

WAVELET-COHERENCE AND MULTIFRACTAL ANALYSIS OF GEOMAGNETIC DISTURBANCES

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Abstract. This work explores the solar wind–magnetosphere interaction during the major geomagnetic disturbances of 2024, with particular focus on the May 11 storm. We examined how variations in the interplanetary magnetic field's B_z component and solar wind dynamic pressure (P_d) translate into magnetic perturbations on Earth. The response of the terrestrial system was evaluated using horizontal field measurements from mid-latitude observatories together with the global SYM-H and auroral AL indices. Time–frequency analysis with wavelet coherence exposed the highly scale-dependent and non-stationary character of the coupling process. In addition, multifractal detrended fluctuation analysis revealed a marked reduction in the Hurst exponent during the May 11 event. This feature was present in both mid-latitude and auroral electrojet records but absent in SYM-H, highlighting distinct regional responses. The absence of this feature in the ring current index, coupled with its presence in mid-latitude and auroral records, indicates that the auroral oval expanded equatorward, leaving a clear imprint at lower latitudes. Our findings highlight that combining localized and global perspectives is essential to fully capture the diverse impacts of severe geomagnetic storms on the near-Earth environment.

Key Words: Space weather, Geomagnetic activity, Coherence analysis, Multifractal analysis.

Introduction

The dynamics of the solar wind and magnetosphere interaction form a fundamental domain of space physics, giving rise to a number of space weather phenomena [1]. The biggest consequence of this interaction is the geomagnetic storm [2], a severe global perturbation of the Earth's magnetic field. These events are not solely of theoretical interest; they have significant practical implications, including the induction of geomagnetically induced currents (GICs) that can damage power grids [3], the disruption of satellite-based communications and navigation systems, and the creation of radiation hazards for both aviation and human spaceflight. Consequently, a comprehensive understanding of the dynamics of these events is essential. This study examines the magnetospheric response to solar wind drivers during the geomagnetic storms of early 2024, integrating both local, ground-based measurements and global geomagnetic indices to provide a multi-scale analysis of the system's complex behavior.

Study area, material, and methods

The primary material for this investigation is the intense space weather events of 2024, most importantly the geomagnetic storm of May 11. Our analysis is based on a multi-source dataset designed to capture both global and local magnetospheric responses.

High-resolution (1-minute) data were utilized from a mid-latitude geomagnetic observatory (like Dusheti, Georgia) to provide a localized perspective on the magnetic field variations. To place these local measurements in a global context, we employed two widely used geomagnetic indices. The Symmetric disturbance index (SYM-H) was used to characterize the evolution of the globally symmetric ring current,

which is a primary driver of magnetic field disturbance during storms [4]. To capture high-latitude activity, we used the Auroral Low (AL) index, which measures the maximum westward auroral electrojet and serves as a key indicator of magnetospheric substorm activity [5].

The external drivers of these magnetospheric changes were characterized using solar wind parameters obtained from the OMNIweb database, time-shifted to the Earth's bow shock nose [6]. We applied Wavelet Coherence Analysis to resolve time–frequency correlations between solar wind drivers and geomagnetic responses, and Multifractal Detrended Fluctuation Analysis (MFDFA) to characterize long-range memory and scaling complexity of the time series.

Results

Wavelet-Coherence analysis.

To explore time-dependent correlations between two signals, we applied wavelet coherence, which maps the correlation of the series across both time and frequency scales. This approach has become a standard tool in space physics and geophysics applications [7,8]. Our analysis reveals that during the intense geomagnetic storms, the coherence between the interplanetary magnetic field. Coherence between B_z and the geomagnetic field's H component covers a wider range of frequencies than during the quiet times. It is noteworthy that the coherence picture between solar wind drivers and the geomagnetic response was different for the AL and SYM-H indices, suggesting that the auroral and ring current systems respond with different frequency-dependent characteristics to the same solar wind drivers. The same analysis was used for pressure (P_d) and the horizontal component of the geomagnetic field, which showcased generally the same but slightly different coherent picture. These results are presented in Fig. 1.

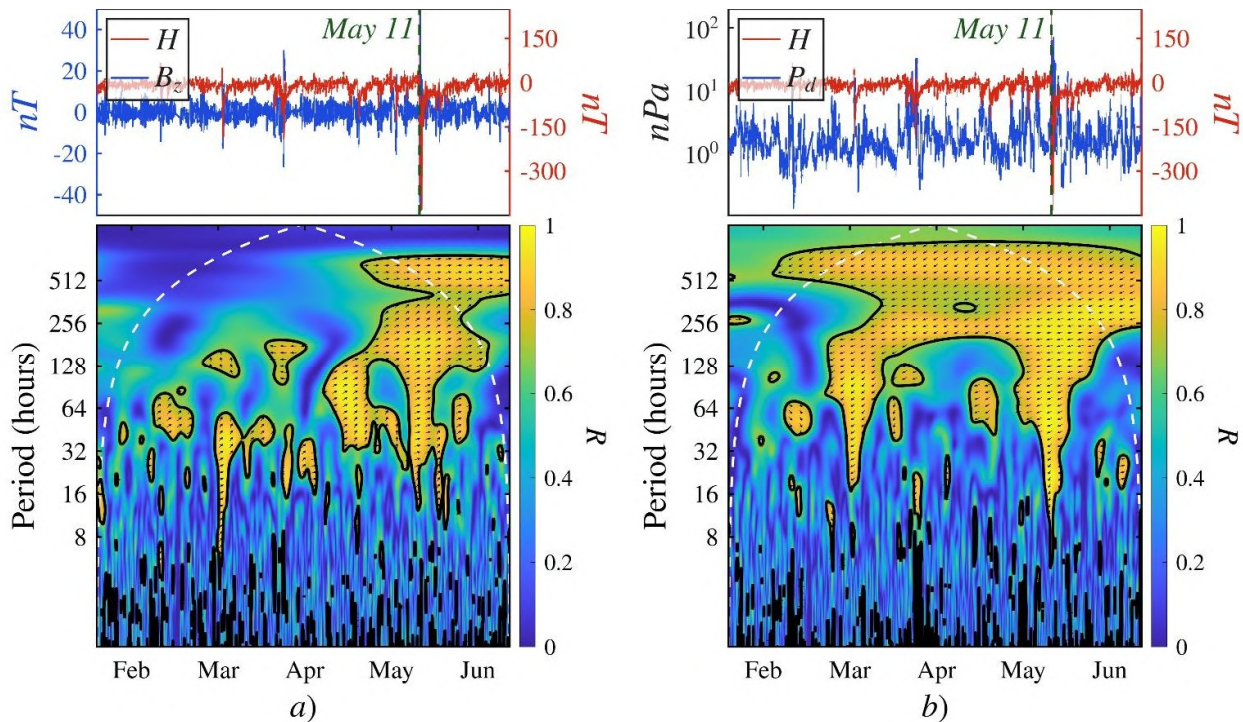


Fig. 1. Wavelet coherence analysis illustrating the coupling between the local horizontal geomagnetic field component (H) and key solar wind drivers. Panel (a) displays the coherence with the z component of the Interplanetary Magnetic Field (B_z), while panel (b) shows the coherence with the solar wind dynamic pressure (P_d).

Multifractal Detrended Fluctuation Analysis.

Detrended fluctuation analysis (DFA) was used to investigate the geomagnetic data, in this case horizontal component of the Earth's magnetic field, recorded at the mid-latitude stations and geomagnetic indices like AL and SYM-H. Through DFA we derived the Hurst exponent, an indicator of whether the fluctuations in the signal are random, persistent, or anti-persistent across scales.

Our analysis showcases the sharp changes in the Hurst exponent associated with the major geomagnetic storms. A particularly interesting result was observed during the intense storm of May 11, 2024. We found a simultaneous sharp drop in the Hurst exponent for both mid-latitude station data and the AL index (Results are shown in Fig. 2). Crucially, this drop was not present in the SYM-H index. This synchronicity suggests a significant expansion of the auroral oval, causing auroral-driven dynamics to directly influence the geomagnetic field at mid-latitudes – a phenomenon not captured by the globally averaged ring current index.

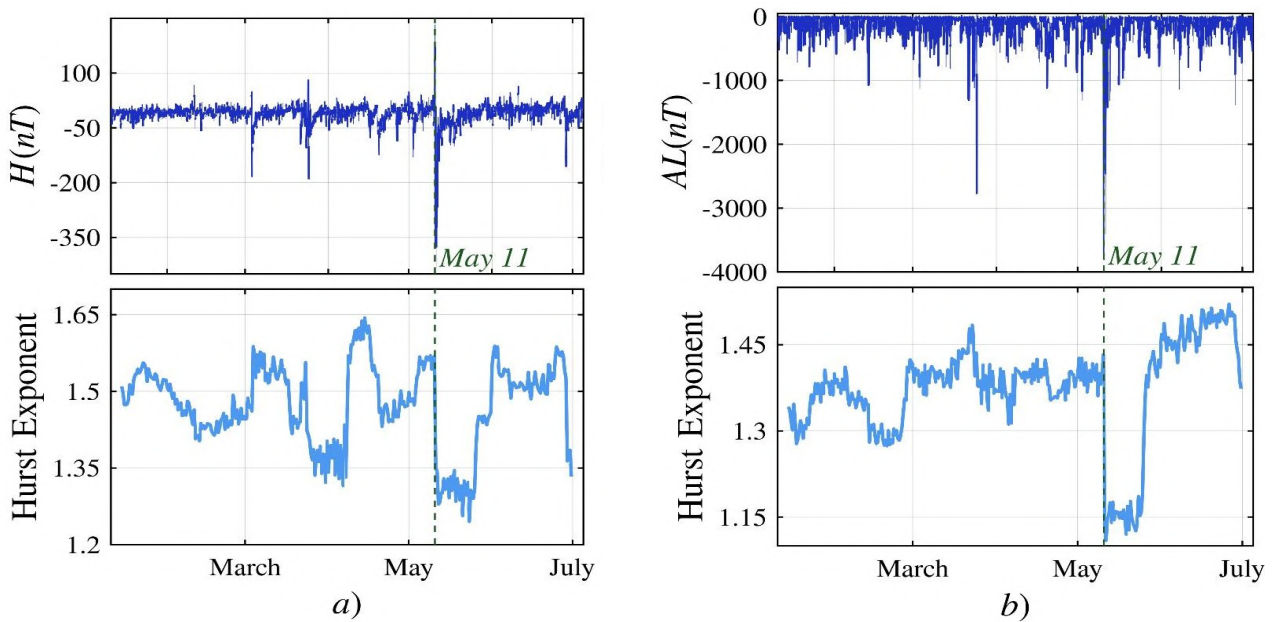


Fig. 2. Panel (a) – Windowed DFA results of the Horizontal component of the Earth’s magnetic field and Panel (b) – Windowed DFA results of the AL index

Furthermore, we conducted preliminary multifractal analysis using multifractal detrended fluctuation analysis (MFDFA) [9] to quantify the complexity of these time series. The results indicate a difference in the multifractal nature:

- The AL index, representing the highly turbulent and intermittent auroral electrojet, is the most multifractal
- The mid-latitude ground station data exhibits a lesser degree of multifractality
- The SYM-H index, which represents the smoother, globally averaged ring current, is the least multifractal of all.

Conclusion

This study analyzed the intense geomagnetic storms of 2024 by comparing local mid-latitude data with global auroral (AL) and ring current (SYM-H) indices. Wavelet coherence analysis revealed the frequency-dependent nature of solar wind-magnetosphere coupling, which differs for the ring current and auroral regions. Most significantly, Detrended Fluctuation Analysis demonstrated that during the May 11 superstorm, the auroral zone expanded to mid-latitudes. This dynamic was captured by the simultaneous change in complexity in local data and the AL index, but was absent in the SYM-H index. The observed hierarchy of multifractality (AL being the most multifractal and followed by mid-latitude H and SYM-H) further quantifies the different levels of complexity in these magnetospheric regions. This work underscores the critical value of combining local and global datasets to build a comprehensive picture of geomagnetic storm dynamics.

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