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Lightning charge moment changes in U.S. High Plains thunderstorms

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[1] We report measurements of impulsive (2 ms) lightning charge moment changes in more than 1000 cloud-to-ground (CG) return strokes detected by the National Lightning Detection Network in three United States High Plains storms during the Severe Thunderstorm Electrification and Precipitation Study (STEPS) field program of 2000. The positive CG strokes (+CGs) in a mesoscale convective system exhibit an unusual charge moment distribution with a small median and long tail. Analysis suggests the presence of two different classes of +CGs in this MCS, one with small charge moment changes ($\leq$50 C km) and the other containing larger charge moment changes (50–1400 C km). The distributions of negative cloud-to-ground stroke charge moment changes are roughly log-normal in shape with means varying from 17.7 to 36.8 C km. When combined with past measurements these means vary by a factor of 4 between storms, and there is probably not a single distribution that represents well all storms. *INDEX TERMS:* 3324 Meteorology and Atmospheric Dynamics: Lightning; 3304 Meteorology and Atmospheric Dynamics: Atmospheric electricity; 3360 Meteorology and Atmospheric Dynamics: Remote sensing. **Citation:** Cummer, S. A., and W. A. Lyons (2004), Lightning charge moment changes in U.S. High Plains thunderstorms, *Geophys. Res. Lett.*, *31*, L05114, doi:10.1029/2003GL019043.

1. Introduction

[2] Some lightning parameters, such as location and peak current, are measured routinely on a continental scale by the National Lightning Detection Network (NLDN) [*Cummins et al.*, 1998]. But measurements of other lightning parameters, particularly those related to charge transfer, are sparse because of the limited spatial range of the techniques used to measure it. These techniques include integration of directly measured current [e.g., *Berger et al.*, 1975], and multi-point electrostatic field measurements [e.g., *Krehbiel et al.*, 1979]. All of these studies were (by necessity) limited in spatial or temporal extent. Consequently, little is known about the variability of lightning charge transfer in different storms, in different geographic locations, and even in different stages of a single storm.

[3] ELF (extremely low frequency, defined for the purposes of this paper as ~10–1500 Hz based on the frequencies used in our analysis) lightning remote sensing [*Cummer and Inan*, 2000], motivated in part by research in sprites and related lightning-ionosphere coupling, has enabled monitoring of current moment and charge moment change (ΔM_q) over large geographical areas. Past lightning measurements with this and related techniques [*Hu et al.*, 2002; *Huang et al.*, 1999] have revealed much about the unusually strong lightning responsible for generating the variety of mesospheric optical emissions now known to exist [*Neubert*, 2003]. In this work, we apply this technique to measure the variability of ΔM_q in all NLDN-detected cloud to ground (CG) lightning strokes in individual storms, including the less powerful "normal" lightning strokes for which fewer remote measurements exist.

2. Instruments, Data, and Analysis Techniques

[4] The details of the technique used here to measure lightning current moment from distant ELF electromagnetic measurements have been described by *Cummer and Inan* [2000]. This technique has been applied to measuring sprite-producing lightning ΔM_q [*Cummer*, 2003, and references therein]. Lightning ΔM_q has also been measured using sub-ELF (~1–50 Hz) Schumann resonance waveforms [*Burke and Jones*, 1996; *Huang et al.*, 1999]. However, to detect and measure every NLDN-detected CG stroke in a storm (including the small ones) with roughly one millisecond time resolution requires the higher ELF frequencies used in this work.

[5] During the summer of 2000, in support of the Severe Thunderstorm Electrification and Precipitation Study (STEPS) field program, we recorded continuously at Duke University ELF magnetic field waveforms from lightning (see *Hu et al.* [2002] for more experimental details). The sensor was located at a field site (35.975°N, −79.100°E), and with GPS absolute timing we could unambiguously identify the ELF waveform radiated by every NLDN-detected return stroke identified for analysis.

[6] Lightning current and channel length are not separately measurable at ELF. Since the lightning channel length is much shorter than one electromagnetic wavelength at ELF, the effective source for the electromagnetic radiation from lightning is the current moment waveform. Consequently current moment and ΔM_q are the parameters we measure and analyze herein. We emphasize that the measured current moment and ΔM_q are only vertical; low frequency radiation from horizontal elements of the lightning channel is much weaker and often not detectable at the long distances involved. The measurements we present are

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of physical ΔM_q, i.e., the total charge moved times the channel length from cloud to ground.

[7] We report the ΔM_q in only the first two milliseconds of the discharge (essentially the return stroke), and following *Berger et al.* [1975] we call this the impulse ΔM_q. Longer time currents associated with big return strokes can be also reliably measured with this technique if the longer currents are big enough or the source-receiver distance is sufficiently short. But our goal of measuring every NLDN-detected stroke in a given time and space window requires that many small strokes be measured, and only the impulse ΔM_q can be reliably measured for all strokes at the distances (roughly 2000 km) involved. Note that care is required in comparing the results presented here to other ΔM_q measurements [*Hu et al.*, 2002; *Huang et al.*, 1999] in which the duration over which ΔM_q is measured is significantly different from 2 ms. Note also that our measured distributions include both first and subsequent strokes.

[8] The reported measurements depend on the absolute calibration of the sensor and of the measured propagation impulse response. There is thus an absolute error in all the reported measurements in the estimated range (based on unpublished initial comparisons of this data set with other measurements and techniques) of −33%/+50%. The relative error between all of the measurements on a single day is much smaller (±10%) and thus the measured shape of the distributions are robust.

[9] We report measurements from three different storms: two on 25 June 2000 and one on 4 July 2000. These storms were chosen because they are also being analyzed in a study of sprites produced by two of these storms, and because relatively low noise in the ELF data on these two days gave high quality ΔM_q measurements. National Lightning Detection Network (NLDN) data were used to select the lightning strokes for analysis.

3. Charge Moment Change Distributions

[10] The 4 July 2000 storms consisted of two very large mesoscale convective systems (MCSs) which propagated eastward through Kansas and Nebraska. These storms have previously been described and investigated by *Price et al.* [2002]. The latitude window used to isolate the strokes associated with these storms ranged from 38 to 42°N, and the longitude window ranged from −100 to −96°E.

[11] In this geographic window the NLDN recorded 738 −CG strokes during the 0500–0501, 0529–0531, and 0559–0600 UT periods (this subset of −CGs was required to give a manageable number of events). The radiated field waveform from each of these strokes was identifiable in the ELF magnetic field data recorded at Duke University approximately 2000 km away. The ELF data indicated that the polarity of 14 of these was not consistent with the NLDN measurement; they were thus not −CG strokes but probably ionospheric reflections associated with +CG strokes (K. Cummins, personal communication). These 14 were removed from the analysis, leaving 724 confirmed −CG strokes. The NLDN also recorded 454 +CG strokes during the entire 0500–0600 UT period, and after removing 52 that were in the same way probable ionospheric reflections from −CG strokes, 392 confirmed +CG strokes remained. Recognizing that the NLDN-detected ≤10 kA peak current +CGs include many misidentified cloud discharges [*Cummins et al.*, 1998], we removed also these from the distribution, leaving 312 +CGs.

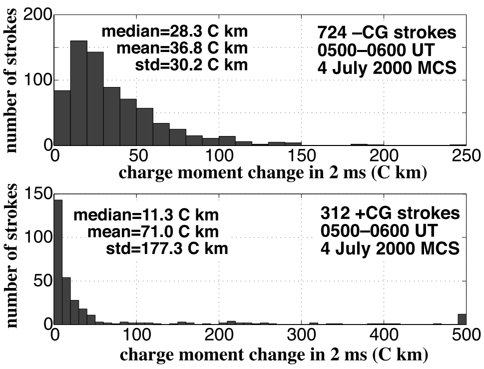

Figure 1. Histograms of impulse (first 2 ms) charge moment changes in +CG and −CG strokes during a one hour period within a High Plains MCS. The last bin in the +CG distribution contains 12 charge moment changes up to 1365 C km.

[12] Figure 1 shows ΔM_q histograms of the July 4 −CGs and +CGs along with their medians, means, and standard deviations. The −CG distribution is smooth and is roughly log-normal, a shape that is seen in many other lightning parameters [*Uman*, 1987, p. 339]. The +CG distribution, interestingly, has a much smaller median than the −CG distribution but exhibits a very long tail containing ΔM_q much larger than any in the −CG data (up to 1365 C km). Even removing the ≤15 kA +CGs only shifts the median to 18.2 C km. We thus believe that the small median +CG ΔM_q is not due to cloud discharge contamination.

[13] We analyzed in an identical way 73 −CGs and 85 +CGs (no ≤10 kA strokes needed to be excluded) from two isolated storm cells on June 25, 2000. Scattered convection over the Colorado, Nebraska, and Kansas High Plains produced an area of scattered multicellular convective storms, plus one isolated and intense storm which frequently exhibited supercellular characteristics. The 85 +CG strokes were recorded during the mature and decaying stages of the supercell defined by latitude 39.6 to 40.2 N, longitude −101.9 to −101.0 E, and 0300 to 0530 UT. The 73 −CG strokes were recorded in adjacent storm cells defined by latitude 39.9 to 40.8 N, longitude −103.0 to −102.4 E, and 0420 to 0600 UT. The supercell contained too few −CGs and the other cells contained too few +CGs for meaningful statistics. Five −CGs and one +CG identified by the NLDN were removed from the June 25 data sets due to NLDN polarity errors.

[14] The data from these two days yield 4 different impulse ΔM_q distributions, shown in Figure 2. For comparison also shown are past measurements from *Berger et al.* [1975] (as reported by [*Uman*, 1987, p. 124]) and *Brook et al.* [1962]. *Berger et al.*'s [1975] impulse charge measurements (which were derived from measurements of 207 −CGs and only 25 +CGs) have been converted to charge moment by multiplying by an assumed charge removal altitude of 8 km [*Krehbiel*, 1986]. We have also only included *Brook et al.* [1962]'s measurements of 93 strokes in discrete flashes (Table 1 of that paper) to ensure comparability with our impulse ΔM_q measurements. Note that because *Brook et al.* [1962] define charge moment

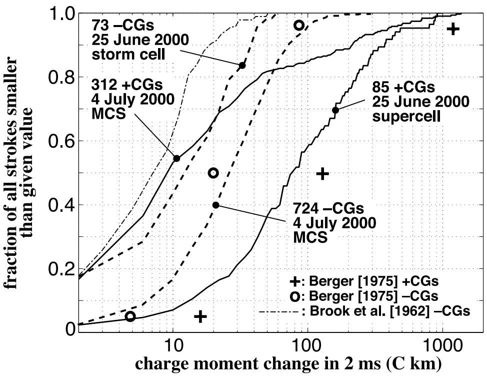

Figure 2. Measured cumulative distribution functions of impulse charge moment change (2 ms) for 4 separate CG populations with past measurements for comparison.

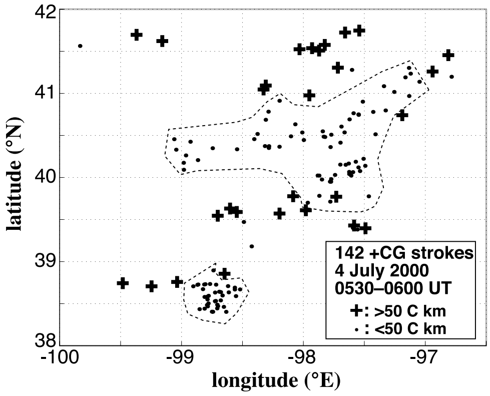

Figure 3. Spatial distribution of >50 C km and <50 C km +CG strokes on 4 July 2000. Two relatively simple boundaries have been sketched that nearly separate these two populations that are divided by the breakpoint in the total charge moment distribution, which suggests that they are in some way distinct.

as twice charge times distance while we define it as charge times distance, their reported charge moments must be halved before comparison to ours.

[15] All but one of the distributions are roughly log-normal in shape. As expected, +CGs have generally larger charge moments and a broader distribution than −CGs. But there are substantial differences between the distributions in individual storms. Table 1 summarizes these distributions with their means, medians, and standard deviations. Our new measurements indicate significant storm-to-storm (and perhaps region-to-region) variability in lightning charge moment changes: more than a factor of 2 in −CGs, increasing to a factor of 4 when past measurements are included.

[16] The +CG distributions are even more variable, largely due to the unusual 4 July 2000 +CG distribution (the MCS). In this storm, the median +CG ΔM_q is unexpectedly smaller than that for −CGs. This distribution is not log-normal in shape; it has many more very small and very large events than the other measured distributions. There also appears to be a breakpoint near 50 C km where the distribution changes quantitatively. This breakpoint can be seen in both Figures 1 and 2. We show below how this overall distribution appears to be a superposition of two distinct populations of +CGs, each of which follows its own smooth occurrence distribution.

4. Spatial Distribution of 4 July 2000 +CG Strokes

[17] We explore the spatial distribution of the >50 C km and <50 C km +CGs in the 4 July 2000 MCS. Figure 3 plots the location (latitude and longitude) of the 142 NLDN-recorded and confirmed >10 kA +CG strokes in the MCS between 0530 and 0600 UT. Based on the breakpoint in the impulse ΔM_q distribution in Figure 2, we plot the 28 >50 C km strokes with a different symbol (+) than the <50 C km strokes (.) to highlight any differences in the spatial distributions of these two populations. (Temporal clustering was also searched for and not found). The figure indicates that the strokes >50 C km occur almost exclusively on the edges of the larger regions producing the smaller <50 C km strokes. In other words, a relatively simple closed boundary can be drawn that separates almost all of the smaller +CG strokes from almost all of the bigger +CG strokes. Overlaying this distribution on a simultaneous radar image (not shown) indicates that the larger +CG strokes are almost all in the outer part of the stratiform region, while the smaller +CG strokes are close to the convective cores.

Table 1. Statistical Summary of Stroke Impulse Charge Moment Changes

Source	# of ev.	Median (C km)	Mean (C km)	Std Dev (C km)
4 July 2000 −CGs	724	28.3	36.8	30.2
25 June 2000 −CGs	73	13.5	17.7	14.0
Berger [1975] −CGs	207	20.0		
Brook et al. [1962] −CGs	93	8.3	10.1	8.5
4 July 2000 +CGs	312	11.3	71.0	177.3
25 June 2000 +CGs	85	79.4	153.6	194.6
Berger [1975] +CGs	25	128.0		

[18] A similar spatial separation between positive and negative CGs has been observed previously [*Lyons*, 1996], but the above analysis indicates that there are two distinct classes of +CGs in this MCS, each with significantly different charge transfer characteristics and spatial distributions. We anticipate that other characteristics of these two classes of +CG lightning, such as initiation altitude and the in-cloud horizontal extent of the lightning channels, are also different. This result also supports the notion that the charge separation mechanisms, subsequent transport and resultant spatial distributions of charge pools may be distinctly different in an MCS from those found in other lightning-producing cloud systems, as suggested by *Marshall et al.* [1996]. We plan to analyze the +CG lightning in more MCSs to determine whether the unusual impulse ΔM_q distribution and spatial separation between large and small strokes is a common characteristic of MCS-class storms. No similar spatial separation between large and small impulse ΔM_q +CGs in the 25 June 2000 supercell was found.

5. Conclusions

[19] We report lightning impulsive charge moment changes of every NLDN-detected CG stroke in specified

time windows in three individual storms. This resulted in four different statistical distributions: +CGs in an MCS, −CGs in an MCS, +CGs in a supercell, and −CGs in a small multicellular storm cluster. Except for the MCS +CGs, the distributions are log-normal in shape, but the median and mean impulse ΔM_q vary by as much as a factor of 4 between storms.

[20] The MCS +CG impulsive charge moment change distribution is unusual, with more very small (the median is 11.3 C km) and more large events than the other distributions. Moreover, there is a distinct spatial separation between the large +CG charge moment changes, which occur on the outer part of the MCS stratiform region, and the small +CG charge moment changes, which occur in the convective core. This suggests the presence of two distinct classes of +CG in this storm that likely reflect differences in charge separation and distribution in this MCS (and maybe most MCSs).

[21] This work demonstrates the value of ELF-based lightning remote sensing in which a single sensor thousands of km away from the storm can measure current moment waveforms of essentially every stroke in the storm with approximately 1 ms time resolution. We plan further and broader application of this technique to hopefully improve our fundamental understanding of lightning parameters and and their variability in individual storms, resulting in a valuable experimental tool to explore the relationship of lightning and meteorology.

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References

Berger, K., R. B. Anderson, and H. Kroninger (1975), Parameters of lightning flashes, *Electra*, *80*, 223–237.

Brook, M., N. Kitagawa, and E. J. Workman (1962), Quantitative study of strokes and continuing currents in lightning discharges to ground, *J. Geophys. Res.*, *67*, 649–659.

Burke, C. P., and D. L. Jones (1996), On the polarity and continuing currents in unusually large lightning flashes deduced from ELF events, *J. Atmos. Terr. Phys.*, *58*, 40–531.

Cummer, S. A. (2003), Current moment in sprite-producing lightning, *J. Atmos. Solar-Terr. Phys.*, *65*, 499–508.

Cummer, S. A., and U. S. Inan (2000), Modeling ELF radio atmospheric propagation and extracting lightning currents from ELF observations, *Radio Sci.*, *35*(2), 385–394.

Cummins, K. L., M. J. Murphy, E. A. Bardo, W. L. Hiscox, R. B. Pyle, and A. E. Pifer (1998), A combined TOAMDF technology upgrade of the US National Lightning Detection Network, *J. Geophys. Res.*, *103*(D8), 9035–9044.

Hu, W., S. A. Cummer, W. A. Lyons, and T. E. Nelson (2002), Lightning charge moment changes for the initiation of sprites, *Geophys. Res. Lett.*, *29*(8), 1279, doi:10.1029/2001GL014593.

Huang, E., E. Williams, R. Boldi, S. Heckman, W. Lyons, M. Taylor, T. Nelson, and C. Wong (1999), Criteria for sprites and elves based on schumann resonance observations, *J. Geophys. Res.*, *104*(D14), 16,943–16,964.

Krehbiel, P. R. (1986), The electrical structure of thunderstorms, in *The Earth's Electrical Environment*, Studies in Geophysics, pp. 90–113, Nat. Acad. Press, Washington, D. C.

Krehbiel, P. R., M. Brook, and R. A. McCrory (1979), An analysis of the charge structure of lightning discharges to ground, *J. Geophys. Res.*, *84*, 2432–2456.

Lyons, W. A. (1996), Sprite observations above the U.S. High Plains in relation to their parent thunderstorm systems, *J. Geophys. Res.*, *101*(D23), 29,641–29,652.

Marshall, T. C., M. Stolzenburg, and W. D. Rust (1996), Electric field measurements above mesoscale convective systems, *J. Geophys. Res.*, *101*(D3), 6979–6996.

Neubert, T. (2003), On sprites and their exotic kin, *Science*, *300*, 747–748.

Price, C., M. Asfur, W. Lyons, and T. Nelson (2002), An improved ELFVLF method for globally geolocating sprite-producing lightning, *Geophys. Res. Lett.*, *29*(3), 1031, doi:10.1029/2001GL013519.

Uman, M. A. (1987), *The Lightning Discharge*, Academic, San Diego, Calif.

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