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First versus subsequent return-stroke current and field peaks in negative cloud-to-ground lightning discharges

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[1] We examine relative magnitudes of electric field peaks of first and subsequent return strokes in negative cloud-to-ground lightning flashes recorded in Florida, Austria, Brazil, and Sweden. On average, the electric field peak of the first stroke is appreciably, 1.7 to 2.4 times, larger than the field peak of the subsequent stroke (except for studies in Austria where the ratio varies from 1.0 to 2.3, depending on methodology and instrumentation). Similar results were previously reported from electric field studies in Florida, Sweden, and Sri Lanka. For comparison, directly measured peak currents for first strokes are, on average, a factor of 2.3 to 2.5 larger than those for subsequent strokes. There are some discrepancies between first versus subsequent stroke intensities reported from different studies based on data reported by lightning locating systems (LLS). The ratio of LLS-reported peak currents for first and subsequent strokes confirmed by video records is 1.7 to 2.1 in Brazil, while in the United States (Arizona, Texas, Oklahoma, and the Great Plains) it varies from 1.1 to 1.6, depending on methodology used. The smaller ratios derived from the LLS studies are likely to be due to poor detection of relatively small subsequent strokes. The smaller values in Austria are possibly related (at least in part) to the higher percentage (about 50% versus 24–38% in other studies) of flashes with at least one subsequent stroke greater than the first. The effects of excluding single-stroke flashes or subsequent strokes in newly formed channels appear to be relatively small.

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1. Introduction

[2] Return-stroke peak currents and electric and magnetic peak fields are often used to measure relative intensity of first and subsequent strokes. It is generally thought that for negative cloud-to-ground lightning discharges first strokes are typically a factor of 2 to 3 larger than subsequent strokes [e.g., *Berger et al.*, 1975; *Rakov et al.*, 1994; *Cooray and Perez*, 1994; *Cooray and Jayaratne*, 1994; *Visacro et al.*, 2004]. In contrast, peak currents inferred from measured fields by lightning locating systems (LLSs) for first and subsequent strokes are often not much different from each other [e.g., *Diendorfer et al.*, 1998; *Rakov and Uman*, 2003, chap. 17]. In this paper, we examine relative intensities of first and subsequent strokes using electric field data recently acquired in Florida, Austria, [*Schulz and Diendorfer*, 2006], Brazil [*Oliveira Filho et al.*, 2007], and Sweden [*Schulz et al.*, 2008], as well as results of recent LLS studies conducted in conjunction with video observations in USA [*Biagi et al.*, 2007; *Krider et al.*, 2007] and Brazil [*Saba et al.*, 2006a].

2. Methodology

[3] There are different approaches to estimating relative intensity of first and subsequent strokes. One approach is to form the ratio of geometric mean (GM), arithmetic mean (AM), or median intensities of first strokes and all subsequent strokes combined. This approach was used, for example, by *Rakov and Uman* [1990a, 1990b] and *Diendorfer et al.* [1998]. Usually, intensities of strokes in single-stroke flashes are included, which results in a somewhat lower first-to-subsequent-stroke ratio than in the absence of single-stroke flashes, since strokes in single-stroke flashes are on average smaller than first strokes in multiple-stroke flashes. Another approach is to form the ratios for individual subsequent strokes and then find the AM, GM, or median of the resultant statistical distribution. This approach was employed, for example, by *Thottappillil*

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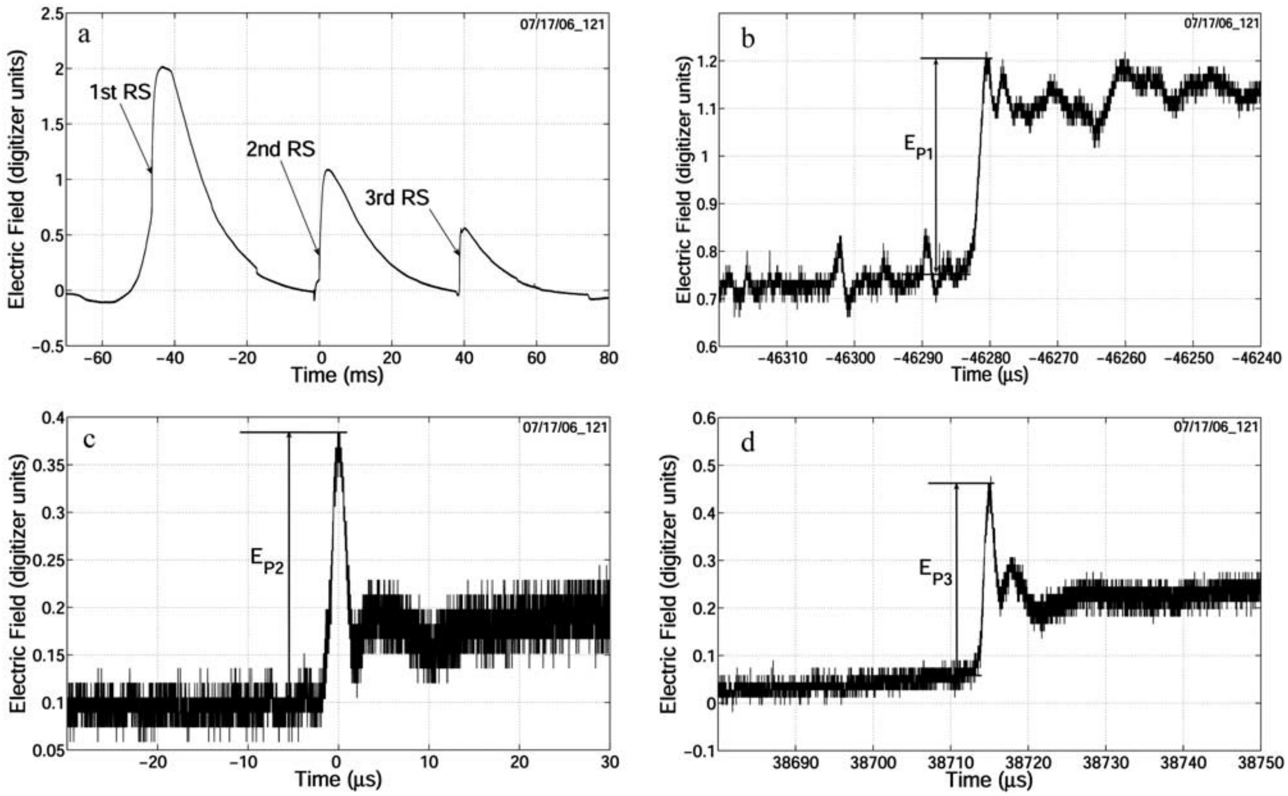

Figure 1. (a). Typical electric field record of a multiple-stroke negative cloud-to-ground flash in Florida with three return strokes (RS) shown on a 150-ms timescale. (b) Electric field of the first return stroke, on an 80-μs timescale, of flash shown in Figure 1a. (c) Electric field of the second return stroke, on a 60-μs timescale. (d) Electric field of the third return stroke, on a 70-μs timescale. Initial (radiation) electric field peaks of return strokes of order 1, 2, and 3 are labeled as E_{P1}, E_{P2}, and E_{P3}, respectively. Note that radiation field peaks seen in Figures 1b–1d are not resolved in Figure 1a.

et al. [1992], *Cooray and Perez* [1994], and *Cooray and Jayaratne* [1994]. Clearly, it applies only to multiple-stroke flashes. For either of the two approaches, the use of GM (or median) values, as opposed to AM values, should probably be preferred, because distributions of current or field peaks or distributions of the ratios are close to lognormal. It is worth noting that subsequent strokes creating new terminations on ground are on average larger than subsequent strokes following previously formed channels [*Rakov et al.*, 1994], so that the occurrence of new channel terminations can potentially influence the field ratios examined here.

[4] We compiled statistical distributions of the ratio of first to corresponding subsequent return-stroke electric field peaks and the ratio of subsequent to corresponding first return-stroke field peaks for Florida, Austria, Brazil, and Sweden. Then the AM and GM for each of the two distributions were calculated. Ratios of AM (GM, median) first to AM (GM, median) subsequent stroke peaks were also computed, when possible. Further, we examined relative magnitudes of strokes of different order for Florida [*Rakov and Uman*, 1990b] (also the present study), Austria [*Diendorfer et al.*, 1998; *Schulz and Diendorfer*, 2006], Brazil [*Oliveira Filho et al.*, 2007], and Sweden [*Schulz et al.*, 2008]. For the present study in Florida, we normalized the electric field peak of each subsequent stroke in a particular flash with respect to the field peak of the first return stroke in that flash. Then, for each stroke order (sequential number of a stroke in a flash), the geometric mean of the normalized field peaks was calculated. For all the other studies, the GM field peaks for subsequent strokes were normalized to the GM field peak for first strokes (including those in single-stroke flashes for data of *Rakov and Uman* [1990b] and *Diendorfer et al.* [1998]).

[5] Note that while computing the ratios for Florida, Austria, Sweden, and Brazil, it has been assumed that for flashes having multiple ground terminations the distances from the antenna to all terminations are approximately the same. This assumption is justified when distances between different channel terminations of the same flash are small compared to the distance between them and the antenna. For the overwhelming majority of flashes examined here the distances were larger than 20 km, which is much greater than the geometric mean separation of 1.7 km between multiple channel terminations within a flash estimated in Florida by *Thottappillil et al.* [1992].

3. Instrumentation and Data

[6] A brief description of the electric field measurement systems used in Florida, Austria, Brazil, and Sweden and

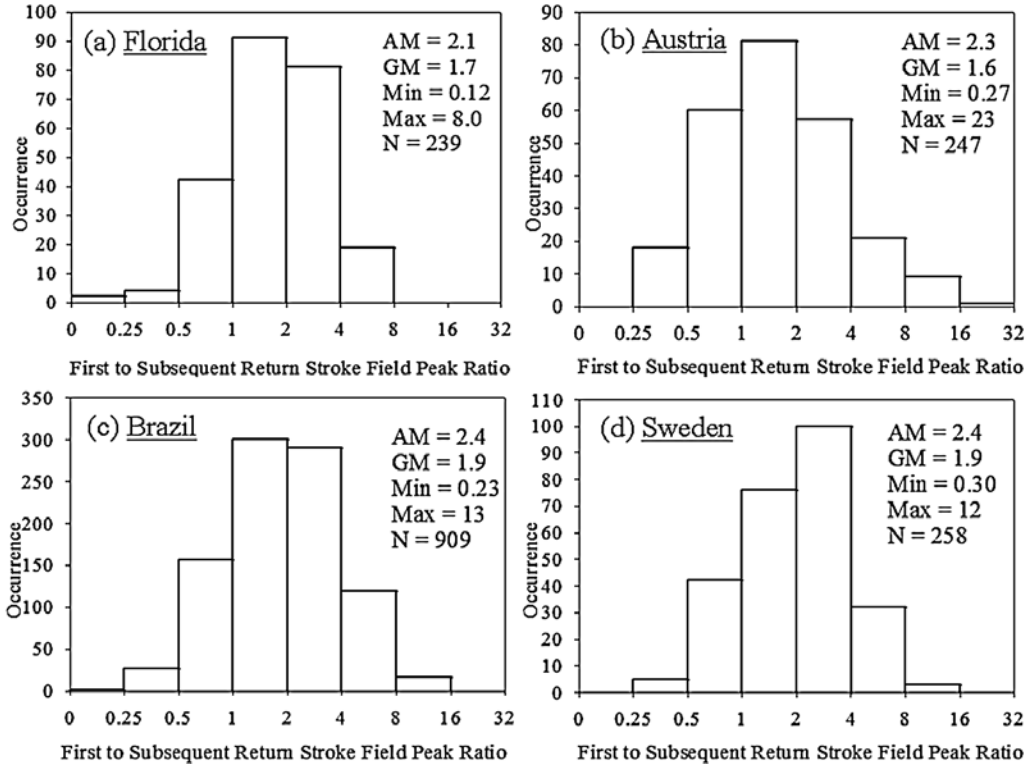

Figure 2. Histogram of the ratio of the first-to-subsequent-return-stroke electric field peak for multiple-stroke negative cloud-to-ground lightning flashes in (a) Florida, (b) Austria, (c) Brazil, and (d) Sweden.

the data analyzed in this paper is given below, followed by an overview of pertinent output of lightning locating systems.

3.1. Electric Field Measurements, Florida

[7] The electric field measuring system used to acquire the data analyzed in this paper has been described by *Nag and Rakov* [2008]. Electric field signals from a flat-plate antenna and associated electronics were relayed to a digitizing oscilloscope via a fiber-optic link. The sampling interval was 10 ns. The measurement system had a useful frequency bandwidth of 16 Hz to 10 MHz. The record length was 200 ms. Using thunder ranging and the characteristic features of return-stroke electric field waveforms at known distances in the 50 to 250 km range [*Pavlick et al.*, 2002, Figure 5] we estimated that the majority of our records were due to lightning discharges occurring at distances ranging from a few to about a hundred kilometers from the field measuring station. An example of electric field record of multiple-stroke negative cloud-to-ground discharge in this data set is shown in Figure 1. The data set consists of 176 multiple-stroke negative cloud-to-ground flashes recorded on 15 and 17 July 2006 in Gainesville, Florida. Each of the 176 records was examined to measure the amplitude of the initial (radiation) electric field peak (in digitizer units) of individual return-stroke waveform. Electric field peaks of subsequent strokes were normalized with respect to the electric field peak of the corresponding first stroke.

[8] It should be noted that the maximum number of strokes per flash in the Florida data set is four, although some higher-order strokes were likely missed owing to limited record length of 200 ms. Since higher-order return strokes are expected to have somewhat smaller peak fields [*Rakov and Uman*, 1990b], the ratio of the first to subsequent return-stroke field peaks based on this Florida data set should be viewed as a lower bound (the actual value can be somewhat higher).

3.2. Electric Field Measurements, Austria

[9] The electric field measuring system used to acquire the data analyzed in this paper has been described by *Schulz and Diendorfer* [2006]. The system could record fields continuously during the entire thunderstorm. A fiber-optic link was used to relay signals from a flat-plate antenna to a digitizing oscilloscope. The sampling interval was 200 ns. The measurement system had a useful frequency bandwidth of 350 Hz to 1.5 MHz. Electric field records of lightning discharges occurring at distances of 50 to 100 km from the field measuring station were included in the data set analyzed in this paper. This data set consists of 81 multiple-stroke negative cloud-to-ground flashes recorded during about one hour on 11 July 2005 in Bad Voeslau, Austria. Lightning locating system (ALDIS) data were used to normalize electric field peaks to 100 km.

3.3. Electric Field Measurements, Brazil

[10] The electric field measuring system used in Brazil was the same as that used in Austria and described above, but a double-shielded coaxial cable instead of the fiber optic link was used to transmit signals from the antenna to the digitizer. The data set analyzed in this paper consists of 259 multiple-stroke negative cloud-to-ground flashes occurring within 200 km of the field measuring station that were

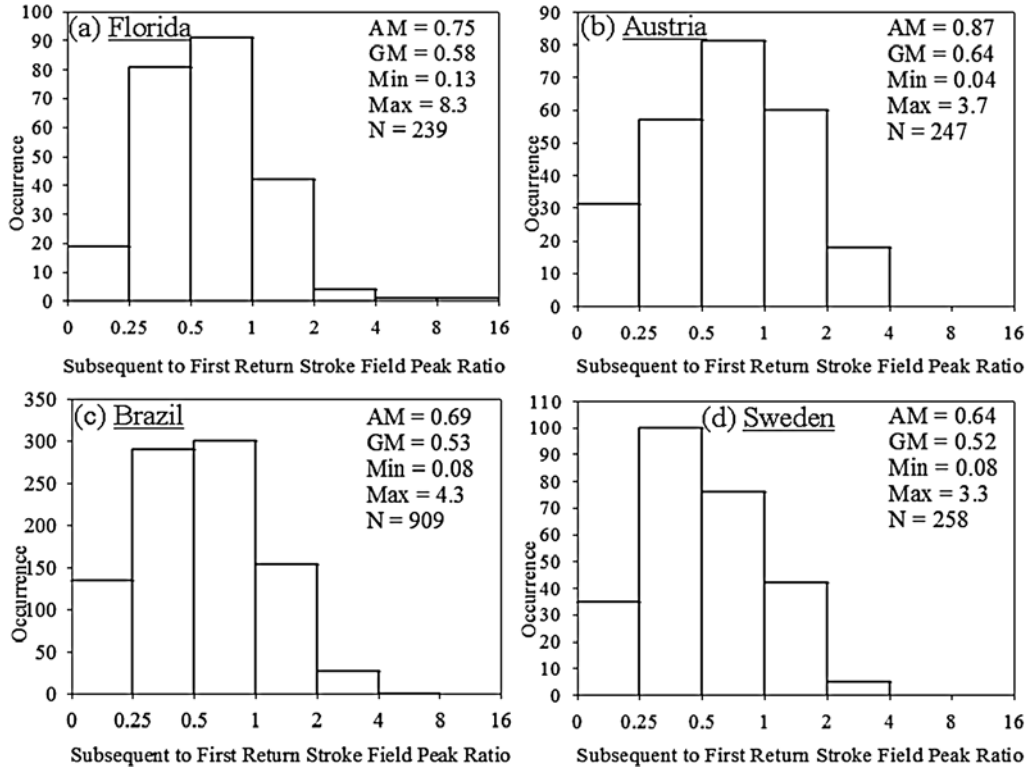

Figure 3. Histogram of the ratio of the subsequent-to-first-return-stroke electric field peak for multiple-stroke negative cloud-to-ground lightning flashes in (a) Florida, (b) Austria, (c) Brazil, and (d) Sweden.

recorded during 1 hour each on 11 February and on 11 March 2007 in São José dos Campos, Brazil. Electric field peaks were normalized to 100 km using lightning locating system (BrasilDat) data. Additional information is given by *Oliveira Filho et al.* [2007].

3.4. Electric Field Measurements, Sweden

[11] The electric field measuring system was the same as that used in Brazil, although the antenna was installed on the top of a building, while in Brazil (and in Austria) it was installed at ground level. A total of 93 multiple-stroke negative cloud-to-ground flashes occurring at distances ranging from 20 to 60 km on 24 July 2006 in Uppsala, Sweden, are analyzed in this paper. Electric field peaks were normalized to 100 km using lightning locating system data. Additional information is given by *Schulz et al.* [2008].

3.5. Lightning Locating Systems

[12] Modern multiple-station lightning locating systems (LLSs) output a peak current estimate for each stroke using the measured magnetic radiation field peaks and distances to the ground strike point reported by individual sensors. The field and current peaks are usually assumed to be proportional to each other. For data examined in this paper, the magnetic field-to-current conversion factor was 0.185 for the U.S. and Brazilian systems and 0.23 for the Austrian system, where the magnetic field was expressed in so-called LLP units. In the U.S. and Brazilian systems, a model was employed to increase the measured field peak (normalized to 100 km) in order to compensate for its attenuation due to propagation over finitely conducting ground, while no such model was implemented in the Austrian system. In this study, we used only those LLS-reported events confirmed by video records as having cloud-to-ground channels, except for the Austrian LLS data for which no video records were available.

4. Analysis and Discussions

[13] Figure 2 shows the distributions of the ratio of the first return-stroke field peak to the corresponding subsequent return-stroke field peak for Florida, Austria, Brazil, and Sweden. The arithmetic and geometric means of the ratio were, respectively, 2.1 and 1.7 for Florida, 2.3 and 1.6 for Austria, and 2.4 and 1.9 for either Brazil or Sweden. Thus, on average, the electric field peak of the first stroke is roughly 2 times larger than the field peak of the subsequent stroke. Distributions of the ratio of the subsequent to the corresponding first return-stroke field peaks, shown in Figure 3 are characterized by arithmetic and geometric means, respectively, of 0.75 and 0.58 for Florida, 0.87 and 0.64 for Austria, 0.69 and 0.53 for Brazil, and 0.64 and 0.52 for Sweden. The geometric mean electric field peaks for strokes of different order normalized (as described in section 2 and in the caption of Figure 4) to the corresponding first stroke field peak from different studies in Florida, Austria, Brazil, and Sweden are shown in Figure 4.

[14] Data of *Rakov and Uman* [1990b] were acquired near Tampa, Florida, in 1979. The normalized field peaks for subsequent strokes in the 1979 and 2006 Florida data (see bars labeled A and B, respectively, in Figure 4) are

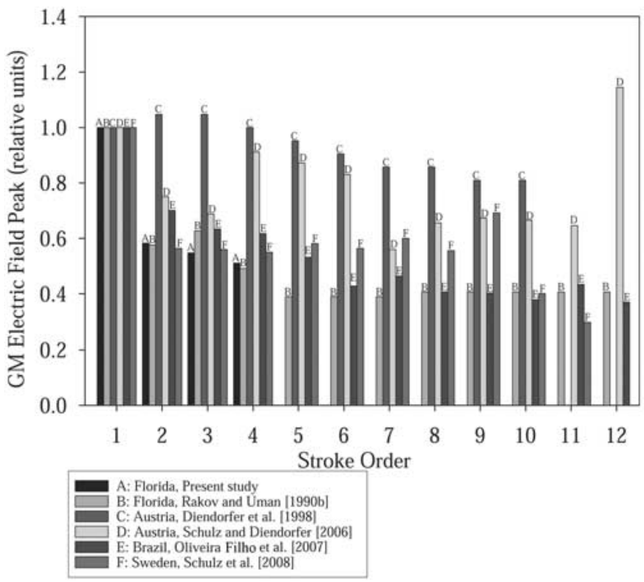

Figure 4. Geometric mean (GM) electric field peaks for strokes of different order estimated from different studies, labeled A, B, C, D, E, and F. For A, field peaks of subsequent strokes of different order are normalized to the electric field peak of the corresponding first return stroke and for B, C, D, E, and F the GM field peaks of subsequent strokes of different order are normalized to the GM field peak for first strokes (including those in single-stroke flashes for B and C). Sample size for strokes of order 12 in study D was as low as three (there were six in study E, and for study B the value is the average for 53 strokes of order 8 through 18).

found to be in good agreement, confirming the notion that the electric field (or current peak) of the first return stroke is appreciably larger than that of the subsequent stroke. In contrast, *Diendorfer et al.* [1998], who examined return strokes recorded by the Austrian lightning locating system (ALDIS), found the values of the field peaks (and ALDIS-reported peak currents, assumed to be proportional to measured field peaks) of the first and subsequent strokes to be approximately equal (see bars labeled C in Figure 4). Further, *Rakov and Uman* [2003, chap. 17] noted that similar first and subsequent stroke intensities were reported by the U.S. National Lightning Detection Network (NLDN) prior to its 2002 upgrade [*Cummins et al.*, 2006]. Geometric mean values of the electric field peak for subsequent strokes of different order found from electric field measurements in Austria (see bars labeled D in Figure 4) are generally larger than the corresponding values in other studies, except for those based on ALDIS data, particularly for stroke order 12. However, the later value may be unreliable owing to the small sample size (there were only three strokes of order 12 in study D).

[15] We discuss next recent LLS studies conducted in conjunction with video observations. *Saba et al.* [2006a], using data from the Brazilian lightning locating system (BrasilDat), found the mean peak current of 55 first return strokes (28.3 kA) to be 2.1 times the mean peak current of 193 subsequent return strokes (13.5 kA). The corresponding ratio of geometric mean values is 1.7. Note that Saba et al.'s data are for strokes followed by continuing currents with durations ranging from 4 to 350 ms and are accompanied by high-speed (1000 frames per second) video records. The presence of continuing currents with durations down to a few milliseconds is unlikely to introduce any significant bias in LLS-inferred peak currents. Indeed, *Shindo and Uman* [1989] found that geometric mean electric field peak (normalized to 100 km) for return strokes followed by "questionable" continuing currents with durations ranging from 1 to 10 ms was equal to that for "regular" subsequent return strokes (not followed by any continuing current). *Biagi et al.* [2007] examined post-2002-upgrade NLDN data (for 2003 and 2004) that were confirmed by ordinary video camera records in Arizona, Texas, and Oklahoma and reported the ratio of GM first to GM subsequent current peaks to be 1.3 and 1.2 in Arizona and Texas-Oklahoma, respectively. From a similar study in the Great Plains of eastern Colorado, western Kansas, and western Nebraska, the value of the ratio estimated from 2005 NLDN data is 1.3 [*Krider et al.*, 2007].

[16] Table 1 summarizes the values of first to subsequent stroke electric field (or current) peak ratio estimated in different studies. The ratio varies from 1.0 to 2.5. The lowest value, 1.0, corresponds to the LLS study in Austria. The highest values, 2.3 to 2.5, correspond to direct current measurements on towers.

[17] Assuming that the radiation field peak is roughly proportional to the product of the current and return-stroke speed, we infer that the smaller ratio for fields than for currents implies a lower average return-stroke speed for first strokes than for subsequent strokes. This is consistent with optical speed measurements [*Idone and Orville*, 1982], who reported mean speeds of 9.6×10^7 m/s and 1.2×10^8 m/s for 17 first and 46 subsequent strokes, respectively. The difference, though, is not very large.

[18] Alternatively, the higher ratios for directly measured currents (relative to the ratios for fields) could be due to the lack of new channel terminations for currents, since subsequent strokes in newly formed channels are on average larger than those in previously formed ones [*Rakov et al.*, 1994]. However, the ratios do not change much if the strokes in the newly formed channels are excluded (see Table 2): for Florida data of *Rakov and Uman* [1990a, 1990b] the ratio of GM field peaks increases from 2.0 to 2.2 and for data of *Biagi et al.* [2007] and *Krider et al.* [2007] they remain unchanged at 1.3, 1.2 and 1.3 in Arizona, Texas-Oklahoma, and the Great Plains, respectively.

[19] Note that, the ratios in Table 1 calculated from LLS studies (ALDIS, BrasilDat, and NLDN), are for both multiple- and single-stroke flashes combined. As noted in section 2, this may result in some underestimation of the first-to-subsequent-stroke ratio, since strokes in single-stroke flashes are on average smaller than first strokes in multiple-stroke flashes. The ratios of GM first to GM subsequent current peaks estimated from NLDN data in Texas-Oklahoma and the Great Plains are, respectively, 1.4 and 1.5, when only multiple-stroke flashes are considered (see Table 3), somewhat larger than 1.2 and 1.3, respectively, estimated for the case when both multiple- and single-stroke flashes were combined (see Table 1). On the other hand, when single-stroke flashes are excluded, the

Table 1. Summary of First to Subsequent Stroke Electric Field or Current Peak Ratios Estimated From Different Studies

Reference(s) and Location	AM of First to Subsequent Stroke Peak Ratio	Ratio of AM First to AM Subsequent Stroke Peak	GM of First to Subsequent Stroke Peak Ratio	Ratio of GM First to GM Subsequent Stroke Peak	Ratio of Median First to Median Subsequent Stroke Peak	Number of Subsequent Strokes	Number of First Strokes	Number of Single–Stroke Flashes	Stroke Identification Method
				Electric Field					
Rakov and Uman [1990a, 1990b], Florida	–	1.9	–	2.0[a]	–	270	76	13	Electric field and TV records
Diendorfer et al. [1998], Austria	–	–	–	1.0	1.0	53,443	43,133	24,120	LLS reports
Schulz and Diendorfer [2006], Austria	2.3	1.4	1.6	1.3	1.1	247	81	0	Electric field records
Oliveira Filho et al. [2007], Brazil	2.4	1.7	1.9	1.7	1.8	909	259	0	Electric field records
Schulz et al. [2008], Sweden	2.4	2.0	1.9	1.8	2.0	258	93	0	Electric field records
Present study, Florida	2.1	–	1.7	–	1.7[b]	239	176	0	Electric field records
				Current					
Berger et al. [1975], Switzerland	–	–	–	–	2.5	135	101	~50	Direct current measurements
Anderson and Eriksson [1980], Switzerland	–	–	–	2.3	2.3	114	75	–	Direct current measurements
Visacro et al. [2004], Brazil	–	–	–	2.5	2.5	59	31	15	Direct current measurements
Saba et al. [2006a], Brazil	–	2.1[c]	–	1.7[c]	1.6[c]	193	55	16	LLS reports confirmed by video records
Biagi et al. [2007], Arizona	–	1.5	–	1.3	1.2	1602	953	388	LLS reports confirmed by video records
Biagi et al. [2007], Texas-Oklahoma	–	1.6	–	1.2	1.1	371	273	131	LLS reports confirmed by video records
Krider et al. [2007], Great Plains	–	1.3	–	1.3	1.2	150	90	40	LLS reports confirmed by video records

[a]For all subsequent strokes combined. For subsequent strokes following a previously formed channel, *Rakov et al.* [1994] reported the ratio to be 2.2.
[b]The median of the ratio of first to corresponding subsequent stroke peak (in multiple-stroke flashes), not the ratio of the medians of the first and subsequent stroke peaks, as for other studies in this column.
[c]For strokes followed by continuing currents with durations ranging from 4 to 350 ms.

Table 2. Summary of First to Subsequent Stroke Electric Field or Current Peak Ratios for Subsequent Strokes Following a Previously Formed Channel

Reference(s) and Location	Ratio of GM First to GM Subsequent Stroke Peak for All Subsequent Strokes Combined[a]	Ratio of GM First to GM Subsequent Stroke Peak for Subsequent Strokes Following a Previously Formed Channel	Stroke Identification Method
Rakov and Uman [1990a, 1990b], Florida	2.0	2.2	Electric field and TV records
Biagi et al. [2007], Arizona	1.3	1.3	LLS reports confirmed by video records
Biagi et al. [2007], Texas-Oklahoma	1.2	1.2	LLS reports confirmed by video records
Krider et al. [2007], Great Plains	1.3	1.3	LLS reports confirmed by video records

[a]Taken from Table 1. Both subsequent strokes following a previously formed channel and those creating new terminations on ground are included.

ratio of GMs for Arizona remains unchanged at 1.3. For the electric field measurements of *Rakov and Uman* [1990a, 1990b] in Florida the ratio of GMs after excluding single-stroke flashes changed only slightly, from 2.0 to 2.1. Overall, the effect of excluding single-stroke flashes appears to be relatively small.

[20] Table 4 summarizes the values of subsequent to first stroke electric field (or current) peak ratio estimated in different studies. All the geometric mean ratios and ratios of geometric means and medians are between 0.40 and 0.76, except for those based on LLS reports, which range from 0.60 to 0.93. The arithmetic mean ratios and ratios of arithmetic means in Table 4 range from 0.48 to 0.87.

[21] The question remains if the observed discrepancies are due to differences in lightning characteristics in different geographical locations or due to different instrumentation and methodologies involved. We will discuss each of these two possibilities below.

[22] From the methodology point of view, the NLDN (prior to the 2002 upgrade) and ALDIS results could be due to poor detection of relatively small subsequent strokes, rejection of the first stroke by the waveform discrimination algorithm and acceptance of the second stroke as the first stroke, and misclassification of a preliminary-breakdown pulse (associated with an in-cloud process) as the first return stroke. More research is needed to quantify these effects. Also, the accuracy of first stroke peak current estimates derived from LLSs data has not yet been confirmed by independent measurements [e.g., *Krider et al.*, 2007]. Additionally, time resolution of video records (17 ms in work by *Biagi et al.* [2007] versus 1 ms in work by *Saba et al.* [2006a]) can play a role in detecting smaller subsequent strokes. *Saba et al.* [2006b] estimated that 19% of the total number of strokes in their study would be missed if an ordinary video camera with 17 ms time resolution (interfield interval) were used.

[23] On the other hand, the occurrence of larger than first subsequent strokes can vary for different types of storms or for different locations. Table 5 presents a summary of percentages of multiple-stroke flashes with at least one subsequent stroke field peak greater than the first and percentages of subsequent strokes with field peaks greater than the first estimated in different studies. In Florida, Austria, Brazil, and Sweden, respectively, 21, 32, 20, and 18% of the subsequent strokes were found to have field peaks greater than that of the first stroke. Percentages of flashes containing at least one subsequent stroke with field peak greater than that of the first stroke in these studies were 24, 49, 38, and 32%, respectively. Also given in Table 5 are the percentages estimated from earlier electric field measurements in Sri Lanka and Sweden and from LLS reports in Austria. The highest percentages of flashes with at least one subsequent stroke field peak greater than the first were reported in Austria (49% for *Schulz and Diendorfer* [2006] and 51% for *Diendorfer et al.* [1998]). This possibly explains (at least in part) the smaller first-to-subsequent-stroke field peak ratio estimated from the Austrian studies compared to those for other regions in the world. It is

Table 3. Summary of First to Subsequent Stroke Electric Field or Current Peak Ratios for Multiple-Stroke Flashes Only[a]

Reference(s) and Location	Ratio of AM First to AM Subsequent Stroke Peak	Ratio of GM First to GM Subsequent Stroke Peak	Ratio of Median First to Median Subsequent Stroke Peak	Number of Subsequent Strokes	Number of First Strokes	Stroke Identification Method
Rakov and Uman [1990a, 1990b], Florida	2.0 (1.9)	2.1 (2.0)	–	270	63	Electric field and TV records
Biagi et al. [2007], Arizona	1.3 (1.5)	1.3 (1.3)	1.3 (1.2)	1602	565	LLS reports confirmed by video records
Biagi et al. [2007], Texas-Oklahoma	1.5 (1.6)	1.4 (1.2)	1.3 (1.1)	371	142	LLS reports confirmed by video records
Krider et al. [2007], Great Plains	1.5 (1.3)	1.5 (1.3)	1.5 (1.2)	150	50	LLS reports confirmed by video records

[a]Values in the parentheses are taken from Table 1 and correspond to both multiple- and single-stroke flashes combined. It appears that the ratios are not much influenced by the exclusion of single-stroke flashes.

Table 4. Summary of Subsequent to First Stroke Electric Field or Current Peak Ratio Estimated From Different Studies

Reference(s) and Location	AM of Subsequent to First Stroke Peak Ratio	Ratio of AM Subsequent to AM First Stroke Peak	GM of Subsequent to First Stroke Peak Ratio	Ratio of GM Subsequent to GM First Stroke Peak	Ratio of Median Subsequent to Median First Stroke Peak	Number of Subsequent Strokes	Number of First Strokes	Number of Single–Stroke Flashes	Stroke Identification Method
				Electric Field					
Rakov and Uman [1990a, 1990b], Florida	–	0.52	–	0.49[a]	–	270	76	13	Electric field and TV records
		0.49		0.47	–	270	63	0	Electric field and TV records
Thottappillil et al. [1992], Florida	–	–	0.42[b]	–	–	199	46	0	Electric field and TV records
Cooray and Perez [1994], Sweden	0.63	–	0.51	–	–	314	–	0	Electric field records
Cooray and Jayaratne [1994], Sri Lanka	0.55	–	0.43	–	–	284	81	0	Electric field records
Diendorfer et al. [1998], Austria	–	–	–	1.0	1.0	53,443	43,133	24,120	LLS reports
Schulz and Diendorfer [2006], Austria	0.87	0.71	0.64	0.76	0.90	247	81	0	Electric field records
Oliveira Filho et al. [2007], Brazil	0.69	0.59	0.53	0.58	0.55	909	259	0	Electric field records
Schulz et al. [2008], Sweden	0.64	0.51	0.52	0.56	0.50	258	93	0	Electric field records
Present study, Florida	0.75	–	0.58	–	0.57[c]	239	176	0	Electric field records
				Current					
Berger et al. [1975], Switzerland	–	–	–	–	0.40	135	101	~50	Direct current measurements
Anderson and Eriksson [1980], Switzerland	–	–	–	0.43	0.43	114	75	–	Direct current measurements
Visacro et al. [2004], Brazil	–	–	–	0.40	0.40	59	31	15	Direct current measurements
Saba et al. [2006a], Brazil	–	0.48[d]	–	0.60[d]	0.64[d]	193	55	16	LLS reports confirmed by video records
Biagi et al. [2007], Arizona	–	0.65[e]	–	0.78	0.81	1602	953	388	LLS reports confirmed by video records
Biagi et al. [2007], Texas-Oklahoma	–	0.63[e]	–	0.83	0.93	371	273	131	LLS reports confirmed by video records
Krider et al. [2007], Great Plains	–	0.78[f]	–	0.78	0.81[f]	150	90	40	LLS reports confirmed by video records

[a]For all subsequent strokes combined. For subsequent strokes following a previously formed channel, *Rakov et al.* [1994] reported the ratio to be 0.46.
[b]For all subsequent strokes combined. For subsequent strokes following a previously formed channel, *Thottappillil et al.* [1992] reported the GM ratio to be 0.39 (176 events).
[c]The median of the ratio of subsequent to corresponding first stroke peaks (in multiple-stroke flashes), not the ratio of the medians of subsequent and first stroke peaks, as for other studies in this column.
[d]For strokes followed by continuing currents with durations ranging from 4 to 350 ms.
[e]For all subsequent strokes combined. For subsequent strokes following a previously formed channel, *Biagi et al.* [2007] reported the ratio to be 0.61 and 0.59 for Arizona and Texas-Oklahoma, respectively.
[f]For all subsequent strokes combined. For subsequent strokes following a previously formed channel, *Krider et al.* [2007] reported the ratio of arithmetic means to be 0.75 and the ratio of medians to be 0.70.

Table 5. Summary of Multiple-Stroke Flash Characteristics Reported in Different Studies

Reference(s) and Location	Total Number of Flashes	Percentage of Flashes With at Least One Subsequent Stroke Field Peak Greater Than the First	Percentage of Subsequent Strokes With Field Peaks Greater Than the First	Stroke Identification Method
Thottappillil et al. [1992], Florida	46	33	13	Electric field and TV records
Cooray and Perez [1994], Sweden	276	24	15	Electric field records
Cooray and Jayaratne [1994], Sri Lanka	81	35	12	Electric field records
Diendorfer et al. [1998], Austria	15905	51	–	LLS reports
Schulz and Diendorfer [2006], Austria	81	49	32	Electric field records
Oliveira Filho et al. [2007], Brazil	259	38	20	Electric field records
Schulz et al. [2008], Sweden	93	32	18	Electric field records
Present study, Florida	176	24	21	Electric field records

presently not known if the larger subsequent strokes in Austria are associated with new channel terminations on ground or not.

5. Summary

[24] Relative magnitudes of electric field peaks of first and subsequent return strokes in negative cloud-to-ground lightning flashes recorded in Florida, Austria, Brazil, and Sweden are analyzed in this study. On average, the electric field peak of the first stroke is appreciably, 1.7 to 2.4 times, larger than the field peak of the subsequent stroke (except for studies in Austria where the ratio varies from 1.0 to 2.3, depending on methodology and instrumentation). Similar results were previously reported from electric field studies in Florida, Sweden, and Sri Lanka by *Rakov et al.* [1994], *Cooray and Perez* [1994], and *Cooray and Jayaratne* [1994], respectively. For comparison, directly measured peak currents for first strokes are, on average, a factor of 2.3 to 2.5 larger than those for subsequent strokes [*Berger et al.*, 1975; *Anderson and Eriksson*, 1980; *Visacro et al.*, 2004]. The generally larger ratio for currents than for fields possibly implies a lower average return-stroke speed for first strokes than for subsequent strokes. There appear to be some differences between first versus subsequent stroke intensities reported from different studies based on data reported by lightning locating systems (LLSs). The ratio of LLS-reported peak currents for first and subsequent strokes confirmed by video records is 1.7 to 2.1 in Brazil (for strokes followed by continuing currents with durations ranging from 4 to 350 ms), while in the U.S. (Arizona, Texas, Oklahoma, and the Great Plains) it varies from 1.1 to 1.6, depending on methodology used. Ratios involving arithmetic means are generally larger than those involving geometric means. The smaller ratios derived from the LLS studies are likely to be due to poor detection of relatively small subsequent strokes. The smaller values in Austria are possibly related (at least in part) to the higher percentage (about 50% versus 24 to 38% in other studies) of flashes with at least one subsequent stroke greater than the first. The effects on the ratio of excluding single-stroke flashes or subsequent strokes in newly formed channels appear to be relatively small. Additional data are needed to further clarify the issue of relative intensity of first and subsequent strokes in different geographical locations, as well as possible instrumental and methodological biases involved.

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