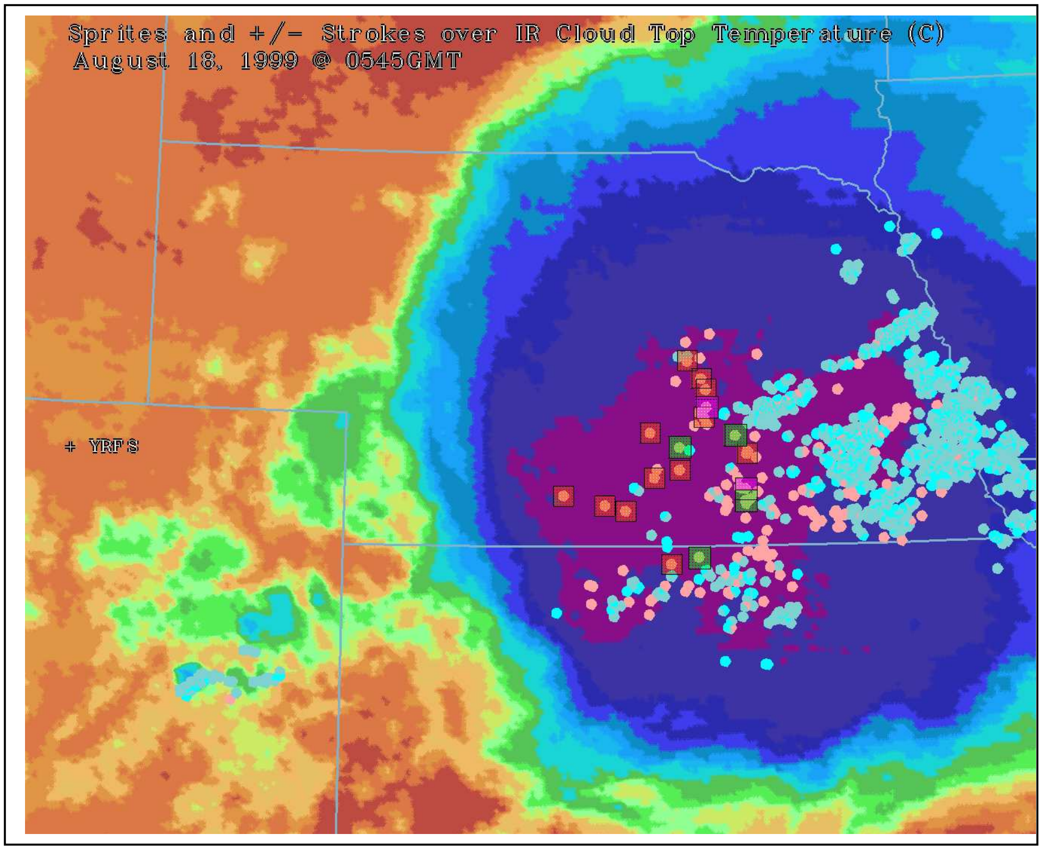


Figure 1. False color GOES IR image of MCC over Kansas and Nebraska, 0545 UTC 18 August 1999. NLDN negative CGs shown in blue, with positive CGs in red. SP+CGs indicated by boxes. The sprite producers tend to be confined to a relatively small portion of the trailing stratiform region (Lyons et al. 2000).

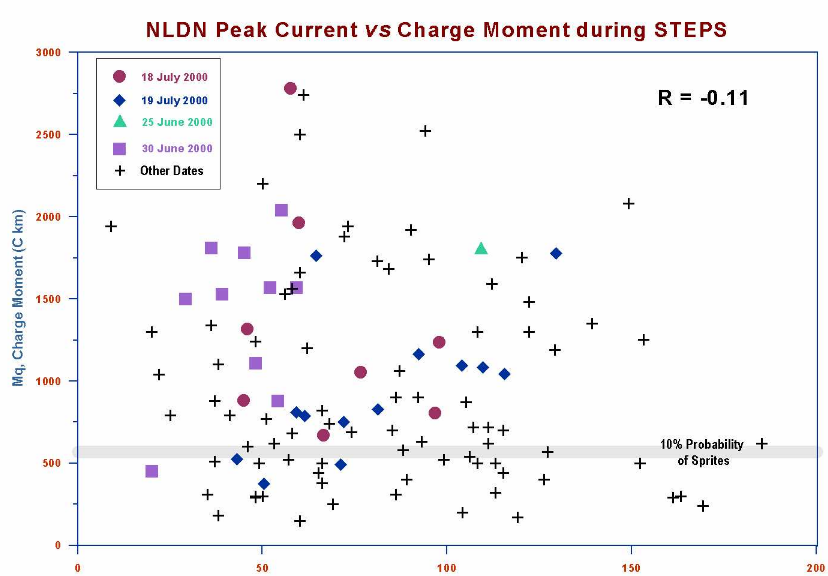


Figure 2. NLDN peak currents plotted against charge moment changes (6-10 ms or longer) for STEPS SP+CGs.

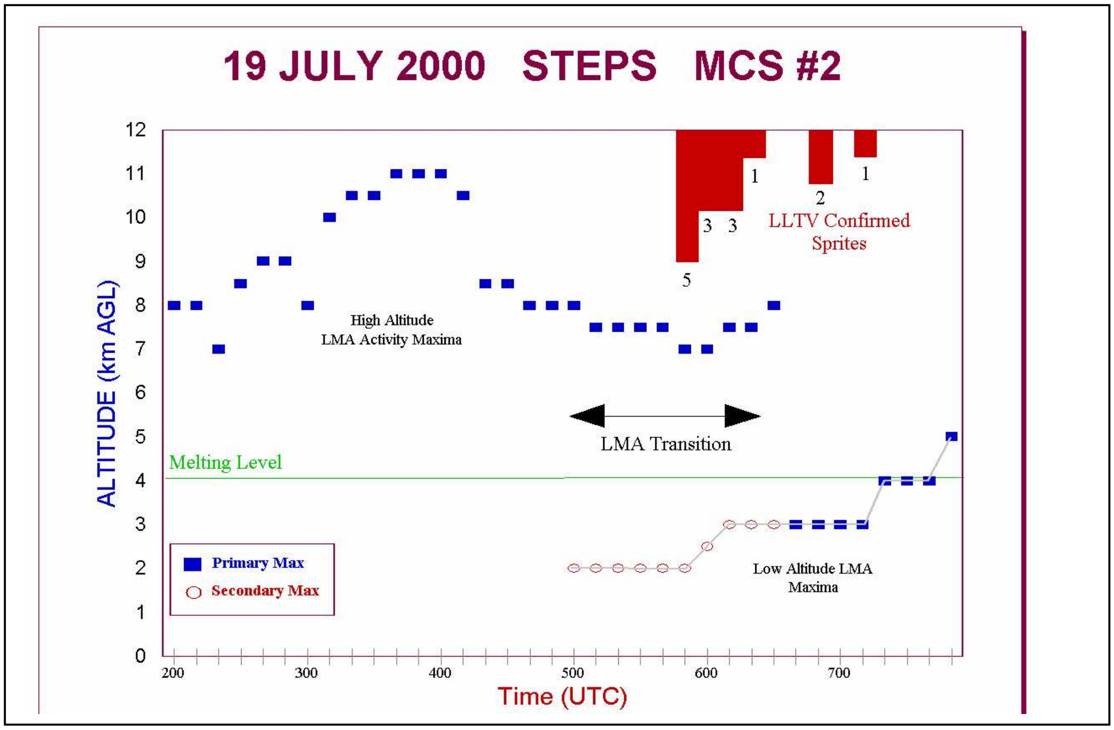


Figure 3. Time history of the centroid of VHF emissions as an MCS passes over the LMA during STEPS, on 19 July 2000. Note that during the mature stage of the storm activity is centered from 8 to 11 km AGL. As the storm further matures, a secondary maximum develops at low levels, and at this point +CGs begin producing sprites (Lyons et al 2003b).

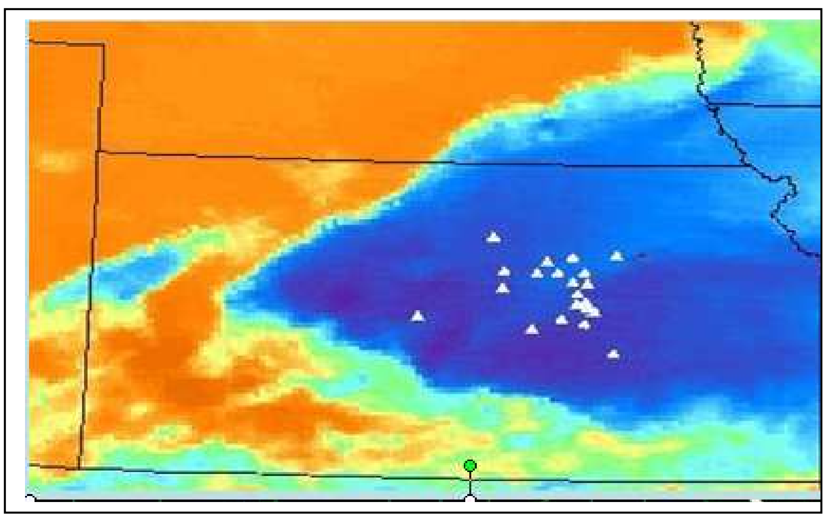


Figure 4. False color GOES IR at 0500 UTC 30 June 2000, showing the location of SP+CGs during the past half hour. Almost all were associated with large charge moment change +CGs in the leading stratiform precipitation region.

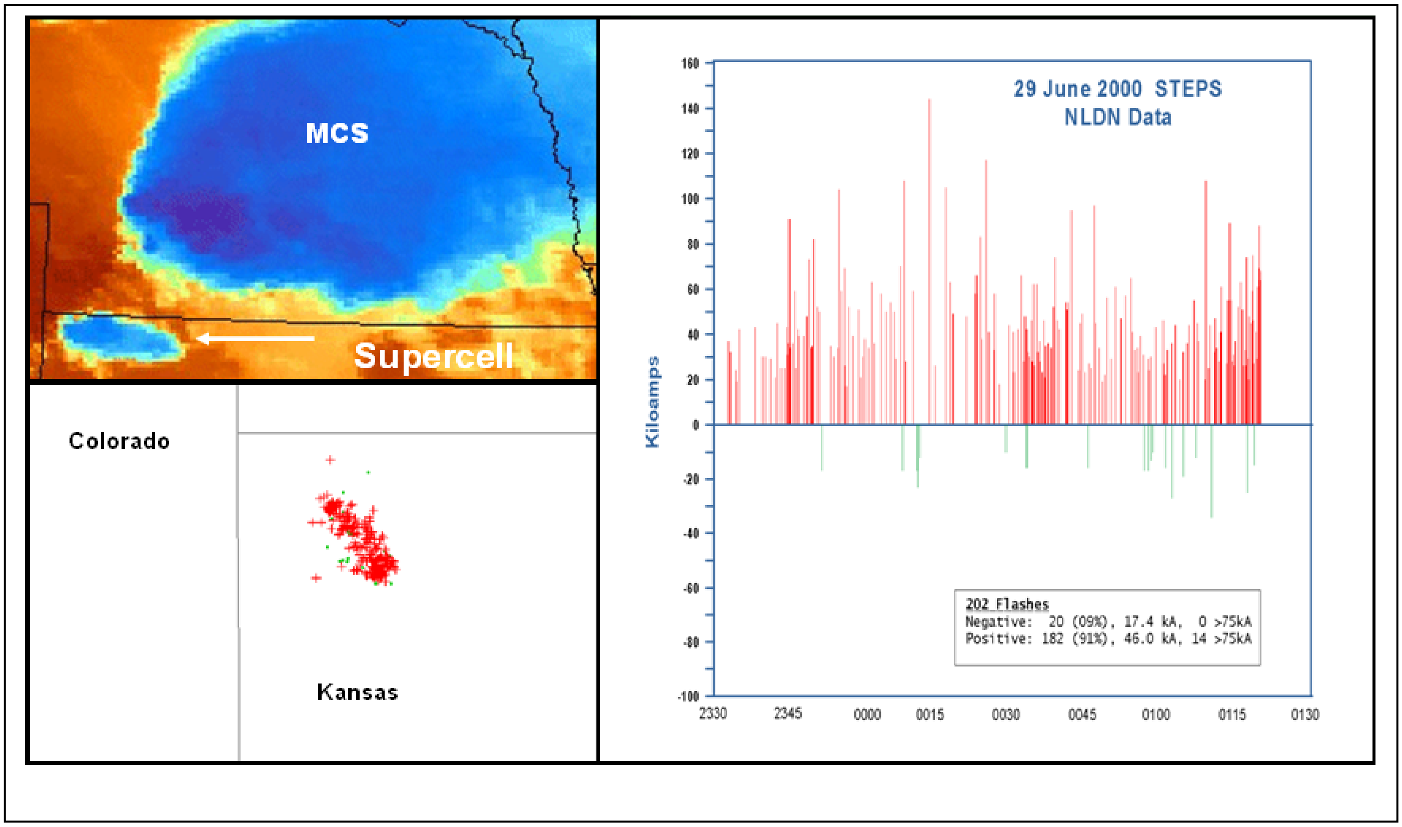


Figure 5. GOES IR showing both supercell and developing MCS in Nebraska at 0000 UTC 30 June 2000, along with track of NLDN CGs (red positive, green negative) and the time history of the peak currents.

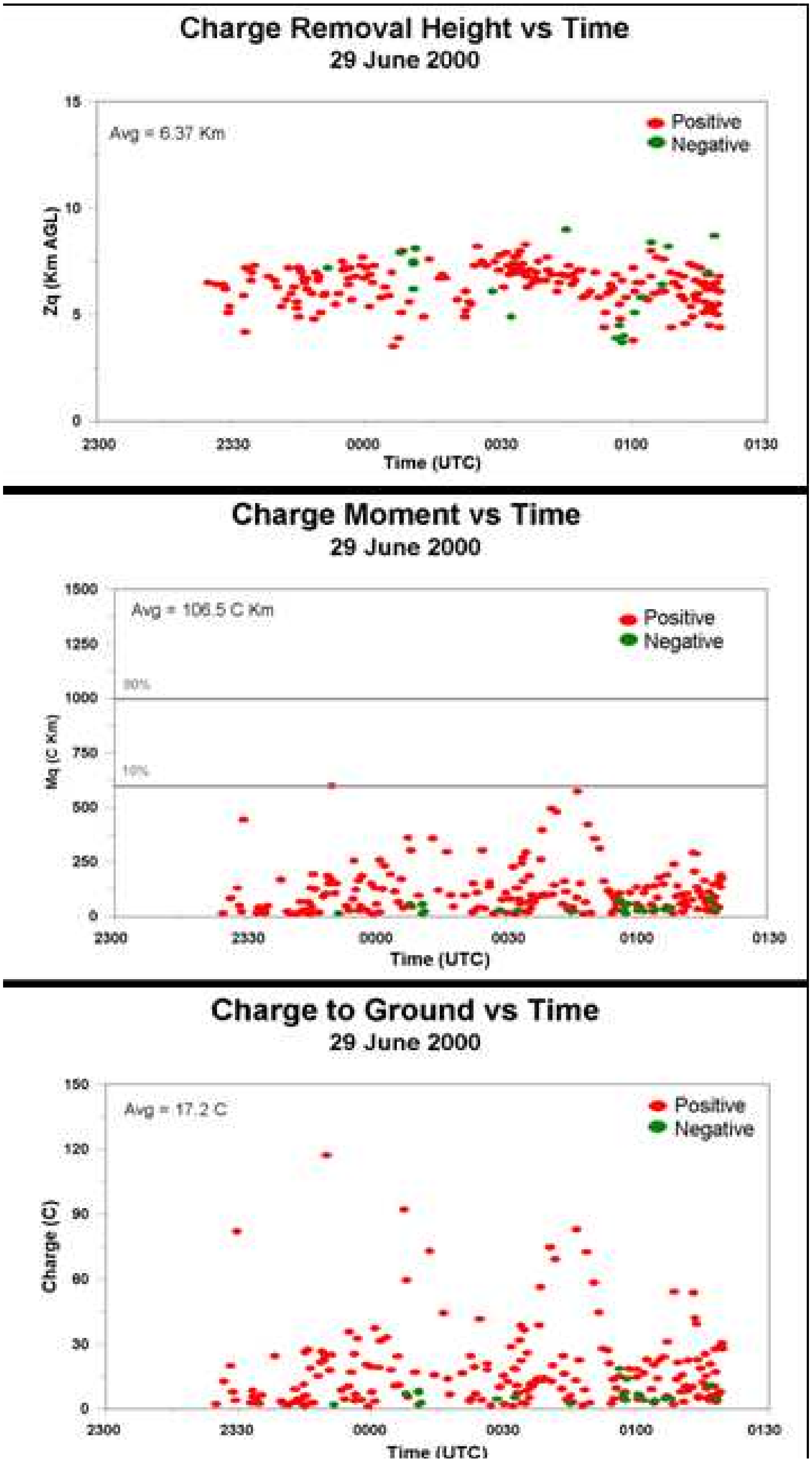


Figure 6 (a) height of charge removal for CGs from supercell in LMA on 29-30 June 2000, (b) computed charge moment change, and (c) charge lowered to ground.

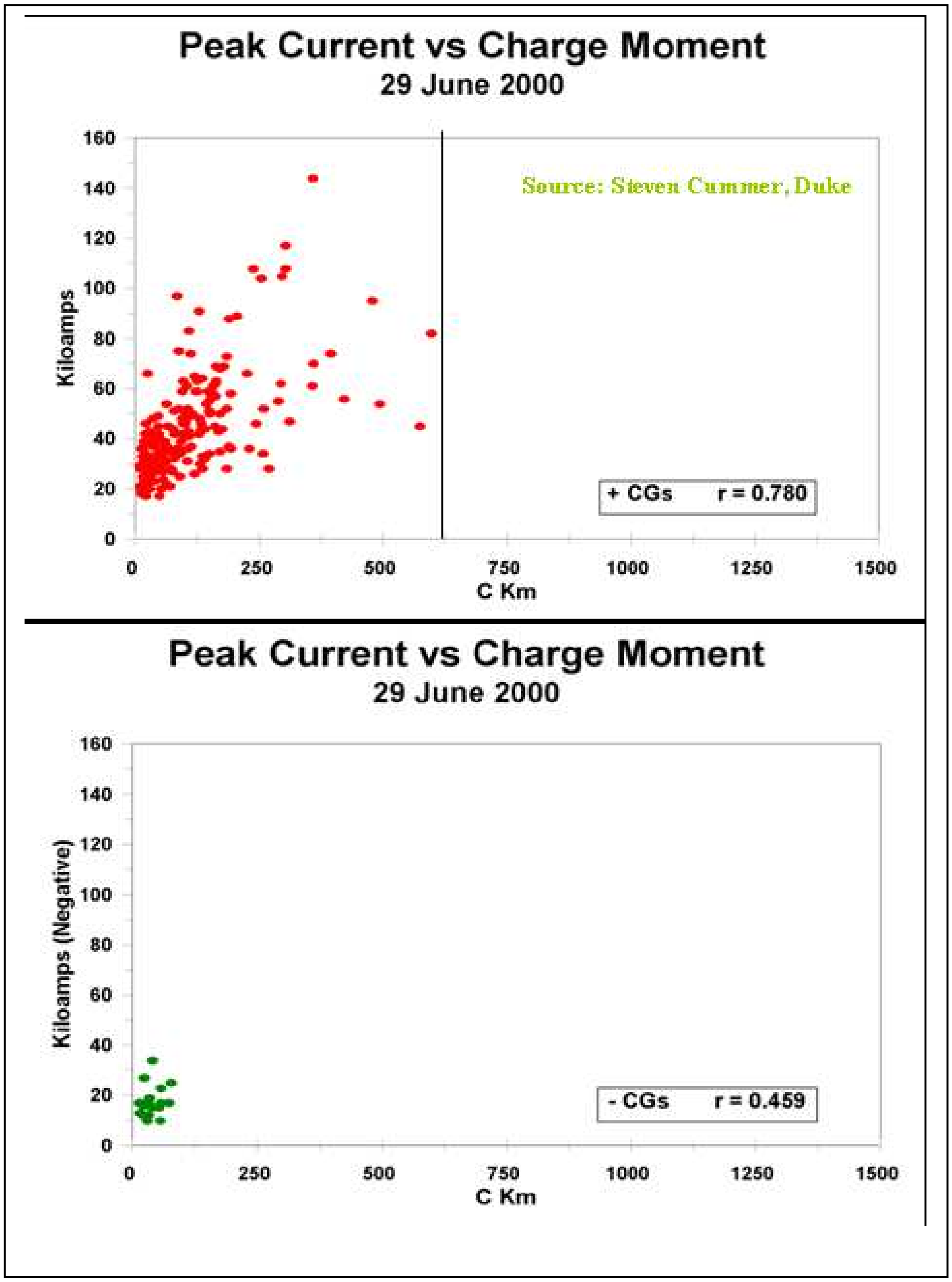


Figure 7. Computed charge moment changes for both positive and negative CGs plotted against NLDN peak currents, 29-30 June 2000 STEPS supercell. Note that, while fairly large, the +CGs do not exceed 600 C km, the nominal threshold for sprites, and are also substantially larger than for negatives CGs.

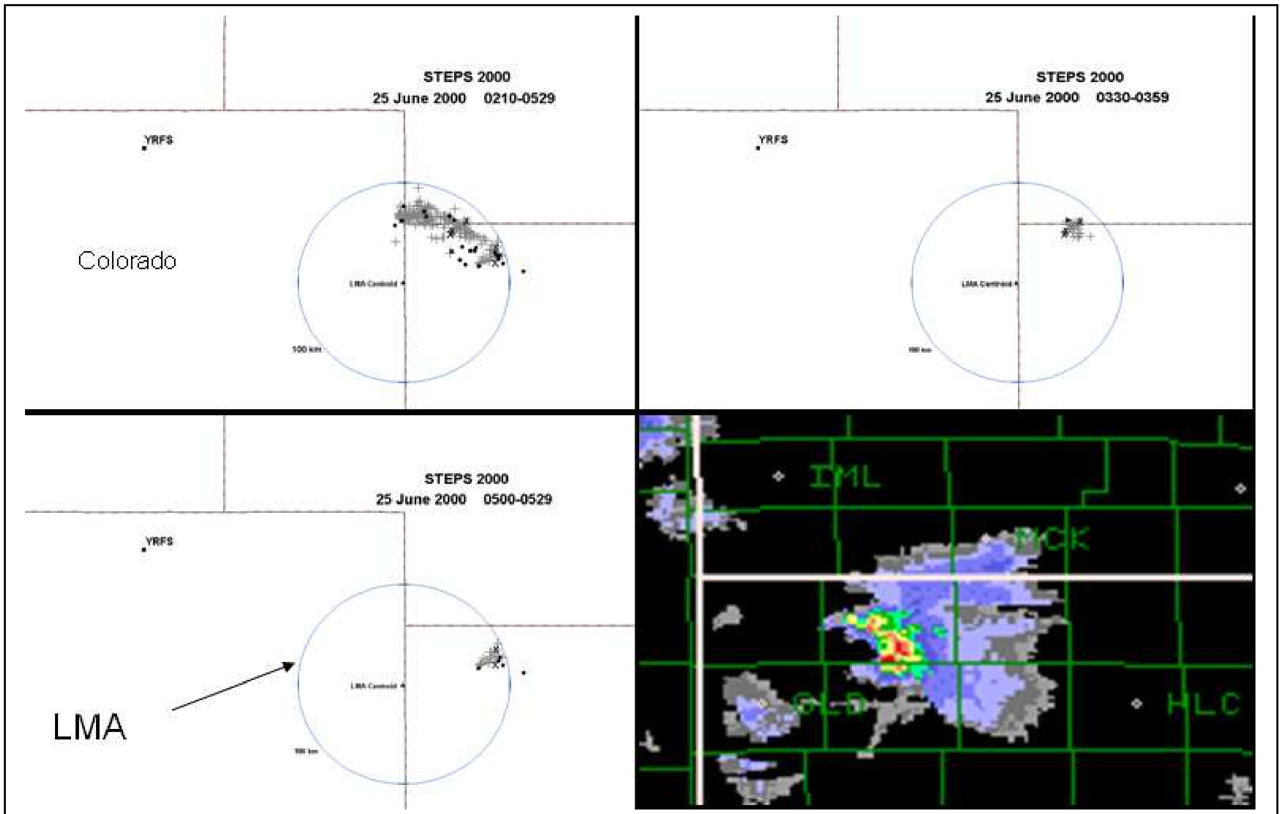


Figure 8. Plots of NLDN CGs (positives grey, negative black) for periods 0210—0529 UTC, 0330-0359 UTC (during peak of storm), and 0500-0529 UTC during the "end-of-sprites" phase, 25 June 2000, plus the NEXRAD image for 0515 UTC. The sprite occurred well west of the high reflectivity core that remained.

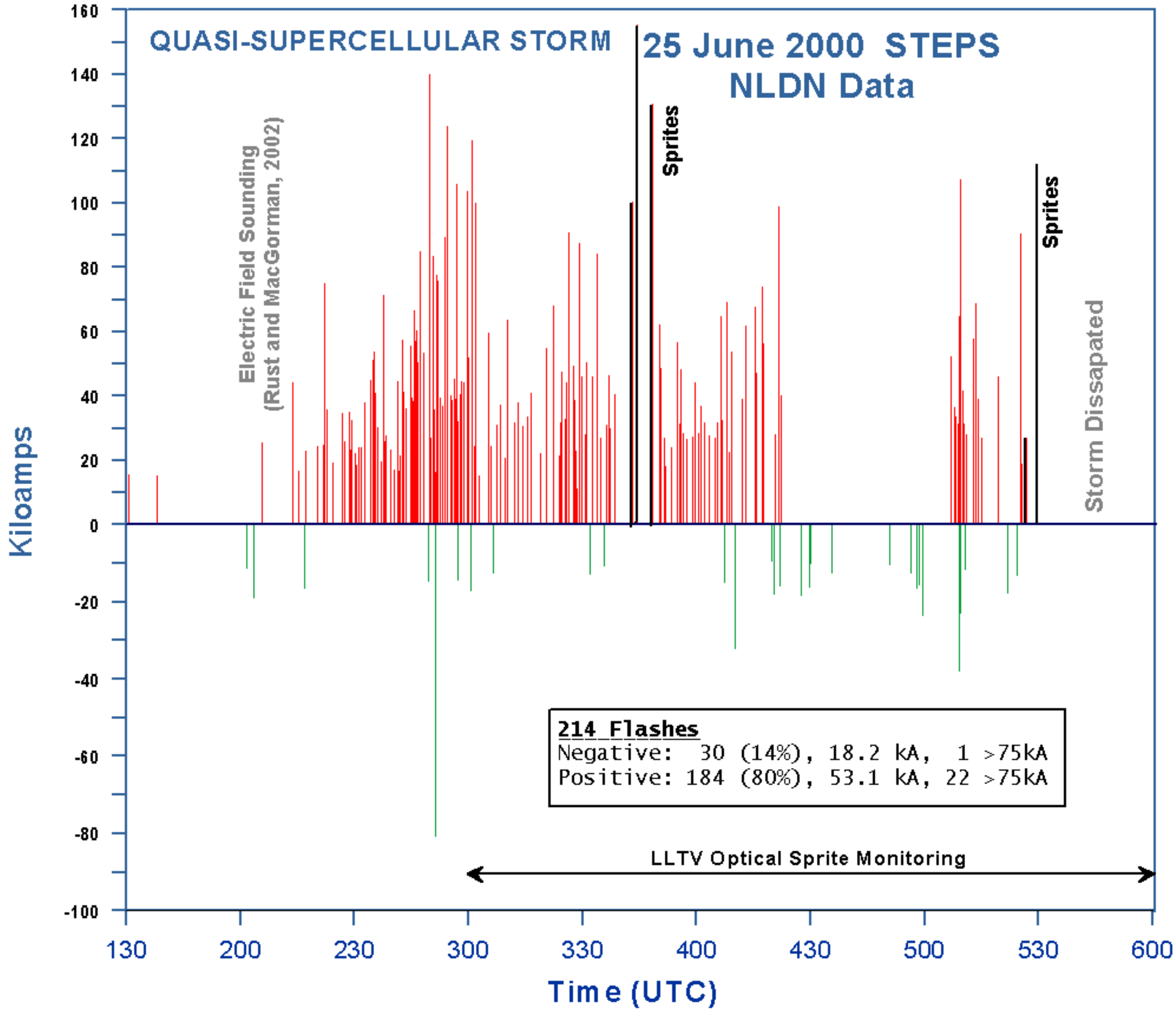


Figure 9. Plot of NLDN CG peak currents for 25 June 2000 supercell (up/red are positive). The five sprite events are highlighted in black. The sudden lull in +CGs before the onset of the storm's decaying phase is not easily understood.

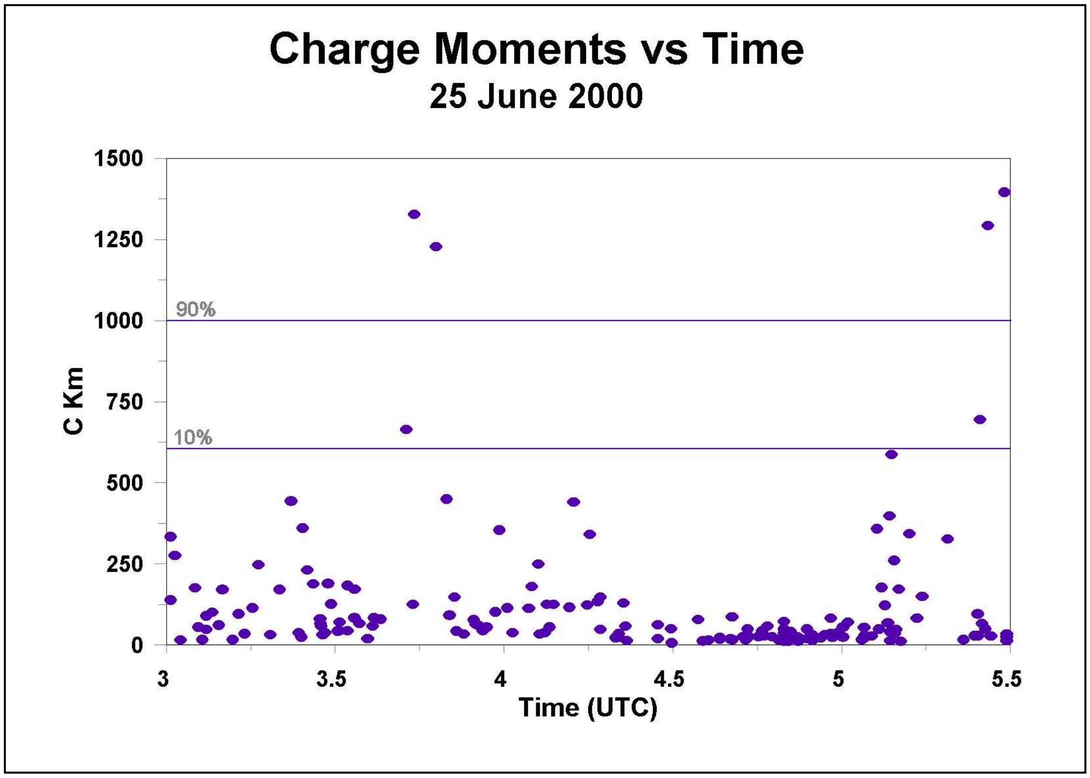


Figure 10. Computed charge moment changes for the supercell of 25 June 2000. The last two +CGs of the storm produced large events, both of which triggered sprites. Also during the most intense phase of the storm, three of four successive +CGs produced charge moments changes large enough to trigger small sprites.

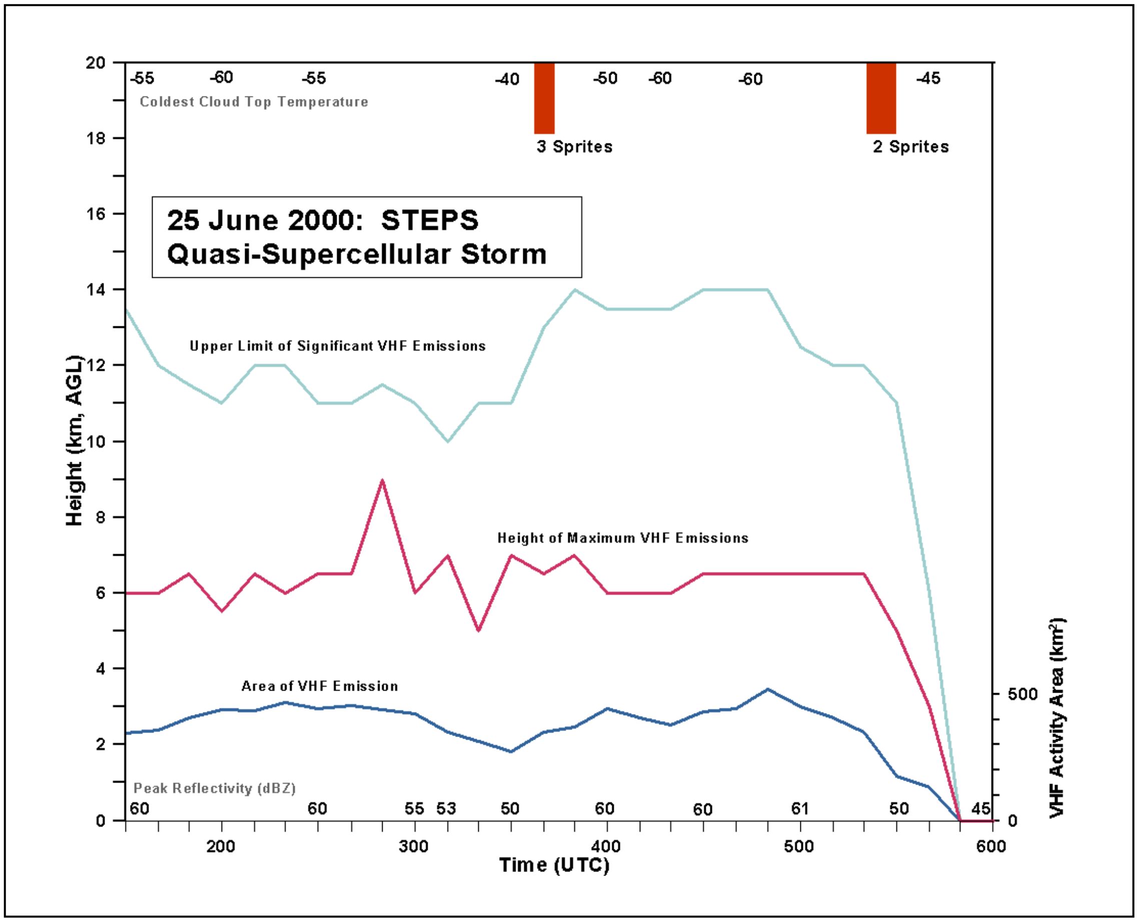
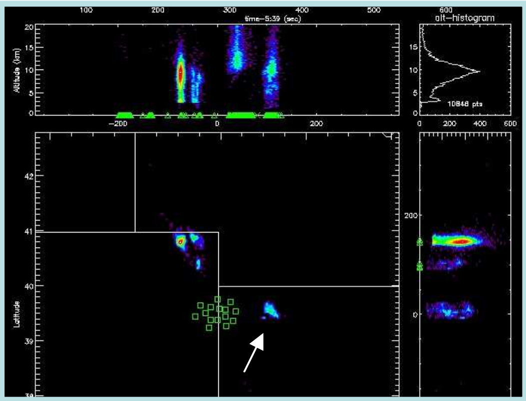
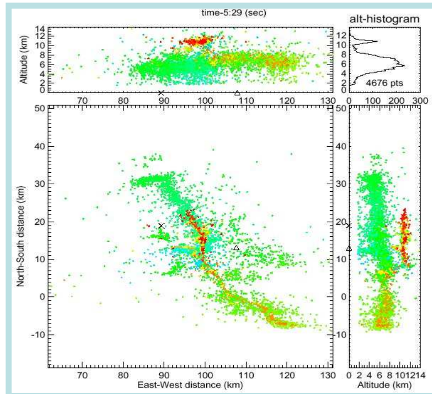
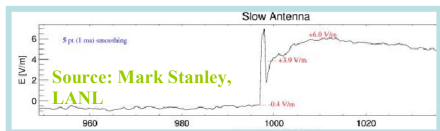


Figure 11. History of centroid of the maximum, as well as the maximum height and area of VHF emissions from the LMA during the passage of the 25 June 2000 supercell. The time of occurrence of the two clusters of sprites are indicated at the top.

Storm Type: Supercells the last +CG of the storm at 0529 UT





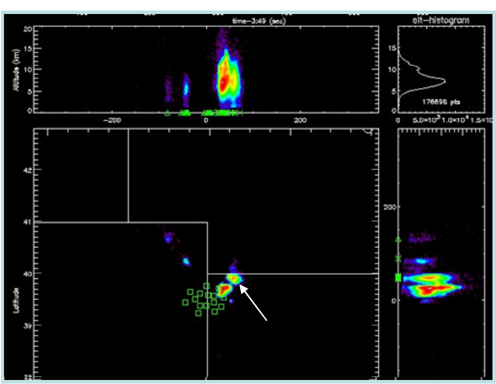


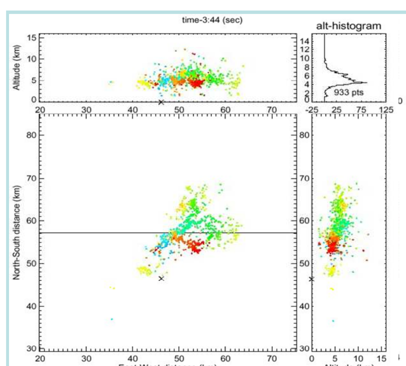
NLDN: + 109 kA
NEXRAD AREA: 10,100 km2
Mq = 1396 C km
Zq = 5 km
C = 280 C
LMA Discharge Area = 1200 km^2
Discharge Layer Depth = 1000 m
Initial Charge Density? = 1.0 nC/m^3

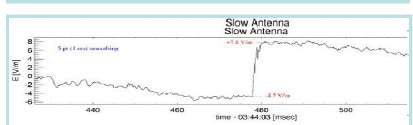
Character: significant continuing current

0 - 10 ms:	14 kA
0 -2.5 ms:	28 kA
2.5 - 5 ms:	6.1 kA
5 - 10 ms:	11.0 kA

Storm Type: Supercells Sprite at mature stage of the storm at 0344 UTC







NLDN: + 155 kA
NEXRAD AREA: 7527 km^2
Mq = 1327 C km
Zq = 4.0 km
C = 330 C
LMA Discharge Area = 160 km^2
Discharge Layer Depth = 1500 m
Initial Charge? = 5.5 nC/m^3

Character: smaller CC - more impulsive

0 - 10 ms:	16.2 kA
0 -2.5 ms:	54.6 kA
2.5 - 5 ms:	3.0 kA
5 - 10 ms:	3.8 kA

Figure 12 (top) and Figure 13 (bottom)

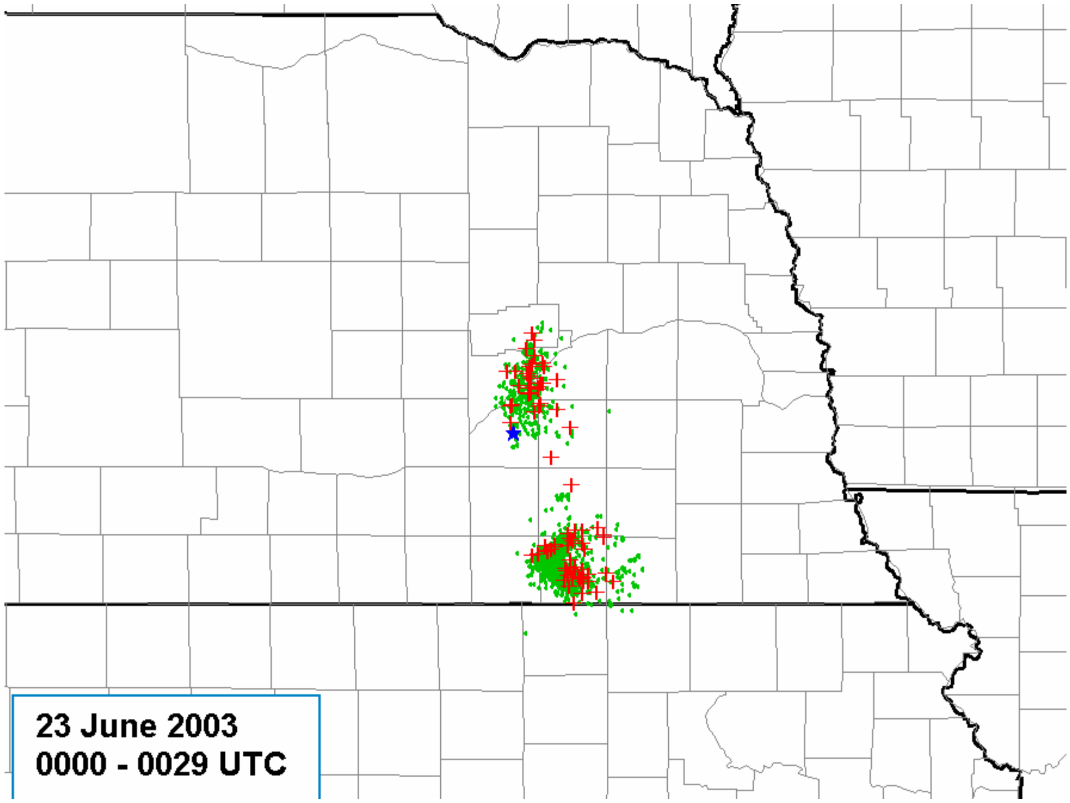


Figure 15. CGs from NLDN (green = negative) from two supercells in Nebraska, 0000 – 0030 UTC 23 June 2003. Blue star shows location of record hail fall.

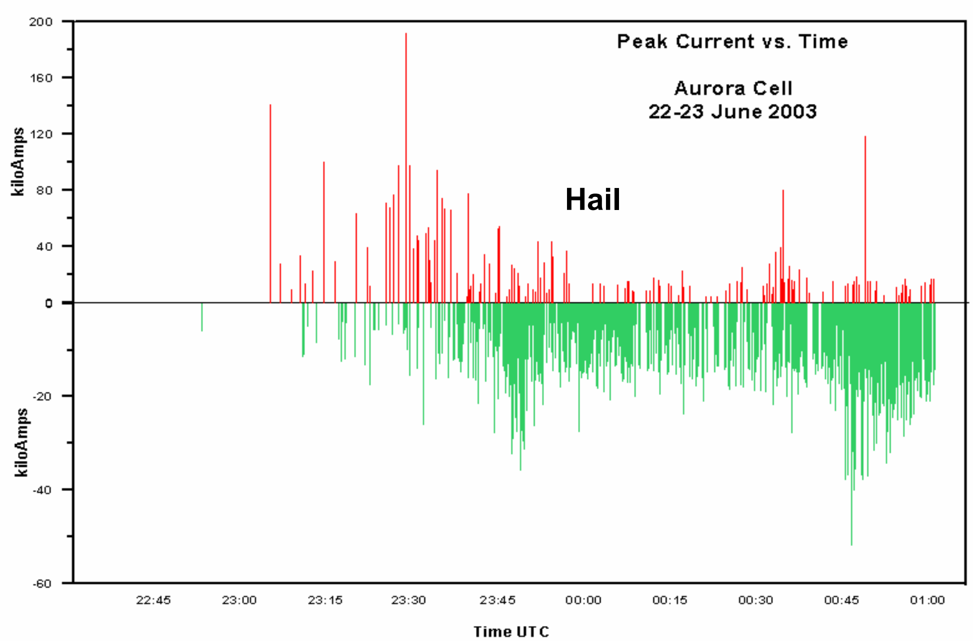


Figure 16. NLDN peak currents as a function of time from the supercell producing the U.S. record hail stone (0005 UCT, 23 June 2003).