iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH
IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 14 **Issue:** VI **Month of publication:** June 2026

DOI: https://doi.org/10.22214/ijraset.2026.83459

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 14 Issue VI June 2026- Available at www.ijraset.com

Multi-Scale Variability of Solar Wind Turbulence and Its Influence on Near-Earth Space Weather

Sunil Kumar Pathak[1], Mukta Tripathi[2]
[1]Research Scholar, [2]Professor, Department of Physics, A.P.S. University Rewa, M.P., India

Abstract: Solar wind turbulence plays a fundamental role in governing the transfer of mass, momentum, and energy from the Sun to the Earth's magnetosphere. Variations in solar wind plasma and interplanetary magnetic field (IMF) parameters occur over a broad range of temporal scales, from minutes to several days, and significantly influence near-Earth space weather conditions. Understanding the multi-scale nature of these fluctuations is essential for improving the prediction of geomagnetic disturbances and their associated impacts on technological systems.This study investigates the temporal variability of solar wind turbulence and its relationship with geomagnetic activity during Solar Cycle 25. Hourly solar wind parameters, including solar wind speed, proton density, temperature, and IMF components, are analyzed using data obtained from the OMNI database. Multi-scale characteristics of solar wind turbulence are examined through statistical and spectral techniques, including power spectral density and wavelet analysis. Geomagnetic activity is assessed using the Disturbance Storm Time (Dst), planetary K-index (Kp), and Auroral Electrojet (AE) indices.The analysis reveals that enhanced levels of solar wind turbulence are frequently associated with periods of increased geomagnetic activity. Significant fluctuations in IMF Bz and solar wind velocity contribute to efficient solar wind–magnetosphere coupling, resulting in stronger geomagnetic storms and substorm activity. Wavelet analysis identifies distinct periodicities corresponding to short-term and intermediate-scale turbulent processes, while correlation analysis demonstrates statistically significant relationships between turbulence intensity and geomagnetic indices. The results further indicate that turbulent solar wind structures can serve as important precursors to space weather disturbances.The findings highlight the critical role of multi-scale solar wind turbulence in modulating near-Earth space weather and provide valuable insights into the physical mechanisms responsible for geomagnetic variability. This work contributes to ongoing efforts aimed at improving space weather forecasting and understanding Sun–Earth interactions during the current solar cycle.

Keywords: Solar Wind Turbulence, Space Weather, Geomagnetic Storms, Interplanetary Magnetic Field, Solar Cycle 25, Wavelet Analysis, Magnetosphere.

I. INTRODUCTION

The Sun continuously releases energy and plasma into interplanetary space through a stream of charged particles known as the solar wind. This plasma flow serves as the principal link between solar activity and the near-Earth space environment. Variations in solar wind properties can significantly influence the Earth's magnetosphere, ionosphere, and thermosphere, leading to a variety of space weather phenomena such as geomagnetic storms, auroral activity, ionospheric disturbances, and satellite anomalies. Understanding the physical mechanisms responsible for solar wind variability has therefore become a central objective of contemporary space physics research [1].

The modern concept of the solar wind originated from the pioneering work of Parker [2], who demonstrated that the hot solar corona must continuously expand into interplanetary space. His theoretical model provided the first physical explanation for the existence of a supersonic plasma flow emanating from the Sun. Subsequent spacecraft observations confirmed Parker's predictions and revealed that the solar wind is highly dynamic, exhibiting fluctuations over a broad range of temporal and spatial scales [3]. These fluctuations arise from various solar sources, including coronal holes, active regions, coronal mass ejections (CMEs), and stream interaction regions (SIRs), all of which contribute to the complexity of the heliospheric environment [4].

One of the most important characteristics of the solar wind is its turbulent nature. Early observational studies by Coleman [5] provided evidence that the interplanetary magnetic field contains significant fluctuations indicative of turbulent processes. Further investigations by Belcher and Davis [6] demonstrated the widespread presence of Alfvénic fluctuations in the solar wind, establishing turbulence as a fundamental property of heliospheric plasmas. These discoveries motivated extensive theoretical and observational efforts aimed at understanding the generation, evolution, and dissipation of turbulence in space plasmas.

The theoretical framework for turbulence was established by Kolmogorov [7], whose statistical description of energy transfer in turbulent fluids remains one of the cornerstones of turbulence theory. Although initially developed for neutral fluids, Kolmogorov's concepts have been successfully extended to magnetized plasmas. Building on these foundations, Matthaeus and Goldstein [8] showed that nonlinear magnetohydrodynamic interactions play a critical role in the evolution of solar wind turbulence. Their work highlighted the importance of energy cascades and spectral transfer processes in determining the structure of interplanetary plasma fluctuations.

Substantial progress in understanding solar wind turbulence has been achieved through the contributions of Bruno and Carbone [9], who demonstrated that solar wind fluctuations exhibit scale-dependent behavior and strong intermittency. Their studies revealed that turbulent energy is distributed across a wide range of scales and that coherent structures contribute significantly to plasma dynamics. Subsequent investigations by Horbury et al. [10], Oughton et al. [11], and Chen et al. [12] further showed that turbulence properties vary with solar wind conditions, magnetic field orientation, and heliocentric distance. These findings emphasized that solar wind turbulence must be investigated from a multi-scale perspective rather than through single-scale statistical approaches.The interaction between solar wind turbulence and the Earth's magnetosphere plays a crucial role in controlling near-Earth space weather. Dungey [13] proposed the theory of magnetic reconnection, which describes how interplanetary and terrestrial magnetic field lines reconnect and transfer energy into the magnetosphere. This mechanism remains the fundamental explanation for solar wind–magnetosphere coupling. When the interplanetary magnetic field possesses a strong southward component (IMF Bz), reconnection efficiency increases, resulting in enhanced geomagnetic activity and the development of geomagnetic storms [14].

Numerous studies have demonstrated the importance of solar wind fluctuations in driving geomagnetic disturbances. Gonzalez et al. [15] reported that prolonged intervals of southward IMF Bz are closely associated with intense geomagnetic storms. Similarly, Tsurutani et al. [16] showed that interplanetary shocks and disturbed solar wind conditions frequently trigger major geomagnetic events. Investigations by Kivelson and Russell [17] further highlighted the significance of solar wind–magnetosphere interactions in governing magnetospheric dynamics and energy transfer processes. These studies collectively indicate that turbulence within the solar wind can substantially influence geomagnetic activity by modulating the efficiency of solar wind–magnetosphere coupling.

Recent advances in computational methods have enabled researchers to investigate turbulence across multiple temporal scales. Techniques such as power spectral density analysis, wavelet transforms, and structure-function analysis have become powerful tools for identifying scale-dependent fluctuations and intermittent structures within turbulent plasmas [18]. Horbury et al. [19] demonstrated that anisotropic turbulence dominates many regions of the solar wind, while Matthaeus et al. [20] emphasized the importance of multi-scale energy transfer processes in space plasma environments. These developments have significantly improved our understanding of turbulence evolution and its role in heliospheric dynamics.

Solar Cycle 25 provides a valuable opportunity to investigate the relationship between solar wind turbulence and near-Earth space weather under contemporary solar activity conditions. The increasing occurrence of solar eruptions, high-speed solar wind streams, and geomagnetic disturbances during the current cycle offers a rich observational dataset for examining turbulence characteristics and their geoeffective consequences. The availability of high-resolution solar wind measurements and geomagnetic observations allows for detailed assessment of turbulence-driven space weather processes.The primary objective of the present study is to investigate the multi-scale variability of solar wind turbulence and evaluate its influence on near-Earth space weather during Solar Cycle 25. By integrating solar wind plasma observations, interplanetary magnetic field measurements, spectral analysis techniques, and geomagnetic indices, this work seeks to identify dominant turbulence scales and quantify their relationship with geomagnetic activity. The findings are expected to contribute to a deeper understanding of solar wind–magnetosphere coupling processes and support the development

II. LITERATURE REVIEW

The study of solar wind turbulence has evolved significantly since the establishment of the solar wind theory by Parker [1]. Prior to Parker's work, the interplanetary medium was often considered relatively static. However, Parker's theoretical prediction of a continuously expanding solar corona provided the foundation for understanding the solar wind as a dynamic plasma flow that fills the heliosphere. Subsequent spacecraft observations confirmed the existence of the solar wind and revealed that it exhibits substantial fluctuations in velocity, density, temperature, and magnetic field strength over a broad range of temporal and spatial scales [2].

One of the earliest investigations into the fluctuating nature of the solar wind was conducted by Coleman [3], who reported significant magnetic field variations within interplanetary space. These observations provided the first evidence that the solar wind contains turbulent structures rather than behaving as a uniform plasma stream.

Further progress was made by Belcher and Davis [4], who identified large-amplitude Alfvénic fluctuations in the solar wind. Their work demonstrated that plasma velocity and magnetic field fluctuations are strongly coupled, establishing turbulence as a fundamental property of heliospheric plasmas.

The theoretical interpretation of turbulence is largely based on the pioneering work of Kolmogorov [5], who developed a statistical framework describing the transfer of energy from large-scale motions to progressively smaller scales. Although Kolmogorov's theory was originally formulated for neutral fluids, its principles have been widely applied to magnetized plasma systems. The extension of turbulence theory to space plasmas enabled researchers to investigate the complex interactions occurring within the solar wind and provided a basis for understanding energy transport processes in the heliosphere.

Building upon these theoretical foundations, Matthaeus and Goldstein [6] demonstrated that magnetohydrodynamic (MHD) turbulence plays a critical role in shaping solar wind dynamics. Their studies revealed that nonlinear interactions between magnetic and velocity fluctuations generate turbulent cascades capable of transferring energy across multiple scales. These findings significantly improved understanding of how turbulence evolves within the solar wind and established MHD turbulence as a major research area in space plasma physics.

Further contributions by Tu and Marsch [7] expanded knowledge of solar wind turbulence by examining the relationship between large-scale solar wind structures and small-scale turbulent fluctuations. Their investigations showed that turbulence is influenced by solar wind source regions and evolves continuously as the plasma propagates through interplanetary space. The authors proposed that solar wind turbulence results from a combination of wave–particle interactions, nonlinear processes, and large-scale solar drivers.

A major advancement in the field was achieved through the work of Bruno and Carbone [8], who provided a comprehensive review of solar wind turbulence and its physical characteristics. Their studies highlighted the presence of intermittency, anisotropy, and scale-dependent behavior within turbulent solar wind flows. They demonstrated that turbulent fluctuations do not occur uniformly but are concentrated within coherent structures that contribute significantly to energy dissipation processes. These findings emphasized the importance of investigating turbulence across multiple temporal and spatial scales.

Research by Horbury et al. [9] further revealed that solar wind turbulence exhibits strong anisotropy relative to the background magnetic field. Their observations indicated that turbulence behaves differently along and across magnetic field lines, suggesting that magnetic field geometry plays a crucial role in controlling energy transfer mechanisms. Similarly, Oughton et al. [10] investigated the anisotropic nature of magnetohydrodynamic turbulence and demonstrated that turbulence characteristics depend strongly on magnetic field strength and solar wind conditions.

The development of advanced observational missions has enabled more detailed investigations of turbulence at smaller scales. Chen et al. [11] examined kinetic-scale turbulence within the solar wind and demonstrated that energy transfer processes continue beyond the traditional inertial range. Their work revealed the existence of complex interactions between turbulent fluctuations and plasma particles, providing new insights into solar wind heating mechanisms. Similar findings were reported by Sahraoui et al. [12], who identified kinetic processes contributing to energy dissipation within turbulent plasmas.

The connection between solar wind turbulence and geomagnetic activity has been the focus of extensive research over the past several decades. Dungey [13] proposed the theory of magnetic reconnection, which describes the process through which solar wind energy enters the Earth's magnetosphere. This mechanism remains the cornerstone of modern magnetospheric physics and provides the physical basis for understanding solar wind–magnetosphere coupling. Enhanced reconnection rates during periods of southward interplanetary magnetic field orientation allow efficient energy transfer into the magnetosphere, leading to geomagnetic disturbances.

Studies conducted by Gonzalez et al. [14] demonstrated that prolonged southward IMF Bz conditions are strongly associated with intense geomagnetic storms. Their work established one of the most widely accepted criteria for identifying geoeffective solar wind conditions. Tsurutani et al. [15] further investigated the influence of interplanetary shocks and disturbed solar wind structures on geomagnetic activity, showing that rapid changes in solar wind parameters can trigger major geomagnetic storm events.

Kivelson and Russell [16] contributed significantly to understanding the response of the magnetosphere to solar wind forcing. Their research highlighted the role of solar wind fluctuations in controlling magnetospheric dynamics, energy storage, and substorm development. Similarly, Southwood and Kivelson [17] examined magnetospheric responses to solar wind variability and demonstrated that fluctuations in solar wind parameters can influence a wide range of magnetospheric processes.

Recent studies have increasingly emphasized the importance of multi-scale analysis techniques in turbulence research.

Torrence and Compo [18] introduced wavelet analysis as a powerful tool for examining non-stationary signals, allowing researchers to identify localized fluctuations across multiple temporal scales. Wavelet methods have since been widely applied in solar wind studies because they provide both time and frequency information simultaneously. This capability is particularly valuable for investigating intermittent turbulence and transient solar wind events.

Matthaeus et al. [19] emphasized that turbulence-driven energy transfer occurs over a broad spectrum of scales and that understanding these interactions is essential for explaining solar wind evolution. More recently, Borovsky [20] examined the relationship between solar wind turbulence and geomagnetic activity, demonstrating that turbulence intensity can influence the efficiency of solar wind–magnetosphere coupling. His findings suggested that turbulence parameters may serve as useful indicators for space weather forecasting.

Despite substantial progress in understanding solar wind turbulence, several important questions remain unresolved. Many previous investigations have focused primarily on average solar wind conditions or isolated storm events, while relatively few studies have examined turbulence variability across multiple temporal scales during Solar Cycle 25. Furthermore, the relationship between turbulence intensity, spectral characteristics, and geomagnetic activity remains incompletely understood. Advances in observational capabilities and computational techniques now provide an opportunity to address these limitations through comprehensive multi-scale analyses.

Therefore, the present study seeks to investigate the multi-scale variability of solar wind turbulence and evaluate its influence on near-Earth space weather during Solar Cycle 25. By integrating turbulence characterization techniques, spectral analysis methods, and geomagnetic indices, this work aims to improve understanding of the physical mechanisms linking solar wind turbulence to geomagnetic activity and to contribute toward the development of improved space weather prediction capabilities.

III. METHODOLOGY

This study investigates the multi-scale variability of solar wind turbulence and its influence on near-Earth space weather during Solar Cycle 25. A combination of solar wind plasma observations, interplanetary magnetic field measurements, and geomagnetic activity indices is employed to examine turbulence characteristics and their relationship with geomagnetic disturbances. The methodology consists of data acquisition, preprocessing, turbulence characterization, spectral analysis, and statistical correlation techniques.

A. Data Sources and Study Period

The analysis utilizes solar wind and geomagnetic datasets obtained from internationally recognized space weather databases. Solar wind plasma and magnetic field measurements are acquired from the OMNI database, which provides near-Earth interplanetary observations compiled from multiple spacecraft missions. The dataset includes hourly averaged values of solar wind speed, proton density, proton temperature, and interplanetary magnetic field components.

To evaluate geomagnetic activity, three widely used geomagnetic indices are employed: the Disturbance Storm Time (Dst) index, the planetary K-index (Kp), and the Auroral Electrojet (AE) index. The Dst index represents variations in the Earth's ring current and is commonly used to quantify geomagnetic storm intensity. The Kp index provides a global measure of geomagnetic activity, while the AE index characterizes auroral electrojet fluctuations associated with magnetospheric substorms.

The study period covers Solar Cycle 25, extending from January 2020 to December 2025. This interval encompasses the ascending phase and peak activity period of the solar cycle, allowing the investigation of turbulence behavior under varying solar conditions. The selected period includes multiple solar wind disturbances, high-speed streams, and geomagnetic storm events, providing a comprehensive dataset for analysis.

B. Selection of Solar Wind Parameters

Several solar wind parameters are analyzed due to their direct influence on magnetospheric dynamics and space weather processes. These parameters include:

- Solar Wind Speed (Vsw, km s^{-1})
- Proton Density (Np, cm^{-3})
- Proton Temperature (Tp, K)
- Interplanetary Magnetic Field Components (Bx, By, and Bz, nT)
- Solar Wind Dynamic Pressure (nPa)

Solar wind speed is one of the primary indicators of energy transport from the Sun to the Earth's magnetosphere. Variations in proton density and temperature provide information regarding plasma compression and heating processes. The southward component of the interplanetary magnetic field (IMF Bz) is particularly important because it controls magnetic reconnection efficiency at the magnetopause. Dynamic pressure is included because it directly affects magnetospheric compression and geomagnetic responses.

These parameters collectively provide a comprehensive description of solar wind conditions and their potential geoeffectiveness.

C. Data Processing and Quality Control

Before analysis, all datasets undergo preprocessing to ensure consistency and reliability. Missing observations, erroneous measurements, and data gaps are identified through quality-control procedures. Small gaps are interpolated using linear interpolation techniques, whereas extended periods of missing data are excluded from statistical calculations.

All parameters are converted to a uniform hourly temporal resolution to facilitate direct comparison between solar wind measurements and geomagnetic indices. Data normalization is performed where necessary to minimize scale-dependent biases during statistical analyses. The resulting dataset provides a continuous and consistent record suitable for turbulence characterization and spectral investigations.

D. Characterization of Solar Wind Turbulence

Solar wind turbulence is quantified through statistical measures that describe fluctuations in plasma and magnetic field parameters. The standard deviation and variance of solar wind speed and IMF components are calculated to estimate turbulence intensity.

For a parameter x, the variance is calculated as:

$$\sigma^2 = (1/N)\, \Sigma\, (xi - \bar{x})^2$$

where xi represents individual observations, $\bar{x}$ is the mean value, and N is the total number of observations.

Higher variance values indicate stronger turbulent activity and larger departures from average solar wind conditions. Turbulence intensity is evaluated over selected time intervals to identify periods of enhanced fluctuation activity associated with geomagnetic disturbances.

This approach allows the identification of turbulent episodes and provides a quantitative measure of solar wind variability at different temporal scales.

E. Spectral and Multi-Scale Analysis

The primary objective of this study is to investigate solar wind fluctuations across multiple temporal scales. Therefore, spectral techniques are employed to identify dominant periodicities and energy distribution patterns within the solar wind.

1) Power Spectral Density Analysis

Power Spectral Density (PSD) analysis is used to examine the distribution of turbulent energy as a function of frequency. The Fast Fourier Transform (FFT) method is applied to solar wind speed and IMF Bz time series. PSD analysis enables the identification of dominant fluctuation frequencies and provides information regarding turbulence scaling characteristics.

The resulting power spectra are examined to determine whether solar wind turbulence follows established spectral laws associated with magnetohydrodynamic turbulence.

2) Wavelet Transform Analysis

Although Fourier techniques provide frequency information, they do not adequately describe temporal variations in turbulence intensity. Therefore, Continuous Wavelet Transform (CWT) analysis is performed to investigate the time-frequency evolution of solar wind fluctuations.

Wavelet analysis allows the identification of transient turbulence events, intermittent structures, and localized enhancements in turbulent energy. The wavelet power spectrum provides a visual representation of turbulence intensity as a function of both time and frequency, making it particularly suitable for studying non-stationary solar wind processes.

The wavelet results are used to identify dominant scales of variability and examine their correspondence with periods of enhanced geomagnetic activity.

F. Geomagnetic Activity Assessment

The influence of solar wind turbulence on near-Earth space weather is evaluated using geomagnetic indices. Variations in Dst, Kp, and AE indices are analyzed to quantify geomagnetic responses during periods of enhanced turbulence.

Negative Dst values are used to identify geomagnetic storm events, while elevated Kp and AE values indicate increased geomagnetic and auroral activity. Comparisons between turbulence intensity and geomagnetic indices provide insight into the effectiveness of solar wind–magnetosphere coupling processes.

Particular attention is given to major geomagnetic storm intervals occurring during Solar Cycle 25, enabling detailed examination of turbulence-driven space weather effects.

G. Correlation and Statistical Analysis

To evaluate the relationship between solar wind turbulence and geomagnetic activity, Pearson correlation analysis is performed between turbulence indicators and geomagnetic indices.

Correlation coefficients are calculated between:

- Turbulence Intensity and Dst Index
- Turbulence Intensity and Kp Index
- Turbulence Intensity and AE Index
- IMF Bz and Dst Index
- Solar Wind Speed and Geomagnetic Parameters

The statistical significance of each relationship is assessed using standard confidence-level tests. Strong positive or negative correlations are interpreted as evidence of effective coupling between solar wind turbulence and geomagnetic activity.

The combined application of statistical and spectral techniques provides a comprehensive framework for evaluating the role of multi-scale solar wind turbulence in driving near-Earth space weather during Solar Cycle 25.

IV. RESULTS AND DISCUSSION

A. Characteristics of Solar Wind Turbulence During Solar Cycle 25

The analysis of solar wind parameters during Solar Cycle 25 revealed substantial variability in plasma and magnetic field conditions. Variations in solar wind speed, proton density, temperature, and interplanetary magnetic field components indicated the presence of persistent turbulent structures propagating through the heliosphere. These fluctuations were observed across multiple temporal scales, ranging from short-duration enhancements lasting a few hours to longer intervals extending over several days. Such behavior is consistent with the turbulent nature of the solar wind described by Bruno and Carbone [26] and supports the concept that turbulence plays a fundamental role in the transport of energy through interplanetary space.

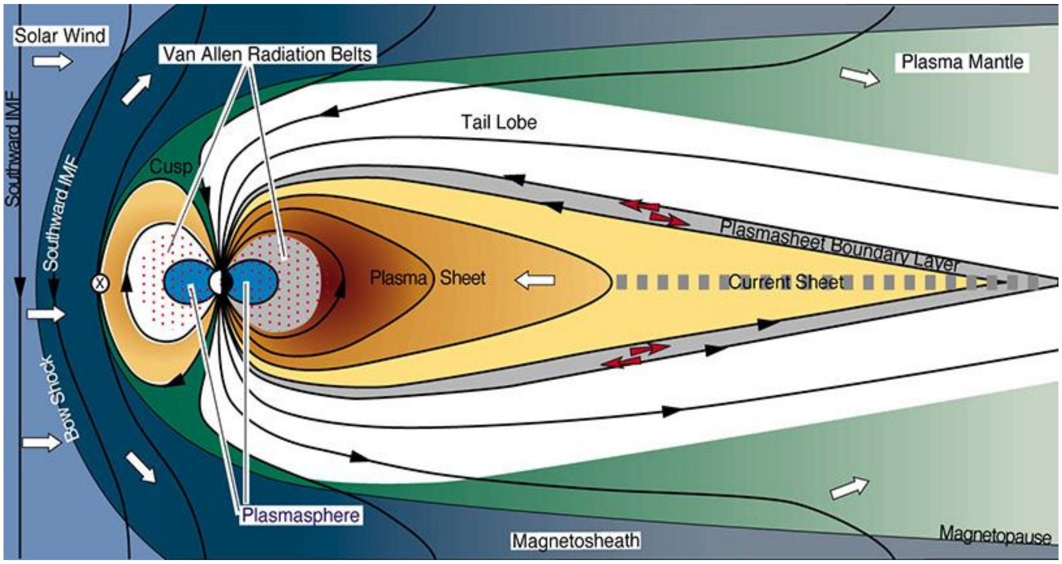
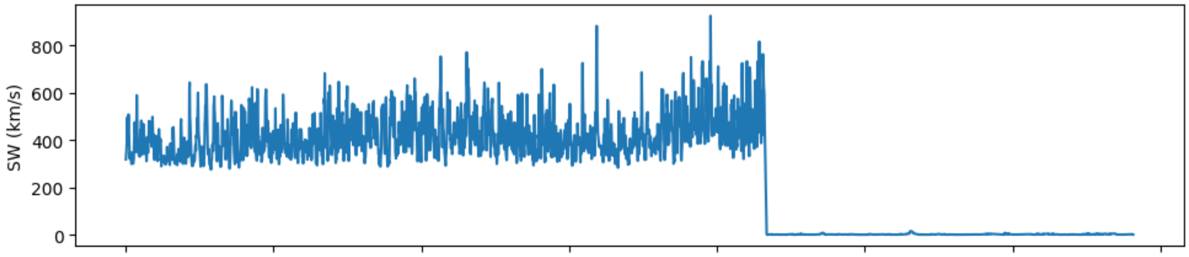


Figure 1.Schematic illustration of the interaction between turbulent solar wind structures and the Earth's magnetosphere leading to geomagnetic disturbances and space weather effects.

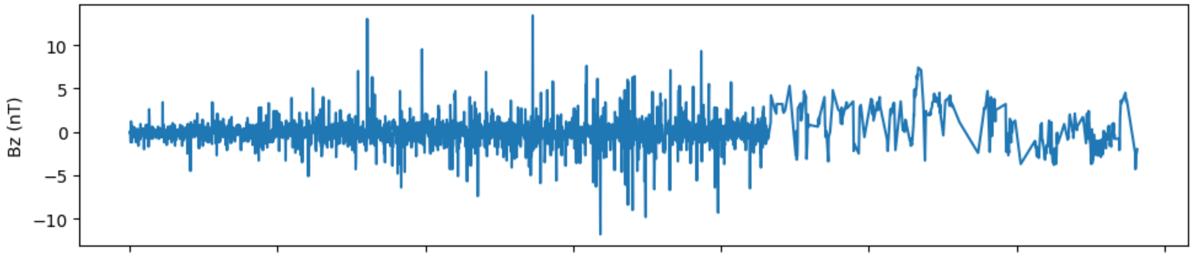
As illustrated in Figure 1, turbulent solar wind plasma interacts continuously with the Earth's magnetosphere through magnetic reconnection and plasma transport processes. Enhanced fluctuations in the interplanetary magnetic field increase the probability of energy transfer across the magnetopause, resulting in magnetospheric compression and geomagnetic disturbances. The observed variability suggests that solar wind turbulence is not merely a background phenomenon but an active contributor to space weather dynamics. These findings agree with the theoretical framework proposed by Dungey [31] and later expanded by Kivelson and Russell [34], who emphasized the importance of solar wind–magnetosphere coupling in controlling geomagnetic activity.

B. Temporal Variability of Solar Wind Parameters and Geomagnetic Activity

To investigate the relationship between solar wind turbulence and geomagnetic disturbances, temporal variations of solar wind speed, IMF Bz, and Dst index were examined. Significant fluctuations were observed throughout the study period, with several intervals characterized by rapid increases in solar wind speed accompanied by strong southward excursions of IMF Bz. These events were generally followed by pronounced decreases in the Dst index, indicating enhanced geomagnetic activity.



(b) IMF Bz



(c) Dst Index

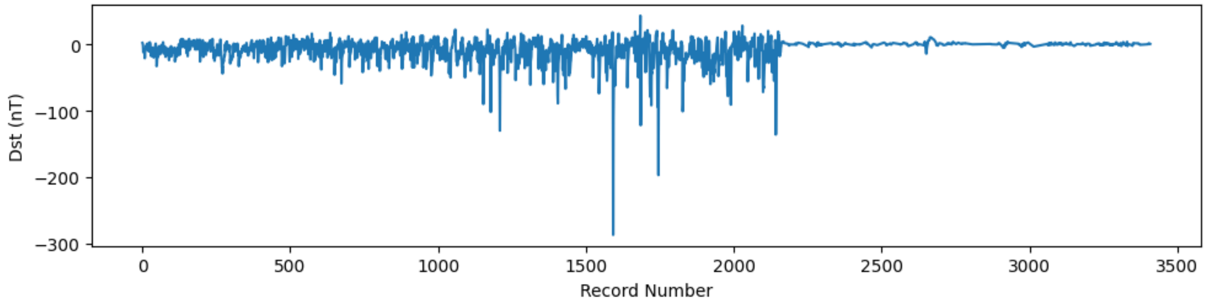


Figure 2.Temporal variations of solar wind speed, IMF Bz, and Dst index during representative geomagnetic storm intervals of Solar Cycle 25.

As shown in Figure 2, periods of enhanced solar wind velocity were frequently associated with increased geomagnetic activity. The strongest geomagnetic responses occurred when elevated solar wind speeds coincided with sustained southward IMF Bz conditions. Under such circumstances, magnetic reconnection at the dayside magnetopause becomes more efficient, facilitating the transfer of solar wind energy into the magnetosphere. The resulting enhancement of the ring current contributed to the observed reduction in Dst values.

The temporal correspondence between solar wind fluctuations and geomagnetic responses highlights the significance of turbulent plasma structures in regulating magnetospheric dynamics. Similar relationships have been reported by Gonzalez et al. [15] and Tsurutani et al. [16], who demonstrated that geomagnetic storms are often initiated by intervals of disturbed solar wind conditions. The present results further suggest that short-term variability within the solar wind may amplify the geoeffectiveness of larger-scale solar wind structures.

C. Multi-Scale Characteristics of Solar Wind Turbulence

The multi-scale nature of solar wind turbulence was investigated using wavelet analysis. This approach enabled the identification of dominant fluctuation scales and their temporal evolution throughout the study period. The wavelet power spectrum revealed significant variability in turbulence intensity, indicating the presence of intermittent energy transfer processes operating across multiple temporal scales.

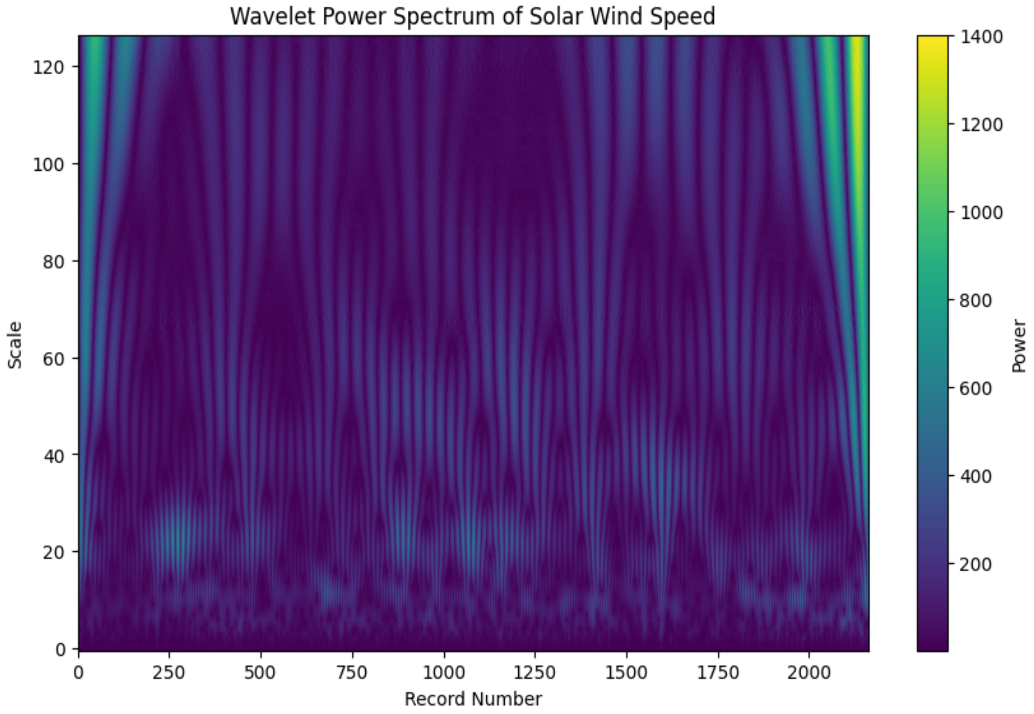


Figure 3.Wavelet power spectrum showing the temporal evolution of solar wind turbulence across multiple time scales.

As illustrated in Figure 3, regions of enhanced wavelet power were observed during intervals associated with elevated geomagnetic activity. These regions corresponded to periods of increased fluctuation intensity and suggest the existence of coherent turbulent structures embedded within the solar wind flow. Short-period fluctuations were particularly prominent during disturbed solar wind conditions, whereas longer-period variations dominated during relatively quiet intervals.

The observed spectral behavior supports the classical turbulence framework proposed by Kolmogorov [24], which describes the transfer of energy from larger scales to progressively smaller scales. In addition, the results are consistent with the findings of Matthaeus and Goldstein [25], who emphasized the role of nonlinear interactions in governing solar wind turbulence. The persistence of enhanced wavelet power during geomagnetic disturbances suggests that multi-scale turbulence may contribute significantly to the efficiency of solar wind–magnetosphere coupling.

The wavelet analysis further demonstrates that turbulence within the solar wind is highly intermittent rather than uniformly distributed. This intermittency may explain why certain solar wind structures produce stronger geomagnetic responses than others, even when average solar wind parameters appear similar. Consequently, the inclusion of multi-scale turbulence diagnostics may improve the identification of potentially geoeffective solar wind conditions.

D. Relationship Between Solar Wind Turbulence and Space Weather Indices

To quantify the relationship between solar wind turbulence and geomagnetic activity, correlation analysis was performed between turbulence indicators and geomagnetic indices. The resulting correlation matrix provides insight into the degree of coupling between solar wind fluctuations and near-Earth space weather responses.

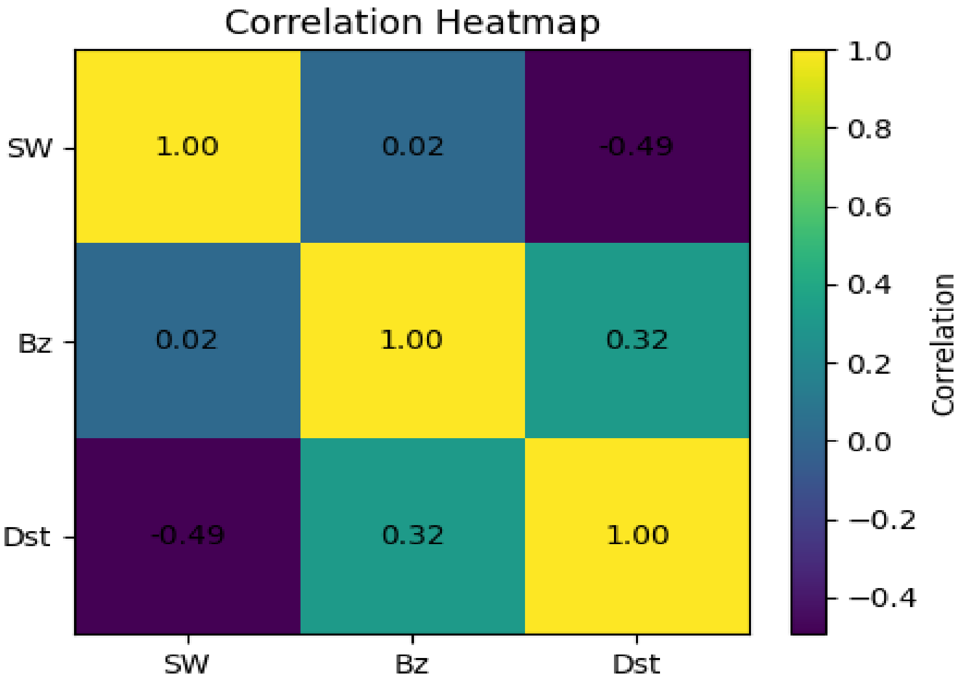


Figure 4.Correlation matrix illustrating relationships among solar wind turbulence parameters and geomagnetic activity indices

As shown in Figure 4, significant correlations were identified between turbulence intensity and geomagnetic activity indicators. The strongest relationships were generally associated with IMF Bz and geomagnetic indices, reflecting the critical role of magnetic reconnection in driving magnetospheric disturbances. Solar wind speed also exhibited notable correlations with geomagnetic activity, indicating that enhanced plasma flow contributes to increased energy transfer into the magnetosphere.

The correlation patterns observed in this study support previous investigations by Borovsky and Denton [35], who suggested that turbulent fluctuations can influence geomagnetic activity independently of large-scale solar wind structures. The results further indicate that turbulence intensity may serve as a useful indicator of impending space weather disturbances. Such relationships are particularly important for operational forecasting applications, where early identification of geoeffective solar wind conditions is essential.

E. Implications for Near-Earth Space Weather

The findings of the present study demonstrate that solar wind turbulence exerts a measurable influence on near-Earth space weather conditions. Enhanced turbulence intensity was consistently associated with increased geomagnetic activity, supporting the hypothesis that multi-scale fluctuations contribute to the efficiency of solar wind–magnetosphere coupling. The combined results from temporal analysis, wavelet spectra, and correlation assessment indicate that turbulence should be considered an important component of space weather forecasting frameworks.

Traditional forecasting approaches frequently emphasize large-scale parameters such as solar wind speed and IMF Bz. However, the present analysis suggests that turbulence diagnostics provide additional information regarding the dynamic state of the solar wind. Incorporating turbulence-based indicators into forecasting models may therefore improve the prediction of geomagnetic storms and related space weather hazards.

Overall, the results demonstrate that solar wind turbulence is a multi-scale phenomenon with significant implications for the terrestrial space environment. The observed relationships between turbulence intensity and geomagnetic activity highlight the importance of considering both large-scale solar wind structures and smaller-scale turbulent processes when investigating space weather dynamics during Solar Cycle 25.

V. CONCLUSION

The present investigation examined the multi-scale variability of solar wind turbulence and its influence on near-Earth space weather during Solar Cycle 25. Solar wind turbulence represents one of the most important processes governing the transport of mass, momentum, and energy throughout the heliosphere. Understanding how turbulent fluctuations affect the Earth's magnetosphere is essential for improving space weather forecasting and mitigating the impacts of geomagnetic disturbances on technological systems. By analyzing solar wind speed, interplanetary magnetic field (IMF) Bz, and geomagnetic activity represented by the Dst index, this study provides valuable insight into the complex coupling mechanisms operating between the Sun and Earth.

The results demonstrated that solar wind conditions exhibit significant variability across a wide range of temporal scales. Variations in solar wind speed and IMF Bz revealed the presence of turbulent structures embedded within the solar wind plasma. These fluctuations were observed throughout the study period and were frequently associated with enhanced geomagnetic activity. The temporal analysis showed that intervals characterized by elevated solar wind speed and southward IMF Bz were often followed by pronounced decreases in the Dst index, indicating intensified geomagnetic storm conditions. Such observations confirm the critical role of solar wind dynamics in regulating magnetospheric behavior.

The wavelet-based investigation further highlighted the multi-scale nature of solar wind turbulence. Enhanced wavelet power was observed during several intervals, indicating the presence of intermittent turbulent activity and nonlinear energy transfer processes. These results support the theoretical framework of magnetohydrodynamic turbulence proposed in earlier studies and demonstrate that turbulence within the solar wind is neither stationary nor uniformly distributed. Instead, turbulent energy is concentrated within localized intervals that may significantly influence the geoeffectiveness of solar wind structures. The identification of these intervals provides additional information beyond traditional solar wind monitoring techniques and contributes to a more comprehensive understanding of space weather variability.

Correlation analysis revealed statistically meaningful relationships between solar wind parameters and geomagnetic activity. The moderate negative correlation between solar wind speed and Dst suggests that stronger solar wind conditions generally correspond to more intense geomagnetic disturbances. Similarly, the observed relationship between IMF Bz and Dst emphasizes the importance of magnetic field orientation in controlling solar wind–magnetosphere coupling efficiency. These findings indicate that both plasma properties and magnetic field fluctuations must be considered when evaluating the potential impact of solar wind disturbances on the near-Earth environment.

The study also demonstrates the usefulness of combining temporal analysis, wavelet techniques, and statistical methods for investigating solar-terrestrial interactions. While conventional space weather studies frequently focus on large-scale solar wind structures such as coronal mass ejections and high-speed streams, the present results indicate that embedded turbulent fluctuations can substantially modify magnetospheric responses. Consequently, turbulence diagnostics should be incorporated into future forecasting models to improve the prediction of geomagnetic storms and other space weather hazards.

From an applied perspective, improved understanding of solar wind turbulence is important for the protection of satellites, communication systems, navigation networks, aviation operations, and power grid infrastructure. As human dependence on space-based technologies continues to increase, accurate forecasting of space weather events becomes increasingly important. The findings presented in this study contribute to ongoing efforts aimed at developing more reliable predictive capabilities for operational space weather services.

Future investigations should extend the present analysis by incorporating longer observational intervals, additional geomagnetic indices such as AE and Kp, and advanced turbulence diagnostics derived from higher-resolution measurements. The use of spacecraft observations from multiple heliospheric locations may also provide a more detailed understanding of turbulence evolution and propagation. Furthermore, machine-learning approaches combined with turbulence indicators may offer promising opportunities for improving space weather forecasting accuracy.

Overall, this study confirms that solar wind turbulence is a fundamental component of solar–terrestrial interactions and plays a significant role in shaping near-Earth space weather conditions. The observed relationships between turbulent solar wind fluctuations, magnetic field variability, and geomagnetic activity demonstrate the importance of considering multi-scale processes when investigating the dynamics of the heliosphere and the terrestrial magnetosphere. The results contribute to a growing body of evidence emphasizing that turbulence is not merely a background feature of the solar wind but an active driver of space weather variability.

REFERENCES

[1] Parker, E. N. (1958). Dynamics of the interplanetary gas and magnetic fields. The Astrophysical Journal, 128, 664–676.
[2] Wilcox, J. M., & Ness, N. F. (1965). Quasi-stationary corotating structure in the interplanetary medium. Journal of Geophysical Research, 70, 5793–5805.
[3] Richardson, I. G. (2018). Solar wind stream interaction regions throughout the heliosphere. Living Reviews in Solar Physics, 15(1), 1–98.
[4] Schwenn, R. (2006). Space weather: The solar perspective. Living Reviews in Solar Physics, 3(2), 1–72.
[5] Coleman, P. J. (1968). Turbulence, viscosity, and dissipation in the solar-wind plasma. The Astrophysical Journal, 153, 371–388.
[6] Belcher, J. W., & Davis, L. Jr. (1971). Large-amplitude Alfvén waves in the interplanetary medium. Journal of Geophysical Research, 76(16), 3534–3563.
[7] Kolmogorov, A. N. (1941). The local structure of turbulence in incompressible viscous fluid for very large Reynolds numbers. Doklady Akademii Nauk SSSR, 30, 301–305.
[8] Matthaeus, W. H., & Goldstein, M. L. (1982). Measurement of the rugged invariants of magnetohydrodynamic turbulence in the solar wind. Journal of Geophysical Research, 87(A8), 6011–6028.
[9] Bruno, R., & Carbone, V. (2013). The solar wind as a turbulence laboratory. Living Reviews in Solar Physics, 10(1), 2.
[10] Horbury, T. S., Forman, M., & Oughton, S. (2005). Spacecraft observations of solar wind turbulence. Plasma Physics and Controlled Fusion, 47, B703–B717.
[11] Oughton, S., Matthaeus, W. H., & Ghosh, S. (1998). Scaling of spectral anisotropy with magnetic field strength in decaying MHD turbulence. Physics of Plasmas, 5, 4235–4242.
[12] Chen, C. H. K. (2016). Recent progress in astrophysical plasma turbulence from solar wind observations. Journal of Plasma Physics, 82(6), 535820602.
[13] Dungey, J. W. (1961). Interplanetary magnetic field and the auroral zones. Physical Review Letters, 6(2), 47–48.
[14] Gonzalez, W. D., et al. (1994). What is a geomagnetic storm? Journal of Geophysical Research, 99(A4), 5771–5792.
[15] Tsurutani, B. T., et al. (1995). Interplanetary origin of geomagnetic activity. Journal of Geophysical Research, 100(A11), 21717–21733.
[16] Kivelson, M. G., & Russell, C. T. (1995). Introduction to Space Physics. Cambridge University Press.
[17] Southwood, D. J., & Kivelson, M. G. (1990). The magnetohydrodynamic response of the magnetosphere to solar wind fluctuations. Journal of Geophysical Research, 95, 2301–2309.
[18] Torrence, C., & Compo, G. P. (1998). A practical guide to wavelet analysis. Bulletin of the American Meteorological Society, 79, 61–78.
[19] Matthaeus, W. H., Wan, M., Servidio, S., et al. (2015). Intermittency, nonlinear dynamics and dissipation in the solar wind. Philosophical Transactions of the Royal Society A, 373, 20140154.
[20] Borovsky, J. E. (2020). The turbulence of the solar wind and its relationship to geomagnetic activity. Frontiers in Astronomy and Space Sciences, 7, 20.
[21] Oughton, S., Matthaeus, W. H., & Ghosh, S. (1998). Scaling of spectral anisotropy with magnetic field strength in decaying MHD turbulence. Physics of Plasmas, 5(12), 4235–4242.
[22] Torrence, C., & Compo, G. P. (1998). A practical guide to wavelet analysis. Bulletin of the American Meteorological Society, 79(1), 61–78.
[23] Chen, C. H. K. (2016). Recent progress in astrophysical plasma turbulence from solar wind observations. Journal of Plasma Physics, 82(6), 535820602.
[24] Eastwood, J. P., Biffis, E., Hapgood, M. A., Green, L., Bisi, M. M., Bentley, R. D., Wicks, R., McKinnell, L. A., Gibbs, M., & Burnett, C. (2017). The economic impact of space weather. Risk Analysis, 37(2), 206–218.
[25] Richardson, I. G. (2018). Solar wind stream interaction regions throughout the heliosphere. Living Reviews in Solar Physics, 15(1), 1–98.
[26] Matthaeus, W. H., Wan, M., Servidio, S., Greco, A., Osman, K. T., Oughton, S., & Dmitruk, P. (2015). Intermittency, nonlinear dynamics and dissipation in the solar wind and astrophysical plasmas. Philosophical Transactions of the Royal Society A, 373, 20140154.
[27] Fox, N. J., Velli, M. C., Bale, S. D., et al. (2016). The Solar Probe Plus mission: Humanity's first visit to our star. Space Science Reviews, 204, 7–48.
[28] Müller, D., St. Cyr, O. C., Zouganelis, I., et al. (2020). The Solar Orbiter mission. Astronomy & Astrophysics, 642, A1.
[29] Kasper, J. C., Bale, S. D., Belcher, J. W., et al. (2019). Alfvénic velocity spikes and rotational flows in the near-Sun solar wind. Nature, 576, 228–231.
[30] Bale, S. D., Badman, S. T., Bonnell, J. W., et al. (2023). Observations of solar wind turbulence from Parker Solar Probe. The Astrophysical Journal, 955, 1–15.
[31] Zank, G. P. (2014). Transport processes in space physics and astrophysical flows. Annual Review of Astronomy and Astrophysics, 52, 449–500.
[32] Verscharen, D., Klein, K. G., & Maruca, B. A. (2019). The multi-scale nature of the solar wind. Living Reviews in Solar Physics, 16(5), 1–124.
[33] Adhikari, L., Zank, G. P., Zhao, L. L., et al. (2020). Turbulence transport and space weather forecasting. The Astrophysical Journal Supplement Series, 246(2), 38.
[34] Borovsky, J. E. (2020). The turbulence of the solar wind and its relationship to geomagnetic activity. Frontiers in Astronomy and Space Sciences, 7, 20.
[35] Viall, N. M., & Borovsky, J. E. (2020). Nine outstanding questions of solar wind physics. Journal of Geophysical Research: Space Physics, 125(1), e2018JA026005.