Large Peak Current Cloud-to-Ground Lightning Flashes during the Summer Months in the Contiguous United States

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(Manuscript received 7 July 1997, in final form 10 November 1997)

ABSTRACT

A clear association between large peak current cloud-to-ground lightning flashes of positive polarity and sprites and elves in the stratosphere and mesosphere has been previously demonstrated. This paper reports on the first climatology of large peak current cloud-to-ground (LPCCG) lightning flashes compiled from the U.S. National Lightning Detection Network. Analysis of almost 60 million CG flashes from 14 summer months (1991–95) reveals distinct geographic differences in the distribution of positive and negative polarity LPCCGs, arbitrarily defined as flashes with peak currents ≥75 kA. Large peak current positive CGs (LPC+CGs) are concentrated in the High Plains and upper Midwest, the region in which a large majority of optical sprite and elves observations have been obtained. By contrast, large peak current negative CGs (LPC−CGs) preferentially occur over the coastal waters of the Gulf of Mexico and the southeastern United States. A total of 1.46 million LPCCGs were found, of which only 13.7% were +CGs. Almost 70% of the LPC+CGs, however, occurred in the central United States (30°–50°N, 88°–110°W). The percentage of all LPCCGs that were positive approached 30% in the central United States compared to 4.5% for the remainder of the country. A +CG is 3.1 times more likely to exceed 75 kA than is a −CG flash on a national basis. Yet in terms of absolute numbers for all ranges of peak current ≥75 kA, negative CGs are clearly dominant. For peak currents ≥75 and 200 kA, negative CGs outnumbered positive CGs by ratios of 6.4 and 4.1, respectively. In the central United States, however, during evening hours the number of LPC+CGs almost reaches parity with LPC−CGs. Average stroke multiplicity also exhibited regional differences. Over a half million negative CGs and over 1000 positive CGs were found with multiplicity ≥10.

1. Introduction

Starting with the first known low-light television (LLTV) image in 1989 of what are now called sprites (Franz et al. 1990), literally thousands of sprite events have been captured on video tape (Lyons 1994a,b; Sentman et al. 1995). These transient luminous events (TLEs), typically centered in the 50–60-km altitude range, can extend vertically from as low as 25 km to as high as 95 km, spanning the mesosphere and stratosphere. They can range from less than 1 km to over a 100 km in breadth (Figs. 1a,b). They appear to be a response, at least in part, to electric breakdowns induced by quasi-electrostatic fields resulting from massive charge transfers associated with lightning flashes in the parent thunderstorms below (Boccippio et al. 1995; Pasko et al. 1995). Recently, additional classes of TLEs have been discovered. Elves, first detected from the surface by Lyons et al. (1994) and confirmed by Fukunishi et al. (1996) are brief (submillisecond) rapidly expanding disks of light centered between 85 and 95 km that can attain diameters of greater than 200 km (Fig. 1c). These optical luminosities appear to result from heating by the electromagnetic pulse (EMP) emitted from lightning discharges in the cloud below (Inan et al. 1997; Taranenko et al. 1996). A third type of TLE, the comparatively rare blue jet, was documented by Wescott et al. (1995) and Lyons and Nelson (1995). The highly collimated pillars of blue light appear to shoot upward from the anvils of severe storms at speeds on the order of 100 km s^{-1} reaching heights of 40–50 km. Figure 2 shows a schematic description of the characteristics of the several TLEs identified to date.

Ongoing research is uncovering various associations between TLEs and terrestrial lightning discharges. The blue jet does not appear to be coincident with specific cloud-to-ground (CG) lightning flashes, although there is evidence that after such events negative CG flashes (−CG) in the parent storm pause for one or two seconds (Wescott et al. 1995). On the other hand, both sprites (Lyons 1996a; Boccippio et al. 1995; Dowden et al. 1996) and elves (Lyons and Nelson 1995) appear to be

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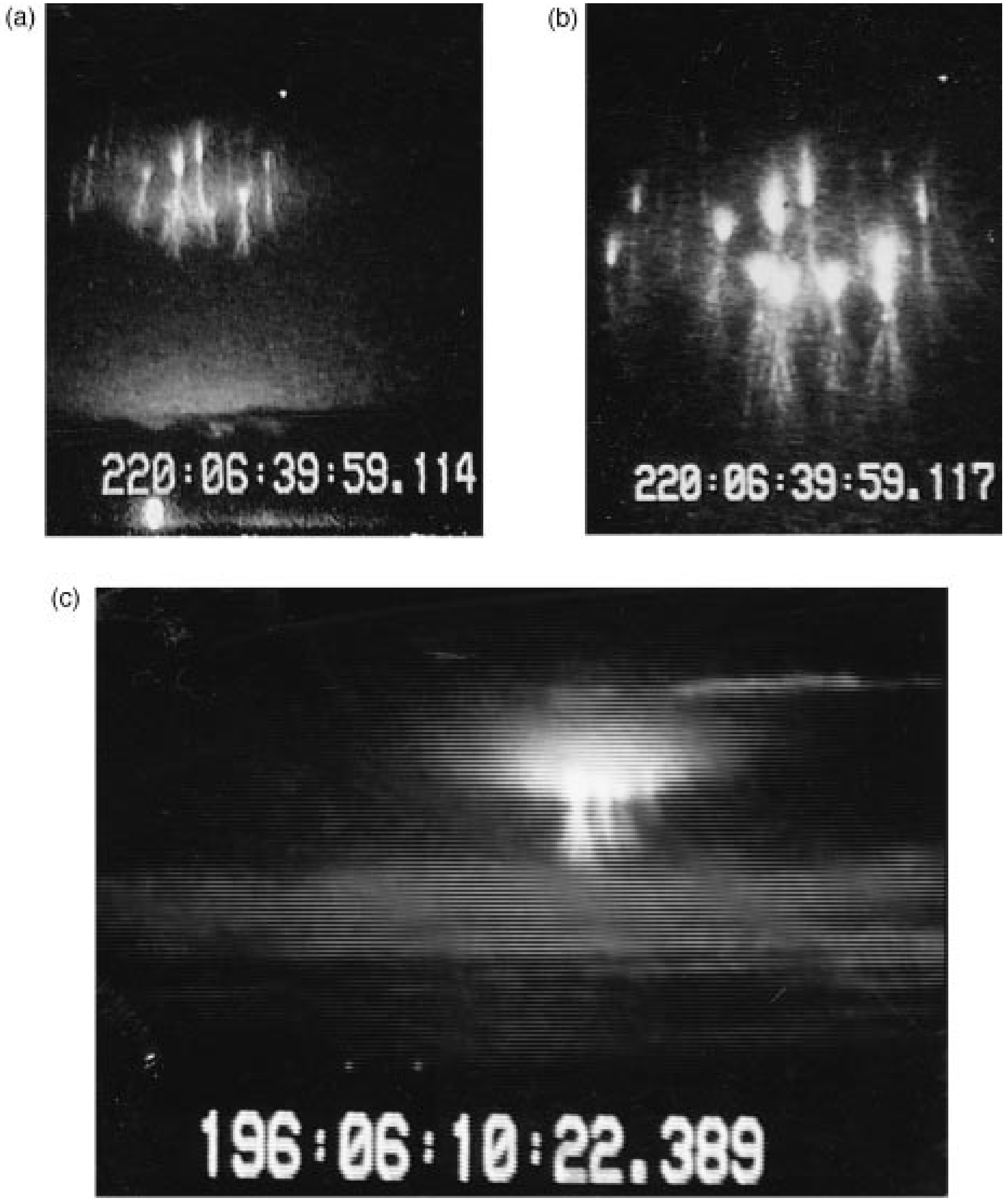

FIG. 1. (a) Low-light television view of a complex sprite associated with a +CG flash (illuminating the cloud below) about 220 km east-southeast of the Yucca Ridge Field Station, Fort Collins, CO, at 0639:59.114 UTC 7 August 1996. (b) Close-up view of the same sprite with the 16.7-ms image integration ending some 3 ms later. Note the apparent downward extension of the tendrils. The top of the sprite luminosity is about 90 km with the tendrils extending downward below 45 km. The bright spot above and to the right of the sprite is Saturn. (c) An elve and a sprite captured together at 0610 UTC 15 July 1995 during the same 16.7-ms integration of a video field. The event is 325 km distant. The top of the luminous disk produced by the elve is around 90 km.

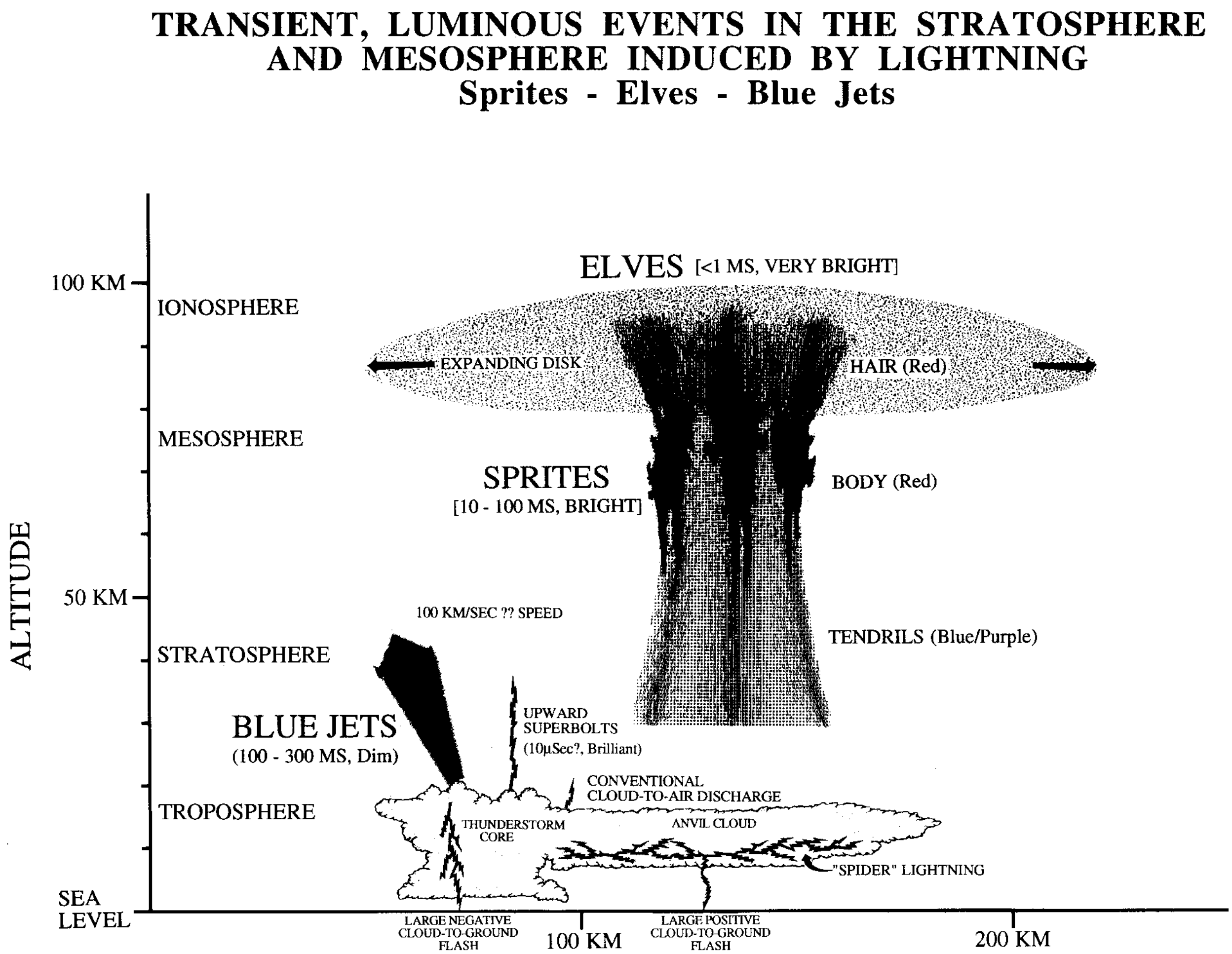

FIG. 2. Schematic of the known morphology of sprites, elves, and blue jets and their relationship to the underlying thunderstorm and lightning. Graphic courtesy C. S. Keen, Mankato State University.

almost uniquely associated with positive CG flashes (+CG). Moreover, the +CGs associated with sprites typically have larger average peak currents (I_{max}) than other +CGs within the same storm. For instance, during the High Plains mesoscale convective system (MCS) of 6 August 1994, the sprite +CG values of I_{max} averaged 81 kA versus 30 kA for the other +CGs in the same system. Work currently under way by the authors suggests that most +CGs associated with elves may have even larger average I_{max} than sprite producers. At least one case study (Lyons 1996a) found that stroke multiplicity averaged 1.41 for sprite +CGs versus 1.13 for others in the storm. To date no sprite has been conclusively linked to a parent CG of negative polarity. The overwhelming majority of CGs associated with elves appear to be of positive polarity.

Sprites and elves are most easily detected using LLTVs deployed during the night (Franz et al. 1990; Lyons 1994b; Winckler et al. 1996). In a typical six-week summer campaign, on the order of a thousand such events can be observed from the Yucca Ridge Field Station near Fort Collins, Colorado (Lyons et al. 1994; Lyons 1996b). Yucca Ridge has hosted sprite observation campaigns each summer since 1993. There has been a high success rate in identifying sprite-generating storms from the multitude of candidate targets present within the 1.5 million square kilometer viewing region. This resulted from the empirical observation that in order to generate a significant number of sprites and elves, an MCS generally requires a radar echo area (>20 dBZ) of at least 15 000–20 000 km^2 and a stratiform precipitation region containing numerous +CGs. The +CGs are often arrayed in the classic bipolar spatial pattern (Orville et al. 1988). While sprites have been occasionally observed worldwide from the space shuttle (Vaughan et al. 1992; Lyons and Williams 1993; Boeck et al. 1995) and by aircraft over the Tropics, the vast majority of LLTV sprite observations have come from the U.S. High Plains and upper Midwest (Franz 1990; Lyons 1994a; Sentman et al. 1995; Winckler 1995; Lyons 1996a). This fact is due to the large number of nocturnal storms in the region, the location of the investigating teams, and the generally excellent summer viewing conditions throughout this area. It is also due in large part, we believe, to the electrical characteristics of the storms in this region. Rutledge and MacGorman (1988, 1990) and Reap and MacGorman (1989) were among the first to demonstrate the relatively high number of storms in the interior of the United States with high +CG rates. MCSs with significant numbers of +CGs within their stratiform precipitation systems have been analyzed by Rutledge et al. (1993). Stolzenburg (1994) and Branick and Doswell (1992) also describe a class of smaller, supercell tornadic and hailstorms containing clusters of +CGs, often with relatively high peak currents, that frequent this same general region in the late afternoon. Thus several types of high +CG rate storms are common in this region. Evidence to date suggests that sprites are in most cases associated only with larger MCSs (Lyons 1996a). Numerous LLTV observations made by the authors of smaller supercells, even those with many large peak current positive CGs (LPC+CGs), indicate supercells rarely produce sprites and elves.

Various techniques have been proposed to identify and roughly locate sprites or their associated CGs by using perturbations on broadcast (very low frequency) VLF signals (Inan et al. 1995; Dowden et al. 1996) as well as natural VLF and (extremely low frequency) ELF emissions from the atmospheric electrical phenomena themselves (Williams et al. 1996; Reising et al. 1996). In particular, the ELF phenomenon known as a Schumann resonance Q burst appears strongly correlated with sprite-producing +CGs (Boccippio et al. 1995). Techniques are being developed to monitor and locate Q bursts on a global scale (Williams et al. 1996). Other VLF signatures (slow tails) are thought to be related to +CGs associated with sprites (Reising et al. 1996; Fullekrug et al. 1996). Obtaining a better understanding of the climatology of large peak current CG (LPCCG) flashes that are associated with sprites and elves will greatly assist in the design of global radio frequency remote sensing systems and the interpretation of their results.

2. A preliminary investigation

The most extensive compilation of CG flash measurements currently available is from the U.S. National Lightning Detection Network (NLDN). The NLDN has gradually evolved over the past 15 years from a regional network serving the East Coast (Orville et al. 1987) into a comprehensive national resource serving the contiguous United Sates and adjacent waters (Cummins et al. 1996).

In a preliminary study, Lyons (1996a) mapped all LPC+CG events with measured $I_{max} \geq 75$ kA between the hours of 0300 and 0900 UTC during the months of July–August 1993 and June–August 1994. The plot showed a notable concentration of LPC+CGs within a broad belt starting from eastern New Mexico and extending north-northeastward through Kansas and into Minnesota, a region roughly characterized as the High Plains and upper Midwest. This is precisely the same region in which the large majority of sprite LLTV observations have been made. A map of the more intense ($I_{max} \geq 100$ kA) LPC+CGs for a single month (July 1993) shows basically the same pattern (Fig. 3). This map also yields evidence of smaller-scale clustering of the LPC+CGs, presumably associated with individual storm systems.

3. A climatology of large peak current CGs

The intriguing correlation between individual sprites observed by LLTV and LPC+CGs, as well as the apparent concentration of LPC+CGs in the region known to experience a large number of sprite-generating storms, motivated a more in-depth climatological investigation. Utilizing NLDN data already in-house, we processed only the summer months during which sprites and elves are known to exhibit their highest frequency. A total of 14 months were used: June (1991, 1994, 1995), July (1991, 1993–95), August (1991, 1993–95), and September (1991, 1994–95). A total of 59.3 million CG flashes were analyzed. This period included a variety of major weather events including part of the Midwest flooding of summer 1993. We note July of that year registered a total of 7.1 million flashes in the network. September 1991 was the least active month, with 1.6 million flashes.

A summary of the statistics generated are presented by month in Table 1. The NLDN data were sorted in a number of ways. The number of −CGs and +CGs were tallied by month, along with the number of LPCCGs with $I_{max} \geq 75$ kA and ≥200 kA. Average stroke multiplicity was also computed for all CGs and LPCCGs. These were summed in 48 km × 48 km bins, the same as the manually digitized radar (MDR) grid that has been used in some prior stroke density mapping studies (Reap and MacGorman 1989). Files were created of the location of all LPCCGs with $I_{max} \geq 200$ and all CG flashes of either polarity with stroke multiplicity ≥10. In addition, the data were also summarized hourly, allowing examination of diurnal trends of LPCCG flash rates for the contiguous United States as well as a region termed the central United States (30°–50° N and 88°–110° W).

A census of LPCCGs of both polarities was prepared for both the entire network and the central United States. There were a total of 1.46 million LPCCGs, representing 2.46% of all flashes. The percentage of −CGs with $I_{max} \geq 75$ kA was 2.28% (1.26 million), whereas more than three times as many (7.37%) of the +CGs had $I_{max} \geq 75$ kA (197 000). In the same dataset there were 8772 −CGs and 2121 +CGs with $I_{max} \geq 200$ kA, and 52 −CGs and 12 +CGs with $I_{max} \geq 400$ kA. Nationwide, the largest −CG peak current found was 957 kA com-

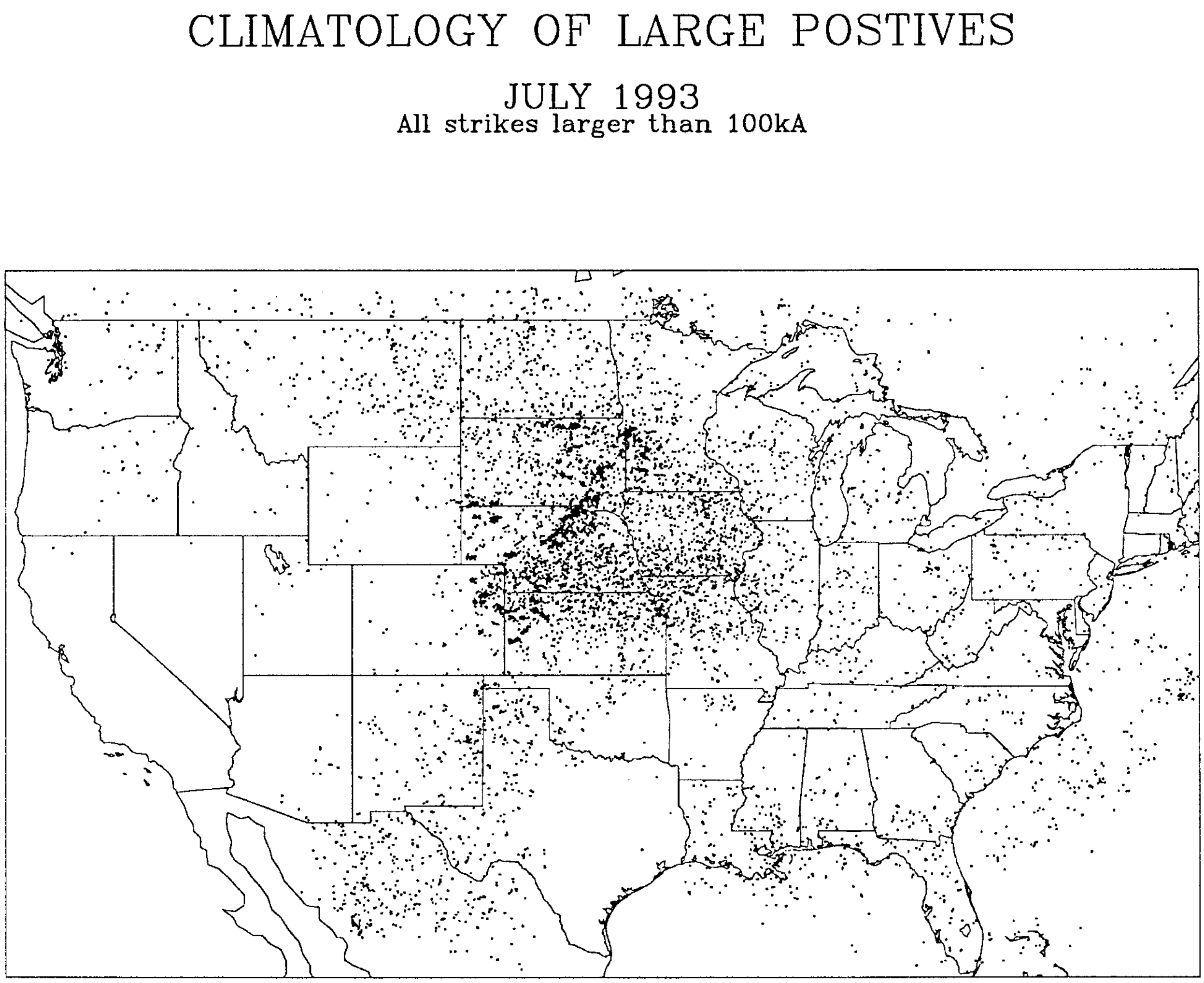

FIG. 3. Plot of the locations of all +CG flashes from the NLDN having first stroke peak currents (I_{max}) of 100 kA or greater during the month of July 1993.

pared to the largest +CG I_{max} of 580 kA. These statistics contrast sharply with early assessments of lightning characteristics using 1984–85 data from the prototype East Coast regional network by Orville et al. (1987), in which it was stated that few −CGs should have I_{max} values much greater than 100 kA. As illustrated by Figs. 4a,b, for all values of $I_{max} \geq 75$ kA, the large −CGs outnumbered the large +CG events by considerable margins, although the disparity was substantially less in the central United States subdomain. In the central United States, there were 132 000 LPC+CGs. This constituted 67% of the LPC+CGs recorded by the entire NLDN. By comparison, the LPC−CG count in the central United States was 317 000. This represents only 26% of the NLDN total LPC−CGs and indicates that large negative peak current events, while more numerous, were not concentrated in the central United States as were the large positive events.

The number of LPCCGs of both polarities for the entire network and the central United States were summed on an hourly basis for the entire data record (Figs. 5a,b). At all hours in both domains the LPC−CGs outnumber the LPC+CGs. We note, however, that in the central United States the two polarities nearly reach parity in the hours between 0000 and 0700 UTC. This time period comprises much of the period when MCS systems are developing and are observed to be generating sprites and elves.

Flash densities for all CGs of both polarities and all peak currents for the 14 summer month period were computed and displayed using the 48 km × 48 km MDR grid scheme (Fig. 6). The 14-month flash densities are expressed in flashes per square kilometer. The pattern is generally similar to the annual flash densities first reported for 1989 data (Orville 1991b), for the 1989–91 period (Orville 1994) and the 1992–95 period (Orville and Silver 1997). Peak values nearing 40 flashes km^{-2} (14 months) are found in central Florida, the region commonly experiencing annual maxima. Regional maxima can also be found in the Ohio River Valley and

TABLE 1. Summary of NLDN data used in this study.

Month/year	Total flashes, thousands polarities: Both	Negative	Positive	% Pos	Negative CGs ≤ −75 kA: Total	%	Positive CGs ≥75 kA: Total	%	Negative CGs ≤ −200 kA: Total	Positive CGs ≥200 kA: Total	Stroke multiplicity ≥10: Neg CG	Pos CG	Average peak current (kA) all flashes: Neg CG	Pos CG
Jun 91	3296	3160	136	4.12	65 022	2.06	18 381	13.55	230	57	29 200	34	−31.7	43.6
Jul 91	4208	4099	109	2.59	126 836	3.09	11 702	10.76	422	37	36 846	23	−33.1	40.1
Aug 91	3387	3312	75	2.19	96 103	2.90	7813	10.53	377	38	30 185	14	−32.5	41.8
Sep 91	1582	1536	46	2.89	64 678	4.21	5292	11.57	745	97	13 016	5	−34.5	43.1
Jul 93	7071	6809	262	3.71	102 435	1.50	23 604	8.78	362	141	88 316	264	−30.3	37.5
Aug 93	5528	5353	175	3.18	113 435	2.11	16 011	9.12	594	105	74 194	169	−31.1	37.5
Jun 94	5845	5607	238	4.07	95 557	1.70	20 356	8.56	463	137	66 082	131	−29.9	36.5
Jul 94	5886	5638	248	4.20	106 291	1.88	19 547	7.88	542	112	68 812	156	−29.8	35.8
Aug 94	4123	3969	154	3.73	85 431	2.15	11 926	7.75	406	62	45 935	65	−30.1	36.3
Sep 94	1782	1701	81	4.52	52 808	3.10	5994	7.43	213	65	13 934	15	−31.6	36.6
Jun 95	3945	3622	323	8.20	75 293	2.08	18 113	5.60	985	255	9044	18	−26.2	28.4
Jul 95	5900	5519	381	6.46	136 177	2.47	18 119	4.75	1806	252	13 071	53	−28.1	26.0
Aug 95	4448	4156	292	6.56	90 693	2.18	14 800	5.07	1207	180	11 776	37	−27.7	29.9
Sep 95	2348	2184	164	7.03	52 519	2.40	6 770	4.10	420	583	8453	18	−28.3	28.8
Total	59 349	56 665	2684	4.52	1 263 278	2.38	197 870	7.37	8772	2121	508 844	1002	−30.4	35.5

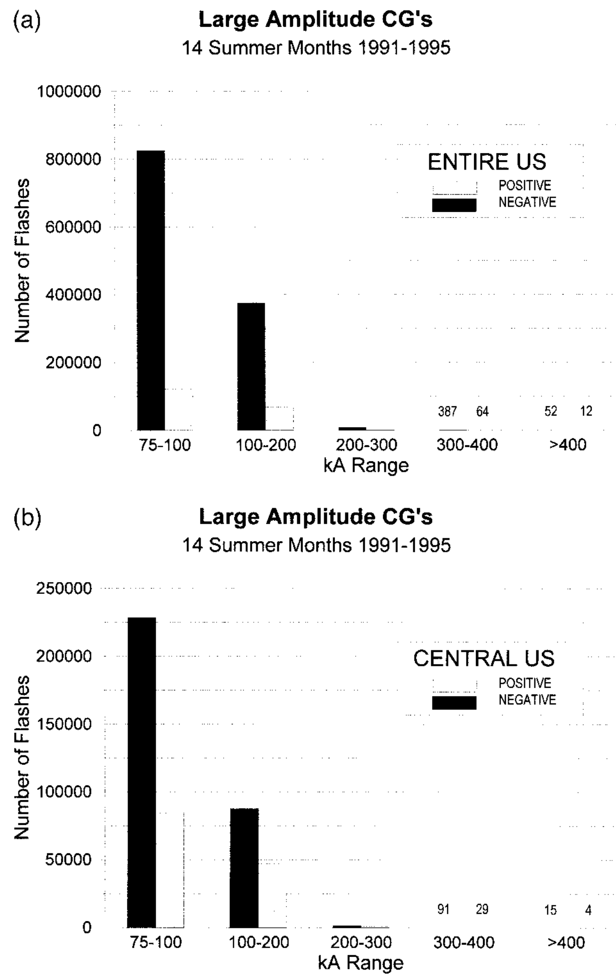

FIG. 4. (a) Distribution by peak current intensity of the frequency of LPC−CG and LPC+CGs for the 14 summer months over the entire NLDN network. (b) As in (a) but only for flashes within the central United States (30°–50°N; 88°–100°W).

along the Gulf Coast, two areas which in recent years have had some of the nation's higher flash densities. The rapid fall off in total flash densities outward from the gulf and Atlantic coastlines represents, in part, decreasing detection efficiency values, but also the sharp differences in flash densities known to exist between continental and marine areas (Orville and Henderson 1986). This decrease in overall flash density east of the Georgia–South Carolina coast is noted in the July–August climatology compiled for the Olympics (Livingston et al. 1996).

A very different picture emerges, however, when one segregates the LPCCGs by polarity and plots their flash density. The LPC−CGs (Fig. 7) reveal a pattern in which the highest flash densities are found over the ocean off the southeastern United States and gulf coastlines. While the higher LPC−CGs flash densities do appear to ''bleed'' somewhat inland in the southeast, there appear to be distinct overland and overwater re-

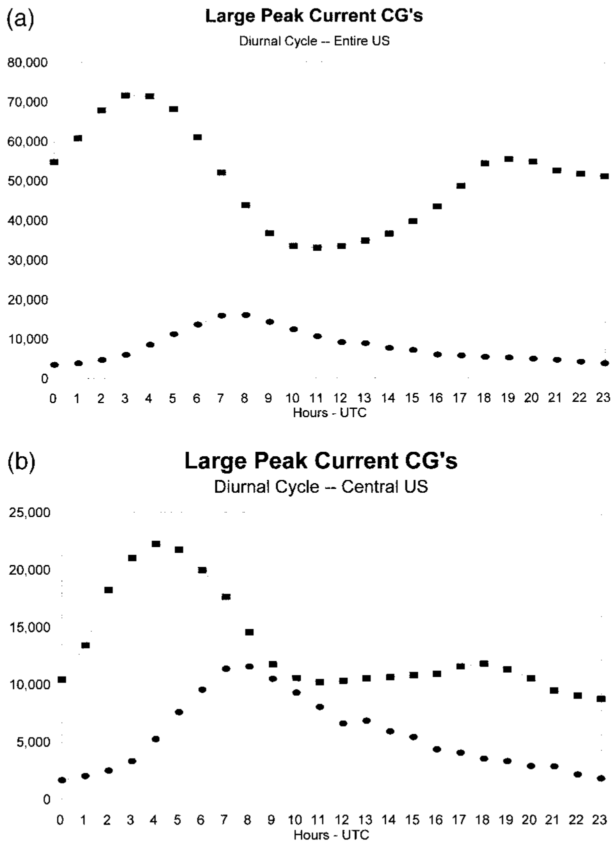

FIG. 5. (a) Diurnal distribution of LPC−CGs (box) and LPC+CGs (oval) during the 14 summer months over the entire NLDN network. The timescale, in UTC, starts with the local noon in the interior of the United States. (b) As in (a) but only for flashes within the central United States.

gimes. The LPC−CG densities in central Florida are comparable to those over portions of the interior of the eastern United States. A highly localized maximum in the region east of New Orleans is quite noticeable. It is only loosely correlated with the total flash density maxima. Whether this ‘‘hot spot’’ represents a true meteorological phenomenon or a sensor performance or calibration problem cannot be determined within the scope of this study. In Fig. 7, the unshaded areas are those that have fewer than 25 LPC−CGs per MDR grid cell.

The distribution of LPC+CGs (Fig. 8) is entirely different from both the overall summer flash density and the LPC−CG patterns. A very well-defined corridor emerges from eastern New Mexico north-northeastward into Minnesota. This is the same region with a climatological maximum of annual +CG flash densities and percent occurrence for all peak currents (Orville and Silver 1997). Maximum LPC+CG densities within the corridor reach 0.17 flashes km^{-2} (per 14 months). Not surprisingly, this region also coincides with the heart of the ‘‘sprite belt’’ determined by numerous optical measurements made by various research groups from sites in Colorado, Wyoming, Minnesota, and New Mexico. A secondary maximum in northwestern Mexico is most likely associated with the intense MCSs that develop in this region during the southwestern monsoon (Farfan and Zehnder 1994). Only those MDR cells with greater than 25 events were used to compute flash density.

The preceding maps represent absolute values of LPCCG occurrences. Figures 9 and 10 show the distribution of the percentages of all NLDN CGs that have $I_{max} \geq 75$ kA. Figure 9 shows that, on a percentage basis, the region with more than 5% of all flashes being −CGs with $I_{max} \geq 75$ kA is confined to the ocean, in the northern Gulf of Mexico and off the southeast coast-

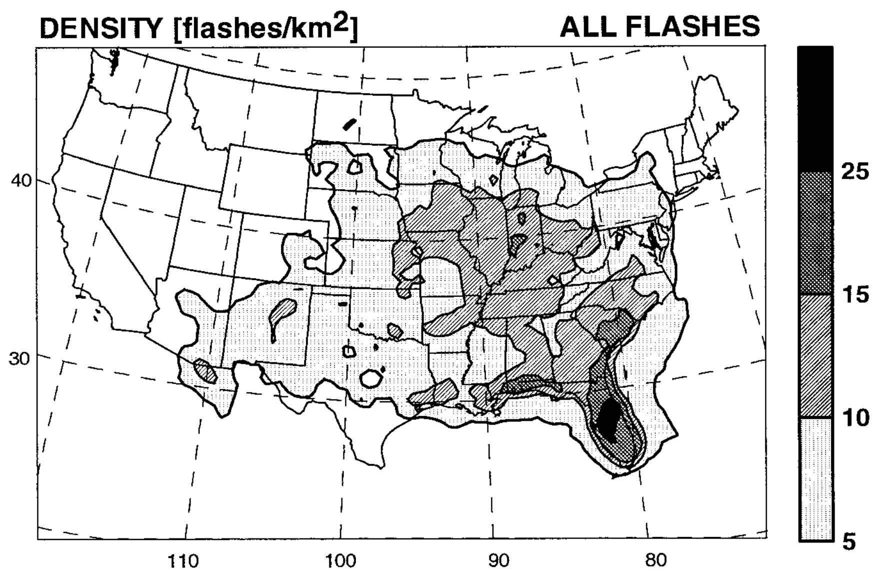

FIG. 6. Flash densities over the 14 summer month period, in flashes per square kilometer, for all flashes measured by the NLDN. Maximum values approach 40 flashes km^{-2} in central Florida.

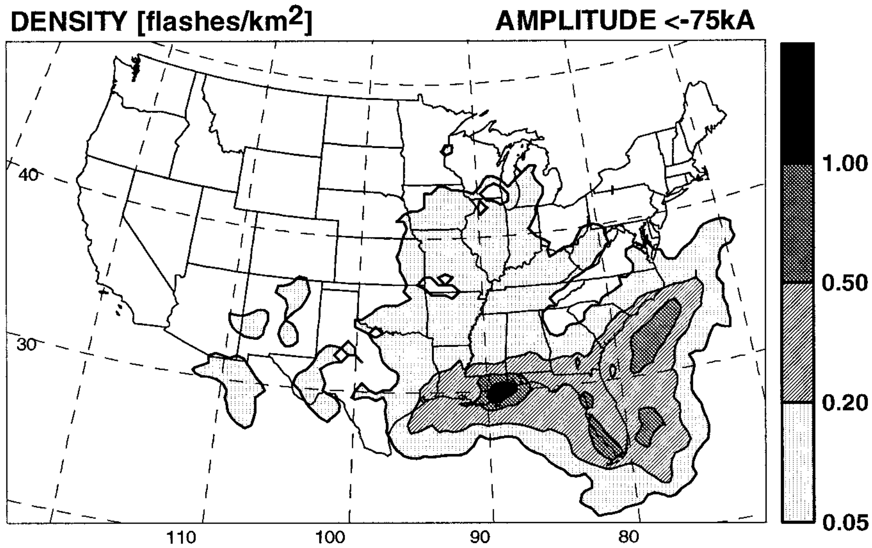

FIG. 7. Flash densities over the 14 summer months for large peak current negative CG flashes, $I_{max} \geq 75$ kA, in flashes per square kilometer.

line. Those values of 10% or higher in the far offshore region are most likely artifacts resulting from the increasing minimum detectable signals required for detection as one moves further away from the network. Over most of the interior of the United States, the percentage of CGs with $I_{max} \geq 75$ kA is less than 1% of the total. Figure 10 highlights the region where a significant percentage of all flashes are +CGs with $I_{max} \geq 75$ kA. Values of 1%–3% or more are scattered from eastern Colorado into northern Minnesota. The northwestern Mexican hot spot is also evident.

Plots of all the individual LPCCGs are not practical due to their great number. The subset of CGs of both polarities with $I_{max} \geq 200$ kA, however, are shown in Figs. 11 and 12. Not unexpectedly, the same basic patterns emerge for both negative and positive LPCCGs. While the same distinct regional clustering is evident in the plots of individual very large peak current CGs, one can also note that, while substantially fewer in number, LPCCGs do occur occasionally almost everywhere in the network.

We also investigated stroke multiplicity to ascertain whether there were regional differences and whether the LPCCGs might have different characteristics. The average stroke multiplicity for these 14 months for all flashes of all intensities shows multiplicity generally

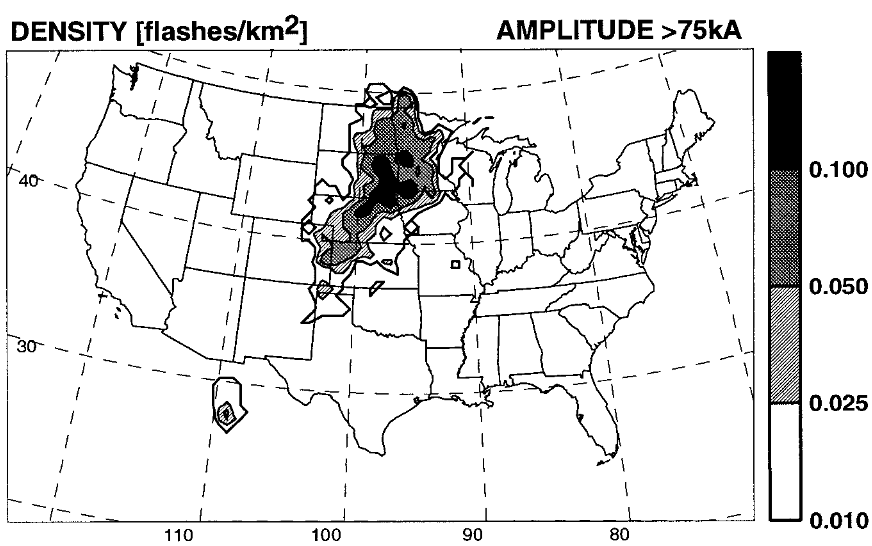

FIG. 8. Flash densities over the 14 summer months for large peak current positive CG flashes with peak currents $I_{max} \geq 75$ kA, in flashes per square kilometer. Densities in the upper Midwest exceed 0.1 flashes km^{-2} with a maximum of 0.17 flashes km^{-2}.

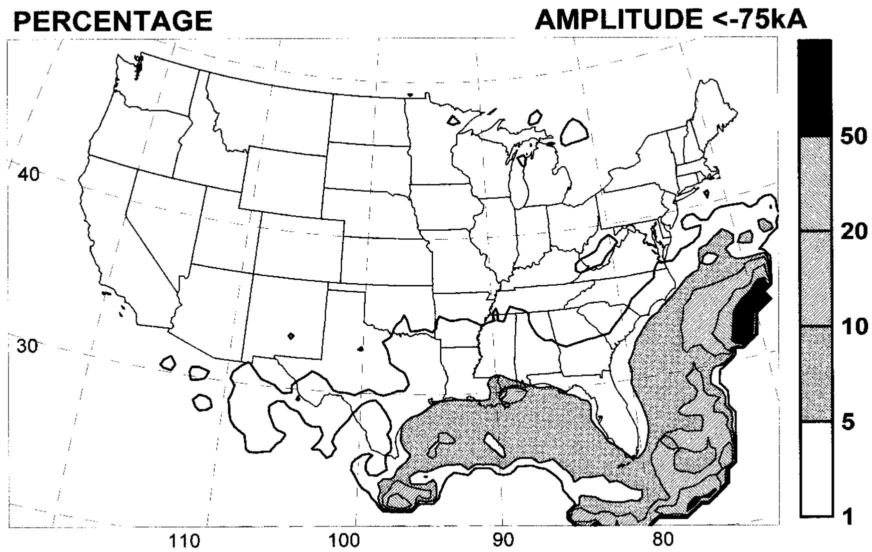

FIG. 9. Percentage of all CG flashes that are negative CGs with $I_{max} \geq 75$ kA. High percentages ($\gtrsim$10%) more than several hundred kilometers offshore are artifacts of the increasing minimum detectable current required for detection at larger ranges from the NLDN perimeter.

greater than 2 (Fig. 13). There are several regions with multiplicity >3, notably peninsular Florida and the upper Midwest. In the west, multiplicity is often less than 2, except for a few regions of enhanced values in southern California. The areas in white represent regions with relatively few flashes for which no multiplicity value was computed. Since −CGs dominate the total flash population, the multiplicity values for −CGs are essentially the same. LPC−CGs flashes, however, appear to have greater multiplicity values than their smaller intensity counterparts over much of the nation (Fig. 14). Large areas with multiplicity ≥4 are found scattered through the eastern two-thirds of the nation. Some regions in the West and New England had insufficient numbers of LPC−CGs to compute a meaningful value. As for +CG flashes, they are often assumed to be overwhelmingly single stroke events. However, multiplicity values substantially greater than 1 are widespread, with peaks approaching 2 in portions of the upper Mississippi Valley (Fig. 15). For those cells with sufficient LPC+CGs to compute multiplicity values (Fig. 16), the multiplicity is comparable to or perhaps slightly higher than the smaller peak current +CGs. The region of higher multiplicity values, however, for LPC+CGs is shifted farther west toward the sprite region.

We also investigated the occurrence of CGs, irrespective of I_{max}, with multiplicities of 10 or greater. Given their huge number (more than a half million, most of negative polarity), it was not possible to plot individually all flashes with multiplicity ≥10 for the entire 14-month period. The map showing the −CGs with multiplicity ≥10 for July 1993, however, is fairly typical (Fig. 17). Large clusters of −CGs with many high multiplicity strokes are scattered throughout the United States including Florida, the High Plains, and the Midwest (this latter being partially related to the intense 1993 storms associated with the severe flooding).

A surprising number of +CGs with 10 or greater strokes were also found (Fig. 18). These high multiplicity +CGs show a pattern not dissimilar to that for high multiplicity negative CGs. High multiplicity CGs of either polarity appear to be rather uncommon over saltwater regions. This may be due in part to decreasing DEs for the typically lower peak current found in subsequent strokes in multiple stroke flashes.

4. Discussion

Given the large regional variations in lightning characteristics one might ask if they are truly meteorological in nature or could they perhaps be in part artifacts of the measurements? Lightning detection and location technologies and their implementation were undergoing significant changes during the 1991–95 study period (Cummins et al. 1996). Care must be taken in comparing flash data not only from different networks but also networks such as NLDN, which are constantly undergoing substantial improvements in locational accuracy (LA) and detection efficiency (DE) resulting from the blending of the original magnetic direction finding (MDF) technology in place in 1991 with time-of-arrival (TOA) systems brought on-line by 1995 (Holle and Lopez 1993). As discussed below, the key point of this paper, that there are substantial regional differences in the occurrence of LPCCG of both polarities, is believed to be relatively insensitive to these network changes.

In 1991 the network-averaged LA was thought to be in the 4–8-km range (using the 50% semimajor axis statistic) with dramatic improvements of LA to 0.5–1.0 km achieved by 1995 (Idone 1997, personal commu-

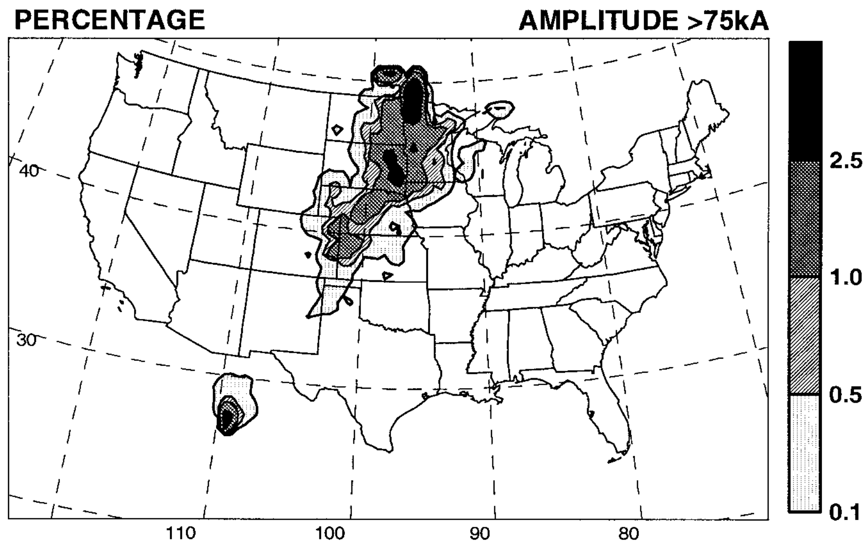

FIG. 10. Percentage of all CG flashes that are positive CGs with $I_{max} \geq 75$ kA. Peak values exceed 4% in northern Minnesota, in the approximate location of the first known video record of a sprite (Franz et al. 1990).

nication). The LA statistic is fairly uniform over land areas in the 48 contiguous states though it does deteriorate fairly rapidly more than 200 km beyond the network boundaries. Thus, given the large size of the analysis grid used to compute flash densities, LA values are not a factor throughout the 5-yr span of this study.

According to Cummins et al. (1996), network DE has also improved from less than 70% in 1991 to the current 80%–90% range, with the best performance in the High Plains and eastern United States. The 1994 network upgrade resulted in both negative and especially positive average CG peak currents skewing markedly lower after September 1994 (Wacker and Orville 1996) as more and more smaller flashes were detected (also evident in Table 1). The conversion to the new sensors, along with decreasing the pulsewidth detection criteria from 10 to 7 μs, greatly increased the DE especially for small peak current +CG events (Wacker and Orville 1996). The NLDN annual national percentages of detected CG of positive polarity from 1989 through 1995 were 3.1%, 2.8%, 4.0%, 4.2%, 4.6%, 4.9%, and 9.3% (Wacker and Orville 1996). It appears that there exists a class of small peak current +CGs, which, when detected by older systems in the past, were often assumed to represent ''con-

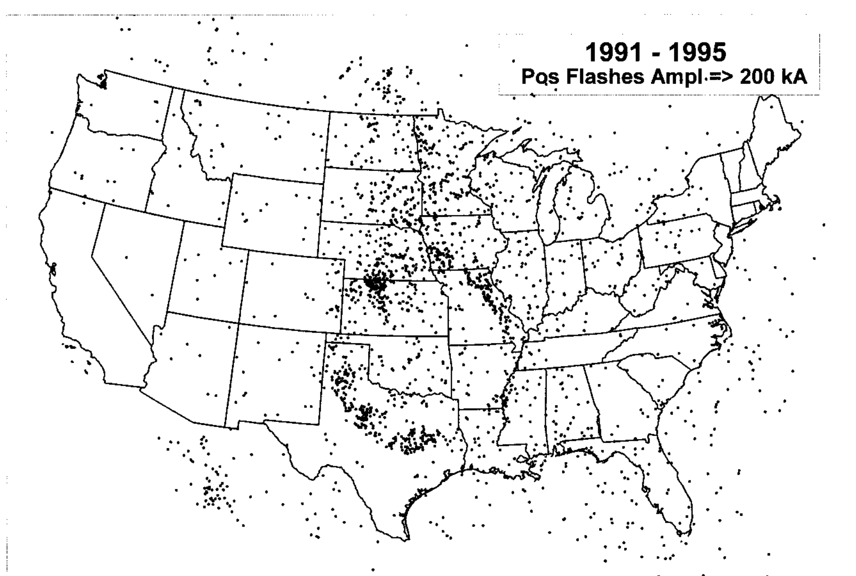

FIG. 11. Plot of all positive CGs (2121 total) having $I_{max} \geq 200$ kA during the 14 summer month period.

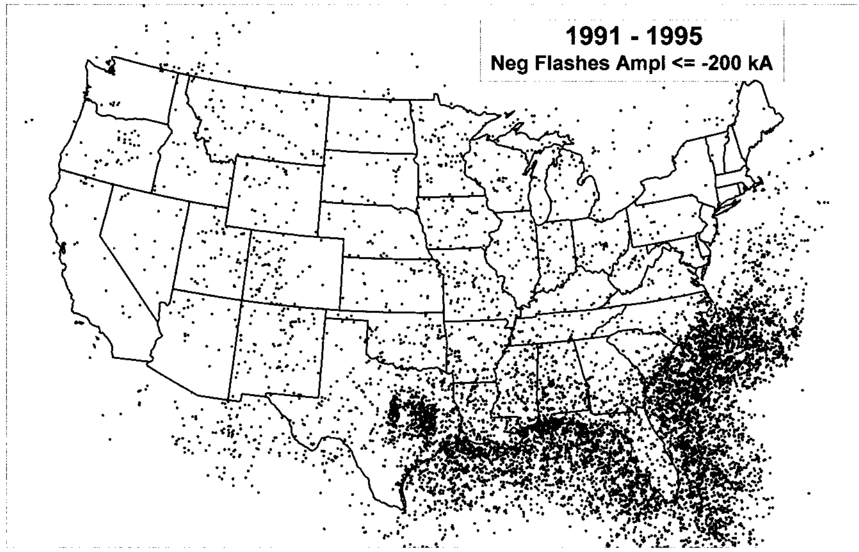

FIG. 12. Plot of all negative CGs (8772 total) having $I_{max} \geq 200$ kA during the 14 summer month period.

tamination'' from intracloud discharges. Pinto et al. (1996), using a TOA system in Brazil, is among several studies that suggest the apparent increase in the DE for small amplitude +CGs appears to be mostly real with only some contribution due to misidentification of cloud flashes. The DE falls off rapidly after the first 200 km beyond the borders and coastline. The DE decline outside the network is manifested by increases in the minimum detectable signal (peak current) required for detection (Lyons et al. 1989). Computer simulations (Cummins et al. 1996) also demonstrate that the DE would have to be less that 50% in order to have significant impact upon the detection of flashes with I_{max} values greater than the median (roughly 30 kA). The flash densities in this paper are computed with the actual reported data from the NLDN. No adjustments for subunity DEs have been attempted.

There have been ongoing investigations concerning the accuracy of the NLDN in determining I_{max} for large peak current events. The NLDN actually measures signal strength (in LLP units), which then must be converted into an estimate of I_{max}. Limited calibration of NLDN peak currents has been attempted using ground truth measurements obtained during rocket-triggered lightning studies (Orville 1991a). That study suggested a conversion of $I_{max} = 2.3$ kA $+ 0.19 \times$ LLP units, al-

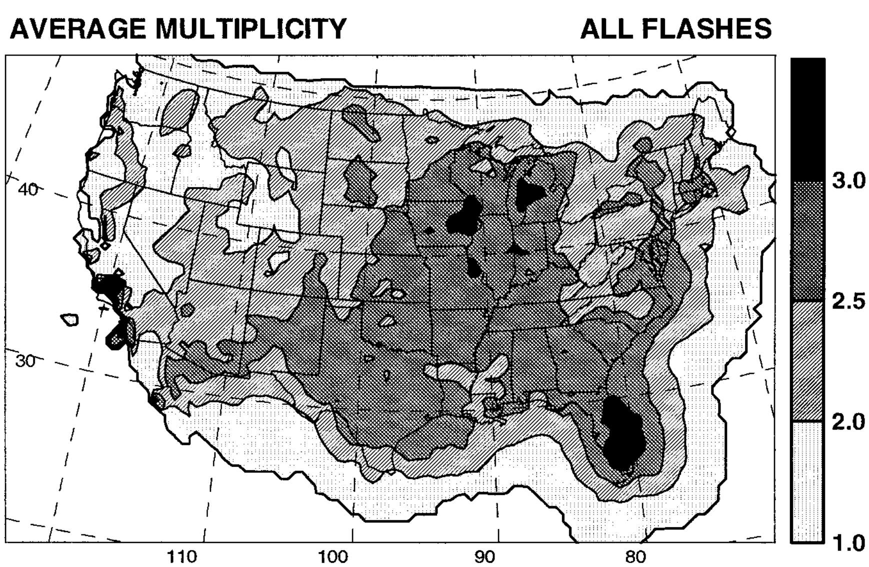

FIG. 13. Average multiplicity for the NLDN for all flashes during the 14 summer months studied. Grid cells left blank had too few flashes to obtain a representative sample.

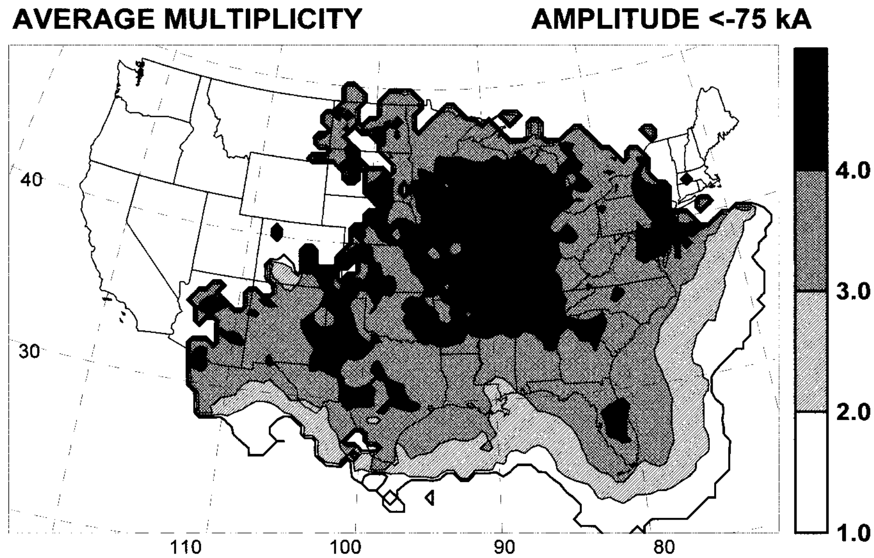

FIG. 14. Average multiplicity for large peak current ($I_{max} \geq 75$ kA) negative CGs in the NLDN during the 14 summer months studied. Grid cells left blank had too few flashes to obtain a representative sample.

though the widely used conversion of $I_{max} = 0.2 \cdot \mathrm{LLP}$ units introduces errors of less than 5%. However, that study did not deal with any events known to have values $I_{max} > 60$ kA. A reexamination of the NLDN calibration by Idone et al. (1993) suggested a revised formulation, $I_{max} = 4.2\ \mathrm{kA} + 0.17 \cdot \mathrm{LLP}$ units. It was held to be accurate to better than 15% in the 15–60 kA range and should be valid for $I_{max} > 60$ kA to about the 15% level. For this study we converted the NLDN data using the relationship $I_{max} = 0.185 \cdot \mathrm{LLP}$ units as suggested by the NLDN operator (Cummins et al. 1996), which for a 75 kA peak current results in computed values within 3% of the Idone et al. (1993) formulation. The I_{max} values used herein refer to that of the first stroke in a given flash, which is often assumed to represent the largest current in a multistroke event. Recent studies have found this often not to be the case (Pinto et al. 1996; Thottappillil et al. 1992). It is unclear how this might, if at all, impact our conclusions.

There have been relatively few case studies of spatial distributions of peak currents. Beasley (1985) reviews a long history of investigation of +CGs and notes that these events tend to be more common in several regions, including the severe spring and summer storms of the

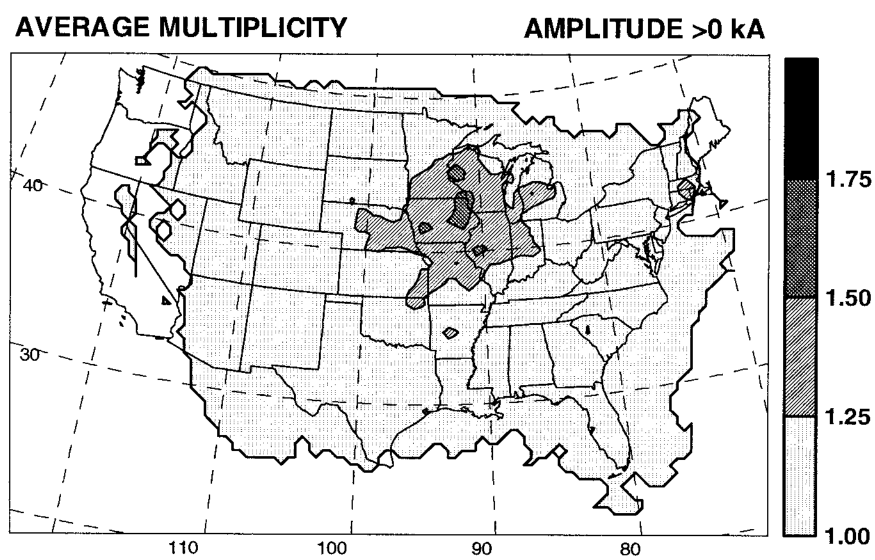

FIG. 15. Average multiplicity for just the positive CGs recorded by the NLDN during the 14 summer months studied. Grid cells left blank had too few flashes to obtain a representative sample.

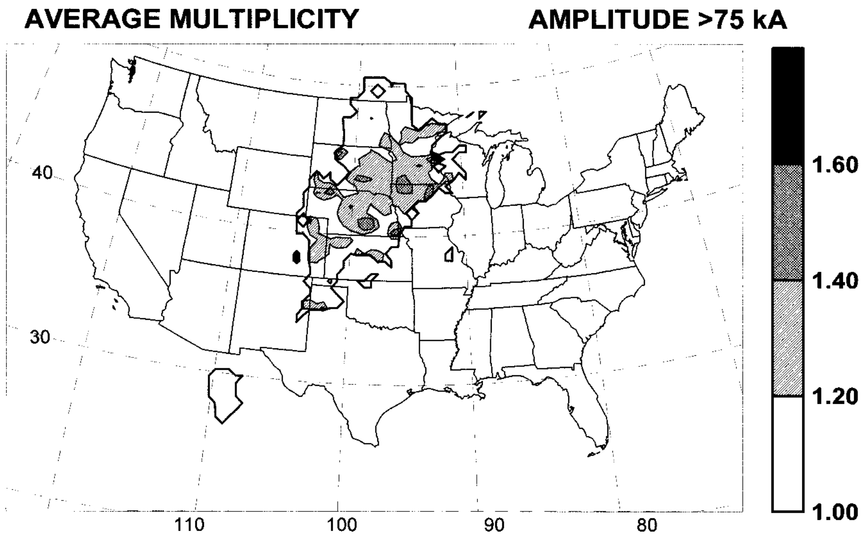

FIG. 16. Average multiplicity for large peak current ($I_{max} \geq 75$ kA) positive CGs in the NLDN during the 14 summer months studied. Grid cells left blank had too few flashes to obtain a representative sample.

Great Plains of the United States. Petersen and Rutledge (1992) examined peak current distributions within both large midlatitude and tropical MCSs. They concluded that the magnitude of the +CG peak current increases in time with the growth of the stratiform region, and reaches peak values when the stratiform regions were most intense. In the 10–11 June 1985 PRE-STORM MCS, +CG peak current maxima (minima) were associated with the stratiform (convective) precipitation areas in 90% (80%) of the time intervals examined. By contrast the maximum and minimum −CG peak currents always appeared inside the convective regions.

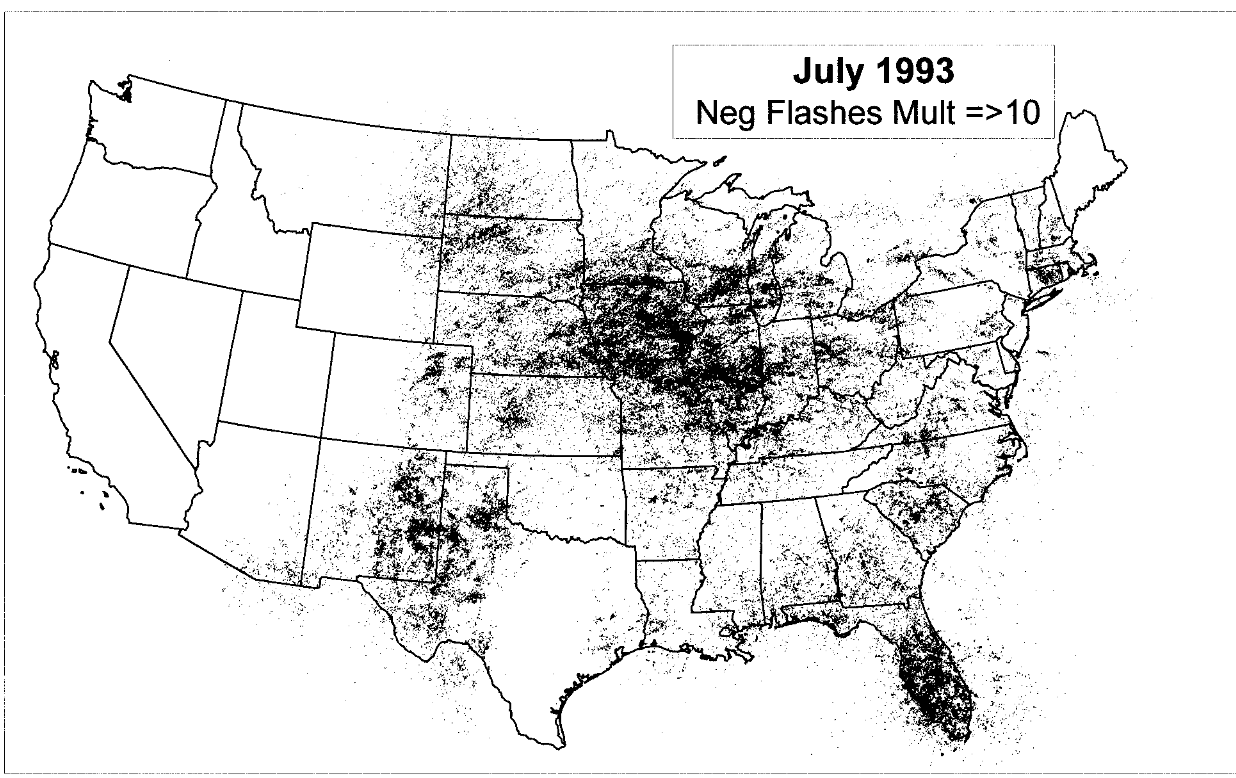

FIG. 17. Plot of the location of NLDN negative CG flashes (88 316 total) with multiplicity of ≥10 during the month of July 1993.

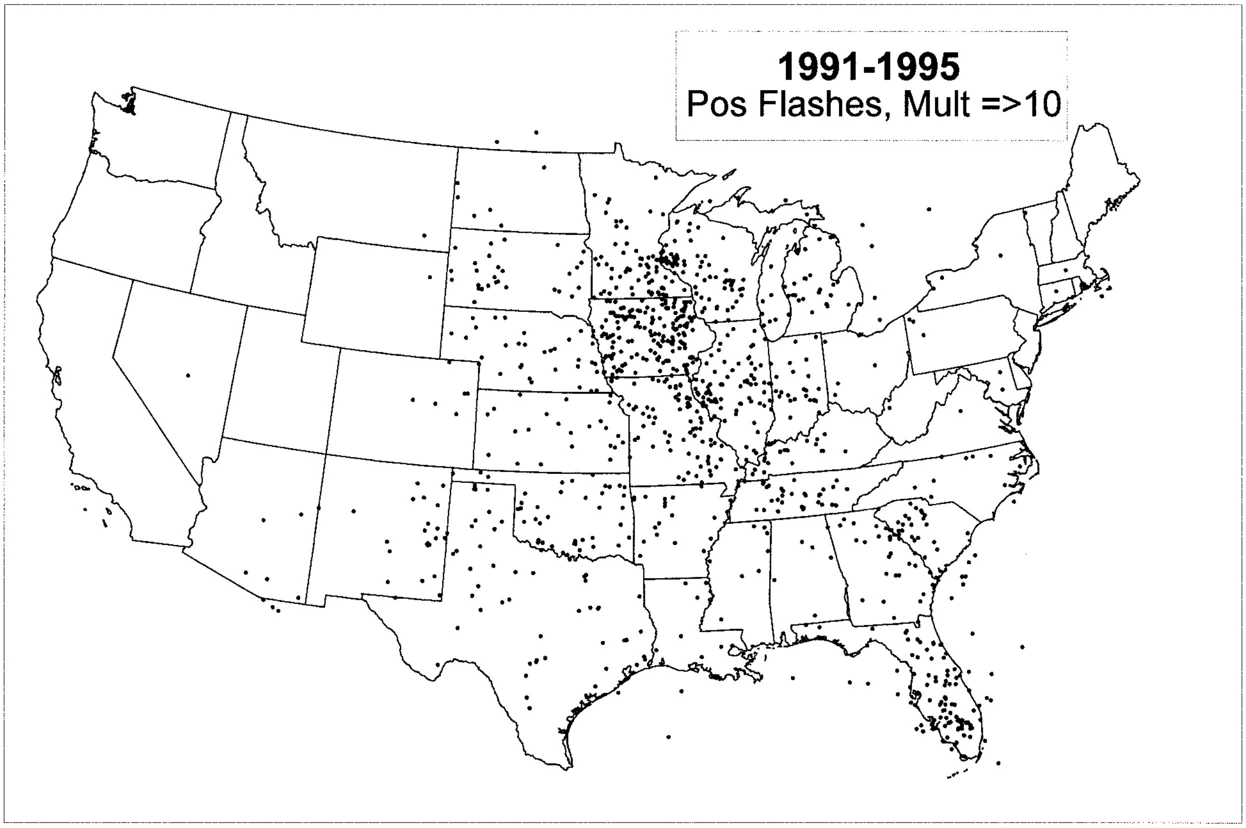

FIG. 18. Plot of the location of NLDN positive CG flashes (1002 total) with multiplicity of ≥10 during the 14 summer month study.

Such studies offer more evidence of the role of in situ charging mechanisms within the stratiform region of MCS, which allows for repeated +CG generation in these regions (Rutledge et al. 1993). This may also account for the frequently observed bipolar CG pattern (Orville et al. 1988) that is associated with sprite and elve-generating storms. Large dendritic or "spider lightning" discharges, vast networks of horizontally branching lightning associated with +CG flashes with significant continuing currents, have been implicated as a possible necessary condition for sprite generation (Boccippio et al. 1995; Lyons 1996a; Reising et al. 1996; Williams et al. 1996). Stolzenburg et al. (1994) documented horizontal layers, up to hundreds of kilometers across, of both positive and negative charge in large MCS stratiform regions. Marshall et al. (1996) used balloon-borne electric field measurements at 10–16-km altitude above large MCS showing strong electric field discontinuities associated with +CGs between 20 and 154 kA. Similar responses were not found with −CG events. Marshall et al. (1996) presented model calculations simulating the electric field change that would occur if the lightning discharged in horizontally extensive charge layers within the underlying MCS stratiform region. The results supported the idea that sprites may be initiated by above-cloud field changes caused by +CGs that discharge a horizontally extensive charge reservoir in the MCS stratiform region.

Other classes of storms in the interior of the United States also produce large numbers of +CGs. Branick and Doswell (1992) document clustering of +CGs associated with some tornadic supercell thunderstorms in the central United States. Summer +CG rates in late afternoon and early evening Great Plains supercells can reach 67 flashes per 5 min (Stolzenburg 1994). These clusters of +CGs have peak currents averaging some 70 kA, substantially larger than the regional +CG average (Orville et al. 1987; Wacker and Orville 1996). As previously mentioned, such supercells, often an order of magnitude smaller in size than the nocturnal MCSs of the region, have yet to be observed producing substantial numbers of sprites or elves. Thus not all the LPC+CGs in the interior United States are likely to be associated with TLEs, but a significant, and yet to be determined, percentage are likely to be related to sprites and elves.

Large MCSs, presumably generating LPC+CGs, are not unique to the interior of the United States. Satellite studies have documented the frequent occurrence of storms that appear capable of generating sprites throughout Central and South America, Africa, eastern Europe, and parts of Asia and northern Australia (Laing and

Fritsch 1997; Mohr and Zipser 1996). Williams et al. (1996) has demonstrated that there are frequent ELF Schumann resonance transients emanating from these regions, which provide additional support to the idea that sprites can occur within many large MCS with substantial stratiform precipitation regions and LPC+CG generation. Relationships that may exist between LPC+CGs, sprites, and the optical superbolts reported by military satellites (Turman 1977) are also of interest.

The values of stroke multiplicity found herein generally agree with the few previous studies conducted. Reap and MacGorman (1989), using data from a regional MDF network in the central United States, found multiplicity = 3.5 for −CGs and multiplicity = 2.7 for +CGs (not stratified by I_{max}). A southern Brazilian TOA network yielded a −CG multiplicity =2.9 and +CG multiplicity =2.2 for 300 000 strokes (Pinto et al. 1996). The multiplicity distributions in the Brazilian network had values of multiplicity ≥10 for only 0.2% for −CGs, four times less than the rate in the NLDN. In the Brazilian network there were no +CGs with multiplicity ≥10 (out of 103 000 strokes).

5. Conclusions

This paper presents the first known extended climatology of LPCCGs of both polarities in the context of their relationship with sprites and elves. It is believed the 1991–95 NLDN dataset is sufficiently homogeneous for our specific application. Almost 60 million CG flashes from portions of four summers were processed. Large numbers of high peak current ($I_{max} \geq 75$ kA) CGs of both polarities were found. The percentage of +CGs that have $I_{max} \geq 75$ kA is significantly larger than for CGs (7.4% vs 2.4%). The absolute number of LPC–CGs, however, exceeds their +CG counterparts by 6.3 times. This dominance, however, was much less pronounced in the central part of the United States. In fact, in the premidnight hours (local time) in the central United States, LPC+CG frequencies nearly matched those for LPC–CGs. A plot of LPCCG flash densities segregated by polarity shows a clear geographical separation between the two classes of events. Perhaps not unexpectedly, the LPC+CGs were tightly concentrated in the High Plains–upper Midwest corridor in which the majority of optical observations of sprites and elves has been obtained to date. The concentrations of LPC+CGs in this region are likely associated with at least two classes of summer thunderstorms known to produce copious numbers of +CGs: supercells and nocturnal MCSs. The latter are thought to have the necessary attributes (large stratiform region allowing for LPC+CGs associated with horizontally extensive dendritic discharges) to generate sprites. Other regions around the globe with a high frequency of large nocturnal MCS storms are therefore candidates for regional maxima of sprite and elve activity. These are regions where long-range monitoring of VLF and ELF signatures known to be associated with TLEs should be focused. Not expected, however, was the unusually high percentage of CGs of negative polarity with $I_{max} \geq 75$ kA found over the saltwaters of the northern Gulf of Mexico and off the southeastern U.S. coastline. The reason for the large number of intense −CGs in this region is not clear. While perhaps associated with the high conductivity of the underlying saltwater, the fact that this pattern tends to extend more than 100 km inland suggests that surface characteristics are not the only causative factor.

Exactly why some LPC+CGs produce sprites and elves, but many others do not, is not clear, as is the reason for the apparent lack of optical emissions from LPC−CGs. Coordinated remote sensing studies of the entire discharge associated with LPCCGs including the use of 3D mapping technologies such as LDAR and video imaging of the lightning in the stratiform region could prove highly useful.

There have been relatively few studies of stroke multiplicity. This study found significant geographic differences in multiplicity as a function of both peak current and polarity. CGs with multiplicity ≥10 were found to be restricted mostly to land areas. Surprisingly over 1000 +CGs with a reported multiplicity ≥10 were found.

Studies by Pierce (1970) and Orville (1990) have suggested that there may be general latitudinal trends in average stroke multiplicity (smaller values poleward) and average peak current (higher values equatorward). While this indeed may be the case, it is apparent from this study that there are substantial regional-scale perturbations in these parameters that will make it difficult to readily determine global-scale patterns.

Lightning protection engineering guidelines generally assume average peak current values, perhaps differentiating between mean values of positive and negative flashes. Certain parts of the nation, however, have markedly higher concentrations of LPC+CGs and possibly longer and more powerful continuing currents. The engineering implications for utilities and other lightning-sensitive installations are unknown but there may be a need to take these findings under consideration. Similarly, while lightning flash densities are markedly lower in marine areas, this study finds that over portions of the U.S. coastal waters there is a greatly elevated probability that any −CG encountered may have a very large peak current.

Recent attempts to estimate NO_x production from lightning using NLDN data (Biazar and McNider 1995) have assumed spatially homogeneous distributions of peak currents. Especially if NO_x production were found to be nonlinearly related to peak current, the regional differences in LPCCG flash densities may prove important.

The reader should note that a complete set of color illustrations supplementing this paper can be found at http://www.FMA-Research.com.

Acknowledgments. This research was conducted with support from the National Aeronautics and Space Administration, Kennedy Space Center, under SBIR Contracts NAS10-11974 and NAS10-12113. We acknowledge the considerable support of and interactions with Global Atmospherics, Inc., and in particular, Ken Cummins. We would like to acknowledge the valuable contributions during the several SPRITE campaigns conducted at Yucca Ridge with a number of individuals including Russ Armstrong, Ron Bentti, William Boeck, James Brundell, Richard Dowden, Hiroshi Fukunishi, Emily Glass, Les Hale, Umran Inan, Paul Krehbiel, Carl Lennon, Launa Maier, Lee Marshall, Steven Mende, Robert Nemzek, Rick Rairden, Steven Reising, Michael Taylor, Davis Sentman, Mark Stanley, David Suszcynsky, Yukihiro Takahashi, Roland Tsunoda, Otha H. Vaughan Jr., Gene Wescott, and especially John R. Winckler and Earle Williams. Cecil S. Keen, Mankato State University, graciously contributed technical illustrations. Technical editing prior to submission was done by Liv Nordem Lyons.

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