The North American Lightning Detection Network (NALDN)—Analysis of Flash Data: 2001–09

RICHARD E. ORVILLE
Department of Atmospheric Sciences, Texas A&M University, College Station, Texas

GARY R. HUFFINES
School of Earth Sciences and Physics, University of Northern Colorado, Greeley, Colorado

WILLIAM R. BURROWS
Cloud Physics and Severe Weather Research Section, Environment Canada, Edmonton, Alberta, Canada

KENNETH L. CUMMINS
Institute for Atmospheric Physics, The University of Arizona, Tucson, Arizona

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ABSTRACT

Cloud-to-ground (CG) lightning data have been analyzed for the years 2001–09 for North America, which includes Alaska, Canada, and the lower 48 U.S. states. Flashes recorded within the North American Lightning Detection Network (NALDN) are examined. No corrections for detection efficiency variability are made over the 9 yr of the dataset or over the large geographical area comprising North America. There were network changes in the NALDN during the 9 yr, but these changes have not been corrected for nor have the recorded data been altered in any way with the exception that all positive lightning reports with peak currents less than 15 kA have been deleted. Thus, the reader should be aware that secular changes are not just climatological in nature. All data were analyzed with a spatial resolution of 20 km. The analyses presented in this work provide a synoptic view of the interannual variability of lightning observations in North America, including the impacts of physical changes in the network during the 9 yr of study. These data complement and extend previous analyses that evaluate the U.S. NLDN during periods of upgrade. The total (negative and positive) flashes for ground flash density, the percentage of positive lightning, and the positive flash density have been analyzed. Furthermore, the negative and positive first stroke peak currents and the flash multiplicity have been examined. The highest flash densities in Canada are along the U.S.–Canadian border (1–2 flashes per square kilometer) and in the United States along the Gulf of Mexico coast from Texas through Florida (exceeding 14 flashes per square kilometer in Florida). The Gulf Stream is “outlined” by higher flash densities off the east coast of the United States. Maximum annual positive flash densities in Canada range primarily from 0.01 to 0.3 flashes per square kilometer, and in the United States to over 0.5 flashes per square kilometer in the Midwest and in the states of Louisiana and Mississippi. The annual percentage of positive lightning to ground varies from less than 2% over Florida to values exceeding 25% off the West Coast, Alaska, and the Yukon. A localized maximum in the percentage of positive lightning in the NALDN occurs in Manitoba and western Ontario, just north of North Dakota and Minnesota.

When averaged over North America, first stroke negative median peak currents range from 19.8 kA in 2001 to 16.0 kA in 2009 and for all years, average 16.1 kA. First stroke positive median peak currents range from a high of 29.0 kA in 2008 and 2009 to a low of 23.3 kA in 2003 with a median of 25.7 kA for all years. There is a relatively sharp transition from low to high median negative peak currents along the Gulf and Atlantic coasts of the United States. No sharp transitions are observed for the median positive peak currents. Relatively lower positive peak currents occur throughout the southeastern United States. The highest values of mean negative multiplicity exceed 3.0 strokes per flash in the NALDN with some variation over the 9 yr. Lower values of mean negative multiplicity occur in the western United States. Positive flash mean multiplicity is slightly higher than 1.1, with the highest values of 1.7 observed in the southwestern states. As has been noted in prior research, CG lightning has significant variations from storm to storm as well as between geographical regions and/or seasons and, consequently, a single distribution for any lightning parameter, such as multiplicity or peak current, may not be sufficient to represent or describe the parameter.

Corresponding author address: Richard E. Orville, Dept. of Atmospheric Sciences, Texas A&M University, College Station, TX 77843-3150.
E-mail: rorville@tamu.edu

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1. Introduction

Lightning incidence throughout northern Mexico, the continental United States, Canada, Alaska, and nearby coastal waters is currently observed by the North American Lightning Detection Network (NALDN). This network is operated as a seamless integration of the Canadian Lightning Detection Network (CLDN) and the U.S. National Lightning Detection Network (NLDN). Our summaries of annual lightning flash characteristics for the continental United States began in 1989 (Orville 1991, 2008). Papers summarizing lightning incidence observed by the NLDN in subsequent years include 1990–91 by (Orville 1994), 1992–95 by Orville and Silver (1997), 1995–97 by Orville and Huffines (1999), 1995–99 by Zajac and Rutledge (2001), and a summary of the first decade of operation (1989–98) by Orville and Huffines (2001). Following the creation of the NALDN in 1998, a first analysis of lightning incidence throughout the continental United States and Canada during 1998–2000 was reported by Orville et al. (2002). In this paper, we extend the analyses over the years 2001–09 for all flash characteristics reported by the NALDN. Technical descriptions of the NLDN and NALDN are provided by Cummins et al. (1998) and Cummins and Murphy (2009), respectively.

Our summary of annual lightning flash characteristics for the continental United States began in 1989 (Orville 1991, 2008) and have expanded through the years with the addition of sensors to make up the North American Lightning Detection Network (NALDN). Papers summarizing the network and its data in the intervening years include 1990–91 (Orville 1994), 1992–95 by Orville and Silver (1997), 1995–97 by Orville and Huffines (1999), by Cummins et al. (1998), 1995–99 by Zajac and Rutledge (2001) and a summary of the first decade of operation, 1989–98, by Orville and Huffines (2001). The first three years of operation of the NALDN, 1998–2000, were summarized in reports by Orville et al. (2002) and Burrows et al. (2002). In this paper, we extend the analyses over the years 2001 through 2009 for all flash characteristics in the NALDN.

For the benefit of the first-time reader, we summarize the introductory comments of Cummins and Murphy (2009). We report on cloud-to-ground (CG) lightning flashes that transfer negative or positive electrical charge in one or more locations. Much of this charge is transferred in a sequence of individual return strokes; although in some +CG strikes, the continuing current can lower more charge than the return stroke. The return strokes have a nominal duration of 10s of microseconds and are typically separated in time by 20–100 ms. A lightning flash typically contains 2–4 return strokes, but may contain as few as 1 or as many as 26 strokes (Kitagawa et al. 1962). The number of strokes in a flash is frequently referred to as the multiplicity.

2. Data

The distribution of sensors in the network has evolved with time. Figure 1 in Orville et al. (2002) is an accurate depiction of the sensor locations in 2001, but we update this map with our current Fig. 1, which shows the present distribution of 200 sensors. Assuming a nominal detection range of 600 km for each sensor, the area covered by the combined, integrated networks is approximately 20 million km² and is shown in gray. This distribution is a homogenous set of installations over latitudes ranging from 25° to 70° in the west, and 25° to 60° in the east. The Alaska sensors contribute to this dataset starting in 2002. In Canada, two IMPACT-ES sensors were added to the northern Yukon Territory in 2003, and one IMPACT-ES sensor to east-central British Columbia in 2009. Each year since 2005, four to seven LPATS sensors (total of 22) were replaced with LS7000 sensors (Väisälä new IMPACT sensor), which provide time-of-arrival and direction finder information. As part of a 2002–03 upgrade, all NLDN sensors were replaced by improved IMPACT-ESP sensors in the continental United States and eight additional sensors were added to the network (Cummins et al. 2006). Since the U.S. sensors now provide both time-of-arrival and direction finder information, just two sensors are needed to report an event. Väisälä estimates that the NALDN now provides an overall cloud-to-ground detection efficiency (DE) that is better than 90% throughout the continental United States and southern Canada, and that the DE for all CG strokes is in the range of 60%–80% (Cummins et al. 2006).
TABLE 1. Cloud-to-ground flash characteristics in the NALDN for the years 2001–09. (Flashes with positive peak currents <15 kA have been deleted and are not part of any analysis in this paper.)

<table>
<thead>
<tr>
<th>Year</th>
<th>No. of flashes</th>
<th>No. of negative flashes</th>
<th>No. of positive flashes</th>
<th>Percent positive flashes</th>
<th>Median negative peak current (kA)</th>
<th>Median positive peak current (kA)</th>
<th>Negative multiplicity</th>
<th>Positive multiplicity</th>
</tr>
</thead>
<tbody>
<tr>
<td>2001</td>
<td>25 588 983</td>
<td>23 766 832</td>
<td>1 822 151</td>
<td>7.1</td>
<td>−19.8</td>
<td>28.0</td>
<td>2.2</td>
<td>1.1</td>
</tr>
<tr>
<td>2002</td>
<td>28 132 127</td>
<td>26 517 422</td>
<td>1 614 705</td>
<td>5.7</td>
<td>−16.7</td>
<td>26.0</td>
<td>2.5</td>
<td>1.2</td>
</tr>
<tr>
<td>2003</td>
<td>34 566 203</td>
<td>32 902 066</td>
<td>1 664 137</td>
<td>4.8</td>
<td>−14.5</td>
<td>23.3</td>
<td>2.5</td>
<td>1.4</td>
</tr>
<tr>
<td>2004</td>
<td>34 979 527</td>
<td>33 063 593</td>
<td>1 915 934</td>
<td>5.5</td>
<td>−14.8</td>
<td>23.6</td>
<td>2.6</td>
<td>1.5</td>
</tr>
<tr>
<td>2005</td>
<td>35 140 730</td>
<td>33 103 810</td>
<td>2 036 920</td>
<td>5.9</td>
<td>−15.6</td>
<td>23.4</td>
<td>2.4</td>
<td>1.4</td>
</tr>
<tr>
<td>2006</td>
<td>32 648 685</td>
<td>30 712 700</td>
<td>1 935 985</td>
<td>5.9</td>
<td>−16.4</td>
<td>24.0</td>
<td>2.5</td>
<td>1.5</td>
</tr>
<tr>
<td>2007</td>
<td>30 379 579</td>
<td>28 506 618</td>
<td>1 872 961</td>
<td>6.2</td>
<td>−16.0</td>
<td>29.0</td>
<td>2.4</td>
<td>1.4</td>
</tr>
<tr>
<td>2008</td>
<td>31 860 540</td>
<td>29 418 922</td>
<td>2 441 618</td>
<td>7.7</td>
<td>−16.1</td>
<td>25.7</td>
<td>2.5</td>
<td>1.4</td>
</tr>
</tbody>
</table>

2006). Results of this improvement are reported upon by Biagi et al. (2007) in a thorough analysis of the network performance in southern Arizona and in northern Texas and southern Oklahoma in 2003 and 2004. Biagi et al. estimate that the flash detection efficiency in these regions is now 90%–95%. It should be noted that the 2002–03 upgrade did not alter the sensor configuration in Canada so that it continues to have a mix of LPATS and IMPACT sensors. This upgrade contributes to the transition to a larger total CG flash count beginning in 2003.

Four additional changes to the network have been implemented since the 2002–03 upgrade. In July 2004, the propagation model used to estimate peak current values was “tuned” to compensate for altered sensor baselines and network geometry (Cummins et al. 2006). This modification resulted in an average increase in estimated peak current of 14%, matching better with the findings of Jerauld et al. (2005). The addition of cloud discharge reports in the NLDN occurred in April 2006, but these reports are not in our database. Also in 2006, the NLDN added two sensors southeast of Florida, extending the coverage of the northern Caribbean. Finally, in 2008 the NALDN location algorithm was modified to allow better offshore reporting (i.e., at a greater distance). This increased the coverage offshore and in northern Mexico in 2008.

It is important to note that we continue to eliminate all low peak current positive flashes from our analyses. This was initially done in Orville et al. (2002) for positive peak currents less than 10 kA, but was later revised to <15 kA upon the recommendation by K. Cummins (2005, personal communication). In effect, positive flashes with peak currents less than +15 kA have been deleted from our database and since April 2006 have not been part of the Vaisala flash dataset sent to us each month.

A recent paper by Fleenor et al. (2009) offers a cautionary note to the reader in interpreting all analyses that we present. Fleenor et al. conducted a field campaign in the central Great Plains to obtain video imagery of lightning in correlation with reports from the NLDN and broadband electric field waveforms from the Los Alamos Sferic Array (LASA). Based on the LASA waveforms, a total of 204 out of 376 (54%) NLDN reports of CG lightning strokes were determined to be for cloud pulses. The misclassified negative reports had Ip values ranging from 3.8 to 29.7 kA, but only 58 (24%) of these had Ip > 10 kA and only one misclassified positive report had Ip > 20 kA. A similar study by Biagi et al. (2007) in the Texas–Oklahoma and Arizona region indicates that this level of misclassification may be unique to the central Great Plains, but further studies will be required.

We report on the total CG flash density, the positive flash density, the annual percentage of positive flashes, the peak currents, and the flash multiplicity in North America for the years 2001–09. In addition, we show the geographical distribution of all flash characteristics throughout the largest broadband (VLF–LF) network in the world covering approximately 20 million km².

3. Results

All results for the NALDN are summarized into categories of total flash density, positive flash density, percent positive, first stroke peak currents for both polarities, and multiplicity for both polarities. Flash characteristics vary through the 9 of our analyses, but these variations are, in part, the result of new sensor installations and proprietary algorithm modifications in addition to the natural variations of thunderstorm frequency from year to year.

Table 1 provides a summary of annual counts and statistics. The annual number of negative flashes increased by about 20% starting in 2003, presumably due to the NLDN upgrade in 2002–03. The number of positive...
flashes is more stable between 2001 and 2007, but increases by about 20% in 2008–09. This may be due to an increased number of positive flash reports at the edges of the network coverage area, which was extended in 2008. Further discussion of Table 1 will be provided in later subsections.

a. Flash density

Annual flash density maps for all recorded cloud-to-ground lightning in the NALDN are shown for the years 2001–09, in Fig. 2 including a summary map for the 9 yr of study (Fig. 2j).

The highest flash density varies through the years with maxima in Florida in most years, but sharing these maxima with various regions in the central United States since 2002. The enhancements to the network’s detection efficiency after 2001–02, referred to as the 2002–03 upgrade (Cummins and Murphy 2009), are apparent starting in 2003. In this year and later years we see for the first time values of 14+ flashes per square kilometer in the central United States and Florida. The year 2006 is significant in that the annual maximum lightning flash density (14+) is in the southern Illinois–Kentucky border area with lower values occurring in Florida. The extended coverage provided by the two additional sensors off the east coast of Florida is also clear, starting in 2006. An additional extension of coverage into the Atlantic, central Gulf of Mexico, and northern Mexico starting in 2008 is the result of the location algorithm change discussed in the previous section. Overall, the interannual variability over Canada and continental United States is quite modest.

The 9-yr summary map (Fig. 2j) smoothes out the annual variations and provides maximum flash density values that we have previously noted in Florida and the central United States with decreasing values toward the western states, the northern states, and into Canada, particularly in the provinces of Alberta, Saskatchewan, Manitoba, and Ontario (1–2 flashes per square kilometer

![Fig. 2. Mean annual ground flash density maps in North America for the individual years (a) 2001, (b) 2002, (c) 2003, (d) 2004, (e) 2005, (f) 2006, (g) 2007, (h) 2008, (i) 2009, and (j) the annual average summary map for all 9 yr (2001–09).]
per year). Minima, less than 0.1 flashes per square kilometer per year, occur along the West Coast and in northern Canada with only slightly higher values (0.1–0.5 flashes per square kilometer per year) in Alaska.

Local maxima occur along the southern coast of the United States from Texas to northern Florida with values exceeding 9 flashes per square kilometer per year. The effects of the Gulf Stream are readily apparent in all years, producing enhanced lightning ground strikes predominately in the winter months (not shown here) as first noted by Biswas and Hobbs (1990) in their analysis of lightning data from the Genesis of Atlantic Low Experiment (GALE) in the late 1980s.

b. Positive flash density

The annual positive flash density maps in North America (Fig. 3) show distinct variations and differences from
the total flash density maps in Fig. 2. Maxima occur throughout the central part of the United States in all years with relatively lower values in Florida. Significant positive flash densities occur in the central and upper Great Plains in all years (Fig. 3). Note the enhancement of the flash density in 2004 and in subsequent years in the central United States resulting from the network’s 2002–03 upgrade (Cummins and Murphy 2009). The years 2008–09 are dramatically different with an enhanced positive flash density throughout the central United States. Of particular note is the increased 2008–09 positive flash density in the western mountains of Mexico, just south of the Arizona–New Mexico border, an enhancement that has appeared occasionally in previous years. This pattern of behavior is probably made clearer as a result of the extension of range provided by the location algorithm change in 2008.

Figure 3j summarizes the average annual positive flash density for the years 2001–09. Note the highest values, for example, in the states of Nebraska, Kansas, Oklahoma, and Louisiana, with the relatively low values in Florida. The Gulf Stream is “outlined” with higher positive flash densities off the East Coast.

c. Percent positive polarity

The annual percentage of flashes lowering positive charge to ground, ignoring positive peak currents less than 15 kA, is summarized in Fig. 4 and in Table 1. The Fig. 4 maps include a summary map for the 9 yr of study (2001–09; i.e., Fig. 4j). The annual percentage of positive lightning is greater than 20% in the Great Plains in 2001, but is somewhat less in all subsequent years, perhaps resulting from the improved detection of CG flashes as a result of the 2002–03 upgrade, as well as a modest change in the acceptance criteria for positive flashes. The highest annual values are greater than 25% off the West Coast, Alaska, and the Yukon. High values exceeding 15% occur throughout the Great Plains, and increase to more than 25% in Manitoba (2005–07). The summary map (Fig. 4j) shows a maximum percentage of positive lightning for the NALDN in Manitoba and
western Ontario, just north of North Dakota, and Minnesota. The high percentage of positive flashes along the West Coast appears at the coast and seems to increase abruptly from less than 15%–20% to more than 25%. Most of these flashes occur in October–March and are, therefore, associated with winter convection. The large percentage positive at the edges of the network coverage are in Mexico, the Gulf, and off the Atlantic coast is likely due to an inability to detect lower-current negative flashes. Most of these flashes occur during the warm seasons. Florida again attracts our attention, as a positive flash density minimum over the state outlines an annual percentage of positive flashes that is less than 5%, precisely over the land area with the highest total of lightning flashes to ground.

Table 1 summarizes the percent of positive flashes for the NALDN year by year for the period 2001–09. Variations amount to less than a few percent for the years
2001–06, averaging approximately 5%–7%, but increased slightly in the 2008–09 period to 7.7%. The network upgrade in 2002–03 appears to have had little effect on the overall percentage of detected positive lightning, which averages 6.2% for the 9-yr period of analysis.

d. Median peak currents

Median first stroke peak currents for the NALDN are summarized in Table 1 for 9 yr. Negative median peak currents range from 19.3 kA in 2001 (pre-upgrade) to 15.0 kA in 2009 and for all years have an average of 15.4 kA. Except for 2001, the median peak currents range from 14 to 16 kA. Positive median peak currents range from a high of 27.9 kA in 2001 to 21.9 kA in 2007 and for all years result in a median of 23.8 kA. The larger median peak currents in 2002 and some lower mean multiplicity in 2001–02 reflect the somewhat lower sensitivity of the NLDN before completion of the 2002–03 upgrade. The ~1-kA increase in median negative peak current starting in 2005 (relative to 2003–04) may be the result of the recalibration of the propagation model in mid-2004. This increase is not evident for positive first strokes. However, the median positive peak current shows a distinct increase from ~24 to 29 kA in 2008–09, likely due to the reporting of only high-current positive discharges at the (extended) edges of the network, as illustrated below. We repeat that all positive peak currents of <15 kA are deleted from our database. In addition, all negative first stroke peak currents were retained (Wilson et al. 2009).

The geographical variations of the median peak currents are of interest. Annual negative median first stroke peak currents are plotted individually for the years 2001–09 in Fig. 5 with a mean summary map shown in Fig. 5j. The highest mean negative currents appear in 2001 and range on the order of 20–24 kA at lower latitudes along the southern fringe of the NALDN, generally decreasing with increasing latitudes. This has been identified previously by Orville et al. (2002) in their analysis of the lightning data for 1998–2000. This does not appear in subsequent years (2002–09), potentially due to increased
sensitivity in the lower latitudes following the 2002–03 upgrade. Note that there is a tendency for the highest peak negative currents to occur at the edges of the network coverage. This reflects the increasing distance of the lightning sources from the sensors (Fig. 1), and hence their inability to report low current strokes with increasing range. In Fig. 5a the small geographical area of low peak currents off the Nova Scotia coast is the result of an erratic operation of a sensor, which was not dependable in 2001.

There is a relatively sharp transition from low to high median negative peak currents along the Gulf and Atlantic coasts of the United States that is shown in Fig. 5. This sharp transition was first noticed by Lyons et al. (1998) and confirmed by Orville and Huffines (2001). This relatively sharp transition of the negative peak...
current does not occur around freshwater sources such as the Great Lakes. Cummins et al. (2005) has suggested that enhanced negative CG peak currents are the result of 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 negative CG multiplicity and peak currents are absent over the freshwater Great Lakes, thus indicating that differences are associated with the saltwater properties of the ocean.

In contrast to negative peak currents, the geographical distribution of the median positive peak currents (Fig. 6) is significantly different, as previously noted by Orville et al. (2002). There is not a sharp transition at the coast. Positive peak current values over land show continuity at the coast over the ocean. As the distance from the coasts and from the sensors increases, range filtering occurs and higher median peak currents are recorded.

Over land, we note that the highest median positive peak currents occur in the upper Midwest and Great Plains of the United States and continue into southern Manitoba in Canada. Relatively high peak positive currents are seen in the Midwest and are probably associated with the mesoscale convective systems that occur often in this area and were first reported by Lyons et al. (1998). Lyons noted that “concentrations of large positive current CGs in this region are likely associated with at least two classes of thunderstorms known to produce copious number of positive CGs: supercells and nocturnal MCSs.” This is consistent with our observation of a high percentage of positive lightning in the Midwest (Fig. 4). Zajac and Rutledge (2001) investigated ground flash activity over the United States. They report that the storms in the central Great Plains were characterized by predominately positive lightning, high positive flash rate, and large positive peak currents (e.g., Fig. 6). This, coupled with the findings of Fleenor et al. (2009), suggest that the maximum (both occurrence and high peak current) over this region is caused by intense convective elements—either isolated or organized into convective lines—but not exclusively mesoscale convective systems.
Finally, it should be noted in Fig. 6 that large areas of relatively lower positive peak currents occur throughout the southeastern part of the United States.

e. Multiplicity

The geographical distributions of the mean negative and mean positive multiplicities are shown in Figs. 7 and 8. The highest values of mean annual negative multiplicity exceed 3.0 strokes per flash in the NALDN with some geographical variation over the 9 yr of study. The highest values over the landmass occur in Alberta and Florida (2001); Quebec (2002); Montana, Wyoming, and the Gulf coast, (2002–09); and Arizona and New Mexico (2007–09). After the 2002–03 upgrade, a distinct minimum occurs in the negative multiplicity in the Great
Plains and upper Midwest. We note, however, that the overall pattern of negative multiplicity after the 2002–03 upgrade (i.e., 2003–09) appears to be stable and consistent from year to year.

We observe a higher negative multiplicity in 2002, following the upgrade compared to 2001. The higher values exceeding 3.0 continue annually through our most recent 2009 analysis. Lower values of mean negative multiplicity are observed to occur in the western United States. As noted by Rudlosky and Fuelberg (2010), mean negative multiplicity appears to be negatively correlated with both positive and negative median peak currents.

The positive multiplicity in Alaska and Canada is consistent throughout all years, with the highest values of the mean positive multiplicity just slightly higher than 1.1 located in the same regions in which higher mean negative multiplicity occurs. Positive flashes remain at a slightly higher mean than one and are consistent with the observation that positive flashes most often have only one stroke. However, positive multiplicity in the United States increased by about 30% from 2001 to 2004, following the 2002–03 upgrade. The highest values of the positive flash multiplicity occur in the southwestern United States with values exceeding 1.7. High values also occur in the southeastern United States. The summary multiplicity map for 2001–09 (Fig. 8j) clearly shows higher values in the southeastern states, but with the highest values of 1.7+ appearing in the southwestern states. There is no clear explanation for these high values. Since the NALDN reports the polarity of the flash as the polarity of the first stroke, some of these events will be bipolar flashes that are better detected following the upgrade. Since the largest positive multiplicities occur in the area of the U.S. Rocky Mountains, there may be terrain effects that increase the occurrence of bipolar flashes. It is also likely that the polarity and classification errors noted by Fleenor et al. (2009) contribute to an (erroneously) positive large multiplicity. This behavior was also reported by Rudlosky and Fuelberg, and requires further study.

**Fig. 6.** As in Fig. 2, but for median first stroke peak currents for positive flashes.
Biagi et al. (2009) conducted four field campaigns in 2003 and 2004 in Arizona and northern Texas to evaluate the NLDN after the 2002–03 upgrade. They observed a general increase in the NLDN negative multiplicity and concluded that it was the result of improved detection of low-amplitude subsequent strokes. On a regional basis, Biagi et al. noted that the NLDN upgrade did not change the negative NLDN multiplicity in Texas–Oklahoma, but it did increase the multiplicity in southern Arizona. They concluded that CG lightning has significant variations from storm to storm as well as between geographic regions and/or seasons and, consequently, a single distribution may not be sufficient for describing the characteristics of any given lightning parameter, such as the multiplicity or peak current.
4. Discussion and conclusions

The mapping of the cloud-to-ground lightning from 2001 through 2009 represents a significant extension of our first paper presenting the initial data for the North American Lightning Detection Network during 1998–2000 (Orville et al. 2002). We continue to see a complex lightning pattern showing strong geographical and interannual variations with substantial influences by elevated terrain features and major land–water boundaries.

In our analyses, the flash density variations in Fig. 2 continue to show variations similar to what has been previously published, although we have extended our analyses to include Alaska. The total ground flash density shows a significant increase in 2003 (Fig. 2c) and in subsequent years in response to the 2002–03 upgrade, particularly in the central United States. The positive flash density also has a maximum in the central United States, with peaks in Nebraska and along the Gulf of Mexico coast in the states of Louisiana and Mississippi. The peak positive flash density values in Florida (Fig. 3j) are less than half of the peak values in the central United States. This is consistent with the minimum percentage of positive flashes to ground (Fig. 4j) that seem to outline lower Florida. The Gulf Stream ground flash maximum is apparent in all years, as first identified by Biswas and Hobbs (1990).

The percentage of positive flashes to ground (Fig. 4j) exceeds 25% off the West Coast and has a relatively sharp boundary at the coast of northern California, Oregon, Washington, and extending northward along British Columbia to Alaska. We also note positive flash percentages exceeding 25% in Alaska and the Yukon, which is reported for the first time as we extend our analysis (Fig. 1) to include the Alaskan lightning data. A high percentage of positive lightning occurs in the central and upper Great Plains in 2001 and extends into Manitoba, Canada. Although the percentages are reduced in subsequent years resulting from the 2002–03 upgrade, this region still exhibits a very high percentage of positive flashes.
Interannual variability in lightning parameters is rather modest, but shows clear changes associated with changes in the NALDN. Flash counts and flash multiplicities are moderately increased due to the 2002–03 NLDN upgrade. The large increase in positive multiplicity in some regions may be caused by the misclassification of NLDN reports, and may require video-based validation studies such as those carried out by Biagi et al. (2007) and Fleenor et al. (2009). The extended range of the network due to additional sensors (2006) and a modification to the location algorithm (2008) is apparent in the annual maps.

A curious transition in negative peak currents continues to appear at the coastal interface of the western United States in Fig. 5j. Note the abrupt change from less than 24 kA to more than 24 kA. The suggestion by
Cummins et al. (2006) that coastal peak current maxima relate to differences in the attachment process of the first CG return strokes to saltwater surfaces may apply to this observation. A similar change occurs for positive lightning along the West Coast. The peak positive peak currents along the West Coast in Fig. 6j are on the order of 40 kA or higher, but then decrease to less than 30 kA inland along the coast of northern California, Oregon, and Washington. No similar change in peak currents appears along the east coast of North America. It is possible that the large positive peak currents along the west coast are associated with the specific behavior of winter storms (widespread convection and low freezing levels)—the primary source of lightning in this area.

It is obvious that the observed differences in the CG lightning characteristics are a complicated mix of NALDN measurement capabilities and meteorological variability over North America. Future studies will include a closer examination of seasonal variability and storm-scale changes to understand the geographical variations that characterize the NALDN patterns.

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REFERENCES


