Cloud-to-Ground Lightning in the United States: NLDN Results in the First Decade, 1989–98

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ABSTRACT

The physical and geographical characteristics of over 216 million cloud-to-ground lightning flashes recorded during the first decade (1989–98) of operation of the National Lightning Detection Network (NLDN) covering the entire continental United States are presented. These characteristics include the total cloud-to-ground flash density, the positive flash density, the percentage of positive flashes, the first stroke negative and positive peak currents, and the multiplicity for negative and positive flashes. All analyses were done with a spatial resolution of 0.2° corresponding to an approximate resolution of 20 km. Flash densities were not corrected for detection efficiency; the measured values are presented. The maximum measured flash density is found to exceed 9 flashes km^{-2} across Florida in the Tampa–Orlando–Cape Canaveral corridor, near Fort Myers, and between Lake Okeechobee and the Atlantic Ocean. The mean monthly flash count peaks in July at approximately 5.5 million flashes. Positive flash density maxima, greater than 0.4 flashes km^{-2} occur in southern Florida; Houston, Texas; and along the Texas–Louisiana border. A broad region of relatively high positive density also occurs throughout the Midwest. The mean monthly positive flash count peaks in June and July at approximately 240 000 flashes in each month.

The annual mean percentage of lightning that lowered positive charge was highest in the upper Midwest, exceeding 10% or 20% throughout most of the region. High percentages are also characteristic along the West Coast. The annual percentage of positive lightning has increased from 3% in 1989 to approximately 9% in 1998. The authors believe the increase is the result of improved sensor detection capability in the past decade. The mean monthly percentage of positive lightning flashes ranged from 4% in August to 17% in December for the decade. The annual median negative peak current ranged from 30 kA in 1989, decreasing steadily to about 20 kA in 1998. The annual median positive peak current ranged from 55 kA in 1989 decreasing to about 22 kA in 1998. The annual median peak negative and positive currents have approximately the same value since 1995, the first year after the NLDN upgrade. The monthly median first stroke peak currents for the decade peak in the winter and reach a minimum in May (positive current) and July (negative current). The mean monthly negative multiplicity for the decade ranges from 2.1 in February to 2.5 from June to October. The mean monthly positive multiplicity is approximately 1.2 throughout the year. The diurnal variation of the maximum flash rate over land was examined and found to peak during 1200–2000 local time (LT) with an exception for the upper Midwest, which peaked during 2000–0400 LT. Over water surrounding the continental United States, the lightning flash rate peaks primarily in the morning hours from 0400 to 1200 LT.

1. Introduction

Cloud-to-ground lightning flash densities are of fundamental interest. Uman (1987, 37–57) devotes most of chapter 2 on lightning phenomenology to results of flash density determinations beginning with the earliest of Brooks (1925) to estimate the global flashing rate to those of Prentice (1977) who summarized flash density measurements using flash counters, visual observations, and the measurement of electric field changes. In later years, Piepgrass et al. (1982) used a network of 26 electric field mills at the Kennedy Space Center, Florida, to estimate total flash densities for the summer months June and July for the years 1974–80. A few years later, flash density measurements were obtained using early versions of the lightning detection networks based on wideband magnetic direction finders installed in Florida (Maier et al. 1979; Peckham et al. 1984) and northeastern Colorado (López and Holle 1986).

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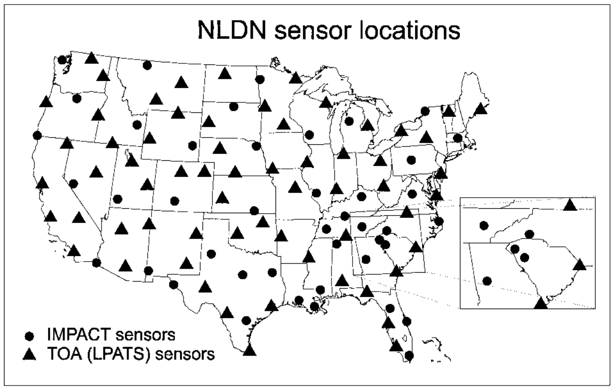

FIG. 1. Lightning sensor locations are shown in the National Lightning Detection Network. The locations of the IMPACT [direction finding (DF) and time of arrival (TOA) method] sensors are plotted with a filled circle; the locations of the Lightning Positioning and Tracking System (LPATS)(TOA) sensors are plotted with a filled triangle. The inset shows a cluster of IMPACT sensors in the western Carolinas.

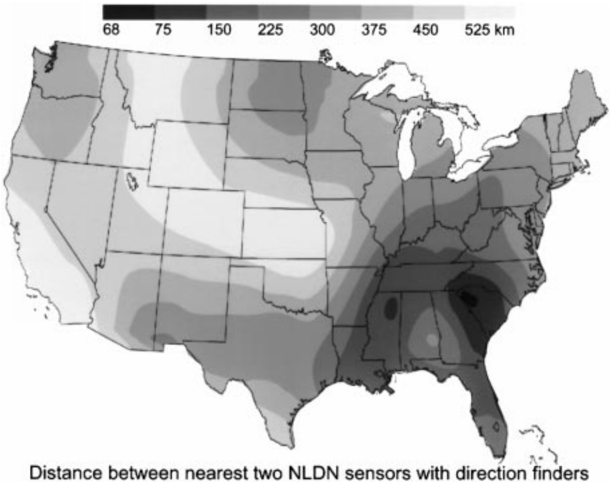

FIG. 2. The distance between the nearest pair of sensors with a direction finder capability (IMPACT sensor) is calculated and contoured. The closest IMPACT sensors are located in the Carolinas and the farthest apart are in western states. A lightning flash must be detected by at least one IMPACT sensor to be recorded.

Lightning detection networks using magnetic direction finders were extended to other parts of the continental United States as more regional networks were installed (Orville et al. 1983; Orville and Songster 1987; Orville et al. 1987). The interest in flash densities extends to season (Moore and Orville 1990; Biswas and Hobbs 1990; Dodge and Burpee 1993), region (Changnon 1988a,b), latitude (Mackerras and Darveniza 1994), topography (Reap 1986; Rakov et al. 1989; Watson et al. 1991), storm type (Rakov and Dulzon 1986; Holle and López 1993), diurnal controls (Watson et al. 1994b; Watson and Holle 1996), and different weather regimes (Watson et al. 1994a).

Flash densities using the National Lightning Detection Network (NLDN) were first reported for 1989 by Orville (1991) and extended to subsequent years by Orville (1994), Orville and Silver (1997), and Orville and Huffines (1999). In this paper we report on the first decade of measurements of cloud-to-ground lightning in the contiguous United States using the NLDN database of 216 million cloud-to-ground flashes. We calculate the mean annual flash density, the mean annual positive flash density, the percentage of positive flashes, the median peak currents for both negative and positive flashes, and the mean multiplicities for flashes of both polarities. To the best of our knowledge, this lightning dataset is the longest in time and largest in geographical extent that has ever been compiled. Uman (1987, p. 38) noted, ‘‘While an accurate flash density may be obtained in, say, 1 year, the average yearly flash density itself is highly variable so that many years of measurements are required to obtain a meaningful overall average flash density.’’ The data, results, and discussion presented in the following sections, we believe, are based on meaningful overall averages.

2. Data

The lightning data were originally obtained by the NLDN, which was established in the 1980s at the State University of New York at Albany under support from the Electric Power Research Institute and later transferred to the private sector, now Global Atmospherics, Inc. The complete coverage of the continental United States began in 1989 (Fig. 2 of Orville 1991) and continues today as shown in Fig. 1. For the present analysis, we examine the data from January 1989 through December 1998 and ignore most of the changes in the NLDN configuration and sensor characteristics (Cummins et al. 1998; Wacker and Orville 1999a,b) over the same period. This is because they cannot be easily quantified and do not affect the results presented in this paper. There is, however, one exception. Beginning in 1995, we have eliminated positive flashes from our database with peak currents less than 10 kA as suggested by Cummins et al. (1998) and explained by Wacker and Orville (1999a,b). To quote Cummins et al., ‘‘We recommend that the subset of small positive discharges with peak currents less than 10 kA be regarded as cloud discharges unless they are verified to be cloud-to-ground.’’ We agree.

No corrections for detection efficiency, defined as the number of flashes detected divided by the number that occur, are made in our analysis; we graph the measured values. The reason for this is that there has been a steady improvement in the detection efficiency from an estimated 70% in 1989 (Orville 1991) to 80%–90% since 1995 (Cummins et al. 1998). In addition, the detection efficiency varies with location in the United States. Note the contours in Fig. 2, which show the distance between the nearest two NLDN sensors with direction finders. This is significant because detection by at least one Im-

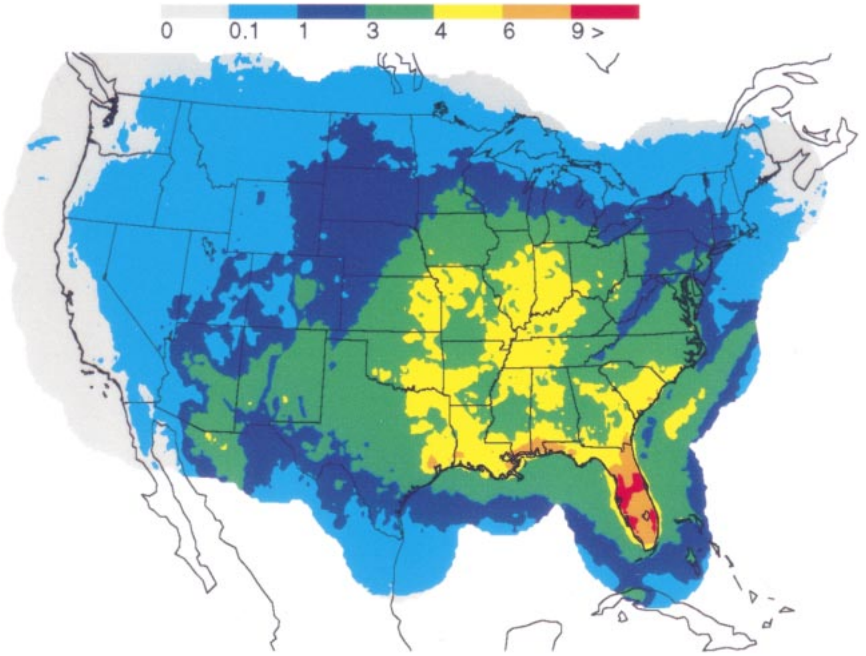

FIG. 3. The mean annual flash density is contoured for the continental United States. Over 216 millions flashes from 1989 to 1998 were processed to produce this map. No corrections for detection efficiency have been applied.

proved Accuracy from Combined Technology (IMPACT) sensor is required for the flash to be recorded. Figure 2 shows that the distance between two IMPACT sensors varies from less than 75 km to more than 525 km. Consequently, the detection efficiency varies over the United States. As a result, we report only the measured values and caution the reader to be aware of varying detection efficiency over the continental United States, which does affect the measured flash density. We also make no corrections in the flash density analyses for multiple terminations per flash, which are estimated by Rakov et al. (1994) to be 1.7 for Florida thunderstorms with similar values for New Mexico (Kitagawa et al. 1962). Similar values may apply to other parts of the United States.

All geographical plots in this paper are done with a spatial resolution of 0.2° corresponding to an approximate resolution of 20 km. Latitudinal lines converge significantly over a north–south geographical area as large as the United States. Consequently, the area over which the flash density is calculated varies from 425 km^2 at 30°N to 350 km^2 at 45°N. Our flash density calculations are exact and compensate for the changing area as the latitudinal lines converge.

3. Results

All results are summarized in categories of flash density, percent positive, peak currents, and multiplicity.

a. Flash density

The mean annual density for 216 million cloud-to-ground lightning flashes is plotted in Fig. 3 for the continental United States and the area adjacent to the borders. A distance of 400 km, selected by the authors, to the closest sensor determines the extent of the plotted area. Global Atmospherics, Inc., the operator of the NLDN, clips the data at 625 km from a sensor, but we choose a more conservative distance of 400 km for our analyses. Note that the highest mean annual flash density occurs in Florida with values exceeding 9 flashes km^{-2} in an area that extends from Tampa on the west coast to the Kennedy Space Center on the east coast of Florida. Similar high values occur between Lake Okeechobee and the east coast of Florida and were first reported by Hodanish et al. (1997). Undoubtedly, this is a region of convergence between the lake and the Atlantic Ocean. Relatively high flash density values, 4–6 flashes km^{-2}, extend along the Gulf Coast and into the Midwest. Note the local minimum of flash density, ranging from 1 to 3 flashes km^{-2} that extends over the Appalachian Mountains in western Virginia. The effect of the Gulf Stream on the annual flash density is readily apparent off the Carolina coast with values as high as 4–6 flashes km^{-2}. A close examination of Fig. 3 shows a flash density enhancement near Galveston Bay, Texas, and near the city of Houston. Flash density enhancements associated with cities have been reported previously by Westcott (1995) using data from the NLDN. Just to the east of

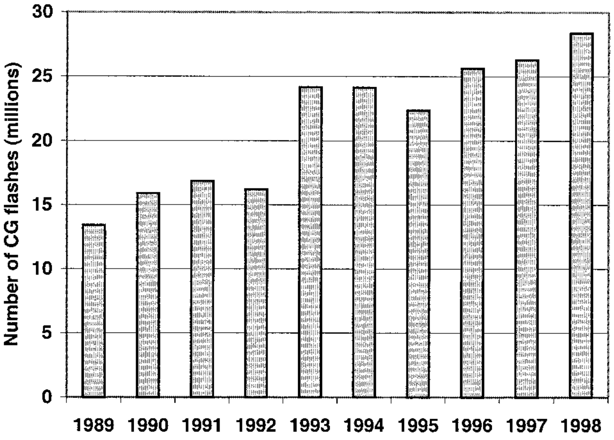

FIG. 4. The annual cloud-to-ground flash counts are shown for the 10 yr from 1989 through 1998. The increase in 1993 is believed to be primarily the result of thunderstorms associated with the meteorological conditions that produced extensive flooding in the Midwest. In 1994 the network was upgraded (Cummins et al. 1998) and the result was an increase in the detection efficiency. Consequently, we see a higher number of cloud-to-ground lightning flashes from 1994 through 1998.

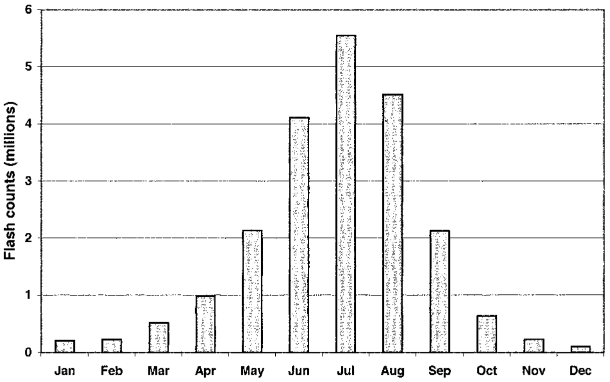

FIG. 5. The mean monthly flash counts for the decade show symmetry around the maximum in July followed by low values recorded from Nov through Feb.

Houston, we see another maximum near the city of Lake Charles, Louisiana, that we believe to be associated with the oil refineries near Lake Charles. A narrow north–south strip of 1–3 flashes km^{-2} surrounded by higher flash densities is apparent in central New Mexico corresponding to the Rio Grande river valley. A flash density value, 3–4 flashes km^{-2}, extends into Arizona and is associated with the Mogollon Rim, the White Mountains, and higher terrain east of Tucson and is discussed by Watson et al. (1994a,b) and Maddox et al. (1997).

We note in presenting these results in Fig. 3 that two patterns emerge in the amount of cloud-to-ground lightning over elevated terrain. In the Appalachian Mountains, the lightning flash density decreases relative to the surrounding areas. This area of the continental United States is dominated by frontal passages and the associated cloud-to-ground lightning is less over the mountains. On the other hand, the mountains in Arizona and surrounding the Rio Grande in the New Mexico area are characterized by relatively higher cloud-to-ground lightning flash densities compared to the valley of the Rio Grande. We note that convective summer thunderstorms dominate in the Southwest and are more likely to form over the mountains. This explanation is consistent with our observations.

The mean annual cloud-to-ground flash counts graphed in Fig. 3 are broken down into annual counts in Fig. 4, which shows an increase from approximately 14 million in 1989 to 28 million in 1998. The increase in the measured counts in the mid- 1990s is caused, we believe, by the natural increase in 1993 associated with the thunderstorms and extensive flooding in the Midwest that summer and the NLDN upgrade in 1994–95 documented by Cummins et al. (1998). Annual values of flash density for the United States appear to now range from 25 to 30 million flashes with a detection efficiency of 80%–90%.

The mean monthly distribution for the cloud-to-ground lightning over the last decade is shown in Fig. 5. The plot is symmetrical about July, which has a mean value of 5.5 million flashes. A minimum in the flash density occurs in December, although only a few hundred thousand flashes, on the average, occur in the months of November–February.

b. Positive flash density

In this section we separate the positive flashes from the total flash count and just analyze the flashes that lower positive charge to ground. Positive flashes, first identified by Berger (1967) in strikes to the towers on Mount San Salvatore, Lugano, Switzerland, were later confirmed by Rust et al. (1981) to be a frequent type of ground flash. In Fig. 6, we contour the mean annual positive flash density for the past decade. The highest values occur in Florida but have a different pattern across the state than that shown in Fig. 3. Note the highest values, greater than 0.4 flashes km^{-2} occur not only in Florida, but also in the vicinity of Houston and near the Texas–Louisiana border. Relatively high values of the positive flash density extend throughout the Midwest. Localized high values appear in Oklahoma, Mississippi, and just east of New Orleans, Louisiana.

Annual positive flash counts over the first decade of the NLDN operation are plotted in Fig. 7. The flash count was approximately 0.5 million from 1989 to 1992, increasing to 1.0 million in 1993–94, and then increasing significantly in 1995–98 to over 2 million flashes per year. Recall that we have eliminated positive flashes with peak currents less than 10 kA, so the increase in 1995 is believed to be primarily from an increased sensitivity of the NLDN to detect weak positive flashes. Increasing the sensitivity of the NLDN to detect lower peak current cloud-to-ground flashes was one of the

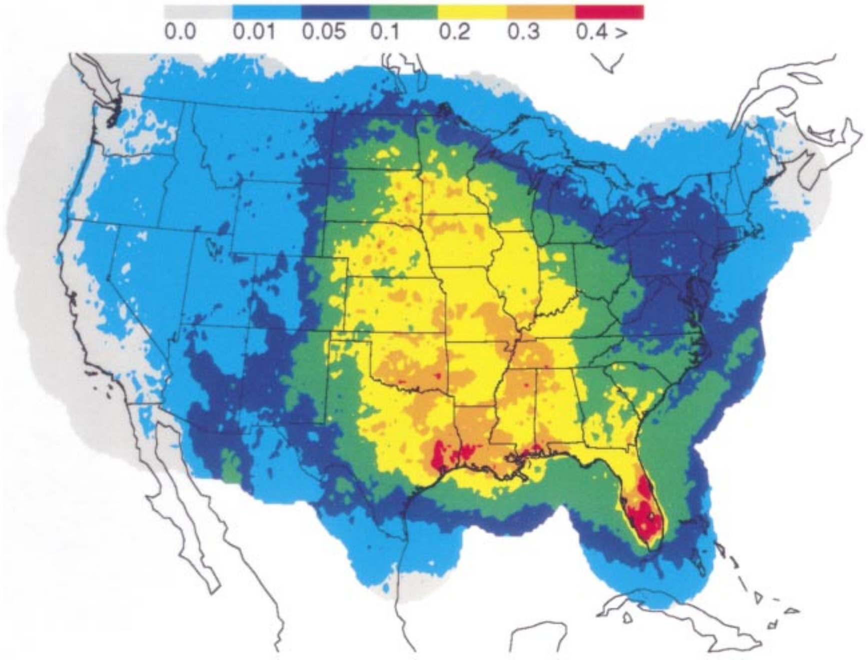

FIG. 6. The mean annual positive flash density shows maxima in southern Florida and along the Gulf Coast. Peak values occur in the Houston area, on the Texas–Louisiana border, and on the Mississippi–Alabama border. A broad area of 0.2–0.3 positive flashes km^{-2} and higher extends through the middle of the continental United States.

objectives of the NLDN upgrade (Cummins et al. 1998) and it appears to have been successful, although we believe the contamination from intracloud flashes has also increased.

The mean monthly positive flash count for the decade, 1989–98, is shown in Fig. 8. The positive flash count is at a maximum in June and July with an approximate symmetric decrease on either side of these two months. This graph might suggest that the positive flash count peaks earlier than the total flash count (negative flashes mostly; Fig. 5).

We have made a point of eliminating the positive flashes with peak currents less than 10 kA detected by the NLDN beginning in 1995. To examine the geographic distribution of these flashes, we put the positive flashes with peak currents less than 10 kA into a separate file and then plotted them on a map of the United States. Figure 9 is the result. Annual values exceeding 1.0 flash km^{-2} occur in Florida, Louisiana, Tennessee, and on the North Carolina–South Carolina border. All maxima regions in Fig. 9 are explained by the local clustering of two or more IMPACT sensors shown in Fig. 1, whose

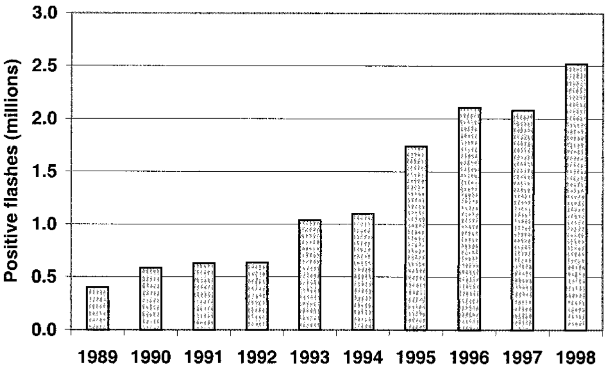

FIG. 7. The number of positive flashes recorded increased dramatically in 1995, primarily from the enhanced sensitivity of the NLDN sensors. Positive flashes with peak currents less than 10 kA recorded since 1994 are not included in this dataset as we believe they are primarily intracloud flashes (Wacker and Orville 1999a,b).

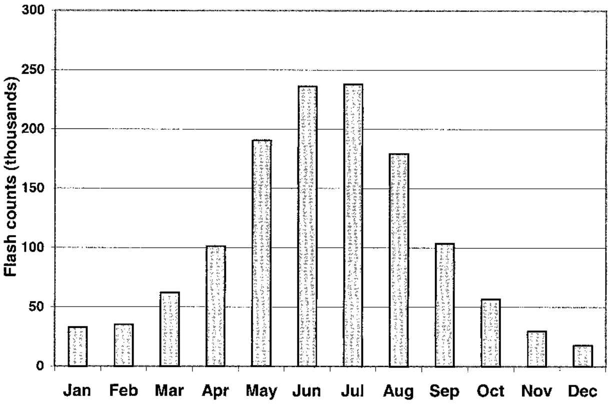

FIG. 8. The mean monthly positive flash counts show a broad 2-month peak (Jun and Jul) with symmetrically lower values on either side of this maximum.

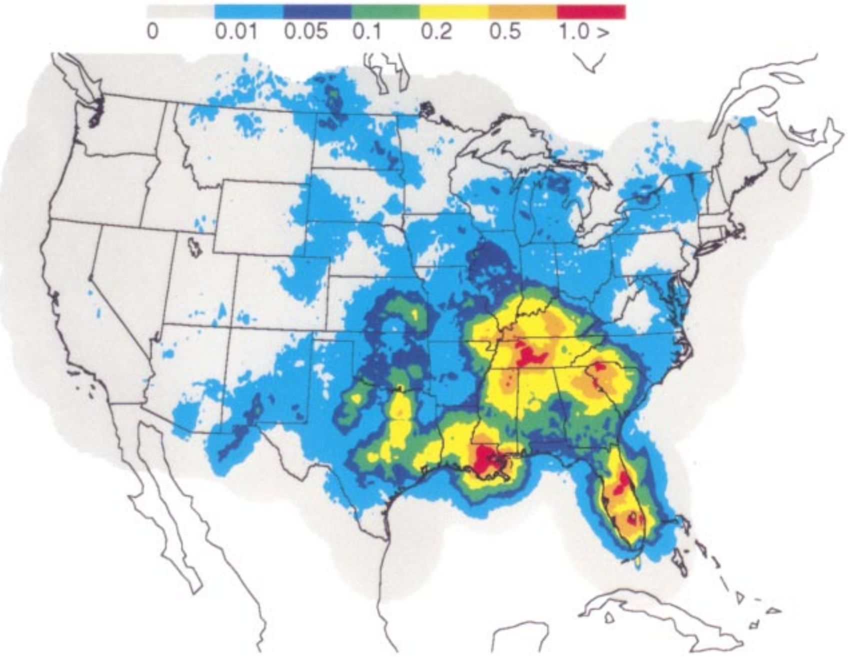

FIG. 9. What is the distribution of ''positive flashes'' with peak currents less than 10 kA? The answer is plotted in this map, which shows 1995–1998 mean annual concentrations (flashes km^{-2} yr^{-1}) in Tennessee, the western Carolinas, the New Orleans area, and central Florida. These flashes have been deleted from our analyzed dataset, as we believe they are primarily intracloud flashes. The effect on the total cloud-to-ground flash density is a maximum (red) of about 1 flash km^{-2}.

criterion were relaxed in order to maximize detection of small cloud-to-ground lightning flashes. We now turn to an examination of the ratio of the positive flash count to the total flash count, defined as the percent positive.

c. *Percent positive polarity*

The mean annual percentage of flashes lowering positive charge to ground is plotted in Fig. 10 for the decade, 1989–98. High values extend from the Colorado–Kansas border to Minnesota and into Canada. Similar high values occur along the West Coast from lower California to Vancouver, British Columbia. We note that the lowest values occur in Florida and over the Gulf Stream, regions identified previously as having relatively high flash densities. With the expansion of the lightning detection network into Canada, it will be interesting to observe if the high percentage of positive lightning extends into Canada in the areas now covered by the Canadian Lightning Detection Network.

The annual percentage of positive lightning, shown in Fig. 11, was approximately 3%–4% for the first 6 yr of the operation of the NLDN, jumping to about 8% in 1995. The reasons for the higher values since 1995 are the increased sensitivity of the network to weak positive flashes, which had previously gone undetected (Cummins et al. 1998). Some of the increase may be the result of an increase in the detection of intracloud flashes (Wacker and Orville 1999a,b) although we have eliminated from our database the positive flashes with peak currents less than 10 kA. Indeed, it was Cummins et al. (1998, p. 9042), soon after the upgrade, who cautioned, ''that the subset of small positive discharges with peak currents less than 10 kA be regarded as cloud discharges unless they are verified to be cloud-to-ground.''

The mean monthly percentage of positive flashes is plotted in Fig. 12. It varies considerably throughout the year, from a high (16%–18%) in the winter, December and January, to a low (4%–5%) in the summer months of July and August. This pattern is consistent and appears each year. Although there is considerable geographical variation of the percentage of positive flashes as shown in Fig. 10, the reason for the seasonal variation is a matter of conjecture. Brook et al. (1982) in a study of winter thunderstorms in Japan found a remarkable relationship between the vertical wind shear through the cloud and the fraction of positive ground strokes produced in a storm. Apparently, the existence of wind shear facilitates the discharge of positive electricity from high in a cloud by providing significant horizontal displacement between the upper and the lower negative charges. A minimum value of 1.5 m s^{-1} km^{-1} was found and Brook et al. speculated that this value might be the value below which no positive ground strokes occur. On the other hand, it may be easier to observe summer storms and look for the occurrence of positive flashes with significant shear in the cloud layer. This study re-

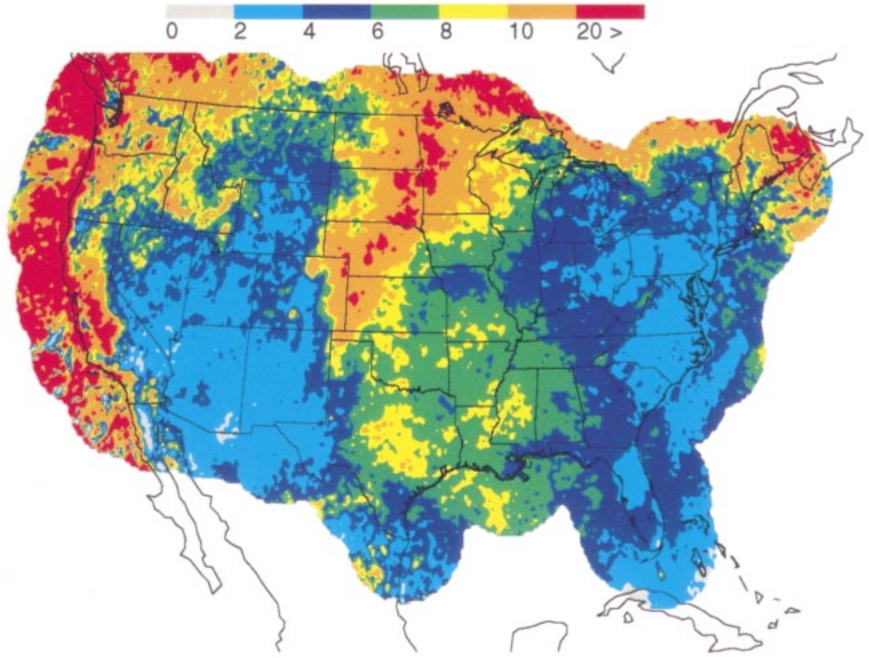

FIG. 10. The percentage of flashes lowering positive charge to ground is shown to vary considerably with latitude and longitude. High percentages, greater than 20%, occur throughout the upper Midwest and along the West Coast. The high values, we note, are an average over 10 yr and occurred primarily before the installation of the Canadian Lightning Detection Network (CLDN) in 1998. Recent data from the CLDN would, we believe, lower the high percentage of positive lightning recorded along the U.S.–Canadian border.

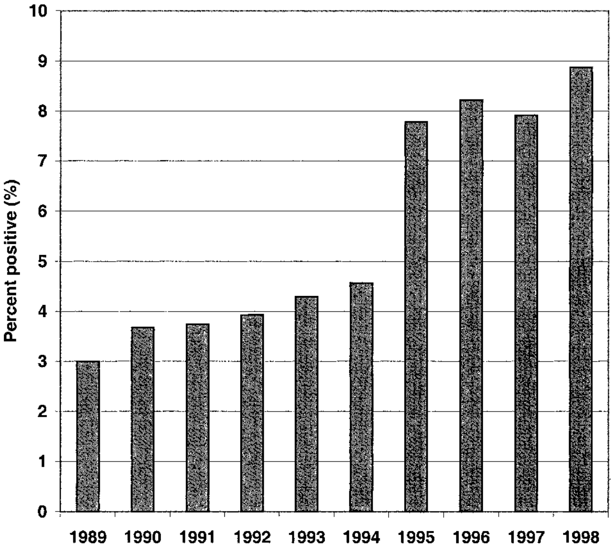

FIG. 11. The percentage of the total cloud-to-ground lightning that lowers positive charge is plotted from 1989 through 1998. Note the effect of increasing the sensitivity of the NLDN in 1995, which raised the percentage from about 4% to the current level of approximately 8%–9%.

mains to be completed and the subject is still a matter of speculation.

d. Median peak currents

The geographical distribution of median peak currents for the detected negative flashes is shown in Fig. 13. Only the peak current for the first stroke in the flash is analyzed. Within the continental United States over land, the highest values occur along the southern states from Texas to Florida, ranging from 27 to 30 kA. The

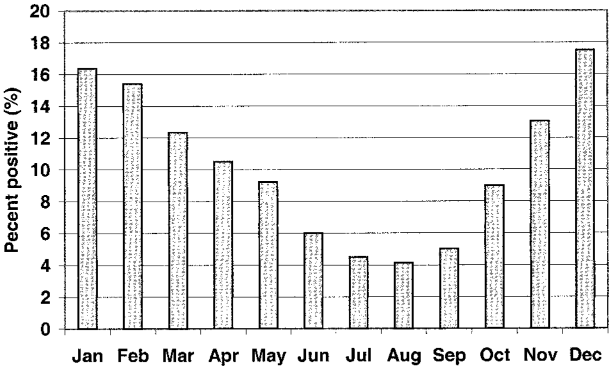

FIG. 12. The variation of the mean monthly percentage of positive lightning shows a monthly variation, peaking in the winter and reaching a minimum in the summer. The reason for this variation is, at present, unknown.

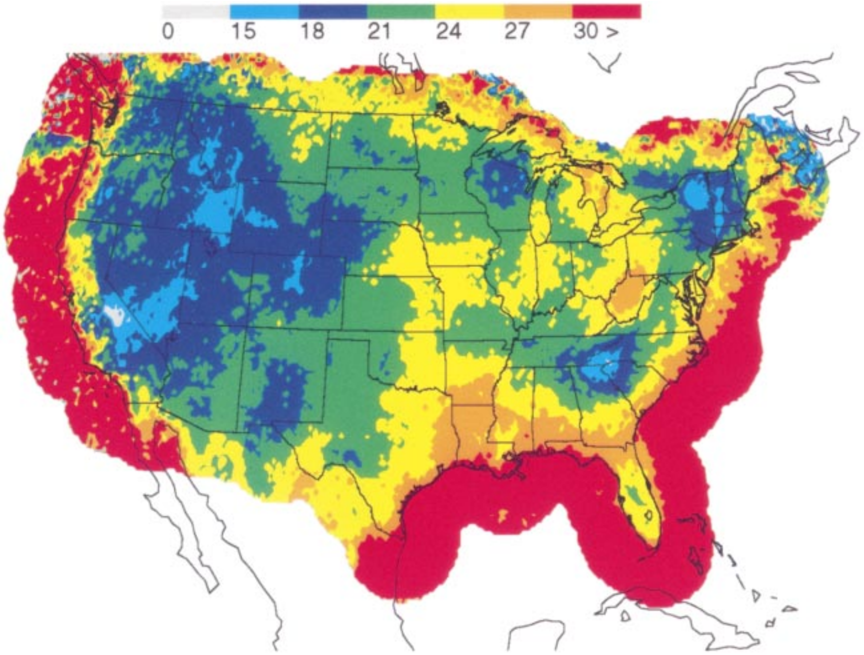

FIG. 13. The median annual peak negative current varies significantly with latitude and longitude. Within the continental United States, the lowest values occur in the west over the Rocky Mountain range. The highest values are recorded along the coast where the seawater conductivity minimizes the signal attenuation. Note that this attenuation is absent in the data recorded over land south of the border in Mexico, as the recorded peak currents are continuous in magnitude across the border.

lowest values, 15–21 kA, occur in the western United States, upper Midwest, New England, and in the western Carolinas. We note that there is no apparent latitude dependence as first hypothesized by Pierce (1970), Takeuti et al. (1975), and reported by Orville (1990) using 1988 data from the East Coast network. Outside the continental United States, we note the following in Fig. 13. Over water, we see the red area indicating peak currents greater than 30 kA. Over land in Mexico and Canada, we see negative peak currents less than 30 kA. This suggests that the higher conductivity of the ocean water surface causes less attenuation than the relatively lower conductivity of the land surface. Therefore, a higher peak current is calculated from the radiation field produced by lightning flashes over the ocean. This effect, if true, should also be apparent for positive flashes, but we will see in the next paragraph that it is not observed. Also, we note that if conductivity were the reason, we would not see the abrupt change in the negative peak current at the land–sea interface.

The median peak currents for the detected positive flashes are shown in Fig. 14. In contrast to Fig. 13, we note that within the United States borders, the lowest values (15–25 kA) occur in the southeastern part of the United States and the highest values (greater than 35 kA) occur in the upper Midwest, continuing into Canada. Beyond the border of the United States, high values occur along the west coast, south of Texas, and off the New England coast. Low peak currents, less than 25 kA, are observed in the Gulf and the waters surrounding Florida, Georgia, and South Carolina. In contrast to the negative peak currents, there is no abrupt change in the peak current at the land–ocean boundary for positive flashes. If ocean conductivity and propagation over saltwater were the cause, then the effect should not be a function of polarity and it would not occur at the land–sea interface. At the moment, we have no explanation for this observation.

The median annual peak currents have not been constant in the first decade of the NLDN operation. Figure 15 shows that there has been a continuing decrease in the peak current for both positive and negative currents. Of particular interest, we believe, is the apparent convergence of the two curves over the decade. In 1989, the first year of the operation of the NLDN, the median positive peak current was approximately 55 kA and the median negative peak current was 30 kA. Both values have continued to decrease through the decade, until approximately 20–22 kA was the median value for both positive and negative peak currents in the last three years, 1996–98. The largest change occurred in the transition period from 1994 to 1995, when the NLDN was upgraded and the sensors were modified (Cummins et al. 1998). The enhanced sensitivity of the sensors described by Cummins et al. probably accounts for the lowering of the median peak currents as more low peak current ground flashes (previously undetected) were recorded.

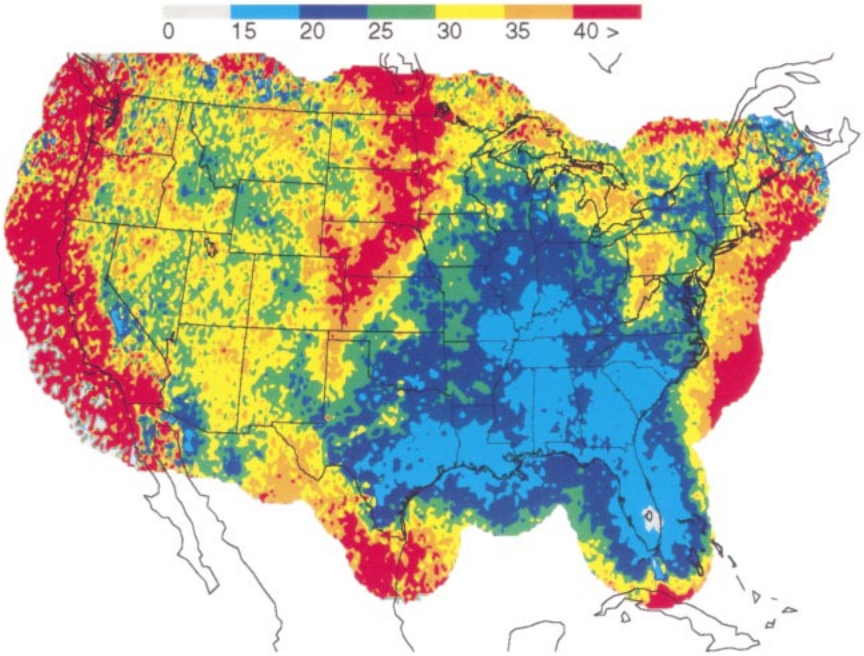

FIG. 14. The median annual peak current has maxima throughout the upper Midwest from Colorado to the Canadian border. To the east, the values decrease significantly reaching median values less than 15 kA in the Lake Okeechobee area.

The median monthly peak currents (Fig. 16) have consistently varied over the year throughout the decade for both positive and negative flashes. Highest values occur in the winter and the lowest values in the summer. A closer examination, however, shows that the minimum negative peak current occurs in May and leads the minimum in the positive peak current by about 2 months. The variation from a high in the winter to a low in the summer may be explained by the observations of Brook (1992). He found from a study of winter storms in Albany, New York, and an incomplete summer study that 1) radiation associated with breakdown, that is, the stepped leader, is greater in winter than in summer, and 2) the velocity of the leaders is a factor of 2 or 3 greater in winter. Thus, electric fields initiating lightning in winter appear to be greater than in summer. As a result, since stored energy is proportional to the square of the field, winter discharges may be considerably more energetic than in summer and hence have a higher peak current. This explanation is consistent with the monthly median peak current variation in Fig. 16.

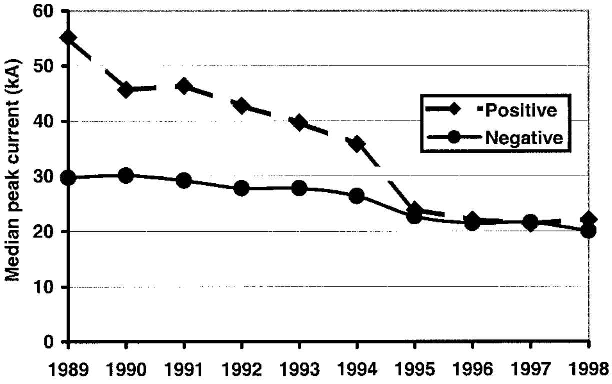

FIG. 15. The median peak currents have shown a systematic variation over the past decade. Note that the first stroke peak currents for positive and negative flashes converged in 1995, the first year of the improved NLDN sensitivity. It appears that the convergence is the result of the enhanced network sensitivity and not related, in our opinion, to any change in the characteristics of cloud-to-ground lightning through the decade.

e. Multiplicity

The geographical distribution of negative and positive multiplicity is shown in Figs. 17 and 18, respectively. We note that the highest negative multiplicity occurs throughout the Midwest and in Florida. Low values are found in the in the West, particularly along the West Coast. In the East, we see the lowest negative multiplicity in the area overlying the borders of Pennsylvania, Maryland, and West Virginia.

The mean positive multiplicity in Fig. 18 shows significant variation if we plot small increments. Note that the values extend from 1.0 to just over 1.3 strokes per flash. The highest values occur in the upper Midwest, decreasing in all directions to the borders of the continental United States. Relatively high values, in the range of 1.2–1.3 occur in central Florida in the same area where we found a higher value of the mean annual positive flash density (Fig. 6).

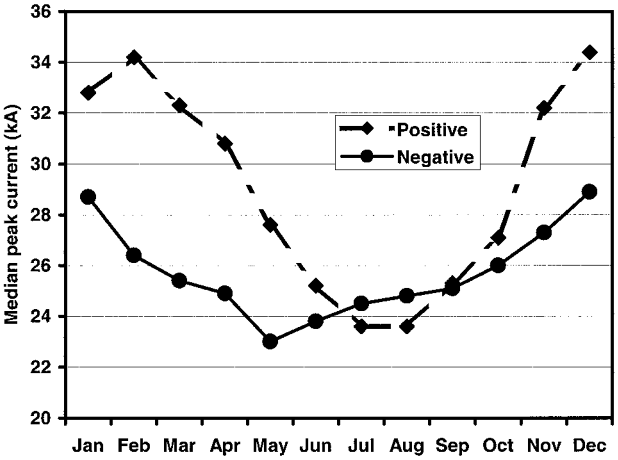

FIG. 16. The median peak currents for both negative and positive first strokes vary throughout the year. Negative peak currents reach a minimum in May, positive peak currents in Jul. These median values for each month reflect the median for the respective month in each of the previous 10 yr. Thus, the positive values for each month tend to be larger than the negative values, as is apparent from the respective annual values plotted in Fig. 15.

The mean monthly multiplicity for negative and positive flashes is graphed in Fig. 19. Negative values range from 2.0 to 2.5 through the year with the highest values occurring in summer months and early fall. The positive multiplicity shows no significant variation with month, being slightly over 1.0 throughout the year.

The annual mean multiplicity, on the other hand, Fig. 20, shows some variation over the past 10 yr. Note that the negative multiplicity is slightly over 2.5 for the years 1989–94, then decreasing to slightly over 2.0 in the years 1995–98. This change is the result of upgrading the NLDN in 1994–95 (Cummins et al. 1998, their Fig. 10), which included a change in the algorithm from an angle-based method to a location-based multiplicity estimate to classify strokes into flashes. If the upgrade merely increased the sensitivity to weak strokes, then we would expect an increase in negative multiplicity. The decrease, however, results from the algorithm change.

f. Diurnal variation of maximum flash rate

The time of the maximum flash rate was calculated with respect to the local time and the results plotted in Fig. 21a with a time resolution of 4 h, and in Fig. 21b with two time intervals; one in the afternoon–early evening [1200–2000 local time (LT)] and the remaining time through the night and early morning hours. Note that the time for the maximum flash rate over land is 1200–2000 LT with the exception of late evening and early morning hours in the central part of the United States. Over water, there is a clear tendency for the lightning maximum flash rate to peak at night and in the early morning hours with the exception of the water close to Florida where the peak lightning flash rate is from 1600 to 2000 LT (Fig. 21a). Perhaps the time shift from ‘‘yellow to red’’ in Fig. 21a on the east coast of

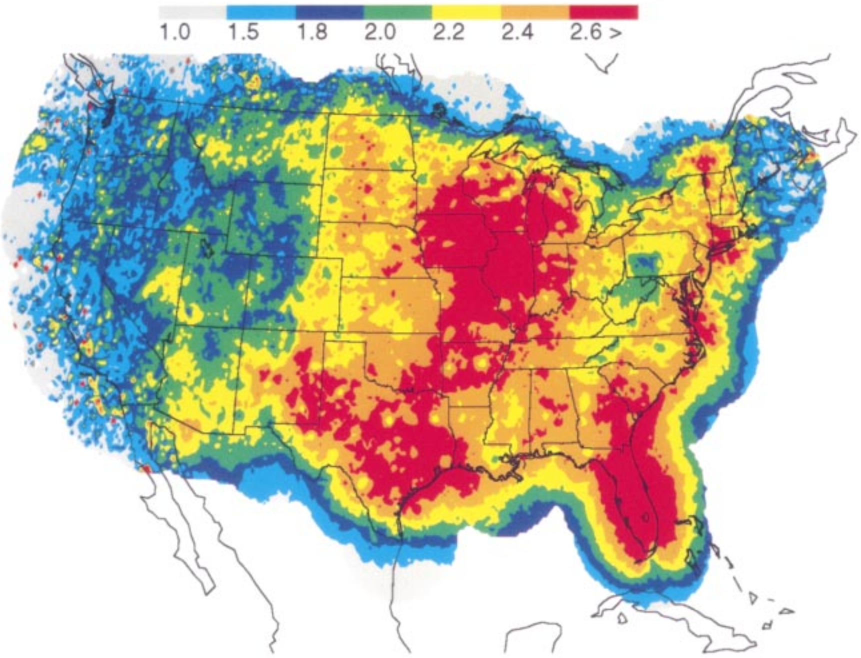

FIG. 17. The mean negative multiplicity for the decade shows maxima, greater than 2.6 strokes per flash, throughout the midsection of the United States and in Florida. Lower values are noted over the Appalachian Mountains and in the western states. The map is fringed with lower values because of the lower detection efficiency at greater distances from the sensors.

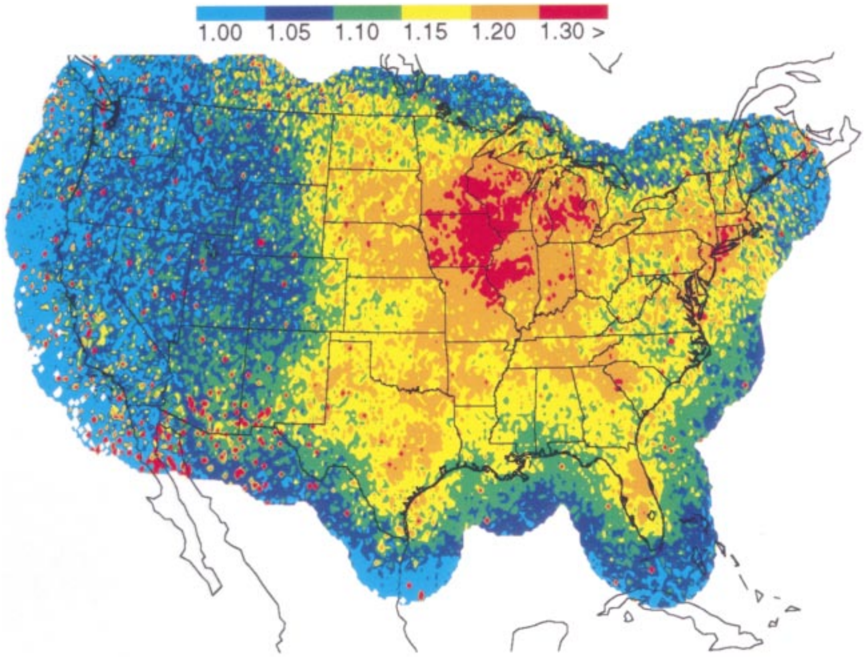

FIG. 18. The mean positive multiplicity peaks in the upper Midwest with values greater than 1.3, but then decreases to lower values in all directions from the peak. Interestingly, the lowest values are found over the Rocky Mountain range.

Florida reflects the west to east drift of thunderstorms over land in the afternoon, 1200–1600 LT (yellow), to over the ocean in the late afternoon hours, 1600–2000 LT (red).

This is not the first report of the maximum in the diurnal cycle of thunderstorm frequency (Wallace 1975), but it is the first report of the hour of the maximum cloud-to-ground lightning rate for the continental United States and the surrounding waters. For the first time we see the large shift in the time of maximum flash rate at the land–water interface. It will be interesting to continue the type of analysis reproduced in Fig. 21 by examining the maximum flash rate as a function of season and of month.

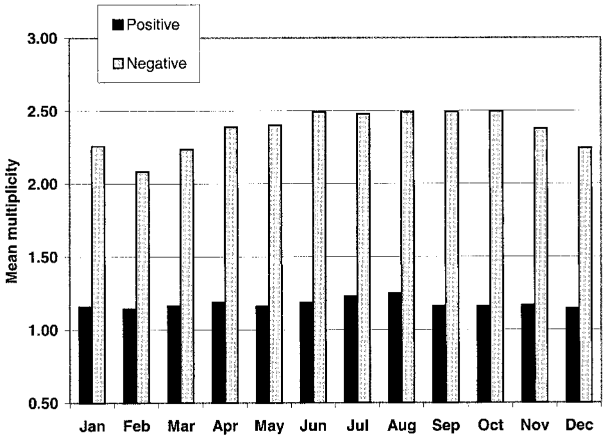

FIG. 19. The mean monthly multiplicity shows little variation through the year; negative flashes ranging from 2.0 to 2.5, positive flashes from approximately 1.2 to 1.3.

4. Discussion

The mapping of 216 million flashes over a period of 10 yr obscures the year-to-year variation, but reveals the climatological patterns in the lightning data. A major

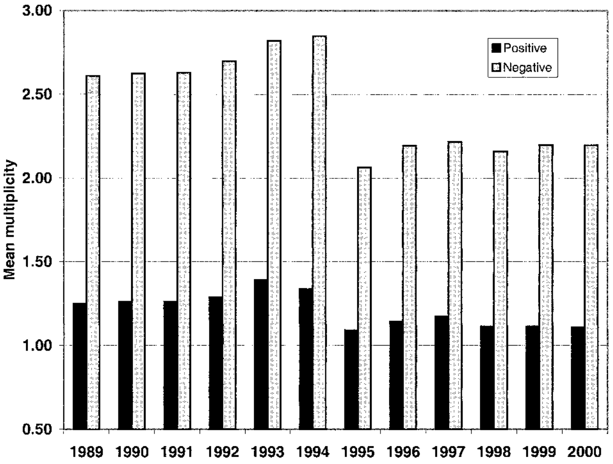

FIG. 20. The annual mean multiplicity is approximately constant through the year. The decrease in the negative multiplicity in 1995 and later corresponds to the upgrade to the NLDN and the implementation of new algorithms to process the lightning stroke data into flashes.

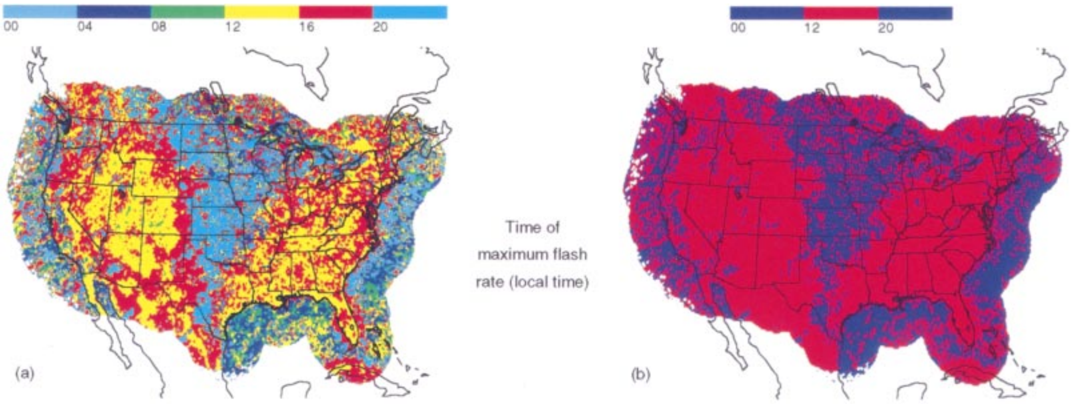

FIG. 21. The time of maximum flash rate is calculated for the different time zones and plotted with respect to the local time for (a) 4-h time intervals, and (b) 1200–2000 and 2000–1200 LT intervals. Note the dominant time over land is in the afternoon hours with the exception of the evening hours, 2000–0800 LT in the upper central United States. At the land–water interface, there is an abrupt shift to maximum lightning rates in the night and morning hours over the water.

improvement in the network detection efficiency occurred in the 1994–95 period when the sensors were upgraded (Cummins et al. 1998). This improvement also had the side effect of increasing the detection of intracloud flashes, which we have identified in the dataset as positive flashes with peak currents less than 10 kA (Wacker and Orville 1999a,b). In the near future we need to develop algorithms to properly classify the intracloud flashes in the NLDN dataset as present interest now extends to detecting and mapping total flashes, that is, both cloud-to-ground and intracloud flashes.

It is clear from Fig. 3 that there is a significant latitudinal and longitudinal variation in the flash density over the continental United States. The 10-yr average shows maxima in Florida from Tampa to Cape Canaveral and between Lake Okeechobee and the Atlantic Ocean. Secondary maxima occur along the Gulf Coast, on the Texas–Louisiana border, and over Houston. In general, the flash density decreases at higher latitudes with significantly lower values over the Appalachian Mountains and the Rocky Mountain range in the West.

We suggest that the longitudinal variation of the flash density is related primarily to topography of the continental United States. On a line of constant latitude through the middle of the United States from the West Coast to the East Coast in Fig. 3, we see low flash density values of less than 1 flash km^{-2} increasing to 4–6 flashes km^{-2} in the Midwest, than decreasing to 1–3 flashes km^{-2} over the Appalachian Mountains in West Virginia. The flash density values then increase in Virginia and decrease further toward the East Coast and beyond for lightning frequency over the Atlantic Ocean.

These 10-yr summary variations are consistent with the NLDN flash density values reported in previous annual studies (e.g., Orville 1991; Orville and Silver 1997; Orville and Huffines 1999). They are not consistent, however, with flash density values obtained on a smaller scale with changing topography. Rakov et al. (1989) using a single-station lightning locating system in the north Caucasus region of Russia found a factor of 1.7 higher value for the cloud-to-ground flash density for a mountainous area compared to that of a plain terrain area. Reap (1986) analyzed cloud-to-ground lightning data for the summers of 1983 and 1984 in the western states. He found the cloud-to-ground lightning activity increased with increasing terrain elevation from sea level to almost 3 km.

López and Holle (1986) studied the spatial distributions of lightning in central Florida and found them closely related to topographical features. They found the highest flash density from Cape Canaveral northward along the coast, and westward from the cape to Orlando, the westward limit of their observations. Reap (1994) extended the flash density study to all of Florida and identified organized coastal maxima related to the land–sea-breeze convergence zones. He identified the maxima from Tampa to Cape Canaveral. We see the same maxima in Fig. 3 with the additional maxima near Fort Myers on the west coast of Florida and in the region between Lake Okeechobee and the Atlantic Ocean. The latter region is a geographical area of convergence of low-level flow between the lake and the ocean and was first identified in the lightning data analyzed by Hodanish et al. (1997, their Fig. 1).

The geographical distribution of the mean annual positive flash density, Fig. 6, is interesting when compared to the geographical distribution of the median peak positive current, Fig. 14. Note that there is roughly an inverse relationship in that the lowest flash densities occur in the West whereas in Fig. 14 the highest peak positive currents occur in the West and Midwest. In the southeastern part of the United States we see that the highest positive flash density, Fig. 6, corresponds to roughly the geographical area of the lowest median peak positive current, Fig. 14. This suggests the possible inverse relationship of more positive flashes associated with lower positive peak currents, for example, in the southeastern United States, particularly Florida. An alternate suggestion, however, is that the observation merely reflects the closer spacing of the NLDN sensors shown in Fig. 1. Consequently, more positive lightning is detected in the Southeast with lower peak currents. The increased number of flashes would be consistent with a lower median peak current.

The geographical distribution of the percentage of positive flashes, Fig. 10, shows some similarity to the geographical distribution of the median peak positive currents, Fig. 14. A broad maximum extends from the Canadian border into Colorado in both figures. A high percentage of positive flashes and high median peak positive currents are observed along the West Coast. Similarly, minima in these quantities are observed to occur in the southeastern part of the United States. The geographical distribution of the positive multiplicity is seen to vary little over the United States, but the maximum (Fig. 18) does occur in the same region as the highest median peak positive current, namely the upper Midwest. Outside the borders of the United States, the median positive peak current increases and the multiplicity decreases. Both observations are consistent with the lightning source being farther from the NLDN sensors.

5. Conclusions

Cloud-to-ground lightning flashes recorded in the continental United States for the first decade of the NLDN operation, 1989–98, have been analyzed for geographical distribution of total flashes, positive flashes, percentage of positive flashes, negative and positive first stroke peak currents, and negative and positive flash multiplicity. In short, we have the first look at the ‘‘lightning climate’’ of the United States. In summary, the results are as follows.

1) The total measured flash count for the decade is 216 million cloud-to-ground flashes.
2) The areas of maximum annual flash density, greater than 9 flashes km^{-2}, occur in Florida in the Tampa–Orlando–Cape Canaveral corridor across Florida. There are similar high flash densities in the area of Fort Myers and between Lake Okeechobee and the Atlantic coast of Florida. Relatively high values of flash density are also seen along the Gulf Coast and in the area of Houston, recently identified as the city with the highest air pollution in the United States. [Westcott (1995) first used the NLDN to discover enhanced cloud-to-ground lightning activity around major urban areas. Reasons for these enhancements suggested by Westcott include increased urban-related condensation nuclei, urban population and size, and the presence of distinct topographic features in and around cities.]
3) The mean monthly flash count for the decade peaks in July at approximately 5.5 million flashes.
4) Positive flash density maxima (greater than 0.4 flashes km^{-2}) occur in southern Florida, Houston, and along the Texas–Louisiana border. A broad region of relatively high positive density occurs throughout the Midwest.
5) The mean monthly positive flash count peaks in June and July at approximately 240 000 flashes per month in each month.
6) The annual mean percentage of lightning that lowered positive charge was highest in the upper Midwest, exceeding 10%–20% throughout much of the region. High percentages are also characteristic along the West Coast. The annual percentage of positive lightning has increased from 3% in 1989 to approximately 9% in 1998. We believe the increase is the result of improved sensor detection capability in the past decade.
7) The mean monthly percentage of positive lightning flashes ranged from 4% in August to 17% in December for the decade.
8) The annual median negative peak current ranged from 30 kA in 1989 decreasing steadily to about 20 kA in 1998. The annual median positive peak current ranged from 55 kA in 1989 decreasing to about 22 kA in 1998. The annual median peak negative and positive currents have approximately the same value since 1995, the first year after the NLDN upgrade.
9) The monthly median first stroke peak currents for the decade peak in the winter and reach a minimum in May (positive current) and July (negative current).
10) The mean monthly negative multiplicity for the decade ranges from 2.1 in February to 2.5 from June to October. The mean monthly positive multiplicity is approximately 1.2 throughout the year.
11) The diurnal variation of the maximum flash rate over land was found to peak during 1200–2000 LT with an exception for the upper Midwest, which peaked during 2000–0400 LT. Over water surrounding the continental United States, the lightning flash rate peaks at night and in the morning hours.

Many questions remain to be answered from the first presentation of a decade of cloud-to-ground lightning over a region as large as the continental United States. We anticipate continuing these studies on a regional scale similar to those first presented by Hodanish et al. (1997). We do not have an explanation for all the observations presented here, but we report these results from the first decade of NLDN operation in the hopes of stimulating further research and discussion. Further analysis on a seasonal basis and in varying meteorological conditions should yield insight into the reasons for the changing lightning characteristics as a function of time and space.

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