Summer Thunderstorm Associated with Cluster of Blue Jets and Starters in Japan

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ABSTRACT: A cluster of blue jets and blue starters was observed, for the first time, over the Northern Kanto area of Japan on 15 August 2008. Sixty blue jets and blue starters were observed, and their emissions continued intermittently for more than 20 min. Characteristics of lightning and storm associated with blue jets and blue starters were analyzed. Consequently, we found that both blue jets and blue starters were produced by the same storm, and they are clustered in the limited area of an overshooting storm top with large Vertically Integrated Liquid (VIL) value and vigorous –CG activities. The number of negative cloud-to-ground strokes (–CGs) and intra-cloud discharges (ICs) increased just before a blue jet and showed a significant reduction after the blue jet. However, the –CG activities began to decay 0.5 s before a blue starter, although IC activities were very active ±1 s of a blue starter. The results of our analysis seem to show that the emissions of blue jet and blue starter and type of jets (whether a blue jet or a blue starter is emitted) may depend on the amount of upper positive charges accumulated, lightning characteristics, and electrical evolution of a storm.

INTRODUCTION

Jet-like Transient Luminous Events (TLEs) are categorized on the basis of their color, terminal altitude, and morphology as a blue jet (jet), a blue starter (starter), and a gigantic jet. In particular, it is difficult to observe jets and starters from the ground because their terminal altitude is lower than that of other TLEs such as elves and sprites, which emerge in the mesosphere. The visibility of blue/violet emissions decreases rapidly with distance, when viewed from the lower troposphere. Hence, the observation of jet/starter over land has been reported in only few papers written by Wescott et al. [1995, 1996, 1998, 2001], Lyons et al. [2003] and Chou [2011]. Wescott et al [1995] reported on jet/starter that appeared over Arkansas during the Sprite 94 aircraft campaign were detected using a color video camera, and the authors were the first to analyze the relationship between CGs and jet/starter. The phenomena propagated upwards from the top of the parent thunderstorm, with very active lightning discharge, and penetrated into the stratosphere. Their structure is described as a narrow cone of blue light, which reach terminal altitudes of 40–50 km. Fifty one jets were observed in a 22 min interval during a storm over

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Arkansas. Furthermore, they reported 30 examples of starter that were bright and blue in color, but not jets. They reached a much lower altitude than the jets and protruded upwards from the cloud top (17–18 km) to a maximum height of 25.5 km.

Wescott et al. [1998] noted that jets are not associated with positive CGs (+CGs) and they do not have a 1:1 relationship with –CGs. They occurred near the centroid of the spatial distribution of –CGs. Also, there was no discernible one-to-one coincidence of starters with CG lightning flashes of either polarity. Time sequences of cumulative distribution pattern of –CGs were compared for jets and starters. –CG activities with jets are the obvious increase just preceding a jet, while a lull following the jets is similar to the pattern of starters. Chou et al. [2011] observed jets, starters, and GJs occurring above a summer thunderstorm in China. They categorized some patterns of “optical strokes” analyzed by video images. They also found four types of patterns and show that one of them is similar to Wescott et al. [1996, 1998]. However, very few global observational data on jets and starters have been investigated so far. Therefore, we do not understand the characteristics of lightning discharges that result in jet/starters. For example, whether the lightning activity or the amount of charge removed from the parent thunderstorm is more important in the generation of jet/starters is yet to be determined. In addition, as Wescott et al. [1998] mentioned, data on whether jet/starters produce unique ULF, ELF, and VLF signatures are not available. In order to clarify the characteristics of lightning discharge associated with jet/starters, we analyzed VHF/LF lightning activities, CG polarities, and peak current by using the operational VHF/LF lightning mapping system and the charge moment change (CMC) estimated by our ELF detector.

A cluster of jets and starters were first detected above the northern Kanto area of Japan in summer [Suzuki et al. 2012]. These events were simultaneously observed by several monochrome and color CCD cameras at the same observatory on 15 August 2008. In this paper, we present new observational results for the parent storm structure and the characteristics of CG and IC lightning discharges causative to jets and starters.

INSTRUMENTS AND DATA

Figure 1 shows sample images of a jet (top) and a starter (bottom). All the video images were captured from the same place in Tokyo. The jet/starter events were recorded by 3 monochrome and one color high sensitivity CCD cameras, simultaneously. Terminal altitude of this jet reached 41.4 km. Figure 2 shows the deployment of instruments. On the same day, VHF/LF lightning mapping data and ELF waveform data were also observed for the same events. The three monochrome CCD cameras used here are as follows:two Watec 100N and CBC HG1208FCS-HSP 12 mm F0.8 lens with a horizontal field of view (FOV.H) of 31.2° and one Watec 100N and CBC HG0608FCS-HSP 6 mm F0.8 (FOV.H:56.7°). The color CCD camera was an NDTC NC-680 and Pentax H6Z810 8–48 mm F1.0 (FOV.H: 43.3°–7.7°). Time stamps synchronized by a network time protocol (NTP) were inserted on the video frame. We compared each time stamp of video frames of 4 cameras. Time stamps recorded in the video field almost agreed with each other and maximum time errors were estimated less than 50 ms (3 fields). In order to determine the exact event time, we calibrated the timing of optical observations by comparing the ELF transient with the GPS time stamp vs. the optical flash with the NTP time stamp in the video fields, as described by van der Velde et al. [2010].

We used VHF/LF lightning mapping data, which were observed by the Lightning Detection Network (LIDEN) operated by Japan Meteorological Agency (JMA) [Japan Meteorological Agency, 2001]. The lightning mapping network system based on Surveillance et Alerte Foudre par Interférometrie Radioélectrique (SAFIR) [Kawasaki et al. 1994] consists of 30 GPS-synchronized detection sites [http://www.jma.go.jp/jma/kishou/know/toppuu/thunder1-2.html]. The LIDEN is a hybrid system of an interferometric technique and a time of arrival method (TOA). This system receives VHF signals with bandwidth of 0.6 MHz between 110 and 118 MHz, and LF signals from 300 Hz to 3 MHz. Every site has a single VHF array of 5 dipole antennas and an LF detector. At each site we only determine the azimuth of VHF radiation source from a lightning channel determined by the interferometric technique. Furthermore, several properties of CGs observed by the LF detector at each site (CG location detection time of an event, peak amplitude of the electric field, rise and decay times of the electric field) are also analyzed. The locations of VHF source associated with ICs are triangulated by the direction angles measured by at least two VHF arrays. 2-D locations of CGs detected by several LF detectors are determined by the TOA method.

The electromagnetic field in the ELF band associated with jets and starters was measured using two induction coils and a capacitive antenna at Moshiri (44.22˚N, 142.16˚E) in Hokkaido, Japan [Hobara et al. 2000; Ando et al. 2005; Matsudo et al. 2007]. The vertical component of the electric field (Ez) and the two horizontal components of the magnetic field (Bx, By) were detected. The sampling rate of analog-digital converter was 4 kHz. ELF detector was

Figure 1. Samples of blue jets and blue starters. A sample of the blue jets observed from Tokyo at 1035:36 UTC on 15 August 2008 (top). A sample of the blue starters at 1034:23 UTC on the same day (bottom).

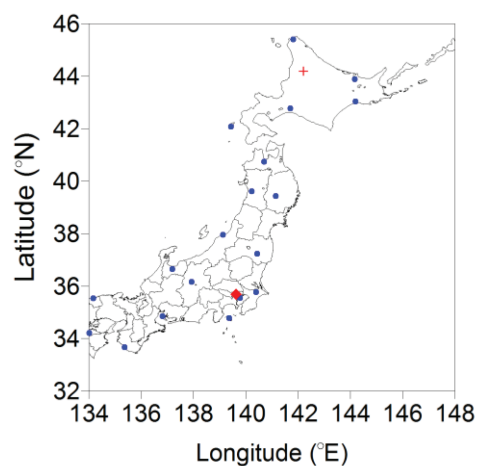

Figure 2. Deployments of Instruments. The diamond shows the location of optical site. The cross indicates ELF sensor. The dots show LIDEN sites.

synchronized with a GPS clock. The time-integrated vertical CMC was estimated by the observed ELF waveform [e.g., Huang et al. 1999].

RESULTS

Blue jets and blue starters emerged

Seventeen blue jets and 43 blue starters (a total 60 of jets and starters) were observed intermittently between 1022 and 1043 UTC on 15 August 2008. An average frequency of jet/starter emissions was 3 min^{-1} during the period, but we did not detect any other type of TLEs during the active jet/starter emissions. Figure 3 shows the time sequence of jet/starter emissions. The first emission was a starter and began at 1022 UTC; the first jet emerged at 1023 UTC. Three minutes after the first emission (first period), jets and starters were temporally suspended for about 3 min. They resumed at 1028 UTC and finished at 1043 UTC (second period). The emission rate of all jets and starters between 1022 and 1043 UTC was 3 min^{-1} (jets: 0.9 min^{-1}; starters: 2.2 min^{-1}). The highest emission rates for the jets and starters were 3 and 7 min^{-1}, respectively. Overall, the second period had more active emissions than the first period.

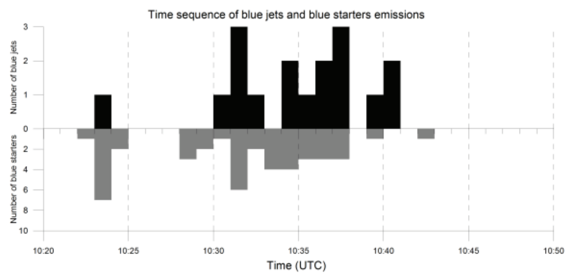

Figure 3. Time sequence of blue jet and blue starter emissions

Figure 4 shows the time durations of jets and starters. Lifetimes of jet/starter were analyzed by the time stamp in the video field. The jets lasted between 30 and 450 ms, while the duration of starters was in a range from 30 to 150 ms. Median durations of jets/starters were 60–90 ms and 30–60 ms, respectively. The longest duration of jets and starters were 422 and 141 ms. The duration of jets reported by Wescott et al. [1995] is at most 200–300 ms with the overall brightness of jets decaying simultaneously along the entire jets. The lifetime of starters has not been reported so far, but our observation indicated that most of starters last less than 90 ms. The overall duration of jets was longer than that of starters.

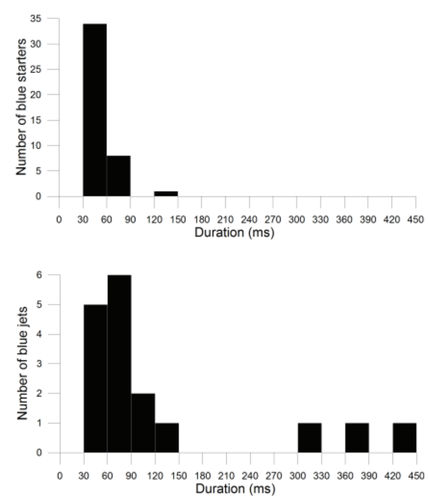

Figure 4. Time durations of blue jets and blue starters.

Storm and lightning associated with blue jets and blue starters

1) *Storm analysis*

Figure 5 shows azimuths of each jet/starter observed from Tokyo, lightning map and storm structure. The diamond sign indicates the location of the CCD cameras, and the lines from the diamond sign show the azimuths of jet/starter. Figure 5(a) shows the jet/starter azimuths from the observer that are superimposed onto the IR image at 1100 UTC. Figure 5(b) shows enlarged images of the rectangular area in Figure 5(a). The azimuths are superimposed onto the radar echo top height image at 1020–1030 UTC. Figure 5(c) is a composite radar image at 1020–1030 UTC in the same area of Figure 5(b). CGs (plus or minus signs indicate CGs polarity) and VHF lightning sources (dots) 1 s before and after the jets and starters emerged are plotted in Figures 5(b) and 5(c). At 0900 UTC, a jet/starter-producing storm system appeared on the JMA composite weather radar image. The developing storm system moved very slowly in a northeasterly direction. A group of convective clouds appeared in the IR image at 1100 UTC, which was the nearest measured time to the beginning of the jet/starter emissions. It had a large oval-shaped cloud canopy after 1200 UTC. The size of the cloud canopy was 75 × 50 km (defined by the cloud tops colder than –32˚C). The well-developed cloud canopy reached a size of 185 × 110 km at 1200 UTC, which was when the storm system was the most vertically developed. Most of the azimuth lines were oriented to and concentrated in narrow angles. We found only one storm system located on the azimuth lines of the observed jets/starters. The map of the radar echo top height indicated that this storm system consisted of two convective cells. The largest cell and the cell located on its southwest side (southwestern cell) were accompanied by strong lightning activity. However, only the largest cell, which had the most lightning activity, produced jets and starters; this cell developed at an altitude of more than 16 km when jets and starters were emitted. The overshooting cloud top reached an estimated altitude of ~17.5 km, as observed from jet/starter images before the closer anvil clouds blocked the overshooting cloud top (before 1025 UTC). The center of the largest cell was

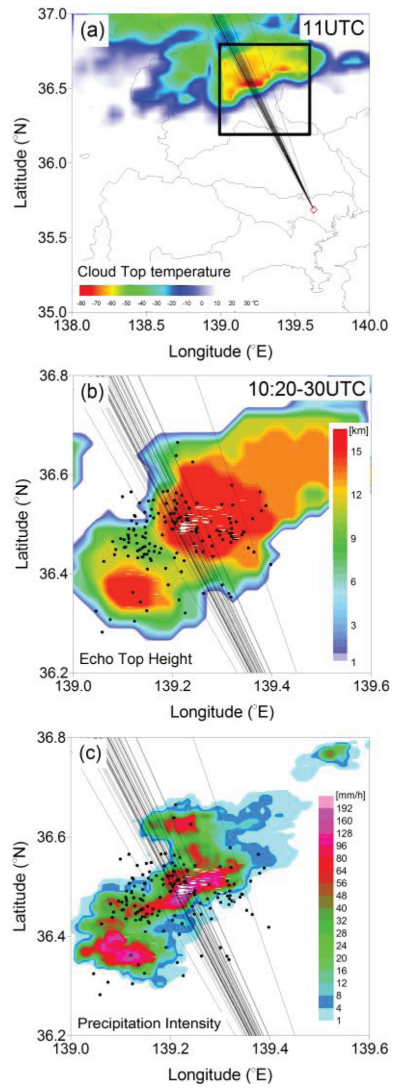

Figure 5. Azimuths of each blue jet and blue starter from the observer lightning map and storm. (a) The azimuths (lines) of blue jets and blue starters from the observer that are superimposed onto the IR image at 1100 UTC. (b) Enlarged radar echo top images of the rectangular area in (a). The azimuths are superimposed onto the radar echo top height image at 1020–1030 UTC. (c) A composite radar image at 1020–1030 UTC in the same area of (b). Cloud-to-ground strokes (plus or minus signs indicate polarity of strokes) and VHF lightning sources (dots) 1 s before and after the blue jets and blue starters emerged are plotted in (b) and (c).

located at a distance of 100 km from the observational site. The height of the echo top stayed the same during the jet/starter emission period. The strongest precipitation value (>192 mm/h) near the ground was estimated under the western part of the largest cell (corresponding to the overshooting cloud top). Many CGs were mapped on the overshooting cloud top, while VHF lightning sources were distributed inside and outside on its southwestern side. These cells had lifetimes of at least 2.5 h.

Figure 6 shows the Vertically Integrated Liquid (VIL) map and all jet/starter azimuths from the observer. The crosses and dots are VHF source and CGs 1 s before and after the event (10:23.32±1), respectively. The most important point is that jets and starters emerged and concentrated just above the core with the largest VIL value (probably containing hail). The VIL core is similar to the overshooting cloud top rather than precipitation area near the ground. This may indicate that the VIL core located in the upper part of storm (in the overshooting cloud top). Thereby, jet/starter may be induced by the charge accumulated in the upper part of convective core in the storm, which contain large amount of precipitation with hail.

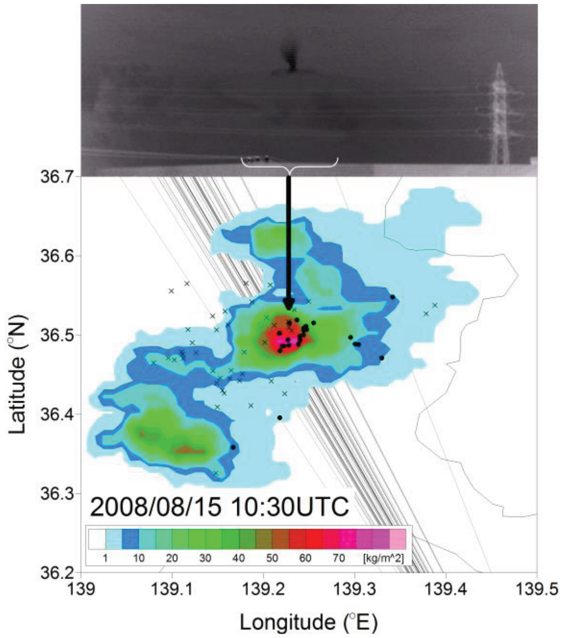

Figure 6. Vertically Integrated Liquid map and azimuths of blue jet and blue starter events from observer. The event (picture) was observed at 1023.32 UTC. The crosses and the dots are VHF source and CGs 1 s before and after the event (1023.32±1), respectively.

2) Lightning analysis

Figure 7 shows the CGs location map (a) and time sequence of lightning activities (b). Figure 7(a) is the distribution of CGs from 0900 to 1300 UTC and the azimuth of the observed jet/starter. A remarkable CG cluster was found on the azimuth lines of the jet/starter, but there was no other CG cluster between the observer and remarkable cluster. The jets and starters were emerged during the remarkable increase in CGs (arrow in the upper bar graph in Figure 7(b)). Except for the decaying phase of lightning activity (after 1140 UTC), CG activity was relatively higher than VHF activity before the jet/starter emissions, whereas the reverse was true after the end of the jets and starters period.

Characteristics of CG and IC associated with jets and starters were investigated, in the same way as Wescott et al. [1995] reported. We only analyzed jets and starters in such a way that there were not any other events which appeared within 5 s of each other so that we exclude the same flash associated with other jets and starters. Then, we found 9 jets and 28 starters without other events within 5 s.

The analyses of number of CG and VHF events associated with jet/starter events estimated by LIDEN were only analysed in which no other events appeared within 5 s of each other, so we exclude the same flash associated with other jets and starters.

Figure 8 shows the histogram of number of CGs (Figure 8(a)) and VHF sources (Figure 8(b)) in the northern Kanto area within 5 s of 9 jet events. There is a peak number of CGs and VHF sources within 0.5 s before jets emission. Both counts of CGs and VHF sources associated with jets suddenly increased within 1 s before jets emission and quickly decreased after jets. Except just before the jets (within 0.5 s), both CG and VHF sources are relatively at low activities.

Figure 9 shows the same as Figure 8, but for 28 starter events. CGs suddenly increased 1 s before the starter, and they began to decrease within 0.5 s before the starter emission. However, VHF sources increased within 1 s of the starter emission, and we found that such the same long period of increasing in the time sequence of VHF sources with jets was not observed. We should note that very vigorous CG activities were finished before starter emissions. Whereas, VHF radiation (probably an IC component) activity increased 1 s before the starter and continuously until about 1 s after the starter. The peak time of CGs with the starter was 0.5 s earlier than that with jet. The CG activity with both jets and starters kept silence until several seconds after an event. The important point is that the characteristics of VHF (IC) and CG lightning were slightly different for jets and starters. That is, it seems that jets were strongly connected with active CGs/ICs but starters would be weakly connected with CGs but related to ICs.

Jet/starter-producing CGs associated with ELF transients were also investigated and we found many transients on the ELF waveform during the 1s of a jet/starter. We analyzed CMC values corresponding to five bright jet/starter events and confirmed that no CG was detected within 1 s of jet excluding the Kanto area. The CMC within 1s of the jet/starter emission was on the order of –200 C·km ~ –100 C·km. If we assume the removed negative charge at an altitude of 8 km corresponding to a mid-level negative charge

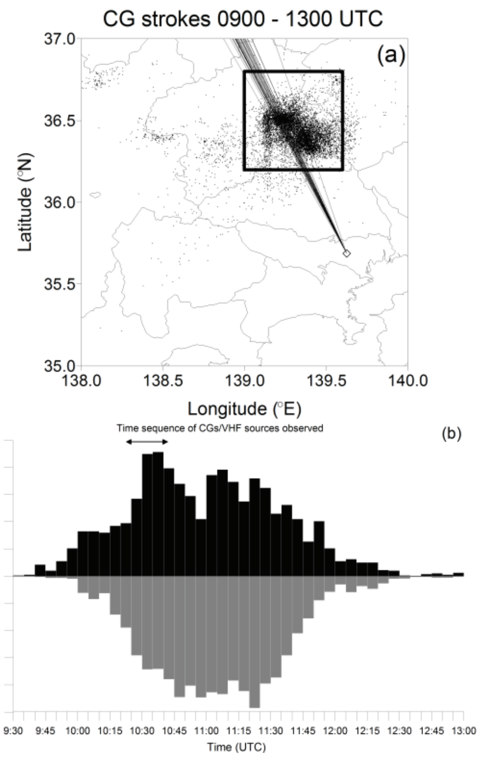

Figure 7. The CGs location map (a) and time sequence of lightning activities (b) from 0900 UTC to 1300 UTC. The lines are azimuth from observer to events. Arrow in (b) shows the period of blue jets and blue starters emerged.

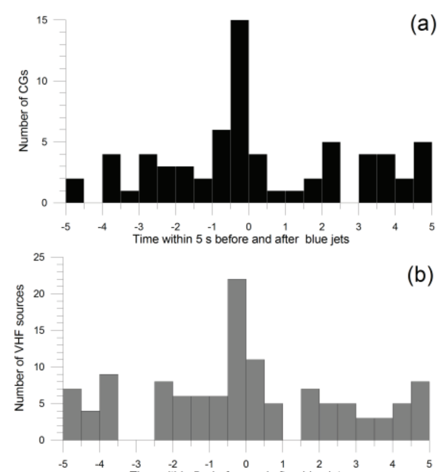

Figure 8. The histogram of number of (a) CGs and (b) ICs in the northern Kanto within 5 s of 9 jet events.

center in the ordinary summer thunderstorm [Riousset et al., 2010], the total negative charge values related to the jet/starter emissions would be ~–25 and ~–10 C, respectively. Therefore, we found that jets can be triggered by the removal of small charges at most –25 C from the parent thunderstorm, such as Riousset et al. [2010] documented. These values of charge are the same as the normal charge removed by CGs. This observational result suggests that the preceding CGs within 1 s are only the trigger for these five jet/starter emissions.

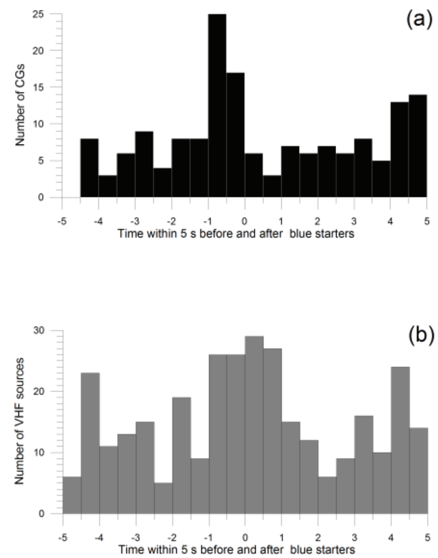

Figure 9. The same as Figure 8, but for 28 starter events.

CONCLUSIONS

The summer jets/starters were first observed in the northern Kanto area in Japan. The phenomenon is very rarely detected from the ground because the strong atmospheric reduction (of blue color) and thunderstorm conditions (widely extended stratiform and/or anvil cloud) prevent the observation from far and near the emerging place of the phenomenon [e.g., Wescott et al., 1995]. Fortunately, we had an opportunity to analyze jets/starters and their triggered CG and IC lightning characteristics and activities. Then, we found the following unique characteristics of lightning and storm accompanied by blue jets and blue starters:

1. Relationship between lightning and blue jets and blue starters

(a) The number of –CGs and ICs increased just before a blue jet and showed a significant reduction after the blue jet

(b) The –CG activities began to decay 0.5 s before a blue starter, although IC activities were very active ±1 s of a blue starter

(c) The blue jets and blue starters emerged during an occurrence of very active –CGs but relatively inactive ICs in the storm.

(d) The charge moment change within ±1 s of the blue jets and blue starters, as calculated from extremely low frequency transients associated with CGs, were ~–200 and ~–100 C·km, respectively.

2. Storm producing blue jets and blue starters

(a) The blue jets and blue starters are clustered in a limited area of overshooting storm top with large VIL value and vigorous –CG activities.

(b) The same storm produced both a cluster of blue jets and blue starters.

(c) The blue jets and blue starters may be produced by large amount of positive charge associated with the decrease in negative charge from the storm by vigorous–CG activities.

Consequently, the results of our analysis seem to show that the emissions of jet/starter and type of jets (whether a jet or a starter is emitted) may depend on the amount of upper positive charges accumulated, lightning characteristics, and electrical evolution of a storm.

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