

Relativistic runaway electron avalanches: unified density-dependent scaling and transport
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1. Community Comment CC1 — Ekaterina Svechnikova

Comment from referee/community member	Author's response	Author's changes in manuscript
The main limitation is that the degree of universality remains insufficiently demonstrated. The results are based on four high-altitude station configurations, one simulation framework, idealized vertically uniform electric-field layers, and a fixed post-field propagation distance. These assumptions are reasonable for a controlled scaling study, but they are much simpler than real thunderstorm environments, where electric fields are nonuniform, time-dependent, and often organized in complex multi-cell structures.	The controlled and idealized configuration used in the present study was chosen to systematically examine the effects of atmospheric density and electric-field strength on RREA development and subsequent particle transport under comparable simulation conditions. The uniform vertical electric-field layers are not intended to reproduce the complete, event-specific electric-field structure of real thunderstorms. Rather, this configuration provides a controlled modeling framework because the spatial structure and vertical extent of strong electric fields inside thunderclouds are not sufficiently constrained by direct measurements. The applicability of the results obtained within this framework should therefore not be extended to arbitrary thunderstorm configurations without additional validation. This limitation is now stated more explicitly in the revised manuscript, and the conclusions are formulated within the scope of the present CORSIKA simulation framework.	Section 2 now describes the atmospheric electric field explicitly as a vertically oriented uniform 2000 m layer and links this idealized setup to Chilingarian et al. (2026). The Introduction states that reliable measurements of the spatial and temporal electric-field structure inside thunderclouds remain limited. The Conclusions now explicitly limit the scope of the results: “These results are derived for the idealized uniform electric-field configurations considered here and should not be generalized to arbitrary thunderstorm electric-field structures without further validation.”
Several additions would considerably strengthen the result: comparison with other Monte Carlo tools, more explicit uncertainty estimates for the fitted parameters, sensitivity tests to field geometry and fitting range, analysis of different post-field gap lengths, and validation against observed TGE or gamma-ray glow spectra.	The uncertainties of the fitted parameters are now explicitly reported, including the station-specific K coefficients and the parameters of the joint density-dependent fit, $K=(6.39\pm0.26)\times10^3$ kV and $a=-0.923\pm0.083$. In addition, the post-field transport analysis has been extended from the original 100 m separation to 25, 50, 100, and 200 m, allowing the distance dependence of the electron and gamma-ray spectra and particle counts to be examined directly. A systematic comparison with independent Monte Carlo frameworks and sensitivity tests using nonuniform electric-field geometries would require additional simulations beyond the present CORSIKA configuration.	Section 3 now reports propagated fit-derived uncertainties for the station-specific coefficients: $K_{\text{Aragats}}=(10.2\pm0.4)\times10^3$ kV, $K_{\text{LHAASO}}=(11.2\pm0.3)\times10^3$ kV, $K_{\text{Lomnický štít}}=(8.9\pm0.4)\times10^3$ kV, and $K_{\text{Nor Amberg}}=(8.6\pm0.2)\times10^3$ kV. The joint density-dependent fit is reported as $K=(6.39\pm0.26)\times10^3$ kV and $a=-0.923\pm0.083$. Section 4 has been expanded to include detector distances of 25, 50, 100, and 200 m, with the corresponding electron and gamma-ray spectra shown in Fig. 3 and particle counts shown in Fig. 4.

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	Similarly, a quantitative comparison with observed TGE or gamma-ray glow spectra would require event-specific information on the thunderstorm electric-field structure, field termination height, atmospheric conditions, and detector response. These analyses are therefore not included in the present study.	
Such checks would make the proposed scaling more robust, better calibrated, and more clearly positioned relative to existing RREA parameterizations.	The revised manuscript places the proposed empirical scaling more explicitly in the context of previous RREA parameterizations and limits its interpretation to the atmospheric conditions and simulation configurations investigated here.	The Introduction now discusses Dwyer (2003) and Coleman and Dwyer (2006), including the dependence of the reported parameterizations on electric-field range and atmospheric conditions. Section 3 additionally compares the present avalanche lengths with previous calculations using the conventional density-scaled variables E_z/n and $n \cdot \lambda_{\text{eff}}$, citing Coleman and Dwyer (2006), Dwyer et al. (2012), and Skeltved et al. (2014). The Conclusions explicitly restrict the applicability of the results to the idealized configurations studied.
A minor stylistic point is that the manuscript is written by a single author but frequently uses collective formulations such as “we show” and “we develop.” Replacing these phrases with passive constructions or formulations such as “this work shows” would improve stylistic clarity.	The manuscript has been revised throughout to replace collective first-person formulations with passive constructions or neutral formulations, improving stylistic consistency.	Collective first-person formulations were replaced by passive or neutral single-author constructions throughout the manuscript, including the Abstract, methodological descriptions, results, and Conclusions.

2. Referee Comment RC1 — Anonymous Referee #1

Comment from referee/community member	Author's response	Author's changes in manuscript
Introduction, around the lines 26–27, recently discovered flickering gamma ray flashes (FGFs) should be added into the list of phenomena for completeness (e.g., Østgaard et al., 2024; Marisaldi et al., 2024).	Flickering gamma-ray flashes (FGFs) have been added to the list of high-energy atmospheric phenomena in the Introduction, together with the suggested references to Østgaard et al. (2024) and Marisaldi et al. (2024).	The Introduction now includes FGFs in the list of high-energy atmospheric phenomena and cites Østgaard et al. (2024) and Marisaldi et al. (2024). Both references were added to the bibliography.
It would be useful to briefly mention/discuss the fact that there are theories which consider more complex RREA, the so-called relativistic feedback	A brief discussion of the relativistic feedback mechanism has been added to the Introduction, including its role in initiating successive avalanches	The Introduction now contains a paragraph describing relativistic feedback through backward-propagating positrons and high-energy photons,

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mechanism (e.g., Dwyer, 2003).	through backward-propagating positrons and high-energy photons, with reference to Dwyer (2003). The revised text also distinguishes this mechanism from the conventional RREA development considered in the present study.	noting that feedback can become self-sustaining under sufficiently strong and extended fields. The manuscript also states that the present study considers conventional RREA development.
Simulations are performed for four selected high-altitude observatories/stations. I recommend providing 1 or 2 references related to the observations of thunderstorm ground enhancement at each station.	References to thunderstorm-related particle-enhancement observations have been added for all four high-altitude sites considered in the simulations: Aragats (Chilingarian et al., 2022, 2024), Nor Amberd (Chilingarian et al., 2025), Lomnický Štít (Chum et al., 2020; Kisvárdai et al., 2025), and LHAASO (LHAASO Collaboration, 2023).	Section 2 now gives observational references for each simulated site: Aragats (Chilingarian et al., 2022, 2024), Nor Amberd (Chilingarian et al., 2025), Lomnický Štít (Chum et al., 2020; Kisvárdai et al., 2025), and LHAASO (LHAASO Collaboration, 2023). The corresponding references are included in the bibliography.
Around lines 86–88, this simplified configuration should be justified by a reference. Is the electric field (in Section 3) really constant/uniform within a vertical range of 2000 m in the simulations? In addition, I believe that the range of 2000 m should be shortly discussed with respect to the avalanche length.	The simulation configuration has been clarified in the revised manuscript. The electric field is modeled as a vertically oriented, uniform field throughout the 2000 m acceleration layer. The same idealized configuration was used in the previous CORSIKA study of Chilingarian et al. (2026), which is now cited in support of the adopted setup. The role of the 2000 m field-layer thickness has also been clarified in relation to the simulated avalanche lengths. As shown in Sect. 3, the 2000 m layer is substantially longer than the effective avalanche lengths obtained for the electric-field conditions considered, allowing avalanche multiplication to develop within the acceleration region before the particles leave the field.	Section 2 now states that the field is a vertically oriented uniform 2000 m layer and cites Chilingarian et al. (2026) for the adopted idealized setup. The text further explains that 2000 m exceeds the effective avalanche lengths obtained under all simulated field conditions, allowing avalanche multiplication to develop before particles leave the acceleration region. Section 3 specifies the common fitting interval $d=200\text{--}2000$ m.
Equation on line 135. Introduce/specify H_{st} in the equation.	H_{st} is now explicitly defined when it is first introduced.	Immediately after Eq. (2), H_{st} is explicitly defined as the altitude of the observational station above sea level.
Equation on line 178, specify i (which values of electric field and how many values were used?).	The index i is now explicitly defined as labeling the four electric-field values used for each station. The values are 180, 190, 200, and 210 kV/m for	Section 2 now lists the four applied-field values for each station through the stated ranges and 10 kV/m step: 180–210 kV/m (LHAASO), 200–230 kV/m

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	LHAASO; 200, 210, 220, and 230 kV/m for Aragats; 210, 220, 230, and 240 kV/m for Lomnický Štít; and 230, 240, 250, and 260 kV/m for Nor Amberd. These values are now specified in the revised manuscript.	(Aragats), 210–240 kV/m (Lomnický Štít), and 230–260 kV/m (Nor Amberd). In Sect. 3, the text below Eq. (8) explicitly states that i labels the four simulated supercritical electric-field values used for each station in the least-squares fit.
Sections 3 and 4, I suggest numbering all the equations that are written on separate lines (not only those, which are referenced later in the text).	All equations displayed on separate lines throughout the manuscript have been numbered consistently in the revised version.	Displayed equations in Sects. 3 and 4 have been numbered consistently. The revised manuscript now numbers the avalanche-development equations, fitting relations, FPD relations, bootstrap relation, and stopping-power relation in a continuous sequence.
I think it would be useful to briefly discuss/show the change of energy spectra and counts for electrons and photons as a function of distance between the exit and detector (not only for 100 m).	The post-field transport analysis has been extended to field-to-detector distances of 25, 50, 100, and 200 m. The revised manuscript now presents the evolution of both electron and gamma-ray counts and their energy spectra as a function of propagation distance beyond the lower boundary of the electric-field region. These additional simulations allow the different attenuation behavior of the electron and gamma-ray components to be systematically studied and extend the original analysis beyond the previously considered 100 m separation.	Section 4 now includes Aragats simulations with detector positions 25, 50, 100, and 200 m below the lower field boundary. Figure 3 presents the electron and gamma-ray energy spectra at these distances, and Fig. 4 presents the corresponding particle counts. The text describes the rapid attenuation of electrons and the more gradual attenuation of gamma rays with increasing field-free propagation distance.
Line 41: “... development of the relativistic runaway electron avalanche (RREA, ...” → “... development of the relativistic runaway electron avalanche (RREA) theory ...”.	The wording has been corrected as suggested to “the development of the relativistic runaway electron avalanche (RREA) theory.”	The Introduction now uses the wording “the development of the relativistic runaway electron avalanche (RREA) theory.”
Equation (1). It would useful to mention already here that $E_{th}(h)$ depends on the air density.	The density dependence of $E_{th}(h)$ is now stated explicitly when Eq. (1) is introduced, with $E_{th}(h)=E_0\rho(h)/\rho_0$.	The text immediately following Eq. (1) now defines the runaway threshold as $E_{th}(h)=E_0\cdot\rho/\rho_0$ and identifies ρ_0 as the sea-level density and ρ as the density at altitude z . Section 2 further writes the same scaling as $E_{th}(h)=E_0\cdot n(h)$, where $n(h)=\rho(h)/\rho_0$.

3. Community Comment CC2 — Pavel Klimov

Comment from referee/community member	Author's response	Author's changes in manuscript
For example, how significant is the discrepancy between the K coefficients given for different stations on page 6? It's clear they differ, but the calculation accuracy and method errors aren't provided. And if they're on the order of 10%, then the first two numbers (10.2 and 11.2) are barely distinguishable. So, it is better to demonstrate numbers with errors, as it is done in the second part of the work, where free path distance is discussed.	The uncertainties of the station-specific K coefficients have now been explicitly evaluated and included in the revised manuscript. The effective avalanche length λ_{eff} is obtained from the slope of the linear fit to $\ln N_e(d)$, and the standard error of this slope is propagated first to λ_{eff} and subsequently to the fitted coefficient K. The resulting values are $K_{\text{Aragats}}=(10.2\pm0.4)\times10^3$ kV, $K_{\text{LHAASO}}=(11.2\pm0.3)\times10^3$ kV, $K_{\text{Lomnický Štít}}=(8.9\pm0.4)\times10^3$ kV, and $K_{\text{Nor Amberd}}=(8.6\pm0.2)\times10^3$ kV. Some neighboring values show partial overlap within their fit-derived uncertainties. We therefore interpret the result as station-to-station variability within the atmospheric conditions considered, rather than claiming that every pair of station-specific coefficients is individually distinct. These uncertainties represent the statistical uncertainties from the fitting procedure and do not include possible systematic uncertainties associated with the atmospheric profile, field geometry, fitting interval, or CORSIKA physics settings.	Section 3 now explains the uncertainty propagation from the fitted slope b to λ_{eff} and then to the station-specific coefficient K. Equation (9) gives the propagated K uncertainty. The revised values are reported explicitly for all four stations and are repeated in Table 1. The discussion now notes partial overlap among some neighboring uncertainty intervals and interprets the result as station-to-station variability rather than pairwise statistical separation.
A similar question concerns the value of the coefficient “a”, introduced on page 7. It turned out to be -0.92, but could it simply be -1? Which, in principle, might be logical: the normalized K coefficient should be divided by the density.	The generalized empirical relation was fitted jointly to the combined dataset from all four stations, with K and a optimized simultaneously. The joint fit gives $K=(6.39\pm0.26)\times10^3$ kV and $a=-0.923\pm0.083$. The fitted value of a is statistically consistent with $a=-1$. However, in the generalized relation $\lambda_{\text{eff}}=K\cdot n^a/(E_z-E_{\text{th}})$, the density dependence of the runaway threshold is already included through $E_{\text{th}}=E_0\cdot n$. The factor n^a therefore represents an additional empirical density dependence beyond the threshold scaling. Thus, although $a=-0.923\pm0.083$ is consistent with -1, it should not be interpreted as a recovery of the classical inverse-	Equation (10) and the accompanying text now define a as an empirical exponent describing an additional density dependence beyond the density already included in $E_{\text{th}}=E_0\cdot n$. The joint-fit result $K=(6.39\pm0.26)\times10^3$ kV and $a=-0.923\pm0.083$ is reported in Sect. 3 and summarized in the Conclusions. The manuscript explicitly interprets the fitted exponent as an additional approximately inverse density dependence, rather than as a redefinition of the threshold scaling.

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	density scaling. The fitted values of K and a are retained because they are obtained directly from the joint optimization of the simulation dataset.	
Another point is: Is it possible to say something about correspondence of the spectra presented in fig 3 and 4 to the experimental ones, measured at the stations? It is beyond the scope of the paper, but it is interesting to know, how realistic these simulated spectra.	A direct quantitative comparison with measured spectra would require information on the actual thunderstorm electric-field geometry, field termination height, detector response, and event-specific atmospheric conditions. These quantities are not constrained within the present simulation setup, and such a comparison is therefore beyond the scope of the present study. The spectra referred to as Figs. 3 and 4 in the original manuscript are presented as Figs. 5 and 6 in the revised manuscript. They are used to characterize the simulated exit-to-detector transport in the 100 m configuration, rather than to reproduce a particular observed TGE spectrum. A quantitative simulation-to-observation comparison, including detector response and event-specific electric-field configurations, would require a dedicated study.	The revised manuscript frames the spectral analysis as a simulation-based transport study rather than an event-specific reconstruction. Section 4 now separates the distance-dependent transport results (Figs. 3–4) from the 100 m exit/detector spectral comparison used for the FPD calibration (Figs. 5–6). The Conclusions explicitly state that the results are derived for idealized uniform electric-field configurations and should not be generalized to arbitrary thunderstorm structures without further validation.
One more minor comment: lines 53–55 in the sentence “While this equation has been widely applied, it does not explicitly account for variations in AEF and atmospheric density and is often limited to narrow altitude and AEF ranges.” it is better to give values of altitude ranges and AEF to which the equation is applied and give references.	The corresponding discussion has been revised to avoid assigning a single altitude or electric-field range to the classical relation, because previous parameterizations were obtained under different electric-field and atmospheric-density conditions. The revised Introduction now states that Dwyer (2003) reported $K \approx 7.2 \times 10^3$ kV, while Coleman and Dwyer (2006) reported a related parameterization for electric fields above 300 kV/m and a different empirical fit for fields closer to the runaway threshold. Their scaling of the electric field and avalanche length to equivalent sea-level values is also discussed. The applicability of the avalanche-length parameterization is therefore described in relation to the electric-field range and atmospheric conditions for which the corresponding parameterization was obtained, with the relevant	The Introduction now replaces the earlier broad statement with a literature-based description of the applicable regimes. It reports Dwyer (2003), notes the Coleman and Dwyer (2006) parameterization for fields above 300 kV/m and their different fit near the runaway threshold, and states that they scaled electric field and avalanche length to equivalent sea-level values. The text now explicitly links the applicability of a parameterization to the electric-field range and atmospheric conditions under which it was obtained.

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	references included.	

4. Referee Comment RC2 — Anonymous Referee #2

Comment from referee/community member	Author's response	Author's changes in manuscript
The methodology suffers from a significant flaw. As I understand the manuscript, the parameterization used to characterize the field excess (as termed by the author) is not scaled consistently. Dwyer's formula (eq. 1) is a local relation that applies to reduced electric fields. In the present study, however, it appears that only the threshold field, E_{th}, is scaled with altitude, while the applied electric field is not.	The electric-field ranges were selected separately for each observational site to obtain sustained supercritical RREA multiplication under the corresponding atmospheric conditions. This selection was guided by the previous CORSIKA study (Chilingarian et al., 2026), in which the RREA initiation threshold was investigated as a function of altitude and atmospheric density. In the present study, the runaway threshold is defined as $E_{th}(h)=E_0 \cdot n(h)$, where $n(h)=\rho(h)/\rho_0$ and $E_0=284$ kV/m. Thus, the density entering the empirical parameterization is a station-specific reference value. The ranges used were 180–210 kV/m for LHAASO, 200–230 kV/m for Aragats, 210–240 kV/m for Lomnický Štít, and 230–260 kV/m for Nor Amberd. The revised manuscript now states this procedure explicitly.	Section 2 now states that the applied fields were selected separately for each site with respect to the local density-dependent runaway threshold. It defines $E_{th}(h)=E_0 \cdot n(h)$, $n(h)=\rho(h)/\rho_0$, $E_0=284$ kV/m, and the station-specific reference density at the midpoint of the 2000 m field layer. The applied-field ranges are listed explicitly for all four sites, and the dimensionless ratio E/E_{th} is introduced as a measure of the degree of field supercriticality under the local atmospheric conditions.
The manuscript questions the invariance of the coefficient K, yet no physical justification is provided for why this invariance should fail. As written, the paper effectively claims a breakdown of similarity laws for RREAs. Such a claim requires compelling theoretical or numerical evidence.	Applying the classical parameterization separately to the four stations gives $K_{station}$ values ranging from 8.6×10^3 to 11.2×10^3 kV, with the station-specific fit uncertainties now reported in the revised manuscript. A simultaneous fit of Eq. (1) to all 16 simulation points gives $K_{fit} \approx 9.58 \times 10^3$ kV, which is used as reference for comparison with the generalized empirical relation. The generalized relation was fitted jointly to the combined dataset, yielding $K \approx (6.39 \pm 0.26) \times 10^3$ kV and $a = -0.923 \pm 0.083$. The factor n^a represents an additional density dependence beyond that already included through $E_{th}=E_0 \cdot n$. Within the present CORSIKA dataset, this term reduces the inter-station scatter and increases the coefficient of determination from $R^2=0.90$ to $R^2=0.99$. Equation	Section 3 no longer frames the result as a failure of RREA similarity laws. It first evaluates the standard empirical relation at each station and with a simultaneous 16-point fit ($K_{fit} \approx 9.58 \times 10^3$ kV), then introduces Eq. (10) as an additional empirical density-dependent parameterization for the effective avalanche lengths obtained over finite 2000 m field regions. The text explicitly states that n^a is an additional density dependence beyond the threshold scaling and reports the improvement from $R^2 \approx 0.90$ to $R^2 \approx 0.99$.

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	(10) is therefore presented as an empirical parameterization of the effective avalanche lengths obtained for the finite 2000 m field regions considered in this study.	
Finally, a substantial body of relevant literature is omitted from the bibliography and discussion. The manuscript does not adequately place its results in the context of previous work.	The literature review has been expanded to include previous studies of RREA microphysics, relativistic feedback, and Monte Carlo modeling. The discussion of the avalanche-length parameterization now includes Coleman and Dwyer (2006), including their density scaling and the parameterizations reported for different electric-field ranges. The revised Introduction also clarifies the applicability of the avalanche-length parameterization with respect to electric-field range and atmospheric conditions.	The Introduction now cites and discusses representative analytical, numerical, and Monte Carlo RREA studies, including Babich et al. (2001), Dwyer (2003), Coleman and Dwyer (2006), Dwyer et al. (2012), and Skeltved et al. (2014). Coleman and Dwyer (2006) are discussed explicitly in relation to field-range dependence and sea-level similarity scaling. Section 3 also compares the present results with earlier calculations using E_z/n and $n \cdot \lambda_{\text{eff}}$.
l. 13. ‘Coefficient K’ is not defined at this point, nor is it defined later in the abstract.	The Abstract has been revised so that the coefficient K is no longer introduced there before being defined. K is defined together with Eq. (1) in the Introduction.	The Abstract no longer introduces K as an undefined coefficient. K is defined in the Introduction immediately after Eq. (1), together with the units of E_z , E_{th} , λ , and K.
l. 24. Replace ‘climatology’ with ‘meteorology’.	This has been corrected.	The Introduction now uses “meteorology” in place of “climatology.”
l. 31. Not all of the listed phenomena are bursts; for example, gamma-ray glows are not.	The wording has been revised so that the listed high-energy atmospheric phenomena are not collectively characterized as bursts.	The Introduction now refers to TGEs, gamma-ray glows, TGFs, and FGFs collectively as “high-energy atmospheric phenomena,” not as bursts.
l. 36. In addition to empirical models, many first-principles models (both self-consistent and non-self-consistent) have been developed and published. The understanding of the microphysics of RREAs is considerably more advanced than implied by the manuscript.	The corresponding statement has been revised, and the discussion has been expanded to acknowledge both empirical and first-principles approaches.	The Introduction now states that RREA development has been investigated using analytical, numerical, and Monte Carlo approaches, with representative references, while empirical and semi-empirical formulations are described as useful reduced descriptions rather than as the only available modeling framework.
Equation (1) (and similarly throughout the manuscript): insert a space between the equation and the equation number.	The equation formatting has been corrected consistently throughout the manuscript.	Displayed-equation formatting and numbering were standardized throughout the revised manuscript, including the equations in Sects. 3 and 4.

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l. 53. The most commonly used value of K in the literature is not simply 7200 kV, but probably that reported by Coleman and Dwyer (GRL, 33, L11810, 2006), who reported two different values depending on the electric-field range considered.	Coleman and Dwyer (2006) has been included and the discussion of the literature values of K has been revised accordingly.	The Introduction now reports Dwyer (2003), $K \approx 7.2 \times 10^3$ kV, and discusses Coleman and Dwyer (2006), including their parameterization for fields above 300 kV/m and their different empirical fit close to the runaway threshold. Their density scaling to equivalent sea-level quantities is also noted.
l. 61. The complexity and variability of atmospheric electric fields are not, in themselves, an obstacle [...] What currently limits more accurate modeling and interpretation of observations is the lack of reliable measurements of the electric-field structure within thunderstorms.	The statement has been revised to identify uncertainty in the thunderstorm electric-field structure as the principal limitation.	The Introduction now states that the atmospheric environment is difficult to characterize particularly because reliable measurements of the spatial and temporal structure of electric fields inside thunderclouds remain limited.
l. 63. Monte Carlo simulations have been extensively used to study RREAs and related phenomena in a large body of published work, none of which is cited here.	The literature review has been expanded to include representative previous Monte Carlo studies of RREAs and related high-energy atmospheric phenomena.	The Introduction now cites representative Monte Carlo and numerical studies, including Babich et al. (2001), Coleman and Dwyer (2006), Dwyer et al. (2012), and Skeltved et al. (2014), and the bibliography has been expanded accordingly.
l. 135. H _{st} is not defined.	H _{st} is now explicitly defined when first introduced.	The text immediately following Eq. (2) defines H _{st} as the altitude of the observational station above sea level.
l. 160. The term ‘extensively’ should be supported by appropriate references.	Appropriate references have been added.	The literature discussion in the Introduction now contains explicit references to representative analytical, numerical, and Monte Carlo RREA studies. The unsupported generic statement was replaced by a referenced description of previous work.
l. 163. The statement that ‘the universality of the coefficient K’ remains unresolved is misleading. Within the assumption of locality, its scale invariance is well understood.	The original wording has been revised. The manuscript now presents the analysis as an assessment of how consistently the classical empirical avalanche-length parameterization describes the effective avalanche lengths obtained from the CORSIKA simulations across the atmospheric conditions considered in this study.	Section 3 now states that the CORSIKA simulations are used to examine how consistently a single coefficient K describes the effective avalanche lengths obtained for the four observational sites. The revised text avoids presenting the study as a test of the fundamental universality or scale invariance of local RREA similarity laws.

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l. 199. Please compare these results with previous studies. Many are cited in Dwyer et al. (Space Science Reviews, 2012), and numerous additional studies have appeared since then.	The revised manuscript now includes an explicit comparison with previous RREA calculations using the conventional density-scaled variables E_z/n and $n \cdot \lambda_{\text{eff}}$. Representative results are compared with the ranges reported in Coleman and Dwyer (2006), Dwyer et al. (2012), and Skeltved et al. (2014).	Section 3 now contains a direct comparison in the conventional similarity-scaled variables E_z/n and $n \cdot \lambda_{\text{eff}}$. It cites Coleman and Dwyer (2006), Dwyer et al. (2012), and Skeltved et al. (2014), and gives an Aragats example at $E_z=210$ kV/m with $E_z/n \approx 334$ kV/m and $n \cdot \lambda_{\text{eff}} \approx 201$ m.
l. 200. This discrepancy arises because the formula is not scaled consistently.	This point is addressed in the response to the first Major Comment and has been clarified accordingly in the revised manuscript.	Section 2 now explicitly explains how the site-dependent absolute field ranges were selected relative to the local density-dependent runaway threshold and defines the station reference density. Section 3 additionally compares the results in conventional density-scaled variables, clarifying the distinction between the local classical relation and the effective finite-layer quantities analyzed here.
l. 284. E_e^{max} should be defined before being introduced.	E^{max} , including E_e^{max} and E_γ^{max} , is now explicitly defined before use as the characteristic maximum energy determined from the spectral distributions. In the revised manuscript, it is taken as the highest energy for which at least three consecutive energy bins contain more than five counts, reducing sensitivity to isolated high-energy outliers.	Section 4 now defines the characteristic E^{max} before the statistical FPD analysis. It is the highest energy for which at least three consecutive energy bins contain more than five counts. The electron and gamma-ray characteristic maxima are then used consistently in the FPD calibration.
l. 288. The reference to electron-positron pair production is puzzling. It is unclear why this interaction is singled out, whereas photoelectric absorption and Compton scattering, which are generally much more relevant in this energy range, are not mentioned.	The passage has been revised to avoid undue emphasis on pair production and to provide a more balanced description of the relevant photon-interaction processes during post-field transport, including Compton scattering and photoelectric absorption.	Section 4 now describes gamma-ray propagation in terms of stochastic photon interactions whose probabilities depend on energy and explicitly lists Compton scattering, photoelectric absorption, and electron-positron pair production rather than singling out pair production.

Additional validation included in the revised manuscript

During the revision, an additional validation of the FPD estimate was performed using 50 independent CORSIKA simulations for the Aragats station at an electric field of 210 kV/m, with a 50 m distance between the lower boundary of the electric-field region and the detector level. The reconstructed FPD distribution

has a median of 69.9 m, with a 16th–84th percentile interval of 58.65–77.35 m. This additional validation and the corresponding discussion have been included in Sect. 4 of the revised manuscript.