PROCEEDINGS OF SCIENCE

Contemplating the observed relationship between the global electric circuit and GRAPES-3 thunderstorm-induced muon events

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Thunderstorms, lightning, and the Global Electric Circuit (GEC) are interconnected, and their studies have significant implications for understanding the global climate. Solar insolation plays a role in linking lightning distribution to Earth's climate. Extensive research on the GEC has aimed to establish a connection between variations in the fair-weather electric field (known as the Carnegie curve) and global variations in electrified weather, using lightning rates as a proxy. Thunderstorm-induced muon events (TIMEs) are observed when strong electric fields in thunderstorms modulate muon acceleration, leading to changes in their count rate at the observational level. In this study, we report a substantial number of TIMEs observed continuously over a fifteen-year period (2006-2020). Furthermore, we examine the diurnal distribution patterns of these events by comparing them with the Carnegie curve. The observed comparative pattern stimulates contemplation about the relationship between the GEC and TIMEs and suggests the former's potential role in the formation of the latter.

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1. Introduction

Thunderstorms, lightning, and the global electric circuit (GEC) are interconnected phenomena, and the study of these elements holds significant implications for enhancing our grasp of the global climate. GEC is a vast network of electrical currents that flow through Earth's atmosphere [1]. Thunderstorm activity gives rise to charge imbalances, culminating in lightning discharges and the establishment of the GEC. This circuit encompasses fair-weather electric fields, generator currents driven by thunderstorms, and upper atmospheric return currents. Importantly, the influence of the GEC stretches beyond the confines of Earth's atmosphere; it interacts with space weather phenomena such as solar radiation and cosmic rays. Grasping the intricacies of the GEC is pivotal for accurate weather forecasting, investigating atmospheric electricity, and enriching our comprehension of Earth's dynamic system. Climate models' projections of a warmer planet underscore its significant impact on lightning, thunderstorm patterns, and severe weather events, potentially resulting in fewer but more intense thunderstorms. There are predictions of a 10% increase in lightning for each degree rise in temperature [2,3]. Extensive research on the GEC has concentrated on establishing a connection between fair-weather field variations, often referred to as the Carnegie curve, and global disparities in electrified weather by utilizing lightning rates as a proxy [4-6]. In recent decades, numerous spatial and temporal patterns of global lightning studies have developed using observations from satellites [7,8].

Thunderstorm-induced muon events (TIMEs) are observed when the powerful electric fields within thunderstorms influence muon acceleration, leading to changes in their observed count rate. These TIMEs demonstrate latitude dependence, directional anisotropy, and a temporal correlation with thunderstorms. Scientists from diverse fields, such as cosmic ray researchers, atmospheric scientists, and climatologists, utilize a combination of ground-based and space-based experiments, along with mathematical modeling, to delve into the intricacies of thunderstorms, lightning, and their implications for the global climate. The GRAPES-3 experiment, situated in Ooty (at a latitude of 11.4°N, longitude 76.7°E, and altitude of 2200 m), employs a suite of 16 tracking muon telescopes to annually monitor approximately one and a half trillion muons, yielding invaluable data for the investigation of these phenomena [9-13]. This report presents a comprehensive analysis of statistically significant TIMEs observed between 2006 and 2020, contributing to a deeper understanding of this intriguing phenomenon. Notably, the groundbreaking thunderstorm-induced muon event was observed at GRAPES-3 [11].

The experimental site is located within the Nilgiris mountain range, which is a segment of the broader Western Ghats mountain chain along the western edge of India. Throughout the paper, we have considered Indian Standard Time as the local time (UTC + 5.5 hours). In the following section, a comprehensive description of the GRAPES-3 tracking muon telescope is presented, emphasizing its significant relevance in this context.

2. The tracking muon telescope at GRAPES-3

The telescope consists of four super-modules, each has four modules [9-12]. Each module has a sensitive area of 35 square meters, making a total of 560 square meters for the telescope. The proportional counter (PRC) is the core of the muon telescope fabricated from a six-meter-long steel pipe with a square cross-section of 10 x 10 square centimeters. Each module coists of four layers of 58 PRCs, with alternate layers aligned in mutually orthogonal directions.

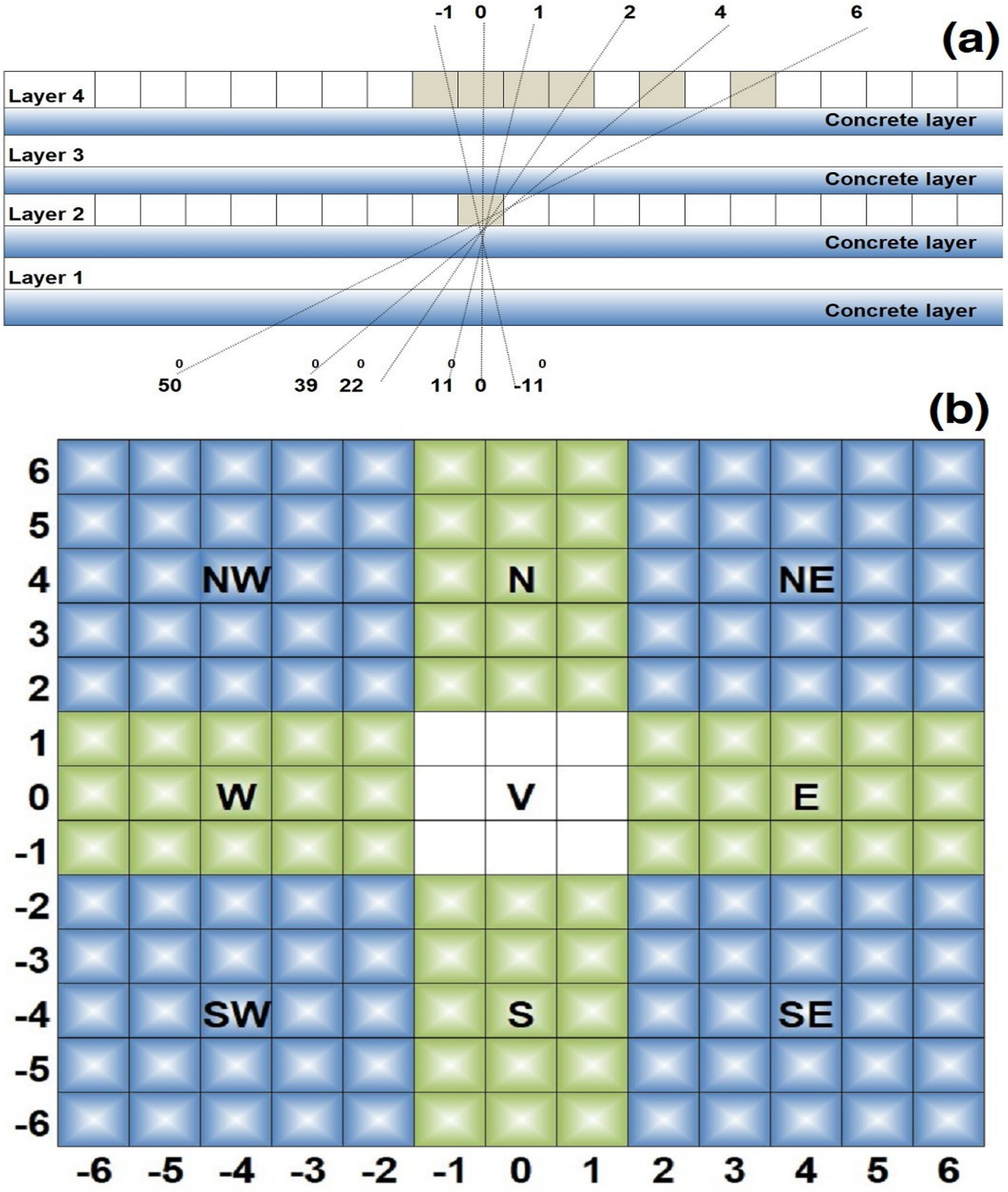

Figure 1: (a) Muon direction reconstruction utilizing the PRC geometry within a single projection plane. The selection of muon arrival angles relies on triggered PRCs, encompassing one from the lower layer and another selected from the 13 PRCs in the upper layer. Triggered PRCs are represented as filled squares. (b) A schematic illustrating the arrangement of 169 muon directions subsequently amalgamated into nine broader directions. The central 3 x 3 vertical direction (V), along with the four 3 x 5 cardinal points (N, E, W, and S), and the four 5 x 5 ordinal directions (NE, SE, SW, and NW), are also indicated.

The vertical separation of the two PRC layers in the same projection plane was ~ 50 cm allowing measurement of the muon track direction with an accuracy of about 4° in each projected plane. The concrete block absorbers fill the gap in all four layers of PRCs arranged in mutually orthogonal directions. We used a concrete absorber to achieve an energy threshold of one GeV for vertical muons arranged as an inverted pyramidal shape with absorber coverage up to 45° for incident muons. The arrangement resulted in the muon telescope having an energy threshold of sec Θ GeV for the muons incident at a zenith angle of Θ. The arrival direction of a muon was determined for each triggered PRC in the lower layer by combining it with the one directly above (the central) and six each on either side and binned into 13 different directions (Figure 1a). The directional binning of each of the two orthogonal projection planes resulted in a muon direction map of 169 solid angles (13 x 13), which contents were recorded once every 10 s, generating a continuous record of the directional flux of muons in the sky (Figure 1b) [9].

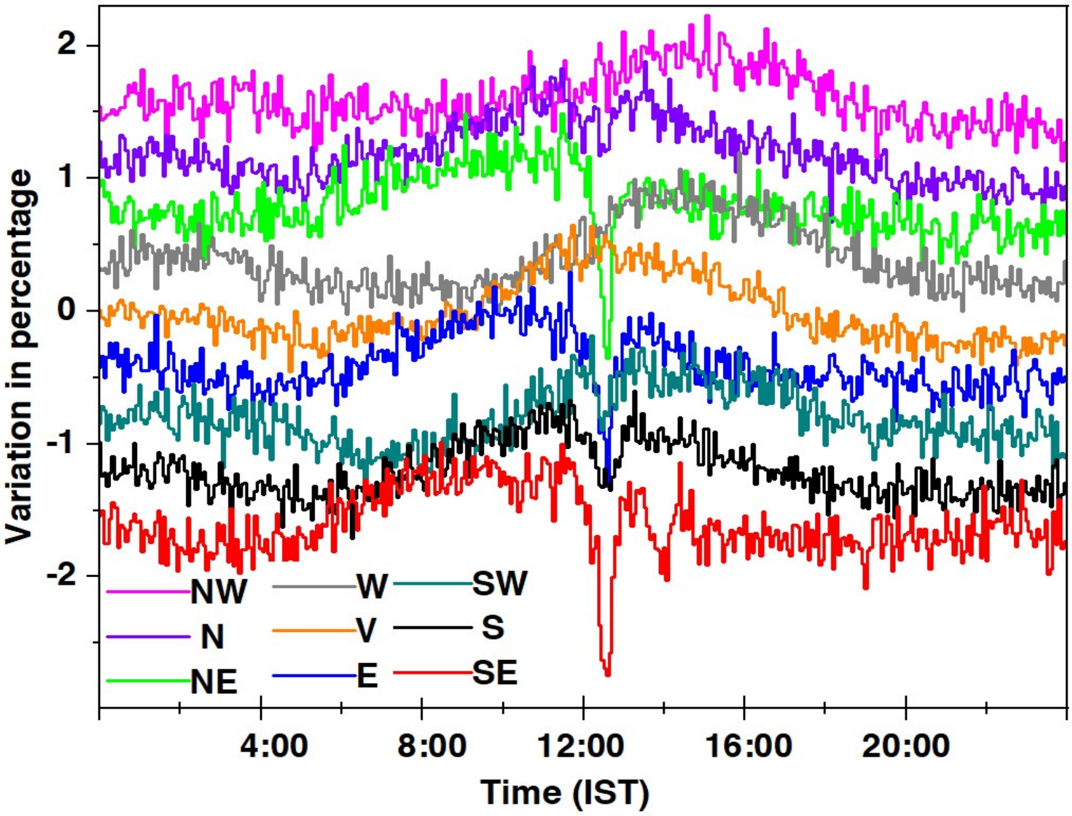

Figure 2: Variations in muon intensity are depicted across nine broader directional bins for an event. The alteration in the vertical direction is highlighted in orange. For the directions indicated above, a consistent value in increments of 0.4 has been added, while for the directions below the vertical orientation, a uniform value in multiples of 0.4 has been subtracted to enhance the clarity of data visualization.

During thunderstorm activity, the GRAPES-3 muon rate exhibits distinct characteristics, including abrupt reductions or increases followed by subsequent recovery over time spans ranging from about 10 minutes to a couple of hours. These decreases or increases possess specific traits: they are non-uniform, confined to narrow solid angles, and specific to certain events. An illustrative event is presented in Figure 2, where all nine directional plots initially display consistent features until around 12:00 hours. Subsequently, changes become evident in numerous directions, followed by a recovery. Notably, considerable decreases were observed in the eastern, southern, and south-eastern directions, with the latter (SE) direction experiencing the most substantial reduction of up to 1.7%.

3. Results and Discussions

The temporal data for the observed events spanning fifteen years were aggregated on an hourly basis, considering them to initiate at the beginning of each hour. The resulting distribution of diurnal events is depicted in Figure 3 (shown as the blue curve), highlighting a substantial fluctuation. It can be observed that event occurrences exhibit a peak after noon, maintain elevated levels until late evening, and subsequently decrease until around 20:00 hours. However, the numbers experience a resurgence around 22:30 hours after a period of decrease and remain elevated until the early morning hours, albeit with a declining trend during the morning hours.

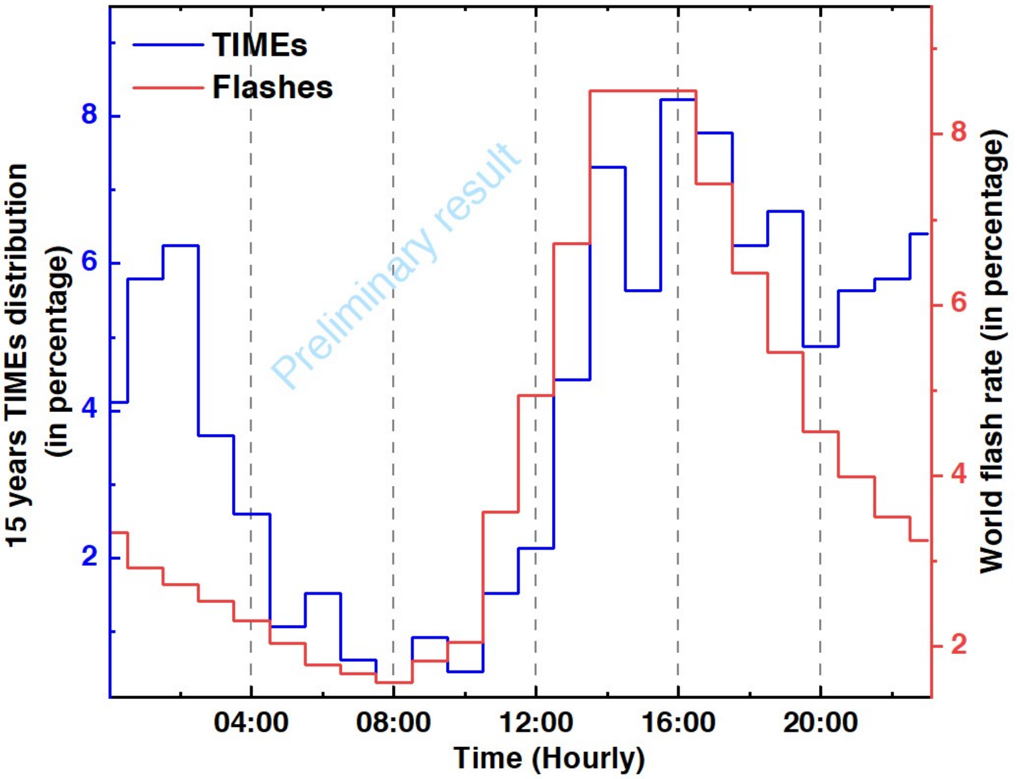

Figure 3: Comparative diurnal variation (in percentage) of the TIMEs (blue curve) for the period of 15 years period with flashes observed in the world (red curve). The latter information was based on satellite data reported by Blakeslee *et al.* (2014) for 15 years period (not continuous and different combinations).

High-altitude aircraft observations of electrified clouds enable the calculation of currents flowing within the global electric circuit [6-8]. Thunderstorms and other electrified clouds serve as sources for variations in the fair-weather electric field [14-16], often referred to as the Carnegie curve. To better comprehend the processes contributing to the formation of these thunderstorm-induced muon events, we have endeavored to compare them with lightning flash rate data obtained from high-altitude aircraft observations [6, 7], presented in Figure 3 (depicted by the red curve). This curve illustrates the global annual diurnal lightning variation for the entire world in local time (as a percentage). The graph indicates that lightning activity reaches its peak in the late afternoon (between 15:00 and 17:00 hours), with the fewest flashes occurring in the late morning (between 09:00 and 11:00 hours). A comparison between these two plots reveals that while global lightning activity experiences a notable decrease after early evening, the number of TIMEs remains substantial until late evening before decreasing sharply. From morning until noon, the event statistics remain minimal and align closely with the global lightning trend. The observation of thunderstorms during late-night hours is atypical, although several similar reports from the midwestern United States have been documented [4, 16-18]. Despite the higher activity reports from Oceanic or coastal areas during late night to early morning hours, the observation is intriguing considering Ooty's location within mountainous terrain.

3.5. Summary and scope for future work

The study presented in this work involves a comparison between observed TIMEs and the lightning flash rate data obtained from high-altitude aircraft observations. The results exhibit a noteworthy correlation, suggesting the potential for additional research into the observed trends. This report emphasizes the identification of numerous statistically significant events spanning the years 2006 to 2020 [19]. It marks the inaugural instance of a strong correlation observed between TIMEs variation and the Carnegie curve. With the accumulation of more data and a deeper understanding, the evolving landscape will become clearer.

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