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Seasonal Variation Analysis for Solar Activity Influence on "Planetarische Kennziffer" (Kp) Index during Solar Cycle 23

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Abstract

In this research paper, we explore how the K index changes in connection with shifts in solar activity throughout Solar Cycle 23. We examine indicators of solar activity such as sunspot numbers, radio solar flux (measured at 10.7 cm), and sunspot area to understand their impact on the K index. This study is notable for providing comprehensive information on these characteristics to offer a clearer picture of how fluctuations in solar activity relate to variations in the K index. By analyzing data from the peak of Solar Cycle 23—specifically when the sunspot area exceeds 500 micro-hemispheres—we observe a clear correlation between the F10.7 index and the Kp index. The findings demonstrate consistent associations between the Kp index and solar flux levels over time, suggesting that solar flux may serve as a reliable indicator of disturbances in Earth's geomagnetic field. The research covers the authors' understanding of the interaction between solar activity and geomagnetic conditions, which is crucial for predicting space weather and mitigating its effects on Earth's technological systems. The knowledge gained from this research highlights the importance of monitoring solar flux and sunspot activity to forecast periods of heightened activity during solar cycles.

Keywords

Geomagnetic Activity, Solar Activity, Solar Cycle 23 Sunspot Area, Kp Index

1. Introduction

The solar wind, which emanates from the Sun and flows outward, envelops the

Earth in a constantly moving stream of plasma and magnetic fields. This persistent solar wind has a significant influence on the behaviour of Earth's magnetosphere. For instance, particle precipitation from the solar wind and plasma accumulation in the magnetotail are primary drivers of auroral activity [1]. These energetic particles transfer energy to atmospheric particles, producing the visually striking phenomenon known as the aurora.

Between 1996 and 2008, distinct characteristics emerged during both the ascending and descending phases of Solar Cycle 23. Notably, the unusually prolonged solar minimum (e.g., Kane 2005) [2] has drawn considerable attention, as it plays a critical role in the interpretation of geomagnetic indices. This period is thus considered crucial for the study of solar-terrestrial interactions.

Numerous studies have investigated the relationship between geomagnetic indices—such as the Kp index and solar activity, particularly in relation to sunspot counts and sunspot area (**Figure 1**). Solar Cycle 23 stands out for its extended minimum phase marked by significantly low sunspot numbers. This unique condition presents a valuable opportunity to examine how diminished solar activity correlates with geomagnetic behaviour. While previous research has laid the groundwork for understanding these dynamics, much of it has focused on periods of heightened solar activity, leaving a gap in knowledge regarding the effects of low solar activity on geomagnetic indices [3].

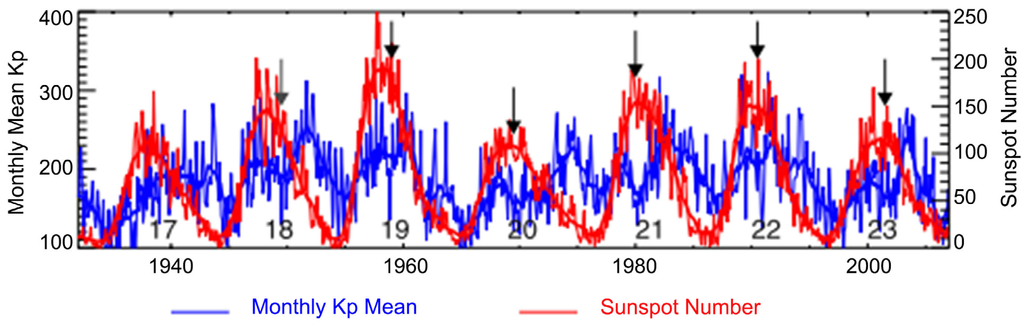


Figure 1. Showing the monthly mean value of Kp index during the 17th to 23rd solar cycle is presented together with the sunspot number. Variations of Kp index basically follow the sunspot number [4].

Our study highlights the seasonal fluctuations in Kp index behaviour and examines the broader relationship between solar activity and geomagnetic indices. Previous research has demonstrated that geomagnetic activity can vary significantly with the seasons, particularly around the equinoxes. While these seasonal patterns have been acknowledged, further investigation is needed to understand how the unique features of Solar Cycle 23 may alter or amplify these trends. Understanding these seasonal fluctuations is crucial for improving the accuracy of geomagnetic storm forecasts and mitigating their potential impacts on communication and technological infrastructure [5] [6].

Gleason and Aboy noted the erratic fluctuations of the Kp index—a key component of geomagnetic activity—across different seasons, suggesting that these variations require further study. Research has also shown that annual trends in geomagnetic activity are most pronounced during the equinoctial periods, when the alignment of Earth's geomagnetic field with the interplanetary magnetic field (IMF) allows for more effective coupling with solar wind energy. This alignment makes Earth's magnetosphere more susceptible to disturbances, increasing geomagnetic activity during these times. Although seasonal dependencies in geomagnetic indices like the Kp index are well documented, the distinctive nature of Solar Cycle 23 may either amplify or suppress these variations. As such, this cycle presents a valuable opportunity to investigate how periods of low solar activity influence deviations from established seasonal patterns.

By analysing the Solar Cycle 23 period, our study addresses a notable gap in the literature concerning how low levels of solar activity influence seasonal changes in geomagnetic behaviour. This research contributes to the growing body of knowledge on the relationship between solar activity and geomagnetic indices, emphasizing that even atypical solar cycles can significantly affect these interactions. Recognizing and quantifying these effects is essential for the development of robust forecasting models. Such models are increasingly important in today's technologically dependent world, where even minor disturbances in Earth's geomagnetic field can disrupt navigation systems, communications, and power grids [7] [8].

2. Literature Review

The analysis of solar wind magnetosphere interaction is as old as space physics, with pioneering works demonstrating the importance of solar activity for geomagnetic activity. Chapman and Ferraro (1941) appeared to be pioneers and the first to provided concepts about the effects of solar storms on the magnetic environment of the Earth and energy transfer from solar wind particles to the magnetosphere causes geomagnetic storms. These basic investigations formed the basis for further research into the complexity of the solar-terrestrial connection, where it has been established that solar wind velocity, density and magnetic fields have a substantial effect on geomagnetic activity as described by the Kp index. Since then many other researches have been done to explore these solar-terrestrial relations, with particularly stressing necessity of taking into account various phases of the solar cycle [9].

Among different indices that characterize the level of geomagnetic activity, the Kp index proved to be one of the most important indices used in space weather studies. Bartels (1932) already created the measurement for geomagnetic storm intensity as Kp index which varies from 0 to 9. Since then, the Kp index is used routinely, and is applied broadly in space weather research for operating and prospecting geomagnetic storms [10]. Tsurutani *et al.*, [11] have investigated this fact when pointing to the frequently observed solar wind conditions as well as the strong interplanetary magnetic field leading to the Kp index enhancement. However, most of the initial attempts were carried out during periods of high intensity solar storms, aimed at determining their effect on the geomagnetic environment.

Since this focus has placed much importance on particular periods, there is inadequate information available on how minimum solar conditions such as those of the Solar Cycle 23 extended minimum impact certain values of the geomagnetic indices [11].

Solar Cycle 23 that started in 1996 up to 2008 has been of interesting history because it was characterized by an unexpected extra-long solar minimum period. As Kane pointed out in his recent article, this cycle was characterized by an unusually lengthy and dormant solar minimum, one that has been named as having one of the longest records of low levels of sunspot activity. This long minimum has since formed the basis of extended research because it offered scientists the chance to study how the magnetosphere of Earth reacts to lasting low solar activity. A few researchers claim that this protracted minimum might affect the typical response of the Earth's magnetic field to conditions in a manner that has been detected during other low-solar-activity intervals. The effect of such extended interval of silence on the parameters such as Kp index, however, merits further research.

There are many cases reported in previous studies that phenomena associated with geomagnetic activity are most intense around equinoctial periods only. Equinoctial hypothesis has been expressed by Russell and McPherron [12] stating that geomagnetic field of the Earth gets closely aligned to IMF during equinox period which enhanced energy coupling from the solar wind into the magnetosphere [12]. These seasonal effects have also been supported by numerous studies, such as the work of Cliver *et al.* (2000) who probe increased geomagnetic activity during equinox periods because of appropriate IMF configurations. Despite such previous explorations of climatic annual variations, behaviors of Solar Cycle 23, which is differently featured from those that came before it, may well engage or change these annually predictable traits, hence, a need to investigate the effects of seasons taking into consideration the contested protracted solar minimum phase [13].

In spite of the significant progress made in the study of GM and its source, the prior achievements and numerous studies have primarily focused the articles and research on high solar activity periods, means maximum phases with high sunspot and flaring activity [4]. It has been the active periods that have attracted the interest of many researchers because during intense geomagnetic storms, satellites, communication and power systems can be affected. Nevertheless, fewer studies have been made with low activity periods and the behavior of different indices such as the Kp index during the absence of solar activity. Since Solar Cycle 23 experienced a lengthy low level of solar activity, what we propose is that low-Kp conditions may demonstrate other patterns of geomagnetic activity and seasonal responses [14].

Besides emphasizing the reaction to solar and seasonal stimuli, it is witnessing the emergence of a demand for further investigations on the predictability of geomagnetic indexes, such as Kp index, under various solar conditions. Research by

Richardson and Cane (2012) clearly reveals that many space weather forecasts have higher variability, correlation and prediction error rates of geomagnetic storms while the sun is quiet. These restrictions are suggesting the need to research geomagnetic indices in various solar conditions in order to enhance calibration declaration. Investigating the dependency of the Kp index on seasonal changes and its low activity phase behavior during Solar Cycle 23 plays significant roles for enhancing the uncertainties of Kp prediction models under the other vital conditions necessary for vital infrastructures that require credible space weather forecasts [15].

I. Tsagouri [16] discusses the significant impact that geomagnetic storms have on the Earth's upper atmosphere, particularly emphasizing how the highly variable solar wind energy input into the magnetosphere alters ionospheric structure. During such storm events, interactions between ionospheric plasma and atmospheric neutrals result in substantial fluctuations in peak electron density, manifesting as positive or negative ionospheric storms. These large-scale electron density variations have critical implications for the performance and reliability of technological systems, especially those reliant on radio signal propagation and satellite-based navigation.

Ionospheric storms have therefore been the subject of extensive research in recent decades. A comprehensive understanding of their behavior has emerged, positioning them as a crucial component in the broader solar-terrestrial interaction system. Despite these advances, ionospheric storms remain a dynamic area of research due to ongoing developments in geospace modeling, real-time monitoring capabilities, and evolving technological requirements.

The paper offers a concise survey of the current understanding of ionospheric storm responses, particularly at mid-latitudes, focusing on the morphological characteristics and occurrence patterns of these disturbances. Special attention is given to the triggering role of solar wind conditions, which continue to present interpretive challenges and remain central to improving forecasting and mitigation strategies in space weather research.

Toriumi *et al.* [17] emphasized that the formation of extremely hot outer stellar atmospheres is one of the most prominent manifestations of magnetic activity in late-type dwarf stars, including the Sun. These outer layers—the chromosphere, transition region, and corona—are widely believed to be heated by the dissipation of energy transported upward from the stellar surface via magnetic fields. This heating process is reflected in spectral line fluxes at various wavelengths, which exhibit power-law relationships with surface magnetic flux over a wide range of formation temperatures. These relationships appear to be universal among the Sun and Sun-like stars, regardless of their age or magnetic activity level.

In thier study, the authors compiled a comprehensive catalog of power-law indices correlating solar activity proxies with various spectral line fluxes. Compared to previous research, this work significantly expands the scope by:

- Increasing the number of solar activity proxies, which now include total mag-

netic flux, sunspot number, sunspot area, and the F10.7 cm radio flux;
- Doubling the number of spectral lines analyzed.

In their research the extended dataset enables detailed investigation of flux–flux scaling laws across spectral lines originating from different temperature regions, from the corona (log(T/K) ≈ 6 - 7) to the chromosphere (log(T/K) ≈ 4). Furthermore, the catalog facilitates the reconstruction of historical solar spectral fluxes and can be applied to studies of F-, G-, and K-type dwarfs as well as modeled stellar atmospheres.

A. Espuña Fontcuberta *et al.* [6] emphasize that predicting the solar magnetic cycle is of critical importance for humanity. In this context, a novel development is the application of machine learning algorithms for solar cycle forecasting. Various approaches have been developed for this purpose, though no consensus has yet emerged among different techniques, including both data-driven and physics-based methods.

In their study, the authors evaluate the performance of four machine learning algorithms, all belonging to the class of Recurrent Neural Networks (RNNs), for predicting simulated sunspot cycles based on a well-established, stochastically forced, nonlinear time-delay solar dynamo model. Among the models tested, the Echo State Network (ESN) demonstrated the best performance. However, its predictability is limited to only one future sunspot cycle, which aligns with current physical understanding.

The authors then trained the ESN and a modified version (MESN) using historical solar cycle observations to forecast Solar Cycles 22 - 25. Their models produced accurate hindcasts for Solar Cycles 22 through 24. For Solar Cycle 25, the ESN forecasts a peak amplitude of 131 ± 14 sunspots around July 2024, with a cycle length of approximately 10 years. The MESN predicts a peak of 137 ± 2 sunspots around April 2024, with a similar cycle duration.

Qualitatively, both models suggest that Cycle 25 will be slightly stronger than Cycle 24, but weaker than Cycle 23. This research presents a hybrid approach that bridges the gap between physics-based models and machine learning methods, achieving promising consistency across diverse forecasting techniques.

B. L., M. I. Desai *et al.* [5] reported on the annual variation of quiet-time suprathermal ion composition for elements ranging from carbon (C) through iron (Fe), using data from the Advanced Composition Explorer (ACE)/Ultra-Low Energy Isotope Spectrometer (ULEIS). Their analysis covered the energy range 0.3 MeV/nucleon to 1.28 MeV/nucleon over the period 1998 to 2019, encompassing the rising phase of Solar Cycle 23 through the declining phase of Solar Cycle 24.

Their findings include:
- Quiet-time suprathermal ion abundances closely resemble those of corotating interaction region (CIR)-associated particles during solar minima.
- During solar maxima, quiet-time suprathermals exhibit mass-to-charge ratio (M/Q) fractionation similar to that observed in large gradual solar energetic

particle (GSEP) events.

- Variability within the quiet-time suprathermal ion population increases with M/Q, mirroring the variability patterns found in GSEP events.

From these observations, the authors infer that quiet-time suprathermal ions are likely remnants of CIR-related activity during solar minima, and residuals from GSEP events during solar maxima. Additionally, and somewhat unexpectedly, the study finds that sulfur (S) behaves like a low first ionization potential (FIP) ion in the suprathermal regime. This behavior suggests it originates from low-FIP solar sources, offering new insights into the compositional dynamics of suprathermal ion populations.

Eid A. Amin *et al.* [18] investigated the relationship between geomagnetic storms and solar events, compiling a comprehensive catalog of multi-source geomagnetic storms spanning the period from August 1996 to December 2019. Their study focuses on assessing how solar activity influences geomagnetic storm characteristics, particularly during the minimum and maximum phases of Solar Cycles 23 and 24. The results indicate that geomagnetic activity was more intense during Cycle 23 compared to Cycle 24.

A total of 104 geomagnetic storms were identified, each associated with a minimum Dst index of ≤−100 nT, classifying them as intense. A strong correlation was found between the number of storm events and average sunspot numbers (correlation coefficient CC = 0.73), underscoring the direct relationship between solar activity and geomagnetic disturbances. The majority of these storms were associated with coronal mass ejections (CMEs) and solar flares, with relatively few linked to other interplanetary sources.

The study determined that the average CME speed for storms contributing to geomagnetic disturbances was approximately 876 km/s, and a moderate correlation was observed between CME speed and Dst index (R = 0.61). Among the CME-driven events, 63% were full halo CMEs, while 37% were partial or narrower halo CMEs. Notably, seven of the most severe storms during Solar Cycle 23 exhibited a magnetic H-component exceeding 400 nT, reflecting their extreme intensity.

The analysis further incorporated multiple geophysical and solar wind parameters, including solar wind speed, Dst index, Ap index, Kp index, auroral electrojet (AE) index, and the north–south component of the interplanetary magnetic field (IMF-Bz). These parameters were statistically examined to establish the connection between storm occurrences and specific solar drivers such as CMEs, solar flares, and corotating interaction regions (CIRs). This multi-dimensional approach provides a robust characterization of geomagnetic storm behavior during two contrasting solar cycles.

3. Methodology

This research adopts a quantitative operational framework to analyze the correlation between solar activity and geomagnetic activity during Solar Cycle 23, covering the period from 1996 to 2008. The methodology integrates data from multiple sources, including ensemble average daily sunspot area, F10.7 solar radio flux, and the Kp index—widely used as a global measure of geomagnetic activity—to assess both long-term and short-term behavioural trends.

At the methodological level, the study leverages the advantages of a seasonal and, more specifically, a fine-grained (microscopic) approach, enabling detailed observation of how geomagnetic indices respond to solar activity across different time scales. The research process involves data cleaning, feature selection and transformation, exploratory data analysis, correlation analysis, and predictive modelling.

This multilevel strategy facilitates a comprehensive analysis of Solar Cycle 23, with particular attention to the extended minimum phase. It also seeks to uncover patterns and insights that could enhance the accuracy of space weather forecasting during periods of low solar activity, contributing valuable guidance for future solar cycles.

3.1. Data Collection and Preprocessing

The dataset used in this study encompasses three primary indices of solar and geomagnetic activity: Sunspot area, 10.7 cm solar radio flux (F10.7), Kp index data was collected during the period 1996-2008. Sunspot area data was used based on the Royal Observatory, Greenwich USAF/NOAA Sunspot Data site and F10.7 index data were downloaded from Space Weather Canada (Natural Resources Canada) to determine the solar activity levels. The Kp index values, indicative of geomagnetic activity, were collected from the NOAA's geomagnetic indices archive at "https://www.ncei.noaa.gov/products/geomagnetic-indices" site [19]. Some checks were conducted on the data values to detect missing values, and where such values were found, gap filling was done using linear interpolation to ensure continuity of the analysis.

The sunspot area data is given in millionths of a solar hemisphere "(MH), where 1000 MH is approximately, equal to 3.0437 million square kilometers خn the other hand the F10.7 index data is in Solar Flux Units (SFU), where 1SFU corresponds to 10^{-22} $W \cdot m^{-2} \cdot Hz^{-1}$, Indeed, as Kp index which is quasi-logarithmic index ranging from 0 to 9, if the Kp is equal to or larger than 5, it indicates a geomagnetic storm. Each of these indices was then processed to make timeframes standard, where required monthly data was converted into the daily average to match the other indices [20].

3.2. Feature Extraction and Seasonal Analysis

The dataset utilized in this study includes three primary indices of solar and geomagnetic activity: sunspot area, 10.7 cm solar radio flux (F10.7), and the Kp index, covering the period from 1996 to 2008. Sunspot area data were obtained from the Royal Observatory, Greenwich–USAF/NOAA Sunspot Data archive. The F10.7 solar radio flux data were sourced from Space Weather Canada (Natural Resources

Canada) to represent solar activity levels. Kp index values, which reflect global geomagnetic activity, were retrieved from the NOAA Geomagnetic Indices Archive at: https://www.ncei.noaa.gov/products/geomagnetic-indices [19].

To ensure data continuity, preliminary checks were performed to identify any missing values. Where gaps were detected, linear interpolation was applied to fill them appropriately.

The sunspot area is expressed in millionths of a solar hemisphere (MH), where 1000 MH is approximately equivalent to 3.0437 million square kilometers. The F10.7 index is measured in Solar Flux Units (SFU), where 1 SFU = 10^{-22} W·m^{-2}·Hz^{-1}. The Kp index is a quasi-logarithmic scale ranging from 0 to 9; values of Kp ≥ 5 indicate the occurrence of a geomagnetic storm.

All three indices were processed to ensure consistent temporal resolution. Where necessary, monthly data were converted to daily averages to match the temporal scale of the other datasets [20].

3.3. Microscopic Analysis of Short-Term Fluctuations in the Kp Index

To achieve a detailed, microscale representation of the Kp index, we extracted short-term fluctuations using three-hour intervals, consistent with NOAA's three-hourly K-index records. By analyzing data at this higher temporal resolution, the study aimed to identify high-frequency variability in geomagnetic activity, potentially linked to sudden solar events such as solar flares or coronal mass ejections (CMEs). This high-resolution approach enabled the detection of subtle disturbances in geomagnetic dynamics (GM) that might be overlooked when using coarser temporal aggregations, such as daily or monthly averages [21].

To further investigate these fluctuations, wavelet transform methods were employed to analyze the Kp index time series. This technique facilitated the examination of both high-frequency oscillations and low-frequency trends, enabling the isolation of periodic behaviors and abrupt variations associated with solar storms or transitional solar phases [22]. The wavelet decomposition proved particularly effective in highlighting transient features within the Kp index that may not be captured through conventional statistical approaches.

The authors decided to use sunspot areas greater than or equal to 500 millionths of a solar hemisphere (MH) in this study is grounded in both physical and analytical reasoning as follows:

✓ Association with High-Intensity Solar Events:

Sunspots are regions of intense magnetic activity on the solar surface and are often linked with major solar phenomena such as solar flares and coronal mass ejections (CMEs). These phenomena are primary drivers of disturbances in the solar wind and the interplanetary magnetic field (IMF), both of which play critical roles in triggering geomagnetic storms reflected by increases in the Kp index. Empirical studies have shown that larger sunspots (≥500 MH) are significantly more likely to be associated with such geoeffective events, hence justifying the threshold for isolating impactful solar activity.

✓ Filtering for Statistically Significant Events:

Using a sunspot area threshold of 500 MH serves to filter out minor or less influential sunspot groups that may not have a notable geomagnetic impact. This improves the signal-to-noise ratio in the data, allowing for clearer detection of correlations between solar activity and geomagnetic responses. It also ensures that statistical analyses and correlation models are built on meaningful solar inputs with known geophysical relevance.

✓ Consistency with Previous Research:

Prior studies investigating the geo-effectiveness of sunspots (e.g., Cliver *et al.*, 2000; Kane, 2010) have demonstrated that larger sunspots correlate more strongly with elevated Kp and Dst index values. By aligning with this methodological precedent, the current research remains consistent with established approaches, thereby enhancing comparability and credibility.

✓ Targeting Peak Solar Activity Intervals:

Solar Cycle 23 featured several high-activity periods, during which sunspot areas frequently exceeded 500 MH. By focusing on such intervals, this study is able to specifically analyze how intense solar outputs influence the Earth's magnetosphere, with minimal confounding from background solar activity. This selection is particularly useful in exploring the delayed or immediate effects on the Kp index during different solar phases (ascending, peak, descending, and minimum).

✓ Ensuring Analytical Robustness:

Restricting the dataset to high-sunspot-area events aids in producing statistically robust and interpretable results, especially when using methods such as polynomial regression, cross-correlation, and time series forecasting. It allows for meaningful seasonal and phase-specific analysis without the dilution effects of low-impact events.

3.4. Correlational Analysis and Statistical Testing

This study investigates the correlation between sunspot area and one of the key indicators of geomagnetic activity—the Kp index—using Pearson's correlation and cross-correlation coefficients, incorporating both lagged and unlagged values of the indicators. This approach is particularly useful for identifying time-shifted correlations between solar activity and the Earth's magnetospheric response. Cross-correlation analysis was extended across various time intervals to determine whether geomagnetic responses varied in accordance with the different phases of Solar Cycle 23.

In addition, Analysis of Variance (ANOVA) was employed to assess differences in Kp index values across different seasons of the year. This statistical technique was used to evaluate the significance of seasonal fluctuations and to test the hypothesis concerning the extended minimum phase of Solar Cycle 23. By comparing geomagnetic activity during this prolonged minimum with typical seasonal variations, the ANOVA results helped validate the unique impact of this solar minimum on Kp index behavior.

3.5. Modeling and Forecasting of Kp Index Variations

As part of the methodologies employed in the seasonal and short-term analyses, an ARIMA (Auto Regressive Integrated Moving Average) model was incorporated to forecast short-term variations in the Kp index under different solar activity states. The ARIMA model was selected for its effectiveness in handling non-stationary time series data, and it was further optimized to ensure the best model fit. In addition, Seasonal ARIMA (SARIMA) models were utilized to account for the periodic nature of geomagnetic activity, particularly the seasonal peaks observed around the equinoxes.

To enhance forecasting accuracy, machine learning models—specifically, Support Vector Regression (SVR) and Random Forest Regression—were also developed. These models used sunspot area and F10.7 solar flux data as input features to predict Kp index values. Model performance was evaluated using standard metrics such as Root Mean Square Error (RMSE) and Mean Absolute Error (MAE), allowing for the assessment of each model's ability to capture both seasonal patterns and short-term fluctuations in geomagnetic activity.

3.6. Interpretation and Validation of Findings

The seasonal and microscale results were analyzed and compared with findings from previous studies on Solar Cycle 23. To validate the performance of the forecasting models, a split-sample validation approach was employed, dividing the dataset into an estimation period (1996-2004) and a verification period (2005-2008). The models were tested against actual Kp index values from the verification phase to evaluate their predictive performance under varying solar conditions.

This validation process was critical for assessing the models' robustness, particularly during periods of low solar magnetic activity. The results contribute to a deeper understanding of how geomagnetic activity responds to changes in solar behavior, especially during extended solar minima. Ultimately, these insights support the improvement of space weather prediction models, which are essential for safeguarding technological systems affected by geomagnetic disturbances.

4. Results and Discussion

To investigate the relationship between solar activity and the Kp index during Solar Cycle 23, we focused our analysis on periods where the sunspot area was greater than or equal to 500 millionths of a solar hemisphere (MH). This threshold was selected because larger sunspot areas are typically associated with stronger solar magnetic fields and heightened solar activity, including solar flares and coronal mass ejections (CMEs). These phenomena intensify solar wind parameters, which in turn influence the Earth's magnetosphere and often lead to elevated Kp index values, indicating geomagnetic storms.

By concentrating on sunspot areas ≥ 500 MH, the analysis isolates periods of significant solar activity, ensuring that the impact on geomagnetic indices can be assessed with greater statistical relevance. This targeted approach allows for a clearer examination of how intense solar events drive geomagnetic variability, thereby enhancing our understanding of the dynamic interaction between solar and geomagnetic activity.

The Relation between the Solar Activity and Kp Index Data for Sunspots Area Greater than or Equal 500

We conducted a series of statistical analyses, including polynomial fitting and correlation analysis, to evaluate the relationship between solar activity indices—namely sunspot number, sunspot area, and solar radio flux (F10.7)—and the Kp index. Polynomial fitting was particularly useful in capturing seasonal variations in the Kp index and its nonlinear correlation with solar activity indicators. **Figure 1** illustrates the relationship between solar activity and the Kp index for sunspot areas ≥ 500 millionths of a solar hemisphere (MH) during Solar Cycle 23.

To model the trend of the Kp index over time, a third-order polynomial was applied. This choice was informed by its flexibility in capturing nonlinear, cyclic patterns characteristic of solar activity, while avoiding the overfitting often associated with higher-order polynomials. The Akaike Information Criterion (AIC) supported the selection of the third-order model, as it yielded significantly lower AIC values compared to linear or quadratic alternatives.

While previous studies (e.g., [23]) have examined the general relationship between sunspot area and geomagnetic indices across multiple solar cycles, our analysis focuses on the distinct features of Solar Cycle 23. One notable finding is the dynamic behavior of the Kp index during the prolonged solar minimum, which revealed short-term geomagnetic fluctuations even in the presence of low overall solar activity. These findings suggest a more complex interaction between solar and geomagnetic processes than previously reported, especially during low solar output periods.

Our seasonal analysis also builds on the work of [24], which documented periodic variations in geomagnetic indices. However, we emphasize the previously underexplored asymmetry between the spring and autumn equinoxes during Solar Cycle 23. This asymmetry, identified in our data, highlights unique seasonal dependencies within solar-terrestrial interactions that have not been thoroughly addressed in prior literature. These insights provide a new perspective on seasonal geomagnetic behavior during atypical solar cycles.

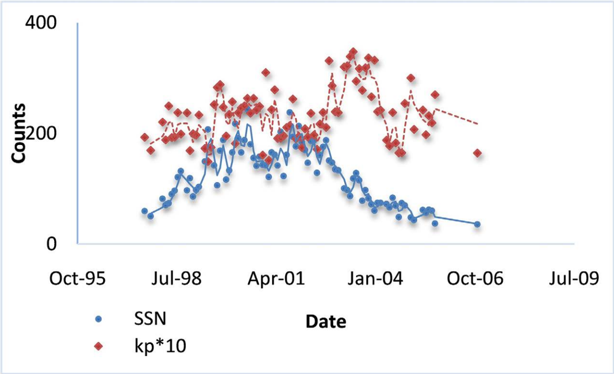
In addition to polynomial fitting, we performed regression analyses, including Pearson correlation coefficients, to quantify the relationship between sunspot area and Kp index values.

Summary of Graphical Results:

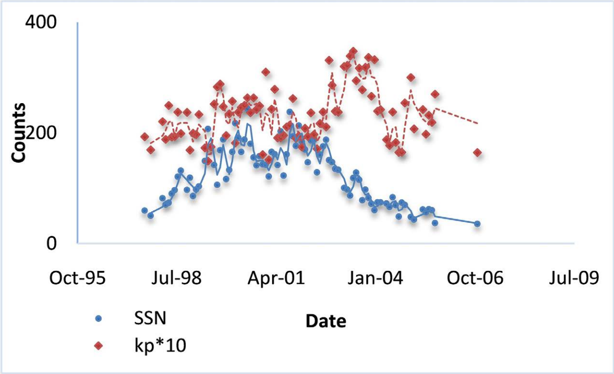
Figure 2(a) shows the relationship between monthly average sunspot number and the monthly average Kp index. During the ascending and descending phases of the solar cycle, a direct correlation is observed, where increases in sunspot number are followed shortly by increases in the Kp index, and vice versa. During the solar maximum, both indices fluctuate in a synchronous pattern, rising and falling together.

Figure 2(b) illustrates the relationship between monthly average F10.7 solar flux and the monthly average Kp index. Similar to sunspot numbers, there is a lagged correlation during the ascending and descending phases, while synchronous variability is evident during the solar maximum.

Figure 2(c) depicts the relationship between monthly average sunspot area and the monthly average Kp index. A consistent pattern emerges where increases in sunspot area precede increases in the Kp index. During the peak of Solar Cycle 23, both indices exhibit parallel fluctuations, further supporting a strong connection between large sunspot regions and geomagnetic activity.



(a)



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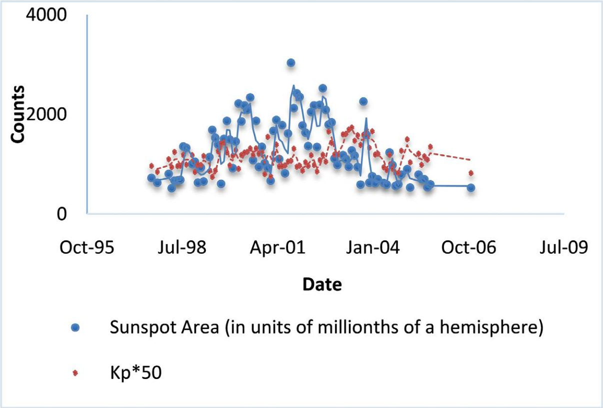


(c)

Figure 2. Analysis: Relationship between solar activity and the Kp index during solar cycle 23.

Figure 2(a) illustrates the relationship between sunspot numbers and the Kp index during Solar Cycle 23. The y-axis, labeled "Counts," represents the frequency of recorded Kp index values corresponding to specific sunspot numbers. The plot reveals a clear pattern of co-variation, where increases in sunspot numbers are generally associated with elevated Kp index values, particularly during the ascending and descending phases of the solar cycle. This relationship becomes more synchronous during the solar maximum, indicating heightened geomagnetic activity during peak solar conditions.

Figure 2(b) presents the correlation between the 10.7 cm solar radio flux (F10.7) and the Kp index for the same period. As with Figure 2(a), the y-axis indicates the frequency of Kp index occurrences for corresponding F10.7 values. The data demonstrates a positive correlation, where higher solar radio flux levels are aligned with increased Kp index values, reinforcing the connection between solar radiative output and geomagnetic disturbances.

Figure 2(c) focuses specifically on sunspot areas greater than or equal to 500 millionths of a solar hemisphere (MH) and their relationship with the Kp index. The "Counts" on the y-axis reflect the frequency of Kp index values observed in conjunction with these larger sunspot regions. This targeted analysis confirms a stronger correlation between intense solar activity—indicated by large sunspot areas—and elevated Kp index values. The results suggest that such regions are more likely to produce significant solar events, including flares and coronal mass ejections (CMEs), which in turn lead to increased geomagnetic activity.

Taken together, the three subfigures of Figure 2 collectively demonstrate a robust correlation between solar activity indicators (sunspot number, solar flux, and large sunspot area) and the Kp index, particularly during periods of peak solar activity. The co-variation observed in Figure 2(a) and Figure 2(b) aligns with prior research, which indicates that increased solar activity facilitates the emission of energetic particles and the modulation of magnetic fields—both of which enhance magnetospheric disturbances, as captured by the Kp index.

Figure 2(c) strengthens this conclusion by isolating events with sunspot areas ≥ 500 MH, highlighting a more focused and statistically significant correlation. These findings support the hypothesis that larger sunspot areas are directly linked to stronger geomagnetic responses and are key drivers in modulating the Earth's magnetosphere.

Conclusion of the graph:

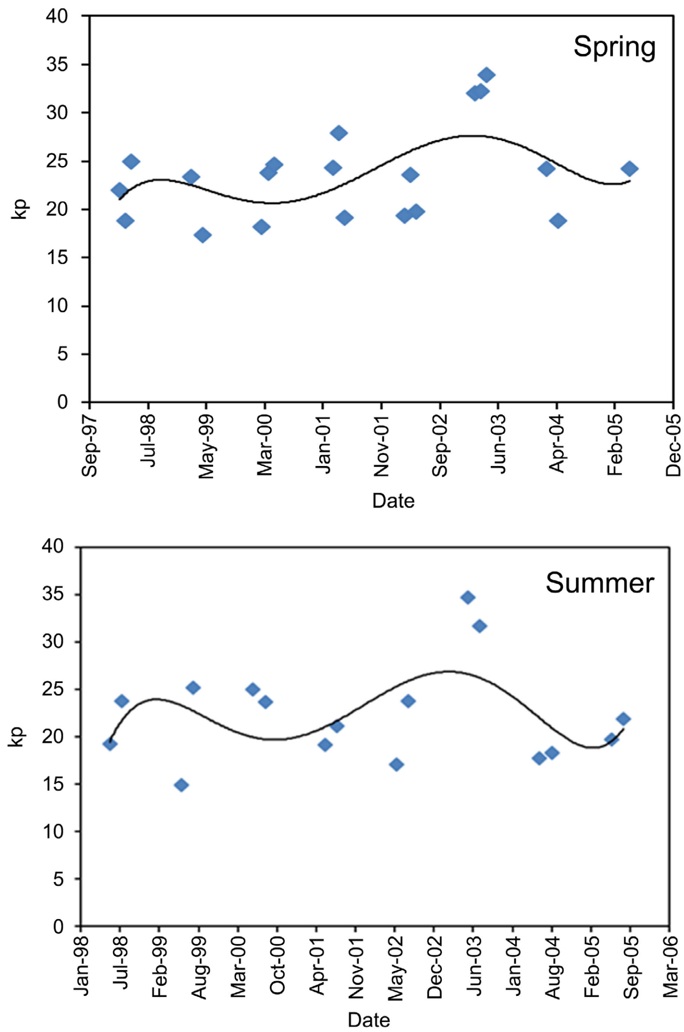
The patterns shown in Figure 2 substantiate a direct connection between solar activity and geomagnetic disturbance, as measured by the Kp index. The strongest correlations occur during the solar maximum and in the presence of large sunspot areas, emphasizing their role as primary contributors to heightened space weather activity during Solar Cycle 23.4.2. Seasonal Distributions of Kp Index and F10.7: during Solar Cycle 23.

Also, we focused on studying the relation between Kp index and the solar activity during solar cycle 23. We filtered data to four season categories which are (Spring, Summer, Autumn and Winter), then carrying out some statistical analysis and drawing graphs show the trend of the solar flux F10.7 and Kp index data for sunspots area data greater than or equal 500 for the whole cycle. Summary of these results are tabulated in **Table 1**, where R^2 is the root mean square.

Table 1. The seasonal variation of the Kp index, highlighting the highest and lowest values recorded during each season.

Seasons	Maximum value of the monthly average Kp index	Minimum value of the monthly average Kp index	Trend	Equation	R^2 value
Spring	34 at April 2002	17th May 1999	Polynomial of order 2	$Y = 3.018x^2 + 560{,}085x - 4 \times 10^8$	0.3
Summer	35 at June 2003	14th June 1999	Polynomial of order 3	$Y = 0.0001x^3 - 5.3301x^2 + 99{,}262x - 7 \times 108$	0.2
Autumn	34 at Nov. 2003	16th Nov. 2006	Polynomial of order 3	$Y = 0.0013x^3 + 35.054x^2 - 519{,}992x + 3 \times 109$	0.3
Winter	33 at Jan. 2004	15th Feb. 2001	Polynomial of order 3	$Y = 0.0016x^3 - 45.224x^2 + 671{,}742x - 4 \times 109$	0.4

As shown in **Figure 3** which illustrates the relation between monthly average Kp index and date of the period from 1996 to 2008.



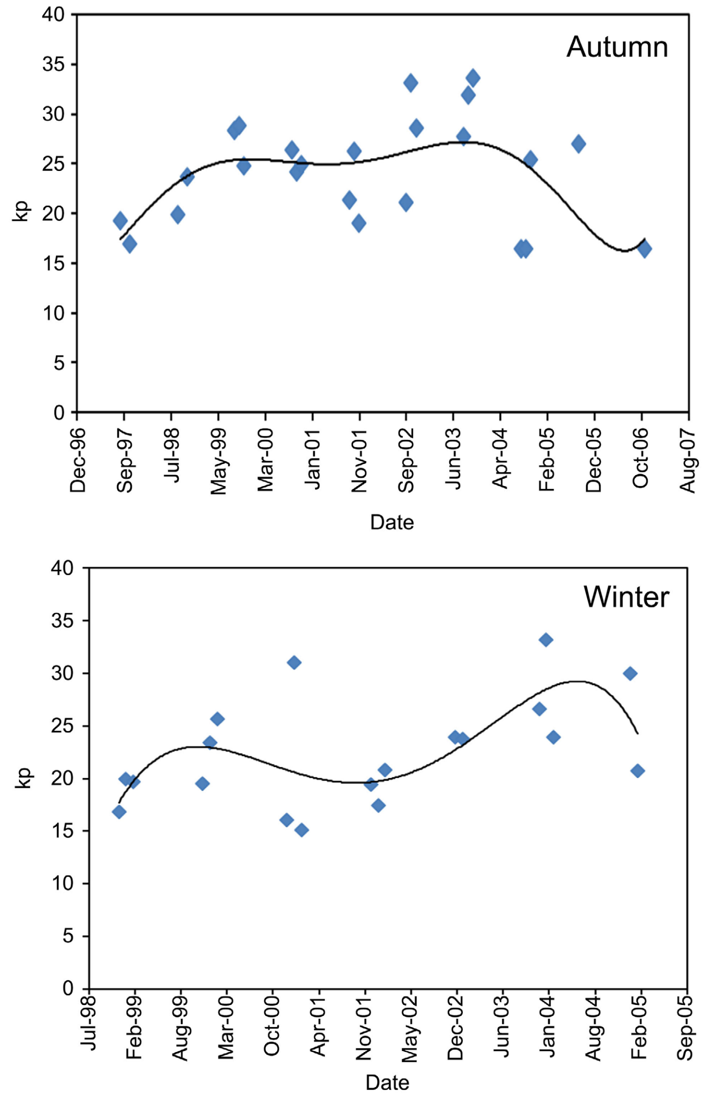
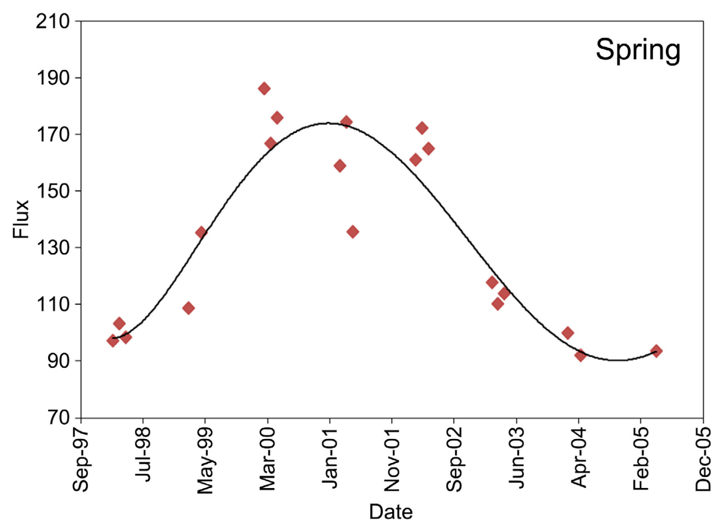


Figure 3. Presents the time variation of the Kp index across different seasons during solar cycle 23.



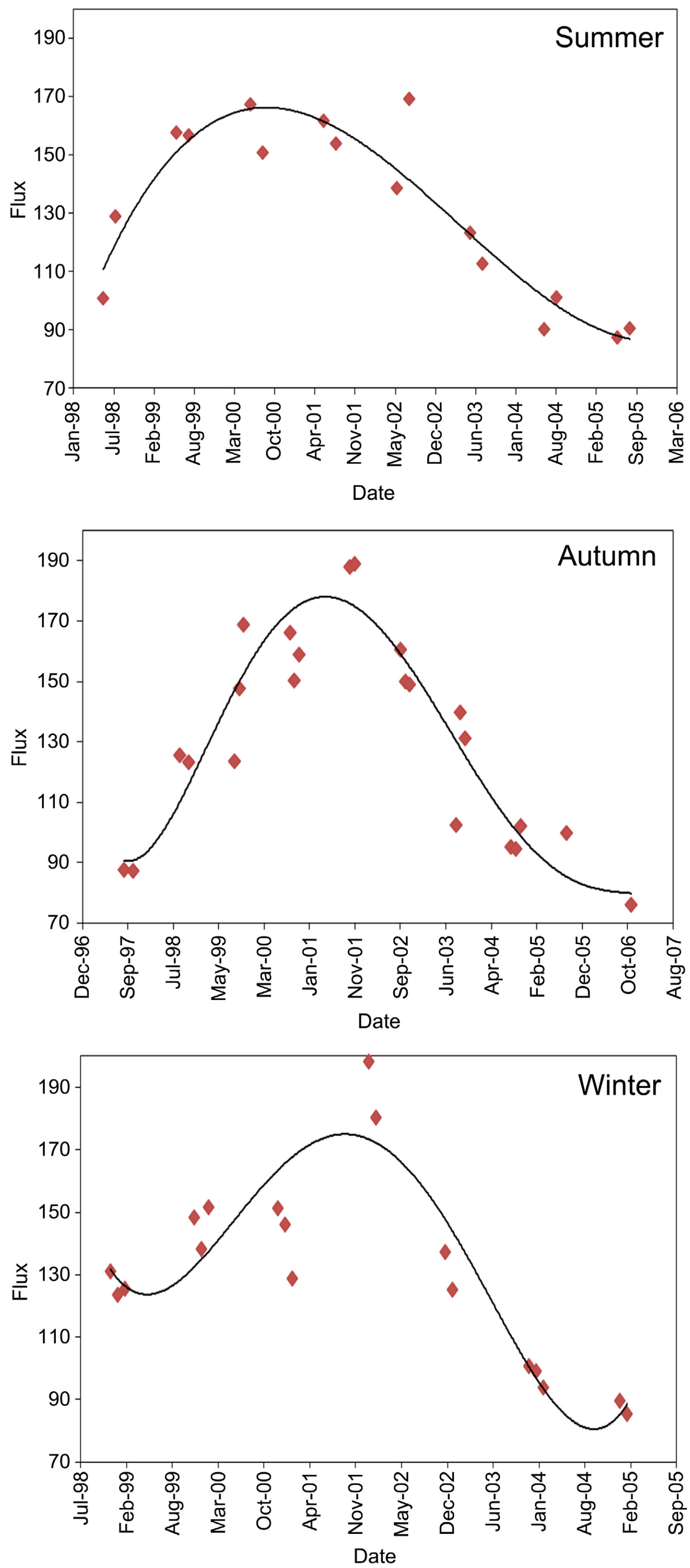


Figure 4. Relation between monthly average 10.7 cm solar radio flux and date of the period from 1996 to 2008.

As shown in Figure 4 which illustrates the relation between monthly average 10.7 cm solar radio flux and date of the period from 1996 to 2008.

Summary of these results are tabulated in Table 2, where R^2 is the route mean square.

Table 2. Summary of the relation between monthly average 10.7 solar flux and date of the period from 1996 to 2008.

Seasons	Maximum value of the monthly average 10.7 cm solar radio flux	Minimum values of the monthly average 10.7 cm solar radio flux	Trend	Equation	R^2 value
Spring	186 at Mar. 2000	• 97 at Mar. 1998 • 92 at May 2004	Polynomial of order 3	$Y = 0.0002x^3 + 8.1148x^2 - 152{,}041x + 10^9$	0.8
Summer	169 at Aug. 2002	• 87 at June 2005 • 90 at June 2004	Polynomial of order 2	$Y = 0.0026x^2 + 97.492x - 10^6$	0.9
Autumn	213 at Sep. 2001	• 76 at Nov. 2006 • 87 at Sep. 1997	Polynomial of order 2	$Y = 3.5814x^2 - 67{,}382x + 5 \times 10^8$	0.8
Winter	210 at Dec. 2001	• 85 at Feb. 2005 • 90 at Jan. 2005	Polynomial of order 2	$Y = 0.6558\ x^2 - 16{,}270\ x + 2 \times 10^8$	0.8

5. Conclusions

This study investigates the relationship between various solar activity indicators (including sunspot area, F10.7 index) and the behavior of the Kp index during Solar Cycle 23 using multiple analytical and statistical methods.

We conclude that there is a direct correlation between the F10.7 index for sunspot areas greater than or equal to 500 millionths of a solar hemisphere (MH) and the Kp index during Solar Cycle 23. A time lag is observed in the response of the Kp index to solar activity changes during the ascending and descending phases of the cycle. However, during the solar maximum, this relationship becomes almost synchronous.

Seasonal variations of the Kp index and F10.7 index were analyzed, revealing distinct patterns:

- ✓ Spring (1996-2008): The Kp index variation follows a second-order polynomial distribution with a maximum value of 34 in April 2002 and a minimum of 17 in May 1999, with an R^2 value of 0.3. In contrast, the F10.7 index follows a third-order polynomial distribution, peaking at 186 in March 2000, with two minima at 97 in March 1998 and 92 in May 2004, yielding an R^2 of 0.8.
- ✓ Summer (1996-2008): The Kp index variation follows a third-order polynomial distribution with a maximum value of 35 in June 2003 and a minimum of 14 in June 1999, with an R^2 of 0.2. The F10.7 index, on the other hand, follows a second-order polynomial distribution, peaking at 169 in August 2002, with minima at 87 in June 2005 and 90 in June 2004, yielding an R^2 of 0.9.
- ✓ Autumn (1996-2008): The Kp index variation follows a third-order polynomial distribution with a maximum of 34 in November 2003 and a minimum of 16 in November 2006, with an R^2 of 0.3. The F10.7 index follows a second-order polynomial distribution, with a maximum of 213 in September 2001 and two minima at 76 in November 2006 and 87 in September 1997, yielding an R^2

of 0.8.

- ✓ Winter (1996-2008): The Kp index variation follows a third-order polynomial distribution with a maximum of 33 in January 2004 and a minimum of 15 in February 2001, with an R^2 of 0.4. The F10.7 index follows a second-order polynomial distribution, peaking at 210 in December 2001 and minima at 85 in February 2005 and 90 in January 2005, yielding an R^2 of 0.8.

These results contribute new insights into Solar Cycle 23, particularly regarding its impact on the Kp index during solar minimum. Notably, our findings highlight short-term fluctuations in the Kp index during low solar activity periods and emphasize asymmetric seasonal variations in geomagnetic responses, particularly between the spring and autumn equinoxes. These insights add a new dimension to previous research on the solar-terrestrial interaction, especially in relation to solar minimum conditions.

Furthermore, we confirm that solar activity has significant effects on Earth in various ways. Increased solar activity leads to enhanced emissions of X-rays and extreme ultraviolet radiation from the Sun, which cause dramatic changes in the Earth's upper atmosphere. This atmospheric heating increases both the temperature and density of the atmosphere at high spacecraft altitudes.

In addition, the frequency of coronal mass ejections (CMEs) and solar flares increases, raising the likelihood of spacecraft instrument damage due to energetic particles accelerated during these events. These solar energetic particles also pose a health risk to astronauts in space and airline passengers traveling on high-altitude polar routes.

Overall, the present study underscores the complex relationship between solar activity and geomagnetic disturbances, offering valuable insights into how variations in solar behavior influence space weather phenomena and their impact on both spacecraft systems and human health.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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