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Key Points:
- Positive PB pulses (the same initial polarity as the positive return stroke) in 40 +CGs and negative PB pulses in 6 +CGs were located
- Positive PB pulses were produced by upward negative leaders and negative PB pulses by downward negative leaders
- Negative leaders producing negative PB pulses in +CGs first developed downward but would move back upward before the return stroke

Supporting Information:
- Supporting Information S1

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Locating Preliminary Breakdown Pulses in Positive Cloud-to-Ground Lightning

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Abstract This paper provides the first concrete evidence that preliminary breakdown (PB) pulses of either polarity in positive cloud-to-ground (+CG) lightning are produced by negative leaders. Three-dimensional location results of PB pulses in 46 +CG flashes are analyzed. The majority (40) of the +CG flashes started with positive PB pulses (+PBPs), the same polarity as the positive return stroke. Location results showed that +PBPs were produced by leaders propagating upward, which were determined to be negative leaders based on PB pulse polarities. Similarly, for the negative PB pulses (−PBPs) found in six +CG flashes, location results showed that they were produced by leaders propagating downward, and we determined that these were also negative leaders. Upward negative leaders producing +PBPs in +CG lightning are very similar to those in intracloud lightning. They usually propagate upward before turning in a horizontal direction. Downward negative leaders producing −PBPs in +CG lightning are more complicated. They usually move back upward after a period of downward propagation. Positive leaders could not be detected, but their possible propagations are analyzed along with possible charge structures for different types of PB pulses. We also demonstrate that PB pulse studies based on single-site records are potentially unreliable.

Plain Language Summary Lightning flashes usually start with a train of bipolar pulses called preliminary breakdown (PB) pulses. In negative cloud-to-ground (−CG) flashes, PB pulses usually have negative initial polarity, the same as the negative return stroke. However, in +CG flashes, PB pulses with either polarity have been observed by many studies. PB pulses in +CG flashes are usually explained by the movement of positive leaders because a positive leader connecting the ground is always necessary for a +CG flash. In this study, we provide the first concrete evidence that PB pulses of both polarities are produced by negative leaders. Specifically, positive PB pulses are produced by upward-propagating negative leaders and negative PB pulses are produced by downward-propagating negative leaders. Possible charge structures for different types of PB pulses in +CG flashes are also discussed.

1. Introduction

On wideband electric field change (E-change) waveforms, lightning flashes usually start with a series of bipolar pulses called preliminary breakdown (PB) pulses or initial breakdown pulses. Numerous studies have been devoted to the analysis of PB pulse characteristics (Johari et al., 2016, and references therein). With the development of low-frequency (LF) lightning locating systems, PB pulses in both negative cloud-to-ground (−CG) lightning and intracloud (IC) lightning have been located in three dimensions (3-D), and it is now very clear that PB pulses in −CG lightning and IC lightning are usually produced by negative leaders going downward and upward, respectively, from a negative charge region (Bitzer et al., 2013; Karunarathne et al., 2013; Wu et al., 2015). However, location results of PB pulses in positive CG (+CG) lightning have not yet been reported in any study, mainly due to the paucity of +CG flashes.

Many studies have found that PB pulses in +CG lightning are much more complicated than those in −CG lightning. While the initial polarity of PB pulses in −CG lightning is usually negative (using the physics sign convention), the same as the negative return stroke, the initial polarity of PB pulses in +CG lightning can be either positive or negative (Gomes & Cooray, 2004; Johari et al., 2016; Nag & Rakov, 2012; Qie et al., 2013; Schumann et al., 2013; Ushio et al., 1998; Wu et al., 2013; Zhang et al., 2013). To further complicate this problem, some studies reported observations of PB pulses with no clear polarity (Gomes & Cooray, 2004; Qie et al., 2013) and multiple pulse trains with opposite polarities (Gomes & Cooray, 2004; Johari et al., 2016; Zhang et al., 2013).

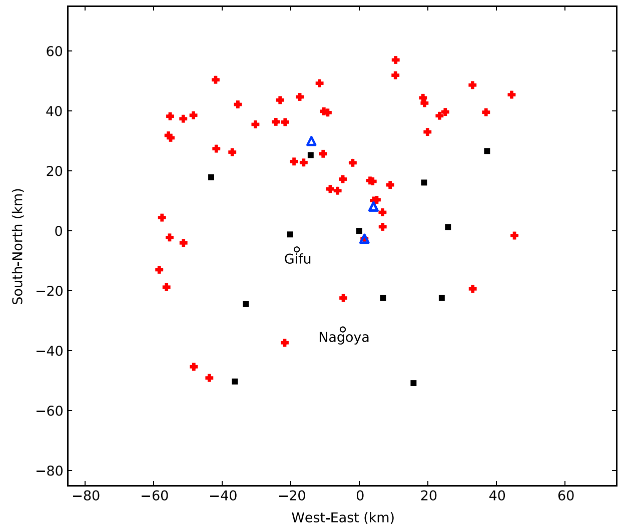

Figure 1. Twelve sites of FALMA during the summer observation of 2017 and locations of all return strokes produced by 46 positive cloud-to-ground flashes analyzed in this paper. Black rectangles represent sites of FALMA. The latitude and longitude of the site at (0, 0) is (35.475°E, 136.960°N). Red pluses represent positive return strokes. Blue triangles represent negative return strokes. FALMA = Fast Antenna Lightning Mapping Array.

The above studies also propose various theories to explain the physical processes responsible for different types of PB pulses in +CG lightning. As a positive leader connecting the ground is always a necessary part in a +CG flash, PB pulses in +CG lightning are usually explained by the development of a positive leader (Nag & Rakov, 2012; Qie et al., 2013; Wu et al., 2013). For example, Nag and Rakov (2012) attributed the positive PB pulses (the same polarity as the positive return stroke) to the downward movement of a positive leader. They also noted that there was no explanation for PB pulses exhibiting both polarities.

However, there is accumulating evidence that +CG flashes usually start with a negative leader going upward similar to IC flashes as revealed by the Lightning Mapping Array (LMA) (Lu et al., 2009; van der Velde et al., 2014; van der Velde & Montanyà, 2013; Wiens et al., 2005). The positive leader still exists; according to the bidirectional leader concept (e.g., Mazur & Ruhnke, 1993), as the negative leader develops upward, the positive leader develops simultaneously in the opposite direction. However, the positive leader usually radiates much more weakly in radio frequencies than the negative leader does and thus cannot be effectively located on most occasions (e.g., Shao et al., 1999). Considering the above evidence, it is very likely that PB pulses in +CG lightning are produced by negative leaders.

In fact, the idea that a +CG flash starts with both positive and negative leaders and the negative leader produces the PB pulses was suggested by Kawasaki and Mazur (1992) more than 20 years ago, but this idea seems to have been overlooked by recent research. In this study, we will provide the first concrete evidence that PB pulses of both polarities in +CG lightning are produced by negative leaders based on the 3-D location results of PB pulses in 46 +CG flashes.

2. Observation and Data

Data in this study were obtained with an LF lightning mapping system, the Fast Antenna Lightning Mapping Array (FALMA) established in Gifu, Japan. During the summer of 2017, FALMA was comprised of 12 fast antenna sites as indicated by the black squares in Figure 1. The fast antenna receives radio waves in the frequency range of about 500 Hz to 500 kHz and has a time constant of about 200 μs. A sampling rate of 25 MS/s was used in order to achieve a high timing accuracy. The time-of-arrival technique was employed for lightning locating, but we also used waveform correlation to match peaks at different sites, similar to the technique used by Lyu et al. (2014). In order to reduce noise and increase location accuracy, only the frequency band of 200 to 500 kHz was used for locating. These efforts have significantly improved location results over traditional LF systems. The location accuracy of FALMA in the horizontal direction over the network is estimated to be around 20 m. More details of FALMA can be found in Wu et al. (2018).

A total of 46 +CG flashes are analyzed in this study. These are +CG flashes produced inside or near the network of FALMA and can be located relatively accurately.

PB pulses in this study are defined as a series of consecutive pulses with the same initial polarity at the beginning of a lightning flash. According to our data, it seems that all lightning flashes start with multiple pulses with the same initial polarity, and we treat these pulses as PB pulses. This definition is similar to that in Wu et al. (2015). Note that location results are needed to identify the beginning of a lightning flash as it happens that multiple flashes at different locations occur in the same period and produce overlapping waveforms.

Sometimes PB pulses in +CG lightning are weak and precede the return stroke by a long time. As a result, the data acquisition system, which has a pretrigger time of 100 ms, failed to record these PB pulses. Such records usually start with small pulses not triggering the system and therefore the beginning of the flash cannot be determined. These instances are not included in this paper. According to our data, it seems that all +CG flashes start with PB pulses. Marshall et al. (2014) suggested that all −CG flashes start with PB pulses, and we speculate that it is possible to extend this conclusion to +CG flashes. However, caution is needed as the definition of PB pulses may be different in different studies.

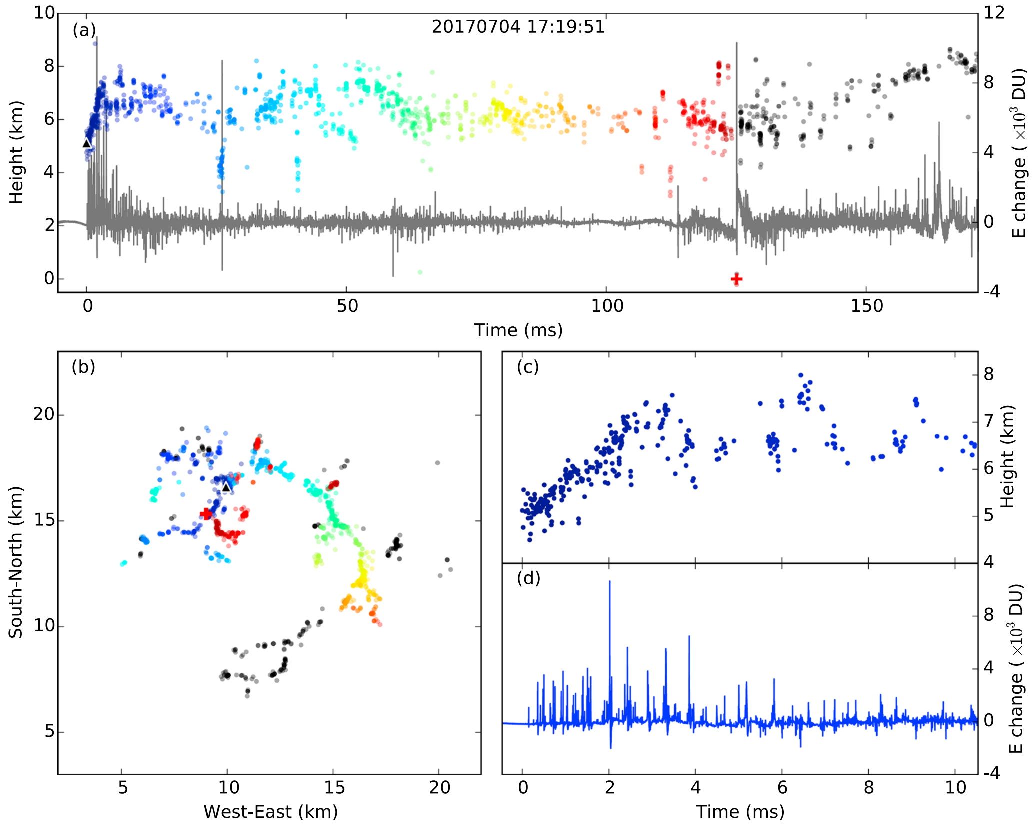

Figure 2. A positive cloud-to-ground flash starting with positive preliminary breakdown pulses. Figures 2a and 2b show sources and E-change waveform up to 180 ms from the initiation of this flash. The first source is represented by a black triangle and the return stroke by a red plus sign. Sources before the return stroke are color coded by the time. Sources after the return stroke are shown in black. Figures 2c and 2d show sources and E-change waveform during the first 10 ms of this flash. DU = digital unit; E-change = electric field change.

Of the 46 +CG flashes analyzed in this paper, 36 produced only one positive return stroke. In seven +CG flashes, two positive return strokes were produced, and always with two different terminations. In the remaining three cases, a positive return stroke was followed by one or more negative return strokes, but in only one of these three cases the negative return strokes had the same termination as the positive return stroke. A total of 53 positive return strokes and 6 negative return strokes (with three different terminations) are produced by these +CG flashes. Locations of these return strokes are shown in Figure 1.

The physics sign convention is used in this paper, so a positive return stroke produces a positive E-change pulse. We will call PB pulses with the initial polarity the same as the positive return stroke positive PB pulses (+PBPs) and those with opposite polarity negative PB pulses (−PBPs). Of the 46 +CG flashes, 40 flashes started with +PBPs and 6 started with −PBPs.

As the fast antennas were not calibrated, the magnitude of E-field changes is shown in the digital unit.

3. Results

3.1. Location Results of +PBPs

The majority (40 out of 46) of +CG flashes analyzed in this study started with +PBPs. This is in agreement with previous studies (Gomes & Cooray, 2004; Nag & Rakov, 2012; Qie et al., 2013; Schumann et al., 2013; Zhang et al., 2013). Initial leaders producing +PBPs in +CG flashes seem to be very similar. We will provide two examples to illustrate their characteristics.

3.1.1. Example One

Figure 2 shows a typical example of a +CG flash starting with +PBPs. This flash lasted for 527 ms and produced one positive return stroke at 125.1 ms as indicated by the red plus sign in Figure 2. Sources up to

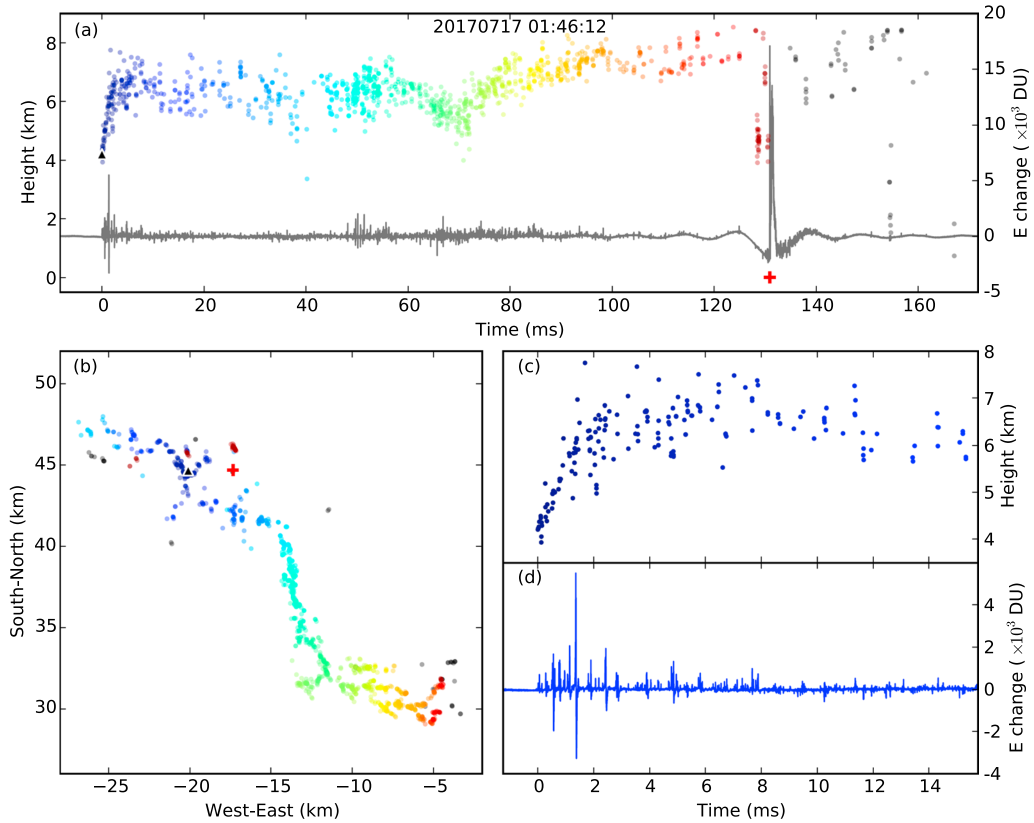

Figure 3. The second example of a positive cloud-to-ground flash starting with positive preliminary breakdown pulses. Subplots are arranged as in Figure 2. This flash lasts for a short time, and Figures 3a and 3b include all sources of this flash. DU = digital unit; E-change = electric field change.

180 ms after the initiation are shown in Figures 2a and 2b, with sources after the return stroke shown in black. According to the location results in Figures 2a and 2b, we can see this flash started with a leader progressing upward and then propagating mainly horizontally with several branches, very similar to an IC flash. This is consistent with +CG observations with the LMA (Lu et al., 2009; van der Velde et al., 2014; van der Velde & Montanyà, 2013; Wiens et al., 2005) and also agrees with many observations that +CG flashes are usually accompanied by IC flashes (Kong et al., 2008; Saba et al., 2009; Shao et al., 1999). From Figure 2b we can see the negative leader progressed horizontally away from the initiation location for about 10 km when the positive return stroke was produced near the initiation location. Some sources were located near the location of the return stroke from about 10 ms before the return stroke, but no positive leader progressing downward to the ground could be identified. After the return stroke, the horizontal negative leader seemed to continue progressing, as shown by the black sources in Figure 2b.

Figures 2c and 2d show source heights and E-change waveform at the beginning of this flash. A leader going upward can be clearly seen, which corresponds to +PBPs. We also confirmed that all sites recorded positive pulses at the beginning (waveforms recorded by all sites are provided as Figure S1 in the supporting information). When the leader turned to the horizontal direction, the pulse polarity started to change and pulses of both polarities were recorded. This type of PB is similar to that in IC flashes (Wu et al., 2015). According to the pulse polarity and the leader direction, we determined that the initial upward leader producing +PBPs was a negative leader.

3.1.2. Example Two

The second example of a +CG flash starting with +PBPs is shown in Figure 3. This is a very simple +CG flash lasting for only about 166 ms. The positive return stroke was produced at 130.9 ms. Processes before the return stroke are very similar to those in Figure 2. The initial leader propagated upward and then turned to the horizontal direction and progressed away from the initiation location. The positive return stroke was

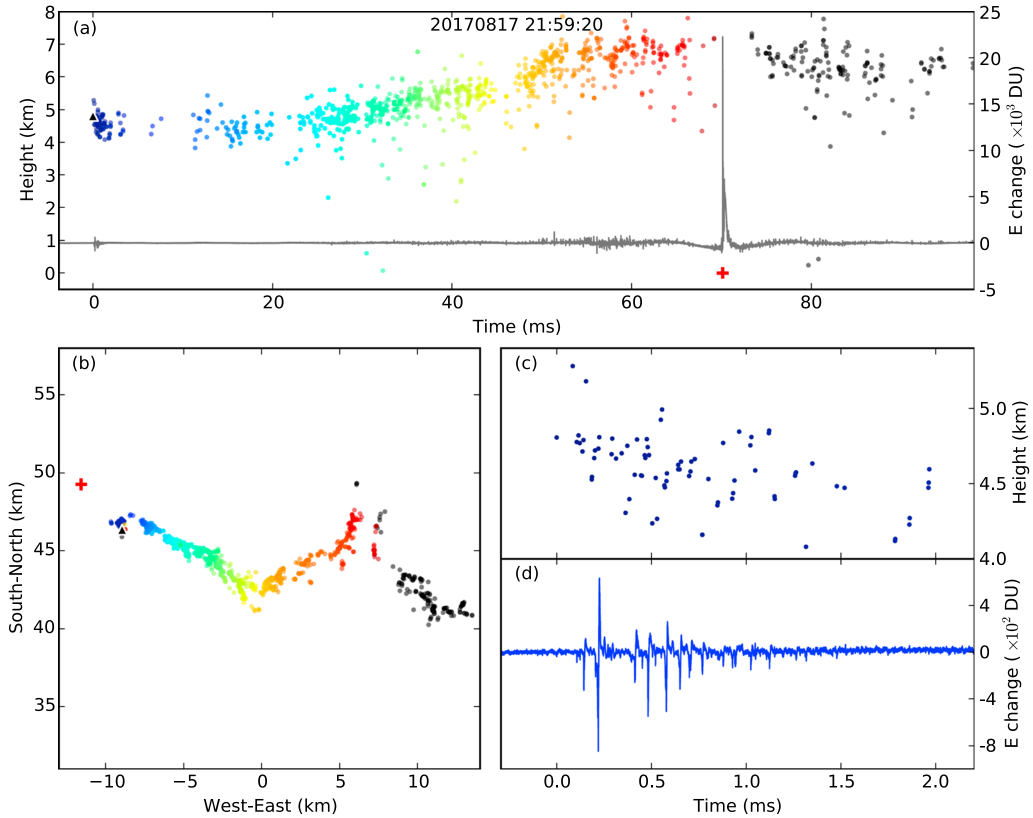

Figure 4. The first example of a positive cloud-to-ground flash starting with negative preliminary breakdown pulses. Subplots are arranged as in Figure 2. DU = digital unit; E-change = electric field change.

also produced near the initiation location. However, in this case, no leader development after the return stroke could be identified. Sources after the return stroke seemed to be produced at the tips of existing branches and only lasted for about 35 ms.

Figures 3c and 3d show the sources and E-change waveform during the first 16 ms of this flash. Similar to the example in Figure 2, the initial upward leader produced +PBPs; after the leader turned to the horizontal direction, the pulse polarity started to change. We confirmed that all sites recorded positive pulses at the beginning of this flash (waveforms are provided in Figure S2 in the supporting information). Based on these results, we determined that the +PBPs in this flash were also produced by an upward negative leader.

3.2. Location Results of −PBPs

Out of 46 +CG flashes analyzed in this paper, only 6 flashes started with −PBPs. However, leaders producing −PBPs seem to be more complicated. In this section, we will analyze three examples to demonstrate that −PBPs in +CG flashes are also produced by negative leaders.

3.2.1. Example One

Figure 4 shows the first example of a +CG flash starting with −PBPs. This +CG flash lasted for 650 ms, and the positive return stroke was produced at 70.1 ms. Sources up to 98 ms from the initiation are plotted in Figures 4a and 4b. This flash is outside of the network of FALMA and height results in Figure 4a are scattered, but we can still see a leader first moving downward for a short time and then gradually propagating upward until the return stroke. Similar to the examples in Figures 2 and 3, the return stroke was produced near the initiation location. No sources were located near the return stroke. Sources after the return stroke mainly showed horizontal propagations, and it seems that the existing leader continued progressing after the return stroke, but with an abrupt change in direction.

Sources and E-change waveform during the initial downward propagation are shown in Figures 3c and 3d. A downward leader can be identified and this leader produced −PBPs. We also confirmed that all sites

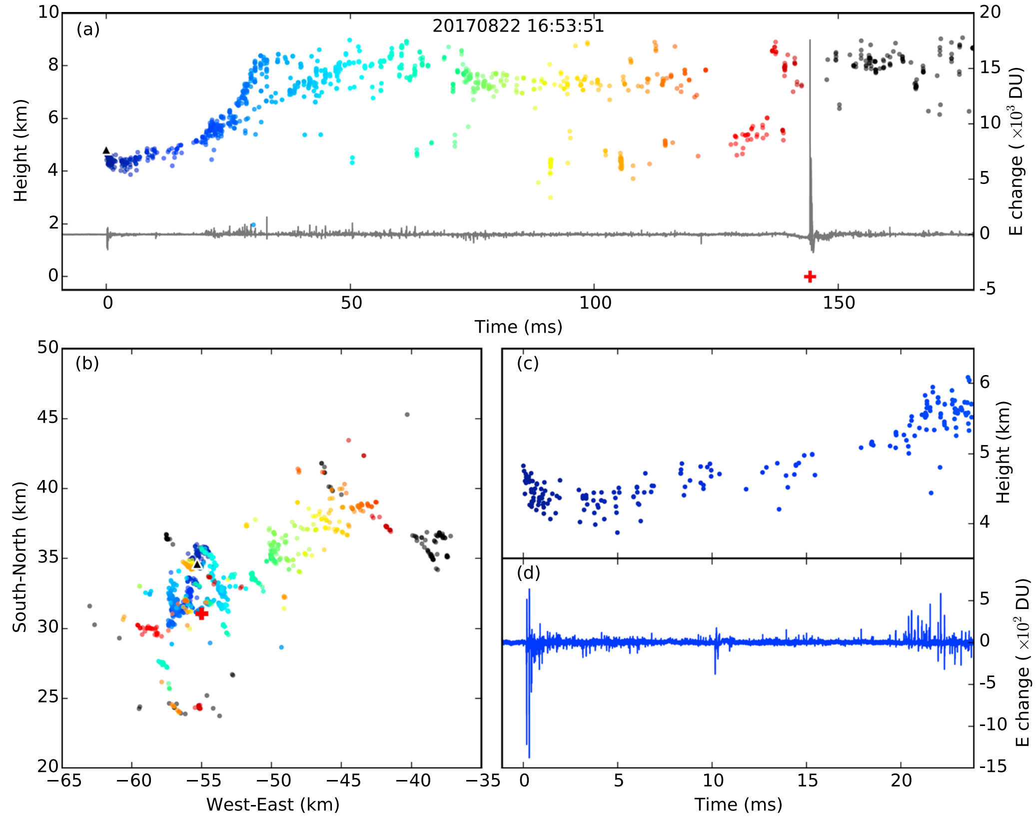

Figure 5. The second example of a positive cloud-to-ground flash starting with negative preliminary breakdown pulses. Subplots are arranged as in Figure 2. DU = digital unit; E-change = electric field change.

recorded negative pulses, which are provided in Figure S3 in the supporting information. Therefore, we determined that the −PBPs in this flash were produced by a downward negative leader.

3.2.2. Example Two

The second example of a +CG flash starting with −PBPs is shown in Figure 5. This flash lasted for 1,192 ms. Sources up to 178 ms after the initiation are shown in Figures 5a and 5b. The positive return stroke was produced at 144.2 ms. Similar to the example in Figure 4, the initial leader in this flash also first moved downward for a short time and then propagated upward. However, in this example, the leader turned to the horizontal direction more than 100 ms before the return stroke. There were also some scattered sources at a lower layer, from about 4 to 5 km, probably produced by recoil leaders. From Figure 5b, we cannot identify clear channels. It seems that the initial leader developed into many channels progressing in different directions. However, the positive return stroke was still located near the initiation location.

Figures 5c and 5d show sources and E-change waveform during the first 24 ms of this flash. Similar to the example in Figure 4, we confirmed that during the downward development of the initial leader, all sites recorded −PBPs (provided in Figure S4 in the supporting information), and we determined that the −PBPs in this flash were also produced by a downward negative leader. It is worth noting that from about 20 ms in Figures 5c and 5d, a train of positive pulses were recorded, which were produced by the negative leader propagating upward. This explains reports of PB pulses exhibiting both polarities in the literature (Gomes & Cooray, 2004; Johari et al., 2016; Zhang et al., 2013). It also demonstrates that this type of PB pulse results from a negative leader that first propagates downward and then propagates upward.

In fact, we do not think it is appropriate to include the second pulse train, which has the opposite polarity to the first pulse train as a PB pulse train. It seems that as long as a leader has mainly vertical movements, it can produce a train of pulses with the same polarity, similar to PB pulses, but the leader does not necessarily have any direct connection to the PB.

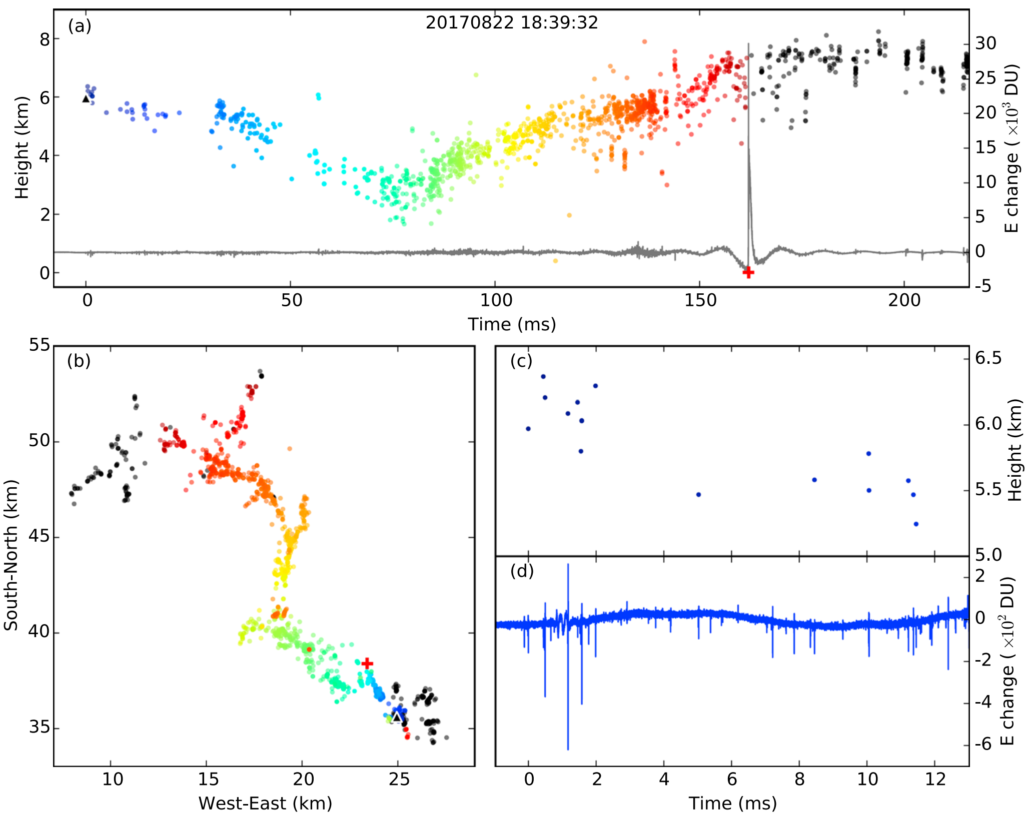

Figure 6. The third example of a positive cloud-to-ground flash starting with negative preliminary breakdown pulses. Subplots are arranged as in Figure 2. DU = digital unit; E-change = electric field change.

3.2.3. Example Three

Figure 6 shows the third example of a +CG flash starting with −PBPs, which differs significantly from the two examples discussed above. This flash lasted for 660 ms; sources up to 216 ms after the initiation are shown in Figures 6a and 6b. The positive return stroke was produced at 161.5 ms. The initial leader first kept moving gradually downward for about 80 ms and descended from 6 km to about 2 km. The leader then gradually moved upward to about 7 km before the positive return stroke. From Figure 6b we can see the leader propagated away from the initiation location with several branches for about 20 km. The positive return stroke was produced near the initiation location and seemed to have no influence on the leader development.

Figures 6c and 6d show sources and E-change waveform during the first 13 ms of this flash. A downward leader producing negative pulses can be identified, indicating the −PBPs in this flash were also produced by a downward negative leader.

The PB pulses in this example were extremely weak and the E-change waveform in Figure 6d was recorded by the closest site. Waveforms during the first 2 ms recorded by all 12 sites are shown in Figure 7. In waveforms recorded by many sites, PB pulses are hardly recognizable. On the other hand, a large and slow change can be recognized, which was probably produced by a very distant return stroke. This example illustrates the potential problems for PB pulse studies using single-site records. First, PB pulses can be buried in the background noise, which can lead to the false conclusion that the flash does not start with PB pulses. This problem was also pointed out by Marshall et al. (2014). Second, multiple flashes can occur simultaneously at different locations, which may make the PB pulses in some flashes appear complicated or abnormal. We suspect that this is the possible reason for the PB pulses with irregular initial polarity reported by Gomes and Cooray (2004) and *chaotic*-type PB pulses reported by Qie et al. (2013). Three more cases of PB pulses accompanied with waveforms produced by other flashes are shown in Figure S5 in the supporting information. These cases all belong to the 46 +CG flashes analyzed in this study. In other words, PB pulses in at least 4 of 46 flashes cannot be

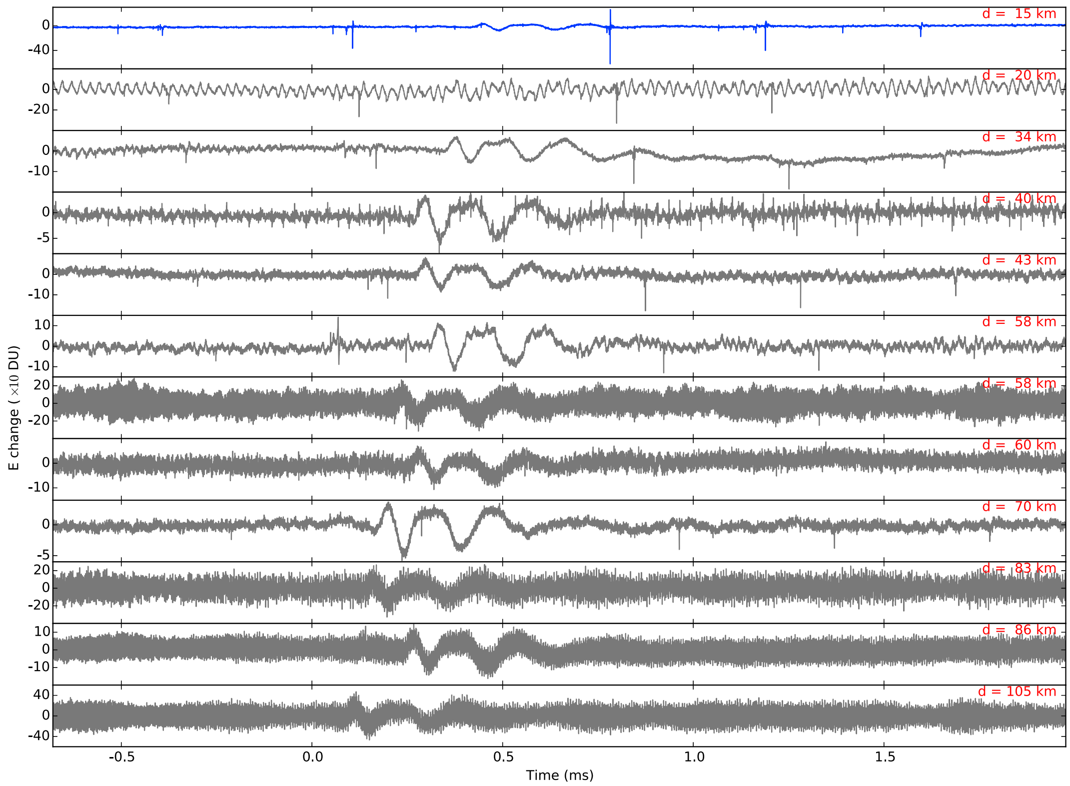

Figure 7. E-change waveforms of the PB pulses of the positive cloud-to-ground flash in Figure 6 recorded at 12 sites. These PB pulses were extremely weak and were not recognized by many sites. Time zero corresponds to the time of the first located source in this flash. The waveform in blue color is also plotted in Figure 6d. The horizontal distance between the first source and each site is indicated by the value of *d* in each subplot. DU = digital unit; E-change = electric field change; PB = preliminary breakdown.

correctly recognized without detailed location results. This result fully shows the potential unreliability of PB pulse studies based on single-site records.

3.2.4. The Remaining Three Cases

For the remaining three +CG flashes starting with −PBPs, one flash is similar to the first example in Figure 4 and another flash is similar to the third example in Figure 6. For the final flash, we found that the initial leader producing −PBPs propagated downward and thus was a negative leader. After the downward leader, sources were scattered either because of the inaccuracy in location results or complicated branches. In short, we determined that −PBPs in all six +CG flashes were produced by downward negative leaders.

4. Summary and Discussion

Based on the 3-D location results of PB pulses in 46 +CG flashes, this study determined that these PB pulses were all produced by negative leaders. Out of 46 +CG flashes analyzed in this paper, 40 flashes started with +PBPs, which were produced by negative leaders propagating upward. The remaining six flashes started with −PBPs, which were produced by negative leaders propagating downward.

Although the possibility that PB pulses in +CG flashes are produced by negative leaders has been rarely mentioned in previous studies, it is actually an expected result. It is well-known that positive leaders usually develop continuously while negative leaders are stepped. In −CG and IC flashes, PB pulses were observed to correspond to light bursts of negative initial leaders (Stolzenburg et al., 2013), indicating that PB pulses were produced by the stepping of negative leaders. In +CG flashes, other than the positive initial leaders which later contact the ground, there are also negative initial leaders according to the bidirectional leader concept (e.g., Mazur & Ruhnke, 1993) and LMA observations (van der Velde et al., 2014). It is a natural result that PB pulses in +CG flashes are produced by the negative initial leaders rather than the positive initial leaders.

The +PBPs in +CG flashes are very similar to those in IC flashes, both of which are produced by upward-moving negative leaders. However, there are also some differences. In the case of IC flashes, the positive leader usually propagates horizontally when the negative leader develops upward. The positive leader usually cannot be directly detected but can be inferred from the sources of recoil leaders traversing the positive leader channels. To demonstrate that our system can readily detect sources from recoil leaders, an example of an IC flash is shown in Figure S6 in the supporting information. In the case of +CG flashes starting with +PBPs, it seems that no sources from recoil leaders can be detected, as can be seen from the examples in Figures 2 and 3. These examples indicate that the positive leader does not have much interaction with negative charges. Therefore, the possible charge structure for +PBPs in +CG flashes is a relatively small negative charge region below a larger positive charge region, and these +CG flashes are initiated between these two charge regions. This result is consistent with the report of the presence of a lower negative charge region in thunderstorms producing +CG flashes (Rust et al., 2005; Wiens et al., 2005).

Only six +CG flashes started with −PBPs. We determined that −PBPs were produced by downward negative leaders, but the behavior of these negative leaders was more complicated. It is somewhat difficult to imagine a +CG flash starting with a downward negative leader because the necessary component for a +CG flash is a downward positive leader. However, as demonstrated in section 3.2, the downward negative leader always returns upward before the positive return stroke, so the positive leader may first move upward or horizontally for a short period before turning downward to the ground. The problem then is determining what kind of charge structure can produce these types of positive and negative leaders. Considering the fact that −PBPs in +CG flashes are relatively rare, the responsible charge structure should also be rare. It may include horizontally stacked positive and negative charge regions. The negative leader first develops downward from the negative charge region. After moving horizontally for a while, it may get to a location below a positive charge region and then move upward. The positive leader may first develop in the negative charge region in the horizontal or upward direction. Later it is possible to progress out of the negative charge region and turn to the ground.

The above analyses are speculation. Further studies on the charge structure producing different types of PB pulses are certainly needed. In our future study, we will include all IC flashes and −CG flashes produced in the same thunderstorm as +CG flashes and analyze the thunderstorm charge structure responsible for different types of PB pulses in +CG flashes.

Acknowledgments
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