Relationship between preliminary breakdown and charge structure in thunderstorm

Satoru Yoshida[1,*], Ting Wu[2], Tomoo Ushio[2], Kenichi Kusunoki[1]

1. Meteorological Research Institute, Tuskuba, Ibaraki, Japan
2. Graduate School of Engineering, Osaka University, Suita, Osaka, Osaka

ABSTRACT: We have been designing and developing Broadband Observation network for Lightning and Thunderstorm (BOLT) which detects EM waves associated with lightning and locates the radiation sources using time of arrival technique. We have been conducting observation campaign with the BOLT in Kansai, Japan, from October 2012 in order to further understand relationship between preliminary breakdown (PB) and charge structure in thunderstorms. We located a total of 94 flashes involving PB pulse trains in one thunderstorm. We found that most of the -PB pulses trains, whose initial half-cycle polarity is negative in atmospheric electricity sign convention, are located more than 5 km in altitude, while most of +PB pulse trains are located less than 5 km in altitude. From a comparison of radar reflectivity factor estimated by a phased array radar, it is found that most of the +PB and –PB pulses, respectively, occurred in the lower part or below the high reflectivity regions, and in the upper part or above the high reflectivity region. These results indicate that the difference of the polarity of PB pulses is determined by the polarity of charge region around locations of PB pulses.

INTRODUCTION

Preliminary breakdown (PB) is a lightning process that initiates a stepped leader followed by intracloud (IC) and cloud-to-ground (CG) discharges. PB usually produces a train of bipolar pulses lasting tens microseconds on electric field change waveform. A lot of researchers reported that PB pulses have relationship with lightning development and/or thunderstorm structure. Rakov and Uman [2003] summarized that pulse width and interpulse duration of PB range from 20 to 40 μs and 70 to 130 μs, respectively, for PB initiating downward negative lightning. Nag and Rakov [2009] reported that PB followed by negative return strokes has relation to amount of lower positive charge regions. Marshall et al. [2013] suggested that PB is a potential source to produce a terrestrial gamma ray flash (TGF).

Several case studies for lightning discharges reported that negative PB (-PB) with negative initial half-cycle initiates IC flashes and positive PB (+PB) initiates negative CG flashes. However, -PB pulse trains initiated sometimes a negative CG flashes [i.e., Bitzer et al., 2013]. For further understanding of characteristics of PB, especially polarity of PB pulses, and relation to lightning discharges following PB process and thunderstorm structures, we examined source locations of PB with weather radar observation

* Contact information: Satoru Yoshida, Meteorological Research Institute, Tsukuba, Ibaraki, Japan, Email: syoshida@mri-jma.go.jp

data.

OBSERVATION

We conducted field observations with Broadband Observation network for Lightning and Thunderstorm (BOLT) and a phased array radar (PAR) in Kinki, Japan. BOLT is a LF sensor network, currently consisting of 11 sensors around Osaka. Sensors of BOLT recorded emissions from lightning discharges and located pulse peaks of waveforms in 3D using time of arrival (TOA) method. At each station electromagnetic waves from lightning was detected by an antenna and the signal is low-pass filtered to 500 kHz and recorded with 16 bit resolution at a sampling rate of 4 MHz. The RC time constant for each sensor was about 200 μs. Each sensor was GPS time synchronized with accuracy of less than 250 ns. Full details of the BOLT are available in Yoshida et al. [2014]. BOLT locates in 3D development of whole structure of lightning discharges, including PB, stepped leaders, negative recoil leaders, and return strokes. Figure 1 shows a typical example of a PB train that initiated a downward negative lightning. In this paper we employ atmospheric electricity sign convention for electric fields, in which a positive electric field change corresponds to negative return strokes. We defined PB pulses that meet three conditions shown below. Firstly, pulse width are between 20 and 40 μs for +PB and between 20 and 60μs for -PB. Secondly, interpulse duration of PB trains, comprising several PB pulses, is less than 2 ms. Lastly, one PB pulse train involves more than 4 pulses. One example of PB pulse trains recorded on one station of BOLT is depicted in Figure 2. This CG flash began with PB pulses and initiated a negative return stroke.

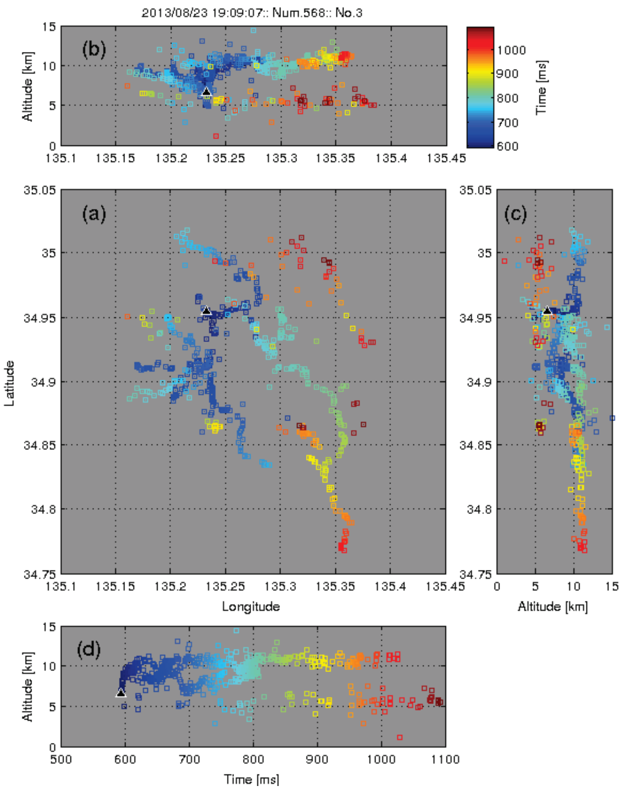

Figure 1. An example of a cloud-to-cloud flash of the BOLT source locations; (a) plane view, (b) and (c) vertical cross sections, and (d) altitude progressions. The BOLT first source and the other source locations are indicated by triangles and squares, respectively.

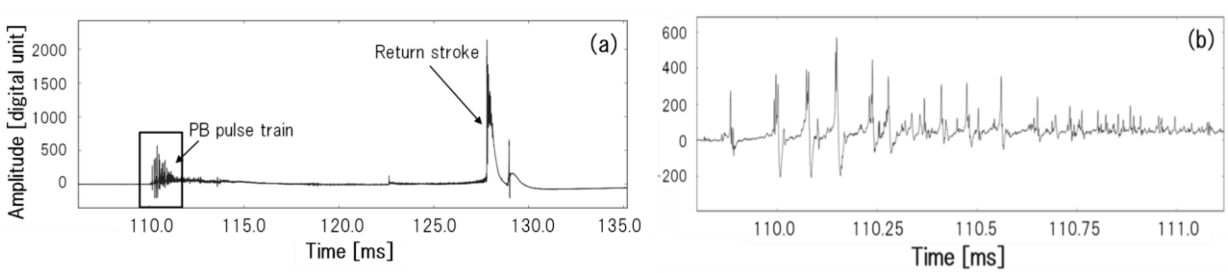

Figure 2. A typical example of preliminary breakdown pulses; (a) a whole structure of a sensor of BOLT associated with a negative CG flash and (b) expanded view of preliminary breakdown pulses.

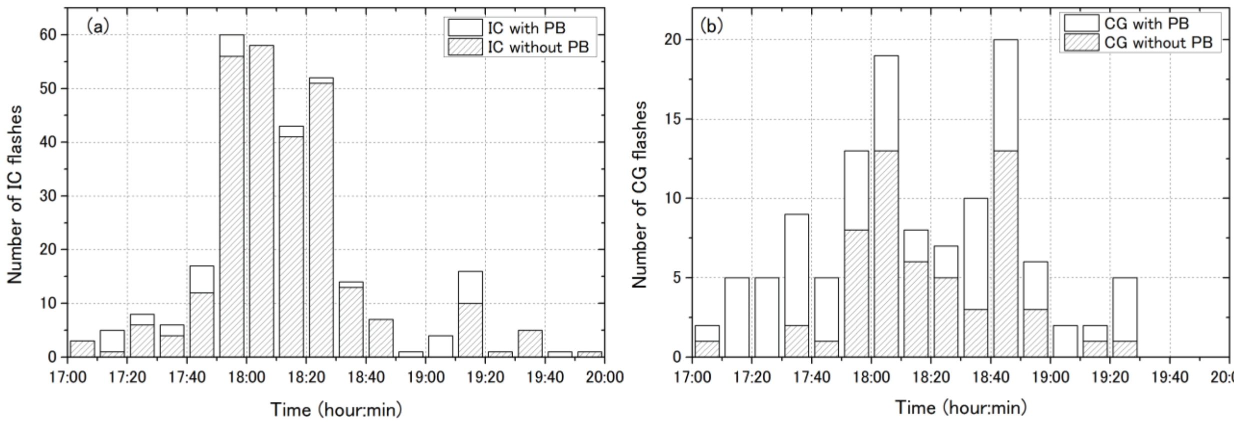

Figure 3. Number of lightning flashes per 10 min in the thunderstorm; (a) IC and (b) CG.

PAR is an X-band fast scanning weather radar, employing electrical scanning in elevation direction and mechanical scanning in azimuth direction, so that it observes precipitation and provides reflectivity factor and Doppler velocity in 3D every 10 second at the fastest mode. We operated the PAR in a mode in which one volume scan took 30 second and the coverage of it was 60 km. Azimuth and elevation resolution was 1.2 and 0.9 degree, respectively. Further, range resolution of it was 100 m.

RESULTS AND DISCUSSION

Thunderstorms that involved a lot of convective cells and lightning discharges passed over the observation area of the PAR on October 28 2012. At that time BOLT consisted of 6 stations. We focus on one thunderstorm in which BOLT located a total of 420 flashes (302 IC and 118 CG flashes). 33 of 302 IC flashes involved PB and 61 of 118 CG flashes had PB process in the beginning of the events. PB pulses in the IC flashes were irregular compared to PB pulse trains of CG flashes in this study, similar to previous observation results [Kitagawa and Brook 1960; Bitzer et al., 2013]. It seems that the identification of PB pulse failed in some PB pulse candidates in IC flashes since the PB pulse shape were irregular. So we speculate more than 33 IC flashes involved PB process in their beginning stage.

Figure 3 shows that number of lightning flashes per 10 min in the thunderstorm; (a) IC and (b) CG. The figure indicate that the thunderstorm became mature stage between 17:50 and 18:30 since lightning

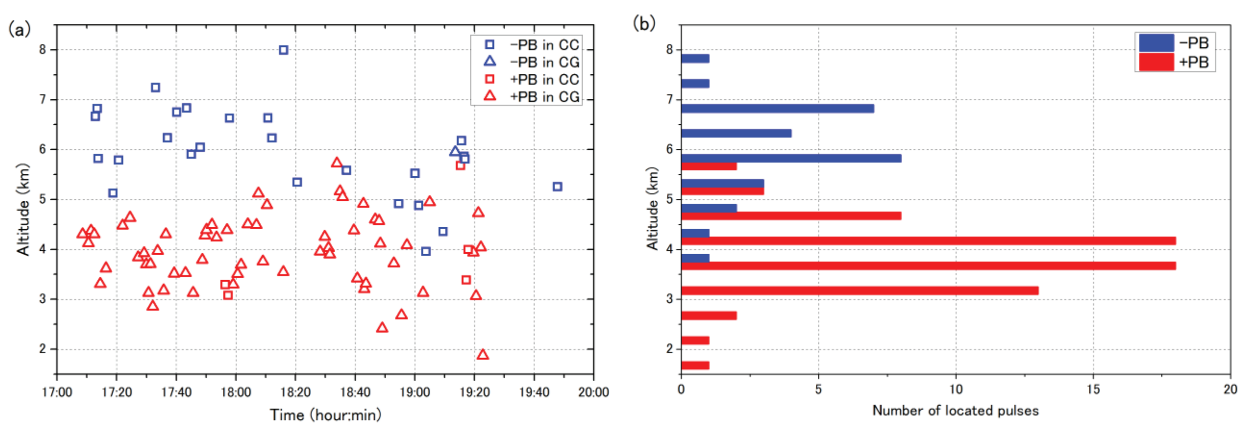

Figure 4. Number of CC and CG flashes, respectively, per 10 min in the thunderstorm.

activity was the most severe during the period. It is found that no significant different in number of PB pulses in the thunderstorm as the thunderstorm developed. Figure 4(a) shows the altitude of the initial PB pulses in PB trains. Figure 4(a) clearly shows that –PB pulses are located higher altitude than +PB during developing and mature stage of the thunderstorm (between 17:00 and 18:30). Most of –PB are located at altitudes of from 5 km to 7 km, while most of +PB are located at altitudes less than 5 km. This fact is also recognized in Figure 4(b), showing histogram of altitudes of the initial PB. This trend is remarkable between 17:00 and 18:30 when the thunderstorm were in the developing and mature stage.

Taking into account the fact that lightning discharges are generally initiated between negative and positive charge regions, we speculate that –PB and +PB, respectively, occurred between main positive and negative charge regions, and between main negative and pocket positive charge regions. In other words, the polarity is determined by charge structure where PB occurs. During dissipating stage (after 18:30) the altitudes of -PB, however, apparently descended. Figure 5 shows BOLT source locations superimposed on vertical cross sections of reflectivity factor estimated by the PAR during (a) the developing stage and (b) dissipating stage. These figures indicate that the initiation of the flashes (indicated by triangles) are located upper side of the high reflectivity cores, corresponding to graupel or/and hail region. With the non-inductive charging mechanism, the high reflectivity cores were likely to be charged negatively. Figure 5(b) shows high reflectivity core during the dissipating stage lowered as well as the echo top of the thunderstorm compared to the developing stage in Figure 5(a). This implies that the main negative charge region descended during the dissipating stage. We speculate that the change of charge structure caused the lowering of the –PB altitudes.

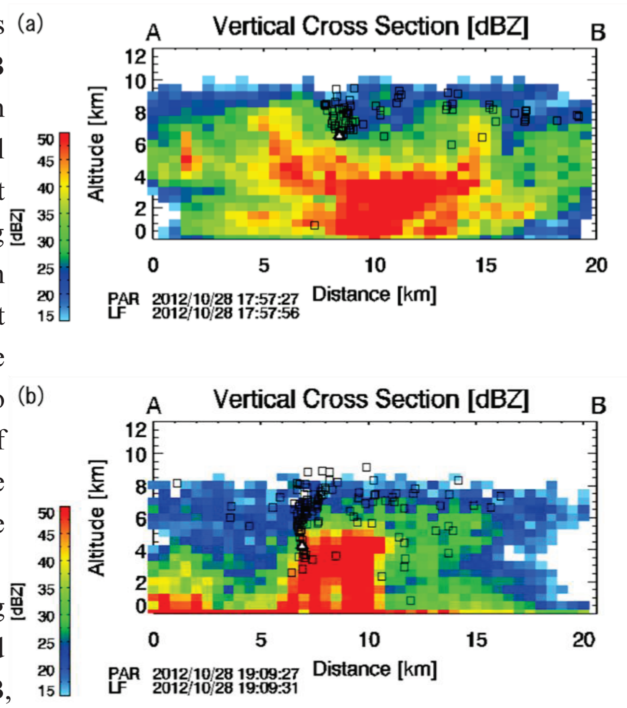

Fig. 5. BOLT source locations of cloud-to-cloud flashes superimposed on vertical cross sections of radar reflectivity. The triangles (△) and squares (□) indicate the initiation of LF sources and other sources, respectively.

CONCLUSIONS

We examined BOLT source locations and radar reflectivity factor estimated by PAR. The first remarkable result is that most of the initial pulses of positive and negative PB pulse trains are located less than 5 km and more than 5 km. Although the source location altitudes of –PB descended in the dissipating stage of the thunderstorm, this trend is clearly recognized. It is well-know that lightning flashes began between negative and positive charge region, where ambient electric field exceeds threshold value for breakdown. This idea and the results shown hear suggest that polarity of PB pulses depend on charge structure of thunderstorm.

ACKNOWLEDGMENTS

This work was supported in part by Japanese Ministry of Education, Science, Sports and Culture, a Japanese Grant-in-Aid for Scientific Research.

REFERENCES

Bitzer, P. M., H. J. Christian, M. Stewart, J. Burchfield, S. Podgorny, D. Corredor, J. Hall, E. Kuznetsov, and V. Franklin (2013), Characterization and applications of VLF/LF source locations from lightning using the Huntsville Alabama Marx Meter Array, *J. Geophys. Res.*, *118*, 8, doi:10.1002/jgrd.50271.

Karunarathne, S., T. C. Marshall, M. Stolzenburg, N. Karunarathna, L. E. Vickers, T. A. Warner, and R. E. Orville (2013), Locating initial breakdown pulses using electric field change network, *J. Geophys. Res.*, *118*, pp. 7129-7141, doi:10.1002/jgrd50441.

Kitagawa, N., andM. Brook (1960), A comparison of intracloud and cloud-to-ground lightning discharges, *J. Geophys. Res.*, *65*(4), 1189–1201.

Marshall, W. Schulz, N. Karunarathna, S. Karunarathne, M. Stolzenburg, C. Vergeiner, and T. Warner (2014), On the percentage of lightning flashes that begin with initial breakdown pulses, *J. Geophys. Res.*, *119*, doi:10.1002/2013JD020854.

Nag, A., and V. A. Rakov (2009), Some inferences on the role of lower positive charge region in facilitating different types of lightning, *Geophys. Res. Lett.*, *36*, L05815, doi:10.1029/2008GL036783.

Rakov, V. A., and M. A. Uman (2003), Lightning: Physics and Effects, Cambridge Univ. Press, Cambridge, U. K.

Yoshida, S., Ting Wu, Tomoo Ushio, Y. Takayanagi, Lightning observation in 3D using a multi LF sensor network and comparison with radar reflectivity, IEEJ Trans. FM., 134, 4, doi:10.1541/ieejfms.134.188, pp. 188-194.