P1.12 CHARACTERISTICS OF CLOUD-TO-GROUND LIGHTNING IN WARM-SEASON THUNDERSTORMS

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1. INTRODUCTION

Five measurement campaigns have been conducted in southern Arizona (AZ), northern Texas and southern Oklahoma (TX-OK), and in the Great Plains (GP) of eastern Colorado, western Kansas and western Nebraska in order to evaluate the performance of the U.S. National Lightning Detection Network™ (NLDN) after an upgrade in 2002-2003 [Cramer et al., 2004; Kehoe and Krider, 2004; Cummins et al., 2006; Biagi et al., 2007]. This dataset has also been used to quantify how the characteristics of confirmed cloud-to-ground (CG) flashes vary with geographic region. In each campaign, lightning was recorded using digital video cameras that were synchronized to GPS time (with 16.7 msec resolution, see Parker and Krider (2003) and Biagi et al. (2007)), and the results were compared with NLDN reports that provided the time, polarity, location, and an estimate of the peak current (I_p) for each stroke [Cummins et al., 1998].

In the GP, radar imagery was combined with NLDN reports to show when and where in the storm development the positive and negative flashes occurred, and to determine if the flashes we recorded were biased by the sampling. In this paper, we will discuss the parameters of positive and negative CG flashes in all three regions and summarize the radar results in the GP.

2. RESULTS

2.1 *Negative strokes*

The values of I_p for negative strokes recorded on video varied considerably between different recording sessions in all geographic regions [Biagi et al., 2007]. Table 1 summarizes the mean and median values of I_p in AZ in 2003 and 2004, TX-OK in 2003 and 2004, and the GP of eastern Colorado, western Kansas and western Nebraska in 2005. Results are listed separately for first strokes, subsequent strokes (SS) that created a new ground contact, and subsequent strokes that remained in a pre-existing channel. Table 1 also shows the mean NLDN detection efficiency (DE) in each region for each type of stroke and the overall flash DE. Note that the flash DE is greater than 90% in all regions.

The distributions of I_p for negative first strokes are shown in Figure 1. Note in Table 1 that the median I_p for first strokes in TX-OK is 18% less than the median in AZ, and the median I_p in the GP is 13 % larger than in AZ. Given the large sample sizes, these differences are likely significant. The median I_p for subsequent strokes that produced a new ground contact also vary between regions, while the median I_p values for subsequent strokes that remain in a pre-existing channel are similar in all regions. The standard deviation of first strokes in TX-OK is much larger than in AZ and in the GP, primarily because TX-OK has greater fractions of both low and high values of $|I_p|$ (see Figure 1).

2.2 *Negative multiplicity and number of ground contacts per flash*

Values of video multiplicity are listed in Table 2. Note that when the $|I_p|$ of the first stroke is ≤ 10 kA, the multiplicity tends to be smaller than when the $|I_p|$ > 10 kA in all regions. The largest multiplicity (3.6) in Table 2 was in AZ. Because the time-resolution of the video camera was limited to 16.7 ms, we expect that all multiplicities in Table 2 actually underestimate the true values by about 11% [Biagi et al., 2007].

The percentage of negative CG flashes that produce a given number of ground contacts (GC) are summarized in Table 3. It should be noted that the fractions of flashes that produce a single ground contact, and the average number of ground contacts per negative CG flash, are similar in all regions.

2.3 *Positive Strokes*

An unexpectedly large number of positive CG flashes, relative to negative (204 positive flashes and 103 negative flashes) were recorded on video in the GP 2005 campaign, and the number and percentage of positive flashes varied considerably between recording

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	No. of Video Strokes	No. of NLDN Strokes	NLDN Flash DE (%)	NLDN Stroke DE (%)	Mean I_p (SD) (kA)	Median I_p (kA)
AZ 2003-2004						
First-strokes	1012	953	94	94	-19.7 (10.5)	-16.9
SS with NGC	444	355		80	-15.0 (11.2)	-15.4
SS in a PEC	1894	1247		67	-14.9 (8.3)	-12.7
TX-OK 2003-2004						
First strokes	318	273	92	86	-19.2 (17.8)	-13.8
SS with NGC	126	101		80	-15.6 (8.5)	-13.9
SS in a PEC	338	270		80	-13.9 (8.0)	-12
GP 2005*						
First-strokes	112	90	91	80	-23.2 (13.6)	-19.5
SS with NGC	61	50		82	-19.4 (8.6)	-17.6
SS in a PEC	130	100		77	-17.5 (11.3)	-13.7

*Flashes not reported by the NLDN were assumed to have a negative polarity if the flash occurred in a negative dominated storm or if the flash had multiple strokes. All other uncorrelated flashes were assumed to be positive.

Table 1. NLDN detection efficiency (DE) and the mean (and standard deviation, SD) and median values of Ip for negative first strokes, subsequent strokes (SS) that produced new ground contacts (NGC), and SS that remained in a pre-existing channel (PEC).

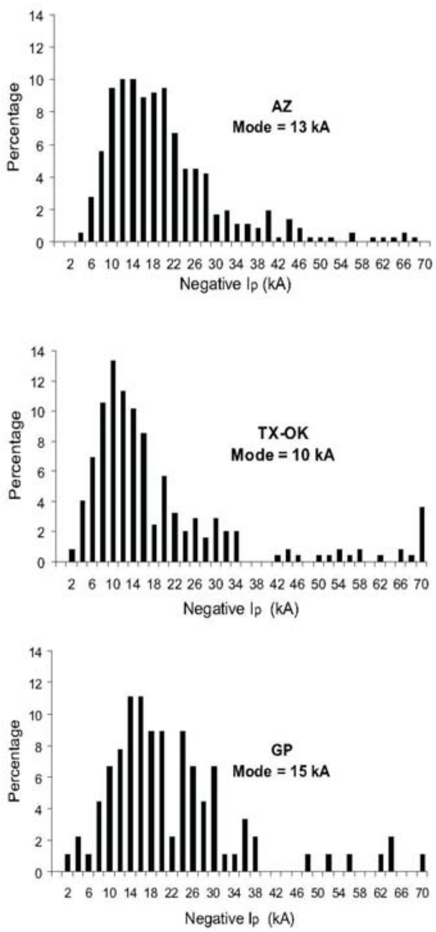

Figure 1. Distributions of negative Ip values for first strokes in AZ, TX-OK and the GP. Nine first strokes had $|I_p|$ ≤ 5 kA.

First Stroke Amplitude	No. of Flashes	% Single Stroke	Multiplicity Mean (SD)
AZ 2003-2004			
$\|I_p\| \leq$ 10 kA	83	45	2.4 (2.0)
$\|I_p\| >$ 10 kA	893	28	3.6 (2.7)
TX-OK 2003-2004			
$\|I_p\| \leq$ 10 kA	72	52	2.3 (2.1)
$\|I_p\| >$ 10 kA	238	32	2.7 (1.9)
GP 2005			
$\|I_p\| \leq$ 10 kA	8	75	1.6 (1.3)
$\|I_p\| >$ 10 kA	82	44	2.5 (1.9)

Table 2. The mean video multiplicity (and standard deviation) of negative flashes in AZ, TX-OK, and the GP for low and high |Ip|.

No. of GC	AZ (%)	TX-OK (%)	GP (%)
1	68.3	70.0	68.0
2	23.7	22.3	16.1
3	6.0	8.4	10.7
4	1.4	0	6.25
5	0.6	0.3	0
Mean GC per flash	1.42	1.40	1.56

Table 3. Percentage of negative flashes that produced the number of ground contacts (GC).

sessions, as described by Fleenor et al. (2008). Previous studies have shown that the GP region contains high fractions of both positive and negative lightning (Zajac and Rutledge, 2000; Orville and Huffines (2001)). Figure 2 shows the distributions of I_p for all positive strokes that were confirmed to be CG on video in the GP and TX-OK. (Only about 3% of all flashes recorded in the AZ campaigns were positive, and those are not included in Figure 2.)

In the GP, only 9 out of 204 (4.4%) of the positive flashes produced 2 strokes, and 4 of these produced a new ground contact on the second stroke.

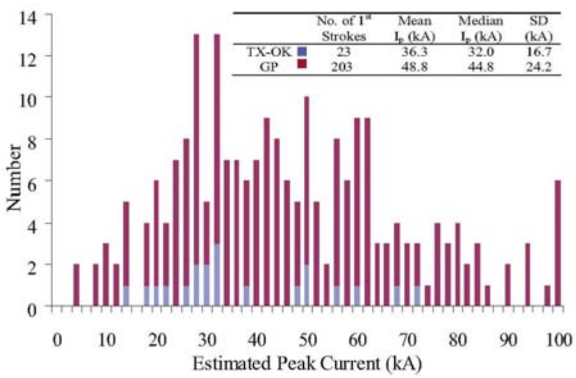

Figure 2. Distributions of positive Ip values for first strokes in the GP and TX-OK. Six first strokes had an $I_p \leq 10$ kA.

2.4 *Radar Analysis*

In order to determine if the CG strokes recorded on video were biased by the sampling or storm characteristics, the composite radar reflectivity and the NLDN data were analyzed further. The NLDN data in consecutive 15-minute intervals were overlaid on the reflectivity pattern so that each 15-minute interval was centered on the time of the radar scan. The storms recorded on video were grouped into two categories: single-cell thunderstorms and multiple-cell thunderstorms. For this study, a storm that appeared to be a single, isolated cell on radar for its entire life cycle was regarded as a single-cell thunderstorm. Any storm that did not meet this criterion on radar was regarded as a multiple-cell thunderstorm.

2.4.1 *Single-Cell Storms*

Nine of our recording sessions were of single-cell storms as seen on radar, and of these, 5 were dominated by negative CG strokes on video, and 4 were dominated by positive CG strokes on video. Figures 3 and 4 show a portion of the life-cycles of 2 single-cell storms; one on July 7, 2005 that was dominated by negative strokes (Figure 3), and one on July 4, 2005 that was dominated by positive strokes (Figure 4). Positive NLDN reports are indicated by a '+', and negative NLDN reports are indicated by a '-'. The location of the video camera location is indicated by a black star, the maximum azimuthal extent of the flashes recorded on video is shown by the black lines, and the NLDN reports that were recorded on video are circled in white. For these figures, the low-amplitude NLDN reports (e.g. negative strokes with an $|I_p| \leq 10$ kA and positive strokes with an $I_p \leq 20$ kA) were removed since many of these events in the GP are likely cloud pulses [Biagi et al., 2007; Fleenor et al. (2008)]. From these maps, it is clear that the dominant NLDN polarity recorded on video is associated with flashes occurring near the convective core, and all single-cell storms exhibited this pattern.

Prior studies have shown that a large fraction of positive flashes can occur during the mature and dissipating stages of thunderstorms (Fuquay, 1982; Seimon, 1993; MacGorman and Burgess, 1994; Carey and Rutledge, 1998; Lang et al, 2004), and that the dominant polarity can change as the storm evolves with time (Seimon, 1993; MacGorman and Burgess, 1994). Therefore, the dominant polarity of our sessions could be biased if the recording session covered only a portion of the storm life-cycle. In order to investigate this possibility, frequency histograms of the NLDN stroke reports, after filtering out all reports with a low-amplitude $|I_p|$, were plotted for all single-cell storms in our dataset starting one hour before the session started, and going to one hour after the session ended. The single-cell storms for the negative dominated sessions showed a clear tendency for negative strokes to dominate before, during (between the dotted lines), and after the video recording session, but only 1 out of 4 of the single-cell storms for sessions that were dominated by positive strokes on video showed a clear tendency for positive strokes to dominate for the entire the video recording session. The other 3 positive-dominated sessions had a period that was dominated by positive CG's, but this period was preceded by a period that was dominated by negative CG's. Figure 5 shows the 5-minute CG stroke rates of the large negative and positive NLDN reports before, during (between the dotted lines), and after the latter 3 sessions. A negative-dominated period occurred toward the beginning of these storms when the storms were less organized on radar, and this period was followed by a positive-dominated period that occurred when the composite reflectivity reached a maximum.

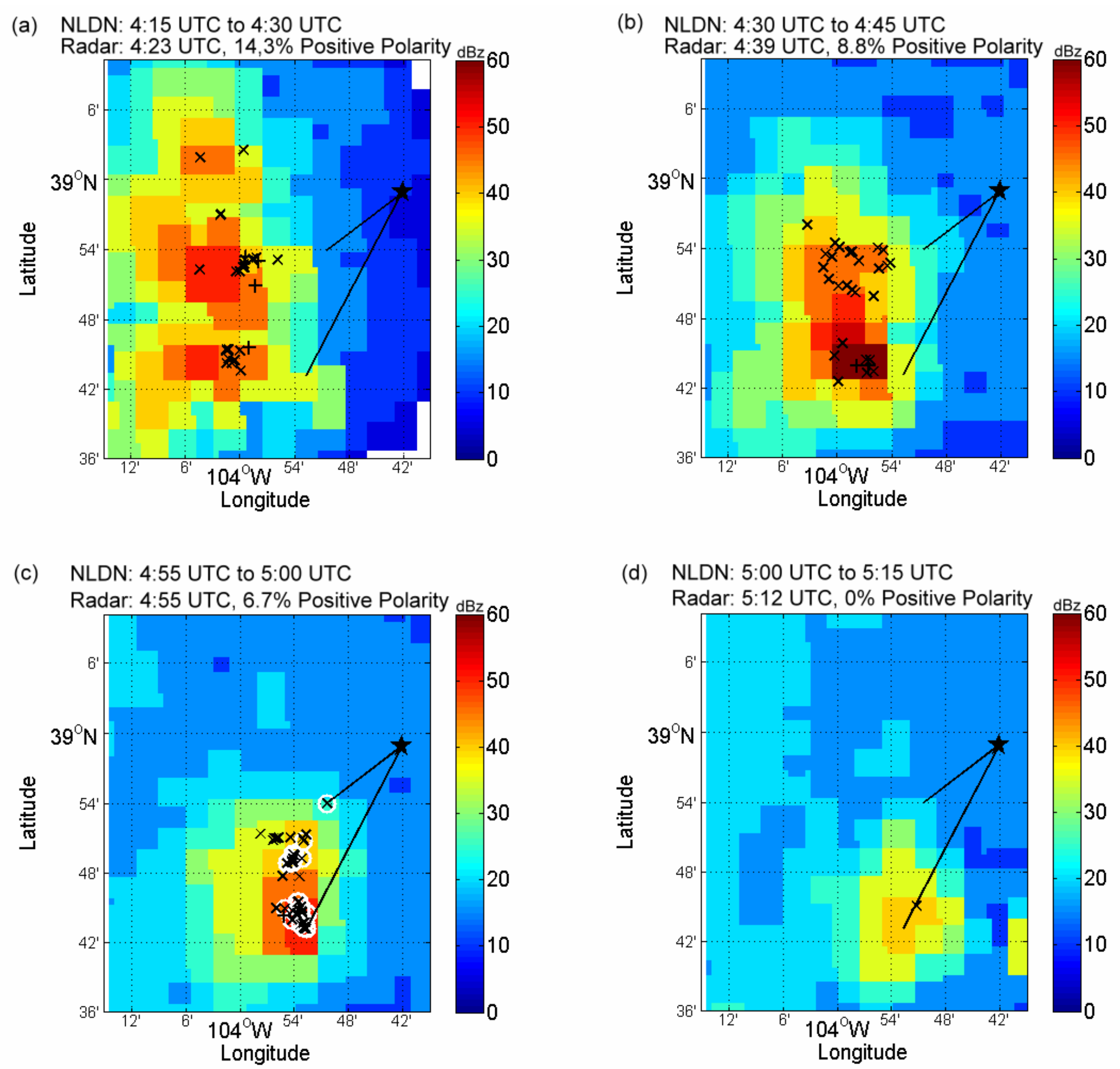

Figure 3. Composite reflectivity contours and the locations of NLDN stroke reports for a single-cell storm on July 7, 2005. The times of the radar scans are (a) 4:23 UTC, (b) 4:39 UTC, (c) 4:55 UTC, and (d) 5:12 UTC. The locations and polarities of NLDN stroke reports are shown with a '+' for positive strokes and an 'x' for negative strokes. Only negative NLDN reports with $|I_p|$ > 10 kA and positive NLDN reports with I_p > 20 kA are shown. The NLDN reports that were correlated with video strokes are circled in white, the camera location is indicated by a star, and the maximum azimuthal extent of the NLDN reports are shown by the solid lines.

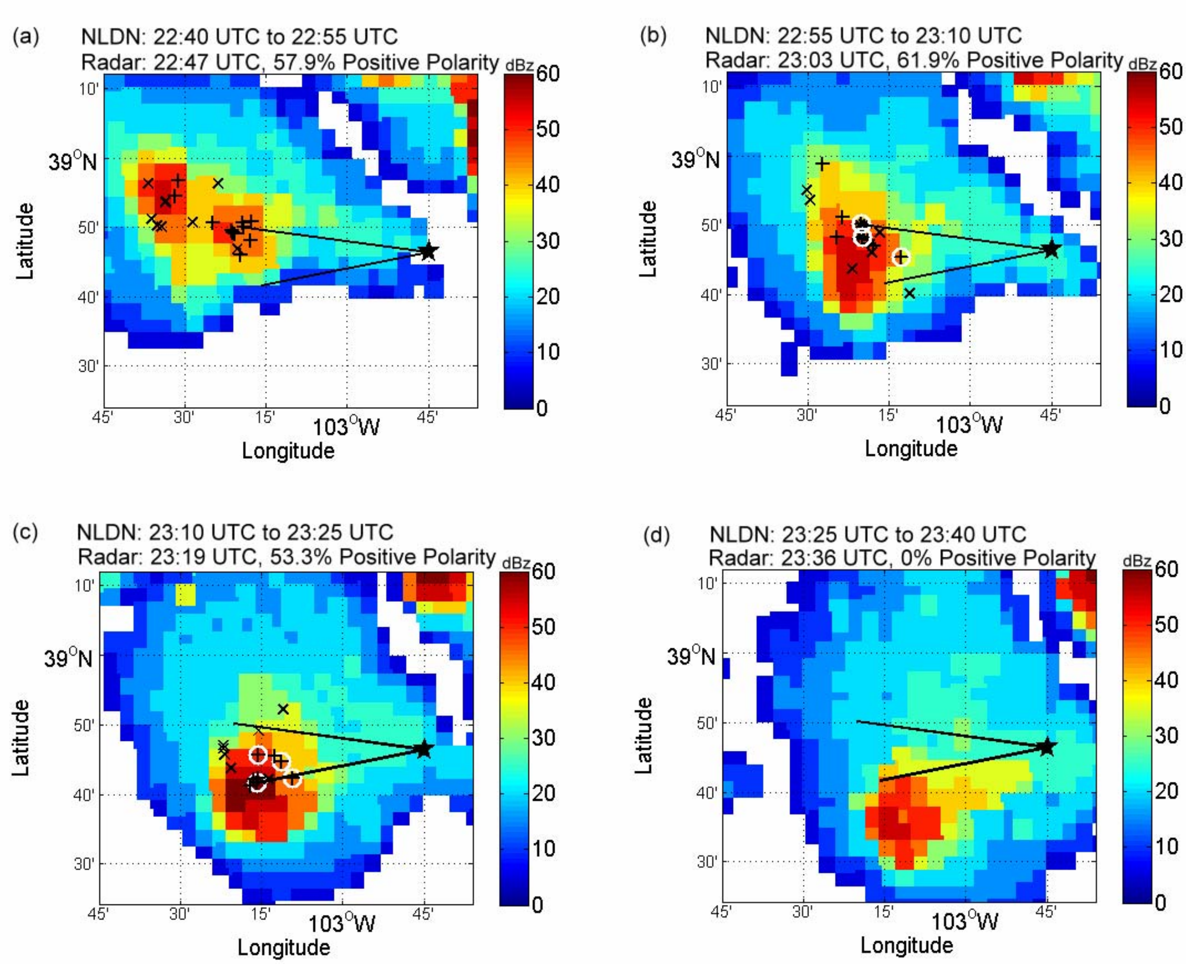

Figure 4. The same as Figure 11, except for July 4, 2005 and the times of the radar scans are (a) 22:47 UTC, (b) 23:03 UTC, (c) 23:19 UTC, and (d) 23:36 UTC.

2.4.2 *Multiple-cell Thunderstorms*

There were 8 video recording sessions of multiple-cell storms: 2 were dominated by negative strokes and 6 were dominated by positive strokes. A session was defined in terms of the recording interval at each camera location, and only 3 different multiple-cell storms were recorded during these 8 sessions. Figure 6 shows distributions of the large negative and positive NLDN stroke reports in 3 multiple-cell storm complexes. Here, the NLDN reports start one hour before the start of the first recording session and end one hour after the last recording session ended. The spatial domain for the NLDN reports covered the entire multiple-cell storm, and remained constant for the entire time period. Because of the large spatial domain, there were a few flashes that occurred in small storms that passed through the domain that were not part of the multiple-cell storm of interest. These NLDN reports are a very small fraction of the total. Note that the dominant polarity of the recording session does not always agree with the dominant polarity of the NLDN reports. This occurs because even though negative NLDN reports dominate the multiple-cell storms most of the time, there are still small regions within the larger storm complex that are dominated by positive strokes. For example, video session 5 recorded primarily negative polarity strokes and session 6 recorded primarily positive strokes. However the larger storm during both of these sessions was dominated by negative NLDN reports (see Figure 6b). Therefore, while our video sessions accurately represented the polarity of flashes occurring in the localized region of the camera, they did not accurately represent the dominant polarity of flashes in the larger storm.

Figures 7a and 7b show 15-minute periods of NLDN stroke locations and the associated (mid-period) composite radar reflectivity taken from successive 1 hour intervals during video recording sessions 5 and 6, respectively. In Figure 7a, it is clear that the eastern portion of the storm (i.e. near the camera location for session 5) is dominated by large, negative reports, but regions in the western portion of the storm have a much higher fraction of large, positive reports. For session 6

(Figure 7b), one of the positive regions of the storm is being recorded on video, and the negative-dominated portion of the storm recorded during session 5 has moved further to the east. Since we recorded just small regions of these large multiple-cell storms, we clearly tended to obtain lightning of only one polarity. Thus, in multiple-cell storms, our video recording sessions do not accurately represent all the CG strokes that occurred, but are representative of just the local region that was recorded on video.

3. DISCUSSION

The characteristics of negative and positive cloud-to-ground lightning were analyzed in 3 different regions: Southern Arizona; northern Texas and southern Oklahoma; and the Great Plains of eastern Colorado, western Kansas, and western Nebraska. As seen in Tables 1 & 2, there are significant differences in the inferred peak current distributions and mean stroke multiplicity between the 3 regions.

The median I_p for negative first strokes in all 3 regions is significantly lower than the values commonly found in the engineering literature (Rakov and Uman, Ch. 1), and the median I_p for positive first strokes is higher than the values commonly found in the engineering literature (Rakov and Uman, Ch. 1). Given that the NLDN misses some low-current strokes [Biagi et al., 2007], the actual medians of I_p will be lower than the values in Table 1 and Figure 1.

Spatial relationships between the radar reflectivity and lightning were determined for both single-cell storms and multiple-cell storms. For the single-cell storms, the dominant polarity during a video recording session was representative of the storm polarity during that session, but was not always representative of the dominant storm polarity before and/or after the recording session. During multiple-cell storms, we were only able to record small portions of the larger storms, and therefore, tended to only record one polarity. In both cases, the positive CG lightning recorded on video was occurring within, or near, a convective core on radar.

Single-cell storms tended to produce one polarity of CG strokes at a time. In 3 of the 4 single-cell storms that contained a period dominated by positive polarity, that polarity was preceded by a period of negative polarity (see Figure 13). The positive dominated periods occurred during the time of maximum composite reflectivity on radar. Seimon (1993) and MacGorman and Burgess (1994) found 11 storms where the dominant polarity switched from positive to negative sometime during the mature stage. Although these storms did not produce a long period of negative-dominated strokes before the period dominated by positive strokes (as in our study), several of the storms began with a period of infrequent negative CG strokes. These negative CG strokes occurred when the storms were weaker and less organized.

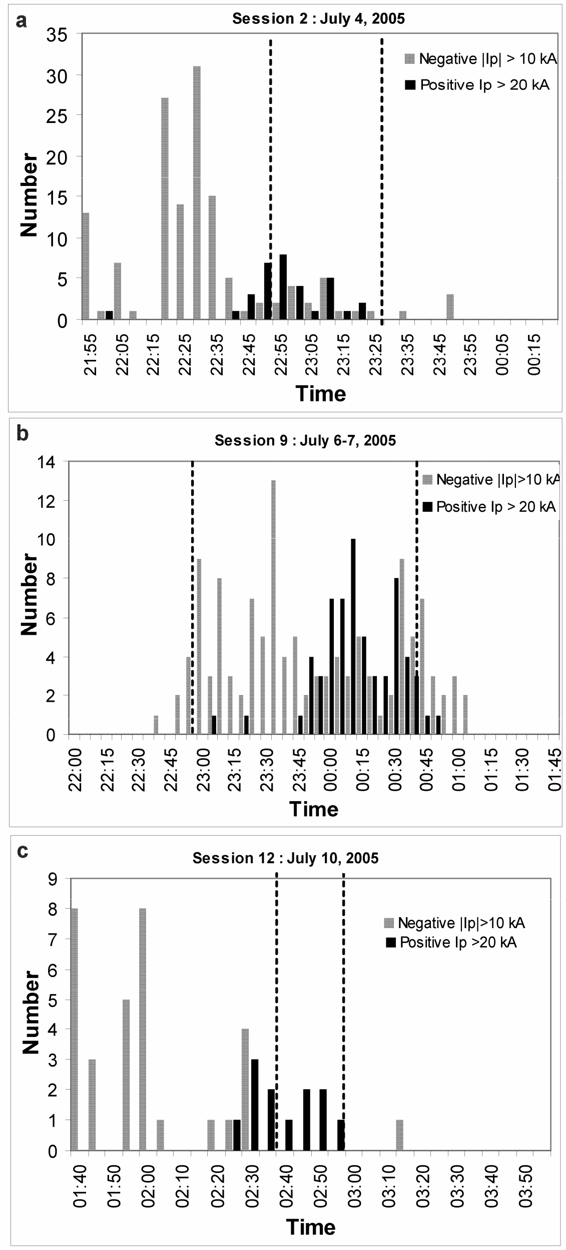

Figure 5. Distribution of the occurrence and polarity of all NLDN stroke reports in three positive-dominated sessions during single-cell storms starting one hour before the recording session began to one hour after the recording session ended for a) session 2, b) session 9, and c) session 12. Note: Only negative NLDN reports with $|I_p|$ > 10 kA and positive reports with I_p > 20 kA have been included in these plots.

Multiple-cell storms tended to be dominated by negative strokes most of the time, but had small regions within the larger storm complex that were dominated by positive strokes. The broad spatial patterns of negative and positive strokes in multiple-cell storms were similar to the patterns described by Stolzenburg (1990).

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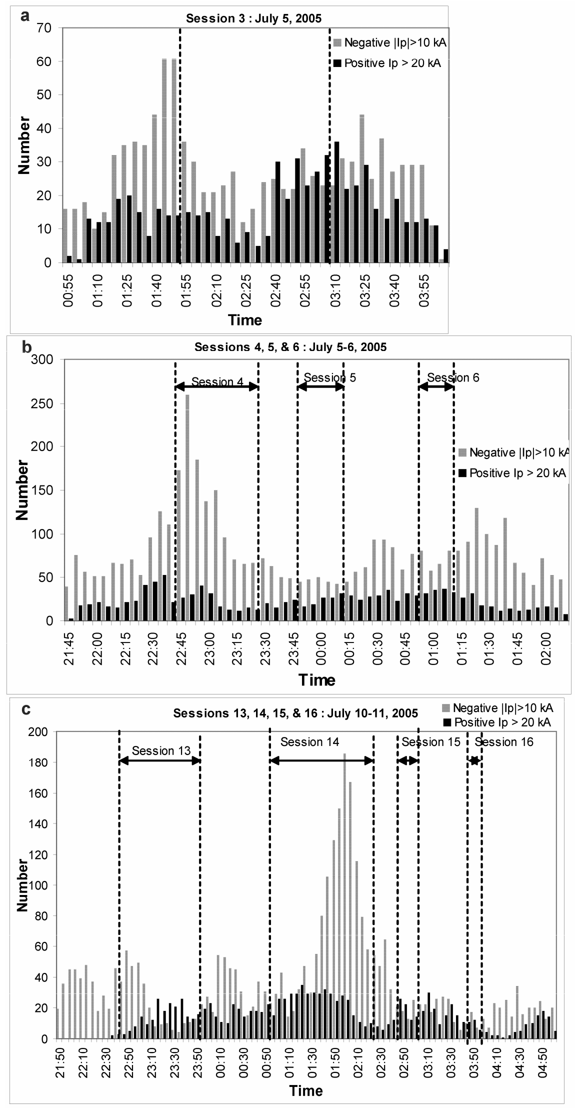

Figure 6. Distributions of the occurrence and polarity of all NLDN stroke reports in three multiple-cell storms from one hour before the recording sessions started to one hour after the recording sessions ended for a) session 3, b) sessions 4, 5, and 6,, and c) session 13, 14, 15, and 16. Only negative reports with $|I_p|$ > 10 kA and positive reports with an I_p > 20 kA have been included in these plots.

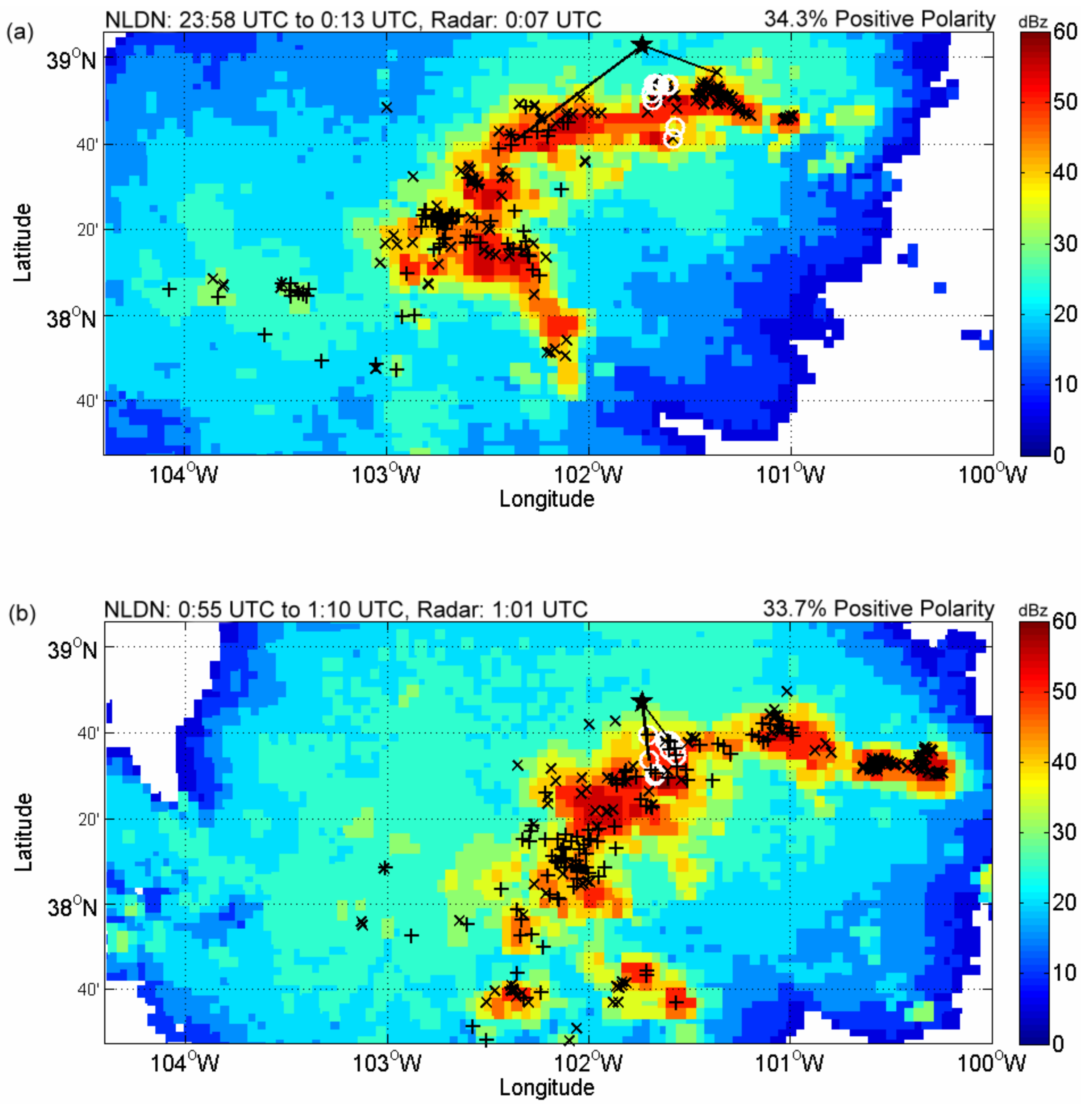

Figure 7. The same as Figure 3, except for a multiple-cell thunderstorm on July 5-6, 2005 for (a) session 5 at 0:07 UTC, and (b) session 6 at 1:01 UTC.

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