Revista Mexicana de Astronomía y Astrofísica, 61, 233-239, (2025)

OPEN ACCESS https://doi.org/10.22201/ia.01851101p.2025.61.03.11

# High-Energy Neutron Enhancements Not Classified as GLEs: A Case Study Using Ground-Based Neutron Monitor Data

**E. Tirado-Bueno** [1], **J. E. Mendoza-Torres** [2] **and C. Amador-Meléndez** [1]

[1] *Instituto Nacional de Astrofísica, Óptica y Electrónica, Posgrado en Ciencia y Tecnología del Espacio, Luis Enrique Erro # 1, Santa María Tonantzintla, Puebla, México*
[2] *Instituto Nacional de Astrofísica, Óptica y Electrónica, Coordinación de Astrofísica, Luis Enrique Erro # 1, Santa María Tonantzintla, Puebla, México*

**Keywords:** *cosmic rays, particle emission, flares, solar-terrestrial relations*

### Abstract

During their propagation through the interplanetary medium, cosmic rays interact with solar and interplanetary structures, which can cause fluctuations in their intensity observed at ground level. In this work, we apply a statistical method of overlapping epochs to analyze the effect of solar flares and energetic particle events on the intensity of cosmic radiation, considering periods of low geomagnetic activity and a 24-hour interval before and after the onset of the events. Our objective is to identify possible variations of tiny amplitude, observable simultaneously at different monitoring stations. The results indicate that solar flares, whether accompanied by energetic particle events or not, are not associated with noticeable increases in the cosmic ray intensity. This suggests that small increases may go undetected without specific treatment to highlight subtle variations.

### Resumen

Durante su propagación por el medio interplanetario, los rayos cósmicos interactúan con estructuras solares e interplanetarias, generando variaciones en su intensidad observadas en tierra. En este trabajo se aplica el método de épocas superpuestas para analizar el efecto de las erupciones solares y los eventos de partículas energéticas sobre la radiación cósmica, considerando periodos de baja actividad geomagnética y un intervalo de 24 horas antes y después de los eventos. El objetivo es detectar variaciones de pequeña amplitud observables simultáneamente en distintas estaciones. Los resultados muestran que las erupciones solares, con o sin eventos de partículas energéticas, no producen aumentos significativos en la intensidad de los rayos cósmicos, lo que sugiere que posibles incrementos menores requieren un tratamiento específico para ser detectados.

**Corresponding author:** Eduardo Tirado-Bueno *E-mail address:* etirado@inaoep.mx
**Received:** August 11, 2025 **Accepted:** October 28, 2025

## 1. INTRODUCTION

During solar explosive events, such as solar flares and coronal mass ejections, the Sun releases and accelerates energetic particles known as solar energetic particles (SEPs) in the solar corona and upper atmosphere (Desai & Giacalone, 2016). The first direct observation of these particles was conducted in 1942 (Forbush, 1946). SEPs events are traditionally classified into two categories, *impulsive* and *gradual* (or more details, see Reames, 1999, and references therein), based on their temporal characteristics and particle composition. Impulsive events were previously linked to enhanced $He^3$ abundance, whereas gradual events were thought to be related to shock waves driven by coronal mass ejections (CMEs). However, recent studies have questioned the two-category model. Notably, even the most significant SEP events were found to contain $He^3$ enhancements, which were once considered typical only for impulsive events. Additionally, the anticipated bimodal distribution of electron-to-proton ratios, which is expected to differentiate between impulsive and gradual events, has not been observed in recent studies (see, e.g. Cane et al., 2010). The lack of a distinct bimodal signature suggests that the conventional classification may not accurately reflect the complexities of SEP events.

This situation is further complicated by significant solar proton events, which are typically categorized as gradual and associated with shocks. These events display a wide distribution in the solar longitude. While this distribution was previously interpreted as evidence of CME shock dynamics, more recent research has suggested that even localized particle releases can lead to widespread solar energetic particle (SEP) events across the Sun. This phenomenon occurs due to particle transport within the heliosphere, including the movement of particles across magnetic-field lines (Richardson et al., 2014).

Depending on the energy of the particles, SEP events can last from several hours to several days, when particle speeds reach relativistic regimes. In most SEP events, particles can accelerate to energies as high as gigaelectron volts (GeV). These high-energy particles can reach the Earth's atmosphere, where they interact with atmospheric nuclei and generate cosmic-ray-induced cascades of secondary particles that travel down to the ground (Dorman, 2004; Grieder, 2010, and references therein) if the primary high-energy particle has sufficient energy to surpass the geomagnetic rigidity cutoff (Bazilevskaya, 2005).

The intensity of secondary particles produced in these air showers can be detected on the Earth's surface using neutron monitors (NMs). During a SEP event, which occurs only several times per solar cycle (Shea & Smart, 2000), there is a significant enhancement in the count rates of high-energy particles penetrating the Earth's atmosphere, exceeding the atmospheric cutoff. Therefore, the population of particles significantly increases, and the intensity recorded by the NMs is considerably enhanced (Usoskin et al., 2011). In other words, if we detect an increase in the count rates of neutrons in at least two monitors located at different sites, including one at sea level, this is known as *Ground Level Enhancement* (GLE) (Poluianov et al., 2017). These coincident signals must correspond to enhanced proton flux measured by the space-borne instrument(s). In this context, we say that GLE has occurred.

In this study, our focus is on a specific class of events with energy levels exceeding 300 MeV/n, which generate a significant increase in the intensity of the secondary particles, even without the presence of a ground-level enhancement event. These types of events may result from energetic phenomena in the Sun, which produce free neutrons. This flux of neutrons results in a signal that can be detected in the intensity recorded by neutron monitors outside the context of GLEs. This neutron intensity signal likely corresponds to what researchers describe as the precursor signal. Eruptive solar events generate GLE precursors, but these precursors can occur independently of a significant release of charged particles that would typically trigger a GLE. The term *precursor* describes this signal because it reaches the Earth before any GLE is linked to the same impulsive event. In particular, (Augusto et al., 2005) found that solar flares and/or SEPs may be associated with an increase in the intensity of cosmic rays observed at ground level. Analyzing the properties of these signals through the superposition of various events may reveal valuable insights about subsequent GLEs. Temporary enhancements in the neutron intensity at Earth do not cause GLEs; such enhancements have been observed even when no GLE occurs (Watanabe et al., 2008).

## 2. INSTRUMENTATION

As mentioned above, neutron monitors are among the most suitable instruments for measuring the products generated in an air shower resulting from the interaction of a primary cosmic ray with atmospheric nuclei present in the Earth's atmosphere. The instrument consists of four components (Bütikofer, 2018). (1.) A **reflector**, a layer of polyethylene that encapsulates the entire detector, is intended to isolate the detector from low-energy neutrons present in the atmosphere. Thus, only high-energy neutrons from the cosmic ray cascade penetrate; (2.) the **producer**, made of lead, whose function is to generate low-energy neutrons for each high-energy neutron that interacts in the monitor; (3) the **moderator**, which consists of a polyethylene tube whose purpose is to decrease the energy of the secondary neutrons generated in the producer; and finally (4.) the **proportional counters**, which are steel tubes filled with gas. The tube acts as the cathode and the central wire acts as an anode to collect the electric pulses generated by the protons, after interacting with the $^3He$ nuclei in the NM-64 model (Simnett, 2017).

**Table 1.** Specifications of selected Neutron Monitors (Courtesy: Neutron Monitor Database)

| Monitor | Lat. (°) | Lon. (°) | Cutoff Rigidity (GV) | Detector Type |
|---|---|---|---|---|
| MCMU | 77.95 S | 166.60 E | 0.30 | NM-64 |
| FSMT | 60.02 N | 111.93 W | 0.30 | NM-64 |
| INVK | 68.36 N | 133.72 W | 0.30 | NM-64 |
| NAIN | 56.55 N | 061.68 W | 0.30 | NM-64 |
| THUL | 76.50 N | 068.70 W | 0.30 | NM-64 |
| APTY | 67.57 N | 033.40 E | 0.65 | NM-64 |
| OULU | 65.05 N | 025.47 E | 0.80 | NM-64 |
| NEWK | 39.68 N | 075.75 W | 2.40 | NM-64 |
| HRMS | 34.43 N | 019.23 E | 4.58 | NM-64 |

In this study, we analyzed data collected by neutron monitors, which detect high-energy cosmic rays at the ground level. The analysis considered the counts recorded by the monitors listed in Table 1. Most of these detectors belong to the NM-64 type, a standardized design developed in the 1960s that ensures high stability, sensitivity, and comparability for observations at different sites.

Each monitoring station has a specific geomagnetic cutoff rigidity, which defines the minimum rigidity required for a cosmic particle to reach the atmosphere at that location. The geomagnetic latitude and Earth's magnetic field configuration determine this cutoff. The selected monitors span a range of rigidities, from polar stations that virtually do not have geomagnetic filtering to mid-latitude sites with limited access to low-energy particles.

Knowledge of the various meteorological effects is necessary in any investigation of the temporal variations of cosmic rays when measured by detectors located at ground level. The corrections applied to the data from these stations depend on the meteorological coefficients of the intensity recorded by the detector. It has been observed that cosmic ray intensity variations detected on Earth are well correlated with variations in local meteorological parameters, particularly atmospheric pressure (Tirado-Bueno et al., 2021). This allows one to make corrections to the observed flux of CR due to this influence, leaving variations due to other causes, such as interplanetary or galactic origins. In addition, the mitigation of the local meteorological trend's influence on the cosmic ray intensity makes the corrected values more sensitive to variations in a transient character. On the other hand, although local meteorological conditions at the Earth's surface are important in determining the intensity, conditions at different altitudes in the atmosphere also play a role in the resulting flux. This means that the integrated effect of the atmosphere on the paths of the cosmic rays results in the observed intensity at the surface.

## 3. SUPERPOSED EPOCH ANALYSIS

In an attempt to identify increases in the neutron count rates associated with impulsive solar events (although possibly unrelated to GLEs), we performed a *Superposed Epoch Analysis* (SEA), commonly employed to determine if an event affects a physical process that is fundamentally random or whose

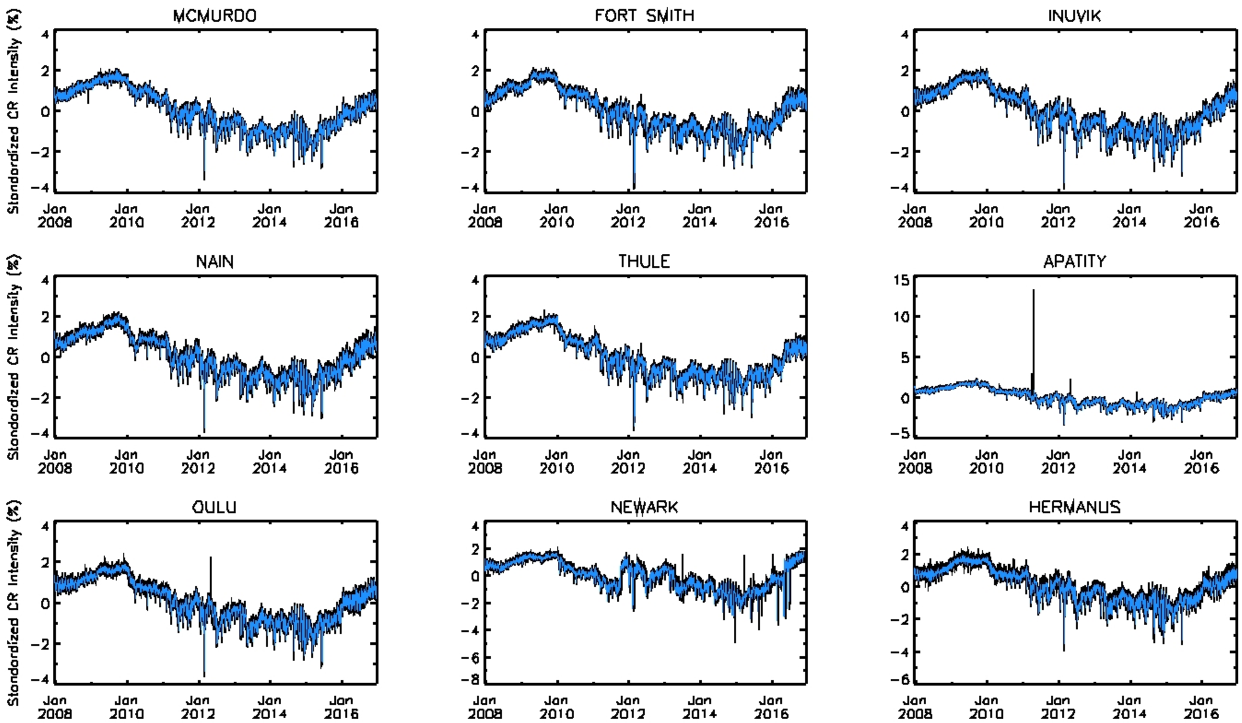


**Figure 1.** Number of counts per hour (black curve) recorded by the neutron monitors listed in Table 1, with panels arranged from left to right. The blue curve represents a moving average with a 24−hour window from January 2008 to December 2016.

measurements are subject to perturbations caused by random noise (Jamison & Regal, 1979). This method was first used to study the temporal variation of geomagnetic data, which exhibit a 27-day periodicity (Chree, 1912, 1913). Since then, this technique has been applied in several disciplines, either to investigate the relationship between two distinct phenomena or to search for periodicity. The SEA method is based on the selection of data subsets, where key data points in a time series must be identified using certain criteria. For example, the occurrence of unusual events in one or more datasets (Chree, 1912; Forbush et al., 1983). By averaging such consecutive key events, stochastic variability is reduced such that low-amplitude signals can be identified (Laken & Čalogović, 2013).

In general, an $X_i$ time series is composed of a deterministic component $D_i$, a stochastic component $N_i$, and a low-amplitude repetitive signal $S_i$. Before applying the SEA method, it is advisable to eliminate variations in the $X_i$ signal that are not associated with the $S_i$ signal, thereby reducing the signal-to-noise ratio. There is limited knowledge on the properties of a signal within a dataset. Therefore, we calculated a moving average, $F_i$, of the dataset, $X_i$ (see Figure 1). By subtracting the $F_i$ values from $X_i$, we obtain $A_i$, which represents a high-pass filtering of the dataset; thus, it is referred to as an anomaly or excess curve (see Figure 2).

With prior knowledge of the type of feature in the time series, we proceed to construct a composite matrix $M_{j,t}$ (see Equation 1) from the values of $A_i$, where $j = 1, \ldots, n$ lists the $n$ composite events (rows of the matrix), and $t$ is the corresponding time scale (columns of the matrix).

$$M_{j,t} = \begin{pmatrix} A_{1,-t'} & \cdots & A_{1,t'=0} & \cdots & A_{1,+t'} \\ A_{2,-t'} & \cdots & A_{2,t'=0} & \cdots & A_{2,+t'} \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ A_{n,-t'} & \cdots & A_{n,t'=0} & \cdots & A_{n,+t'} \end{pmatrix}. \tag{1}$$

In any of the $n$ events in the composite matrix, it would not be very easy to determine the presence of a signal at $t' = 0$ objectively. However, by averaging the $n$ events that make up the matrix together, a composite average can be obtained (see Equation 2),

$$C_t = \frac{1}{n}\sum_{j=0}^{n+1} M_{j,t}. \tag{2}$$

The standard error of the mean ($\Delta C_t$) at $t$, $\sigma$ represents the standard deviation of the dataset, and the square root of the number of events decreases the noise of the signal $S_i$ (Laken & Čalogović, 2013), as expressed in Equation 3:

$$\Delta C_t = \frac{\sigma}{\sqrt{n}}. \tag{3}$$

## 4. DATA ANALYSIS

The variations in cosmic ray intensity data were analyzed for two different types of events that occur on the Sun: **(I)** solar flares with a maximum in the $X$−ray flux greater than or equal to the $M1$ class of the Geostationary Operational Environmental Satellite (GOES), and are not precursors of any energetic particle event; **(II)** intense solar proton events with a flux of protons having energies above 100 MeV detected by the particle measurement instruments onboard GOES. To avoid the effects of other solar and/or geomagnetic disturbances, solar flares and SEPs events were chosen such that the $Kp$ index $< 4.0$ and the $Dst$ index

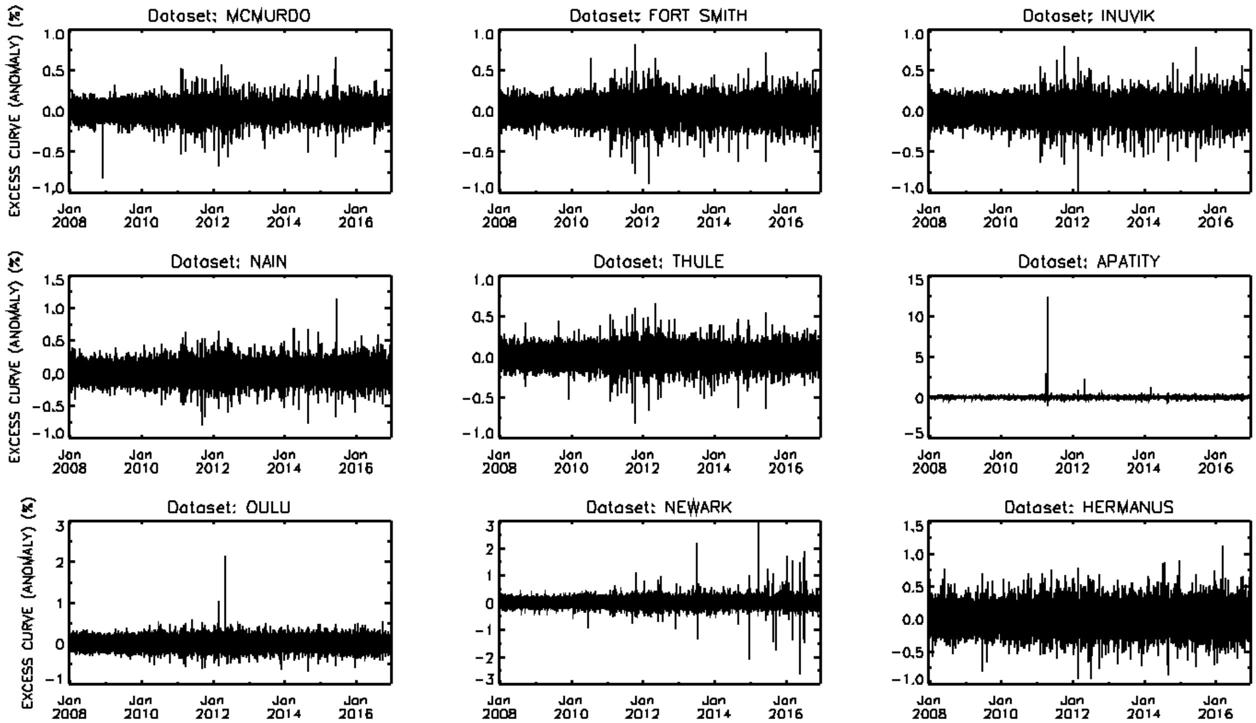


**Figure 2.** Anomaly or (excess curve) resulting from applying a high-pass filter to the cosmic ray intensity recorded by NMs and shown in Figure 1.

$\geq -15.0$ nT for two consecutive days. That is, these must be the values one day before and one day after the selected events, representing the most stable conditions of the interplanetary magnetic field. Similarly, those events for which a Forbush decrease occurred during these two days were not included in the analysis.

The methodology used in the analysis is as follows: first, the different sets of cosmic ray intensity measurements recorded on neutron monitors were standardized to create a new dataset with a zero mean and a standard deviation of one unit. Second, the moving average of the new cosmic ray intensity dataset was calculated using a 24-hour window for the different neutron monitor counts from January 2008 to December 2016. The difference between the values of the moving average and the intensity of the cosmic rays was then calculated to obtain the excess curve.

Finally, for each event, a 24-hour time window was selected before and after the start time of each event to avoid the influence of long-term variations in the dataset that correspond to the cosmic ray intensity measurements. In particular, the particles emitted in these events are expected to take less than 1 day to reach Earth, because they would have a speed close to the speed of light; in the case of solar flares, the increase in 1.0 to 8.0 Å $X$−ray is used as the onset. Similarly, for SEPs, it is described as an onset, characterized by an increase in proton flux with $E \geq 100$ MeV, as recorded by the GOES satellite.

## 5. RESULTS

In this section, the behavior of the intensity of cosmic radiation is characterized, related to solar events (flares and SEPs): for this purpose, the counts of neutron monitors are used (see Table 1), which are located at different latitudes and longitudes, and, with varying values of their adequate cutoff rigidity. The following subsections present the results of this analysis.

### 5.1. Case I. Cosmic radiation intensity response to solar flares events

Figure 3 shows the results of **Case I**, which were obtained using the SEA methodology, as outlined in Section 3. This method is applied to 409 solar eruptions with a classification greater than or equal to $M1$ of GOES, that met the criteria described above, in section 4 to eliminate disturbances related to the arrival of interplanetary structures on Earth for the period from January 2008 to December 2016. The error bars were calculated from the standard error of the mean (see Equation 3). Figure 3 shows that the variability of the curves varies within −0.05 % and 0.05 %, it can be seen that the curve after the event shows the same behavior seen in the previous period, which indicates that no significant effects are found in the number of cosmic ray intensity counts for 24 hours before and after the start of the solar flare.

### 5.2. Case II. Cosmic radiation intensity response to SEPs events

Below, we present the results of **Case II**, which analyzed 20 SPEs recorded between January 2008 and December 2016. Similar to **Case I**, events with perturbations related to the arrival of interplanetary structures to Earth are removed, and the error bars represent twice the standard error of the mean (see Equation 3). During the analysis period, a particular event occurred on May 17, 2012. This event is related to an evident increase in cosmic ray intensity, known as a *Ground Level Enhancement* (GLE-71), according to the literature. For further details, please refer to the GLE Database. We then performed an additional analysis to verify whether the effect of GLE-71 was relevant to obtaining the results.

For this purpose, the event corresponding to GLE-71 was removed from the analysis, and we only kept 19 SEP events to

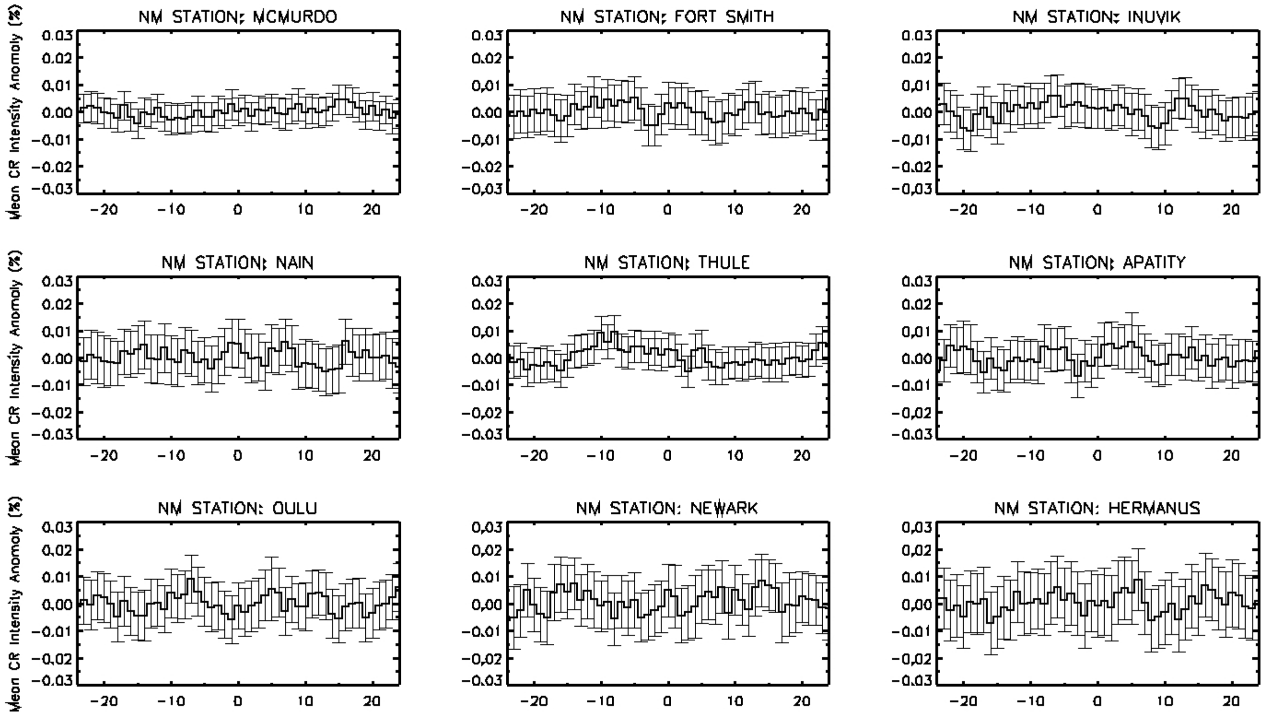


**Figure 3.** *Superposed Epoch Analysis* of the deviation of cosmic ray intensity to solar flares for the NMs listed in Table 1 with panels arranged from left to right. Time zero was the start time of the solar flare. Error bars represent twice the standard error of the mean.

which the superposed epoch analysis was applied. In Figure 4, the blue curve represents the 19 events without considering the GLE-71. In Figure 5, the continuous black curve corresponds to the case where GLE-71 is considered. In addition, a continuous red curve is superimposed in Figures 4 and 5, which shows the total number of SEPs events (34) without removing the conditions associated with solar and/or geomagnetic disturbances during the period covered by the work.

## 6. SUMMARY AND CONCLUSIONS

The results of the variations in cosmic ray intensity under certain conditions are shown, and the measurements are made with different neutron monitors during the occurrence of solar flares in which SEPs events do not occur (**Case I**) and during SEPs events (**Case II**). As mentioned above, this analysis does not consider events in which a Forbush decrease and/or geomagnetic storms occurred on two consecutive days around the start time of the event.

For **Case I**, there were no relevant changes in the intensity of the cosmic radiation. This means that there were no significant deviations from the number of cosmic ray counts for the neutron monitors considered in this study. This result indicates that solar flares do not emit small amounts of particles (invisible in individual observations) that can be detected in an overlapping analysis of several events.

However, when studying SEP events (**Case II**) that are not associated with GLEs, it is not possible to distinguish a significant increase in the deviation curve of the intensity of cosmic rays. For a more detailed study and with greater statistics of this effect, it was also considered to aggregate all the events, within which some were avoided due to their influence with geomagnetic effects ($Kp > 4.0$ and $Dst \geq -15.0$ nT), even so, no significant changes are observed in the excess curve that results from the analysis of superposed epochs.

To summarize, for the case of solar energetic particles, the analysis of overlapping epochs reveals no significant changes in cosmic ray intensity within the 48 hours surrounding the onset, except when the solar proton event is extremely intense, indicating the presence of a Ground Level Enhancement (GLE). In such cases, an increase in the intensity of the cosmic particles was observed in the neutron monitors. Notably, during the period from January 2008 to December 2016, only one very intense proton event accompanied by a GLE was observed.

Verifying the hypothesis that each SPE event can cause an increase (almost invisible) in the intensity of cosmic rays does not seem to be valid. The method applied—designed precisely to reveal small variations in a data series—did not indicate the existence of a slight variation in the intensity of the events analyzed.

It is worth mentioning that in this study, the influence of solar flares and SEPs on cosmic ray intensity was only observed when SEPs events were already related to GLEs, as expected. It should be noted that the GLEs had a short duration of 6 hours. Because hourly data were analyzed, very short events (less than 1 hour) were not considered. In future work, it would be convenient to use a resolution of minutes instead of hours to better visualize this type of event.

The authors gratefully acknowledge the research team of the Neutron Monitor Database project for providing the high-resolution neutron monitoring data. E. Tirado-Bueno, J. E. Mendoza-Torres, and C. Amador-Meléndez would like to acknowledge SECIHTI (formerly known as CONAHCyT) for the

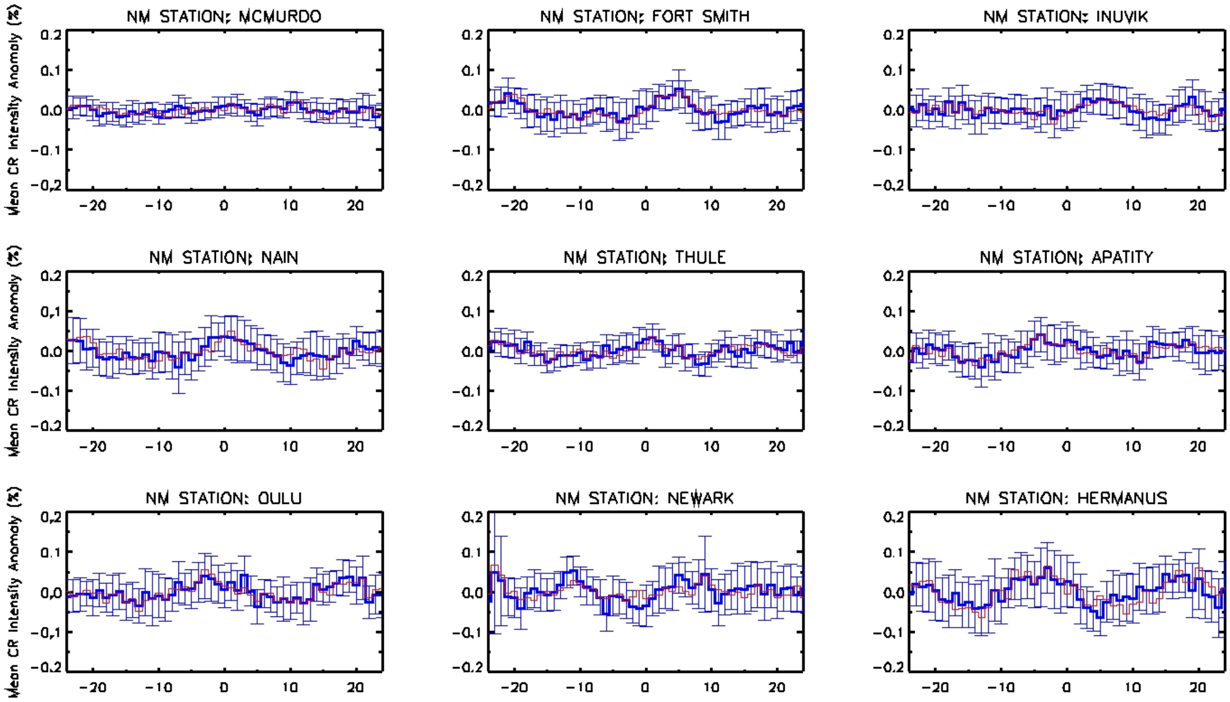


**Figure 4.** *Superposed Epoch Analysis* of the deviation of cosmic ray intensity to SEPs without the presence of GLE-71 for the NMs listed in Table 1 with panels arranged from left to right. Time zero is the start time of the SEP. Error bars represent twice the standard error of the mean.

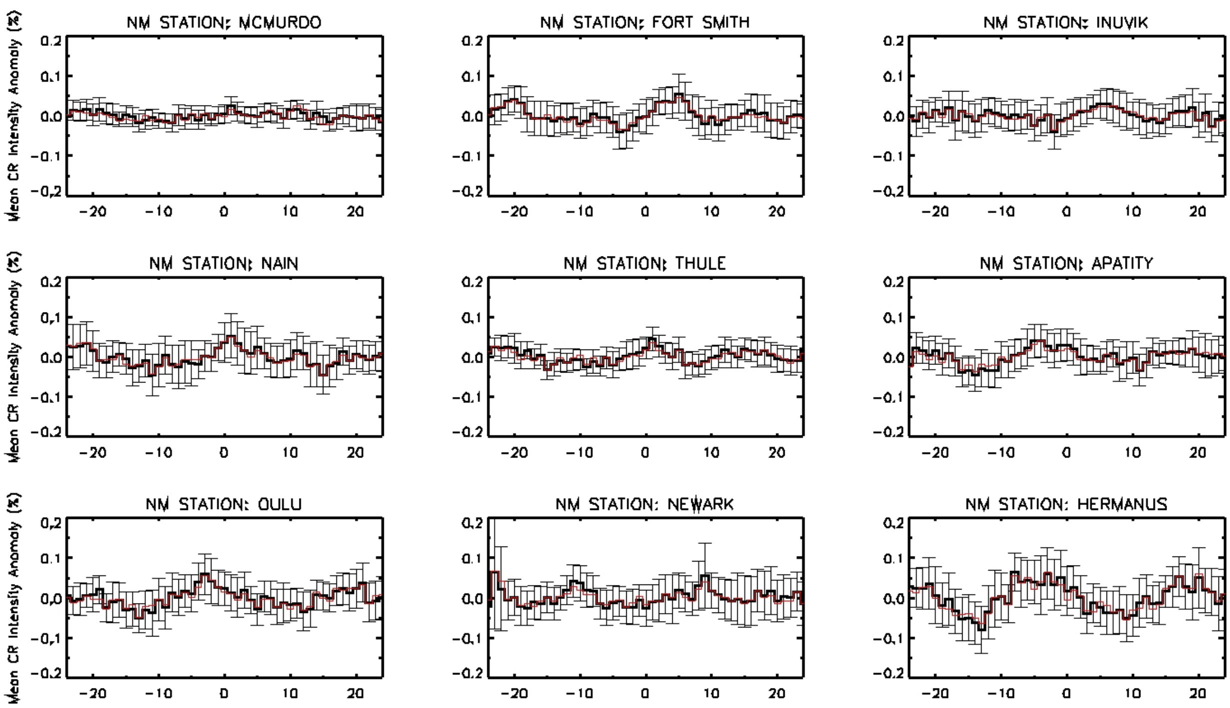


**Figure 5.** *Superposed Epoch Analysis* of the deviation of cosmic ray intensity to SEPs with the presence of GLE-71 for the NMs listed in Table 1 with panels arranged from left to right. Time zero is the start time of the SEP. Error bars represent twice the standard error of the mean.

funding. We are grateful to Rafael R. S. de Mendonça for insightful discussions and helpful suggestions during the preparation of this work; we also want to express our sincere gratitude to Victor David Juárez Cortés for their invaluable assistance with proofreading this manuscript. We would also like to express our appreciation to the anonymous reviewers for their valuable time, insightful comments, and constructive suggestions, which have significantly improved the quality and clarity of this manuscript.

## REFERENCES

Augusto, C., Navia, C. E., & Robba, M. 2005, PhRvD, 71, 103011, doi: https://doi.org/10.1103/PhysRevD.71.103011

Bazilevskaya, G. 2005, AdSpR, 35, 458, doi: https://doi.org/10.1016/j.asr.2004.11.019

Bütikofer, R. 2018, Solar Particle Radiation Storms Forecasting and Analysis: The HESPERIA HORIZON 2020 Project and Beyond, 95, doi: https://doi.org/10.1007/978-3-319-60051-2

Cane, H. V., Richardson, I. G., & von Rosenvinge, T. T. 2010, JGRA, 115, A08101, doi: 10.1029/2009JA014848

Chree, C. 1912, Studies in Terrestrial Magnetism (Macmillan). https://books.google.com/books/about/Studies_in_Terrestrial_Magnetism.html?id=zdtYAAAAYAAJ

—. 1913, RSPTA, 212, 75, doi: https://doi.org/10.1098/rsta.1913.0003

Desai, M., & Giacalone, J. 2016, LRSP, 13, 3, doi: https://doi.org/10.1007/s41116-016-0002-5

Dorman, L. I. 2004, Cosmic rays in the Earth's atmosphere and underground, Vol. 303 (Springer Science & Business Media), doi: https://doi.org/10.1007/978-1-4020-2113-8

Forbush, S., Pomerantz, M., Duggal, S., & Tsao, C. 1983, in IAUC, Vol. 66, Cambridge University Press, 113–122, doi: 10.1017/S0252921100095452

Forbush, S. E. 1946, PhRv, 70, 771, doi: https://doi.org/10.1103/PhysRev.70.771

Grieder, P. K. 2010, Extensive air showers: high energy phenomena and astrophysical aspects-a tutorial, reference manual and data book (Springer Science & Business Media), doi: https://doi.org/10.1007/978-3-540-76941-5

Jamison, B., & Regal, R. 1979, in Solar-Terrestrial Influences on Weather and Climate: Proceedings of a Symposium/Workshop held at the Fawcett Center for Tomorrow, The Ohio State University, Columbus, Ohio, 24–28 August, 1978, Springer, 175–179, doi: https://doi.org/10.1007/978-94-009-9428-7

Laken, B. A., & Čalogović, J. 2013, JSWSC, 3, A29, doi: https://doi.org/10.1051/swsc/2013051

Poluianov, S., Usoskin, I., Mishev, A., Shea, M., & Smart, D. 2017, SoPh, 292, 176, doi: https://doi.org/10.1007/s11207-017-1202-4

Reames, D. V. 1999, SSRv, 90, 413, doi: https://doi.org/10.1023/A:1005105831781

Richardson, I., Von Rosenvinge, T., Cane, H., et al. 2014, SoPh, 289, 3059, doi: https://doi.org/10.1007/s11207-014-0524-8

Shea, M., & Smart, D. 2000, SSRv, 93, 229, doi: https://doi.org/10.1023/A:1026500713452

Simnett, G. M. 2017, Energetic Particles in the Heliosphere (Switzerland, Springer), doi: https://doi.org/10.1007/978-3-319-43495-7

Tirado-Bueno, E., Mendoza-Torres, J. E., & de Mendonça, R. R. 2021, AdSpR, 68, 2631, doi: https://doi.org/10.1016/j.asr.2021.04.034

Usoskin, I. G., Bazilevskaya, G. A., & Kovaltsov, G. A. 2011, JGRA, 116, doi: https://doi.org/10.1029/2010JA016105

Watanabe, K., Murphy, R., Muraki, Y., et al. 2008, in Proceedings of the 30th international cosmic ray conference, Vol. 1, 37–40