Journal of the Georgian Geophysical Society, e-ISSN: 2667-9973, p-ISSN: 1512-1127
Physics of Solid Earth, Atmosphere, Ocean and Space Plasma, v.28(1), 2025, pp. 87 - 95

Wavelet Coherence Analysis of Magnetic Declination During Quiet and Disturbed Geomagnetic Activity

Oleg A. Kharshiladze, Luka K. Tsulukidze, Mariam J. Martiashvili

M. Nodia Institute of Geophysics of the I. Javakhishvili Tbilisi State University, Georgia
e-mail: luka.tsulukidze617@ens.tsu.edu.ge

ABSTRACT

This study investigates characteristics of magnetic declination (D) at the mid-latitude Dusheti Geophysical Observatory and it's coupling to solar wind during both quiet and disturbed periods, with a specific focus on the intense storm of May 11, 2024. We analyze one-minute resolution geomagnetic and solar wind data from July 2023 to July 2024, . Using power spectral density (PSD) and continuous wavelet transform (CWT), we characterize the spectral behavior of declination. The analysis confirms the persistent presence of diurnal (24h) and semidiurnal (12h) periodicities, characteristic of the quiet time, also a period of 8h, while demonstrating significant spectral broadening during the geomagnetic storm. We then employ wavelet coherence analysis to quantify the coupling between declination and the IMF magnitude (B), its southward component (Bz), and the solar wind velocity (v). The results reveal distinct coupling mechanisms: coherence with B is dependent on storm intensity, being strong only during the intense May 11 storm. In contrast, coherence with Bz is robust and significant during both intense (May 11) and moderate (April 19) storms, highlighting its fundamental role in driving disturbances in geomagnetic data regardless of storm intensity. This work demonstrates the effectiveness of wavelet coherence for evaluating solar wind magnetosphere coupling at different frequencies.

Key words: *Magnetic declination, Magnetic storm, Solar wind, Interplanetary magnetic field, Wavelet transform, Wavelet coherence.*

Introduction

The geomagnetic field is a complex phenomenon characterized by a non-uniform spatial structure and a wide spectrum of temporal variations. Its origins are twofold, with sources located both deep within the planet and in the near-Earth space environment. The primary contributor is the geodynamo, a process driven by the rotation and convection of the Earth's liquid, conductive outer core [1]. This internal source generates the main magnetic field and its slowly evolving secular variations, which occur over timescales of years to millennia.

Complementing the main field are external sources situated in the ionosphere and magnetosphere. These regions contain complex and dynamic systems of electrical currents that are shaped by the Earth's intrinsic magnetic field. The interaction between these currents and the solar wind—a stream of charged particles flowing from the Sun—produces a variety of magnetic effects observed on the ground [2]. These effects range from regular daily variations to sporadic and intense disturbances, with timescales spanning from seconds to several days.

The Earth's magnetic field vector is described by several components, including magnetic declination (D). As the angle between magnetic and geographic north, declination is particularly sensitive to magnetospheric state changes and fluctuates significantly during magnetic storms, making it a valuable parameter for this study [4].

The most significant manifestation of the Sun-Earth connection is the magnetic storm, a global disturbance of the magnetosphere that serves as a key indicator of space weather. These storms are primarily caused by energetic solar events that intensify the solar wind, leading to a strong interaction with the Earth's magnetosphere [3]. The resulting deformation of the magnetic field induces powerful currents in the upper atmosphere, which are observed on the ground as magnetic storms. The intensity of this activity is often quantified using indices such as the Kp [5], Ae, and Dst [6].

The impact of geomagnetic disturbances is not uniform across the globe; it is strongly dependent on latitude [7]. In the auroral zones, near the magnetic poles, storms are most frequent and intense, causing sharp deviations in the magnetic field. At mid-latitudes, where the Dusheti Geophysical Observatory (DGG) is located, the effects are less severe but still significant. In contrast, the equatorial regions are generally more stable due to the horizontal orientation of the magnetic field lines.

While magnetic declination is traditionally understood as a slowly varying and predictable quantity for a given location, magnetic storms are rapid, intense, and unpredictable phenomena. A fundamental question arises from this contrast: can the intense, short-term processes of a magnetic storm influence the behavior of magnetic declination, and is there a quantifiable connection between them?

This study aims to investigate this relationship by analyzing high-resolution magnetic declination data from the Dusheti Geophysical Observatory. We focus on its spectral characteristics during both geomagnetically quiet periods and the intense magnetic storm of May 11, 2024. Using wavelet transform analysis and power spectral density (PSD), we will examine the frequency and energy distribution of declination variations. Furthermore, we will employ wavelet coherence analysis to evaluate the correlation between declination and key solar wind parameters and interplanetary magnetic field (IMF) data, trying to understand the nature of magnetospheric coupling during both calm and storm conditions.

Data and methods

To fully characterize the geomagnetic field at a specific location, it is described by a vector, which can be broken down into several standard components. The vector is defined by its orthogonal coordinates: the northward component (X), the eastward component (Y), and the vertical component (Z), directed towards the Earth's center. From these, other critical parameters can be derived, including the total intensity (F), the horizontal component (H), the inclination (J), and the declination (D). These are calculated as follows:

$$D = \arctan\left(\frac{x}{y}\right), \quad F = \sqrt{H^2 + Z^2}$$

$$J = \arctan\left(\frac{Z}{H}\right), \quad H = \sqrt{X^2 + Y^2}$$

In this study, our primary focus is on magnetic declination (D), which is a highly informative parameter. It is exceptionally sensitive to the state of the magnetosphere, and its variations clearly reflect even subtle magnetic activity [4]. During geomagnetically quiet periods, declination exhibits slow, predictable changes. However, during magnetic storms, it is characterized by large-amplitude, chaotic fluctuations, providing a clear signal of the disturbance. The geomagnetic data for this research were obtained from the Dusheti Geophysical Observatory (TBS Geographic Latitude: 42.09° Geographic Longitude: 44.70° The dataset spans from July 2023 to July 2024 and consists of one-minute resolution recordings of the H, Z and D. Any gaps present in the time series were filled using linear interpolation to ensure a continuous dataset for spectral analysis.

To investigate the relationship between ground-based magnetic field variations and extraterrestrial drivers, we utilized high-resolution solar wind and Interplanetary Magnetic Field (IMF) data. This data was acquired from the NASA/GSFC OMNIWeb data repository [8]. The selected parameters are: B The magnitude of the Interplanetary Magnetic Field, B_z - The z component of the IMF in Geocentric Solar Magnetospheric (GSM) coordinates, V - The bulk flow velocity of the solar wind.These parameters were also obtained at a one-minute time resolution to match the geomagnetic data. Similar to the TBS data, any gaps in the OMNIWeb time series were filled using linear interpolation.

Wavelet transform

The continuous wavelet transform (CWT) decomposes a time series x(t) into time–frequency space by convolving it with scaled and shifted versions of a chosen mother wavelet ψ(t). Unlike the Fourier transform, which assumes stationarity, the CWT adapts its time–frequency resolution to capture both slow and rapid variations—a key advantage for non-stationary signals such as geomagnetic records during storms. Mathematically, the CWT is defined as:

$$W(a,b) = \frac{1}{\sqrt{|a|}} \int_{\infty}^{\infty} x(t)\psi\left(\frac{t-b}{a}\right) dt,$$

where a is the scale (inversely related to frequency), b is the translation (time shift), and the overbar denotes complex conjugation. The resulting wavelet coefficients W(a,b) describe how well the wavelet at a given scale and time matches the signal. Because the wavelet's width adapts with scale, high-frequency (small-scale) features are localized in time while low-frequency (large-scale) features are resolved with finer frequency precision—ideal for capturing both the slow secular variation and rapid storm-time fluctuations of D [9].

Wavelet coherence

To quantify the degree of linear coupling between two non-stationary time series (e.g., magnetic declination D and solar wind parameter B_z), we compute the wavelet coherence:

$$R^2(a,b) = \frac{\left|S\{W_x(a,b)W_y^*(a,b)\}\right|^2}{S\{|W_x(a,b)|^2\}S\left\{\left|W_y^*(a,b)\right|^2\right\}}$$

where W_x is a wavelet transform of the time series and W_y^* is complex conjugate of wavelet transform of second time series. S{·} denotes smoothing in both the time (b) and scale (a) dimensions. Commonly, S is implemented via convolution with a separable Gaussian (or boxcar) kernel in time and a similar window in scale [10].
Likewise, the cross-wavelet spectrum that underpins the coherence is itself smoothed before you extract phase:

$$\phi(a,b) = \tan^{-1}\frac{Im\{\langle W_x W_y^*\rangle\}}{Re\{\langle W_x W_y^*\rangle\}}$$

revealing lead–lag relationships at each scale and time [10].

Power spectral density

The power spectral density (PSD)[11] estimates the distribution of signal power across frequency. For a discretely sampled time series x_n of length N a common unbiased PSD estimator is:

$$PS(f_k) = \frac{\Delta t}{N}\left|\sum_{n=0}^{N-1} x_n e^{-\frac{2\pi i k}{N}}\right|^2$$

This parameter has been used to estimate dominant frequencied for magnetit declination

Results

Analysis of the power spectral density (PSD) of the one-minute declination time series reveals two prominent peaks at periods of approximately 24 h and 12 h. Specifically, the PSD shows a dominant spectral line at 1 cycle per day and a secondary line at 2 cycles per day, with both peaks standing well above the background noise level.

Wavelet power spectra repeats these findings: across the entire July 2023–July 2024 interval, the continuous wavelet transform of D exhibits persistent, high-energy bands at the diurnal (24 h) and semidiurnal (12 h) scales. These bands persist through both geomagnetically quiet and storm intervals, indicating that the underlying mechanism is not storm-specific but a regular, solar-driven modulation of the ionosphere.

The appearance of 24 h and 12 h periodicities in magnetic declination is a classic signature of the solar quiet (Sq) current system: daytime solar ultraviolet radiation increases ionospheric conductivity, driving global current vortices that peak once per day, while the semidiurnal tides in ionospheric density generate the second harmonic [12], PSD and CWT also showcase dominand periodicity at 8 hours, which needs further investigation.

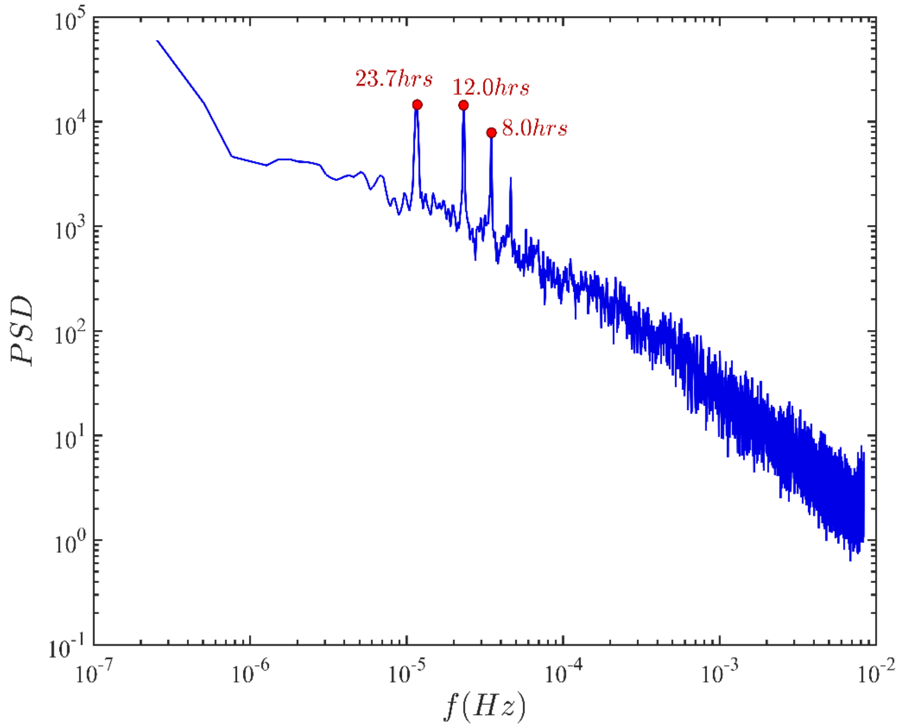

Fig. 1 PSD of magnetic declination D.

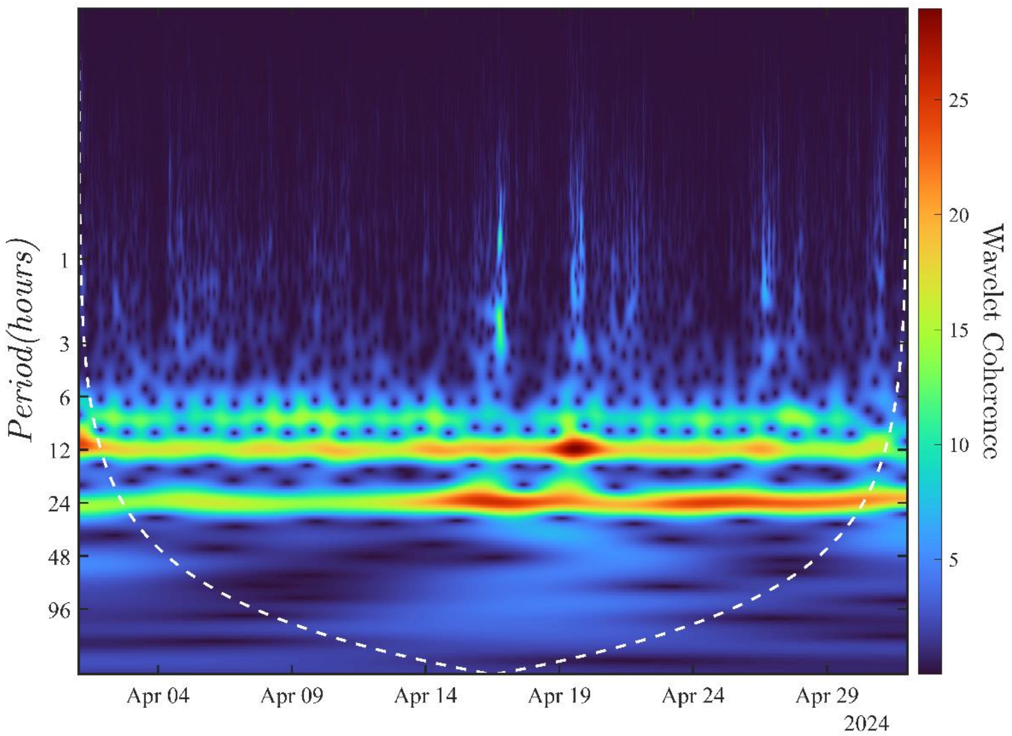

Fig. 2 Wavelet Transform of declination - D from April 1 to May 1 (storm at April 19).

During the intense geomagnetic storm of May 11, 2024, the wavelet spectrum shows a significant change. While the 24-hour peak remains dominant, the spectrum broadens, with a marked increase in wavelet power across a wide range of shorter periods. This indicates the superposition of multi-frequency processes during the storm, causing the declination signal to become more complex and noise-like compared to its structured, quiet-time behavior.

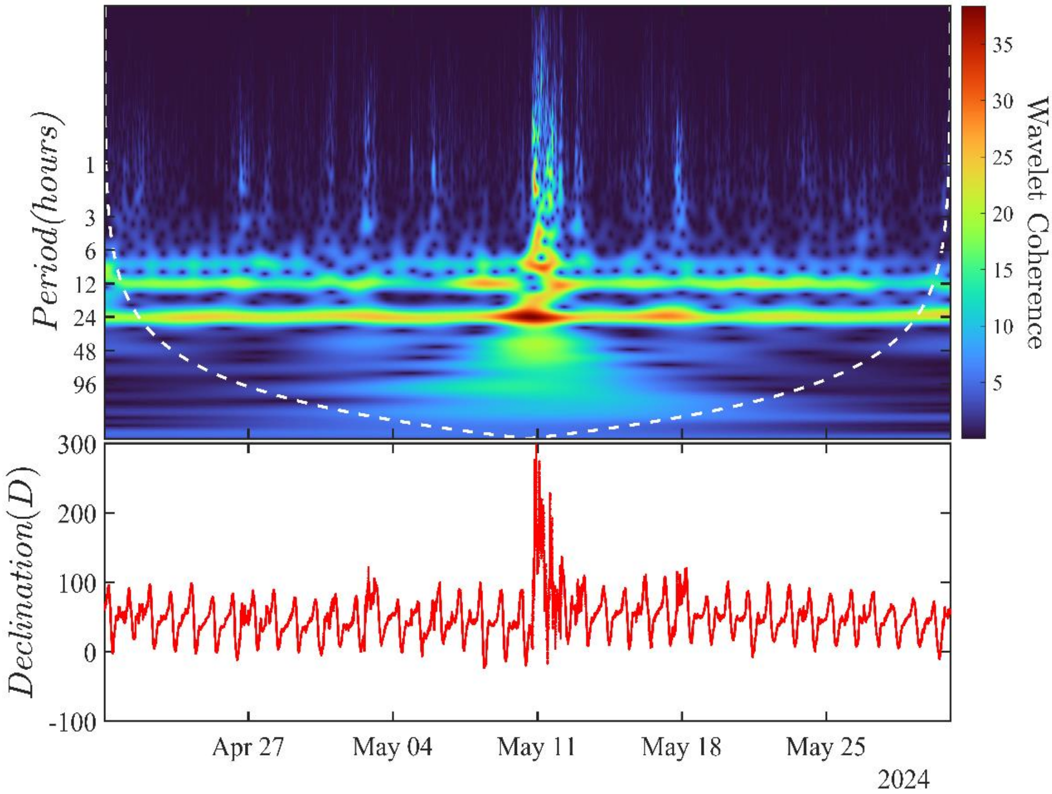

Fig. 3 Wavelet transform of Declination - D during April 20 - May 30 (storm on May 11).

Wavelet coherence

The coupling between the solar wind and the magnetosphere is a complex, multi-frequency process. To investigate this coupling, we performed a wavelet coherence analysis between the declination (D) and key solar wind parameters during the study period, with a focus on the May 2024 storm intervals.

A persistent coherence is observed at long periods (greater than 64 hours) throughout the entire time series. This long-period coherence should be interpreted with some caution due to the wavelet transform's lower time resolution at these scales; however, its persistence is notable. More dynamically, during the major storm on May 11, a distinct region of strong coherence emerges across a broad band of shorter periods (approximately 2-16 hours). A similar, though less intense, region of coherence is also visible at periods of 32-64 hours during the weaker storm event around May 19.

The north-south component of the IMF (B_z) is a primary driver of magnetic storms, with a southward orientation (negative B_z) ensuring magnetic reconnection [13]. Unlike the IMF magnitude, the coherence between D and B_z is significant regardless of storm intensity. A strong coherence is observed during the major storm on May 11, but it is particularly wide and sustained in the 32-128 hour period range during the less intense storm of April 19. The presence of strong coherence during events of differing magnitudes highlights the fundamental role of southward B_z in driving ground-level disturbances; this coupling mechanism appears robust and less dependent on the overall storm intensity.

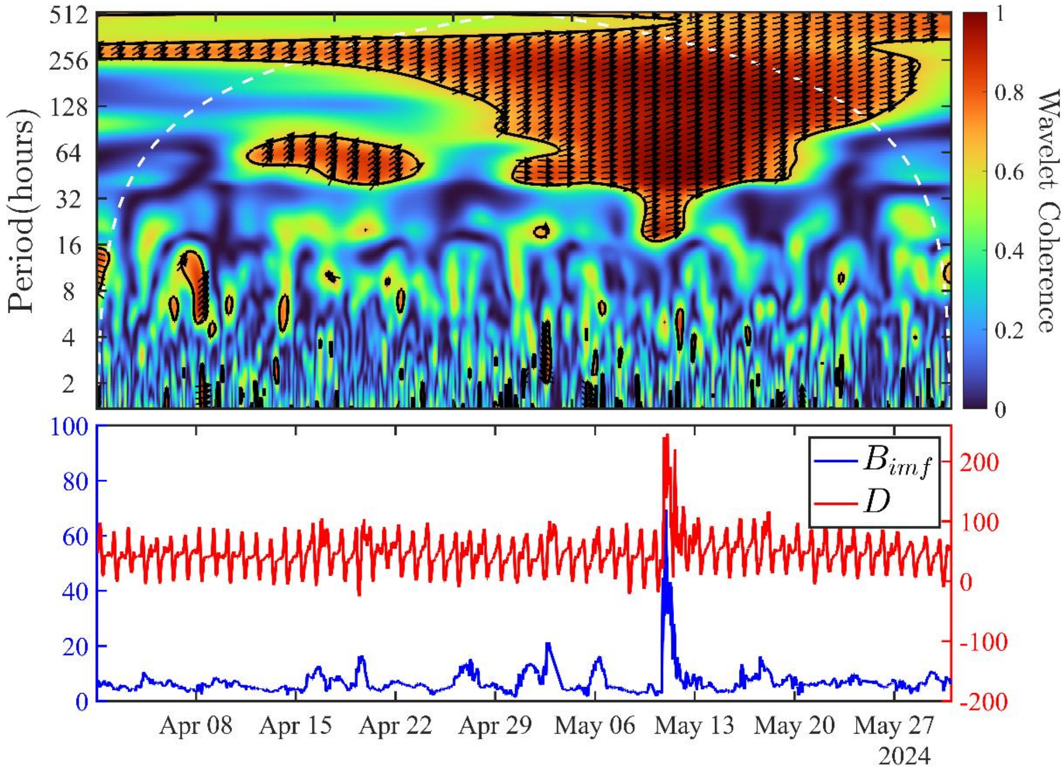

Fig. 4. Wavelet coherence of B_{imf} and D.

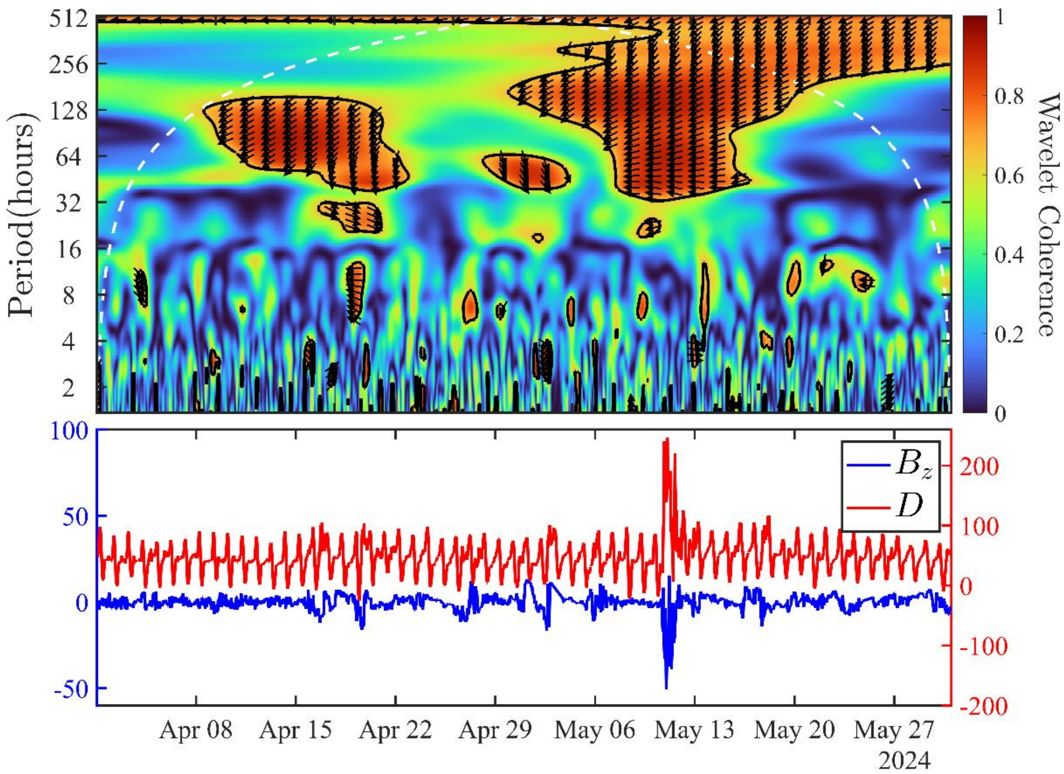

Fig. 5. Wavelet coherence of B_z and D.

The impact of a high-speed solar wind stream is a well-known trigger for geomagnetic storms. The coherence analysis between D and solar wind velocity shows a persistent low-frequency coherence, similar to the other parameters. However, specifically during the major storm of May 11, a distinct island of coherence appears in the 16-32 hour period range. This feature is notably absent during the less intense storm of April

19, which may suggest that solar wind velocity variations in this specific period range played a more significant role in driving the magnetospheric response during the more intense May 11 storm.

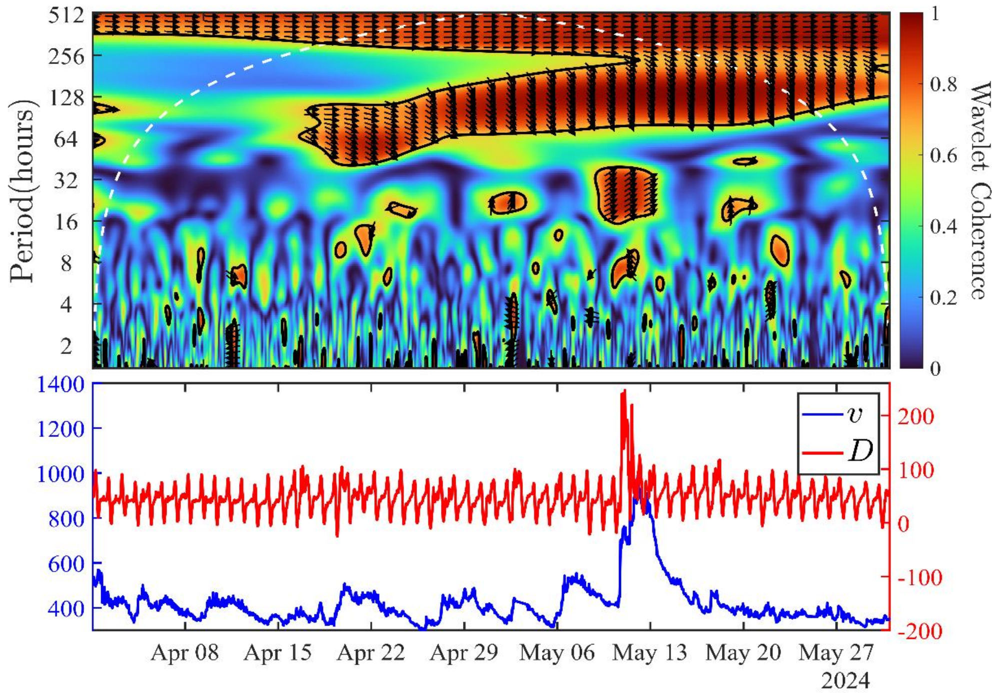

Fig. 6. Wavelet Coherence between flow speed and D.

Conclusion

In this paper, we presented a detailed analysis of magnetic declination variations recorded at the Dusheti Geophysical Observatory and their coherence with key solar wind parameters. By employing spectral and wavelet-based techniques, we aimed to investigate the nature of magnetospheric coupling during both quite time and geomagnetic storms.

First, the spectral analysis of the declination data consistently revealed dominant 24-hour and 12-hour periodicities. These are the well-established signatures of the solar quiet (Sq) current system, confirming the baseline solar-driven behavior at the observatory. 8-hour periodicity was also detected. During the intense May 11, 2024 magnetic storm, the wavelet spectrum showed that these primary cycles were superimposed with a broad spectrum of higher-frequency fluctuations, quantitatively illustrating the transition from a structured signal to a more complex, noise-like state characteristic of storm-time dynamics.

The core of our study focused on the wavelet coherence between declination and solar wind drivers. The results exposed nuanced differences in the coupling mechanisms:

A strong, broad-band coherence with declination was observed only during the most intense storm (May 11), suggesting that coupling related to the overall field magnitude is most effective during highly energetic events.

IMF Southward Component (Bz): In contrast, strong coherence with Bz was significant during both the intense May 11 storm and a less intense event on April 19. This demonstrates that the coupling driven by the southward IMF component—the primary engine for magnetic reconnection—is a fundamental process that operates efficiently regardless of the overall storm intensity.

Solar Wind Velocity (v): Coherence with solar wind speed revealed a unique signature in the 16-32 hour period band exclusively during the major May 11 storm, implying that dynamic pressure changes associated with high-speed streams may excite a distinct magnetospheric response during the most extreme events.

In summary, this work successfully demonstrates that magnetic declination at a single mid-latitude observatory can serve as a sensitive probe of solar wind-magnetosphere coupling. The use of wavelet coherence, in particular, proved to be a powerful tool for distinguishing between the impacts of different solar wind parameters, revealing that while southward Bz provides a fundamental and consistent driver, the roles of IMF magnitude and solar wind velocity can be highly dependent on the specific characteristics and intensity of a geomagnetic storm.

Acknowledgements

The authors wish to thank Tamaz Matiashvili for providing the Dusheti magnetometer data and for sharing his expertise and assistance throughout this work.
O.Kharshiladze was supported by Shota Rustaveli National Scientific Foundation Grant No. FR-22-18445.

References

[1] Merrill R. T., McElhinny M. W., McFadden P. L. The Earth's magnetic field: its history, origin and planetary perspective. Academic Press, 1998.
[2] Kivelson M. G., Russell C.T. Introduction to Space Physics. Cambridge University Press, 1995.
[3] Gonzalez W.D., Joselyn J.A., Kamide Y., Kroehl H.W., Rostoker G., Tsurutani B.T., Vasyliunas V. M. What is a geomagnetic storm? Journal of Geophysical Research: Space Physics, 99(A4), 5771-5792, 1994.
[4] Campbell W.H. Introduction to Geomagnetic Fields. Cambridge University Press, 2023.
[5] Matzka J., Stolle C., Yamazaki Y., Bronkalla O., Morschhauser A. The geomagnetic Kp index and derived indices of geomagnetic activity. Space Weather, 19(5), e2020SW002641, 2021.
[6] Sugiura M., Kamei, T. Equatorial Dst index 1957-1986. IAGA Bulletin No. 40. World Data Center C2 for Geomagnetism, 1991.
[7] Akasofu S.I. The latitudinal profile of the Dst index. Journal of Geophysical Research: Space Physics, 116(A12), 2011.
[8] King J.H., Papitashvili N.E. Omni, combined solar wind plasma moments and interplane-tary magnetic field (IMF) time-shifted to the nose of the Earth's bow shock, plus geomagnetic indices, 1 min data. NASA Space Physics Data Facility, 2020.
[9] Torrence C. Compo, G.P. A Practical Guide to Wavelet Analysis. Bulletin of the American Meteorological Society, 79, 61–78, 1998.
[10] Grinsted A., Moore J.C., Jevrejeva S. Application of the cross wavelet transform and wavelet coherence to geophysical time series. Nonlinear Processes in Geophysics, 11, pp. 561–566, 2004.
[11] Percival D. B., Walden, A.T. Spectral Analysis for Physical Applications. Cambridge University Press, 1993.
[12] Chapman S., Bartels J. Geomagnetism. Oxford University Press, 1940.
[13] Russell C.T. Space physics: An introduction. Cambridge University Press, 2016.

მაგნიტური მიხრილობის ვეივლეტ კოჰერენტული ანალიზი გეომაგნიტური აქტივობის მშვიდ და შეშფოთებების პერიოდებში

ო. ხარშილაძე, ლ.წულუკიძე, მ. მარტიაშვილი

რეზიუმე

ამ კვლევაში განხილულია დუშეთის გეომაგნიტურ ობსერვატორიაში გაზომილი მაგნიტური მიხრილობის (D) მახასიათებლები და მისი ურთიერთქმედება მზის ქართან გეომაგნიტური აქტივობის მშვიდ და შეშფოთებების პერიოდებში, განსაკუთრებული აქცენტით 2024 წლის 11

მაისის ინტენსიურ შტორმზე. ჩვენ გამოვიკვლიეთ მონაცემები ერთი წუთის რეზოლუციით 2023 წლის ივლისიდან 2024 წლის ივლისამდე. სპექტრალური სიმკვრივის და უწყვეტი ვეივლეტ გარდაქმნის გამოყენებით გამოვიკვლიეთ დომინანტი სიხშირეები. ანალიზი ადასტურებს დღიურ (24 სთ) და (12 სთ) პერიოდების არსებობას მშვიდ პერიოდებში, ასევე გამოკვეთილია 8 საათიანი პერიოდი და აჩვენებს სპექტრის მნიშვნელოვან გაფართოებას შტორმის დროს. ამის შემდეგ გამოვიყენეთ ვეივლეტ კოჰერენტული ანალიზი, რათა შეგვეფასებინა D-ის და IMF-ის მოდულის (B), მისი z კომპონენტის (Bz) და მზის ქარის სიჩქარის (v) კავშირი. შედეგები აჩვენებს განსხვავებულ მექანიზმებს: B-თან კოჰერენტულობა დამოკიდებულია შტორმის ინტენსივობაზე და მეტია მძლავრი 11 მაისის შტორმის დროს, ხოლო Bz-თან შეინიშნება მნიშვნელოვანი კოჰერენტობა როგორც ძლიერ (11 მაისი), ისე შედარებით მსუბუქი (19 აპრილი) შტორმების დროს, რაც ადასტურებს Bz-ის მნიშვნელობას მიუხედავად გეომაგნიტური შტორმების ინტენსივობისა. ეს კვლევა ადასტურებს ვეივლეტ კოჰერენტობის ეფექტურობას მზის ქარისა და მაგნიტოსფეროს კავშირის შესაფასებლად.

საკვანძო სიტყვები: მაგნიტური მიხრილობა, მაგნიტური შტორმი, პლანეტათშორისი მაგნიტური ველი, ვეივლეტ ანალიზი, ვეივლეტ კოჰერენტობა

Вейвлет когерентный анализ магнитного склонения в периоды спокойной и возмущённой геомагнитной активности

О. Харшиладзе, Л. Цулукидзе, М. Мартиашвили

Резюме

В данном исследовании изучаются особенности магнитного склонения (D) на геофизической обсерватории г. Душети, расположенной на средних широтах, и его связь с солнечным ветром в периоды спокойной и возмущённой геомагнитной активности, с особым акцентом на мощную бурю 11 мая 2024 г. Анализируются данные с разрешением одна минута по геомагнитным параметрам и параметрам солнечного ветра за период с июля 2023 г. по июль 2024 г. С помощью оценки спектральной плотности мощности (PSD) и непрерывного вейвлет-преобразования (CWT) характеризуется спектральное поведение склонения. Анализ подтверждает стабильное присутствие суточной (24 ч) и полусуточной (12 ч) периодичностей, характерных для спокойных периодов, а также периодичности 8 ч, одновременно демонстрируя значительное расширение спектра во время геомагнитной бури. Далее применяется анализ вейвлет-когерентности для количественной оценки связи между склонением и величиной межпланетного магнитного поля (B), его южным компонентом (Bz) и скоростью солнечного ветра (v). Результаты показывают различные механизмы связи: когерентность с величиной B зависит от интенсивности бури и проявляется значительно лишь во время мощной бури 11 мая. Напротив, когерентность с Bz является устойчивой и значимой как во время мощной бури (11 мая), так и умеренной (19 апреля), что подчёркивает её фундаментальную роль в формировании возмущений геомагнитных данных независимо от силы бури. Работа демонстрирует эффективность вейвлет-когерентного анализа для оценки связи солнечного ветра и магнитосферы на разных частотах.

Ключевые слова: Магнитное склонение, магнитная буря, солнечный ветер, межпланетное магнитное поле, вейвлет-преобразование, вейвлетная когерентность.