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Fundamentals and Data Analysis of Neutron Monitor Systems

Nötron Monitör Sistemlerinin Temelleri ve Verilerinin Analizi

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Abstract

Cosmic Rays (CRs) carry important information for understanding the energetic processes of the universe and space weather events, and Neutron Monitors (NM) are the primary tools for continuously measuring the flux of these particles at ground level. However, NM data are significantly affected by atmospheric pressure changes. This study presents the process and results of removing this atmospheric effect from multi-station data obtained from the global Neutron Monitor Database (NMDB) network. The study utilised raw count and pressure data from 5 different NM stations for the period 2010–2025. The data processing and analysis process was carried out using the Python programming language and the pandas and NumPy libraries; barometric pressure correction was applied to the raw data using the standard Dorman equation. The findings showed that the correction process successfully eliminated pressure-induced noise and sudden fluctuations in the raw data. The corrected data produced much more stable time series and made important signals, such as potential Ground Level Events (GLE) and Forbush Decrease (FD) that were masked in the raw data, more prominent. These results confirm that barometric correction is a critical and necessary pre-processing step for reliable analysis in space weather events and long-term solar modulation studies.

Keywords: Cosmic Rays, Neutron Monitors, NMDB, Pressure Correction, Ground Level Enhancement (GLE), Forbush Decrease (FD)

Öz

Kozmik Işınlar (CRs), evrenin enerjik süreçlerini ve uzay havası olaylarını anlamak için önemli bilgiler taşır ve Nötron Monitörleri (NM) bu parçacıkların yer seviyesindeki akısını sürekli olarak ölçen temel araçlardır. Ancak, NM verileri atmosferik basınç değişimlerinden ciddi şekilde etkilenir. Bu çalışma, küresel Nötron Monitörü Veritabanı (NMDB) ağından alınan çoklu istasyon verilerindeki bu atmosferik etkinin giderilmesi sürecini ve sonuçlarını sunmaktadır. Çalışmada, 2010-2025 periyodu için 5 farklı NM istasyonundan alınan ham sayım ve basınç verileri kullanılmıştır. Veri işleme ve analiz süreci, Python programlama dili ile pandas ve NumPy kütüphaneleri kullanılarak yürütülmüş; ham verilere, standart Dorman denklemi ile barometrik basınç düzeltmesi uygulanmıştır. Bulgular, düzeltme işleminin, ham verilerdeki basınç kaynaklı gürültüyü ve ani dalgalanmaları başarılı bir şekilde ortadan kaldırdığını göstermiştir. Düzeltilmiş veriler, çok daha kararlı zaman serileri ortaya koymuş ve ham veride maskelenmiş olan potansiyel Yer Seviyesi Olayları (GLE) ve Forbush Azalması (FD) gibi önemli sinyallerin belirgin hale gelmesini sağlamıştır. Bu sonuçlar, barometrik düzeltmenin, uzay havası olayları ve uzun vadeli Güneş modülasyonu çalışmalarında güvenilir analizler yapabilmek için kritik ve zorunlu bir ön işleme adımı olduğunu doğrulamaktadır.

Anahtar Kelimeler: Kozmik Işınlar, Nötron Monitörler, NMDB, Basınç Düzeltmesi, Yer Seviyesi Artışları (GLE), Forbush Azalması (FD).

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Introduction

Neutron Monitors (NM) are sensitive detectors designed to indirectly measure the flux of cosmic rays (CRs), which are high-energy particles continuously reaching the Earth's atmosphere from outer space, at ground-based stations. These CRs are products of the most energetic processes in the universe and are essentially a high-energy particle flux. The majority of the flux consists of protons (90%), helium nuclei (alpha particles) (9%), and heavier atomic nuclei (1%) (Gaisser et al., 2016; Polatoğlu & Yeşilyaprak, 2023). The CR spectrum contains very small amounts of electrons and gamma rays. These particles are accelerated to enormous energies in supernova remnants, active galactic nuclei, and other energetic astrophysical phenomena; travel long distances through intergalactic space, and reach Earth (Blasi, 2013). Since they are composed of charged particles, they are affected by magnetic fields within the galaxy and the heliosphere during their journey; this alters their direction of arrival, making it difficult to directly identify their source.

CR research was largely limited to high-altitude balloon measurements until the mid-1940s. The most significant scientific and technological breakthrough in this field occurred in 1948 with the invention of the neutron monitor by physicist John A. Simpson. Simpson's design enabled the continuous and systematic measurement of the secondary neutron flux resulting from CRs' interaction with the atmosphere at the Earth's surface (Simpson, 1951). This invention is considered a turning point in CR physics, as it became a fundamental tool for tracking time-dependent changes in CRs and solar-induced events. This laid the foundations for space weather research, and today, the Neutron Monitor Database (NMDB), used in dozens of observatories around the world, has become an indispensable component of modern astrophysics and geomagnetic research.

The working principle of NMs is based on the indirect detection of ‘Primary Cosmic Rays’ not directly, but through secondary neutrons, which are products of Secondary Cosmic Rays resulting from the interaction of these rays with the atmosphere. Primary cosmic rays are high-energy charged particles of galactic or extragalactic origin, primarily consisting of protons and helium nuclei. When these particles reach the Earth's atmosphere, they collide with air atoms, particularly nitrogen and oxygen, at high energies, initiating particle cascades known as ‘Extensive Air Showers (EAS)’ (Auger et al., 1939). As a result of these chain reactions, a large number of secondary particles (pions, muons, neutrons, electron-positron pairs, neutrinos, etc.) are produced, depending on the energy of the primary particle (Kampert & Unger, 2012). Neutrons, which have a lifetime of 878.4±0.5 seconds and are electrically neutral, are produced in this process through nuclear fission and hadronic interactions (Particle Data Group et al., 2022). Since they do not carry an electric charge, they can travel relatively long distances (approximately 3–10 km) in the atmosphere without being affected by the Earth's magnetic field (Gaisser et al., 2016). This property makes them detectable by NM instruments located at ground level. Monte Carlo simulations have shown that the scattering processes responsible for secondary neutron production are sensitive to the kinetic energy of incoming primary CRs and changes in the density profile of the atmosphere (Heck et al., 1998).

These continuous and sensitive observations play a critical role in understanding the dynamics of space weather events. NM instruments typically record long-term variations in Galactic Cosmic Rays (GCR), such as those associated with the Sun's 11-year sunspot cycle and 22-year magnetic cycle (Potgieter, 2013). In addition, they successfully detect sudden and transient events. When coronal mass ejections (CME) originating from the Sun and the magnetic clouds they create reach Earth, they block CRs from accessing our planet, causing sudden and temporary drops in their density; these events are known as Forbush Decreases (FD) (Cane, 2000). In much rarer cases, the Sun produces such intense events that the accelerated particles increase the radiation level at ground level to a degree that can be easily detected by NM. These events, known as Ground Level Enhancement (GLE) (Plainaki et al., 2007; Polatoğlu, 2025), serve as evidence of the most energetic solar events.

The scientific impacts of CR research are diverse. These studies enhance our understanding of both fundamental physics and interstellar environment dynamics by testing theories regarding particle acceleration and propagation in astrophysical environments. CRs serve as natural probes for obtaining information about magnetic fields and turbulence structures in the galaxy and provide valuable clues about the interstellar medium and galactic wind formation. From a technological perspective, CRs have direct impacts on fields such as space engineering and radiation safety. Secondary particles produced in atmospheric showers pose a serious risk by causing Event Effects (SEEs) in sensitive electronic devices used in space missions and high-altitude aviation (Normand, 1996). Therefore, research on CRs and their atmospheric interactions has also pioneered the development of new detection techniques, advanced simulation tools, and machine learning methods, finding a wide range of applications in both scientific research and applied technologies (Polatoğlu, 2024). In this regard, CRs are both a cornerstone of our efforts to understand the universe and an important area of research that encourages innovative solutions in the fight against their effects on modern technologies.

Table 1. Features of NM64 and IGY monitors.

Feature	IGY Standard	NM64 Standard
Introduction Year	1957	1964
Alias	Simpson Monitor	Super monitor
Counting Efficiency	Standard	High (~3.3 times more than IGY)
Reflector/Moderator	Paraffin	Polyethylene
Design Purpose	First global standard network	To increase sensitivity and counting rate
Current Use	Very rare, mostly for historical data	The main standard for the worldwide network

Working Principles of Neutron Monitors

A standard NM design is typically the International Geophysical Year (IGY) or the IGY monitor developed by Hatton and Carmichael in 1964 to increase the Simpson's International Geophysical Year (IGY) design or the NM64 standard developed by Hatton and Carmichael in 1964 to increase the efficiency and counting rate of the IGY monitor, and is configured to maximise sensitivity to secondary neutrons produced in widespread air showers created by primary cosmic rays with energies above the local geomagnetic cutoff (Hatton, 1971). The characteristics of the NM64 and IGY monitors are shown in Table 1. The basic function of the device is to efficiently capture and count these neutrons produced in the atmosphere and convert them into electrical signals. This detection process occurs as a multi-stage chain of physical reactions through several basic components that work together, and is summarised schematically in Figure 2. An example of an NM chamber (ROME) is shown in Figure 1.

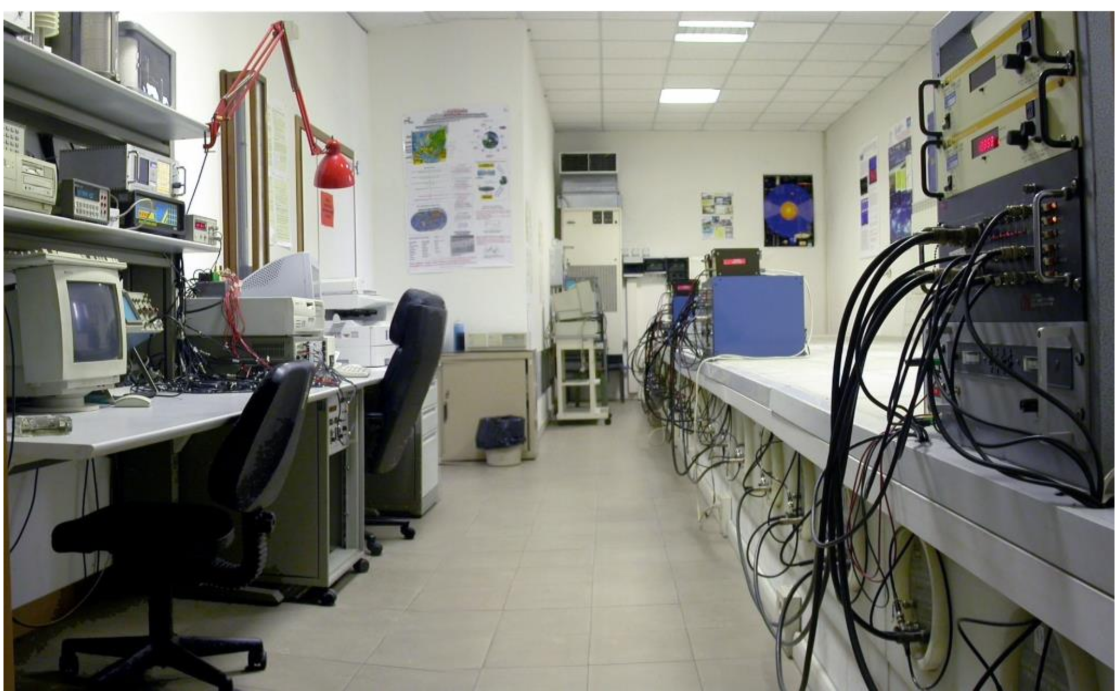

Figure 1. Interior view of the ROME Neutron Monitor station. It is a 20-NM64 type neutron monitor consisting of a total of 20 counter tubes. This structure consists of different units, including three 3-counter units, one 5-counter unit, and one 6-counter unit (NMDB, 2025) (https://www.nmdb.eu/station/rome).

The neutron detection process begins when a secondary neutron from the atmosphere enters the detector and follows these steps:

i. Neutron Multiplication (Lead Producer): A high-energy neutron entering the detector first interacts with the multiplier layer, which consists of thick lead blocks. The collision of the incoming neutron with lead nuclei triggers nuclear reactions known as spallation. As a result of these reactions, a large number of new, lower-energy neutrons are scattered from the single incoming neutron, and the initial signal is amplified (Bauer, 2001).

ii. Neutron Slowdown (Polyethylene Moderator): The fast neutrons emitted by the generator then enter the moderator layer, which surrounds the detector tubes and is typically made of polyethylene. This material, rich in hydrogen atoms, effectively causes fast neutrons to lose their energy through elastic collisions and slows them down to thermal energy levels. This moderation process is of critical importance as it maximises the probability of neutron capture in the next stage (Clem & Dorman, 2000).

iii. Neutron Detection and Signal Generation (Proportional Counter): When a neutron reaches thermal velocity, it loses its energy through numerous elastic collisions with its surroundings (particularly with atoms in the medium) and eventually reaches an average kinetic energy (i.e., thermal equilibrium) corresponding to the temperature of the medium it is in. Thermalised neutrons enter gas-filled proportional counter tubes, which are the heart of the detector and are typically filled with Boron Trifluoride (BF3) or Helium-3 gas. A thermal neutron is captured by the nucleus of a gas atom inside the tube. For example, in the case of BF3 gas, a neutron is captured by a Boron-10 nucleus, triggering the ^{10}B (n, α) reaction. This nuclear reaction produces energetic charged particles (an alpha particle and a Lithium nucleus) capable of ionising the gas. This ionisation creates an electrical pulse within the tube; this pulse is amplified by electronic circuits and counted as a valid 'count' if it exceeds a certain threshold value. These count rates reflect temporal changes in the incoming CR flux (Clem & Dorman, 2000).

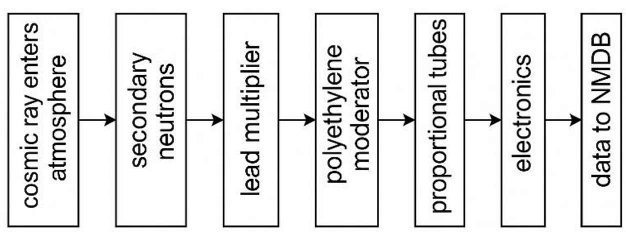

Figure 2. Neutron Monitor (NM) System Working Diagram

The recorded raw count rates are sensitive to changes in CRs flux as well as various local atmospheric and environmental conditions. Therefore, raw data must undergo calibration and correction protocols to ensure reliability before being used in scientific analyses. The main factors affecting data quality are as follows:

- Atmospheric Pressure: This is the most dominant environmental effect on measurements. An increase in air pressure at the station increases the mass thickness of the atmosphere, leading to greater absorption or scattering of secondary neutrons. This reduces the net neutron flux reaching the detector and, consequently, the count rate.

- Temperature and Environmental Conditions: Changes in ambient temperature can affect detector efficiency by altering the density of the moderator material and the reaction kinetics of the counter gases. In addition, structures such as snow, puddles, or buildings in the immediate vicinity of the detector can scatter or absorb incoming neutrons, thereby altering the measured count rate.

Neutron Monitor Database (NMDB) and NM Applications

The NMDB was established to collect, standardise, and make available secondary neutron data on a global scale. The NMDB is a central data repository that stores high-time-resolution data from NM stations located around the world. Funded as an e-Infrastructure project under the European Commission's Seventh Framework Programme (FP7), the NMDB is an international collaboration bringing together research institutions from various countries. Thanks to this initiative, stations in the global network, which have been collecting data for over 60 years, have begun to transmit their data in a standard format and in real time to a centralised system.

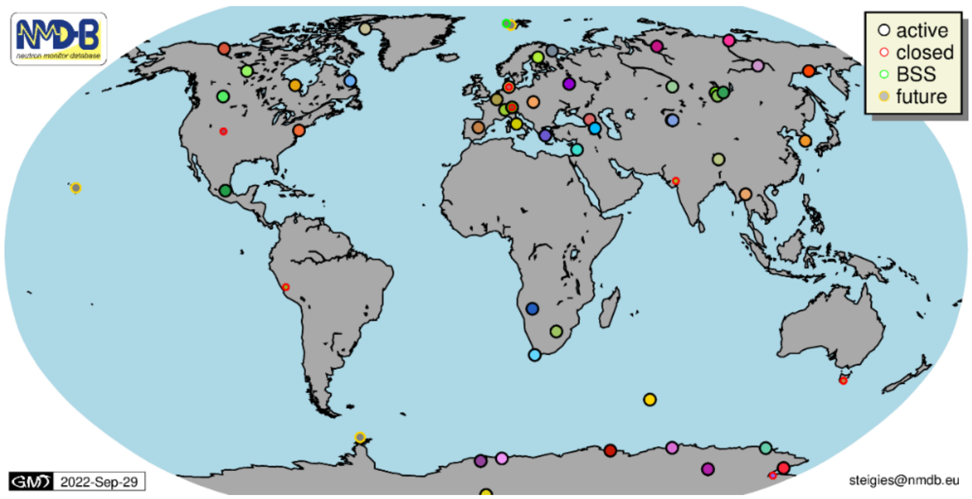

Figure 3. Neutron monitoring stations in the world (NMDB, 2025)

NMDB collects its data from a globally distributed network of NM stations. These stations are geographically distributed from the poles to the equator. Historically, 63 NM stations have been established worldwide. As shown in Figure 3, some of these stations continue to actively collect data today, while others are closed. 56 are active, while 6 are closed. One of these 63 stations is the 'UFSZ' station. This station is slightly different from the others. The UFSZ station operates using 'Bonner spheres.' These spheres, which serve as moderator material within the NM, count neutrons by separating them according to their energy levels. In other words, each neutron interacts with spheres of different sizes inside the station based on its energy level (Thomas & Alevra, 2002).

NM data have versatile applications for understanding Sun-Earth interactions by examining changes in CR density. These applications can be broadly categorised into two main categories: monitoring long-term changes associated with solar activity and detecting and analysing sudden, transient space weather events. Continuous NM data series spanning decades enable the quantitative assessment of long-term relationships, such as the modulation observed in GCR flux during the Sun's 11-year activity cycle. This provides a critical foundation for modelling particle transport processes in the heliosphere and the effects of solar activity on Earth's radiation environment. The most critical application of NM data is the analysis of sudden and potentially dangerous space weather events. Among these events, Solar Energetic Particle (SEP) events originating from the Sun and reaching energies of GeV levels are at the forefront. These most intense SEP events can only be detected at ground level by the global NM network and are referred to as Ground Level Enhancements (GLEs). The confirmation of an event as a GLE is based on the observation of a simultaneous and statistically significant increase in counts at multiple stations in different geographical locations. These rare events, which occur only a few times per solar cycle, serve as natural laboratories for understanding how particles are accelerated to such high energies and propagated in the Sun and heliosphere. The analysis of GLE events requires various advanced techniques that leverage the power of the global NM network:

Time Series Analysis: By examining the temporal variation of count rates at each station, temporal characteristics such as the sudden onset time of the event, the time to reach maximum, and the decay profile are precisely determined.

Spectral and Angular Distribution Analysis: Since each station in the global network has a different cut-off energy and a different 'view' direction, the energy spectrum and angular distribution (anisotropy) of incoming particles can be modelled. This analysis is crucial for revealing the spatial and temporal structure of SEP events and provides direct data for testing particle acceleration models (Plainaki et al., 2007).

Real-Time Warning Systems: NM data is fed in real time into systems that automatically detect GLE events in their initial stages and generate space weather warnings. Systems such as the developed 'GLE Alert Plus' play a critical role in providing timely warnings against radiation risks for technological systems such as high-altitude aviation and satellite operations.

NM data are also used to investigate the characteristics of Forbush Decreases (FD) caused by magnetic clouds associated with coronal mass ejections (CME) from the Sun. The analysis of these events provides fundamental data for the development and validation of space weather prediction models. The effectiveness of all these applications has been enhanced by integrating the data into central databases such as NMDB. These platforms facilitate multi-station analyses, thereby improving the reliability of space weather predictions and deepening our scientific understanding of solar physics.

Thanks to the data provided by the NMDB platform and the atmospheric cascade models developed, significant applications have been developed in the field of cosmic radiation dosimetry in aviation. Among the prominent applications are AVIDOS (Aviation Dosimetry System) (Latocha et al., 2009), designed to calculate and record the radiation doses to which pilots and flight crew are exposed, and EPCARD (European Program Package for the Calculation of Aviation Route Doses) (Schraube et al., 2000), which performs effective dose calculations for flight routes across Europe. These systems model the radiation environment, which varies depending on solar activity and geomagnetic conditions, providing critical information for flight safety and personnel health.

Data and Method

The data used in this study were obtained from the Neutron Monitor Database (NMDB), which provides researchers with high-temporal-resolution CRs data (https://www.nmdb.eu). The NMDB offers great flexibility in data access by providing both user-friendly web interfaces and application programming interfaces (APIs) that enable programmatic access. The raw neutron count rates with a 1-month resolution and the corresponding atmospheric pressure values used in the study were obtained through this platform. The geographical locations and technical specifications of the analysed stations are summarised in Table 2. The study period covers the time interval from 01.01.2010 to 01.01.2025.

Table 2. Neutron monitors and their features

Abbreviation	Station Name	Latitude (°)	Longitude (°)	Altitude (m)	Cut- off Rigidity (GV)
TERA	Terre Adélie	–66.66	140.00	32	0.01
OULU	Oulu	65.05	25.47	15	0.81
NEWK	Newark	39.68	–75.75	50	2.40
ROME	Rome	41.90	12.52	0	6.27
ATHN	Athens	37.97	23.78	260	8.53

The latitude, longitude, altitude, and cut-off rigidity values given in Table 2 are important factors affecting the recorded CR flux. Stations at high magnetic latitudes detect lower-energy CRs, while higher altitudes generally measure higher fluxes due to reduced atmospheric absorption (Gaisser et al., 2016). Cut-off Rigidity defines the minimum rigidity required for a particle to pass through the magnetic field (Simpson et al., 1953) and is lower in regions closer to the poles. This situation leads to stations with low cut-off rigidity detecting a broader energy spectrum. Longitude, on the other hand, can cause stations at the same latitude to have different cut-off rigidity due to the non-homogeneity of the Earth's magnetic field.

In order to follow a repeatable and automated process for data access, NMDB's RESTful API infrastructure was utilised. This approach enabled queries to be created for specific stations and time intervals, and data to be pulled directly into the analysis environment using the Python programming language and the ‘requests’ library. The data provided by NMDB is in a standard plain text (ASCII/CSV) format that is compatible with various computational tools. This allows the data to be efficiently converted into structured data frames using Python libraries such as pandas, NumPy, plot, etc.

These raw census rates, which form the basis of the analyses, contain fluctuations caused by atmospheric pressure changes that can mask the actual signal. Therefore, processing the raw data before using it in subsequent stages is a critical step. The barometric correction procedures and other methodological steps applied to the data are explained in detail in the next section.

Method

The methodology followed in this study involves analysing data obtained from NMDB using a workflow developed in Python. The entire data processing process was carried out programmatically to ensure the reproducibility and accuracy of the results. The raw neutron count rates obtained from the NMDB and the corresponding instantaneous atmospheric pressure (P) data form our basic data set. These data were transferred to a DataFrame object using the pandas library, which provides a powerful and flexible structure for time series analyses. This structure facilitated the organisation, management, and preparation of the dataset for subsequent steps.

One of the most critical pre-processing steps in the analysis of NM data is the correction of atmospheric pressure changes, which are the primary source of non-astrophysical fluctuations. To eliminate this effect, a barometric correction procedure based on the Dorman Equation, which is accepted as standard in the literature, was applied (Dorman, 1991). The relevant formulation is given in Equation 1:

$$N_{corr} = N_{raw} \cdot e^{-\beta(P-P0)} \quad (1)$$

The parameters in the equation are defined and applied as follows. Ncorr: The final count rate corrected for pressure effects and ready for analysis. Nraw: Raw count data. β: The barometric coefficient specific to each observation station, obtained from the literature. P: The instantaneous atmospheric pressure value. P0: The reference pressure is calculated as the average of the pressure series to establish a stable baseline throughout the observation period. This value was calculated using pandas' statistical functions. Numerical calculations such as exponential functions were efficiently performed using the NumPy library, which offers high performance in scientific calculations. At the end of this methodological process, a reliable time series was obtained, free from atmospheric pressure effects, which will serve as the basis for subsequent scientific analyses.

Research Findings

Raw data obtained from NMDB stations, atmospheric conditions affecting these data, and refined results obtained after applying the procedures described in the Method section are presented and interpreted.

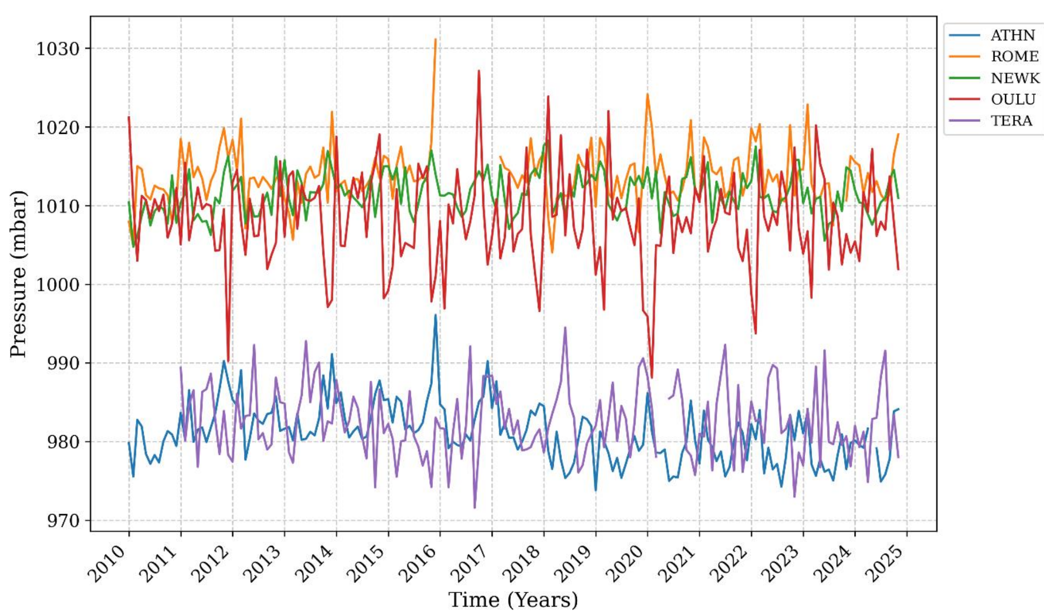

Figure 4. Atmospheric pressure time series for NM stations

Atmospheric pressure is the most important meteorological parameter directly affecting CR count rates at ground level. An increase in pressure increases the mass of the atmosphere, causing more absorption of secondary particles from CRs and thus a decrease in the count rate. Conversely, a decrease in pressure causes an artificial increase in the count rate. As shown in Figure 4, pressure values at stations exhibit significant seasonal and daily fluctuations. These fluctuations create noise in raw CR data, making it difficult to detect real signals.

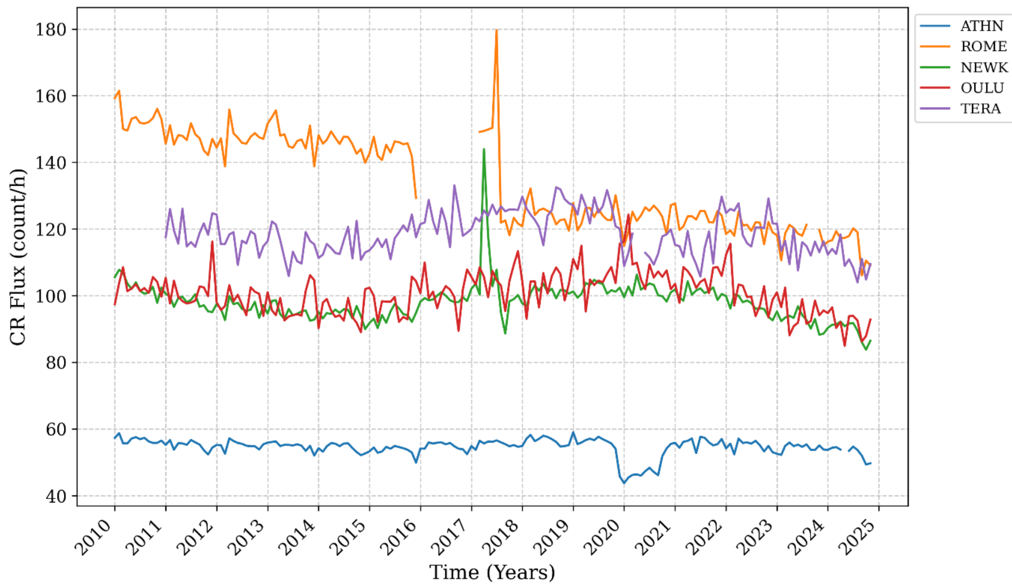

Figure 5. NM raw cosmic ray count time series

The raw data contains both changes caused by real astrophysical processes, such as solar activity, and noise created by atmospheric pressure fluctuations, as shown in Figure 5. The short-term and sharp ups and downs in the graph are largely a reflection of the pressure effect. The sudden spikes and drops observed at many stations are more likely due to changes in local weather conditions than to a real CR event.

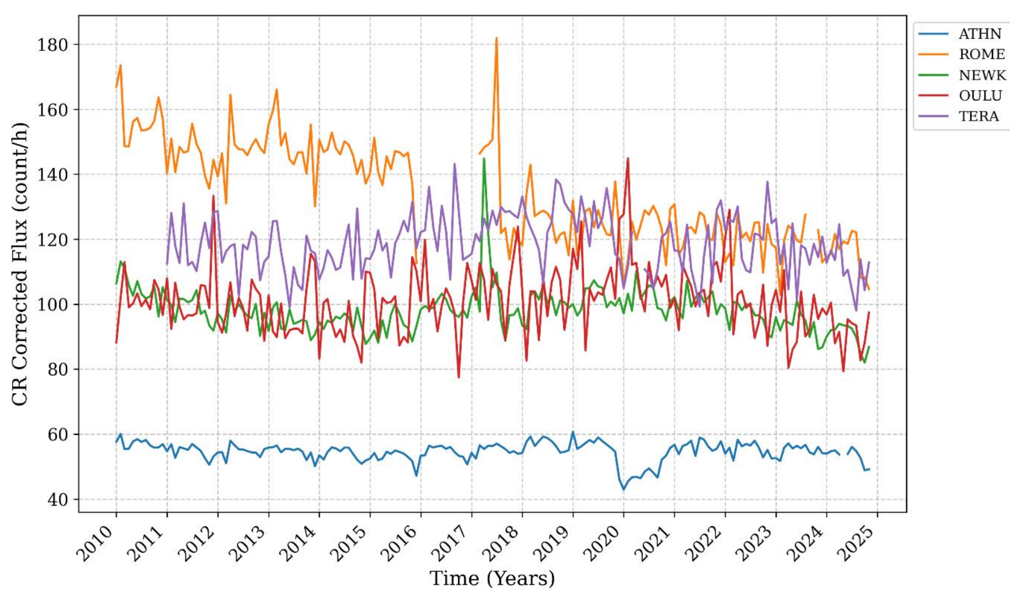

Figure 6. Final CRs time series obtained after applying pressure correction

After applying barometric correction, it can be observed that some of the short-term fluctuations in Figure 5, which are thought to be pressure-related, have decreased or disappeared. The corrected data has the potential to better reflect the actual physical changes in CR flow. For example, a sharp drop or increase observed at a particular station in Figure 5 may turn into a smoother trend or disappear completely when the pressure effect is eliminated in Figure 6. This situation demonstrates that barometric correction is an important step in increasing the comparability and reliability of data obtained from detectors in different geographical locations. When both figures are examined together, the effect of atmospheric pressure on CR measurements and how this effect can be minimised using appropriate correction methods is clearly demonstrated.

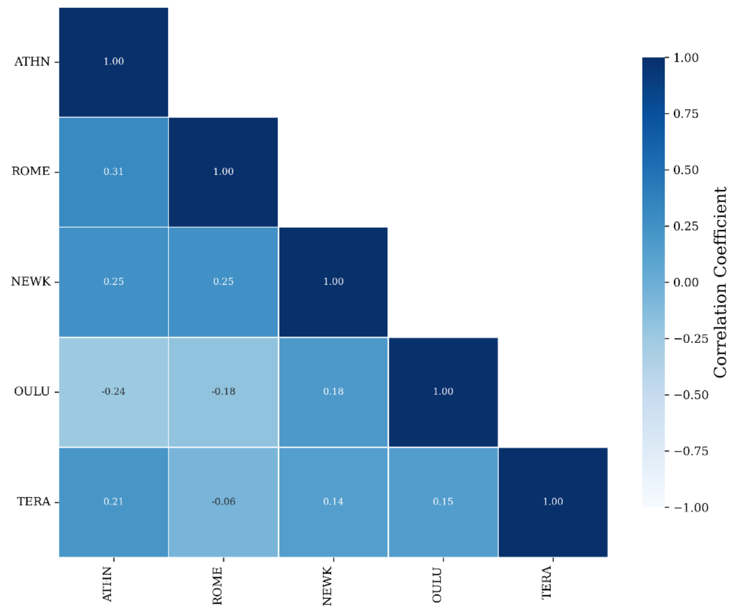

Figure 7. Correlation matrix created for stations

The correlation matrix presented in Figure 7 shows the linear relationship between the corrected CR flux data obtained from five different stations: ATHN, ROME, NEWK, OULU, and TERA. The strongest positive correlation, with a value of 0.31, is observed between the ATHN and ROME stations, and these two stations also exhibit similar positive correlations with NEWK, with values of 0.25, respectively. On the other hand, the OULU station exhibits a negative correlation with ATHN (-0.24) and ROME (-0.18). This situation is due to the stations being located in different locations and at different altitudes, as well as the data not being continuous.

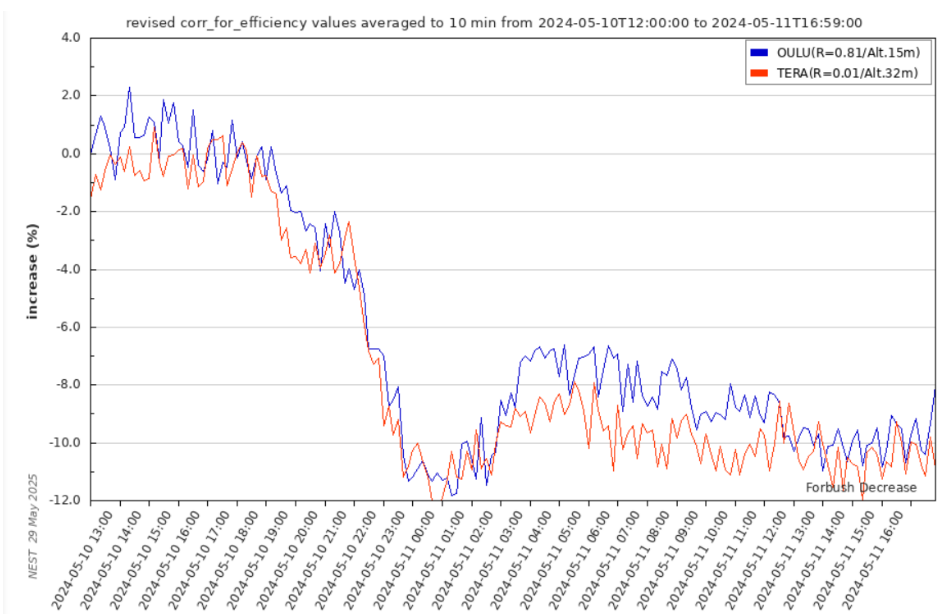

Figure 8. Forbush Decrease (FD) observed from OULU and TERA stations

There was also a significant decrease in CRs at the OULU and TERA stations, which began to become apparent between 19:00 and 20:00 on 10 May 2024 and intensified towards midnight (Figure 8). The largest decrease in CRs flux was recorded in the early hours of 11 May 2024 (00:00-01:00). The flux at the OULU station dropped to approximately -11%, while at the TERA station it reached -12% levels.

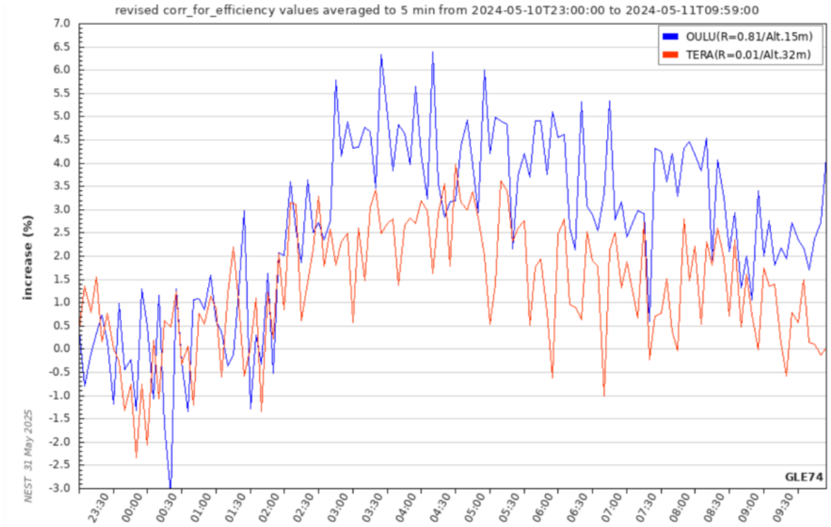

Figure 9. 74th Ground Level Enhancements (GLE) meeting held on 10 May 2024

Figure 9 shows a sudden and significant increase in the CR flux at both stations above the general background fluctuation, which is the most distinctive feature of a typical GLE event. GLE events are characterised by the entry of very high-energy particles from the Sun into the Earth's atmosphere, creating secondary particle showers, which are recorded as a sudden increase in counts by NM or muon detectors on the ground.

Conclusion

In this study, CR count values, and pressure data obtained from NMDB were examined. NM systems, which have been active since the 1960s, provide very important information for solar events, atmospheric air, and space studies. In our study, a correction process was applied to remove the effects of atmospheric pressure from the raw CR data, and the results of this process were evaluated. The research findings clearly show that raw CRs data are significantly affected by irregular fluctuations in atmospheric pressure, which reduces data quality. By applying the barometric correction based on the Dorman equation in the Python environment, it was found that this atmospheric noise was successfully eliminated, resulting in much more stable and smooth time series. This situation unequivocally confirms that atmospheric correction is an indispensable pre-processing step for the reliable investigation of space weather events (such as FD and GLEs) and long-term changes related to solar activity. Correlation analysis performed on the corrected CRs data revealed that the relationships between stations vary depending on factors such as geographical location and cut-off rigidity. However, only the increasing or decreasing trends show similarities in long-term measurements.

Research on CRs and NM systems in Turkey is still in its infancy. Although there are scintillator-based muon detectors in Turkey, there is no active NM station yet. Nevertheless, scientific and academic studies in this field are increasing. In the future, establishing an NM station by leveraging Turkey's geographical location advantage will enable the country to integrate into international space weather and astrophysics research networks, thereby enhancing national scientific capacity and contributing significantly to global data.

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