

Pre- and Postupgrade Distributions of NLDN Reported Cloud-to-Ground Lightning Characteristics in the Contiguous United States

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(Manuscript received 13 November 2009, in final form 16 April 2010)

ABSTRACT

The National Lightning Detection Network (NLDN) underwent a major upgrade during 2002–03 that increased its sensitivity and improved its performance. It is important to examine cloud-to-ground (CG) lightning distributions before and after this upgrade because CG characteristics depend on both measurement capabilities and meteorological variability. This study compares preupgrade (1996–99, 2001) and postupgrade (2004–09) CG distributions over the contiguous United States to examine the influence of the recent upgrade and to provide baseline postupgrade averages. Increased sensitivity explains most of the differences in the pre- and postupgrade distributions, including a general increase in total CG and positive CG (+CG) flash densities. The increase in +CG occurs despite the use of a greater weak +CG threshold for removing ambiguous +CG reports (post 15 kA versus pre 10 kA). Conversely, the average +CG percentage decreased from 10.61% to 8.65% following the upgrade. The average +CG (–CG) multiplicity increased from 1.10 (2.05) before to 1.54 (2.41) after the upgrade. Since true +CG flashes rarely contain more than one return stroke, explanations for the greater than unity +CG multiplicities remain unclear. Postupgrade results indicate that regions with mostly weak peak current +CG flashes now exhibit greater average +CG multiplicities, whereas regions with mainly strong +CG flashes now exhibit smaller average +CG multiplicities. The combination of NLDN performance, meteorological conditions, and physical differences in first –CG return strokes over saltwater produce maxima in –CG multiplicity and peak current over the coastal waters of the southeast United States.

1. Introduction

Lightning-related fatalities and economic losses have inspired extensive cloud-to-ground (CG) lightning research, much of which has used data from the National Lightning Detection Network (NLDN). The NLDN began full-time operation in 1989 (Orville 2008), and changing performance requirements have motivated major upgrades during 1994–95 and 2002–03 (Cummins and Murphy 2009). It is important to examine NLDN-derived CG characteristics following the most recent upgrade because regional verification studies and operational applications require knowledge of its detection capabilities. Lyons et al. (1998) stated that “given the large regional variability in lightning characteristics, one might ask if they are truly meteorological in nature, or

could they be in part artifacts of the measurements?” Cummins et al. (2005) also emphasized the need to differentiate between real climatological differences in measured lightning parameters and the performance of the lightning detection network. Therefore, we apply the same methodology to pre- and postupgrade NLDN datasets to allow direct quantitative comparisons between them and thereby examine the influence of the recent upgrade on observed CG lightning characteristics.

Several climatologies have described CG patterns over the contiguous United States prior to the 2002–03 upgrade (e.g., Orville and Huffines 1999, 2001; Zajac and Rutledge 2001; Orville et al. 2002). These climatologies documented the spatial and temporal distribution of CG flashes, as well as their polarity, estimated peak current I_p , and multiplicity (i.e., number of return strokes). They revealed complex patterns that showed strong geographical, diurnal, and interannual variability (Orville et al. 2002). These studies also related variability in the CG distributions to varying environmental conditions and storm-scale processes. This large-scale

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meteorological variability is not affected by the NLDN technology and should be observed in both the pre- and postupgrade climatologies.

Studies that have examined preupgrade relationships among the polarity, multiplicity, and I_p of CG flashes provided the background and motivation for the present investigation. Approximately 10% of global CG is +CG (Uman 1987), but this percentage varies by region and season (e.g., Orville and Huffines 2001). Positive CG flashes typically consist of a single return stroke (e.g., Lyons et al. 1998), whereas the great majority of -CG flashes contain more than one return stroke, regardless of geographical location and storm type (Rakov and Huffines 2003). Orville et al. (2002) found that the first stroke -CG I_p increases with increasing multiplicity, whereas +CG I_p decreases with increasing multiplicity. Thus, the strongest +CG flashes (greatest I_p) typically contain a single return stroke, while the strongest -CG flashes (greatest $|I_p|$) typically consist of multiple return strokes.

The local mesoscale environment indirectly influences CG polarity by directly controlling storm structure, dynamics, and microphysics, and in turn, storm electrification (Carey and Buffalo 2007). For example, the northern plains almost exclusively exhibit a combination of atmospheric conditions that lead to extraordinary vertical convective development and +CG dominated storms (Williams et al. 2005). They identified a ridge of enhanced wet bulb potential temperatures that originates over the Gulf of Mexico and extends north to south along the eastern margin of the Rocky Mountains from Texas to the Dakotas. They noted an unusual combination of enhanced instability and high cloud-base height (CBH) along and just west of this north-south corridor. Under these conditions, broad updrafts (scaled by higher cloud bases) likely result in less entrainment, greater updraft speeds, faster collision velocities in the mixed phase region, and reversed polarity charging (Carey and Buffalo 2007). This geographic relationship underscores the interdependence between CG characteristics and environmental conditions.

Increased NLDN sensitivity following the 2002-03 upgrade affects CG measurements, and in turn the distributions of CG characteristics (Cummins et al. 2006). This increased sensitivity provides impetus for the present study. However, it is important to note that the increased postupgrade NLDN sensitivity is not uniform and that the relocation of NLDN sensors during the upgrade also likely influences the postupgrade distributions. Cummins et al. (2006) described the postupgrade sensitivity in terms of estimated minimum detectable I_p . Their Fig. 5 showed that the estimated minimum detectable I_p varies regionally from 4 to 6 kA following the upgrade.

Cummins and Murphy (2009) noted that NLDN geometry was not as good near the edges of the network, where sensors were located only on one side of the detected flash rather than encircling its location. We do not directly address the role of sensor locations on the sensitivity of the postupgrade NLDN, but mention it as an additional source of variability as suggested before the upgrade by Orville and Huffines (2001).

2. Data and methods

Our CG dataset was collected by the NLDN, which is owned and operated by Vaisala Inc. The NLDN reports the location, time, polarity, estimated peak current I_p , and multiplicity of CG flashes. The 2002-03 upgrade resulted in a stroke detection efficiency (DE) of 60%-80%, a flash DE of 90%-95%, and a median location accuracy better than 500 m (Cummins and Murphy 2009). The greatest improvements in NLDN detection capability were near the edges of the network, including Florida, the Gulf Coast, the West Coast, and the U.S.-Mexico border (Cummins et al. 2006). Based on rocket-triggered lightning data in Florida, Jerauld et al. (2005) found a postupgrade stroke DE of near 100% for strokes having I_p greater than 30 kA, 60%-70% for strokes between 10-30 kA, and less than 30% for strokes between 5 and 10 kA.

We separately analyzed 5 yr of CG data preceding the 2002-03 upgrade (1996-99, 2001) and 6 yr following the upgrade (2004-09). The year 2000 was omitted because our NLDN archive is incomplete for that year. These relatively short periods can be influenced by individual events and decadal or interannual variability. Therefore, we focus on large-scale CG patterns and their differences in the pre- and postupgrade datasets. The present study only examines the I_p of the first return stroke, with +CG flashes defined by I_p greater than +10 kA (preupgrade), +15 kA (postupgrade), and +20 kA (pre- and postupgrade comparisons).

All CG flashes were counted and averaged within 10×10 km grid cells to compute the average total CG, +CG, and -CG flash density, multiplicity, and I_p . Multiplicity and I_p both were summed within each grid cell and divided by the flash count to obtain averages. Flash counts were divided by the number of years and grid cell area (100 km^2) to obtain units of flashes per kilometers squared per year. Since the choice of map color scales is somewhat arbitrary and can lead to ambiguity, we also computed regionally averaged statistics to allow quantitative pre- and postupgrade comparisons and provide baseline postupgrade regional values. Regional averages were computed by dividing the total domain into five continental regions (Fig. 1) and two

maritime regions (i.e., the Great Lakes and the oceans within 100 km of shore). Their boundaries were based on general climate divisions and CG lightning distributions.

The capabilities and limitations of the NLDN should be discussed before proceeding. Both CG and intracloud (IC) flashes radiate electromagnetic energy over a large range of frequencies, producing pulses with a wide range of rise times and durations (Cummins and Murphy 2009). Lightning detection technologies monitor the low-frequency (LF), very low-frequency (VLF), and very high-frequency (VHF) bands, and then process the detected waveforms to identify and locate CG and IC flashes. Although the NLDN operates in the LF/VLF range and primarily focuses on CG lightning, it also detects pulses produced by strong IC flashes and the in-cloud components of CG flashes (Cummins and Murphy 2009). Following the 1994–95 upgrade, Cummins et al. (1998) suggested that +CG reports with I_p less than 10 kA be considered IC flashes unless confirmed otherwise.

There has been much recent discussion about the appropriate threshold for classifying weak NLDN reports as true CG flashes. Following the 2002–03 upgrade, Cummins et al. (2006) noted that +CG reports with I_p between 10 and 20 kA represent a mixture of CG and IC flashes, and Biagi et al. (2007) suggested the removal of weak +CG reports with I_p less than 15 kA. The number of ambiguous +CG reports (10–20 kA) increased following the 2002–03 upgrade due to the enhanced sensitivity of the new NLDN sensors and the relaxation of waveform criteria to allow limited IC detection (Cummins and Murphy 2009). Specifically, Vaisala removed a narrow peak-to-zero rise time restriction during April 2006 to allow limited IC detection (Cummins et al. 2006).

Removing the rise-time restriction influences the detection and classification of weak NLDN reports. Fleenor et al. (2009) discussed the influence of this NLDN modification based on the results of a field campaign in the central Great Plains during July 2005. They found that 13 of 229 (5.7%) video-recorded +CG strokes were not reported by the NLDN because of short peak-to-zero rise times in their waveforms. Specifically, the small peak-to-zero rise time caused these reports to be misclassified as IC flashes; so they were not reported by the NLDN location algorithm during July 2005. Fleenor et al. (2009) noted that these flashes would be reported as IC flashes by the present NLDN algorithm (since April 2006).

Fleenor et al. (2009) further determined that the present NLDN algorithm (since April 2006) could have reported 18 of 23 unreported single-stroke +CG flashes, but that 7 would have been erroneously classified as IC

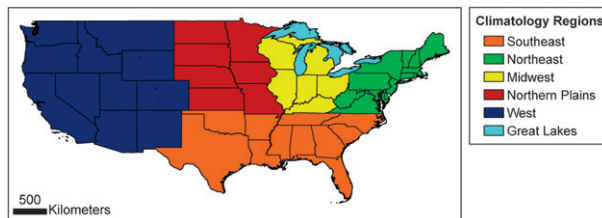


FIG. 1. Areas used to compute regional averages of CG characteristics. These regions are based on general climatic divisions and CG lightning distributions.

flashes. Interestingly, the majority of weak –CG discharges (<10 kA) in +CG dominated storms also have been found to represent misclassified IC flashes (Cummins et al. 2006). Fleenor et al. (2009) examined 204 misclassified CG flashes, noting that the NLDN would categorize 69% of them based on the polarity of the largest rapid excursion of the peak field rather than the polarity of the initial deflection. They found that 59% of the misclassified pulses were assigned an incorrect initial polarity by the NLDN and that the classification problem appeared to be worse when the IC pulses were bipolar with nearly equal positive and negative peak amplitudes. Since weak +CG and –CG NLDN reports influence CG distributions, we discuss their postupgrade influence in the following sections.

3. Results and discussion

We first compare national distributions of annual total CG and strong +CG flash density (>20 kA) before and after the 2002–03 upgrade (Fig. 2). Similar features appear in both the pre- and postupgrade distributions of total CG flash density (Figs. 2a,c) and strong +CG flash density (Figs. 2b,d). The total CG flash density distribution contains maxima over the central and southeast United States (Fig. 2a), with portions of Florida exhibiting greater than 9 CG flashes per kilometers squared per year. Figure 2e illustrates differences in total CG flash density following the upgrade (i.e., postupgrade minus preupgrade). Total CG densities are greater (positive values) in the central, midwest, and northeast United States after the upgrade (>1 flash per kilometers squared per year), whereas smaller postupgrade values (negative values) occur over portions of the west and southeast United States. The greater postupgrade flash densities likely represent the improved detection efficiency mentioned by Cummins et al. (2006). Conversely, reduced flash densities may represent improved classification methods (i.e., strokes versus flashes and IC versus CG) or differences due to interannual or decadal variations in lightning incidence.

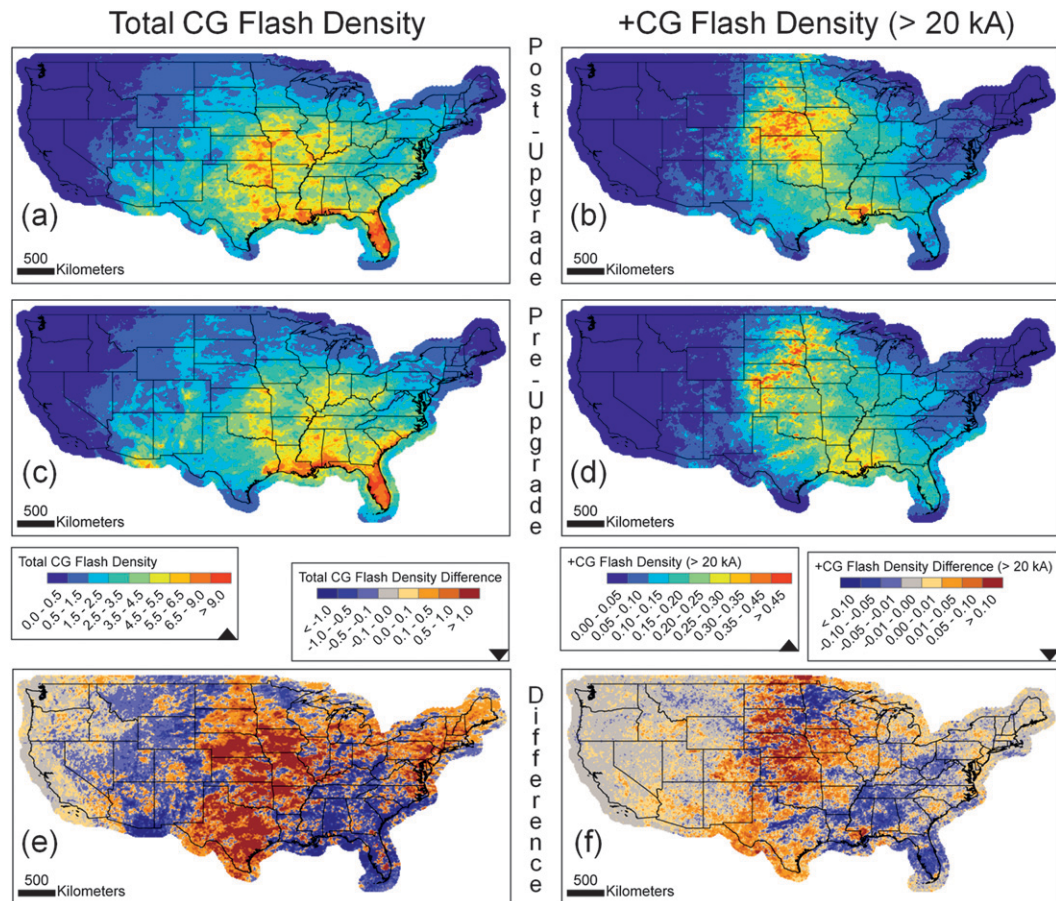


FIG. 2. (a)–(d) The average preupgrade (1996–99, 2001) and postupgrade (2004–09) total CG and strong +CG ($I_p > 20$ kA) flash densities (flashes per kilometers squared per year); (e),(f) differences following the upgrade (postupgrade minus preupgrade). (a) Postupgrade total CG flash density, (b) postupgrade strong +CG flash density, (c) preupgrade total CG flash density, (d) preupgrade strong +CG flash density, (e) difference in total CG flash density, and (f) difference in strong +CG flash density. Note that the pre- and postupgrade flash density distributions share a common color scale, but the color scales differ between the total CG and strong +CG densities.

Biagi et al. (2007) noted that as many as 95% of all +CG reports with I_p exceeding 20 kA are true CG flashes. Therefore, we used this threshold to define strong +CG flashes (>20 kA) for pre- and postupgrade comparisons. The pre- and postupgrade strong +CG flash density distributions generally exhibit similar features (Figs. 2b,d). Postupgrade results (Fig. 2b) show that greater than 0.15 +CG flashes per kilometers squared per year occur throughout the Great Plains, Midwest, and central Gulf Coast, with values exceeding 0.35 +CG flashes per kilometers squared per year over portions of these regions. The strong +CG flash density maximum in the northern plains now covers a larger area (Fig. 2b) and exhibits greater densities following the upgrade (Fig. 2f). Interestingly, the strong +CG flash densities along the border of Louisiana and Mississippi are 0.1 flashes per kilometers squared per year greater after the upgrade, despite a general decrease in the Southeast.

We further examine pre- and postupgrade +CG distributions since they provide additional insight into both NLDN detection capabilities and large-scale meteorological variability (Fig. 3). As noted earlier, there does not appear to be a unique threshold for classifying a weak-positive report as a true +CG stroke; however, an I_p of +15 kA appears to be the value where the number of false CG reports equals the number of correct reports (Biagi et al. 2007).

Figure 3b reveals greater +CG flash densities following the upgrade, despite our use of the 15-kA threshold compared to 10 kA before the upgrade (Fig. 3a). Larger areas of the northern plains and Gulf Coast now exhibit greater than 0.35 +CG flashes per kilometers squared per year (Fig. 3b), and both regions now contain maxima exceeding 0.45 +CG flashes per kilometers squared per year. Conversely, the larger +CG threshold (15 kA) reduces +CG flash densities in Florida. Orville and

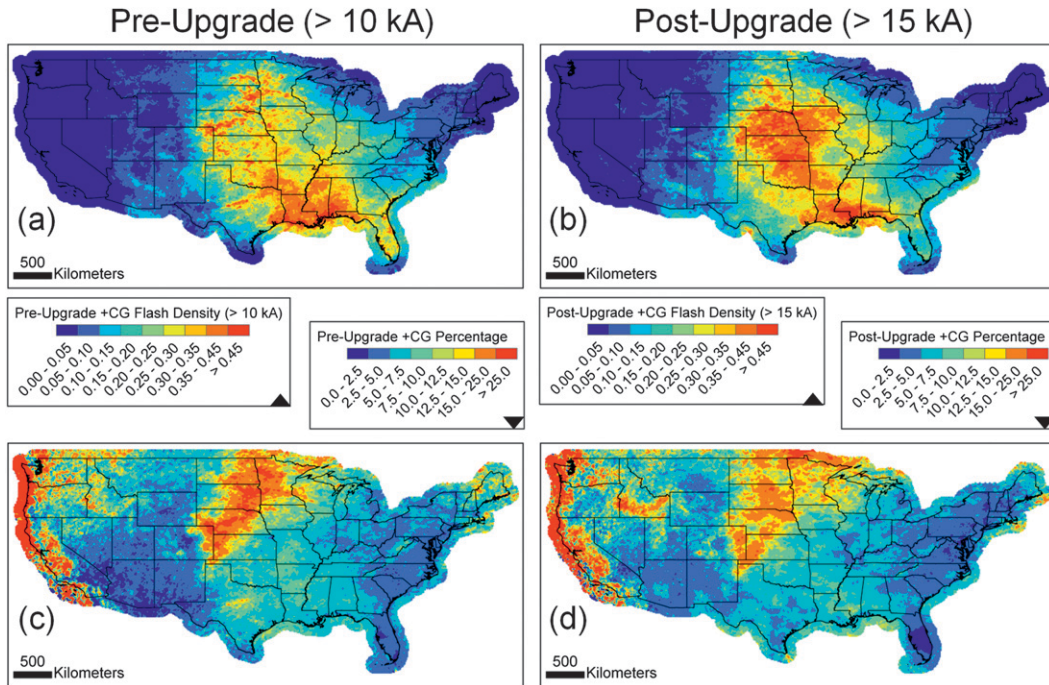


FIG. 3. Average preupgrade (1996–99, 2001) and postupgrade (2004–09) +CG flash density (flashes per kilometers squared per year) and +CG percentage (%). (a) Preupgrade +CG flash density (>10 kA), (b) postupgrade +CG flash density (>15 kA), (c) preupgrade +CG percentage, and (d) postupgrade +CG percentage. Note the expansion of the +CG flash density maximum in the northern plains and the reduced +CG percentage in this region following the upgrade.

Huffines (2001) also described the preupgrade +CG flash density maximum in Florida that is absent in our postupgrade results. Differing meteorological conditions (e.g., extreme individual events and interannual or decadal variability) likely contribute some of the observed differences between pre- and postupgrade periods. However, increased NLDN sensitivity, the use of a different weak +CG threshold, and modified flash discrimination criteria (IC versus CG) may also contribute to the observed differences.

Although +CG flash densities are greater in most regions following the upgrade (Figs. 3a,b), average +CG percentages are generally smaller than before (Figs. 3c,d). The national average +CG percentage decreases from 10.61% before the upgrade to 8.65% afterward (Table 1). Figure 3d reveals that the +CG percentage maximum over the northern plains is larger in area following the upgrade; the +CG percentages generally are greater along the Pacific Coast; and a region of increased values now is apparent in southern Idaho. The greatest regionally averaged +CG percentages (>12%) are located in the northern plains and over the oceans (Table 1), while the smallest average +CG percentages (<6%) occur in the Northeast and Southeast.

The prominent +CG maximum in the northern plains has been well documented (e.g., Lyons et al. 1998;

Orville et al. 2002; Fleenor et al. 2009) and is most evident in the distributions of +CG percentage (Fig. 3d) and +CG I_p (Fig. 4e). The majority of strong +CG flashes (>20 kA) in the northern plains occur in the cores of reversed polarity storms and in the stratiform regions of frequently occurring nocturnal mesoscale convective systems (MCSs; e.g., MacGorman and Burgess 1994; Lyons et al. 1998; Fleenor et al. 2009).

Smith et al. (2000) showed that +CG-dominated storms most often formed near strong gradients of surface equivalent potential temperature θ_e upstream from

TABLE 1. Preupgrade (1996–99, 2001) and postupgrade (2004–09) average +CG percentage for the entire contiguous United States and for each climatological region (Fig. 1). Note that values within 100 km of the United States that are in Mexico and Canada contribute to the overall averages but not to any individual region.

Region	Preupgrade (%)	Postupgrade (%)	Post- minus preupgrade
West	7.51	8.60	+1.09
Northern plains	13.38	12.06	-1.32
Midwest	6.55	6.62	+0.07
Northeast	5.49	3.91	-1.58
Southeast	6.13	5.77	-0.36
Oceans	13.60	13.44	-0.16
Great Lakes	7.37	7.84	+0.47
National avg	10.61	8.65	-1.96

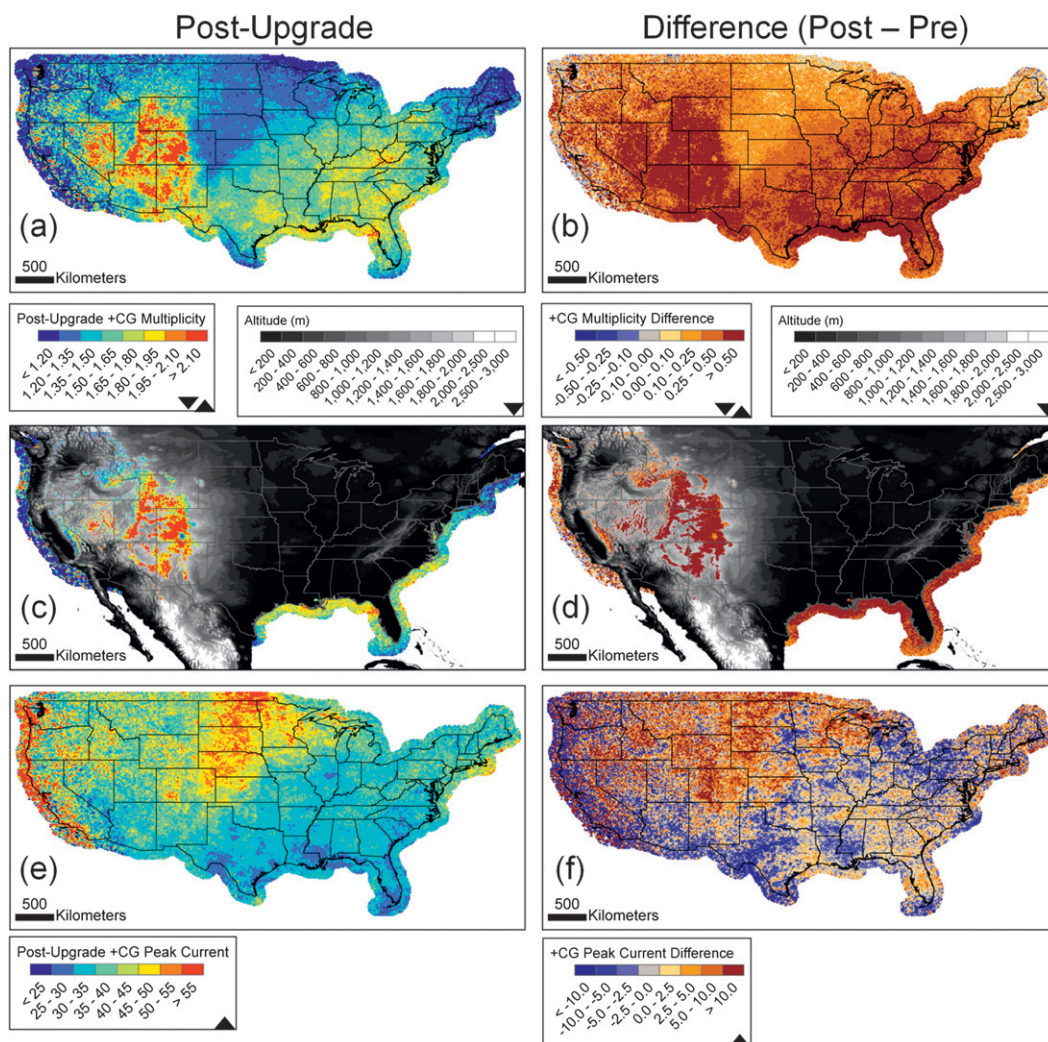


FIG. 4. Average postupgrade (2004–09) +CG multiplicity (number of return strokes), estimated peak current (I_p ; kA), and the difference between the preupgrade (1996–99, 2001) and postupgrade values (postupgrade minus preupgrade). (a) Postupgrade +CG multiplicity; (b) difference in +CG multiplicity; (c) as in (a), but with elevations overlaid and heights above 2000 m set as transparent; (d) as in (b), but with elevations overlaid and heights above 2000 m set as transparent; (e) postupgrade +CG peak current; and (f) difference in +CG peak current. Note the large postupgrade increase in average +CG multiplicity throughout the United States, and the collocation of values exceeding 2.1 and elevations exceeding 2000 m in the Mountain West.

the θ_e maximum. These +CG-dominated storms either intensified as they crossed the θ_e maximum before changing to dominant –CG polarity, or moved adjacent to the θ_e maximum and remained +CG dominated throughout their lifetimes.

Reversed polarity (+CG dominated) storms are most common in relatively dry environments with high cloud bases and shallow warm cloud depths (e.g., Carey and Buffalo 2007). Given the assumption that high liquid water content in the mixed phase region is needed for positive charging of large ice particles, the coincidence of instability and greater CBH may serve to focus clouds

with inverted electrical polarity to the midcontinent (Williams et al. 2005). Conversely, Williams et al. (2005) described the transition to predominantly negative polarity as storms move eastward into areas of lower climatological CBH. Thus, regions having a relatively moist troposphere experience fewer +CG-dominated storms (Knapp 1994).

The southeast United States contains a secondary maximum of +CG flash density along the central Gulf Coast (Fig. 3b) but also exhibits the minimum +CG I_p (32.4 kA; Table 2). Average CG I_p varies regionally due to differences in storm characteristics and network

TABLE 2. Preupgrade (1996–99, 2001) and postupgrade (2004–09) average +CG multiplicity (number of return strokes) and peak current (I_p ; kA) for the entire contiguous United States and for each climatological region (Fig. 1). Note that values within 100 km of the United States that are in Mexico and Canada contribute to the overall averages but not to any individual region.

Region	+CG multiplicity		+CG peak current	
	Preupgrade	Postupgrade	Preupgrade	Postupgrade
West	1.13	1.62	40.5	40.0
Northern plains	1.11	1.36	41.7	43.5
Midwest	1.13	1.54	36.9	36.1
Northeast	1.11	1.50	37.4	35.2
Southeast	1.13	1.63	34.2	32.4
Oceans	1.09	1.53	40.6	38.0
Great Lakes	1.12	1.43	38.4	37.6
National avg	1.10	1.54	32.4	37.9

performance (e.g., Biagi et al. 2007). Although the national average +CG I_p increases following the 2002–03 upgrade (Table 2), the regional average only increases in the northern plains. Surprisingly, regions with mostly strong +CG flashes exhibit relatively small +CG multiplicities (e.g., northern plains; Table 2); whereas regions with mostly weak +CG flashes exhibit greater average +CG multiplicities (e.g., Southeast; Table 2). The reduced occurrence of +CG dominated storms in the Southeast (Knapp 1994) and the tendency for +CG flashes to occur in the periphery of –CG-dominated storms (Engholm et al. 1990) suggest that most true +CG flashes occur outside the deep convection in the Southeast. Conversely, weak +CG reports (15–20 kA) occur most frequently within the main convective region of –CG-dominated storms. Therefore, we speculate that the small average +CG I_p in the Southeast indicates that there are more ambiguous +CG reports than actual strong +CG flashes in this region.

We observe several unusual +CG characteristics following the upgrade, with greater average +CG multiplicities being most notable (Table 2). Although the detection of more single-stroke weak +CG flashes following the upgrade might suggest smaller average +CG multiplicities, surprisingly the national average +CG multiplicity actually increases from 1.10 before the upgrade to 1.54 after (Table 2). This finding is unusual since +CG flashes typically contain only a single return stroke, and multistroke +CG flashes are rare (Rakov 2003). Average +CG multiplicities increase by ~ 0.5 return strokes over much of the contiguous United States (Fig. 4b), with values now exceeding 2 in large portions of the Mountain West (Fig. 4a). Figures 4c,d illustrate the collocation of large average +CG multiplicities and elevations above 2000 m (i.e., the transparent areas). The elevated terrain may influence the physical characteristics

of CG flashes as well as the propagation and detection of their emitted signals.

Explanations for greater postupgrade average +CG multiplicities remain unclear but may include misclassified IC pulses having equally strong positive and negative peak amplitudes (e.g., Fleenor et al. 2009), upward-propagating bipolar flashes with mixed polarity return strokes (e.g., Rakov 2003), or possible effects of elevated rocky terrain. These factors likely combine to produce the greater postupgrade average +CG multiplicities (Figs. 4b,d). For example, upward-propagating bipolar flashes may contribute to the increased +CG multiplicities over the Southeast (Table 2), but the large number of misclassified IC flashes suggests that they are more influential in this –CG-dominated region. Conversely, the terrain complicates CG distributions in the West, which exhibits both above average +CG multiplicity and I_p (Table 2). Specifically, upward-propagating bipolar flashes may occur more frequently over elevated terrain, and the conductivity of the underlying surface has a strong influence on the attenuation of the signal produced by CG flashes (e.g., Honma et al. 1998; Cummins et al. 2005), and in turn the resolution of the NLDN. Therefore, future waveform recording and video observation studies will be required to determine the source of the unusually large postupgrade average +CG multiplicities.

The Pacific Coast also exhibits notable +CG characteristics, with relatively large average +CG percentages ($>30\%$; Fig. 3d) and +CG I_p (>55 kA; Fig. 4e). These +CG maxima likely are descriptive of the common storm types in this region (e.g., winter storms and low-precipitation summer storms). Specifically, similar features appear in the +CG percentage distributions before (Fig. 3c) and after (Fig. 3d) the upgrade, suggesting that large-scale meteorological variability contributes significantly to these +CG maxima. The NLDN detection efficiency may also contribute to the Pacific Coast +CG maxima. Specifically, the location near the edge of the network (Cummins and Murphy 2009) and elevated rocky terrain (e.g., Cummins et al. 2005) complicate the propagation and detection of CG signals in this region. Therefore, future studies also should aim to expand our understanding of +CG patterns along the Pacific Coast.

The distributions of average –CG multiplicity and I_p also differ considerably in the pre- and postupgrade climatologies (Fig. 5). Following the upgrade, the national average –CG multiplicity increases from 2.05 to 2.41 (Table 3), whereas the national average –CG I_p decreases from 23.7 to 18.8 kA. Thus, average –CG multiplicities are now greater over most of the contiguous United States (Fig. 5e), while the average –CG I_p is generally smaller (Fig. 5f). Increased NLDN sensitivity

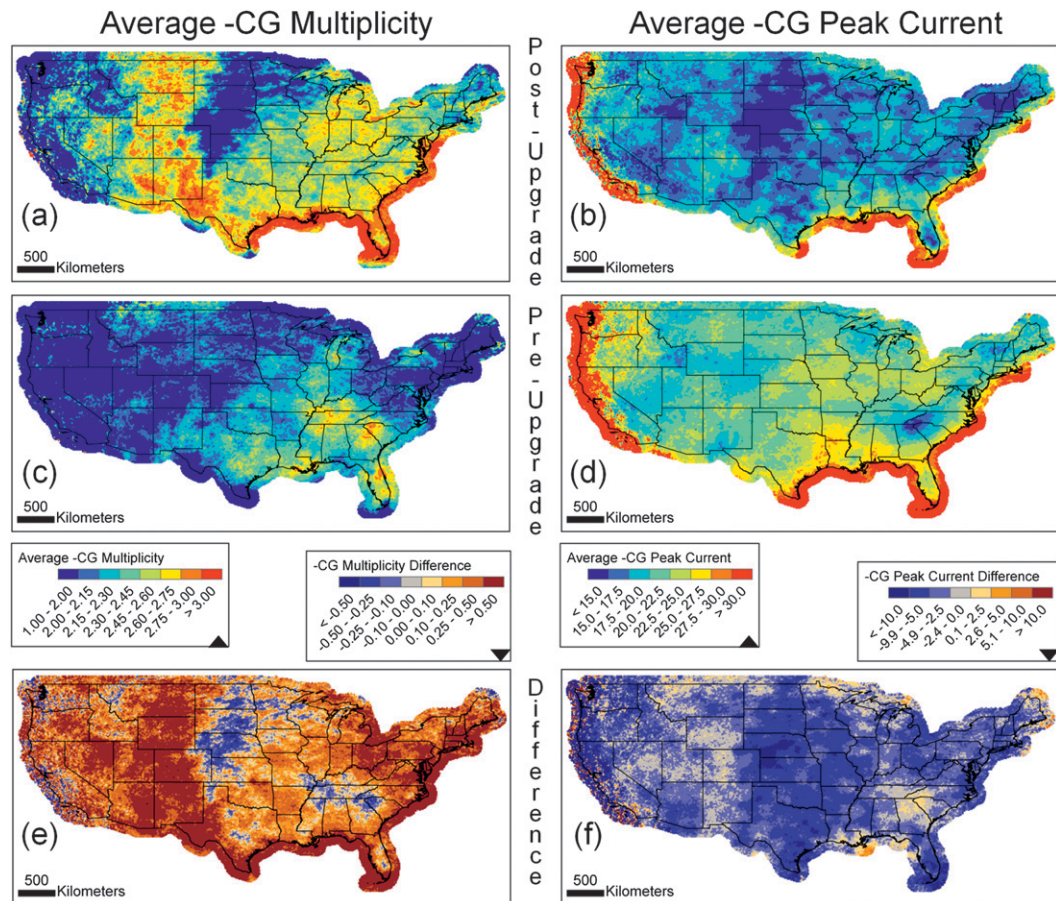


FIG. 5. (a)–(d) The preupgrade (1996–99, 2001) and postupgrade (2004–09) average $-CG$ multiplicity and estimated peak current (I_p ; kA), and (e) and (f) reveal differences following the upgrade (postupgrade minus preupgrade). (a) Postupgrade $-CG$ multiplicity, (b) postupgrade $-CG$ peak current, (c) preupgrade $-CG$ multiplicity, (d) preupgrade $-CG$ peak current, (e) difference in $-CG$ multiplicity, and (f) difference in $-CG$ peak current. Note the coastal maxima in both of the postupgrade distributions and that the postupgrade $-CG$ multiplicity (peak current) generally increased (decreased).

may explain both of these changes. Specifically, the improved detection of weak subsequent strokes may increase average $-CG$ multiplicities, while the improved detection of weak single-stroke flashes may decrease the average $-CG I_p$. Figure 5e also shows a notable increase in average $-CG$ multiplicities in the Mountain West (>0.5), the same region that now exhibits the maximum average $+CG$ multiplicities (>2.10 ; Fig. 4a). However, the greater average $-CG$ multiplicities (Fig. 5a) do not appear as closely related to elevation as the large $+CG$ multiplicities (Fig. 4a). Future research will also be required to more clearly explain the postupgrade $-CG$ multiplicity distributions.

The greatest average $-CG$ multiplicity (Fig. 5a) and largest average $-CG I_p$ (Fig. 5b) occur over the coastal waters of the Gulf of Mexico and Atlantic Ocean. One should note that to lessen the influence of NLDN detection limitations outside of the network (e.g., Cummins

and Murphy 2009) the present study only examines CG flashes within 100 km of the coastline. Table 3 reveals that the oceans exhibit the greatest regional average $-CG$ multiplicity (2.65) and I_p (28.7). The conductivity of the underlying surface strongly influences the attenuation of signals produced by CG flashes (e.g., Honma et al. 1998; Cummins et al. 2005), and in turn may have a modest impact on the detection efficiency of the NLDN. For example, Lyons et al. (1998) suggested that the greater conductivity of saltwater decreases the attenuation of the return stroke signal, leading to improved stroke detection efficiency and greater $-CG$ multiplicity.

Interestingly, Cummins et al. (2005) provided evidence that the enhanced $-CG I_p$ over the oceans (Fig. 5b) may be due to differences in the attachment processes in first $-CG$ return strokes. This enhancement does not occur for positive first strokes (Fig. 4e) or for negative subsequent strokes in preexisting channels

TABLE 3. Preupgrade (1996–99, 2001) and postupgrade (2004–09) average –CG multiplicity (number of return strokes) and peak current (I_p ; kA) for the entire contiguous United States and for each climatological region (Fig. 1). Note that values within 100 km of the United States that are in Mexico and Canada contribute to the overall averages but not to any individual region.

Region	–CG multiplicity		–CG peak current	
	Preupgrade	Postupgrade	Preupgrade	Postupgrade
West	1.89	2.36	–22.5	–18.1
Northern plains	2.07	2.11	–21.8	–15.4
Midwest	2.19	2.48	–21.9	–17.6
Northeast	1.96	2.43	–21.3	–16.9
Southeast	2.31	2.59	–23.5	–18.6
Oceans	2.01	2.65	–34.9	–28.7
Great Lakes	2.12	2.54	–22.3	–18.4
National Avg	2.05	2.41	–23.7	–18.8

(Cummins et al. 2005). They speculated that enhanced –CG I_p is due to a greater peak electric field that seems to be uniquely associated with downward-propagating, negative stepped leaders that attach to a smooth, highly conducting ocean surface. Large average –CG multiplicity and I_p are absent over the freshwater Great Lakes (Table 3), further indicating that differences are associated with saltwater properties over the oceans.

The enhanced offshore –CG multiplicity and I_p exhibit spatial variations (Figs. 5a,b) with some patterns appearing both before and after the upgrade (Fig. 5). For example, note the transition from greater to smaller average –CG multiplicity and I_p from south to north along the Atlantic Coast. Thus, it is likely that much of this offshore variability is meteorological in nature. Although meteorological explanations for the greater average –CG multiplicity and I_p off the Southeast coast remain unclear, these maxima may be related to the mechanisms that have been used to explain the land–sea contrast in –CG flash rates.

Williams et al. (2005) provided evidence that higher flash rates in the tropics, and by assumption larger updrafts, typically occur when the CBH is higher. Their findings support the Williams and Stanfill (2002) suggestion that the height of the cloud base is a key factor in explaining contrasts in lightning between land and ocean. However, Williams et al. (2005) noted that the effect of instability appears to dominate over the effect of CBH in the Southeast compared to regions farther north and west. Thus, greater –CG flash rates over land in the Southeast (Fig. 2a) appear to be associated with both higher cloud bases and greater instability compared to oceanic regions. Although Williams et al. (2005) focused on the thermodynamic aspects of the land–sea contrast in lightning activity, their study and

others (e.g., Williams and Stanfill 2002) also have described the role of land–sea contrasts in aerosol distributions. These thermodynamic and aerosol contrasts are important to our understanding of CG production and storm-scale processes, and must be understood to accurately apply data from newly emerging long-range LF/VLF lightning detection networks.

The northern plains are a final example of the interdependence between CG characteristics and NLDN performance. Both +CG and –CG multiplicities (Figs. 4a and 5a) exhibit minima in this region, nearly coincident with the +CG percentage maximum (Fig. 3d), above-average +CG I_p (Fig. 4e), and below-average –CG I_p (Fig. 5b). NLDN measurement limitations partly explain this collocation since recent studies suggest that +CG-dominated storms in this region often contain large percentages of misclassified single-stroke weak –CG flash reports (I_p between 0 and –10 kA; Cummins and Murphy 2009). These weak cloud pulses explain the minima of –CG multiplicity and I_p in this region. Conversely, strong +CG flashes occur frequently in this region and account for the prominent +CG I_p maximum (Fig. 4e) and +CG multiplicity minimum (Fig. 4a). Thus, this region also illustrates the relative charge dissipation roles of +CG and –CG flashes within storms common to this region.

4. Summary and conclusions

This study has compared spatial patterns of cloud-to-ground (CG) lightning characteristics before and after the 2002–03 upgrade to the National Lightning Detection Network (NLDN). Results show that total CG and positive CG (+CG) flash densities are greater following the upgrade due to increased NLDN sensitivity. Average total CG and +CG flash densities increased more than 1 CG flash per kilometers squared per year and 0.1 +CG flashes per kilometers squared per year in the central United States, respectively, but generally decreased in the Southeast. Total CG flash densities exhibit similar features before and after the upgrade, with maxima in the central and southeast United States. The greatest increase in strong +CG flash density (>20 kA) occurs within the main +CG maximum in the northern plains. Despite our use of a greater weak +CG threshold (15 kA versus 10 kA preupgrade), the +CG flash density maximum in the northern plains expanded to include larger areas with greater than 0.35 +CG flashes per kilometers squared per year. Conversely, the national average +CG percentage decreased from 10.61% before the upgrade to 8.65% afterward.

Results revealed two +CG flash density maxima in both the pre- and postupgrade climatologies, the first

located in the northern plains and the second along the central Gulf Coast. Although the southeast United States contains a secondary +CG flash density maximum, it exhibits minima in average +CG I_p (32.4 kA) and +CG percentage (5.77%). The improved NLDN sensitivity has increased the number of ambiguous weak +CG reports (15–20 kA; Cummins et al. 2006), which may contribute to an expansion of the +CG flash density maximum over the Gulf Coast. Although strong +CG flashes account for the majority of +CG in the northern plains, weak +CG reports (10–20 kA) are more common in the Southeast. We found that regions containing the most weak +CG (–CG) flashes exhibit greater (smaller) average multiplicities, while regions with mostly strong +CG (–CG) flashes exhibit smaller (greater) average multiplicities. Although these findings are consistent with our understanding of –CG flashes, we expected smaller average multiplicities to accompany the increase in single-stroke weak +CG reports. Surprisingly, average postupgrade +CG multiplicities are greater throughout the United States and now exceed 2 in the Mountain West.

Explanations for the large average postupgrade +CG multiplicities (>2) remain unclear; they may include misclassified intracloud (IC) flashes, upward-propagating bipolar CG discharges, or effects of elevated terrain on the physical properties of CG flashes and the propagation and detection of their emitted signals. Fleenor et al. (2009) found that the misclassification problem was enhanced when strong IC pulses had equal positive and negative peak amplitudes, and that the NLDN often assigned incorrect polarities to these flashes. Enhanced NLDN sensitivity and the modification of waveform processing criteria to allow limited IC detection following the upgrade suggest an increased influence of these strong IC events on NLDN-derived CG distributions. Alternatively, Rakov (2003) described a class of CG flashes that exhibit mixed polarity return strokes, noting that they occurred exclusively in upward-propagating CG flashes. Future studies will be required to determine the relative influence of these factors on the greater postupgrade average +CG multiplicities.

The improved NLDN sensitivity and stroke detection efficiency following the 2002–03 upgrade increased the national average –CG multiplicity (2.41 vs 2.05) but decreased the average –CG I_p (18.81 vs 23.71 kA). The –CG multiplicity and I_p are greatest over the coastal waters of the southeast United States (multiplicity >3 and $|I_p| > 27.5$ kA). These –CG maxima are not observed over the Great Lakes, supporting the Cummins et al. (2005) suggestion that coastal –CG I_p maxima relate to differences in the attachment process (i.e., enhanced peak field) of first –CG return strokes to salt-water surfaces. This finding also supports the Lyons et al.

(1998) suggestion that greater –CG multiplicity results from decreased attenuation of the return stroke signal, and the enhanced detection of subsequent strokes, over the highly conductive saltwater. Similar offshore variations in –CG characteristics appear both before and after the upgrade, suggesting meteorological conditions as a source for this common variability. The –CG distributions underscore the complexities between observed CG characteristics, meteorological variability, and NLDN measurement capabilities. These influences must be understood to fully exploit the information contained in the CG distributions.

Despite continuous NLDN observations since 1989, it remains difficult to quantify the relative contributions of measurement capabilities and meteorological variability to explain some of the CG patterns. The present postupgrade averages provide baseline values for regional NLDN verification studies and for operational applications. In addition to regional variability, seasonal variations also must be understood to directly relate CG production to storm-scale processes. Seasonal patterns are best described on the regional scale, so our ongoing research is analyzing seasonal CG patterns in the Southeast, as well as CG variability on the storm scale. Newly developed methodologies allow analyses of lightning and radar parameters within many individual storms, and detailed examination of relationships between CG production and storm-scale processes. Total lightning networks will provide further insights into the many remaining questions, and combinations of CG and IC datasets will ensure that these data are used to best advantage both now and in the future.

Acknowledgments. Funding for this project was provided by the Florida Power and Light Corp. and NOAA/NESDIS through the Northern Gulf Institute. Additional support was provided by the Vaisala Corp., who collected the CG data and provided many insights regarding the NLDN capabilities. We specifically want to thank Ken Cummins and Ron Holle for their tremendous support. Many others also provided valuable insights, encouragement, and support, including Nick Demetriades, Irv Watson, Steve Goodman, Phil Shafer, and Geoffrey Stano. The anonymous reviewers also provided helpful feedback, and we thank them for their many suggestions.

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