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Preliminary breakdown pulses of cloud-to-ground lightning in winter thunderstorms in Japan

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ABSTRACT

Preliminary breakdown pulses (PBP) of 26 positive and 104 negative cloud-to-ground (CG) lightning flashes observed in winter thunderstorms in Hokuriku region of Japan are analyzed. Pulses in PBP train are mainly bipolar. Zero-crossing time of each pulse is about 7 us and total duration of each pulse train is about 1 ms. PBPs in negative CG lightning are classified as “BIL type” (59 cases) and “BL type” (45 cases). “BIL type” PBP contains an intermediate stage with little electric field changes. The time interval between PBP and the first return stroke (PBP–RS interval) is on average 5.4 ms for “BIL type” PBP, while that for “BL type” PBP is only 1.3 ms. Ratio of peak amplitude of PBP to the first return stroke (PBP–RS ratio) is on average 0.47 and 0.44, respectively, for “BIL type” and “BL type” PBPs, but the ratio for “BIL type” PBP has a much wider distribution. It is speculated that the intermediate stage in “BIL type” PBP is caused by horizontal propagation of leader channel. PBPs in positive CG lightning are classified as +PBP (11 cases) and −PBP (15 cases) according to their initial polarities. +PBP and −PBP have similar distributions of both PBP–RS interval and PBP–RS ratio, but their value of PBP–RS interval is much larger and their value of PBP–RS ratio is much smaller than corresponding values of PBPs in negative CG lightning. It is speculated that different initial polarities of +PBP and −PBP in positive CG lightning are caused by different directions of channel propagation.

1. Introduction

It has long been noticed that the first return stroke of cloud-to-ground (CG) lightning is sometimes preceded by a train of bipolar pulses lasting on the order of 1 ms (e.g., Clarence and Malan, 1957) and can be as long as 37 ms (Baharudin et al., 2012a). Such pulse train is generally attributed to preliminary breakdown, the initiation process of a lightning flash, so it is usually called preliminary breakdown pulses (PBP) or initial breakdown pulses. The largest amplitude of PBP is usually much smaller than that of the following first return stroke, but sometimes it can be comparable or even larger than that of return stroke (Brook, 1992; Gomes et al., 1998). The time interval between PBP and the first return stroke is on the order of 10 ms, but can be as long as several hundred milliseconds (Pierce, 1955; Beasley et al., 1982) and as short as 1 ms (Brook, 1992; Ushio et al., 1998). The initial polarity of PBP in negative CG lightning is always the same as that of the first return stroke. However, the situation for positive CG lightning is much more complicated. Opposite initial polarities between PBP and following return stroke are occasionally observed (Ushio et al., 1998; Nag and Rakov, 2012). According to their initial polarities, Gomes and Cooray (2004) classified PBPs in positive CG lightning into four types, including cases of polarity reversal and irregular polarity in PBP train.

The percentage of CG lightning with discernable PBP varies significantly in different studies. As summarized by Nag and Rakov (2009), such percentage apparently varies with latitude. The smallest percentage is 19%, recorded in Sri Lanka (7°N). In regions of higher latitudes, the percentage is much higher, such as 80% in Austria, 90% in Finland and 100% in Sweden. However, a recent observation in Malaysia (1°N) found that 97 out of 100 flashes had detectable PBPs (Baharudin et al., 2012a). All of these observations are for summer time lightning.

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Studies on PBP in winter time lightning are relatively few. Winter lightning is well known for many special features, such as high percentage of positive CG lightning (Brook et al., 1982), upward lightning and bipolar lightning (Narita et al., 1989). It is expected that PBP in winter lightning may also have certain special characteristics. Brook (1992) analyzed PBPs recorded during a winter thunderstorm in Albany N.Y., and found that PBP in negative CG lightning sometimes produced very strong electric field changes, and the interval between PBP and the following return stroke was very short. Ushio et al. (1998) analyzed pulse characteristics of PBP in 19 positive CG flashes observed in Hokuriku region of Japan in winter, which seemed to be similar with those in summer lightning but distinctively different from those in negative winter CG lightning as discussed by Brook (1992).

So far it is still not completely clear what exactly happens during preliminary breakdown pulses. Clarence and Malan (1957) proposed “BIL” model to characterize electric field waveform before the first return stroke, which included preliminary breakdown (B), intermediate stage (I) and stepped leader (L). They attributed the “B” part to vertical discharge between the main negative charge layer and the lower positive charge layer. Beasley et al. (1982) examined in detail the electric field changes preceding first return stroke, and found that only three out of 52 records agreed well with “BIL” model. But a recent study by Makela et al. (2008) found that “BIL” model could successfully describe electric field waveforms of cloud-to-ground lightning flash in Finland, and Baharudin et al. (2012a) reported that 47% of flashes in Malaysia were consistent with “BIL” model. However, the vertical discharge suggested by Clarence and Malan (1957) was not confirmed by further studies, as demonstrated by Krehbiel et al. (1979), Rhodes and Krehbiel (1989) and Shao (1993), preliminary breakdown involved one or more channels extending in largely horizontal directions. Nag and Rakov (2009) proposed four types of channel propagation starting from preliminary breakdown process according to the magnitude of low positive charge region. Their main idea is that PBP is produced by interaction between downward negative leader and the lower positive charge, and strong PBP can be indicative of large lower positive charge.

Due to the complicated nature of preliminary breakdown process, the special feature of winter lightning and the lack of PBP observation in winter lightning, we carried out this study on PBP of winter lightning in Hokuriku region of Japan. We will present statistical results on various characteristics of PBP in both positive and negative CG lightning, and based on the results, we will compare different types of PBPs.

2. Experiment and data

Winter lightning in Hokuriku region of Japan is well known for its unusual characteristics (Brook et al., 1982). For the study of winter lightning, we set up an LF broadband digital interferometer (DITF) in Hokuriku region near the Japan Sea coast during the winter of 2010–2011. This DITF system consisted of four stations, each of which was equipped with a fast antenna with a decay time constant of 200 us. Its frequency band was from 400 Hz to 1 MHz. An A/D converter with 4 MHz sampling rate and 12 bit resolution was utilized to digitize the electric field change signals produced by lightning discharges. All stations are synchronized by GPS receivers.

Stations of this system are shown in Fig. 1, along with locations of CG lightning associated with PBPs analyzed in this study. Distances between these stations are from 5 km to 15 km. 3-D locations of lightning discharges observed simultaneously by four stations are determined by interferometry technique. Compared with traditional DITF in VHF band, this DITF in LF band can

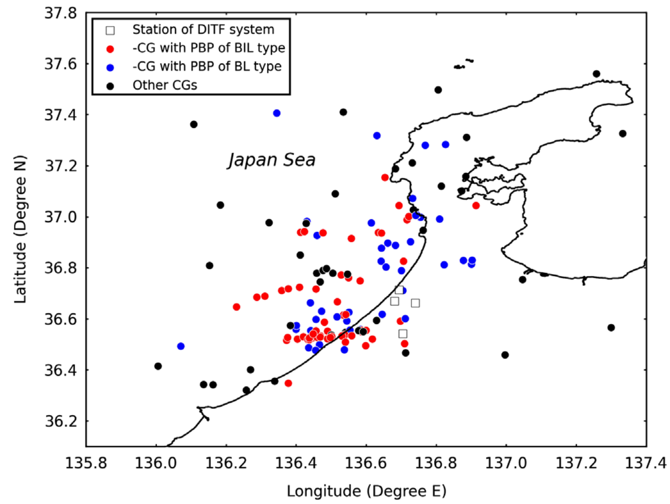

Fig. 1. Locations of stations of DITF system and CG lightning associated with PBP analyzed in this study. Locations of CG lightning are provided by LLS in Japan. Types of PBP are explained in Section 3.

effectively detect lightning discharges in a much wider range, and it can also visualize a rough image of discharge channels, as demonstrated by Takayanagi et al. (2011). However, due to small area covered by this system, it can only accurately locate discharge events close with this network. Therefore, we use the information of lightning location system (LLS) in Japan to get the location of return strokes in this study. LLS in Japan is operated by electric companies of Japan and has a location accuracy of about 0.5 km (Matsui and Takano, 2010).

There are totally 131−CGs and 36 +CGs in this analysis. Due to special features of winter thunderstorm, some waveforms of return strokes are largely different from those in summer thunderstorm, and sometimes it is quite difficult to determine whether one waveform is produced by return stroke. In this study, we only choose those waveforms that we can confidently identify as return stroke, so the actual number of CG lightning during the winter of 2010–2011 is probably larger than the value in this study. According to location information provided by LLS, most of CGs in this study are within 180 km from the observation site.

Criteria for identifying PBPs are similar with previous studies (Nag and Rakov, 2008; Baharudin et al., 2012a, 2012b). Specifically, only pulses with amplitudes larger than twice of noise level are included and one PBP train comprises at least three such pulses and these pulses are mainly bipolar. Due to many special characteristics of lightning flashes in winter thunderstorms, we do not impose more quantitative criteria for selecting PBPs. However, we checked the shape of individual pulse and pulse train for every event to make sure it was not produced by other types of discharges.

Atmospheric sign convention is used throughout this paper, thus a negative return stroke produces initially positive electric field change.

3. Classification of PBP

Among the 131 −CGs, 104 are preceded by PBP train. The initial polarity of PBP is always negative, the same as negative return stroke. For the remaining 27 −CGs, no significant electric field changes other than that of stepped leaders can be found before the return stroke.

For the 104 −CGs preceded by PBP train, 59 of them are similar to the “BIL model” proposed by Clarence and Malan (1957), in

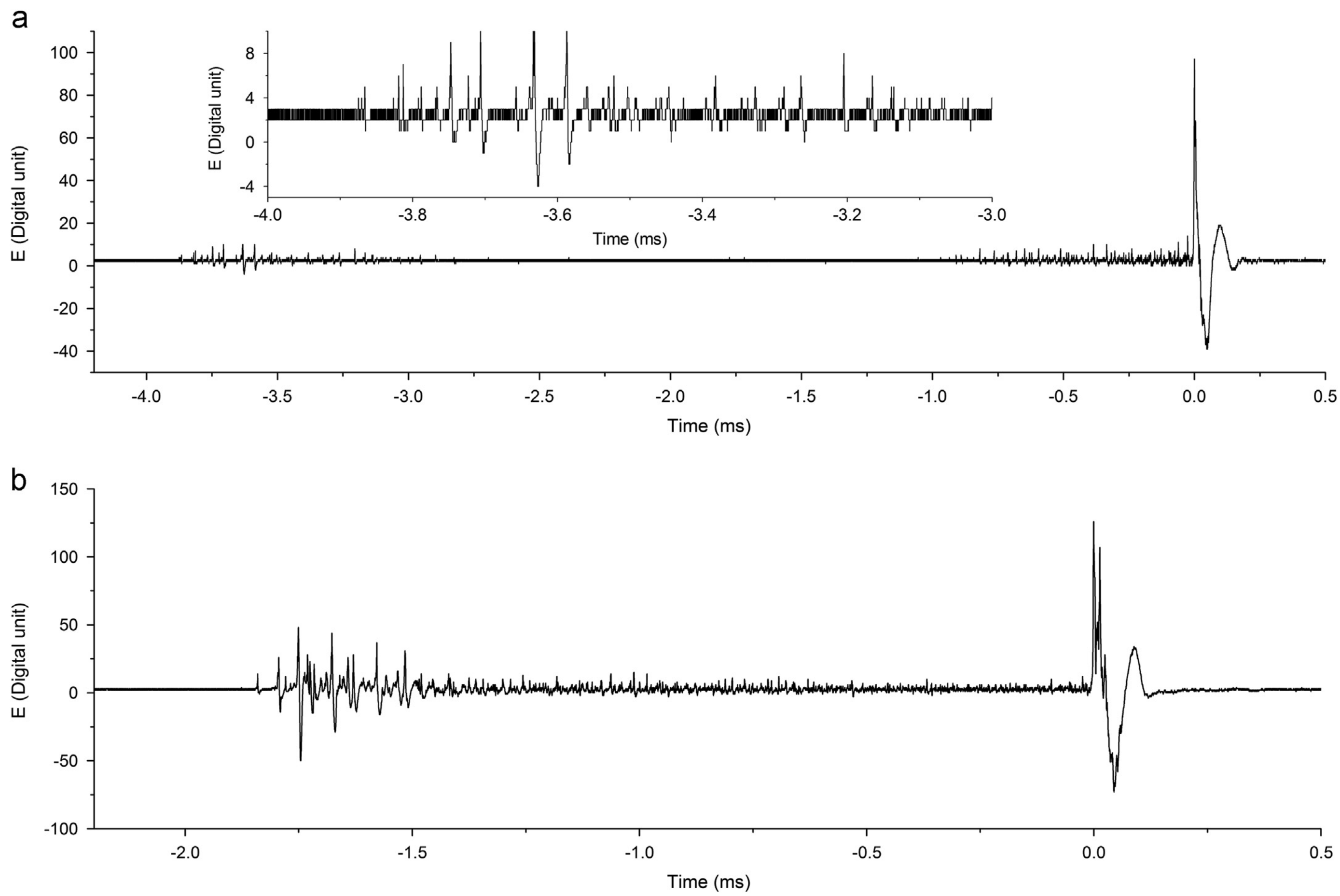

Fig.2. Typical waveforms of PBP of (a) “BIL type” and (b) “BL type” associated with negative CG lightning.

which PBP is followed by an intermediate stage with little electric field changes, and then followed by leader changes and return stroke. One typical example is shown in Fig. 2a. We will call this type of PBP as “BIL type”. In the other 45 cases, PBP is followed directly by small pulses possibly indicative of leader changes and then return stroke without intermediate stage. One typical example is shown in Fig. 2b. For convenience, we will call this type of PBP as “BL type”.

One reason of the disparity between these two types of PBP may be different distances from observation site, as in large distance, small signals produced by stepped leaders may be not detected, resulting in “intermediate stage”. However, this should not be the only reason. As shown in Fig. 1, CG lightning flashes associated with “BIL type” and “BL type” of PBP do not show systematic difference of distance from the observation site. Thus, differences between these two types of PBP should be due to different physical processes of preliminary breakdown or stepped leader.

From another perspective, 104 −CGs that are preceded by PBP include 73 single-stroke −CGs and 31 multiple-stroke −CGs. It is interesting to note that PBPs of 29 multiple-stroke −CGs are “BIL type”, while those of only two multiple-stroke −CGs are “BL type”. For single-stroke −CGs, 30 of them are associated with “BIL type” PBP and the other 43 are associated with “BL type” PBP.

For PBP of +CGs, its initial polarity is not always the same as that of positive return stroke. Of the 36 +CGs analyzed in this study, 11 of them are preceded by PBP with positive initial polarity (+PBP), the same as positive return stroke as shown in Fig. 3a. 15 +CGs are preceded by PBP with negative initial polarity (−PBP) as shown in Fig. 3b. The rest 10 +CGs are not preceded by PBP. It should be noted that the ratio of number of −PBPs to +PBPs is much higher than previous studies (Ushio et al., 1998; Gomes and Cooray, 2004). For PBP of +CG, there is always an intermediate stage with little electric field changes, similar with “BIL type” PBP in −CG.

Numbers of CGs with different types of PBPs are summarized in Table 1.

4. Results

4.1. PBP waveform characteristics

Waveforms of different types of PBP are generally similar with each other. As can be seen in Figs. 2 and 3, each pulse train usually starts with one or two very small pulses, followed by some largest pulses of the train, and ends with pulses of decreasing amplitudes. Pulses in PBP train are mainly bipolar. Pulses at the beginning and middle of the train usually have very clear bipolar feature. However, at the end of the train, pulses sometimes appear as unipolar. For “BL type” PBP in negative CG lightning, the “B” part and “L” part sometimes are difficult to differentiate, as pulses at the end of the train seem to gradually change from bipolar to unipolar. Such an example is given in Fig. 4. It can be seen that before the time of about −0.9 ms, pulses are clearly bipolar, but during the time of −0.9 ms to −0.6 ms, pulses are more like unipolar, and it is difficult to tell whether they belong to PBP or stepped leader pulses. For such cases, defining the end of PBP train is somehow subjective, and it may have up to 0.1 ms error in calculating the duration of PBP train.

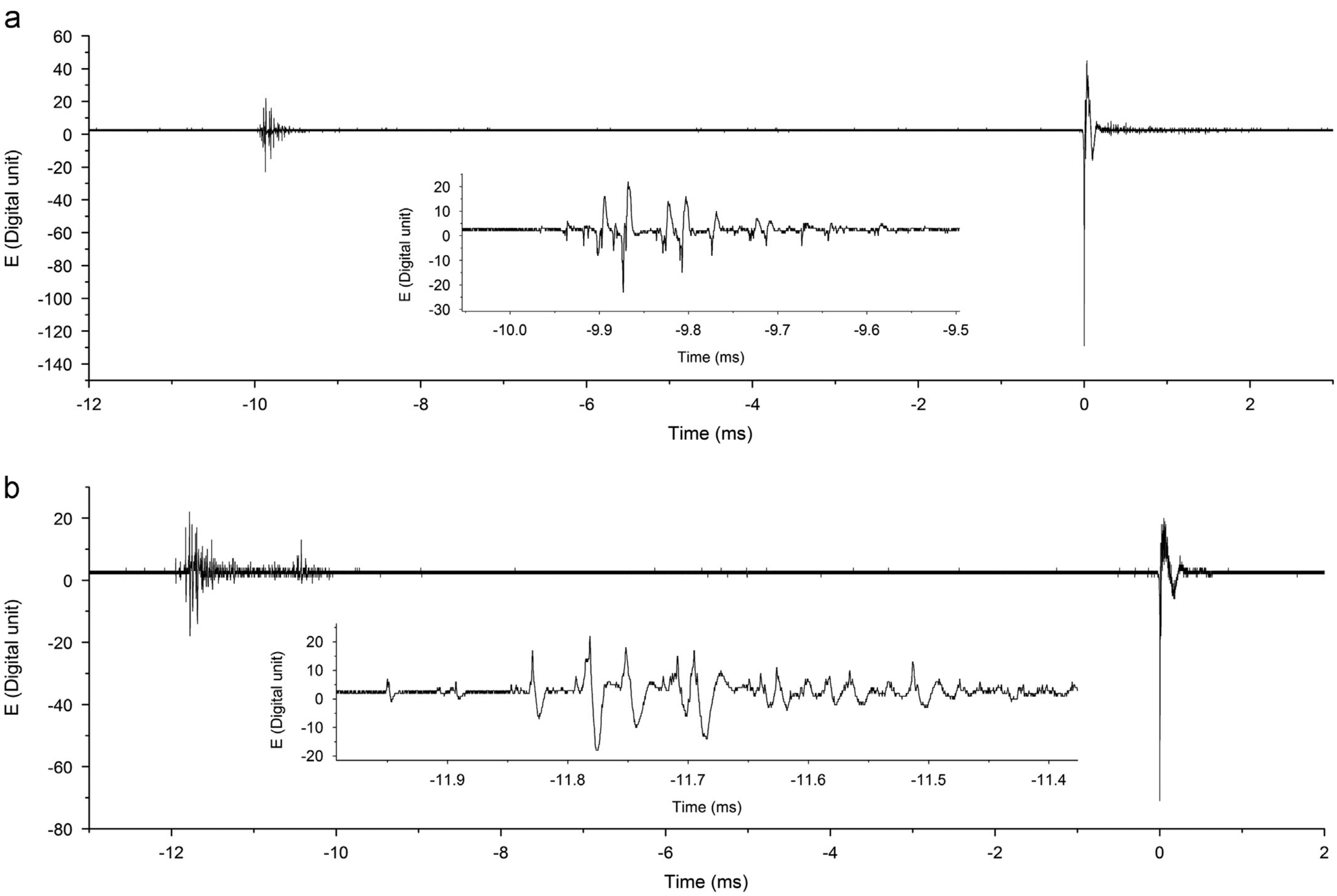

Fig.3. Typical waveforms of PBP of (a) positive initial polarity and (b) negative initial polarity associated with positive CG lightning.

Table 1
Classification of PBP.

CG polarity	PBP type	Stroke multiplicity
−CG 131	BIL type 59	Single stroke 30
		Multiple stroke 29
	BL type 45	Single stroke 43
		Multiple stroke 2
	No PBP 27	Single stroke 10
		Multiple stroke 17
+CG 36	+PBP 11	All single stroke
	–PBP 15	
	No PBP 10	

In order to statistically analyze PBP waveform characteristics, for each pulse train, we calculated the average value of zero-crossing time of each pulse (T_{zc}), average value of time difference between peaks of two successive pulses (T_{diff}), number of pulses (N) and duration of each pulse train (T_{dur}). Results are summarized in Table 2.

The zero-crossing times of different types of PBPs are quite similar. The average zero-crossing times are on average around 7 us. In the study of PBP in positive CG lightning in Sweden reported by Gomes and Cooray (2004), pulse widths of the first half cycle are mostly from 10 us to 20 us, larger than that of this study. However, Ushio et al. (1998) reported that PBPs in winter thunderstorm in Hokuriku region of Japan (the same region as this study) have pulse duration of on average 18 us, which is similar with average zero-crossing time of 7 us in this study.

When comparing between PBPs of "BIL type" and "BL type", differences on T_{diff} (time difference between successive pulses) and N (number of pulses in each train) are quite obvious. T_{diff} of "BIL type" PBP is on average twice as large as that of "BL type" PBP. However, N of "BIL type" PBP is smaller than that of "BL type" PBP, and its maximum and minimum values are also much smaller than those of "BL type" PBP. It should also be noted that T_{dur} (duration of PBP train) of these two types of PBP are similar with each other. So a possible explanation for the differences on T_{diff} and N is that pulses of "BIL type" PBP are relatively weak, and some pulses are not detected. As a result, for "BIL type" PBP, pulse interval is larger and pulse number is smaller while duration of pulse train is close to that of "BL type" PBP.

For the two types of PBPs in positive CG lightning, no significant difference is observed. It indicates that +PBP and −PBP in positive CG lightning are generally the same. When comparing between PBPs of positive and negative CG lightning, one noticeable difference is that PBP of positive CG lightning has relatively larger T_{diff} and smaller N. From this respect, PBP in positive CG lightning is more similar with "BIL type" PBP in negative CG lightning. Actually, all PBPs in positive CG lightning are "BIL type"; that is, they always show an intermediate stage with little electric field changes.

4.2. *Time interval between PBP and the first return stroke*

Time difference between the largest peak of PBP train and the following first return stroke is calculated (designated as PBP–RS interval in following analysis), as shown in Fig. 5. Fig. 5a shows distribution of PBP–RS interval for "BIL type" and "BL type" PBPs in

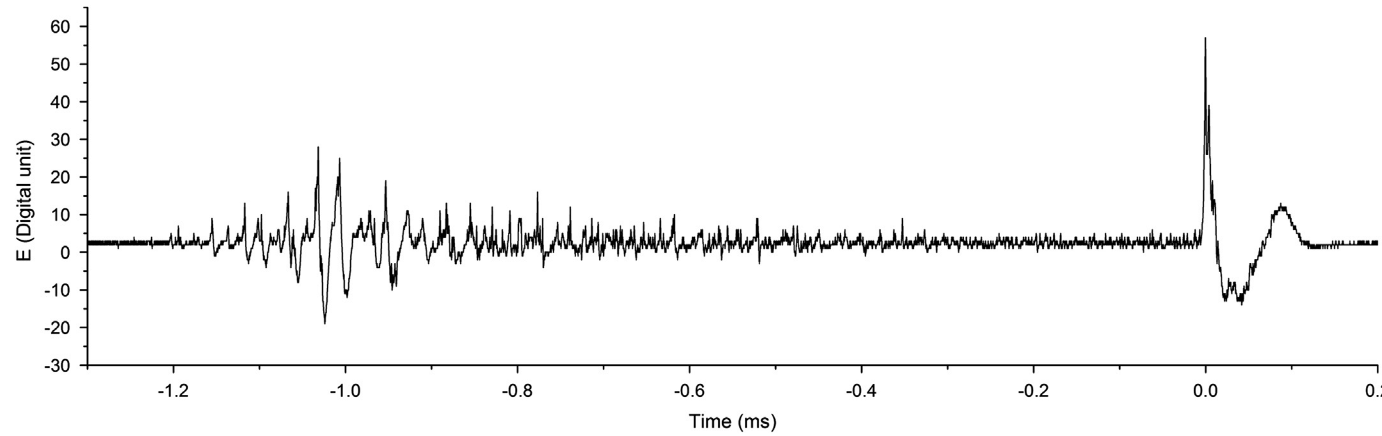

Fig. 4. Example of PBP waveform showing several unipolar pulses during the transition between PBP and stepped leader.

Table 2
Statistics on pulse characteristics of different types of PBP.

	PBP type	T_{zc} (us)			T_{diff} (us)			N			T_{dur} (ms)		
		max	min	mean	max	min	mean	max	min	mean	max	min	mean
–	BIL	12	2.8	6.1	265	8.9	43	156	3	31	2.6	0.13	0.80
CG	BL	15	2.8	7.7	76	4.7	20	207	7	39	2.8	0.13	0.67
+	+PBP	15	4.3	7.3	100	17	44	35	7	19	1.8	0.26	0.81
CG	−PBP	14	3.5	8.4	143	23	47	48	7	22	3.8	0.25	1.1

negative CG lightning. “BL type” PBPs mostly have PBP–RS interval of smaller than 2 ms, with an average value of 1.3 ms. By comparison, only 7 “BIL type” PBPs (12%) have PBP–RS interval of smaller than 2 ms, and ten of them are larger than 10 ms. The average PBP–RS interval for “BIL type” PBP is 5.4 ms, more than four times of that of “BL type”. Median values of PBP–RS interval are 3.6 ms and 1.2 ms, respectively, for “BIL type” and “BL type” PBPs. So PBP–RS interval for “BIL type” PBP is generally larger than that for “BL type” PBP. The average value of PBP–RS interval for all PBPs in negative CG lightning is 3.6 ms.

PBP–RS interval for both “BIL type” and “BL type” PBPs is generally smaller than those reported from summer thunderstorm (Gomes et al., 1998; Makela et al., 2008). However, PBP–RS interval for “BL type” PBP is exceptionally small. Brook (1992) reported that the PBP–RS interval for −CGs in winter thunderstorm in Albany, N. Y. had a mean value of 2.75 ms, which is comparable to 3.6 ms, the mean value for all PBPs in −CGs in our study. However, Brook (1992) reported that the minimum value of PBP–RS interval was 1.5 ms, while in our study, there are 18 PBPs in −CGs with PBP–RS interval below 1 ms, which has never been reported before. Such short time interval should be a manifestation of special characteristics of winter lightning in Hokuriku region of Japan. Indeed, to our best knowledge, there has been no study on PBP of negative CG lightning in winter thunderstorm of Japan. The minimum PBP–RS interval in our study is 0.48 ms, shown in Fig. 6.

PBP–RS interval for 26 PBPs in positive CG lightning has a mean value of 17 ms and maximum and minimum values of 97 ms and 2.7 ms. This is in agreement with that reported by Ushio et al. (1998) in the same region, but it is generally smaller than that reported by Nag and Rakov (2012) in Florida. As shown in Fig. 5b, distributions of PBP–RS interval for +PBP and −PBP have certain differences, with values of +PBP being slightly smaller. But this may be due to small sample. The minimum values of PBP–RS interval for +PBP and −PBP are 2.7 ms and 5.0 ms. Their mean values are 11.6 ms and 21.0 ms, respectively. Such large difference in mean values is mainly because one −PBP has a value of 97.4 ms, much larger than the rest of cases. Their median values, though, are closer, which are 9.1 ms and 14.2 ms.

It is interesting to note that large values of PBP–RS interval in negative CG lightning seem to be associated with certain thunderstorm types. Fig. 7 shows time series of PBP–RS interval on December 7, 2010. Large values of PBP–RS interval tend to cluster together. In our analysis, there are totally 13 cases with PBP–RS interval larger than 6 ms, while 11 of them are produced within 40 min indicated in Fig. 7. So certain type of thunderstorm or certain stage of thunderstorm may be favorable for production of negative CG lightning with larger time difference between PBP and the first return stroke.

4.3. *Ratio of peak amplitude of PBP to first return stroke*

Brook (1992) noted that in winter thunderstorm, negative CG lightning could have very intense PBP that was sometimes even stronger than the return stroke, but positive CG lightning had very weak PBP either in winter or summer. Here we further analyze the ratio of peak amplitude of PBP to the first return stroke (indicated as PBP–RS ratio in following analysis) of both positive and negative CG lightning in winter.

Fig. 8a shows distribution of PBP–RS ratio for “BIL type” and “BL type” PBP in −CGs. For “BIL type” PBPs, 28 of them (47%) have PBP–RS ratio of lower than 0.2, showing quite weak PBP compared with the first return stroke. By comparison, only four “BL type” PBPs (9%) have PBP–RS ratio of lower than 0.2. On the other hand, nine “BIL type” PBPs (15%) have PBP–RS ratio of higher than 1, while the corresponding number for “BL type” PBP is only two (4%). As a result, the mean values of PBP–RS ratio for “BIL type” and “BL type” PBPs are quite close, which are 0.47 and 0.44, respectively.

Fig. 8b shows distribution of PBP–RS ratio for +PBP and −PBP in +CG. The distributions for +PBP and −PBP are quite similar. The mean values are 0.17 and 0.18, respectively, for +PBP and −PBP. It seems that the two types of PBPs in +CG have almost the same intensity. It should also be noted that the maximum value of

PBP–RS ratio is only 0.48 for all +CGs in this study. Therefore, for winter lightning, PBPs in +CGs are much weaker than those in −CGs, and +CGs are unlikely to be associated with very strong PBPs. This conclusion is in agreement with the observation by Brook (1992).

When putting all results of PBP–RS interval and PBP–RS ratio together, as shown in Fig. 9, we have some interesting observation. Fig. 9 shows a scatterplot of PBP–RS interval versus PBP–RS ratio for different types of PBPs. Each point in Fig. 9 represents one CG with PBP. Their distributions are the same as shown in Figs. 5 and 8. However, it is interesting to note that no point in Fig. 9 has both large value of peak ratio and large value of time difference. In other words, if PBP is very strong, the following first return stroke always comes in a short time; on the other hand, if there is a long wait between PBP and the first return stroke, the PBP is always very weak compared with the RS.

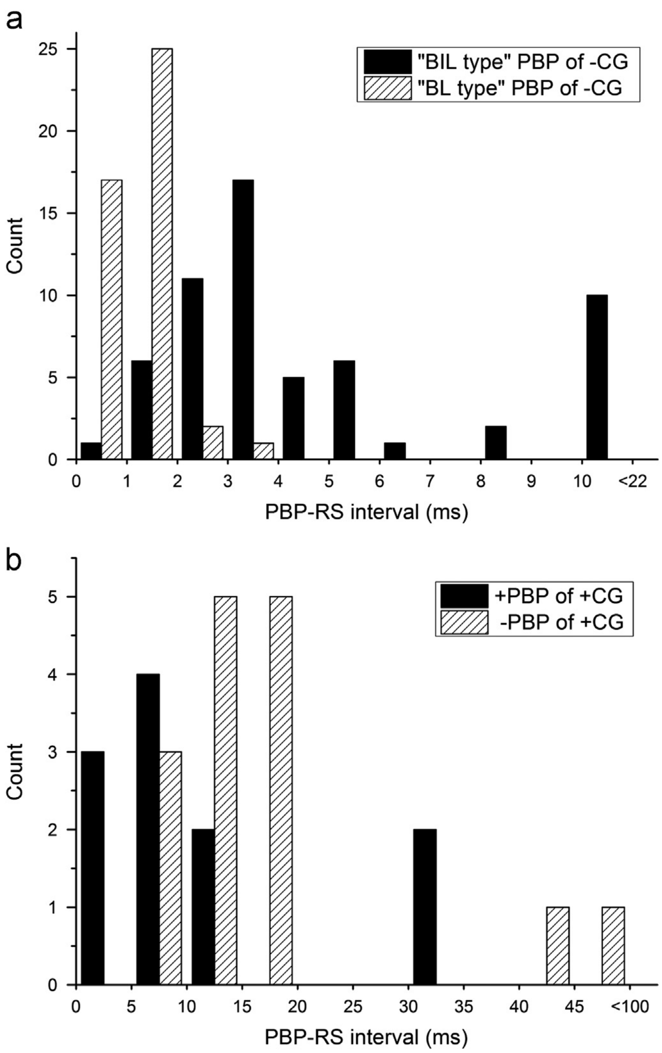

Fig. 5. Distribution of PBP–RS interval for (a) −CG and (b) +CG.

5. Discussions

5.1. Two polarities of PBPs in +CG

It has been reported by many researchers that PBPs with both positive and negative initial polarities are observed (Gomes and Cooray, 2004; Ushio et al., 1998). There are mainly two hypotheses for this phenomenon. One hypothesis is that +CGs with PBPs of different initial polarities are initiated in different charge layers. For example, those initiated above and below the main negative charge layer would have opposite polarities. For a thunderstorm with normal tripolar charge structure, +CGs with +PBPs would be initiated between the upper positive and the main negative charge layers while +CGs with −PBPs would be initiated between the main negative and the lower positive charge layers. However, in such scenario, PBP–RS interval probably would be shorter for −PBPs than for +PBPs, and their intensities should also have certain differences. As shown by our analysis, time differences for −PBPs are almost the same as, if not larger than, those of +PBPs. In fact, based on our analysis, it seems that +PBPs and −PBPs of +CG have almost no difference except of their initial polarities. So our observation does not support this hypothesis.

The second hypothesis is that PBPs of different polarities are due to charges moving in different directions. For example, charges moving toward and away from the observer would produce opposite polarities. In this scenario, PBPs of opposite polarities are produced by the same discharge process and their statistical characteristics should be the same. So this hypothesis is consistent with our observation. This hypothesis can also conveniently explain the observation by Gomes and Cooray (2004) that some PBP trains contain two parts of pulses with opposite initial polarities, as direction of PBP channel is changed during its propagation. Under this hypothesis, PBPs of opposite polarities should account for almost the same percentage, as in our study. However, we are not able to explain why −PBPs are usually much fewer than +PBPs as reported by previous studies (Ushio et al., 1999; Gomes and Cooray, 2004; Nag and Rakov, 2012).

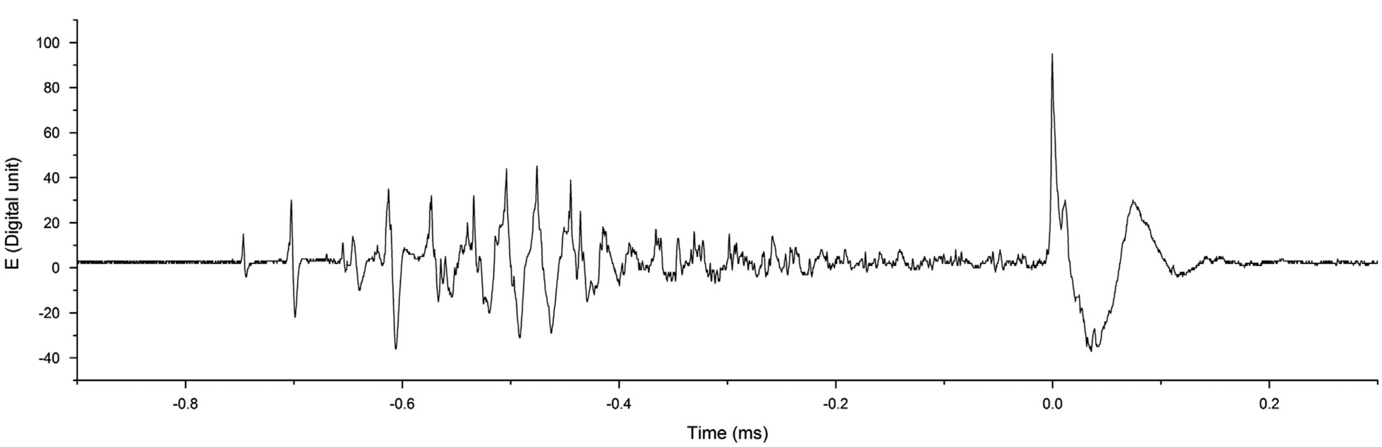

Fig. 6. Waveform of PBP train with a time difference of only 0.48 ms between the peak of PBP and return stroke, the smallest one in this study.

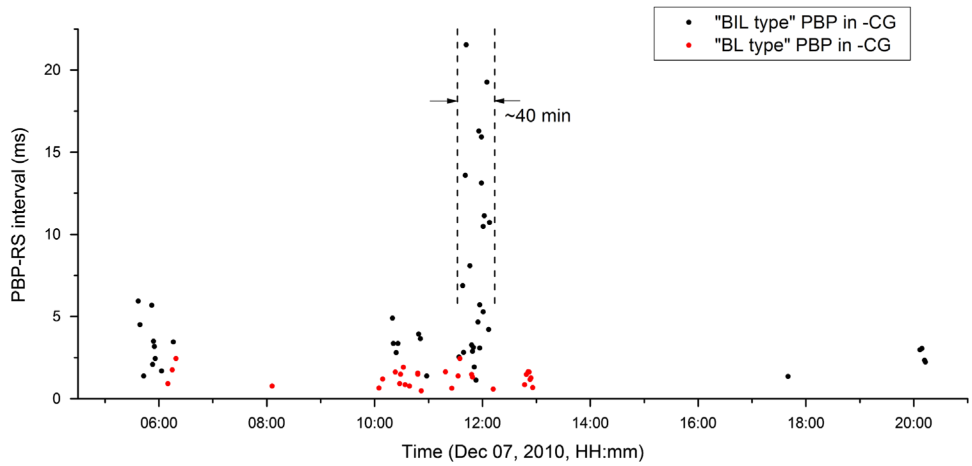

Fig. 7. Time series of PBP–RS interval on December 7, 2010.

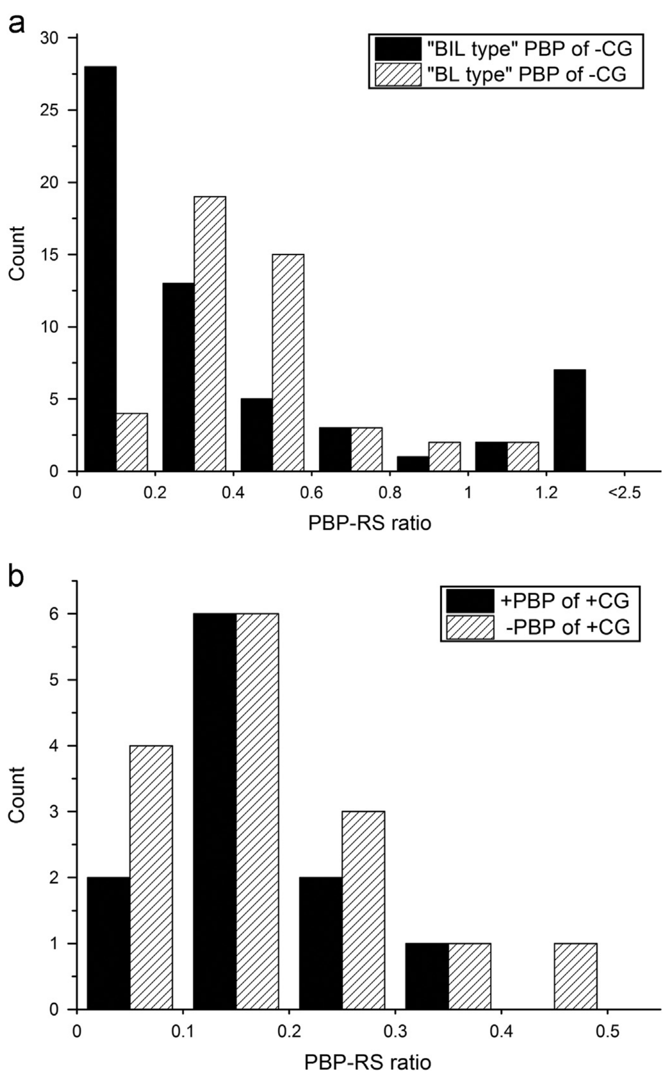

Fig. 8. Distribution of PBP-RS ratio for (a) –CG and (b) +CG.

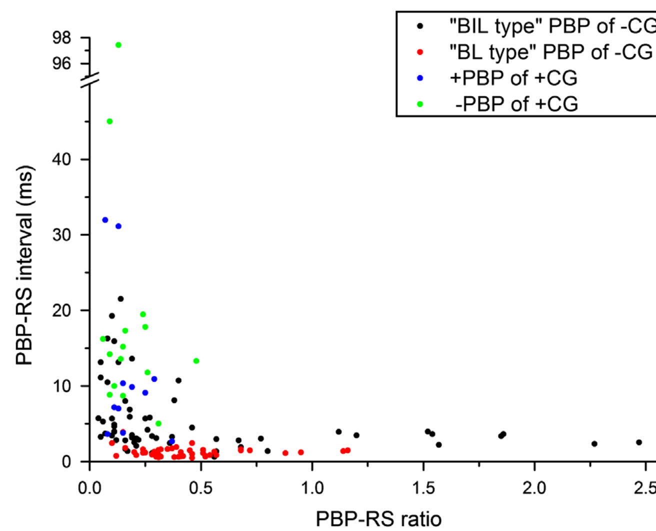

Fig. 9. Scatterplot of PBP–RS interval versus PBP–RS ratio for all types of PBP.

The fact that PBPs of −CG only have one initial polarity indicates that the discharge always starts with charge movement in vertical direction, which may be due to smaller electric potential in the region of −CG initiation compared with that in the region of +CG initiation as further discussed below. However, this is still an open question, and more observations are needed to further investigate this issue.

5.2. *"BIL type" and "BL type" PBPs in −CG*

Fig. 2 shows that locations of −CGs with "BIL type" and "BL type" PBPs do not show any systematic difference. So what causes the "I" part (intermediate stage) of "BIL type" PBP? In other words, what is the difference between "BIL type" and "BL type" PBPs?

Fig. 5a shows that PBP–RS interval of "BIL type" PBP is generally larger than that of "BL type" PBP. This is an expected result, as "BIL type" PBP contains one more stage than "BL type" PBP. Further, Fig. 7 shows that PBPs with large PBP–RS interval (all of them are "BIL type") tend to converge in a short period. Such a period is also characterized by larger-than-normal flash rate. It seems that as thundercloud develops more vigorous, it is more likely to produce PBPs with quite large PBP–RS interval.

Coleman et al. (2008) demonstrated that when there is a potential well between the lightning initiation altitude and the ground, channels propagate horizontally for some time at the altitude of potential well before initiating the first return stroke, resulting in considerably longer time between initiation and return stroke. When there is no potential well, the channel just goes to the ground almost immediately, and the time difference is much smaller. Based on this conclusion, we speculate that the intermediate stage in “BIL type” PBP is caused by horizontal propagation of leader channel. For the same current and velocity and the same distance to the observer, horizontal discharge usually produces a much smaller vertical electric field change than vertical discharge does, so there is little electric field changes during intermediate stage. And because formation of strong potential well requires strong updraft for charge separation, “BIL type” PBPs naturally tend to converge in a short period probably corresponding to intense updraft in the thunderstorm.

Therefore, “BL type” PBP probably does not contain such a horizontal propagation; it just goes right toward the ground, resulting in generally smaller PBP–RS interval. And the fact that very small value of PBP–RS interval (around 1 ms) is much more common in winter lightning may indicate that the lower positive charge in winter thunderstorm is weaker compared with that in summer thunderstorm.

6. Conclusions

104 PBP trains in −CG and 26 PBP trains in +CG are analyzed in this study. Initial polarity of PBP in −CG is always the same as negative return stroke. 59 PBPs in −CG are classified as “BIL type” as they agree well with the “BIL model” proposed by Clarence and Malan (1957) while the rest 45 PBPs are classified as “BL type” because they do not contain the intermediate stage. For PBPs in +CG, 11 of them have the same initial polarity as positive return stroke and the rest 15 PBPs have opposite initial polarity.

Waveform characteristics of different types of PBPs are generally the same. Pulses in PBP train are mainly bipolar. The zero-crossing time is on average around 7 us. Each pulse train has duration of about 1 ms.

Time difference between PBP and the first return stroke (PBP–RS interval) is calculated for each type of PBP. For −CG, “BL type” PBP generally has smaller PBP–RS interval than “BIL type” PBP does. Most of them are smaller than 2 ms, with a minimum value of 0.48 ms and a mean value of 1.3 ms, much smaller than those in summer lightning. The mean value of PBP–RS interval for “BIL type” PBP is 5.4 ms. It seems that “BIL type” PBPs tend to converge in a short period when the thunderstorm is more vigorous. For +CG, PBP–RS intervals for +PBP and −PBP are similar with each other, with median values of 9.1 ms and 14.2 ms.

Ratio of the peak of PBP to the first return stroke (PBP–RS ratio) is also calculated for each type of PBP. PBP–RS ratio of PBPs in −CG is generally larger than that of PBPs in +CG, indicating very strong PBP in −CG in winter. The mean values of PBP–RS ratio for “BIL type” and “BL type” PBPs in −CG are 0.47 and 0.44, while the mean values for +PBP and −PBP in +CG are only 0.17 and 0.18.

+PBP and −PBP in +CG have almost the same characteristics except of their initial polarity, and it is speculated that different initial polarities are caused by different directions of channel propagation. The intermediate stage in “BIL type” PBP is thought to be caused by horizontal propagation of leader channel. Such horizontal propagation produces little vertical electric field changes at the ground and makes the time interval between PBP and the first return stroke longer.

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