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Key Points:

- A special type of lightning discharge called LBE is reported for the first time
- LBE produces single large bipolar waveform different from any other discharges
- LBE is produced in winter thunderstorms and is always located on land

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Large bipolar lightning discharge events in winter thunderstorms in Japan

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Abstract Using a low-frequency lightning location system comprising nine stations, we have observed and analyzed 374 large and bipolar electric field change waveforms that occurred during the winter of 2012–2013. Since the waveforms are different from those produced by any well-studied lightning discharge processes, we refer to these source discharge events using a new name: large bipolar events (LBEs). LBEs can be characterized by the 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 produce very large electric field changes that are even larger than that of positive and negative return strokes. (5) Most LBEs are temporally isolated within several milliseconds but are frequently followed by intracloud discharges after tens of milliseconds. (6) Most LBEs produce a single well-distinguished ionospheric reflection pulse, and the time difference between LBE pulse and the corresponding reflection pulse can be used to calculate ionospheric reflection height. 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 thunderclouds is very close to the top of a tall grounded object.

1. Introduction

Lightning discharges in winter thunderstorms in Japan have many special characteristics. For example, lightning flash rates in winter thunderstorms are much lower than those in summer thunderstorms, and “single-flash” thunderclouds are commonly observed [*Michimoto*, 1993]. Positive cloud-to-ground (CG) flashes account for a high percentage, about 33%, of CG flashes in winter thunderstorms, compared with about 10% in summer thunderstorms [*Suzuki*, 1992]. Upward lightning and bipolar lightning are more common in winter thunderstorms than in summer thunderstorms [*Narita et al*., 1989; *Miyake et al*., 1990]. Fine structures of current waveform and radiation electric field produced by lightning discharges in winter thunderstorms also show many special features that are different from those in summer thunderstorms [*Miyake et al*., 1992; *Ishii and Hojo*, 1989].

Because of its very special characteristics, numerous studies have been devoted to studying winter lightning over the past 30 years. We also have had many experiments near the Japan Sea coast for winter lightning observation. During the winter of 2010–2011, we set up a small low frequency (LF) lightning location system comprising five stations [*Takayanagi et al*., 2013] in Hokuriku region and recorded a type of bipolar waveform that seemed not have been reported before. However, because the location network was too small, most of these discharges could not be accurately located. In order to further study such discharge event, we set up a larger network comprising nine stations in western Japan, two of which are near the Japan Sea coast, before the winter of 2012–2013. Such a network can effectively locate lightning discharges near the Japan Sea coast. During the winter, we successfully recorded and located 374 such large bipolar waveforms.

Because such waveforms are different from those produced by any lightning discharge event known in the literature and because of their large and bipolar features, we refer to their source discharge events as large bipolar events (LBEs). LBEs seem to be only produced in winter thunderstorms in western 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. LBEs seem to carry very strong peak currents, so studying of LBE would be of great importance for lightning protection. In this paper, we will report various characteristics of LBEs and analyze possible discharge processes associated with them.

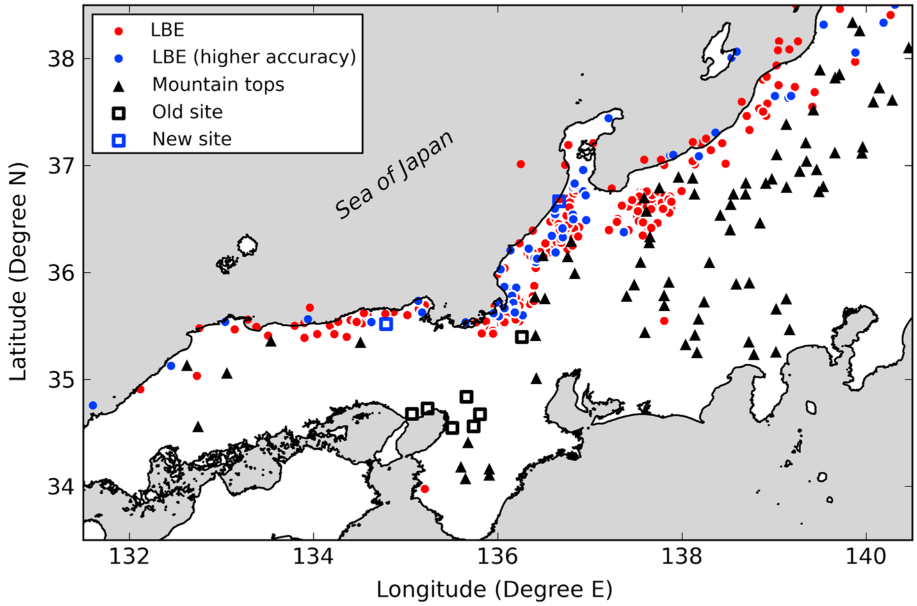

Figure 1. Locations of sites of LF lightning location system (squares) and locations of LBEs (dots).

2. Experiment and Data

In this study, LBEs were recorded by a LF lightning location system comprising nine stations, indicated as squares in Figure 1. Black squares represent old sites that were also used in our previous studies [*Wu et al.*, 2013]. Two blue squares represent new sites that were installed mainly for winter lightning observation. One of them (upper right) was installed on 31 October 2012 and the other one was installed on 20 December 2012. The old sites went through an upgrade from late September to early October of 2012, during which a new recording system based on USRP^{TM} (Universal Software Radio Peripheral, N2x0 series) was used to replace the old system. A major advantage of the new system is that it has zero dead time.

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 the USRP with 4 MS/s sampling rate and time stamped by an embedded GPS disciplined oscillator with timing accuracy of 50 ns. The resolution of the analog-to-digital converter of USRP is 14 bit. The signal goes through a digital decimation filter, and the amplitude of the output signal is in the range of 16 bit ($\pm 2^{15}$).

A total of 374 LBEs were recorded during an observation period from 23 October 2012 to 18 March 2013. The first LBE occurred on 1 November 2012 and the last one on 10 March 2013. Figure 2 shows the number of LBEs observed in each day during this winter. The majority of LBEs were produced during the early and midwinter. Two-dimensional locations of LBEs (latitude and longitude) were determined with time of arrival (TOA) technique.

Atmospheric sign convention is used in this paper. It is interesting to note that all of LBEs produce initial positive electric field changes, so they have the same polarity as negative return stroke (RS).

3. Results

3.1. Waveform Characteristics

Electric field change waveforms of LBEs are the most straightforward evidence that LBEs are different from any well-studied type of lightning discharge events. Figure 3 presents waveforms of a typical LBE recorded at all nine 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 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.

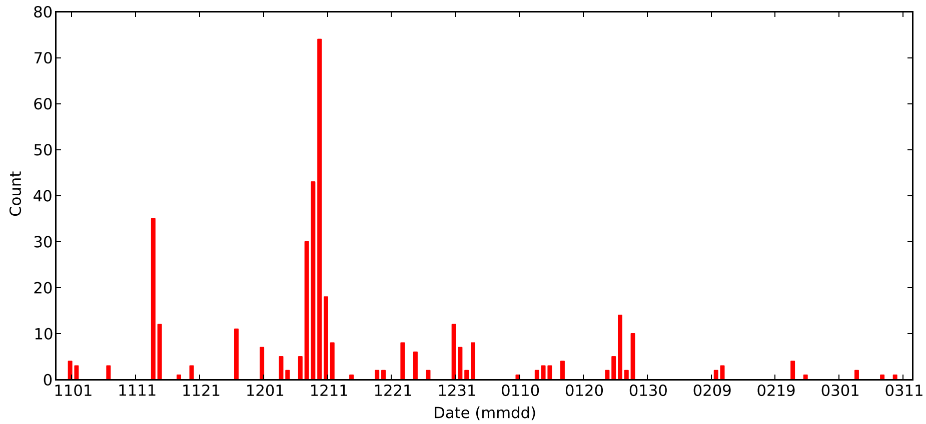

Figure 2. Number of LBEs observed in each day during the winter of 2012–2013.

In order to quantitatively characterize LBE pulse features, we calculate some characteristic parameters including pulse width of the positive cycle (t_P), ratio of rise time to fall time (r_1), ratio of positive to negative pulse widths (r_2), and ratio of positive to negative peak magnitudes (r_3), defined as

$$r_1 = t_r/t_f$$

$$r_2 = t_P/t_N$$

$$r_3 = A_P/A_N$$

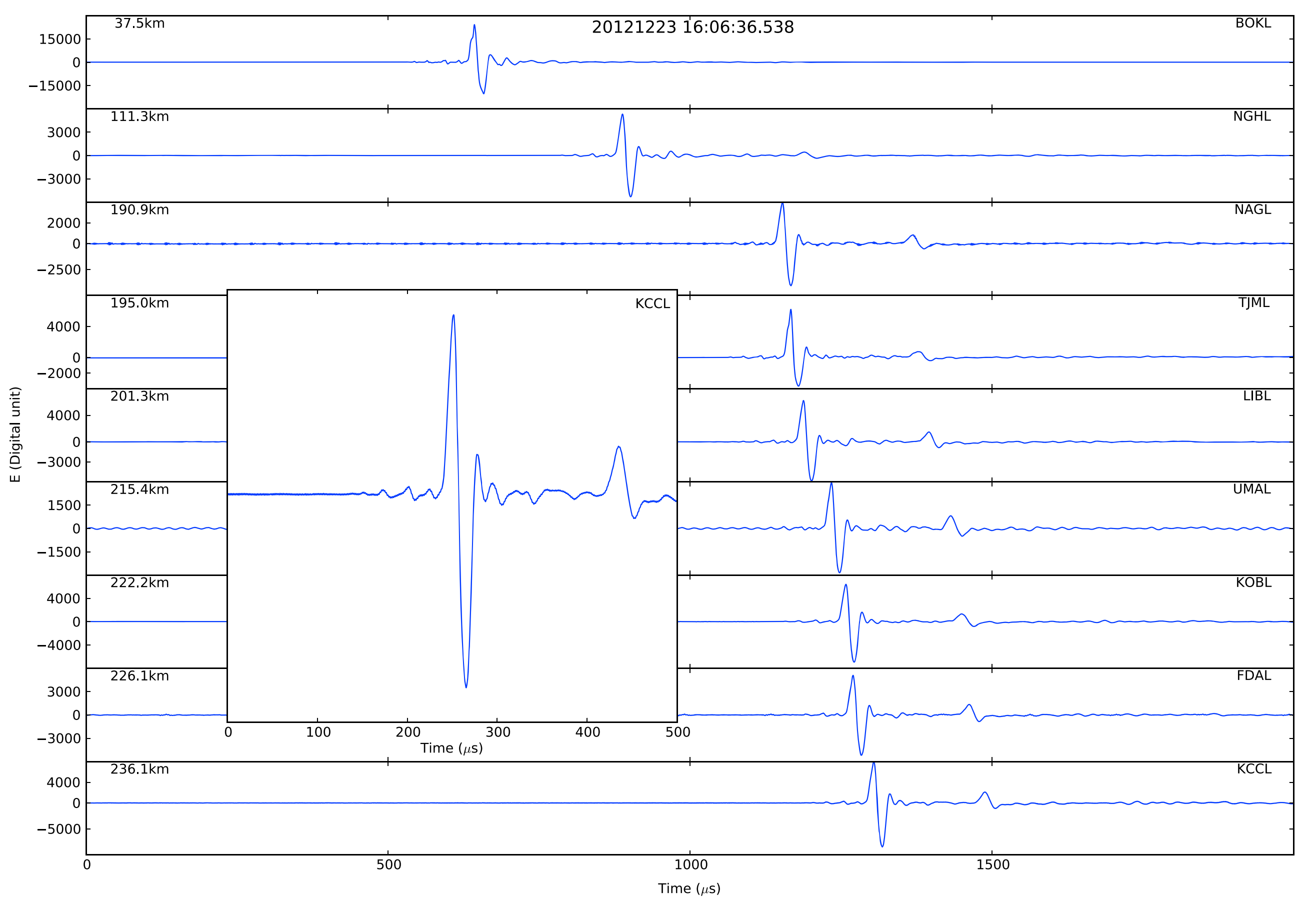

Figure 3. Waveform of a typical LBE recorded by all nine sites. The inset shows an enlarged waveform recorded by one of the sites. Distance of this event to each site and name of each site are respectively shown at top left and top right of each panel.

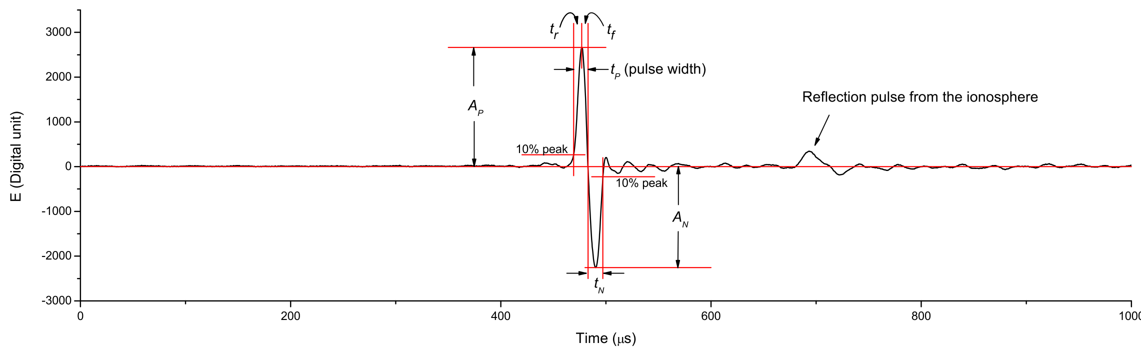

Figure 4. Illustration of characteristic parameters of LBE calculated in section 3.1.

where t_r, t_f, t_P, t_N, A_P, and A_N are all illustrated in Figure 4. Figure 5 shows distributions of t_P, r_1, r_2, and r_3. Here we only use one site's observation data to avoid possible systematic biases between different sites. This site is located near Osaka, and all of LBEs are at least 84 km away, so signals received at this site can be treated as only containing radiation field component. There are 356 LBEs observed by this site.

Figure 5a shows distribution of t_P (pulse width of LBE). Values of t_P are mainly around 15 μs. For 76.4% of LBEs, t_P values are between 10 to 20 μs. The average value is 15.1 μs. Pulse widths of LBEs are generally larger than those of narrow bipolar events (NBEs) but smaller than those of RSs. Pulse widths of NBEs are shorter than 10 μs [*Le Vine*, 1980; *Wu et al.*, 2011], and pulse widths of RSs are generally from 30 to 90 μs, depending on locations, seasons, and whether first or subsequent RS [*Cooray and Lundquist*, 1985; *Lin et al.*, 1979; *Ishii and Hojo*, 1989].

Figure 5b shows distribution of r_1 (ratio of rise time to fall time). For 92.4% of LBEs, r_1 values are larger than 1, indicating LBE pulses usually have slow rising edge and fast falling edge. Such feature is different from RSs, which have much faster rise time than fall time.

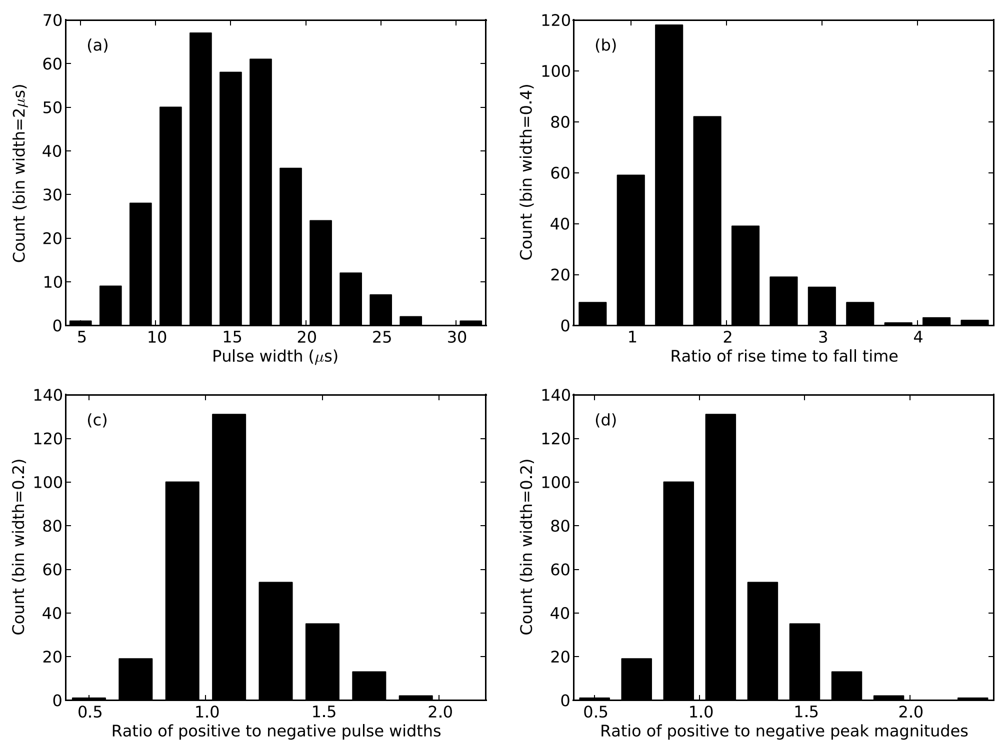

Figure 5. Distributions of (a) pulse width (t_P), (b) ratio of rise time to fall time (r_1), (c) ratio of positive to negative pulse widths (r_2), and (d) ratio of positive to negative peak magnitudes (r_3).

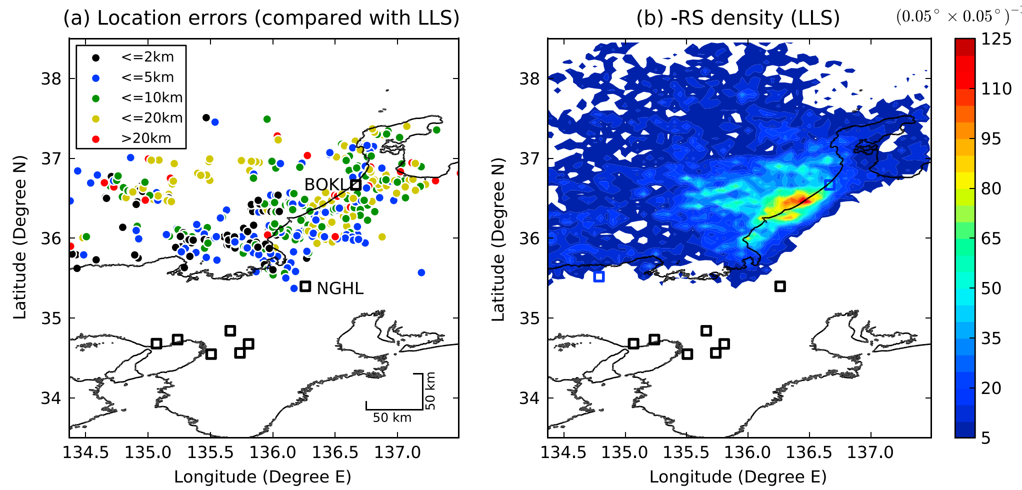

Figure 6. (a) Differences in location results of RSs detected by eight sites of LF lightning location system and LLS of Japan. (b) Density of negative RS recorded by LLS of Japan from 1 November 2012 to 31 January 2013.

Figures 5c and 5d show distributions of r_2 (ratio of positive to negative pulse widths) and r_3 (ratio of positive to negative peak amplitudes). Distributions of r_2 and r_3 are quite similar and both of them are centered around 1. This result indicates that positive and negative cycles of LBE pulses have similar pulse width and peak amplitude. Such features are also different from NBEs, whose radiation fields always show much larger initial peak than overshooting peak [*Smith et al*., 1999]. In fact, the overall waveforms of positive and negative cycles of LBEs are symmetrical to a certain extent as seen in examples in Figures 3 and 4. Such feature is not common for electric field change waveforms produced by lightning discharges.

In conclusion, LBEs produce distinctive single bipolar pulse that is different from any other well-studied lightning discharge events.

3.2. Locations of LBEs

Locations of LBEs are indicated by red and blue dots in Figure 1. LBEs in blue dots were recorded by both of the two new sites represented by blue squares and are treated as having higher location accuracy. These two new sites are essential for locating lightning discharges along the Japan Sea coast, but they have shorter time of operation (see section 2).

A surprising result is that almost all LBEs are located in the land area. As a comparison, Figure 6b shows density of negative RS recorded by lightning location system (LLS) of Japan during the same winter. This system records lightning return strokes and has a nominal location accuracy of 500 m [*Matsui and Takano*, 2010]. Note that we can only use LLS data managed by two electric power companies which cover the area from 134.37 to 137.5° longitude and above about 35.3° latitude, and Figure 6b only shows location results of negative RSs in this region. We can see that the coastal region has the highest density of RS, and most of lightning flashes occur on the sea. In fact, winter thunderstorms in western coast of Japan are developed when cold air masses from the north move over the Japan Sea with relatively warm surface temperature [*Kitagawa and Michimoto*, 1994]. Lightning flashes start a long time before thunderstorms hit the coastal area. *Hojo et al*. [1989], 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 thunderstorms reach the land do they start to occur. *Hojo et al*. [1989] also reported that lightning flashes in winter did not move inland farther than 20–30 km from the coastline. LBEs have a similar feature. Figure 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 western 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.

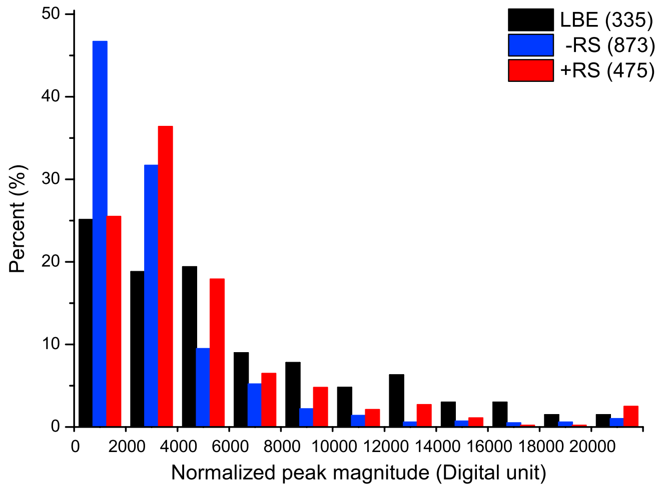

Figure 7. Distribution of normalized peak magnitudes of electric field changes produced by LBE, negative and positive RSs in Japan Sea coast. The number after each legend is the sample size for each type of event.

A few LBEs in Figure 1 seem to be on the sea, but they are probably caused by location errors. Figure 6a is a rough estimation of location errors of our LF lightning location system. We selected some RSs near the Japan Sea coast that were detected by eight sites of our system (except of the upper left one in Figure 1 which only worked from 20 December 2012) and LLS of Japan. Figure 6a shows differences between location results provided by these two systems. We can see that location difference is quite large near the site named BOKL, mainly from 5 to 20 km. This is because this region is far away from other sites, and overall propagation effects on detected waveforms may be significant. Location differences left of the site named NGHL are relatively small, most of which are smaller than 5 km. So LBEs at the middle and left part of Figure 1 should be relatively more accurate while the ones at the upper right part may contain larger location errors, which is probably the reason that some of them are located on the sea.

3.3. Peak Amplitude of Electric Field Change

Another important feature of LBEs is that they produce very large electric field changes, which is also a reason that we call them "large bipolar events." In order to quantitatively evaluate this feature, peak amplitudes of electric field changes produced by LBEs are compared with those produced by positive and negative RSs. Here we also use only one site's observation as in section 3.1. This site is located near Osaka, and all LBEs are at least 84 km away, so their electric field changes can be normalized to 100 km using the simple 1/R distance relation. Positive and negative RSs are also recorded by the same site, and only those in Hokuriku region and within half an hour of a LBE are analyzed. 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 Figure 7. The scale of electric field changes was not calibrated in our experiment, so digital unit (DU) is used in this analysis.

First, we can see distributions of positive and negative RSs have certain differences. The average normalized peak magnitude for negative RSs is 3251 DU, while that for positive RSs is 4697 DU. Distribution of negative RSs shows a rapid and consistent decrease as the peak magnitude increases. There are only 7.0% of negative RSs with normalized peak magnitude of larger than 8000 DU, while the corresponding percentage for positive RSs is 13.6%. This result is in agreement with the well-established notion that some positive CGs can carry extremely large peak current [e.g., *Orville et al*., 1987].

As for LBEs, their distribution has lower percentage below 4000 DU but higher percentage from 4000 to 20,000 DU compared with positive and negative RSs. Of the LBEs, 36.9% have peak values of larger than 6000 DU, compared with 12.2% for negative RSs and 20.1% for positive RSs. The average normalized peak amplitude for LBEs is 6086 DU, about 1.9 times that of negative RSs and 1.3 times that of positive RSs. Therefore, LBEs have a greater tendency to produce very large electric field changes, and they seem to be even more powerful than positive RSs.

Because the electric field change data are not calibrated, we cannot estimate peak currents from them. However, we have LLS data which report peak currents of RSs. Of all the RSs analyzed above, we found 750 −RSs and 423 + RSs that were also detected by LLS. Normalized peak magnitudes of electric field changes in DU (also shown in Figure 7) are compared with peak currents reported by LLS for these RSs, and the result is shown in Figure 8. We can see that the peak current in kiloampere is generally linearly correlated with the normalized peak magnitude in DU, which is an expected result, and the estimated linear regression line is

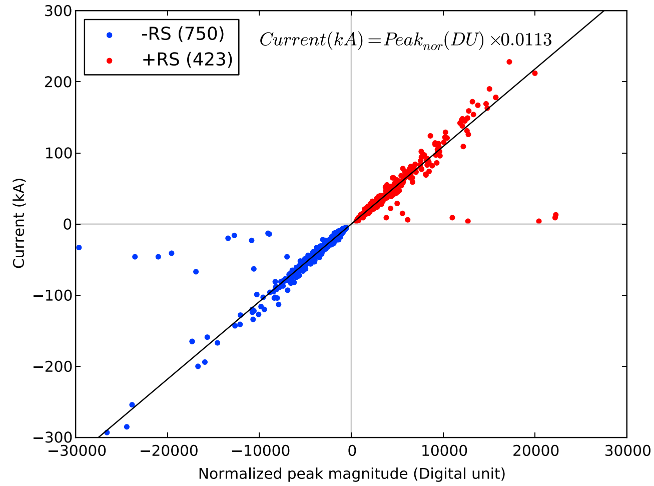

Figure 8. Correlation between normalized peak magnitudes of electric field changes and peak currents reported by LLS of Japan for 750 − RSs and 423 + RSs.

$$I_p = \alpha E_p$$

where I_p is the peak current in kiloampere, E_p is the peak magnitude of electric field change in DU, and $\alpha = 0.0113$ is the coefficient of proportionality.

Note that the time accuracy of LLS data is only 1 ms, so there are maybe some mismatches between LLS data and LF data, which are probably the reason for some points in Figure 8 that are apparently not fitted with the linear relationship.

According to the above relationship, negative and positive RSs analyzed in this section have mean peak currents of −36.7 kA and 53.1 kA, respectively. If we assume peak currents of LBEs follow the same rule as RSs, we can have a very rough estimation of mean peak current of −68.8 kA for LBEs.

3.4. Temporal Relationship With Other Discharge Processes

LBEs appear to be temporally isolated from other discharge processes within at least several milliseconds, such as examples in Figures 3 and 4. However, more careful examinations of the records show that LBEs are frequently associated with other discharge processes within tens of milliseconds. Results are summarized in Table 1. In this analysis, events within 100 ms before or after LBE and located within 15 km of the LBE are treated as associated with the LBE. Of all 374 LBEs, 117 LBEs are isolated, 124 LBEs precede other discharge processes, and 99 LBEs belong to multistroke events (multiple LBEs occurring within 100 ms and within 15 km). The remaining LBEs have other discharge processes before them.

If LBEs belonging to the same multistroke event are grouped together and treated as a single event (similar to multiple RSs being grouped into one flash), 99 LBEs can be grouped into 44 multistroke events, and temporal relationships of these multistroke events with other discharge processes are shown in the parentheses in Table 1. Seventeen of them are isolated and 24 precede other discharge events.

The most common situations are LBEs occurring in isolation or before other discharge processes. However, that some LBEs appear to be isolated may be because they are too far away and other discharge events associated with them are not detected or cannot be accurately located. As a result, the number of LBEs occurring in isolation in Table 1 is an overestimation. Another typical pattern is LBEs occurring tens of milliseconds before other discharge processes or multiple LBEs occurring within tens of milliseconds. An example is shown in Figure 9. Two LBEs occurred within 10 milliseconds, followed by regular intracloud processes after about 50 milliseconds. The second LBE is much weaker than the first one. Horizontal distances between two LBEs are only 0.22 km, indicating that there is probably no horizontal development between them. The following intracloud processes are about 6 km from the second LBE, so they seem to be induced by the preceding LBEs but do not occur at the exact same location as the LBEs. No processes are discernable before the first LBE.

Table 1. Statistics of Temporal Relationship of LBEs With Other Discharge Processes

Total Number	374 (319[a])
Isolated	117 (+17)
Following others	16 (+1)
Preceding others	124 (+24)
Both following and preceding others	18 (+2)
Belong to multistroke event	99 (44 events)

[a]See text for the meaning of the values in parentheses.

The majority of discharge processes following LBEs are similar to the example in Figure 9, showing multiple negative pulses. If the following process has initial positive-going electric field change, it usually only contains one or two irregular pulses. We have only one case in which LBE is followed by RS. In this case, a positive RS occurred about 90 ms after a LBE. Their horizontal distance was about 4 km.

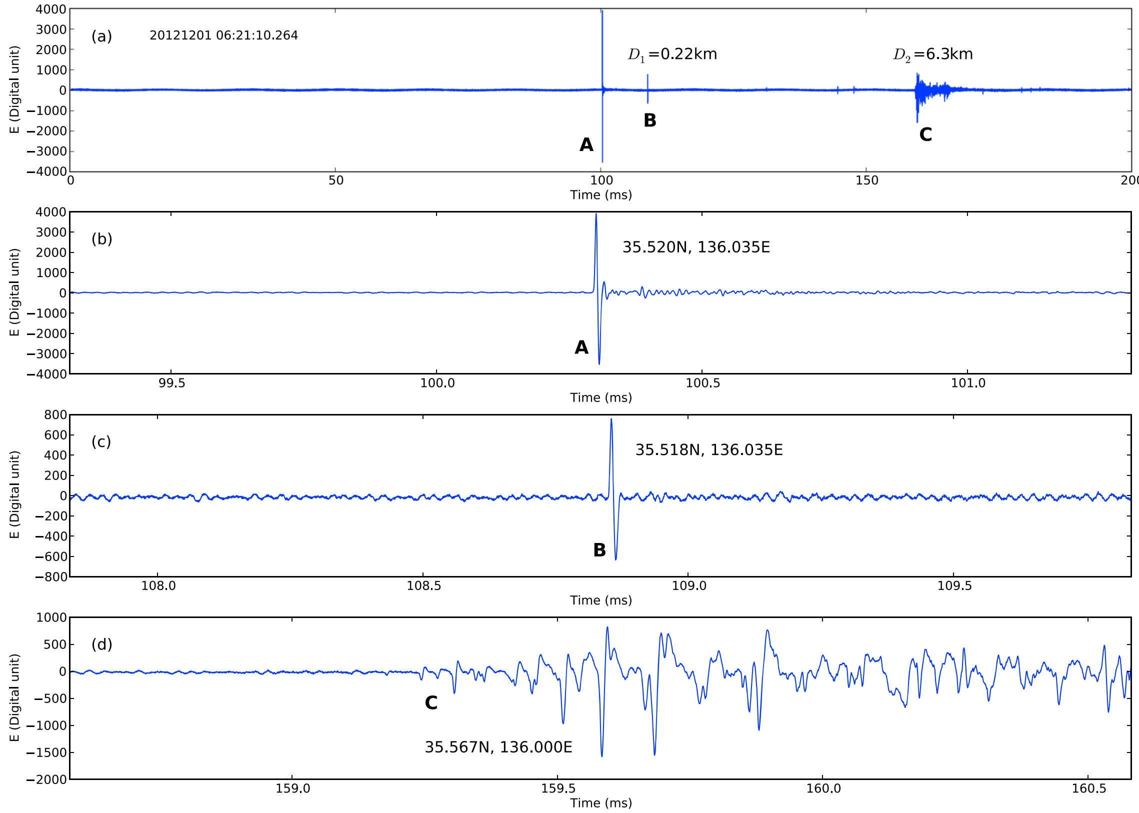

Figure 9. (a) An example of two LBEs occurring within 10 ms followed by regular intracloud processes. D_1 indicates the horizontal distance between the first and the second LBEs. D_2 indicates the horizontal distance between the second LBE and the largest pulse in the following intracloud processes. (b–d) Expanded views of pulses labeled as "A," "B," and "C" in Figure 9a.

3.5. Ionospheric Reflection Pulse

As in LBE examples in Figures 3 and 4, sometimes there is a small pulse following LBE pulse. This small pulse is caused by reflection signal from the ionosphere. Similar reflection signals of NBEs and RSs are commonly observed [*Smith et al.*, 2004; *Wu et al.*, 2012; *Lay and Shao*, 2011] and have been used to infer the electron density profile of the ionosphere [*Shao et al.*, 2013]. Reflection signal of NBEs always forms two pulses, first of which is associated with the signal reflected from the ionosphere and the second with the signal first reflected from the ground and then reflected from the ionosphere. However, there is always only one reflection pulse for LBEs, indicating that sources of LBEs are close to the ground.

Because the 2-D location of every LBE is determined by the LF lightning location system, its distance to each site is readily known, and we can calculate ionospheric reflection height using the following relation:

$$\sqrt{(2H)^2 + D^2} - D = c{\cdot}\Delta t$$

where H is the ionospheric reflection height, D is the horizontal distance between LBE and observation site, $\triangle t$ is the time difference between LBE pulse and its reflection pulse, and c is the speed of light. And we have

$$H = \frac{1}{2}\sqrt{(c{\cdot}\Delta t)^2 + 2{\cdot}D{\cdot}c{\cdot}\Delta t}$$

So observation of LBE by each site can give a result on the ionospheric reflection height.

Such relation is based on two assumptions. First, source heights of LBEs are assumed to be zero. This is a reasonable assumption because sources of LBEs are inferred to be quite close to the ground as analyzed above, which is also a common situation for lightning discharges in winter thunderstorms. Second, the Earth is assumed to be a flat plane. This is reasonable only when the distance between LBE and observation site is small. Therefore, here we only use records of LBEs within 250 km of the observation site. There are 584 records of LBEs with reflection pulse within this range (the same LBE observed by different sites are counted

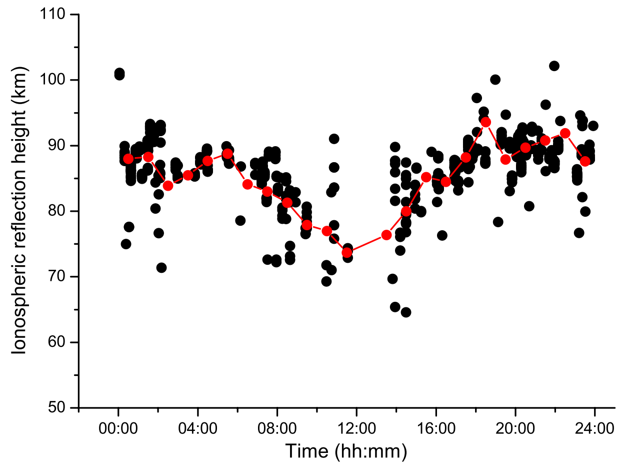

Figure 10. Diurnal variation of ionospheric reflection height calculated from the time difference between LBE pulse and its reflection pulse. Red points indicate hourly average heights.

as different records) and ionospheric reflection heights calculated from these records are shown in Figure 10. Red points indicate average height in each hour. Note that there are no records from 12:00 to 13:00. Ionospheric reflection height shows a clear diurnal variation. Nighttime height is around 90 km, and daytime height decreases to around 75 km. This result agrees well with estimation of ionospheric reflection height using NBE reflection pulses [*Smith et al.*, 2004]. Such diurnal variation also validates 2-D location results of LBEs with TOA technique. It also demonstrates that LBE is a potential candidate for ionospheric sounding [*Jacobson et al.*, 2007]. LBEs have much simpler waveforms than RSs and should be more convenient to be modeled and employed for inferring ionospheric electron properties [*Shao et al.*, 2013].

4. Comparison of LBEs and Other Types of Lightning Discharges

LBEs are basically different from all types of well-studied lightning discharge processes such as RSs, NBEs, and regular intracloud discharges, and now the key question is what kind of process produces LBEs. Based on various characteristics of LBEs presented above, we will compare LBEs with other types of lightning discharges that share certain similarities and analyze physical processes possibly associated with them.

4.1. LBEs and Lightning Discharges on Tall Grounded Objects

The most distinguishing feature of LBEs is that almost none is produced on the sea, and they are very close to the ground, indicating that LBEs are probably associated with tall grounded objects. One possibility is that LBEs are RS-like processes. Multiple LBEs occurring within tens of milliseconds as analyzed in section 3.4 is similar to multiple RSs in a CG. However, normal RS produces 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 LBEs are produced when the negative charge layer in thunderclouds is very close to the top of a tall grounded object as illustrated in Figure 11. 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 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 as in Figure 11 is rare in summer thunderstorms, but it should be much more common in winter thunderstorms. Winter thunderstorms in western coast of Japan have quite low vertical extent, typically only half of that of summer thunderstorms [*Kitagawa and Michimoto*, 1994]. With very low vertical extent, negative charge layer in thunderclouds can be close to high grounded objects such as towers and wind mills, forming a small gap with strong electric field.

That LBEs are associated with such small gap is also supported by the fact that only LBEs of negative polarity have been observed. Winter thunderstorms are found to exhibit a positive dipole or a normal tripole [*Kitagawa and Michimoto*, 1994], so LBEs are 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.

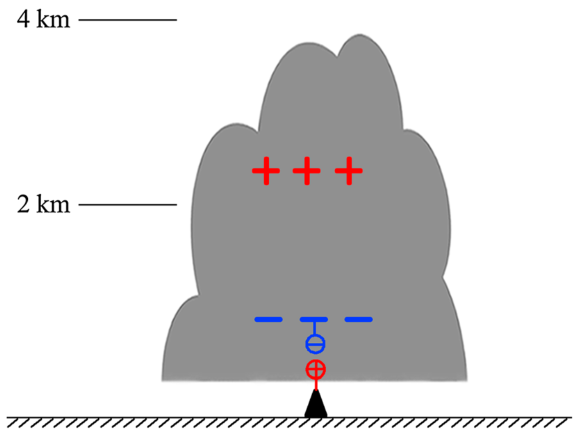

Figure 11. Illustration of possible scenario for LBE production.

It is also possible that LBE is a component of an upward lightning flash. *Ishii and Saito* [2009] presented some waveforms of upward lightning discharges associated with transmission line faults. Some of their waveforms have certain similarities with LBEs. As pointed out by *Wang and Takagi* [2012], a grounded object even with a modest height in the western 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 [*Rakov and Uman*, 2003], no matter it is self-initiated or triggered by nearby lightning discharges [*Wang et al*., 2008; *Warner et al*., 2012]. Some of the ICC pulses may also occur like the scenario shown in Figure 11 and thus radiate LBE pulse waveforms.

4.2. LBE and Preliminary Breakdown

Although LBE pulses have no similarity with PBPs and may not have any association with normal preliminary breakdown processes, a considerable percentage of LBEs in this study are found to be preceding other discharge processes (Table 1) and may serve as a type of special preliminary breakdown process in winter lightning.

Lightning flash rate in winter thunderstorms is known to be much lower than that in summer thunderstorms. Some thunderstorms are reported to produce only a "single flash" [*Michimoto*, 1993]. The main reason for such low flash rate is that winter thunderstorms have small vertical extent and weak convective strength, which hinders effective charge separation and forming of strong electric field. However, as a thunderstorm moves over a high grounded object, although its microphysical properties are not changed, the electric field strength between charge layer and the grounded object increases due to decrease of distance, and as analyzed above, LBEs may occur in such circumstance. After the occurrence of a LBE, a breakdown channel forms between the charge layer and the grounded object. There are possibly other less powerful streamers creating conducting channels inside the cloud as well. Charge structures in the thundercloud are also reorganized due to the discharge. These effects create an environment where lightning flashes are much more easily triggered than in common situations in winter. As a result, LBEs are commonly followed by more discharge processes. In such scenario, LBEs are similar to preliminary breakdown, serving as the initiation process in winter lightning.

However, currently, we are not able to explain why discharges following LBEs are mostly intracloud processes rather than CGs.

4.3. LBE and NBE

LBE and NBE surely have considerable differences. First of all, their electric field change waveforms are different as analyzed in section 3.1. A more fundamental difference is that NBEs are high-altitude intracloud discharges produced in vigorous thunderstorms in summer, [*Jacobson and Heavner*, 2005; *Wiens et al*., 2008; *Wu et al*., 2012, 2013] while LBEs are produced in winter thunderstorms and probably have connections with ground objects.

However, pulse waveforms of LBEs are most similar with those of NBEs. In fact, the original purpose of this winter campaign was to investigate whether winter thunderstorms produce NBEs. We failed to detect any NBE but recorded a type of similar pulses which turned out to be LBEs. Both of LBE and NBE produce isolated, bipolar, and very strong pulses, which distinguish them from the rest of lightning discharges. Another possible similarity is the channel length. Channel lengths of NBEs are inferred to be shorter than 1 km [*Liu et al*., 2012]. LBEs are speculated to be produced in a small gap between grounded objects and negative charge layers in thunderclouds (section 4.1), so they should have much shorter channel lengths compared with RSs, possibly close to those of NBEs.

LBEs and NBEs, respectively, seem to be unique to winter and summer thunderstorms. To our best knowledge, no other type of lightning discharge is unique to either winter or summer thunderstorms. It is possible that the processes responsible for NBEs in summer thunderstorms produce LBEs under different meteorological conditions in winter thunderstorms.

5. Conclusions

A type of special discharge event called LBE is reported. LBEs are observed in winter thunderstorms in Japan Sea coast. Electric field change waveform produced by LBEs is a single bipolar pulse with pulse width around 15 μs and initial polarity the same as that of negative RS. LBE pulses have slow rising edge and fast falling edge, and their positive and negative cycles have similar pulse widths and peak amplitudes. These characteristics make LBE pulses different from all the other electric field change waveforms produced by lightning discharge processes.

Almost all LBEs are located on the land despite the fact that winter lightning flashes in Japan Sea coast are mostly produced on the sea. This indicates that LBEs are probably associated with high grounded objects.

LBEs produce very large electric field changes that are even larger than that produced by some positive and negative RSs. The average normalized peak amplitude of electric field changes produced by LBEs is 1.9 times that of negative RSs and 1.3 times that of positive RSs. The estimated peak currents of LBEs are on average −68.8 kA.

LBEs produce a single pulse that is usually isolated within several milliseconds, but multiple LBEs can occur within tens of milliseconds and intracloud discharge processes are commonly observed tens of milliseconds after LBEs. Only one LBE is recorded as followed by a RS.

LBE signals reflected by the ionosphere produce a single reflection pulse. Ionospheric reflection height is calculated using the time difference between LBE pulse and the reflection pulse and shows an expected diurnal variation.

It is likely that LBEs are produced in a small gap between the main negative charge layer in winter thunderclouds and the top of high grounded objects. Small distance and thus strong electric field between the negative charge layer and the top of high grounded objects are necessary for production of LBEs. This also explains why LBEs are only produced in winter and only one polarity of LBE (lowering negative charges) is observed.

The occurrence of LBEs may be able to create an electrical environment that is favorable for production of intracloud discharges, which are commonly observed to follow LBEs. In this sense, LBEs may serve as a special type of preliminary breakdown in winter lightning.

LBEs and NBEs also share some similarities such as simple bipolar pulse, very large current, short duration, and possibly short channel length. LBEs and NBEs seem to be unique to winter and summer thunderstorms, respectively.

If further studies can provide conclusive evidence that LBEs are associated with tall grounded objects, studying LBEs will have great practical significance. First, LBEs carry strong peak currents that are even larger than those of some positive RSs, so they are probably the most powerful lightning discharges in winter thunderstorms. Second, if LBEs are a component of upward lightning discharges, they may be useful for differentiating upward lightning discharges in winter thunderstorms, which are quite difficult to distinguish by lightning location systems or VHF lightning mapping systems because of their irregular radiation waveforms and low source altitudes in winter.

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