Return-Stroke Multiplicity of Negative Cloud-to-Ground Lightning Flashes

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ABSTRACT

The percentage of negative lightning flashes composed of a single stroke is examined. This percentage is estimated from data reported by the U.S. National Lightning Detection Network (NLDN) for Florida and New Mexico and is compared with that determined from electric field and optical observations in these two states. The latter observations allowed a very accurate stroke count and, therefore, were used as the ground truth in the comparison. The percentage of negative single-stroke flashes reported by the NLDN is a factor of 2–3 higher than from the accurate-stroke-count studies in Florida (44% vs 17%) and is a factor of 3–4 higher in New Mexico (51% vs 14%). The observed discrepancies suggest that many small subsequent strokes are missed by the NLDN because these strokes fail to exceed the system's trigger threshold level so that only one stroke per flash is recorded in many multiple-stroke flashes. The percentage of negative single-stroke flashes reported by the Austrian lightning detection network is 40%, similar to the percentages reported by the NLDN for Florida and New Mexico. Percentages of single-stroke flashes determined from accurate-stroke-count studies in Sweden and Sri Lanka, which represent additional meteorologically distinct regimes, are 18% and 21%, respectively, in fair agreement with the Florida and New Mexico accurate-stroke-count studies. From comparison of the NLDN-reported and ground-truth data, it is possible to estimate the NLDN stroke and flash detection efficiencies. If the NLDN stroke detection efficiency were the same for both first and subsequent strokes, the percentage of single-stroke flashes and number of strokes per flash reported by the NLDN for Florida (44% and 2.4, respectively) would correspond to a stroke detection efficiency of about 40% and a flash detection efficiency of about 78%. A similar approach to the New Mexico data would yield a stroke detection efficiency of about 20% and a flash detection efficiency of about 62%.

1. Introduction

Percentage of single-stroke flashes and number of strokes per flash (sometimes referred to as multiplicity) are lightning characteristics that are clearly sensitive to the reliability of the stroke identification process. The ordinary videotape recording technique alone is not suitable for a precise stroke count because of the missing of strokes that either occur at relatively short time intervals or have poorly defined television images owing to faint or obscured lightning channels. Further, use of electric-field records with time resolution not sufficient to discern the microsecond-scale initial peak characteristic of return strokes to ground (e.g., Malan 1956) inevitably results in the missing of small strokes. To the best of our knowledge, at the time of this writing, only two studies conducted in the United States exist in which the possibility of missing small strokes was practically excluded. Those studies are by Kitagawa et al. (1962), who obtained correlated electric-field and high-speed photographic records in New Mexico, and Beasley et al. (1982) and Master et al. (1984), who obtained correlated electric-field and television records in Florida. Flash multiplicity in the Florida data was analyzed by Thomson et al. (1984), Rakov and Uman (1990), and Rakov et al. (1994).

In this paper, we compare the percentages of negative single-stroke flashes reported by the U.S. National Lightning Detection Network (NLDN) for Florida and New Mexico with their counterparts determined from ''accurate-stroke-count'' studies and reported by Rakov and Uman (1990) and Rakov et al. (1994) for Florida and by Kitagawa et al. (1962) for New Mexico. We additionally consider percentages of single-stroke flashes reported by Cooray and Jayaratne (1994) for Sri Lanka, Cooray and Perez (1994) for Sweden, and Diendorfer et al. (1998) for Austria—the first two studies allowing accurate stroke count, and the latter one being based on data from a lightning detection network. We also review the average number of strokes per flash, a

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characteristic related to the percentage of single-stroke flashes, from both accurate-stroke-count studies and lightning-detection-network data. The accurate-stroke-count studies are based on data from a relatively small number of storms, but, for all practical purposes, they can be used as the ground truth, because the potential effect of the storm-to-storm variation is expected to be considerably smaller than the effect of using different observation techniques that is examined here. Further, we neglect any long-term variations in flash multiplicity in comparing data acquired during different time periods. In summary, we assume that the storms and flashes involved in accurate-stroke-count studies adequately represent the regional lightning populations. Results presented and discussed below support this assumption.

Knowledge of the relative occurrence of single- and multiple-stroke flashes is needed in estimating the probability of successful circuit-breaker reclosure following a lightning-caused outage of the power line (Anderson and Eriksson 1980) and for understanding the reasons for the multicomponent mode of charge transfer to ground in negative lightning. The latter mode is usually attributed to the current cutoff near ground (Krehbiel et al. 1979), although an inhomogeneous distribution of negative charge in the cloud can play a role. There is presently no consensus on why negative flashes are typically composed of 3–5 strokes whereas positive flashes usually have a single stroke followed by continuing current.

The geographical distributions of number of strokes per negative and positive flash for the contiguous United States for 1989–98 are presented by Orville and Huffines (2001, their Figs. 17 and 18). Over this 10-yr period, the annual mean NLDN-reported number of strokes per flash varied from year to year from 2.1 to 2.8 for negative flashes and from 1.1 to 1.4 for positive flashes (Orville and Huffines 2001, Fig. 20). There is a slight decrease in the annual mean number of strokes per flash after the 1994–95 NLDN upgrade that, among other things, included 1) an increase of sensitivity of the sensors, 2) a change of the waveform acceptance criteria, and 3) a change in the algorithm for grouping detected strokes into flashes (Cummins et al. 1998). According to Orville and Huffines (2001), the number of strokes per negative flash ranged from 2.1 in February to 2.5 in June–October. The number of strokes per positive flash was approximately 1.2 throughout the year.

2. Accurate-stroke-count data

Rakov and Uman (1990) and Rakov et al. (1994), who used correlated electric-field and television records, considered strokes to compose a single flash if each stroke occurred within 500 ms of the previous one, regardless of the number of channels to ground and their spatial separation (within the field of view of their television network). About one-half of the 76 flashes in their dataset showed spatially separate ground strike points in the multiple-station television records: 29 flashes (38.2%) produced two strike points, 8 (10.5%) produced three strike points, and 2 (2.6%) produced four strike points. With 37 flashes (48.7%) creating a single strike point, the average number of strike points per flash was 1.67. The distances between separate channel terminations, located with television direction finding and thunder ranging, in a given flash varied from 0.3 to 7.3 km with a geometric mean of 1.7 km (Thottappillil et al. 1992). The percentage of multigrounded flashes and the average number of strike points per flash in New Mexico (Kitagawa et al. 1962) were similar to those in Florida. Valine and Krider (2002) reported 1.45 strike points per flash for Arizona. Note that in some optical studies (e.g., Carte and De Jager 1979; Idone et al. 1998a,b) of lightning flash multiplicity, the occurrence of a new path between the cloud base and ground was treated as the beginning of a new flash, regardless of the time elapsed since the preceding stroke and the likelihood of a common channel section inside the cloud. In our view, this approach inappropriately separates a single multigrounded lightning discharge into two or more ''flashes'' with one ground termination each. Results of the accurate-stroke-count studies in Florida and New Mexico are summarized in Table 1. Florida data were taken near Tampa, and New Mexico data were taken in Socorro. We assume that the Tampa data are representative of the entirity of Florida and that the Socorro data are representative of all of New Mexico. Also given in Table 1 are the number of strokes per flash and percentage of single-stroke flashes estimated from sufficiently resolved, overall flash electric-field records obtained in Sweden and Sri Lanka. In the latter two studies, no information on the number of channels to ground and their spatial separation was available.

Histograms of flashes with different numbers of strokes for Florida and New Mexico are shown in Figs. 1a and 1b, respectively. The percentage of single-stroke flashes in Florida (a coastal subtropical locality at sea level) was found to be 17%, and in New Mexico (an inland locality at about 2 km above sea level) it was found to be 14% (13% for a subset represented in Fig. 1b). The values for Florida and New Mexico are fairly similar to each other. Further, fairly similar percentages of single-stroke flashes were reported for Sri Lanka (21%, Cooray and Jayaratne 1994) and Sweden (18%, Cooray and Perez 1994). Results for Sri Lanka (tropical region) were obtained during three convective thunderstorms; those for Sweden (temperate region) were obtained during two frontal thunderstorms. It follows from Table 1 that, when the possibility of missing strokes is practically excluded, the overwhelming majority (about 80% or more) of negative cloud-to-ground flashes contain more than one stroke, regardless of geographical location and storm type. The average number of strokes per flash in Florida, New Mexico, Sweden, and Sri Lanka were 4.6, 6.4, 3.4, and 4.5, respectively (see Table

TABLE 1. Number of strokes per negative flash (multiplicity) and percentage of single-stroke flashes from accurate-stroke-count studies (GM is geometric mean).

Reference	Geographical location	No. and type of storms	Tot No. of flashes	Avg multiplicity	Max multiplicity	Percentage of single-stroke flashes	GM ratio of subsequent-to first-stroke field peaks*
Rakov and Uman (1990), Rakov et al. (1994)	Tampa, FL	Three convective summer thunderstorms	76	4.6	18	17	0.42
Kitagawa et al. (1962)	Socorro, NM	Three summer night thunderstorms	193	6.4**	26	14	—
Cooray and Perez (1994)	Uppsala, Sweden	Two frontal summer thunderstorms	137	3.4	10	18	0.51
Cooray and Jayaratne (1994)	Colombo, Sri Lanka	Two convective thunderstorms in Apr (intermonsoonal period)	81	4.5	12	21	0.44

* Based on samples different from those used for determining number of strokes per flash and percentage of single-stroke flashes.
** One very active night thunderstorm, for which total number of flashes was 83 and percentage of single-stroke flashes was 13%.

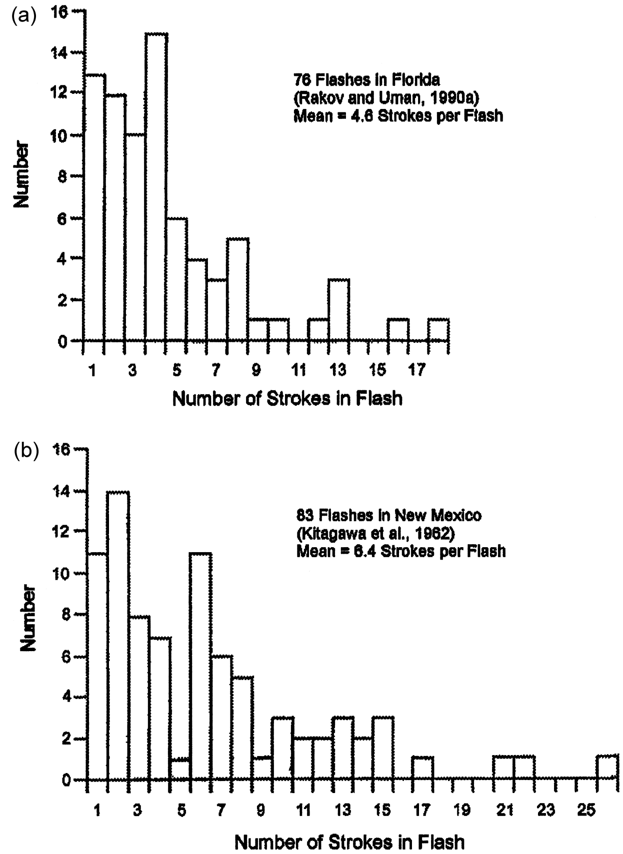

FIG. 1. Histograms of number of strokes per flash from accurate-stroke-count studies: (a) 76 negative flashes in FL and (b) 83 negative flashes in NM. Percentages of single-stroke flashes are 17% and 13% for FL and NM, respectively. Adapted from Rakov and Uman (1990).

1). The average number of strokes per flash in New Mexico is the largest reported in the literature. It is possible that New Mexico cloud-to-ground flashes analyzed by Kitagawa et al. (1962) had access to several thunderstorm cells that were located side by side and were electrically active at the same time.

3. Lightning-detection-network data

In addition to locating lightning strokes, the NLDN and other similar networks group the strokes into flashes and report the number of strokes per flash (often termed multiplicity). The networks also determine polarity and a peak current estimate for each stroke using the measured electric and magnetic radiation field peaks, respectively. Before the 1994–95 NLDN upgrade (Cummins et al. 1998), the number of strokes in a flash was defined as the maximum number of strokes seen by any responding direction-finding station within 2.5° of the first stroke and within 1 s after the first stroke. In the upgraded NLDN, strokes are assigned to a given flash if they occur within 10 km of the first stroke, apparently based on the observations of Thottappillil et al. (1992),

TABLE 2. Number of strokes per negative flash (multiplicity) and percentage of single-stroke flashes based on data from lightning detection networks.

Reference	Geographical location	Obs period	Tot No. of negative flashes	Avg multiplicity	Max multiplicity	Percentage of single-stroke flashes	Ratio of subsequent to first-stroke GM field peaks
Diendorfer et al. (1998)	Austria	1996	46 420	2.7	15*	40	1.0
This study	FL	1995–2001	18 997 390	2.4	15**	44	—
	NM	1995–2001	10 789 675	2.1	15**	51	—
	Contiguous United States	1995–2001	165 074 265	2.2	15**	49	—

* Flashes with more than 15 strokes were recorded as 15-stroke flashes.
** Flashes with more than 15 strokes were recorded as two flashes, a 15-stroke flash and a separate flash containing strokes that occurred after stroke 15.

within a time interval from the previous stroke of 500 ms, with the maximum flash duration being still 1 s. In addition, in the upgraded NLDN, a stroke is included in the flash if it is located within 10–50 km of the first stroke and if the location error ellipses (50%) of these two strokes overlap. The maximum allowed multiplicity is 15, with the 16th stroke being treated as the first stroke in a new flash. Note that the percentage of flashes that have more than 15 strokes has been observed to be 2.6% in Florida and 4.8% in New Mexico (Fig. 1). For the analysis of the percentages of single-stroke flashes presented in this paper, we considered all negative cloud-to-ground flashes (over 165 million for the contiguous United States) recorded by the NLDN during 1995–2001 (after the upgrade). The results are presented in Table 2 and in Figs. 2, 3, and 4.

Geographical distribution of the percentage of negative single-stroke flashes for the contiguous United States is shown in Fig. 2. A 0.2° × 0.2° grid was used, which corresponds to an approximate spatial resolution

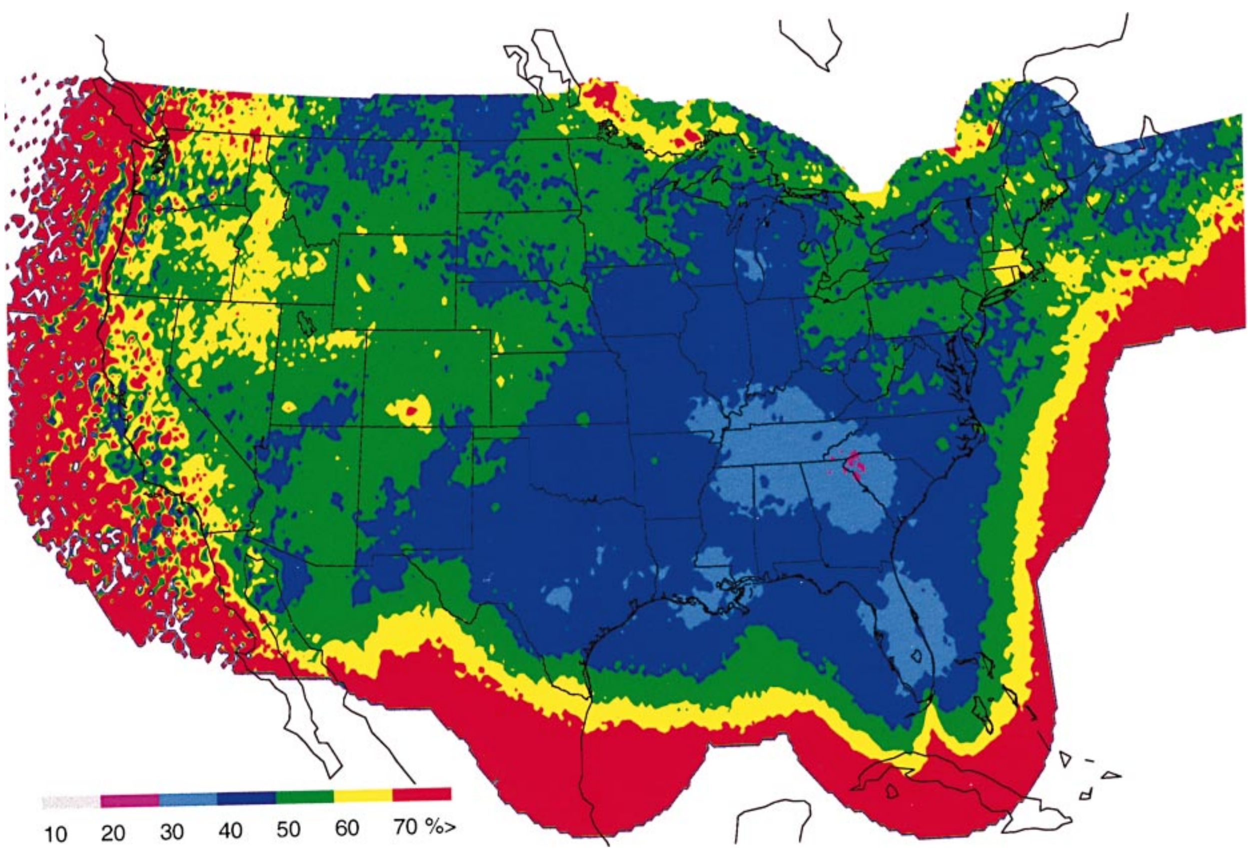

FIG. 2. Spatial distribution of the percentage of negative single-stroke flashes for the contiguous United States. The distribution is based on the NLDN data over a period of 1995–2001.

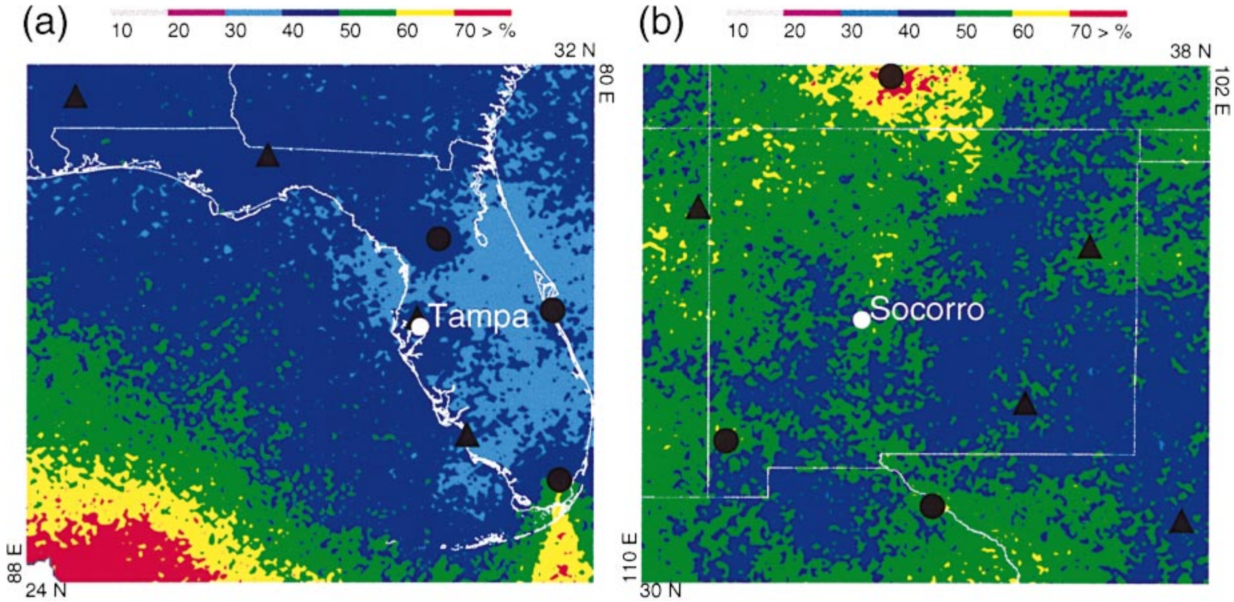

FIG. 3. Same as in Fig. 2 but for (a) FL (18 997 354 negative flashes) and (b) NM (10 789 601 negative flashes). Black circles indicate locations of NLDN magnetic-direction-finding/time-of-arrival [improved accuracy from combined technology (IMPACT)] sensors, and black triangles are locations of NLDN time-of-arrival (lightning positioning and tracking system: LPATS) sensors.

of 20 km. The northern extent of the map was restricted because of data cutoff from the NLDN into Canada. The percentage of negative single-stroke flashes ranges from 30% to 70% over most of the country. Of interest is that there is a tendency for the lower percentage of single-stroke flashes to be observed in the regions where the lightning detection network has a higher density. Similar maps, but using a $0.05° \times 0.05°$ grid (about 5-km resolution), for Florida and New Mexico are shown in Figs. 3a and 3b, respectively.

Histograms of number of strokes per flash as reported by the NLDN for Florida and New Mexico over a period of 1995–2001 are shown in Figs. 4a and 4b, respectively. The corresponding percentages of single-stroke flashes are 44% and 51%. It is clear that the percentage of single-stroke flashes reported by the NLDN is considerably higher than that determined from the accurate-stroke-count studies: a factor of 2–3 in Florida (44% vs 17%) and a factor of 3–4 (51% vs 14%) in New Mexico. The NLDN-reported percentage of negative single-stroke flashes within 50 km of the city center of Tampa is 45%, similar to the average value of 44% for all of Florida, and its counterpart for Socorro is 49%, similar to the average value of 51% for all of New Mexico. The number of strokes per flash for Florida is 2.4, and for New Mexico it is 2.1, in both cases being considerably lower than the values (4.6 for Florida and 6.4 for New Mexico) determined from the accurate-stroke-count studies discussed in section 2. One may argue that the New Mexico data that are characterized by the highest average number of strokes per flash (6.4) and the highest maximum number of strokes per flash (26) are obtained under unusual thunderstorm conditions. However, Rakov et al. (1994) found that many lightning characteristics in the New Mexico dataset are remarkably similar to their counterparts in the Florida dataset.

Rubinstein (1995) proposed a model that allows one to relate 1) the true histogram of flashes with different number of strokes, such as those shown in Figs. 1a and 1b, 2) the stroke detection efficiency (assumed to be the same for both first and subsequent strokes and throughout the network), and 3) the flash detection efficiency. Using this model and Fig. 1a, we found that the NLDN percentage of single-stroke flashes and NLDN number of strokes per flash observed in Florida (44% and 2.4, respectively) would correspond to an NLDN stroke detection efficiency of about 40% and an NLDN flash detection efficiency of about 78%. A similar approach to the New Mexico data would yield a stroke detection efficiency of about 20% and a flash detection efficiency of about 62%. Cummins et al. (1998) previously estimated the stroke detection efficiency of about 50% for the entire NLDN, not far from our estimate for Florida. Idone et al. (1998a,b) estimated stroke and flash detection efficiencies for the NLDN using multiple video cameras. However, they apparently separated each multigrounded lighting discharge into two or more singly grounded ''flashes,'' and so their definition of lightning flash is different from ours (see section 2). Our stroke detection efficiency estimates given above are based on the assumption that the probability of detecting a stroke is independent of stroke order. In reality, the detection efficiency for first strokes should be higher than for subsequent strokes, because the former are characterized by peak currents and peak fields that are a factor of 2–3 larger than for the latter (e.g., Berger and Garbagnati

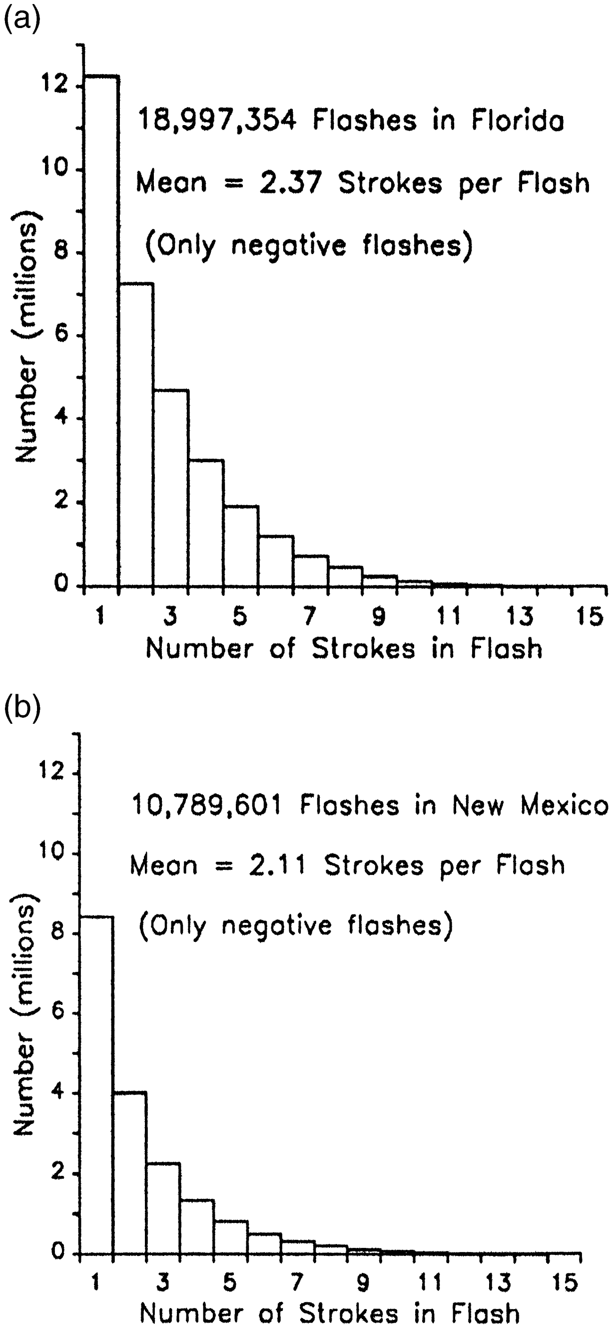

FIG. 4. Histograms of number of strokes per flash as reported by the NLDN for (a) FL and (b) NM. The histograms are for the areas shown in Figs. 3a and 3b for a period of 1995–2001. NLDN-reported percentages of single-stroke flashes are 44% and 51% for FL and NM, respectively.

1984; Rakov et al. 1994; see also the last column of Table 1). Using a model similar to that of Rubinstein (1995) but allowing for different detection efficiencies for first and subsequent strokes, K. Cummins (2002, personal communication) estimated NLDN first-stroke detection efficiency of 70% and NLDN subsequent-stroke detection efficiency of 40% for Florida. The corresponding model-predicted flash detection efficiency is 89%, and the percentage of single-stroke flashes and the number of strokes per flash are 35% and 2.4, respectively, the latter two figures being fairly similar or equal to the NLDN-reported values for Florida (see Table 2).

Also given in Table 2 is the percentage of single-stroke flashes in Austria, based on data for one full year, 1996, from the Austrian Lightning Detection and Information System (ALDIS) network. The analysis was done by Diendorfer et al. (1998) for a circular area with a radius of 100 km inside the perimeter of the ALDIS, this area being characterized by the best detection efficiency within the network. The ALDIS is similar to the NLDN, although the former is denser and more sensitive than the latter. The area of observation in Austria was mostly mountainous, with mountain tops up to 3 km. The percentage of single-stroke flashes in Austria, 40%, is about a factor of 2 higher than in Sweden, 18% (Table 1), the difference being possibly due, at least in part, to the missing of smaller subsequent strokes by the ALDIS. Note that flashes containing more than 15 strokes were recorded by the ALDIS as 15-stroke flashes. The average number of strokes per flash in Austria, estimated from data reported by the ALDIS, is 2.7 (see Table 2), which is similar to the values based on NLDN data but is somewhat lower than the previously cited value (3.4; Table 1) based on an accurate-stroke-count study at another temperate locality in Europe (Sweden). Note that the ratio of subsequent- to first-stroke field peaks (see the last column of Table 1) from ALDIS data is equal to 1, as opposed to 0.42–0.51 from accurate-stroke-count studies (see Table 2). Discussion of this feature is outside the scope of this paper.

It can be inferred from the similarity of the ALDIS and NLDN data and from the estimated significant difference between the stroke and flash detection efficiencies for the NLDN (see above) that the ALDIS also records only one stroke per flash in many multiple-stroke flashes. On the other hand, Diendorfer et al. (2002) reported ALDIS stroke detection efficiency of 86% and corresponding ALDIS flash detection efficiency of 94% for subsequent strokes and other impulsive processes with peak currents greater than 6 kA in upward flashes initiated from the 100-m Gaisberg tower in Austria. Perhaps the 100-m metallic tower served to enhance radiated electromagnetic fields (Rakov 2001), resulting in an increased stroke detection efficiency relative to the case of direct lightning attachment to the ground. Some confirmation of this hypothesis comes from the fact that the ALDIS detects a considerably larger number of strokes per flash in strikes to metallic towers than in strikes to the ground (Diendorfer and Schulz 1998), although the proportion of upward and downward flashes may also play a role.

4. Discussion

It appears from the data presented in Tables 1 and 2 that, regardless of thunderstorm type and geographical location, the percentage of single-stroke flashes estimated from lightning-detection-network data is 40%–51%, whereas the accurate-stroke-count studies yield 14%–21%. We now consider three possible reasons for this discrepancy:

1) The stroke-grouping algorithm of the lightning detection network ''extracts'' one stroke from a flash and assigns it to a separate flash. For the NLDN, this can happen, for example, when a stroke terminates on ground more than 10 km from the first stroke of the flash or when two strokes in a flash appear to be separated by longer than a 500-ms interval, possibly because small strokes between the two are being missed by the system. Both of these situations are unlikely and are not further considered here.
2) Some of the single-stroke flashes reported by the NLDN or ALDIS are actually misidentified cloud flashes (assuming that a cloud flash is unlikely to produce more than one pulse that is accepted by the system as a cloud-to-ground lightning return stroke pulse). If so, the inferred peak currents for such events should be relatively small, and, hence, the exclusion of the smallest negative single-stroke events should bring the NLDN data more in line with the ground-truth data. For positive lightning, usually no strokes with an NLDN-estimated peak current of less than 10 kA are considered, because they are believed to be primarily misidentified cloud flashes (Cummins et al. 1998). It seems to be logical to apply a similar restriction to negative single-stroke flashes in an attempt to eliminate potentially misidentified cloud flashes. However, no more than 5% of negative single-stroke flashes in the NLDN data for either Florida or New Mexico have peak currents less than 10 kA, and their exclusion cannot significantly influence the percentage of negative single-stroke flashes reported by the NLDN. If all negative single-stroke flashes with peak currents of less than 20 kA were excluded from the 1995–2001 NLDN data, the percentages of single-stroke flashes would be 29% and 27% for Florida and New Mexico, respectively. Although these latter percentages are closer to the expected (based on the results of accurate-stroke-count studies) values, it is highly unlikely that the NLDN-reported single-stroke flashes with peak currents in the 10–20-kA range are actually misidentified cloud discharges.
3) For lightning detection networks, many subsequent strokes fail to exceed the system's trigger threshold level, so that in many multiple-stroke flashes only one stroke is recorded. In the ALDIS, the minimum system-estimated current is 2 kA. In the NLDN there is no lower limit for peak currents (values as low as 100 A or less are reported), but the percentage of strokes with peak current below 5 kA is very low (about 0.2%). First strokes are usually larger than subsequent strokes [although one-third of multiple-stroke flashes have at least one subsequent stroke that is larger than the first stroke in the flash (Thottappillil et al. 1992)], and, therefore, the recorded stroke is likely to be the first one. If only one stroke per flash is recorded in many multiple-stroke flashes, the percentage of single-stroke flashes will be overestimated. We consider this reason for the underestimation of the negative flash multiplicity (overestimation of the percentage of negative single-stroke flashes) as the most likely one.

It is conceivable that the ground-truth data used in this study (see Table 1) are influenced by the limited sample sizes (76–193 flashes from 2–3 storms). Indeed, Diendorfer et al. (1998) found from ALDIS data for individual thunderstorm days that the percentage of single-stroke flashes varied significantly from storm to storm (from 30% to 80% with a mean of 40%) and possibly depended on season, type of storm, and so on. However, their minimum value of 30% is still higher than the 14%–21% range reported from accurate-stroke-count studies. Diendorfer et al. (1998) also found a significant variation in the average number of strokes per flash, from 1.2 to 4.2, for individual thunderstorm days in Austria. A similar variability in the average number of strokes per flash was reported from NLDN data by K. Cummins (2002, personal communication). On the other hand, we do not see any reason why two or three storms studied at each of the four geographical locations (see Table 1) would be atypical for the area. More accurate-stroke-count data for various geographical locations and for different types of storms are needed.

The percentage of single-stroke downward flashes determined from direct current measurements on two 70-m mountain-top towers in Switzerland is about 60% (Berger and Garbagnati 1984). This value is about a factor of 3 higher than the accurate-stroke-count value for another temperate locality (Sweden) discussed above. The apparent discrepancy might be related to the fact that essentially all flashes in Sweden were downward flashes to the ground, whereas the two towers in Switzerland received both downward and upward flashes, with the latter being the majority (two-thirds or more). It is conceivable that the charge in thunderstorm cells above the towers was depleted by upward discharges so that downward flashes were more often composed of a single stroke than they would be in the absence of the towers.

5. Concluding remarks

1) The percentage of single-stroke flashes reported by the NLDN is a factor of 2–3 higher than from the accurate-stroke-count studies in Florida (44% vs 17%) and is a factor of 3–4 higher in New Mexico (51% vs 14%).
2) Percentages of single-stroke flashes found from accurate-stroke-count studies for different types of

storms and at different geographical locations, including Florida, New Mexico, Sri Lanka, and Sweden, are fairly similar, ranging from 14% to 21%.
3) It appears that many small subsequent strokes are missed by the NLDN so that only one stroke per flash is recorded in many multiple-stroke flashes. We estimate the NLDN detection efficiency for negative strokes (assumed to be the same for first and subsequent strokes) in Florida and New Mexico to be about 40% and 20%, respectively, which is considerably lower than the corresponding NLDN detection efficiency for flashes, about 78% and 62%, respectively.

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