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Microsecond-scale electric field pulses in cloud lightning discharges

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Abstract. From wideband electric field records acquired using a 12-bit digitizing system with a 500-ns sampling interval, microsecond-scale pulses in different stages of cloud flashes in Florida and New Mexico are analyzed. Pulse occurrence statistics and waveshape characteristics are presented. The larger pulses tend to occur early in the flash, confirming the results of Bils et al. (1988) and in contrast with the three-stage representation of cloud-discharge electric fields suggested by Kitagawa and Brook (1960). Possible explanations for the discrepancy are discussed. The tendency for the larger pulses to occur early in the cloud flash suggests that they are related to the initial in-cloud channel formation processes and contradicts the common view found in the atmospheric radio-noise literature that the main sources of VLF/LF electromagnetic radiation in cloud flashes are the K processes which occur in the final, or J type, part of the cloud discharge.

Introduction

It is common, following the work of *Kitagawa and Brook* [1960, Figure 6] to portray the electric field signature of cloud lightning discharges as composed of three portions which are labeled initial, very active, and final. These three portions were identified by *Kitagawa and Brook* [1960] in records from their two field-measuring systems: one, a "slow antenna," having a 4-s decay time constant and the other, a "fast antenna," having a submillisecond (300 μs or 70 μs) decay time constant and a significantly higher gain than the "slow antenna." The initial portion of the cloud flash was reported to have a duration of typically 100 to 200 ms [*Kitagawa and Brook*, 1960, Figure 11] and to be characterized by microsecond-scale pulses (identified in the fast-antenna records) of relatively small amplitude and by relatively small electrostatic field change (identified in the slow-antenna records). *Kitagawa and Brook* [1960] observed the electrostatic field change during the very active portion to be the largest of the flash and the pulse amplitudes to become much larger than during the initial portion. The final, or J type, portion was reported by *Kitagawa and Brook* [1960] to be similar to the field changes between strokes and after the last stroke of the cloud-to-ground discharge and is characterized by relatively small steplike K field changes. Note that the K changes appear (similar to the steplike field changes during the very active stage) not as steps but rather as pulses if they are recorded with a measuring system having a submillisecond decay time constant [*Thottappillil et al.*, 1990; *Rakov et al.*, 1992], an effect evident in the fast-antenna trace shown by *Kitagawa and Brook* [1960] in the top portion of their Figure 6. Note also that since this trace is displayed on a time scale of about 500 ms, it does not show the microsecond-scale structure of the cloud-flash field.

Recently, the University of Florida lightning research group [*Bils et al.*, 1988], from an analysis of tape-recorded cloud-flash electric fields, found that the largest microsecond-scale pulses occurred predominantly in the early part of the cloud flash, typically in the first 20 ms. This observation is in opposition to the common picture of the cloud discharge just described, according to which the initial typically 100 to 200 ms of the cloud-discharge electric field is characterized by pulses of relatively small amplitude. Additionally, the tendency for the larger microsecond-scale pulses to occur early in the flash contradicts the common view found in the atmospheric radio-noise literature [e.g., *Arnold and Pierce*, 1964; *Pierce*, 1977] that the main sources of VLF/LF electromagnetic radiation in cloud flashes are the K processes which are known to occur in the final stage of the cloud flash.

The three-stage structure of the cloud flash suggested by *Kitagawa and Brook* [1960] is based on their observations of continental thunderstorms in New Mexico at ground elevations of about 2 km above sea level, while the results of *Bils et al.* [1988] are based on the data from one maritime storm in Florida at approximately sea level. Further, the measuring and recording systems in New Mexico and Florida differ appreciably in their time resolution and noise level. To determine if the discrepancy between the New Mexico and the Florida observations is due to the differences in observation techniques or in types of thunderstorm, we have analyzed additional cloud-flash data from both New Mexico and Florida. In both

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locations the data have been acquired with the same 12-bit digitizing system [*Brook*, 1992] characterized by a 500-ns sampling interval with individual record lengths up to a few seconds. The digitizer was fed from a flat-plate antenna via an integrator and a low-pass antialiasing filter with an overall response time to a step function input of about 700 ns. The decay time constant of the system could be selected in the range from tens of microseconds to many seconds. For decay time constant of 10 s, used for acquiring most of the data analyzed here, the useful bandwidth of the system was from 0.1 Hz to just under 1 MHz. The system noise level was as low as ±1 bit (about 5 mV on a 5-V scale). The system was carefully tested using various input signals (square wave, sine wave, etc.) and yielded the expected responses. The software we employed for data analysis allowed us to readily manipulate the display timescale. No smoothing was applied to any records involved in this study. Unfortunately, no absolute-amplitude calibration of the recorded data was obtained.

Data and Results

A summary of the data analyzed is given in Table 1. The New Mexico data were acquired in Socorro, approximately the same location as the data of *Kitagawa and Brook* [1960], while the Florida data were taken at the Kennedy Space Center (KSC) where the previous UF data [*Bils et al.*, 1988] were obtained and, additionally, in Gainesville (north central part of the Florida peninsula). At all three locations a measuring system with a decay time constant of 10 s was used. Following the terminology introduced by *Kitagawa and Brook* [1960], we call this system configuration a "slow antenna." At KSC, a system with a decay time constant of 150 μs and a much higher gain, which we, following *Kitagawa and Brook* [1960], call a "fast antenna," was also employed. This system accentuated the microsecond-scale, predominantly radiation, field variations.

All records analyzed here are longer than 500 ms and contain both early and final (or J type) portions [*Kitagawa and Brook*, 1960]. No reliable information on the distance to the recorded discharges is available. In Figures 1a, 2a, and 3 (top portions) we show examples of the overall electric field changes (as recorded by the slow antenna) due to cloud discharges from KSC, Socorro, and Gainesville, respectively. The field changes are initially negative-going (opposite in polarity to the field change due to a cloud-to-ground discharge lowering negative charge to Earth). Microsecond-scale pulses do not appear in the overall flash electric field changes shown in Figures 1a, 2a, and 3 due to undersampling of the data by the computer plotting program. Figures 1b and 2b show the first 25 ms of the cloud-flash fields presented in Figures 1a and 2a, respectively, plotted with software which searches for minima and maxima instead of taking evenly spaced points so that all prominent pulses are preserved in the plot. The pulse occurrence statistics presented here have been derived from the slow-antenna records. It is worth noting that many of the slow-antenna records (particularly from KSC and Gainesville), presumably at relatively close ranges, contain no pronounced pulse activity. Most likely, the pulses do exist but are undetectable due to being overwhelmed by the electrostatic fields dominant at closer ranges. Those pulseless records are not considered here. The pulse waveshape characteristics were measured from the fast-antenna records which provide better reproduction of the microsecond-scale features than the slow-antenna records. In Figures 4a and 4b we show examples of the typical single-peaked and multiple-peaked pulses, respectively, recorded by the fast antenna.

We identified the larger microsecond-scale pulses in the slow-antenna records and grouped those pulses into three categories according to relative pulse magnitude, as follows: We first found the average peak-to-peak amplitude of the five largest pulses in the flash. Then all pulses with peak-to-peak amplitude greater than or equal to 50% of that average amplitude were labeled "large pulses," pulses with amplitudes between 25% (including 25%) and 50% of the average amplitude were labeled "medium pulses," and pulses between 12.5% (including 12.5%) and 25% of the average amplitude were labeled "small pulses." Pulses that were too small to fit in the "small" category (in some flashes there were hundreds of them) are not included in this analysis. In the Gainesville data (five flashes) it was impossible to sort pulses by their size using the described algorithm due to the very narrow range of observed pulse magnitudes. For each pulse category, when possible, we determined the pulse occurrence distribution in the form of histograms (in 20-ms

Table 1. Summary of Data Analyzed

Geographical Location	Socorro, New Mexico	KSC, Florida	Gainesville, Florida
Time period	August 1989	July, August, 1991	September 1991
Measurement system	slow antenna	slow and fast antennas	slow antenna
Number of flashes	8	4*	5

KSC, Kennedy Space Center.

*Three flashes were recorded simultaneously by the slow and fast antennas; one flash was recorded by the slow antenna only.

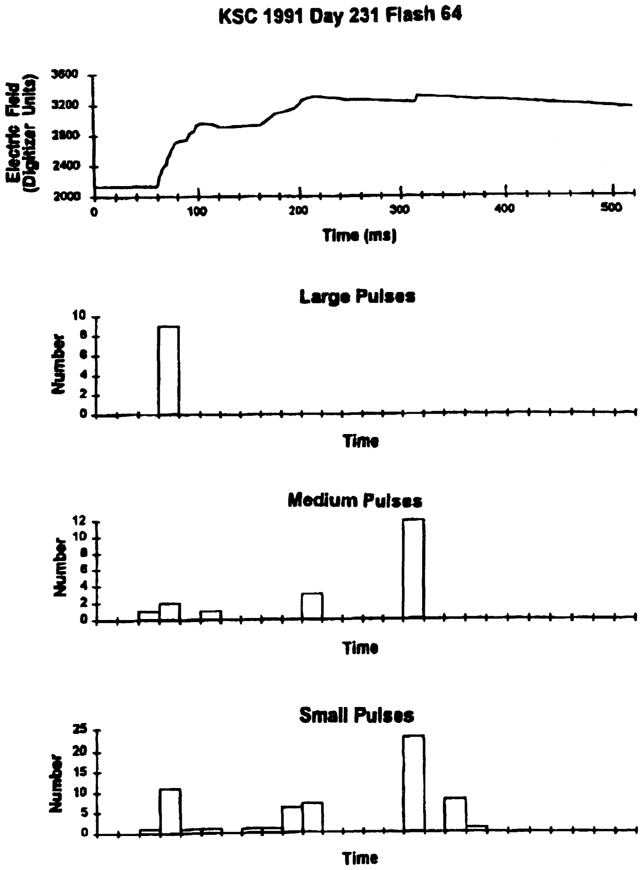

Figure 1a. Histograms of the occurrence of large, medium, and small pulses (defined in the text) in different parts of a cloud flash at the Kennedy Space Center (KSC), Florida, whose overall electric field is shown in the top portion of the figure. The field and histograms are displayed on the same timescale. Negative field change (atmospheric electricity sign convention) deflects upward.

intervals for the overall flash record and, additionally, in 1-ms intervals for the first 25 ms of the discharge). Histograms are shown on the same timescale as the corresponding lightning electric field changes. Figures 1a and 1b show the results for a typical cloud discharge at KSC. Large pulses have a clear tendency to occur early in the flash, in accordance with the previous finding of *Bils et al.* [1988] and in contradiction to the three-stage representation of cloud-flash electric fields suggested by *Kitagawa and Brook* [1960]. Figures 2a and 2b show, in the same format, an example of a cloud flash from New Mexico. The same tendency for the large pulses to occur at the beginning of the discharge is evident. Figure 3 shows the results (all pulses combined in a single category) for a typical flash in Gainesville.

Table 2 gives a summary of the occurrence statistics for the large pulses in the Socorro and KSC flashes. In the table the "early stage" is arbitrarily defined as the first 80 ms after the initial deflection of the electric field from the preceding more-or-less flat level. The rest of the record was termed the "late stage." In most cases the first electrostatic field maximum is attained within the early stage. The "entire flash" in Table 2 is merely the sum of the early and late stages.

Pulse Occurrence Statistics

The larger pulses usually appear at the times of the largest changes in the cloud flash electric field. In most cases this corresponds to the first deflection of the field from the preceding flat level. On average, more than 70% of the large pulses in New Mexico and more than 80% at KSC occurred during the early stage. This observation suggests the relation of those pulses to the initial channel formation processes of the cloud flash. On average, 59% of the large pulses in New Mexico and 66% at KSC occurred during the first 20 ms of the discharge. This result is consistent with the pulse occurrence statistics of *Bils et al.* [1988] and with the cloud-channel formation time of 10 to 30 ms inferred from the multiple-station electric field measurements of *Liu and Krehbiel* [1985]. *Pierce* [1955] also reported that radiation pulses associated with cloud flashes in Great Britain at ranges of 40 to 100 km were usually confined to the first 10 to 20 ms of the flash. It is important to note that, as follows from our data, a significant fraction (more than half in New Mexico and 45% at KSC) of large pulses occur within first 5 ms of the flash, while the typical overall duration of a cloud discharge is some hundreds of milliseconds. There were,

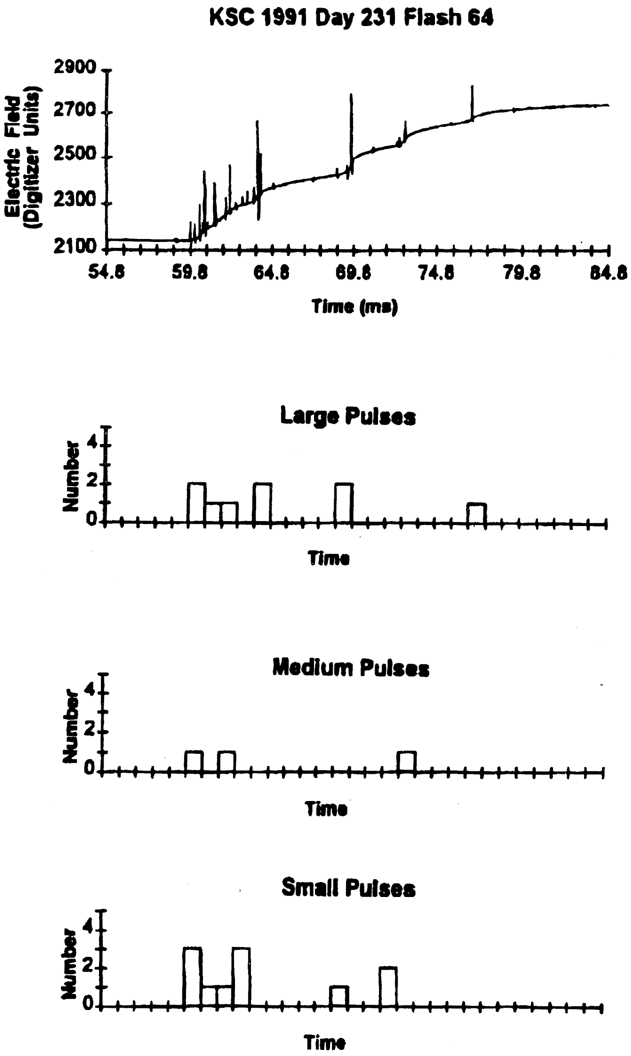

Figure 1b. Similar to Figure 1a but for the first 25 ms of the flash.

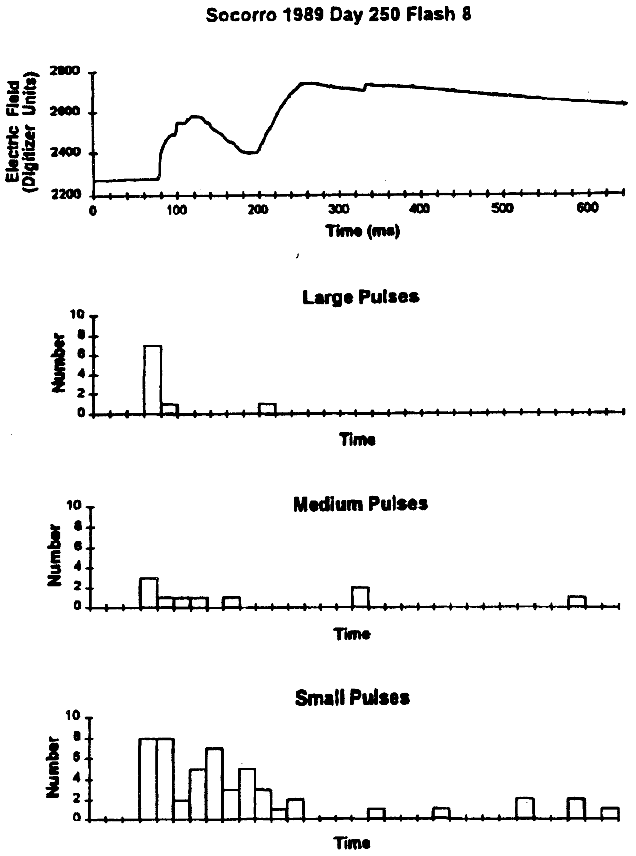

Figure 2a. Similar to Figure 1a but for a flash in Socorro, New Mexico.

on average, 11 large pulses per flash in Socorro and 9.5 at KSC (about 3 times more than the 3.7 pulses detected per flash by *Bils et al.* 1988]. In the Gainesville data (Figure 3) the majority of pulses occurred during the first few tens of milliseconds of the flash, consistent with the occurrence of large pulses in the Socorro and KSC data.

Less than 30% of the large pulses occurred during the late stage of the flash, where the relatively small steplike K field changes usually occur. In many cases a subsidiary burst of large pulses, following the initial group of large pulses, corresponded to a sudden, relatively large increase in the slope of the flash electric field change, perhaps due to the onset of a new in-cloud channel formation process. The fact that the larger pulses tend to avoid the late stage of the flash (although the occurrence of smaller pulses may be largest there), where the K changes are known to occur, indicates that most of the large microsecond-scale field pulses are not produced by K processes. A similar observation has been previously reported by *Bils et al.* [1988]. In fact, with a few exceptions the K-type field steps in the 12 flashes from Socorro and KSC presented in Table 2 did not contain large microsecond-scale pulses, only smaller pulses, if any pulses at all were detectable.

The statistics on the occurrence of the medium and small pulses differ significantly from the statistics for large pulses. For the medium-pulse category the fraction of pulses in the early and late stages was, on average, 51.5% and 47.0%, respectively, in Socorro and 39.1% and 60.4%, respectively, at KSC. In contrast with the large pulses, some medium pulses (1.5% in Socorro and 0.5% at KSC)

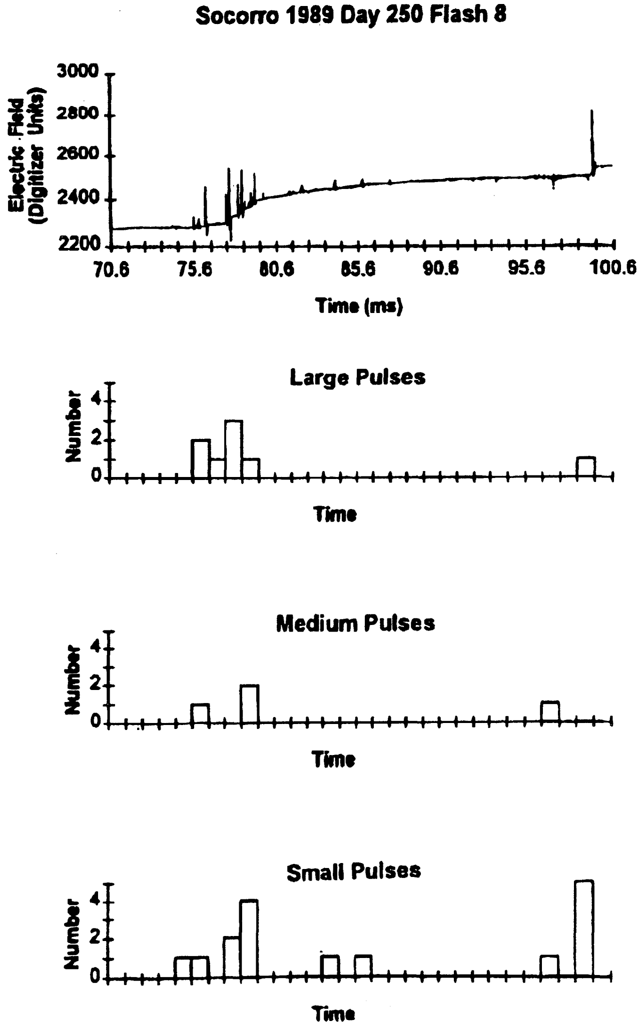

Figure 2b. Similar to Figure 1a but for the first 25 ms of the flash in Socorro, New Mexico, whose overall electric field and histograms are shown in Figure 2a.

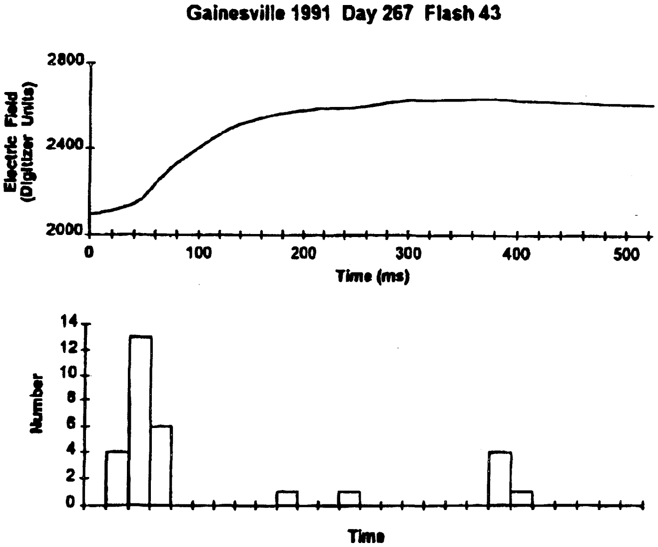

Figure 3. Similar to Figure 1a but for a flash in Gainesville, Florida, with all pulses being combined in a single category.

Table 2. Occurrence of Large Pulses in Different Parts of Cloud Flash

		Number of Pulses Within				
		Early Stage				
Day	Flash	First 5 ms	First 20 ms	First 80 ms	Late Stage	Entire Flash
		Socorro, New Mexico, 1989				
242	76	9	9	10	0	10
246	50	6	6	10	4	14
250	6	2	3	4	13	17
250	7	4	4	6	3	9
250	8	7	8	8	1	9
250	9	7	9	10	0	10
250	12	5	6	7	2	9
250	13	6	6	8	0	8
Total pulses		46	51	63	23	86
Average number of pulses (percentage)		5.8 (53)	6.4 (59)	7.9 (73)	2.9 (27)	11 (100)
		KSC, Florida, 1991				
205	37	6	6	6	0	6
225	297	2	6	7	7	14
231	64	6	9	9	0	9
236	6	3	4	9	0	9
Total pulses		7	25	31	7	38
Average number of pulses (percentage)		4.3 (45)	6.3 (66)	7.8 (82)	1.8 (18)	9.5 (100)

occurred before the initial deflection of the electrostatic field from the preceding flat level, i. e., before the early stage. There were, on average, 17 medium pulses per flash in Socorro and 53 at KSC. For the small-pulse category the fraction of pulses in the early and late stages was, on average, 37.0% and 60.0%, respectively, in Socorro and 37.4% and 61.2%, respectively, at KSC, with 3.0% (Socorro) and 1.4% (KSC) occurring before the early stage. There were, on average, 49 small pulses per flash in Socorro and 185 at KSC. We do not attach much significance to the disparity in the average number of medium and small pulses per flash at the two locations since it might be due to different system gains used to keep lightning signals arriving from different ranges on scale.

Summarizing, using the same measuring and recording system in three geographical locations, we have found the dominant microsecond-scale pulse activity in cloud flashes to occur at the beginning of the flash. This result indicates that most of the larger pulses are not associated with K changes which are known to occur in the late stage of the cloud discharge but presumably with the initial in-cloud channel formation processes.

Pulse Waveshape Characteristics

A summary of the waveshape characteristics of representative large pulses from three cloud flashes that occurred in three different thunderstorms at KSC is presented in Table 3. All the pulses were negative, 17 of them having single-peaked and 6 multiple-peaked waveshapes (see examples in Figure 4). We did not attempt to determine the 30-90% [*Bils et al.*, 1988] or 10-90% [*Medelius et al.*, 1991] risetimes of the pulses, because these times were expected to be comparable to the digitizer sampling interval of 0.5 μs. The pulse waveshape characteristics summarized in Table 3 are, in general, similar to those reported in the literature [e.g.,

Table 3. Characteristics of Large Pulses

	Single-Peaked Pulses			Multiple-Peaked Pulses			All Pulses		
Waveshape Parameter	M	s.d.	N	M	s.d.	N	M	s.d.	N
Total pulse width including overshoot, μs	53	35	17	61	36	6	55	34	23
Full width of the initial peak, μs	25	13	17	27	8.1	6	26	11	23
Initial peak width at 10% peak value, μs	8.2	6.7	16	14	2.7	4	9.2	6.4	20
Initial peak width at half value,* μs	2.8	1.0	17	2.2	.95	4	2.7	1.0	21
Ratio of initial peak to overshoot	5.7	2.1	14	4.1	1.8	4	5.4	2.1	18

M, s.d., and N are the mean value, standard deviation, and sample size, respectively.

*In the case of multiple-peaked pulses, if there was a gap between the peaks at the half initial peak value, this parameter was not measured.

Weidman and Krider, 1979; *Cooray and Lundquist*, 1985; *Bils et al.*, 1988] for cloud flashes.

Discussion

Although we have proved that the major microsecond-scale pulse activity in cloud flashes occurs early in the flash and hence is likely associated with the initial in-cloud channel formation processes, the question remains why *Kitagawa and Brook* [1960] reported that the initial 100 to 200 ms or so of their cloud-discharge electric field were characterized by both small electrostatic field changes and by pulses of relatively small amplitude. From an examination of a sample of the original records of Kitagawa and Brook we have determined that the suggestion of *Bils et al.* [1988] that *Kitagawa and Brook* [1960] had insufficient time resolution to detect microsecond-scale pulses is not valid. Two possible explanations for the apparent dissimilarities between the results of *Kitagawa and Brook* [1960] and those of both *Bils et al.* [1988] and this study follow.

1. The distinction between initial and very active stages was exaggerated by *Kitagawa and Brook* [1960]. Similar to *Bils et al.* [1988] we could decompose our flash records, based on the occurrence of larger pulses, into two stages only: early, where most of the pulses occur, and late, characterized by a lack of the pulses. We were not given any clue which would allow us to separate the early part of the cloud flash records into the initial and very active stages of *Kitagawa and Brook* [1960]. In fact, the main burst of large pulses almost invariably marked the beginning of the cloud flash. Note that *Kitagawa and Brook* [1960] stressed the distinction only between the early and the late stages and exercised caution that "the difference between the initial and very active portions is not always well marked, the transition from one to the other usually being more or less gradual," and that in more than 40%

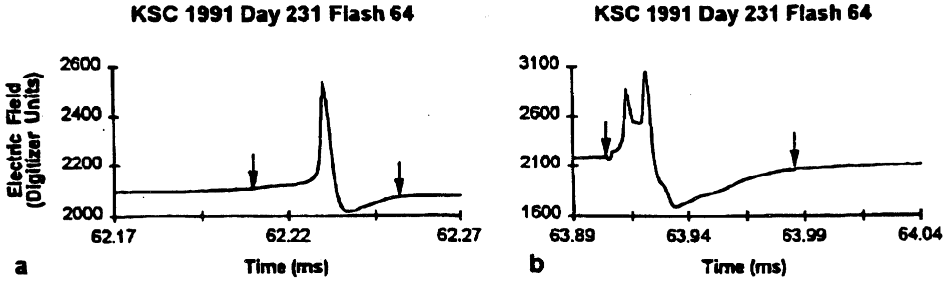

Figure 4. Examples of (a) single-peaked and (b) multiple-peaked electric field pulses in cloud flashes. Both waveforms are from a single KSC flash, belong to the large-pulse category, and occurred within the first 5 ms of the cloud discharge. Negative field change (atmospheric electricity sign convention) deflects upward. The arrows show the starting point and ending point we have chosen for our waveshape parameter measurements.

of the cases examined by *Kitagawa and Brook* [1960] the initial portion was absent. Further, Kitagawa and Brook present only two stages, early (initial) and late, not three, in their abstract and summary. Later, *Ogawa and Brook* [1964] considered the same physical process to be responsible for both the initial and the very active stages and called the entirety of those two "the initial part of the discharge," as opposed to its final part.

2. The scenario of cloud discharge may vary depending on in-cloud conditions. There may be two types of cloud flashes: those exhibiting major pulse activity at the very beginning of the discharge (no initial stage), as observed by *Bils et al.* [1988] and in the present work, and those showing larger microsecond-scale field pulses only after some preliminary, relatively inactive processes have occurred, as reported by *Kitagawa and Brook* [1960]. Some support for this hypothesis comes from *Proctor* [1981] and *Proctor et al.* [1988] who reported, based on VHF imaging of lightning channels in conjunction with electric field measurements, that their observed cloud flashes could be divided into two categories that differ in several respects, one of which being the presence or absence of an initial stage. However, it is not clear if *Proctor* [1981] and *Proctor et al.* [1988] actually adopt the definition of the initial stage of *Kitagawa and Brook* [1960], as they claim. Indeed, *Proctor et al.* [1988] give no figure showing an initial stage of a cloud discharge, and the field change identified as the initial stage (about 17 ms in duration) by *Proctor* [1981] in his Figure 9 is essentially flat and not associated with any pulses in his fast-antenna record (trace labeled "S pulses" in Figure 9 of *Proctor* [1981], only with VHF radiation interpreted by *Proctor* [1981] as being due to ionization of the flash origin. Interestingly, no S pulses appear in the very active stage of this flash either. Thus it appears to us that *Proctor* [1981] could not use the electric field records alone (without VHF imaging) to identify the initial stage of the cloud flash presented in his Figure 9 and, if so, his definition of this stage, in general, may be different from that of *Kitagawa and Brook* [1960].

If we assume, on the other hand, that the example of cloud discharge properties given by *Proctor* [1981] in his Figure 9 is not representative in terms of the electric field records of the 96 total flashes that according to *Proctor* [1981] contain the initial stage, as defined by *Kitagawa and Brook* [1960], the existence of two types of cloud flashes identified by *Proctor* [1981] and *Proctor et al.* [1988] could possibly reconcile our and *Bils et al.*'s [1988] measurements with those of Kitagawa and Brook. According to *Proctor et al.* [1988], cloud flashes lacking the initial stage emitted VHF pulses at high rates (10^5 or more pulses per second) and began in relatively low regions of the cloud (about 5.2 km above mean sea level (amsl)) where the environmental temperature was on average -4.2°C. Interestingly, all cloud-to-ground flashes also originated in these lower cloud regions. According to *Proctor et al.* [1988], cloud flashes that did exhibit the initial stage emitted VHF pulses at low rates (about 10^4 or less pulses per second) and began in appreciably higher cloud regions (about 9 km amsl) where the temperature was on average -23°C. *Proctor* [1981] reported that 96 (61%) of 157 cloud flashes emitted pulses at the lower rates and hence exhibited an initial stage. In VHF images the initial stage appears as stationary ionization of the flash origin, the very active stage is associated with the extension of the main channel, presumably producing radiation field pulses, and the final stage with recoil streamers [*Ogawa and Brook*, 1964] and no further channel extension. Perhaps, the lack of large water drops, known to significantly reduce the breakdown field [e.g., *Macky*, 1931], can at high altitudes inhibit the formation of a developing plasma channel. As a result, some preliminary discharge activity, which manifests itself as an initial stage, may be required to make the higher cloud charge source region capable of generating a self-extending streamer (presumably producing radiation field pulses). In the lower cloud regions the precipitation mix is apparently such as to allow such a self-extending streamer to be formed without such preliminary processes.

Kitagawa and Brook [1960], based on 1400 cloud-flash records, reported that 50 to 60% of all cloud flashes exhibited the relatively inactive initial stage. If about half of cloud flashes contain the initial stage characterized by relatively small pulses, it is difficult to explain why all 17 flashes analyzed here (six came from a single storm in Socorro and five from a single storm in Gainesville) appear to lack that stage. Perhaps the medium pulses and small pulses occurring in 7 (58%) out of 12 flashes from Socorro and KSC during some tens of milliseconds before the early stage, the beginning of which is usually marked by larger pulses, could be interpreted as indicative of the initial stage. However, there was no detectable electrostatic field change corresponding to those preliminary pulses.

Concluding Remarks

As mentioned earlier, we have examined a sample (about 20 cloud flashes) of the original records of Kitagawa and Brook. From this analysis we find that a few flashes can be viewed as having initial, very active, and final portions. However, by far the largest number of flashes exhibited the largest microsecond-scale pulses at the start of the flash. It appears, from the sample of Kitagawa and Brook's data, that the assignment of more than two "portions" to a flash is at best a highly subjective judgment. What is characteristic in the sequence of microsecond-scale pulse activity in a cloud discharge is the occurrence first of an early period associated with the occurrence of many larger pulses followed by a late period showing a significantly lower pulse activity. The later pulses were generally associated with K changes, were usually smaller in amplitude and more irregular in waveshape than the early pulses (see also *Bils et al.* [1988]), and sometimes appeared as trains of band-limited noise, similar to those observed by *Rakov et al.* [1992, Figure 6] in ground-flash K changes.

Based on the dissimilarity between the early and the later microsecond-scale pulse activity in all available electric field data, including the 17 cloud flashes in the present study, the sample of about 20 flashes of Kitagawa and Brook, and the six flashes from *Bils et al.* [1988], it is reasonable to postulate that physical processes occurring during the early and during the late stages of a cloud discharge are essentially different. Thus, based on these electric field data, the characterization of a cloud flash as having an early part followed by a late part would be the most reasonable division, removing most of the subjective judgment involved in the paper of *Kitagawa and Brook* [1960]. On the other hand, the fact that *Proctor* [1981] and *Proctor et al.* [1988] using VHF channel imaging observed that the early part of a cloud flash can involve either one process or two essentially different processes, depending on the height of the flash origin, coupled with the relative paucity of electric field data from cloud flashes that have been examined on a microsecond timescale, does not allow us to embrace a two-stage cloud flash structure without reservation. Clearly, more experimental data on cloud flashes (preferably electric field measurements correlated with VHF channel images) are needed if we are to improve our understanding of the relation between the microsecond-scale pulse structure in the overall cloud-flash electric field records and the physics of the cloud discharge.

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