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Termination of thunderstorm-related bursts of energetic radiation and particles by inverted intracloud and hybrid lightning discharges

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ABSTRACT

Recent studies of thunderstorm-related enhancements of fluxes of energetic radiation and particles at ground level suggest that removal of mid-level negative charge from the cloud by negative cloud-to-ground (-CG) lightning flashes or normal intracloud (IC) flashes serves to abruptly terminate those enhancements. However, it was not clear if the electron-accelerating electric field responsible for flux enhancements at ground was primarily between the main negative charge region and ground (produced due to the dominant effect of negative cloud charge) or between the mid-level negative and lower positive charge regions inside the thundercloud. Here, we report that these flux enhancements can be also abruptly terminated by inverted intracloud flashes and hybrid lightning flashes (inverted IC followed by negative CG). Based on the analysis of 13 events of these two types, we provide first evidence that the electric field between the mid-level negative and lower positive charge regions in the thundercloud can be responsible for the flux enhancements at ground level.

1. Introduction

In recent years, there has been considerable interest in the Thunderstorm Ground Enhancements (TGEs), i.e., enhanced fluxes of electrons, gamma rays, and neutrons detected on Earth's surface during strong overhead thunderstorms (Torii et al., 2009, 2011; Tsuchiya et al., 2007, 2009, 2011, 2012, 2013; Kuroda et al., 2016; Chilingarian et al., 2010, 2011, 2013, 2015, 2016, 2017; Chilingarian and Mkrtchyan, 2012; Chilingarian, 2018; Wada et al., 2018). Some of the TGEs are suddenly terminated by lightning discharges, clearly indicating their association with the electric activity of thunderstorms.

It is widely accepted that TGEs are caused by electrons accelerated and multiplied by strong electric fields in thunderclouds. However, configuration of in-cloud charge regions that produce the accelerating electric field is not yet fully understood, due partly to limited number of observations. Possible scenarios of electron acceleration in the strong electric fields in thunderclouds prior to lightning discharges that can terminate TGEs have been discussed by Tsuchiya et al. (2007, 2011) and Chilingarian and Mkrtchyan, 2012; Chilingarian et al., 2015, and a hypothesis was proposed that the electric field accelerating electrons toward ground, which is responsible for the TGE, is formed by the main (mid-level) negative and lower positive charge regions in the cloud. However, direct proof of the role of this field in producing TGEs was not presented. The lower positive charge region (LPCR) plays an important role in the initiation and development of cloud-to-ground (CG) lightning discharges (Clarence and Malan, 1957; Ogawa, 1993; Qie et al., 2005; Nag and Rakov, 2009). It is generally thought that the LPCR serves to enhance the electric field at the bottom of the negative charge region and thereby facilitate initiation of negative cloud-to-ground lightning (-CG). On the other hand, the LPCR of large magnitude may prevent the occurrence of -CG discharge and lead instead to development of inverted intracloud (IC) discharge between the main negative charge region and the LPCR. Note also that the LPCR serves to reduce the electric field accelerating electrons toward ground in space below the cloud base. As a result, removal of LPCR by lightning has both accelerating and decelerating effects on electrons, depending on altitude (above or below the removed LPCR).

Chilingarian et al. (2017) analyzed 24 cases of TGE termination by lightning observed during 2012–2016. With the 3-cm-thick scintillation detector used in that study, they did not observe any TGE termination by lightning which produced a negative electric field change; that is, for all 24 events, the field change was positive, while the background

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electric field was negative. Further, only two types of flashes were observed to terminate TGEs, namely, -CGs and normal ICs occurring between the main negative and main positive charge regions.

Here, we present analysis and interpretation of observational data for 13 events of TGE termination by lightning events all of which produced negative change of the near-surface electrostatic field.

Our observations show that TGEs can be abruptly terminated by inverted ICs occurring between the mid-level negative charge region and the LPCR and by hybrid flashes (an inverted IC followed by a -CG). This constitutes the first experimental evidence that the conditions for electron acceleration toward ground needed for production of TGEs can be created between the mid-level negative charge region and the LCPR.

1.1. Instrumentation and methodology

TGEs are defined here as enhanced fluxes of both energetic radiation and energetic particles, but we will use the term "particle flux" for brevity. Throughout this paper, we use the atmospheric electricity sign convention, according to which the downward directed electric field or field change vector is positive.

The data examined in this paper were acquired at the ASEC located at an altitude of 3200 m above sea level on Mount Aragats (Armenia). All TGEs presented here were detected by a 60-cm-thick plastic scintillator detector with an area of 1 m^2. The detector is sensitive to gamma radiation in the energy range from 4 MeV to 100 MeV, and to electrons with energy above 6 MeV. The detection efficiency is ~98% for electrons and ~50% for gamma rays. The signal from the detector was recorded at a sampling interval of 2 s. The near-surface electrostatic field changes were measured by a network of five field mills (Boltek EFM-100), three of which were placed at the Aragats station, one at the Nor Amberd station at a distance of 12.8 km from Aragats, and one at the Yerevan station, at a distance of 39.1 km from Aragats. The electrostatic field changes were recorded at a sampling interval of 1 s. The fast wideband electric field waveforms produced by lightning discharges were recorded with a circular flat-plate antenna followed by a passive integrator. The output of the integrator was connected via a 60 cm double-shielded coaxial cable to a Picoscope 5244B digitizing oscilloscope. The frequency bandwidth of the wideband electric field measuring system was 50 Hz to 12 MHz (the RC decay time constant was 3 ms). The record length was 1 s including 200 ms pretrigger time and 800 ms posttrigger time. The sampling rate was 25 MS/s (sampling interval of 40 ns), and the amplitude resolution was 8 bit.

The methodology used in this study for lightning type identification is described in detail in the paper by Chilingarian et al. (2017).

The overall methodology of lightning type identification is illustrated in Fig. 1 and includes the following steps:

Step 1. First we check the polarity of electrostatic field change ΔE at the Aragats station which in this study is always the closest to the lightning flash. If ΔE > 0, the flash is classified as either -CG or normal-polarity IC that occurred within the reversal distance (see Eq.3.4 of Rakov and Uman (2003)) of the Aragats station. If ΔE < 0, the flash is classified as +CG or inverted-polarity IC that occurred within the reversal distance (see Eq.3.4 of Rakov and Uman (2003)) of the Aragats station.

Step 2. Next, in order to resolve the ambiguity between CGs and ICs in Step 1 above, we check if the polarity of electrostatic field change ΔE reverses with distance, additionally using our remote field mills (usually the one at Nor Amberd). Polarity reversal of electric field change with distance can occur only for cloud discharges, while the polarity of electric field changes produced by CGs is always independent of distance (see Ch.3 of Rakov and Uman (2003).

Step 3. In order to distinguish between ICs and hybrid flashes (IC followed by CG), we examine fast electric field records in which we search for characteristic return stroke (RS) signatures. Since RS occurs only as a result of lightning contact with the ground, the presence of RS signatures is indicative of CGs. If at least one RS signature is found, but ΔE reversed with distance, the flash is identified as hybrid.

1.2. Data and analysis

During 2017–2018, we observed 26 new events of TGE termination by lightning, and additionally found 5 events in the 2012–2016 data by searching records acquired with a 60-cm-thick plastic scintillation detector, which is more sensitive to small changes of fluxes of energetic radiation and particles than the previously used 3-cm-thick detector. As a result, we collected a total of 55 events of TGE termination by lightning observed during 2012–2018. For 13 out of the 55 events, the background electric field was positive and the change of the near-surface electrostatic field produced by lightning was negative. We identified 6 out of the 13 events as inverted ICs, and 7 as hybrid lightning composed of an inverted IC (occurring between the main negative charge region and the LPCR) followed by -CG. Thus, two new types of events are now introduced in the classification scheme suggested in Chilingarian et al. (2017). It is important to note that both newly identified types of terminating flashes include the discharge between the main (mid-level) negative charge region and the LPCR. Analysis shows that the drops of fluxes of energetic radiation and particles associated with two new types of events are significantly smaller compared to those which produce positive field changes, and their observation has been made possible only because of using more sensitive detector.

For each of the 13 TGE events we analyzed the signal from particle detector, the near-surface electrostatic field measured by the field mills located at Aragats and at Nor Amberd, and fast wideband electric (E) field record. For all the 13 lightning flashes which produced negative field changes at Aragats, the polarity reversal of field change with distance has been detected, which is indicative of cloud discharges. However, the records of fast wideband E field produced by some of these flashes contain evidence of CG strokes. Specifically, for 7 out of the 13 events there are relatively wide pulses of positive polarity which can be attributed to return strokes of negative cloud-to-ground lightning. No optical data are available for the 13 flashes. Data and analysis of three events are given below, and the data for ten events are given in the supporting information (Supporting Information 1). The three events are representative of TGE termination by two types of lightning flashes, namely, by inverted ICs and hybrid flashes. They show two scenarios of TGE termination: 1) by a single inverted IC flash which was isolated on a time scale of several minutes, and 2) by two sequential lightning flashes (hybrid flash and inverted IC) that were separated by ~3 min with the particle flux increasing between the flashes.

1.3. July17, 2018, 12:15:44.190 UTC (inverted IC)

Particle flux and field mill records for TGE abruptly terminated by this lightning flash are presented in Fig. 2. The particle flux measured at Aragats by the 60-cm detector (2-s time series) is shown in panel (a), and the near-surface electrostatic field measured at Aragats and Nor Amberd (1-s time series) are shown in panels (b) and (c), respectively. The fast change of the electrostatic field caused by the lightning discharge leads to abrupt reduction of the particle flux by ~14%. The polarity of electrostatic field change at the Aragats station is negative, but at the Nor Amberd station it is positive; that is, polarity reversal with distance is detected. Therefore, this lightning can be identified as an intracloud flash, because the polarity reversal with distance is expected only when an elevated vertical dipole is neutralized (does not occur when there is charge transfer to ground). The larger field change detected at Aragats corresponds to a closer distance and its polarity is negative, which is indicative of inverted intracloud flash neutralizing a dipole whose positive charge was below negative. Identification of this event as a cloud flash is further supported by the fast E field record (Fig. 3) which contains only short bipolar pulses of microsecond and sub-microsecond duration and no signatures characteristic of return

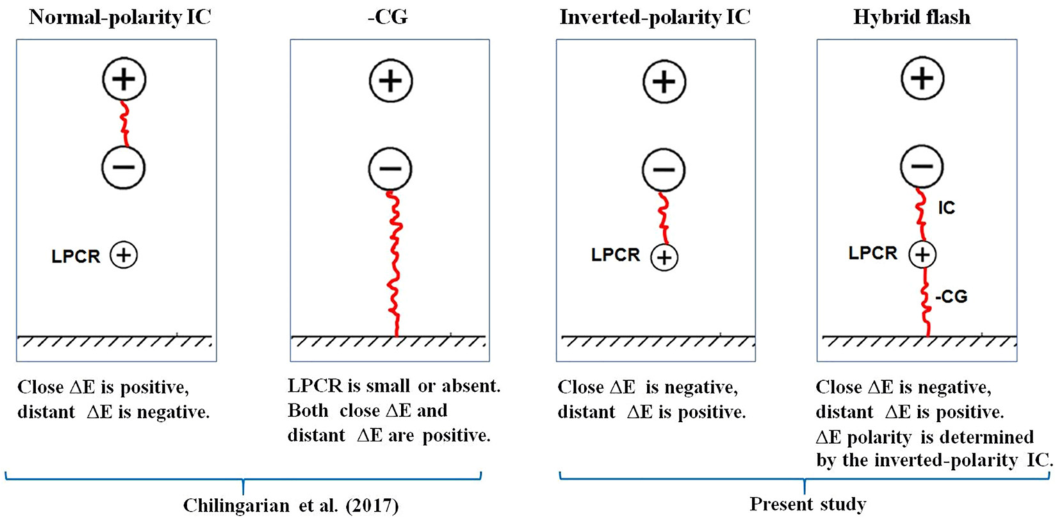

Fig. 1. Illustration of our criteria for lightning type identification. In the hybrid flash, an inverted-polarity IC is followed by a –CG (identified in fast electric field records), with the LPCR being largely consumed in the course of the inverted-polarity IC. The latter dominates the overall ΔE because of the detected polarity reversal with distance (there is no polarity reversal for -CG). The atmospheric electricity sign convention is used here.

strokes.

1.4. Events of July 6, 2016, 08:32:55 UTC (hybrid flash) and 08:36:10 UTC (inverted IC)

Fig. 4 shows effects of two lightning flashes, N1 and N2, on the enhanced particle flux that was observed on July 6, 2016. First we will consider the TGE terminated by flash N1 that occurred at 08:32:55 UTC. An abrupt decrease of particle count rate by ~14% is observed at the time of fast negative change of electrostatic field. As seen from panels (b) and (c) in Fig. 4, the electrostatic field changes detected by two field mills at Aragats and at Nor Amberd have opposite polarities (ignoring a relatively small negative excursion prior to the main signature at Nor Amberd); that is, polarity reversal with distance is detected. Based on this fact, one could classify this lightning as an inverted IC. However, this identification is not supported by the fast E field record shown in Fig. 5. The record contains a sequence of short pulses characteristic of in-cloud discharge activity followed by two strong and relatively wide pulses of positive polarity at approximately 392 ms and 464 ms after the trigger (see panels d and e). The risetimes of these two pulses are about 8–10 µs, and the peak-to-zero fall times are 100–160 µs. We attribute these two pulses to return strokes of

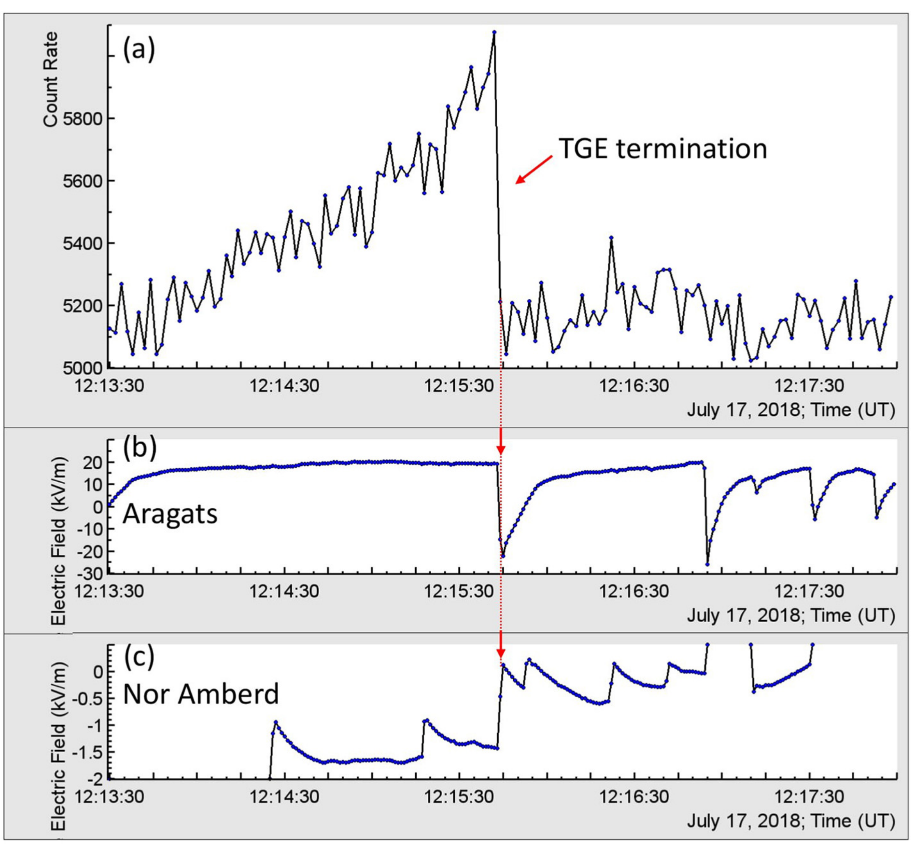

Fig. 2. Particle flux at Aragats (a) and electrostatic field changes recorded by the field mills at Aragats (b), and at Nor Amberd (c) (separated by 12.8 km) for TGE-terminating lightning flash that occurred at 12:15:44.190 UTC on July 17, 2018. The larger field change at Aragats (see panel b) has negative polarity (note different amplitude scales in (b) and (c)).

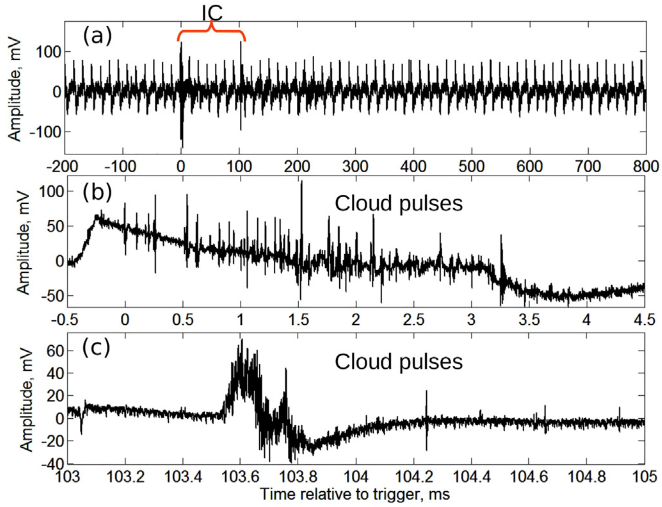

Fig. 3. Fast electric field record of lightning flash that occurred at 12:15:44.190 UTC on July 17, 2018, shown on three different time scales. Entire waveform is shown in panel (a), expanded waveforms are shown in (b) and (c). No signatures of cloud-to-ground strokes are seen.

negative cloud-to-ground (-CG) lightning.

It is worth noting that this lightning flash was detected by the WWLLN network. Thus, in spite of detected polarity reversal with distance which is expected only when an elevated vertical dipole is neutralized, this event cannot be classified as "pure" inverted IC flash. More likely, this flash is of hybrid type, when an inverted IC flash is followed a few hundred milliseconds later by a –CG lightning. Such flashes were examined, for example, by Pawar and Kamra (2004), by Nag and Rakov, 2009, Fig. 3b, by Coleman et al. (2008), and by Lu et al. (2012). It is important to note that the polarity of two pulses attributed to return strokes is positive, corresponding to removal of negative charge from the cloud and its transfer to ground. This charge removal should have produced static field changes of positive polarity at any distance, whereas the polarity of electrostatic field change at the closer station shown in Fig. 4b is negative.

Individual contributions of the IC and CG parts of the hybrid flash could not be resolved in field mill records due to 1-s sampling interval. The negative polarity of electrostatic field change is determined by the dominant contribution from the neutralization (complete or partial) of LPCR by the inverted IC flash. Certainly, the mid-level negative charge of the cloud is also reduced both by the negative cloud-to-ground discharge and by the inverted IC discharge. The contribution of the reduction of higher-altitude mid-level negative charge is dominant at Nor Amberd, where the near-surface electrostatic field change is positive.

Next we will consider flash N2, that occurred on July 6, 2016 at 08:36:10 UTC, about 3 min after flash N1 (see Fig. 4). An abrupt decrease of particle count rate by ~7% is observed at the time of this flash. The electrostatic field changes detected by two field mills in Aragats and Nor Amberd have opposite polarities, and the larger field change detected at Aragats has negative polarity. Examination of the fast E field record (see Fig. 6) shows that it contains only short bipolar pulses of microsecond and submicrosecond duration. Therefore, this lightning event can be identified as an inverted IC flash. Note that the particle flux was increasing between flashes N1 and N2, which is indicative of the recovery of electric field causing acceleration of electrons and enhancement of energetic radiation detectable at ground level.

2. Discussion

It is generally accepted that the dipolar or tripolar cloud charge structure is applicable to a great variety of storms including summer storms in Florida, mountain storms in New Mexico, and winter storms in Japan (see, for example, Figs. 3.4, 3.6, 3.7, and 3.9 and Table 3.1 of

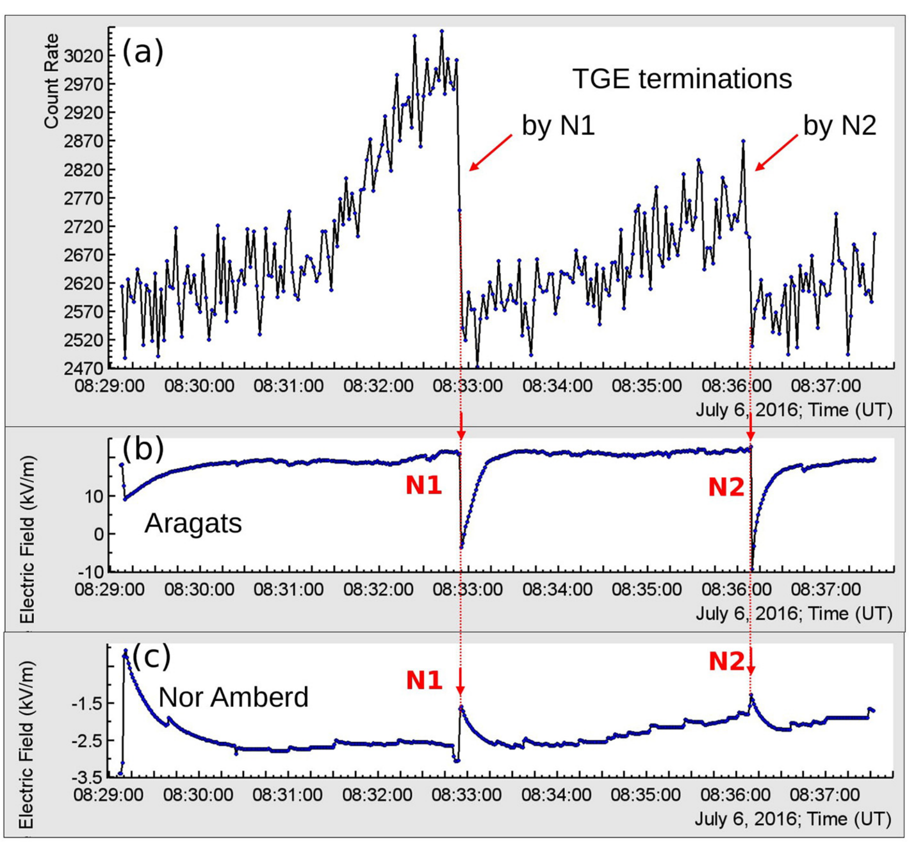

Fig. 4. Particle flux at Aragats (a) and electrostatic field changes recorded by the field mills at Aragats (b), and at Nor Amberd (c) for TGEs terminated by two lightning flashes that occurred at 08:32:55.253 UTC (N1) and at 08:36:10.460 UTC (N2) on July 6, 2016. For both flashes, the larger field change at Aragats (see panel b) has negative polarity.

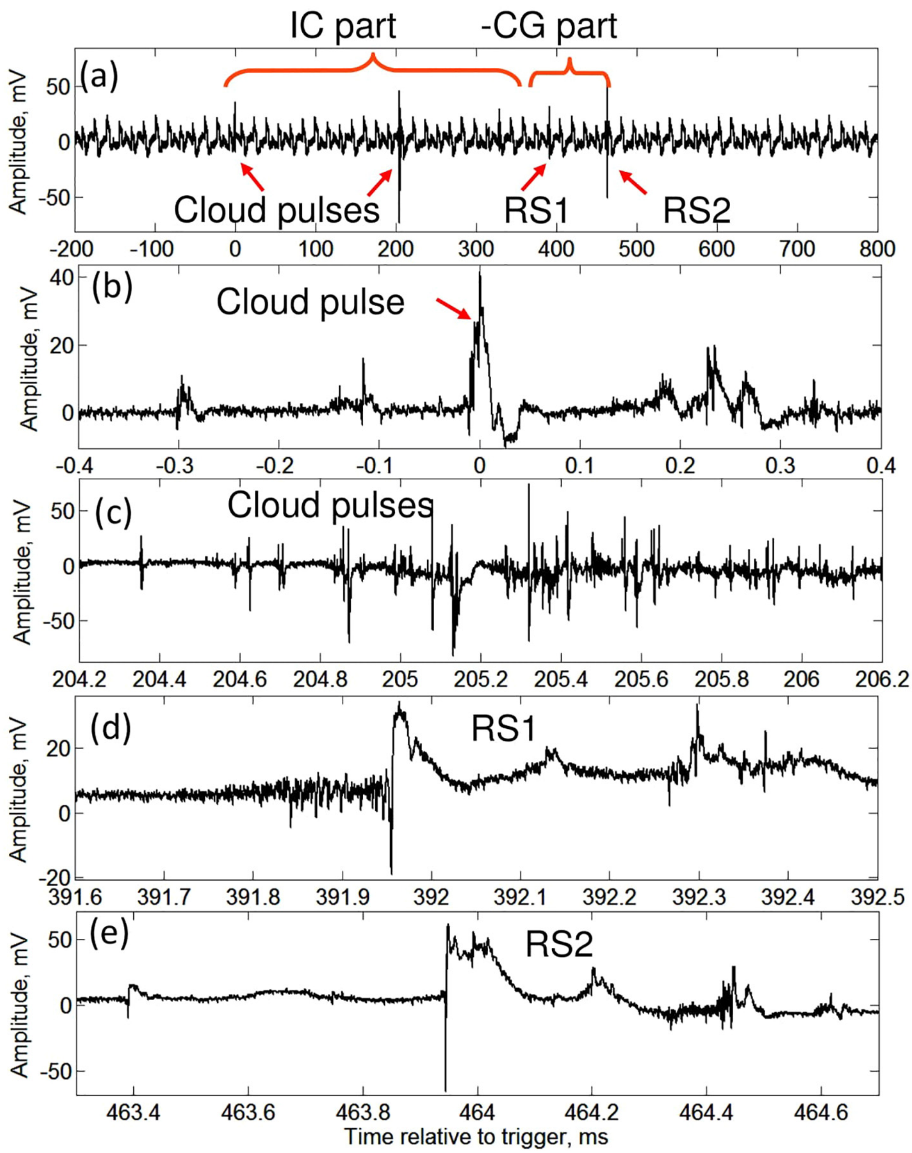

Fig. 5. Fast electric field record of lightning flash N1 that occurred at 08:32:55.253 UTC on July6, 2016. Entire waveform is shown in panel (a), expanded waveforms are shown in (b), (c), and (d). This flash was hybrid (composed of IC and –CG parts), similar to the flash represented in Fig. 3b of Nag and Rakov (2009).

Rakov and Uman, 2003), although additional charge regions can be formed away from the center of convection (see Fig. 3.11 of Rakov and Uman, 2003). In the absence of electric field soundings of thunderclouds in Armenia, we presently have to rely on the soundings of similar storms in New Mexico (see, for example, Fig. 3.9 of Rakov and Uman, 2003). We interpret our observations assuming a tripolar model of the normal-polarity thundercloud charge structure. For all 13 events the reversal of polarity of electrostatic field change with distance has been detected, and the closer field change was negative. This clearly indicates that the partially destroyed dipole was negative (negative charge above positive). The presence of the LPCR above the detector and its discharge by lightning flashes is supported by the fact that the background electric field before the discharge and the recovered field after the discharge were positive for all 13 events, and this field usually remains positive (downward-directed) for about an hour during thunderstorm.

Direct evidence of partial or full neutralization of the LPCR is the occurrence of inverted- polarity IC or hybrid flash (inverted IC followed by negative CG). The occurrence of inverted IC is detected by applying the following 2 criteria:1) the polarity of larger electrostatic field change (corresponding to the closer station) is negative, and 2) polarity reversal of electrostatic field change with distance is detected. An inverted IC (whether it is followed by negative CG or not) always indicates that the LPCR was partially or fully neutralized. These criteria are illustrated in Fig. 1, along with the criteria used for identification of normal ICs and –CGs.

Based on the analysis of new data presented here and on a reassessment of previously acquired data, the classification of lightning types for the entirety of all 55 TGE-terminating events is summarized as follows. Lightning type was identified for 49 events. For 26 out of 49 events (~47%), the lightning flashes have been identified as normal ICs, 10 events (~18%) as negative CGs, 6 events (~11%) as inverted ICs, and 7 events (~13%) as hybrid flashes. For 6 events detected during 2012–2014 the type of lightning could not be identified unambiguously. Analysis of particle flux drop for 49 TGE-terminating lightning events whose type was identified in this study shows that the TGEs terminated by inverted IC flashes and by hybrid flashes have much smaller drops of particle flux (8% and 6%) than those for -CGs (29%) and for normal ICs (20%). We believe that a smaller drop of particle flux is associated with a smaller change of electron-accelerating electric field. The change of electric field caused by inverted ICs is relatively small because it is limited by the magnitude of the lower

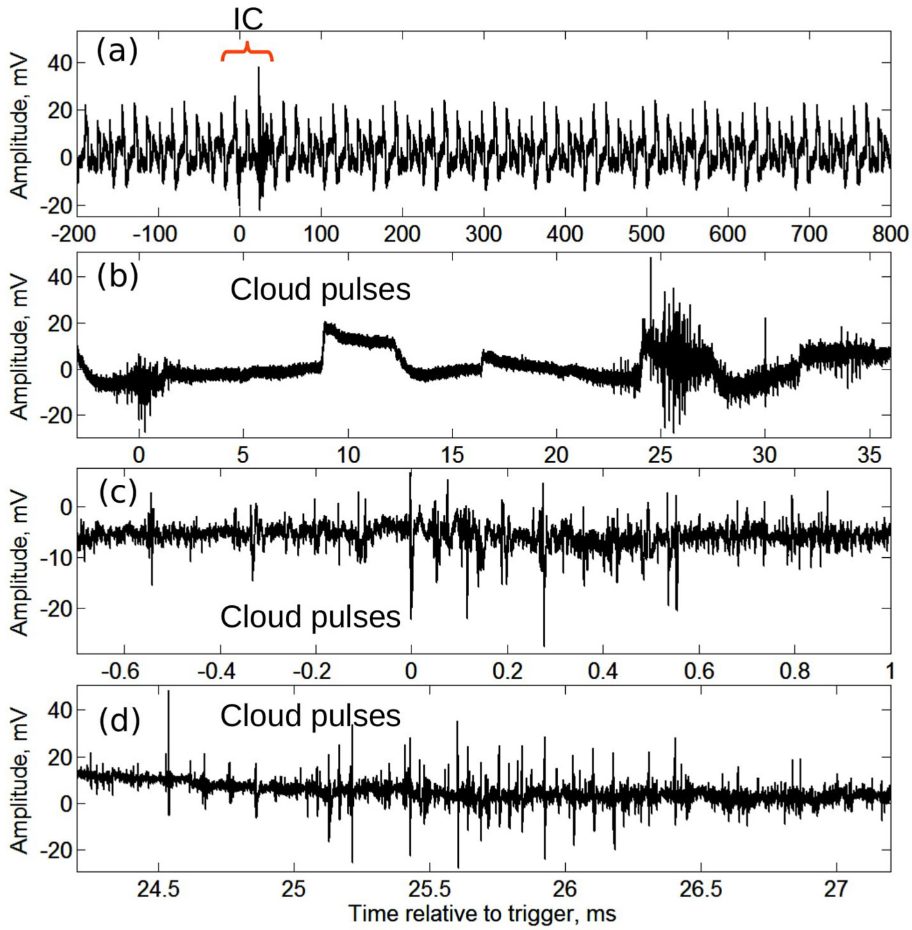

Fig. 6. Fast electric field record of lightning flash N2 that occurred at 08:36:10 UTC on July 6, 2016. Entire waveform is shown in panel (a), expanded waveforms are shown in (b), (c), and (d). This flash was an inverted IC, similar to the flash represented in Fig. 3a of Nag and Rakov (2009).

positive charge which is normally considerably smaller than that of either main negative or upper positive charges. Relatively small drops of particle flux in the case of hybrid flashes are presently not fully understood. Parameters of 55 TGE termination events observed during 2012–2018 are given in the Supporting Information 1 and Supporting Information 2.

3. Summary

We observed 13 cases of minute-scale TGE termination by lightning discharges which produced negative changes of the near-surface electrostatic field. Out of the 13 events, 6 have been identified as inverted ICs, and 7 as hybrid flashes, in which an inverted IC was followed by a –CG. Occurrence of inverted IC and hybrid flashes requires the existence of the LPCR at the bottom of the cloud, as visualized in Fig. 3 of Nag and Rakov (2009). Observation of TGEs terminated by these two lightning types is the first direct evidence that one of the electron accelerators responsible for TGEs is formed between the mid-level negative charge region and the LCPR.

Summarizing the results of previous analysis (Chilingarian et al., 2017) and the results obtained in this study we conclude that the following four types of lightning can terminate TGEs: normal ICs, negative CGs, inverted ICs, and hybrid flashes (an inverted IC followed by a -CG.), all of which neutralize some amount of charge in the main negative charge region, and thus reduce the electron accelerating electric field responsible for TGEs. Termination of TGEs by inverted ICs and hybrid flashes constitutes the first experimental evidence that the conditions for electron acceleration toward ground needed for production of TGEs can be created between the mid-level negative charge region and the LCPR.

Data availability

The data for this paper are available via the multivariate visualization software ADEI on the Web page of the Cosmic Ray Division (CRD) of the Yerevan Physics Institute http://adei.crd.yerphi.am/adei.

Acknowledgments

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.atmosres.2019.104713.

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