Lightning Ground Flash Density and Thunderstorm Duration in the Continental United States: 1989–96

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(Manuscript received 16 March 1998, in final form 25 August 1998)

ABSTRACT

The mean annual flash density, thunderstorm duration, and flash rates were calculated using 121.7 million cloud-to-ground lightning flashes in the continental United States for the period 1989–96. Florida had flash densities over 11 flashes km^{-2} yr^{-1}, while the Midwest, Oklahoma, Texas, and the Gulf Coast had densities greater than 7 flashes km^{-2} yr^{-1}. There was a relative minimum in flash density (three flashes km^{-2} yr^{-1}) in the Appalachian Mountains and Missouri. Thunderstorm duration values exceeded 120 h yr^{-1} in Florida and 105 h yr^{-1} in New Mexico, Arizona, and the Gulf Coast. The maximum annual flash rates exceeded 45 flashes h^{-1} in the Midwest, along the Florida coasts, and along the mid-Atlantic coast with the minimum flash rates, 15 flashes h^{-1}, over the Appalachian and Rocky Mountains. The relationship between thunderstorm duration and flash density is $Flash\_Density = 0.024(Flash\_Hours)^{1.29}$ producing expected flash densities that are within 30% of the measured densities for over 70% of the nation, with the greatest errors, over 80%, in the intermountain region of the Rockies.

1. Introduction

Information on annual thunderstorm duration is of great interest to many different groups such as power generation facilities, construction companies, and federal and local government agencies. A comprehensive climatology of thunderstorm duration is required to provide accurate information for all areas in the continental United States. This study provides the information using cloud-to-ground lightning data from 1989–96. A relationship between thunderstorm duration and flash densities is also found in an attempt to provide a method of estimating the flash density based strictly on the number of hours of lightning per year for a given location.

Previous studies have included thunderstorm duration across the United States (MacGorman et al. 1984; Changnon 1985), the relationship between thunderstorm duration and flash density (Changnon 1988a, 1988b, 1989; Reap and Orville 1990), and the number of thunderstorm events compared with the flash density (Changnon 1993; Changnon et al. 1988). Each of these studies used observed reports of thunder or lightning overhead to determine the thunderstorm duration. MacGorman et al. and Changnon point out that this method provides a long period of record for the thunder data, usually over 30 years. But Changnon (1993) also shows that the thunder reports may not coincide with the actual beginning and ending of lightning as an observer may not hear the first peal of thunder. Sites may continue to report thunderstorms beyond the cessation of thunder (U.S. Department of Commerce 1975). Several factors can lead to errors including increased background noise at a location, observers being too occupied with other aspects of the storm to remember when the thunder ceased, and a tendency to include thunder in the observations when lightning is visible, but distant. These are understandable limitations in the thunder data, and can misrepresent the duration of thunderstorms.

The National Lightning Detection Network (NLDN) has measured cloud-to-ground (CG) lightning for the contiguous United States since 1989. Annual flash densities were calculated from these data (Orville 1991, 1994; Orville and Silver 1997). The next step is to estimate the duration of storms using the same data. While this is only an estimate, since a thunderstorm may produce only intracloud (IC) lightning and the NLDN only detects CG lightning (Krider et al. 1976, 1980), the duration of electrical storms can be approximated by the detection of CG lighting.

This study includes only the contiguous United States. The data were restricted to the landmass to avoid possible variations in network performance over land versus over water. All lightning references are for CG

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TABLE 1. Number of detected CG flashes over the contiguous United States.

Year	All flashes (10^6)	Positive flashes (10^6)
1989	10.857	0.349
1990	12.601	0.530
1991	13.206	0.569
1992	13.203	0.577
1993	20.191	0.970
1994	19.884	1.042
1995	17.474	1.731
1996	19.680	2.184
Total	127.096	7.952

flashes unless otherwise noted. A lightning flash may include several strokes, but the multiplicity of each flash is not considered here.

2. Data

The NLDN is a system of over 100 sensors including both wideband direction finders and time-of-arrival sensors. Sensor locations have been published on several occasions (Orville 1991, 1994; Orville and Silver 1997; Cummins et al. 1998) and will not be repeated here. The overall detection efficiency of the NLDN is assumed to be about 70% (Mach et al. 1986; Orville 1994), although a 1994 upgrade in the network improved that value as noted by Cummins at al. Since the majority of this study covers the time period prior to this upgrade, the 70% detection efficiency was assumed for all the data. In order to compensate for detection efficiency the number of flashes was multiplied by 1.4. Location errors are on the order of 10 km or less and do not affect this study. All flashes, both positive and negative, are included.

The data for this study were organized into 0.2° × 0.2° latitude and longitude grids, which gives a resolution of approximately 22 km in the north–south direction and 18 km in the east–west direction at 35°N latitude. Each cell approximates the region where lightning would be observed, as thunder can be heard to a distance of 8–20 km (MacGorman et al. 1984; Changnon 1989; Reap and Orville 1990). Flash densities were calculated using the area for each individual grid, which changes in size with latitude.

No attempt was made to limit any region based on the number of flashes detected within the grid (Reap and Orville 1990; Changnon 1993). A single flash at any grid point counted the same as if there were multiple flashes. While it is possible to have an errant flash location generate an erroneous count in the flash density and flash hours, the effect on our study is assumed to be small. This assumption is reasonable since the study includes all flashes occurring in the 8-yr period of record (Table 1). Since the flash hours are calculated by 15-min intervals, the overall effect of errant flash locations on storm duration is small when averaged over the eight years.

3. Results

The number of flashes occurring from 1989 to 1996 was counted for each latitude and longitude grid resulting in the number of flashes per square kilometer or the flash density (when divided by the area of the grid). Likewise, the number of hours that each grid location experienced any lightning was determined in order to calculate the mean flash hours. This is comparable to the number of hours that thunder is observed at a location during the year and gives an estimate of the annual duration of thunderstorms. Using the number of flashes and the number of hours when flashes occurred, we can determine a mean flash rate for each of the grids. The number of flashes each year across the United States is substantial (Table 1).

The number of flashes over the continental United States (Table 1) shows two distinct periods. The flash counts are 10 to 13 million flashes per year from 1989 to 1992 and 17 to 20 million flashes from 1993 to 1996. The increase in 1993 was due to the large number of storms associated with the heavy precipitation and flooding in the midwest. From 1994 on, the increased flash counts can be attributed to the network upgrade (Cummins et al. 1998). Positive flash counts show the same general trend only the values for 1995–96 are 2–4 times the values prior to the upgrade. This is a dramatic difference compared to the total CG flash count indicating that the network upgrade had a larger effect on the detection of positive flashes than the negative flashes.

a. Flash density

The mean annual flash density for 1989–96 (Fig. 1) indicates a maximum over central Florida (11+ flashes km^{-2} yr^{-1}) and relative maxima (seven flashes km^{-2} yr^{-1}) over southern Indiana, southern Oklahoma, and along southeastern Texas and the Gulf Coast. Relative minima (three flashes km^{-2} yr^{-1}) exist over the Appalachian Mountains (the Virginias), southern Missouri, and along the Rio Grande. These features were noted in previous studies of individual years (Orville 1991, 1994; Orville and Silver 1997) and, as one would expect, there is good agreement between the individual years and the 8-yr mean.

There is a noticeable lack of lightning in the west coast states (California, Oregon, and Washington) as well as Idaho and Maine. The annual studies previously published (Orville 1991, 1994; Orville and Silver 1997) show similarly low densities for these regions. No explanation for this is offered here.

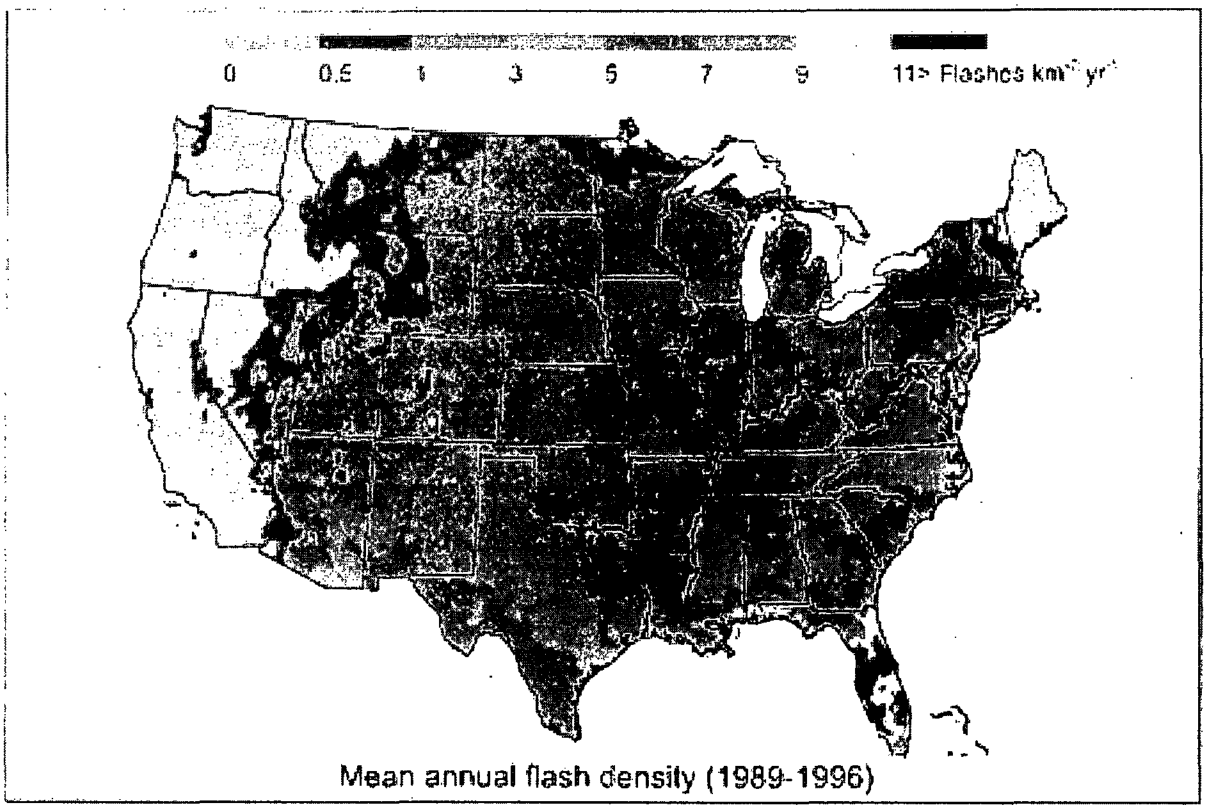

FIG. 1. Mean annual flash density for 1989–96 (flashes km^{-2} yr^{-1}). The data are corrected for an estimated detection efficiency of 70% by multiplying all values by 1.4.

b. Flash hours

The duration of thunderstorms is determined by counting the number of 15-min intervals when any lightning flash is detected by the NLDN within a grid and then dividing by 4 to yield flash hours. This means that the storm ends when no lightning is detected during a 15-min time block. This method differs from the traditional calculation of thunderstorm duration since we use lightning detection instead of audible thunder (MacGorman et al. 1984; Changnon 1985, 1988a,b, 1989, 1993; Reap and Orville 1990). The grid size was selected to allow comparison with thunder hours, as MacGorman et al. and Changnon previously noted that thunder is only audible within about 8–20 km of the flash. This hearing limitation defines an area of 200–1200 km^2. Our study uses a grid of approximately 370 km^2, although the grid size varies with latitude as mentioned earlier. The distance from the center of the grid to a corner is within the limitation of hearing. Thunder is heard from both CG and IC lightning while the NLDN only detects CG lightning (Krider et al. 1976, 1980). This can lower our duration values as storms having IC but no CG flashes can occur within a given time block.

As the flash hours are not a count of the number of flashes in a grid but rather the periods when a lightning flash occurred, these values were not corrected for detection efficiency. The resulting mean annual flash hours are depicted in Fig. 2. The maximum annual thunder hours is over the Florida peninsula. There are also maxima (90 h or more) in New Mexico, eastern Arizona, Oklahoma, and along the Gulf Coast. One can also see a trough in the plains extending from the eastern Dakotas to eastern Colorado. The general features compare well with previous thunder data (MacGorman et al. 1984; Changnon 1988) in the eastern states but not as well in the mountain areas. That is to be expected as terrain features and fewer observing stations in the mountains would tend to degrade the audible detection of thunder, but have a lesser effect on the NLDN detection.

c. Mean annual flash rate

We determine the mean flash rate (Fig. 3) by dividing the total number of flashes in each grid (corrected for detection efficiency) by the number of hours when lightning occurred. This is an approximation of the flash rate because a grid can have electrical activity that ends shortly after the time block (or starts shortly before) yet that entire time period would be included, which would

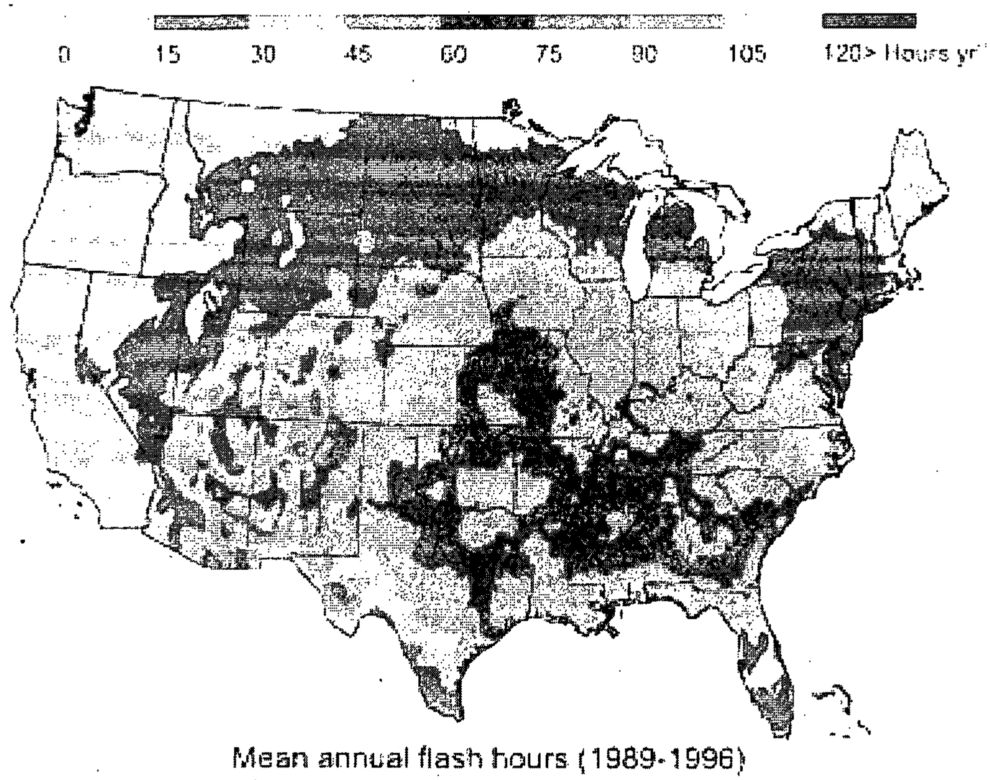

FIG. 2. Mean annual flash hours for 1989–96 (h yr^{-1}).

reduce the actual values. There are pronounced maxima of 45 or more flashes per flash hour over the midwest (Illinois and Indiana), the Florida coast and along the mid-Atlantic coast with minima over the Appalachian and Rocky Mountains. The minimum over the Appalachians matches the minimum found in the flash densities over the same region (Orville and Silver 1997).

d. Flash density versus flash hours

To compare the flash density and the flash hours, a scatterplot was made of the mean annual flash density versus flash hours (Fig. 4). A line fit to these data yields a relationship of flash density (flashes km^{-2} yr^{-1}) as a function of flash hours (h yr^{-1}),

$$\text{Flash\_Density} = 0.024(\text{Flash\_Hours})^{1.29}. \quad (1)$$

This is based on 21 072 grids having flash hour values of at least 0.1 and gives a correlation coefficient of 0.973. This relationship differs slightly from an earlier study (MacGorman et al. 1984). MacGorman's study was limited to a region in Florida and another in Oklahoma and lightning data (negative flashes only) were collected for 2–3 months at each location. The thunder hours used were over periods from 8 years to more than 30 years per site; this study covers only 8 years.

While the flash density and flash hours are highly correlated, it is important to note that Eq. (1) is not completely accurate for the entire region of study. An analysis of the difference in the actual and predicted flash densities (as a percentage of the actual value) shows relatively good agreement over most of the United States (Fig. 5). The region with the highest difference is in the intermountain region of Colorado and Utah. This region has a flash rate of less than 15 flashes h^{-1} (Fig. 3). Figure 6 shows the count of grid boxes having differences at or below a given percentage. Over 70% of all the grid boxes have expected flash densities that differ less than 30% from the actual flash densities.

4. Discussion

It is enlightening to see the comparisons between the flash density and the duration of thunderstorms in Fig. 4. The two distributions do not agree linearly across the United States, but there is good agreement on an exponential scale. It is also interesting to note the highest flash rates (Fig. 3), based on our definition of flash rate, occur in the Midwest and in Florida. One might expect

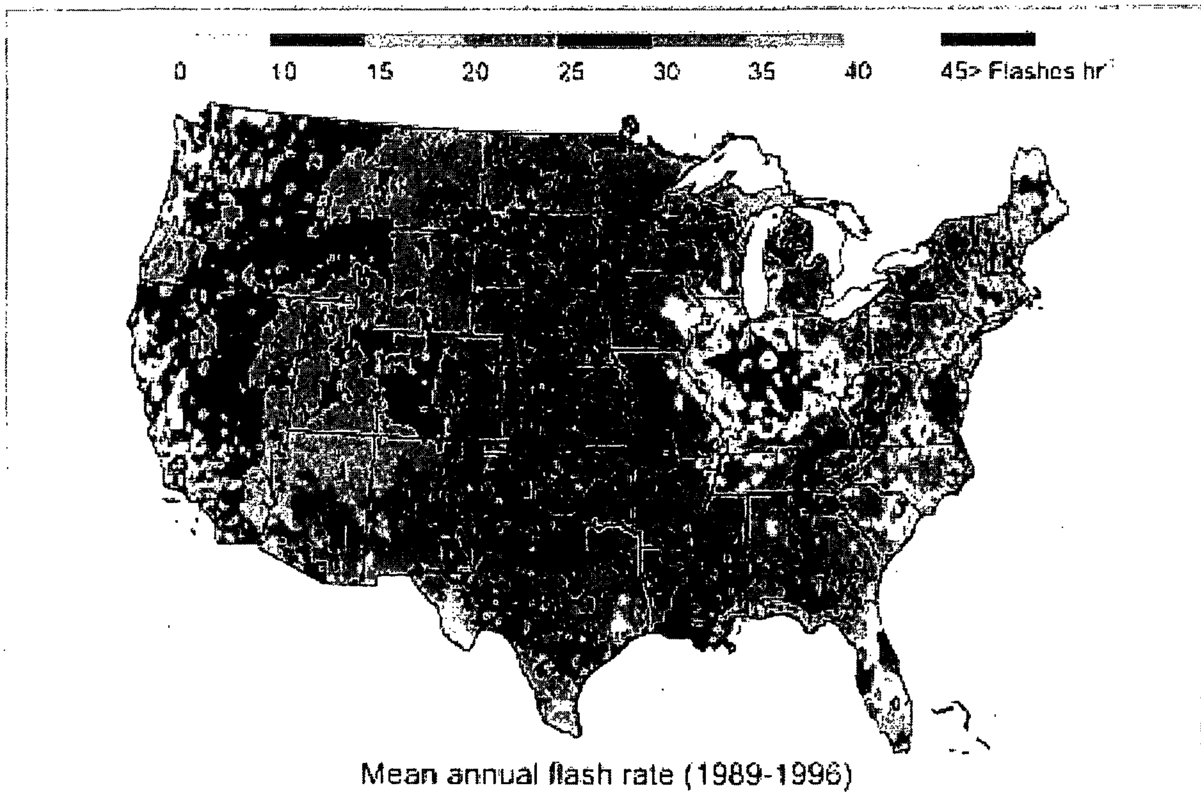

FIG. 3. Mean annual flash rate for 1989–96 (flashes h^{-1}). The number of flashes in each grid was divided by the number of hours that flashes were detected by the NLDN. (The grid resolution was 0.2° × 0.2° latitude and longitude.) The data are corrected for detection efficiency.

the Florida maximum based on the consistently higher flash densities there, while the maximum in the midwest is not as obvious.

a. Flash hours

This is a count of the number of 15-min intervals when any flash occurred, divided by 4. A limitation with this definition is a possible exaggeration of the duration of the lightning events. Consider a possible scenario of a storm generating only two lightning flashes in a grid. If one flash occurred at 2 min before the hour and the next at 2 min after the hour, this counts as 0.5 flash hours in our definition, when the actual event only spanned 4 min. Although this does not occur frequently, it can happen.

While the flash hours may tend toward larger values the general features are representative. The higher values along the Gulf Coast and over the Florida peninsula (Fig. 2) are indicative of sea breeze convection. The lower values in the Great Plains would imply a lower number of storms per year (probably more frontal based thunderstorms with fewer in the winter months).

It should be noted that the size of each grid box has an effect on the calculation of thunderstorm duration. As a storm passes through a region, it will spend less time in a smaller area than in a larger one. This may have an effect on our study. While the grid resolution is 0.2° × 0.2° latitude and longitude, the east–west distance along a grid box decreases as the latitude increas-

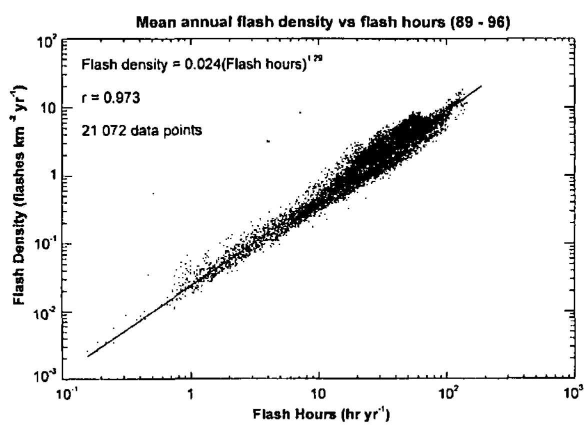

FIG. 4. Mean annual flash density vs mean annual flash hours. There are 21 072 grids used for this comparison and a least squares method is used to fit the line. The flash densities are corrected for detection efficiency.

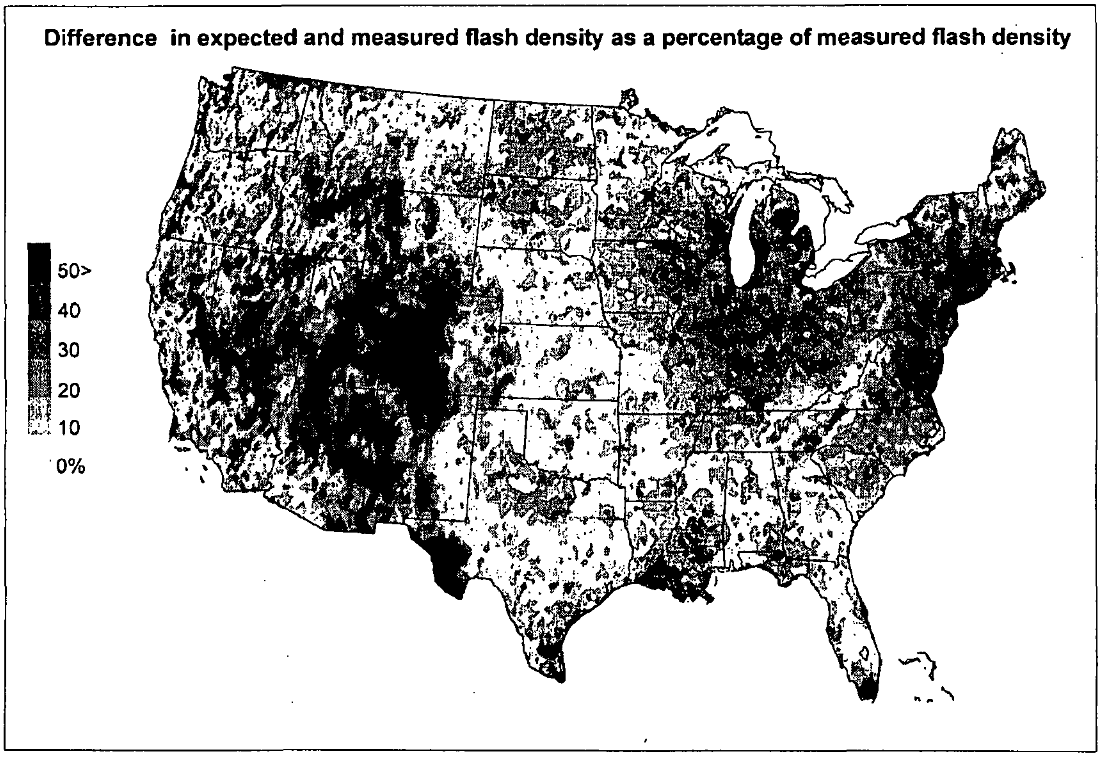

FIG. 5. The difference between the expected and measured flash density values (flashes km^{-2} yr^{-1}) as a percentage of the measured flash density. Data are organized on a 0.2° × 0.2° grid and cover a period from 1989 through 1996. The expected flash density is based on the duration of thunderstorm defined by the flash hours.

es. The area of grid boxes varies from 433 km^2 at 27°N to 320 km^2 at 49°N. Any possible inference on the annual thunderstorm duration as it relates to latitude (Reap and Orville 1990) would have to take the grid changes into consideration.

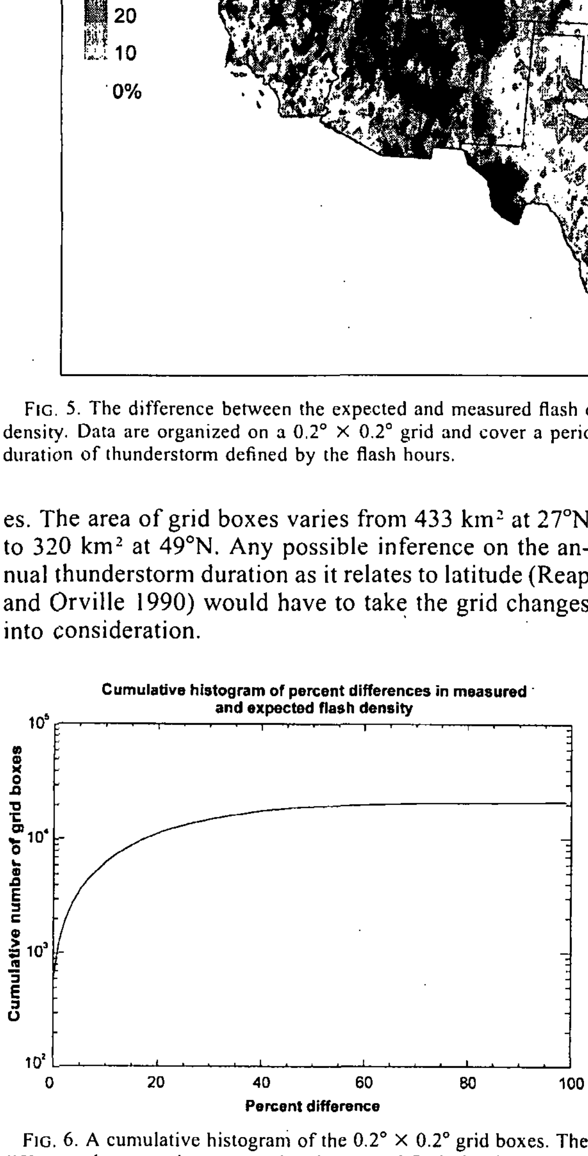

FIG. 6. A cumulative histogram of the 0.2° × 0.2° grid boxes. The difference between the measured and expected flash density (flashes km^{-2} yr^{-1}) is expressed as a percentage of the measured flash density. The expected flash density is calculated from the thunderstorm duration (flash hours).

b. Flash rate

The variability in the east–west component of the grid resolution with latitude should not play as important a role with the flash rate as it did with the flash hours. As the number of flashes and the thunderstorm duration were found for each grid location, a smaller grid box would yield both fewer flashes and a shorter duration. While it is uncertain that these decreases are proportionate, it is not believed to be a significant source of error.

c. Flash density versus flash hours

MacGorman et al. (1984) determined a relationship between the duration of thunder (thunder hours) and flash density,

$$\text{Flash\_Density} = 0.054(\text{Thunder\_Hours})^{1.1}. \quad (2)$$

We note that the calculated exponent based on the data analyzed, 1.29 in Eq. (1), is different from that in Eq. (2) as is the coefficient, 0.024 in Eq. (1). MacGorman et al. used two regions (Florida and Oklahoma) for their study and a time period of 2–3 months. The relationship in Eq. (1) yields an expected flash density for a single annual flash hour of approximately 10 flashes per year in a 400-km^2 region.

Based strictly on the correlation coefficient for the relationship in Eq. (1), it appears to be a good approximation to the flash density based on the duration of lightning. Further investigation reveals general agreement between the expected and actual flash density, with large deviations in the Rocky Mountain region and near the District of Columbia and in Massachusetts (Fig. 5). Over 70% of the country has expected flash densities accurate to within 30% of the actual value (Fig. 6).

The differences in expected flash density based on the relationship in (1) and the measured values (Fig. 5) indicate areas with large errors when viewed on a percentage basis. The differences in the Rocky Mountains appear to be large since the measured flash densities are rather small in this region. Any deviations from the measured values would produce a high percent error.

There are also large errors near the District of Columbia and Massachusetts. These errors are most likely due to locally higher flash densities in these areas without substantial changes in the thunderstorm durations. Localized variations are to be expected when applying a comparison to a large region.

5. Conclusions

Lightning data from the NLDN can be used to determine the annual thunderstorm duration within the United States. The results agree well with the values obtained from surface observations (MacGorman et al. 1984; Changnon 1988; Reap and Orville 1990). Flash hours, calculated from CG lightning data, depend largely on the grid size, so it is critical to select the proper grid spacing. A 0.2° grid approximates the area for which an observer would be able to accurately report thunder, which can only be heard 8–15 km from the lightning flash.

Annual flash density and thunderstorm duration or flash hours have a high correlation, which indicates a strong agreement between the measured density and the expected flash density calculated from Eq. (1). The flash density calculated from this relationship is within 30% of the measured value for over 70% of the United States. One should be cautious in using such a relationship for the entire country as the intermountain region of the Rockies shows errors of over 80%. It is apparent that a general relationship between thunderstorm duration and cloud-to-ground flash density can apply to limited regions, but not the entire country.

A new climatology dataset based on the NLDN data has the potential to provide more comprehensive coverage of the United States than previous first-order thunder data allowed. Remote regions without observing sites now have data coverage. This becomes more important when considering the trend toward automated weather observations that do not include thunder data.

Acknowledgments. The lightning data were obtained from the Global Atmospherics, Inc., Tucson, Arizona. Data handling at Texas A&M University is under the direction of Jerry Guynes and Robert White and we thank them for their assistance. We thank the United States Air Force for supporting Major Huffines during this research. Special thanks go to Barbara Orville for her editing assistance. This project is part of a lightning program supported by the National Science Foundation (ATM-9806189) and the National Oceanic and Atmospheric Administration (Cooperative Agreement NA87WA0063).

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