The daily cloud-to-ground lightning flash density in the contiguous United States and Finland

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ABSTRACT

A method is developed to quantify thunderstorm intensity according to cloud-to-ground lightning flashes (hereafter, ground flashes) determined by a lightning-location sensor network. The method is based on the daily ground flash density N_D, calculated on 20 km $\times$ 20 km fixed squares. Because the square size roughly corresponds to the area covered by a typical thunderstorm cell, the flash density for one square defines a unit thunderstorm for the purposes of this study. This method is tested with ground flash data obtained from two nationwide lightning location systems: the National Lightning Detection Network (NLDN) in the contiguous United States and the portion of the Nordic Lightning Information System (NORDLIS) in Finland. The distribution of daily ground flash density N_D is computed for all of Finland and four 800 000 km^2 regions in the United States (identified as West, Central, East, and Florida). Although Finland and all four U.S. regions have median values of N_D of 0.01–0.03 flashes km^{-2} day^{-1}—indicating that the majority of thunderstorms are relatively weak and do not differ geographically—the most intense 1% of the storms (as measured by the 99th percentiles of the N_D distributions within each region) show much larger differences among regions. For example, the most intense 1% of the N_D distributions is 1.3 flash km^{-2} day^{-1} in the United States–Central region, but only 0.2 flash km^{-2} day^{-1} in Finland. The spatial distribution of the most intense 1% of the N_D distributions illustrates that the most intense thunderstorms occur in the central United States and upper Midwest, which differs from the maxima of the average annual flash density N_A and the number of thunderstorm days T_D, both of which occur in Florida and along the coast of the Gulf of Mexico. This method for using

N_D to quantify thunderstorm intensity is applicable to any region as long as the detection efficiency of the lightning location network is high enough or known. This method can also be employed in operational forecasting to provide a quantitative measure of the lightning intensity of thunderstorms relative to climatology.

1. Introduction

The intensity of a thunderstorm can be expressed in several ways. For example, in the United States, a severe thunderstorm is defined as a storm producing lightning/thunder and large hail [1 inch (2.5 cm) and larger (changed from 3/4 inch as of January 2010; G. Carbin 2010, personal communication)], strong gusts [50 kts (26 m s^{-1}) and higher], and/or a tornado (e.g., Galway 1989). Thunderstorm intensity might also be expressed by the incurred damages, although the damage depends on where the storm occurred and the full extent of the damage may not always be known or represented with the available reports (e.g., Speheger et al. 2002; Trapp et al. 2006; Doswell et al. 2009). Another measure is the kinematic intensity, an index measuring storm intensity derived from the peak vertical velocity, updraft volume, and vertical airmass flux in the mixed-phase region (Lang and Rutledge 2002). Unfortunately, computing this index requires specialized measurements from multiple instrumentation, so it is not practical over large geographical areas. Another way to express the intensity of a thunderstorm is by some measure of a thunderstorm-related phenomenon (e.g., precipitation, lightning). For example, lightning-location data from surface-based or satellite-based sensors can be used to derive a direct measure of the production rate of lightning in the thunderstorm and consequently its intensity. Specifically, Zipser et al. (2006) discussed several measures of the intensity of convective storms as measured remotely from satellite.

Two measures that can be derived from the lightning location data are the cloud-to-ground flash rate and cloud-to-ground flash density (hereafter, *ground flash rate* and *ground flash density*). These quantities have been used widely since the introduction of modern lightning location systems (e.g., Peckham et al. 1984; Orville 1991; Orville and

Silver 1997; Huffines and Orville 1999; Orville and Huffines 2001; Zajac and Rutledge 2001). Ground flash rate is expressed as the number of flashes per unit time per unit area, and ground flash density is the ground flash rate integrated over time, expressed as the number of flashes per unit area (usually km^{-2}). In the same way that instantaneous precipitation rate from radar data or rain-gauge data can be used as a measure of the intensity of precipitation, the ground flash rate from a lightning detection network can be used as a measure of the intensity of a thunderstorm. Similarly, the total precipitation over the course of a day or a year is the total depth of water that fell, analogous to the ground flash density, which is an integrated quantity describing the average intensity of a thunderstorm or thunderstorms over a particular region. Ground flash density was first obtained from flash-counter networks (e.g., Prentice 1972) and later obtained from lightning location systems (e.g., Orville et al. 1983, 2002; Pinto et al. 2003; Schulz et al. 2005; Soriano et al. 2005; Orville 2008; Antonescu and Burcea 2010). Nevertheless, these lightning location systems are not perfect because of their imperfect detection efficiency (e.g., Biagi et al. 2007) and the potential for the misclassification of cloud flashes (e.g., Cummins et al. 1998; Cummins and Murphy 2009).

For long-term statistics in climatological studies, the annual ground flash density N_A has been in wide use for decades. With lightning location systems, a common time scale and grid size for many studies typically has been adopted. A spatial scale has been adopted of about 0.2° latitude × 0.2° longitude, which at low or middle latitudes corresponds roughly to grid cells roughly 20 km on a side or an area of 400 km^2. This grid size corresponds approximately to the human observing area for visual observations of lightning and thunder (e.g., Fleagle 1949) and to the area of a typical thunderstorm cell. Using these standard values, the annual ground flash density N_A can be compared for many regions around the world, ranging from high values of ground flash density in central Africa, Florida, and Brazil exceeding 10 flashes km^{-2} yr^{-1} (e.g., Hodanish et al. 1997; Pinto et al. 1999, 2003; Zajac and Rutledge 2001; Christian et al. 2003; Rudlosky and Fuelberg 2010), to values in the Spanish Basque Country of 4–5 flashes km^{-2} yr^{-1} (Areitio et al. 2001), to regions in Finland and Romania having maximum values of about 2–3 flashes km^{-2} yr^{-1} in years with strong thunderstorms (Tuomi and Mäkelä 2009; Antonescu and Burcea 2010).

Although these studies using the annual ground flash density N_A provide information on the intensity of all thunderstorms combined, they do not provide information about the intensity of *individual thunderstorms*. For example, a climate with a short thunderstorm season lasting a few months, but with a relatively few intense storms, may yield similar values of N_A to a climate with weak or moderate storms uniformly throughout the year.

Despite the value in maps of annual ground flash density, we wish to devise a measure of intensity for individual thunderstorms using ground flash density. To do this, we reconsider the space and time scales involved. We choose the same area as above (400 km^2), for reasons discussed previously. For the time scale, we choose one day for two reasons. First, the traditional thunderstorm day, T_D, (as measured, for example, by human observers) is defined as a 24-h period, so comparisons between these two different measures is natural. Second, although individual convective cells last less than an hour and organized mesoscale convective systems can last many hours, usually only one thunderstorm event takes place at a given point within a 24-h period. In situations when more than one thunderstorm event occurs within the grid cell, they may, for statistical purposes, be treated as one thunderstorm. When this happens, the reduced number of storms is offset by higher flash density per storm.

The purpose of this paper is to show the utility of lightning-location data to quantify the intensity of the lightning flash rate in a thunderstorm using the daily ground flash density N_D and to compare this measure to the annual ground flash density N_A and the number of thunderstorm days T_D. In this way, we can map the geographical distribution of thunderstorm intensity. Section 2 of this paper describes the data and methods, and section 3 compares and contrasts the annual ground flash density, the number of thunderstorm days, and the daily ground flash density. The calculations in this paper are also compared to previously published research. Section 4 discusses possible applications of ground flash density to researchers and forecasters, and section 5 concludes this paper.

2. Data and methods

We first present the mathematical functions used for the analysis of the lightning data. Let n_D be the number of ground flashes per day in a 20 km × 20 km square, and N_D be the ground flash density of that square (i.e., n_D divided by 400 km^2 [ground flashes km^{-2} day^{-1}]). Days with no lightning have been omitted from our dataset (i.e., $n_D > 0$ and $N_D > 0$). In addition, let i = 1, 2, 3, ..., 365y be the index of a particular day during the study period of y years. Therefore, n_{Di} describes the number of ground flashes in a square on the ith day. In each square, the distribution of ground flashes per day can be represented with the set $F(n_D)$:

$$F(n_D) = \{n_{D1}, n_{D2}, \ldots, n_{Di}\}, \;\; n_{Di} > 0 \,. \qquad (1)$$

This distribution starts from one flash per square per day, which is equal to N_D = 0.0025 ground flashes km^{-2} day^{-1}, and extends to the maximum observed value. Because each of the squares has its own distribution for the daily occurrence of lightning, the percentiles of the distribution describe the rarity of a certain n_D value occurring within the square. For example, the 50th percentile of n_D (the median) is the 50th percentile value of n_D for the distribution of $F(n_D)$. For the purposes of this paper, we study the 50th, 10th and 1st percentiles from the complementary cumulative distribution, denoted as $p_{50}(N_D)$, $p_{10}(N_D)$ and $p_1(N_D)$, respectively.

Furthermore, the average annual ground flash density N_A [ground flashes km^{-2} yr^{-1}] is the accumulated number of flashes in a square during the study period divided by the number of years and the size of the square, and N_A can be expressed with set $F(n_D)$:

$$N_A = \frac{\sum_{i=1}^{y\times 365} n_{Di}}{y \times 400\, km^2} \,, \;\; n_{Di} > 0 \,. \qquad (2)$$

The average annual number of thunderstorm days in a square, T_D [days yr^{-1}], is defined as the number of those days in a square during which lightning has occurred (i.e., n_{Di}> 0) divided by the number of years y.

We have analyzed lightning separately for the United States and Finland, countries that have similar lightning location systems. The U.S. National Lightning Detection Network (NLDN) consists of more than a hundred sensors distributed around the United States (Cummins et al. 1998; Cummins and Murphy 2009). The Nordic

Lightning Information System (NORDLIS) in northern Europe is a cooperative network consisting of about 30 sensors in Norway, Sweden, Finland, and Estonia (Tuomi and Mäkelä 2008). Besides its own national sensor data, each of the participating countries also receives the sensor data from the other Nordic countries. Each country processes the sensor data themselves except Estonia, which receives the processed data from the Finnish Meteorological Institute. The NORDLIS cooperation makes possible a wider coverage, higher accuracy, and higher detection efficiency than what would be obtained only with the national networks. NLDN and NORDLIS both use the same sensor type (so-called IMPACT-type or its successors manufactured by Vaisala Inc.), so the data should be nearly comparable.

In this study, a ground flash is represented as the first reported stroke. The dataset consists of 103 816 116 ground flashes between January 2003 and October 2007 from the United States (data from November and December 2007 were not available at the time of the analysis, and their omission from this analysis should not substantively change our results) and 2 090 348 ground flashes between January 2002 and December 2009 from Finland. Although both networks have been in operation since at least the 1990s, we have selected a shorter, more recent period for this study to ensure the data from both networks is of high quality. Specifically, the choice of the U.S. data starting in 2003 ensures that the data is nearly all within a period after a major upgrade of the network (Cummins and Murphy 2009; Rudlosky and Fuelberg 2010), and full NORDLIS cooperation began in 2002.

To construct a gridded dataset of daily ground flash density N_D, the United States and Finland are divided into grids of 20 km × 20 km (400 km^2) squares. The number of analyzed squares is about 50 000 in the United States and about 2300 in Finland. We have also converted the lightning data from the original World Geodetic System geographical coordinate system (WGS84) into the km-based Universal Transverse Mercator (UTM) system to provide easier analysis of the data into the 20 km $\times$ 20 km squares. The total number of flashes within each 20 km $\times$ 20 km square is determined for each day in the dataset, where a day is defined from 0000 UTC to 0000 UTC.

Once this analysis is completed, each 20 km $\times$ 20 km square has its own unique distribution $F(N_D)$, which shows how frequently the square experiences thunderstorm days of a certain N_D. A slightly similar technique has been used in Zipser et al. (2006), who studied the global distribution and occurrence of the most intense thunderstorms. Their satellite-based optical total lightning data consisted of both cloud and ground flashes. We will discuss some of their results later in this article.

If only one thunderstorm passes over a 20 km $\times$ 20 km square during a day, the total distribution of N_D at any given square over many years can be viewed as an intensity distribution of individual thunderstorms. This assumption is generally valid in Finland where several storms occurring within one grid square during a day is rare. However, this assumption may be less valid in some regions of the United States that are prone to frequent thunderstorms. Furthermore, our method ignores cell motion, the actual position of cells with respect to the grid squares, and the actual duration of the thunderstorms. Accounting for these neglected effects would require different methods, such as cell tracking, but those methods would have their own ambiguities. Thus, we stick with our present method because our purpose is not to give statistics of thunderstorms *following* *their motion*, but to provide statistics about how *different fixed locations* experience thunderstorms per day and per year.

3. Results

We present maps of the average annual flash density N_A (section 3a) and the average annual number of thunderstorm days T_D (section 3b) because these parameters have been frequently used in the past. Then, we present maps of some statistics from the distribution of daily ground flash density N_D (section 3c), which can be related to the intensity of individual thunderstorm days. The annual cycle of N_D is presented in section 3d, and the relationship between T_D and N_A is explored in section 3e.

a. The average annual ground flash density (N_A)

Values of the highest average annual ground flash density N_A exceed 10 flashes km^{-2} yr^{-1} in Florida and approach 10 flashes km^{-2} yr^{-1} in the coastal areas near the Gulf of Mexico and in the central parts of United States (Fig. 1a). A region of moderate values (4–10 flashes km^{-2} yr^{-1}) extends from Texas northeastward to the Midwest and the Ohio River Valley. In contrast, the western United States and extreme northern areas experience relatively few strikes per year, with values of N_A well below 1 flash km^{-2} yr^{-1}. These results are consistent with previous research displaying the average annual ground flash density over the United States for other time periods (e.g., 1989–1991: Plate 4a in Orville 1994; 1992–1995: Fig. 3 in Orville and Silver 1997; 1989–1996: Fig. 1 in

Huffines and Orville 1999; 1995–1999: Fig. 7 in Zajac and Rutledge 2001; 1998–2000: Fig. 12 in Orville 2008; 2004–2009: Fig. 2a in Rudlosky and Fuelberg 2010). Maxima around some urban areas in our data may be due to cloud-to-ground lightning enhancement (e.g., Westcott 1995; Soriano and de Pablo 2002; Naccarato et al. 2003; Kar et al. 2009), although not all areas identified in the literature as having enhancements show up as clearly as others in Fig. 1a. For example, areas near Houston and in southern Louisiana (e.g., Steiger et al. 2002; Steiger and Orville 2003) show enhancements, although Atlanta (e.g., Stallins et al. 2006) shows only a weak enhancement, if any, in this dataset.

In Finland, the values of N_A are considerably lower (less than 1 flash km^{-2} yr^{-1}, comparable to the western United States), with the highest values in central and western Finland (Fig. 1b). Lightning enhancements near urban areas seem unlikely to explain these maxima in Finland for two reasons. First, the air is cleaner in general in Finland, and, second, the aerosol content in Finland peaks in the late winter and early spring (e.g., Antilla and Salmi 2006) before the thunderstorm season starts. Several studies (e.g., Naccarato et al. 2003; Kar et al. 2007, 2009) have shown a relationship between cloud-to-ground lightning flashes and PM10 (aerosols smaller than 10 μm in diameter), but if this relationship were to hold in Finland, the lightning would be enhanced in the most populated cities in southern Finland where PM10 is highest (Anttila and Salmi 2006).

Generally, there is no major geographical variation in N_A across Finland because of the much smaller area and more homogeneous climate of Finland relative to the United States and because the annual variation in the occurrence of thunderstorms is much greater in Finland than in the United States (cf. Fig. 3 in Tuomi and Mäkelä 2008 and

Fig. 2 in Orville and Huffines 1999), and this variation smoothes the field of N_A in Fig. 1b.

b. The average annual number of thunderstorm days

Figure 2 shows the average number of thunderstorm days per year T_D in each 20 km × 20 km square. High values (about 100 days yr^{-1}) occur in Florida, near the Gulf of Mexico, and over the southern Rocky Mountains. In contrast, the central and eastern United States have lower values (30–60 days yr^{-1}). These results are similar to (albeit perhaps a bit higher than) previously published studies of thunderstorm days (e.g., MacGorman et al. 1984, adapted in Fig. 1 of Orville 1991; Fig. 8a in Zajac and Rutledge 2001) and is similar in shape to the mean annual flash hours in Huffines and Orville (1999, their Fig. 2), except for a maximum in eastern Oklahoma and Kansas not reproduced in Fig. 2a.

Comparing Figs. 1a and 2a suggests that (i) the high N_A values in Florida and near the Gulf of Mexico are mainly due to the larger number of days with thunderstorms, and (ii) the high N_A values in the central and eastern United States are the consequence of more intense thunderstorms, but fewer thunderstorm days per year.

In Finland (Fig. 2b), about 12–15 thunderstorm days yr^{-1} occur throughout the whole country, except for the northernmost parts which show smaller values (< 10 days yr^{-1}) as a result of the shorter summer season. Similar values of the annual number of thunderstorm days are found in a global map published by the World Meteorological Organization in 1956 [reproduced as Fig. 2.8 in Rakov and Uman (2003, p. 36)].

c. The daily ground flash density (N_D)

To show the distributions of daily ground flash density for each of about 50 000 squares in the United States would be excessive. Instead, we consider four distinct climatological regions of the United States, identified as West, Central, East, and Florida (Fig. 3). The surface area of each region is the same (800 000 km^2). For Florida, the data from grid squares over the land and the surrounding waters are calculated separately.

Figures 4a–e shows the distributions of N_D for all of Finland and each of the four regions in the United States. The distributions for regions with less frequent thunderstorms (United States–West and Finland) have a steep decline indicating that the extremely high N_D values (5–10 flashes km^{-2} yr^{-1}) do not occur (Figs. 4a,e). For comparison, U.S. regions with more frequent thunderstorms (Central, East, and Florida) have a more gentle decline toward higher values of N_D (Figs. 4b,c,d). Over the United States–Florida region, the slope to the graph of the data over land has a gentler decline than that over the surrounding waters (Fig. 4d).

To compare these six graphs directly, these data can be plotted as complementary cumulative frequency distributions, where the values along the *y* axis indicate the percentage of thunderstorm days during which a certain value of N_D is exceeded (Fig. 4f). The median values (50% on the *y* axis) for each region are about 0.01–0.03 flashes km^{-2} day^{-1} (Fig. 4f; Table 1). However, for smaller percentages (i.e., more intense thunderstorms), the complementary cumulative curves are more dissimilar to each other. For example, the densities at 10%, $p_{10}(N_D)$, range from 0.05 flashes km^{-2} day^{-1} in Finland to 0.3 flashes km^{-2} day^{-1} in the United States–Central region, and the densities at 1%, $p_1(N_D)$, range from 0.2 flashes km^{-2} day^{-1} in Finland to 1.3 flashes km^{-2} day^{-1} in the United States–Central region (Fig. 4f; Table 1). These percentages mean that, in the United States–Central region, for example, 1% of thunderstorm days produce a daily ground flash density N_D of 1.3 flashes km^{-2} day^{-1} or higher.

Table 1 shows the median, 10%, 1%, and maximum N_D values for each region. Interestingly, the highest observed value in Florida is larger over the sea than over the land, and this square is located just off the coast (at 4280 km E, 840 km N in Figs. 1, 2, 3, 5 and 8). Seity et al. (2001) found that most of the thunderstorms over the sea develop close to the coastline in France. The thunderstorm climate of Estonia also shows more frequent lightning over the sea near the coast during intense frontal thunderstorms (Enno 2009).

The highest observed value of N_D across the United States occurred within a 20 km $\times$ 20 km square in northern Kansas on 23 June 2003 (at 2480 km E, 1760 km N in Figs. 1, 2, 3, 5 and 8). The value was 13.2 flashes km^{-2} day^{-1} and resulted from 5276 located ground flashes. This day featured a nearly stationary mesoscale convective system that produced 15 tornadoes in Kansas and Nebraska, as well as numerous severe-hail reports (http://www.spc.noaa.gov/climo/reports/030622_rpts.html).

Figure 5 maps the values of $p_1(N_D)$ in the United States and Finland. Although Fig. 5 can be drawn for any percentile, regional differences would be diminished for larger percentages as the curves in Fig. 4f become closer together. For example, $p_{50}(N_D)$ would have little spatial variation, as is apparent from the similarity of the 50% values for each region (Table 1).

In the United States, the largest values of $p_1(N_D)$ occur along the arc from Texas to the Midwest (Fig. 5a). Florida has much lower values (Fig. 5a), which suggests that the most intense storms are not as frequent in Florida as in that arc, despite the large number of flashes and thunderstorm days in Florida (Figs. 1a and 2a). Zipser et al. (2006) studied the occurrence of the most intense thunderstorms in the Tropics using data from satellite-based sensors. Their Figs. 3 and 6a–b show that intense thunderstorms are relatively frequent in the United States–Central region compared to Florida, consistent with our results.

In Finland, $p_1(N_D)$ values are much smaller and there are no major gradients, except along the western coast of Finland near the Gulf of Bothnia (Fig. 5b). This enhancement may be related to coastal effects, such as the sea-breeze convergence, during suitable conditions for intense thunderstorms. Anecdotal evidence seems to indicate local enhancement in this area, especially during several consecutive days in 2003 when intense storms developed near the coastline of western Finland. The storms moved quite slowly to the East and caused locally high ground flash densities. This evolution of convective storms for this particular period might be indicative of a larger number of events given that the climatology reveals such a pattern, indicating a topic for further research.

d. Annual cycle of the daily ground flash density (N_D)

The monthly distributions of $p_1(N_D)$ and all ground flashes for each region are shown in Fig. 6. If the $p_1(N_D)$ curve (solid line) has a higher percentage than the “all” curve (dashed line), then a high number of ground flashes during that month are produced by the most intense storms. The annual cycle of N_D is broadly similar in all regions; the percentages increase starting from early summer, peak in July–August, and decrease towards the autumn. The United States–Central region has a broad peak with a June maximum (Fig. 6b). The midsummer peak is most pronounced in the western United States and Finland, and is even narrower in Finland, indicating the shorter season for thunderstorms (Figs. 6a,f). However, in Finland (Fig. 6f), the percentage of $p_1(N_D)$ is higher in May than in June, which suggests that, during the study period (2002–2009), June atmospheric conditions have not been favorable for intense thunderstorms, although more ground flashes occur on average in June than in May (Tuomi and Mäkelä 2008). Indeed, Tuomi and Mäkelä (2008) showed that the Finnish thunderstorm season does not start gradually, but rather with a few intense thunderstorm days in May, before a period in June of less intense thunderstorms. This decrease in the intensity of Finnish thunderstorms in June is supported by the 1930–2006 large-hail climatology of Tuovinen et al. (2009, their Fig. 3). They found that more large hail (2.0–3.9 cm in diameter) falls in June than in May, but the occurrence of very large hail (at least 4.0 cm in diameter) is more common during the last two weeks of May than during the first two weeks of June. We must emphasize, however, that the high annual variation of convective storms and their less frequent occurrence in Finland means comparing different studies over different time periods may produce differing results.

In the central United States and Florida (Figs. 6b,d,e), the distributions are broader throughout the year, suggesting that intense storms are not uncommon in March–April and as late as September–October. Comparing the solid and dashed lines in Fig. 6, all areas show that the percentages of the $p_1(N_D)$ (solid) are higher than the percentage of all flashes (dashed) in the midsummer and lower in the early and late summer. Thus, a large fraction of midsummer flashes are from very intense storms. In the Florida–land region (Fig. 6d), this feature is not so well pronounced, indicating that the high percentage of ground flashes is not so dependent on the most intense storms, but the high number of thunderstorms, in general.

e. The relationship between T_D and N_A

Following previous work summarized in Rakov and Uman (2003, p. 35), Fig. 7 shows the relationship between T_D and N_A for the whole U.S. and Finnish datasets, as well as the four regions of the United States separately. As Rakov and Uman (2003) discuss, this relationship can be used to estimate N_A globally because T_D data has been collected for decades all around the world. Despite the considerable scatter in plots such as Fig. 7, N_A can be estimated in areas where modern lightning location systems are not available.

The most common way to apply a fit to this data is through a linear least-squares regression method in log–log space to an equation of the form $N_A = aT_D^b$. The coefficients a and b have been calculated from the data. However, as the actual relationship between T_D and N_A is not linear, any correlation coefficient is valid only in log–log space. The best regression model fit to all of the U.S. and Finnish data has a form $N_A = 0.007T_D^{1.61}$ (solid line in Fig. 7), with a linear correlation coefficient $r = 0.97$. Fig. 7 also shows two other previously published regression lines for Australia ($N_A = 0.012T_D^{1.4}$; Kuleshov and Jayaratne 2004) and for South Africa ($N_A = 0.04T_D^{1.25}$; Anderson et al. 1984). The Australian dotted line more closely matches the data in Fig. 7 for smaller T_D, whereas the South African dashed line more closely matches the data for larger T_D. The different lines and their relationship to our dataset suggest the limited applicability of curves outside of the area for which they were calculated.

This point is further emphasized when data from the different regions in our dataset are displayed as different colored symbols in Fig. 7.. Table 2 shows the regional regression model fits and statistics of each of the regional datasets, showing quite a bit of variability among the regions. Florida (yellow) has the largest average values of N_A and T_D (averages of the squares of Florida are 8.2 flashes km^{-2} yr^{-1} and 80.1 days yr^{-1}), whereas the United States–Central region (purple) has lower values (averages are 6.1 flashes km^{-2} yr^{-1} and 48.7 days yr^{-1}). However, more ground flashes occur per day in the United States–Central region on average, as shown by the differences in the regression model equations of the different regions. In Finland (green), the average values of N_A and T_D are small (Table 2), which can be related to the short thunderstorm season at these higher latitudes (60°N–70°N). In the United States–West region (blue), the average values are close to Finland, but in the United States–East (cyan), the average values are considerably higher (Table 2).

These results can be shown more clearly if we define an average increase rate for each regional curve as

$$\frac{N_{Amax} - N_{Amin}}{T_{Dmax} - T_{Dmin}} \quad . \qquad (3)$$

If the value of this rate of rise is high, it means that only a small increment in T_D causes a relatively large increase in N_A, which is an obvious result in the region where intense thunderstorms occur. The values of this increase rate for each region are shown in Table

2. The United States–Central region has the largest value (0.22 flashes km^{-2} day^{-1}), indicating that a given annual ground flash density is obtained with fewer thunderstorm days, and Finland has the smallest value (0.03 flashes km^{-2} day^{-1}).

If N_A is divided by T_D, the resulting quantity measures the average ground flash density per thunderstorm day (Fig. 8). This quantity further indicates the differences of thunderstorm days in different geographical locations. In the United States, the highest values are found in the region extending from Texas to Iowa–Illinois (about 0.2 flashes km^{-2} day^{-1}) and in Florida (about 0.15 flashes km^{-2} day^{-1}). The value over Finland is nearly constant at around 0.03 flashes km^{-2} day^{-1}, and the highest value is only 0.08 flashes km^{-2} day^{-1}. However, the values in northern Finland are similar to those in southern Finland, indicating that, despite the shorter thunderstorm season in the north, individual thunderstorm days do not differ much across Finland.

To summarize this section: although there are large differences in the number of thunderstorm days and in the annual average ground flash density between different regions in our dataset, there is consistency among the different ways to compare the data, suggesting that the local number of thunderstorm days can be used to explain the annual ground flash density.

4. Applications of daily flash density

There are different kinds of lightning location systems worldwide, both ground-based and satellite-based, from which some are able to detect primarily ground lightning and some total lightning (i.e., cloud flashes plus ground flashes). Our method of determining the daily ground flash density is applicable to any system with ground flash data and a detection efficiency high enough or known. A similar method could be used on total lightning data, but the present coverage of total lightning systems is limited compared to ground lightning networks. As satellite-based lightning imagers will be launched in geostationary orbit in the coming years (e.g., Christian et al. 1989; Stuhlmann et al. 2005), a near-global analysis will be possible. However, as the satellite-based detectors measure total lightning, the statistics computed from satellite using total lightning flashes may be different from the statistics computed from ground-based networks using ground flashes.

An interesting extension to this study would be to include data from Central Africa, South America, and Indonesia, which are regions of large ground flash density with a large number of intense events (Rodger et al. 2006; Zipser et al. 2006). The results would quantify the intensity of the thunderstorms there and indicate if the high ground flash density values in these areas are due to moderate but almost constant thunderstorm activity per year or due to a short thunderstorm season with extremely intense thunderstorm days. The results would also serve as a further test of Zipser et al. (2006), showing where the most intense thunderstorms on Earth are found.

The results of this study can be used to quantify the intensity of individual thunderstorms. Once the distribution of N_D for a given area is known, the distribution can be used to create an intensity scale according to the rarity of a certain ground flash density. For example, if N_D exceeds the 1% percentile density value, *on a statistical basis* we could classify the storm for example as "exceptionally intense" because of the rarity of such an N_D value occurring.

Indeed, at the Finnish Meteorological Institute, we have tested a real-time five-scale intensity classification product based on the method presented in this paper (Table 3). Ground flash densities are classified into five classes from least intense (L1) to most intense (L5) (Table 3). We have created this classification so that the least intense class constitutes 88% of all daily ground flash densities from the complementary cumulative distribution of Fig. 4f, the two most intense levels (L4 and L5) constitute 1%, and the most intense level (L5) constitutes only 0.02% from the distribution. These last two choices are to ensure that when this high value is exceeded, it can be fairly classified as an extremely rare thunderstorm.

In real time, as the number of ground flashes increases in a grid square, the product displays the increasing intensity of the storm at that grid square. An example of how this product works is shown from 10 July 2006 (Fig. 9). Figure 9a shows the traditional lightning product showing each flash as an individual location. Although lightning has occurred over much of southern and eastern Finland, it is difficult to give an objective answer about the intensity of the lightning merely from this figure.

Figure 9b shows the same lightning data, but now plotted as N_D according to the method presented in this article. The data are analyzed on 20 km $\times$ 20 km squares, and the values on each square and the colors of each square indicate the ground flash density in flashes per 100 km^{-2} (to plot the values in whole numbers rather than decimal values).

This product is useful for nowcasting, because a forecaster sees in real time how the intensity of lightning is developing and in what directions the most intense storms are moving. Also, archived daily maps can be used to pinpoint areas of intense lightning for later scientific or forensic research. When this data is imported into Geographical

Information System (GIS) software, properties of the grid squares (e.g., population density) can be visualized, as well.

5. Conclusions

A method to quantify the intensity of individual thunderstorm days according to ground flashes has been developed. The intensity of a thunderstorm is defined as the daily ground flash density, N_D, calculated on a 20 km $\times$ 20 km fixed square. The square size has been chosen because it roughly corresponds to the typical size of a thunderstorm cell. The lightning observations are based on a lightning location system and the analysis covers the United States and Finland. If only one thunderstorm moves over a square during a given day, our results can be related to the intensity of individual thunderstorms (i.e., the flashes accumulated in a square during a day from a single storm). This assumption works well in Finland, but may not work as well in other locations where multiple storms may pass over a given area during one day.

The motivation for this paper is to show the distribution of the daily ground flash density in different areas, and especially the fraction and rarity of those storms that produce extremely large numbers of flashes. The distributions of N_D show that the majority of storms are relatively weak regardless of location: the 50% (median) value in the distribution is 0.01–0.03 ground flashes km^{-2} day^{-1}. However, the distributions of N_D show large differences for the larger values of ground flash density. For example, in the United States–Central region, 1% of storms produce flash densities exceeding 1 ground flash km^{-2} day^{-1}, whereas, in Finland and the United States–West region, the 1% value is about 0.2 ground flash km^{-2} day^{-1}.

An important result from this study is that the daily ground flash density can show that some areas receiving a high annual number of ground flashes are the result of a large number of weak to moderate storms over a longer season (e.g., Florida, southern United States along the Gulf of Mexico), not the result of a few intense storms that produce copious lightning. Such a conclusion cannot be reached from the average annual flash density N_A distributions alone, which do not consider the thunderstorm days individually.

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REFERENCES

Anderson, R. B., H. Kroninger, H. R. Niekerk, and D. W. Meal, 1984: Development and field evaluation of a lightning earth-flash counter. *IEE Proceedings A*, **131**, 118–124.

Antonescu, B., and S. Burcea, 2010: A cloud-to-ground lightning climatology for Romania. *Mon. Wea. Rev.*, **138,** 579–591.

Anttila, P., and T. Salmi, 2006: Characterizing temporal and spatial patterns of urban PM10 using six years of Finnish monitoring data. *Bor. Environ. Res.*, **11**, 463–479.

Areitio, J., A. Ezcurra, and I. Herrero, 2001: Cloud-to-ground lightning characteristics in the Spanish Basque Country area during the period 1992–1996. *J. Atmos. Solar-Terrestrial Physics*, **63,** 1005–1015.

Biagi, C. J., K. L. Cummins, K. E. Kehoe, and E. P. Krider, 2007: National Lightning Detection Network (NLDN) performance in southern Arizona, Texas, and Oklahoma in 2003–2004. *J. Geophys. Res.*, **112**, D05208, doi: 10.1029/2006JD007341.

Christian, H. J., R. J. Blakeslee, and S. J. Goodman, 1989: The detection of lightning from geostationary orbit. *J. Geophys. Res.*, **94**, 13 329–13 337.

Christian, H. J., R. J. Blakeslee, D. J. Boccippio, W. L. Boeck, D. E. Buechler, K. T. Driscoll, S. J. Goodman, J. M. Hall, W. J. Koshak, D. M. Mach, and M. F. Stewart, 2003: Global frequency and distribution of lightning as observed from space by the Optical Transient Detector. *J. Geophys. Res.*, **108**, 4005, doi:10.1029/2002JD002347.

Cummins, K. L., M. J. Murphy, E. A. Bardo, W. L. Hiscox, R. B. Pyle, and A. E. Pifer, 1998: A combined TOA/MDF technology upgrade of the U.S. National Lightning Detection Network. *J. Geophys. Res.*, **103**, 9035–9044.

Cummins, K. L., and M. J. Murphy, 2009: An overview of lightning locating systems: History, techniques, and data uses, with an in-depth look at the U.S. NLDN. *IEEE Trans. on Electromagnetic Compatibility*, **51**, 499–518.

Doswell, C. A. III, H. E. Brooks, and N. Dotzek, 2009: On the implementation of the enhanced Fujita scale in the USA. *Atmos. Res.,* **93,** 554–563.

Enno, S.-E., 2009: Spatial and temporal distribution of cloud-to-ground lightning over Estonia during 2005–2008. *Fifth European Conference on Severe Storms*, Landshut, Germany, European Severe Storms Laboratory, 2 p. [Available online at http://www.essl.org/ECSS/2009/preprints/P07-10-enno.pdf.]

Fleagle, R. G., 1949: The audibility of thunder. *J. Acoustical Soc. Amer.*, **21**, 411–412.

Galway, J. G., 1989: The evolution of severe thunderstorm criteria within the Weather Service. *Wea. Forecasting,* **4,** 585–592.

Hodanish, S., D. Sharp, W. Collins, C. Paxton, and R. E. Orville, 1997: A 10-yr monthly lightning climatology of Florida: 1986–95. *Wea. Forecasting*, **12**, 439–448.

Huffines, G. R., and R. E. Orville, 1999: Lightning ground flash density and thunderstorm duration in the continental United States: 1989–96. *J. Appl. Meteor.*, **38**, 1013–1019.

Kar, S. K., Y.-A. Liou, and K.-J. Ha, 2009: Aerosol effects on the enhancement of cloud-to-ground lightning over major urban areas of South Korea. *Atmos. Res.*, **92,** 80–87.

Kuleshov, Y., and E. R. Jayaratne, 2004: Estimates of lightning ground flash density in Australia and its relationship to thunder-days. *Aust. Met. Mag.*, **53**, 189–196.

Lang, T. J., and S. A. Rutledge, 2002: Relationships between convective storm kinematics, precipitation, and lightning. *Mon. Wea. Rev.*, **130,** 2492–2506.

MacGorman, D. R., M. W. Maier, and W. D. Rust, 1984: *Lightning strike density for the contiguous United States from thunderstorm duration records.* Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission, 44 pp.

Naccarato, K. P., O. Pinto Jr., and I. R. C. A. Pinto, 2003: Evidence of thermal and aerosol effects on the cloud-to-ground lightning density and polarity over large urban areas of southeastern Brazil. *Geophys. Res. Lett.*, **30,** 1674.

Orville, R. E., 1991: Lightning ground flash density in the contiguous United States—1989. *Mon. Wea. Rev.*, **119**, 573–577.

Orville, R. E., 1994: Cloud-to-ground lightning flash characteristics in the contiguous United States: 1989–1991. *J. Geophys. Res.*, **99**, 10 833–10 841.

Orville, R. E., 2008: Development of the National Lightning Detection Network. *Bull. Amer. Meteor. Soc.*, **89**, 180–190.

Orville, R. E., R. W. Henderson, and L. F. Bosart, 1983: An East Coast lightning detection network. *Bull. Amer. Meteor. Soc.*, **64**, 1029–1030.

Orville, R. E., and G. R. Huffines, 1999: Lightning ground flash measurements over the contiguous United States: 1995–97. *Mon. Wea. Rev.*, **127**, 2693–2703.

Orville, R. E., and G. R. Huffines, 2001: Cloud-to-ground lightning in the United States: NLDN results in the first decade, 1989–1998. *Mon. Wea. Rev.*, **129**, 1179–1193.

Orville, R. E., G. R. Huffines, W. R. Burrows, R. L. Holle, and K. L. Cummins, 2002: The North American Lightning Detection Network (NALDN)—First Results: 1998–2000. *Mon. Wea. Rev.*, **130,** 2098–2109.

Orville, R. E., and A. C. Silver, 1997: Lightning ground flash density in the contiguous United States: 1992–1995. *Mon. Wea. Rev.*, **125**, 631–638.

Peckham, D. W., M. A. Uman, and C. E. Wilcox Jr., 1984: Lightning phenomenology in the Tampa Bay area. *J. Geophys. Res.*, **89**, 789–805.

Pinto, O., Jr., I. R. C. A. Pinto, M. A. S. S. Gomes, I. Vitorello, A. L. Padilha, J. H. Diniz, A. M. Carvalho, and A. C. Filho, 1999: Cloud-to-ground lightning in southeastern Brazil in 1993. 1. Geographical distribution. *J. Geophys. Res.*, **104,** 31 369–31 379.

Pinto, O., Jr., I. R. C. A. Pinto, J. H. Diniz, A. C. Filho, L. C. L. Cherchiglia, and A. M. Carvalho, 2003: A seven-year study about the negative cloud-to-ground lightning flash characteristics in southeastern Brazil. *J. Atmos. Solar-Terrestrial Physics*, **65,** 739–748.

Prentice, S. A., 1972: CIGRE lightning flash counter. *Electra*, **22**, 149–171.

Rakov, V. A., and M. A. Uman, 2003: *Lightning Physics and Effects.* Cambridge, 687 pp.

Rodger, C. J., S. Werner, J. B. Brundell, E. H. Lay, N. R. Thomson, R. H. Holzworth, and R. L. Dowden, 2006: Detection efficiency of the VLF World-Wide Lightning Location Network (WWLLN): Initial case study. *Ann. Geophys.*, **24**, 3197–3214.

Rudlosky, S. D., and H. E. Fuelberg, 2010: Pre- and post-upgrade distributions of NLDN reported cloud-to-ground lightning characteristics in the contiguous United States. *Mon. Wea. Rev.*, doi: 10.1175/2010MWR3283.1.

Schulz, W., K. Cummins, G. Diendorfer, and M. Dorninger, 2005: Cloud-to-ground lightning in Austria: A 10-year study using data from a lightning location system. *J. Geophys. Res.*, **110,** D09101.

Seity, Y., S. Soula, and H. Sauvageot, 2001: Lightning and precipitation relationship in coastal thunderstorms. *J. Geophys. Res.*, **106**, 22 801–22 816.

Soriano, L. R., and F. de Pablo, 2002: Effect of small urban areas in central Spain on the enhancement of cloud-to-ground lightning activity. *Atmos. Env.*, **36**, 2809–2816.

Soriano, L. R., F. de Pablo, and C. Tomas, 2005: Ten-year study of cloud-to-ground lightning activity in the Iberian Peninsula. *J. Atmospheric and Solar-Terrestrial Phys.*, **67**, 1632–1639.

Speheger, D. A., C. A. Doswell III, and G. J. Stumpf, 2002: The tornadoes of 3 May 1999: Event verification in central Oklahoma and related issues. *Wea. Forecasting,* **17,** 362–381.

Stallins, J. A., M. L. Bentley, and L. S. Rose, 2006: Cloud-to-ground flash patterns for Atlanta, Georgia (USA) from 1992 to 2003. *Clim. Res.*, **30,** 99–112.

Steiger, S. M., and R. E. Orville, 2003: Cloud-to-ground lightning enhancement over southern Louisiana. *Geophys. Res. Lett.*, **30,** 1975.

Steiger, S. M., R. E. Orville, and G. Huffines, 2002: Cloud-to-ground lightning characteristics over Houston, Texas: 1989–2000. *J. Geophys. Res.*, **107,** 4117.

Stuhlmann, R., A. Rodriguez, S. Tjemkes, J. Grandell, A. Arriaga, J. Bézy, D. Aminou, and P. Bensi, 2005: Plans for EUMETSAT's Third Generation Meteosat geostationary satellite programme. *Adv. Space Res.,* **36,** 975–981.

Trapp, R. J., D. M. Wheatley, N. T. Atkins, R. W. Przybylinski, and R. Wolf, 2006: Buyer beware: Some words of caution on the use of severe wind reports in postevent assessment and research. *Wea. Forecasting,* **21,** 408–415.

Tuomi, T. J., and A. Mäkelä, 2008: Thunderstorm climate of Finland 1998–2007. *Geophysica*, **44**, 1–8.

Tuomi, T. J., and A. Mäkelä, 2009: Lightning observations in Finland, 2009. *Reports of Finnish Meteorological Institute*, **2009:5**, 51 pp. [Available from http://helda.helsinki.fi/bitstream/handle/10138/14831/2009nro5.pdf.]

Tuovinen, J.-P., A.-J. Punkka, J. Rauhala, H. Hohti, and D. M. Schultz, 2009: Climatology of severe hail in Finland: 1930–2006. *Mon. Wea. Rev.*, **137**, 2238–2249.

Westcott, N. E., 1995: Summertime cloud-to-ground lightning activity around major Midwestern urban areas. *J. Appl. Meteor.*, **34,** 1633–1642.

Zajac, B. A., and S. A. Rutledge, 2001: Cloud-to-ground lightning activity in the contiguous United States from 1995 to 1999. *Mon. Wea. Rev.*, **129**, 999–1019.

Zipser, E. J., D. J. Cecil, C. Liu, S. W. Nesbitt, and D. P. Yorty, 2006: Where are the most intense thunderstorms on Earth? *Bull. Amer. Meteor. Soc.*, **87**, 1057–1071.

Tables

Table 1. Some statistics of the complementary cumulative distributions of daily ground flash densities for regions shown in Fig. 3 and for Finland. The two values for Florida are for land and water areas.

Region	$p_{50}(N_D)$ [flashes km^{-2} day^{-1}]	$p_{10}(N_D)$ [flashes km^{-2} day^{-1}]	$p_1(N_D)$ [flashes km^{-2} day^{-1}]	Maximum [flashes km^{-2} day^{-1}]
United States–Central	0.03	0.30	1.27	13.19
United States–Florida (land)	0.03	0.25	0.93	4.57
United States–Florida (water)	0.02	0.16	0.65	10.15
United States–East	0.02	0.19	0.77	6.50
United States–West	0.01	0.10	0.61	2.02
Finland	0.01	0.06	0.23	2.10

Table 2. Regression models and the average increase rate for the different regions in Fig. 7.

Region	Regression model	r	Average T_D (days yr^{-1})	Average N_A (flashes km^{-2} yr^{-1})	Average increase rate (flashes km^{-2} day^{-1})
United States–Central	$N_A = 0.005T_D^{1.81}$	0.67	48.7	6.1	0.22
United States–Florida (land)	$N_A = 0.004T_D^{1.71}$	0.80	80.1	8.2	0.17
United States–Florida (water)	$N_A = 0.003T_D^{1.76}$	0.84	50.4	3.5	0.13
United States–East	$N_A = 0.024T_D^{1.33}$	0.79	38.2	3.1	0.10
United States–West	$N_A = 0.013T_D^{1.36}$	0.91	31.8	1.5	0.06
Finland	$N_A = 0.019T_D^{1.2}$	0.96	9.2	0.3	0.03

Table 3. The ground lightning intensity classification used at the Finnish Meteorological Institute. The last column indicates the percentage value of the intensity level from the complementary cumulative distribution of Fig. 4f.

Classification	Ground flash density (flashes km^{-2} day^{-1})	Percentage (%)
L5	$N_D > 0.8$	0.02
L4	$0.25 < N_D \leq 0.8$	0.98
L3	$0.08 < N_D \leq 0.25$	5.0
L2	$0.025 < N_D \leq 0.08$	6.0
L1	$0 < N_D \leq 0.025$	88.0

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$0.007 T_D^{1.61}$, and the two other fits are $N_A = 0.04 T_D^{1.25}$ (Anderson et al. 1984, dashed), and $N_A = 0.012 T_D^{1.4}$ (Kuleshov and Jayaratne 2004, dotted). Table 2 shows the regional fit equations.

Figure 8. The ratio between the average annual ground flash density N_A and the average annual thunderstorm day number T_D (in ground flashes km^{-2} day^{-1}, shaded) for (a) the contiguous United States and (b) Finland.

Figure 9. (a) The 12 189 ground flashes across Finland on 10 July 2006. The inset color table indicates the UTC hour of the flashes (LST=UTC+3 h) and the number of ground flashes during that hour in the contiguous Finland. (b) Daily ground flash density map [flashes (100 km^2)$^{-1}$ day^{-1}] showing the intensity of lightning in five classes L1–L5.

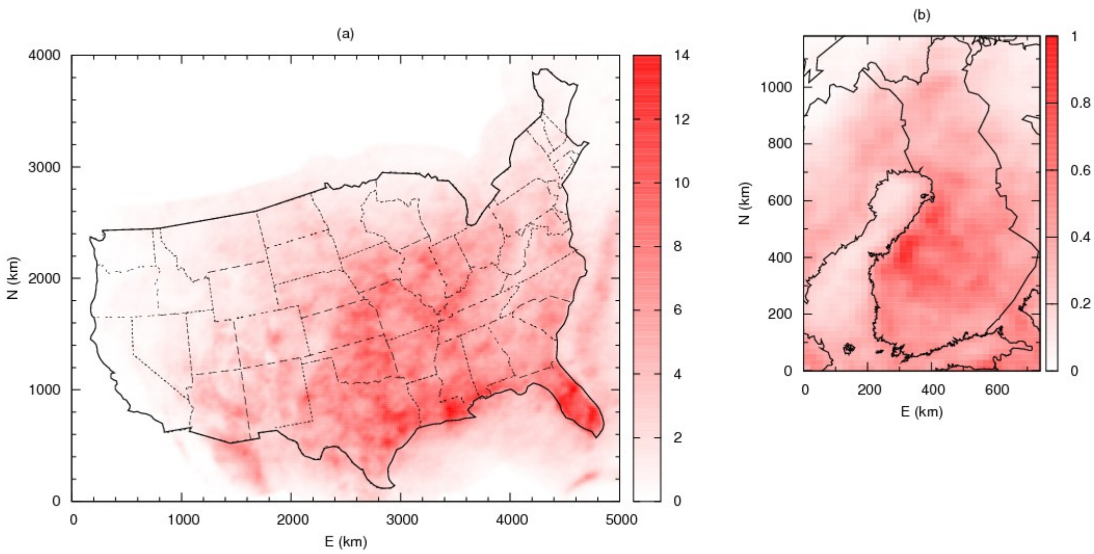

Figure 1. The average annual ground flash density N_A for (a) the contiguous United States and (b) Finland. Note the different color scales.

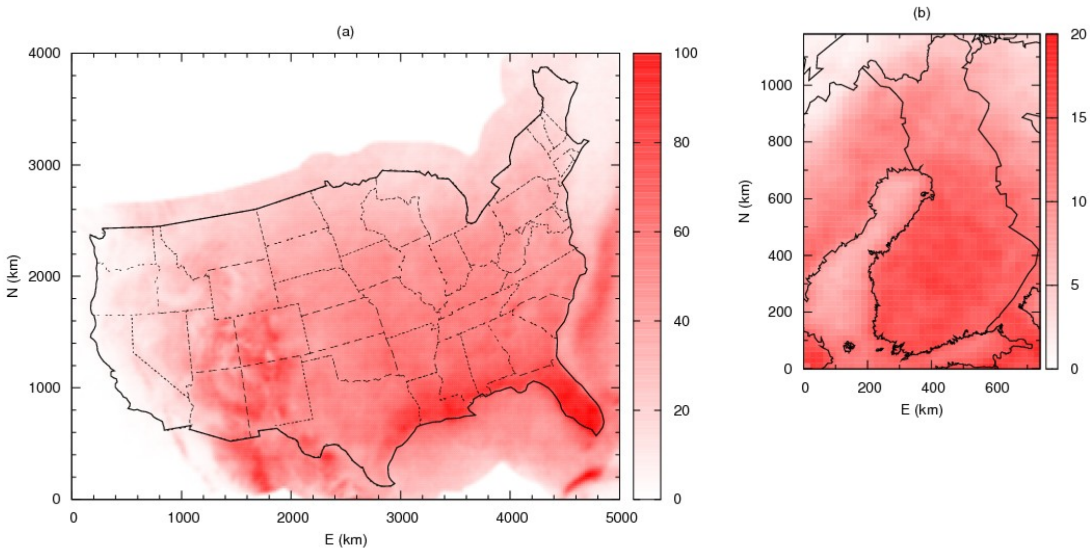

Figure 2. The average annual number of thunderstorm days T_D for (a) the contiguous United States and (b) Finland. Note the different color scales.

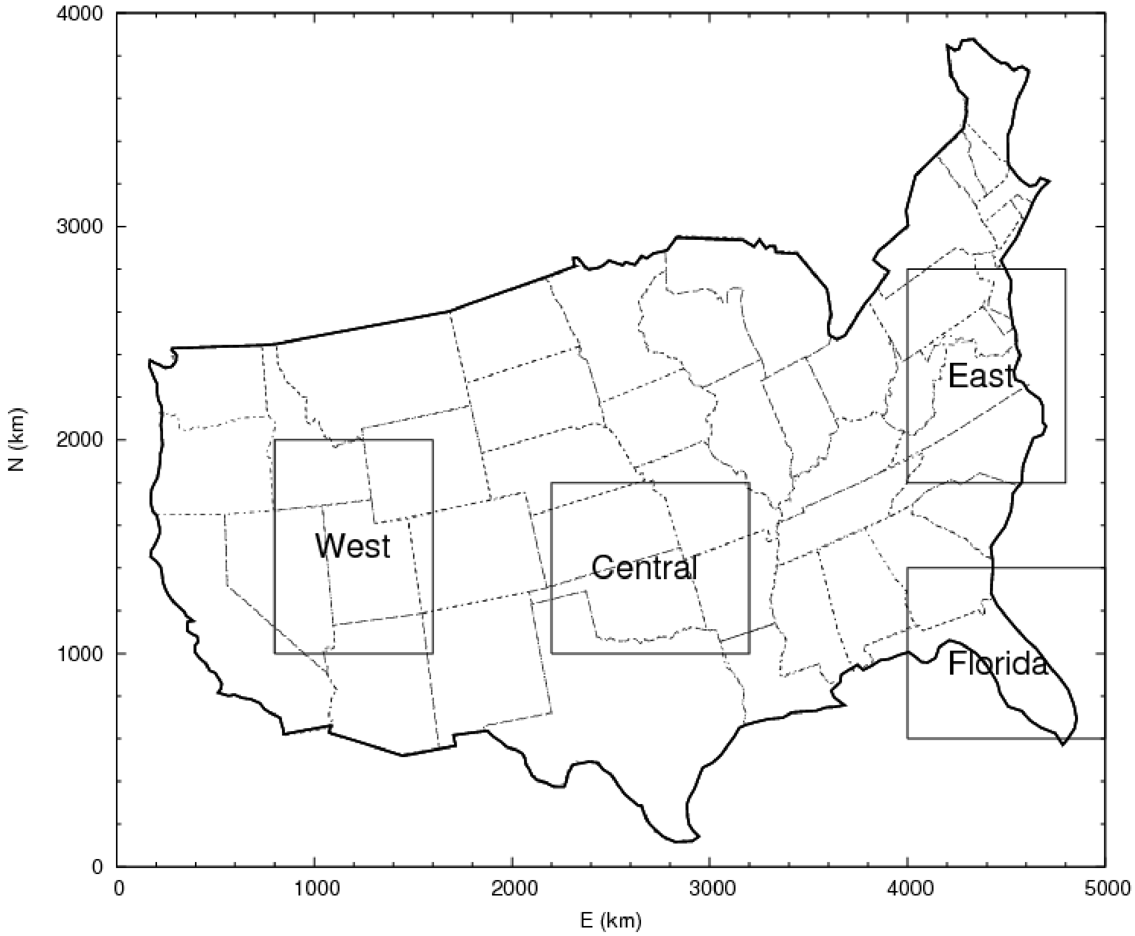

Figure 3. The four regional divisions of the United States used in the analysis of Figs. 4, 6, and 7.

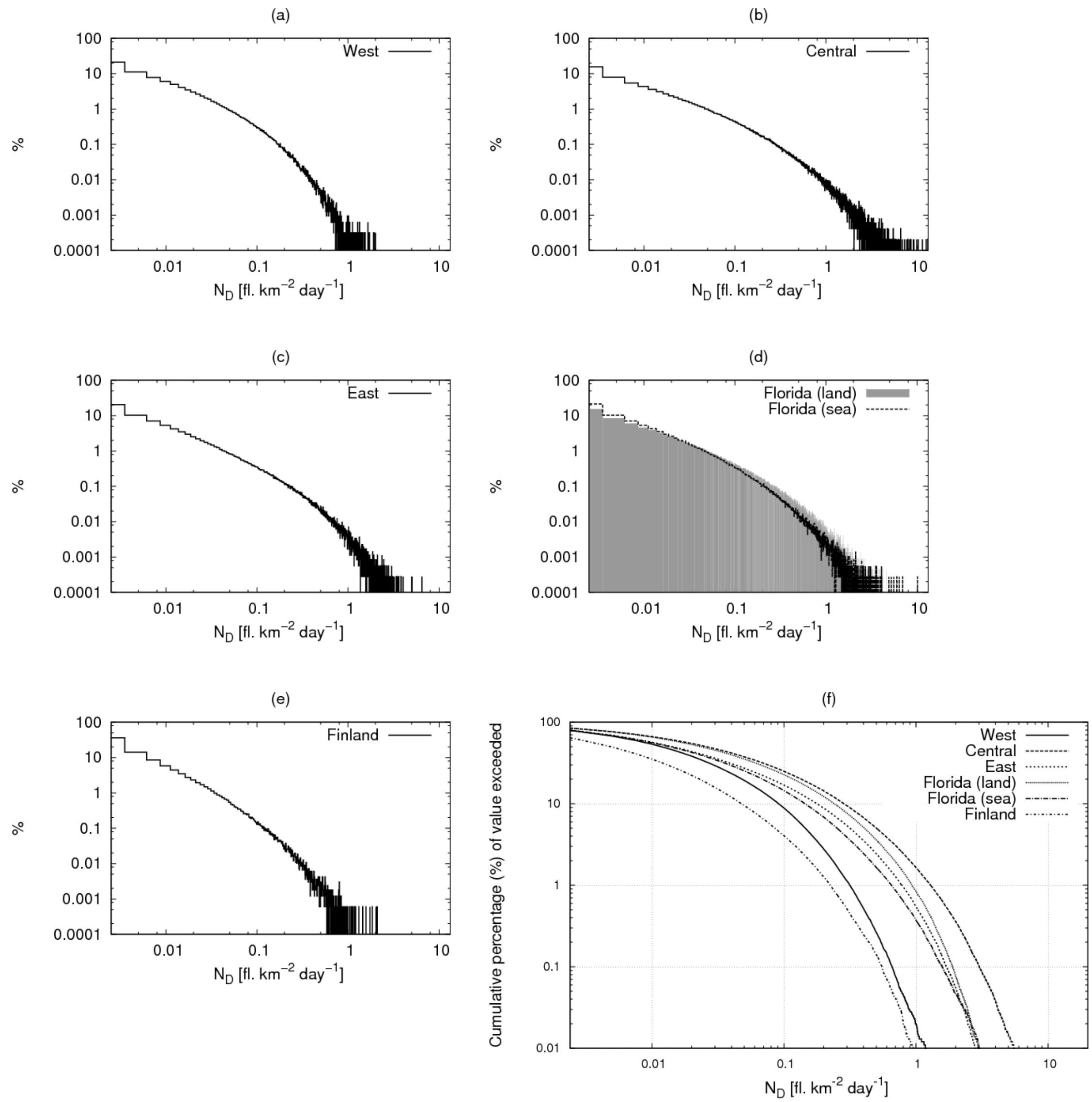

Figure 4. Distributions of N_D for different regions in the United States (shown in Fig. 3) and for Finland. The lower right figure is the complementary cumulative distribution. The x axis starts from 0.0025 (i.e., one flash in a 20 km $\times$ 20 km square per day).

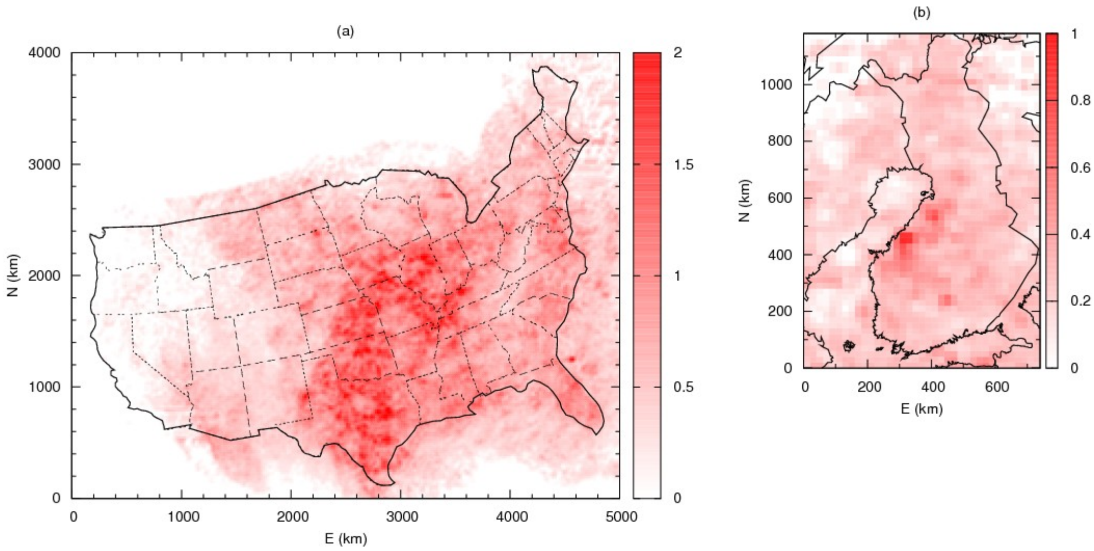

Figure 5. The $p_1(N_D)$ ground flash density values for (a) the contiguous United States and (b) Finland. Note the different color scales.

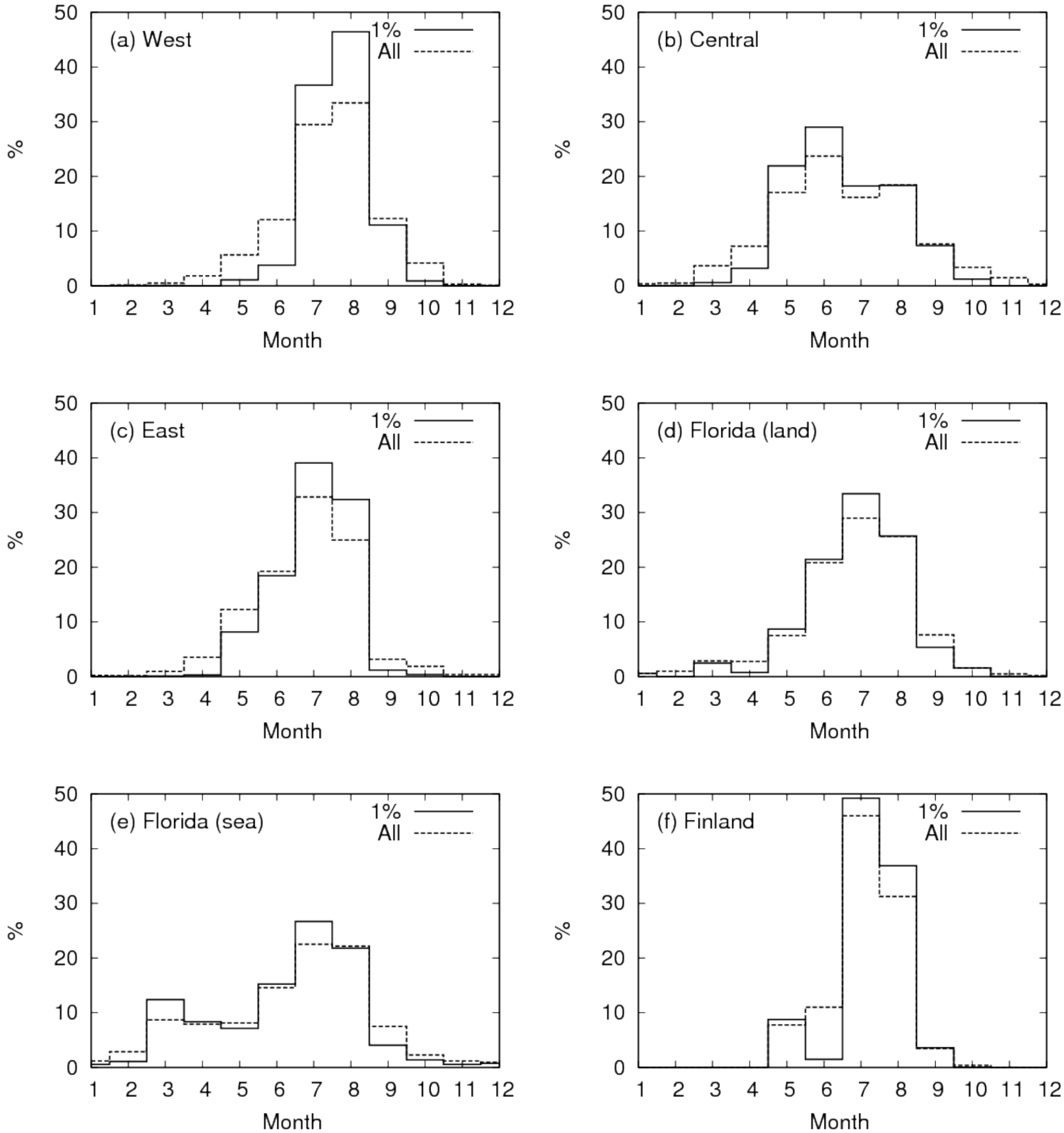

Figure 6. The monthly distributions of the $p_1(N_D)$ ground flash density values. The values for each region are shown in Table 1.

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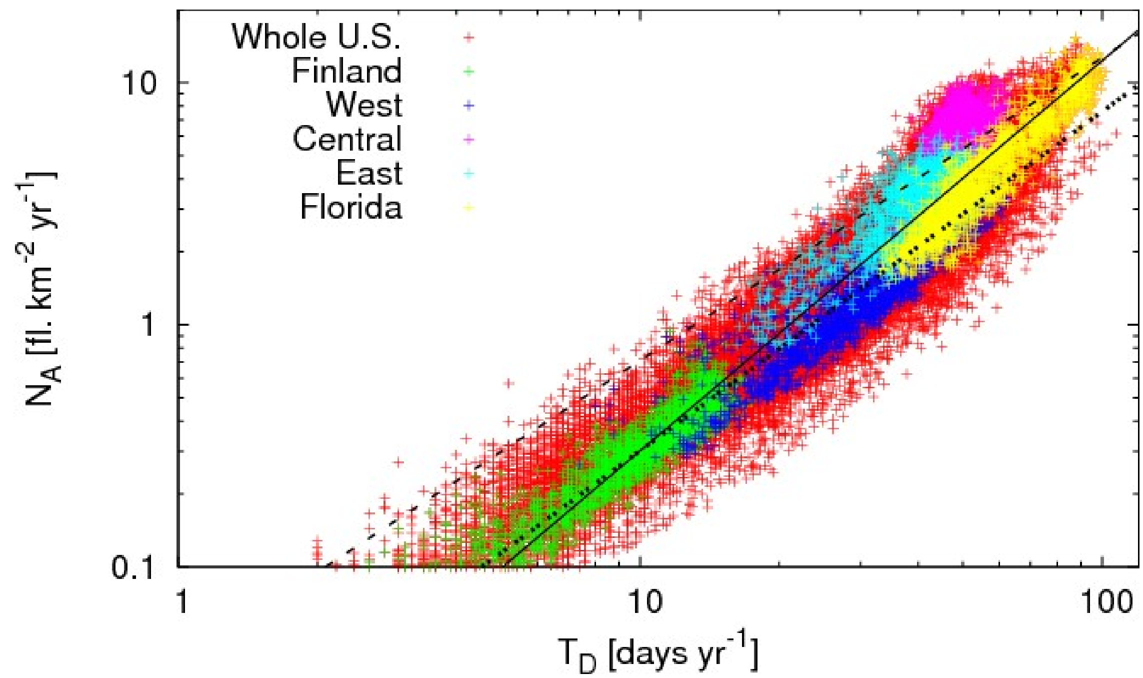

Figure 7. Scatterplot showing the relationship between T_D and N_A for all of the 20 km × 20 km squares in the U.S. and Finland (red) with the regional data points in different colors. The solid line is the least-squares fit for all the U.S. and Finnish data is $N_A = 0.007T_D^{1.61}$, and the two other fits are $N_A = 0.04T_D^{1.25}$ (Anderson et al. 1984, dashed), and $N_A = 0.012T_D^{1.4}$ (Kuleshov and Jayaratne 2004, dotted). Table 2 shows the regional fit equations.

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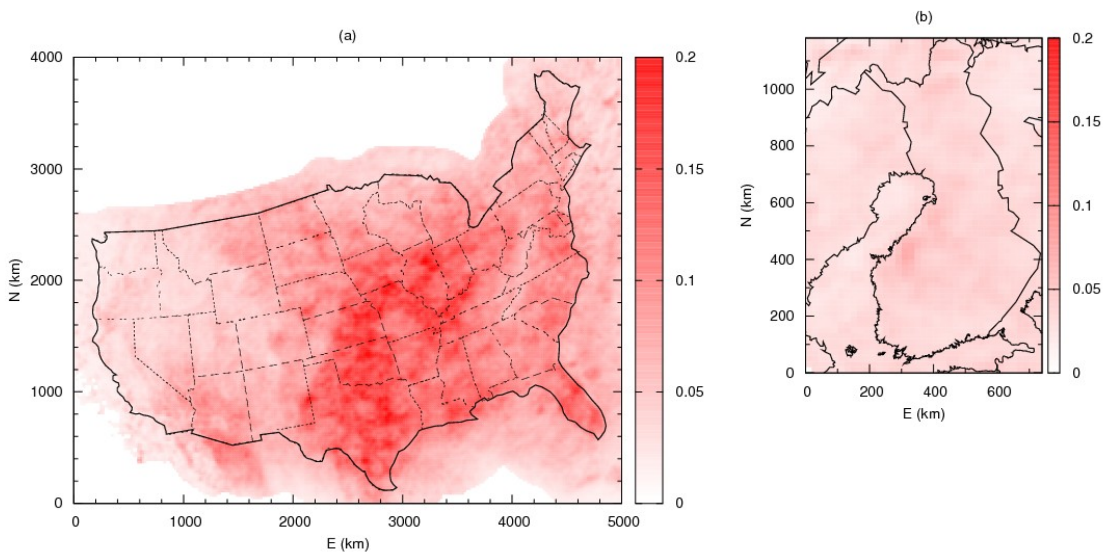

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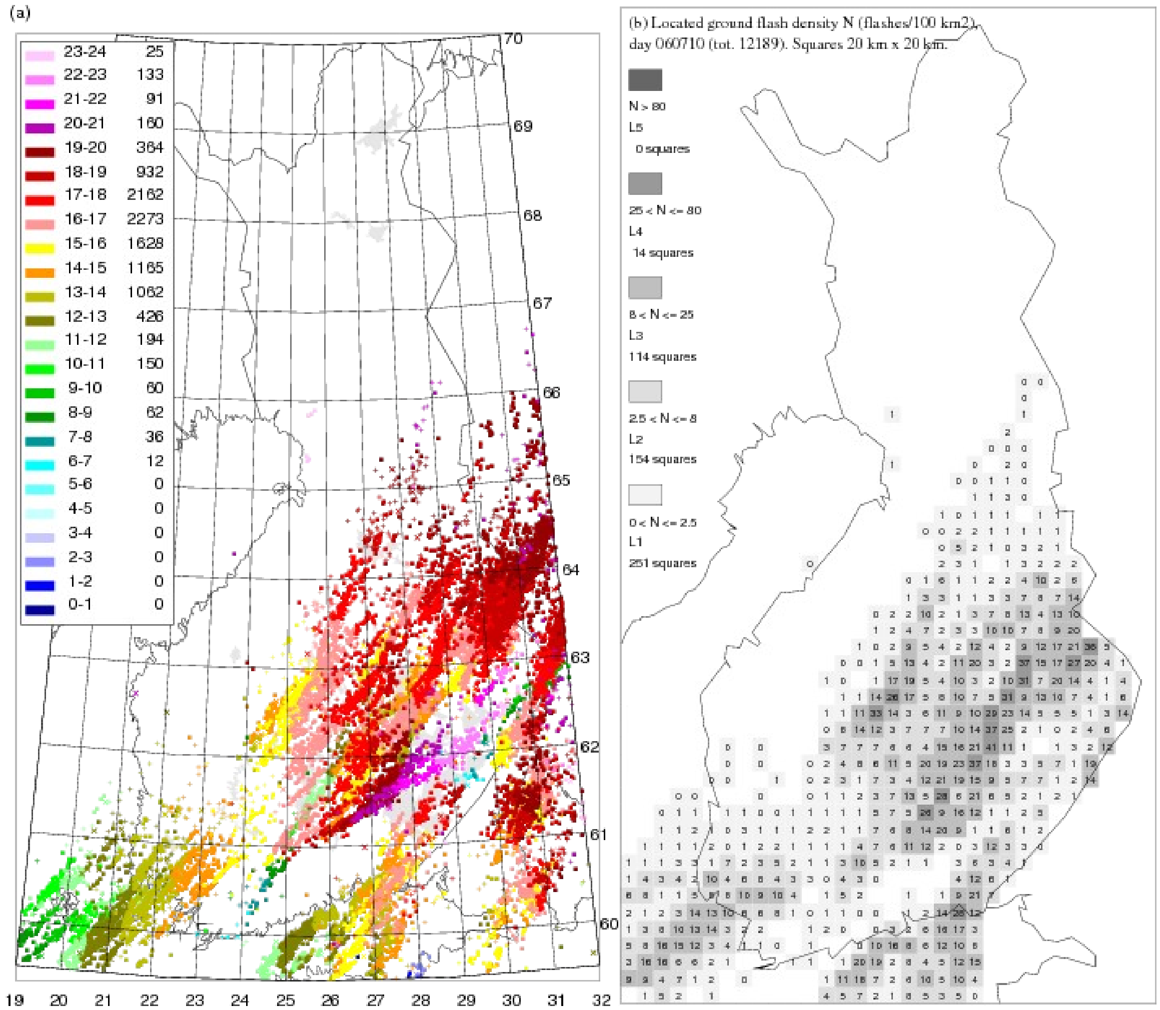

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