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Corrigendum to "Termination of thunderstorm-related bursts of energetic radiation and particles by inverted intracloud and hybrid lightning discharges" [Atmospheric Research, 233 (2020), 104713-104720]

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A B S T R A C T

The authors would like to apologize for any inconvenience caused by our conclusion on the frequency of lightning flashes of different types terminated by Thunderstorm Ground Enhancements (TGEs) and that TGEs associated with inverted IC flashes and hybrid flashes caused relatively small particle flux drops (Chilingarian et al., 2020). We recently analyzed different types of lightning flashes that terminate TGEs using a significantly enlarged data sample (163 TGE events instead of 49) observed from 2012 to 2021 (Soghomonyan et al., 2021). Our analysis of this three times larger dataset has led to results that do not support some of our previous conclusions based on smaller statistics. Therefore, we present a new analysis of the expanded database and compare our previous and current findings on the relationship between particle fluxes and lightning discharges.

1. Introduction

Our previous paper (Chillingarian et al., 2020) presents the classification of lightning discharges that suddenly terminate the enhanced flux of atmospheric electrons and gamma rays. These particle bursts, known as thunderstorm ground enhancements (TGEs), were introduced by Chilingarian et al., 2010, 2011. TGEs are caused by relativistic runaway electron avalanches (RREA, Gurevich et al., 1992), which occur in thunderclouds. TGEs can be abruptly terminated by normal polarity intracloud lightning and by negative cloud-to-ground flashes (-CG). Further, if a lower positive charge region (LPCR, Kuettner, 1950; Nag and Rakov, 2009) is present, two other types of atmospheric discharges can terminate TGE, namely the inverted ICs occurring between the mid-level negative charge region and the LPCR and hybrid flashes (an inverted IC followed by a -CG). In (Chillingarian et al., 2020), we presented the first experimental evidence that the conditions for electron acceleration toward the ground needed for the production of TGEs can be created between the mid-level negative charge region and the LCPR. The methodology was based on a multivariate analysis of particle intensity measured by large scintillators, near-surface electric fields measured by BOLTEK's EFM 100 electric mills, and fast *E*-field waveforms recorded with a circular flat-plate antenna followed by a passive integrator. That methodology also included the lightning-type identification algorithm developed by (Chilingarian et al., 2017). That algorithm is illustrated in Fig. 1. First, we analyzed the polarity of the electrostatic field change ΔE at the Aragats (closest) station. If ΔE is positive, the flash is classified as either -CG or normal-polarity IC (Fig. 1a and b) within the reversal distance; see Eq.3.4 of Rakov and Uman (2003). If ΔE is negative, the flash is classified as +CG or inverted-polarity IC within the reversal distance; see Eq.3.4 of Rakov and Uman (2003). Next, to resolve the ambiguity between CGs and ICs, we checked if the polarity of the electrostatic field change ΔE reverses with distance, using a distant station (usually one at 13 km distance, in Nor Amberd). Finally, to distinguish between inverted IC (Fig. 1c) and hybrid flash (IC followed by -CG, Fig. 1d), we examined fast electric field records and searched for characteristic return stroke (RS) signatures. Since RS occurs only due to lightning leader contact with the ground, RS signatures are indicative of CGs. If at least one RS signature is found, but ΔE polarity is reversed with distance, the flash is identified as hybrid (Fig. 1d).

Out of 13 TGEs terminations by lightning discharges, 6 have been identified as inverted ICs, and 7 as hybrid flashes, in which a –CG followed an inverted IC. The 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

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the electron accelerators responsible for TGEs is formed between the mid-level negative charge region and the LPCR.

The analysis of the lightning types that abruptly terminate TGEs is of interest because the electric field environment supporting TGE onset is still poorly understood. The interplay of the particle fluxes, lightning flashes, and electric field spatial distribution is to be understood in much more detail. As was mentioned by (Wada et al., 2023), "Since gamma-ray glows are produced in thunderclouds, not in lightning discharges, the lightning mapping technique is not applicable to most glows. On the other hand, it can be a powerful tool when a gamma-ray glow is terminated with a lightning discharge."

This report presents an updated analysis of the interaction of particle fluxes and lightning discharges based on the larger statistics.

2. Statistical analysis of the 163 TGEs terminated by lightning flashes

Table 1 shows that the normal polarity IC and -CG lightning flashes terminated >60% of the TGE events. Near-surface close electric field change for these events is positive. The close electric field change is negative for the inverted IC and hybrid flashes. In our previous paper (Chillingarian et al., 2020), we stated 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%)". As seen in Table 1, with considerably larger statistics, the percentages of TGEs of different intensities (medium-strong-weak) for negative close *E*-field changes (inverted ICs and hybrid flashes) are similar to their counterparts for positive close E-field changes (normal ICs and -CG). The share of weak TGEs (<10% particle flux drop) in the 2 classes is approximately the same (33% and 35%). Thus, our new finding does not support our previous conclusion, based on three times fewer statistics, that TGEs terminated by inverted IC flashes and hybrid flashes are associated with relatively small particle flux drops (Chillingarian et al., 2020).

Table 2 presents the percentages of different lightning types that terminated the 163 TGEs. We made this distribution separately for two classes of atmospheric discharges according to the polarity change (increase of NSEF during discharge – positive, decrease – negative). This table significantly differs from the percentages based on smaller statistics. In (Chillingarian et al., 2020), ~47% of the lightning flashes terminating TGEs have been identified as normal ICs, ~18% as -CGs, ~11% as inverted ICs, and ~ 13% as hybrid flashes. As one can see from the last row of Table 2, the share of -CGs is much higher, 49.3%, and the share of normal polarity ICs is much smaller, only 11.3%.

Table 2 has fewer events than Table 1 (150 vs 163) due to the failures of the electric mill EFM-100 at the distant Nor Amberd station. This failure prevented the identification of lightning type according to the scheme depicted in Fig. 1. Additionally, there were 3 events with the positive close electric field change, which could not be classified as per Fig. 1. The percentage of such events (2%) is negligible so that they do not materially affect our inferences presented in this paper.

In addition, we present a new analysis of TGE events from the Mendeley data set (Soghomonyan et al., 2021). Fig. 2 presents the distances to the lightning flash that interrupts TGE. The vast majority of TGEs were terminated by the nearby flashes at distances <10 km.

Another interesting plot is the occurrence of TGEs terminated by lightning flashes in different months, shown in Fig. 3. As expected, most events occurred from May to July when the lightning activity was maximum.

Table 1
Distribution of 163 TGEs by the sign of close electric field change and magnitude of particle flux drop.

Sign of close Electric Field Change	Expected lightning type	Particle flux drop medium	Particle flux drop large	Particle flux drop small
Negative 57 (35%)	Inverted IC and Hybrid	11 (19%)	26 (46%)	20 (35%)
Positive 106 (65%)	Normal IC & -CG	27 (25%)	44 (42%)	35 (33%)
Total 163 (100%)		38 (23%)	70 (43%)	55 (34%)

Table 2
The percentages of four lightning types (see Fig. 1) terminating TGEs.

Sign of close Electric Field Change	Normal IC%	-CG %	Inverted IC%	Inverted IC followed by -CG%	Unindefied (%)	Total %
Negative 56 events	0.0	0.0	17.3	20.0	0.0	37.3
Positive 94 events	11.3	49.3	0.0	0	2	62.7
Total 150 events	11.3	49.3	17.3	20.0	2	100

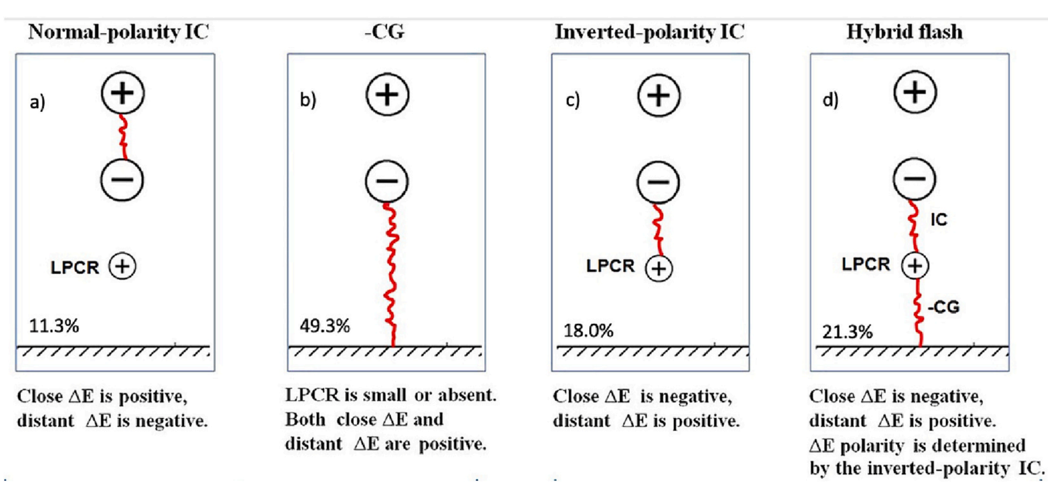

Fig. 1. Illustration of 4 types of lightning flashes that abruptly terminated TGEs, adapted from Chillingarian et al., 2020. Atmospheric electricity sign convention, according to which positive ΔE vector points downward, is used.

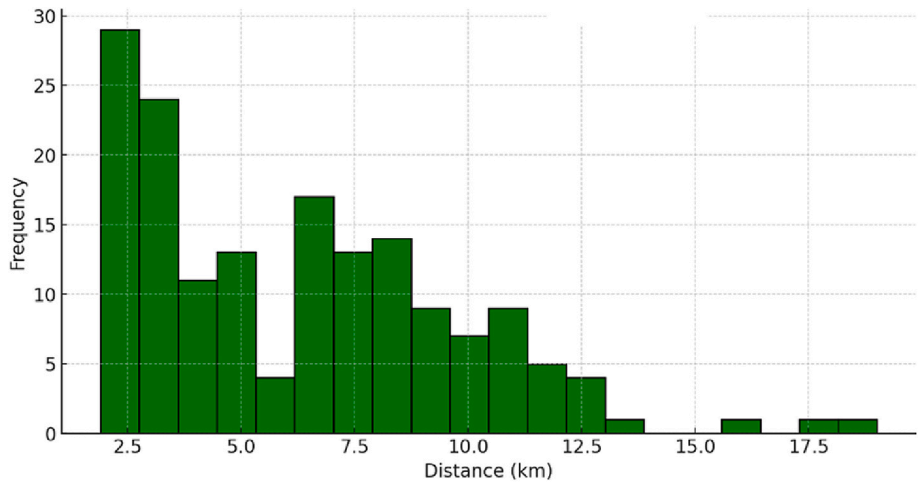

Fig. 2. The distribution of the distances to the lightning flash estimated by the BOLTEK's EFM 100 electric field mill.

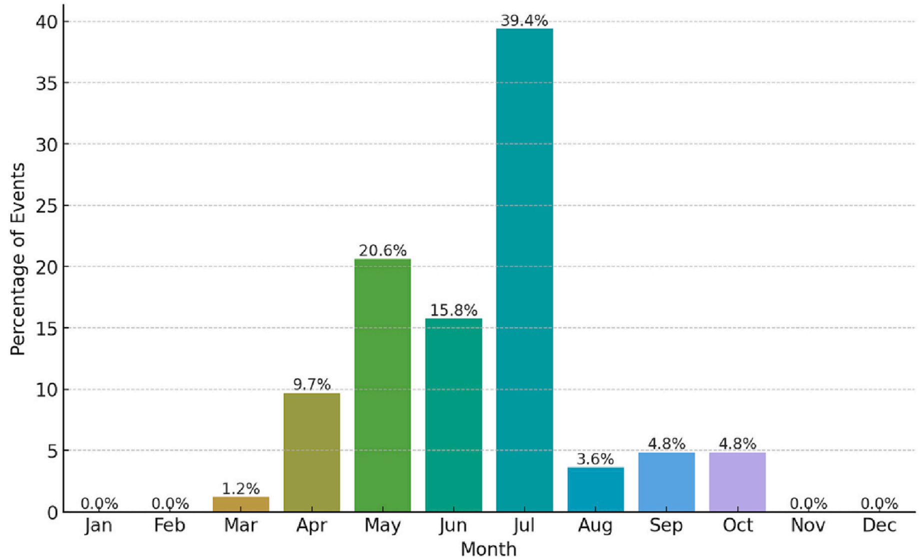

Fig. 3. Occurrence (in percent) of TGEs terminated by lightning flashes in different months.

Data availability

Data on this article (EXEL Table of 163 events) can be found online at Soghomonyan, Suren; Chilingarian, Ashot, Khanikyants, Yeghia (2021). The raw data and plots are available via the multivariate visualization software ADEI on the Cosmic Ray Division (CRD) Web page of the Yerevan Physics Institute: http://adei.crd.yerphi.am/adei.

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