PROCEEDINGS OF SCIENCE

Seasonal variation of thuderstorm-induced muon events observed at GRAPES-3

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The thunderstorm-induced muon events (TIMEs) are observed when the strong electric fields in thunderstorms modulate muon acceleration, resulting in their altered count rate at the observational level. Because of the GRAPES-3 experiment's remarkable directional accuracy, it is well-suited for investigating these TIMEs. May shows the maximum number of observed events, whereas the minimum is in January. The spring (from March to May) was the season with the most frequent, followed by autumn (from September to November), summer (June to August), and winter (December to February). The number of events during spring and autumn is well-correlated with the warmer pre-southwest and relatively colder northeastern monsoon seasons, respectively. Surprisingly fewer events were observed during the summer, and only a few were observed during winter.

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1. Introduction

Thunderstorm-induced muon events (TIMEs) arise from the interaction between cosmic ray showers and thunderstorms, resulting in a modification of the detected muon count. Muons, generated when cosmic rays, predominantly protons, collide with molecules in the Earth's atmosphere, are affected by the electrical potential within thunderstorms. The voltage is influenced by various factors, such as the charge distribution within the storm cloud, the strength of the convective updrafts, and the presence of ice particles or supercooled water droplets. These factors collectively contribute to creating regions with high electric potential, subsequently influencing the cosmic ray showers and the energy of muons. Investigating these muon events yields valuable insights into the intricate relationship between atmospheric physics, particle interactions, and extreme weather phenomena. These studies enhance our comprehension of astrophysics and contribute to advancements in atmospheric science.

Moreover, observing seasonal variations in TIMEs depends on the ever-shifting atmospheric conditions throughout the year, encompassing temperature, humidity, and convective activity. Unraveling these seasonal patterns deepens our understanding of the intricate dynamics among cosmic rays, thunderstorms, and atmospheric phenomena, contributing to our knowledge of astrophysics and meteorology. In the northern hemisphere, spring welcomes warmer temperatures and heightened convective activity, fostering more frequent thunderstorms. These energetic electrical fields modulate muon acceleration, resulting in an increased count rate of TIMEs. Summer brings intensified convective activity, higher temperatures, and elevated humidity levels, creating favorable conditions for thunderstorm formation. Consequently, the number of detected TIMEs may vary during summer. Autumn introduces shifting weather patterns and atmospheric conditions that favor thunderstorm development. While winter experiences fewer thunderstorms, they can still occur under specific atmospheric conditions. Notably, the thunderstorm-induced muon event that led to our recent groundbreaking report was observed during winter [3].

Furthermore, these TIMEs demonstrate latitude dependence, directional anisotropy, and temporal correlation with thunderstorms. Scientists from various disciplines, including cosmic ray researchers, atmospheric scientists, and climatologists, employ ground-based and space-based experiments and mathematical modeling to investigate thunderstorms, lightning, and their impact on global climate. The GRAPES-3 experiment, located at Ooty (11.4°N latitude, 76.7°E longitude, 2200 m altitude), employs multiple tracking muon telescopes to monitor approximately one and a half trillion muons annually, providing invaluable data for the study of these phenomena [1-4]. This report comprehensively analyzes statistically significant TIMEs observed between 2006 and 2020, contributing to a deeper understanding of this intriguing phenomenon.

The experimental site belongs to the Nilgiris mountain range that forms a part of a larger chain of Western Ghats mountains along the western side of India. Despite being in the tropics, Ooty prevails with a subtropical highland climate with pleasant mild conditions. Nighttime is typically chilly from December to February. The monthly mean value of temperatures is relatively consistent throughout the year, with average high day temperatures ranging from 18 to 22 °C and average low night temperatures between 5–12 °C. The annual average precipitation is

~ 1250mm, with a markedly drier season from December to February [6-8]. Throughout the paper, we have considered Indian Standard Time as the local time (UTC + 5.5 hours). In the next section, we have provided a detailed description of the GRAPES-3 tracking muon telescope and highlighted its significant potential in this context.

2. The GRAPES-3 tracking muon telescope

The GRAPES-3 experiment consists of two principal components. The first component is an extensive air shower array (with ~ 400 plastic scintillator detectors) deployed in a symmetric hexagonal geometry designed to study the primary cosmic rays (Figure 1a). The other component is a large area tracking muon telescope (Figure 1b). The tracking muon telescope consists of sixteen independent modules, each comprised of four layers of 58 proportional counters (PRCs), with alternate layers aligned in mutually orthogonal directions. A 15 cm thick cement concrete block separates the successive layers. The four-layer muon module configuration allowed the reconstruction of each muon track in two mutually orthogonal planes.

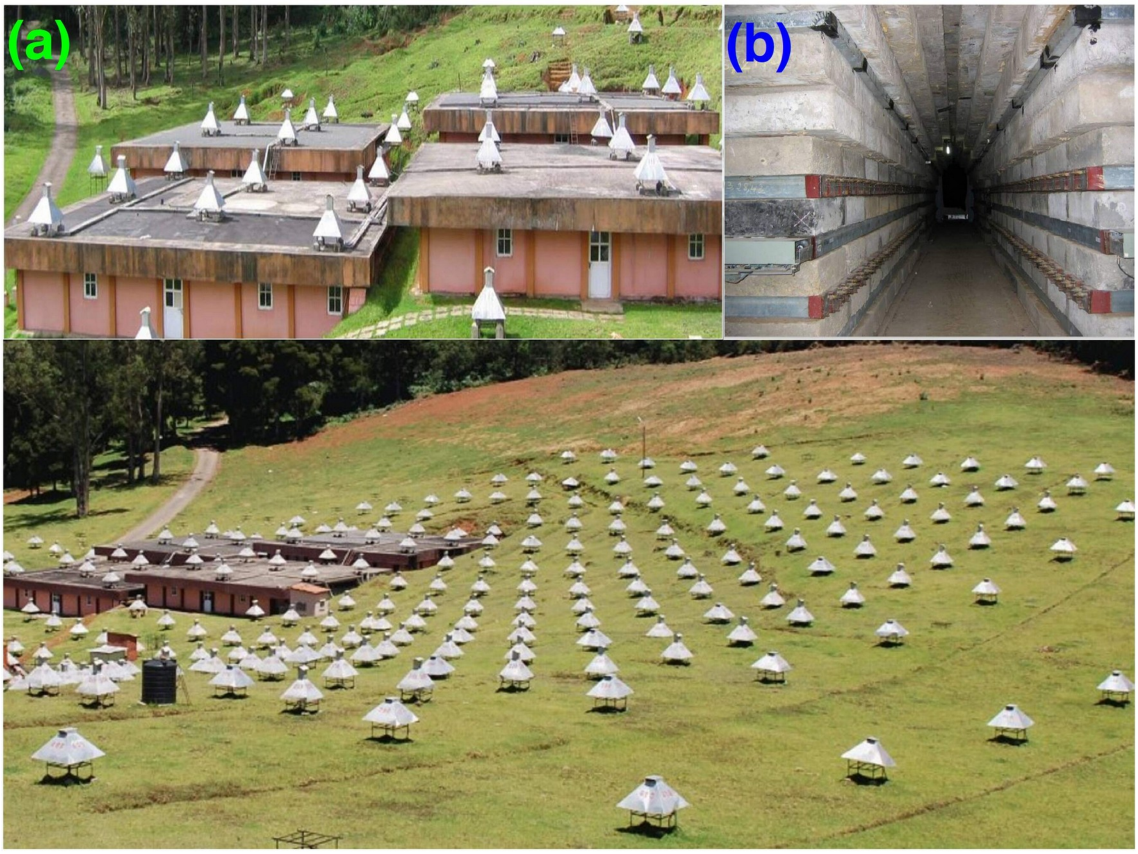

Figure 1: A view of the GRAPES-3 array showing cone-shaped electron detectors and the four super-modules housing the muon detectors on the left. Inset: (a) A closer view of the four super-modules hosting all 16 modules. Few electron detectors are placed above the super-modules as part of the array (b) An inside view of a super-module showing the proportional counters and layers of concrete blocks for two of the four modules. The remaining two modules are further inside.

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. 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 [1].

Powerful thunderstorms generate high voltage, impacting the characteristics of airborne muons and leading to the detection of thunderstorm-induced muon events (TIMEs) at the observational level. In an upward-going electrical field, positive muons experience deceleration, while negative muons undergo acceleration. Conversely, positive muons gain energy through acceleration in a downward-looking field, whereas negative muons decelerate. The GRAPES-3 muon telescope operates without a magnetic field, rendering it unable to distinguish between positive and negative muons. Since positive muons outnumber negative muons and the prevalence of upward-going fields in most events, a typical observation with this setup reveals a decrease in detected muons.

3. Results and Discussions

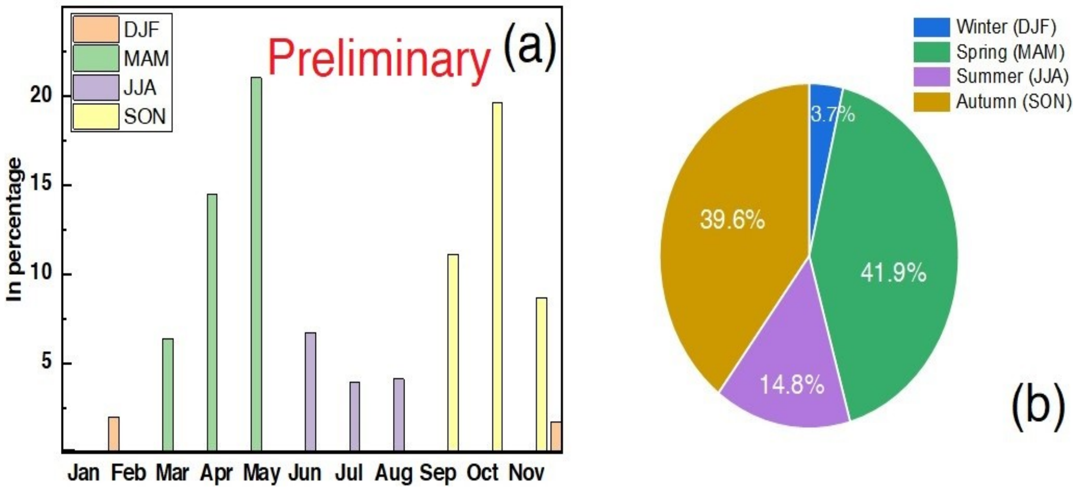

Figure 2 (a) Variation of monthly distribution of TIMEs in percentage of the total events, (b) Observed variation of events in different seasons (in percentage) has been provided in Pi-chart for better presentation. Spring and Autumn dominates the chart. Surprisingly, limited events were observed during Summer season that represents one of the major monsoon periods.

Figure 2a shows the monthly event distribution for all these years. May shows the maximum number of observed events, whereas the minimum is in January. The spring was the season with the most frequent, followed by autumn, summer, and winter. Tropical Indian Oceans' dipole mode is known to affect the monsoonal circulation in the Indian subcontinent[8-10]. May has the reported [10, 12] maximum frequency of lightning flashes and thunderstorm activity over the Indian subcontinent. They also observed higher thunderstorm activity occurs late at night and in the early morning hours during May. The number of events during spring and autumn is well-correlated with the warmer pre-southwest and relatively colder northeastern monsoon seasons, respectively [9, 10, 11]. Surprisingly, the observed events during the summer season are very low and warrant further investigation, as earlier reports show the majority of rain during this period in Ooty and the Indian peninsula (10, 12]. The expected limited number of events observed during winter is likely due to the sporadic occurrence of thunderstorms due to lower moisture content and colder temperature [12, 13].

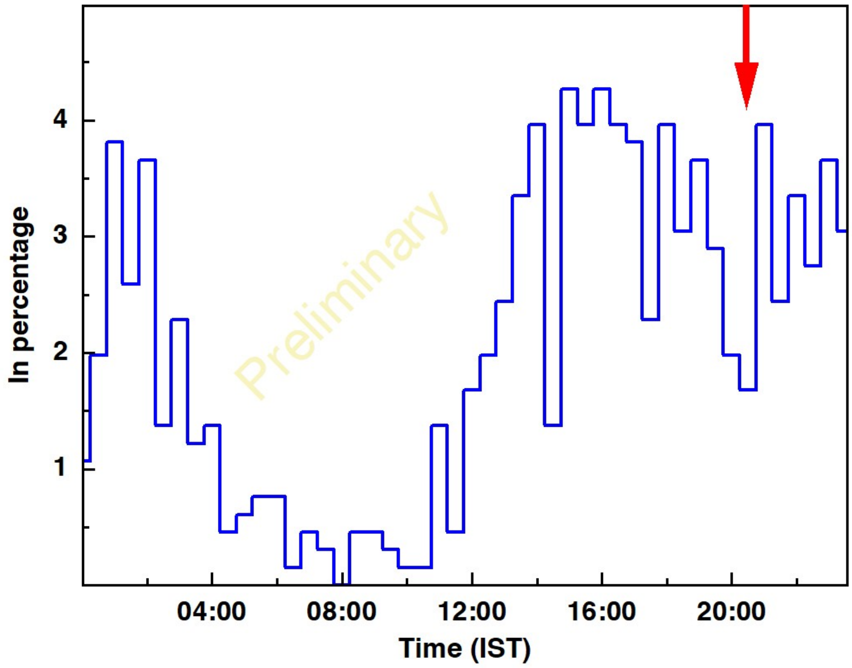

Figure 3: Diurnal variation of the events for the period 2006-2020 (in percentage)

The temporal information for the observed events during the fifteen years was grouped half-hourly and treated as if they commenced on that half-hour. The resultant diurnal event distribution is plotted in Figure 3, which shows significant variation. One can observe that the occurrence of the events peaking up after noon remains high till late evening and then reduces till 20:00 hours. However, the numbers again increased around 22:30 hours after they started to subdued and remained high till early morning, though in decreasing numbers during morning hours. Observing these events during the afternoon – evening – late evening hours is somewhat understood, considering the general thunderstorm patterns observed. However, the large number of events before and after midnight makes them other than an ordinary and open door for extensive investigation for in-detailed understanding, even though they appear to have similarities with certain regional thunderstorms occurrence to a certain extent. The top red arrow indicates the separation point between late evening and pre-midnight events, indicating the role of two separate processes in force.

For a better understanding of the processes affecting different seasons, the events were plotted for various seasons, as presented in Figure 4. While winter (Figure 4a) witnesses sporadic events, spring has surprises (Figure 4b), with an overall trend following Figure 3. Summer is dominated by afternoon-late afternoon events, a typical thunderstorm pattern. Considering that the level of greenhouse gases remains minimal during this season, their role during other seasons poses an essential factor. Most complexities arise during autumn (Figure 4d) when pre- and post-midnight events become prominent.

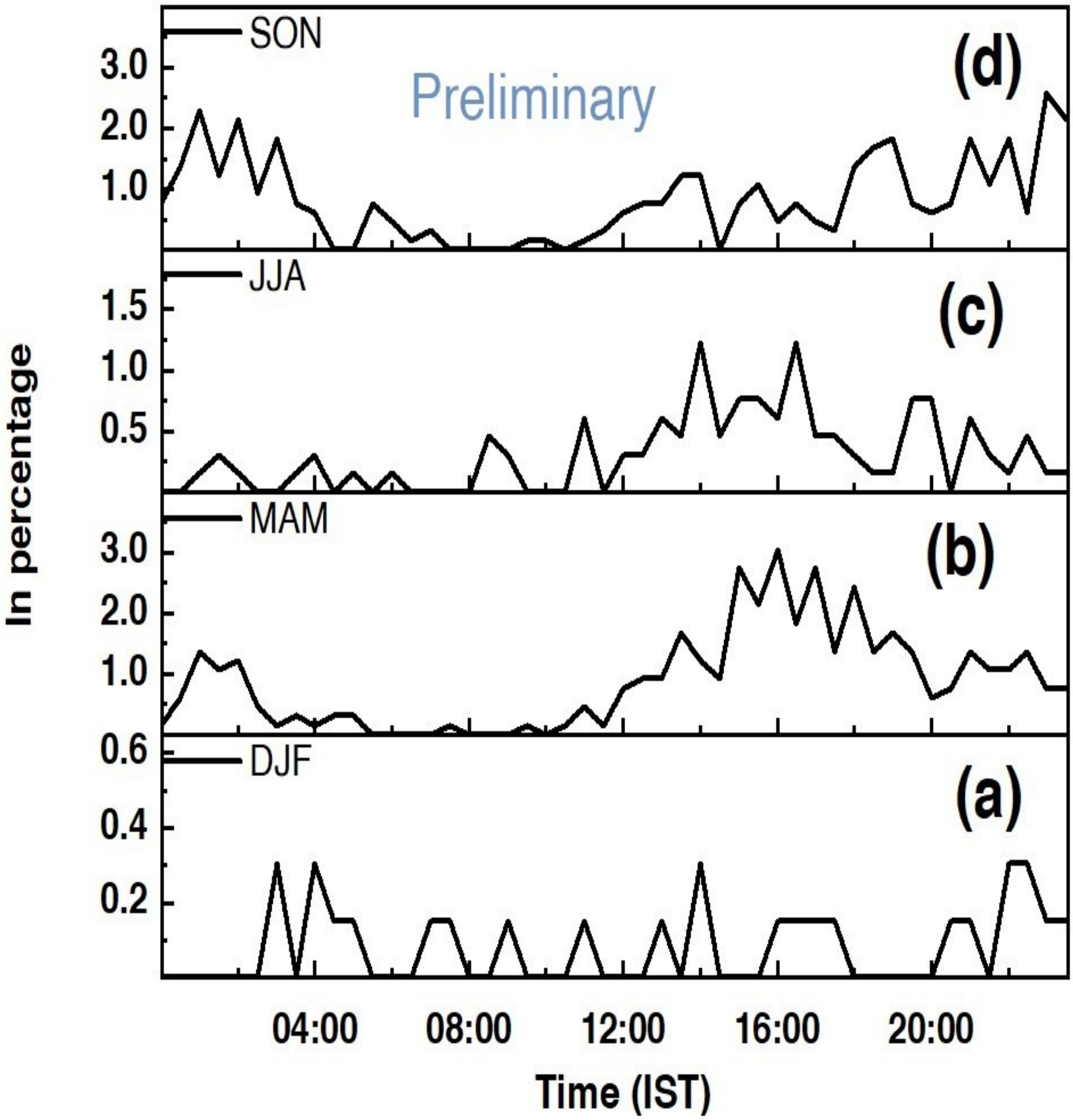

Figure 4: Diurnal variation of the TIMEs during different seasons (in percentage)

5. Summary and scope for future work

At GRAPES-3, we have continuously observed TIMEs for over two decades. This report presents many statistically significant events observed during the fifteen years from 2006 to 2020. This is the first-ever report on seasonal variations of TIMEs from an experiment covering such a prolonged duration without interruption.

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References

[1] Y. Hayashi *et al.*, *A large area muon tracking detector for ultra-high energy cosmic ray astrophysics - the GRAPES-3 experiment. Nucl. Instr. Meth. A* **545** (2005) 643

[2] S.K. Gupta, *Recent results from the GRAPES-3 experiment. EPJ Web Conferences* **52**(2013) 04005.

[3] B. Hariharan *et al.*, *Measurement of the Electrical Properties of a Thundercloud Through Muon Imaging by the GRAPES-3 Experiment. Phys. Rev. Lett.,* 122 (2019) 105101.

[4] T. Nonaka *et al.*, *Did the 28 October 2003 solar flare accelerate protons to ≳20GeV? A study of the subsequent Forbush decrease with the GRAPES-3 tracking muon telescope. Phys. Rev. D* **74** (2006) 052003.

[5] P.K. Nayak *et al.*, Ob*servation of thunderstorm-induced muon events in GRAPES-3 experiment, J. Atmos. Solar-Terr Phys., (2023) (under review)*

[6] Kokilavani *et al.*, *Decadal study of changing frequency and intensity of rainfall for selected locations of Tamil Nadu, Curr. Wor. Env.* 16 (2021) 898.

[7] C. Udayasoorian *et al.*, *Aerosol black carbon characteristics over a high-altitude WesternGhats location in Southern India. Ann. Geophys*. 32 (2014) 1361.

[8] N.H. Saji *et al.*, *A dipolemode in thetropical Indian Ocean. Nature* **401** (1999) 360.

[9] M.R. Ranalkar and H. Chaudhari, *Seasonal variation of lightning activity over the Indian subcontinent. Meteorol. Atmos. Phys.*104 (2009) 125.

[10] A. Witze, *Why Extreme rains are getting worse. Nature* **563** (2018) 458.

[11] P.K. Nayak et al., Contemplating the observed relationship between the global electric circuit and GRAPES-3 thunderstorm-induced muon events, *PoS (ICRC2023)* 404.

[12] G.K. Manohar et al., *Thunderstorm activity over India and the Indian southwestmonsoon. J. Geophys. Res.*, **104** (1999) 4169.

[13] J.M. Wallace, *Diurnal variations in precipitation and thunderstorm frequency over the conterminous United States*. Mon. Weather Rev. **103** (1975) 406.