End of Storm Oscillation and Thunderstorm Ground Enhancement

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Abstract

During the abrupt changes of the near-surface (NS) field according to the end of storm oscillations (EOSO) scenario, we observe prolonged thunderstorm ground enhancements (TGE). The EOSO starts with the reduction of the lower positively charged region (LPCR) with the following falling of the near-surface (NS) electric field in the deep negative domain for 12 minutes. During these minutes we observe prolonged TGE and graupel fall. Afterward, the NS field returns again to a positive value, although smaller than the initial one. Finally, the field returns to fair-weather conditions. Thus, the ending phase of the storm is followed by the degradation of all 3 charged layers of a tripole.

Plain language summary

Many species of elementary particles are born in the terrestrial atmosphere by high-energy protons and fully-stripped nuclei accelerated at exotic galactic sources. During thunderstorms, in addition to this more-or-less constant flux, electrons and gamma rays are produced by the most powerful natural electron accelerator operated in the electrifying atmosphere. Huge fluxes of electrons and gamma rays can exceed the background up to 100 times and pose yet not estimated influence on the climate. More than 2,000 thunderstorms are active throughout the world at a given moment, producing nearly 100 flashes per second. The overall surface of the thunderous atmosphere each moment can be estimated as 200,000 km^2, and according to our estimates, $1.3*10^{16}$ gamma rays with energies above 300 keV are hitting the earth's surface each second. The long-term effects of this radiation on humans should be thoroughly examined.

1. **Introduction**

In spite of many experimental and theoretical studies the relationships between storm dynamics, severe weather, and lightning activity have been least understood (Pawar, et al., 2010). The end of storm oscillations (EOSO) observed at many locations worldwide are closely related to the cloud charge structure, height of the site, and storm dynamics demonstrating different sequences of the field polarities as storm decays. Dependent on the sign of the lowest charge the sequence of the changing near-surface (NS)electric field polarities can be different at different locations and for different storms. However, adding to the NS electric field measurements, the TGE particle registration, and graupel fall observation the EOSO and the electric field structure in the lower part of the atmosphere can be characterized with more details.

It is widely accepted, that the cloud charge structure for a typical thunderstorm contains an upper positive charge region consisting of ice crystals, a main negative charge region consisting of both graupel and ice crystals, and a lower positive charge region consisting of graupel (Kuettener, 1950). The electric charge of graupel is positive at temperatures warmer than -10° C, and negative at temperatures cooler than -10° C (Takahashi, 1978, Wada et al., 2021). In review (Williams, 1989) was stated that the tripolar structure of thunderstorms is supported by a wide variety of observations and that temperature appears to be the most important single parameter in controlling the polarity of charge acquired by the precipitation particles. When graupel falls into the region warmer than -10° C, a charge reversal will occur in the central part of the storm, and the graupel population will change the charge from negative to positive. Large and dense graupel population either suspended in the middle of the thunderstorm cloud or falling toward the earth's surface constitutes a "moving" lower positive charge region (LPCR). The dipole formed by the LPCR and relatively stable main negative (MN) charge region significantly intensify the electric field of the dipole formed by the MN and its mirror image in the ground (MN-MIRR, first scenario of RREA initiation, see Fig.1 in Chilingarian et al., 2020, 2021a). A free electron entering the strong and extended electric field accelerates and unleashes the relativistic runaway electron avalanches (RREA, Gurevich et al., 1992). The RREA is a threshold process, which occurred only if the electric field exceeds the critical value in a region of the vertical extent of about 1–2 km. When the second scenario of the RREA origination (MN-MIRR plus MN-LPCR) is realized the electric field in the cloud frequently surpasses the critical value and an intense RREA ends up in an extreme thunderstorm ground enhancement (TGE, Chilingarian et al., 2010, 2011) sometimes exceeding the background level of gamma rays and electrons up to hundred times (Chum et al., 2021). After the graupel fall, the surface electric field again is controlled by the main negative charge region only.

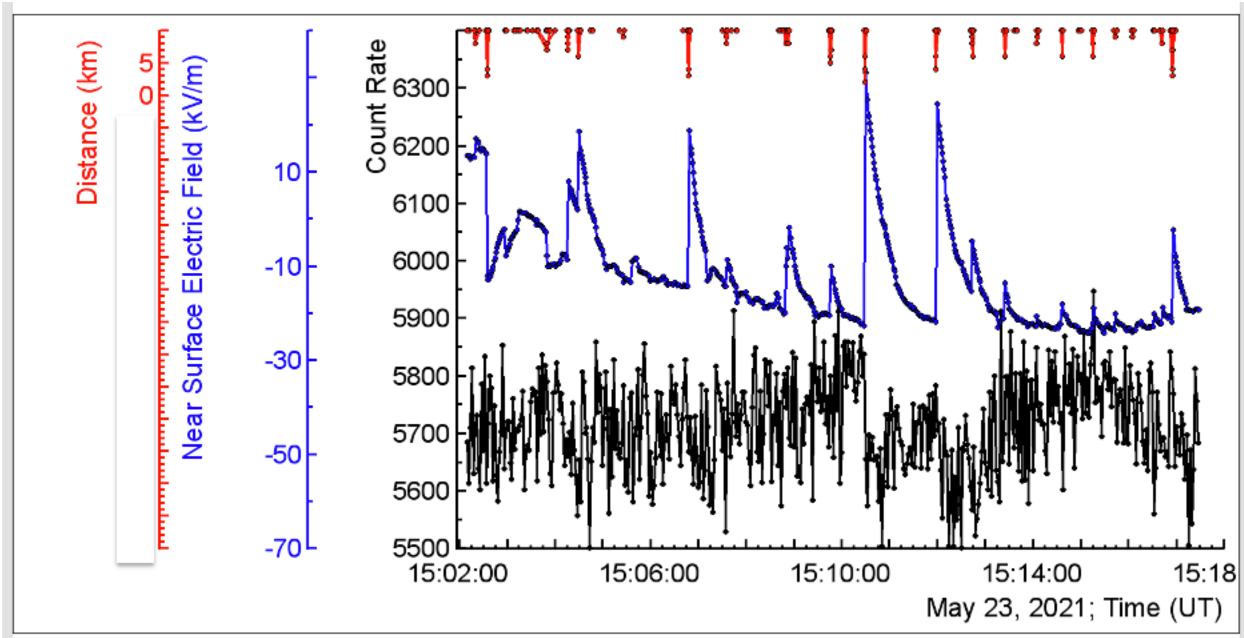
In this letter we discuss the observation of the 24 May 2021 storm on Aragats, during which the NS electric field beneath the decaying thunderstorm makes several characteristic polarity changes over a period of 60 min; this behavior is called the end-of-storm oscillation (EOSO, Stolzenburg, et al., 2008, Marshall et all., 2009). We analyze the evolution of the EOSO invoking information on TGE electron and gamma ray energy spectra and on electron-to-gamma ray ratio. Thus, demonstrating lowering and consequent decaying of LPCR. Detection of the graupel fall during TGE confirms our inference on LPCR dissipation.

1. Comparative analysis of 23 - 25 May 2021 thunderstorms

The time series of count rates of electron and gamma ray fluxes, as well, as the energy release histograms, are measured by Aragats solar neutron telescope (ASNT, see detector description in Chilingarian et al., 2016 and Chilinarian et al., 2017a). By the estimation of the spectrometer response function with

GEANT4 code, we recover differential energy spectra of both charged and neutral fluxes if a sufficient number of electrons and gamma rays reach the earth's surface. The lightning identification and distance to lightning flash estimation are done by monitoring of disturbances of the near-surface (NS) electric field with the network of EFF-100 electric mills of BOLTEK company and with Worldwide lightning location network (WWLLN), one of the nodes of which is located at CRD headquarters premises. Meteorological measurements are made with the DAVIS weather station. Panoramic cameras are used for the monitoring of skies above Aragats.

In this letter, we present results of the multivariate analysis of the measurements performed during 3 storms that occurred at Aragats in the end of May 2021. On May 23 storm duration was 6 hours with more than a hundred registered lightning flashes. In Fig 1, we present a 16-minute period of the thunderstorm with 2 TGEs terminated by the lightning flashes distance to which are denoted by red lines (1.6 and 5.4 km). The abrupt termination of the TGE can be followed by both time series of the particle detector count rates (black), and – by disturbances of the NS electric field (blue). TGEs were terminated on the initial stage of development, duration of each was 20 sec; the NS electric field was in the negative domain, the amplitude of the NS field surge caused by 2 terminating lightning flashes was 50 kV/m. The electric field recovery after lightning strikes were very fast (a few seconds). In the first part of the storm numerous attempts to start TGE were registered by the ASNT spectrometer. It is interesting to note that a new TGE started just after lightning terminates the previous one during the electric field recovering stage. This is evidence of the largely electrified atmosphere when lowering of the potential drop (voltage) by lightning flash did not quench fully electrostatic field and the field very fast returned to the high values exceeding the critical threshold for starting a new runaway process. There is some kind of interplay between lightning activity and TGE development. When an electric field is very large above the station, multiple RREAs started, however, the combination of the very strong electric field and intense ionization made by the RREA electrons leads to an early stop of RREA by the lightning flash. The electron flux of started RREA opens an ionization path to the lightning leader as was discussed in (Chilingarian et al., 2017b). Numerous examples of the TGEs preceding lightning flashes are shown in the Mendeley dataset (Soghomonyan et al., 2021a). This dataset and other publications unambiguously show that MeV energy particles are not produced by the lightning bolt, but are multiplied and accelerated in the strong electric fields by the RREA process. For many years we perform monitoring of lightning flashes and particle detector signals synchronized with nanosecond accuracy. During these years we did not register any coincidence of thousands of nearby lightning flashes with particle bursts in scintillators, in NaI crystals, and in proportional chambers of neutron monitor (Chilingarian et al., 2019).



Fi 1. A pattern of the progress of the storm on Aragats on 23 May. Disturbances of the NS electric field (blue), count rate of ASNT spectrometer (black), and distance to lightning (red).

During the second storm that occurred the next day on May 24 and lasted for 3 hours (see Fig. 2), the electrification of the atmosphere above the station was much smaller. Multiple nearby lightning flashes occurred only during the first hour of the storm from 13:30 to 14:30. After the active phase of the storm, we detect the end-of-storm-oscillation (EOSO). The NS electric field at the ground beneath decaying thunderstorm makes several polarity changes over a period of 60 minutes, beginning with a positive field dominated by positive charge overhead, in 2 minutes electric field reversal occurred and the NS field was for 8 minutes in the deep negative domain. We use the atmospheric electricity sign convention, according to which the downward directed electric field or field change vector is positive. This period of negative field was followed by a slower return to a weaker than the initial positive field, which returns in an hour after to additional oscillation to fair weather value. During mostly negative NS electric field (dominated by the negative charge overhead) the TGE started and smoothly finished without being disturbed by a lightning flash. The total duration of TGE was (12 minutes) and the intensity of gamma ray and electron fluxes were sufficient to allow the differential energy spectra recovery, see Table 1.

Thus, owing to the possibility of observing EOSO simultaneously with registered electron and gamma ray fluxes, we can classify TGEs according to the pattern of the NS electric field disturbances. In the classification of NS electric field disturbances, we outline 4 categories (Chilingarian & Mkrtchyan, 2012), and the fourth most complicated type, namely, “Multiple disturbances of a near-surface electrical field accompanied by numerous flashes of lightning”, we do not analyze, leaving it for the later publications.

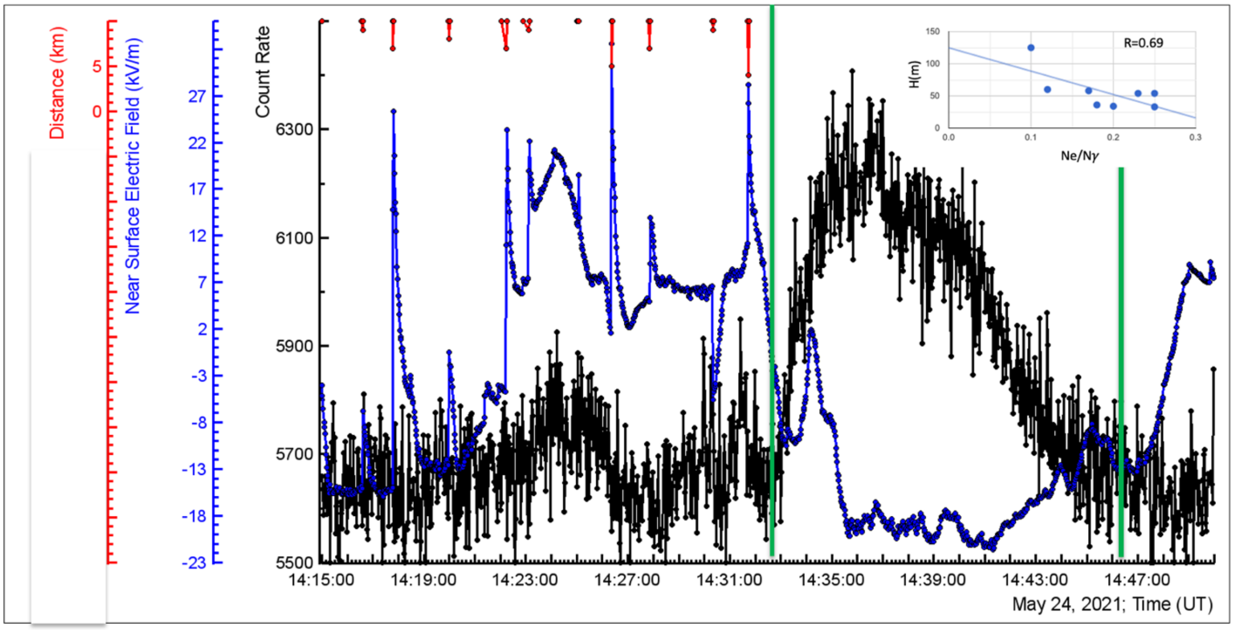


Figure 2. A pattern of the EOSO progress at the end of the storm on Aragats on 24 May. Disturbances of the NS electric field (blue), count rate of ASNT spectrometer (black), and distance to lightning (red). By the vertical green lines, we outline 12 minutes of TGE duration and graupel fall. In the inset, we show the relation of electron-to-gamma ray ratio to the recovered height above ground where the strong accelerating field is terminated obtained according to the algorithm described in (Chilingarian et al., 2021c).

The energy spectra, those parameters are posted in Table 1 were approximated by the power-law dependence; the power-law indices were roughly constant during 8 minutes of the TGE mature phase and equal to 2.0 for electron spectrum and 2.4 – for gamma ray spectrum (Table 1). As it is expected due to large ionization losses of electrons the intensities and maximal energies of the electron flux are smaller than the same parameters of the gamma ray flux. However, the proximity of maximal energies of both TGE species demonstrates that the strong accelerating electric field in the atmosphere was rather low above the earth’s surface. The electron-to-gamma ray ratio is a very good indicator of the strong electric field height above the ground. At the exit from the strong electric field, the electron flux attenuates very fast and if this height is larger than 200 m practically it is impossible to recover the electron energy spectrum, the flux was dominated by the gamma ray flux, which is 50 times more intensive than the electron flux. In (Chilingarian et al., 2021c) we present a simplified algorithm of the strong field height estimation based on the maximum energies of the gamma ray and electron energy spectra.

In Table 1 we present the main characteristics of the EOSO-TGE event for 8 minutes of the maximum TGE flux. In the second and third columns – the power law fit indices for the electron and gamma ray spectra; in the fourth and fifth the integral energy spectrum of both fluxes for energies larger than 7 MeV; in the sixth – the electron-to-gamma ray ratio; in the seventh and eighth – maximal energies of differential energy spectra for both species; and in the last – an approximate estimate of termination height of the strong accelerating electric field (according to the algorithm from Chilingarian et al., 2021c). We can see in the table very large values of the *electron-to-gamma ray ratio*, corresponding to low locations of the strong electric field above the earth's surface.

Table 1. Parameters of gamma ray and electron energy spectra measured on 24 May 2021

Time	**Power index Electr.**	**Power index**	**N of Electrons with Ee >7Mev**	**N of Gamma rays with E >7Mev**	**Ne/N E>7MeV**	**Emax Electrons**	**Emax Gamma rays**	**H(m)**
14:34	**1.91**	**2.42**	**8.23E+06**	**2.98E+03**	**0.12**	**24**	**30**	**60**
14:35	**2.02**	**2.35**	**9.16E+09**	**2.27E+03**	**0.10**	**29**	**45**	**125**
14:36	**1.88**	**2.3**	**1.53E+08**	**3.58E+03**	**0.18**	**27**	**28**	**36**
14:37	**1.72**	**2.36**	**1.29E+07**	**3.72E+03**	**0.17**	**29**	**34**	**58**
14:38	**1.95**	**2.42**	**1.64E+07**	**3.24E+03**	**0.23**	**27**	**31**	**54**
14:39	**1.62**	**2.44**	**1.64E+06**	**3.66E+03**	**0.25**	**27**	**31**	**54**
14:40	**1.52**	**2.42**	**1.69E+06**	**3.80E+03**	**0.25**	**27**	**28**	**33**
14:41	**1.69**	**2.31**	**1.09E+05**	**3.44E+03**	**0.20**	**27**	**28**	**34**

Development and decay of the LPCR are controlled by the graupel movement in the atmosphere and by the changing temperature profile (Kuettner, 1950, Williams, 1989). When LPCR fully screens the detector site we observe a positive electric field; when LPCR decays the surface detectors are exposed to the charge of the main negative (MN) layer, and, if because this charge is sufficiently large TGE continued and reach large intensities. Sure, LPCR does not screen the MN all the time, there can be several transient cases as demonstrated by Nag and Rakov in their famous paper (Nag & Rakov, 2009). The graupel fall, coincides with the start of the NS electric field reversal, and with the TGE start, and the finish – with the TGE flux decay. Thus, we can conclude that EOSO starts with LPCR decay, afterward continued with the decay of the MN layer, and in the end – decay of the main positive layer. The graduate finishing of the storm coincides with the degradation of all 3 charged layers of a tripole. The same behavior of the NS electric field, with the graupel fall, is typical for the storms on the Tibetan plateau in China (Que et al.2005, Zhang et al., 2018). Typically, conditions at the ground during EOSOs in NM storms over Langmuir Lab would be rainfall and surface temperature there is usually 15-20 C^o. We can assume that the charge sitting on the graupel is reversed to positive when the graupel has grown big at temperatures larger than -10C, or even larger than -15C (Takanashi, 1978, BERDEKLIS and LIST, 2001). Thus, using adiabatic lapse rate (-9.8C per 1 km) we come to an estimate of the possible LPCR emerging height at 3 km or more. It is natural that in New Mexico storms between ground and LPCR there could exist several differently charged regions and the sequence of the NS electric field polarity reversals when these regions are ”landed” can be arbitrary. For Aragats EOSO the pattern is more-or-less stable because we select EOSO events when we observe TGEs, that occurred mostly at surface temperatures -2-+2C. Thus, we can estimate the charged reversal height 1-1.5 km above the ground where temperatures reach a freezing level of -10 - -15C. The strong electric field can be extended low, below 100 m when the falling positively charged graupel is “lowering” the plate of the “capacitor”. Thus, the vertical extent of the accelerating field is not stable and completely decays with graupel fall. On 24 May, the duration of TGE coinciding with graupel fall was 12 minutes, in agreement with 1-1.5 km LPCR vertical size, if we assume 0.1-0.2 km/min graupel fall speed.

On 25 May during a 1-hour long storm (the first category according to classification introduced in Chilingarian and Mkrtchyan, 2012, Fig. 5), no nearby lightning flashes were registered at all. TGE was lengthy, its duration was 18 minutes and particle flux continued both during positive and negative NS electric field, demonstrating that both main scenarios of TGE initiation (with and without emerging LPCR) can be rather smoothly continued. The NS electric field is an illustration of decay of a mature LPCR and turning from the second scenario of the RREA initiation (2 dipoles MN-MIRR and MN-LPCR are accelerated electrons) to the first one (only dipole MN-LPCR accelerates electrons, see Fig. 1 in Chilingarian et al., 2021a). Also, it is worth noticing an intense graupel fall during positive NS field, which is evidence of the decay of the LPCR that is “sitting” on graupels.

In Table 2 we summarize characteristics of TGEs registered on Aragats during storms at the end of May 2021.

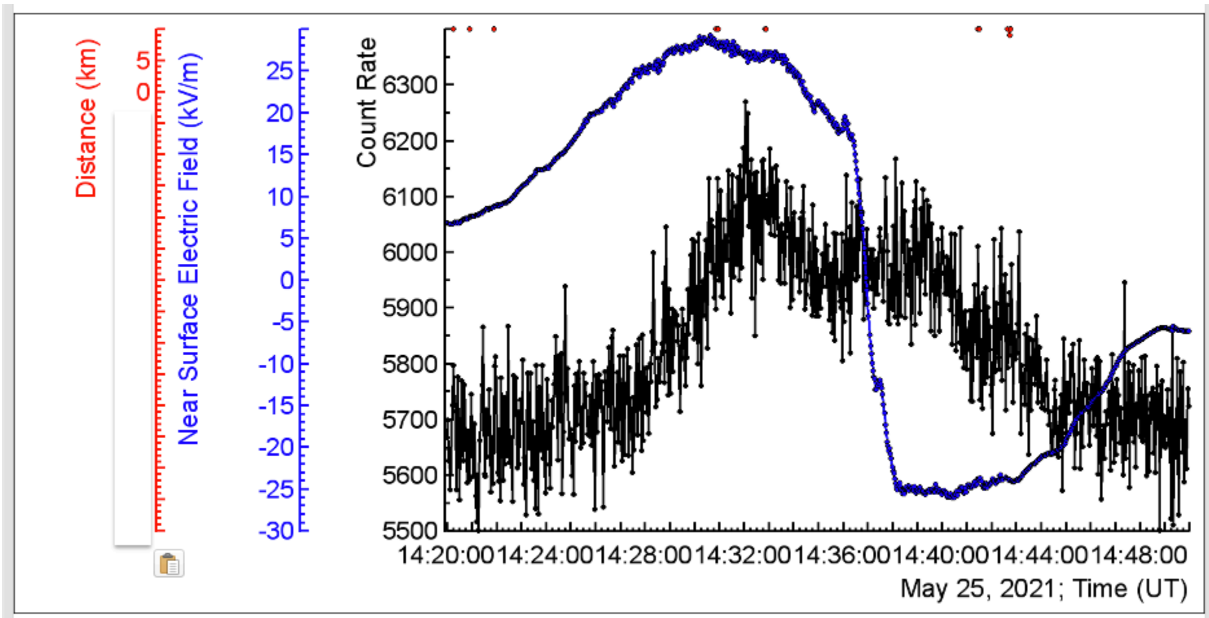


Figure 3. A pattern of the progress of the storm on Aragats on 25 May. a) The distance to the cloud base. b) Images of the graupel fall. c) Disturbances of the near NS electric field (blue), count rate of ASNT spectrometer (black), and distance to lightning (red).

In the first 2 columns we post the TGE start and finish times; in the third - the percent of flux enhancement relative to pre-TGE value; in the fourth – mean NS electric field during TGE (on May 25 there were 2 distinct values of NS field separated by a slash); in the fifth column – the mean temperature and distance to cloud base separated by a slash; it the sixth – the time of a terminating of the lightning flash (if any); in the seventh – distance to lightning flash; in the last column - NS electric fields before and after the lightning flash, again separated by a slash.

Table 2. Parameters of the TGE events and terminating lightning flashes during May storms on Aragats

TGE start	TGE termination	TGE%	Mean Field kV/m	T ©, Dist. Cloud(m)	Time of Flash	Dist. to flash (km)	El. Field change kV/m
	TGEs on 23 May,15:00-15:20, totally 30 lightning flashes on < 10 km distance						
15:10	15:19:30	2.	-20	4.2/300	15:19:30	1.6	-21/+31
15:10:50	15:12	1.1	-3	4/300	15:12	5.4	-21/+24
TGE on 24 May,14:20-14:48, totally 15 lightning flashes on < 10 km distance							
14:23:01	14:26:20	4.5	17	4.5/470	14:26:20	4.4	2/32
14:32:50	14:45:10	12.7	-19	1.6/200			

TGE on 25 May,14:20-14:48, totally no lightning flashes on < 10 km distance				
14:26:45	**14:44:45**	**10/8**	**+28/-25**	**3.0/240**

From the development pattern of this storm (confirmed by the storm that occurred on the previous day, May 24) we can conclude, that the RREAs are developing in a huge area in the thundercloud. Near the active lightning region, multiple RREAs are started (and consequently are registered as their surface offspring's – TGEs), and they are frequently terminated by lightning flashes and restarted several times at recovering of the strong electric field. If the lightning active zone is far (>10 km) from particle detectors we observe long-lasting TGE (from the long-lasting parent RREAs) without their termination by lightning flashes. Thus, the typical TGE on Aragats covered an area where multiple TGEs occurred all terminated by lightning flashes, and a peripheral zone, where lightning activity is reduced allowing long-lasting TGEs to finish smoothly.

Discussion and conclusions

Strong electric fields in thunderclouds give rise to RREAs, which end up as TGEs registered by surface particle detectors. Observation of three sequential TGEs at the end of May 2021 allows us to understand the interrelation of particle fluxes and the structure of the atmospheric electric field.

For the first time, we describe an EOSO accompanied by the graupel fall and intense flux of the gamma rays and electrons. The sequence of the oscillations of the NS electric field along with the dynamic of the registered TGE flux and graupel fall proves the EOSO model as a sequent lowering and decaying of the tripole charged layers. Three TGEs observed at the end of May 2021 on Aragats demonstrate a rich variability of the electron accelerator operation modes depending on the proximity of the particle detector site to the active storm zone.

On 23 May when the storm was just above particle detectors (at distances 1.6

– 5.4 km) nearby lightning flashes terminate RREA after a few tens of seconds. If the storm active zone is far away from particle detectors (>10 km) the TGE extends 12 and 18 minutes and smoothly terminates when conditions of the atmospheric electric field fail to support RREA. Thus, the RREA can be unleashed in a very large spatial domain around the storm, reaching several km in radii. From the energy spectra of a TGE registered on May 30, 2018 (Chilingarian et al., 2018) we estimate the total number of gamma rays (with energies above 300 keV) hitting the earth's surface to be $1.3*10^6/m^2$min. Assuming that 2000 thunderstorms are active on the globe and that the overall surface of the thunderous atmosphere each moment can be estimated as 2.000 * 100 km^2 = 200,000 km^2 (0.04% of the globe surface), we come to an estimate of 10^{16} gamma rays are hitting the earth's surface each second!

Data Availability Statement

The data for this study are available on the WEB page of the Cosmic Ray Division (CRD) of the Yerevan Physics Institute, http://adei.crd.yerphi.am /adei and in the Mendeley datasets (Soghomonyan et al., 2021a, 2021b and Chilingarian and Hovsepyan, 2021).

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