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Investigating the influence of cosmic rays on atmospheric electric fields and tropical temperature anomalies using GRAPES-3

B. Hariharan,[a,*] S.K. Gupta,[a] Y. Hayashi,[b] P. Jagadeesan,[a] A. Jain,[a] S. Kawakami,[b] A. Kamiya,[c] M. Karthik,[a] H. Kito,[c] T. Koi,[d] H. Kojima,[e] P.K. Mohanty,[a] Y. Muraki,[f] T. Nakamura,[g] P.K. Nayak,[a] T. Nonaka,[h] A. Oshima,[d] S. Paul,[a] M. Rameez,[a] K. Ramesh,[a] S. Shibata,[f] T. Tabata,[d] H. Takamaru,[d] H. Tanaka,[c] K. Tanaka[i] and K. Yamazaki[d]

[a] *Tata Institute of Fundamental Research, Homi Bhabha Road, Mumbai 400005, India*

[b] *Osaka Metropolitan University, Sugimoto-cho, Osaka 558-8585, Japan*

[c] *Department of Innovative Energy Science and Engineering, Chubu University, Kasugai, Aichi 487-8501, Japan*

[d] *Faculty of Science and Engineering, Chubu University, Kasugai, Aichi 487-8501, Japan*

[e] *Chubu Astronomical Observatory, Kasugai, Aichi 487-8501, Japan*

[f] *Institute for Space-Earth Environmental Research, Nagoya University, Nagoya 464-8601, Japan*

[f] *Center for Muon Science and Technology, Chubu University, Kasugai, Aichi 487-8501, Japan*

[g] *Faculty of Science, Kochi University, Kochi 870-8072, Japan*

[h] *Institute for Cosmic Ray Research, Tokyo University, Kashiwa, Chiba 277-8582, Japan*

[i] *Hiroshima City University, Hiroshima 731-3166, Japan*

E-mail: 89hariharan@gmail.com

[*] Speaker

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The atmospheric electric field (AEF) is an important property of the Earth's atmosphere and varies because of the effects of local weather, seasonal variations, and global electrical circuits. During fair weather conditions, the AEF is measured to have an ambient field of about a few hundred volts per meter (V/m) near the ground. The resultant positive field is an outcome of a complex process of electrification of the atmosphere of the Earth. Hence, the ambient field is dependent on various local weather parameters such as wind, humidity, temperature, pressure, etc. Moreover, cosmic rays (CRs), which are high-energy particles originating from outer space, play a crucial role in influencing the AEF. Studying these variations helps us better understand weather, climate, and how the Earth's surface interacts with the atmosphere. GRAPES-3 is a ground-based CR observatory located at Ooty on the Nilgiri plateau in India. In April 2011, four electric field mills (EFMs) were installed around GRAPES-3 to study how CR secondaries interact with AEF; since then, they have been in continuous operation of measuring AEF every 50 milliseconds. We studied the time variation of the ambient AEF measured from these four EFMs since April 2011 with the CR measurements and also found a modest connection with the tropical temperature anomaly.

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1. Introduction

The GRAPES-3 (Gamma Ray Astronomy at PeV EnergieS – phase 3) experiment is a ground-based cosmic ray (CR) observatory located in Ooty, India. It consists of two main detector systems: a compact array of 400 plastic scintillator detectors (G3SD) [1] and a large-area high-resolution tracking muon telescope (G3MT) [2]. Although the experiment's primary goal is to investigate high-energy CRs and their secondary products, it has also proven instrumental in exploring atmospheric and near-Earth space phenomena. The G3SD captures secondary particles produced by extensive air showers (EAS) resulting from the interaction of high-energy CRs with the Earth's atmosphere. A critical feature of the experiment is the G3MT, which measures the angular distribution of muons with energies above 1 GeV, enabling detailed studies of transient atmospheric events such as thunderstorms. Notably, the GRAPES-3 collaboration reported the estimation of exceptionally large electric potentials exceeding one billion volts linked to intense thunderstorm activity [3, 4].

To augment atmospheric research, an array of four widely spaced electric field mills (EFMs) was deployed around the GRAPES-3 site. These EFMs have been operating continuously since April 2011, delivering uninterrupted, high-resolution data on atmospheric electric field (AEF) variations associated with thunderstorm activity. The long-term dataset offers critical insights into atmospheric dynamics, including cloud development, thunderstorm evolution, and localized weather phenomena. During active thunderstorm conditions, the AEF undergoes rapid fluctuations often reaching several kilovolts per meter due to the movement of charged regions within thunderclouds relative to the observer (i.e., ground). Lightning discharges cause sharp, short-lived surges in the electric field, sometimes within fractions of a second. These processes are modulated by various atmospheric parameters, including temperature, pressure, humidity, and wind. Thunderstorms, therefore, serve as natural laboratories for probing high-energy atmospheric phenomena such as electric field transients and lightning initiation. This study presents a comprehensive analysis of ambient AEF using high-resolution data collected over more than a decade from all four EFMs. The long-term variation in ambient electric fields reveals a subtle correlation with the tropical temperature anomaly (TTA), suggesting a possible climatic connection between regional temperature variations and the intensity or frequency of thunderstorm activity.

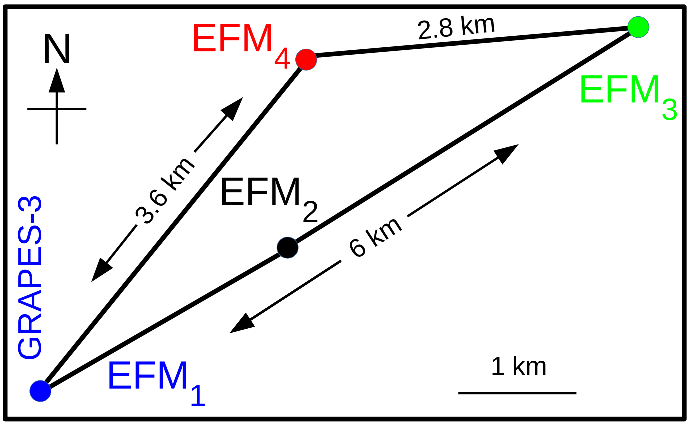

Figure 1: Deployment of four widely-spaced electric field mills (EFMs) around GRAPES-3.

2. Electric field measurements

The AEF, expressed in volts per meter (V/m), is a key parameter in understanding the dynamics of thunderstorms and related electrical phenomena. Precise measurements of the AEF offer valuable insights into the internal charge structure of thunderclouds, mechanisms of lightning initiation, and the overall behavior of the atmospheric electric circuit. EFMs are compact, durable, and highly sensitive instruments widely used for such measurements. These devices operate on the principle of a capacitance electrometer, wherein a rotating or oscillating shutter intermittently exposes a sensing electrode to the ambient electric field. This interaction induces a periodic signal proportional to the field strength, which is then processed electronically to yield the AEF. EFMs are extensively employed in atmospheric science due to their ability to deliver continuous, high-temporal-resolution measurements of both local and regional electric fields [5]. In the present study, we utilized Boltek EFM-100 electric field mills installed at multiple locations surrounding the GRAPES-3 observatory to monitor AEF variations [6]. These instruments offer a temporal resolution of 50 milliseconds (ms) and a sensitivity of 0.01 kilovolts per meter (kV/m). Under fair-weather conditions, the AEF typically exhibits a small, positive field of approximately 0.1 kV/m at ground level, consistent with the globally accepted fair-weather electric field profile.

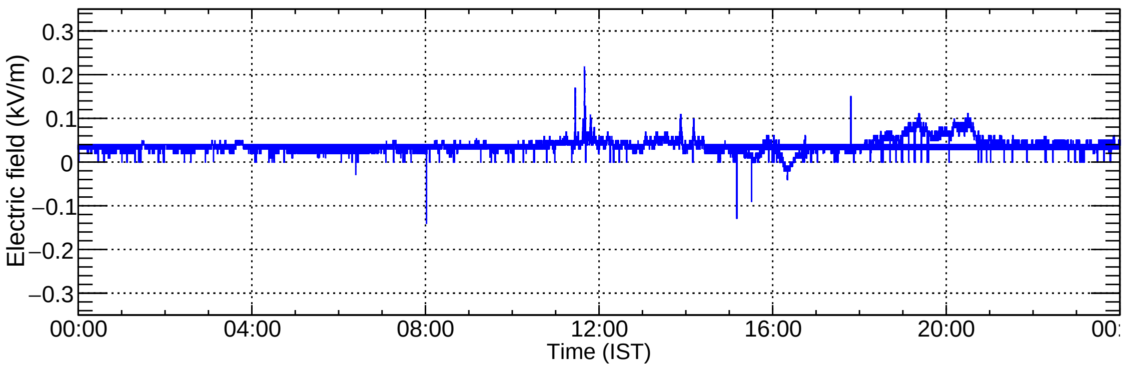

Figure 2: Atmospheric electric field (AEF) variation recorded at GRAPES-3 (EFM_1) on June 2, 2020.

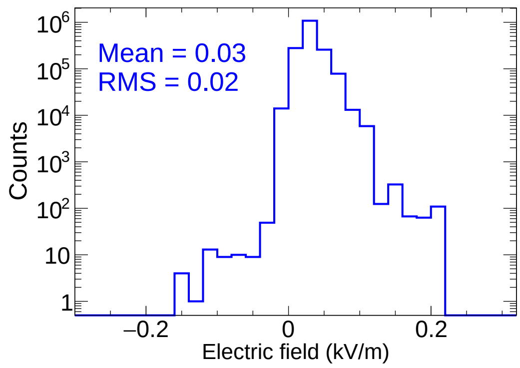

Figure 3: Distribution of atmospheric electric field (AEF) measurements recorded at GRAPES-3 (EFM_1) on June 2, 2020.

As shown in Figure 1, a network of four EFMs, designated EFM_1 through EFM_4, has been deployed across a broad area around the GRAPES-3 facility to capture spatial variations in the electric field during thunderstorm activity. EFM_1, located within the GRAPES-3 premises, serves as the central reference station. Although the Boltek EFMs are omnidirectional, capable of detecting electric fields irrespective of direction, their distributed configuration allows for the assessment of thundercloud motion. By analyzing time-stamped changes in field magnitude across the EFM array, it becomes feasible to track the evolution and propagation of thunderstorm systems. This technique has been successfully applied in earlier GRAPES-3 investigations to characterize the dynamics of thunderclouds and their associated electrical phenomena [3]. Figure 2 shows the AEF recorded at GRAPES-3 (EFM_1 on June 2, 2020. The stable profile indicates that there was no thunderstorm activity on that day. Figure 3 shows the distribution of one day AEF measurements with 50 ms time-resolution (86400 sec $\times$ 20 samples/sec = 1728000 samples). The distribution shows a mean value of +0.03±0.02 kV/m, implies the positive fair-weather field. Although, the distribution appears asymmetric, the small rms (twice the resolution of the instrument) indicates the stability in the fair-weather field during normal days.

3. Effects of atmospheric electric field on cosmic ray intensity

During thunderstorm conditions, the AEF can reach magnitudes of several kilovolts per meter (kV/m), which significantly alters the propagation of secondary charged particles produced in EASs. These field-induced effects modulate the flux of muons reaching the ground. The vertical electric fields within thunderclouds can accelerate or decelerate the charged particles, thereby influencing the number and energy spectrum of secondaries generated in the cascading particle showers. Observations from the G3MT have revealed measurable variations in muon intensity correlated with changes in the AEF during thunderstorm episodes. In particular, rapid enhancements or depletions in the muon flux, occurring over short time scales (order of a few tens of minutes), have been linked to the development and movement of strong electric fields within the troposphere. These variations are often anisotropic, suggesting directional dependence aligned with thundercloud geometry and motion.

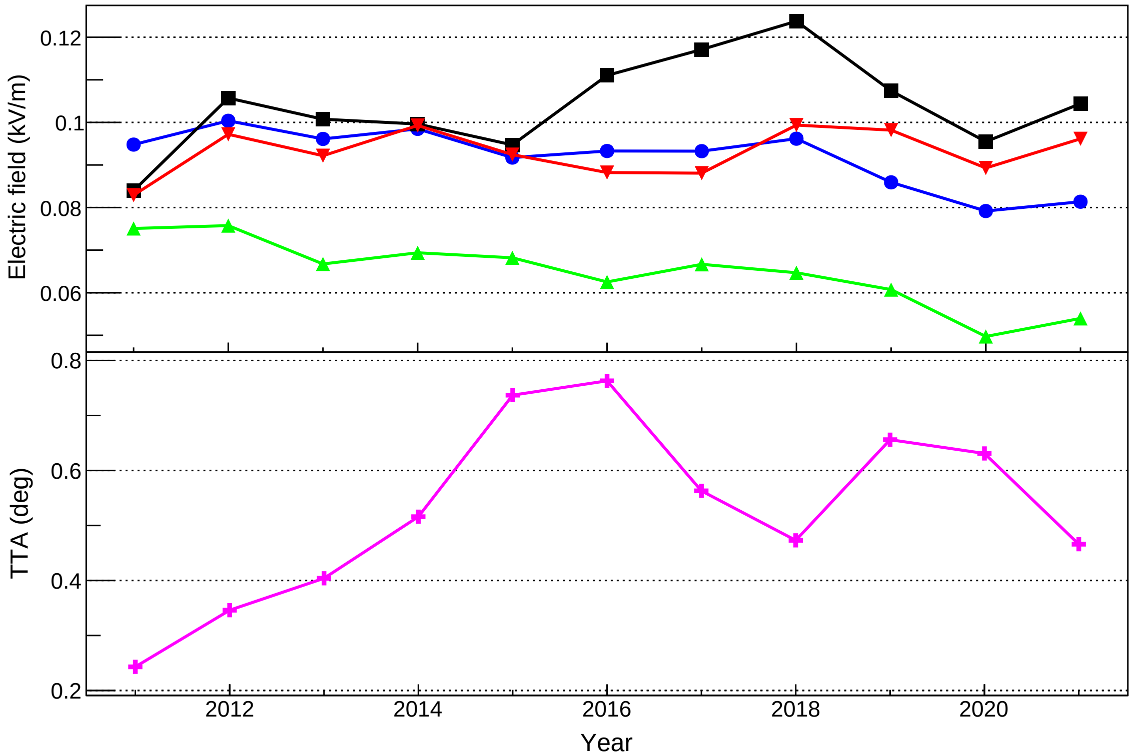

Figure 4: Annual variation of ambient atmospheric electric field (AEF) measurements in comparison with tropical temperature anomaly (TTA).

One of the most significant findings by the GRAPES-3 collaboration was the detection of a sharp decrease in muon intensity associated with a large-scale thunderstorm, from which the team inferred the presence of an exceptionally high electric potential of >1.3 GV within the thunderstorm [3]. This demonstrated that thunderclouds could momentarily act as gigantic natural particle accelerators, capable of influencing CR propagation on regional scales. Thus, the GRAPES-3 experiment provides compelling evidence that AEFs, particularly during thunderstorms, can induce significant and measurable modulations in the ground-level CR intensity. Continued observations of such effects contribute not only to CR physics, but also to our understanding of atmospheric electricity and thunderstorm dynamics.

4. Correlation of ambient atmospheric electric field with tropical temperature anomaly

To effectively derive ambient AEF, annual AEF data were analyzed as shown in Figure 3. During thunderstorms, the distributions exhibited extended tails reaching several tens of kV/m due to field enhancements from turbulent conditions. These outliers were systematically excluded, and the remaining data were averaged to represent ambient AEF. Using EFM data from all four stations from 2011 to 2021, ambient AEF profiles were constructed. Figure 4 shows the annual variation of AEF (top panel) and tropical temperature anomaly (TTA) (bottom panel) [9] for the same period. Both parameters display consistent trends, suggesting systematic changes in AEF alongside rising TTA, which increases from about 0.2°C to 0.8°C, with stronger year-to-year fluctuations. Correlation analysis between AEF and TTA yields coefficients of –0.38, 0.25, –0.49, and 0.05 for EFMs 1 to 4, respectively. EFM_1 and EFM_3 show moderate anticorrelation, EFM_2 a weak positive correlation, and EFM_4 no significant dependence. The negative dependences observed in two EFMs may reflect the influence of rising tropical temperatures on atmospheric convection and thunderstorm activity, which modulate near-surface electric fields. Increased convection due to warming can lead to more frequent or intense storms, enhancing ground-level electric fields. These observations suggest that ambient AEF responds to broader climate variability and can act as an indicator of changing atmospheric conditions.

However, thunderstorm development is largely driven by localized factors like temperature gradients, humidity, and terrain. While TTA may influence the larger atmospheric background, local dynamics remain dominant. Expanding the EFM network spatially would reduce local biases and improve detection of climate-related trends in thunderstorm activity. Such a system would complement traditional meteorological monitoring by offering valuable data for studying thunderstorm evolution, tracking lightning, and enhancing early warning capabilities. The long-term AEF monitoring at GRAPES-3 demonstrates the potential of such measurements in advancing our understanding of atmospheric electricity and climate interactions.

5. Summary

The GRAPES-3 experiment in Ooty, India, primarily designed for studying CRs, has also become a valuable platform for investigating atmospheric electric phenomena. Since 2011, four electric field mills (EFMs) have been continuously monitoring the atmospheric electric field (AEF) at high temporal resolution. Under fair-weather conditions, the AEF maintains a steady positive value (~0.1 kV/m), while during thunderstorms, it can surge to several kilovolts per meter. These field variations affect the propagation of CR secondaries, particularly muons, which are recorded by the GRAPES-3 Muon Telescope. Significant deviations in muon intensity have been linked to strong electric fields in thunderclouds, including a recorded case of over 1.3 GV potential, demonstrating that thunderclouds can act as natural particle accelerators.

Long-term analysis of AEF data, after removing storm-related outliers mainly caused by the turbulent storm conditions, reveals a consistent trend in ambient AEF from 2011 to 2021. This trend shows a modest correlation with the tropical temperature anomaly (TTA) in two EFM stations. Correlation coefficients vary across the four EFMs, with some stations showing moderate anticorrelation with TTA. These results suggest a potential climatic influence where increased tropical temperatures enhance convection and thunderstorm activity, thereby modulating AEF. However, local weather conditions remain the primary drivers of thunderstorm development. The study highlights the importance of a spatially distributed EFM network for better understanding of climate electricity interactions and enhancing weather monitoring and early warning systems.

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