Thunderstorm ground enhancements observed on Aragats mountain in Armenia in the wintertime

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Abstract

Thunderstorm ground enhancements (TGEs) occur in the Spring-Autumn seasons at Aragats due to warm air updrafts that cause hydrometeor charging. However, particle detectors recorded three TGEs within 10 hours on February 7, 2023, despite the temperature being -10C°. Upon analyzing the energy spectra of TGE electrons and gamma rays, it was discovered that the atmospheric electric field strength above Aragats, at heights 3300-5300 m, could be around 2.1 kV/cm even in winter. We provide details on the fluxes and energy spectra of TGE electrons and gamma rays, as well as discuss models of cloud electrification in winter.

Introduction

During thunderstorms, electron-gamma ray avalanches can contribute additional electrons, gamma rays, and occasionally neutrons to the ambient population of cosmic rays (CR). Over the past ten years, particle detectors on Mt. Aragats in Armenia, Mt. Lomnicky Stit in Slovakia, and Mt. Musala in Bulgaria (now also on Mt. Zugspitze in Germany) have detected many thunderstorm ground enhancements (TGEs [1,2]). These TGEs are sudden increases in cosmic ray fluxes, with the most prominent being over 100 times stronger than the background [3]. The acceleration and multiplication of free atmospheric electrons can occur if the intracloud electric field is larger than the "critical" value that depends on the air density [4-6]. Suppose an electron is exposed to an electric field that provides it with more energy than it loses through ionization, i.e., the intracloud electric field is above the critical value. In that case, the electron will "run away," knock out atomic electrons, born bremsstrahlung gamma rays, and so on. This can lead to an electron-gamma ray avalanche that may reach the ground and be recorded as a TGE. The theory of this relativistic runaway avalanche (RREA) is explained in [7], while the TGE model is described in [8]. A vast amount of TGE events is available in the fully described form in the Mendeley datasets [9-11] and the database of the Cosmic Ray Division of Yerevan Physics Institute [12]. The particle detectors and data analysis methods are explained in [13-15] and in the supplemented materials.

At the Aragats research station, which sits at an altitude of 3200 meters, most TGEs occur between April and October. At this time, the near-surface electric field (NSEF) can range from -30 to +20 kV/m, while the outside temperature usually hovers around -3C +3C. Based on the RREA simulations, we assume that electron acceleration occurred at altitudes 3.3 – 6.3 km and prolonged for 1-2 km. Thus, the intracloud electric field can exceed 2.1 kV/cm (the critical value at ≈3 km height, see Table 4 of supplemented materials). However, in the winter (November - March), NSEF disturbances are minor, and the intracloud electric field is not expected to reach the "critical" value needed to trigger electron-photon avalanches. Due to the Radon circulation

effect [16], charged aerosols with attached Radon progeny are lifted by the enhanced NSEF, causing prolonged peaks in the time series of low-threshold spectrometers [17]. However, particle detectors with high energy thresholds (>7 MeV) do not register any enhancement since the gamma ray energy emitted by long-lived Radon isotopes (214Pb and 214Bi) is below 1 MeV [18].
During winter, when the temperature was -10C°, we noticed an electron flux on February 7, 2023. Upon further investigation, we discovered over ten Wintertime TGEs (refer to Fig.1) in our database. Usually, we don't detect Wintertime TGE due to the thick snow covering the experimental halls and outside detectors, reducing particle fluxes. However, this year, strong winds blew the snow off the roofs, allowing particle detectors to register enhanced fluxes.

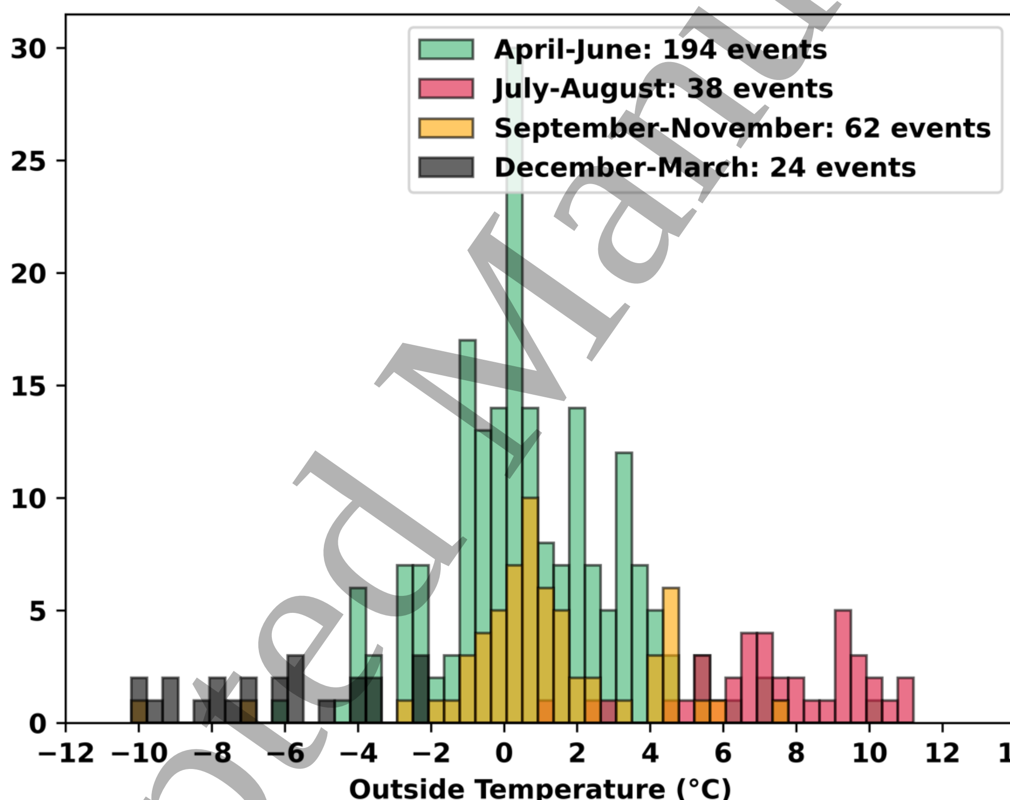

Figure 1. The histogram of the frequency of TGE occurrences related to outside temperatures varies depending on the season. The Wintertime TGEs are represented by black bars, and the overlapping distributions are displayed in slightly different colors.

Figure 1 presents a histogram showcasing the correlation between TGE frequency and outside temperature. The histogram is color-coded to represent the four seasons. We intend to display the overlapping distributions, which results in the colors of red overlapping on yellow and green overlapping on red, creating slightly different shades. Over the course of 11 years (from 2013 to winter 2023), electric field sensors and weather stations installed on Aragats detected 318 TGE events. Between 2008-2012, there were 277 TGE events observed [19]. Altogether, there were approximately 600 TGE events. To confirm TGEs, three independent particle detectors had to demonstrate simultaneous peaks larger than 3σ in the count rate time series, and the NSEF absolute value had to exceed five kV/m. For more information, please refer to the supplemented materials.

Based on data from the Aragats research station, most TGEs (80%) happened in Spring and Autumn when the temperature outside was between -3C° and +3C° and clouds were shallow (yellow and green on the histogram). This occurred due to the standard cloud electrification process, where warm air updraft and hydrometeor tension caused charge separation, and the emergence of lower dipole accelerated electrons downward [20]. Only 6% of TGEs happened in Wintertime (shown as black) when the cold temperatures made it difficult for warm air updraft.

In contrast, the Wintertime gamma glows (similar to TGEs but do not involve registering electrons) are commonly seen on the northwest coast of Japan. This occurs when cold and dry seasonal winds blow in from Siberia and mix with the Tsushima warm current, creating an upward current of air that triggers thunderstorms [21]. Hydrometeors that contribute to electrical charging, such as ice crystals and graupels, are generated at an altitude where the temperature ranges from -10°C to 0°C or higher. This altitude is typically around 3 km for summer thunderstorms but less than 1 km for winter due to lower surface temperatures. Consequently, the charge centers are low, which enables gamma rays to reach the ground and be detected.

1. Observation of enhanced particle fluxes on Mt. Aragats on 7 February 2023

At Aragats, various particle detectors measure almost all CR species' intensity and energy spectra. One such detector is "STAND3," which is utilized in TGE identification. The detector consists of four layers of vertically stacked 3-cm-thick scintillators with a sensitive area of 1-m^2 each. The light from the scintillator is transmitted through optical spectrum-shift fibers, reradiated to the long-wavelength region, and passed to the photomultiplier (PMT FEU-115M). The maximum luminescence occurs at the 420-nm wavelength, with a luminescence time of approximately 2.3 ns. The STAND3 detector can be adjusted by varying the high voltage applied to the PMT and setting the shaper-discriminator's thresholds. The discrimination level is chosen to ensure signal detection while suppressing photomultiplier noise as much as possible. By detecting signals from all four layers, charged particles with energy thresholds ranging from 10 MeV ("1000" coincidence, signal only in the upper layer) to 40 MeV ("1111" coincidence, signals in all layers) can be selected. The significance of TGE is determined by how many standard deviations the maximum 1-minute count rate deviates from the average fair-weather value (Nσ). These values are typically identified through the count rates of the STAND3 detector. The NSEF was measured using the BOLTEK's electric mill EFM 100, while the DAVIS weather station monitored the external temperature and other weather parameters.
In Figure 2, we show the time series of the count rate of the STAND3 detector's coincidence "1000", the NSEF disturbances, and the outside temperature. The NSEF disturbances during the first TGE ranged from -15 kV/m to +9 kV/m; the outside temperature was -10C; the TGE significance was ≈ 10σ. For the Spring – Autumn TGEs, the NSEF disturbances during

thunderstorms range from -30 to +20 kV/m, while the outside temperature usually hovers around -3C +3C. Relative humidity was 92%, and atmospheric pressure was 673.6 millibar.

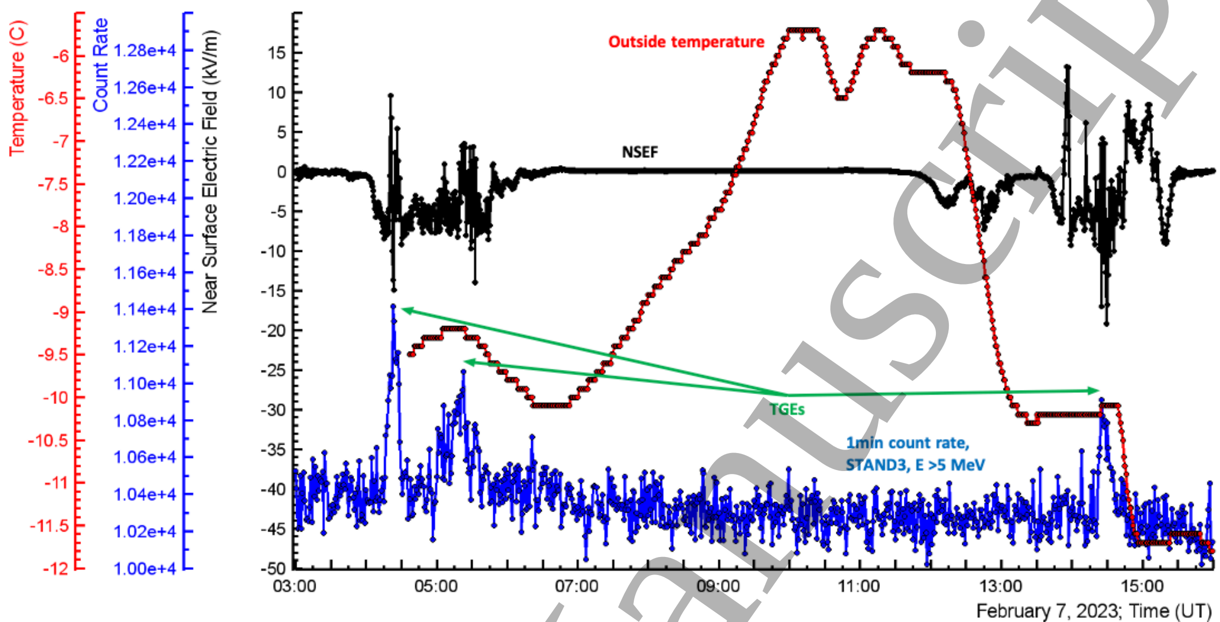

Figure 2. Black - disturbances of NSEF, measured by the electric mill EFM-100 produced by Boltek firm; blue- time series of count rate of upper scintillator of STAND3 detector ("1000" coincidence, signal only in the upper scintillator of the stacked assembly); red – outside temperature measured by Davis weather station. By green arrows, we show 3 TGEs that occurred within ≈10 hours.

Table 1 provides a summary of the Winter TGE events. The data indicates that the TGE events were of low to medium significance and lasted longer than those in Spring and Autumn due to the absence of nearby lightning strikes to end them. Additionally, the outside temperatures during these events exceeded the Winter average. Furthermore, the NSEF did not reach the same values as those observed in Spring and Autumn.

Table 1. Winter TGE events occurred in 2013-2023

Date	Duration (minutes)	Significance (Nσ)	Outside Temp (C°)	NSEF (kV/m)
March 4, 2013	14:53 – 15:17	12	-6	-8 - +8
March 4, 2016	19:03 - 19:12	11	-2	-8 - +10
November 30, 2017	3:33 – 3:48	45	-7	-5 – +1
December 30, 2017	16:28 – 16:38	9	-4	-14 - +9
December 30, 2017	17:50 – 17:54	12	-4	-15- - +10
February 13, 2018	14:22 – 14:32	6	-7	-18 - +6
March 9, 2018	4:15 – 4:25	8	-4	-5 - +1
December 26, 2019	2:35 – 2:41	12	-9.3	-6 - +6
November 10,2021	0:48 – 1:13	6	-6	-13 – +1.7

December 1, 2021 (4)	10:0713:06	3-5	-5 - -6	-18 - +8
December 21,2021	12:00 – 12:11	7.5	-10	-14 – +9
8 March, 2021	10:40 – 11:0	8	-8	-10 - +14
February 7, 2023	4:15 – 4:31	10	-9,5	-15 – +9
February 7, 2023	5:11 – 5:28	7	-9,3	-14 – +3.5
February 7, 2023	14:21 – 14:39	9	-10,2	-19 – +13

Figure 3 shows the integral energy spectra of TGE gamma rays (3a and 3c) and electrons (3b and 3d) measured by the ASNT (Aragats solar neutron telescope, see supplemented materials) detector's 60 cm thick scintillator. Electrons lose energy faster than gamma rays due to ionization, making TGEs predominantly composed of gamma rays if particles depart the field above 100 m from the ground. The presence of electrons in the flux on 7 February was confirmed by the "1110" coincidence of the STAND3 detector (energy threshold 30 MeV). The measured electron flux enabled us to estimate that the electric field during the first TGE reached ≈ 2.1 kV/m at ≈3300 height (100 m above the spectrometer). This is the first time we measured the electron flux during Wintertime. For the rest of the Wintertime TGEs collected in Table 1 and shown in Fig. 1 in black, the share of electrons was too small to allow the energy spectrum recovery. We utilized the MINUIT code from the CERN program library [22] to fit the integral energy spectra with an exponential function. Further details about the spectrometer and energy spectra recovery method are available in the supplemented materials.

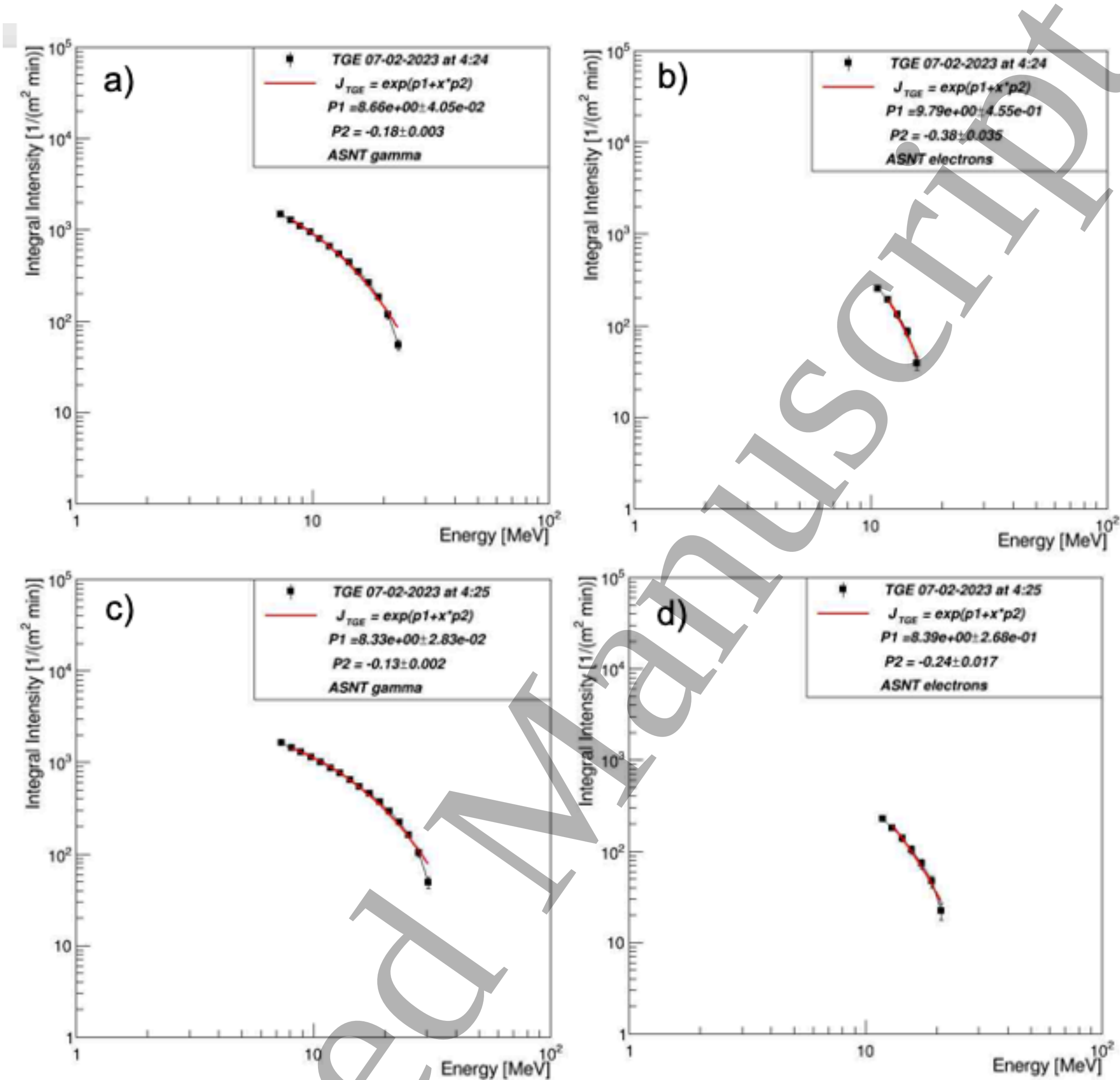

Figure 3. The differential energy spectra of TGE electrons (red) and gamma rays (black) recovered from energy release histograms measured by the ASNT spectrometer.

2. The model of the wintertime TGE

In Figure 4, we have provided a closer view of the first TGE. The NSEF was positive between 4:20 and 4:22, illustrated with rose lines in the figure. Based on the electric field sensor reading, we can determine the charge above and infer that a lower positive charge region (LPCR) formed. The dipole, which caused electrons to move downward, was positioned between MN (main negative) and LPCR [23]. The LPCR is a short-term structure situated on graupel. Between 4:22 and 4:25, the graupel falls, and there is no obstruction between the ground and the main negative layer. Thus, NSEF becomes deeply negative, reflecting a large negative charge of the MN. Now, the dipole consists of the MN and its mirror in the ground (MIRR). Electrons are accelerated downward by both dipoles MN-LPCR and MN-MIRR. The former operates when LPCR is mature and low and "screens" ground from MN, while the latter works when LPCR decays and MN is significant.

To detect TGE electron flux and recover their energy spectrum, the electric field should be at least 100-150 meters above ground [24]. If the field ends higher (let's assume 200 m), the spectrometer can only detect a limited number of electrons whose energies are above 40 MeV at the entrance from the electric field. Lower energies will not be attenuated in the thick air above the spectrometer (the energy threshold of the spectrometer is 10 MeV). As a result, only a few electrons with energy greater than 10 MeV (equivalent to 40 MeV at the entrance from the electric field) can be detected, as shown in Figures 3b and 3d. Table 7 in the supplementary materials provides additional information on the attenuation of electrons in the air.

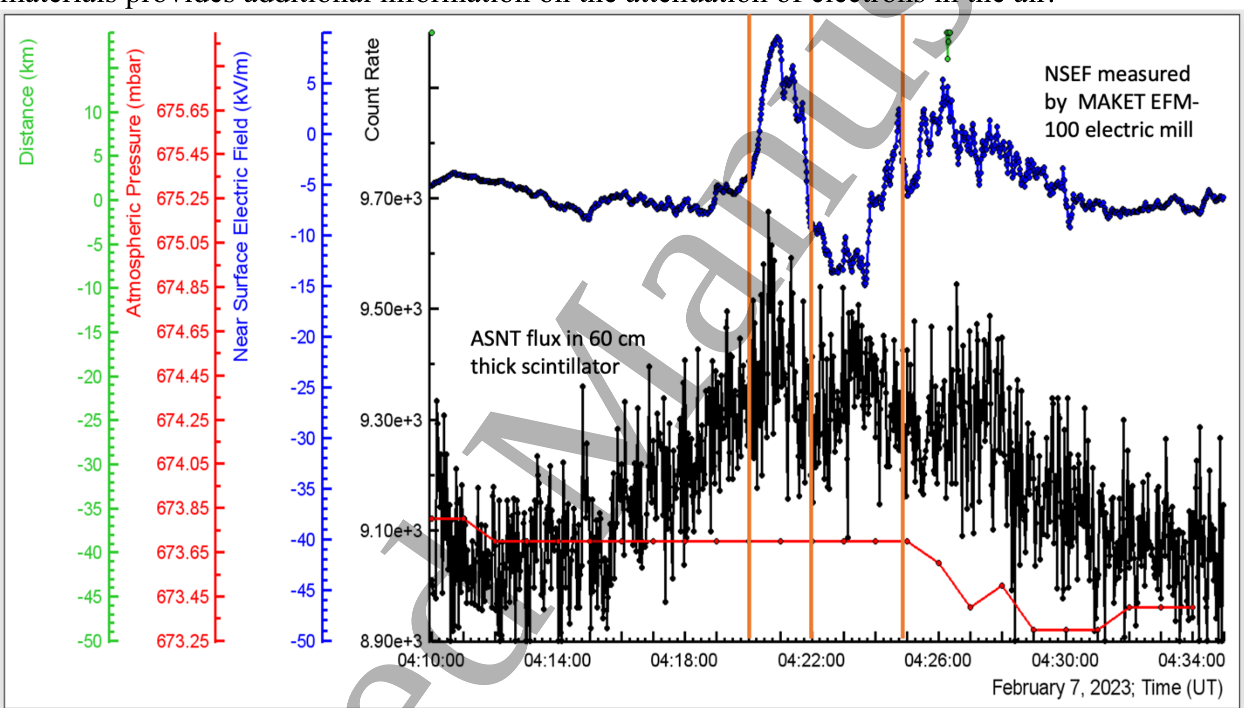

Figure 4. The zoomed version of the first TGE occurred on 7 February 2023. By the black curve, we show 1-minute time series of the upper scintillator of the STAND3 detector; by the blue line – disturbances of the NSEF; by the red curve – the atmospheric pressure; and by the green line – nearby atmospheric discharge. Rose lines show periods of different NSEF polarity.

The TGE event was confirmed by analyzing the state of the atmosphere using the Weather Research and Forecasting (WRF) model [25]. The modeling revealed a dense cluster of graupel particles above the station when the TGE was registered, see Fig. 5a. In contrast, snow particles were detected above the particle detectors from around 3:00 to 7:00 UT, see Fig. 5b. The cloud's height was approximately 4 km. The graupel particles were below the snow particles. As a result, the LPCR is made up of positively-charged graupel, and the cloud's electrical structure can be described as a dipole, with the main negative charge region formed by snow particles and the LPCR formed by graupel particles, between 4:22 and 4:25.

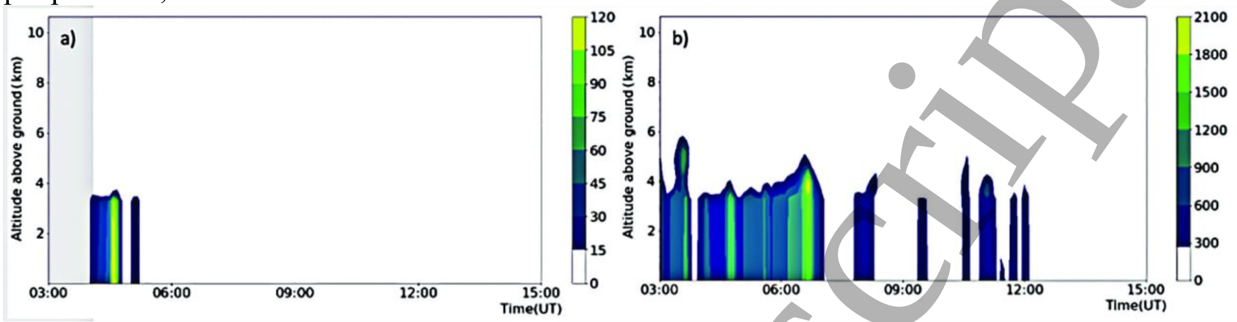

Figure 5. a) the modeled density of graupel particles (mg/m^3) above Aragats on February 7; b) the same for the snow particles. We explain the colors related to the hydrometeor density (mg/m^3) on the right side of each frame.

3. Discussion and conclusion

On February 7th, a large TGE occurred in Aragats, which raised questions about its origin. We have collected detailed information about the TGE and weather conditions. Our analysis of the electron energy spectrum and hydrometeor density, measured through WRF simulations, confirmed a significant TGE event on that day. Among the Wintertime TGEs listed in Table 1 and depicted in black in Fig. 1, the 7 February event was the sole where a significant amount of electrons reached the ground, allowing us to obtain the energy spectrum. It is common to observe Winter TGEs (air glows) in Japan [21]. However, it is difficult to attribute the TGEs seen on Aragats to an updraft of warm air due to the cold temperatures and deep snow coverage prevalent in the environment at 3200 m. Thus, we are exploring alternative explanations for this phenomenon.

Based on the data from Bolteck's lightning locator network, several atmospheric discharges were identified near Ararat Mountain (south of Aragats) and then moved towards Aragats, as illustrated in Fig. 6. On February 7th, the weather in the area was unusually warm. For example, the temperature at Zvartnots airport (35 km from Aragats) and +2C in Igdir (Turkey, 70 km from Aragats) were 0°C. At Igdir, the wind was blowing from the North-North-East towards Aragats, with stratocumulus clouds moving at wind speeds of 50-60 m/s at 3,000 m. Graupel falls were reported by the meteorological service of Zvartnots airport at night. Thus, clouds with a strong electric field inside can move from the south towards Aragats, leading to a powerful Wintertime TGE.

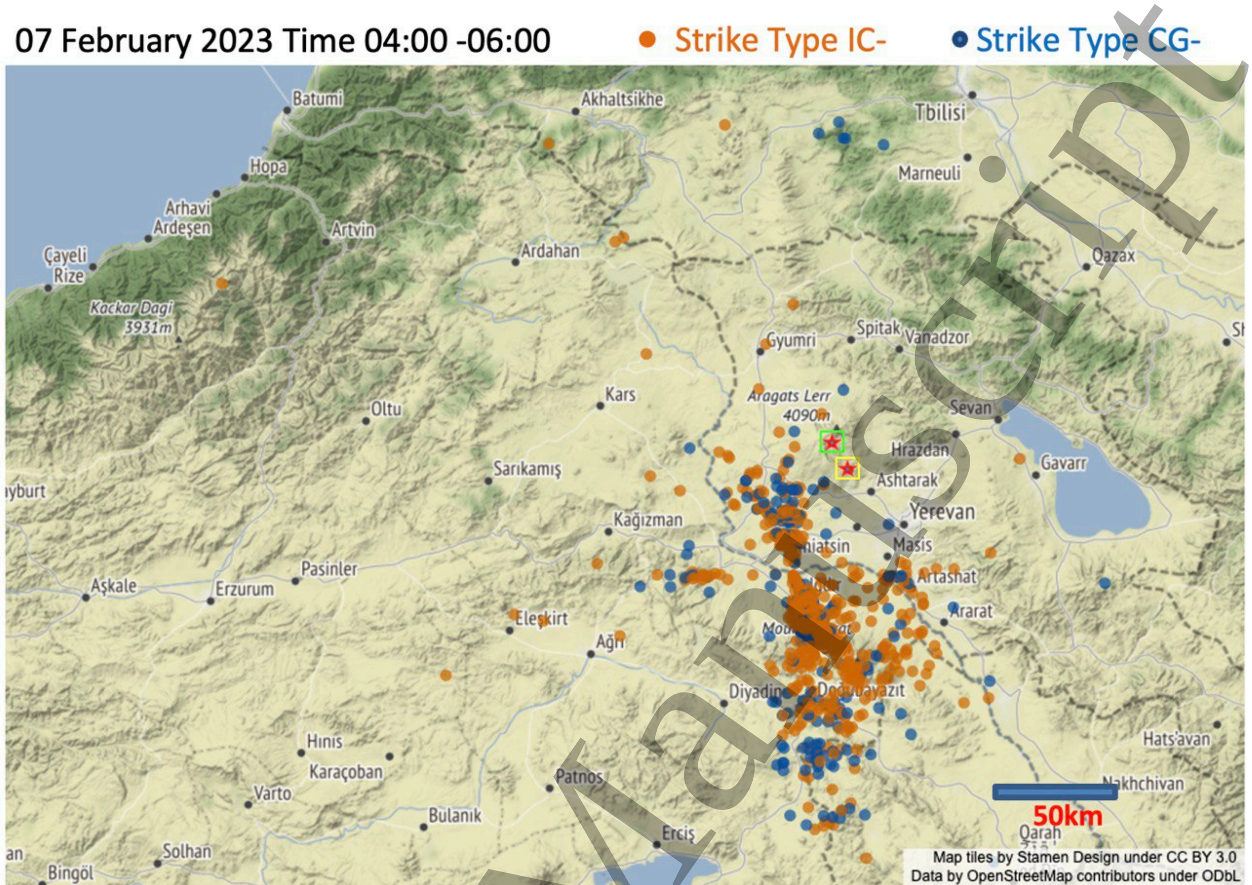

Figure 6. Lightning activity in the south from Aragats on February 7, 2023. The chart shows a cumulative picture of lightning flashes from 00:4 to 00:6 UT. Intracloud flashes are marked in red, while cloud-to-ground flashes are shown in blue. The chart also indicates the location of the Aragats and Nor Amberd stations with asterisks.

Another possible reason for the TGE on February 7th could be attributed to the electrification of clouds caused by wind. A study [26] discusses a different way of atmospheric electrification called wind-field thunderstorms. When ice crystals and graupel collide in a windy atmosphere, charge separation occurs, forming layers with different charges. During wind-field thunderstorms, the strong wind velocities occur mostly horizontally but with a strong vertical shear, so the charge separation happens along a large slanted path. Additionally, winter clouds are usually shallow and close to the ground, confirmed by WRF modeling.

Even during winter, when temperatures can be extremely low, warm air updrafts are still possible. Updrafts can occur if there is a temperature difference between the rising air and the surrounding air. It's possible that a nearby large lake covered in ice could reflect the sun's radiation onto the atmosphere and heat the air above the station, creating the conditions for an updraft.

TGE event on February 7th, 2023, could be caused by the three scenarios mentioned above, individually or in combination. We intend to research Wintertime TGEs using meteorological drones to gain further insight. This will enable us to measure wind speed and atmosphere electrification up to 500 meters above Aragats.

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