



1 Threshold Atmospheric Electric Fields for Initiating Relativistic Runaway Electron 2 Avalanches: Theoretical Estimates and CORSIKA Simulations

3 Ashot Chilingarian*, Liza Hovhannisyan, Mary Zazyan

4 A I Alikhanyan national lab (Yerevan Physics Institute), Alikhanyan Brothers 2, Yerevan
5 36, Armenia

6 *corresponding author chili@aragats.am

7 Abstract

8 We examine the threshold Atmospheric Electric Field (Eth) needed to initiate a runaway
9 avalanche process in Earth's atmosphere. We compare the traditional, thirty-year-old
10 theoretical threshold value with its recently updated value, along with the threshold
11 derived from CORSIKA-simulated avalanches (Ez). The altitude dependence of these
12 threshold values is analyzed, considering changes in air density and their effects on
13 avalanche development. This study is vital for understanding high-energy atmospheric
14 phenomena in both the lower and upper atmosphere, including thunderstorm ground
15 enhancements (TGEs) and gamma glows, as well as for refining AEF models based on
16 particle flux measurements.

17 Short Summary

18 Thunderstorms can accelerate particles in the atmosphere, producing bursts of radiation at
19 the ground. We investigated how strong the electric field inside a cloud must be to start
20 such events. Using advanced computer simulations and comparing with measurements
21 from mountain stations, we found that fields must be stronger than earlier theory
22 suggested. Our results improve understanding of storm electricity and its role in natural
23 radiation.

24 Highlights

- 25 • Introduces a refined framework for determining threshold atmospheric electric
26 fields (Eth) needed to initiate relativistic runaway electron avalanches (RREAs)
27 and thunderstorm ground enhancements (TGEs).
- 28 • Compares classical ($E_{th} \approx 2.80 \times n$) and updated ($E_{th} \approx 2.67 \times n$) theoretical
29 thresholds with altitude-dependent thresholds derived from CORSIKA
30 simulations.
- 31 • Demonstrates that realistic avalanche development requires fields 15–22%
32 stronger than theoretical values, depending on altitude and air density.
- 33 • Provides a reproducible simulation methodology for integrating experimental
34 particle flux measurements into atmospheric electricity models across multiple
35 research stations.



36 Introduction

37 Free electrons are abundant in the troposphere. The altitude where their density reaches
38 its highest point—called the Regener–Pfotzer maximum—depends on various factors,
39 including the geomagnetic cutoff rigidity (R_c), the type of particles being measured, and
40 the phase and strength of the solar cycle. Recent observations, supported by PARMA4.0
41 calculations (Sato, 2016), show that at middle to low latitudes ($R_c = 3\text{--}8$ GV), the highest
42 flux of charged particles occurs at altitudes around 12–14 km (see Fig. 4 in Ambrozova et
43 al., 2023).

44 Atmospheric electric fields (AEFs) generated by thunderstorms transfer energy to free
45 electrons, accelerate them, and, under certain conditions, induce electron-photon
46 avalanches. In 1992, Gurevich, Milikh, and Roussel-Dupré identified the conditions
47 necessary for extensive multiplication of electrons from each energetic seed electron
48 injected into a strong AEF region (Gurevich et al., 1992). This process is known as the
49 Relativistic Runaway Electron Avalanche (RREA; Babich et al., 2001; Alexeenko et al.,
50 2002). A numerical approach for solving the relativistic Boltzmann equation for runaway
51 electron beams (Symbalisty et al., 1998) aids in estimating the threshold AEF (Babich et
52 al., 2001; Dwyer et al., 2003) required to trigger RREA. As demonstrated by GEANT4
53 and CORSIKA simulations (Chilingarian et al., 2012, 2022), the RREA process is a
54 threshold phenomenon, with avalanches initiating when the atmospheric AEF exceeds a
55 certain threshold, which depends on the air density. The AEF must also be sufficiently
56 extended to support the growth of avalanches. At standard temperature and pressure in
57 dry air at sea level, $E_{th} \approx 2.80 \cdot n$ kV/cm, where air density n is relative to the
58 International Standard Atmosphere (ISA) sea-level value (see the recent update of the
59 threshold energy $E_{th} \approx 2.67 \cdot n$ kV/cm in Dwyer and Rassoul, 2024).

60 This threshold field is slightly higher than the breakeven field, which corresponds to the
61 electron energy at which minimum ionization occurs. If electrons traveled exactly along
62 AEF lines, it would define the threshold for runaway electron propagation and the start of
63 avalanche formation. However, the paths of electrons deviate due to Coulomb scattering
64 with atomic nuclei and Møller scattering with atomic electrons, causing deviations from
65 the near-vertical AEF. Additionally, secondary electrons produced by Møller scattering
66 are not generated along the field line; therefore, AEFs 10-20% stronger are required for
67 electrons to run away and trigger an avalanche.

68 1. Corsika simulations of RREAs reaching on Aragats stations

69 To understand how avalanches develop in an electrified atmosphere and to compare the
70 new and updated E_{th} with the particle intensity growth, we used the CORSIKA code
71 (Heck et al., 1998), version 7400, which takes into account the effect of AEFs on particle



72 transport (Butnik et al., 2010). The growth of RREA definitely increases the cloud's
73 electrical conductivity. Numerous studies (Marshall et al., 1995; Stolzenburg et al., 2007)
74 have indicated that lightning flashes occur after the RREA threshold exceeds 20-30%.
75 RREA simulation codes do not include a lightning initiation mechanism. Therefore, one
76 can artificially raise the AEF strength beyond a realistic value to produce billions of
77 avalanche particles; however, this approach lacks physical justification. As a result, we
78 do not test AEFs stronger than 2.2 kV/m at altitudes of 3-6 km. The RREA simulation
79 was performed for vertical seed electrons with a uniform AEF that exceeded the E_{th} by a
80 few tens of percent. An introduced fixed uniform AEF shifts the surplus to E_{th} at different
81 heights by different percent, corresponding to air density. The seed electron energy
82 spectrum was based on the EXPACS WEB calculator (Sato, 2018), following a power
83 law with an index of 1.173 for energies from 1 to 300 MeV. During TGE events on
84 Aragats, the typical distance to the cloud base is estimated to be 25–200 m (see Fig. 17 in
85 Chilingarian et al., 2020); therefore, in our simulations, particle propagation continued in
86 dense air for an additional 25, 50, 100, and 200 meters before detection. The simulations
87 included 1,000 to 10,000 events for AEF strengths from 1.55 to 2.5 kV/cm. Electron and
88 gamma-ray propagation was tracked until their energies dropped to 0.05 MeV. The
89 CORSIKA code models RREA development, calculating the number of electrons and
90 gamma rays at various stages within the AEF, every 200 m.

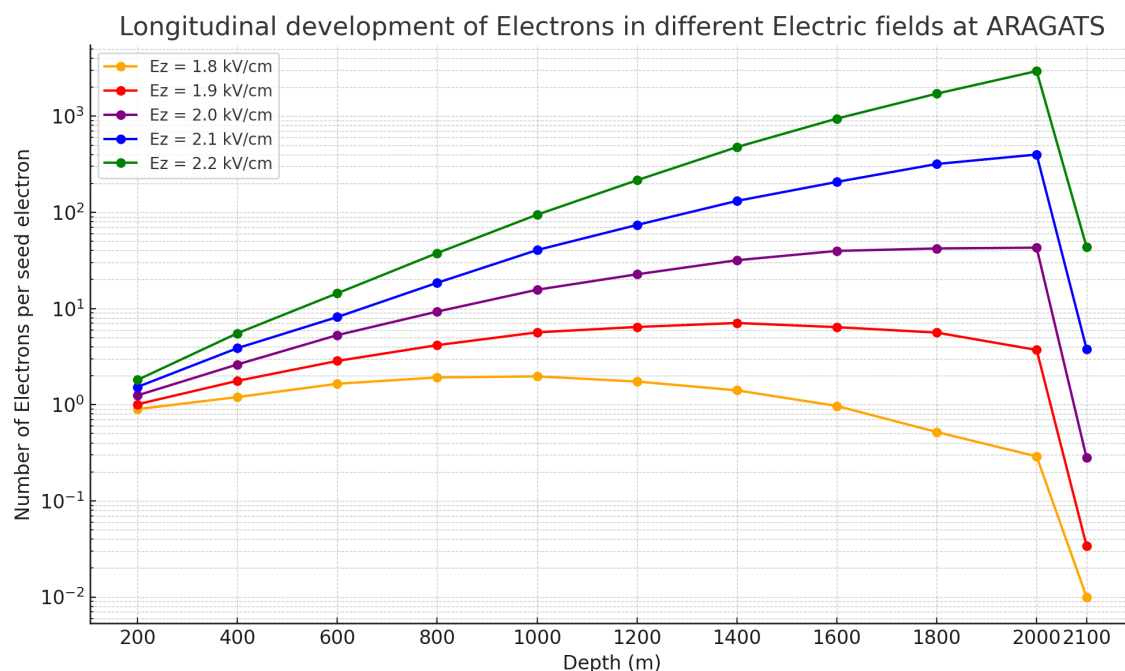
91 Besides the Aragats and Nor Amberd research stations on the slopes of Mt. Aragats in
92 Armenia, we also conducted simulations for Slovakian and Chinese research stations at
93 Lomnický Štít and the Tibetan plateau. LHAASO (Large High Altitude Air Shower
94 Observatory) is situated at 4410 meters above sea level. It provides an ideal platform for
95 studying atmospheric particle acceleration due to its thin atmosphere and high likelihood
96 of runaway electron avalanche formation. We present CORSIKA simulation results
97 showing increases in electron and photon fluxes under AEF strengths ranging from 1.55
98 to 1.9 kV/m. The number of electrons and photons was recorded at depths ranging from
99 6510 meters to 4510 meters.

100 Lomnický Štít is located at an altitude of 2630 meters in Slovakia. CORSIKA simulations
101 were performed for various vertical AEFs ranging from 1.9 to 2.3 kV/cm. The number of
102 electrons and photons was recorded at depths ranging from 4734 meters to 2734 meters.
103 Significant increases in flux were observed with stronger fields, confirming the
104 development of robust RREA. Saturation trends in the growth of electrons and photons
105 suggest that the threshold field, E_{th} , at Lomnický Štít is approximately 2.3 kV/cm. These
106 results support earlier findings from Aragats and Nor Amberd and emphasize the altitude
107 dependence of E_{th} . Due to the thinner air, at Lhaso, the TGEs occurred at a much lower
108 value of 1.7 kV/m.

109 In Figures 1-4, we display the development of RRE avalanches at different atmospheric
110 depths and for various physically justified strengths of the AEF. The curves are scaled for
111 a single seed electron for easier comparison with experimentally measured intensities.
112 For each lower value of AEF, we observe saturation of the particle flux; the RREA



113 process attenuates before reaching the observation level (see the red and yellow curves in
114 Figs. 1-4).
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117 **Figure 1. Development of the RRE avalanche in the atmosphere. The avalanche**
118 **started at 5400 meters above sea level, which is 2100 meters higher than the Aragats**
119 **station. The number of avalanche particles is calculated every 200 meters. After**
120 **leaving the AEF, the movement of avalanche particles is tracked for an additional**
121 **100 meters before reaching the station.**

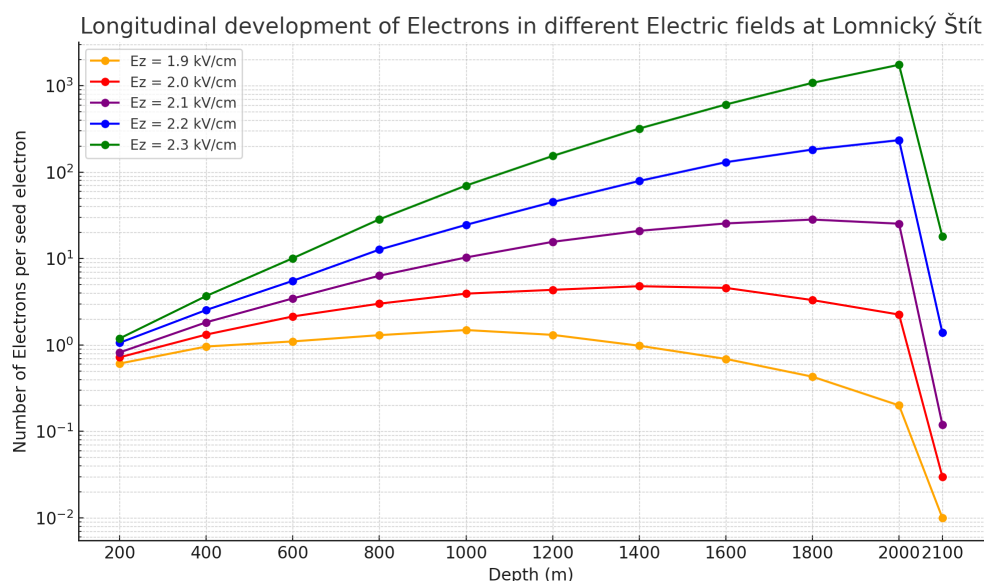


Figure 2. Development of the RRE avalanche in the atmosphere. The avalanche started at 4730 meters above sea level, which is 2100 meters higher than the Lomnický Stit station. The number of avalanche particles is calculated every 200 meters. After leaving the AEF, the movement of avalanche particles is tracked for an additional 100 meters before reaching the station.

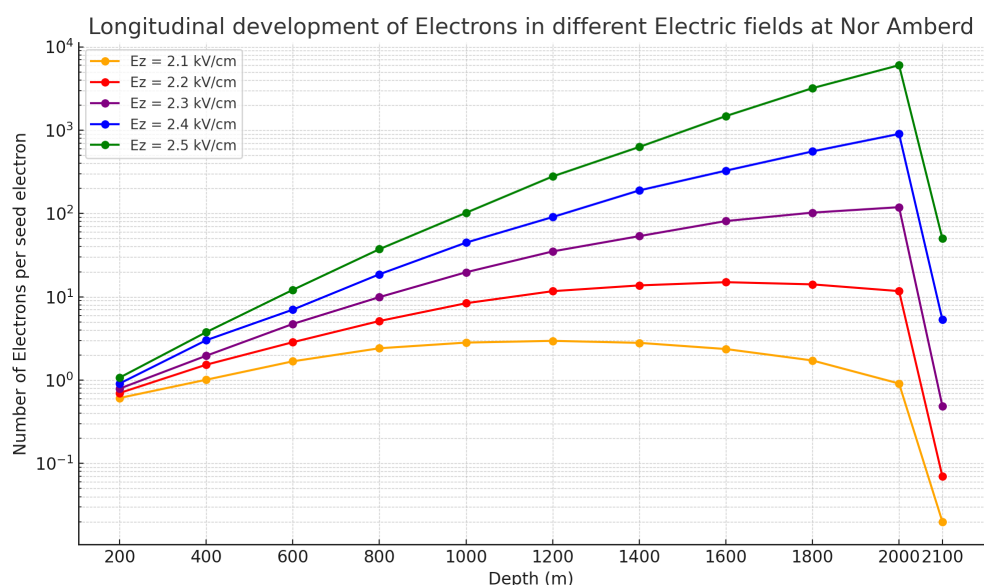


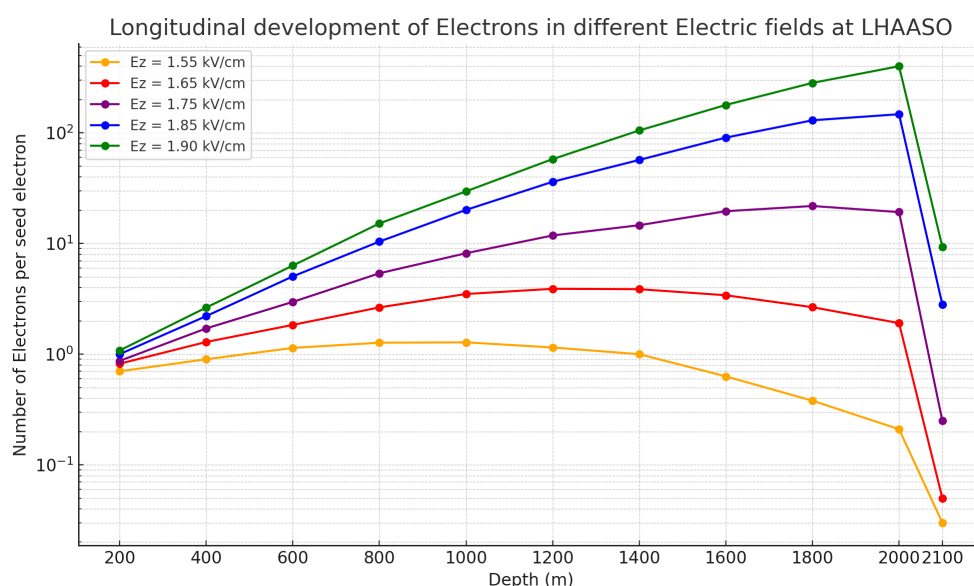
Figure 3. Development of the RRE avalanche in the atmosphere. The avalanche began at 4100 m a.s.l. (0 meters depth), which is 2100 meters above the Nor Amberd station. The number of avalanche particles is calculated every 200 meters. After



132 exiting the AEF, the propagation of avalanche particles is tracked for an additional
133 100 meters before reaching the station.

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137 **Figure 4. Development of the RRE avalanche in the atmosphere. The avalanche**
138 **started at 6510 meters above sea level, which is 2100 meters higher than the**
139 **LHAASO station. The number of avalanche particles is calculated every 200 meters.**
140 **After leaving the AEF, the movement of avalanche particles is tracked for an**
141 **additional 100 meters before reaching the station.**

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143 We estimate the “simulated” thresholds, E_z values, at the heights at which the amount of
144 avalanche particles stops rising, as shown in Fig. 5.

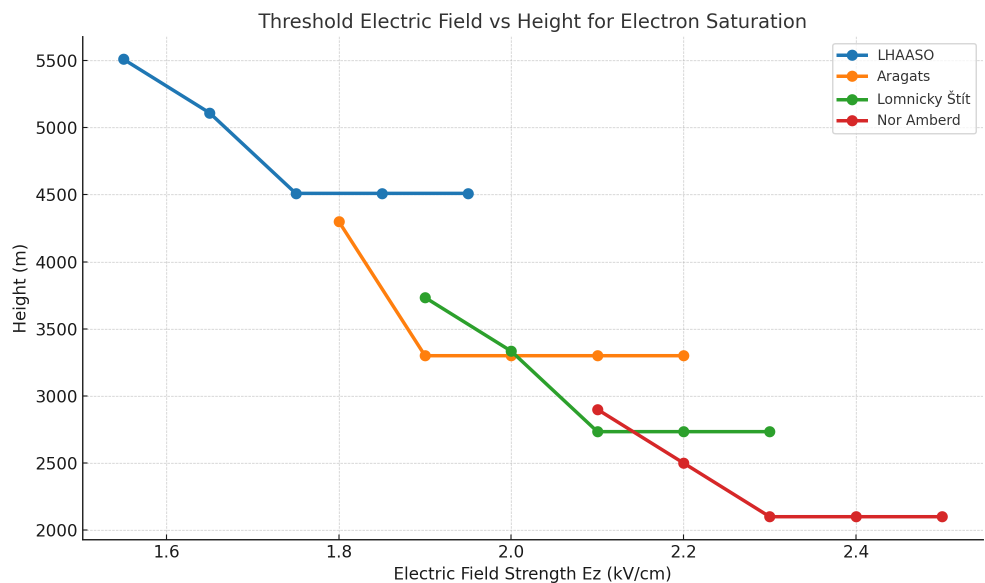
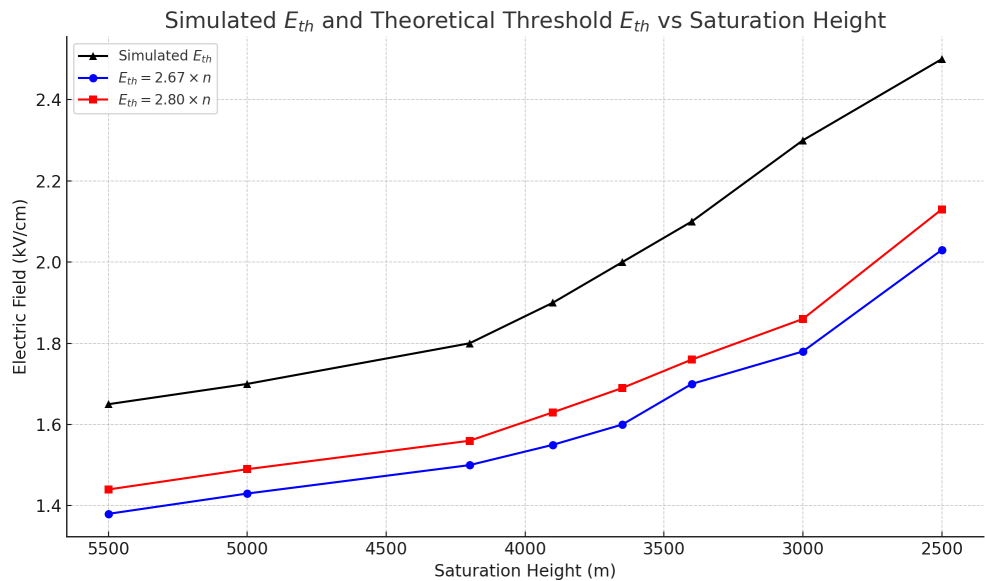


Figure 5. The electric field strengths (E_{th}) at the point when the RREA particle flux began to decline for 4 stations located at altitudes ranging from 2000 to 4100 meters.

In Figure 6 and Table 1, we compare the “simulated” threshold E_z with the theoretical ones. Simulations show higher values than theoretical estimates, especially for high E_{th} values (low altitudes) at all four research stations. The relative air density n is calculated using an exponential atmospheric model. Threshold fields are computed as $2.67 \times n$ and $2.80 \times n$, representing the updated and theoretical thresholds, respectively. The percentage of enhancement indicates how much the applied field exceeds the theoretical thresholds. Strong AEFs, where the cascade did not attenuate, were not included in the table.



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Figure 6. The dependence of the heights in the atmosphere and the corresponding threshold AEF to start RREA for theoretical and simulated values.

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Table 1. Excess of E_z over E_{th} . Stopping altitudes and theoretical threshold field comparisons for heights 2500- 5550 m.

Input E_z (kV/cm)	Enhancement Stops at h(m)	n (relative density)	$2.67 \times n$ (kV/cm)	$2.80 \times n$ (kV/cm)	Rel. Excess. (%) (2.80)	Rel. Excess. (%) (2.67)	Site
1.55	5510	0.465	1.24	1.30	19.0	24.8	LHAASO (4400 m)
1.65	5110	0.492	1.31	1.38	19.8	25.7	LHAASO (4400 m)
1.8	4200.0	0.558	1.49	1.56	15.2	20.8	Aragats (3200 m)
1.9	3900.0	0.582	1.55	1.63	16.6	22.3	Aragats (3200 m)
1.9	3734	0.595	1.59	1.67	14.0	19.5	Lomnický Štít (2630 m)
2.0	3334	0.629	1.68	1.76	13.5	19.0	Lomnický Štít (2630 m)



2.1	2700.0	0.687	1.84	1.92	9.1	14.4	Nor Amberd (2000 m)
2.2	2500.0	0.707	1.89	1.98	11.2	16.6	Nor Amberd (2000 m)

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164 **2. Discussion and conclusion**

165 Although both the classical threshold field ($E_{th} \approx 2.80 \times n$ kV/cm) and its updated
166 version ($E_{th} \approx 2.67 \times n$ kV/cm) are derived under idealized assumptions, the difference
167 between them results from refinements in modeling particle energy loss processes. The
168 earlier estimate of $2.80 \times n$ was based on basic energy balance considerations using older
169 ionization loss models and assumed monoenergetic electrons. This threshold is slightly
170 above the breakeven field, where energy gain equals average energy loss. The updated
171 $2.67 \times n$ value, introduced by Dwyer and Rassoul (2024), incorporates more accurate
172 relativistic Boltzmann solutions, improved ionization and bremsstrahlung cross-sections,
173 and a probabilistic treatment of runaway thresholds across realistic energy spectra. While
174 both thresholds assume idealized, field-aligned electron motion in a uniform medium, the
175 updated value is physically more consistent. It predicts a slightly lower field strength
176 needed for initial runaway. However, CORSIKA simulations show that this refined
177 threshold is insufficient for sustained avalanche growth under real atmospheric conditions
178 due to scattering and finite path effects. Moreover, it deviates more from the simulated
179 value than the “classical” 30-year-old estimate.

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181 Multiple physical processes act to inhibit ideal runaway propagation. Coulomb scattering
182 with atmospheric nuclei and Møller scattering with electrons cause substantial angular
183 deflection and energy redistribution. Secondary electrons are not generated strictly along
184 the field direction, and many lose energy before gaining sufficient momentum to continue
185 avalanche growth. As a result, electrons must be accelerated in stronger-than-threshold
186 fields to overcome these losses and maintain avalanche conditions.

187 CORSIKA simulations, which incorporate all major interaction mechanisms—including
188 Coulomb and Møller scattering, bremsstrahlung losses, finite propagation distances, and
189 realistic secondary cosmic ray spectra—demonstrate that avalanches only fully develop
190 when the applied field exceeds the theoretical threshold by a measurable margin. For the
191 updated $2.67 \times n$ value, we observe a required excess of approximately 20–22% at the
192 Aragats station (~ 3200 – 4200 m a.s.l.), whereas for the classical $2.80 \times n$ threshold, the
193 excess is typically 15–17%.

194 Interestingly, this required excess decreases with increasing air density, as observed in
195 the Nor Amberd simulations. At lower altitudes (~ 2500 – 2700 m a.s.l.), the difference
196 between the applied and threshold fields is reduced: only 14–16% above $2.67 \times n$, and
197 about 9–11% above $2.80 \times n$. This trend can be explained as follows:

198 In denser air, the chances of energy loss interactions increase, but so does the likelihood
199 of electron multiplication through ionization and bremsstrahlung over shorter distances.
200 The avalanche can develop more quickly because seed electrons encounter more target



atoms in a given path length. As a result, the necessary “headroom” above the threshold field for sustained multiplication is smaller. Simply put, the efficiency of avalanche formation improves in denser air, even though the absolute threshold field is higher. This results in a smaller relative excess being required above the theoretical threshold.

Therefore, although the threshold field scales linearly with air density, the required enhancement factor does not. It decreases with increasing density due to a balance between energy loss and multiplication processes, all of which are faithfully captured in the CORSIKA simulation framework. This emphasizes the importance of altitude-dependent analysis in interpreting Thunderstorm Ground Enhancements (TGEs) and suggests that scaling laws based solely on density may overlook subtler effects arising from atmospheric structure and shower development dynamics.

Code and data availability

Data archive on TGE event is reposted on the Mendelay site at

<https://doi.org/10.17632/8gtdbh59z> (Chilingarian et al., 2024).

Data archive on CORSIKA simulations (RREA development in the atmosphere above 4 sites) is available at the link:

http://crd.yerphi.am/CORSIKA_Simulations

Author contribution

AC and MZ designed the simulation experiments with the CORSIKA code, and LH performed the simulations. AC prepared the manuscript with contributions from all co-authors

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