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

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A B S T R A C T

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 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).

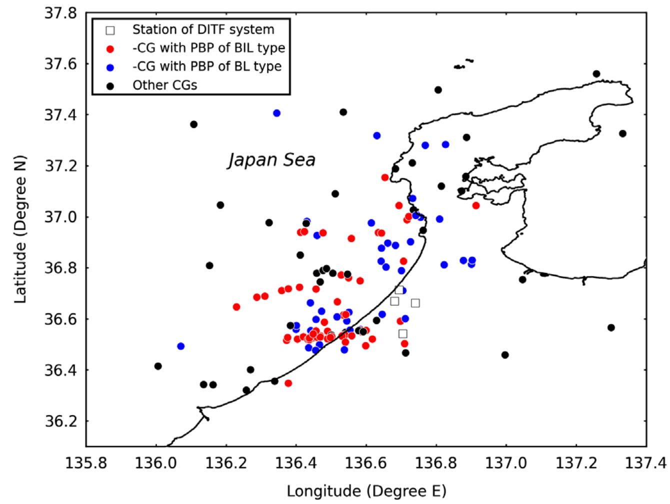

Fig. 1. Locations of stations of DITF system and CG lightning associated with PBP analyzed in this study. Locations of CG lightning are provided by LLS in Japan. Types of PBP are explained in Section 3.

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