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Transient luminous events above two mesoscale convective systems: Charge moment change analysis

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[1] Charge moment change (ΔM_Q) data were examined for 41 positive cloud-to-ground (+CG) lightning discharges that were parents of transient luminous events (TLEs; mainly sprites) over two different storms: 9 May (20 parents) and 20 June 2007 (21). Data were broken down by contributions from the impulse ΔM_Q ($i\Delta M_Q$), within the first 2 ms of the return stroke, and the ΔM_Q from the continuing current (CC), which can last tens of ms afterward. Three-dimensional lightning mapping data provided positions for the in-cloud components of the parent +CGs. Charge and charge density neutralized by the strokes were estimated. The 20 June parents were more impulsive than 9 May, with increased $i\Delta M_Q$ and CC amplitude but reduced CC duration. Total ΔM_Q values between the two storms were very similar, averaging ~1800 C km. Estimated charge density on 20 June was nearly twice that on 9 May, consistent with the 20 June storm being more intense with a stronger electrical generator. Lightning metrics were analyzed for 9 high- $i\Delta M_Q$ (>300 C km) +CGs that did not produce an observable TLE on 20 June, and compared to that day's TLE parents. Non-TLE +CGs had reduced CC magnitudes and duration, with less total ΔM_Q. Photogrammetric estimates of TLE azimuthal swaths were positively correlated with similar metrics of the in-cloud portions of the parent +CGs, as well with total ΔM_Q. The implications of all these results for the ΔM_Q theory of sprite initiation, and for the relationship between sprite development and in-cloud discharging, are discussed.

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1. Introduction

1.1. Relationship Between Charge Moment Change and Transient Luminous Events

[2] Sprites are a type of transient luminous event (TLE) that occurs above some thunderstorms during certain phases of their life cycle [*Lyons et al.*, 2009]. Current theory holds that sprites occur due to dielectric breakdown near the base of the ionosphere, near 75 km height [*Stanley et al.*, 1999; *Pasko*, 2010]. This breakdown normally is the result of a strong transient electric field after the removal of large amounts of charge in a cloud-to-ground (CG) lightning flash [*Pasko et al.*, 1996, 1997; *Williams*, 2001; *Pasko*, 2010]. Related to sprites - and often occurring just prior to them - are halos, which have a significant lateral extent [*Barrington-Leigh et al.*, 2001; *Frey et al.*, 2007; *Pasko*, 2010].

[3] An important metric that controls the likelihood of dielectric breakdown in the mesosphere is the charge moment change (ΔM_Q) [*Wilson*, 1924] produced by the parent tropospheric lightning stroke:

$$\Delta M_Q(t) = Z_Q(t) \times Q(t)\,(\mathrm{C\,km}), \tag{1}$$

where Z_Q is the altitude (above ground level, AGL) from which the charge Q is lowered to ground, both as functions of time t. Total ΔM_Q values generally need to be on the order of hundreds of C km for mesospheric breakdown to occur [*Cummer and Inan*, 1997; *Pasko et al.*, 1997; *Huang et al.*, 1999; *Williams*, 2001; *Hu et al.*, 2002, 2007; *Cummer*, 2003; *Cummer and Lyons*, 2005], which is very large compared to ΔM_Q values in average CG strokes [*Rakov and Uman*, 2003; *Cummer and Lyons*, 2004].

[4] In the warm season, these large ΔM_Q values are the result of discharging of hundreds of C of positive charge within a laterally extensive layer in the stratiform region of a mesoscale convective system (MCS) [*Houze et al.*, 1990] by energetic positive CG (+CG) lightning [*Rutledge and MacGorman*, 1988; *Marshall and Rust*, 1993; *Boccippio et al.*,

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1995; *Lyons*, 1996; *Marshall et al.*, 1996; *Williams*, 1998; *Marshall et al.*, 2001; *Williams*, 2001; *Lyons et al.*, 2003; *Williams and Yair*, 2006; *Lang et al.*, 2010; *Lu et al.*, 2010].

[5] *Williams* [1998] and *Lyons et al.* [2003] suggested that in MCS stratiform regions, the volume discharged for TLE parents may often reside near the melting layer. *Lang et al.* [2010] noted, however, that the particular charge layer involved in TLE-parent lightning can vary between different MCSs, and does not necessarily reside at a particular altitude for all storms. The reason for this may have to do with morphological differences between MCSs, which can control where charge is produced, how much charge may be present, and how this charge is produced and advected within the stratiform region. The implication of this hypothesis is that different MCSs may feature different Z_Q, as well as different charge amounts (i.e., charge densities) in the stratiform region. This has implications for the average ΔM_Q values produced by lightning in different MCSs, and thus the relative propensity of different MCSs to produce a TLE. The present study tests this hypothesis from *Lang et al.* [2010], by examining differences in ΔM_Q observations from two MCSs.

1.2. The Question of Energetic Lightning That Does Not Produce a TLE

[6] Recently, S. A. Cummer et al. (Initial results from a network for real-time lightning impulse charge moment change measurements, manuscript in preparation, 2011) described a network of electromagnetic sensors monitoring the frequency band between <1 Hz and 30 kHz, from which the impulse charge moment change (charge moment within 2 ms of the return stroke; $i\Delta M_Q$) can be obtained in real time from CG discharges that strike most of the contiguous United States. The data also can be laboriously post-processed to estimate the total ΔM_Q amount per stroke, including the contribution from the continuing current (CC). *Lyons et al.* [2009] noted that high-$i\Delta M_Q$ (>300 C km) positive CGs (+CGs) have a 75–80% or greater chance to produce a TLE, especially a sprite. Thus, the network is an effective tool for determining the TLE-producing potential of U.S. storms in real time.

[7] However, it is unclear what is different about the minority of high-$i\Delta M_Q$ positive strokes that apparently do not produce a TLE. Based on recent studies [*Hiraki and Fukunishi*, 2006; *Asano et al.*, 2008, 2009b; *Li et al.*, 2008; *Gamerota et al.*, 2011], the temporal evolution of parent-lightning ΔM_Q, as well as current moment, may play an important role. Indeed, one possibility is that non-TLE energetic lightning may not "follow up" with substantial continuing current, relative to TLE parents.

[8] For example, simulations [*Yashunin et al.*, 2007; *Asano et al.*, 2009b] have suggested and measurements [*Li et al.*, 2008; *Gamerota et al.*, 2011] have shown that delayed sprites may occur due to variations in the continuing current (i.e., M components) of energetic CGs. A M-component with duration of 10 ms or longer (called a "slow intensification" by *Li et al.* [2008]) can significantly increase the high altitude electric fields due to nonlinear attachment, heating and ionization, and thus increase the chance of sprite initiation. Excluding the effects of slow intensifications, a discharge with weaker continuing current, then, may lack the ability to produce a delayed sprite. Thus, if a +CG did not produce a sprite quickly (1–10 ms) after the return stroke, then it may not produce one at all. A goal of the present study is to compare total ΔM_Q and continuing currents between energetic lightning that produces a TLE, and those that do not, to see if this hypothesis has any support.

1.3. TLE Location and Morphology Relative to Parent Lightning Characteristics

[9] *Lyons* [1996] found that most sprites occur within 50 km of the parent lightning's ground-strike location. However, longer displacements are possible. Indeed, significant horizontal displacement of sprites has been studied several times since then [*Yashunin et al.*, 2007; *Asano et al.*, 2009a; *Soula et al.*, 2010; *van der Velde et al.*, 2010]. This displacement may be related to the behavior of in-cloud components of the parent lightning [*Yashunin et al.*, 2007; *Asano et al.*, 2009a]. That sprite-parent lightning can display extensive horizontal in-cloud discharging is well known [*Stanley*, 2000; *Ohkubo et al.*, 2005; *van der Velde et al.*, 2006, 2010; *Marshall et al.*, 2007; *Lang et al.*, 2010].

[10] Therefore, it is reasonable to hypothesize that the horizontal extent of TLEs associated with lightning strikes (which can be influenced by both the size of the TLEs as well as the quantity occurring with a particular CG) may be related to the horizontal extent of the in-cloud component of the parent lightning. This hypothesis will be tested as part of this study.

1.4. Approach of This Work

[11] This study focused on TLEs produced by two different MCSs that occurred in Oklahoma during the warm season of 2007, the same two storms studied by *Lang et al.* [2010]. The first, 9 May, was an asymmetric MCS that contained a mesoscale convective vortex as well as substantial embedded convection in its stratiform region. This MCS produced 25 observed TLEs during two hours of observations. The second, 20 June, was an enormous symmetric MCS that produced 282 observed TLEs during 4 h of observations.

[12] The available TLE video data featured a time resolution of 16.7 ms, which as *Li et al.* [2008] noted is not fine enough to link TLE evolution with precise variations in parent-lightning characteristics. Thus, the results presented herein will focus on bulk differences between TLE-parent lightning between the two storms, as well as between TLE parents and energetic lightning that did not produce a TLE. Only one video camera was available, so triangulation of TLE positions was not possible. However, as will be shown, it was still possible to explore relationships between one-dimensional estimates of TLE breadth and parent lightning characteristics.

2. Data and Methodology

[13] The details of the observing network for the 2007 storms was covered in depth by *Lang et al.* [2010]. Thus, only the highlights most relevant to the present study are reviewed here.

2.1. Video TLE Monitoring

[14] Video observation of TLEs was accomplished at Yucca Ridge Field Station near Fort Collins, CO, using a Watec 902H U camera with a wide-angle (6.0 mm, ~55° horizontal field of view) f/0.8 lens mounted in a steerable camera housing. A global positioning system receiver and

video time-stamping system imprinted ms-resolution time hacks on each 16.7-ms video field.

[15] Basic photogrammetry was performed on TLE video images, using known landmarks such as particular lights or buildings in the city of Windsor, CO. This photogrammetry recovered the largest azimuthal extents (i.e., left and right boundary azimuths) of 45 TLEs from 9 May and 20 June, with an estimated uncertainty of 0.5°. It should be understood that what is termed an individual TLE using the camera may in fact be made up of one or more separate sprite, halo, or elve events associated with a single parent +CG (e.g., "dancer" sprites [*Williams et al.*, 2010]). Due to the excellent viewing conditions on 9 May and 20 June 2007 [*Lang et al.*, 2010], confidence is reasonably high that the non-TLE energetic discharges analyzed in this study in fact did not produce a TLE observable by the camera.

[16] Similar to *Lang et al.* [2010], the TLEs considered in this study contained a mix of mainly sprites, with a few standalone halos or elves (two elves total). The latter were considered alongside sprites because *Lang et al.* [2010] found the parent lightning for different categories of TLEs to be morphologically similar for these storms. In addition, elves and halos were difficult to distinguish from one another, due to the storms' long distances from Yucca Ridge, and there is a known similarity in parent-lightning processes that lead to halos and sprites [e.g., *Pasko*, 2010]. Thus, all of these different TLEs were considered together.

2.2. National Lightning Detection Network

[17] National Lightning Detection Network (NLDN) stroke-level data were used in this study the same way they were used by *Lang et al.* [2010]. Parent CGs were matched to observed TLEs via the methodology of *Lyons et al.* [2003, 2008], which compared TLE timing and azimuth to NLDN strike timing and location. This study was confined to TLEs with a detected parent +CG flash, and to a few energetic +CGs with no observed TLEs.

2.3. Charge Moment Change Network

[18] Based on the availability of data, the charge moment change for events on 9 May and 20 June are inferred from post-processing with measured magnetic fields from two different systems. For the events on 9 May, the lightning radiated magnetic fields were measured by Duke University's Ultra Low Frequency (ULF)/Extremely Low Frequency (ELF) system. This system contains a pair of coils that continuously record vector magnetic fields in a frequency band of 0.1 Hz to 500 Hz with a sampling rate of 2.5 kHz. For events on 20 June, the lightning radiated magnetic fields were measured by the ΔM_Q system at Yucca Ridge Field Station. In this system, a pair of magnetic sensors measures lightning radiated magnetic fields from 1 Hz to 25 kHz in triggered mode and to 1 kHz in the continuous mode. For both systems, their lower cutoff (0.1 Hz and 1 Hz) enable the identification of slow-varying continuing current for durations from tens to several hundred milliseconds. Measurements from these systems have been quantitatively compared and typically yield inferred charge moment changes that agree within 10%.

[19] With these remotely measured magnetic fields and known lightning locations, the charge ΔM_Q was inferred with a deconvolution technique [*Cummer and Inan*, 1997, 2000; *Cummer*, 2003] that has been applied extensively in related studies. For each event, the total current moment waveform is estimated from the starting of lightning return stroke to the end of the detectable slow continuing current, and then integrated over different durations to obtain charge moment changes. The charge moment change within the first 2 ms was empirically defined as $i\Delta M_Q$, which mainly includes the contributions from the lightning return stroke and the long impulse current [*Gomes and Cooray*, 1998]. Thus the difference between ΔM_Q and $i\Delta M_Q$ is the contribution from the continuing current. The total ΔM_Q and the CC ΔM_Q are estimated for the entire time window of the lightning discharge. Since sprites usually initiate before the end of the continuing current, these quantities are not the sprite-producing ΔM_Q but can be treated as an upper bound. In this work, this upper bound was applied in the following analysis since the 16.7-ms uncertainty does not allow the determination of the exact ΔM_Q at sprite initiation time.

2.4. Oklahoma Lightning Mapping Array

[20] This study used many of the same TLE parents flashes viewed by the Oklahoma Lightning Mapping Array (LMA) in the work by *Lang et al.* [2010]. See that reference for more information on how individual TLE parents were identified and isolated for further analysis. This same procedure was used to obtain data for non-TLE parent discharges.

[21] For determining altitudes of collections of Very High Frequency (VHF) sources observed by the LMA, the following procedure was used. The altitude during the $i\Delta M_Q$ portion of the stroke was determined by the mean of sources occurring 5 ms prior to the CG through 2 ms afterward ($Z_{i\Delta M_Q}$). The preceding 5 ms was used to include enough VHF sources to keep $i\Delta M_Q$ altitudes stable; otherwise, there often could be only a small number of points, decreasing confidence in the computed means. The continuing current altitude was determined by the mean of sources occurring after the first 2 ms of the return stroke through the end of the continuing current (often tens of ms later; Z_{CC}). The altitude associated with the entire stroke was taken as the mean of the union of these two sets ($i\Delta M_Q$ and CC) of VHF sources (Z_{total}).

[22] Sources occurring during the TLE were determined using the temporal limits of the video imagery containing the observed TLE. As discussed above, the video imagery was limited to 16.7-ms resolution. However, VHF sources during TLEs were well behaved (i.e., tended to cluster in a specific region during a particular time period longer than a few ms), so the coarse temporal resolution did not affect results significantly.

3. Results

3.1. The 9 May 2007 Versus 20 June 2007 Charge Moment Change and Lightning Morphology

3.1.1. On the Representativeness of the Data Samples

[23] Total charge moment data were retrieved for a total of 20 TLE-parent discharges on 9 May and another 21 parents on 20 June, with the results shown in Table 1. The 9 May set includes the vast majority of the 25 TLEs observed in this case [*Lang et al.*, 2010], and thus was clearly representative of the overall population of 9 May parents. However, the 20 June parents with total ΔM_Q calculated were less than

Table 1. Median Values for 20 TLE-Parent Discharges on 9 May 2007, and 21 Parents on 20 June 2007[a]

	9 May 2007	20 June 2007	Significance (%)
iΔM$_Q$ (C km)	229.0	405.0	99.9
$Z_{i\Delta M_Q}$ (km AGL)	5.7	7.5	>99.9
$Q_{i\Delta M_Q}$ (C)	41.7	58.2	95.0
CC duration (ms)	148	62	>99.9
CC amplitude (kA km)	11.7	28.4	>99.9
CC ΔM$_Q$ (C km)	1606.0	1440.0	4.2
Z_{CC} (km AGL)	5.7	8.0	>99.9
Q_{CC} (C)	310.4	178.5	83.3
Total ΔM$_Q$ (C km)	1792.0	1812.0	67.8
Z_{total} (km AGL)	5.7	8.0	>99.9
Q_{total} (C)	337.9	264.9	53.5
Total sources	363	153	99.9
Volume discharged (km^3)	268	146	99.7
Density of charge neutralized (C km^3)	1.0	1.8	97.5
Source rate (s^{-1})	2836.1	2362.3	39.8

[a]Domain of calculations is limited by 5 ms prior to each TLE-parent CG stroke through the end of detectable continuing current. Significance of differences computed via Rank-Sum test. Acronyms and other symbols defined in text.

10% of the 282 TLEs observed on that day, so some justification of this day's data set is necessary.

[24] On 20 June most TLEs occurred well beyond the effective range of 200 km from the Oklahoma LMA [*MacGorman et al.*, 2008]. *Lang et al.* [2010] had to limit their LMA analysis to the 49 TLE parents within 175 km of the network's centroid. It was not possible to significantly extend this analysis further in range without compromising data quality. In fact, *Lang et al.* [2010] performed substantial ancillary analysis to prove that useful vertical structure information was retrievable for flashes beyond 100 km distance, the typically cited three-dimensional analysis range of the Oklahoma LMA [*MacGorman et al.*, 2008]. Thus, for this study the maximum possible number of includable 20 June TLE parents was 49.

[25] Now 21 is a large fraction of 49, but to further ensure that the subset of 21 discharges analyzed for total ΔM$_Q$ were representative of the 49 potential parents from *Lang et al.* [2010], the distributions for various estimates from that paper (i.e., parent flash initiation altitude, initiation reflectivity, parent CG peak current, altitude of LMA sources during the TLE, and flash area) were compared statistically. None of the distributions of these parameters for the subset of 21 parent discharges with ΔM$_Q$ data, and for the entire 49 parents, were significantly different at greater than 95% confidence (via the nonparametric Rank-Sum test). In fact, nothing even broke the 80% confidence level.

3.1.2. Charge Moment Change Analysis

[26] With the representativeness of the 20 June sample established, Table 1 was created from the analysis of the LMA and total ΔM$_Q$ data for the 9 May and 20 June TLE parents. The 20 June parents featured higher iΔM$_Q$ as well as higher $Z_{i\Delta M_Q}$. Dividing iΔM$_Q$ for each parent by its $Z_{i\Delta M_Q}$ recovered the total charge lowered to ground during the first 2 ms ($Q_{i\Delta M_Q}$). Here, too, 20 June was larger than 9 May.

[27] Continuing current duration during 20 June was less than half that of 9 May, yet its amplitude was more than twice as large. The end result was the CC charge moment change was not statistically different between the two storms. Despite the VHF source altitude differences during the CC phase, total charge lowered during the continuing current (Q_{CC}) also was not significantly different, statistically speaking. However, the absolute difference in median Q_{CC} was large, 310.4 C for 9 May versus 178.5 C for 20 June. Mean Q_{CC} values, which are not shown in Table 1, were closer together: 278.3 C on 9 May to 221.5 C on 20 June. Basically, the distributions for Q_{CC} on both days had large standard deviations (~170 C each), so despite the large absolute difference there was little statistical confidence in the result.

[28] Total ΔM$_Q$ was very similar between the two storms, but again due to altitude differences this led to a smaller median value for total charge neutralized (Q_{total}) by 20 June TLE parents (264.9 C), compared to 9 May (337.9 C). However, this result was not statistically significant, for the same reason that the Q_{CC} results were not.

[29] Largely due to the longer CC duration, 9 May TLE-parent discharges featured a larger median number of LMA sources during the entirety of the stroke, 363 versus 153 for 20 June. The Cartesian space for each LMA-mapped flash was broken up into 1-km by 1-km by 1-km cubes (on the same order of the resolution of the LMA for these storms [*Lang et al.*, 2010]), and every cube that contained an LMA source was counted to compute total storm volume discharged by the parent stroke. Unsurprisingly, due to its larger number of LMA sources, 9 May also featured larger volumes. Dividing total charge by the volume for each stroke gives a rough estimate of the density of charge neutralized by each flash: 1.0 C km^{-3} for 9 May versus 1.8 C km^{-3} for 20 June were the median values. Since there is no consensus on what percentage of charge in a volume is depleted by lightning flashes, for these density estimates 100% of the charge in the flash volume was assumed to have been depleted.

[30] These estimates are undoubtedly very rough and are only meant for relative comparison between the two storms in question, 9 May and 20 June. Indeed, the flash-volume methodology in this study likely provided smaller estimates for flash volume (and thus higher estimates for charge density) than the methodologies of other studies [e.g., *Lyons et al.*, 2008]. However, the estimated charge density values are of the same order of those measured by balloon soundings [e.g., *Marshall and Rust*, 1993].

3.1.3. Sensitivity Studies

[31] Now, the median range to the LMA sources related to the 21 TLE parents from 20 June was 115 km from the LMA centroid, while all of the 9 May parents occurred within 100 km of the LMA [*Lang et al.*, 2010]. Therefore, since the number of LMA sources was strongly correlated to the volume discharged (Table 1; Spearman's rank correlation between these parameters was >0.98 for either day), it is important to rule out LMA source detection efficiency differences as the main driver of the observed differences in volume discharged and charge density.

[32] Source rates from the LMA were computed as a function of distance for the same 0500–0510 UTC period on 20 June analyzed by *Lang et al.* [2010, Appendix]. As discussed by *Lang et al.* [2010], during this time the convective line of the storm was aligned nearly east-west right through the center of the LMA, making this an ideal time to examine how source rates fell off with distance. These rates were compared to mean reflectivity structure from the

Table 2. Median Values for 21 TLE-Parent Discharges, as Well as 9 High-iΔM_Q (>300 C km) Discharges That Did Not Produce Detectable TLEs, on 20 June 2007[a]

	TLE	No TLE	>20% Difference?
iΔM_Q (C km)	405.0	494.0	Yes
$Z_{i\Delta M_Q}$ (km AGL)	7.5	7.8	No
$Q_{i\Delta M_Q}$ (C)	58.2	66.3	No
CC duration (ms)	62	49	Yes
CC amplitude (kA km)	28.4	17.0	Yes
CC ΔM_Q (C km)	1440.0	888.0	Yes
Z_{CC} (km AGL)	8.0	7.7	No
Q_{CC} (C)	178.5	112.7	Yes
Total ΔM_Q (C km)	1812.0	1391.0	Yes
Z_{total} (km AGL)	8.0	7.7	No
Q_{total} (C)	264.9	184.2	Yes
Total sources	153	169	No
Volume discharged (km^3)	146	142	No
Density of charge neutralized (C km^3)	1.8	1.8	No

[a]Domain of calculations is limited by 5 ms prior to each TLE-parent CG stroke through the end of detectable continuing current.

0503 UTC volume of the three-dimensional radar mosaics discussed by *Lang et al.* [2010]. This analysis was qualitatively similar to that performed by *Ely et al.* [2008] to examine the detection efficiency of another VHF mapping system. Based on this analysis, it was determined that LMA source rates closely follow variations in radar structure out to at least 120 km. After this distance, LMA detection efficiency reductions may impact results.

[33] Twelve of the 21 TLE parents on 20 June were within 120 km of the Oklahoma LMA. Recalculating 20 June statistics for just these 12 discharges did not change results. Medians for total sources and volume discharged were unchanged from the numbers in Table 1 (even means changed less than 3% for each), while median density of charge neutralized actually increased to 2.0 C km^{-3}. Meanwhile, the differences in these parameters compared to 9 May remained statistically significant at greater than 95% confidence.

[34] Another way to estimate the effect of detection efficiency on results was to compare source rates during the TLE-parent strokes for each storm, which are presented in the last line of Table 1. While the median rate for 9 May was about 20% higher than for 20 June, the difference was not statistically significant. Moreover, this difference does not explain the more than double the number of sources per TLE parent on 9 May.

[35] Based on all these results, it is reasonable to attribute the bulk of the observed differences in terms of LMA source numbers, volume discharged, and density of charge neutralized to the fact that 9 May TLE parents had significantly longer CC durations, and significantly lower CC magnitudes, compared to 20 June.

3.2. The 20 June 2007 TLE Parents Versus Energetic Non-TLE Strokes

[36] Total charge moment change and VHF lightning mapper data were analyzed for 9 discharges during the 20 June storm that had iΔM_Q > 300 C km but did not produce an observed TLE. This was too few to produce results that were statistically significant at a very high confidence level (e.g., 95%), but it was worthwhile to examine differences in the characteristics of these discharges relative to the 21 TLE-parent +CGs from 20 June, in order to test hypotheses to explain why some energetic discharges do not produce TLEs (Table 2).

[37] Major differences in stroke parameters are defined arbitrarily as those where non-TLE discharges differ in excess of 20% from TLE parents. Perhaps the most fruitful future research on this issue should focus on those parameters. The first one of these in Table 2 is iΔM_Q itself. However, given the 300-C-km criterion for defining an energetic non-TLE +CG, whereas no such criterion existed for TLE parents, this result was unsurprising. Interestingly, however, the large difference did not extend to impulse charge.

[38] Indeed, the largest differences were seen in the continuing current estimates between the two types of discharges. Continuing-current duration, amplitude, ΔM_Q, and charge all were greater in the TLE parents, and this led to their overall advantage in terms of total ΔM_Q as well as total charge neutralized. There was very little difference in the median volume discharged during the entire stroke, or in the estimated density of neutralized charge. Median distance to the non-TLE discharges was just under 105 km, only 10 km less than for TLE parents. Thus, LMA distance was not an important factor in the observed differences.

[39] The lack of a large difference in median charge density is curious, given the smaller Q_{total} for non-TLE strokes yet the similar volumes discharged. As it turns out, there was a large difference in the means for this parameter: 2.8 C km^{-3} for TLE producers versus 2.1 C km^{-3} for non-TLE producers. Standard deviations for this estimate were similarly large: 2.5 C km^{-3} and 1.3 C km^{-3}, respectively. This is definitely one parameter that would benefit from having more samples, but it is possible that non-TLE strokes neutralized smaller charge densities, on average.

[40] Several studies have examined the possibility that prior lightning discharges may pre-condition the ionosphere by affecting electron densities, and thereby ionospheric conductivity, via lightning-driven electromagnetic pulse (EMP) [*Taranenko et al.*, 1993; *Rodger et al.*, 2001; *Lay et al.*, 2010]. According to these studies, it may take several minutes for these electron-density changes to relax, and the EMP-driven effects can occur over lateral distances on the order a few hundred km. Such processes therefore could impact the probability that a particular CG would initiate a TLE.

[41] Based on this, the behavior of NLDN-detected CGs were examined for 10 min prior to, and within 250 km range of, each of the 21 TLE-parent CGs, as well as the 9 non-parents. For this analysis +CGs were included only if their peak current exceeded 10 kA, following *Lang et al.* [2010]. TLE parents had in the median 5733 -CGs and 322 +CGs prior to their occurrence, while non-TLE +CGs had only 4785 -CGs and 241 +CGs. These differences met or exceeded the 20% difference threshold used in Table 2. However, EMP effects on the ionosphere are normally driven by the highest peak current strokes [*Rodger et al.*, 2001], so for only strokes with 50 kA or more of peak current, the corresponding medians were 88 -CGs and 23 +CGs for TLE parents versus 53 -CGs and 21 +CGs for non-TLE strokes. The -CG and all-CG numbers still exceeded 20% difference in this case. However, sensitivity studies that reduced the distance and

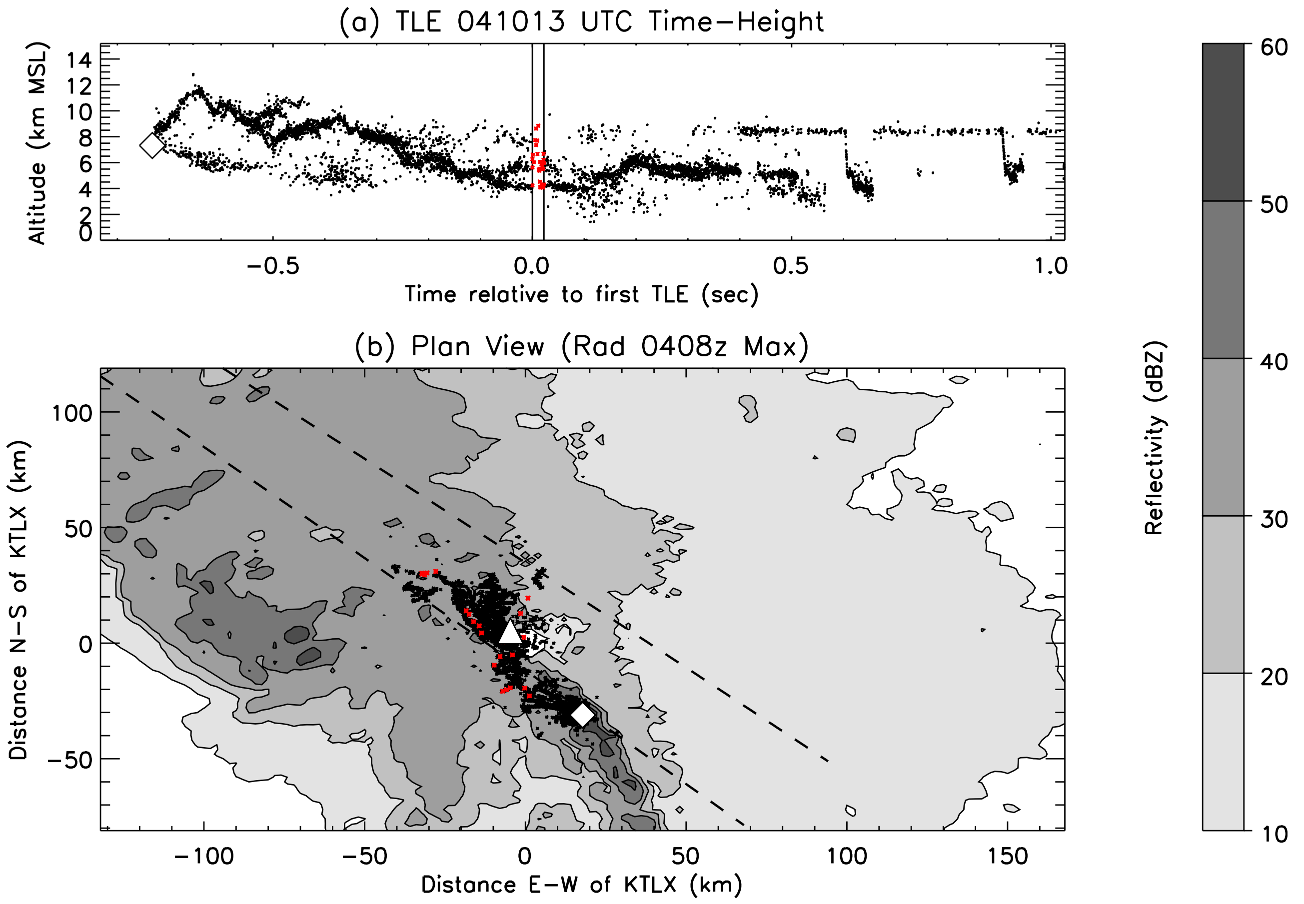

Figure 1. (a) Time-height plot of VHF source locations associated with a TLE-parent flash that occurred near 041013 UTC on 9 May 2007. Shown are the initiation height (diamond) and source locations during the flash (dots). The window of time during the TLE is indicated by the vertical lines and the red dots. (b) Plan view of the flash showing composite radar reflectivity (shaded contours), source locations (dots), TLE interval sources (red dots), initiation location (diamond), and TLE-parent +CG (triangle). The dashed lines indicate the azimuthal swath of the TLE observed on video from Yucca Ridge Field Station.

time thresholds tended to mute the differences between TLE-parent and non-TLE strokes, and using higher peak current thresholds also muted these differences, or made the sample sizes too small to be useful.

3.3. Azimuthal Sizes of TLEs

[42] Since multiple video camera observations of TLEs and thus triangulation of their locations were not available, the next best thing was to compare relationships between parent flash structure and the azimuthal spread of the TLEs from Yucca Ridge. Given left and right azimuth limits from a known location (Yucca Ridge Field Station), the spherical law of cosines was used to derive the horizontal swath in the vicinity of the Oklahoma LMA encompassing each observed TLE. Examples of how this compares to the locations of VHF sources are shown in Figures 1 (9 May TLE parent) and 2 (20 June parent). In these two cases, the azimuthal swath of the TLE contained the majority of all VHF sources in the entire parent flash (i.e., including all sources before, during, and after the TLE), as well as the vast majority of all VHF sources during the TLE itself.

[43] Extending this analysis to 45 analyzed TLEs from both days resulted in Table 3, which shows median fractions of VHF sources contained within the TLE azimuthal swaths for the two storms in this study. The median fraction of entire parent flashes within TLE swaths is over 70% for the two storms, and over 90% when considering only sources during the TLE. The flashes in Figures 1 and 2 closely match the median fractions for their respective days, and thus can be considered good representative examples. Overall, these results provide good evidence that, at least in the single dimension of azimuth, TLEs in these storms closely matched the locations of the in-cloud components of their parent flashes.

[44] Relationships between the widths of TLE azimuthal swaths and various parent-lightning characteristics are shown in Figure 3. In Figure 3a the TLE swaths are compared to the

Table 3. Median Fractions of VHF Sources Contained Within the Azimuthal Swath of TLEs Observed on Video From Yucca Ridge Field Station

	All Sources in Flash	Sources During TLE Only
9 May (23 TLEs)	78.6%	98.1%
20 June (22 TLEs)	71.3%	91.7%

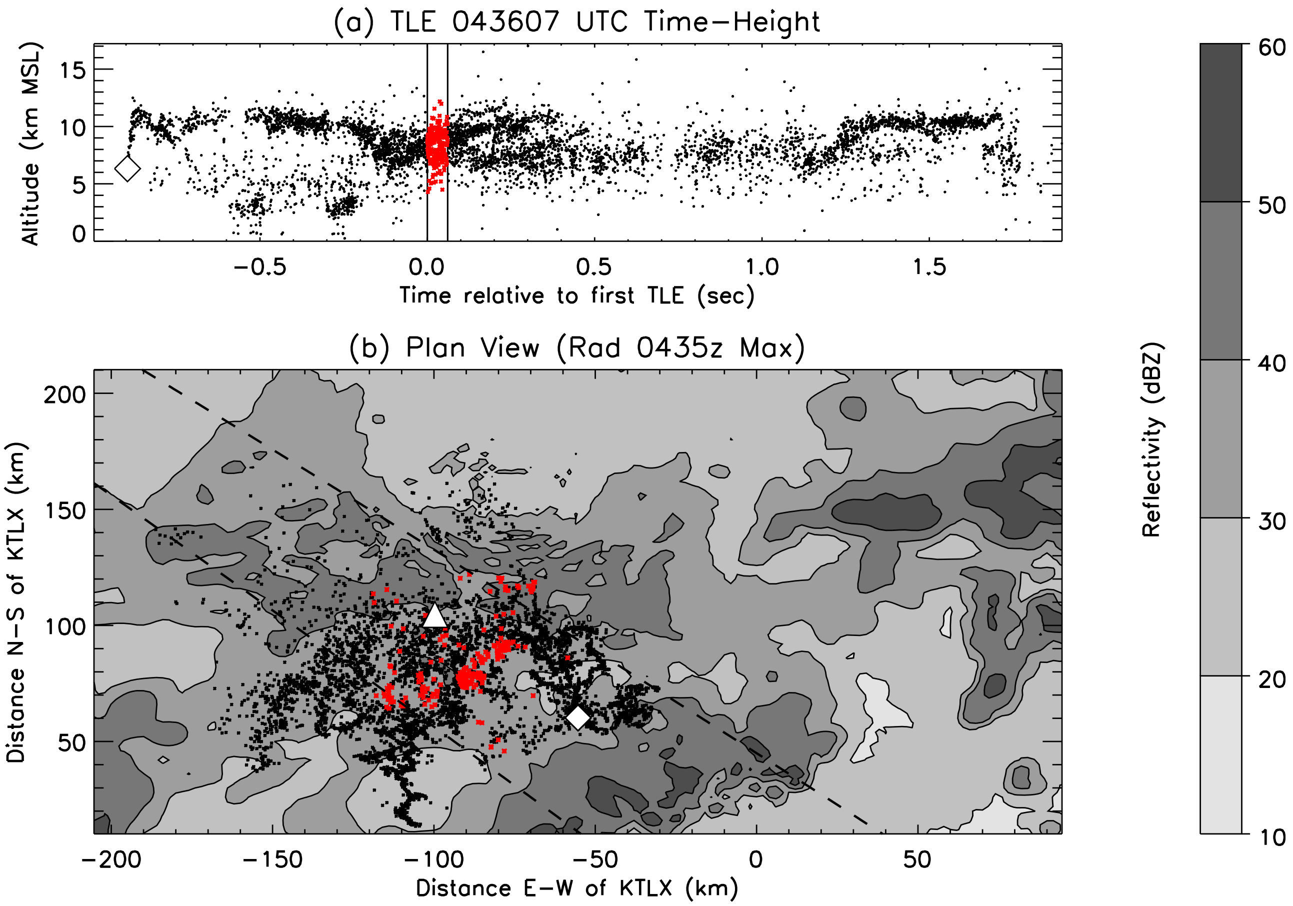

Figure 2. Same as Figure 1 but for a TLE-parent flash around 043607 UTC on 20 June 2007.

azimuthal swath (relative to Yucca Ridge) mapped out by all VHF sources in the parent flash. Essentially, the spherical law of cosines was used to determine the azimuth of every VHF source relative to Yucca Ridge, with the difference between the right and left limits defined as Δ. This comparison was repeated for the Δ of sources just during the TLE (Figure 3b) as well as the standard deviations (σ) of all source azimuths (Figure 3c) and sources only during the TLE (not shown). In all cases, TLE azimuthal swath was positively correlated (Spearman's rank correlation, r) with both Δ and σ, whether for the entire flash or just during the TLE. These correlations, while weak, were statistically significant at better than 95% confidence (Figures 3a–3c). The weakest correlation was for σ of sources just during the TLE ($r = 0.34$, not shown), though this was statistically significant as well. The fact that all of these various measures of flash extent were positively correlated with TLE extent is evidence that parent-flash sizes may have influenced the horizontal extent of their TLEs.

[45] TLE swaths also were compared against 41 of the 45 TLEs that were included in the total ΔM_Q analysis (Figure 3d). A statistically significant positive correlation ($r = 0.43$) was found between total ΔM_Q of the parent stroke and TLE swath, suggesting that total ΔM_Q may also have influenced TLE size in this one dimension. Total charge moment change was not significantly correlated with the azimuthal spread of VHF sources, except for Δ of all parent flash sources ($r = 0.39$).

[46] For all of these analyses, both the right and left azimuth limits of the TLE estimated from Yucca Ridge video were widened by 0.5°. This was done for two reasons. First, the uncertainty in these estimates was about 0.5° (section 2.1). Second, one of the TLEs (around 032638 UTC on 20 June) was extremely narrow, with its right and left azimuths both measured as 126.5°. Thus, the azimuth limits needed to be extended to provide a finite width. The basic results were not sensitive to the choice of this constant, however. For example, widening right and left TLE limits by only 0.1° caused the median fractions for all 45 TLEs to be changed to 57.1% (all sources) and 82.1% (sources during TLE). Thus, the basic conclusion stands that the majority of all VHF sources from a parent flash, as well as the vast majority of VHF sources during the TLE, were contained in the azimuthal swath of the TLE itself. The choice of azimuthal widening did not affect correlations (Figure 3) since this was a constant added to all TLEs.

4. Discussion and Conclusions

4.1. TLE-Parent Discharges on 9 May Versus 20 June

[47] Results from the comparison of 9 May and 20 June 2007 TLE-parent discharges suggest some interesting dif-

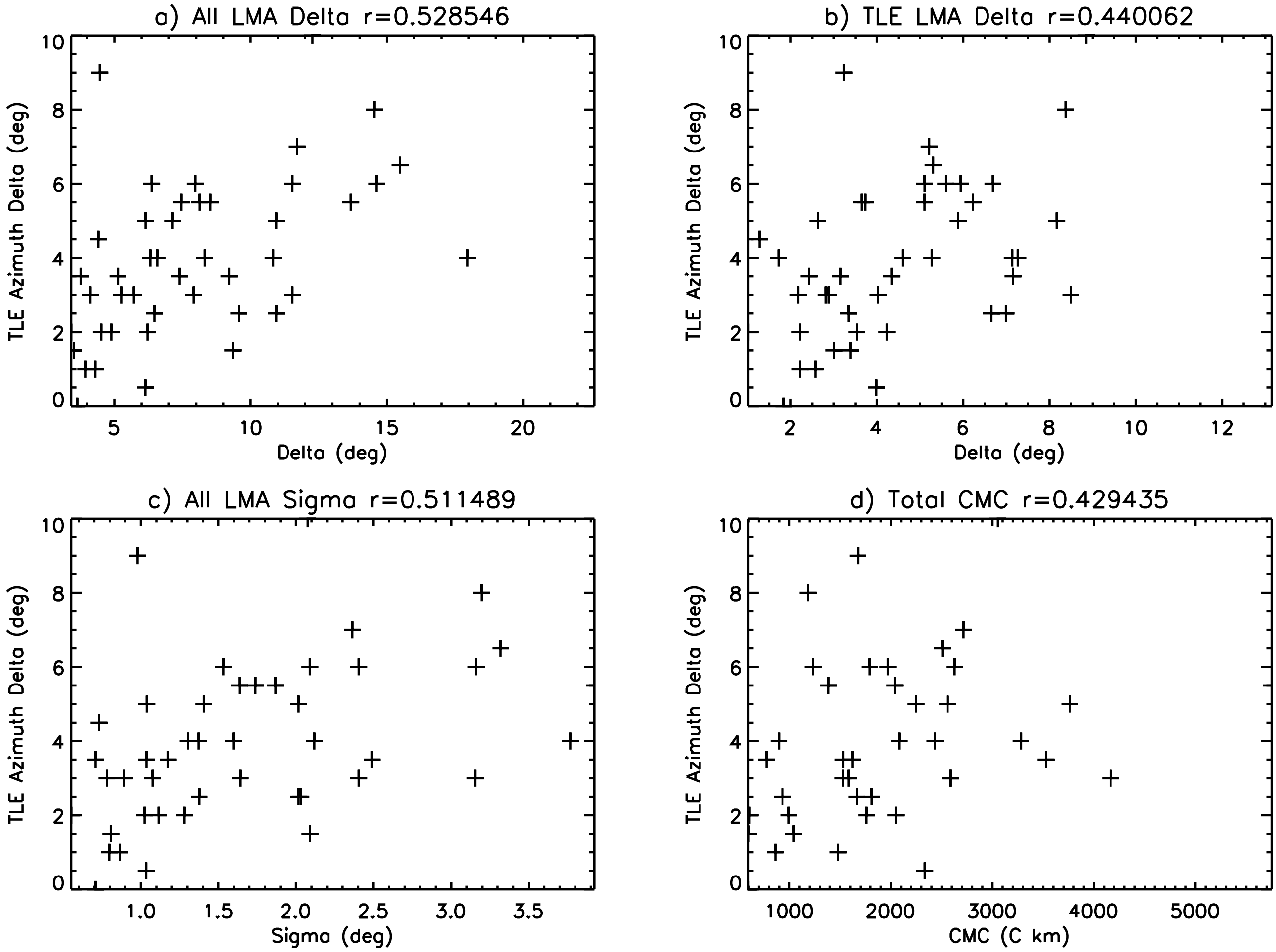

Figure 3. (a) Azimuthal width of VHF sources for 45 TLE-parent flashes on 9 May and 20 June 2007 (Δ), versus width of the azimuthal swath of TLEs observed on video, all relative to Yucca Ridge Field Station. (b) Same as Figure 3a but for VHF sources only during the observed TLEs. (c) Same as Figure 3a but for the standard deviation of azimuthal widths for all VHF sources during the parent flashes (σ). (d) Same as Figure 3a but for total ΔM_Q estimates from 41 TLE parents during 9 May and 20 June. Spearman's rank correlation coefficients (*r*) are all listed, and are all significant at better than 95% confidence.

ferences between the two storms' lightning characteristics. The 20 June strokes were more impulsive, with larger $i\Delta M_Q$ and $Q_{i\Delta M_Q}$, coupled with shorter yet more intense continuing current. This meant smaller values for Q_{CC} and Q_{total}, although these differences were not statistically significant. However, due to the higher altitude of the main stratiform positive charge layer in the 20 June storm (at least in terms of lightning activity [*Lang et al.*, 2010]), total ΔM_Q values were nearly identical to those on 9 May, about 1800 C km.

[48] Why were the TLE parents on 20 June more impulsive? One possibility is the larger estimated density of charge neutralized on that day. Access to greater charge densities may have allowed TLE parents on 20 June to produce large ΔM_Q values more quickly than 9 May.

[49] *Lang et al.* [2010] attributed the flash altitude differences between 9 May and 20 June to their different mesoscale structures. It is reasonable also to attribute the estimated differences in charge density to this as well. The 20 June storm was far larger and much more intense than 9 May, based on their radar-observed structures. In addition, the 20 June storm's electrical activity was significantly larger than 9 May, in terms of both VHF source and CG stroke rates [*Lang et al.*, 2010]. In light of this evidence for a stronger electrical generator in 20 June, it is not surprising to find that the estimated density of charge tapped by TLE parents also was greater.

4.2. TLE-Parent Versus Energetic Non-TLE Discharges

[50] Although some previous studies [e.g., *Cummer and Lyons*, 2005] have analyzed the differences between TLE-producing and non-TLE-producing discharges in the same storm, none have accounted for continuing current charge transfer. Due to the lack of samples in the present study, only very preliminary conclusions can be drawn on systematic differences in characteristics between TLE parents and energetic discharges that do not produce TLEs. Indeed, the best that can be done is to develop specific hypotheses for further testing. It appears, somewhat unsurprisingly, that the key difference may lie in the continuing current. Non-TLE dis-

charges had smaller and shorter continuing currents than TLE parents, and this led to less total charge and less total ΔM_Q for the former category of lightning. Though the evidence was decidedly mixed, it is possible that non-TLE strokes tended to neutralize smaller charge densities than TLE parents. One hypothesis, developed from these results, is that non-TLE discharges are those that tend to encounter regions of reduced charge density compared to TLE-parent +CGs, and this tends to limit the continuing current, which is the main contributor to total ΔM_Q.

[51] While this is supportive of the present consensus that charge moment change is a key determinant in the production of TLEs, especially sprites, the non-TLE strokes still had large ΔM_Q values, nearly 1400 C km on average. Indeed, many sprite-parent +CGs have featured ΔM_Q values of this magnitude, or even less (see *Pasko* [2010] for a review). Five of the 21 analyzed TLE parents on 20 June, as well as 7 of the 20 TLE parents on 9 May, also had total ΔM_Q values less than 1400 C km. Thus, the results also reinforce the general consensus that ΔM_Q is at best an imperfect statistical predictor of sprites. While large ΔM_Q values tend to be associated with a greater propensity to produce a sprite, there likely would be a non-negligible false alarm rate with any sprite predictor based solely on total ΔM_Q.

[52] Understanding why this is so is a key area of research in the TLE community. Recent modeling [e.g., *Hiraki and Fukunishi*, 2006; *Asano et al.*, 2008, 2009b] suggests that the time variation of the ΔM_Q, along with parent-lightning current moment, may play an important role in determining sprite potential. Measurements [*Li et al.*, 2008; *Gamerota et al.*, 2011] confirm that variations in the continuing current, such as M-components, combined with ionospheric nonlinearities contribute critically to delayed sprite production. Thus, an energetic lightning discharge that did not quickly produce a sprite would have its chances further hampered if its continuing current was relatively low or lacked M-components in the continuing current, thus reducing the chance of a delayed sprite as well. The results of this study are limited by sample size, but are supportive of this interpretation.

[53] It is possible that some or all of the non-TLE discharges in this study did in fact produce a TLE, but one that was too dim to be discernible using the Yucca Ridge camera. For example, it is well known that sprites can vary greatly in brightness, and that this may be related to the strength of the mesospheric electric field [*Stenbaek-Nielsen et al.*, 2007; *Liu et al.*, 2009]. However, even if this were the case, this study's results remain relevant as this possibility assumes a quantitative difference in TLE luminosity, which may be relatable to the observed differences in continuing current and ΔM_Q. In addition, variability in the conductivity of the mesosphere may partly control the dependence of sprite production on ΔM_Q, although this should not vary considerably during a single case like 20 June 2007 [*Cummer and Lyons*, 2005].

[54] However, the role of pre-conditioning the ionosphere by previous CGs was nevertheless examined, and it was the case that CGs were more prevalent prior to TLE parents compared to non-TLE strokes. Thus, if EMP from the prior CGs made the ionosphere more receptive to TLE occurrence, then better pre-conditioning may have played a role in assisting the TLE-parent strokes. However, these differences between categories tended to be much smaller when tighter distance, time, and peak current criteria were applied. This meant that there was very little difference between TLE/non-TLE categories when considering only very highest peak current CGs, closest in time and space to one of the 30 TLE or non-TLE strokes examined in this study. Therefore, the results were mixed, but further analysis of this type appears warranted.

[55] Although our results indicate continuing current is an important statistical difference between the TLE-producing and energetic non-TLE-producing discharges, continuing current cannot play a role in producing prompt sprites that follow closely after the return stroke. Limited statistics suggest that roughly 50% of sprites occur within 10 ms of the lightning return stroke [*Li et al.*, 2008]. The observed robust connection between sprites and continuing current suggests that high subsequent continuing current may be linked to other charge transfer characteristics early in the flash, and probably merits further exploration.

4.3. Azimuthal Sizes of TLEs

[56] The video-derived azimuthal swaths of 45 TLEs were compared to the LMA-mapped horizontal structures of their parent flashes. While the results were limited by the one-dimensional nature of the analysis, the majority of VHF sources associated with a TLE-parent flash, as well as the vast majority of sources during the TLE itself, were contained within the azimuthal swath of the TLE. This suggests that TLEs tend to occur over the location of the neutralization of in-cloud charge, a conclusion supported by other research [*Yashunin et al.*, 2007; *Asano et al.*, 2009a; *van der Velde et al.*, 2010].

[57] Moreover, the horizontal extent of the parent lightning was weakly correlated with the horizontal extent of the TLE itself. Total ΔM_Q also was positively correlated with TLE swath size. These observations are consistent with the theory that sprites are caused by the neutralization of horizontally extensive stratiform charge layers [e.g., *Williams and Yair*, 2006]. Under this theory, as a larger area of stratiform charge is neutralized, a larger area of the upper atmosphere becomes stressed, which should tend to increase the size or quantity of TLEs that are associated with a particular +CG. Similarly, assuming a constant charge density in a layer at a given altitude, the main way to increase the charge moment change would be to discharge a larger area. This also would lead to total ΔM_Q being positively correlated with TLE horizontal extent, as observed.

4.4. Further Research

[58] The best way to improve upon the current study would be to increase its sample size. What is required is high-speed camera observations of more TLE-parent CGs within precipitating systems within range of lightning mapping systems, with correlated multiple high-speed video TLE observations allowing triangulation of their location and size, as well as resolving its temporal evolution. In addition, the TLE community needs to continue refining the charge moment change model for sprite production, in order to verify and explain any large ΔM_Q discharges that do not produce sprites, and to better understand the role of continuing current in sprite production. Most of this study's authors are involved in a planned 4-year program, called Physical Origins of Coupling to the upper Atmosphere from Lightning (PhOCAL) and

funded by the Defense Advanced Research Projects Agency (DARPA), which among other things seeks to address these two areas of research. Thus, further work on these problems is in progress, with results hopefully presented in future papers.

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