Initial stage in lightning initiated from tall objects and in rocket-triggered lightning

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[1] We examine the characteristics of the initial stage (IS) in object-initiated lightning derived from current measurements on the Gaisberg tower (100 m, Austria), the Peissenberg tower (160 m, Germany), and the Fukui chimney (200 m, Japan) and their counterparts in rocket-triggered lightning in Florida. All lightning events analyzed here effectively transported negative charge to ground. For rocket-triggered lightning the geometric mean (GM) values of the three overall characteristics of the initial stage, duration, charge transfer, and average current, are similar to their counterparts for the Gaisberg tower flashes and the Peissenberg tower flashes, while the Fukui chimney flashes are characterized by a shorter GM IS duration and a larger average current. The GM IS charge transfer for the Fukui chimney flashes is similar to that in the other three data sets. The GM values of the action integral differ considerably among the four data sets, with the Fukui action integral being the largest. The observed differences in the IS duration between the Fukui data set and all other data considered here are probably related to the differences in the lower current limits, while the differences in the action integral cannot be explained by the instrumental effects only. There appear to be two types of initial stage in upward lightning. The first type exhibits pulsations (ringing) during the initial portion of the IS, and the second type does not. The occurrence of these types of IS appears to depend on geographical location. The characteristics of pulses superimposed on the initial continuous current (ICC pulses) in object-initiated (Gaisberg, Peissenberg, and Fukui) lightning are similar within a factor of 2 but differ more significantly from their counterparts in rocket-triggered lightning. Specifically, the ICC pulses in object-initiated lightning exhibit larger peaks, shorter risetimes, and shorter half-peak widths than do the ICC pulses in rocket-triggered lightning.

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1. Introduction

[2] A number of researchers have studied lightning initiated by an upward leader that originates from tall man-made structures and propagates toward the charged cloud overhead [e.g., *McEachron*, 1939, 1941; *Hagenguth and Anderson*, 1952; *Berger*, 1967, 1977; *Berger et al.*, 1975]. We refer to such object-initiated lightning as natural upward lightning. The upward leader bridges the gap between the grounded object and cloud and establishes an initial continuous current (ICC) with a duration of some hundreds of milliseconds and an amplitude of some tens to some thousands of amperes. The upward leader and the ICC constitute the initial stage (IS) of natural upward lightning. In most cases the IS contains current pulses superimposed on the slowly varying continuous current. These pulses are often referred to as initial continuous current (ICC) pulses. After the cessation of the ICC, one or more downward leader/upward return stroke sequences may occur. *Berger* [1977] reported that ICC pulses were relatively small, less than 10 kA, while return stroke current pulses had peaks mostly in the range from 10 to 30 kA. *Fuchs et al.* [1998], from Peissenberg tower studies, reported a median peak current for ICC pulses of 3.9 kA, about a factor of 2 lower than the geometric mean peak current of 8.5 kA for return stroke current pulses observed on that tower. It is worth noting that *Fuchs et al.* [1998] did

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Table 1. General Characterization of Data Sets Used in This Study

Experimental Site	Height, m	Location	Altitude Above Sea Level, m	Heights of Isotherms, km: 0°C	Heights of Isotherms, km: −10°C	Observation Period for Data Set Used in This Study	Number of Flashes Analyzed	Percentage of Flashes With Return Strokes	Number of ICC Pulses Analyzed
ICLRT (rocket-triggered lightning)	~300[a]	Camp Blanding, Florida	20–25	4, summer	6, summer	1996, 1997, 1999, 2000	45	75	247–296
Gaisberg tower	100	Salzburg, Austria	1287	–	2.8, Nov.–March; 4.5, April–Oct.	2000	74	40	345–378
Peissenberg tower	160	Munich, Germany	937	–	–	1996–1999	21	60	124
Fukui chimney	200	Fukui, Japan	0	<1	1–3, Nov.–March	1996–1999	36	14	231

[a]Typical length of the triggering wire at the time of initiation of upward positive leader.

not include in their statistics the smaller ICC pulses (less than 1 kA or so).

[3] Rocket-triggered lightning is also initiated by an upward leader propagating from the upper end of a vertical grounded wire extended below the charged cloud by a small rocket. Following the electrical explosion of the triggering wire and its replacement by an upward leader plasma channel [*Rakov et al.*, 2003], the phenomenology of rocket-triggered lightning [e.g., *Rakov*, 1999] is apparently similar to that of the upward lightning initiated from grounded tall structures discussed above.

[4] *Hubert* [1984] was the first to compare the characteristics of rocket-triggered lightning with those of upward lightning initiated from grounded man-made objects. He stated that triggered lightning "largely surpasses" natural upward lightning in terms of the "maximum intensity" (peak current) and the electric charge transferred by the flash. *Uman* [1987] also compared rocket-triggered lightning with upward lightning initiated from tall objects and found no apparent differences in terms of the flash duration and flash charge. It is worth noting that *Hubert* [1984] apparently lumped data for flashes with and without return strokes. As a result, the relatively low value of "maximum intensity" (0.25 kA) quoted by *Hubert* [1984] with reference to *Berger* [1967, 1977] is largely determined by upward flashes without return strokes. *Uman* [1987] apparently considered only natural upward flashes with return strokes, which explains the discrepancy between his results and those of *Hubert* [1984]. Additionally, at least in the case of rocket-triggered flashes, neither *Hubert* [1984] nor *Uman* [1987] distinguished between current pulses due to downward leader/upward return stroke sequences and current pulses occurring during the initial stage (ICC pulses). These two types of pulses likely involve different mechanisms leading to the observed differences in their characteristics [*Rakov et al.*, 2001].

[5] In this international collaborative study, we compare the characteristics of the IS (including ICC pulses) in rocket-triggered lightning in Florida with their counterparts in natural upward lightning as observed on (1) the Gaisberg tower (100 m, Austria), (2) the Peissenberg tower (160 m, Germany), and (3) the Fukui chimney (200 m, Japan). All flashes considered here effectively transported negative charge to ground. The duration, charge, average current, and action integral of the IS determined from direct current measurements were used to characterize the initial stage. The peak, duration, risetime, and half-peak width were used to characterize the ICC pulses.

[6] *Wang et al.* [1999] have studied the electrical characteristics of the IS in rocket-triggered lightning. In most cases, the IS contained current pulses (ICC pulses) superimposed on the slowly varying continuous current. A statistical comparison between these ICC pulses and the M component pulses superimposed on continuing currents following return strokes in triggered lightning studied by *Wang et al.* [1999] indicated that both types of pulses are due to similar physical processes. It follows that the ICC pulses in natural upward lightning should be similar to the M-component-type pulses, although no quantitative confir-

Table 2. Instrumentation Summary

Observation Site	Current Measuring Device	Recorder	Measurement Limits: Lower, A	Measurement Limits: Upper, kA	System Bandwidth	Trigger Threshold, A	Sampling Rate, MHz	Vertical Resolution, bits	Recording Duration, ms	Memory, megawords
ICLRT (rocket-triggered lightning)	shunt, 1 mohm	magnetic tape records, subsequently digitized	20	2	dc: 400 kHz	continuous recordings	≤0.025 (1996, 1997, 1999) ≥0.25 (2000)	–	1000	–
Gaisberg tower	shunt, 0.25 mohm	DSO (National Instruments PCI-5102)	ch. 1, 17; ch. 2, 330	ch.1, 2.1; ch. 2, 40	0–3.2 MHz	200	20	8	800	16
Peissenberg tower	current transformer (Pearson coil)	DSO (LeCroy 9310AL)	ch. 1, 15; ch. 2, 300	ch.1, 2.1; ch. 2, 40	0.15 Hz to 200 kHz	1: i = 2 kA; or 2: di/dt = 5 kA/μs; or 3: Q = 25 mC	1	8	1000	1
Fukui chimney	shunt (R1, 10 mohm; R2, 2 mohm)	ALCS	R1, 200[a]; R2, 500	R1, 13; R2, 150	rectangular wave response: <100 ns	500	5	10	400	2

[a]The measurement system for Fukui chimney cannot measure the current in the range from −200 A to +200 A.

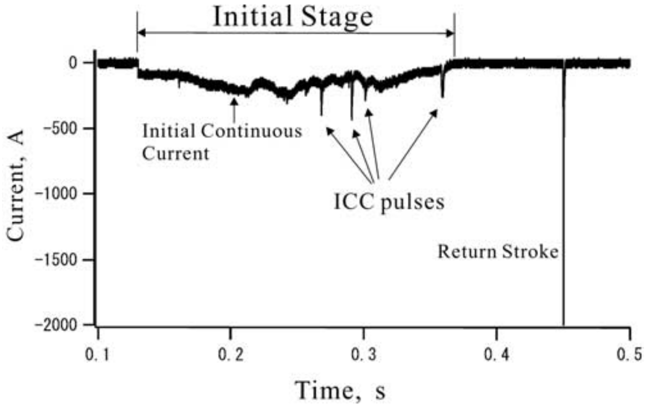

Figure 1. Overall current waveform of the initial stage followed by one return stroke pulse in Florida rocket-triggered lightning.

mation of this inference is available. In this study, both similarities and differences between the rocket-triggered lightning and the natural upward lightning are observed.

[7] In Japan, many upward lightning flashes have been observed during winter thunderstorms on the coast of the Japan Sea. We call such lightning winter lightning. A number of researchers have reported that the features of winter lightning are very different from those of the more common lightning during summer thunderstorms [e.g., *Asakawa et al.*, 1997; *Miyake et al.*, 1992; *Wada et al.*, 1996]. However, a quantitative comparison of the overall characteristics of the IS in winter lightning in Japan and in upward lightning in other geographical locations has not been done yet. We compared the characteristics of the IS of upward lightning for Fukui chimney in Japan, Peissenberg tower in Germany, Gaisberg tower in Austria, and those of rocket-triggered lightning in Florida. The Fukui chimney data are only for cold season lightning, Florida triggered lightning data include only warm-season (summer) lightning, and the Gaisberg tower and Peissenberg tower data sets contain both warm- and cold-season lightning. We examined the influence of season on the characteristics of the IS. Additionally, geographical variations of the IS characteristics are discussed.

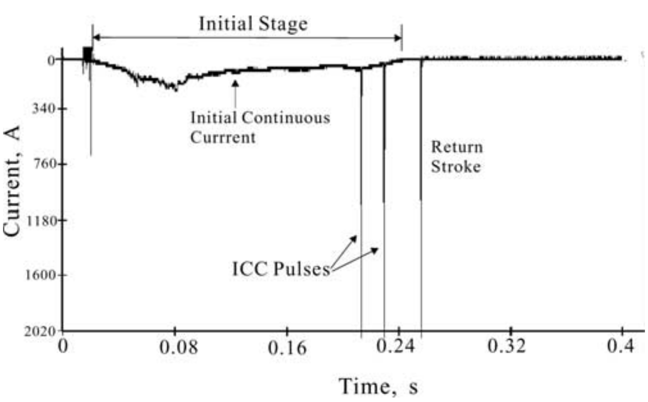

Figure 2. Overall current waveform of the initial stage followed by one return stroke pulse in an upward flash at the Gaisberg tower, Austria.

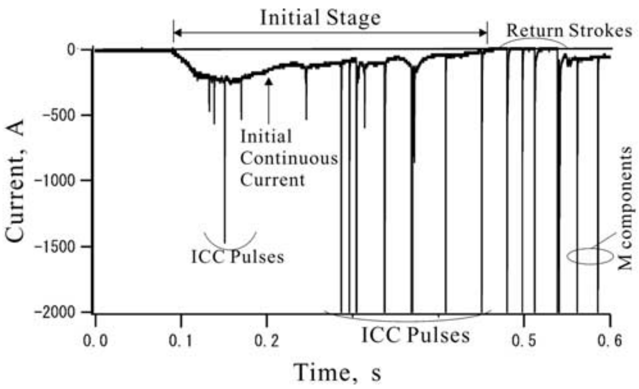

Figure 3. Overall current waveform of the initial stage followed by four return stroke pulses in an upward flash at the Peissenberg tower, Germany.

2. Data

[8] This section describes the characteristics of the measuring systems used at the four different observation sites located in Florida, Austria, Germany, and Japan. Table 1 gives geographical and meteorological information for each observation site. Table 2 summarizes the specifications of the instruments used.

2.1. Rocket-Triggered Lightning (Florida)

[9] The rocket-triggered lightning experiments were conducted at the International Center for Lightning Research and Testing (ICLRT) at Camp Blanding, Florida. The rocket launchers were located on flat ground, 20–30 m above sea level (see Table 1). As noted earlier, all of the lightning flashes were triggered during summer. The altitude of the −10°C isotherm in Florida is about 6 km [*Uman*, 1987]. Typically, an upward leader is initiated from the upper end of the vertical grounded wire when the rocket extends that wire to a height of about 300 m. More information on the rocket-and-wire lightning triggering technique is given, for example, by *Rakov* [1999].

[10] Current waveforms of the initial stage were measured with a 1 mΩ current viewing resistor (see Table 2). The resistor was inserted between the base of the strike rod and ground. The signal from the current viewing resistor was transmitted to the instrumentation facility by a fiber-optic link. The data were recorded on magnetic tape with a bandwidth from dc to 400 kHz and an effective noise level of approximately 20 A. We digitized the tape records from 1996 and 1997 at a sampling interval of 40 μs, from 1999 at a sampling interval of 80 μs, and from 2000 at a sampling interval of a few microseconds.

[11] We used 45 negative upward flashes containing 296 ICC pulses for this study. Figure 1 shows a typical overall current waveform of the IS followed by one return stroke pulse in Florida rocket-triggered lightning.

2.2. Gaisberg Tower Lightning (Austria)

[12] The Gaisberg tower is located on the top of a 1287 m mountain near Salzburg, Austria. The height of the tower is 100 m. At Gaisberg, the average altitude of the −10°C

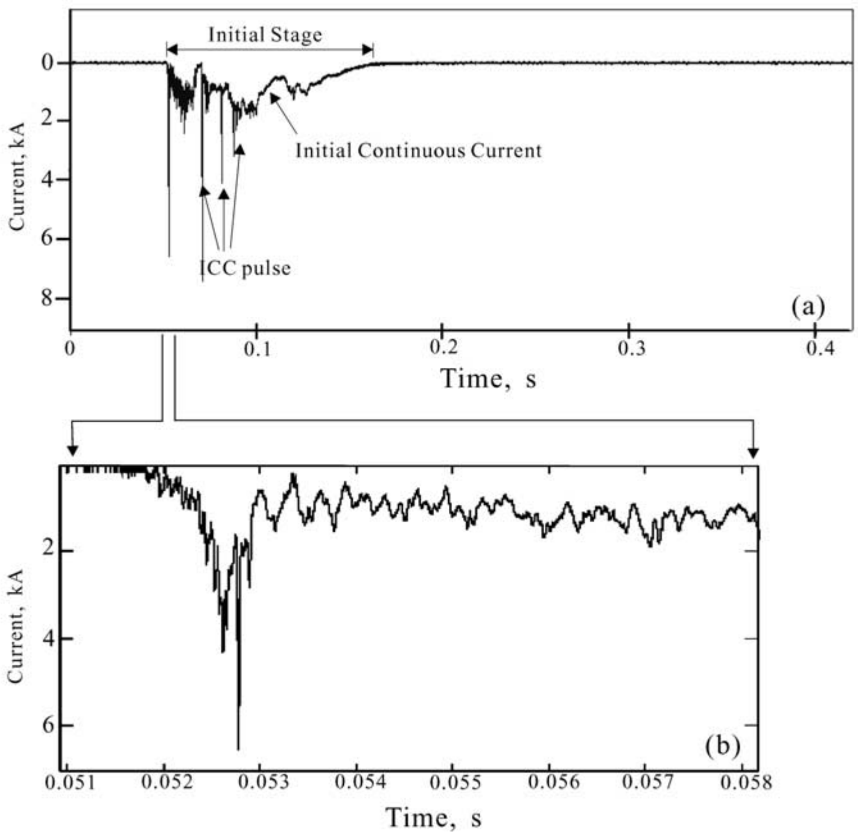

Figure 4. (a) Overall current waveform of the initial stage not followed by return stroke pulses in an upward flash at the Fukui chimney, Japan; (b) initial portion of the IS that shows pulsations (see section 4.2).

isotherm is 4.5 km during the summer and 2.8 km during the winter. Lightning flashes occurring in both winter and summer were observed at Gaisberg.

[13] 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 of 0.25 mΩ having a bandwidth of DC to 3.2 MHz [*Diendorfer et al.*, 2000]. A fiber-optic link was used for transmission of the shunt output signal to a digital recorder. Two separate fiber-optic channels of different sensitivity were used: 0–2.1 kA and 0–40 kA. The signals were recorded by an 8 bit digitizing board (upper frequency response 15 MHz; memory 16 MB) installed in a personal computer. The trigger threshold of the recording system was set at 200 A. The lower measurement limit was 17 A.

[14] A total of 74 negative upward flashes containing 378 ICC pulses were used in this analysis. Unfortunately, the measurement system for large currents (0–40 kA) experienced difficulties: current waveforms with large peaks and short risetimes were distorted. As a result, 26 pulses that

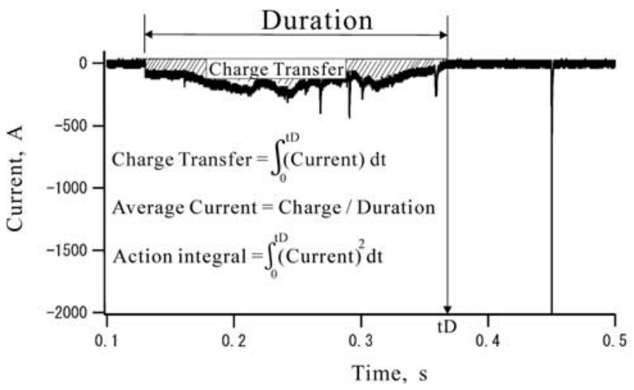

Figure 5. Definitions of overall characteristics (duration, charge transfer, average current, and action integral) of the initial stage in upward flashes, illustrated using the current waveform shown in Figure 1.

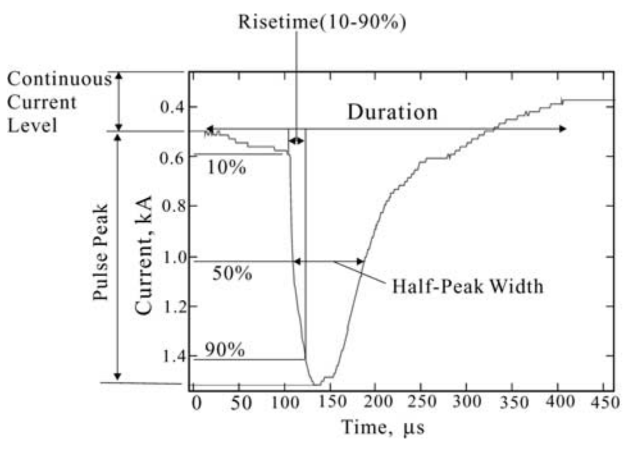

Figure 6. Definitions of the parameters (peak, duration, risetime, and half-peak width) of ICC pulses.

Table 3. Overall Characteristics (Geometric Mean Values) of the Initial Stage of Rocket-Triggered and Natural Upward Lightning

Experimental Site	Sample Size	Duration, ms	Charge Transfer, C	Average Current, A	Action Integral, 10^3 A^2s
ICLRT (rocket-triggered lightning), Florida	45	305	30.4	99.6	8.5
Gaisberg tower, Austria	74	231	29.1	126	1.5
Peissenberg tower, Germany	21	290	38.5	133	3.5
Fukui chimney, Japan[a]	36	>82.5	>38.3 (>36.8)	465	40 (34)

[a]Values in parentheses are calculated from the current data limited to 2 kA in order to make the Fukui data (upper current measurement limit of 13 kA) comparable to the other data sets (upper current measurement limit of 2–2.1 kA).

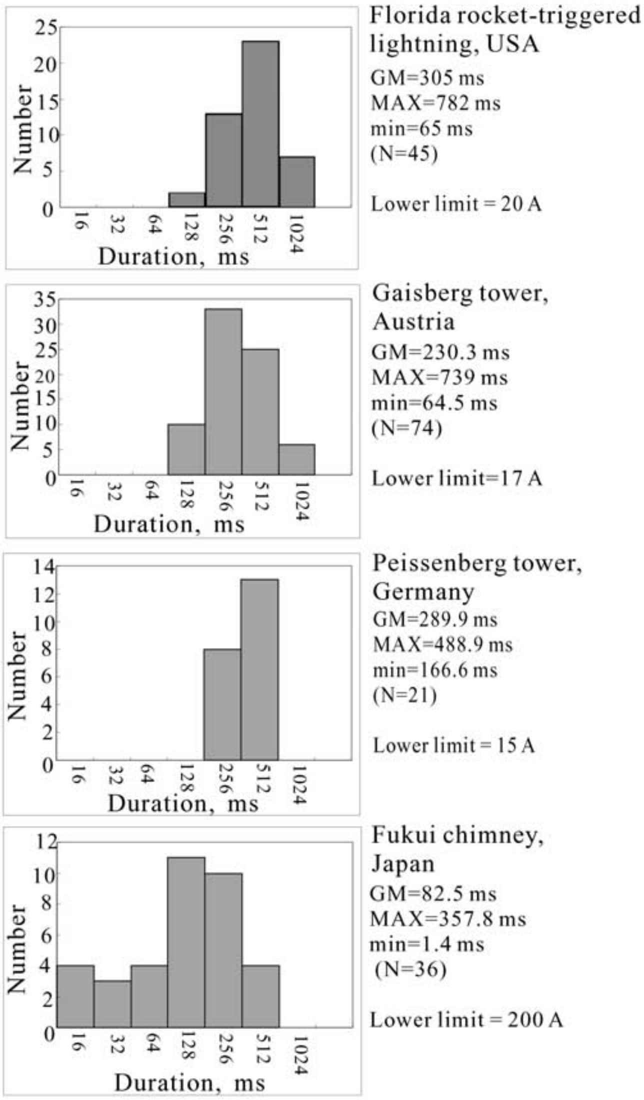

Figure 7. Histograms of the duration of the initial stage. The geometric mean (GM), maximum (MAX), and minimum (min) values are indicated beside each histogram. Sample sizes are given in parentheses. The lower (upper) current measurement limit was 200 A (13 kA) for the Fukui data set and 15–20 A (2–2.1 kA) for the other three data sets.

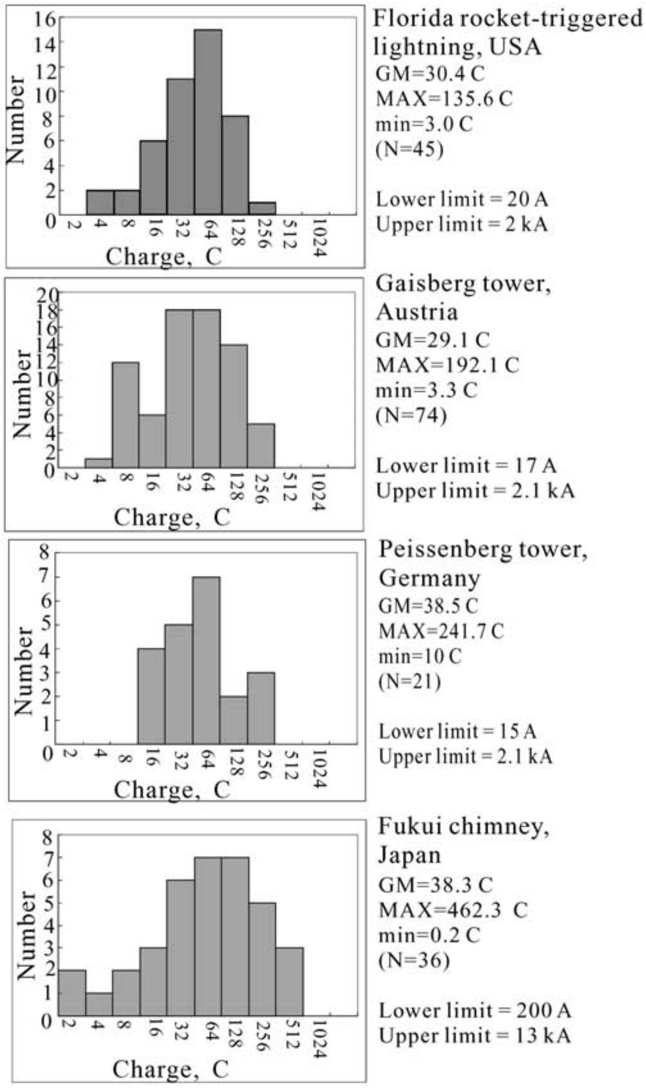

Figure 8. Histograms of the charge transfer of the initial stage. The geometric mean (GM), maximum (MAX), and minimum (min) values are indicated beside each histogram. Sample sizes are given in parentheses. The charge transfer was evaluated from the low-level current record. The lower (upper) current measurement limit was 200 A (13 kA) for the Fukui data set and 15–20 A (2–2.1 kA) for the other three data sets.

had large peaks (>2 kA) and short risetimes were not suitable for analysis. Figure 2 shows a typical overall current waveform of the IS followed by one return stroke pulse recorded on the Gaisberg tower.

2.3. Peissenberg Tower Lightning (Germany)

[15] The Peissenberg tower is located about 60 km southwest of Munich, Germany, on a ridge (about 950 m above sea level) called "Hoher Peissenberg." The height of the Peissenberg tower is about 160 m. The average temperature at the ground surface is around 0°C in winter and above 10°C in summer. Lightning flashes in both winter and summer were observed at the Peissenberg tower. However, 19 of 21 upward flashes examined here were observed in winter season.

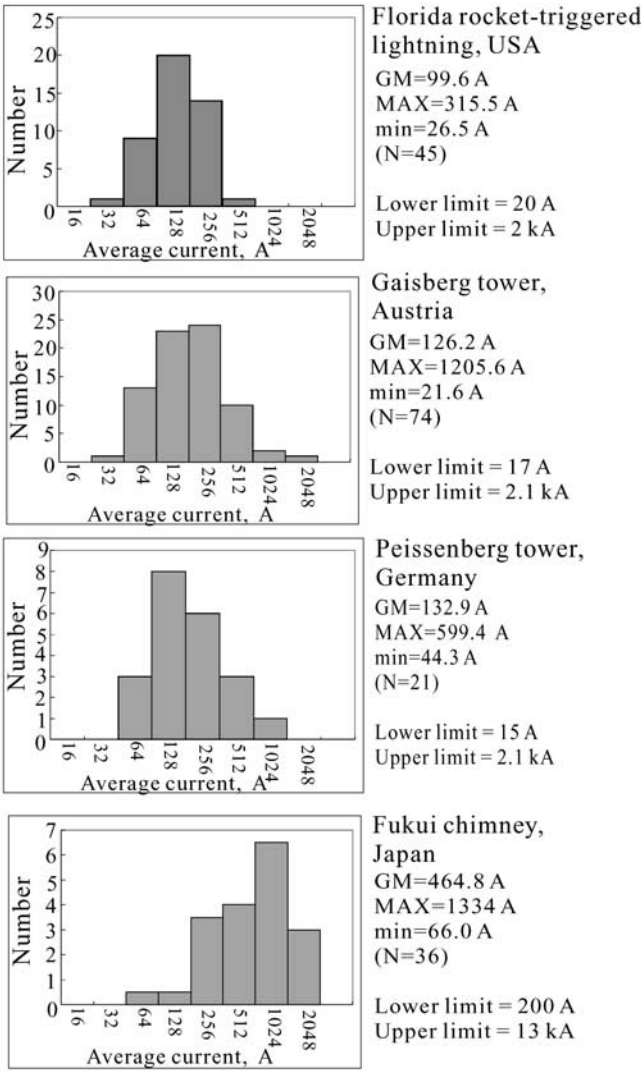

Figure 9. Histograms of the average current of the initial stage. The geometric mean (GM), maximum (MAX), and minimum (min) values are indicated beside each histogram. Sample sizes are given in parentheses. The lower (upper) current measurement limit was 200 A (13 kA) for the Fukui data set and 15–20 A (2–2.1 kA) for the other three data sets.

[16] Lightning currents were measured with a current transformer (Pearson CT: 0.15 Hz to 200 kHz) [*Heidler et al.*, 2000] installed at the top of the tower. The output signal was transmitted via a coaxial cable from the top of the tower to the current measuring station at the base of the tower. Signals were recorded by a digital oscilloscope with a storage capability of 1 million points using a sampling rate of 1 MHz. The lower current measurement limit was 15 A. The measuring system was triggered whenever one of the three following conditions was fulfilled: (1) The current measured at the top of the tower exceeded a threshold of 2 kA. (2) The di/dt signal at the top of the tower exceeded a threshold of 5 kA/μs. (3) The integrated current (charge transfer) exceeded a threshold of 25 mC.

[17] A total of 21 upward negative flashes containing 124 ICC pulses (120 in winter and 4 in summer) were used in this study. Figure 3 shows a typical overall current waveform of the IS followed by four return stroke pulses recorded at the Peissenberg tower.

2.4. Fukui Chimney Lightning (Japan)

[18] What is often referred to as the Fukui chimney is actually the chimney of the Mikuni cooperative power station located at the Fukui thermal plant station on the coast of the Japan Sea. The height of the chimney is 200 m. Most of the lightning flashes occurred in winter, from November to February. The altitude of the −10°C isotherm is 1–3 km during winter.

[19] The current was measured with two coaxial shunts (current viewing resistors; 2 mΩ and 10 mΩ) [*Wada et al.*, 1996]. The 2 mΩ shunt was used for measuring large

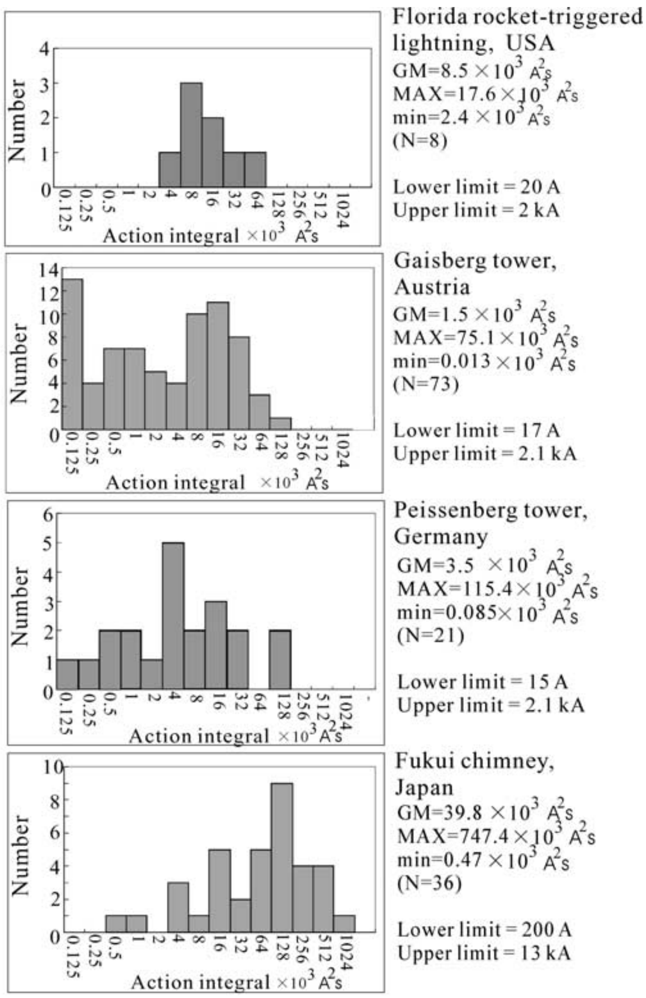

Figure 10. Histograms of the action integral ($\int i^2 dt$) of the initial stage. The geometric mean (GM), maximum (MAX), and minimum (min) values are indicated beside each histogram. Sample sizes are given in parentheses. The action integral was evaluated from the low-level current record. The lower (upper) current measurement limit was 200 A (13 kA) for the Fukui data set and 15–20 A (2–2.1 kA) for the other three data sets.

Table 4. Parameters (Geometric Mean Values) of ICC Pulses in Rocket-Triggered Lightning and in Natural Upward Lightning[a]

Experimental Site	Sample Size	Peak, A	Duration, ms	Risetime, μs	Half-Peak Width, μs
ICLRT (rocket-triggered lightning), Florida	247–296 (all data)	113, N = 296	2.59, N = 254	464, N = 267	943, N = 247
ICLRT (rocket-triggered lightning), Florida	110 (2000 data)	76.6	3.18	517	1079
Gaisberg tower, Austria	345–378	>377, N = 352	1.20, N = 378	<110, N = 345	276, N = 349
Peissenberg tower, Germany	124	512	0.833	60.9	153
Fukui chimney, Japan	231	781	0.514	44.2	141
Lightning-triggering sites in Florida and Alabama, M components[b]	113–124	117, N = 124	2.10, N = 114	422, N = 124	800, N = 113

[a]Additionally included (see the last entry) are parameters of M component current pulses in rocket-triggered lightning.
[b]*Thottappillil et al.* [1995].

currents (8–150 kA) and the 10 mΩ shunt for measuring small currents (0.2–13 kA). The output signals from the shunts were recorded by a 10-bit digital recorder (2 megawords, 5 MHz). The current measurement systems employed fiber-optic links connecting the shunt to the digital recorder. The trigger level of the measuring system was 500 A. Logarithmic amplifiers were used in the current measurement system of the Fukui chimney that did not allow measurement of currents less than 200 A (absolute value), while current above 200 A were correctly measured.

[20] We used 36 upward negative flashes containing 231 ICC pulses in this study. Figure 4a shows a typical overall current waveform of the IS not followed by return stroke pulses.

3. Analysis and Results

3.1. Definitions of the Parameters

[21] The definitions of the terms used in this paper to describe various features of the current records are as follows (Figures 5 and 6 illustrate how the various measured parameters are defined): The duration of the initial stage (IS) is the time interval from the initial deflection of the slowly varying IS current from zero to the time at which the

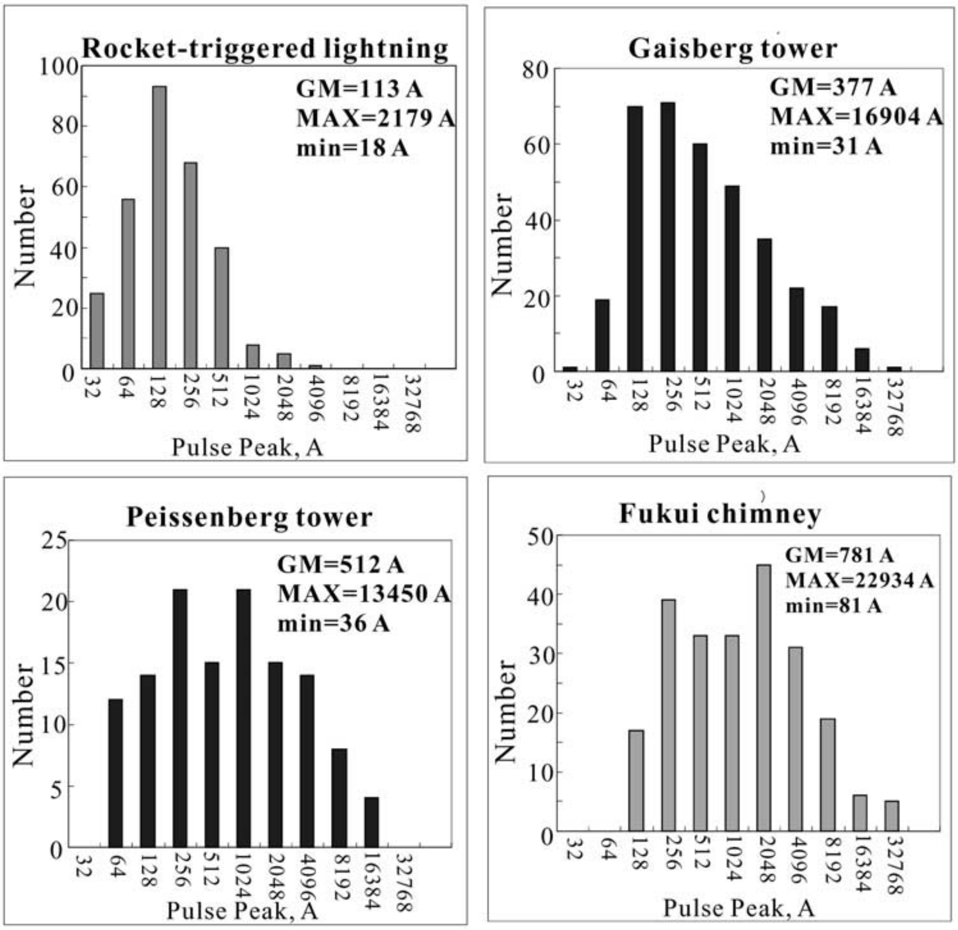

Figure 11. Histograms of the peak of ICC pulses. The geometric mean (GM), maximum (MAX), and minimum (min) values are indicated on each histogram.

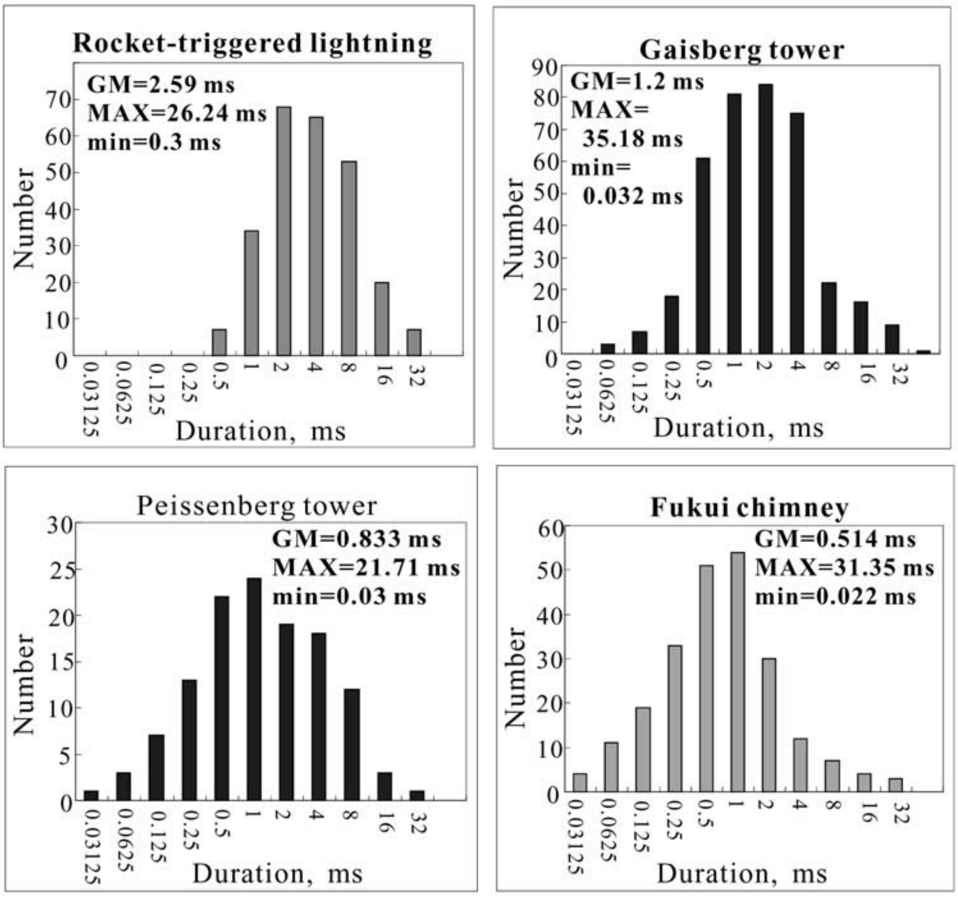

Figure 12. Histograms of the duration of ICC pulses. The geometric mean (GM), maximum (MAX), and minimum (min) values are indicated on each histogram.

measured current becomes indistinguishable from the noise level (see Figure 5). The IS charge transfer is the charge transferred during the initial stage, found as the integral of current over the entire IS duration (see Figure 5). The IS average current is the IS charge divided by the IS duration. The IS action integral is the integral of the square of current over the entire IS duration. It is the energy that would be dissipated in a 1 Ω resistor if the IS current were to flow through it. The overall characteristics of the IS were calculated using low-level current records. For characterizing the ICC pulse, the parameters and the definitions introduced by. *Wang et al.* [1999] are adopted (see Figure 6). The peak of an ICC pulse is the difference between the maximum value of the current pulse and the preceding continuous current level. The duration of an ICC pulse is the time interval from the beginning of the wave front to the somewhat subjectively selected point at which the trailing edge of the current pulse becomes indistinguishable from the overall continuous current waveform. The risetime of an ICC pulse is the time interval on the wave front between the 10% and 90% values of the peak. The half-peak width of an ICC pulse is the time interval between the 50% values of the peak on the wave front and on the falling portion of the pulse.

3.2. Overall Initial Stage

[22] Table 3 gives the geometric mean (GM) values of the overall characteristics of the IS: duration, charge transfer, average current, and action integral. The IS duration, charge transfer, and average current for rocket-triggered lightning are similar to their counterparts for Gaisberg tower flashes and Peissenberg tower flashes, while the Fukui chimney data are characterized by a shorter IS duration and a larger average current. The IS charge transfer for the Fukui chimney flashes is similar to those in the other three data sets. The IS action integrals differ considerably among the four data sets, ranging from 1.5×10^3 A^2s for the Gaisberg tower to 4.0×10^4 A^2s for the Fukui chimney.

[23] The histograms of the overall characteristics of the IS for Florida, Austria, Germany, and Japan are shown in Figures 7, 8, 9, and 10. The shapes of the histograms for the Peissenberg tower flashes and the Gaisberg tower flashes are similar to those for Florida rocket-triggered flashes. This suggests that the IS of rocket-triggered lightning is similar to that of natural upward lightning. However, the shapes of the histograms for the Fukui chimney flashes are somewhat different from the others. The data for the Fukui chimney flashes contain small values of IS charge transfer and IS duration, not seen in the other upward lightning data sets. The average current and the average action integral for the Fukui flashes are much larger than those in the other upward lightning data sets.

[24] One likely reason for the relatively short IS duration for the Fukui chimney flashes is its underestimation due to

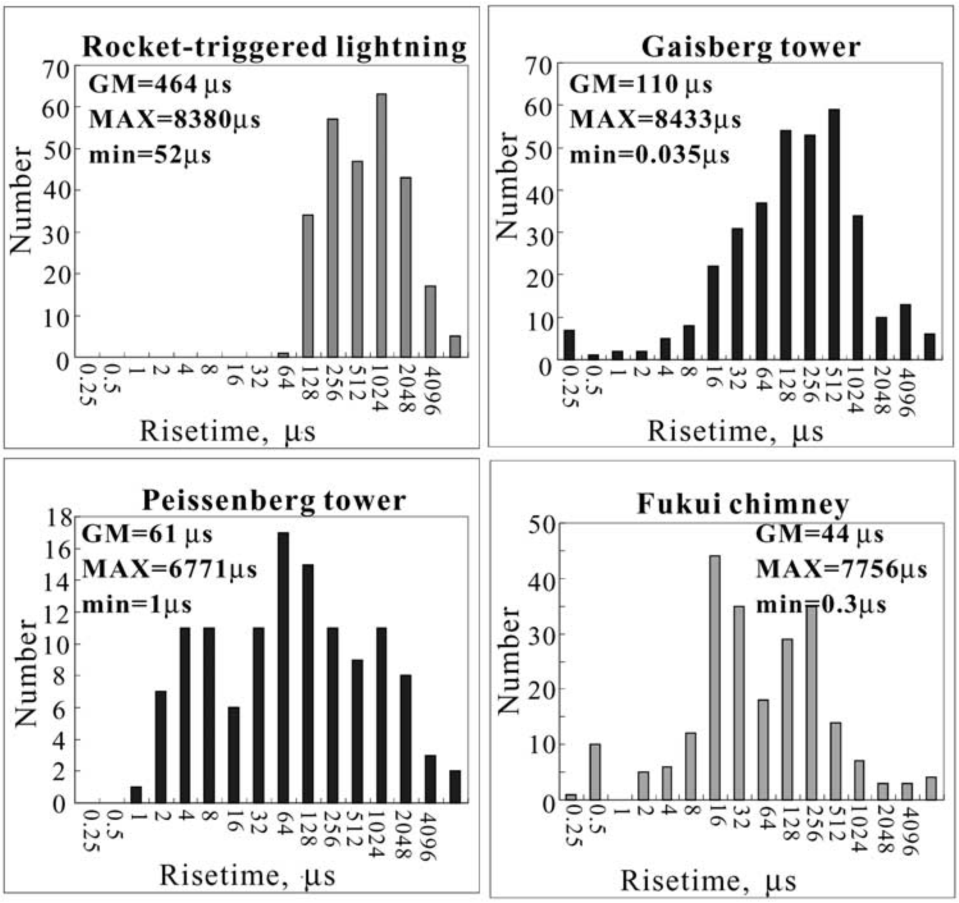

Figure 13. Histograms of the risetime of ICC pulses. The geometric mean (GM), maximum (MAX), and minimum (min) values are indicated on each histogram.

the relatively high lower current measurement limit (see Table 2). The charge transfer and action integral for the Fukui chimney should be also influenced by the lower current measurement limit and therefore are underestimated, although this effect may be partially compensated by a relatively high upper current measurement limit at Fukui. Indeed, the upper current measurement limit in Fukui chimney data is 13 kA, while for the other sites it is about 2 kA (see Table 2). In order to estimate the influence on the upper limit of the current measurement system, we additionally calculated the IS charge transfer and action integral for the Fukui chimney using portions of current records limited to 2 kA. The results are shown in the parentheses in Table 3. The action integral calculated from the current data for Fukui chimney flashes limited to 2 kA is still considerably larger than that for Peissenberg tower, Gaisberg tower, and Florida rocket-triggered flashes. Thus the larger action integral for Fukui chimney cannot be explained only by the different characteristics of the current measurement systems.

[25] In summary, the IS of rocket-triggered lightning is generally (in most respects) similar to that of natural upward lightning, except for Fukui chimney flashes. The differences between the Fukui data and the other data considered here in the IS duration can be explained by the relatively high lower limit of the current measurement system at Fukui. The IS in Fukui chimney flashes is characterized by considerably larger action integral compared to the other data sets considered here.

3.3. ICC Pulses

[26] Table 4 gives the GM values of peak, duration, risetime, and half-peak width of ICC pulses. The peak and risetime for the Gaisberg tower data are underestimated, because the waveforms of 26 ICC pulses that are larger than 2 kA and have risetimes less than 10 μs are distorted because of a problem with the measurement system. The peak, risetime and half-peak width for the Florida rocket triggered lightning data are underestimated, because the sampling interval for the data from 1996, 1997 and 1999, 40 or 80 μs, is potentially inadequate. In Table 4, the characteristics of ICC pulses evaluated from all Florida data combined and from 2000 data only (sampling interval of a few microseconds) are shown to estimate the possible bias due to insufficient sampling rate. Even though the tape records from 2000 are digitized at a sampling interval of a few microseconds, the duration, risetime, and half-peak width for 2000 data are larger than those for all Florida data combined. This result suggests that the bias due to insufficient sampling rate for the Florida rocket-triggered lightning is not too large. Parameters (GM values) of ICC pulses in the Peissenberg tower flashes, Gaisberg tower flashes, and Fukui chimney flashes are similar to each other within a factor of 2 or so,

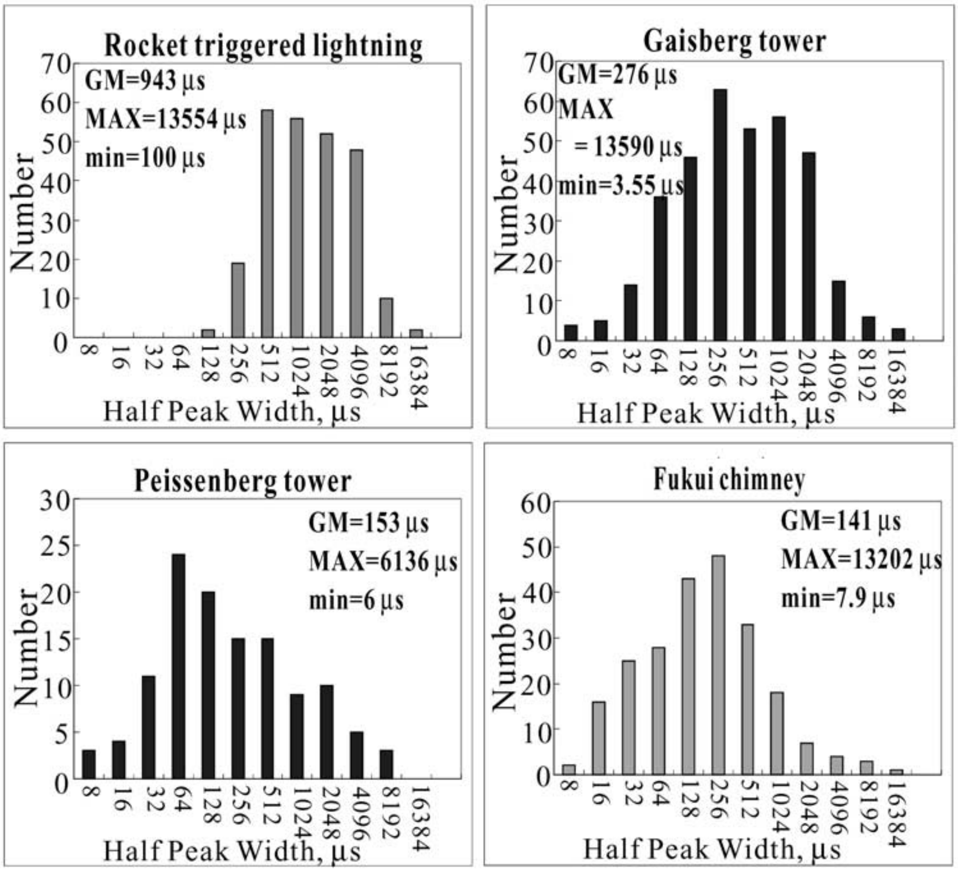

Figure 14. Histograms of the half-peak width of ICC pulses. The geometric mean (GM), maximum (MAX), and minimum (min) values are indicated on each histogram.

suggesting that the parameters of ICC pulses in natural upward lightning are independent of geographical location. On the other hand, they differ more significantly from their counterparts in Florida rocket-triggered lightning. ICC pulses in the Peissenberg tower flashes, the Gaisberg tower flashes, and the Fukui chimney flashes exhibit larger peaks, shorter half-peak widths, and durations than do ICC pulses in Florida rocket-triggered lightning.

[27] M component is an impulsive process occurring in the lightning channel that carries continuing current. An M component involves a downward progressing incident current wave and an upward progressing current wave that is a reflection of the incident wave from the ground [*Rakov et al.*, 1995]. Parameters of ICC pulses in Florida rocket-triggered lightning examined here are similar to those of M component pulses in rocket-triggered lightning studied by *Thottappillil et al.* [1995], these M component pulses being also included in Table 4 for comparison. This result is in support of the conclusion of *Wang et al.* [1999] that the physical processes behind the ICC pulses in rocket-triggered lightning are similar to those involved in M components.

[28] Figures 11, 12, 13, and 14 show histograms of peak, duration, risetime, and half-peak width, respectively, of ICC pulses in rocket-triggered lightning and in natural upward lightning (Peissenberg tower flashes, Gaisberg tower flashes, and Fukui chimney flashes). These figures show that the ICC pulses in Florida rocket-triggered lightning do not exhibit large peaks (>4096 A), short durations (<300 μs), short risetimes (<32 μs), and short half-peak widths (<64 μs), while the ICC pulses in natural upward lightning do. Thus ICC pulses in natural upward lightning appear to be statistically different from ICC pulses in rocket-triggered lightning.

[29] Some of the ICC pulses in natural upward lightning have waveshapes that are similar to the waveshape characteristic of return stroke pulses [*Fisher et al.*, 1993], as illustrated in Figure 15b. Their risetimes are less than 1 μs and the peaks are larger than 2 kA. In Florida rocket-triggered lightning flashes, such sharp and large pulses have not been observed. The histogram of the risetime for the Peissenberg tower flashes (see Figure 13) exhibits a second peak at several microseconds. This peak suggests that the processes producing ICC pulses with risetimes of the order of some microseconds or less are different from those producing ICC pulses with risetimes of the order of tens to hundreds of microseconds or more. The possible origins of the ICC pulses are discussed in section 4.3.

4. Discussion

4.1. Overall Characteristics of Initial Stage Versus Season

[30] As seen in Table 3, Fukui chimney flashes are characterized by a shorter GM initial stage duration, a

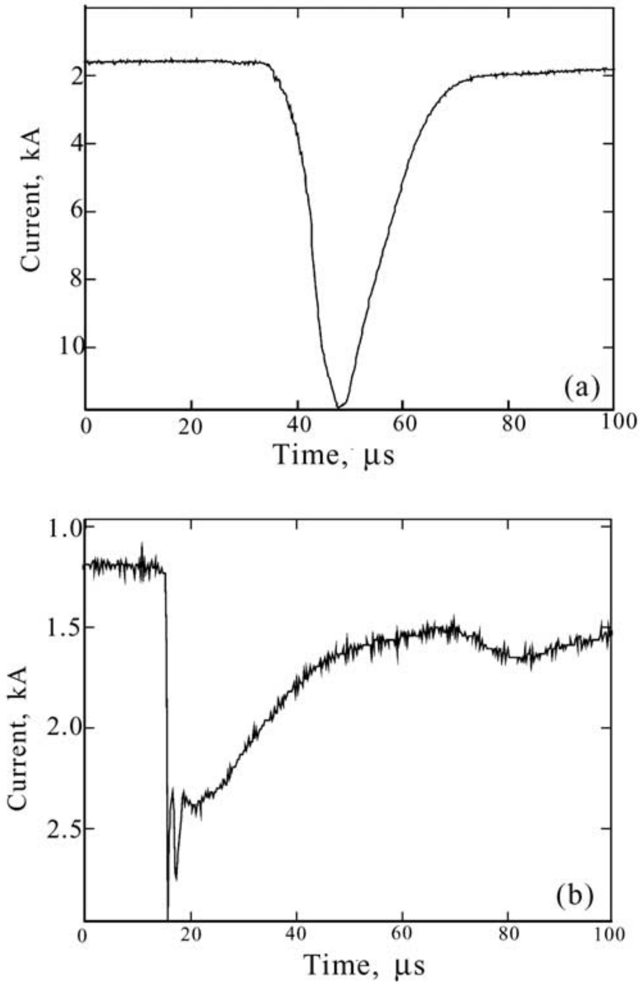

Figure 15. Examples of waveshapes of ICC pulses. (a) Slow rise pulse (risetime 7.9 μs); (b) fast rise pulse (risetime 0.4 μs).

larger GM average current, and a larger GM action integral than flashes in the other three data sets, although the disparities in the duration may be, at least in part, due to a considerably higher minimum current that could be measured at Fukui chimney. Since all the Fukui chimney flashes considered here occurred from November to March, it is believed that the characteristic features of these flashes may be due to the properties of winter thunderclouds [*Sugimoto et al.*, 2002]. In particular, the winter thunderclouds are characterized by their relative proximity to the ground [*Kitagawa*, 1992].

[31] In the following, we compare the overall characteristics of the Gaisberg tower flashes in winter (October–March: 38 flashes) with those in summer (April–September: 36 flashes). The duration of the IS in summer (249 ms) is somewhat longer than that in winter (217 ms). The charge, the average current, and the action integral of the IS (charge = 34.6 C, average current = 135 A, action integral = 3.1×10^3 A^2s) in summer are somewhat larger than those (charge = 29.3 C, average current = 124 A, action integral = 1.1×10^3 A^2s) in winter. The altitude of the $-10°$ isotherm during winter in the vicinity of the Gaisberg tower is about 2.8 km (not far from 1 to 3 km for winter clouds in the vicinity of Fukui chimney), and during summer it is about 4.5 km (see Table 1). Thus the Gaisberg tower data acquired in winter and in summer appear not to support the notion that winter lightning in Japan is more energetic because of a smaller gap between the cloud charge and the strike object. Parameters of ICC pulses as a function of season are discussed in section 4.3.

4.2. Pulsation in IS Current Waveforms

[32] We observed two types of initial stage in upward lightning. In the first, the initial portion of the IS current waveform exhibits pulsations, as seen in Figure 4 for a Fukui chimney flash. Figures 16 and 17 show examples of pulsating IS current waveforms in Gaisberg tower flashes and Peissenberg tower flashes, respectively. These pulsations appear as ringing (a train of more or less regularly spaced pulses) and are different from ICC pulses analyzed in section 3.3. In the second type, the initial portion of the IS current waveform is relatively smooth, as seen in Figures 1, 2, and 3. Here, we label the first type as P (P for "pulsating") and the second as S (S for "smooth").

[33] Gaisberg tower flashes and Peissenberg tower flashes exhibit both types of IS current waveforms. The percentage of type P for Gaisberg tower flashes is 16%, and for Peissenberg tower flashes it is 29%. In the Fukui chimney data, most of the upward flashes have type P IS current waveforms. Some pulsating IS current waveforms were also observed in Florida rocket-triggered lightning [*Rakov et al.*, 2003]. However, there were no pulsating IS current waveforms in the Florida data set examined here.

[34] Table 5 gives a summary of the features of the type P initial stage. The periods of pulsation in different locations are similar. The average values of the period range from 78 to 148 μs. The pulsation lasts for about 10–20 ms after the beginning of the waveform. If the average speed of the upward leader is about 10^5 m/s [e.g., *Rakov*, 1999], the upward leader reaches an altitude of 1–2 km at the time of cessation of the pulsation. The main charge source in thunderclouds is expected to be located at higher altitudes even in winter. From this, we infer that the pulsation is the phenomenon related to propagation of upward leaders before they arrive at the main charge source in the cloud. *Wada et al.* [1996] reported that the pulsation of current during the IS at the Fukui chimney was associated with the pulsation of luminosity of the upward leader channel. *Rakov et al.* [2003], who observed type P initial stage in Florida rocket-triggered lightning, suggested that the pulsation of current is associated with stepping of upward positive leader. Additionally, *Idone* [1992] found that luminosity waves associated with individual steps of the upward positive leader in rocket triggered lightning propagated from the leader tip down the channel to ground. Thus it is likely that the pulsation of current during the IS observed in this study is due to the stepping processes of the upward leader.

[35] In the Gaisberg tower flashes, most of the pulsating waveforms were observed in the warm season (10 in summer and 2 in winter). On the other hand, most of the Peissenberg tower flashes and all Fukui chimney flashes examined in this paper occurred in winter. Thus the

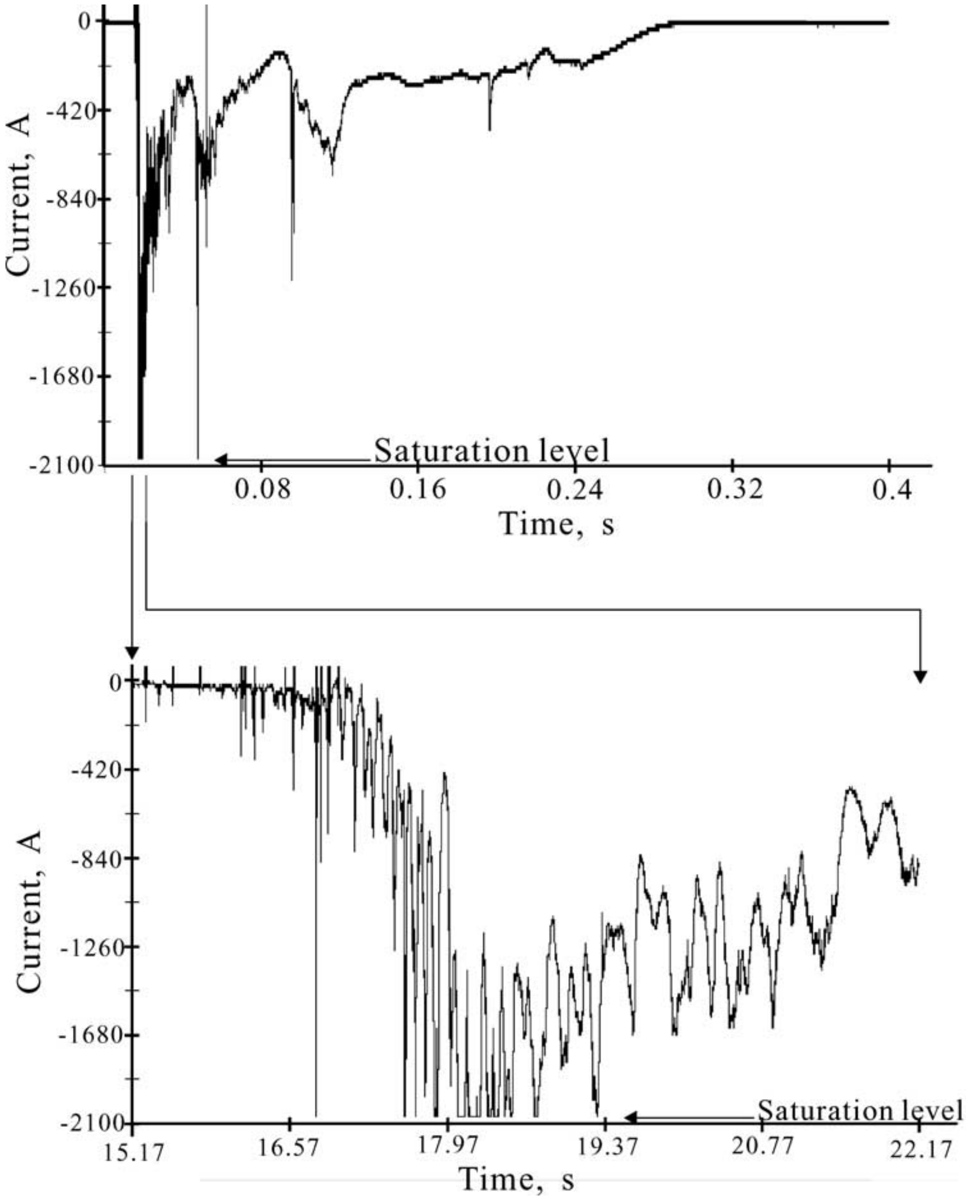

Figure 16. Current waveforms of the initial stage exhibiting pulsations during its initial portion in a Gaisberg tower flash (see section 4.2).

occurrence of the pulsation apparently does not depend on season.

[36] The overall characteristics of the IS current waveforms of type P and type S are compared in Table 6. The IS duration of type P is not much different from that of the type S. On the other hand, the charge, the average current, and the action integral of the type P waveforms are larger (particularly the action integral) than those of type S. The GM value of the action integral for Fukui chimney flashes, which are all of type P, is also very large. Thus upward flashes with the IS of type P involve larger energy than upward flashes with the IS of type S. We summarize the characteristics of the IS of type P as follows: (1) The percentage of the type P initial stage varies from 16 to more that 90% depending on location. (2) The pulsation of the current occurs during the first 10–20 ms, that is, during the upward positive leader stage of the discharge. (3) The occurrence of the type P initial stage appears to be independent of season. (4) Upward flashes with type P initial stage are characterized by higher energy than those with type S initial stage.

4.3. Possible Origins of ICC Pulses

[37] As seen in Table 4, ICC pulses in natural upward lightning and in Florida rocket-triggered lightning are different. The ICC pulses in object-initiated lightning exhibit larger peaks, shorter risetimes, and shorter half-peak widths than do the initial stage pulses in rocket-triggered lightning. Some ICC pulses in natural upward lightning exhibit a risetime of less than 1 μs, as shown in Figure 15b, comparable to the risetime of current pulses associated with return strokes. The number of ICC pulses that exhibited risetimes less than 1 μs is 11 in the Fukui chimney, 1 in the Peissenberg tower, and 10 in the Gaisberg tower data. There are no pulses with risetimes less than 1 μs in the Florida rocket-triggered lightning data.

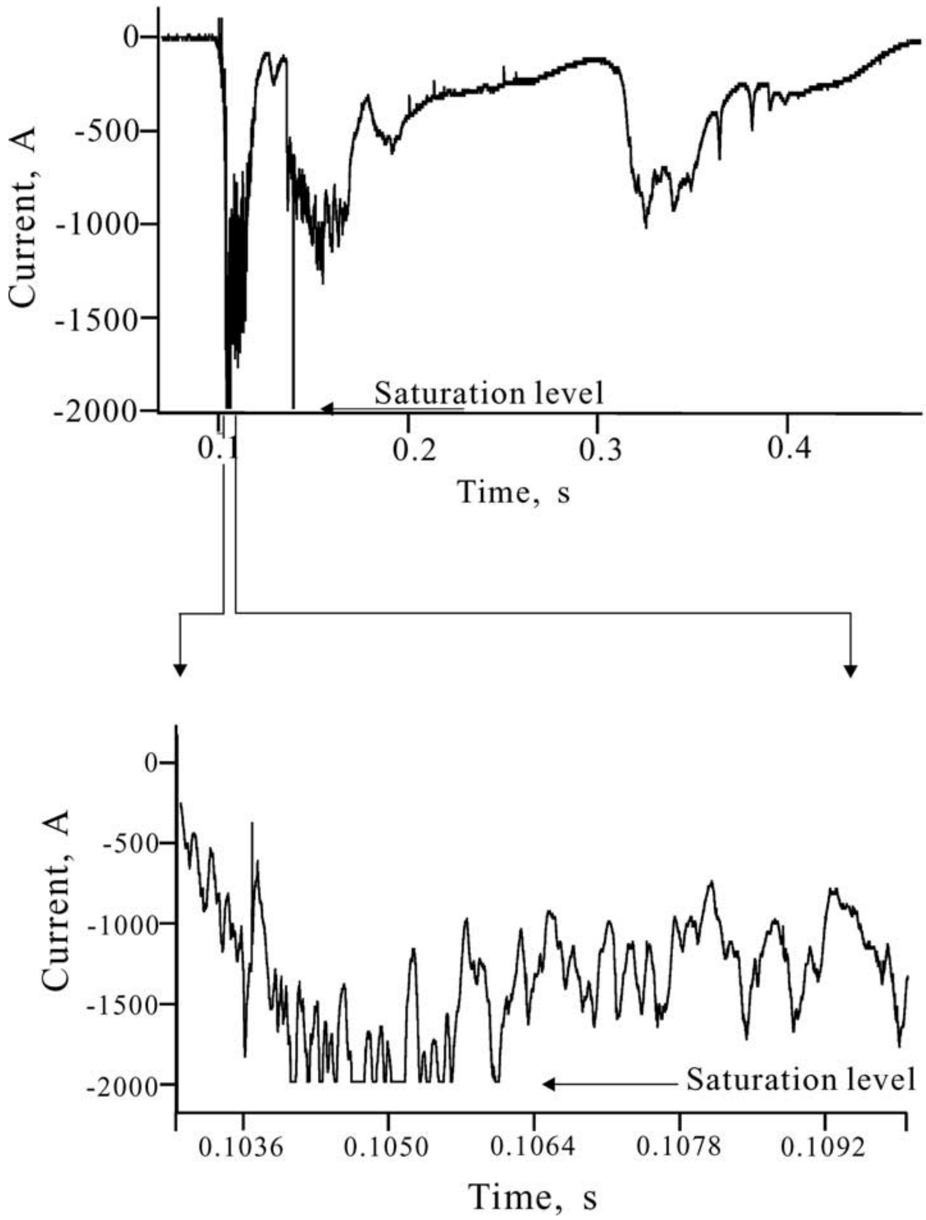

Figure 17. Current waveforms of the initial stage exhibiting pulsations during its initial portion in a Peissenberg tower flash (see section 4.2).

[38] There are two possible reasons for the apparent dissimilarity between the pulses in object-initiated flashes and those in rocket-triggered lightning. First, multiple upward branches could have facilitated the simultaneous occurrence of a continuous current in one branch and a downward leader in another branch in object-initiated flashes. The optical observations of Monte San Salvatore [*Berger*, 1967] and Ostankino tower flashes [*Gorin et al.*, 1975] show evidence for such a scenario. This hypothesis (further discussed in section 5 below) implies that triggered lightning flashes in Florida are less likely to have upward branches originating near the strike point than does lightning at the Gaisberg tower, the Peissenberg tower, and the Fukui chimney. Second, the charge sources for initial stage

Table 5. Characterization of the P Type of Initial Stage in Natural Upward Lightning

Experimental Site	Sample Size	Percent of Type P, %	Period of Ringing, μs Minimum	Median	Maximum	Pulsation Duration, ms
Gaisberg tower	74	16	12.4	7 8	1808	11
Peissenberg tower	21	29	14.9	1 4 8	6309	19
Fukui chimney	36	>90	13.8	8 3	1013	11

Table 6. Overall Characteristics (Geometric Mean Values) of the Two Types of Initial Stage in Natural Upward Lightning

Experimental Site	Type of IS	Sample Size	Duration, ms	Charge, C	Average Current, A	Action Integral, 10^3 A^2s
Gaisberg tower (Austria)	P	12	276	63.3	229	9.0
Gaisberg tower (Austria)	S	62	223	25.0	112	1.1
Peissenberg tower (Germany)	P	6	257	59.1	230	11
Peissenberg tower (Germany)	S	15	304	32.5	107	2.3
Fukui chimney (Japan)	P	33	>73.1	>31.9	437	33
Fukui chimney (Japan)	S	0	–	–	–	–

current pulses in thunderclouds over the tall objects in Austria, Germany, and Japan might be located closer to the lightning attachment point than the sources of initial stage current pulses in Florida. In this case, because of the shorter propagation path between the in-cloud source and the lightning attachment point, the fronts of the downward propagating current waves in object-initiated flashes might have suffered less degradation due to dispersion and attenuation than their counterparts in Florida rocket-triggered flashes.

[39] In order to test the latter hypothesis, we compare in Table 7 parameters of ICC pulses in Gaisberg tower flashes that occurred in summer and in winter. It is expected that cloud charge sources in winter are lower than those in summer (see Table 1, where the height of the $-10°C$ isotherm approximately indicates the source height [e.g., *Uman*, 1987]). If this hypothesis is true, ICC pulses in winter flashes should exhibit larger peaks, shorter risetimes, and shorter half-peak widths than ICC pulses in summer flashes. As seen in Table 7, all the parameters are similar (given the limited sample sizes), except for the risetime, which is appreciably smaller in winter than in summer. This latter observation supports the suggested influence of the cloud charge source height (via the propagation path length) on the parameters of ICC pulses. More data are needed to draw more reliable conclusions.

5. Summary and Concluding Remarks

[40] We compared the overall characteristics of the IS and the parameters of ICC pulses in Florida rocket-triggered lightning with those in natural upward lightning initiated from the Gaisberg tower, Peissenberg tower, and Fukui chimney). The geometric mean (GM) values of the three overall characteristics of the IS, duration (T), charge transfer (Q), and average current (I), for rocket-triggered lightning (T = 305 ms, Q = 30.4 C, I = 99.6 A) are similar to their counterparts for Gaisberg tower flashes (T = 235 ms, Q = 29.6 C, I = 126 A) and Peissenberg tower flashes (T = 290 ms, Q = 38.5 C, I = 133 A), while the Fukui chimney flashes are characterized by a shorter GM initial stage duration (T = 82.5 ms) and a larger average current (I = 465 A). The GM initial stage charge transfer for the Fukui chimney flashes is 38.9 C, similar to the GM values in the other three data sets. The GM values of action integral differ considerably among the four data sets, with the value for rocket-triggered lightning, 8.5×10^3 A^2s, being larger than the values for the Gaisberg tower 1.5×10^3 A^2s and for the Peissenberg tower 3.5×10^3 A^2s, but smaller than for the Fukui chimney 40×10^3 A^2s. Thus it appears that the initial stage of rocket-triggered lightning is generally (in most respects) similar to that of natural upward lightning, except for Fukui chimney flashes. The observed differences in the IS duration between the Fukui data set and all other data considered here is probably related to the differences in the lower current measurement limits: about 200 A for the Fukui data set versus 15–20 A for the other three data sets. It appears that even accounting for all the instrumental effects, the action integral for Fukui flashes is considerably larger than for the other three data sets.

[41] ICC pulses in natural upward lightning appear to be similar in different geographical locations (Austria, Germany, Japan), while parameters of ICC pulses in Florida rocket-triggered lightning are different from those in natural upward lightning. The GM values of the parameters of ICC pulses, peak (P), duration (D), risetime (R), half-peak width (H), for Gaisberg tower flashes (P = >377 A, D = 1.2 ms, R = 110 μs, H = 276 μs), Peissenberg tower flashes (P = 512 A, D = 0.833 ms, R = 60.9 μs, H = 153 μs), and Fukui chimney (P = 781 A, D = 0.514 ms, R = 44.2 μs, H = 141 μs) are similar, while ICC pulses in Florida rocket-triggered lightning are characterized by a smaller GM peak (P = 113 A), longer duration (D = 2.59 ms), larger risetime (R = 464 μs) and larger half-peak width (H = 943 μs). It is worth noting that the peak, risetime, and half-peak width for Florida rocket-triggered lightning are underestimated because of the insufficient sampling rate in 1996, 1997, and 1999, although the bias is probably not too large. ICC pulses in rocket-triggered lightning are similar to M component pulses in rocket-triggered lightning in the same location (Florida).

[42] Larger and sharper ICC pulses in natural upward lightning in Austria, Germany, and Japan, not observed in Florida rocket-triggered lightning, might be associated with downward leader/upward return stroke sequences in one branch while another branch was carrying a continuous current, the two branches originating from a common channel section attached to the strike object. This scenario (observed in other experiments [e.g., *Berger*, 1967; *Gorin et al.*, 1975]) implies that the branch carrying the leader/return stroke sequence decayed to such a point that an M component type process was not possible, and the leader process was required to transport charge along this essentially nonconducting path [*Rakov et al.*, 2001]. Additionally, larger and sharper pulses in natural upward lightning in Austria, Germany, and Japan could be due to the shorter propagation path

Table 7. Parameters (Median Values) of ICC Pulses in Gaisberg Tower Flashes as a Function of Season

Season	Sample Size	Peak, A	Duration, ms	Risetime, μs	HPW,[a] μs
Winter	160	319	1.03	74.9	298
Summer	218	368	1.25	134	269

[a]HPW, half-peak width.

(compared to Florida rocket-triggered lightning) between the cloud charge source and the lightning attachment point, so that these pulses suffered less degradation while traversing resistive channels. The lack of sharp ICC pulses in Florida rocket-triggered lightning suggests that lightning channels in Florida (1) are longer and (2) less often have upward branches originating at relatively low altitudes than do channels of natural upward flashes in Austria, Germany, and Japan. Both these features appear to be consistent with optical observations and with the fact that the cloud charge source in Florida (in summer) is located at higher altitudes than in Austria, Germany, and Japan in any season and particularly in winter.

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