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Coherent Analysis of Intense Geomagnetic Disturbances Using Dusheti Observatory Data and the DST Index

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ABSTRACT

Geomagnetic storms are intense disturbances in Earth's magnetosphere that can disrupt technological systems and impact human health. This study investigates the dynamics of solar-terrestrial interactions using data from the Dusheti Observatory and global geomagnetic indices. We examined the relationships between the interplanetary magnetic field (IMF), sunspot numbers, and the H-component of the geomagnetic field during the period from 2023 to 2024, focusing on the unprecedented geomagnetic storm of May 11, 2024. Through wavelet coherence and cross-correlation analyses, we identified significant interactions between solar and geomagnetic activity, with coherence patterns emerging well before the storm onset. The analysis of six solar cycles (1964–2024) revealed correlation at lag of 5 days, highlighting the potential predictive utility of sunspot numbers. This study also validated the reliability of local geomagnetic data, emphasizing its importance for understanding the regional manifestations of global geomagnetic events in Georgia. The findings contribute to the development of improved predictive models for geomagnetic disturbances and underscore the need for localized studies to better mitigate the risks associated with space weather.
Key words: *Geomagnetic storms, Dusheti observatory, Interplanetary magnetic field, DST index, Wavelet coherence, cross-correlation, Space weather prediction*

Introduction

Geomagnetic storms cause significant disruptions and sharp drops in Earth's magnetic field, they are primarily driven by the interaction between solar wind, the interplanetary magnetic field (IMF) and Earth's magnetic field. Geomagnetic storm of 11 may 2024 was the most powerful storm of 21st century and captured global attention [1].

The dynamics of these storms stem from nonlinear interactions between the Sun's plasma outflows and Earth's magnetic field, which underscores the need to study their evolution and coupling with external drivers such as the IMF and solar activity. To better understand these processes, this study examines geomagnetic data from the Dusheti Observatory and Disturbance Storm Time (DST) index, a global measure of geomagnetic storm intensity. The DST index quantifies magnetic field variations due to ring currents formed during storms [2]. Comparing them validated the accuracy of Dusheti's H component data, providing a foundation for further analysis of geomagnetic perturbations. We also explore relationships between geomagnetic field variations, IMF, and solar activity (sunspot numbers). Wavelet coherence and cross-correlation methods were used to analyze these connections, with a focus on identifying patterns that might serve as predictors for geomagnetic storms. Understanding these relationships is critical, as intense geomagnetic storms have significant implications for technology, infrastructure, and human health, Our primary interest lies in understanding how these storms impact Georgia, using Dusheti Observatory's data to gain insights into local manifestations of global geomagnetic events [3, 4].

This work aims to study quantifiable patterns and correlations between the geomagnetic field, the IMF, and solar activity during periods of intense geomagnetic activity. By doing so, we hope to enhance predictive capabilities for geomagnetic disturbances, which could mitigate the risks posed by space weather and contribute to a better understanding of geomagnetic storm dynamics in both global and regional contexts [4, 5].

Data and methods

The study focuses on data collected from August 2023 to July 2024, analyzing different time periods to uncover relationships between geomagnetic field variations, sunspot numbers, and the interplanetary magnetic field (IMF). A key focus is the geomagnetic storm on May 11, 2024 (Fig. 1 and 2), one of the largest recorded during this period (Figure 2). The data used includes the DST index and sunspot numbers obtained from NASA's OMNIWeb service [7], alongside the H-component of the geomagnetic field recorded at the Dusheti observatory (station code: TBS, Geographic coordinates: 42.08°N, 44.7°E. Geomagnetic coordinates: 37.96°N, 117.16°E. Altitude: 982 m) in Georgia. All of the datasets have a resolution of one hour, enabling high-precision temporal analysis. Missing data points were addressed using linear interpolation to ensure continuity.

To investigate correlations between these datasets, we employed wavelet coherence analysis and cross-correlation techniques. Wavelet coherence is particularly suited for identifying and quantifying relationships between nonstationary signals across time and frequency domains. This method allows for a detailed exploration of how the phase and amplitude relationships between signals evolve over time, even in regions where individual wavelet coefficients are weak. By revealing periods and frequencies where the signals are coherent, wavelet coherence enhances our ability to identify and interpret significant patterns.

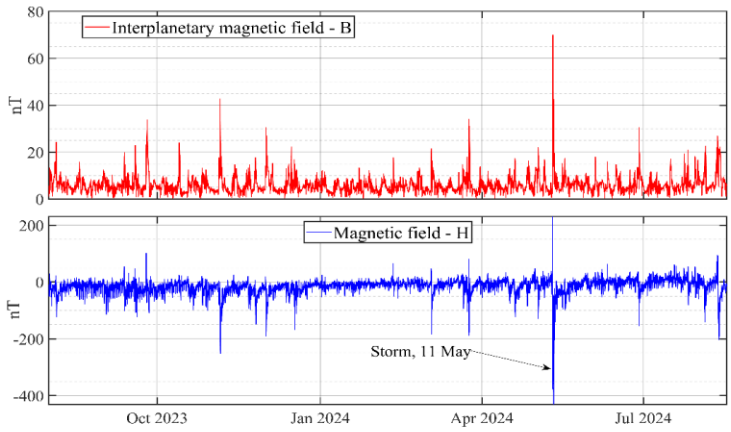

Fig. 1. B - Interplanetary magnetic field and H component of geomagnetic field.

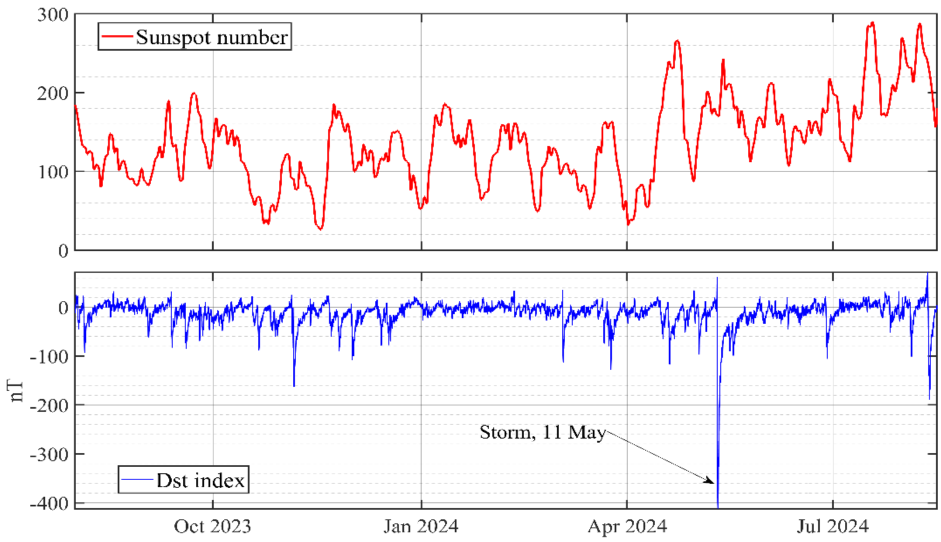

Fig. 2. Sunspot numbers and Dst index.

In addition to wavelet coherence, we divided the sunspot and DST data into six sections corresponding to solar cycles. This segmentation enabled a detailed cross-correlation analysis for each cycle. The cross-correlation function was calculated for detrended datasets, where trends were removed using moving averages, with windows of 365 days. This detrending process ensured that only fluctuations relevant to the study's objectives were analyzed. Than for the cross-correlation analysis: Each solar cycle segment was independently analyzed to compute the cross-correlation function over a maximum lag of 90 days. Correlation coefficients (ρ) and corresponding lags were calculated for each segment to determine the temporal relationship between the detrended sunspot and DST datasets. The results from all six segments were combined using a mathematical approach to aggregate the correlation results: The datasets were analyzed for their common signs at each lag to determine a consensus sign. The combined correlation was computed as the geometric mean of the absolute values of the segment correlations, weighted by the common sign.

This method provides a comprehensive view of the relationships between sunspot numbers and geomagnetic field variations across solar cycles, highlighting both consistent and cycle-specific patterns. The results have implications for understanding how solar activity influences Earth's geomagnetic environment and for identifying potential predictors of geomagnetic disturbances.

Results and discussion

Wavelet-Coherence analysis. The wavelet coherence analysis of the interplanetary magnetic field (IMF) and the H-component of the geomagnetic field at different time periods reveal interesting relationships between the two signals. In Figure 3, we see that from february to August 2024, the IMF and geomagnetic field exhibit coherence at the lowest frequencies. However, during geomagnetic storms, coherence becomes visible at higher frequencies, even before the storms begin. During intense geomagnetic storms, the coherence spans a broader spectrum of frequencies, extending to even lower periodicities. This suggests that geomagnetic storms influence the dynamics of the IMF and geomagnetic field across a wide range of frequencies, enhancing coherence between the two signals.

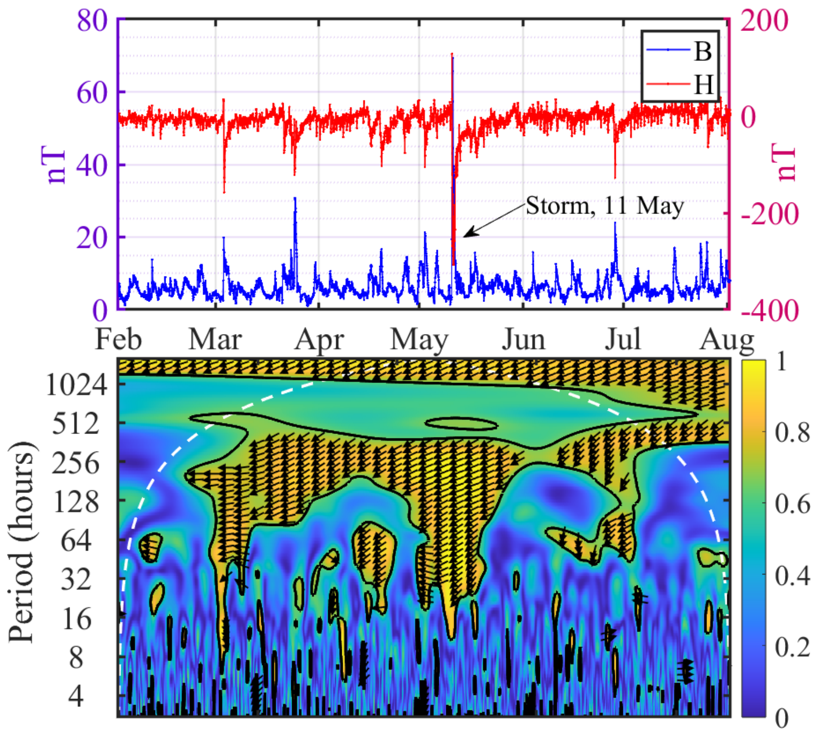

Fig. 3. Wavelet coherence between IMF and H component of geomagnetic field.

We applied the same method to analyze the coherence between sunspot numbers and both the H-component of the geomagnetic field and the DST index. Fig. 4 and 5 reveal coherence in both cases well before the geomagnetic storm occurs. This is indicated by the yellow regions on the plots, which appear as early as mid-March, approximately two months prior to the storm. These findings are particularly intriguing as they highlight the potential for using the relationship between sunspot numbers, geomagnetic data, and the DST index as an early indicator of strong geomagnetic storms. However, further investigation is required to fully understand and validate this predictive capability.

Cross-correlation. In this study, we utilized the cross-correlation method to analyze the relationship between sunspot numbers and the Dst index on a larger scale. The data, spanning from 1964 to 2024, was segmented according to six solar cycles (the last cycle being incomplete). For each solar cycle, we measured the cross-correlation between these datasets and aggregated the results.

Our findings, presented in Fig. 6, indicate a cross-correlation of 8% with a 5-day lag. These results suggest the potential utility of sunspot numbers as a predictive indicator for geomagnetic activities.

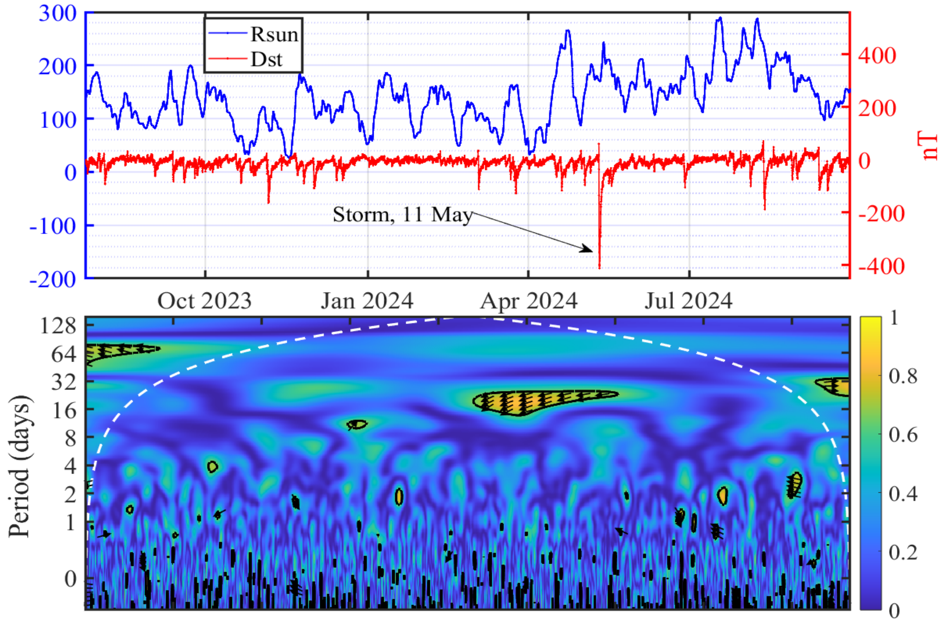

Fig. 4. Wavelet Coherence of sunspot number and DST index.

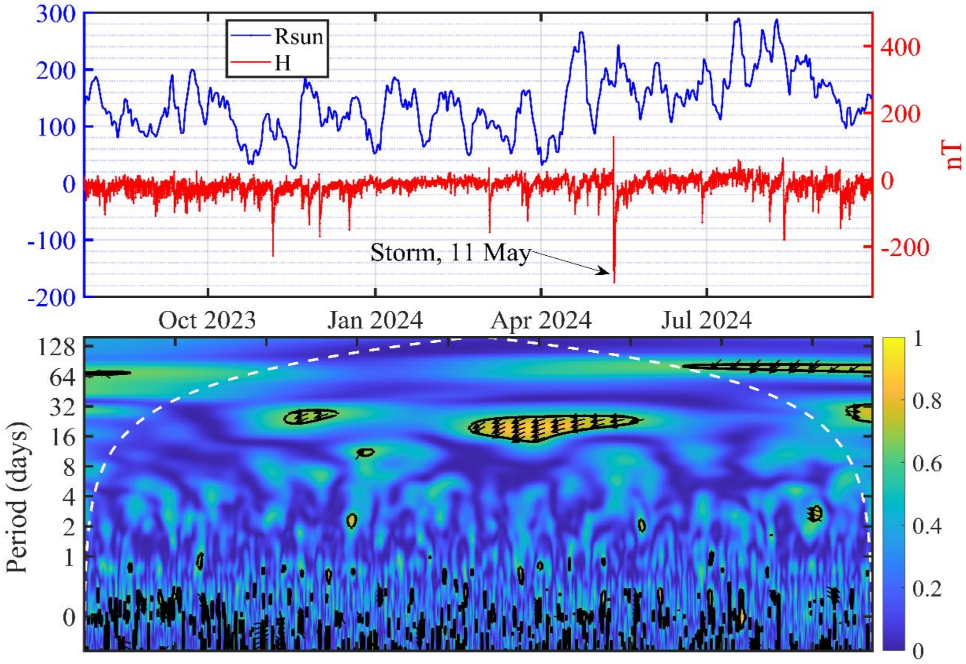

Fig. 5. Wavelet Coherence of sunspot number and H component of magnetic field.

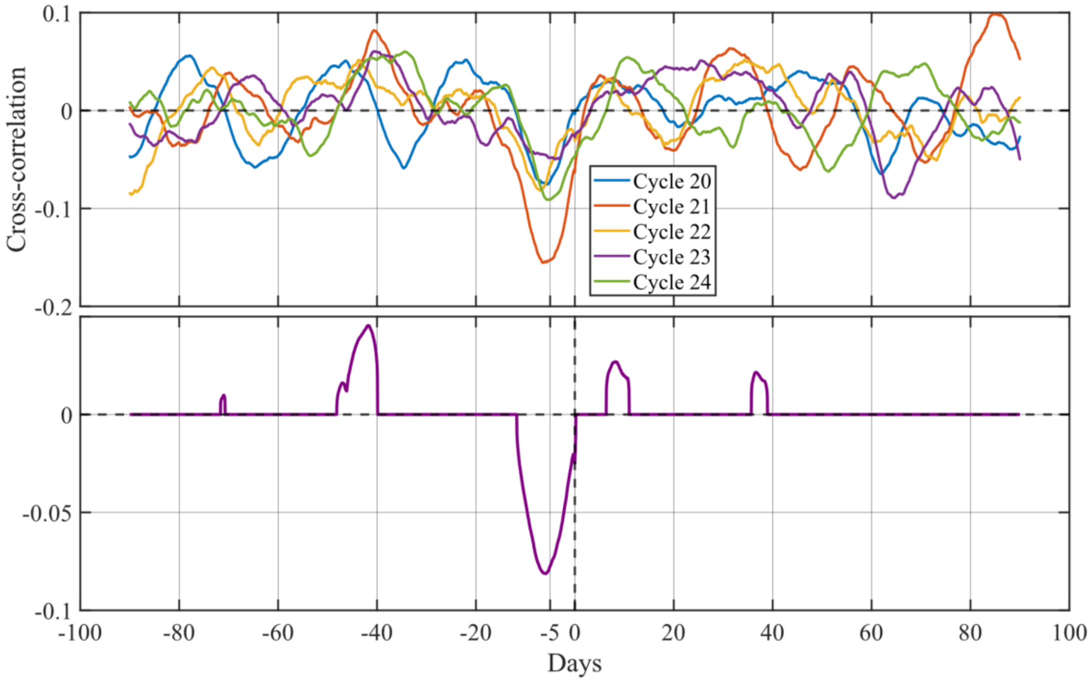

Fig. 6. Cross-Correlations of sunspot number and DST index.

Conclusion

This study provides a comprehensive analysis of the relationships between solar activity, the interplanetary magnetic field (IMF), and geomagnetic variations, with a particular focus on the geomagnetic storm of May 11, 2024. By utilizing high-resolution data from the Dusheti Observatory and global indices such as the Dst index, we validated the accuracy of local geomagnetic field measurements and explored their connections to solar drivers.

The wavelet coherence analysis revealed significant patterns of interaction between solar and geomagnetic datasets, particularly the ability to detect coherence at higher frequencies preceding geomagnetic storms. This underscores the potential for using sunspot numbers and IMF data as early indicators of geomagnetic disturbances. Cross-correlation analysis further supported this potential, demonstrating a measurable lagged relationship between sunspot activity and geomagnetic indices across multiple solar cycles.

These findings enhance our understanding of the dynamics of geomagnetic storms and their coupling with solar activity. They also highlight the potential for predictive modeling, which could mitigate the impacts of space weather events on infrastructure, technology, and human health. Future studies should focus on refining these methods and incorporating additional datasets to improve the robustness and accuracy of predictions.

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მძლავრი გეომაგნიტური შეშფოთებების კოჰერენტული ანალიზი დუშეთის ობსერვატორიის მონაცემებისა და DST ინდექსის მაგალითზე

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რეზიუმე

გეომაგნიტურმა ქარიშხალებს შეუძლიათ წყობიდან გამოიყვანონ ტექნოლოგიური სისტემები და გავლენა მოახდინონ ადამიანის ჯანმრთელობაზე. ამ კვლევაში განვიხილეთ მზე-დედამიწის ურთიერთქმედების დინამიკა დუშეთის ობსერვატორიის და გლობალური გეომაგნიტური ინდექსების გამოყენებით. ჩვენ გამოვიკვლიეთ ურთიერთობა პლანეტათაშორის მაგნიტურ ველს (IMF), მზის ლაქების რიცხვებსა და გეომაგნიტური ველის H - კომპონენტს შორის 2023 წლის აგვისტოდან 2024 წლის ივლისამდე პერიოდში, განსაკუთრებული ყურადღება გამახვილდა 2024 წლის 11 მაისის გეომაგნიტურ ქარიშხალზე. ვეივლეტ კოჰერენტული ანალიზით, ჩვენ გამოვავლინეთ მნიშვნელოვანი ურთიერთქმედებები მზის და გეომაგნიტურ მონაცემებს შორის, თანმიმდევრული პატერნებით რომლებიც ჩნდება ქარიშხლის დაწყებამდე. მზის ციკლების მიხედვით კორელაციურმა ანალიზმა (1964–2024) გამოავლინა 15 პროცენტიანი კორელაცია 5 დღის ჩამორჩენაზე, რაც ხაზს უსვამს მზის ლაქების რიცხვების პოტენციალს მაგნიტური ქარიშხლების წინასწარმეტყველებაში. ამ კვლევამ ასევე დაადასტურა ადგილობრივი გეომაგნიტური მონაცემების სანდოობა, ხაზი გაუსვა მის მნიშვნელობას საქართველოში გლობალური გეომაგნიტური მოვლენების რეგიონული გამოვლინებების გასაანიზებლად შედეგები ხელს უწყობს გეომაგნიტური ქარიშხლების გაუმჯობესებული პროგნოზირების მოდელების შემუშავებას და ხაზს უსვამს ლოკალიზებული კვლევების საჭიროებას კოსმოსურ ამინდთან დაკავშირებული რისკების უკეთ გასანალიზებლად.
საკვანძო სიტყვები: გეომაგნიტური შტორმები, დუშეთის ობსერვატორია, პლანეტათაშორისი მაგნიტური ველი, DST ინდექსი, ვეივლეტ კოჰერენტობა, კორელაციური ანალიზი, კოსმოსური ამინდი.

Когерентный анализ мощных геомагнитных возмущений на примере данных обсерватории Душети и индекса DST

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Х. Элбакидзе, Т. Матиашвили**

Резюме

Геомагнитные бури — это интенсивные возмущения в магнитосфере Земли, способные нарушать работу технологических систем и оказывать влияние на здоровье человека. В данном исследовании анализируется динамика солнечно-земных взаимодействий с использованием данных обсерватории

Душети и глобальных геомагнитных индексов. Мы изучили взаимосвязи между межпланетным магнитным полем (IMF), числом солнечных пятен, индексом DST и H-компонентой геомагнитного поля в период с 2023 по 2024 год, сосредоточив внимание на геомагнитной буре 11 мая 2024 года. С помощью анализа вейвлет-когерентности и кросс-корреляции были выявлены значимые взаимодействия между солнечными и геомагнитными сигналами, при этом когерентность проявляется задолго до начала бури. Анализ шести солнечных циклов (1964–2024) показал наличие корреляции с задержкой в 5 дней, что подчеркивает потенциальную прогностическую полезность числа солнечных пятен. В исследовании также была подтверждена надежность локальных геомагнитных данных, что подчеркивает их важность для понимания региональных проявлений глобальных геомагнитных событий в Грузии. Полученные результаты способствуют разработке усовершенствованных прогностических моделей геомагнитных возмущений и подчеркивают необходимость проведения локальных исследований для эффективного снижения рисков, связанных с космической погодой.
Ключевые слова: Геомагнитные бури, Душетская обсерватория, Межпланетное магнитное поле, DST-индекс, Вейвлет-когерентность, кросс-корреляция, Прогноз космической погоды.