**VARIATION OF SOLAR WIND AND GEOMAGNETIC PARAMETERS DURING ASCENDING AND DECLINING PHASES OF SOLAR CYCLES 23 AND 24**

**Abstract**

This study examines the relationship between solar wind dynamics and geomagnetic activity during the ascending (ASC) and declining (DSC) phases of Solar Cycles (SCs) 23 (1996–2008) and 24 (2008–2019), which exhibited contrasting levels of solar activity. High-resolution solar wind parameters—including speed (SWS), plasma density (SWPD), temperature (SWT), and interplanetary magnetic field (IMF) components—are analyzed alongside geomagnetic indices (Dst, ap, and Kp) to quantify phase-dependent relationships using correlation analysis and linear regression modeling. The results reveal significant differences in solar-terrestrial coupling between the two cycles. Sunspot number (SSN) and IMF exhibit comparable correlations (r ~0.7) across the ASC and DSC phases of SC 23 and SC 24. However, the correlation between SSN and SWT/SWS is stronger in SC 23 (r ~0.4/0.3) than in SC 24 (r ~0.3/0.2). Additionally, SWPD and SSN display a negative correlation during the ASC phases—more pronounced in SC 23—but no correlation during the DSC phases. SSN also exhibits a mild correlation with geomagnetic indices (r ≥ 0.3). The IMF demonstrates distinct relationships with SWT and SWS, maintaining a positive correlation of varying strength across phases, whereas its correlation with SWPD is negative during the ASC phases but positive during the DSC phases. Moreover, IMF, SWS, and SWT exhibit positive correlations with geomagnetic indices, though with varying strengths. These findings underscore the influence of SC amplitude and phase on the efficiency of solar wind energy transfer into Earth's magnetosphere. The efficiency of this transfer is not uniform but varies depending on the strength of the solar cycle and its phase. Stronger cycles (e.g., SC 23) generally facilitate more efficient energy transfer and enhanced geomagnetic activity. Furthermore, distinct solar wind-magnetosphere coupling mechanisms are evident in different phases, with coronal mass ejections playing a dominant role during the ASC phase and high-speed solar wind streams prevailing during the DSC phase, as suggested by previous studies. By contrasting two solar cycles with distinct characteristics—SC 24 being notably weaker—this study advances the understanding of long-term space weather variability and provides empirical constraints for models predicting geomagnetic responses to evolving solar wind conditions. The results highlight the necessity of phase- and cycle-specific approaches to enhance space weather forecasting and improve resilience across solar maxima and minima.

Key words: Solar Wind, Geomagnetic Parameters, Solar Cycles, charged particles

**Introduction**

The solar wind, which consists of a continuous stream of charged particles emitted by the Sun, plays a crucial role in driving geomagnetic activity by interacting with Earth’s magnetosphere, thereby influencing space weather phenomena that have significant implications for technological systems and infrastructure, as extensively documented in previous studies (Richardson & Cane, 2012). These interactions exhibit substantial variability throughout the approximately 11-year solar cycle (SC), which is traditionally divided into distinct phases, including the ascending phase (ASC) leading to solar maximum, a peak phase characterized by heightened solar activity, and the declining phase (DSC) that eventually returns to solar minimum, each of which is associated with unique solar wind conditions and resultant geomagnetic responses. A thorough understanding of the fluctuations in key solar wind parameters—such as solar wind speed (SWS), solar wind proton density (SWPD), solar wind temperature (SWT), and interplanetary magnetic field (IMF) strength—as well as the variations in geomagnetic indices, including the Kp index, the disturbance storm time (Dst) index, and the ap index, is essential for improving space weather prediction models and mitigating potential disruptions to satellite operations, communication networks, and power grids. The ASC and DSC phases of SCs exhibit distinct solar wind structures, which include but are not limited to coronal mass ejections (CMEs), high-speed solar wind streams, and regions of slow solar wind, each of which contributes to different geomagnetic responses, thereby necessitating a comprehensive understanding of their individual and collective effects on space weather dynamics to enhance predictive capabilities and preparedness strategies (Tsurutani et al., 2006).

SCs 23 (1996–2008) and 24 (2008–2019) provide a valuable comparative framework for investigating these variations, which differ significantly in their respective intensities and dynamic characteristics, with SC 23 experiencing a relatively strong solar maximum. In contrast, SC 24 was considerably weaker and was notable for exhibiting the lowest sunspot numbers in a century as well as an extended minimum phase (Gopalswamy et al., 2014; Russell et al., 2010). Despite its overall lower intensity, SC 24 produced significant geomagnetic disturbances, in part due to a higher occurrence of high-speed solar wind streams originating from coronal holes during its DSC phase. This phenomenon has been extensively analyzed and corroborated by recent studies (Turner et al., 2021). These high-speed solar wind streams, which often carry enhanced IMF magnitudes and exhibit fluctuating orientations, have been shown to drive recurrent geomagnetic storms even during periods of relatively low overall solar activity, highlighting the importance of persistent solar wind structures in modulating space weather effects (Kilpua et al., 2015a). Furthermore, the nature and intensity of geomagnetic disturbances are modulated by several interrelated factors, including the southward component of the IMF, which has been identified as a key driver of magnetic reconnection and is instrumental in determining the efficiency of energy transfer from the solar wind to the magnetosphere (Lockwood et al., 2019). The contrasting characteristics of SCs 23 and 24 underscore the complex interplay between solar wind properties and geomagnetic responses, thereby necessitating a more nuanced analysis of phase-specific variations in solar wind and their associated geomagnetic impacts. SC 23, which peaked in activity around the year 2001, reached a relatively strong maximum in comparison to SC 24, which was significantly weaker, exhibited a lower frequency of sunspots and diminished solar activity, and reached its peak around the year 2014 (Pesnell, 2016). The distinct solar wind conditions associated with the ASC and DSC phases of each solar cycle further illustrate the inherent variability of space weather dynamics, as the ASC phase is typically marked by increasing solar activity, frequent CMEs, and elevated occurrences of high-speed solar wind streams, whereas the DSC phase is generally characterized by a higher prevalence of high-speed solar wind streams originating from coronal holes (Richardson, 2018).

Although extensive research has been conducted to examine solar wind and geomagnetic parameters across entire solar cycles (Richardson & Cane, 2012), detailed phase-specific comparisons between SCs 23 and 24 remain relatively limited, with particular gaps in understanding the nuanced differences in solar wind properties and their corresponding geomagnetic responses. For instance, SC 24’s ASC phase was unusually prolonged and subdued, while its DSC phase exhibited persistent coronal hole activity, a pattern that stands in stark contrast to the more symmetrical structure observed in SC 23 (Gopalswamy et al., 2014). The ASC phase of the solar cycle, which is characterized by a progressive increase in solar activity, sunspot number, and the frequency of solar flares, naturally leads to a corresponding rise in the occurrence of CMEs and other solar wind disturbances that exert considerable influence on the Earth's magnetosphere. Multiple studies have demonstrated that this period is associated with a significantly higher frequency of CMEs, as the increasing complexity of the Sun’s magnetic field enhances the likelihood of magnetic reconnection and energy release, thereby driving interplanetary shocks that elevate solar wind speed and density, which in turn culminates in more intense geomagnetic storms (Webb & Howard, 2012). Additionally, an in-depth examination of solar wind parameters conducted by Kane (2010), which encompassed data spanning SCs 20 through 23, revealed that the ASC phase is characterized by a pronounced increase in solar wind speed, dynamic pressure, and IMF intensity, all of which contribute to enhanced geomagnetic activity. Furthermore, the ASC phase is notable for the elevated occurrence of solar energetic particle events, as energetic particles generated by CME-driven shocks frequently interact with the magnetosphere and ionosphere, leading to a variety of space weather phenomena, including radiation belt enhancements and ionospheric disturbances, with significant implications for both satellite operations and ground-based communication systems (Gopalswamy et al., 2008).

The DSC phase of the SC, while marked by a reduction in sunspot numbers and flare activity, nonetheless exhibits distinct solar wind patterns that exert considerable influence on geomagnetic conditions, particularly due to the prevalence of recurrent high-speed solar wind streams originating from coronal holes, which persist for extended durations and interact with slower-moving solar wind, forming co-rotating interaction regions that contribute to moderate yet prolonged geomagnetic disturbances (Richardson, 2018). Although the overall frequency of CMEs decreases during this phase, long-lived coronal holes continue to produce intense solar wind disturbances that, in some instances, give rise to geomagnetic storms comparable in magnitude to those observed during the more active phases of the solar cycle (Borovsky & Denton, 2006). Furthermore, research has indicated that solar wind structures present during the DSC phase tend to be more geoeffective in sustaining prolonged geomagnetic activity, as high-speed solar wind stream-driven disturbances exert extended impacts on the magnetosphere, leading to persistent auroral enhancements and geomagnetic storms that extend to mid-latitude regions, thereby influencing both the ionosphere and ground-based technological infrastructure (Tsurutani et al., 2006).

Given the pronounced differences between SC 23 and SC 24, an in-depth analysis of the variations in solar wind parameters and geomagnetic responses across their ASC and DSC phases provides valuable insights into space weather dynamics and the intricate Sun-Earth connection, particularly concerning the disproportionate influences exerted by distinct solar wind structures, such as the dominance of coronal mass ejections during solar maxima and the prevalence of high-speed solar wind streams during periods of solar minimum. Investigating these variations is critical for disentangling the specific contributions of different solar drivers to space weather hazards and for enhancing predictive models aimed at mitigating their potential impacts on modern technological infrastructure.

This study addresses the necessity to statistically analyze the relationships between solar wind (SWT, SWPD, SWS), IMF, and geomagnetic (Kp, ap, Dst) parameters during the ASC and DSC)phases of SCs 23 and 24. By comparing these phases across the two cycles, we aim to conduct an in-depth investigation into how variations in solar activity—particularly differences in its strength and associated solar wind structures—influence geomagnetic conditions. Such an analysis is critical for advancing our understanding of long-term space weather dynamics and their terrestrial impacts. The relevance of this work lies in its potential to enhance space weather forecasting capabilities. Improved predictions are vital for safeguarding critical infrastructure, including satellites, power grids, and communication systems, against solar-driven disturbances. Furthermore, the study holds significance in the context of SC24’s notably weaker solar activity and its implications for future cycles. Observations suggest a possible continuation of this DSC trend (McComas et al., 2013), underscoring the need to refine mitigation strategies and preparedness for space weather events. Ultimately, this research seeks to elucidate the drivers of solar wind variability and geomagnetic responses during ASC and DSC phases, providing insights that bridge solar-terrestrial interactions and practical applications in space weather resilience.

In Onuchukwu et al. (2024), we analyzed phase-dependent variations in cosmic ray intensities as a function of solar activity fluctuations during the ASC and DSC phases of the SC. Building upon this foundation, the present study aims to specifically investigate variations in solar wind properties and geomagnetic parameters across the ASC and DSC phases of SCs 23 and 24.

**2. METHODOLOGY**

**Data Description**

The daily average sunspot data were obtained from the World Data Center SILSO, Royal Observatory of Belgium, Brussels (http://www.sidc.be/SILSO/). According to SILSO, SC 23 started in August 1996, lasted for 12.25 years, reached its maximum in November 2001, and ended in November 2008. SC 24, started in December 2008, reached its maximum in April 2014, lasting for 11 years and ending in November 2019. The daily average solar wind parameters between 1996 and 2019 (solar wind temperature (SWT (K)), solar wind plasma density (SWPD (N/cm3), solar wind speed (SWS (km/s)), the interplanetary magnetic field (IMF (nT)), and the geomagnetic activity indices - ($Kp$) (measured three hourly), Dst (measured one hourly), and ap (measured three hourly) ) were obtained from <https://omniweb.gsfc.nasa.gov/>.

We formed two subsamples for each SC: the ASC phase and the DSC phase. According to SILSO, the ASC phase of SC 23 lasted from August 1996 to November 2001, while the DSC phase for SC 23 was from December 2011 to November 2012. For SC 24, the ASC phase was from December 2008 to April 2014, and the DSC phase was from May 2014 to November 2019.

### **3. Results** **and Discussion**

### We conducted a linear regression analysis to evaluate potential correlations between the studied parameters and generate scatter plots for each parameter pair to visualize their relationships. The correlation coefficient and linear regression fit results to the parameters studied are given in Tables 1 and 2. For regression fit, we utilized logarithmic values to account for the broad range of data, ensuring a more uniform distribution. Additionally, for Dst values, which include negative measurements, we employed the magnitude to maintain consistency in analysis. We expect our findings to remain statistically significant, as we are primarily examining the relationships across different phases of the SCs.

**Table 1: Correlation Coefficient Amongst the Studied Parameter**

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **parameter** | **ASC** **23** | **DSC** **23** | **ASC** **24** | **DSC** **24** | **parameter** | **ASC** **23** | **DSC** **23** | **ASC** **24** | **DSC** **24** |
|  | **r** | **r** | **r** | **r** |  | **r** | **r** | **r** | **r** |
| **SSN/ IMF** | **0.62** | **0.79** | **0.60** | **0.71** | **IMF/**$Dst$ | **0.32** | **0.57** | **0.64** | **0.62** |
| **SSN/SWT** | **0.38** | **0.43** | **0.27** | **0.25** | **IMF/**$ap$ | **0.66** | **0.72** | **0.62** | **0.59** |
| **SSN/SWPD** | **-0.60** | **-0.03** | **-0.25** | **-0.07** | **SWT/**$Kp$ | **0.74** | **0.89** | **0.78** | **0.82** |
| **SSN/SWS** | **0.31** | **0.23** | **0.19** | **0.10** | **SWT/**$Dst$ | **0.14** | **0.60** | **0.54** | **0.57** |
| **SSN/**$Kp$ | **0.34** | **0.62** | **0.41** | **0.47** | **SWT/**$ap$ | **0.63** | **0.74** | **0.68** | **0.76** |
| **SSN/**$Dst$ | **-0.02** | **0.41** | **0.43** | **0.42** | **SWPD/**$Kp$ | **-0.47** | **-0.19** | **-0.23** | **-0.19** |
| **SSN/**$ap$ | **0.32** | **0.51** | **0.34** | **0.37** | **SWPD/**$Dst$ | **0.06** | **-0.15** | **-0.19** | **-0.13** |
| **IMF/SWT** | **0.53** | **0.66** | **0.60** | **0.54** | **SWPD/**$ap$ | **-0.25** | **0.04** | **-0.06** | **-0.08** |
| **IMF/SWPD** | **-0.29** | **0.18** | **-0.08** | **0.17** | **SWS/**$Kp$ | **0.81** | **0.78** | **0.79** | **0.78** |
| **IMF/SWS** | **0.47** | **0.41** | **0.52** | **0.30** | **SWS/**$Dst$ | **0.22** | **0.57** | **0.54** | **0.53** |
| **IMF/**$Kp$ | **0.59** | **0.79** | **0.73** | **0.67** | **SWS/**$ap$ | **0.66** | **0.57** | **0.61** | **0.69** |

**Table 2: Linear Regression Fits to the Logarithm Values of the Studied Parameters**

|  |  |  |  |
| --- | --- | --- | --- |
|  | SC | ASC | DSC |
| 1 | SC 23 | logIMF=(0.08±0.05)logSSN+0.65 | logIMF=(0.15±0.06)logSSN+0.52 |
| SC 24 | logIMF=(0.25±0.06)logSSN+0.49 | logIMF=(0.09±0.05)logSSN+0.61 |
| 2 | SC 23 | logSWT=(0.07±0.13)logSSN+4.78 | logSWT=(0.12±0.13)logSSN+4.82 |
| SC 24 | logSWT=(0.50±0.10)logSSN+4.44 | logSWT=(0.07±0.12)logSSN+4.81 |
| 3 | SC 23 | logSWPD=-(0.11±0.10)logSSN+1.00 | logSWPD=(0.02±0.10)logSSN+0.68 |
| SC 24 | logSWPD=-(0.03±0.08)logSSN+0.73 | logSWPD=(0.01±0.07)logSSN+0.78 |
| 4 | SC 23 | logSWS=(0.01±0.04)logSSN+2.59 | logSWS=(0.02±0.05)logSSN+2.62 |
| SC 24 | logSWS=(0.14±0.03)logSSN+2.49 | logSWS=(0.01±0.04)logSSN+:2.61 |
| 5 | SC 23 | logKp=(0.05±0.10)logSSN+1.19 | logKp=(0.15±0.11)logSSN+1.05 |
| SC 24 | logKp=(0.67±0.12)logSSN+0.59 | logKp=(0.10±0.10)logSSN+1.09 |
| 6 | SC 23 | log|Dst|=-(0.05±0.40)logSSN+1.14 | log|Dst|=(0.24±0.29)logSSN+0.66 |
| SC 24 | log|Dst|=(0.85±0.34)logSSN+0.19 | log|Dst|=(0.28±0.35)logSSN+0.51 |
| 7 | SC 23 | logap=(0.09±0.16)logSSN+0.81 | logap=(0.21±0.18)logSSN+0.64 |
| SC 24 | logap=(01.64±0.54)logSSN+0.34 | logap=(0.12±0.14)logSSN+0.72 |
| 8 | SC 23 | logIMF=(0.25±0.05)logSWT-0.42 | logIMF=(0.50±0.08)logSWT-1.77 |
| SC 24 | logIMF=(0.33±0.06)logSWT-0.89 | logIMF=(0.33±0.06)logSWT-0.88 |
| 9 | SC 23 | logIMF=-(0.16±0.06)logSWPD+0.92 | logIMF=(0.21±0.11)logSWPD+0.61 |
| SC 24 | logIMF=-(0.07±0.07)logSWPD+0.72 | logIMF=(0.17±0.07)logSWPD+0.59 |
| 10 | SC 23 | logIMF=(0.78±0.05)logSWS-1.24 | logIMF=(0.87±0.11)logSWS-1.57 |
| SC 24 | logIMF=(0.95±0.06)logSWS-1.79 | logIMF=(0.56±0.07)logSWS-0.74 |
| 11 | SC 23 | logKp=(1.01±0.08)logIMF+0.49 | logKp=(1.03±0.09)logIMF+0.51 |
| SC 24 | logKp=(1.71±0.11)logIMF-0.06 | logKp=(1.05±0.09)logIMF+0.46 |
| 12 | SC 23 | log|Dst|=(1.92±0.38)logIMF-0.47 | log|Dst|=(1.71±0.27)log|Dst|-0.25 |
| SC 24 | log|Dst|=(3.31±0.29)logIMF-1.41 | log|Dst|=(3.27±0.31)logIMF-1.49 |
| 13 | SC 23 | logap=(1.79±0.12)logIMF-0.44 | logap=(1.42±0.15)logIMF-0.09 |
| SC 24 | logap=(6.05±0.43)logIMF-2.52 | logap=(1.25±0.13)logIMF-0.03 |
| 14 | SC 23 | logKp= (0.58±0.07)logSWT-1.55 | logKp=(0.88±0.07)logSWT-3.13 |
| SC 24 | logKp= (0.99±0.10)logSWT-3.69 | logKp=(0.78±0.07)logSWT-2.61 |
| 15 | SC 23 | log|Dst|= (0.39±0.40)logSWT-0.86 | log|Dst|=(1.38±0.26)logSWT-5.88 |
| SC 24 | log|Dst|= (1.62±0.31)logSWT-6.96 | log|Dst|=(1.80±0.33)logSWT-7.93 |
| 16 | SC 23 | logap= (0.78±0.13)logSWT-2.84 | logap=(1.11±0.15)logSWT-4.60 |
| SC 24 | logap= (2.01±0.55)logSWT-8.14 | logap=(0.98±0.11)logSWT-3.91 |
| 17 | SC 23 | logKp=-(0.44±0.09)logSWPD+1.63 | logKp=-(0.28±0.14)logSWPD+1.48 |
| SC 24 | logKp=-(0.47±0.16)logSWPD+1.41 | logKp=-(0.31±0.12)logSWPD+1.45 |
| 18 | SC 23 | log|Dst|=(0.27±0.40)logSWPD+0.84 | log|Dst|=-(0.50±0.33)logSWPD+1.38 |
| SC 24 | log|Dst|=-(0.82±0.37)logSWPD+1.40 | logDst|=-(0.45±0.39) logSWPD+1.21 |
| 19 | SC 23 | logap=-(0.38±0.16)logSWPD+1.28 | logap=(0.10±0.22)logSWPD+0.89 |
| SC 24 | logap=-(1.61±0.59)logSWPD+2.68 | logap=-(0.17±0.16)logSWPD+1.01 |
| 20 | SC 23 | logKp=(2.25±0.06)logSWS-4.61 | logKp=(2.18±0.09)logKp-4.51 |
| SC 24 | logKp=(3.38±0.10)logSWS-7.68 | logKp=(2.29±0.07)logKp-4.79 |
| 21 | SC 23 | log|Dst|=(2.21±0.39)logSWS-4.72 | log|Dst|=(3.66±0.27)log|Dst|-8.70 |
| SC 24 | log|Dst|=(5.21±0.31)logSWS-12.67 | log|Dst|=(5.16±0.34)log|Dst|-12.67 |
| 22 | SC 23 | logap=(2.93±0.12)logSWS-6.69 | logap=(2.41±0.18)logap-5.42 |
| SC 24 | logap=(4.89±0.58)logSWS-11.12 | logap=(2.74±0.12)logap-6.31 |

**3.1 SSN vs IMF, Solar Wind Parameters and Geomagnetic Indices**

Fig 1 represents the log-log plot of the monthly average values SSN vs IMF for the ASC and the DSC phases of SC 23 and 24.

**Fig 1: log-log Plot of the Monthly Average Values of SSN vs IMF for the ASC and the DSC Phases of SC 23 and 24**

During the ASC and DSC phases of SCs 23 and 24, the relationship between IMF and SSN varied in strength and predictability. In SC 23’s ASC phase, a weak positive slope (0.08) and moderate correlation (*r* = 0.6) indicated limited sensitivity, while the DSC phase showed a stronger relationship (slope = 0.15, *r* ≈ 0.8) with reduced uncertainty (Owens et al., 2021). SC 24’s ASC phase exhibited the highest slope (0.25) but a similar moderate correlation (*r* ≈ 0.6), whereas its DSC phase had slightly reduced sensitivity (slope = 0.12) but a stronger correlation (*r* ≈ 0.7). Across both cycles, DSC phases consistently demonstrated stronger linearity (*r* ≈ 0.7–0.8) than ASC phases (*r* ≈ 0.6), suggesting IMF predictability is enhanced during solar decline (Lockwood et al., 2019). These results align with studies linking solar wind dynamics to SSN variations (Richardson & Cane, 2010).

Figure 2 shows log-log plots of monthly SSN versus SWT across ASC and DSC phases of SCs 23 and 24. In SC 23’s ASC phase, a weak positive slope (0.07) and low correlation (*r* ≈ 0.4) reflect minimal SWT-SSN sensitivity, with high uncertainty (Owens et al., 2021). The DSC phase shows a marginally higher slope (0.10) but a similar *r* ≈ 0.4. SC 24’s ASC phase has the steepest slope (0.5) yet the weakest correlation (*r* ≈ 0.3), while its DSC phase reverts to a lower slope (0.07) and *r* ≈ 0.3. Across both cycles, correlations remain weak (*r* = 0.3–0.4), suggesting SSN alone poorly predicts SWT variability, likely due to external solar wind drivers (Richardson & Cane, 2010). The higher ASC slope in SC 24 implies transient sensitivity shifts, though low correlations emphasize multifactorial SWT influences (Lockwood et al., 2019).

**Fig 2: log-log Plot of the Monthly Average Values of SSN vs SWT for the ASC and the DSC Phases of SC 23 and 24**

Fig 3 displays log-log plots of monthly SSN versus solar SWPD during ASC and DSC phases of SCs 23 and 24. The ASC phase of SC 23 shows a moderate negative correlation (*r* ≈ −0.6) and slope (−0.11 ± 0.10), suggesting a weak inverse SWPD-SSN relationship, while its DSC phase exhibits negligible correlation (*r* ≤ −0.1) and near-flat slope (0.02) (Lockwood et al., 2019). In SC 24, ASC and DSC phases both show minimal correlations (*r* ≈ −0.3 and *r* ≈ −0.1, respectively) and near-zero slopes (−0.03 ± 0.08 and 0.01), indicating consistently weak SWPD-SSN relationships. The stronger inverse correlation during SC 23’s ASC phase implies transient solar activity influences on SWPD, absent in SC 24 and DSC phases, where external factors likely dominate (Richardson & Cane, 2010). These results highlight variability in solar wind-SSN coupling across cycles and phases (Owens et al., 2021).

**Fig 3: log-log Plot of the Monthly Average Values of SSN vs SWPD for the ASC and the DSC Phases of SCs 23 and 24**

**Fig 4: log-log Plot of the Monthly Average Values of SSN vs SWS for the ASC and the DSC Phases of SCs 23 and 24**

Fig 4 examines monthly SSN versus SWS across ASC and DSC phases of SCs 23 and 24. SC 24’s ASC phase shows the highest sensitivity (slope = 0.14) but weak correlation (*r* = 0.2), while SC 23’s phases have minimal slopes (0.01–0.02) and low correlations (*r* = 0.2–0.3). SC 24’s DSC phase exhibits negligible sensitivity (slope = 0.01, *r* = 0.1). Consistent intercepts suggest stable baseline SWS, independent of SSN (Lockwood et al., 2019). Despite SC 24’s ASC-phase sensitivity, universally low correlations (*r* ≤ 0.3) imply SSN poorly predicts SWS, highlighting dominant roles of coronal holes, heliospheric fields, or transient events in SWS variability (Richardson & Cane, 2010; Owens et al., 2021).

**Fig 5: log-log Plot of the Monthly Average Values of SSN vs** $Kp$ **for the ASC and the DSC Phases of SC 23 and 24**

**Fig 6: log-log Plot of the Monthly Average Values of SSN vs** $\left|Dst\right|$ **for the ASC and the DSC Phases of SC 23 and 24**

Figs 5–7 analyze log-log relationships between monthly SSN and geomagnetic indices (Kp, |Dst|, ap) across ASC and DSC phases of SCs 23 and 24. SC 23’s ASC phase shows weak SSN-Kp/ap correlations (*r* $\~$0.3) and negligible SSN-Dst linkage, while its DSC phase exhibits moderate correlations (Kp: *r*$\~$0.6; ap: *r*$\~$0.5; , |Dst|: *r*$\~$0.4). SC 24’s ASC phase demonstrates stronger SSN-Dst coupling (*r* = 0.43) compared to SC 23, though all correlations remain modest (Kp: *r* $\~$0.4; ap: *r*$\~$0.3). Both cycles’ DSC phases show moderate correlations (SC 24: Kp *r*$\~$0.5; , |Dst| *r*$\~$0.4), with SC 24’s ASC phase displaying the highest slopes, suggesting heightened but limited sensitivity of geomagnetic activity to SSN. Universally low correlations (*r* ≤ 0.6) underscore the secondary role of SSN relative to transient solar events or solar wind structures in driving geomagnetic variability (Richardson & Cane, 2010; Lockwood et al., 2019; (Owens et al., 2021).

**Fig 7: log-log Plot of the Monthly Average Values of SSN vs** $ap$ **for the ASC and the DSC Phases of SC 23 and 24**

 **3.2 IMF vs Solar Wind Parameters and Geomagnetic Indices**

**Fig 8: log-log Plot of the Monthly Average Values IMF vs SWT for the ASC and the DSC Phases of SCs 23 and 24**

Fig 8 illustrates the log-log relationship between the monthly average IMF and SWT during the ASC and DSC phases of SCs 23 and 24. In SC 23, the ASC phase exhibits a moderate IMF-SWT dependence (slope = 0.25, r $\~$ 0.5), while the DSC phase shows a stronger relationship (slope = 0.50, r$\~$ 0.7). Conversely, SC 24 maintains a consistent IMF-SWT dependency across both phases (slope = 0.33), with the ASC phase having a slightly higher correlation (r $\~$ 0.6) than the DSC phase (r $\~$ 0.5). These findings suggest that SWT's influence on IMF varies between cycles and phases, with SC 23's DSC phase showing the highest sensitivity. Understanding these variations is crucial for predicting space weather and assessing its potential impacts on Earth's space environment.

 **Fig 9 log-log Plot of the Monthly Average Values of IMF vs SWPD for the ASC and the DSC Phases of SCs 23 and 24.**

Fig 9 illustrates the log-log relationship between the monthly average IMF and SWPD during the ASC and DSC phases of SCs 23 and 24. In SC 23, the ASC phase shows a weak negative correlation (slope = -0.16, r $\~$ -0.3), while the DSC phase exhibits a weak positive correlation (slope = 0.21, r $\~$ 0.2). Conversely, SC 24 demonstrates negligible correlations in both phases, with the ASC phase having a slope of -0.07 (r $\~$-0.1) and the DSC phase having a slope of 0.17 (r $\~$0.2). These findings suggest that SWPD's influence on IMF varies between cycles and phases, with SC 23 showing more pronounced phase-dependent interactions, whereas SC 24 indicates minimal dependency (Kitajima et al., 2022; Sun et al., 2024a).

Fig 10 illustrates the log-log relationship between the monthly average IMF and SWS during the ASC and DSC phases SCs 23 and 24. In SC 23, the ASC phase exhibits a slope of 0.78, while the DSC phase shows a slightly higher slope of 0.87, indicating increased IMF sensitivity to SWS during the DSC phase. Conversely, SC 24's ASC phase presents the highest slope of 0.95, suggesting a strong IMF-SWS relationship, whereas the DSC phase has the lowest slope of 0.56, implying a weaker dependency. Correlation coefficients further support these observations: SC 23's ASC phase correlates with r $\~$ 0.5, and the DSC phase r $\~$ 0.4; SC 24's ASC phase shows the strongest correlation at r$\~$0.5, while the DSC phase is the weakest at r$\~$0.3. These findings suggest that IMF-SWS relationships vary between solar cycles and their respective phases, with SC 24's ASC phase demonstrating the most pronounced correlation. According to Özgüç et al., (2016), Pishkalo (2017), Grandin et al., (2020), and Sun et al., (2024b), who obtained similar correlations between IMF and solar wind parameters, understanding such variations is crucial for space weather dynamics and improving predictive models

**Fig 10: log-log Plot of the Monthly Average Values of IMF vs SWS for the ASC and the DSC Phases of SCs 23 and 24**

**Fig 11: log-log Plot of the Monthly Average Values of IMF vs** $Kp$ **for the ASC and the DSC Phases of SCs 23 and 24**

**Fig 12: log-log Plot of the Monthly Average Values of IMF vs** $\left|Dst\right|$ **for the ASC and the DSC Phases of SCs 23 and 24**

Fig 11-13 show the log-log relationships between IMF and geomagnetic indices (Kp, |Dst|, and ap) during the ASC and DSC phases of SCs 23 and 24, with regression details in Tables 1 and 2. In SC 23, the ASC phase shows a moderate correlation between Kp and IMF (slope = 1.01), a weaker correlation for |Dst| (slope = 1.71), and a stronger IMF dependency for ap (slope = 1.79). The DSC phase strengthens the Kp correlation (slope = 1.03) while maintaining similar sensitivities for Dst and ap. In contrast, SC 24 demonstrates a stronger correlation in the ASC phase, with Kp (slope = 1.71), Dst (slope = 3.31), and ap (slope = 6.05) exhibiting significantly higher sensitivities.

**Fig 13: log-log Plot of the Monthly Average Values of IMF vs** $ap$ **for the ASC and the DSC Phases of SC 23 and 24**

The DSC phase maintains a strong relationship, with |Dst| (slope = 3.27) and ap (slope = 1.05) showing continued responsiveness to IMF changes. Comparing the two SCs, SC 23 exhibits stronger IMF-geomagnetic index correlations in the DSC phase, whereas SC 24 maintains high correlation levels in both phases, particularly for Kp and |Dst| in the ASC phase. The substantial increase in slope values for Dst and ap in SC 24 suggests heightened geomagnetic activity, likely driven by enhanced solar-interplanetary interactions. These results align with previous findings indicating that SC 24 experienced increased solar wind coupling with geomagnetic indices due to shifts in solar wind properties (Grandin et al., 2020; Kiyani et al., 2023). The stronger IMF-geomagnetic response in SC 24 supports the notion that interplanetary conditions played a crucial role in intensifying geomagnetic disturbances (Sun et al., 2024b).

**3.3 Scatter Plots between Solar Wind Parameters with Geomagnetic Indices**

**Fig 14: log-log Plot of the Monthly Average Values of SWT vs** $Kp$ **for the ASC and the DSC Phases of SC 23 and 24**

**Fig 15: log-log Plot of the Monthly Average Values of SWT vs** $\left|Dst\right|$ **for the ASC and the DSC Phases of SC 23 and 24**

**Fig 16: log-log Plot of the Monthly Average Values of SWT vs** $ap$ **for the ASC and the DSC Phases of SCs 23 and 24**

Figs 14–16 illustrate the log-log relationships between SWT and geomagnetic indices (Kp, |Dst|, and ap) during the ASC and DSC phases of SCs 23 and 24, with correlation details in Tables 1 and 2. In SC 23, Kp and ap show moderate correlations with SWT in the ASC phase (slopes = 0.58 and 0.78, respectively), while |Dst| exhibits a weak correlation. In the DSC phase, all indices strengthen their correlation, with Kp (slope = 0.88) and ap (slope = 1.11) showing strong dependencies, and |Dst| (slope = 1.38) demonstrating increased sensitivity. SC 24 exhibits stronger SWT-geomagnetic index relationships than SC 23, particularly in the ASC phase. The Kp index (slope = 0.99) shows an almost proportional increase with SWT, while |Dst| (slope = 1.62) and ap (slope = 2.01) exhibit stronger dependencies compared to SC 23. In the DSC phase, all indices maintain strong correlations, with |Dst| (slope = 1.80) and ap (slope = 0.98) continuing to show substantial increases. Across both cycles, the Kp index remains the most consistently correlated with SWT, while |Dst| shows the weakest correlation, particularly in ASC phases. The ap index exhibits intermediate correlation strength but is generally stronger in DSC phases.

These results suggest that geomagnetic activity, as indicated by Kp and ap indices, is significantly influenced by SWT, particularly during the DSC phases of SCs. The stronger correlations in SC 24 align with findings that highlight increased solar wind-geomagnetic coupling due to variations in solar wind parameters during this cycle (Grandin et al., 2020; Owens & Lockwood, 2022; Zhao et al., 2023). The increased sensitivity of |Dst| and ap indices in SC 24 further supports the idea that changing interplanetary conditions played a crucial role in intensifying geomagnetic responses (Smith & Jones, 2020; Richardson et al., 2021).

Figs 17-19 present log-log plots of the monthly average SWPD versus geomagnetic indices (Kp, |Dst|, and ap) during the ASC and DSC phases of SCs 23 and 24, with regression fits detailed in Tables 1 and 2. In SC 23, the Kp index exhibits a moderate inverse correlation with SWPD in the ASC phase (r = -0.47), which weakens during the DSC phase (r $\~$-0.2). Similarly, the ap index shows a moderate inverse relationship in the ASC phase (r$\~$ -0.3) but becomes negligible in the DSC phase (r $\leq $0.1). The Dst index, however, shows no correlation in the ASC phase (r$\leq $0.1) and a weak inverse relationship in the DSC phase (r$\~$-0.2). In SC 24, the inverse correlation between SWPD and Kp weakens further, with r = -0.3 in the ASC phase and r$\~$-0.2 in the DSC phase. The Dst index shows a weak inverse correlation in both phases (r$\~$-0.19 in ASC and r$\~$-0.1 in DSC), while the ap index exhibits negligible correlations (r$\~$-0.1 in ASC and in DSC).

Overall, the correlation coefficients suggest that SWPD alone is a poor predictor of geomagnetic indices, with only weak inverse relationships observed. The ASC phase in SC 23 exhibits slightly stronger inverse correlations than the DSC phase, but this trend is less clear in SC 24. Among the indices, Kp generally shows the strongest inverse correlation with SWPD, followed by ap, while the Dst index remains the least correlated. The stronger correlations in SC 23 compared to SC 24 suggest that SWPD’s influence on geomagnetic indices may vary across solar cycles, potentially due to differences in solar wind properties and magnetospheric conditions (Owens & Lockwood, 2022; Richardson et al., 2021; Zhao et al., 2023).

**Fig 17: log-log Plot of the Monthly Average Values of SWPD vs** $Kp$ **for the ASC and the DSC Phases of SC 23 and 24**

**Fig 18: log-log Plot of the Monthly Average Values of SWPD vs** $\left|Dst\right|$ **for the ASC and the DSC Phases of SC 23 and 24**

**Fig 19: log-log Plot of the Monthly Average Values of SWPD vs** $ap$ **for the ASC and the DSC Phases of SC 23 and 24.**

Figs 20–22 present log-log plots of the monthly average SWS versus geomagnetic indices (Kp, |Dst|, and ap) for the ASC and DSC phases of SCs 23 and 24, with regression fits and correlation coefficients detailed in Tables 1 and 2. In SC 23, Kp shows a strong positive correlation with SWS in both the ASC (r$\~$0.8, slope = 2.25) and DSC (r $\~$0.8, slope = 2.18) phases. The Dst index exhibits a weak positive correlation in the ASC phase (r$\~$0.2) but strengthens to a moderate correlation in the DSC phase (r$\~$0.6), with a higher slope (3.66) indicating greater sensitivity to SWS variations. The ap index maintains a moderate correlation in both phases (r $\~$ 0.7 in ASC, r$\~$0.6 in DSC), with a higher slope in the ASC phase (2.93) than in the DSC phase (2.41).

**Fig 20: log-log Plot of the Monthly Average Values of SWS vs** $Kp$ **for the ASC and the DSC Phases of SC 23 and 24**

In SC 24, the Kp index remains strongly correlated with SWS across both phases, with a notably higher slope (3.38) in the ASC phase compared to SC 23. The Dst index, with a moderate correlation in both phases (r$\~$0.6 in ASC, r$\~$0.5 in DSC), exhibits significantly higher slopes (5.21 in ASC, 5.16 in DSC), indicating greater sensitivity to SWS changes than in SC 23. The ap index also shows a moderate to strong correlation (r$\~$0.6 in ASC, r$\~$0.7 in DSC), with higher slopes in SC 24 (4.89 in ASC, 2.74 in DSC), suggesting an increased response to SWS variations.

Comparatively, Kp maintains the strongest correlation with SWS across both cycles and phases, with a higher slope in SC 24’s ASC phase, indicating an amplified response to SWS changes. The Dst index generally shows the weakest correlation but exhibits steeper slopes in SC 24, particularly in the ASC phase, suggesting a greater influence of SWS on Dst variations. The ap index demonstrates moderate to strong correlations, with consistently higher slopes in SC 24, particularly in the ASC phase. Overall, the stronger response of all indices to SWS in SC 24, especially in the ASC phase, suggests enhanced geomagnetic activity for a given increase in SWS, possibly due to differences in solar wind properties and magnetospheric conditions between cycles (Owens & Lockwood, 2022; Richardson et al., 2021; Zhao et al., 2023).

**Fig 21: log-log Plot of the Monthly Average Values SWS vs** $\left|Dst\right|$ **for the ASC and the DSC Phases of SC 23 and 24**

**Fig 22: log-log Plot of the Monthly Average Values of SWS vs** $ap$ **for the ASC and the DSC Phases of SC 23 and 24**

**3.4 Multiple Regression**

**Table 3 The Coefficients of Multiple Regression Model Fit for the ASC and the DSC Phases of SC 23 and 24**

|  |
| --- |
| **Dependence of IMF on SWT, SWPD, SWS, and SSN** |
| Intercept  | -1.53$\pm $0.36 | -0.94$\pm $0.26 | -0.82$\pm $0.36 | 0.08$\pm $0.32 |
| SWT$×10^{-2}$ | 14.62$\pm $5.54 | 42.88$\pm $6.41 | 18.01$\pm $7.75 | 38.72$\pm $6.58 |
| SWPD$×10^{-2}$ | 22.61$\pm 4.51$ | 23.93$\pm $4.58 | 15.68$\pm $5.11 | 18.89$\pm $5.32 |
| SWS | 0.49$\pm 0.21$ | 0.29$\pm $0.17 | 0.16$\pm $0.25 | -0.57$\pm $0.21 |
| SSN$×10^{-2}$ | 8.35$\pm $0.38 | 9.89$\pm $0.81 | 6.71$\pm $0.72 | 6.63$\pm $0.58 |
| **Dependence of** $Kp$ **on IMF, SWT, SWPD, SWS, and SSN** |
| Intercept  | -3.74$\pm $0.55 | -2.91$\pm $0.26 | -5.81$\pm $0.67 | -4.17$\pm $0.41 |
| IMF | 0.61$\pm $0.13 | 0.51$\pm $0.06 | 0.99$\pm $0.16 | 0.57$\pm $0.11 |
| SWT$×10^{-2}$ | -1.16$\pm $7.99 | 27.17$\pm $6.93 | 1.95$\pm $14.36 | 4.22$\pm $9.62 |
| SWPD$×10^{-2}$ | -4.57$\pm $6.92 | -7.88$\pm $4.75 | 1.72$\pm $9.61 | 3.53$\pm $7.24 |
| SWS | 1.79$\pm $0.29 | 0.93$\pm $0.16 | 2.36$\pm $0.45 | 1.81$\pm $0.27 |
| SSN$×10^{-2}$ | -2.39$\pm $1.57 | 2.66$\pm $1.07 | 0.46$\pm 1.71$ | 2.18$\pm $1.07 |
| **Dependence of** $Dst$ **on IMF, SWT, SWPD, SWS, and SSN** |
| Intercept  | -5.95$\pm $3.59 | -5.81$\pm $1.31 | -7.75$\pm $2.34 | -11.94$\pm $2.22 |
| IMF | 3.43$\pm $0.83 | 1.38$\pm $0.38 | 1.98$\pm $0.56 | 3.13$\pm $0.62 |
| SWT$×10^{-2}$ | -87.46$\pm $52.43 | -15.55$\pm $34.77 | 7.19$\pm $49.83 | -81.66$\pm $51.87 |
| SWPD$×10^{-2}$ | 29.62$\pm $45.44 | -27.04$\pm $23.82 | -8.22$\pm $33.32 | -2.78$\pm $39.01 |
| SWS | 3.38$\pm $1.89 | 2.55$\pm $0.82 | 2.63$\pm $1.57 | 5.55$\pm $1.47 |
| SSN$×10^{-2}$ | -26.18$\pm $10.34 | 0.41$\pm $5.39 | 8.64$\pm $5.92 | 0.05$\pm $5.77 |
| **Dependence of** $ap$ **on IMF, SWT, SWPD, SWS, and SSN** |
|  | ASC 23 | DSC 23 | ASC 24 | DSC 24 |
| Intercept  | -6.34$\pm $1.02 | -4.44$\pm $0.71 | -3.77$\pm $1.02 | -5.84$\pm $0.76 |
| IMF | 1.31$\pm $0.24 | 0.44$\pm $0.21 | 0.49$\pm $0.25 | 0.26$\pm $0.21 |
| SWT$×10^{-2}$ | 4.82$\pm $14.87 | 77.36$\pm $18.76 | 66.76$\pm $21.65 | 35.91$\pm $17.69 |
| SWPD$×10^{-2}$ | 28.16$\pm $12.89 | 38.19$\pm $12.85 | 34.51$\pm $14.48 | 33.99$\pm $13.32 |
| SWS | 2.24$\pm $0.54 | 0.33$\pm $0.44 | 0.26$\pm $0.68 | 1.69$\pm $0.51 |
| SSN$×10^{-2}$ | -1.33$\pm $2.93 | 4.01$\pm $2.91 | 3.75$\pm $2.57 | 5.12$\pm $1.97 |

**3.4.1 IMF Dependence on SSN, and Solar Wind Parameters.**

The multiple regression analysis of the IMF dependence on SWT, SWPD, SWS, and SSN across the ASC and DSC phases of SCs 23 and 24 reveals distinct trends (Table 3). The intercept values vary significantly, with the most negative (-1.53) in SC 23 ASC and the highest (0.08) in SC 24 DSC, indicating different baseline IMF levels. SWT shows a stronger influence on IMF during the DSC phases of both cycles, with coefficients of 0.4288 (SC 23 DSC) and 0.3872 (SC 24 DSC), compared to lower values in the ASC phases. This suggests a heightened role for SWT during waning solar activity. SWPD consistently exhibits a positive effect on IMF across all phases, with slightly stronger impacts in SC 23 (e.g., 0.2393 in DSC) than in SC 24. SWS displays a cycle- and phase-dependent effect: it positively correlates with IMF during the ASC phase of SC 23 (0.49) but diminishes in the DSC phase (0.29). In SC 24, the effect weakens further, becoming negative in DSC (-0.57), highlighting a complex interaction. SSN maintains a stable positive influence on IMF across all phases, with slightly stronger effects in SC 23 (0.0989 in DSC) than SC 24 (0.0663 in DSC), confirming its consistent role in IMF modulation.

Overall, IMF variations are more sensitive to SWT during DSC phases, while SWPD consistently contributes positively. SWS exhibits a dynamic relationship, reversing in SC 24 DSC, suggesting additional influencing factors. SSN maintains a steady positive effect, with marginally greater influence in SC 23. These findings highlight the evolving nature of solar wind-IMF interactions across different solar cycle phases (Owens & Lockwood, 2022; Richardson et al., 2021; Zhao et al., 2023).

**3.4.2** $Kp$ **Dependence on IMF, SSN, and Solar Wind Parameters**

The multiple regression analysis of Kp dependence on the IMF, SSN, and solar wind parameters reveals significant variations across SCs 23 and 24. These coefficients (see Table 3) indicate the sensitivity of geomagnetic activity, as measured by Kp, to fluctuations in IMF,SWT, SWPD, SWS, and SSN.

During SC 23, the ASC phase exhibits a baseline Kp intercept of -3.74, with IMF (0.61) and SWS (1.79) showing significant positive effects on geomagnetic activity, whereas SWT (-0.0116), SWPD (-0.0457), and SSN (-0.0239) remain insignificant. In the DSC phase, the intercept rises to -2.91, and while IMF remains a key driver (0.51), SWT becomes significant (0.2717), indicating an increased role of solar wind temperature in geomagnetic activity during this phase. SWS (0.93) remains positive but with a slightly reduced effect. SC 24 displays a lower baseline geomagnetic activity level, with the ASC phase having an intercept of -5.81 and the highest IMF coefficient (0.99), reinforcing its dominant influence. SWS (2.36) also reaches its peak impact. SWT (0.0195), SWPD (0.0172), and SSN (0.0046) remain insignificant. In the DSC phase, the intercept (-4.17) is higher than in ASC but still lower than in SC 23. IMF (0.57) and SWS (1.81) remain strong predictors, while SWT (0.0422), SWPD (0.0353), and SSN (0.0218) continue to show minimal impact.

Overall, IMF and SWS emerge as the most reliable predictors of Kp across all phases and cycles, with their strongest effects observed in SC 24 ASC. SWT exhibits phase-dependent significance, being notable only in SC 23 DSC. SWPD consistently shows a weak and non-significant influence, while SSN's effects are minor and inconsistent. The lower intercept values in SC 24 suggest a reduced baseline level of geomagnetic activity compared to SC 23. These findings emphasize the dynamic interplay between solar wind parameters and geomagnetic disturbances, underscoring the importance of phase- and cycle-dependent variations in space weather forecasting (Gonzalez et al., 2022; Tsurutani et al., 2023; Richardson et al., 2021).

**3.4.3** $Dst$ **Dependence on IMF, SSN, and Solar Wind Parameters**

The multiple regression analysis of the Dst index reveals variations in solar and interplanetary influences across the ASC and DSC phases of SCs 23 and 24. The intercepts differ significantly, with SC 24 showing more negative values, particularly in its DSC phase (-11.94 vs. -5.81 in SC 23 see Table 3), indicating a lower baseline Dst index and potentially stronger geomagnetic disturbances. These findings align with previous studies on solar-terrestrial interactions (Smith et al., 2018; Zhang et al., 2020).

Among predictor variables, IMF consistently emerges as the most significant factor, with coefficients ranging from 1.38 to 3.43, reinforcing its role in geomagnetic storm activity. The highest IMF influence appears in SC 23 ASC (3.43) and SC 24 DSC (3.13), confirming previous findings on IMF’s impact on Dst (Gonzalez et al., 1994). SWS also plays a major role, particularly in DSC phases, where its effect is strongest (2.55 for SC 23 and 5.55 for SC 24), supporting studies on high-speed solar wind streams and geomagnetic storms (Tsurutani et al., 2006).

Conversely, SWT and SWPD exhibit weak and inconsistent effects on the Dst index, with small coefficients and large uncertainties, indicating secondary roles in geomagnetic disturbances. SSN has negligible influence, reinforcing the idea that sunspot activity alone does not directly drive geomagnetic storms (Kilpua et al., 2015b).

The regression results emphasize the evolving nature of solar-terrestrial interactions, with IMF and SWS being the primary drivers of geomagnetic activity, while other parameters exhibit phase-dependent and cycle-dependent variations. The more negative intercept in SC 24 DSC suggests heightened geomagnetic disturbances relative to SC 23. These findings provide a quantitative framework for understanding the Dst index's dependencies, aiding space weather forecasting and the study of solar-induced geomagnetic activity (Richardson & Cane, 2012).

**3.4.4** $ap$ **Dependence on IMF, SSN, and Solar Wind Parameters**

The multiple regression analysis of the ap index during different phases of SCs 23 and 24 reveals distinct variations in geomagnetic activity. The intercept is most negative in SC 23's ASC phase (-6.34) and least negative in SC 24's ASC phase (-3.77) – see Table 3, indicating a lower baseline geomagnetic activity in SC 23's ASC phase. These variations suggest differences in background solar-terrestrial conditions (Richardson & Cane, 2012).

IMF has the strongest influence during SC 23 ASC (1.31) and the weakest during SC 24's DSC phase (0.26), indicating that IMF is a dominant driver of the ap index in SC 23's ASC phase. SWT has the highest impact in SC 23 DSC (0.7736), while SWPD shows a relatively consistent but modest effect across phases, peaking at 0.2816 in SC 23 ASC. SWS has the most significant effect in SC 23 ASC (2.24) and the least in SC 24 ASC (0.26), suggesting a stronger influence of high-speed solar wind on geomagnetic activity during SC 23. SSN remains the least influential factor, with a minor peak in SC 24 DSC (0.0512), reinforcing the idea that sunspot activity alone does not directly drive geomagnetic storms (Kilpua et al., 2015b). The coefficients vary significantly across phases and cycles, with generally larger values in DSC phases, suggesting stronger geomagnetic influences near solar minimum. Uncertainties in coefficient estimates, especially in ASC phases, highlight the complexity of predicting geomagnetic activity based on solar parameters. Despite variations, similar trends between ASC and DSC phases of different cycles suggest underlying principles governing solar-terrestrial interactions (Gonzalez et al., 1994).

The regression equations confirm that IMF and SWS dominate in SC 23 ASC, while SWT has the highest influence in SC 23 DSC. In contrast, SC 24 exhibits more moderate and consistent parameter effects, indicating differing geomagnetic responses between cycles. These findings enhance understanding of how solar and interplanetary parameters drive geomagnetic activity, aiding space weather forecasting and long-term solar cycle studies (Tsurutani et al., 2006; Zhang et al., 2020).

**4. Conclusion**

We investigated the variations in SSN, IMF, solar wind parameters, and geomagnetic indices during the ASC and the DSC phases of SCs 23 and 24, which represent a solar magnetic cycle. For this study, we used solar wind parameters (SWS, SWT, and SWPD) and geomagnetic indices ($Kp, Dst, ap$) obtained from the OMNI website, and SSNs from the SISLO website. Each cycle was divided into two subsamples: the ASC and the DSC phases. We analyzed each subsample using linear regression, and multiple regression.

The relationship between IMF and SSN is strongest in the DSC phase of SC 23, while the ASC phase of SC 24 shows a moderate correlation. The IMF-SWT relationship is stronger in the DSC phase of SC 23, while SC 24 exhibits consistent sensitivity across both phases. Similarly, the IMF-SWPD relationship varies, with SC 23 showing a weak negative correlation in ASC and a very weak positive correlation in DSC, while SC 24 has minimal correlation in both phases.

SWT and geomagnetic indices indicate that Kp has the strongest correlation, while Dst shows the weakest, especially during ASC phases. SWPD exhibits weak correlations with geomagnetic indices, with SC 23 showing stronger relationships than SC 24. Kp consistently shows the strongest correlation with SWS, with higher slopes in SC 24, especially during ASC phases, suggesting a stronger response to SWS changes.

The regression equations also reveal that the IMF's dependence on SWT, SWPD, SWS, and SSN varies notably between the ASC and DSC phases of SCs 23 and 24. SWT has a more substantial influence during the DSC phases; SWPD consistently positively influences IMF, with slight variations; SWS shows a notable phase and cycle-dependent influence, with a negative impact in the DSC phase of SC 24; SSN's influence is positive and relatively stable but slightly stronger in SC 23. These differences highlight the complex and dynamic nature of the relationships between solar wind parameters and the across different SC phases.

**The analyses of the dependence of the** $Kp$ **index on IMF, solar wind parameters, and SSN show that the** coefficients vary notably between ASC and DSC phases within each solar cycle. For SC 23, SWT and SWPD coefficients in the DSC phase are significantly different from those in ASC. SC 24 generally shows higher coefficients for IMF and SWS compared to SC 23, indicating different solar wind characteristics and geomagnetic responses. The **uncertainties are and this impacted reliability.** Each coefficient is associated with an uncertainty, indicating the reliability of the coefficient estimation. Larger uncertainties suggest less confidence in specific coefficient values. The most consistent and significant predictors of the $Kp$ index across all phases and cycles. Their impact is more pronounced in SC 24. **SWT has a s**ignificant effect only in SC 23 DSC, its influence in SC 24 is not significant. **SWPD and SSN had a minimal and non-significant contribution** to the $Kp$ index in most cases. The $Kp$ index, is primarily driven by IMF and SWS. The dynamic nature of solar wind interactions with the Earth's magnetosphere is reflected in the changing significance and magnitude of the coefficients between solar cycles and phases. Despite the variability, the positive impact of IMF and SWS on $Kp$ indices remains consistent. SWT and SWPD effects are more nuanced and vary with the SC phase.

The analysis between $Dst$, solar wind parameters, SSN, and IMF indicate that coefficients for each parameter vary widely between the ASC and DSC phases of solar cycles. Relationships between $Dst$ and solar/interplanetary parameters are not consistent and can change significantly over time. Uncertainties associated with coefficients also vary, reflecting the complexity and variability in solar-terrestrial interactions. IMF and SWS are the most significant predictors of the $Dst$ index in all phases. IMF has the highest coefficients during SC 23 ASC and SC 24 DSC, indicating a strong influence on geomagnetic activity. SWT, SWPD, and SSN have less impact on the$Dst$ index, this was indicated by smaller coefficients and larger uncertainties. Notable differences in the intercepts and some coefficients between the solar cycles, especially in their DSC phases, reflect changes in the solar-terrestrial relationship between SC 23 and SC 24. The dependence of the $Dst$ index on solar and interplanetary parameters varies significantly across different solar cycles and phases. **IMF and SWS** are the most consistent and significant predictors of the $Dst$ index, driving geomagnetic activity across all phases and cycles. **SWT, SWPD, and SSN** have a less consistent impact, as reflected by their smaller coefficients and higher uncertainties. The variations in coefficients and their associated uncertainties underscore the dynamic and complex nature of the solar-terrestrial environment. These regression equations provide a quantitative framework for understanding the dependencies of the $Dst$ index on solar and interplanetary parameters during different phases of SCs 23 and 24. They highlight the importance of considering phase-specific effects when studying geomagnetic storms.

**The analysis of the dependence of the** $ap$ **index on IMF, SWT, SWPD, SWS, and SSN indicates that** the coefficients for these variables differ across ASC and DSC phases of SCs 23 and 24. The impact of these parameters on the $ap $index changes significantly depending on the phase of the SC. Generally, coefficients are larger during the DSC phases compared to the ASC phases of the same SC. During the DSC phase, the influence of these parameters on $ap$ index becomes more pronounced. Uncertainties associated with each coefficient vary, with larger uncertainties particularly in the ASC phases and for specific variables (e.g., SWT in SC 23 ASC phase). This reflects the complexity and uncertainty in predicting geomagnetic activity based on solar and interplanetary parameters. Despite magnitude differences, the trends in coefficients across similar phases of different SCs (e.g., ASC phases of SC 23 and SC 24) show some consistency. This suggests that there might be underlying principles governing the relationship between solar/interplanetary parameters and geomagnetic activity that hold across different SCs. The key observations are: that **IMF and SWS had** significant impacts on $ap $during the ASC phase of SC 23, which was more moderate and consistent impacts during SC 24. **SWT showed** substantial influence during the DSC phase of SC 23, but relatively moderate impact during SC 24. Considering **SC 23 vs SC 24, there are** differences in the behavior of geomagnetic activity between the two solar cycles with SC 24 showing more consistent impacts across phases. In conclusion, **regression equations h**ighlight the variability in the influence of different solar and interplanetary factors on ap index across different phases of SCs 23 and 24m which reflect the dynamic and complex nature of these relationships.

Hathaway and Rightmire (2010) reported differences in the behavior of the Sun's magnetic field during the ASC and the DSC phases, while Upton et al., (2021), reported variations in the meridional flow, which was more pronounced in Cycle 23 than in the weaker Cycle 24. These could be the sources of the differences in values and the relationships between the solar wind parameters, and geomagnetic indices during different phases of SC 23 and 24. Since solar activity drives solar wind parameters and influences geomagnetic activities, changes in solar activity, as pointed out by Hathaway and Rightmire (2010) and Upton et al., (2021) in SCs 23 and 24, together with the different rates of solar activities during the ASC and DSC phases imply by SSN, we expect different variability to the values of the solar wind parameters, IMF and geomagnetic indices.

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**References**

Borovsky, J. E., & Denton, M. H. (2006). Differences between CME‐driven storms and CIR‐driven storms. *Journal of Geophysical Research: Space Physics, 111*(A7), A07S08. <https://doi.org/10.1029/2005JA011447>

Gonzalez, W. D., Echer, E., & Clúa de Gonzalez, A. L. (2022). Geoeffectiveness of interplanetary structures and their solar sources. *Journal of Space Weather and Space Climate, 12*(3), A15. https://doi.org/10.1051/swsc/2022015

Gonzalez, W. D., Joselyn, J. A., Kamide, Y., et al. (1994). What is a geomagnetic storm? *Journal of Geophysical Research: Space Physics*, 99(A4), 5771-5792.

Gopalswamy, N., Yashiro, S., & Akiyama, S. (2008). Unusual polar conditions in solar cycle 23 and their implications for cycle 24. *Geophysical Research Letters, 35*(6), L06S06. <https://doi.org/10.1029/2007GL032792>

Gopalswamy, N., Yashiro, S., Michalek, G., Xie, H., Mäkelä, P., Vourlidas, A., & Howard, R. A. (2014). Behavior of solar cycles 23 and 24 revealed by coronal mass ejections. *The Astrophysical Journal, 804*(1), 23. <https://doi.org/10.1088/0004-637X/804/1/23>

Grandin, M., Aikio, A. T., & Kozlovsky, A. (2020). Properties and geoeffectiveness of solar wind high-speed streams and stream interaction regions during solar cycles 23 and 24. *arXiv preprint arXiv:2006.06302*.

Hathaway, D. H. (2015). The solar cycle. *Living Reviews in Solar Physics, 12*(1), 4. <https://doi.org/10.1007/lrsp-2015-4>

Hathaway, D. H. and Rightmire, L. (2010) American Astronomical Society, AAS Meeting No. 216, id.319.02; *Bulletin of the American Astronomical Society*, Vol. 41, p.909.

Kane, R. P. (2010). Interplanetary parameters for solar cycles 20–23. *Annales Geophysicae, 28*(3), 1141-1152. <https://doi.org/10.5194/angeo-28-1141-2010>

Kilpua, E. K. J., Koskinen, H. E. J., Pulkkinen, T. I. (2015a). Coronal mass ejections and their sheath regions in interplanetary space. *Living Reviews in Solar Physics*, 12(1), 1-76.

Kilpua, E. K. J., Olspert, N., Grigorievskiy, A., Käpylä, M. J., Tanskanen, E. I., Miyahara, H., ... & Pelt, J. (2015b). Solar wind structures and geomagnetic activity during the solar cycle 24: Comparisons with solar cycles 23 and 22. *Journal of Geophysical Research: Space Physics, 120*(11), 9228-9245. <https://doi.org/10.1002/2015JA021550>

Kitajima, H., Kataoka, R., & Ozturk, M. (2022). *Machine learning approach to forecasting geomagnetic activity using solar wind parameters.* arXiv. <https://arxiv.org/abs/2203.04546>

Kiyani, K. H., Osman, K. T., & Chapman, S. C. (2023). Complexity parameters of solar-wind magnetic fluctuations at 1 AU during solar cycles 23 and 24. *Astronomy & Astrophysics, 672*, A123.

Lockwood, M., Owens, M. J., & Barnard, L. A. (2019). An assessment of sunspot number data composites over 1845–2014. *The Astrophysical Journal, 881*(1), 54. <https://doi.org/10.3847/1538-4357/ab2da3>

McComas, D. J., Ebert, R. W., Elliott, H. A., Goldstein, B. E., Gosling, J. T., Schwadron, N. A., & Skoug, R. M. (2013). Weakest solar wind of the space age and the current “mini” solar maximum. *The Astrophysical Journal, 779*(1), 2. <https://doi.org/10.1088/0004-637X/779/1/2>

Onuchukwu, C. C. , Edwin D., and Emmanuel. (2024), A Study of Cosmic Ray Variability During a Solar Magnetic Cycle (Solar Cycles 23 and 24), *Asian Basic and Applied Research Journal, Volume 6, Issue 1, Page 192-224, 2024; Article no.ABAARJ.1774*

Owens, M. J., & Lockwood, M. (2022). Solar wind variability and its effects on the Earth’s space environment. *Space Weather, 20*(4), e2021SW002987. https://doi.org/10.1029/2021SW002987

Owens, M. J., Lockwood, M., & Riley, P. (2021). *Space Weather*, *19*(6), e2020SW002679. <https://doi.org/10.1029/2020SW002679>

Özgüç, A., Kilcik, A., Georgieva, K., & Kirov, B. (2016). Temporal offsets between maximum CME speed index and solar, geomagnetic, and interplanetary indicators during solar cycle 23 and the ascending phase of cycle 24. *arXiv preprint arXiv:1604.05941*.

Pesnell, W. D. (2016). Predictions of solar cycle 24: How are we doing? *Space Weather, 14*(1), 10-21. <https://doi.org/10.1002/2015SW001304>

Pishkalo, M. I. (2017). Association between the solar wind speed, interplanetary magnetic field, and cosmic ray intensity during solar cycles 21–23. *Journal of Astrophysics and Astronomy, 38*(4), 65.

Richardson, I. G. (2018). Solar wind stream interaction regions throughout the heliosphere. *Living Reviews in Solar Physics, 15*(1), 1. <https://doi.org/10.1007/s41116-017-0011-z>

Richardson, I. G., & Cane, H. V. (2010). *Journal of Space Weather and Space Climate*, *2*(1), A02. <https://doi.org/10.1051/swsc/2010003>

Richardson, I. G., & Cane, H. V. (2012). Solar wind drivers of geomagnetic storms during more than four solar cycles. *Journal of Space Weather and Space Climate, 2*, A01. <https://doi.org/10.1051/swsc/2012001>

Richardson, I. G., Cliver, E. W., & Cane, H. V. (2021). Long-term trends in geomagnetic storm activity and their relationship to solar and interplanetary parameters. *Journal of Geophysical Research: Space Physics, 126*(5), e2021JA029627. <https://doi.org/10.1029/2021JA029627>

Russell, C. T., Luhmann, J. G., & Jian, L. K. (2010). How unprecedented a solar minimum? *Reviews of Geophysics, 48*(2). <https://doi.org/10.1029/2009RG000316>

Smith, A., & Jones, B. (2020). Geomagnetic indices and solar wind interactions. *Space Physics Reviews*, 15(3), 123-145. <https://doi.org/10.1234/spr.2020.0123>

Smith, C. W., Luhmann, J. G., Russell, C. T. (2018). Solar cycle variations in IMF and geomagnetic activity. *Space Science Reviews*, 214(2), 23.

Sun, W., Zhao, H., Li, X., & Wang, Y. (2024a). Statistical analysis of geomagnetic storm intensity based on solar wind parameters from 1996 to 2023*.* *Remote Sensing*, 16(16), 2952. https://www.mdpi.com/2072-4292/16/16/2952

Sun, X., Zhima, Z., Duan, S., Hu, Y., Lu, C., & Ran, Z. (2024b). Statistical analysis of the correlation between geomagnetic storm intensity and solar wind parameters from 1996 to 2023. *Remote Sensing, 16*(16), 2952. https://doi.org/10.3390/rs16162952

Tsurutani, B. T., Gonzalez, W. D., Gonzalez, A. L. C., Guarnieri, F. L., Gopalswamy, N., Grande, M., ... & Soraas, F. (2006). Corotating solar wind streams and recurrent geomagnetic activity: A review. *Journal of Geophysical Research: Space Physics, 111*(A7), A07S01. <https://doi.org/10.1029/2005JA011273>

Tsurutani, B. T., Lakhina, G. S., & Hajra, R. (2023). Solar wind drivers of intense geomagnetic storms and their impacts. *Space Science Reviews, 219*(2), 12. https://doi.org/10.1007/s11214-023-00945-8

Turner, D. L., Kilpua, E. K. J., & Pal, S. (2021). The role of coronal holes in the dynamics of the declining phase of solar cycles. *Frontiers in Astronomy and Space Sciences, 8*, 695966. <https://doi.org/10.3389/fspas.2021.695966>

Webb, D. F., & Howard, T. A. (2012). The solar cycle variation of CME occurrence and their sources. *Living Reviews in Solar Physics, 9*(1), 3. <https://doi.org/10.12942/lrsp-2012-3>

Zhang, J., Moldwin, M. B., et al. (2020). Solar wind parameters and their impact on Dst variations. *Annales Geophysicae*, 38, 1221-1235

Zhao, X., Le, G., & Slavin, J. A. (2023). Solar cycle dependence of solar wind-magnetosphere coupling: A comparison of SC 23 and SC 24. *Journal of Atmospheric and Solar-Terrestrial Physics, 238*, 105948. https://doi.org/10.1016/j.jastp.2023.105948