P2.16 LIGHTNING CHARACTERISTICS OF THE AURORA, NE RECORD HAILSTONE-PRODUCING SUPERCELL OF 22-23 JUNE 2003 DURING BAMEX

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1. INTRODUCTION

The Bow Echo and Mesoscale Convective Vortex Experiment (BAMEX) was conducted during the summer of 2003 in the north-central U.S. (Davis et al. 2004).The primary focus of the project was the dynamics of large mesoscale convective systems (MCSs). As MCSs often evolve upscale from localized storms, it is not surprising that many supercells were also present within the experimental domain. On the afternoon and evening of 22-23 June 2003, two extraordinary supercell-like storms formed in south-central Nebraska (Fig. 1), presaging the formation of a MCS several hours later. The southern-most cell, called the Superior supercell, contained the most intense mesocyclone yet documented. Airborne Doppler radar detected a vortex 9 km in diameter with a 118 m s^{-1} velocity differential. Just two counties to the northwest another intense storm, the Aurora supercell, produced the largest confirmed hail stone in the U.S. (18.75 inches, [47.6 cm] circumference). While the dynamics of these storms are being widely investigated (Wakimoto et al. 2004), this paper will investigate the electrical characteristics of these unique events.

MCS lightning has been extensively researched. The discovery that mesospheric sprites (Franz et al. 1990) above the U.S. High Plains MCSs are associated with positive cloud-to-ground (+CG) lightning (Lyons 1996) has focused additional attention on the unusual characteristics of sprite parent +CGs (SP+CGs) (Boccippio et al. 1995; Huang et al. 1999; Hu et al. 2002). While the peak currents of SP+CGs are 25-50% higher than other +CGs in the same storm, peak current proves a poor sprite predictor. As initially suggested by 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 Q, the amount of charge lowered. [Note this second term is most appropriately considered as a function of time.] During the 2000 Severe Thunderstorm Electrification and Precipitation Study (STEPS), sprite-producing MCSs were investigated using peak current data from the National Lighting Detection Network (NLDN), a 3-D lightning mapping array, and ELF/VLF sensors from which $\Delta M_q(t)$ can be extracted for storms occurring up to several thousands of kilometers away (Lang et al. 2004; Cummer and Inan 2000; Hu et al. 2002). The STEPS SP+CGs were typically found within a portion of the trailing stratiform region of mature MCSs which had attained a size of >10,000 km^2 (>10 dBZ reflectivity). Consistent with theories of conventional dielectric breakdown, an apparent minimum threshold in $\Delta M_q(t)$ between 300 and 600 C km appears necessary (and sufficient?) for sprite initiation. This value is dependent upon both the duration of time over which $\Delta M_q(t)$ is extracted as well as night to night changes in mesospheric conductivity (Cummer and Lyons 2004 a, b). For a typical MCS (19 July 2000), the average $\Delta M_q(t)$ for an SP+CG was ~800 C km (Lyons et al. 2003a).

A decade of low-light video sprite monitoring from Colorado's Yucca Ridge Field Station (YRFS) suggests that sprites, while common above many MCSs, are extremely rare above supercells, save during their dying stages when they may develop more extensive stratiform precipitation regions. Given that supercells are often extremely electrically active, and many are dominated by positive polarity flashes, this discrepancy was very puzzling.

During STEPS, the electrical nature of supercells were investigated using the added resource of ELF/VLF $\Delta M_q(t)$ retrievals. The daytime supercell of 29 June 2000 exhibited an inverted (negative over positive dipole) polarity structure (Rust and MacGorman 2002). The storm had 80% +CGs during its lifetime, with average +CG peak currents of 53 kA (12%>75 kA). The –CG average peak current was 18 kA (Lyons and Cummer 2004). While many +CG $\Delta M_q(t)$ values exceeded 100 C km, none peaked above the 600 C km threshold at which a 10% probability of a sprite could be expected. Moreover, few –CGs produced $\Delta M_q(t)$ >50 C km. A nocturnal supercell on 25 June 2000, allowed for optical sprite monitoring. Five sprites were recorded, two from the very last +CGs of the decaying storm ($\Delta M_q(t)$ >1000 C KM). Three small events did occur during the most intense phase of the supercell (Lyons and Cummer 2004). These +CGs were highly impulsive but powerful enough ($\Delta M_q(t)$ >800 C km) to initiate sprites. But these appeared exceptions to the general rule for supercells to have few +CG and no -CG $\Delta M_q(t)$ values anywhere near the sprite triggering threshold. Duke University's routine $\Delta M_q(t)$ monitoring during BAMEX provided an opportunity to explore the electrical nature of these extreme convective events.

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2. BAMEX AND DATA UTILZIED

As detailed by Davis et al. (2004), BAMEX deployed an extensive array of aircraft, mobile and remote sensing systems, with a primary focus on large MCSs. The supercells of 22-23 June were serendipitous occurrences which were partially monitored by research platforms (Wakimoto et al. 2004). We herein investigate the several stages of the developing convection on the evening of 22-23 June 2003 using conventional GOES and NEXRAD images, rawinsondes and NLDN stroke-level CG data, augmented by charge moment change data.

The Duke University ELF/VLF system, operating in a triggered mode, captured the larger impulse charge moment changes (i$\Delta M_q(t)$), during the first 2 ms of the CG event. During STEPS, continuous mode monitoring allowed retrieval of i$\Delta M_q(t)$ from virtually all CGs above a minimal detectible signature of ~5 C km (Cummer and Lyons 2004 a,b). During the BAMEX study, most CGs with i$\Delta M_q(t)$ >10-20 C km (still quite small) were likely captured. As the BAMEX domain was so far east of YRFS, LLTV sprite monitoring was not undertaken.

3. METEOROLOGICAL ENVIRONMENT

During the late afternoon of 22 June, a diffuse north-south stationary front was present in central Nebraska. A more distinctive feature was the remnant outflow boundary from earlier convection. Surface dewpoints were 20-24ºC. Late afternoon temperatures reaching 28-31ºC suggested lifted condensation levels in the 1000-1500 meter range. Soundings at 0000 UTC showed regional CAPE values in the 3000-3500 J kg^{-1} range. CAPE as high as 4000 J kg^{-1} at the time of convective initiation was accompanied by an unusual, near circular hodograph from the surface to 620 mb (Wakimoto et al. 2004). While the term "supercell" has been applied to the initial convective structures which emerged, it is being rather loosely applied. The Aurora "supercell" may have been a multi-celled system during much of its lifetime, with the hail falling from the southernmost reflectivity maximum. The Superior supercell was extremely well organized for about one hour, but was also multi-cellular at times. In any case, these county-sized storms contained extreme updrafts as evidence by the huge hail and 18-19 km radar echo tops.

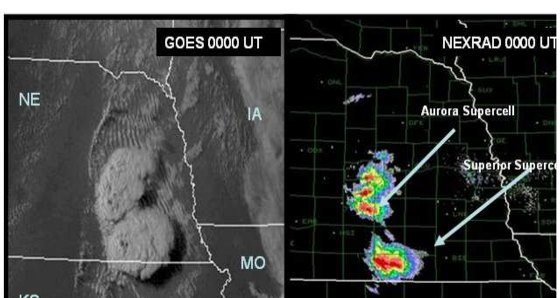

Fig.1 GOES and NEXRAD at 0000 UT

4. THE AURORA SUPERCELL

The Aurora cell produced its first CG (a negative) shortly before 2300 UTC. During the 2300-2330 UTC period, the storm was nearly 50% positive, with mean positive peak currents of 55 kA (largest 192 kA). In the 2325-2335 UTC time frame, presumably as the record hail stone's updraft was just becoming organized, the percent positive peaked at 57% (Table 1). Almost two thirds of the +CGs generated detectable i$\Delta M_q(t)$ with an average value of 133 C km and a peak of 200 C km. Though below sprite-producing values these are larger than "normal" (Rakov and Uman 2003) and comparable to those found in STEPS supercells. By contrast, the –CGs had both small peak currents (10 kA) and undetectable i$\Delta M_q(t)$. In the half hour before the record hail fall at 0005 UTC, the CG flash rate increased rapidly (to 14.3 CG/min), but became strongly negatively dominated (93%). Mean negative peak currents remained small (9 kA, with the largest 27 kA) and no –CGs could generate a detectable i$\Delta M_q(t)$.

By 0005 UTC, small the small negative events continued and only a few low peak current an one low i$\Delta M_q(t)$ +CGs were detected. In addition to the record hail stone, smaller hail fell though out the area and an F0 tornado touched down 6 km northwest of Aurora at 0012 UTC.

This cell remained distinct from the developing MCS until about 0100 UTC. By 0025-0035 UTC, the cell's lightning characteristics had continued to evolve. The overall flash rate remained around 14 CG/min, but rebounded to 25% positive. However peak currents for negatives (-10 kA) and positives (18 kA) remained low, as did the i$\Delta M_q(t)$ values for –CGs.

Table 1. 23 June 2003 Electrical Characteristics
2 ms charge moment changes and NLDN statistics

	Aurora Hail			Superor Mesocyclone	Maturing MCS
	2325-2335	2355-0005	0025-0035	0255-0305	0555-0605
CG Rate (per minute)	4.7	14.3	13.7	299	287
Percent Positive	57	7	25	6	9
Mean +CG peak current	55	17	18	12	19
Max +CG peak current	192	37	80	39	143
% +CGs with I ΔMq	63	14	16	5	2
Avg. +CG I ΔMq	113	37	99	22	11
Max +CG I ΔMq	200	37	124	81	22
Mean - CG peak current	-10	-9	-10	-16	-16
Max -CG peak current	-26	-27	-22	-83	-117
% -CGs with I ΔMq	0	0	<2	17	6
Avg. -CG I ΔMq	0	0	9	28	25
Max -CG I ΔMq	0	0	12	139	82

Figure 2 shows a plot of NLDN for the Aurora cell (star marks the hail stone fall) and the developing Superior supercell (2330-2359 UTC), as well as the Aurora cell NLDN event time line. Only during the period more than 30 minutes before the hail fall (2325-2235 UTC) did these CGs produced any i$\Delta M_q(t)$ values of consequence, and only then from +CGs.

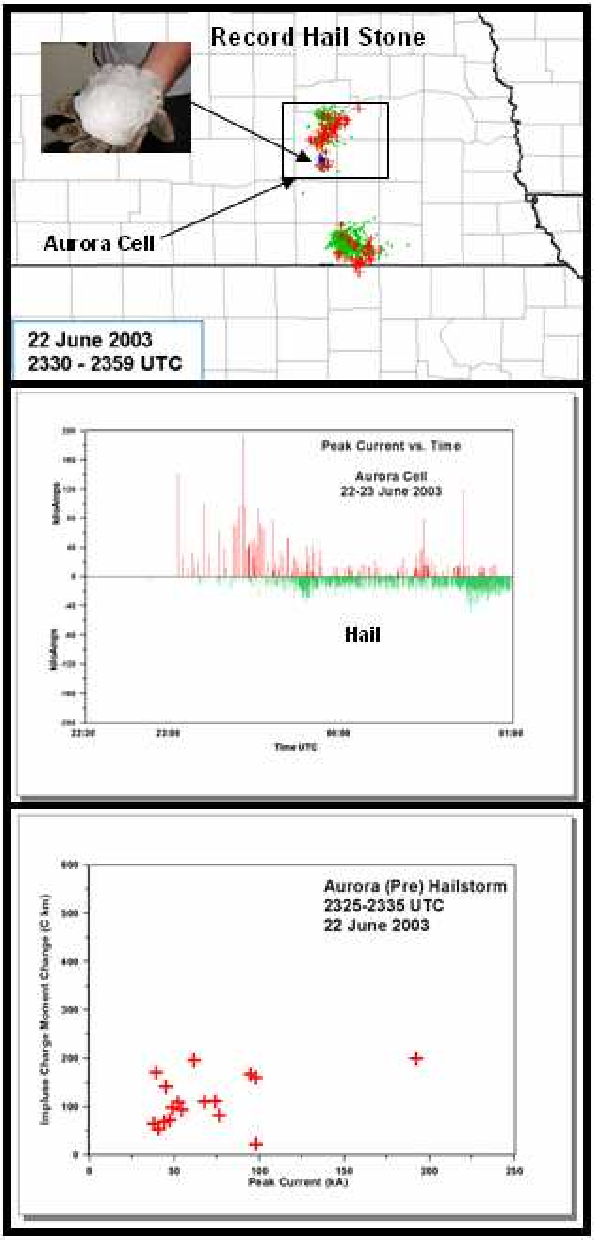

Figure 2. (top) NLDN CGs between 2300-2359 UTC. Star indicates hail fall location. The rectangle surrounds the storm for which the NLDN time history is plotted (middle). The plot of charge moment changes versus their +CG peak currents between 2325 and 2335 UCT (bottom) mark the only period during the storm when large values of charge were being lowered to the surface. (Red cross +CGs)

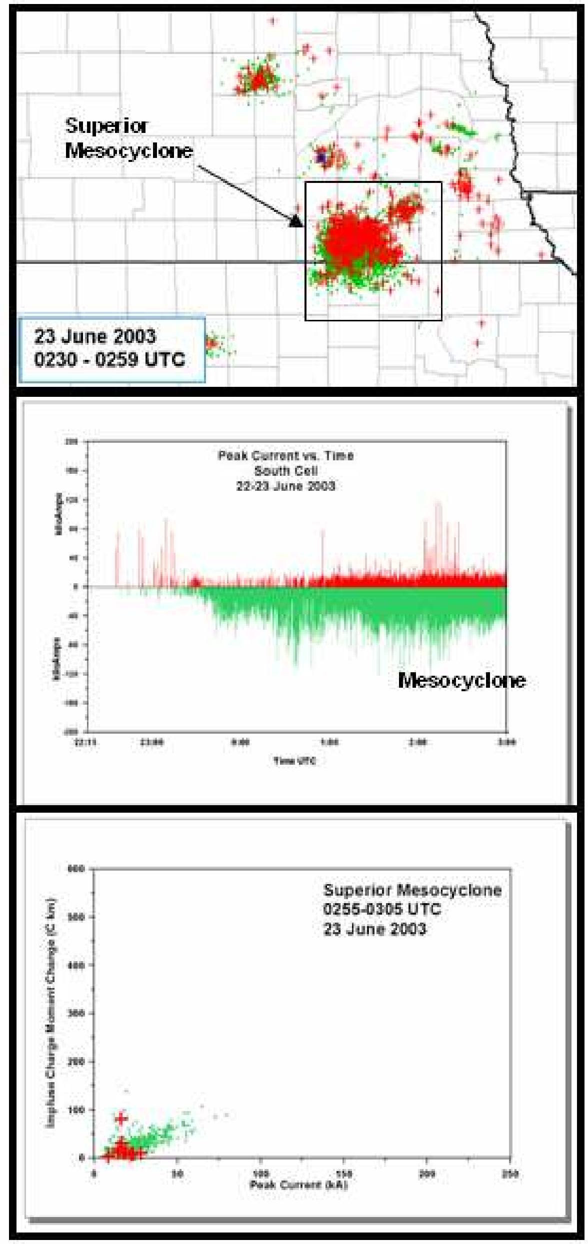

Figure 3. Similar to Fig 2, except showing the NLDN events from 2300 to 2359 UTC (top), the NLDN timeline (0000-0300 UTC) (middle), and the $i\Delta M_q(t)$ – peak current relationships for those very few CGs powerful enough to lower detectable amounts of charge to ground during a ten minute period during the most intense stage of the record mesocyclone (bottom).

5. THE SUPERIOR SUPERCELL

The storm system which evolved into the Superior mesocyclone began at approximately the same time as the Aurora cell. During its first hour it was likewise strongly positive (45%). As with the northern cell, after this initial growth phase, the CG rates increased significantly, percent positives dropped to less than 5%, +CG peak currents fell rapidly from 40 kA to 10-15 kA, and the negative CG peak currents remained small (11-18 kA). At the time of the record mesocyclone (0255-0305 UTC), the CG rate was an impressive 299 min^{-1}, and only 6% positive. Of those

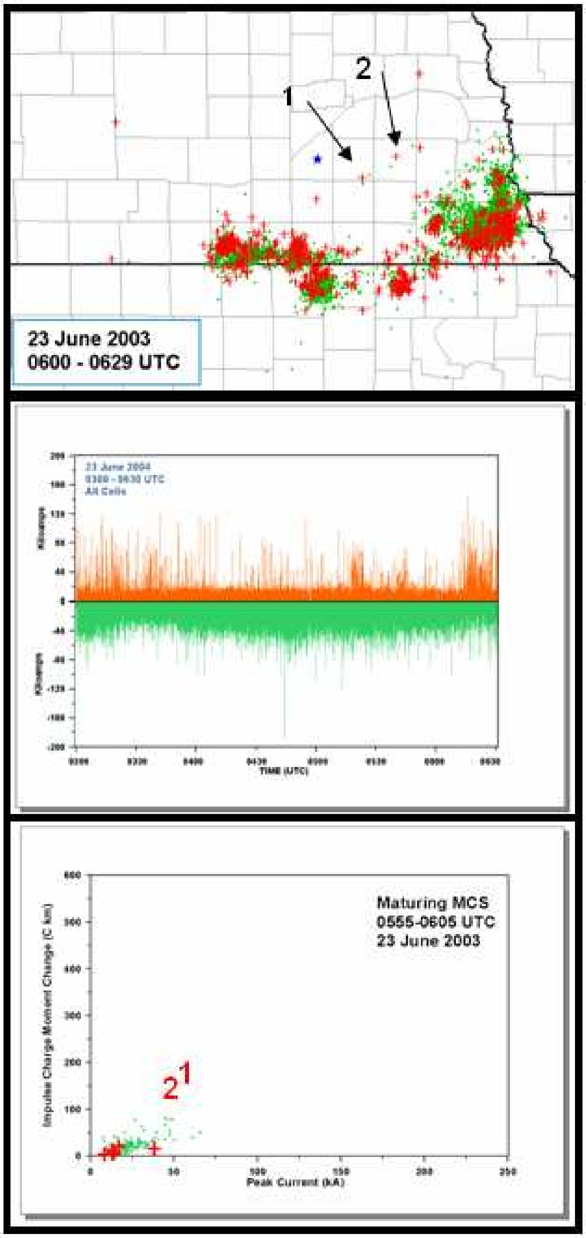

Figure 4. (top) NLDN CGs between 0600-0630 UTC, including two +CGs in the developing stratiform region The NLDN time history is plotted (middle). The plot of charge moment changes versus their CG peak currents between 0555 and 0605 UCT (bottom) are compared to the two +CGs about 20 minuets later in the organizing stratiform region (green negative, red crosses/numbers positive).

positives, less than 5% had detectable $i\Delta M_q(t)$ signatures, with very small average values of 22 C km Atypical of supercells, a greater percent of the -CGs (17%) produced detectable impulse charge moment changes, but these also had rather small mean (28 C km) and peak (131 C km) values. It is very unlikely that this dynamically intense cell's lightning was initiating sprites during its mature stage.

6. THE MATURING MCS STAGE

Between 0300 and 0630 UTC, convection became more widespread through extreme southeast Nebraska, though severe weather reports waned. The convection appeared to be organized more as clusters of intense cells. MCS-like characteristics, including a large stratiform region with secondary precipitation maxima (Schuur and Rutledge 2000), did not begin to emerge until after around 0600. Figure 4 shows CG activity clustered in several centers, with both polarities co-located in these convective cores. CG rates exceeded 20,000 hr^{-1} but the positives remained between 6 and 11 %. The NLDN time line in Fig, 4 shows patterns typical of more conventional convection, though the mean peak currents for the +CGs (15-18 kA) and the –CGs (15-18 kA) both remained somewhat smaller than the climatological norm. There were occasional large peak current events, largely absent during the intense hail and mesocyclone stages earlier in the evening.

Inspection of the $i\Delta M_q(t)$ signatures between 0555 and 0605 UTC showed that only 2% of the +CGs and 6% of the –CGs had detectable values, and these remained very small, averaging a mere 11 and 25 C km respectively (Table 1).

After 0600 UTC, radar began to show a semblance of an organized stratiform precipitation region to the north of the intense cells, suggesting the convection was maturing into a more typical MCS structure. Around 0620 UTC, two +CGs were noted (Fig 4) well to the north of the main activity. The peak currents were 55 and 47 kA, but the $i\Delta M_q(t)$ values were 175 and 166 C km respectively, much larger than those sampled in the cores 10 to 20 minutes previously. This suggests microphysical conditions in the developing stratiform region were evolving towards the production of large charge moment change strokes more typical of SP+CGs. As seen in many sprite-generating MCSs, these larger charge moment events were closer to the edge of the storm's precipitation shield than the convective cores.

7. DISCUSION AND CONCLUSIONS.

The search for consistent lightning polarity signatures indicative of intense hail storms has produced a variety of both intriguing (Reap and MacGorman 1989; Rust el. 1991; Stolzenburg 1994; MacGorman and Rust 1998) but ultimately inconsistent results (Carey et al. 2003). A similar state exists with respect to NLDN tornadic signatures (Brannick and Doswell 1992; Curran and Rust 1992; Seimon 1993; Perez et al. 1997; Bluestein and MacGorman 1998). The recent availability of an additional metric, charge moment change, which is roughly proportional to the charge lowered to ground (in this paper, during the impulsive first 2 ms of the stroke), allows may allow additional insights into severe storm electrical activity.

On 22-23 June 2003, the BAMEX storms which developed in a nominally uniform and highly unstable air mass exhibited a variety of behaviors. The quasi-supercellular storm which evolved to produce the U.S. record hailstone initially began as a relatively low CG rate storm, but almost 50% positive with many large peak currents and substantial (>100 C km) i$\Delta M_q(t)$ values (though still below sprite-triggering thresholds). During the half hour before the record hail fall, stroke rates increased, and became overwhelmingly negative in polarity with both mean and maximum peak currents being exceptionally small (~10/~25 kA). While many hail storms have been associated with large peak current +CGs (Curran and Rust 1992; Stolzenburg 1994), low peak current –CG dominated hail storms have also been reported (Soula et al. 2004). The lack of detectable i$\Delta M_q(t)$ values from these –CGs suggests an interesting possibility. The conventional application of NBLDN data (Cummins et al 1998) often segregates +CG strokes of < 10 kA, as these likely represent IC contamination. But this assumption assumes a normal dipole structure for the storm. Could the Aurora supercell have been inverted, as found during the STPES program (Rust and MacGorman 2002)? In this case might not IC discharges be mis-classified by the NLDN as negative stokes?

The storm which generated to intense Superior mesocyclone and tornadoes showed a somewhat similar evolution. Except this storm, at the time of the record mesocyclone, was producing almost exclusively negative CGs with small (16 kA) peak currents at rates approaching 17,000 per hour. Again, could this storm have been an inverted dipole with many IC events being sensed as small peak current –CGs?

Naturally, a key missing component from this study is IC flash rates such as from an LMA or LDAR-II system, allowing assessment of storm total lightning. The Superior cell does stand in marked contrast, however, to the anomalously low –CG rate supercell (though having extremely high IC rates) investigated during STERAO-A (Lang et al. 2000).

As the convection evolved on this evening, it gradually began to resemble a more classical MCS after 0600 UTC. A few “stray” +CGs began to be detected in the developing stratiform region well away from the convective cores. Only these +CGs had i$\Delta M_q(t)$ values above 100 kA, suggesting microphysical conditions in this remote portion of the storm were beginning to resemble those in which SP+CGs normally develop (Williams 1998; Lyons 1996)

What ultimately controls the polarity (and peak currents and charge lowered) of supercell lightning remains an unresolved issue. The relationship of the storms the theta-e ridges (Smith et al. 2000), the height of the cloud base (Williams et al. 2004) and the updraft size and intensity (Lang and Rutledge 2003) have all been suggested as factors. The new metric, charge moment change, a surrogate for charge lowered to ground, extracted from ELF/VLF signatures, may help provide insight into this question.

8. ACKNOWLEDGEMENTS

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

defined as the product of Z_q, the mean altitude (AGL) from which the charge is lowered to ground, and Q, the amount of charge lowered. [Note this second term is most appropriately considered as a function of time.] During the 2000 Severe Thunderstorm Electrification and Precipitation Study (STEPS), sprite-producing MCSs were investigated using peak current data from the National Lighting Detection Network (NLDN), a 3-D lightning mapping array, and ELF/VLF sensors from which $\Delta M_q(t)$ can be extracted for storms occurring up to several thousands of kilometers away (Lang et al. 2004; Cummer and Inan 2000; Hu et al. 2002). The STEPS SP+CGs were typically found within a portion of the trailing stratiform region of mature MCSs which had attained a size of >10,000 km^2 (>10 dBZ reflectivity). Consistent with theories of conventional dielectric breakdown, an apparent minimum threshold in $\Delta M_q(t)$ between 300 and 600 C km appears necessary (and sufficient?) for sprite initiation. This value is dependent upon both the duration of time over which $\Delta M_q(t)$ is extracted as well as night to night changes in mesospheric conductivity (Cummer and Lyons 2004 a, b). For a typical MCS (19 July 2000), the average $\Delta M_q(t)$ for an SP+CG was ~800 C km (Lyons et al. 2003a).

A decade of low-light video sprite monitoring from Colorado's Yucca Ridge Field Station (YRFS) suggests that sprites, while common above many MCSs, are extremely rare above supercells, save during their dying stages when they may develop more extensive stratiform precipitation regions. Given that supercells are often extremely electrically active, and many are dominated by positive polarity flashes, this discrepancy was very puzzling.

During STEPS, the electrical nature of supercells were investigated using the added resource of ELF/VLF $\Delta M_q(t)$ retrievals. The daytime supercell of 29 June 2000 exhibited an inverted (negative over positive dipole) polarity structure (Rust and MacGorman 2002). The storm had 80% +CGs during its lifetime, with average +CG peak currents of 53 kA (12%>75 kA). The –CG average peak current was 18 kA (Lyons and Cummer 2004). While many +CG $\Delta M_q(t)$ values exceeded 100 C km, none peaked above the 600 C km threshold at which a 10% probability of a sprite could be expected. Moreover, few –CGs produced $\Delta M_q(t)$ >50 C km. A nocturnal supercell on 25 June 2000, allowed for optical sprite monitoring. Five sprites were recorded, two from the very last +CGs of the decaying storm ($\Delta M_q(t)$ >1000 C KM). Three small events did occur during the most intense phase of the supercell (Lyons and Cummer 2004). These +CGs were highly impulsive but powerful enough ($\Delta M_q(t)$ >800 C km) to initiate sprites. But these appeared exceptions to the general rule for supercells to have few +CG and no -CG $\Delta M_q(t)$ values anywhere near the sprite triggering threshold. Duke University's routine $\Delta M_q(t)$ monitoring during BAMEX provided an opportunity to explore the electrical nature of these extreme convective events.

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2. BAMEX AND DATA UTILZIED

As detailed by Davis et al. (2004), BAMEX deployed an extensive array of aircraft, mobile and remote sensing systems, with a primary focus on large MCSs. The supercells of 22-23 June were serendipitous occurrences which were partially monitored by research platforms (Wakimoto et al. 2004). We herein investigate the several stages of the developing convection on the evening of 22-23 June 2003 using conventional GOES and NEXRAD images, rawinsondes and NLDN stroke-level CG data, augmented by charge moment change data.

The Duke University ELF/VLF system, operating in a triggered mode, captured the larger impulse charge moment changes ($i\Delta M_q(t)$), during the first 2 ms of the CG event. During STEPS, continuous mode monitoring allowed retrieval of $i\Delta M_q(t)$ from virtually all CGs above a minimal detectible signature of ~5 C km (Cummer and Lyons 2004 a,b). During the BAMEX study, most CGs with $i\Delta M_q(t)$ >10-20 C km (still quite small) were likely captured. As the BAMEX domain was so far east of YRFS, LLTV sprite monitoring was not undertaken.

3. METEOROLOGICAL ENVIRONMENT

During the late afternoon of 22 June, a diffuse north-south stationary front was present in central Nebraska. A more distinctive feature was the remnant outflow boundary from earlier convection. Surface dewpoints were 20-24ºC. Late afternoon temperatures reaching 28-31ºC suggested lifted condensation levels in the 1000-1500 meter range. Soundings at 0000 UTC showed regional CAPE values in the 3000-3500 J kg^{-1} range. CAPE as high as 4000 J kg^{-1} at the time of convective initiation was accompanied by an unusual, near circular hodograph from the surface to 620 mb (Wakimoto et al. 2004). While the term "supercell" has been applied to the initial convective structures which emerged, it is being rather loosely applied. The Aurora "supercell" may have been a multi-celled system during much of its lifetime, with the hail falling from the southernmost reflectivity maximum. The Superior supercell was extremely well organized for about one hour, but was also multi-cellular at times. In any case, these county-sized storms contained extreme updrafts as evidence by the huge hail and 18-19 km radar echo tops.

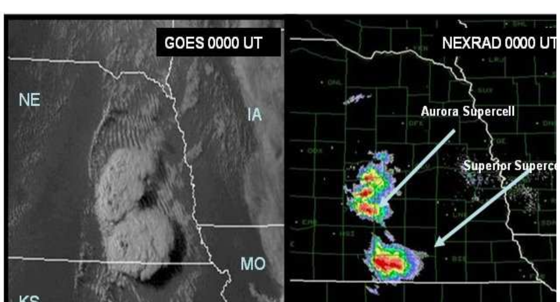

Fig.1 GOES and NEXRAD at 0000 UT

4. THE AURORA SUPERCELL

The Aurora cell produced its first CG (a negative) shortly before 2300 UTC. During the 2300-2330 UTC period, the storm was nearly 50% positive, with mean positive peak currents of 55 kA (largest 192 kA). In the 2325-2335 UTC time frame, presumably as the record hail stone's updraft was just becoming organized, the percent positive peaked at 57% (Table 1). Almost two thirds of the +CGs generated detectable $i\Delta M_q(t)$ with an average value of 133 C km and a peak of 200 C km. Though below sprite-producing values these are larger than "normal" (Rakov and Uman 2003) and comparable to those found in STEPS supercells. By contrast, the –CGs had both small peak currents (10 kA) and undetectable $i\Delta M_q(t)$. In the half hour before the record hail fall at 0005 UTC, the CG flash rate increased rapidly (to 14.3 CG/min), but became strongly negatively dominated (93%). Mean negative peak currents remained small (9 kA, with the largest 27 kA) and no –CGs could generate a detectable $i\Delta M_q(t)$.

By 0005 UTC, small the small negative events continued and only a few low peak current an one low $i\Delta M_q(t)$ +CGs were detected. In addition to the record hail stone, smaller hail fell though out the area and an F0 tornado touched down 6 km northwest of Aurora at 0012 UTC.

This cell remained distinct from the developing MCS until about 0100 UTC. By 0025-0035 UTC, the cell's lightning characteristics had continued to evolve. The overall flash rate remained around 14 CG/min, but rebounded to 25% positive. However peak currents for negatives (-10 kA) and positives (18 kA) remained low, as did the $i\Delta M_q(t)$ values for –CGs.

Table 1. 23 June 2003 Electrical Characteristics
2 ms charge moment changes and NLDN statistics

	Aurora Hail			Superor Mesocyclone	Maturing MCS
	2325-2335	2355-0005	0025-0035	0255-0305	0555-0605
CG Rate (per minute)	4.7	14.3	13.7	299	287
Percent Positive	57	7	25	6	9
Mean +CG peak current	55	17	18	12	19
Max +CG peak current	192	37	80	39	143
% +CGs with I ΔMq	63	14	16	5	2
Avg. +CG I ΔMq	113	37	99	22	11
Max +CG I ΔMq	200	37	124	81	22
Mean - CG peak current	-10	-9	-10	-16	-16
Max -CG peak current	-26	-27	-22	-83	-117
% -CGs with I ΔMq	0	0	<2	17	6
Avg. -CG I ΔMq	0	0	9	28	25
Max -CG I ΔMq	0	0	12	139	82

Figure 2 shows a plot of NLDN for the Aurora cell (star marks the hail stone fall) and the developing Superior supercell (2330-2359 UTC), as well as the Aurora cell NLDN event time line. Only during the period more than 30 minutes before the hail fall (2325-2235 UTC) did these CGs produced any $i\Delta M_q(t)$ values of consequence, and only then from +CGs.

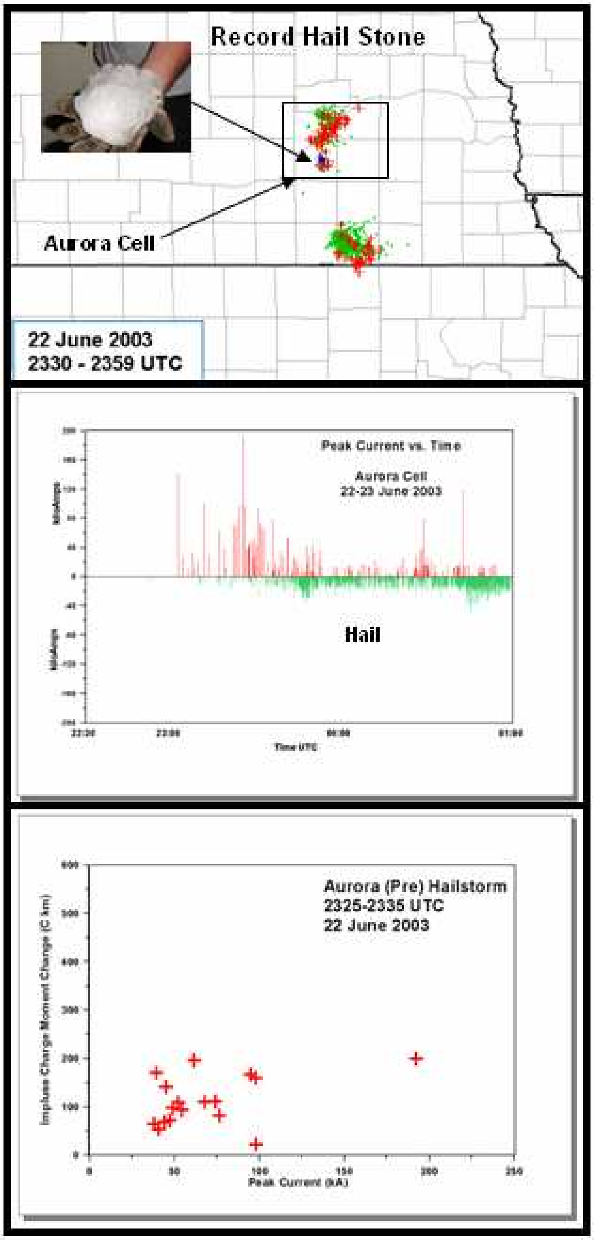

Figure 2. (top) NLDN CGs between 2300-2359 UTC. Star indicates hail fall location. The rectangle surrounds the storm for which the NLDN time history is plotted (middle). The plot of charge moment changes versus their +CG peak currents between 2325 and 2335 UCT (bottom) mark the only period during the storm when large values of charge were being lowered to the surface. (Red cross +CGs)

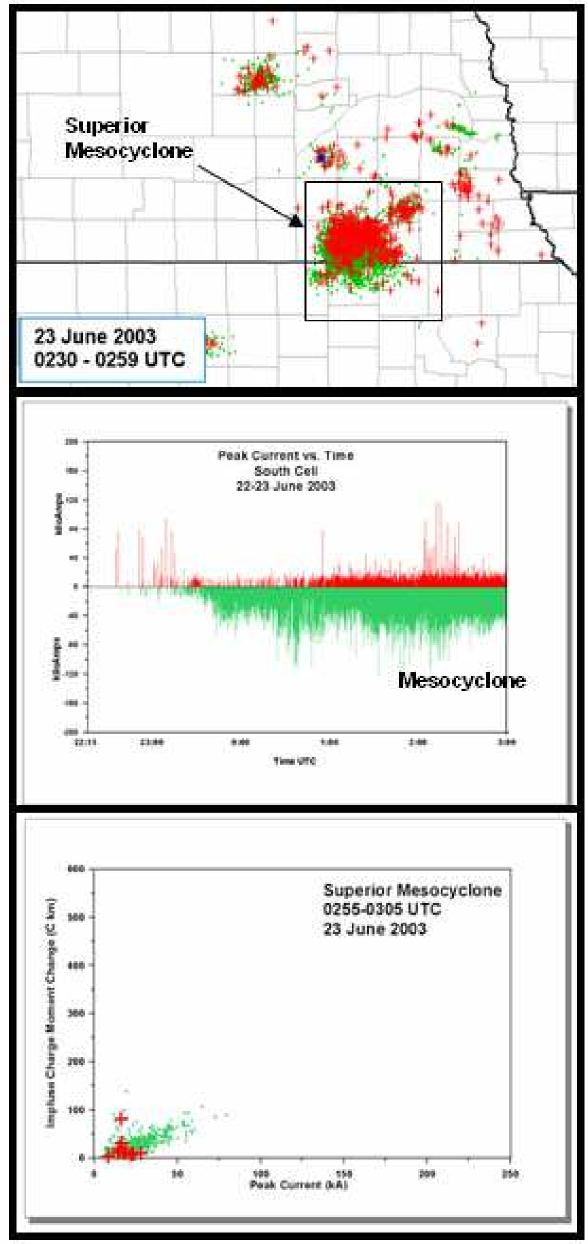

Figure 3. Similar to Fig 2, except showing the NLDN events from 2300 to 2359 UTC (top), the NLDN timeline (0000-0300 UTC) (middle), and the $i\Delta M_q(t)$ – peak current relationships for those very few CGs powerful enough to lower detectable amounts of charge to ground during a ten minute period during the most intense stage of the record mesocyclone (bottom).

5. THE SUPERIOR SUPERCELL

The storm system which evolved into the Superior mesocyclone began at approximately the same time as the Aurora cell. During its first hour it was likewise strongly positive (45%). As with the northern cell, after this initial growth phase, the CG rates increased significantly, percent positives dropped to less than 5%, +CG peak currents fell rapidly from 40 kA to 10-15 kA, and the negative CG peak currents remained small (11-18 kA). At the time of the record mesocyclone (0255-0305 UTC), the CG rate was an impressive 299 min^{-1}, and only 6% positive. Of those

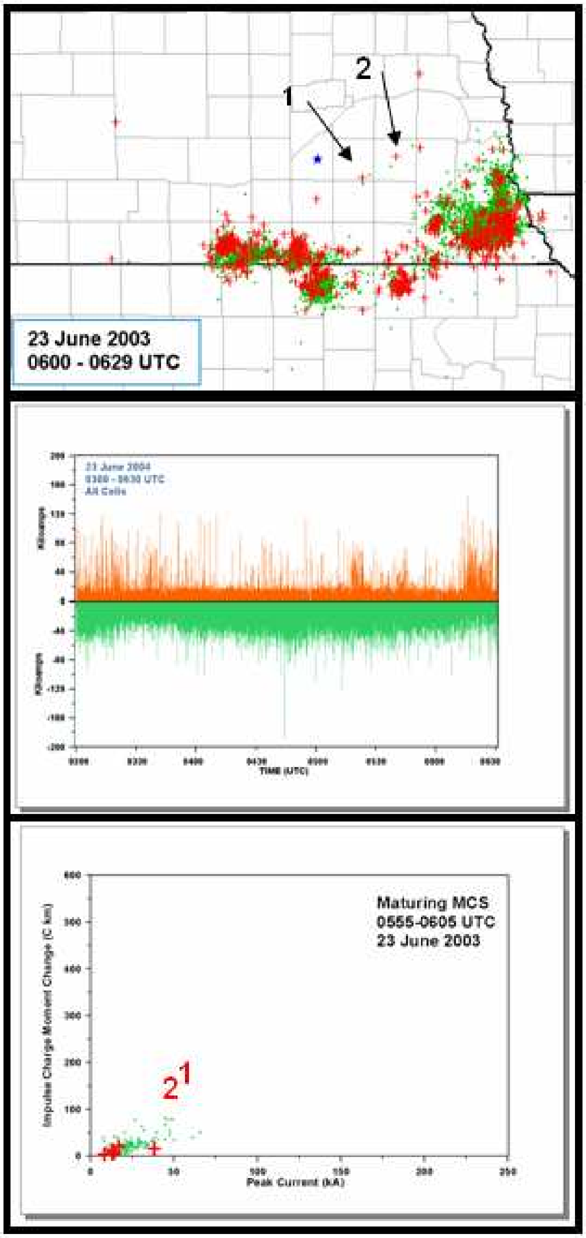

Figure 4. (top) NLDN CGs between 0600-0630 UTC, including two +CGs in the developing stratiform region The NLDN time history is plotted (middle). The plot of charge moment changes versus their CG peak currents between 0555 and 0605 UCT (bottom) are compared to the two +CGs about 20 minuets later in the organizing stratiform region (green negative, red crosses/numbers positive).

positives, less than 5% had detectable i$\Delta M_q(t)$ signatures, with very small average values of 22 C km Atypical of supercells, a greater percent of the -CGs (17%) produced detectable impulse charge moment changes, but these also had rather small mean (28 C km) and peak (131 C km) values. It is very unlikely that this dynamically intense cell's lightning was initiating sprites during its mature stage.

6. THE MATURING MCS STAGE

Between 0300 and 0630 UTC, convection became more widespread through extreme southeast Nebraska, though severe weather reports waned. The convection appeared to be organized more as clusters of intense cells. MCS-like characteristics, including a large stratiform region with secondary precipitation maxima (Schuur and Rutledge 2000), did not begin to emerge until after around 0600. Figure 4 shows CG activity clustered in several centers, with both polarities co-located in these convective cores. CG rates exceeded 20,000 hr^{-1} but the positives remained between 6 and 11 %. The NLDN time line in Fig, 4 shows patterns typical of more conventional convection, though the mean peak currents for the +CGs (15-18 kA) and the –CGs (15-18 kA) both remained somewhat smaller than the climatological norm. There were occasional large peak current events, largely absent during the intense hail and mesocyclone stages earlier in the evening.

Inspection of the i$\Delta M_q(t)$ signatures between 0555 and 0605 UTC showed that only 2% of the +CGs and 6% of the –CGs had detectable values, and these remained very small, averaging a mere 11 and 25 C km respectively (Table 1).

After 0600 UTC, radar began to show a semblance of an organized stratiform precipitation region to the north of the intense cells, suggesting the convection was maturing into a more typical MCS structure. Around 0620 UTC, two +CGs were noted (Fig 4) well to the north of the main activity. The peak currents were 55 and 47 kA, but the i$\Delta M_q(t)$ values were 175 and 166 C km respectively, much larger than those sampled in the cores 10 to 20 minutes previously. This suggests microphysical conditions in the developing stratiform region were evolving towards the production of large charge moment change strokes more typical of SP+CGs. As seen in many sprite-generating MCSs, these larger charge moment events were closer to the edge of the storm's precipitation shield than the convective cores.

7. DISCUSION AND CONCLUSIONS.

The search for consistent lightning polarity signatures indicative of intense hail storms has produced a variety of both intriguing (Reap and MacGorman 1989; Rust el. 1991; Stolzenburg 1994; MacGorman and Rust 1998) but ultimately inconsistent results (Carey et al. 2003). A similar state exists with respect to NLDN tornadic signatures (Brannick and Doswell 1992; Curran and Rust 1992; Seimon 1993; Perez et al. 1997; Bluestein and MacGorman 1998). The recent availability of an additional metric, charge moment change, which is roughly proportional to the charge lowered to ground (in this paper, during the impulsive first 2 ms of the stroke), allows may allow additional insights into severe storm electrical activity.

On 22-23 June 2003, the BAMEX storms which developed in a nominally uniform and highly unstable air mass exhibited a variety of behaviors. The quasi-supercellular storm which evolved to produce the U.S. record hailstone initially began as a relatively low CG rate storm, but almost 50% positive with many large peak currents and substantial (>100 C km) $i\Delta M_q(t)$ values (though still below sprite-triggering thresholds). During the half hour before the record hail fall, stroke rates increased, and became overwhelmingly negative in polarity with both mean and maximum peak currents being exceptionally small (~10/~25 kA). While many hail storms have been associated with large peak current +CGs (Curran and Rust 1992; Stolzenburg 1994), low peak current –CG dominated hail storms have also been reported (Soula et al. 2004). The lack of detectable $i\Delta M_q(t)$ values from these –CGs suggests an interesting possibility. The conventional application of NBLDN data (Cummins et al 1998) often segregates +CG strokes of < 10 kA, as these likely represent IC contamination. But this assumption assumes a normal dipole structure for the storm. Could the Aurora supercell have been inverted, as found during the STPES program (Rust and MacGorman 2002)? In this case might not IC discharges be mis-classified by the NLDN as negative stokes?

The storm which generated to intense Superior mesocyclone and tornadoes showed a somewhat similar evolution. Except this storm, at the time of the record mesocyclone, was producing almost exclusively negative CGs with small (16 kA) peak currents at rates approaching 17,000 per hour. Again, could this storm have been an inverted dipole with many IC events being sensed as small peak current –CGs?

Naturally, a key missing component from this study is IC flash rates such as from an LMA or LDAR-II system, allowing assessment of storm total lightning. The Superior cell does stand in marked contrast, however, to the anomalously low –CG rate supercell (though having extremely high IC rates) investigated during STERAO-A (Lang et al. 2000).

As the convection evolved on this evening, it gradually began to resemble a more classical MCS after 0600 UTC. A few "stray" +CGs began to be detected in the developing stratiform region well away from the convective cores. Only these +CGs had $i\Delta M_q(t)$ values above 100 kA, suggesting microphysical conditions in this remote portion of the storm were beginning to resemble those in which SP+CGs normally develop (Williams 1998; Lyons 1996)

What ultimately controls the polarity (and peak currents and charge lowered) of supercell lightning remains an unresolved issue. The relationship of the storms the theta-e ridges (Smith et al. 2000), the height of the cloud base (Williams et al. 2004) and the updraft size and intensity (Lang and Rutledge 2003) have all been suggested as factors. The new metric, charge moment change, a surrogate for charge lowered to ground, extracted from ELF/VLF signatures, may help provide insight into this question.

8. ACKNOWLEDGEMENTS

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P2.16 **LIGHTNING CHARACTERISTICS OF THE AURORA, NE RECORD HAILSTONE-PRODUCING SUPERCELL OF 22-23 JUNE 2003 DURING BAMEX**

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1. INTRODUCTION

The Bow Echo and Mesoscale Convective Vortex Experiment (BAMEX) was conducted during the summer of 2003 in the north-central U.S. (Davis et al. 2004).The primary focus of the project was the dynamics of large mesoscale convective systems (MCSs). As MCSs often evolve upscale from localized storms, it is not surprising that many supercells were also present within the experimental domain. On the afternoon and evening of 22-23 June 2003, two extraordinary supercell-like storms formed in south-central Nebraska (Fig. 1), presaging the formation of a MCS several hours later. The southern-most cell, called the Superior supercell, contained the most intense mesocyclone yet documented. Airborne Doppler radar detected a vortex 9 km in diameter with a 118 m s^{-1} velocity differential. Just two counties to the northwest another intense storm, the Aurora supercell, produced the largest confirmed hail stone in the U.S. (18.75 inches, [47.6 cm] circumference). While the dynamics of these storms are being widely investigated (Wakimoto et al. 2004), this paper will investigate the electrical characteristics of these unique events.

MCS lightning has been extensively researched. The discovery that mesospheric sprites (Franz et al. 1990) above the U.S. High Plains MCSs are associated with positive cloud-to-ground (+CG) lightning (Lyons 1996) has focused additional attention on the unusual characteristics of sprite parent +CGs (SP+CGs) (Boccippio et al. 1995; Huang et al. 1999; Hu et al. 2002). While the peak currents of SP+CGs are 25-50% higher than other +CGs in the same storm, peak current proves a poor sprite predictor. As initially suggested by 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 Q, the amount of charge lowered. [Note this second term is most appropriately considered as a function of time.] During the 2000 Severe Thunderstorm Electrification and Precipitation Study (STEPS), sprite-producing MCSs were investigated using peak current data from the National Lighting Detection Network (NLDN), a 3-D lightning mapping array, and ELF/VLF sensors from which $\Delta M_q(t)$ can be extracted for storms occurring up to several thousands of kilometers away (Lang et al. 2004; Cummer and Inan 2000; Hu et al. 2002). The STEPS SP+CGs were typically found within a portion of the trailing stratiform region of mature MCSs which had attained a size of >10,000 km^2 (>10 dBZ reflectivity). Consistent with theories of conventional dielectric breakdown, an apparent minimum threshold in $\Delta M_q(t)$ between 300 and 600 C km appears necessary (and sufficient?) for sprite initiation. This value is dependent upon both the duration of time over which $\Delta M_q(t)$ is extracted as well as night to night changes in mesospheric conductivity (Cummer and Lyons 2004 a, b). For a typical MCS (19 July 2000), the average $\Delta M_q(t)$ for an SP+CG was ~800 C km (Lyons et al. 2003a).

A decade of low-light video sprite monitoring from Colorado's Yucca Ridge Field Station (YRFS) suggests that sprites, while common above many MCSs, are extremely rare above supercells, save during their dying stages when they may develop more extensive stratiform precipitation regions. Given that supercells are often extremely electrically active, and many are dominated by positive polarity flashes, this discrepancy was very puzzling.

During STEPS, the electrical nature of supercells were investigated using the added resource of ELF/VLF $\Delta M_q(t)$ retrievals. The daytime supercell of 29 June 2000 exhibited an inverted (negative over positive dipole) polarity structure (Rust and MacGorman 2002). The storm had 80% +CGs during its lifetime, with average +CG peak currents of 53 kA (12%>75 kA). The –CG average peak current was 18 kA (Lyons and Cummer 2004). While many +CG $\Delta M_q(t)$ values exceeded 100 C km, none peaked above the 600 C km threshold at which a 10% probability of a sprite could be expected. Moreover, few –CGs produced $\Delta M_q(t)$ >50 C km. A nocturnal supercell on 25 June 2000, allowed for optical sprite monitoring. Five sprites were recorded, two from the very last +CGs of the decaying storm ($\Delta M_q(t)$ >1000 C KM). Three small events did occur during the most intense phase of the supercell (Lyons and Cummer 2004). These +CGs were highly impulsive but powerful enough ($\Delta M_q(t)$ >800 C km) to initiate sprites. But these appeared exceptions to the general rule for supercells to have few +CG and no -CG $\Delta M_q(t)$ values anywhere near the sprite triggering threshold. Duke University's routine $\Delta M_q(t)$ monitoring during BAMEX provided an opportunity to explore the electrical nature of these extreme convective events.

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2. BAMEX AND DATA UTILZIED

As detailed by Davis et al. (2004), BAMEX deployed an extensive array of aircraft, mobile and remote sensing systems, with a primary focus on large MCSs. The supercells of 22-23 June were serendipitous occurrences which were partially monitored by research platforms (Wakimoto et al. 2004). We herein investigate the several stages of the developing convection on the evening of 22-23 June 2003 using conventional GOES and NEXRAD images, rawinsondes and NLDN stroke-level CG data, augmented by charge moment change data.

The Duke University ELF/VLF system, operating in a triggered mode, captured the larger impulse charge moment changes ($i\Delta M_q(t)$), during the first 2 ms of the CG event. During STEPS, continuous mode monitoring allowed retrieval of $i\Delta M_q(t)$ from virtually all CGs above a minimal detectible signature of ~5 C km (Cummer and Lyons 2004 a,b). During the BAMEX study, most CGs with $i\Delta M_q(t)$ >10-20 C km (still quite small) were likely captured. As the BAMEX domain was so far east of YRFS, LLTV sprite monitoring was not undertaken.

3. METEOROLOGICAL ENVIRONMENT

During the late afternoon of 22 June, a diffuse north-south stationary front was present in central Nebraska. A more distinctive feature was the remnant outflow boundary from earlier convection. Surface dewpoints were 20-24ºC. Late afternoon temperatures reaching 28-31ºC suggested lifted condensation levels in the 1000-1500 meter range. Soundings at 0000 UTC showed regional CAPE values in the 3000-3500 J kg^{-1} range. CAPE as high as 4000 J kg^{-1} at the time of convective initiation was accompanied by an unusual, near circular hodograph from the surface to 620 mb (Wakimoto et al. 2004). While the term "supercell" has been applied to the initial convective structures which emerged, it is being rather loosely applied. The Aurora "supercell" may have been a multi-celled system during much of its lifetime, with the hail falling from the southernmost reflectivity maximum. The Superior supercell was extremely well organized for about one hour, but was also multi-cellular at times. In any case, these county-sized storms contained extreme updrafts as evidence by the huge hail and 18-19 km radar echo tops.

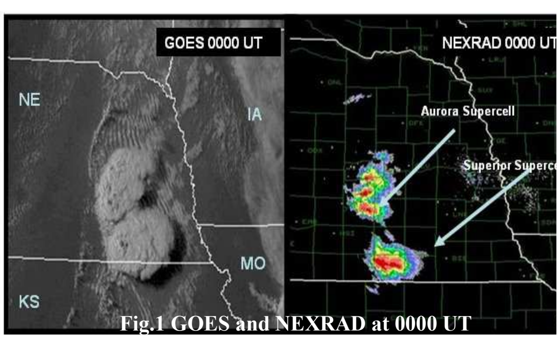

Fig.1 GOES and NEXRAD at 0000 UT

4. THE AURORA SUPERCELL

The Aurora cell produced its first CG (a negative) shortly before 2300 UTC. During the 2300-2330 UTC period, the storm was nearly 50% positive, with mean positive peak currents of 55 kA (largest 192 kA). In the 2325-2335 UTC time frame, presumably as the record hail stone's updraft was just becoming organized, the percent positive peaked at 57% (Table 1). Almost two thirds of the +CGs generated detectable $i\Delta M_q(t)$ with an average value of 133 C km and a peak of 200 C km. Though below sprite-producing values these are larger than "normal" (Rakov and Uman 2003) and comparable to those found in STEPS supercells. By contrast, the –CGs had both small peak currents (10 kA) and undetectable $i\Delta M_q(t)$. In the half hour before the record hail fall at 0005 UTC, the CG flash rate increased rapidly (to 14.3 CG/min), but became strongly negatively dominated (93%). Mean negative peak currents remained small (9 kA, with the largest 27 kA) and no –CGs could generate a detectable $i\Delta M_q(t)$.

By 0005 UTC, small the small negative events continued and only a few low peak current an one low $i\Delta M_q(t)$ +CGs were detected. In addition to the record hail stone, smaller hail fell though out the area and an F0 tornado touched down 6 km northwest of Aurora at 0012 UTC.

This cell remained distinct from the developing MCS until about 0100 UTC. By 0025-0035 UTC, the cell's lightning characteristics had continued to evolve. The overall flash rate remained around 14 CG/min, but rebounded to 25% positive. However peak currents for negatives (-10 kA) and positives (18 kA) remained low, as did the $i\Delta M_q(t)$ values for –CGs.

Table 1. 23 June 2003 Electrical Characteristics
2 ms charge moment changes and NLDN statistics

	Aurora Hail			Superor Mesocyclone	Maturing MCS
	2325-2335	2355-0005	0025-0035	0255-0305	0555-0605
CG Rate (per minute)	4.7	14.3	13.7	299	287
Percent Positive	57	7	25	6	9
Mean +CG peak current	55	17	18	12	19
Max +CG peak current	192	37	80	39	143
% +CGs with I ΔMq	63	14	16	5	2
Avg. +CG I ΔMq	113	37	99	22	11
Max +CG I ΔMq	200	37	124	81	22
Mean - CG peak current	-10	-9	-10	-16	-16
Max -CG peak current	-26	-27	-22	-83	-117
% -CGs with I ΔMq	0	0	<2	17	6
Avg. -CG I ΔMq	0	0	9	28	25
Max -CG I ΔMq	0	0	12	139	82

Figure 2 shows a plot of NLDN for the Aurora cell (star marks the hail stone fall) and the developing Superior supercell (2330-2359 UTC), as well as the Aurora cell NLDN event time line. Only during the period more than 30 minutes before the hail fall (2325-2235 UTC) did these CGs produced any $i\Delta M_q(t)$ values of consequence, and only then from +CGs.

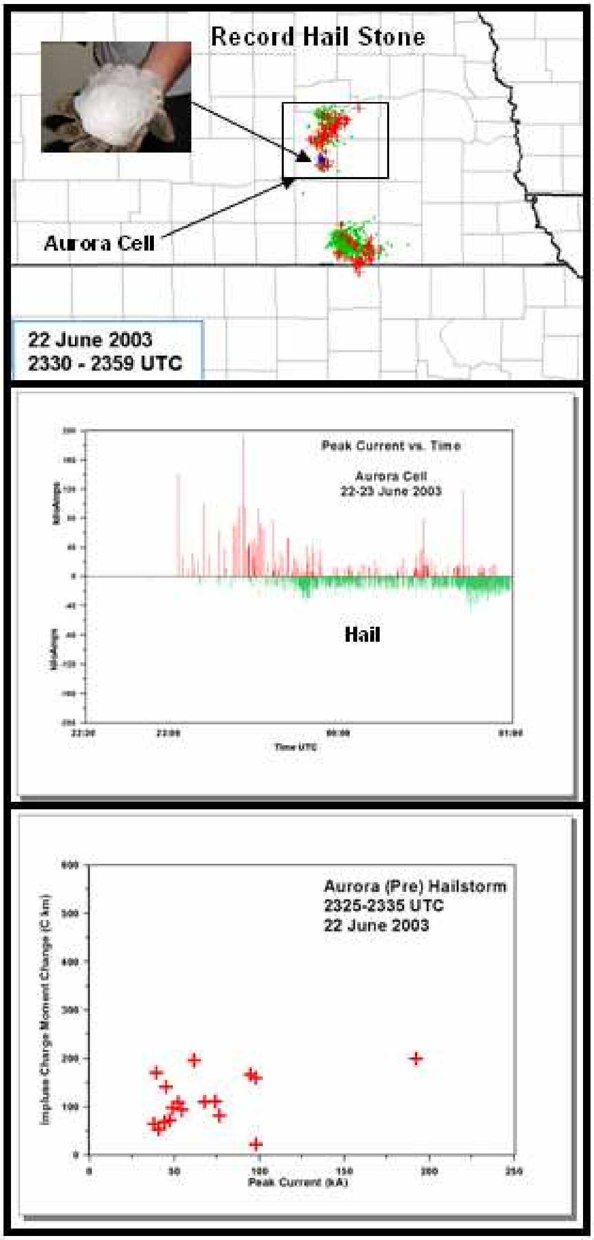

Figure 2. (top) NLDN CGs between 2300-2359 UTC. Star indicates hail fall location. The rectangle surrounds the storm for which the NLDN time history is plotted (middle). The plot of charge moment changes versus their +CG peak currents between 2325 and 2335 UCT (bottom) mark the only period during the storm when large values of charge were being lowered to the surface. (Red cross +CGs)

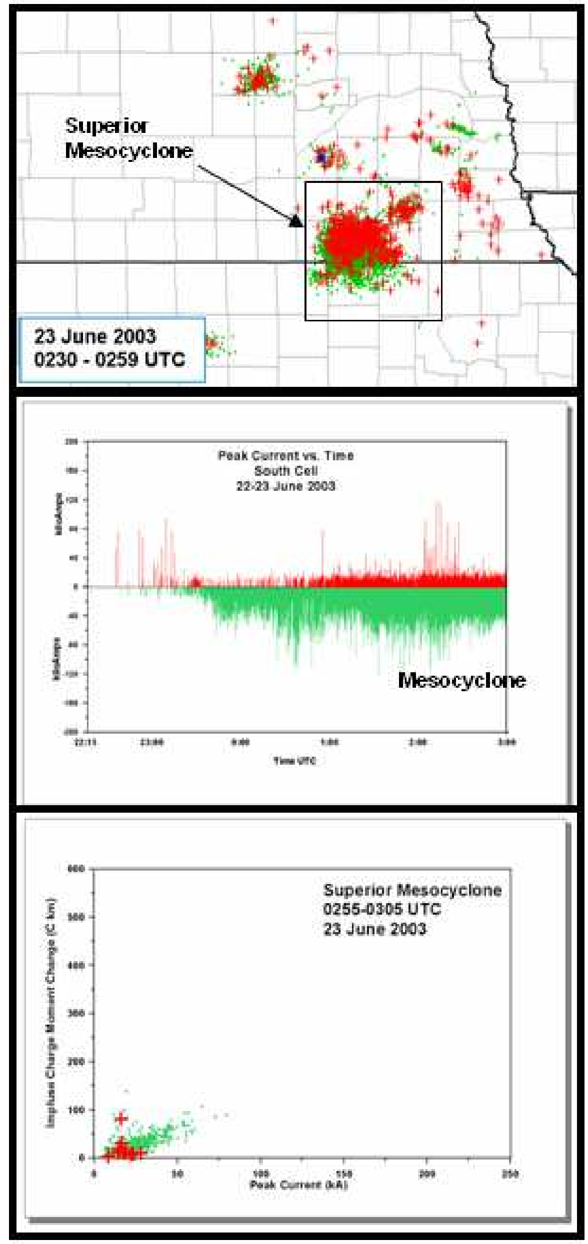

Figure 3. Similar to Fig 2, except showing the NLDN events from 2300 to 2359 UTC (top), the NLDN timeline (0000-0300 UTC) (middle), and the $i\Delta M_q(t)$ – peak current relationships for those very few CGs powerful enough to lower detectable amounts of charge to ground during a ten minute period during the most intense stage of the record mesocyclone (bottom).

5. THE SUPERIOR SUPERCELL

The storm system which evolved into the Superior mesocyclone began at approximately the same time as the Aurora cell. During its first hour it was likewise strongly positive (45%). As with the northern cell, after this initial growth phase, the CG rates increased significantly, percent positives dropped to less than 5%, +CG peak currents fell rapidly from 40 kA to 10-15 kA, and the negative CG peak currents remained small (11-18 kA). At the time of the record mesocyclone (0255-0305 UTC), the CG rate was an impressive 299 min^{-1}, and only 6% positive. Of those

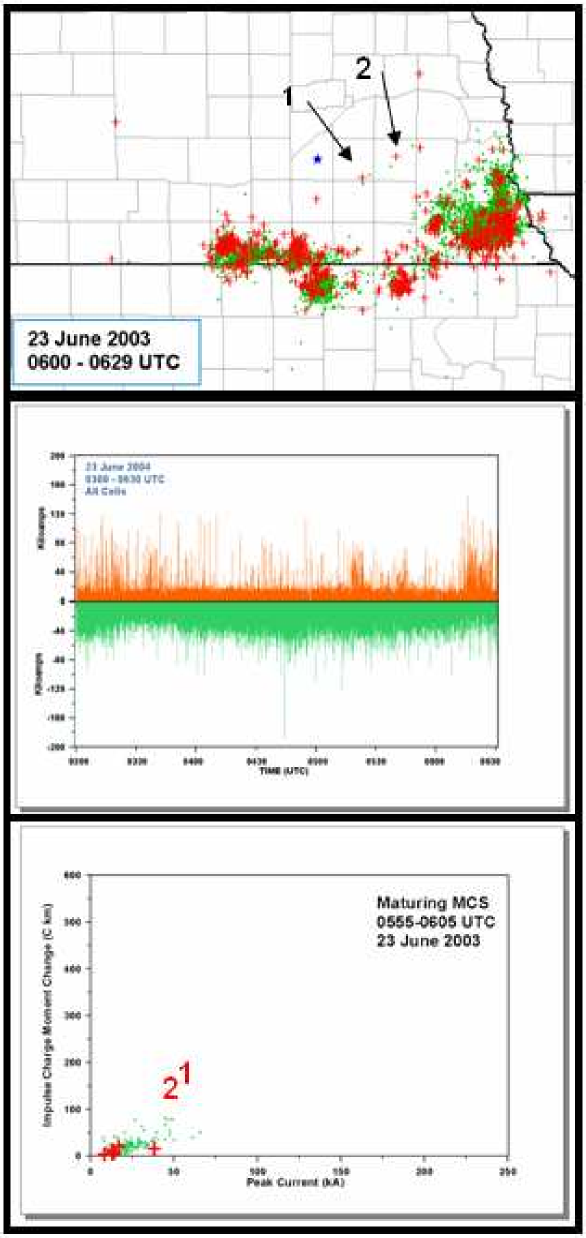

Figure 4. (top) NLDN CGs between 0600-0630 UTC, including two +CGs in the developing stratiform region The NLDN time history is plotted (middle). The plot of charge moment changes versus their CG peak currents between 0555 and 0605 UCT (bottom) are compared to the two +CGs about 20 minuets later in the organizing stratiform region (green negative, red crosses/numbers positive).

positives, less than 5% had detectable $i\Delta M_q(t)$ signatures, with very small average values of 22 C km Atypical of supercells, a greater percent of the -CGs (17%) produced detectable impulse charge moment changes, but these also had rather small mean (28 C km) and peak (131 C km) values. It is very unlikely that this dynamically intense cell's lightning was initiating sprites during its mature stage.

6. THE MATURING MCS STAGE

Between 0300 and 0630 UTC, convection became more widespread through extreme southeast Nebraska, though severe weather reports waned. The convection appeared to be organized more as clusters of intense cells. MCS-like characteristics, including a large stratiform region with secondary precipitation maxima (Schuur and Rutledge 2000), did not begin to emerge until after around 0600. Figure 4 shows CG activity clustered in several centers, with both polarities co-located in these convective cores. CG rates exceeded 20,000 hr^{-1} but the positives remained between 6 and 11 %. The NLDN time line in Fig, 4 shows patterns typical of more conventional convection, though the mean peak currents for the +CGs (15-18 kA) and the –CGs (15-18 kA) both remained somewhat smaller than the climatological norm. There were occasional large peak current events, largely absent during the intense hail and mesocyclone stages earlier in the evening.

Inspection of the $i\Delta M_q(t)$ signatures between 0555 and 0605 UTC showed that only 2% of the +CGs and 6% of the –CGs had detectable values, and these remained very small, averaging a mere 11 and 25 C km respectively (Table 1).

After 0600 UTC, radar began to show a semblance of an organized stratiform precipitation region to the north of the intense cells, suggesting the convection was maturing into a more typical MCS structure. Around 0620 UTC, two +CGs were noted (Fig 4) well to the north of the main activity. The peak currents were 55 and 47 kA, but the $i\Delta M_q(t)$ values were 175 and 166 C km respectively, much larger than those sampled in the cores 10 to 20 minutes previously. This suggests microphysical conditions in the developing stratiform region were evolving towards the production of large charge moment change strokes more typical of SP+CGs. As seen in many sprite-generating MCSs, these larger charge moment events were closer to the edge of the storm's precipitation shield than the convective cores.

7. DISCUSION AND CONCLUSIONS.

The search for consistent lightning polarity signatures indicative of intense hail storms has produced a variety of both intriguing (Reap and MacGorman 1989; Rust el. 1991; Stolzenburg 1994; MacGorman and Rust 1998) but ultimately inconsistent results (Carey et al. 2003). A similar state exists with respect to NLDN tornadic signatures (Brannick and Doswell 1992; Curran and Rust 1992; Seimon 1993; Perez et al. 1997; Bluestein and MacGorman 1998). The recent availability of an additional metric, charge moment change, which is roughly proportional to the charge lowered to ground (in this paper, during the impulsive first 2 ms of the stroke), allows may allow additional insights into severe storm electrical activity.

On 22-23 June 2003, the BAMEX storms which developed in a nominally uniform and highly unstable air mass exhibited a variety of behaviors. The quasi-supercellular storm which evolved to produce the U.S. record hailstone initially began as a relatively low CG rate storm, but almost 50% positive with many large peak currents and substantial (>100 C km) $i\Delta M_q(t)$ values (though still below sprite-triggering thresholds). During the half hour before the record hail fall, stroke rates increased, and became overwhelmingly negative in polarity with both mean and maximum peak currents being exceptionally small (~10/~25 kA). While many hail storms have been associated with large peak current +CGs (Curran and Rust 1992; Stolzenburg 1994), low peak current –CG dominated hail storms have also been reported (Soula et al. 2004). The lack of detectable $i\Delta M_q(t)$ values from these –CGs suggests an interesting possibility. The conventional application of NBLDN data (Cummins et al 1998) often segregates +CG strokes of < 10 kA, as these likely represent IC contamination. But this assumption assumes a normal dipole structure for the storm. Could the Aurora supercell have been inverted, as found during the STPES program (Rust and MacGorman 2002)? In this case might not IC discharges be mis-classified by the NLDN as negative stokes?

The storm which generated to intense Superior mesocyclone and tornadoes showed a somewhat similar evolution. Except this storm, at the time of the record mesocyclone, was producing almost exclusively negative CGs with small (16 kA) peak currents at rates approaching 17,000 per hour. Again, could this storm have been an inverted dipole with many IC events being sensed as small peak current –CGs?

Naturally, a key missing component from this study is IC flash rates such as from an LMA or LDAR-II system, allowing assessment of storm total lightning. The Superior cell does stand in marked contrast, however, to the anomalously low –CG rate supercell (though having extremely high IC rates) investigated during STERAO-A (Lang et al. 2000).

As the convection evolved on this evening, it gradually began to resemble a more classical MCS after 0600 UTC. A few "stray" +CGs began to be detected in the developing stratiform region well away from the convective cores. Only these +CGs had $i\Delta M_q(t)$ values above 100 kA, suggesting microphysical conditions in this remote portion of the storm were beginning to resemble those in which SP+CGs normally develop (Williams 1998; Lyons 1996)

What ultimately controls the polarity (and peak currents and charge lowered) of supercell lightning remains an unresolved issue. The relationship of the storms the theta-e ridges (Smith et al. 2000), the height of the cloud base (Williams et al. 2004) and the updraft size and intensity (Lang and Rutledge 2003) have all been suggested as factors. The new metric, charge moment change, a surrogate for charge lowered to ground, extracted from ELF/VLF signatures, may help provide insight into this question.

8. ACKNOWLEDGEMENTS

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P2.16 **LIGHTNING CHARACTERISTICS OF THE AURORA, NE RECORD HAILSTONE-PRODUCING SUPERCELL OF 22-23 JUNE 2003 DURING BAMEX**

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1. INTRODUCTION

The Bow Echo and Mesoscale Convective Vortex Experiment (BAMEX) was conducted during the summer of 2003 in the north-central U.S. (Davis et al. 2004).The primary focus of the project was the dynamics of large mesoscale convective systems (MCSs). As MCSs often evolve upscale from localized storms, it is not surprising that many supercells were also present within the experimental domain. On the afternoon and evening of 22-23 June 2003, two extraordinary supercell-like storms formed in south-central Nebraska (Fig. 1), presaging the formation of a MCS several hours later. The southern-most cell, called the Superior supercell, contained the most intense mesocyclone yet documented. Airborne Doppler radar detected a vortex 9 km in diameter with a 118 m s^{-1} velocity differential. Just two counties to the northwest another intense storm, the Aurora supercell, produced the largest confirmed hail stone in the U.S. (18.75 inches, [47.6 cm] circumference). While the dynamics of these storms are being widely investigated (Wakimoto et al. 2004), this paper will investigate the electrical characteristics of these unique events.

MCS lightning has been extensively researched. The discovery that mesospheric sprites (Franz et al. 1990) above the U.S. High Plains MCSs are associated with positive cloud-to-ground (+CG) lightning (Lyons 1996) has focused additional attention on the unusual characteristics of sprite parent +CGs (SP+CGs) (Boccippio et al. 1995; Huang et al. 1999; Hu et al. 2002). While the peak currents of SP+CGs are 25-50% higher than other +CGs in the same storm, peak current proves a poor sprite predictor. As initially suggested by 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 Q, the amount of charge lowered. [Note this second term is most appropriately considered as a function of time.] During the 2000 Severe Thunderstorm Electrification and Precipitation Study (STEPS), sprite-producing MCSs were investigated using peak current data from the National Lighting Detection Network (NLDN), a 3-D lightning mapping array, and ELF/VLF sensors from which $\Delta M_q(t)$ can be extracted for storms occurring up to several thousands of kilometers away (Lang et al. 2004; Cummer and Inan 2000; Hu et al. 2002). The STEPS SP+CGs were typically found within a portion of the trailing stratiform region of mature MCSs which had attained a size of >10,000 km^2 (>10 dBZ reflectivity). Consistent with theories of conventional dielectric breakdown, an apparent minimum threshold in $\Delta M_q(t)$ between 300 and 600 C km appears necessary (and sufficient?) for sprite initiation. This value is dependent upon both the duration of time over which $\Delta M_q(t)$ is extracted as well as night to night changes in mesospheric conductivity (Cummer and Lyons 2004 a, b). For a typical MCS (19 July 2000), the average $\Delta M_q(t)$ for an SP+CG was ~800 C km (Lyons et al. 2003a).

A decade of low-light video sprite monitoring from Colorado's Yucca Ridge Field Station (YRFS) suggests that sprites, while common above many MCSs, are extremely rare above supercells, save during their dying stages when they may develop more extensive stratiform precipitation regions. Given that supercells are often extremely electrically active, and many are dominated by positive polarity flashes, this discrepancy was very puzzling.

During STEPS, the electrical nature of supercells were investigated using the added resource of ELF/VLF $\Delta M_q(t)$ retrievals. The daytime supercell of 29 June 2000 exhibited an inverted (negative over positive dipole) polarity structure (Rust and MacGorman 2002). The storm had 80% +CGs during its lifetime, with average +CG peak currents of 53 kA (12%>75 kA). The –CG average peak current was 18 kA (Lyons and Cummer 2004). While many +CG $\Delta M_q(t)$ values exceeded 100 C km, none peaked above the 600 C km threshold at which a 10% probability of a sprite could be expected. Moreover, few –CGs produced $\Delta M_q(t)$ >50 C km. A nocturnal supercell on 25 June 2000, allowed for optical sprite monitoring. Five sprites were recorded, two from the very last +CGs of the decaying storm ($\Delta M_q(t)$ >1000 C KM). Three small events did occur during the most intense phase of the supercell (Lyons and Cummer 2004). These +CGs were highly impulsive but powerful enough ($\Delta M_q(t)$ >800 C km) to initiate sprites. But these appeared exceptions to the general rule for supercells to have few +CG and no -CG $\Delta M_q(t)$ values anywhere near the sprite triggering threshold. Duke University's routine $\Delta M_q(t)$ monitoring during BAMEX provided an opportunity to explore the electrical nature of these extreme convective events.

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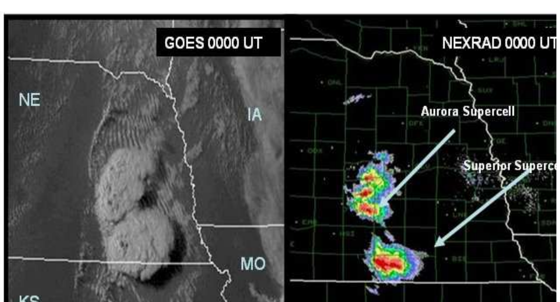

Fig.1 GOES and NEXRAD at 0000 UT

4. THE AURORA SUPERCELL

The Aurora cell produced its first CG (a negative) shortly before 2300 UTC. During the 2300-2330 UTC period, the storm was nearly 50% positive, with mean positive peak currents of 55 kA (largest 192 kA). In the 2325-2335 UTC time frame, presumably as the record hail stone's updraft was just becoming organized, the percent positive peaked at 57% (Table 1). Almost two thirds of the +CGs generated detectable iΔM_q(t) with an average value of 133 C km and a peak of 200 C km. Though below sprite-producing values these are larger than "normal" (Rakov and Uman 2003) and comparable to those found in STEPS supercells. By contrast, the –CGs had both small peak currents (10 kA) and undetectable iΔM_q(t). In the half hour before the record hail fall at 0005 UTC, the CG flash rate increased rapidly (to 14.3 CG/min), but became strongly negatively dominated (93%). Mean negative peak currents remained small (9 kA, with the largest 27 kA) and no –CGs could generate a detectable iΔM_q(t).

By 0005 UTC, small the small negative events continued and only a few low peak current an one low iΔM_q(t) +CGs were detected. In addition to the record hail stone, smaller hail fell though out the area and an F0 tornado touched down 6 km northwest of Aurora at 0012 UTC.

This cell remained distinct from the developing MCS until about 0100 UTC. By 0025-0035 UTC, the cell's lightning characteristics had continued to evolve. The overall flash rate remained around 14 CG/min, but rebounded to 25% positive. However peak currents for negatives (-10 kA) and positives (18 kA) remained low, as did the iΔM_q(t) values for –CGs.

Table 1. 23 June 2003 Electrical Characteristics
2 ms charge moment changes and NLDN statistics

	Aurora Hail			Superior Mesocyclone	Maturing MCS
	2325-2335	*2355-0005*	*0025-0035*	*0255-0305*	*0555-0605*
CG Rate (per minute)	4.7	14.3	13.7	299	287
Percent Positive	57	7	25	6	9
Mean +CG peak current	55	17	18	12	19
Max +CG peak current	192	37	80	39	143
% +CGs with I ΔMq	63	14	16	5	2
Avg. +CG I ΔMq	113	37	99	22	11
Max +CG I ΔMq	200	37	124	81	22
Mean - CG peak current	-10	-9	-10	-16	-16
Max -CG peak current	-26	-27	-22	-83	-117
% -CGs with I ΔMq	0	0	<2	17	6
Avg. -CG I ΔMq	0	0	9	28	25
Max -CG I ΔMq	0	0	12	139	82

Figure 2 shows a plot of NLDN for the Aurora cell (star marks the hail stone fall) and the developing Superior supercell (2330-2359 UTC), as well as the Aurora cell NLDN event time line. Only during the period more than 30 minutes before the hail fall (2325-2235 UTC) did these CGs produced any iΔM_q(t) values of consequence, and only then from +CGs.

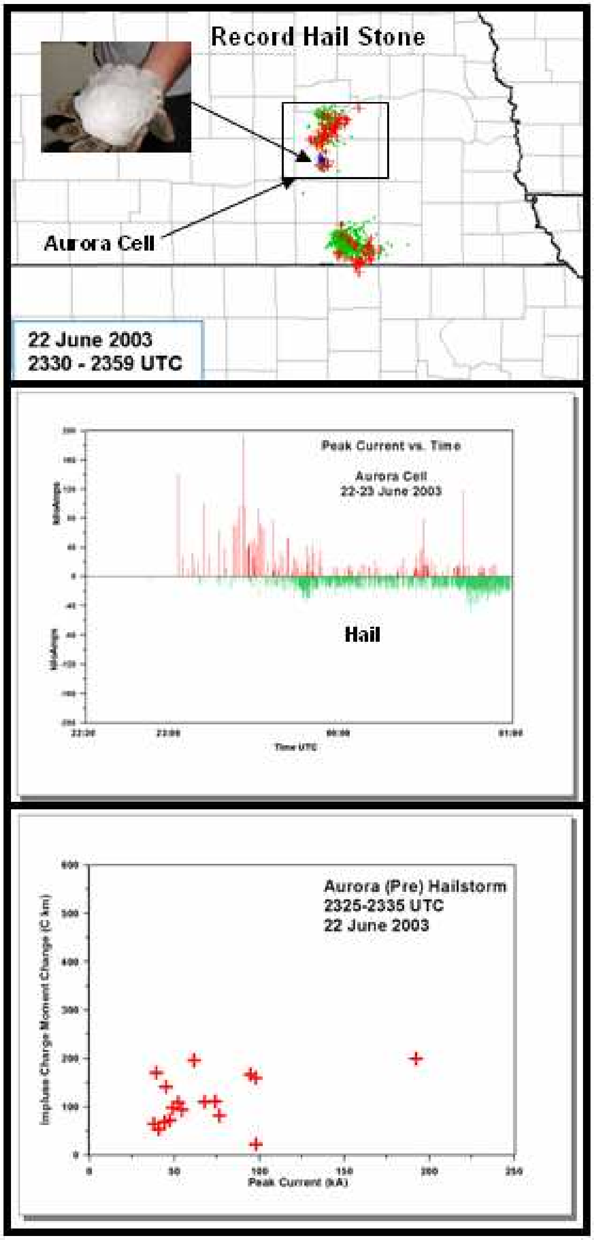

Figure 2. (top) NLDN CGs between 2300-2359 UTC. Star indicates hail fall location. The rectangle surrounds the storm for which the NLDN time history is plotted (middle). The plot of charge moment changes versus their +CG peak currents between 2325 and 2335 UCT (bottom) mark the only period during the storm when large values of charge were being lowered to the surface. (Red cross +CGs)

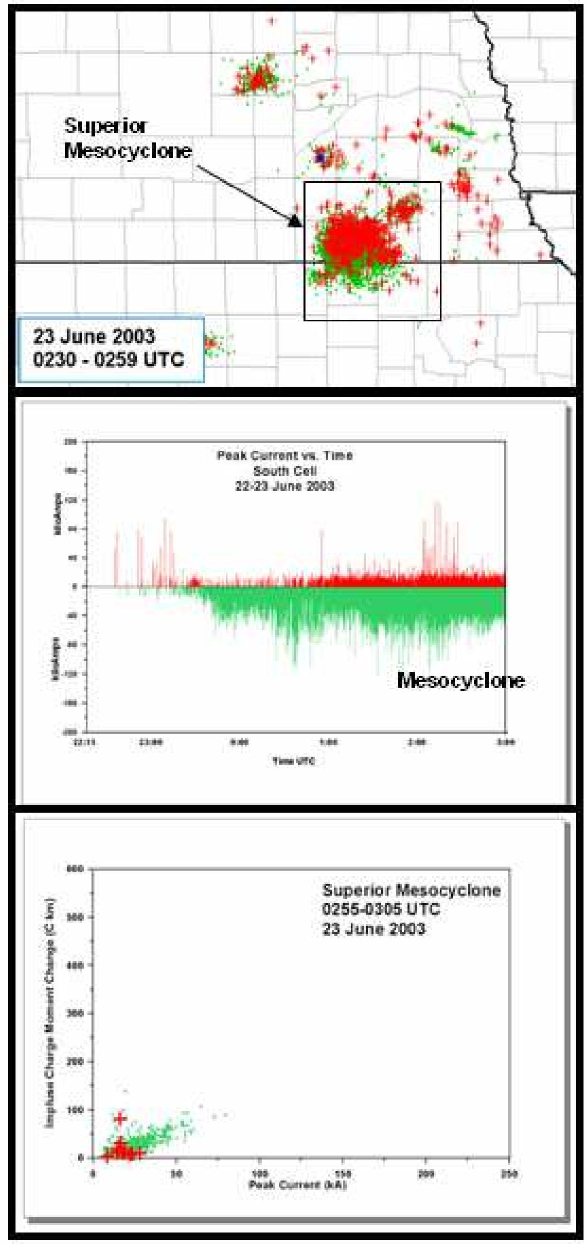

Figure 3. Similar to Fig 2, except showing the NLDN events from 2300 to 2359 UTC (top), the NLDN timeline (0000-0300 UTC) (middle), and the $i\Delta M_q(t)$ – peak current relationships for those very few CGs powerful enough to lower detectable amounts of charge to ground during a ten minute period during the most intense stage of the record mesocyclone (bottom).

5. THE SUPERIOR SUPERCELL

The storm system which evolved into the Superior mesocyclone began at approximately the same time as the Aurora cell. During its first hour it was likewise strongly positive (45%). As with the northern cell, after this initial growth phase, the CG rates increased significantly, percent positives dropped to less than 5%, +CG peak currents fell rapidly from 40 kA to 10-15 kA, and the negative CG peak currents remained small (11-18 kA). At the time of the record mesocyclone (0255-0305 UTC), the CG rate was an impressive 299 min^{-1}, and only 6% positive. Of those

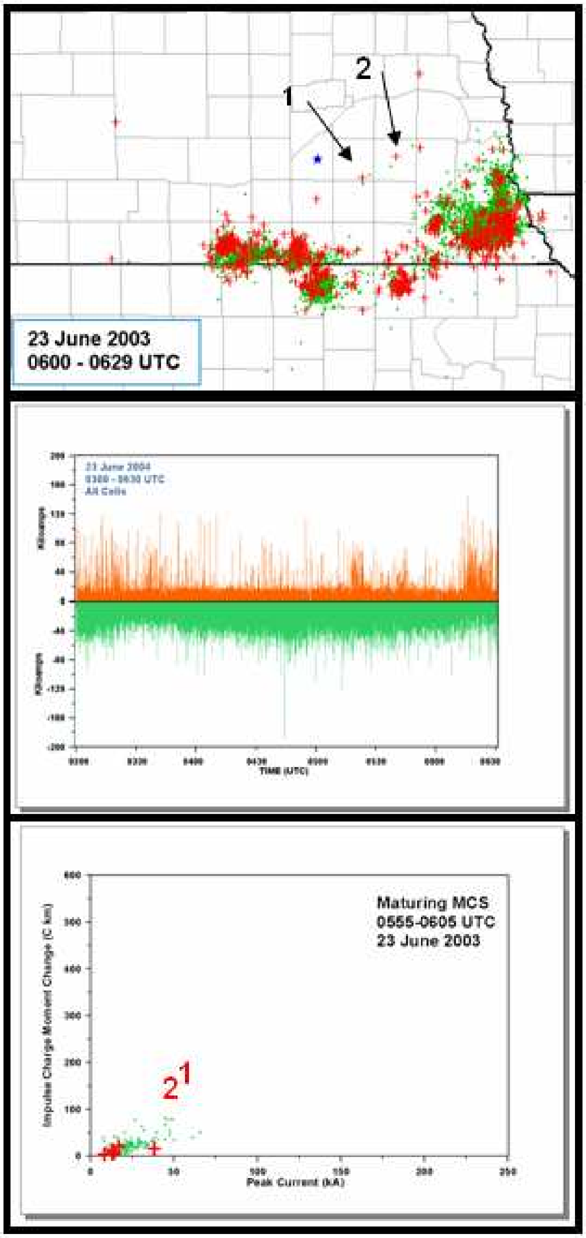

Figure 4. (top) NLDN CGs between 0600-0630 UTC, including two +CGs in the developing stratiform region The NLDN time history is plotted (middle). The plot of charge moment changes versus their CG peak currents between 0555 and 0605 UCT (bottom) are compared to the two +CGs about 20 minuets later in the organizing stratiform region (green negative, red crosses/numbers positive).

positives, less than 5% had detectable $i\Delta M_q(t)$ signatures, with very small average values of 22 C km Atypical of supercells, a greater percent of the -CGs (17%) produced detectable impulse charge moment changes, but these also had rather small mean (28 C km) and peak (131 C km) values. It is very unlikely that this dynamically intense cell's lightning was initiating sprites during its mature stage.

6. THE MATURING MCS STAGE

Between 0300 and 0630 UTC, convection became more widespread through extreme southeast Nebraska, though severe weather reports waned. The convection appeared to be organized more as clusters of intense cells. MCS-like characteristics, including a large stratiform region with secondary precipitation maxima (Schuur and Rutledge 2000), did not begin to emerge until after around 0600. Figure 4 shows CG activity clustered in several centers, with both polarities co-located in these convective cores. CG rates exceeded 20,000 hr^{-1} but the positives remained between 6 and 11 %. The NLDN time line in Fig, 4 shows patterns typical of more conventional convection, though the mean peak currents for the +CGs (15-18 kA) and the –CGs (15-18 kA) both remained somewhat smaller than the climatological norm. There were occasional large peak current events, largely absent during the intense hail and mesocyclone stages earlier in the evening.

Inspection of the $i\Delta M_q(t)$ signatures between 0555 and 0605 UTC showed that only 2% of the +CGs and 6% of the –CGs had detectable values, and these remained very small, averaging a mere 11 and 25 C km respectively (Table 1).

After 0600 UTC, radar began to show a semblance of an organized stratiform precipitation region to the north of the intense cells, suggesting the convection was maturing into a more typical MCS structure. Around 0620 UTC, two +CGs were noted (Fig 4) well to the north of the main activity. The peak currents were 55 and 47 kA, but the $i\Delta M_q(t)$ values were 175 and 166 C km respectively, much larger than those sampled in the cores 10 to 20 minutes previously. This suggests microphysical conditions in the developing stratiform region were evolving towards the production of large charge moment change strokes more typical of SP+CGs. As seen in many sprite-generating MCSs, these larger charge moment events were closer to the edge of the storm's precipitation shield than the convective cores.

7. DISCUSION AND CONCLUSIONS.

The search for consistent lightning polarity signatures indicative of intense hail storms has produced a variety of both intriguing (Reap and MacGorman 1989; Rust el. 1991; Stolzenburg 1994; MacGorman and Rust 1998) but ultimately inconsistent results (Carey et al. 2003). A similar state exists with respect to NLDN tornadic signatures (Brannick and Doswell 1992; Curran and Rust 1992; Seimon 1993; Perez et al. 1997; Bluestein and MacGorman 1998). The recent availability of an additional metric, charge moment change, which is roughly proportional to the charge lowered to ground (in this paper, during the impulsive first 2 ms of the stroke), allows may allow additional insights into severe storm electrical activity.

On 22-23 June 2003, the BAMEX storms which developed in a nominally uniform and highly unstable air mass exhibited a variety of behaviors. The quasi-supercellular storm which evolved to produce the U.S. record hailstone initially began as a relatively low CG rate storm, but almost 50% positive with many large peak currents and substantial (>100 C km) $i\Delta M_q(t)$ values (though still below sprite-triggering thresholds). During the half hour before the record hail fall, stroke rates increased, and became overwhelmingly negative in polarity with both mean and maximum peak currents being exceptionally small (~10/~25 kA). While many hail storms have been associated with large peak current +CGs (Curran and Rust 1992; Stolzenburg 1994), low peak current –CG dominated hail storms have also been reported (Soula et al. 2004). The lack of detectable $i\Delta M_q(t)$ values from these –CGs suggests an interesting possibility. The conventional application of NBLDN data (Cummins et al 1998) often segregates +CG strokes of < 10 kA, as these likely represent IC contamination. But this assumption assumes a normal dipole structure for the storm. Could the Aurora supercell have been inverted, as found during the STPES program (Rust and MacGorman 2002)? In this case might not IC discharges be mis-classified by the NLDN as negative stokes?

The storm which generated to intense Superior mesocyclone and tornadoes showed a somewhat similar evolution. Except this storm, at the time of the record mesocyclone, was producing almost exclusively negative CGs with small (16 kA) peak currents at rates approaching 17,000 per hour. Again, could this storm have been an inverted dipole with many IC events being sensed as small peak current –CGs?

Naturally, a key missing component from this study is IC flash rates such as from an LMA or LDAR-II system, allowing assessment of storm total lightning. The Superior cell does stand in marked contrast, however, to the anomalously low –CG rate supercell (though having extremely high IC rates) investigated during STERAO-A (Lang et al. 2000).

As the convection evolved on this evening, it gradually began to resemble a more classical MCS after 0600 UTC. A few "stray" +CGs began to be detected in the developing stratiform region well away from the convective cores. Only these +CGs had $i\Delta M_q(t)$ values above 100 kA, suggesting microphysical conditions in this remote portion of the storm were beginning to resemble those in which SP+CGs normally develop (Williams 1998; Lyons 1996)

What ultimately controls the polarity (and peak currents and charge lowered) of supercell lightning remains an unresolved issue. The relationship of the storms the theta-e ridges (Smith et al. 2000), the height of the cloud base (Williams et al. 2004) and the updraft size and intensity (Lang and Rutledge 2003) have all been suggested as factors. The new metric, charge moment change, a surrogate for charge lowered to ground, extracted from ELF/VLF signatures, may help provide insight into this question.

8. ACKNOWLEDGEMENTS

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P2.16 LIGHTNING CHARACTERISTICS OF THE AURORA, NE RECORD HAILSTONE-PRODUCING SUPERCELL OF 22-23 JUNE 2003 DURING BAMEX

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1. INTRODUCTION

The Bow Echo and Mesoscale Convective Vortex Experiment (BAMEX) was conducted during the summer of 2003 in the north-central U.S. (Davis et al. 2004).The primary focus of the project was the dynamics of large mesoscale convective systems (MCSs). As MCSs often evolve upscale from localized storms, it is not surprising that many supercells were also present within the experimental domain. On the afternoon and evening of 22-23 June 2003, two extraordinary supercell-like storms formed in south-central Nebraska (Fig. 1), presaging the formation of a MCS several hours later. The southern-most cell, called the Superior supercell, contained the most intense mesocyclone yet documented. Airborne Doppler radar detected a vortex 9 km in diameter with a 118 m s^{-1} velocity differential. Just two counties to the northwest another intense storm, the Aurora supercell, produced the largest confirmed hail stone in the U.S. (18.75 inches, [47.6 cm] circumference). While the dynamics of these storms are being widely investigated (Wakimoto et al. 2004), this paper will investigate the electrical characteristics of these unique events.

MCS lightning has been extensively researched. The discovery that mesospheric sprites (Franz et al. 1990) above the U.S. High Plains MCSs are associated with positive cloud-to-ground (+CG) lightning (Lyons 1996) has focused additional attention on the unusual characteristics of sprite parent +CGs (SP+CGs) (Boccippio et al. 1995; Huang et al. 1999; Hu et al. 2002). While the peak currents of SP+CGs are 25-50% higher than other +CGs in the same storm, peak current proves a poor sprite predictor. As initially suggested by 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 Q, the amount of charge lowered. [Note this second term is most appropriately considered as a function of time.] During the 2000 Severe Thunderstorm Electrification and Precipitation Study (STEPS), sprite-producing MCSs were investigated using peak current data from the National Lighting Detection Network (NLDN), a 3-D lightning mapping array, and ELF/VLF sensors from which $\Delta M_q(t)$ can be extracted for storms occurring up to several thousands of kilometers away (Lang et al. 2004; Cummer and Inan 2000; Hu et al. 2002). The STEPS SP+CGs were typically found within a portion of the trailing stratiform region of mature MCSs which had attained a size of >10,000 km^2 (>10 dBZ reflectivity). Consistent with theories of conventional dielectric breakdown, an apparent minimum threshold in $\Delta M_q(t)$ between 300 and 600 C km appears necessary (and sufficient?) for sprite initiation. This value is dependent upon both the duration of time over which $\Delta M_q(t)$ is extracted as well as night to night changes in mesospheric conductivity (Cummer and Lyons 2004 a, b). For a typical MCS (19 July 2000), the average $\Delta M_q(t)$ for an SP+CG was ~800 C km (Lyons et al. 2003a).

A decade of low-light video sprite monitoring from Colorado's Yucca Ridge Field Station (YRFS) suggests that sprites, while common above many MCSs, are extremely rare above supercells, save during their dying stages when they may develop more extensive stratiform precipitation regions. Given that supercells are often extremely electrically active, and many are dominated by positive polarity flashes, this discrepancy was very puzzling.

During STEPS, the electrical nature of supercells were investigated using the added resource of ELF/VLF $\Delta M_q(t)$ retrievals. The daytime supercell of 29 June 2000 exhibited an inverted (negative over positive dipole) polarity structure (Rust and MacGorman 2002). The storm had 80% +CGs during its lifetime, with average +CG peak currents of 53 kA (12%>75 kA). The –CG average peak current was 18 kA (Lyons and Cummer 2004). While many +CG $\Delta M_q(t)$ values exceeded 100 C km, none peaked above the 600 C km threshold at which a 10% probability of a sprite could be expected. Moreover, few –CGs produced $\Delta M_q(t)$ >50 C km. A nocturnal supercell on 25 June 2000, allowed for optical sprite monitoring. Five sprites were recorded, two from the very last +CGs of the decaying storm ($\Delta M_q(t)$ >1000 C KM). Three small events did occur during the most intense phase of the supercell (Lyons and Cummer 2004). These +CGs were highly impulsive but powerful enough ($\Delta M_q(t)$ >800 C km) to initiate sprites. But these appeared exceptions to the general rule for supercells to have few +CG and no -CG $\Delta M_q(t)$ values anywhere near the sprite triggering threshold. Duke University's routine $\Delta M_q(t)$ monitoring during BAMEX provided an opportunity to explore the electrical nature of these extreme convective events.

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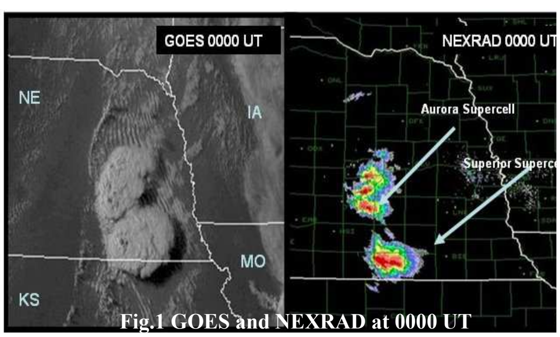
2. BAMEX AND DATA UTILZIED

As detailed by Davis et al. (2004), BAMEX deployed an extensive array of aircraft, mobile and remote sensing systems, with a primary focus on large MCSs. The supercells of 22-23 June were serendipitous occurrences which were partially monitored by research platforms (Wakimoto et al. 2004). We herein investigate the several stages of the developing convection on the evening of 22-23 June 2003 using conventional GOES and NEXRAD images, rawinsondes and NLDN stroke-level CG data, augmented by charge moment change data.

The Duke University ELF/VLF system, operating in a triggered mode, captured the larger impulse charge moment changes ($i\Delta M_q(t)$), during the first 2 ms of the CG event. During STEPS, continuous mode monitoring allowed retrieval of $i\Delta M_q(t)$ from virtually all CGs above a minimal detectible signature of ~5 C km (Cummer and Lyons 2004 a,b). During the BAMEX study, most CGs with $i\Delta M_q(t)$ >10-20 C km (still quite small) were likely captured. As the BAMEX domain was so far east of YRFS, LLTV sprite monitoring was not undertaken.

3. METEOROLOGICAL ENVIRONMENT

During the late afternoon of 22 June, a diffuse north-south stationary front was present in central Nebraska. A more distinctive feature was the remnant outflow boundary from earlier convection. Surface dewpoints were 20-24ºC. Late afternoon temperatures reaching 28-31ºC suggested lifted condensation levels in the 1000-1500 meter range. Soundings at 0000 UTC showed regional CAPE values in the 3000-3500 J kg^{-1} range. CAPE as high as 4000 J kg^{-1} at the time of convective initiation was accompanied by an unusual, near circular hodograph from the surface to 620 mb (Wakimoto et al. 2004). While the term “supercell” has been applied to the initial convective structures which emerged, it is being rather loosely applied. The Aurora “supercell” may have been a multi-celled system during much of its lifetime, with the hail falling from the southernmost reflectivity maximum. The Superior supercell was extremely well organized for about one hour, but was also multi-cellular at times. In any case, these county-sized storms contained extreme updrafts as evidence by the huge hail and 18-19 km radar echo tops.



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Avg. -CG I ΔMq	0	0	9	28	25
Max -CG I ΔMq	0	0	12	139	82

Figure 2 shows a plot of NLDN for the Aurora cell (star marks the hail stone fall) and the developing Superior supercell (2330-2359 UTC), as well as the Aurora cell NLDN event time line. Only during the period more than 30 minutes before the hail fall (2325-2235 UTC) did these CGs produced any $i\Delta M_q(t)$ values of consequence, and only then from +CGs.

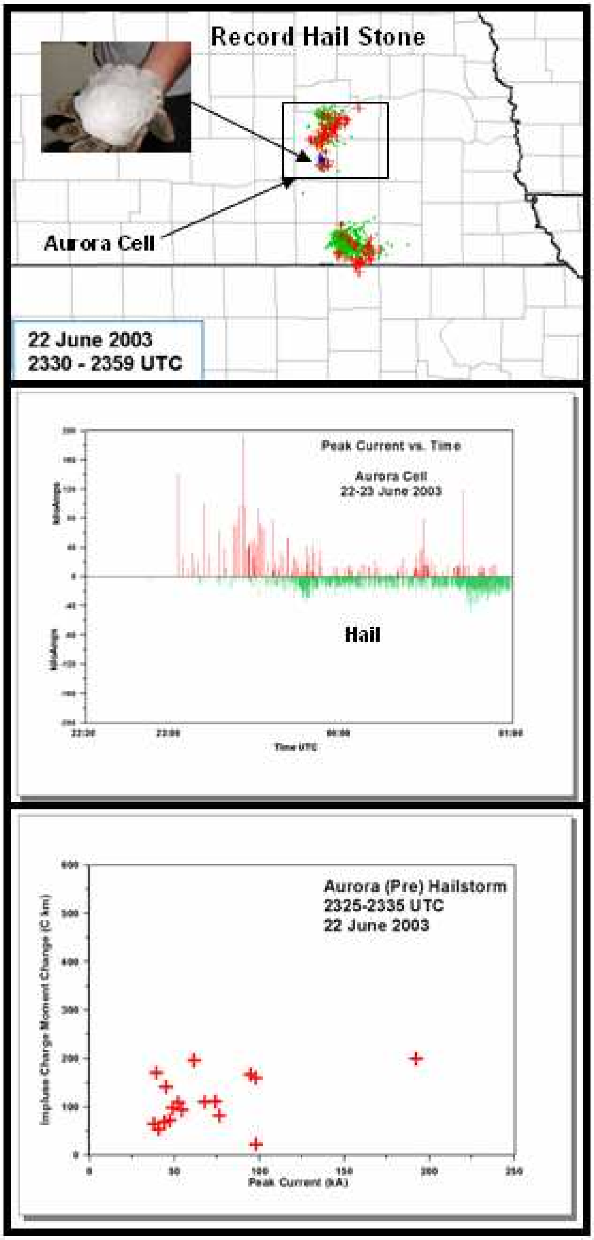

Figure 2. (top) NLDN CGs between 2300-2359 UTC. Star indicates hail fall location. The rectangle surrounds the storm for which the NLDN time history is plotted (middle). The plot of charge moment changes versus their +CG peak currents between 2325 and 2335 UCT (bottom) mark the only period during the storm when large values of charge were being lowered to the surface. (Red cross +CGs)

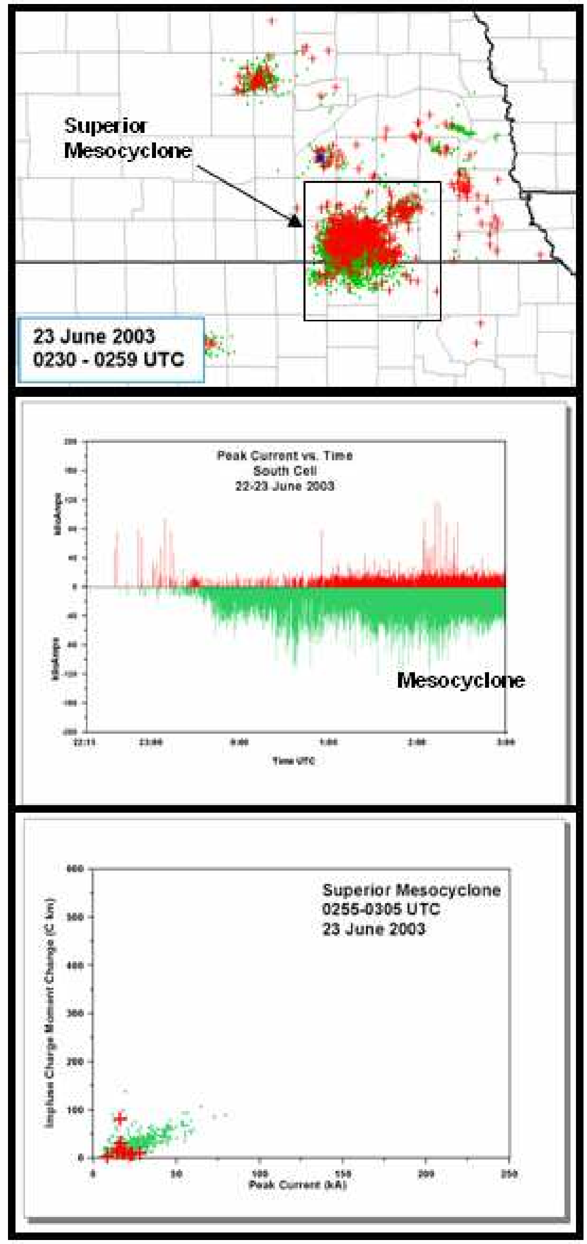

Figure 3. Similar to Fig 2, except showing the NLDN events from 2300 to 2359 UTC (top), the NLDN timeline (0000-0300 UTC) (middle), and the i$\Delta M_q(t)$ – peak current relationships for those very few CGs powerful enough to lower detectable amounts of charge to ground during a ten minute period during the most intense stage of the record mesocyclone (bottom).

5. THE SUPERIOR SUPERCELL

The storm system which evolved into the Superior mesocyclone began at approximately the same time as the Aurora cell. During its first hour it was likewise strongly positive (45%). As with the northern cell, after this initial growth phase, the CG rates increased significantly, percent positives dropped to less than 5%, +CG peak currents fell rapidly from 40 kA to 10-15 kA, and the negative CG peak currents remained small (11-18 kA). At the time of the record mesocyclone (0255-0305 UTC), the CG rate was an impressive 299 min^{-1}, and only 6% positive. Of those

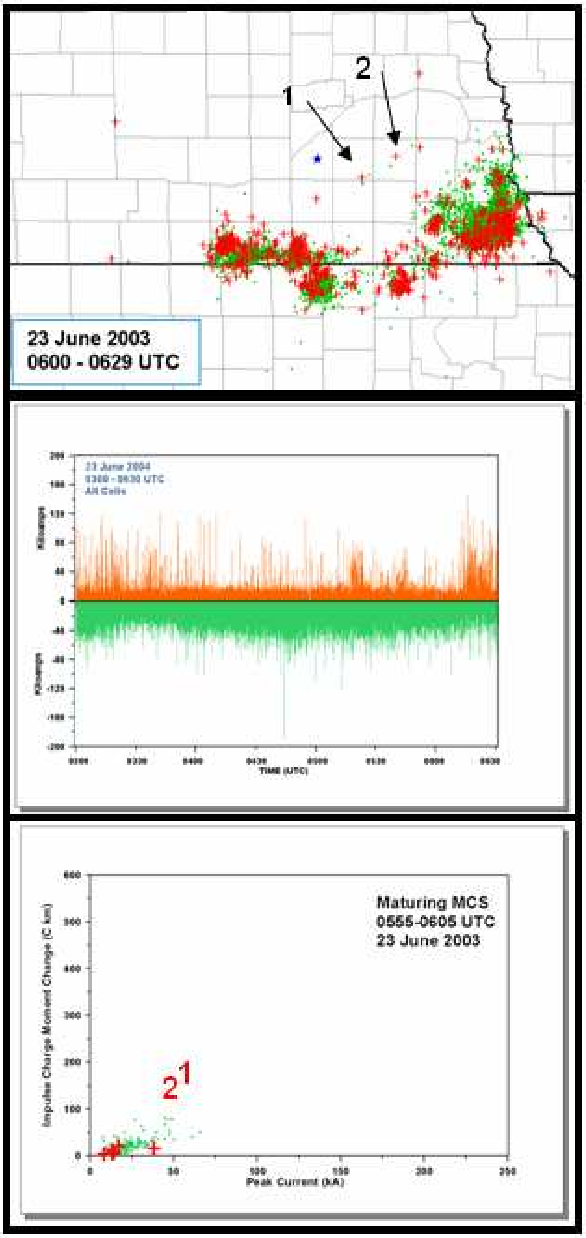

Figure 4. (top) NLDN CGs between 0600-0630 UTC, including two +CGs in the developing stratiform region The NLDN time history is plotted (middle). The plot of charge moment changes versus their CG peak currents between 0555 and 0605 UCT (bottom) are compared to the two +CGs about 20 minuets later in the organizing stratiform region (green negative, red crosses/numbers positive).

positives, less than 5% had detectable i$\Delta M_q(t)$ signatures, with very small average values of 22 C km Atypical of supercells, a greater percent of the -CGs (17%) produced detectable impulse charge moment changes, but these also had rather small mean (28 C km) and peak (131 C km) values. It is very unlikely that this dynamically intense cell's lightning was initiating sprites during its mature stage.

6. THE MATURING MCS STAGE

Between 0300 and 0630 UTC, convection became more widespread through extreme southeast Nebraska, though severe weather reports waned. The convection appeared to be organized more as clusters of intense cells. MCS-like characteristics, including a large stratiform region with secondary precipitation maxima (Schuur and Rutledge 2000), did not begin to emerge until after around 0600. Figure 4 shows CG activity clustered in several centers, with both polarities co-located in these convective cores. CG rates exceeded 20,000 hr^{-1} but the positives remained between 6 and 11 %. The NLDN time line in Fig, 4 shows patterns typical of more conventional convection, though the mean peak currents for the +CGs (15-18 kA) and the –CGs (15-18 kA) both remained somewhat smaller than the climatological norm. There were occasional large peak current events, largely absent during the intense hail and mesocyclone stages earlier in the evening.

Inspection of the i$\Delta M_q(t)$ signatures between 0555 and 0605 UTC showed that only 2% of the +CGs and 6% of the –CGs had detectable values, and these remained very small, averaging a mere 11 and 25 C km respectively (Table 1).

After 0600 UTC, radar began to show a semblance of an organized stratiform precipitation region to the north of the intense cells, suggesting the convection was maturing into a more typical MCS structure. Around 0620 UTC, two +CGs were noted (Fig 4) well to the north of the main activity. The peak currents were 55 and 47 kA, but the i$\Delta M_q(t)$ values were 175 and 166 C km respectively, much larger than those sampled in the cores 10 to 20 minutes previously. This suggests microphysical conditions in the developing stratiform region were evolving towards the production of large charge moment change strokes more typical of SP+CGs. As seen in many sprite-generating MCSs, these larger charge moment events were closer to the edge of the storm's precipitation shield than the convective cores.

7. DISCUSION AND CONCLUSIONS.

The search for consistent lightning polarity signatures indicative of intense hail storms has produced a variety of both intriguing (Reap and MacGorman 1989; Rust el. 1991; Stolzenburg 1994; MacGorman and Rust 1998) but ultimately inconsistent results (Carey et al. 2003). A similar state exists with respect to NLDN tornadic signatures (Brannick and Doswell 1992; Curran and Rust 1992; Seimon 1993; Perez et al. 1997; Bluestein and MacGorman 1998). The recent availability of an additional metric, charge moment change, which is roughly proportional to the charge lowered to ground (in this paper, during the impulsive first 2 ms of the stroke), allows may allow additional insights into severe storm electrical activity.

On 22-23 June 2003, the BAMEX storms which developed in a nominally uniform and highly unstable air mass exhibited a variety of behaviors. The quasi-supercellular storm which evolved to produce the U.S. record hailstone initially began as a relatively low CG rate storm, but almost 50% positive with many large peak currents and substantial (>100 C km) $i\Delta M_q(t)$ values (though still below sprite-triggering thresholds). During the half hour before the record hail fall, stroke rates increased, and became overwhelmingly negative in polarity with both mean and maximum peak currents being exceptionally small (~10/~25 kA). While many hail storms have been associated with large peak current +CGs (Curran and Rust 1992; Stolzenburg 1994), low peak current –CG dominated hail storms have also been reported (Soula et al. 2004). The lack of detectable $i\Delta M_q(t)$ values from these –CGs suggests an interesting possibility. The conventional application of NBLDN data (Cummins et al 1998) often segregates +CG strokes of < 10 kA, as these likely represent IC contamination. But this assumption assumes a normal dipole structure for the storm. Could the Aurora supercell have been inverted, as found during the STPES program (Rust and MacGorman 2002)? In this case might not IC discharges be mis-classified by the NLDN as negative stokes?

The storm which generated to intense Superior mesocyclone and tornadoes showed a somewhat similar evolution. Except this storm, at the time of the record mesocyclone, was producing almost exclusively negative CGs with small (16 kA) peak currents at rates approaching 17,000 per hour. Again, could this storm have been an inverted dipole with many IC events being sensed as small peak current –CGs?

Naturally, a key missing component from this study is IC flash rates such as from an LMA or LDAR-II system, allowing assessment of storm total lightning. The Superior cell does stand in marked contrast, however, to the anomalously low –CG rate supercell (though having extremely high IC rates) investigated during STERAO-A (Lang et al. 2000).

As the convection evolved on this evening, it gradually began to resemble a more classical MCS after 0600 UTC. A few "stray" +CGs began to be detected in the developing stratiform region well away from the convective cores. Only these +CGs had $i\Delta M_q(t)$ values above 100 kA, suggesting microphysical conditions in this remote portion of the storm were beginning to resemble those in which SP+CGs normally develop (Williams 1998; Lyons 1996)

What ultimately controls the polarity (and peak currents and charge lowered) of supercell lightning remains an unresolved issue. The relationship of the storms the theta-e ridges (Smith et al. 2000), the height of the cloud base (Williams et al. 2004) and the updraft size and intensity (Lang and Rutledge 2003) have all been suggested as factors. The new metric, charge moment change, a surrogate for charge lowered to ground, extracted from ELF/VLF signatures, may help provide insight into this question.

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