The Most Powerful Lightning Discharges in Winter Thunderstorms in Japan Sea Coast

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Abstract—Using a low frequency lightning location system comprising 9 stations, we have observed and analyzed 374 large and bipolar electric field change waveforms that occurred during the winter of 2012-2013 in Japan Sea Coast. Since the waveforms are different from those produced by any well-studied lightning discharge processes, in this paper, their source discharge events are called large bipolar events (LBEs). LBEs produce very large electric field changes that are even larger than that of positive and negative return strokes, so they seem to be the most powerful lightning discharges in winter thunderstorms. LBEs can be characterized by following features: (1) All have the same polarity as negative return stroke; (2) All exhibit a single bipolar pulse with a pulse width around 15 μs and similar positive and negative cycles; (3) All are located on the land along the Japan Sea coast, indicating they are probably associated with high grounded objects; (4) Most LBEs are temporally isolated within several milliseconds but are frequently followed by intracloud discharges after tens of milliseconds; (5) Most LBEs produce a single well-distinguished ionospheric reflection pulse. It is speculated that LBE is a type of powerful and transient lightning discharge event produced within a compact region of strong electric field formed when the negative charge layer in thundercloud is very close to the top of a tall grounded object.

Keywords—large bipolar event; winter thunderstorm; winter lightning

I. INTRODUCTION

During the winter of 2012-2013, we recorded a special type of large bipolar pulses produced by lightning discharges. The electric field change waveforms produced by such discharge events are different from those produced by any lightning discharge event known in the literature. Because of their large and bipolar features, we call their source discharge events as large bipolar events (LBEs). LBEs are probably the most powerful lightning discharges in winter thunderstorms, producing electric field changes that are even larger than positive and negative return strokes. LBEs seem to be only produced in winter thunderstorms in west coast of Japan. A very special feature of LBEs is that while they are produced in the coast region, almost none of them are located on the sea. This indicates that LBEs are probably associated with high grounded objects. In this paper, we will report various characteristics of LBE and analyze possible discharge processes associated with it.

II. EXPERIMENT AND DATA

In this study, LBEs were recorded by a low frequency (LF) lightning location system comprising 9 stations, indicated as squares in Fig. 1. Black squares represent old sites that were also used in our previous studies [1]. Two blue squares represent new sites that were installed mainly for winter lightning observation. A fast antenna with a decay time constant of 200 μs and frequency range of 500 Hz to 500 kHz was installed at each site. Electric field change signals produced by lightning discharge events were digitized by USRP with 4-megahertz/sec sampling rate and 14-bit resolution and time stamped by an embedded GPS disciplined oscillator (GPSDO). 2-D locations of LBEs (latitude and longitude) were determined with time-of-arrival (TOA) technique.

A total of 374 LBEs were recorded during an observation period from October 23, 2012 to March 18, 2013. Atmospheric sign convention is used in this paper. It is interesting to note that all of LBEs produce initial positive-going electric field changes, so they have the same polarity as negative return stroke (RS).

III. RESULTS

A. Peak amplitude of electric field change

The most important feature of LBE is that it produces very large electric field changes, which indicates LBE probably carries very large current, so studying of LBE would be of great importance for lightning protection. In order to quantitatively evaluate such feature, peak amplitudes of electric field changes produced by LBEs are compared with those produced by positive and negative RSs. Here we use only the data of one site that is at least 80 km away from all LBEs, so electric field changes of LBEs can be normalized to 100 km using the simple 1/R distance relation. Positive and negative RSs are also recorded by the same site. There are 335 LBEs, 873 negative RSs and 475 positive RSs in this comparison. Distributions of peak magnitudes of their normalized electric field changes are shown in Fig. 2. The scale of electric field changes was not calibrated in our experiment, so digital unit (DU) is used in this analysis.
First, the average normalized peak magnitude for negative RS is 3251.4 DU while that for positive RS is 4697.4 DU. This result is in agreement with the well-established notion that some positive cloud-to-ground (CG) flashes can carry extremely large current [2]. As for LBE, the average normalized peak amplitude is 6086.0 DU, about 1.9 times of that of negative RS and 1.3 times of that of positive RS. Therefore, LBE seems to be even more powerful than CG lightning.

B. Waveform characteristics

Electric field change waveform of LBE is the most straightforward evidence that LBE is different from any well-studied type of lightning discharge events. Fig. 3 presents waveforms of a typical LBE recorded at all 9 stations. LBE pulse waveforms have following common features: (1) It is a single bipolar pulse with initial positive polarity (the same as negative RS); (2) its pulse width is around 15 μs; (3) Positive and negative cycles have similar pulse widths and peak magnitudes; (4) The bipolar pulse has quite smooth change without any other pulses superimposed upon; (5) It is sometimes followed by a small pulse that is inferred to be its reflection signal from the ionosphere.

Pulse width of LBE is mostly around 15 μs. In this study, pulse widths of 76.4% LBEs are between 10 to 20 μs. The average value is 15.1 μs. Pulse width of LBE is generally larger than that of narrow bipolar event (NBE) but smaller than that of RS.

Positive and negative cycles of LBE pulse have similar pulse width and peak amplitude. Such feature is also quite different from NBE, whose radiation field always shows much larger initial peak than overshooting peak [3]. In fact, the overall waveforms of positive and negative cycles of LBE are symmetrical to a certain extent as seen in the example in Fig. 3. Such feature is not common for electric field change waveforms produced by lightning discharges.

C. Locations of LBEs

Locations of LBEs are indicated by red dots in Fig. 1. A surprising result is that almost all LBEs are located on the land area. However, most of lightning flashes in winter in Japan Sea coast occur on the sea. In fact, winter thunderstorms are...
developed when cold air masses from the north move over the Japan Sea with relatively warm surface temperature [4]. Lightning flashes start long time before the thunderstorm hits the coastal area. Hojo et al. [5], based on several years’ observation with a wideband magnetic direction-finding system, also reported that winter lightning flashes in Hokuriku region were mostly detected on the sea. For LBEs, however, it seems that only after the thunderstorm reaches the land that they start to occur. Hojo et al. [5] also reported that lightning flashes in winter did not move inland farther than 20-30 km from the coastline. LBEs have similar feature. Fig. 1 also shows major mountain tops in Japan, and most LBEs do not move over the mountains. As a result, locations of LBEs form a narrow belt along the west coast of Japan.

Occasionally, thunderstorms in winter also develop from the south or southwest of Japan, but we did not record any LBE from these thunderstorms.

D. Temporal relationship with other discharge processes

LBEs appear to be temporally isolated with other discharge processes within at least several milliseconds. However, more careful examinations of the records show that LBEs are frequently associated with other discharge processes within tens of milliseconds. Of all 374 LBEs, 117 LBEs are isolated, 124 LBEs precede other discharge processes, and 99 LBEs belong to multi-stroke events (multiple LBEs occurring within 100 ms and within 15 km). The remaining LBEs have other discharge processes before them. It is interesting to note that the majority of discharge processes following LBEs are intracloud discharges with multiple negative-going pulses. One such example is shown in Fig. 4. We have only one case in which LBE is followed by RS. In this case, a positive RS occurred about 90 ms after the LBE. Their horizontal distance was about 4 km.

IV. DISCUSSIONS

The most distinguishing feature of LBE is that almost none is produced on the sea. Such land-ocean contrast indicates that LBE is probably associated with tall grounded objects. One possibility is that LBE is a RS-like process. Multiple LBEs occurring within tens of milliseconds as shown in Fig. 4 is quite similar with multiple RSs in a CG. However, normal RS produces quite different radiation field from that of LBE and is usually preceded by preliminary breakdown pulses (PBPs) and leader pulses. Considering the large and bipolar radiation waveform and the polarity of LBE, it is speculated that LBE is produced when the negative charge layer in thundercloud is very close to the top of a tall grounded object. In such circumstance, the distance between the negative charge layer and the grounded object is small and the electric field in this region can be exceptionally strong. A relatively long upward positive leader can be initiated by the downward negative leader. Similar amount of charges with opposite polarities can be concentrated on the heads of these two approaching leaders, and a RS-like discharge can occur between the approaching leaders. Such discharge process is confined within a compact

Fig. 3. Waveform of a typical LBE recorded by all nine sites. The inset shows an enlarged waveform recorded by one of the sites. Distance of this event to each site and name of each site are shown at upper left and upper right of each panel.
Fig. 4. An example of two LBEs occurring within 10 milliseconds followed by regular intracloud processes. D₁ indicates the horizontal distance between the first and the second LBEs. D₂ indicates the horizontal distance between the second LBE and the largest pulse in the following intracloud processes.

region of strong electric field and lasts a very short time, so it is possible to produce a large single bipolar pulse like LBE.

Such special circumstance is quite rare in summer thunderstorms, but it should be much more common in winter thunderstorms. Winter thunderstorms in west coast of Japan have quite low vertical extent, typically only half of that of summer thunderstorms [4]. With such low vertical extent, the charge layer in thundercloud can be quite close to high grounded objects such as towers and wind mills, forming a small gap with strong electric field.

That LBE is associated with such small gap is also supported by the fact that only LBEs of negative polarity have been observed. Winter thunderstorm is found to exhibit a positive dipole or a normal tripole [4], so LBE is associated with the discharge between the main negative charge layer and the grounded object. The discharge between the main positive charge layer and the grounded object is not likely to happen (or does not result in LBE even if it happens) because the gap between them is much larger.

It is also possible that LBE is a component of an upward lightning flash. Ishii and Saito [6] presented some waveforms of upward lightning discharges associated with transmission-line faults. Some of their waveforms have certain similarities with LBE. As pointed out by Wang and Takagi [7], a grounded object even with a modest height in the west coast of Japan could experience dozens of upward lightning discharges each winter season. An upward lightning discharge starts with an initial continuous current (ICC) stage that may include many ICC pulses, no matter it is self-initiated or triggered by nearby lightning discharges [8]. Some of the ICC pulses may result in the LBE pulse waveforms.

REFERENCES


