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Statistical Distributions of Lightning Parameters with Emphasis on their Extremely High Values

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The paper is devoted to the review of the data on the lightning parameters necessary for development and perfection of lightning protection systems. It is shown, that down to present time national and international lightning protection standards are based on the Berger's data on distribution of lightning amplitudes currents. Experimental data on amplitude of the return-stroke current the received recently in Brazil, Japan, USA (Florida) and Austria are resulted. It is emphasized, that the given data on currents of a lightning are characterized by a wide scatter that specifies necessity of realization of the further researches. The detailed description of parameters of the return-stroke peak current, including duration of front time, duration of a pulse, a steepness of a current at the front is given. It is emphasized, that median value of amplitude of a current of the first making the return-stroke in 3-4 times is higher than a current of the subsequent components. The analysis measured median (50%) and severe (1%) values of lighting parameters which are necessary for construction of a curve of distribution in the assumption of its submission lognormal law is carried out. Results of theoretical researches are given according to extreme values of currents of a lightning. It is shown, that, depending on length of the lightning channel (from 4 up to 6 kms), the maximal current can vary from 300 kA up to 500 кA. The minimal value of lightning current is appreciated in 2 кA. The analysis of results of new direct measurements has shown, that for a lightning of positive polarity the maximal current can reach 340 кA, that appreciably is higher than a settlement maximum for a lightning of negative polarity (200 кA). Recent theoretical researches have allowed to prove experimentally received lognormal distribution of currents for lightning of negative polarity.

K e y w o r d s: *lightning, return-stroke peak current, first strokes, subsequent strokes, current waveforms, lognormal distribution, front time, steepness, current risetime, positive polarity, negative polarity*

Return-stroke peak current — "classical" distributions. Essentially all national and international lightning protection standards (e.g., IEC 62305-1; IEEE 1243-1997; IEEE 1410-2010 [1—3]) include a statistical distribution of peak currents for first strokes in negative lightning flashes (including the only strokes in single-stroke flashes). This distribution, which is one of the cornerstones of most lightning protection studies, is largely based on direct lightning current measurements conducted in Switzerland from 1963 to 1971 (e.g., Berger et al., 1975 [4]; Berger, 1972 [5]). The cumulative statistical distributions of lightning peak currents for (1) negative first strokes, (2) positive first strokes, and (3) negative subsequent strokes [4] are presented in Fig. 1. The distributions are assumed to be lognormal (because they are positively skewed, that is, exhibit long "tails" extending toward higher values, so that Mean > Median > Mode) and give percent of cases exceeding abscissa value. It is worth noting that directly measured current waveforms of either polarity found in the literature do not exhibit peaks exceeding 300 kA or so, which is consistent with the theoretically estimated upper limit for peak currents in temperate regions [6], while inferences from remotely measured electric and magnetic fields suggest the existence of considerably higher currents. It is important to note, however, that peak current estimates reported by the U.S. National Lightning Detection Network (NLDN) and by other similar systems are based on an empirical formula the validity of which has been tested, using triggered lightning in Florida and instrumented tower in Austria, only for negative subsequent strokes with peakx currents lower than 50 kA [7—10].

The lognormal probability density function for peak current I is given by

$$f(I)\frac{1}{\sqrt{2\pi}\beta t}\exp(-z^2/2), \quad (1)$$

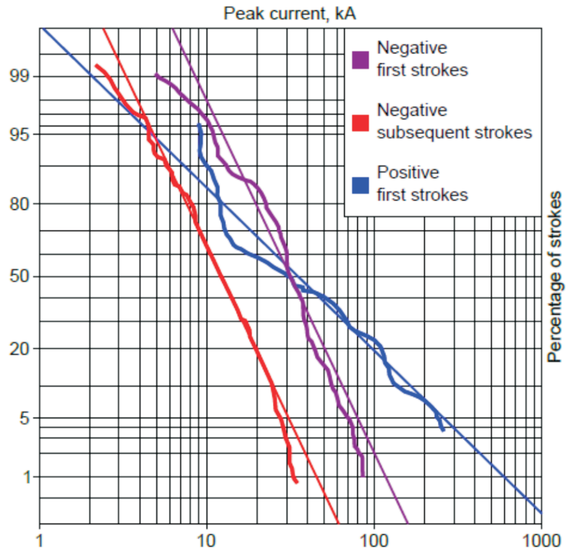

Fig. 1. Cumulative statistical distributions of return-stroke peak current from measurements at the tower top and their lognormal approximations (straight lines) for negative first strokes ($n=101$), negative subsequent strokes ($n=135$), and positive first strokes ($n=26$) [4]

where

$$z=\frac{\ln I - Mean(\ln I)}{\beta}. \quad (2)$$

In (2), ln *I* is the natural (base e) logarithm of *I*, Mean(ln *I*) is the mean value of ln *I*, and $\beta=\sigma_{\ln I}$ is the standard deviation of ln *I*.

For a lognormal distribution, Mean(ln *I*) is equal to both the logarithm of geometric mean (GM) and logarithm of median of *I*. It follows that the antilog of Mean(ln *I*) is the median (50% value) of *I*. Thus, a lognormal distribution is completely described by two parameters, the median and logarithmic standard deviation of the variable. Logarithmic standard deviations of lightning peak currents are often given for base 10 (base 10 logarithms are often denoted lg); those should be multiplied by $\ln_{10}=2.3026$ in order to obtain $\beta=\sigma_{\ln I}$.

The probability for peak current to exceed a specified value *I* is given by

$$P(I)=\int_I^{\infty}\frac{1}{\sqrt{2\pi}\beta I}\exp(-z^2/2)dI. \quad (3)$$

P(*I*) can be evaluated as follows:

$$P(I)=1-\Phi(z)=\frac{1}{2}erfc\left(\frac{z}{\sqrt{2}}\right), \quad (4)$$

where Φ is the cumulative distribution function of the standard normal distribution; *erfc* is the complementary error function.

Only a few percent of negative first strokes exceed 100 kA, while about 20% of positive strokes have been observed to do so. However, it is thought that less than 10% of global cloud-to-ground lightning is positive. About 95% of negative first strokes are expected to exceed 14 kA, 50% exceed 30 kA, and 5% exceed 80 kA (see Table 1). The corresponding values for negative subsequent strokes are 4.6, 12, and 30 kA (see Table 1), and 4.6, 35, and 250 kA for positive strokes (see Table 6). Subsequent strokes are typically less severe in terms of peak current and therefore often neglected in lightning protection studies.

Berger's peak current distribution for negative first strokes shown in Fig. 1 is based on about 100 direct current measurements accompanied by detailed optical observations and, as of today, is thought to be the most accurate one. The minimum peak current value included in Berger's distributions shown in Fig. 1 is 2 kA (note that no first strokes with peak currents below 5 kA were observed). Clearly, the parameters of statistical distributions can be affected by the lower and upper measurement limits. Rakov [11] showed that, for a lognormal distribution, the parameters of a measured, "truncated" distribution and knowledge of the lower measurement limit can be used to recover the parameters of the actual, "untruncated" distribution. He applied the recovery procedure to the various lightning peak current distributions found in the literature and concluded that the peak current distributions [4] can be viewed as practically unaffected by the effective lower measurement limit of 2 kA. Further, it has been shown by Rakov [12] that Berger's peak currents for first strokes, based on measurements at the top of 70-m towers, are not influenced by the transient process (reflections) excited in the tower. For subsequent strokes, reflections are expected to increase the tower-top current by 10% or so. The distribution of peak currents based on measurements on tall instrumented towers may be biased (relative to the ground-surface peak-current distribution) toward higher values due to the peak-current-dependent attractive effect of the tower [13,14]. Borghetti et al. [14], using the electrogeometric model, showed that median values of peak current based on measurements at instrumented towers should be reduced by 20% to 40% (depending on the attractive radius expression) to obtain the corresponding values for flat ground (in the absence of the tower). Interestingly, the electrogeometric model predicts that even the presence of a 5-m tall strike object appreciably alters the flat-ground peak current distribution [15], although in practice this is unlikely because of the influence of neighboring objects such as buildings and trees. As of today, there is no experimental evidence that peak current distributions for downward lightning are materially affected by the presence of the tower [16]. In fact, Popolansky [17] reported that the median negative peak currents for

Table 1

Parameters of downward negative lightning [4]

Parameters	Units	Sample Size	Percent Exceeding Tabulated Value		
			95%	50%	5%
Peak current (minimum 2 kA) First strokes Subsequent strokes	kA	101 135	14 4.6	30 12	80 30
Charge (total charge) First strokes Subsequent strokes Complete flash	C	93 122 94	1.1 0.2 1.3	5.2 1.4 7.5	24 11 40
Impulse charge (excluding continuing current) First strokes Subsequent strokes	C	90 117	1.1 0.22	4.5 0.95	20 4
Front duration (2 kA to peak) First strokes Subsequent strokes	μs	89 118	1.8 0.22	5.5 1.1	18 4.5
Maximum *dI/dt* First strokes Subsequent strokes	kA μs^{-1}	92 122	5.5 12	12 40	32 120
Stroke duration (2 kA to half peak value on the tail) First strokes Subsequent strokes	μs	90 115	30 6.5	75 32	200 140
Action integral (I2dt) First strokes Subsequent strokes	A^2s	91 88	6.0×10^3 5.5×10^2	5.5×10^4 $6.0v10^3$	5.5×10^5 5.2×10^4
Time interval between strokes	ms	133	7	33	150
Flash duration All flashes Excluding single-stroke flashes	ms	94 39	0.15 31	13 180	1100 900

strike objects with heights 15–55 m (n=64) and 56–65 m (n=81) were 30 and 27 kA, respectively, not in support of the expected object-height dependence. For these height ranges, influence of upward lightning is usually neglected. To summarize, it appears that Berger's distributions of peak currents for first and subsequent negative strokes are not materially affected by either lower measurement limit or the presence of the tower.

In lightning protection standards, in order to increase the sample size, Berger's data are often supplemented by limited direct current measurements in South Africa and by less accurate indirect lightning current measurements obtained (in different countries) using magnetic links. There are two main distributions of lightning peak currents for negative first strokes adopted by lightning protection standards: the IEEE distribution [2,3] and CIGRE distribution [18,19]. Both these "global distributions" are presented in Fig. 2.

In the coordinates of Fig. 2 (also Fig. 1), a cumulative lognormal distribution appears as a slanted straight line. Anderson and Eriksson [18] arbitrarily introduced two slanted lines having different slopes (implying a bimodal probability density function) and intersecting at 20 kA to approximate their "global"

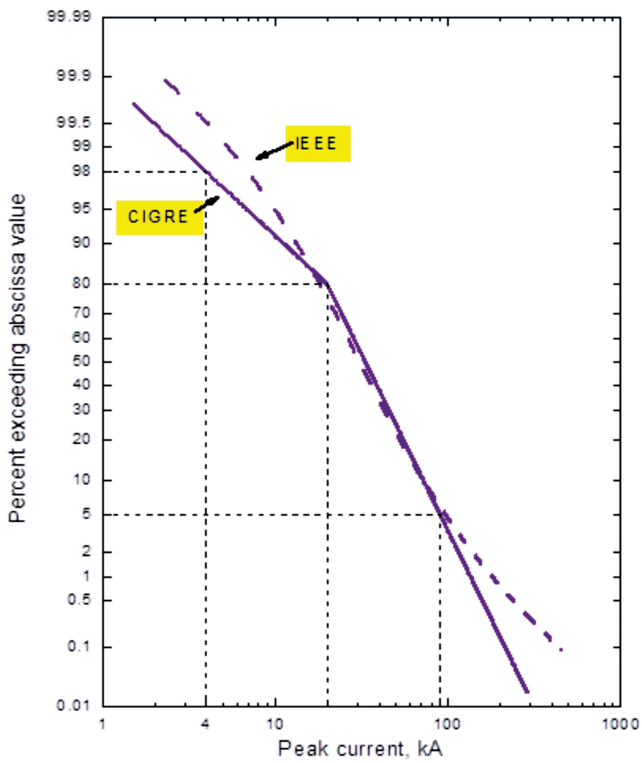

Fig. 2. Cumulative statistical distributions of peak currents for negative first strokes adopted by IEEE and CIGRE and used in various lightning protection standards [19]

peak current distribution based on both direct and indirect (magnetic-link) current measurements. The same approach was adopted in the CIGRE [19]. Note that IEEE Std. [2] makes reference to the two-slope CIGRE distribution as well.

For the CIGRE distribution, 98% of peak currents exceed 4 kA, 80% exceed 20 kA, and 5% exceed 90 kA.

For the IEEE distribution, the "probability to exceed" values are given by the following equation

$$P(I)=\frac{1}{1+(I/31)^{2.6}}, \qquad (5)$$

where $P(I)$ is in per unit and I is in kA.

According to Hileman [20], this equation, usually assumed to be applicable to negative first strokes, is based on data for 624 strokes analyzed by Popolansky [21], whose sample included both positive and negative strokes, as well as strokes in upward lightning. Equation (5) applies to values of I up to 200 kA. For higher peak currents, [2] recommends the use of the two-slope CIGRE distribution, while IEEE Std. [3] apparently relies on the log-normal approximation of Berger's distribution for the global current peak (I_F) found in Table 2. Values of $P(I)$ for I varying from 5 to 200 kA, computed using (5) and expressed in percent, are given in Table 3. The median (50%) peak current value is equal to 31 kA.

In the range of 10 to 100 kA that is well supported by experimental data, the IEEE and CIGRE distributions are very close to each other. Outside that range, the uncertainty, due to relative paucity of data, is apparently too large to allow one to favor either of the two distributions.

The peak-current distribution for subsequent strokes adopted by the IEEE [2, 3] is given by

$$P(I)=\frac{1}{1+(I/12)^{2.7}}, \qquad (6)$$

which is compared with (5) in Table 3. CIGRE recommends for negative subsequent stroke peak currents a log-normal distribution with the median of 12.3 kA and β=0.53 [19], which is also included in IEEE [3] (see Table 2).

We now further discuss the "global" distributions found in most lightning protection standards. They are

Table 2

Lightning current parameters recommend by CIGRE [19] and IEEE [3]

Parameters of lognormal distribution for negative downward flashes				
Parameter	First stroke		Subsequent stroke	
	M, Median	β, logarithmic (base e) standard deviation	M, Median	β, logarithmic (base e) standard deviation
FRONT TIME (μs)				
$t_{d10/90} = T_{10/90}/0.8$	5.63	0.576	0.75	0.921
$t_{d30/90} = T_{30/90}/0.6$	3.83	0.553	0.67	1.013
$t_m = I_F / S_m$	1.28	0.611	0.308	0.708
STEEPNESS (kA/μs)				
S_m, Maximum	24.3	0.599	39.9	0.852
S_{10}, at 10%	2.6	0.921	18.9	1.404
$S_{10/90}$, 10–90%	5.0	0.645	15.4	0.944
$S_{30/90}$, 30–90%	7.2	0.622	20.1	0.967
PEAK (CREST) CURRENT (kA)				
I_I, initial	27.7	0.461	11.8	0.530
I_F, final	31.1	0.484	12.3	0.530
Ratio, I_I/I_F	0.9	0.230	0.9	0.207
OTHER RELEVANT PARAMETERS				
Tail Time to Half Value, th (μs)	77.5	0.577	30.2	0.933
Number of strokes per flash	1	0	2.4	0.96 based on median N_{total} = 3.4
Stroke Charge, Q_I (Coulomb)	4.65	0.882	0.938	0.882
$\int I^2 dt$ ((kA)2s)	0.057	1.373	0.0055	1.366
Interstroke interval (ms)	–	–	35	1.066

Table 3

The IEEE peak current distributions for first and subsequent strokes

Peak current, I, kA		5	10	20	40	60	80	100	200
Percentage exceeding tabulated value, $P(I)$100%	First strokes	99	95	76	34	15	7.8	4.5	0.78
	Subsequent strokes	91	62	20	3.7	1.3	0.59	0.33	0.050

not much different from the distributions based on direct current measurements [4] which are still considered to be the most reliable ones [22]. However, the extremely low and particularly extremely high (greater than 100 kA or so) peak current tails require much larger sample sizes (probably of the order of thousands or more) than presently available (or to be available in the foreseeable future) to bring the uncertainties within an engineering accuracy range.

In this regard, it is natural to attempt to combine as many measurements as possible to increase the sample size and, hence, reduce statistical uncertainties. One such attempt was made by Popolansky [21] who combined direct and indirect (magnetic link) current measurements made on tall objects and on power lines in eight countries. The overall sample size was 624. Later it was realized [18] that some of the indirect measurements on taller objects could be associated with strokes in upward lightning. Since upward lightning is unlikely to occur at objects less than 60 m in height, only measurements on shorter than 60 m objects were retained for compiling the next edition of the "global" peak current distribution. Additionally, all positive current measurements were excluded and 11 current measurements from South Africa were added [18]. The overall sample size became 338. Finally, in CIGRE [19], 70 more measurements (both direct and indirect) from South Africa were added bringing the overall sample size to 408. The majority of the additional 70 currents were obtained by adding typically 4 to 5 partial currents measured with magnetic links installed on wooden poles of the test power distribution line [23].

One concern about the "global" lightning peak current distributions is the inclusion of less accurate indirect (magnetic link) measurements. Even in the case of measurements on simple lightning down-conductors or measurements at vertical strike rods mounted on the top of transmission-line towers, very significant errors are likely. Specifically, magnetic links can be saturated or demagnetized by shaking during their transportation or by incomplete discharges from the strike object top occurring in response to nearby lightning flashes. Bazelyan et al. [24], via modeling, showed that the collapse of charge accumulated at the tip of object (or on the unconnected upward leader) in response to a nearby downward leader can involve kiloampere-scale currents in the object at the time of return stroke initiated by that downward leader. Such induced currents usually have polarity opposite to that of direct negative strikes and, hence, can partially demagnetize the link which previously recorded current of a direct negative strike. Taller objects were found to experience higher induced currents. This effect might be responsible for the observed decrease of median peak current measured using magnetic links with strike-object height, even when objects with heights greater than 65 m (for which upward flashes could be a factor) were excluded [17]. In summary, it is probably best not to "compromise" direct current measurements by combining them with indirect measurements that may contain significant errors.

An additional concern about the "global" lightning peak current distributions is related to inhomogeneity of data coming from different sources and being combined in a single sample. Popolansky [21] noted that out of seven distributions based on indirect current measurements only two (from Czechoslovakia and Poland) were in "very good" agreement with the Swiss distribution based on direct current measurements. For one of the distributions (from the United States), the lowest measured value was 7 kA, which suggests that it might be significantly truncated (depending on logarithmic standard deviation [11]). Nevertheless, the U.S. distribution was included in the later editions of the "global" distributions [18, 19]. Further, 11 peak current values from South Africa were added by Anderson and Eriksson [18], although they suggested a quite different distribution (Median = 41 kA, Min = 10 kA). Out of the 11 values, only 8 were positively identified as corresponding to downward flashes, and 2 other values were measured with magnetic links. There has been a concern that the South African measurements, made at the bottom of the tower, might have been significantly affected by the transient process in the tower (e.g., [25]). Finally, 70 more values (including both direct and indirect measurements) from South Africa were added in CIGRE [19], with most of the values being obtained by summing partial currents measured at multiple poles of a test distribution line. The latter data were acquired during several years for different line configurations (presence or absence of arresters, transformers, and power follow current) [26], which could have introduced additional uncertainties.

In summary, it is not clear if mixing direct current measurements with less accurate indirect ones in the "global" distributions served to build a more statistically reliable distribution; it could have actually amounted to contamination of the relatively high quality data with more numerous data of questionable quality. However, since the "global" distributions have been widely used in lightning protection studies and are not much different from that based on direct measurements only (Median = 30 kA, $\sigma_{\lg I}$ =0.265 for Berger et al.'s distribution for negative first strokes), continued use of these "global" distributions for representing negative first strokes are still recommended (CIGRE [27]).

Return-stroke peak current — recent direct measurements. More recently direct current measurements on instrumented towers were made in Russia, South Africa, Canada, Germany, Brazil, Japan, Austria, and again in Switzerland (on a different tower). Important results from the Brazilian, Japanese, and Austrian studies are reviewed and compared with Berger's data below. Recent direct current measurements for rocket-triggered lightning in Florida are also considered.

Brazil (first strokes, n = 50; subsequent strokes, n = 78). Visacro et al. [28] presented a statistical analysis of parameters derived from lightning current measurements performed in 1985—1996 on the 60-m Morro do Cachimbo tower near Belo Horizonte, Brazil. The tower is located in the tropics (about 20° S) on the mountain (hill) top, 200 m above the surrounding terrain, and about 1,600 m above sea level.

The current measuring system included two Pearson coils, installed at the tower base, with a frequency bandwidth of 100 Hz to 10 MHz that were connected to two oscilloscopes recording with a sampling interval of 50 ns. One coil was used for measuring currents above 20 kA and the other below 20 kA. A calibrated spark gap was used to bypass the latter coil when the current attained 20 kA. Up to 16 current pulses per flash could be recorded, with the individual pulse record length being 400 ms. The trigger threshold was 800 A. The dead time between two consecutive triggers was less than 12 ms.

The current measuring system has been upgraded in 2008. Two new Pearson coils for measuring currents (of either polarity) up to 9 kA and up to 200 kA with bandwidths of 0.25 Hz to 4 MHz and 3 Hz to 1.5 MHz, respectively, were installed (again at the tower base). As of this writing, currents are recorded using a multiple-channel, 12-bit data acquisition system capable of sampling at up to 60 MHz (17-ns sampling interval). No spark gap is used. The trigger thresholds for the lower- and higher-current channels are 60 and 250 A, respectively. The record length is either 1 s with 30-ms pretrigger (33-ns sampling interval) or 0.5 s with 15-ms pretrigger (17-ns sampling interval). Thus, the entire flash current can be continuously recorded since 2008.

Before the 2008 upgrade, currents were measured for 31 first and 59 subsequent strokes in negative downward flashes, with the median peak currents being 45 kA (all values were higher than 20 kA) and 16 kA, respectively [28]. Histograms for the data acquired before the 2008 upgrade are shown in blue in Fig. 3, along with those for the data additionally obtained in 2008—2010 (shown in red). The latest (through 2017) median peak current values for first and subsequent strokes are 43 kA (n=50) and 17 kA (n=78), respectively (S. Visacro, personal communication, 2018). Clearly, these values are higher than their counterparts, 30 kA (n=101) and 12 kA (n = 135) [4]. Possible reasons for the discrepancy include: (1) a relatively small sample size in Brazil, (2) dependence of lightning parameters on geographical location (Brazil versus Switzerland), and (3) different positions of current sensors on the tower at the two locations (bottom of 60-m tower in Brazil vs. top of 70-m towers in Switzerland). For typical first strokes (longer current risetimes), the towers in question are expected to behave as electrically short objects, so that the position of current sensor should not influence measurements. However, for subsequent strokes (shorter current risetimes), the towers may exhibit a distributed-circuit behavior, in which case the peak current measured at the bottom of tower is expected to be more strongly influenced by the transient process in the tower (be higher) compared to the peak current at the top [12, 25]. Visacro and Silveira [29], using a hybrid electromagnetic (HEM) model and assuming a 100-m long upward connecting leader, showed that, for typical subsequent-stroke current rise times, peak currents at the top and bottom of the Morro do Cachimbo tower should be essentially the same. Additional measurements are needed, since the Brazilian sample size is still relatively small. Interestingly, the median peak current in Japan changed from 39 kA to 29 kA as the sample size increased from 35 to 120 (see below). Similarly, the median peak current in South Africa (from measurements on the research mast) changed from 41 kA to 33 kA as the sample size increased from 11 to 29.

Another peculiarity of Brazilian measurements is nonoccurrence of upward flashes with the typical charge transfer of the order of a few tens of coulombs: no upward flashes were observed in 2008—2009 and only relatively weak ones in 2010—2017. The latter (a total of 19 with 4 of them containing leader/return stroke sequences) exhibited charge transfers as low as 0.9 to 5.9 C, with a geometric mean of 3.3 C (S. Visacro, personal communication, 2018).

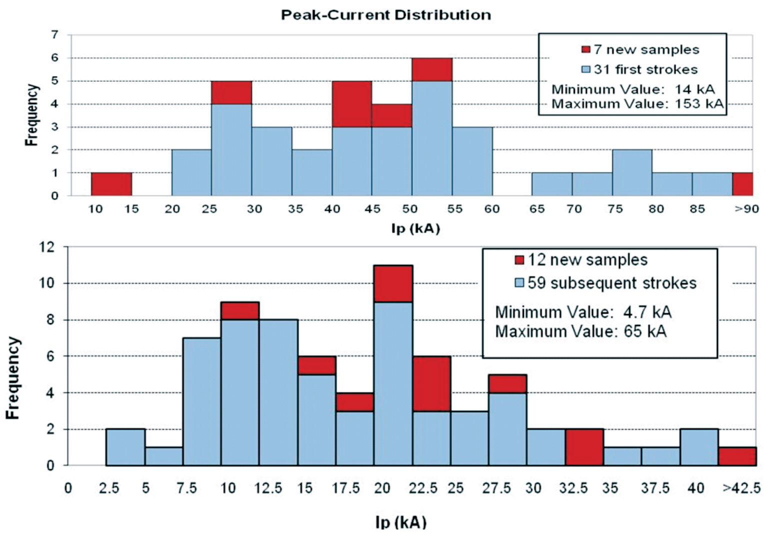

Fig. 3. Histograms of peak current for negative first (top panel; median value = 45 kA, n=38) and subsequent (bottom panel; median value = 18 kA, n=71) strokes from direct measurements in Brazil. Blue color corresponds to measurements in 1985–1998 and red color to measurements in 2009–2010 [70]

Japan (first strokes, n=120). Takami and Okabe [30] presented lightning return-stroke currents directly measured on 60 transmission-line towers (at the top) whose heights ranged from 40 to 140 m (90 m on average). Most of the towers were located on the mountain ridges, at altitudes ranging from 100 m to 1.5 km.

Currents were measured at 2.5-m strike rods installed on tower tops using Rogowski coils with RC external integrators connected, via short shielded cables, to 10-bit memory cards. Each memory card was connected, via a fiber optic cable, to the communication terminal at the base of the tower (data could be read out remotely). The measuring system had a frequency bandwidth of 10 Hz to 1 MHz and recorded currents on two amplitude scales: ±10 kA and ±300 kA. The record length was 3.2 ms, and the sampling interval was 100 ns. The trigger threshold was relatively high, 9 kA. The maximum number of waveforms that could be recorded was 40 (J. Takami, personal communication, 2012).

A total of 120 current waveforms for negative first strokes were obtained from 1994 to 2004. This is the largest sample size for negative first strokes as of today. The median peak current was 29 kA, which is similar to that reported by Berger et al. [4], although the trigger threshold in Japan (9 kA) was higher than in Switzerland. The largest measured peak current was 130 kA. Interestingly, initial data from this Japanese study (for 35 negative first strokes recorded in 1994–1997) yielded the median peak current of 39 kA [31].

Florida (subsequent strokes, n=165). Schoene et al. [32] presented a statistical analysis of the salient characteristics of current waveforms for return strokes in rocket-and-wire triggered lightning flashes. The flashes were triggered during a variety of experiments related to the interaction of lightning with power lines that were conducted from 1999 to 2004 at Camp Blanding, Florida.

Lightning channel-base currents were measured using non-inductive shunts mounted at the bottom of the rocket launcher. Different shunts were used at different launchers, but in all cases the upper frequency response of the shunt exceeded 5 MHz. Shunt output signals were transmitted via fiber optic links (frequency bandwidth from dc to 15 MHz) to different digitizing oscilloscopes. The latter recorded either continuously for 1 or 2 s (at a sampling rate of 1 MHz or 2 MHz) or in a few millisecond long segments (at a sampling rate between 10 MHz and 50 MHz). The data were appropriately low-pass filtered to avoid aliasing.

Histogram of peak currents for 165 return strokes is presented in Fig. 4. The lowest measured current peak was 2.8 kA, and the highest one was 42 kA. The return-stroke current was injected into either one of two test power lines (labeled "direct" in Fig. 4) or into the earth near a power line via a grounding system of the rocket launcher (labeled "nearby" in Fig. 4). The geometric mean return-stroke peak current was found to be 12 kA, which is consistent with those reported from other triggered lightning studies [33]. Further, this parameter was found not to be much influenced by either strike-object geometry or level of man-made grounding, as previously reported by Rakov et al. [34]. Specifically, the peak current was about the same for the cases of current injection into an overhead power line conductor (impedance initially "seen" by lightning at its attachment point of about 200Ω) and into a

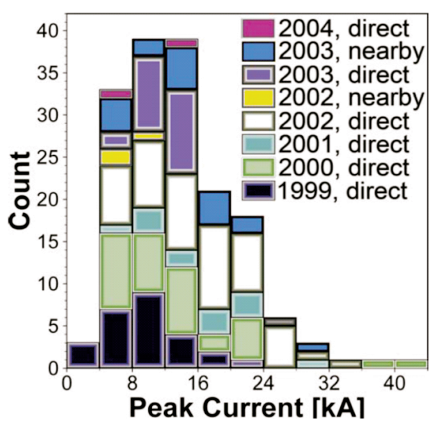

Fig. 4. Histogram of return-stroke peak currents for 165 strokes in rocket-and-wire triggered lightning flashes from Camp Blanding, Florida, 1999–2004 [32]

concentrated grounding system via a short down conductor. However, the means of the 10%–90% current risetimes were significantly different, as discussed above. Cooray and Rakov [35] theoretically showed that the peak current decrease is negligible as the ground conductivity decreases from infinity to 10^{-3} S/m and is about 20% lower (compared to the perfectly conducting ground case) for ground conductivity of 10^{-4} S/m. The effect of ground conductivity on the maximum rate-of-rise was much more significant (see above).

Note that triggered-lightning strokes are initiated by continuously moving dart leaders or by dart-stepped leaders and considered to be similar to subsequent strokes in natural lightning; there is no stepped leader/first return stroke sequence in classical triggered lightning.

Austria (subsequent strokes, n=1,124). Diendorfer et al. [36] analyzed parameters of 457 upward negative flashes initiated from the mountain-top 100-m Gaisberg Tower in 2000–2007. After adding the data acquired in 2008–2015, the sample size for upward negative flashes increased to 775 [37]. The total number of strokes after adding the 2008–2015 data became 1,124. It is worth noting that downward lightning strikes to the Gaisberg Tower are very rare, only 3 (less than 1%) of 341 flashes recorded in 2008–2015 were of downward type (G. Diendorfer, personal communication, 2018).

The overall current waveforms were measured at the base of the air terminal installed on the top of the tower with a current-viewing resistor (shunt) of 0.25 mΩ having a bandwidth of 0 Hz to 3.2 MHz. Fiber optic links (frequency bandwidth from dc to 15 MHz) were used for transmission of the shunt output signal to a digital recorder installed in the building next to the tower. Two separate channels of different sensitivity with current scales of ±2 kA and ±40 kA were used. The signals were recorded at a sampling rate of 20 MHz (50-ns sampling interval) by an 8-bit (presently 12-bit) digitizing board installed in a personal computer. The trigger threshold of the recording system was set to ±200 A. The record length was 800 ms with a pretrigger recording time of 15 ms. A digital low-pass filter with a cut-off frequency of 250 kHz and appropriate offset correction had been applied to the current records before the lightning peak currents were determined.

Upward flashes contain only strokes that are similar to subsequent strokes in natural downward flashes, that is, they do not contain first strokes initiated by downward stepped leaders. Many upward flashes (about two-thirds for the Gaisberg Tower [37]) contain no strokes at all, only the so-called initial-stage current with or without superimposed pulses. In 2000–2007, the median return-stroke peak current was reported to be 9.2 kA (n=615) and after adding the data acquired in 2008–2015 became 9.5 kA (n=1,124) (G. Diendorfer, personal communication, 2018). Both values are somewhat lower than for subsequent strokes in downward flashes and for rocket-triggered-lightning strokes. This could be due to the tall grounded object reducing the distance between the cloud charge source region and the strike point. Indeed, the lower-charge-density downward leaders that are not capable of making their way to flat ground or to a small strike object may be able to make connection to a tall tower. Note that in rocket-triggered lightning the triggering wire is destroyed during the initial stage and downward leaders have to propagate all the way to the relatively small rocket launcher. An additional factor in lowering return-stroke peak currents measured at Gaisberg Tower could be the lower height of cloud charge source region, since many measurements were obtained in cold (non-convective) season [37].

Direct lightning current measurements on instrumented towers should be continued. Currently, direct current measurements are performed, in alphabetical order, on instrumented towers in

Austria (Gaisberg Tower, 100 m),
Brazil (Morro do Cachimbo Tower, 60 m),
Canada (CN Tower, 553 m),
Germany (Peissenberg Tower, 160 m),
Japan (Tokyo Skytree, 634 m), and
Switzerland (Santis Tower, 124 m).

Current waveshape parameters. Lightning parameters, other than lightning peak current, derivable from direct current measurements include the maximum current derivative, average current rate of rise, current risetime, current duration, charge transfer, and action integral (specific energy). Similar to the peak current, the most reliable and complete information on the other parameters is based on the direct current measurements of K. Berger and coworkers in Switzerland. Berger et al. [4] summarized the lightning current parameters for 101 downward negative cloud-to-ground lightning flashes, the types that normally strike flat terrain and structures of moderate height. This summary, which is used to a large extent as a primary reference in the literature on both lightning protection and lightning research, is reproduced in Table 1. The table gives the percentages (95%, 50%, and 5%) of cases exceeding the tabulated values, based on the log-normal approximations to the respective statistical distributions. A similar summary for 26 positive flashes from the same study is given in Table 6. The action integral represents the energy that would be dissipated in a 1-Ω resistor if the lightning

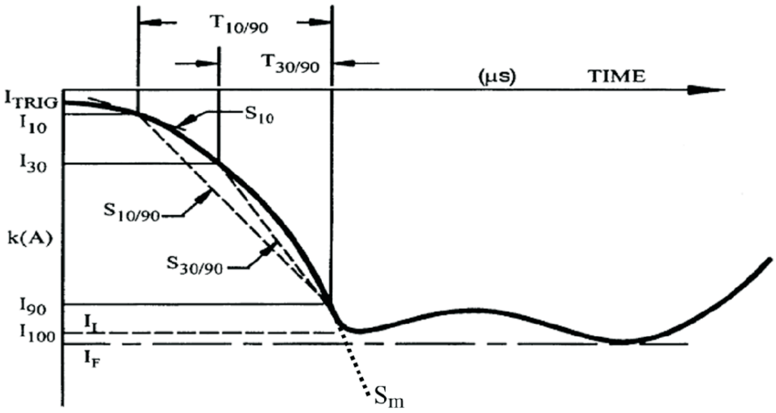

Fig. 5. Description of lightning current waveform parameters. The waveform corresponds to the typical negative first return stroke [3, 19]

Parameter (see above)	Description
I_{10}	10% intercept along the stroke current waveshape
I_{30}	30% intercept along the stroke current waveshape
I_{90}	90% intercept along the stroke current waveshape
$I_{100} = I_I$	Initial peak of current
I_F	Final (global) peak of current (same as peak current without an adjective)
$T_{10/90}$	Time between I_{10} and I_{90} intercepts on the wavefront
$T_{30/90}$	Time between I_{30} and I_{90} intercepts on the wavefront
S_{10}	Instantaneous rate-of-rise of current at I_{10}
$S_{10/90}$	Average steepness (through I_{10} and I_{90} intercepts)
$S_{30/90}$	Average steepness (through I_{30} and I_{90} intercepts)
S_m	Maximum rate-of-rise of current along wavefront, typically at I_{90}
$t_{d10/90}$	Equivalent linear wavefront duration derived from $I_F/S_{10/90}$
$t_{d30/90}$	Equivalent linear wavefront duration derived from $I_F/S_{30/90}$
t_m	Equivalent linear waveform duration derived from I_F/S_m

current were to flow through it. All the parameters presented in Table 1 are estimated from current oscillograms with the shortest measurable time being 0.5 мs [38]. Anderson and Eriksson [18] digitized the return-stroke current oscillograms of Berger et al. [4] and determined additional wavefront parameters. Most of the current waveform parameters are illustrated in Fig. 5. Parameters of lognormal distributions of current waveform parameters (for both first and subsequent strokes) are summarized in Table 2 [3, 19].

Note from Table 1 that the median return-stroke current peak for first strokes is two to three times higher than that for subsequent strokes. Also, negative first strokes transfer about a factor of 4 larger total charge than do negative subsequent strokes. However, subsequent return strokes are characterized by three to four times higher maximum steepness (the current maximum rate of rise).

The median 10%–90% risetime estimated for subsequent strokes by Anderson and Eriksson [18] from Berger et al.'s [4] oscillograms is 0.6 мs, comparable to the median values ranging from 0.3 to 0.6 мs for triggered-lightning strokes [39, 40]. The median 10%–90% current rate of rise reported for natural subsequent strokes by Anderson and Eriksson [18] is 15 kA/мs, almost three times lower than the corresponding value of 44 kA/мs in data of Leteinturier et al. [39] and more than twice lower than the value of 34 kA/мs found by Fisher et al. [40]. The largest value of maximum rate of rise of 411 kA/мs (see Fig. 6) was measured by Leteinturier et al. [39] for a triggered lightning stroke terminating on a launcher grounded to salt water. The corresponding directly measured current was greater than 60 kA, the largest value reported for summer triggered lightning. The mean value of current derivative peak [39] is 110 kA/мs. The higher observed values of current rate of rise for triggered-lightning return strokes than for natural-lightning return strokes are likely to be due to the use of better instrumentation (digital oscilloscopes with better upper frequency response), which implies that the current rate-of-rise parameters reported by Anderson and Eriksson [18] are underestimates. Triggered-lightning data for current rates of rise (see Fig. 6) can be applied to subsequent strokes in natural lightning.

Schoene et al. [32], who presented a statistical analysis of the salient characteristics of current waveforms for 206 return strokes in 46 rocket-triggered-lightning flashes, found

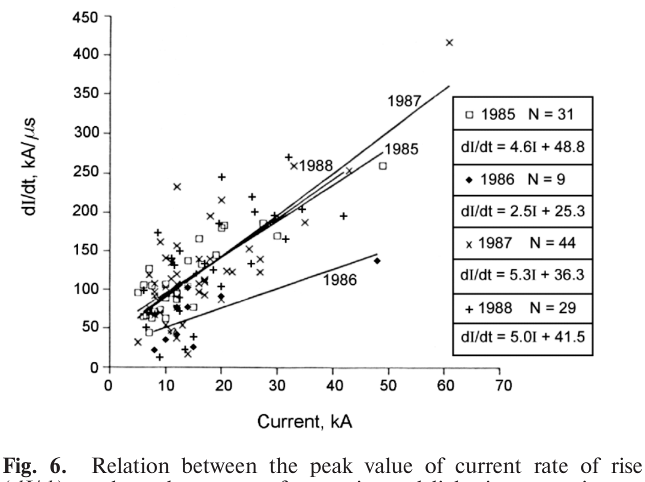

Fig. 6. Relation between the peak value of current rate of rise (*dI*/*dt*) and peak current from triggered-lightning experiments conducted at the NASA Kennedy Space Center, Florida, in 1985, 1987, and 1988 and in France in 1986. The regression line for each year is shown, and the sample size and the regression equation are given [39]

that the means of the 10%–90% current risetimes for strikes to the power line (geometric mean 1.2 мs) and for strikes to the ground nearby (geometric mean 0.4 мs) were significantly different. This indicates that the electrical properties of the strike object affect the risetime. This effect is likely related to the impedance seen by lightning at the strike point and/or to reflections at impedance discontinuities within the strike object, larger effective impedances apparently resulting in larger risetimes. A dependence of the return-stroke current half-peak width on the electrical properties of the strike object was not observed. Cooray and Rakov [35] theoretically showed that the peak value of current rate-of-rise is influenced by ground conductivity: it decreases by about 40% as the ground conductivity decreases from infinity to 10^{-3} S/m and by 83% when the conductivity becomes 10^{-4} S/m. For all their data combined, Schoene et al. [32] reported the geometric mean values of 10%–90% current risetime and current half-peak width to be 0.9 and 1.9 мs, respectively.

Correlations between the parameters. Correlation coefficients for the current waveshape parameters defined in Fig. 5 are summarized in Table 4. Note that there is only one current peak for subsequent strokes, which is labeled I in Table 4.

Anderson and Eriksson [18] gave the following relationships between Sm and S30/90 and peak current I (I in kA and S in kA/мs) for natural lightning:

First strokes:

$$S_m = 3.9 I^{0.55}; \quad S_{30/90} = 3.2 I^{0.25} \qquad (7)$$

Subsequent strokes:

$$S_m = 3.8 I^{0.93}; \; S_{30/90} = 6.9 I^{4.2}. \qquad (8)$$

In (2.7), $I = I_I$. As noted above, the current rate-of-rise parameters estimated by Anderson and Eriksson [18] from Berger et al.'s (1975) oscillograms are likely to be underestimated due to limitations of the instrumentation used by Berger et al.

Positive correlation between the peak value of current rate-of-rise and peak current for triggered lightning is illustrated in Fig. 6. Fisher et al. [40], also for triggered lightning, found a relatively strong positive correlation between the 10%–90% average steepness ($S_{10/90}$) and current peak (correlation coefficient = 0.71) and between the 30%–90% average steepness ($S_{30/90}$) and current peak (correlation coefficient = 0.74). Essentially no linear correlation was found between the current peak and 10%–90% risetime (this was also reported for triggered lightning in China [41]) and between the current peak and current half-peak width. Similarly, but for first strokes in natural lightning, Takami and Okabe [30] observed strong positive correlation between the current steepness characteristics and peak current and weak correlation between the peak current and front duration. Opposite trends for first strokes were reported by Visacro et al. [28].

According to Berger et al. [4], for first and subsequent negative strokes, correlation coefficients between the current peak and stroke duration (the time interval between the 2-kA point on the front and the point on the tail where the current has fallen to 50% of its peak value) are 0.56 and 0.25, respectively. Both values should be considered low, since even in the former case the determination coefficient (the square of the correlation coefficient) is as low as 0.31, which means that only 31% of the variation of one of the parameters is due to variation in the other one, while 69% is due to variation in other (unknown) factors.

All published experimental data regarding the relation between the return-stroke peak current I and charge transfer Q in natural lightning are derived from the data of *K*. Berger and co-workers [4, 5, 38], for lightning striking two towers in Switzerland and two towers in Italy, and have been analyzed by them and by Cooray et al. [42]. According to [42], for natural negative first strokes, there is a linear regression, Q=0.061I (R_2 =0.88, where R_2 is the determination coefficient), for charge transfer to 100 мs, and for natural subsequent strokes, Q=0.028I (R_2 not stated), for charge transfer to 50 мs. In the above equations, charge transfer Q is in coulombs and peak current I is in kiloamperes. Additionally, Schoene et al. [32] have shown that for triggered-lightning strokes (which, as noted above, are similar to natural-lightning subsequent strokes) the scatter-plot of return-stroke peak current versus charge transfer to 1 ms is surprisingly similar to the 1-ms natural-lightning first stroke data of Berger

Table 4

Correlation coefficients between current waveshape parameters defined in Fig. 5 [18]

	$T_{10/90}$	$T_{30/90}$	S_{10}	$S_{10/90}$	$S_{30/90}$	S_m
I_I (first strokes)	0.40	0.47	(0.12)	0.30	(0.19)	0.43
I_F (first strokes)	0.33	0.45	(0.06)	(0.20)	(0.17)	0.38
I_F (subsequent strokes)	(0.15)	(0.00)	(0.05)	0.31	0.23	0.56

Note: Values in the parentheses are not statistically significant at the 5% level.

[5]. The equation for 143 triggered-lightning strokes, as given by Schoene et al. [32], is $I = 12.3Q^{0.54}$ ($R_2 = 0.76$) and the equation for Berger's 89 natural-lightning first strokes is $I = 10.6Q^{0.7}$ ($R_2 = 0.59$). Qie et al. [43] reported that $I = 18.5Q^{0.65^2}$ for 10 triggered-lightning strokes in China.

Schoene et al. [44] examined data on 117 return strokes in 31 rocket-and-wire-triggered lightning flashes acquired during experiments conducted from 1999 through 2004 at Camp Blanding, Florida, in order to relate the peak currents of the lightning return strokes to the corresponding charges transferred during various time intervals within 1 ms after return-stroke initiation. They found that the determination coefficient (R_2) for lightning return-stroke peak current versus the corresponding charge transfer decreases with increasing the duration of the charge transfer starting from return-stroke onset. For example, $R_2 = 0.91$ for a charge transfer duration of 50 мs after return-stroke onset, $R_2 = 0.83$ for a charge transfer duration of 400 мs, and $R_2 = 0.77$ for a charge transfer duration of 1 ms. Their results support the view that (1) the charge deposited on the lower portion of the leader channel determines the current peak and that (2) the charge transferred at later times is increasingly unrelated to both the current peak and the charge deposited on the lower channel section. Additionally, they found that the relation between the return-stroke peak current and charge transfer to 50 мs for triggered lightning in Florida is essentially the same as that reported by Cooray et al. [42] for subsequent strokes in natural lightning in Switzerland, further confirming the view that triggered-lightning strokes are very similar to subsequent strokes in natural lightning.

Median (50%) and severe (1%) values – measurements and extrapolation from measurements.

The probability distribution functions of some lightning parameters have been shown from measured data to be approximately lognormal [45]. For an assumed lognormal distribution, knowledge of the median (50%) and severe (1%) values is sufficient to define the entire distribution. Six important lightning parameters that have been demonstrated to follow the lognormal distribution to a reasonable degree of approximation are the negative first and subsequent return-stroke peak currents [4], the charge transfer to 1 ms for negative first and subsequent return strokes [4], positive first return-stroke peak current [4], and the time interval between negative strokes [46]. Cianos and Pierce [47], in a table reproduced in [45], list 10 lightning parameters that they suggest can be described satisfactorily by a log-normal distribution: flash duration, interstroke interval, return-stroke peak current, flash charge transfer, time to return-stroke current peak, rate of rise of return-stroke current, time to return-stroke current half value, duration of continuing current, continuing current amplitude, and continuing current charge. Nevertheless, some of these parameters are only crudely approximated by the lognormal distribution, and those are certainly not described satisfactorily enough by that distribution to allow adequate prediction of extreme values.

Table 5 contains recommendations [22] for median and severe parameters characteristic of cloud-to-ground lightning from their review of the literature. Negative first and subsequent strokes, positive first strokes, negative and positive continuing currents, and negative and positive flashes are treated separately. All parameters listed in Table 5 represent lightning between the cloud and ground as observed near the ground, where the return-stroke currents exhibit their highest peak values. The characteristics of intracloud lightning, intercloud lightning, and cloud-to-ground lightning far above the ground are much less well studied than cloud-to-ground flashes near the ground, but are generally thought to be less severe.

Table 5

Median (50%) and severe (1%) lightning parameters recommended, based on measurements and extrapolation from measurements, by Gamerota et al. [22]

	Measured Values	
	50%	1%
RETURN STROKE PARAMETERS		
NEGATIVE FIRST STROKES		
(a) Peak current (kA)	30	150
(b) Time from zero to current peak (μs)	5	30
(c) Maximum rate of current rise (kA/μs)	100	400
(d) Time to decay from peak to half-peak value (μs)	70-80	300
(e) Charge transfer (C)	5	40
POSITIVE FIRST STROKES		
(a) Peak current (kA)	35	500
(b) Time to current peak (μs)	10–20	150
(c) Maximum rate of current rise (kA/μs)	100	400
(d) Time to decay to half-peak value (μs)	See Section E	
NEGATIVE SUBSEQUENT STROKES		
(a) Peak current (kA)	10–15	50
(b) Time to current peak (10-90%) (μs)	0.3v0.6	9
(c) Maximum rate of current rise (kA/μs)	100	400
(d)10 to 90% rate of current rise (kA/μs)	30–50	150
(e) Time to decay from peak to half-peak value (μs)	30–40	250
NEGATIVE CONTINUING CURRENT LONGER THAN 40 ms		

(a) Amplitude (A)	100–200	1000
(b) Duration (ms)	100–200	600
(c) Charge transfer (C)	10v20	200
POSITIVE CONTINUING CURRENT		
(a) Amplitude (kA)	1–5	10–30
(b) Duration (ms)	85	1000
(c) Charge transfer (C)	80	700
NEGATIVE FLASH PARAMETERS		
(a) Number of strokes	3–5	25
(b) Interstroke interval (ms)	60	600
(c) Duration (ms)	200	1000
(d) Charge transfer (C)	20	200
(e) Action integral (A^2·s)	8×10^4	3×10^6
POSITIVE FLASH PARAMETERS		
(a) Number of strokes	1	3*
(b) Duration (ms)	85	1000
(c) Charge transfer (C)	80	700
(d) Action integral (A^2·s)	7×105	6×10^7

* Generally separate channels to ground, so for direct current injection there is effectively only one stroke.

There is no consensus in the literature as to what statistical value constitutes a severe case. Many investigators have adopted the 5% values given in [4]. In contrast, 1% was chosen by the sponsor (Lawrence Livermore National Laboratory) of the study of Gamerota et al. [22], for its specific lightning current simulation. Perhaps, “extreme” is a better description of the 1% value than “severe.” Additional information on lightning parameters for various engineering applications is found in the CIGRE [27].

Comments on the choice of the parameters listed in Table 5 are given in Sections A-E below.

A. Return-Stroke Peak Current

The peak current data in Table 5 for positive first strokes (rarely are there positive subsequent strokes) and for first and subsequent negative strokes are taken from [4] and referenced therein. The median (50%) values are relatively well established, and the 1% values are chosen from fitting lognormal distributions to the measured data, although some experimental data near the 1% values of the data-fitting curve are available. There have been direct tower measurements of positive peak currents in excess of 300 kA (Goto and Narita [48]) for lightning in Japanese winter storms. These probably the highest directly measured lightning currents may be from upward-initiated lightning. Additional information on lightning parameters for upward-initiated lightning, including positive and bipolar discharges, is found in the CIGRE [27] (Chapters 7 and 8).

B. Maximum Rate of Return-Stroke Current Rise and Other Rise-to-Peak Characteristics

In tower measurements, such as those presented in [4], this parameter is likely underestimated because of measurement system limitations and the potential influence of the strike object. Schoene et al. [32] have shown that the strike object can affect rise-time parameters and that the highest rate of rise is for a relatively small, well-grounded object. The value of 100 kA/мs, adapted as the 50% maximum rate of rise for both positive strokes and for negative first and subsequent strokes, has been measured on well-grounded strike objects for negative strokes in triggered lightning, those strokes being similar, if not identical, to subsequent strokes in natural negative lightning [32, 40, 49]. The inference that the same 50% maximum rate of rise of current characterizes negative and positive first strokes, as is measured for negative subsequent strokes, follows from the observation that the maximum rate of change of the remote electric field for the three types of return strokes over saltwater (a relatively good conductor) is essentially the same [50–52]. The 1% maximum rate of rise of 400 kA/мs listed in Table 5 is near the largest value measured for a triggered-lightning return stroke, 411 kA/мs [39], and the largest value measured for lightning interaction with an aircraft in flight, 380 kA/мs [53].

Return-stroke current rise-time characteristics such as time to peak and 10 to 90% rise-time are determined from measured triggered-lightning current waveforms and tower current waveforms (primarily [4]), with comparison of the measured current characteristics to electric field and electric field derivative measurements for lightning over salt water being used to infer current characteristics not adequately measured directly [50, 51, 54].

C. Flash Charge Transfer

The charge transfer values in Table 5 are taken primarily from the experimental data of [4] and lognormal distribution fits to those data. For a positive flash, 700 C is inferred from the lognormal distribution fit as the 1% value, whereas the largest measured value in [4] is 400 C at the 4% level. There have been a number of direct tower measurements of both positive and negative charge transfer between 300 and 1000 C for lightning in Japanese winter storms, with one positive charge transfer reported to exceed 3000 C [48, 55]. These charge transfers may not be from cloud-to-ground flashes containing return strokes and initiated in the cloud, but may rather be from upward-initiated lightning. Nevertheless, extreme current waveform statistics should include those salient characteristics of the rarer upward-initiated lightning. Positive charge transfers inferred from remote magnetic fields in [56] and [57] are up to roughly 2000 to 3000 C. The International Standard IEC 62305-1, 3 (2006) lists 300 C as a "severe" charge transfer for all types of flashes.

D. Flash Action Integral

The values for action integral in Table 5 are taken from the data of [4], references to their previous work given in that paper, and lognormal distribution extrapolations of those measurements. It is often difficult to decide when a return-stroke current ends and a continuing current begins, particularly for positive flashes, which almost always exhibit large, long-duration slowly-varying currents following an initial current peak. If such long-duration currents are attributed to continuing current, then it is the continuing current that makes the major contribution to the flash action integral value (and to the charge transferred). It follows that the "time to decay to half-peak value" is not well defined for positive first strokes and hence not specified in Table 5, and the current amplitude assigned to the positive continuing current is also to some extent arbitrary. The International Standard IEC 62305-1, 3 (2006) gives 107 A2·s for a "severe" first-stroke action integral, whereas we give 6×107 A^2·s in Table 5 for the 1% value for a positive flash, consistent with the data of [4].

E. Continuing Current, Negative and Positive

Duration data for negative continuing current longer than 4 ms taken from the high-speed video measurements of [58] indicate that 15 ms is at the 50% level and 550 ms is at the 1% level. Kitagawa et al. [59] report that nearly half of about 200 negative ground flashes they studied exhibited a continuing current interval exceeding 40 ms and one quarter of all interstroke intervals contained such currents. Kitagawa et al. [59] term continuing currents exceeding 40 ms as "long continuing current." In Table 5, we present values only for long continuing currents. Duration data from electric field records and video observations reported in [60] indicate that the median negative long continuing current duration is near 200 ms. Their median duration for four positive long continuing currents is near 150 ms and their maximum duration is near 200 ms. Berger et al. [4] give 85 ms for the median duration of a positive flash and 500 ms for the 5% value, with both durations being predominantly the positive continuing current duration. The median and severe amplitudes of positive continuing current are not well studied. Some evidence for the values given in Table 5 is discussed in [61] (see p. 222).

Extremely high and extremely low current values — theoretical estimates

Cooray and Rakov [6] theoretically estimated the upper and lower limits for peak currents of first strokes in negative flashes. In doing so, they employed an electrostatic model of descending leader in a plane-plane gap, the upper and lower planes representing the cloud and ground, respectively ([42], Fig. 2). The leader channel was simulated by a straight vertical conductor. With this model, one can find (using the charge simulation method) the uniform electric field intensity between the planes corresponding to a given total charge on the leader channel of given length and the average line charge density on the channel section of given length. Cooray and Rakov [6] found the total leader charge using power-law (for estimating maximum current) or linear (for estimating minimum current) empirical relationship between the return-stroke peak current and corresponding charge transferred to ground during the first 100 мs (see their Fig. 1 and Eqs. 1 and 5). It was assumed that the charge transfer to ground after the first 100 мs was associated with cloud charges, as opposed to those deposited on the leader channel and that the charge transfer to ground includes two about equal components: (a) charge drained from the leader channel and (b) charge associated with the induction effect of remaining negative charges in the cloud. (This can be visualized as the total positive charge injected into the channel from the ground being the sum of the positive charge neutralizing negative leader charges and additional positive charge induced on the channel by remaining negative charges in the cloud.)

Upper limit. Cooray and Rakov [6] used their electrostatic model to convert their empirical current/charge (I/Q) relationship to current/ambient electric field (I/E) relationship, which is given by $I = kE0.967$, where I is in kA, E is in kV/m, and k is equal to 2.44, 3.03, and 3.61 for channel lengths of 4, 5, and 6 km, respectively. Clearly, I is nearly proportional to E, and substitution of the upper bound for E into the above equation yields the upper bound for I (different for different values of channel length). Cooray and Rakov [6] assumed the maximum value of E to be 150 kV/m, based on the measured electric field height profiles obtained using instrumented balloons. It is worth noting that such fields are characteristic of cloud altitudes; fields near ground level are considerably lower (of the order of 10 kV/m) due to the effect of corona space charge. The maximum thunderstorm electric field at ground level, 130 kV/m, was measured over the calm water surface, where the effect of corona was minimal [62]. Thus, the case of uniform ambient (large-scale) electric field intensity equal to 150 kV/m represents the "worst" situation and corresponds to the upper bound for lightning peak current. Using the above equation, we obtain maximum currents equal to 310, 385, and 459 kA for channel lengths of 4, 5, and 6 km, respectively. Cooray and

Rakov [6] concluded that the absolute maximum negative return-stroke peak current is about 300 kA (corresponding to shorter channel lengths) for temperate regions and 450–500 kA (corresponding to longer channel lengths) in the tropics.

Lower limit. Intuitively, there should be a minimum charge that allows a descending leader to propagate all the way to the ground. Leaders carrying charges below that threshold would stop propagating in midair and fall in the category of attempted leaders. Since the leader charge is correlated with the return-stroke peak current, there should be also a threshold (lower bound) for the peak current. Cooray and Rakov [6] used their electrostatic model and the minimum line charge density, 50 μC/m, observed for negative long-spark leaders that barely managed to reach the grounded plane, to estimate the minimum return-stroke peak current. In doing so, they used the same experimental data relating the return-stroke peak current to the corresponding charge transferred to ground during the first 100 мs (see Fig. 1 of Cooray and Rakov [6]), but approximated that relationship by a linear equation (a power-law equation was used in estimating the upper bound for peak current). From modeling, it was found that the line charge density (averaged over the bottom 100 m of the leader channel) of 50 μC/m corresponds to a return-stroke peak current of 2 kA. It is important to note that this is a theoretical limit and that, as of today, there are no direct measurements of first return stroke peak currents lower than 5 kA.

Additional information on extreme values of various lightning parameters for different types of lightning is found in [63] and at https://public.tableau.com/profile/epfl.emc.lab#!/vizhome/Book_v2_1/Lightningrecords.

Positive lightning. In spite of recent progress, our knowledge of positive lightning remains considerably poorer than that of negative lightning. Many questions regarding the genesis of positive lightning and its properties cannot be answered without further research. Although positive lightning discharges account for 10% or less of global cloud-to-ground lightning activity, there are five situations that appear to be conducive to the more frequent occurrence of positive lightning. These situations include (1) the dissipating stage of an individual thunderstorm, (2) winter thunderstorms, (3) trailing stratiform regions of mesoscale convective systems, (4) some severe storms, and (5) thunderclouds formed over forest fires or contaminated by smoke.

The highest directly measured lightning currents (near 300 kA; see Fig. 7) and the largest charge transfers (hundreds of coulombs or more) are associated with positive lightning. Two types of impulsive positive current waveforms have been observed and included in the statistics presented by Berger et al. [4]. One type is characterized by risetimes of the order of 10 мs, comparable to those for first strokes in negative lightning, and the other type by considerably longer risetimes, up to hundreds of microseconds. The latter waveforms are apparently associated with very long, 1 to 2 km, upward negative connecting leaders. According to [4], the 50% value of total charge transfer for the 26 positives events is 80 C. The 95% value of total charge transfer in Berger et al.'s data is as high as 20 C, and the 50% and 95% values of impulsive (excluding continuing current) charge transfer for 25 of the 26 events are 16 and 2.0 C, respectively. Out of 30 positive flashes observed at the Santis tower, 5 were interpreted by Romero et al [64] as downward flashes with very long upward connecting leaders, similar to some of the 26 positive flashes [4]. For those 5 Santis tower events, the 50% values of peak current and impulse charge transfer were 32 kA and 13 C, respectively, both being close to their counterparts (35 kA and 16 C) in Berger et al.'s data. For all 30 positive flashes observed at the Santis tower, the minimum, median (50%), and maximum charge transfer values were 2.7, 169, and 913 C, respectively [64].

Brook et al. [65], from their observations in winter in Japan, inferred continuing currents in positive flashes in excess of 10 kA for periods up to 10 ms, implying charge transfers of the order of 100 C. Note that the Brook et al.'s events are usually interpreted as downward lightning (see, for example, Fig. 3.7 of Rakov and Uman [61]).

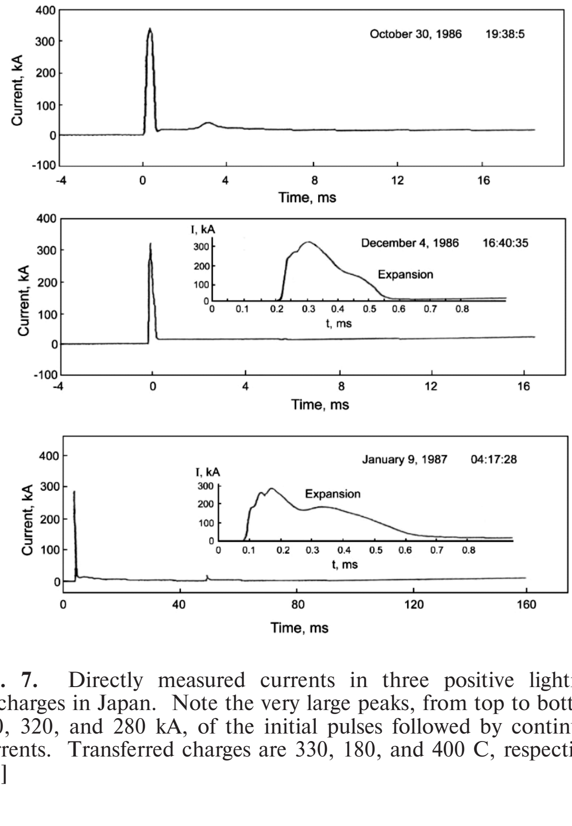

Fig. 7. Directly measured currents in three positive lightning discharges in Japan. Note the very large peaks, from top to bottom, 340, 320, and 280 kA, of the initial pulses followed by continuing currents. Transferred charges are 330, 180, and 400 C, respectively [48]

Table 6

Lightning current parameters for positive flashes [4]

Parameters	Units	Sample Size	Percent Exceeding Tabulated Value			5% Value for Negative First Strokes (for comparison)
			95%	50%	5%	
Peak current (minimum 2 kA)	kA	26	4.6	35	250	80
Charge (total charge)	C	26	20	80	350	24
Impulse charge (excluding continuing current)	C	25	2.0	16	150	20
Front Duration (2 kA to peak)	μs	19	3.5	22	200	18
Maximum *di/dt*	kA/μs	21	0.2	2.4	32	32
Stroke Duration (2 kA to half peak value on the tail)	μs	16	25	230	2000	200
Action integral ($\int i^2 dt$)	A^2s	26	2.5×10^5	6.5×10^5	1.5×10^7	5.5×10^5
Flash Duration	ms	24	14	85	500	–

It is still recommended to use the peak current distribution based on the 26 events recorded by K. Berger (see Fig. 1 and Table 6), even though some of those 26 events are likely to be not of “classical” return-stroke type. However, caution is to be exercised, particularly for the waveshape parameters listed in Table 6, for which sample sizes are smaller than for peak currents. Clearly, additional measurements for positive lightning return strokes are needed to establish reliable distributions of peak current and other parameters for this type of lightning.

Positive flashes are usually composed of a single stroke, although up to four strokes per flash were observed. Positive return strokes often appear to be preceded by significant in-cloud discharge activity and tend to be followed by significant continuing currents. Additional information on positive lightning can be found in CIGRE [27] (Ch. 7).

Upward lightning. Tall objects (higher than 100 m or so) located on flat terrain and objects of moderate height (some tens of meters) located on mountain tops experience primarily upward lightning discharges that are initiated by upward-propagating leaders. Upward (object-initiated) lightning discharges always involve an initial stage that may or may not be followed by downward-leader/upward-return-stroke sequences. The percentage of upward flashes with return strokes varies from 20 to 50%. The initial-stage steady current typically has a magnitude of some hundreds of amperes and typical charge transfers of 30–40 C, and often exhibits superimposed pulses whose peaks range from tens of amperes to several kiloamperes (occasionally a few tens of kiloamperes).

Object-initiated lightning events may occur relatively independent from downward lightning during non-convective season and it has been observed that frequently several flashes were initiated from a tall object within a period of some hours. Diendorfer et al. [66] reported on 20 negative flashes to the Gaisberg Tower during one night in February 2005 (winter season) transferring a total charge of more than 1,800 C to ground. The maximum transferred charge measured in a single upward negative flash to the Gaisberg Tower was 405 C and 1.5% (10/625) of the flashes transferred charges exceeding 300 C, and all those events with large amounts of transferred charge occurred during cold season [67].

Upward lightning discharges can be negative (initiated by an upward positive leader), positive (initiated by an upward negative leader), or bipolar (usually initiated by an upward positive leader). The probability of occurrence of bipolar lightning is about the same as for positive lightning. Median charge transfers for upward positive flashes are comparable (except for that for the Sдntis Tower flashes) to their counterparts for the initial stage of upward negative flashes, while upward positive flashes have shorter durations. This implies a higher average current for upward positive flashes. Also, median action integrals for upward positive flashes are considerably larger than for the initial stage of upward negative flashes.

Additional information on upward lightning can be found in CIGRE [27] (Ch. 8).

Geographical and seasonal variations in lightning parameters. From the information available in the literature at the present time, there is no evidence of a dependence of negative CG lightning parameters on geographical location, except maybe for current intensity (first and subsequent stroke peak currents), for which relatively insignificant (less than 50%), from the engineering point of view, variations may exist. It is important to note, however, that it cannot be ruled out that the observed differences in current measurements are due to reasons other than «geographical location», with limited sample size for some observations being of particular concern. Similarly, no reliable information on seasonal dependence is available. In summary, at the present time, the available information is not sufficient to confirm or refute a hypothesis on dependence of negative CG lightning parameters on geographical location or season. Clearly, exceptions could exist, such as the large, long duration current waveforms observed by Miyake et al. [55] in winter in the coastal area of the Sea of Japan. Further studies are necessary, however, to clarify if the observed exceptions represent actual variations in flash characteristics with the geographical location or represent extreme values of a common distribution.

Additional information on geographical and seasonal variations in lightning parameters can be found in CIGRE [27] (Ch. 9).

On lognormality of lightning peak current distributions. It is widely believed that the statistical distributions of lightning peak currents are nearly lognormal. Slyunyaev et al. [68] tested this hypothesis using the existing data on peak currents and found a theoretical explanation for the observed distributions.

The existing observations (including direct measurements and NLDN-data-based estimates for natural lightning, as well as direct measurements for triggered lightning) indicate that lognormal distributions visually look like good approximations of

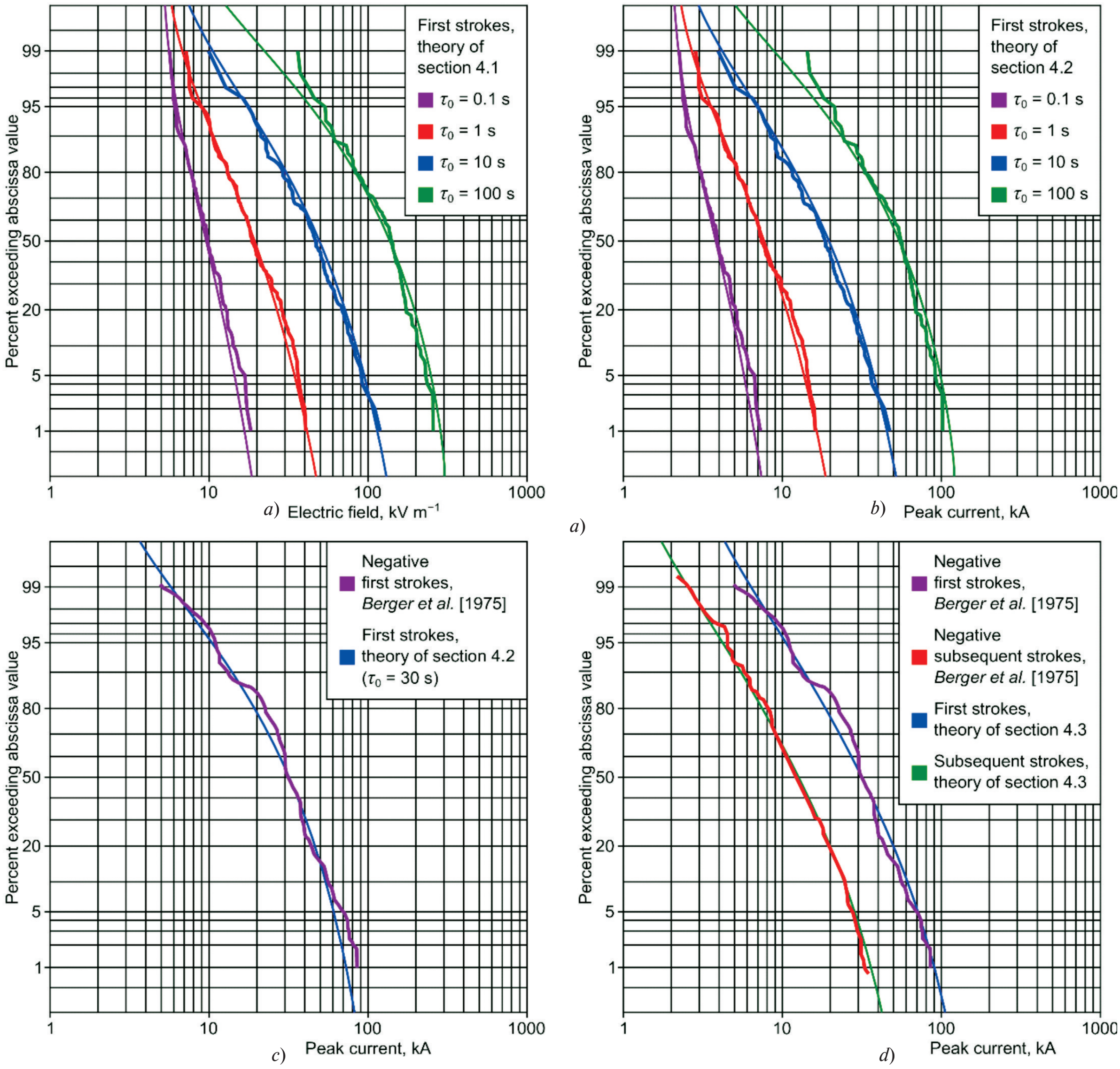

Fig. 8. (*a*) Theoretical cumulative distribution functions of the large-scale electric field immediately before the flash calculated by for $E_0 = 5$ kV/m, $E_1 = 300$ kV/m, and different values of τ_0. Also shown are empirical distribution functions obtained from direct Monte Carlo simulation of the same problem. (*b*) The cumulative distribution functions of the peak current corresponding, via equation (13) of Slyunyaev et al. [68] with $A = 0.4$ (A·m)/V [A·(V/m)], to the large-scale field distributions shown in panel (*a*). (*c*) Comparison of distribution of the peak current in negative first strokes based on the Monte San Salvatore data [4] and that derived from the theoretical model of section 4.2 (with $E_0 = 5$ kV/m, $E_1 = 300$ kV/m, $A = 0.4$ (A·m)/V, and $\tau_0 = 30$ s). (*d*) Comparison of distributions of the peak current in negative first and subsequent strokes based on the Monte San Salvatore data [4] and those derived from the theoretical model of section 4.3 of Slyunyaev et al. [68] (with $E_0 = 10$ kV/m, $E_1 = 300$ kV/m, $BS_0 = 0.4$ (A·m)/V, $\tau_0 = 30$ s, and structure factors S_1 and S_2 distributed uniformly in the intervals $[0.5S_0, 1.5S_0]$ and $[0.2S_0, 0.6S_0]$, respectively)

the observed statistics of peak currents. However, the statistical analysis shows that of all these cases, the lognormal law adequately represents the data only for negative subsequent strokes and positive first (and only) strokes [4] (although in the latter case the sample seems to be too small to make reliable conclusions) and for rocket-triggered lightning strokes studied by Schoene et al. [32]. At the same time, in regard to the results of Berger et al. [4] for negative first strokes, the hypothesis of lognormality is rejected at any reasonable significance level, and none of the NLDN-data-based distributions reported by Nag et al. [69] is strictly lognormal either. The primary reason for rejection of lognormality hypothesis is probably the "inhomogeneity" of the samples.

In order to explain lognormality of negative lightning peak current distributions, Slyunyaev et al. [68] developed a stochastic model of lightning initiation. Assuming linear growth of the large-scale electric field between flashes and the dependence of the discharge probability per unit time on this electric field, they found that the distribution of the magnitude of large-scale electric field immediately before the lightning flash is close to lognormal in a certain range, which leads to a peak current distribution of the same type (see Figs. 8*a* and *b*).

The distribution of the peak current in first or subsequent strokes was expressed in terms of the distributions of the magnitude of pre-first-stroke large-scale electric field and the corresponding structure factor, the coefficient relating the large-scale electric field before the flash and the potential of the leader tip assumed to be linearly related to the peak current.

The peak current distributions based on the developed model (see Figs. 8c and d) agree with the results of observations at least not less well than lognormal fittings do. In particular, the simulated distributions agree well with the data for negative subsequent strokes [4] and for rocket-triggered lightning strokes [32]. The agreement for negative first strokes [4] is poor (as it was for the lognormal approximation), which is apparently due to the fact that the distribution that they reported (the corresponding probability density function, to be exact) is bimodal and cannot be well approximated by relatively simple functions; one of the possible reasons for this observed bimodality is the relatively small size (a total of 101 events) or "inhomogeneity" of the sample. Histograms of peak currents corresponding to cumulative peak current distributions [4] for negative first and subsequent strokes are shown in Fig. 9 *a,b*. The corresponding cumulative peak current distributions are shown in Fig. 1

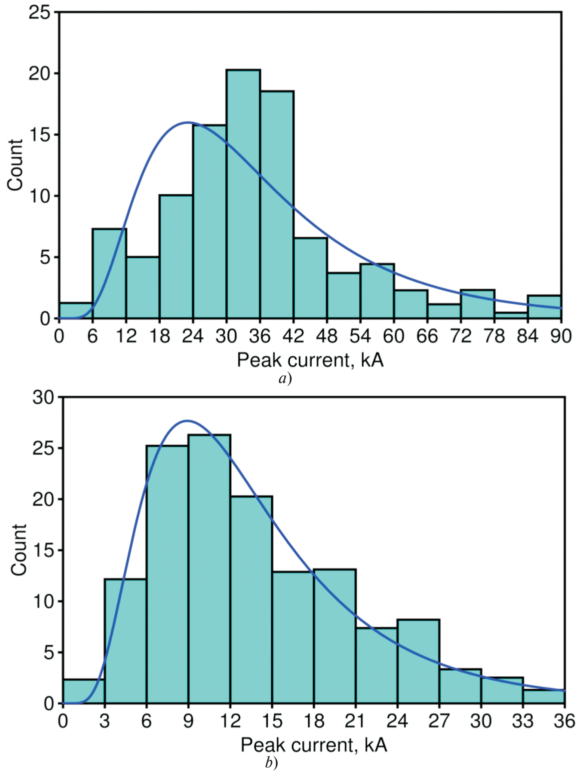

Fig. 9. Histograms of peak currents corresponding to cumulative distributions [4] for: *a*) negative first ($n=101$) and *b*) negative subsequent ($n=135$) strokes

It is quite possible that the distributions of peak currents in lightning flashes are not lognormal in their nature and are close to lognormal only in a certain range of values, as is the case with the model distributions [68].

Summary. 1) CIGRE [27] recommends the use of directly measured currents, as opposed to currents inferred from measured electric or magnetic fields based on empirical formulas or models.

2) To date, the maximum directly measured peak current for positive lightning is about 300 kA, and for negative lightning it is between 150 and 200 kA.

3)According to Gamerota et al. [22], the median (50%) and severe (1%) lightning peak currents are, respectively:

30 kA and 150 kA for negative first strokes,

10–15 kA and 50 kA for negative subsequent strokes, and

35 kA and 500 kA for positive first strokes.

4) Cooray and Rakov [6], based on the maximum measured ambient electric field in thunderstorms (150 kV/m), estimated the upper bound for peak current in negative lightning to be about 300 kA in temperate regions and about 450 kA–500 kA in the tropics.

5) In order to explain lognormality of negative lightning peak current distributions, Slyunyaev et al. [68] developed a stochastic model of lightning

initiation. Assuming linear growth of the large-scale electric field between flashes and the dependence of the discharge probability per unit time on this electric field, they found that the distribution of the magnitude of large-scale electric field immediately before the lightning flash is close to lognormal (in a certain range), which leads to a peak current distribution of the same type.

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Статистические распределения параметров молнии с акцентом на их чрезвычайно высокие значения

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В статье дан обзор литературных данных о параметрах молнии, необходимых для разработки и совершенствования систем молниезащиты. Показано, что национальные и международные нормативные документы базируются на данных по распределению амплитуд токов молнии К. Бергера. Приведены экспериментальные данные по амплитуде тока обратного разряда молнии, полученные в Бразилии, Японии, США (Флорида) и Австрии. Подчеркивается, что приведенные данные по токам молнии характеризуются большим разбросом, что указывает на необходимость проведения дальнейших исследований. Дается подробное описание параметров импульсного тока обратного разряда, включая длительность фронта импульса, длительность импульса, крутизну тока на фронте. Подчеркивается, что среднее значение амплитуды тока первой составляющей обратного разряда в 3–4 раза выше тока последующих составляющих. Проведен анализ измеренных средних (50%) и «жестких» (1%) величин параметров молнии, которые необходимы для построения кривой распределения в предположении подчинения ее логнормальному закону. Приведены результаты теоретических исследований по оценке экстремальных значений токов молнии. Показано, что, в зависимости от длины канала молнии (от 4 до 6 км), максимальный ток может меняться от 300 до 500 кА. Минимальное же значение тока молнии оценено в 2 кА. Анализ результатов новых прямых измерений показал, что для молний положительной полярности максимальная амплитуда ее тока может достигать 340 кА, что заметно выше расчетного максимума для молнии отрицательной полярности (200 кА). Недавние теоретические изыскания позволили обосновать экспериментально полученное логнормальное распределение токов отрицательной молнии

Ключевые слова: *молния, пиковый ток обратного разряда, первые удары, последующие удары, осциллограммы тока, логнормальное распределение, время фронта, крутизна, время нарастания тока, положительная полярность, отрицательная полярность*

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