CHARACTERIZING INTENSE CONVECTION USING CONVENTIONAL AND ADVANCED LIGHTNING METRICS, INCLUDING CHARGE MOMENT CHANGE

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1. INTRODUCTION

In this 300th anniversary of the birth of Benjamin Franklin, we note, that while lightning has been the object of scientific investigation since the mid-18th century, our ability of obtain systematic measurements of lightning's physical parameters over large regions has less than a three decade history. Prior to the development of lightning detection networks, climatological and spatial distributions of parameters related to lightning were limited to what could be extracted from acoustic observations (i.e., thunder day records) and crude flash detection monitors. The establishment of the U.S. National Lightning Detection Network (NLDN) has provided a weather of information about flash, and more recently, return stroke, parameters (Cummins et al, 1998). The analyses of these data sets initially concentrated on basic metrics such as flash density (Orville and Huffines 2002), with some attention paid to distributions over space and time of polarity, average peak current and multiplicity (Orville and Huffines, 2001; Rakov and Huffines 2003). Only recently have additional metrics, such as the distributions of large peak current CGs (LPCCGs), become to be examined. Lyons et al (1998a) reported on a several month period in the spring of 1998 in which not only the polarity of flashes in the central U.S. where highly skewed towards the positive, but peak currents in these events were abnormally high. Speculation continues as to whether it was meteorological factors (drought conditions) or dense plumes of smoke from Mexican forest fires that resulted in the anomaly. Lyons et al. (1998b) also presented to first climatology of LPCCG events using NLDN data. Noted were a significant concentration of +CGs of >75 kA peak currents in a broad band thought he High Plains from New Mexico into Minnesota, primarily during the warm season. Also, and more unexpectedly, was the pronounced enhancement of the density >200 kA negative CGs over the salt water of the Gulf of Mexico and Atlantic. Subsequent studies has detected a ~25% enhancement in the mean peak currents of –CGs in this region as well (Steiger and Orville, 2003). The causes for these patterns remain an area of active debate and research. Figure 1, showing the ratio of the density of >75 kA peak current CGs by polarity illustrates the strong regional control of this parameter. Figure 2, a plot of summertime >200 kA CGs shows the distinct geographic variability of flashes with even the highest peak currents. The LPCCG events were of particular interest in that they suggest geographical and physical; controls on lightning that are not yet understood as well as a possible linkage to transient luminous events (TLEs) in the mesosphere associated with tropospheric lightning discharge. In this paper we will summarize what is known about the phenomenology and meteorology of TLE parent lightning, using not only NLDN data, but introducing the applications of newer remote sensing systems that further extend our quantitative knowledge of the lightning discharge and its impacts. In particular we integrate NLDN information with 3-D lightning mapping arrays (LMA) and newly emerging charge moment change data from analyses of ELF/VLF transients.

2. TRANSIENT LUMINOUS EVENTS

The unanticipated discovery of red sprites in 1989 changed forever our view of the
interactions between tropospheric electrical activity and middle atmospheric optical phenomena (Franz et al. 1990; Lyons and Armstrong 2004). Once thought to be electrically quiescent, the stratosphere and mesosphere are increasingly found to be the home to a growing variety of lightning-related electrical discharges and intense transient electric fields (Lyons 2006). 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. 2003a) continues to engender the need for intensive investigations of this region. However, the relative scarcity and apparently random nature of cloud top discharge events make them difficulty to study in a systematic manner. Red sprites, and to a lesser extent elves (Fukunishi et al. 1996) and halos (Barrington-Leigh 1999), 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, the experimental design also allowed for detailed investigations of mesoscale convective systems (MCSs). Over continental regions, sprites are known to frequently occur in association with positive cloud-to-ground (+CG) strokes in MCSs (Lyons 1994, 1996; Lyons et al. 2000), 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 (Wilson, 1925; Rodger 1999). 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, 1998). Though this mechanism 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. As initially suggested by C.T.R. Wilson (1925), the key metric is the charge moment change:

\[ \Delta M_q(t) = Z_q \times Q(t) \]  

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 that this second term is most appropriately considered as a function of time. New measurement techniques (Cummer and Lyons, 2004, 2005) can now routinely monitor the impulsive charge moment change \( \Delta M_q \), which is that produced by the charge lowered in roughly the first 2 ms of the CG. This is often dominated by the return stroke plus the initial stages of any continuing current.

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, total \( \Delta M_q \) values would need to be on the order of 300 to 1000 C km. These values are many times larger than what have been believed to be the “normal” values for \( \Delta M_q \) (Rakov and Uman 2003). The STEPS program provided ideal circumstances to delve into the characteristics of MCS SP+CG strokes. The key question to be addressed: What is different about those +CGs which trigger sprites? Where in the storms, and during what phase of its life cycle, do these unusual discharges occur?

ELF-based remote sensing methods for the characterization of lightning charge moment changes based upon the concepts proposed by Cummer and Inan (1999), and as exploited for STEPS data by Cummer and Lyons (2004, 2005) has detailed that \( \Delta M_q \) and even \( \Delta M_i \) (if properly employed) can provide a very useful threshold to discriminate between those +CGs which produce sprites (and elves and halos) and those which do not. In this paper we will investigate the characteristics of TLE-producing storms as observed using conventional NLDN data (Cummins et al. 1998), GOES satellite and NEXRAD radar reflectivity, the LMA (Thomas et al. 2004) and charge moment change data from ELF/VLF transient analysis. We will first review the STEPS program and discuss a prototypical sprite-producing MCS and a typical sprite-producing +CG.

3. STEPS 2000

The STEPS program was conducted on the High Plains of eastern Colorado, western Kansas and southwest Nebraska from
22 May through 16 July 2000. The observation 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 100-150 km (for 3-D mapping) and 150-300 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 low-light television cameras (LLTVs) and photometers. These were deployed some 275 km to the northwest at the Yucca Ridge Field Station (YRFS) outside of Ft. Collins, CO. During the campaign, over 1200 TLEs were documented, with over 50 within the prime coverage area of the LMA. Coincident with the optical monitoring, ELF transients were recorded by both MIT (Earle Williams) and Duke University (Steven Cummer) for the purpose of extracting $\Delta M_q$ 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 $\Delta M_q$, and for events within the LMA, $Z_q$ and the computed charge (Q) lowered to ground. It also facilitated 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 lower radar reflectivities once this region had attained a size of >20,000 km$^2$. In addition, Williams (1998) had proposed that the SP+CGs were most likely associated with charge removal ($Z_0$) 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 postulated $Z_0$ values between 10 and 20 km, in part to allow for generation of sufficiently large $\Delta M_q$ to trigger mesospheric breakdown (Rowland 1998).

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). During STEPS, the Duke ELF system obtained the $\Delta M_q$ values for a large number SP+CGs. For those events with CG-to-sprite onset time delays on < -6-10 ms, very little correlation between peak current and $\Delta M_q$ could be found. This is consistent with the notion that for sprites with time delays greater than several milliseconds after the SP+CG that 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 $\Delta M_q$ 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).

4. A PROTOTYPE TLE-PRODUCING MCS

Two modest size mesoscale convective systems (MCS) passed through the LMA domain on 19 July 2000, and are described in detail in Lyons et al. (2003a). Two techniques of estimating changes in vertical charge moment ($\Delta M_q$) yielded averages of ~800 C km (Duke) and ~950 C km (MIT) for 13 sprite-parent +CGs (Lyons et al. 200b). 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) . The average height of charge removal ($Z_0$) 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).

Figure 3 portrays this MCS at the time of one of the SP+CGs presented here in more detail. The +CG event, a 30 kA stroke, occurred at 0600.15.364 UTC. The sprite was rather dim and occurred more than 100 ms after the CG return stroke, indicating a significant role for the continuing current. This is an example of a “long delay” sprite. There are numerous events which appear to occur well under 10 ms after the CG and can be
considered “short delay”, indicating a more impulsive nature of the parent CG and a greater role for the return stroke and the contribution of the immediately following continuing current to the charge moment change. This CG was associated with a total $\Delta M_q$ of 525 C km (as detected by the MIT ELF system). The SP+CG is shown (red lightning bolt) in the GOES Infrared image. We note the sprite occurred above the cold, but not the coldest, part of the MCS cloud canopy (-75°C as indicated by the white area). The SP+CG occurred in the low reflectivity (25 dBZ) portion of the stratiform precipitation, in this case located mostly north of the southeast moving convective core, which had a peak reflectivity of >60 dBZ. Figure 3 shows the CG pattern from the NLDN, in which the convective core was dominated by almost exclusively negative CGs (green dots), with the +CGs (blue crosses) populating the stratiform region. The +CGs producing sprites are indicated with red crosses, with the western-most event being the 0600.15.364 UTC event.

Figure 3 presents a ten minute (0550-0600 UTC) compilation of the VHF source density as monitored by the LMA. The VHF source density in the convective core is two orders of magnitude greater than those occurring in the region of sprite generation. SP+CGs are often found in the low reflectivity portions of the storm, having modest rates of VHS electrical activity. Those SP+CGs which do occur exhibit extremely large $\Delta M_q$ values.

Figure 4 is a newly designed LMA display used for ongoing investigations of lightning discharges generating sprites. The time line is centered on the +CG event time, and extends 300 ms before and after, encompassing the duration of the IC discharge. The VHF sources detected before the +CG are plotted in green. Those occurring between the time of the CG (red triangle) and the optically determined onset of the sprite (to within 17 ms video resolution) are shown in yellow. Those VHF sources occurring while the TLE was optically detectable by the LLTV systems are in pink. The grey points are those sources from the tail end of the cloud discharge after the sprite fades.

In the first 100 ms after the CG return stroke, charge appears to be removed from about the 5 km AGL level. During the period of sprite luminosity, the values drop to about 4 km AGL, which is approximately the altitude of the melting layer. We note that the area from which charge appears to have been drawn from the onset of the CG to the end of the sprite luminosity is ~3000 km². This is larger than the original estimate presented in Lyons et al. (2003b). This results from using undecimated (full resolution) LMA data which shows the IC discharge in much greater detail and area coverage.

We also note in the YZ display panel, that there is as clear slope downward of the VHF sources from 8 -10 km at the onset of the IC to about 4-6 km at its termination. This temporal lowering of the altitude of VHF sources is also evident in the ZT panel on the top. Approximately a third of the SP+CGs in this MCS evidenced a discharge which began near the top of the convective core at the south end of the storm and systematically descended to lower altitudes as it moved northwards into the stratiform region. Similar discharge behaviors were found in the MCS of 16 June 2002 as it approached the Dallas-Fort Worth LDAR II 3-D lightning mapping system by Carey et al. (2005.) The implications of this behavior will be discussed further below.

Note also that the sprite luminosity occurred as the dendritic “spider lightning” branches were systematically propagating tens of kilometers outwards from the +CG attach point. A similar behavior was noted for SP+CGs in MCS storms in Florida by Stanley (1999).

5. CLIMATOLOGICAL CHARACTERISTICS OF TLE-PARENT CGs

A major effort has been expended in creating a database of High Plains TLE events (primarily sprites), and the characteristics of the NLDN-detected parent CGs and their parent storms (mostly MCSs) as determined by GOES and NEXRAD data. This database includes most events observed during STEPS as well as from selected storms spanning the summers of 1995 through 2004. One squall line and two supercell storms are included, though the majority of events are MCSs with trailing stratiform precipitation regions. We will herein briefly summarize the results of this study which is available in Lyons et al. (2006). The NLDN metrics for the parent +CG locations for 2219 TLEs, mostly sprites, were obtained. These events were associated with the eastward propagating summertime nocturnal convection over the US High Plains after sunset (0230-0330 UTC) which permitted LLTV optical monitoring for TLEs.
The peak times for TLE detection from YRFS cameras was from 0400 to 0700 UTC (10 PM to 1 AM local time). The decrease after 0700 UTC is due to weakening of some storm systems after this time, plus increasing distances and/or cloud obscuration and/or (sometimes) terminated monitoring due to the late hour. It is likely that over the US High Plains, the most active time for sprites, halos and elves is plus or minus two hours of local midnight. This corresponds to the period when many convective systems begin developing extensive stratiform precipitation regions.

Most storms, if they produce one TLE, will generally continue doing so for an average of 2.5 hours, with some continuing for six hours or more. Single TLE events do occur, but are quite uncommon. The mean TLE production is 70 events. There are, however, some storms which produce substantially larger numbers of TLEs. One generated approximately 750 events in about 3 hours. The causes of such hyper-active storms are unknown, though Lyons et al. (1998) speculated these storms may be ingesting large amounts of smoke from wildfires.

Most MCSs require several hours before TLE production begins. Using GOES satellite time lapse sequences, we computed the ages of the each system (from when it first became recognizable as an entity) when TLEs were first observed. While a few produced TLEs during their first two or three hours, the majority of the storms were 3 to 8 hours old before activity commenced. This illustrates a long standing forecasting rule of thumb that TLEs most typically are associated with MCSs approaching their late mature stages.

We next compiled the NLDN stroke data for parent +CGs which produced only optically confirmed sprites and those which included elves and halos, some of which were also followed by sprites. Forecasting experience has noted that TLE-producing storms tend to have greater percentages of +CGs than others, but there is great variability from storm to storm (less than 10% to over 90%). One rather consistent feature, however, is that the TLE parent CGs do have higher average peak currents than the other CGs in the same system. For sprite-only events, the average is ~60 kA. However, the large standard deviation (~35 kA) and the wide range of values (< 10 kA to > 250 kA) illustrates that peak current alone is a poor indicator of TLE potential. For those TLE parent CGs inducing elves and halos, the average peak current is even larger, ~115 kA, and again with a large standard deviation of ~46 kA. Thus, the impulsive nature of these return strokes, except in rare cases, does not allow attaining breakdown $\Delta M_q$ values for sprites, though EMP production is sufficient to induce impulsive elves. Evidence is accumulating that some continuing current is almost always involved in sprite and halo production, though the additional required contribution may be fairly small when the initial CG return stroke is highly impulsive.

6. CLIMATOLOGICAL CHARACTERISTICS OF TLE-PRODUCING STORMS

TLEs have been observed above a wide variety of convective systems including MCSs, squall lines, tropical cyclones, winter snow squalls and (rarely) supercells (Lyons 2006). But the vast majority of convective storms do not produce TLEs. Over the central U.S., the most prolific TLE generators are mature MCSs, especially those with significant trailing stratiform precipitation regions. We examined the characteristics of TLE parent CGs with respect to the convective cloud canopy as determined by GOES infrared satellite data. TLEs generally occur within 50 km of their parent CG (Lyons 1996). The NLDN-derived latitude and longitude provides a reasonable surrogate for the TLE location. Figure 5 shows the distribution of IR cloud top temperatures above the TLE-parent +CG for High Plains summertime events. It is apparent that TLEs are largely confined to regions of cold cloud tops, with an average of ~-65°C. These values approximate the typical tropopause temperature for the study region during summer. However, the TLEs usually do not occur beneath the very coldest part of the storm, which is often marked by convective overshooting domes associated with strong convective core updrafts. The distribution of coldest cloud tops anywhere within a TLE-producing system commonly shows temperatures of -70°C or less present in the majority of convective systems producing sprites. The warmest value noted in almost 100 periods of 30 minutes each was -55°C. It appears that a cloud top temperature of -55°C or colder is a necessary, though not sufficient requirement for a convective system over the U.S. High Plains during summer to generate CGs, which in turn trigger TLEs.

Long term forecasting experience has also noted that over the central U.S., TLEs
rarely are associated with smaller convective systems. The distribution of the number of TLEs versus the total area of the storm cloud shield (an IR cloud temperature typically around -30°C) shows no system <20,000 km$^2$ produces sprites. Only 4 storms with a -50°C cloud top canopy area of <20,000 km$^2$ were found to produce TLEs. We would note that to adjust these results for application in different seasons and locales, the cloud top temperatures would need to be compared to prevailing tropopause temperatures.

Using regional NEXRAD mosaics available at 30 minute intervals, we compared NLDN-reported locations of the TLE parent CG to the reflectivity. We note that the lack of temporal coincidence introduces error in the reflectivity determination, but the rather large and fairly homogeneous nature of the patterns in MCSs tends to minimize this shortcoming. Figure 6 shows that TLE parent CGs occur with reflectivity values ranging from 5 dBZ to 65 dBZ. There is, however, a strong preference for the parent CGs to be located outside of the convective cores (>55 dBZ), and being most frequently in the 20 - 45 dBZ range, with the mean and mode value being 35 dBZ. These are values typically associated with secondary precipitation maxima and bright band zones in trailing stratiform regions. Indeed, experience has shown that while TLEs do sometimes occur within convective cores, they are most often concentrated in a portion of the trailing stratiform, often quite close to the trailing edge.

The size of the contiguous precipitation region is also a rather robust requirement. Only a small number of TLEs have been monitored above storms in which the 10 dBZ area was <15,000 km$^2$ (and these were mostly from decaying supercells). For MCSs to have a potential for TLE production, the echo area usually requires a minimum of ~15-20,000 km$^2$. It should also contain a fairly large region of stratiform precipitation with values >25-30 dBZ.

We also examined the maximum reflectivity anywhere in the convective system while it was producing TLEs. It appears a necessary, though not sufficient, condition for High Plains storms to generate sprites is a core reflectivity of at least 55 dBZ with values of 65 dBZ and 70 dBZ being common. Convective cores (>50-55 dBZ) are always present, and can cover an area as large as 15,000 km$^2$.

TLE parentGs occur beneath the colder parts of the cloud canopy, but rarely beneath the coldest portion of the storm top. However, the coldest cloud top temperature (for the summer continental U.S. tropopause) was always colder than -55°C, and often as cold as -70°C to -75°C.

At first glance the findings that the preponderance of TLEs occur at lower level (perhaps near the melting layer) in the weaker reflectivity portions of the trailing stratiform are contradictory with the need for tall, intense convective cores. Yet our understanding of the dynamics and electrical nature of leading-line, trailing-stratiform MCSs are rapidly improving (Demetriades et al. 2004; Davis et al. 2004; Carey et al. 2005). Figure 7, modified from the recent paper by Carey et al. (2005), presents a conceptual illustration of the complex, elevated front-to-rear and low-level rear-to-front flows behind advancing MCS convective lines. Most intriguing was the finding that a number of lightning discharges in one case study initiated near the top of the convective core and then sloped rearward and downward into the bright band region. While it was not known if any of these flashes produced TLEs, this is the behavior of a sprite parent flash illustrated in Figure 4 of this paper. The schematic suggests positively charged ice mass may be distributed upward and then rearward, settling through the regional mesoscale updraft and into the bright band with one or more associated large horizontal laminae of positive charge. Charge advection within such storms may indeed play a role comparable with that of in situ charge generation (Schuur and Rutledge 2000).

Regardless of which is the dominant charge generation process, a continuous, rearward elevated feed of ice mass into the trailing stratiform appears very important. Only relatively brief intervals (typically on the order of an hour) are needed in which TLEs often cease when MCS convective cores fall below “severe” limits (55 dBZ) and cloud tops warm below ~55°C. This may also indicate the relatively frequent occurrence of extensive, front-to-rear descending IC discharges from atop the deep convective core which trigger the large +CG and subsequent spider lightning tapping the positive charge reservoir near the bright band creating large $\Delta M_q$ values in the prototypical MCS sprite event.

7. SPRITES AND SUPERCELLS

Supercells, which were a major focus of STEPS, tend to occur during daylight hours, when LLTV monitoring for TLEs is not feasible. But over the years, enough supercells have
persisted after sunset to state that while supercells often exhibit extremely high intracloud (IC) flash rates and numerous +CGs, they rarely produce TLEs. A case in point occurred on 29 June 2000. After sunset, a large MCS produced 18 sprites over central Kansas. The average peak current was 42 kA, with the mean \( \Delta M_q \) being 1086 C km. All SP+CGs occurred in the lower reflectivity, stratiform region at a considerable distance from the MCS convective cores. 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. This much-investigated tornadic supercell is described in Lang et al. (2004). This right-turning supercell was strongly dominated by positive polarity CGs (91%), whose peak currents averaged 46 kA (Figure 8). The Duke \( \Delta M_q \) 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. 9). No individual +CG had a \( \Delta M_q >600 \) C km, consistent with the scarcity of sprites in most supercells. LMA data for this CGs was processed by CSU (courtesy: Kyle Wiens, now at LANL) which allowed us to plot the typical \( Z_q \) values for such events. With values typically around 7 km AGL, most \( Q \) values for the supercell where 50 C and less, large but not exceptionally so. 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 \( \Delta M_q \) distributions of +CG and –CGs.

The rare exceptions to the rule that supercells make few, if any, sprites tends to occur 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. 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 \( \sim 10,000 \) km$^2$ (See Lyons et al. 2005 for details). ULF observations in California (Martin Fuellekrug, personal communication) showed the parent +CGs produced a classic Q-burst. Thereafter, Duke University 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. 10). 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 –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 \( \Delta M_q \) values. As shown in the summary of LMA observations, the storm-ending sprites occurred as the electrical activity in the upper portion of the storms had largely ended, though VHF sources were still evident in the lower portion of the storm near the melting layer (Figure 11).

However, the Duke ELF transient analysis system had retrieved the \( \Delta M_q \) values (6-10 ms time frame) for a majority of +CGs between 0300 UTC (the onset of LLTV monitoring) and the end of the storm (0530 UTC). The very high values of the “end-of-storm” sprites are evident. But also discovered were three \( \Delta M_q \) 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 easy to have been 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 patterns found for MCSs (Lyons et al. 2003b), the two “end-of-storm” sprites occurred during this collapsing phase. The earlier three sprites are another matter. They occurred during period of presumably strong updrafts and overall high storm electrical activity, when prior experience suggests sprites were most unusual.

Figure 12 summarizes the storm’s electrical structure for 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 \( \Delta M_q \) 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 km², 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/m³. 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 km²) at this time, and the total discharge was also smaller, only about 20 km in horizontal dimension, covering only 160 km². The NLDN peak current was +155 kA and the ∆Mₚ estimated at 1327 C km. Estimating that 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/m³. 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 general 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 be most likely occur near the end of the storm. In rare cases, during the mature storm phase, sufficient charge may be lowered within some very impulsive return strokes to initiate a sprite, and perhaps an elve as well.

Figures 14 and 15 show the charge moment change values retrieved from the CGs of the 25 June supercell. It is immediately clear that the +CGs are associated with larger overall ∆Mₚ values, with 5 of the 6 exceeding the nominal 600 C km threshold producing optically confirmed sprites. The –CGs, by contrast were generally much less than 100 C km, well below sprite threshold. Again, in this storm, the “polarity paradox” for sprites can be ascribed to the lack of –CGs with a sufficiently large ∆Mₚ.

8. THE 23 JUNE 2003 BAMEX SUPERCELLS

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 (the southern cell in our Figure 16) 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. An initial analysis of the lightning characteristics of these supercells are discussed here. The NLDN reported strokes form both storms are plotted in Figure 17, with the blue star indicating the location of the giant hail fall.

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 percentages 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
associated 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 to 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 (Figure 18). 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. In Figure 18, note that at the time of the impact of the giant hail stone (0005 UTC), 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 $\Delta M_q$ 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 $\Delta M_q$ was $\sim$5 C km. The table in Figure 20 shows the analysis of both NLDN polarity and peak current and ELF impulse $\Delta M_q$ 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 $\Delta M_q$ values $>\sim$ 5 C km, and of these 19 were from reported +CGs. 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 $\Delta M_q$ was only 200 C km, not especially large when compared to the other supercells evaluated in this paper. Most striking is the reported 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 $\sim$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. The extremely high surface dewpoints and large CAPE values for these storm environments support recent contentions by Earle Williams (2004, personal communication) that positive CGs in convective cores are more likely to be found in high cloud base storms. This does not explain, however, the burst of +CGs early in the storm's growth period. Many aspects of these storms’ electrical behavior merit considerable further attention. The Superior supercell also appears to have shown similar evolution in its electrical structure, and this will be further investigated (Figure 19).

At this time, we suspect that the large number of small peak current –CGs may in fact be an artifact. While small peak current –CGs can occur in some storms (Biagi et al 2004), we suspect that, especially the Aurora hail storm, possessed updrafts so intense as to have developed an inverted polarity structure (Rust and MacGorman, 2002). In this regime, numerous IC discharges were propagating in the opposite vertical direction than in “normal” storms. The NLDN was thus mis-interpreting some of the more powerful IC discharges not as +CGs (normally discarded for $<10$ kA events in NLDN processing) but as small negative CGs. This particular aspect of intense supercell electrical activity clearly requires additional study, as does the broader issue of exactly what determines to polarity, peak current and charge lowered to ground in supercells.
9. IMPULSE CHARGE MOMENT CHANGES

TLE research has advanced largely due to the ability of LLTV systems to detect luminosity above storms during the dark of night. However, it is clearly desirable to have a surrogate that can work throughout the diurnal cycle, as well as when clouds block the view of ground cameras. From several studies (Hu et al 2002; Lyons et al 2003b) it appears that a relative narrow threshold range of $\Delta M_q$ values exists to allow discriminating those CGs which do and do not produce sprites, halos and elves. The extraction of the full (10 ms or longer) $\Delta M_q$ value from ELF/VLF transient data is still a rather laborious task, which currently limits the extent of both case studies, and especially any potential operational utilization of this parameter. Recent advances in the extraction of the impulse $\Delta M_q$ values (Cummer and Lyons, 2004, 2005) have suggested that an automated approach may in time become feasible. The question then arises as to whether the impulse $\Delta M_q$ contains sufficient predictive value to be a useful discriminator for sprites (high probability of detection, low false alarm rate). Initial tests conducted in conjunction with LLTV monitoring of MCSs from YRFS during the summer of 2005 appear very promising.

Figure 21 shows a GOES IR cloud canopy associated with a developing MCS over the Wyoming-South Dakota border at 0315 UTC on 13 August 2005. This MCS was large enough and tall (cold) enough to produce TLEs, and indeed produced numerous excellent examples recorded in high speed video (Cummer et al. 2006). Figure 22 shows the NLDN stroke data for the 0300-0359 UCT period when the majority (18) of the 33 TLEs recorded that evening occurred (Figure 23). The NLDN peak current plots versus time (Figure 24) shows the storm possessed a moderate number of larger peak current +CGs (those producing TLEs in black), but also many -CGs, some with fairly large peak currents. During peak the TLE-producing period the storm produced 85-90% negative polarity strokes.

We selected the period 0304-0325 UTC, which produced 8 sprites (3 preceded by halos), for more intensive study. The distribution of CG stroke peak currents by polarity (positive Figure 25; negative Figure 26). These show the typical long tail of high peak current +CGs (5 >100 kA) with an average of 22 kA. The average –CG peak current was 15 kA, with none larger than 100 kA. Figure 29 is a tabular summary of the entire storm’s lightning metrics. In general, this was a rather typical MCS, in terms of percent positive, average peak currents and maximum peak currents. Large peak current positives where more numerous than negatives, but not overwhelmingly so.

The retrieved impulse $\Delta M_q$ values for the 0304-0325 UTC period are shown as a histogram in Figures 27 and 28. Here it is very clear that the larger values are confined to positive events. Initial experiences to date have shown that if the impulse $\Delta M_q$ value is above 100 C km, there is an increasing probability that those CGs will produce sprites, halos or elves. In this set, 7 of the 16 +CGs with $\Delta M_q > 100$ C km produced TLEs. (This is actually a lower “hit rate” than in other storms evaluated during the summer, in which the accurate detections ranged from 65% to 90%). It is a marked improvement, in any case, over using other less robust metrics, such as peak current >100 kA. Figure 30 shows those events from this storm, as compared to the actual TLE detections shown in Figure 23.

Most interestingly is the spatial clustering of the TLEs during the 0304-0325 UCT period shown in Figures 31 and 32. This reveals the classic pattern of TLEs being confined to a relatively small portion of the trailing stratiform region, often near the outer edge. Compared to the NDLD CG strokes, the TLE producers are well removed from the convective core strokes at the leading edge. When plotted over radar one can see they are confined to a relatively low reflectivity area, again far removed from the >55 dBZ convective line.

We anticipate ongoing investigations of the utility of using $\Delta M_q$ as a surrogate for TLE detection during the upcoming 2006 and 2007b convective seasons.

10. DISCUSSION AND CONCLUSIONS.

In High Plains MCSs, +CGs producing sufficiently large $\Delta M_q$ values inducing TLEs typically occur (1) in the trailing stratiform region, (2) associated with radar reflectivities of 20-45 dBZ, (3) in radar echoes (>10 dBZ) regions covering >20,000 km², (4) in storms which a peak core reflectivity >55dBZ, (5) beneath the colder, though not usually the coldest, tops, and (6) only in systems with a maximum cloud top temperature of -55°C or less.
The observation that sprites rarely occur during the active phase of High Plains supercells, even though they produce copious numbers of high peak current \( +\text{CGs} \), appears consistent with this notion. The occasional “end-of-storm” sprites occur when the supercell is developing quasi-MCS stratiform region characteristics.

The three sprites during the active stage of the 25 June supercell appear to be a rare exception to the rule. In this case, the charge moments in return strokes associated with very high charge densities in the storm’s convective cores were sufficient to trigger mesospheric breakdown. More typically, \( \Delta M_e \) values in the cores of such storms are insufficient to initiate sprites, perhaps due to the lack of a horizontally extensive pool of positive charge from which to draw.

This begs the larger question of what processes are active in storms to produce CGs with the requisite large \( \Delta M_e \)? The behavior of the Aurora, NE supercell illustrates how complex and variable is the electrical nature of even one class of deep convection.

Our new capability to routinely monitor storms using ELF/VLF transient analysis to estimate charge moment change provides additional metrics by which the electrical activity of convective storms can be characterized (Cummer and Lyons, 2004, 2005).

The “polarity paradox” discussed by Williams et al (2006) finds that globally less than 1% of TLEs observed from land occur with negative CGs, while 10x that number of threshold-exceeding \( \Delta M_e \) events are indicated by ELF analyses. Over the U.S. High Plains, in the storms investigated to date, negative CGs have simply not produced large enough \( \Delta M_e \) to induce TLEs. The mystery may in part be resolved by noting the large number of high peak current (and large EMP) \(-\text{CGs}\) over salt water. Recent analyses of ISUAL satellite measurements have found very large percentages of elves, also with relatively large charge moment changes, from negative CGs over oceans (Cummer, personal communication, 2006).

11. ACKNOWLEDGMENTS

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Rust, W.D. and D.R. MacGorman, 2002: Possibly inverted-polarity electrical structures in thunderstorms during STEPS.


Figure 1. The ratio of the flash density of negative to positive CGs with peak currents >75 kA (1995-2003).

Figure 2. Flashes with peak currents >200 kA (positive red, negative blue) for the periods June-August, 2002-2004.
Figure 3 upper left). Location of a 30 kA sprite parent +CG at 0600.15.346 UTC 19 July 2004 (red lightning symbol), occurring several tens of kilometers north of the coldest cloud tops (white). Figure 3 (upper right). NEXRAD reflectivity mosaic at 0600 UTC showing sprite +CG occurred in the low reflectivity stratiform region of the MCS. Figure 3(lower left) Plot of CGs from 0600 to 0700, with –CGs (green) in storm’s core, +CGs (blue) mostly in the stratiform region and sprite parent +CGs (red). Figure 3 lower right). Density plot of LMA VHF sources from 0550-0600 UTC showing the sprite event occurred well north of the region of maximum storm electrical activity.
Figure 4. LMA displays for sprite-parent CG (red triangle) shown in Figure 3 with color coding as indicated. The sprite luminosity period is shown in pink.

- **Green**: pre CG breakdown
- **Yellow**: CG to TLE onset
- **Pink**: Sprite luminosity detectable
- **Grey**: post sprite

Many SP+CGs trigger above the convective core and move rearward and downward into stratiform to tap positive charge pool.
Figure 5. Cloud top IR temperature above the location of TLE parent +CGs.

But... coldest cloud top in MCS must be < -55°C

Figure 6. Radar reflectivity at the location of TLE parent CGs.

But... the highest value in the MCS MUST be > 55 dBZ
Figure 7. Schematic of MCS with intense leading line and large trailing stratiform (adapted from Carey et al 2005). Many IC charges leading to sprites may start near the top of the convective core and descend rearward and downward into the trailing stratiform, where they trigger a +CG which then taps the large horizontal pool of positive charge near the melting layer which then induces a mesospheric sprite above the storm after sufficient charge is lowered to ground.
Figure 8. NLDN stroke peak current, polarity and times of occurrence for a right-moving tornadic supercell moving through the STEPS LMA domain on the afternoon of 29 June 2000.

Figure 9. Charge moment changes computed using an early version of the Duke ELF/VLF transient analysis system. The nominal threshold for sprite production is about 600 C km.
Figure 10. NLDN stroke peak current, polarity and times of occurrence for a supercell moving through the STEPS LMA domain on the evening of 25 June 2000. Sprite events shown as black.

Figure 11. Analysis of LMA VHF sources for storm in Figure 10. Shown are the maximum height of VHF sources, the height of the maximum electrical activity in the storm and the electrical activity area covered. The occurrence of the sprites are shown on the top.
Figure 12. Characteristics of the last +CG of the storm, which produced a sprite.

- **Storm Type:** Supercells
- **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 km²
- **Discharge Layer Depth:** 1000 m
- **Initial Charge Density:** = 1.0 nC/m³

Character: significant continuing current

- 0 - 10 ms: 14 kA
- 0.25 ms: 28 kA
- 2.5 - 5 ms: 61 kA
- 5 - 10 ms: 11.0 kA

Figure 13. As above except for a sprite-producing +CG during the most intense phase of the supercell.

- **Storm Type:** Supercells
- **Sprite at mature stage of the storm at 0344 UTC**
- **NLDN:** + 155 kA
- **NEXRAD AREA:** 7527 km²
- **Mq:** 1327 C km
- **Zq:** 4.0 km
- **C:** 330 C
- **LMA Discharge Area:** 160 km²
- **Discharge Layer Depth:** 1500 m
- **Initial Charge Density:** = 5.5 nC/m³

Character: smaller CC - more impulsive

- 0 - 10 ms: 162 kA
- 0.25 ms: 54.6 kA
- 2.5 - 5 ms: 3.0 kA
- 5 - 10 ms: 3.8 kA
Figure 14. Retrieved charge moment changes (+CGs) for the sprite producing supercell of 25 June 2000. Five of the 6 +CGs exceeding 600 C km produced a sprite.

Figure 15. Retrieved charge moment changes (-CGs) for the sprite producing supercell of 25 June 2000. No negative CGs produced values even close to the sprite threshold.
Figure 16. GOES visible and NEXRAD reflectivity displays of the two supercells producing the largest hailstone (Aurora) and most intense misocyclone (Superior) ever documented. Images at 0000 UTC 23 June 2003.

Figure 17. NLDN stroke data (negative is green) for the 30 minutes after the images shown above. The blue star represents the location of the giant hail fall at 0005 UTC.
Figure 18. The NLDN stroke history of the Aurora supercell around the time of the giant hall fall, 0005 UTC 23 June 2003.

Figure 19. The NLDN stroke history of the Superior supercell around the time of the giant during the period leading up to the most intense mesocyclone ever recorded (~0300 UTC.)
Table 1. 23 June 2003 Electrical Characteristics

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<th>Superior Mesocyclone</th>
<th>Maturing MCS</th>
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<td>0025-0035</td>
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<tr>
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<tr>
<td>Mean +CG peak current</td>
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Figure 20. Summary of NLDN stroke data and impulse charge moment change retrievals at various stages during the Aurora and Superior supercells, as well as from the MCS which evolved around 0600 UTC.

Figure 21. GOES IR temperature showing an MCS along the Wyoming-South Dakota border at 0315 UTC 13 August 2005 as it was entering its most prolific TLE-producing period.
Figure 22. NLDN stroke data for MCS between 0300-0359 UTC 13 August 2005.

Figure 23. The locations of the 33 TLEs produced from the 13 August 2005 MCS between 0255 and 0526 UTC.
Figure 24. Time history of the NLDN strokes between 0200 and 0600 UTC 13 August 2005. Black indicates TLEs optically confirmed. The LLTV cameras were not turned on until 0250 UTC.
Figure 25. Histogram of the NLDN +CG peak currents during the peak of TLE production.

Figure 26. Histogram of the NLDN -CG peak currents during the peak of TLE production.
Figure 27. Histogram of the NLDN +CG impulse charge moment change during the peak of TLE production.

Figure 28. Histogram of the NLDN -CG impulse charge moment change during the peak of TLE production.
**13-Aug-05 NLDN Statistics**

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**Figure 29. Summary of NLDN stroke data for the TLE producing MCS of 13 August 2005.**

**13 Aug 2005**

- **Strokes > 100 kA**
- **Strokes < -100 kA**

**Figure 30. Location of all CGs of both polarities which exceeded 100 kA peak currents.**
Figure 31. S marks those +CGs which produced optically confirmed TLEs during the 21 minute intensive study period (and which had impulse charge moment changes generally >100 C km).

Figure 32. Red stars marks those +CGs which produced optically confirmed TLEs during the 21 minute intensive study period. As is often the case, they were concentrated in the rear portion of the trailing stratiform region.