Electrification of the thundercloud supporting origination of the relativistic runaway electron avalanches

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Abstract

The problem of thundercloud electrification is one of the most difficult ones in atmospheric physics. The structure of electric fields in the atmosphere still escapes from the detailed *in situ* measurements. Few balloon flights although providing us with overall knowledge of possible structures and strengths of the atmospheric electric fields, cannot reveal the dynamics of the intracloud electric field responsible for intense runaway electron fluxes and atmospheric discharges. To get insight into the charge structure of the thundercloud we use new key evidence – the fluxes of particles from the thundercloud registered on the earth's surface, the so-called Thunderstorm Ground Enhancements – TGEs. TGEs originate from electron acceleration and multiplication processes in the strong electric fields in the atmosphere, and the intensity and energy spectra of electrons and gamma rays as observed at the Earth's surface are directly governed by the charge structure of the cloud. We relate appropriate structures of atmospheric electric fields supporting electron acceleration with patterns of density profiles of the cloud obtained by implementing the weather research and forecast (WRF) model.

1. Introduction

The atmospheric electric fields and atmospheric discharges were intensively investigated in the last decades using radars, 3D lightning mapping arrays (LMA), worldwide lightning location networks (for instance WWLLN), and VHF interferometer systems, all synchronous with measurements of near-surface electric field disturbances. Additional evidence on the formation of the charge structure of the cloud can be obtained from numerical modeling of the state of the atmosphere. Weather Research and Forecasting Model (WRF-model) (https://www.mmm.ucar.edu/weather-research-and-forecasting-model) is widely used in research applications, providing information on the structure and dynamics of all types of convective systems with a horizontal resolution of about 1 km, which is difficult to attain with other methods. A new type of messengers carrying information on the atmospheric field ~~are~~ is cosmic rays, which include electrons, muons, gamma rays, and neutrons (comprising thunderstorm ground enhancements - TGEs) registered on the Earth's surface by networks of elementary particle detectors.

Very specific cloud electrification conditions during thunderstorms give rise to TGEs and muon flux depletion, observing of which discloses the structure and strength of atmospheric electric fields.

The origin of TGE is the relativistic runaway electron avalanche (RREA) developed in the terrestrial atmosphere when the strength of the electric field exceeds a threshold value, which depends on the density of the atmosphere (Gurevich et al., 1992). A region of the upwards directed electric field can provide electron acceleration in the direction of the earth's surface, thus, a positive dipole charge configuration is a necessary condition of TGE origination. The "classical" lower dipole, as it was established in the first half of the last century consists of a negatively charged middle layer and its positively charged "mirror image" on Earth's surface. However, experiments completed during 1945–1948 at the Zugspitze Observatory in Germany (Kuettner, 1950) revealed a more complicated structure of the intracloud electric field. Joachim Kuettner discovered a pocket of positive charge (Lower positive charge region - LPCR) in the base of the cloud and introduced the term "Graupel dipole" referring to the charge structure formed by LPCR and the main negatively charged layer. The localization of charged layers in the thundercloud can be rather sophisticated (see Svechnikova et al., 2020), however, the tripole structure is assumed to be a basic configuration. The three-charge layer arrangement with 2 main charged regions (positive above negative) and - relatively weak lower positively charged region (LPCR) is referred to as the classic tripole (of the charge structure for a cloud with normal electrification). H.Tsuchiya (2011) suggested that warm winds moved from the sea originate winter thunderstorms in Japan with short-lived tripole structures appeared in a thundercloud and accelerate CR electrons toward the bottom positive layer. Chilingarian and Mkrtchyan in (2012) discovered the major role of LPCR in TGE initiation.

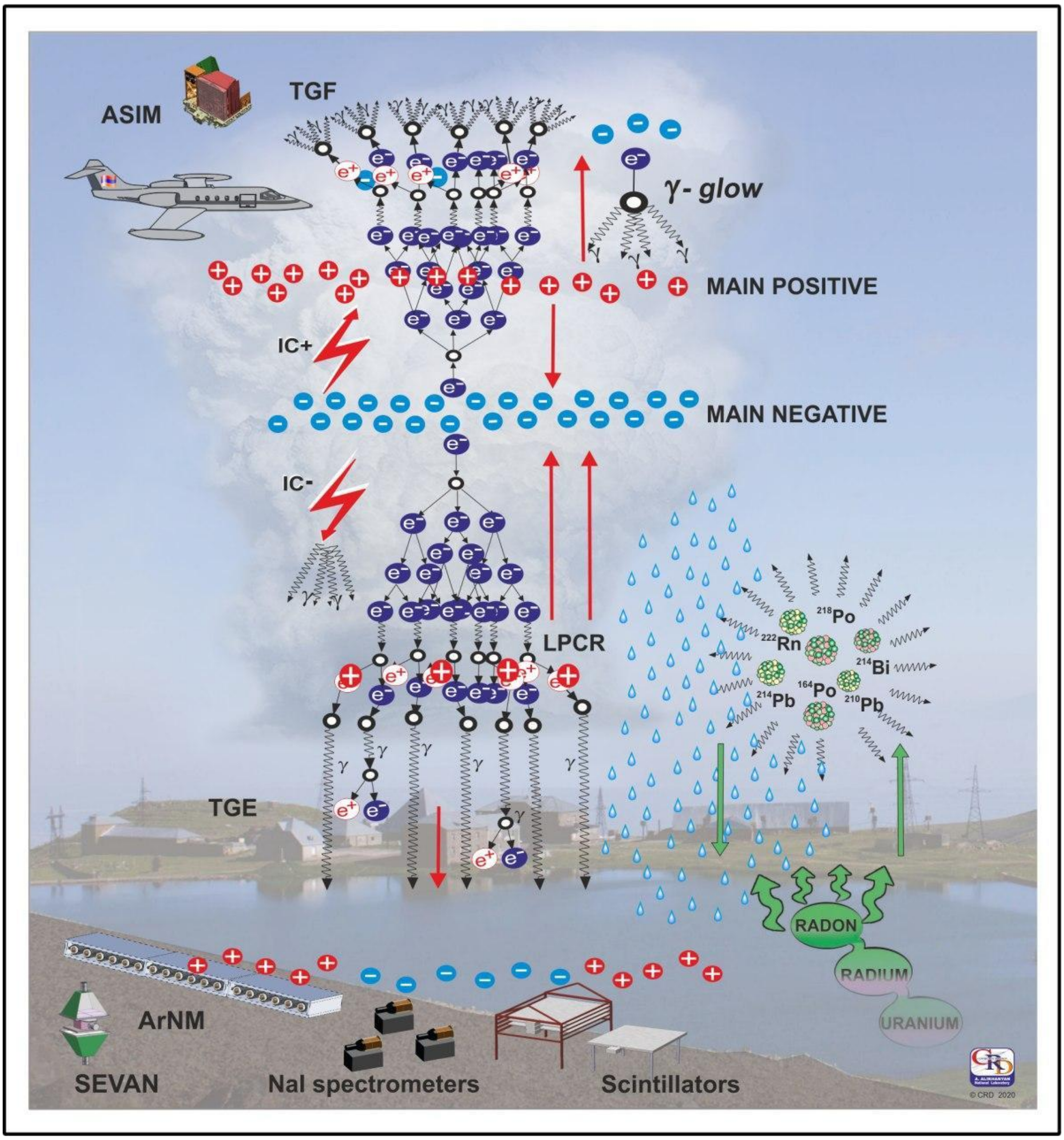

Figure 1. TGE origin. Particle flux initiation in thundercloud on the left side, Rn222 progeny radiation on the right side.

On the left side of the cartoon shown in Fig. 1, we present electron- gamma ray avalanches developed in the lower dipole (TGE) and upper dipole of the thundercloud (so-called terrestrial gamma flashes, TGFs, Fishman et al., 1994). Red arrows denote 3 electric fields: downward directed field in the upper dipole of the cloud formed by the main negative (MN) and upper positive charge, the upward-directed field in the lower dipole formed by MN and the LPCR, and upward-directed field formed by MN and its mirror (MIRR) image in the ground. Throughout this paper, we use the atmospheric electricity sign convention, according to which the downward directed electric field or field change vector is considered to be positive. Thus, the negative field measured by the EFM-100 electric field mill corresponds to the dominant negative charge overhead (upward-directed electric field).

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. The critical field value scales with the air density n as ≈2.8 * n kV/cm, which is ≈1.8 kV/cm for the altitude of 5-6 km a.s.l. typical for the center of the TGE-producing cloud above the Aragats Station.

Following possible scenarios of electron acceleration in the atmospheric electric fields can be considered:

1. The "classical" lower dipole formed by MN-MIRR only (no LPCR). If MN charge is very large inducing a very strong electric field which exceeds the critical value, the RREA can be unleashed and TGE will be large, and energies up to 50 MeV will be observed. The near-surface electric field is deep negative reaching -25 ÷ 30 kV/m for the largest TGEs. Thus, regardless of the cloud base location, the electric field extends almost down to the earth's surface, and both electrons/positrons and gamma rays can be registered by particle detectors and spectrometers.
2. Lower dipole formed by MN-LPCR. For few minutes, when LPCR is mature and screens MN from the detector site, the near-surface field is in the positive domain. TGE can be very intense in Spring when LPCR is very close to the earth's surface (25-100 m). In Summer, the distance to the cloud base is larger (200-400m) and only gamma rays reach the earth's surface and are registered by the particle detectors. Electrons are attenuated in the dense atmosphere. Sometimes, the LCPR is rather large and it can be called also as *"inverse dipole"*. Especially strong LPCR, with a charge comparable with that of MN, can be formed in low clouds of so-called "winter thunderstorms" in Japan (Brook, 1982; Xu, 2016; Wang, 2018). Numerical simulations with the Weather Research and Forecasting Model also reproduce the inverse dipole configuration above Aragats for several TGE events.
3. A mixture of 1 and 2 with different weights. TGE can start with mature LPCR, but after its contraction, only MN sustain a strong electric field. Alternatively, in the middle stage of the first scenario, the LPCR is formed and for a few minutes the near-surface electric field rises and reaches positive values, and then returns again to deep negative values when LPCR is depleted.

Lightning flashes reduce the negative charge above the earth's surface, thus decreasing the electric field in the lower dipole below the RREA threshold. RREA declines and high energy particles are eliminated from the TGE flux. However, a smaller field is still in place and Rn22 progenies continue to enhance the "background" gamma ray flux, initiating long-lasting TGE (Chilingarian, 2017, Chilingarian et al, 2018). TGE continues after the returning of the near-surface electric field strength to the fair-weather value. The rain brings back the Rn222 progeny from the atmosphere to the earth's surface and for several tens of minutes provides additional gamma ray radiation (the washout effect, see Chilingarian et all, 2021). Thus, the scenarios of the origination of the downward electron-accelerating electric field are numerous and the corresponding TGEs may vary in intensity and energy spectra.

Hundreds of TGEs were observed at the Aragats research station in Armenia during the last 10 years (Chilingarian et al., 2017). Numerous particle detectors and field meters are located in three experimental halls as well as outdoors; the facilities are operated all year round providing continuous registration of the time series of charged and neutral particle fluxes on different time scales and energy thresholds. In 2010-2020, the Aragats facilities registered more than 500 TGEs (see the first catalog of TGE events in Chilingarian et al., 2019), most of them originate in cumulonimbus clouds due to charge separation triggered by the moisture updraft of orographic and lake effects.

In this letter, we will present and discuss structures of the atmospheric electric field for an interesting TGE observed on 14 June 2020, during which several scenarios of cloud electrification were realized.

1. A very specific storm on 14 June 2020 with 3 TGE episodes supported by different electric field structures

A short storm of approximately 1.5 hours duration occurred at the beginning of Summer on Aragats, which nonetheless demonstrates 3 different structures of the intracloud electric field supporting TGE origination. In Fig. 2 and Table 1 we show overall characteristics of 3 largest episodes of particle flux enhancement and corresponding values of the TGE significance, energy spectra, main meteorological parameters, as well as distances to nearby lightning flashes, measured by Aragats solar neutron telescope (ASNT), EFM-100 electric mill, and DAVIS automatic weather station.

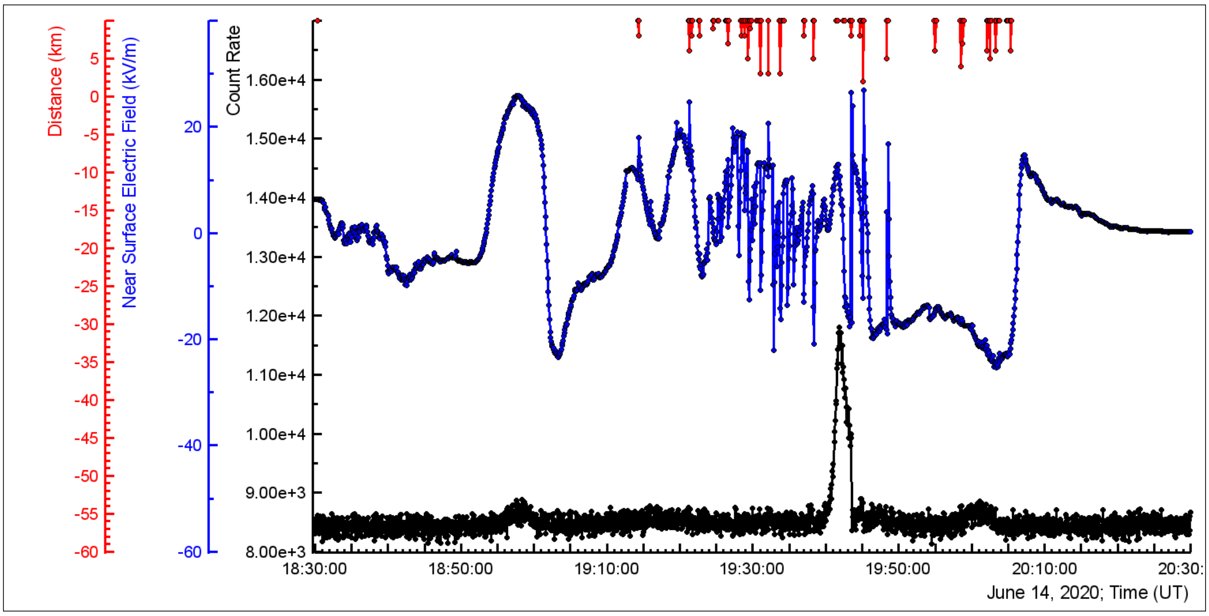

Figure 2. In the bottom of the figure - the time series of 2-sec count rates of ASNT (4 m^2 area, 60 cm thick scintillation spectrometer) are depicted, in the middle – disturbances of the near-surface electric field measured by electric mill EFM-100 located on the roof of MAKET experimental hall, on the top - red lines show the distance to nearby lightning flashed measured by the same electric mill (within 10 km distance).

In Fig. 2 and in Table 1 we can see that the TGE that occurred at 19:42 UT is very large and the only one from 3 when electrons reach the earth surface; 2 small TGEs also are significant, demonstrating sizeable gamma ray flux at the minute of maximal enhancement. Maximum energies of gamma ray for all 3 events exceed 10 MeV. Only RREA developed in the atmosphere can accelerate seed electrons from the ambient population of cosmic rays to such large energy. The maximum energy of gamma rays exceeds the maximum energy of electrons more than 2 times, this indicates that the electric field is terminated at an altitude above 200 m.

Table 1. Characteristics of 3 TGEs (peak significances, integral fluxes, maximum energies of electrons and gamma rays) and meteorological parameters measured and calculated for 3 episodes of particle flux enhancement on 14 June 2020

	18:59 UT	**19:42 UT**	**20:01 UT**
Peak enhancement, 2-sec time series (%)	**5.6**	**40**	**5**
Peak enhancement, N of standard dev.	**3**	**20**	**2.5**
Electron flux >4 MeV ($1/m^2$min)	**-**	**3000**	**-**
Gamma ray flux > 4 MeV ($1/m^2$min)	**2500**	**30000**	**2000**
Electron >4 MeV Max. energy (MeV)	**-**	**20**	**9**
Gamma ray > 4 MeV Max energy (MeV)	**22**	**43**	**17**
Temperature C°	**4.7**	**2.8**	**1.7**
Cloud height (m)	**420**	**210**	**150**
Atm. Pressure (mb)	**693.7**	**693.8**	**694.2**
Rel. humidity (%)	**81**	**85**	**92**

The first TGE that began at 18:57 UT was initiated in a typical inverse dipole configuration. In Fig.3c we show the zoomed version of the TGE. TGE occurred when the near-surface electric field was large and positive for several minutes (≈25 kV/m at a maximum of TGE). The distance to the cloud base was 420 m, see Table 1, thus the electron flux vanished before reaching the ground. The intensity of gamma ray flux reaches 2500 particles per m^2 per minute. RREA gamma ray flux on exit from the cloud was rather large not attenuated fully on the path ≈420m in the dense atmosphere (0.7 atm). During the first TGE no nearby lightning flashes were detected in the circle of 10 km and the near-surface field was changing rather smoothly. In Fig. 3a and b we show the 2-dimension projections of the cloud density simulated using the WRF model. The cloud is formed mainly by graupel- and snow-particles located on altitudes 05.-2 km and 2-6 km above the Aragats station (3200 m) correspondingly. Measured near-surface electric field dynamics and large horizontal size of the “graupel” layer supports the assumption of the «inverted dipole» structure. The vertical extent of the electric field in the cloud can be 2-3 km, enough to allow the development of large electron-photon avalanches on runaway electrons.

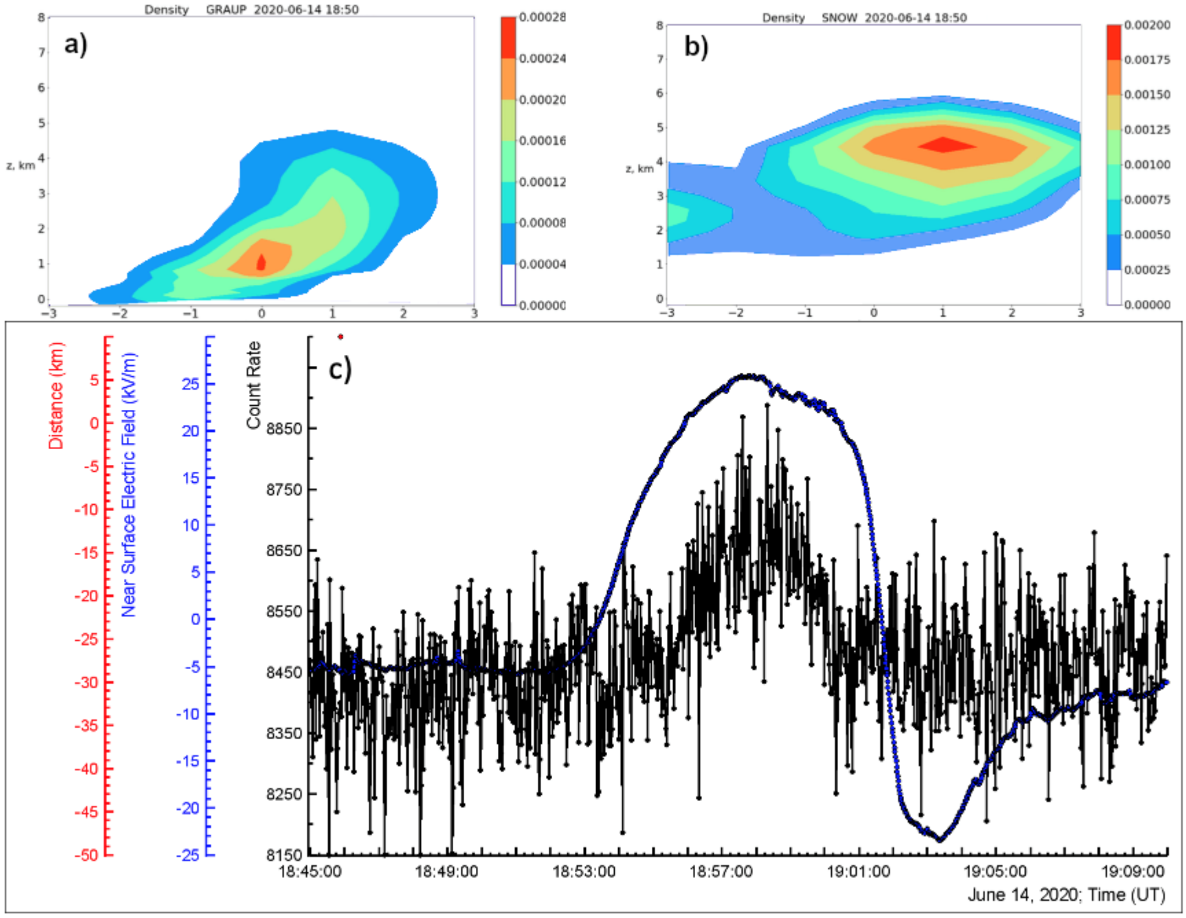

Figure 3. In Fig. 2a and b we demonstrate the 2-dimensional patterns of the hydrometeor density (kg/m^3), according to the simulation using WRF. In Fig 3c we show the zoomed version of the first TGE (the notion is the same as in the Figure 2).

TGE which occurred a half-of hour later after numerous nearby inverted lightning flashes is a classical TGE supported by the mature LPCR and terminated by a -CG lightning occurred at 19:43:33.088, see fig. 4c. The type of lightning was determined by the analysis of electric field changes measured in Aragats and Nor Amberd research stations (13 km apart). The polarity of electric field change was positive, and no polarity reversal of electric field change with distance has been detected, which indicates that only a negative charge was destroyed in the cloud during the lightning flash.

The intensity of the particle flux was rather large. The integral spectrum of electrons at 3200 m was ≈3000 particles per m^2 per minute, and gamma rays – 30000 per m^2 per minute for particles with energies above 4 MeV. In recovering spectra, we use a full simulation of the detector response function. Electron flux at the exit from the cloud at an altitude of ≈220 m has intensity 3 orders of magnitude larger than on earth's surface (obtained from simulations of RREA developed 2 km in the electric field of 1/9-2.1 kV/cm strength). The 2-dimension projections of the cloud density shown in Figs 3a and b showing large scale lower dipole are consistent with the intensity of observed particle fluxes.

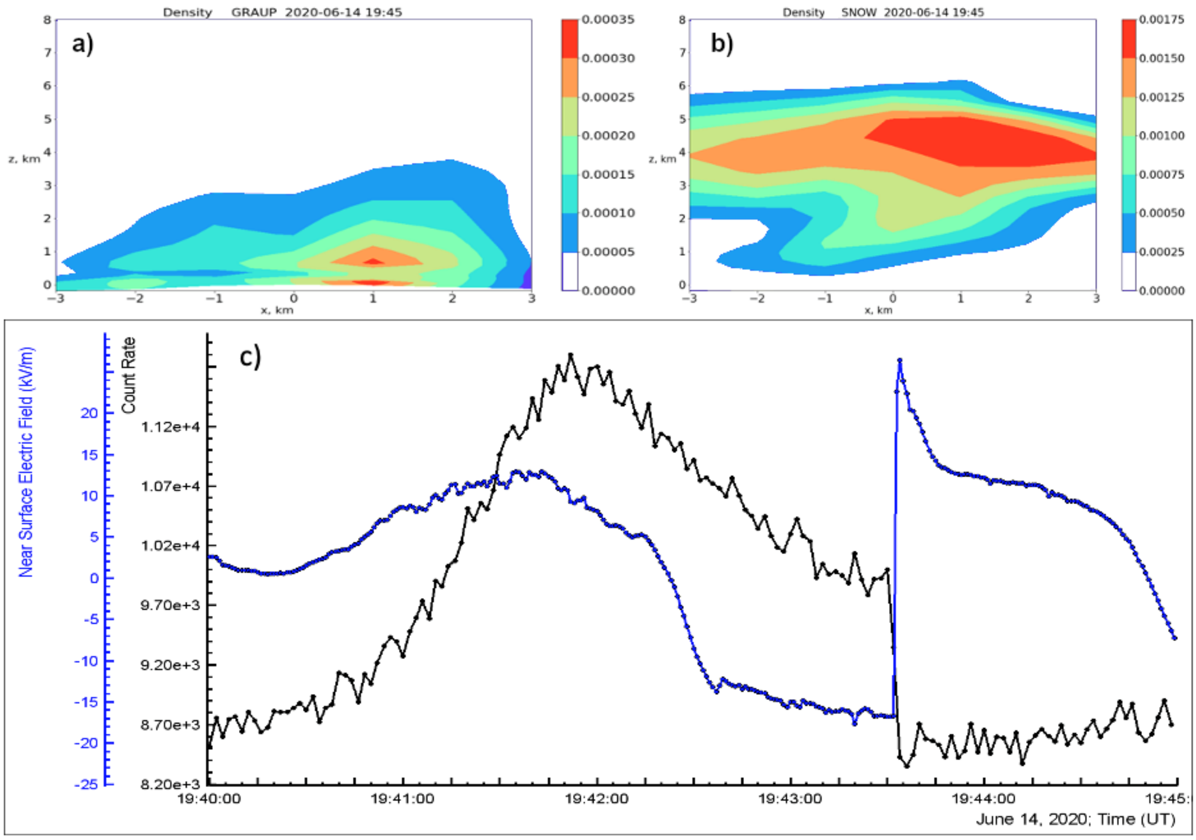

Figure 4. a) and b) 2-dimensional patterns of the hydrometeor density (kg/m^3), according to the simulation using WRF. c) zoomed version of second TGE (the notion is the same as in the Figure 2).

The third TGE that occurred around 20:00 was again of the other type: the electron accelerating field was formed by the main negative layer only that produced the deep negative near-surface electric field on the Earth's surface, see Fig. 5b. No signs of LPCR are seen in the maps of 2-dimension projections of the cloud density, see Fig. 5a. The size of the main negative layer is rather small (compare with the one shown in Fig 4b when we have much larger TGE with RREA electrons reaching the earth's surface) and correspondingly, the gamma ray flux was 15 times less than that for the TGE that occurred at 19:43 (Table 1).

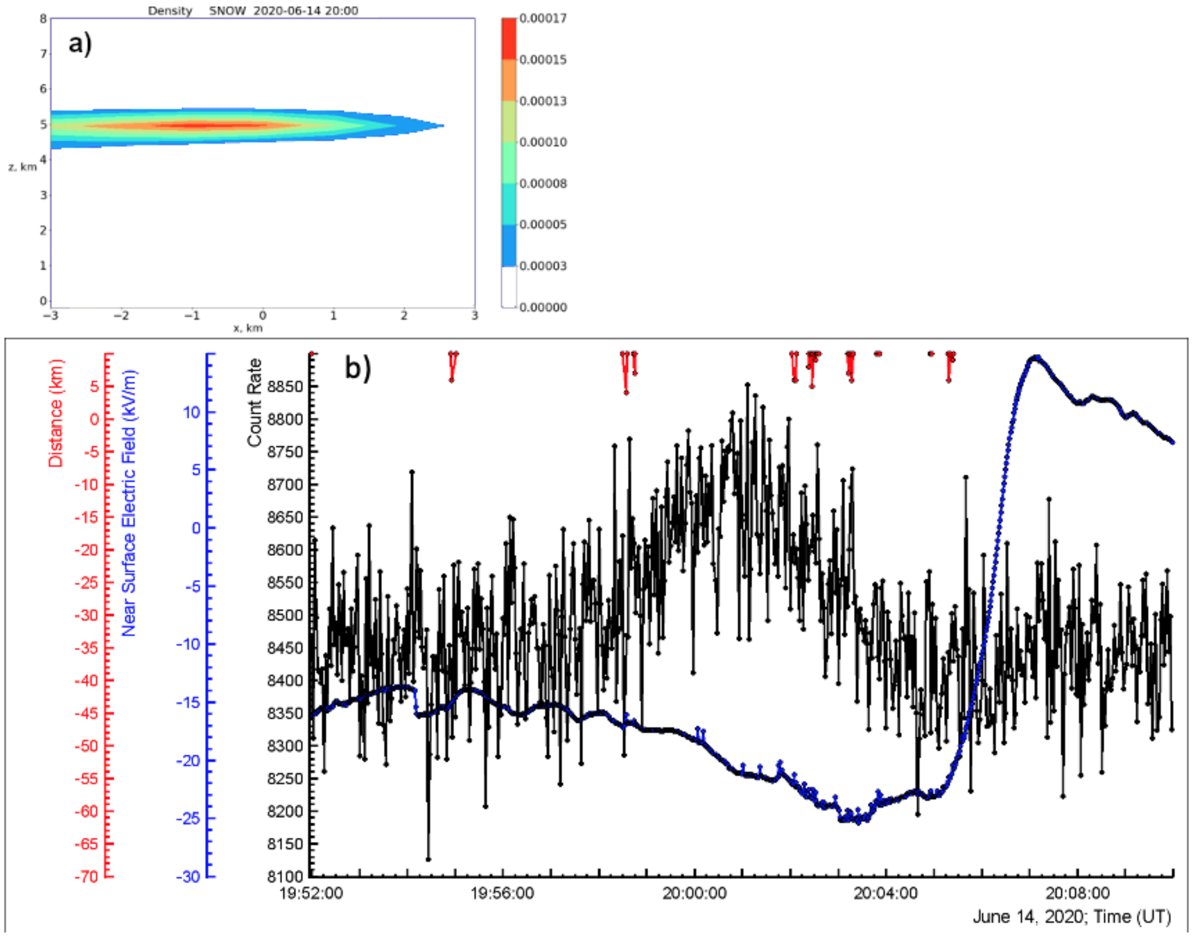

Figure 5. a) 2-dimensional pattern of the hydrometeor density (kg/m3), according to the simulation using WRF, b) zoomed version of third TGE (the notion is the same as in the Figure 2).

3. Conclusions

We demonstrate 3 different configurations of the atmospheric electric field leading to the emergence of the RREA process and TGEs registered by the ASNT spectrometer. We explain the mechanisms of dipole origination and show how the emerged electrical structures in the atmosphere lead to the enhanced fluxes of electrons and gamma ray. Both measured parameters of particle fluxes and hydrometeors density maps obtained using the WRF model give a consistent explanation of the atmospheric electric structures supported by 3 TGEs that occurred on 14 June 2020.

Acknowledgement

We thank the staff of the Aragats Space Environmental Center for the operation of particle detectors on Mount Aragats. A. C. thanks S. Soghomonyan for the valuable comments and for the useful, multiyear discussions on the origin of the atmospheric electric field. The authors thank S. Chilingaryan for his continuous efforts at maintaining and improving Web-based data analysis facilities for a large stream of data coming online from the Mount Aragats research station.

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