

Interplanetary Magnetic Field -Solar Wind Coupling and Geomagnetic Response during Solar Cycles 23,24 and 25

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The present study investigates the variation in the geomagnetic storms, measured by Dst and Kp indices (with Kp scaled as $Kp \times 10$ for consistency) in relation to the southward component of the interplanetary magnetic field (IMF) B_z component, solar wind speed (V) and the product of the solar wind speed V and IMF B_z for the three consecutive solar cycles (SCs) 23,24 and the rising phase of SC 25. The study enhances understanding of the dependency of geomagnetic activities on interplanetary parameters. From this study it is found that the product of V and B_z as the most geoeffective parameter and produces significant disturbance in Earth's magnetospheric conditions compared to V or B_z alone, this is because when solar wind speed V combines with southward magnetic field (B_z) it enhances the magnetic reconnection due to which plasma flow speed suddenly increases and the induced electric field swaps the charge particles, which enhances the geomagnetic activities. The study also determined the correlation coefficient between the Dst index and VB_z for these three SCs, which are (0.7, 0.65 and 0.5), and between the Kp index and VB_z is (-0.7, -0.65 and 0.55), respectively. The Kp index shows resemblance with the solar wind speed V, i.e. both these parameter reaches to its peak values corresponding to Dst minima. Furthermore, this study also investigated the variation of Dst and Kp index with solar wind speed V and IMF B_z separately and found that the correlation between these parameters is moderate across all three SCs. This suggests that solar wind speed (V) or IMF (B_z) alone is not sufficient to produce intense geomagnetic storms. Additionally, there is an average time lag of 1 to 2 days between B_z minima and Dst minima, which indicates a complex mechanism involved in magnetic reconnection between Earth's magnetosphere and IMF, the Dst and Kp indices found to vary inversely with respect to each other (during sharp dip in Dst Kp index reach to its peak value), also the geomagnetic activities during SC 23 and the rising phase of SC 25 is comparatively high and shows resemblance, which suggests the same kind of variation may also be expected for the SC 25 as that of SC 23 which helps in predicting space weather conditions.

Keywords: Solar wind speed (V), Geomagnetic storm (GS), Kp index, Interplanetary magnetic field (IMF), Disturbance storm time index (Dst)

1 Introduction

Solar wind is a stream of charged particles that mainly consists of protons, electrons and heavy ions¹. It originates from the Sun's corona and plays an important role in the modulation of space weather conditions. It is a key factor in determining the intensity of GS and variation in Kp index, based on their velocities, solar winds are classified into three categories, slow speed solar wind (300-500 Km/s) originated near Sun's equatorial belt², high speed solar wind (600 to 800 Km/sec) originated in coronal holes³ and very high-speed solar wind originated in the large-scale plasma eruptions on the Sun's surface, with speed exceeding (2000 Km/sec)⁴. When the solar winds enter the magnetosphere, it produces a ring current⁵. This ring current generates an additional

magnetic field, which is opposite to the Earth's magnetic field. As a result, the Earth's magnetic field conditions are disturbed, which is known as a geomagnetic storm (GS).

The IMF is an expansion of the Sun's magnetic field, carried outward from the solar corona by the solar winds. The coupling between the Earth's magnetosphere and the IMF is the primary cause of geomagnetic storms⁶. The interplanetary origins of geomagnetic storms are associated with large-scale structures such as interplanetary coronal mass ejection (ICME) and the corotating interaction regions (CIRs), which act as the main carriers of the southward component of IMF⁷⁻⁹. When the B_z component of IMF reconnects with Earth's magnetic field, it allows mass and energy to enter Earth's magnetosphere, which quantifies the Kp index value. A higher value of the Kp index indicates a strong geomagnetic storm.

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The high-speed SW and CMEs are the key drivers of GS, whose strength is measured by the Kp index¹⁰, according to several studies the production of geomagnetic storms is results of interactions between solar wind parameters and the Earth's magnetosphere¹¹⁻¹⁴, Specifically the southward component (Bz) of the IMF, it is significant because it triggers magnetic reconnection at the magnetopause, but most of the studies shows that IMF. B_z Alone is insufficient to fully describe the intensity of a geomagnetic storm. The combined parameter VBz, representing the product of solar wind speed V and IMF Bz, serves as a more effective indicator of geo effectiveness, as it accounts for both the strength of the magnetic field and the efficiency of energy transfer.

The Intensity of a geomagnetic storm is commonly characterised using the Kp and Dst indices. The Kp index is calculated by taking the average of all the K values recorded at 13 geomagnetic observatories worldwide, making it a global indicator for measuring Geomagnetic activities. The Kp index used for space weather forecasting¹⁵ it ranges from 0 to 9. When the value of the Kp index becomes greater than 6, it indicates strong geomagnetic storms. While the horizontal component of the Earth's magnetic field measured at four low-latitude, near-equatorial geomagnetic observatories is averaged to determine the value of the Dst index, according to the different values of Dst, GSs are classified as moderated ($-100 \text{ nT} < \text{Dst} \leq -50 \text{ nT}$), intense GS ($-100 \text{ nT} \geq \text{Dst} \geq -250 \text{ nT}$) and super intense $-250 \text{ nT} \geq \text{Dst}$).

2 Data Sources and Methodology

For the present study, the Superposed Epoch Chree analysis method¹⁶ is used, considering the occurrence day of a moderated geomagnetic storm ($-100 \text{ nT} < \text{Dst} \leq -50 \text{ nT}$) as the zero-epoch day (key event). The six days preceding the occurrence (zero-epoch) day of storm are assumed as $-1, -2, -3, -4, -5, -6$ days, while the six days following the zero-epoch day are denoted as $+1, +2, +3, +4, +5, +6$ days, since a ± 6 -day window provide a balance, it allows capturing the full evolution of storms and also reduce overlapping between consecutive events. The average value for these days corresponds to every year, and a graph is plotted between two or three parameters to visualise their variation with respect to each other. The daily average value of the Kp index, Dst, solar wind speed and IMF Bz are taken from the omniweb interface

(omniweb.gsfc.nasa.gov/form/dx1.html) for the period 1997 to 2024. The correlation coefficient between the above variable also determined using the Karl Pearson correlation coefficient formula $r = \frac{\sum(x_i - \bar{x})(y_i - \bar{y})}{\sigma_x \sigma_y}$ for each year, and then their average for different solar cycles and compare them with each other to verify their relationships and effects on each other.

3 Results

3.1 Dst and Kp Indices

The Dst index is used to measure large-scale geomagnetic storms. Dst shows the severity of geomagnetic storms, and it is not directly responsible for disturbance in the communication and navigation system¹⁷. In contrast, the Kp index is derived from multiple mid-altitude geomagnetic observatories around the world, making it a global indicator for geomagnetic activities. It is directly responsible for the communication and navigation systems disturbances¹⁸, Kp indicates early disturbances in Earth's magnetic field conditions and strong geomagnetic disturbances are often observed corresponding to high Kp values ($\text{Kp} > 1$)¹⁸. The present study revealed that the Kp index and Dst for most of the years from 1997-2024 are inversely correlated with each other, i.e., the peak value of the Kp index aligns with the Dst minimum (Fig.1), which implies that a rise in geomagnetic activity typically leads to the occurrence of geomagnetic storms. Also, for the years when the value of the Kp index is high a strong dip in Dst values, which suggests that the two parameters are highly interrelated with each other, and both measure geomagnetic activities. The correlation coefficient between these two parameters is significantly high, approximately (-0.8) (Table 1). For the years (1998, 2017, 2022 and 2024), the Kp index either leads or lags the Dst minimum by 1 or 2 electric field swaps the charge particles days, which indicates a complex coupling mechanism between solar wind and Earth's magnetosphere.

3.2 Dst and Kp indices Variation with Solar Wind Speed

The Dst index is commonly used to monitor the geomagnetic storm. Dst is influenced by many interplanetary parameters such as the solar wind speed, plasma density and interplanetary magnetic field, etc., among these, the solar wind speed plays a crucial role, which significantly affects the

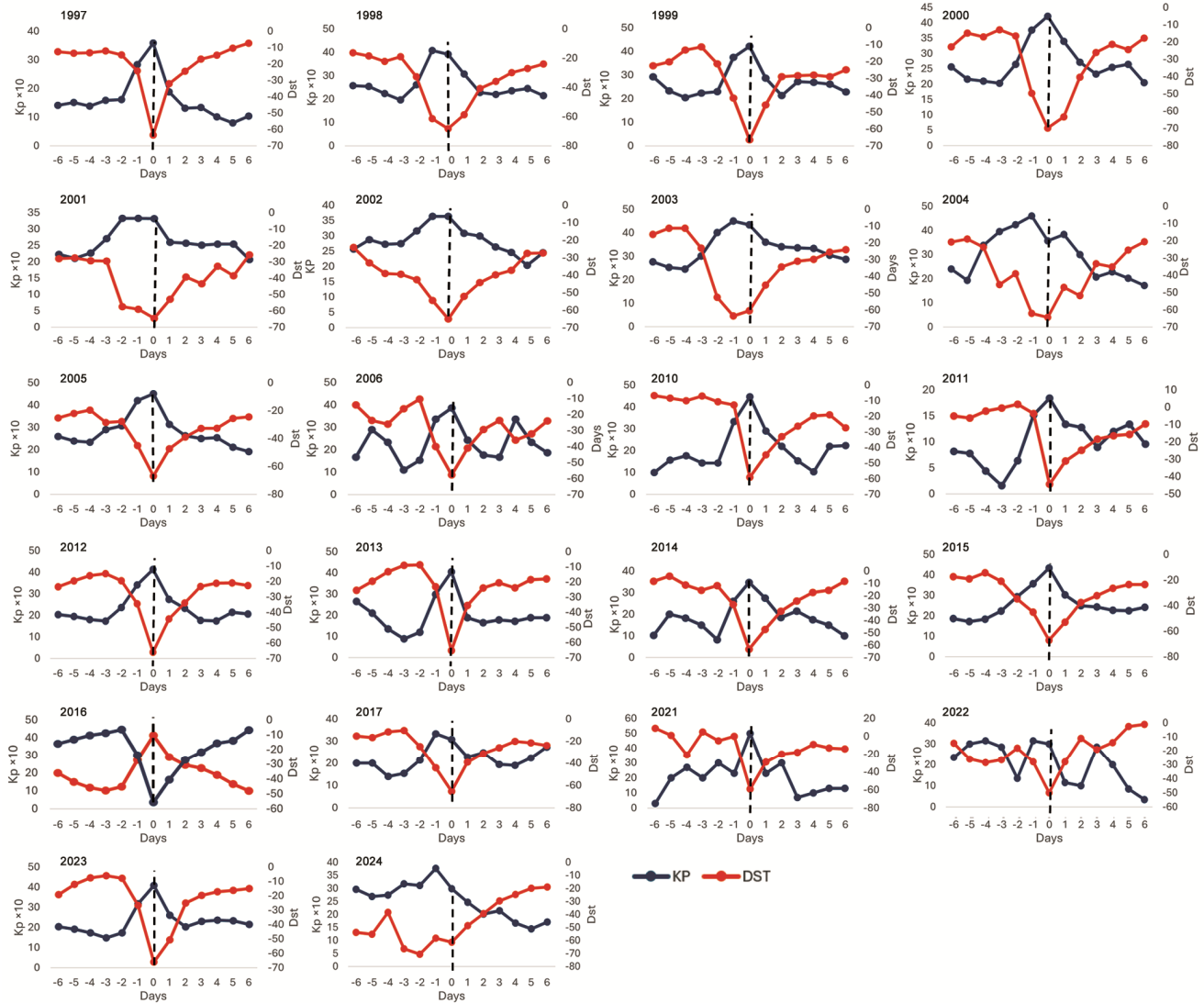


Fig. 1 — Chree analysis results from –6 to +6 days with respect to the occurrence day of the GS (zero epoch day). To study the pattern of the Dst and Kp indices, the variation of their mean values is plotted for solar cycles 23, 24 and 25

Table 1 — Average correlation coefficient between various parameters

Correlation coefficient	SC 23	SC 24	SC25
Dst and V_{B_z}	0.70	0.63	0.50
Kp and V_{B_z}	-0.70	-0.65	-0.55
Dst and Solar Wind	-0.47	-0.67	-0.45
Dst and B_z	0.67	0.56	0.34
KP and Solar Wind	0.46	0.37	0.31
Kp and B_z	-0.55	-0.47	-0.31
Dst and Kp	-0.78	-0.68	-0.82

magnetospheric conditions and produces GSs. When the value of the solar wind speed increases the Dst value become more and more negative, From the study it found that for most of the years of SC 23, 24 and 25 the Dst value decreases gradually with Solar wind

speed and become minimum when solar wind speed reaches to its maxima, after that when solar wind speed starts decreasing Dst increases gradually which is also found by many researchers¹⁹ they reported that CIRs linked with fast speed solar wind produce a GS²⁰ with gradual decrease in the Dst value. The years 1999, 2002, 2005, 2012, 2017, 2021 and 2023 exhibit strong geomagnetic events, with sharp spikes in the solar wind speed and correspondingly sudden drop in Dst value (Fig 2), The variation between the SW speed and Dst is not very sharp for all the years, this is because Solar wind speed alone is not sufficient to produce GS, it's is the product of the solar wind speed and the IMF B_z which is responsible for producing sudden depression in Dst value²¹.

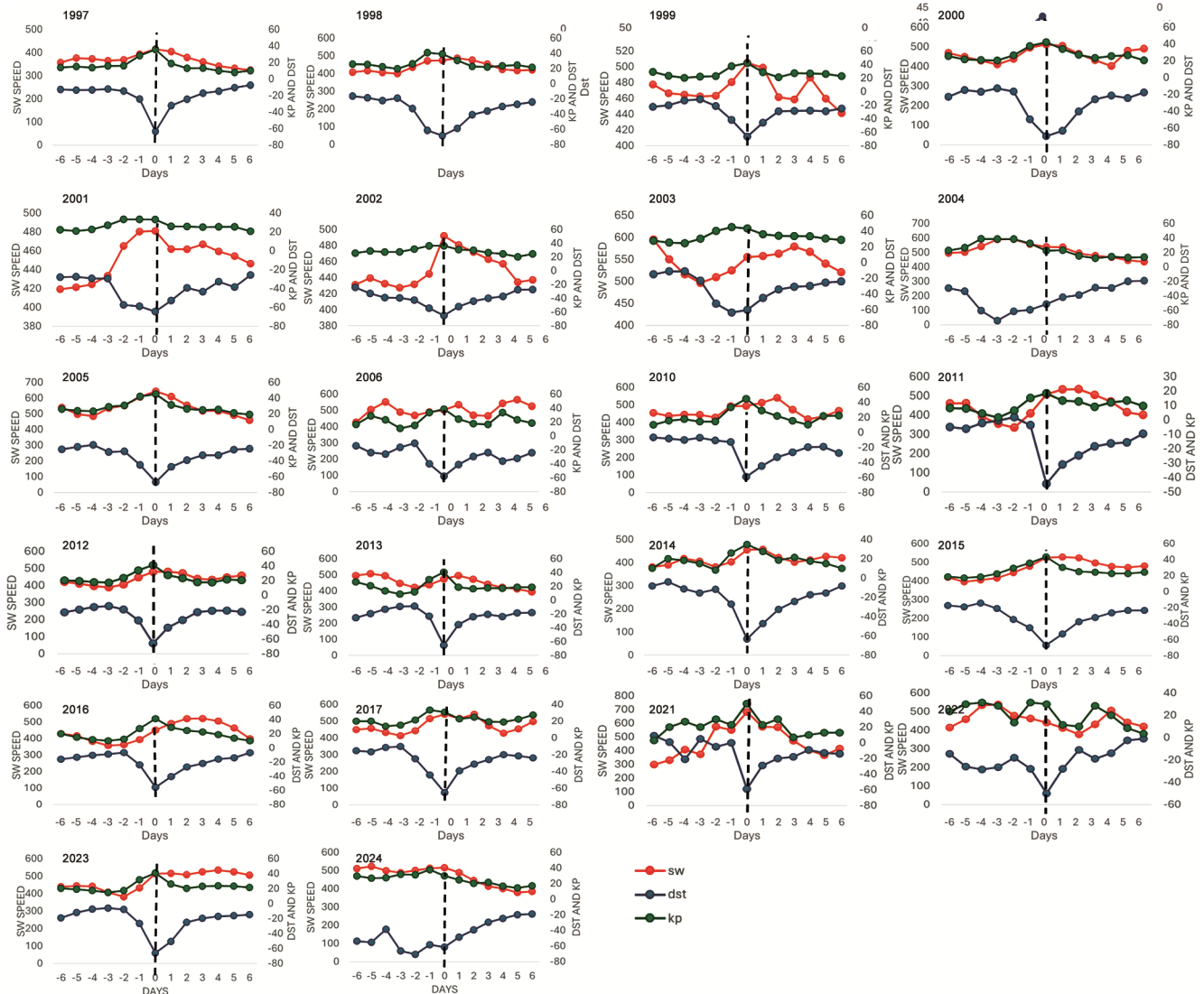


Fig. 2 — Chree analysis results from -6 to $+6$ days with respect to the occurrence day of GS (zero epoch day). To study the patterns of Dst, Kp index and solar wind speed, the variation in their mean values is plotted for solar cycles 23, 24 and 25

The Kp index is a Parameter that measures the intensity of geomagnetic activities. Many studies have shown that an increase in the solar wind speed is associated with geomagnetic disturbances, and the solar wind speed and plasma density affect the intensity of the GS, which is measured via the Kp index. In this study, it was found that the value of the Kp index increases with Solar wind speed in a similar pattern, which indicates that these two parameters are highly correlated with each other. These findings support Richardson et al., who reported that the Kp index increases with an increase in the solar wind speed. Based on the study of Dst and Kp index with solar wind speed, it was observed that solar wind speed is the key driver of both Dst and Kp index,

and Kp index acts as an indicator of geomagnetic disturbances on Earth.

3.3 Dst and Kp Index Variation with IMF Bz

Solar winds carry the IMF towards Earth's magnetosphere. The southward components of IMF ($B_z < 0$) play a crucial role in disturbing the Earth's geomagnetic conditions, when the IMF Bz is anti-parallel to the Earth's magnetic field, due to magnetic reconnection, a magnetic pause is produced²² and this magnetic pause allows solar wind energy to enter the magnetosphere and produce geomagnetic disturbance. The intensity of GSs depends directly on the negative value of B_z ; it is well established that when the negative B_z value changes by a small amount, it has a

measurable effect on geomagnetic conditions²³. This study revealed that when IMF Bz value starts decreasing, the Dst index also decreases and reaches a minimum along with Bz which is in good agreement with previous studies²⁴, but the Kp index shows inverse relationship with IMF Bz i.e Kp starts increasing and become maximum corresponds to Bz

minima, also from the study it found that during the ascending and descending phases of solar cycles the solar activities are less and a low negative Bz values, while during solar maxima the IMF bz coincides with a high Kp index and significant a dip in Dst is observed. From Fig. 3, it found that for most of the years of Sc 23, 24 and 25, peaks of Dst minima

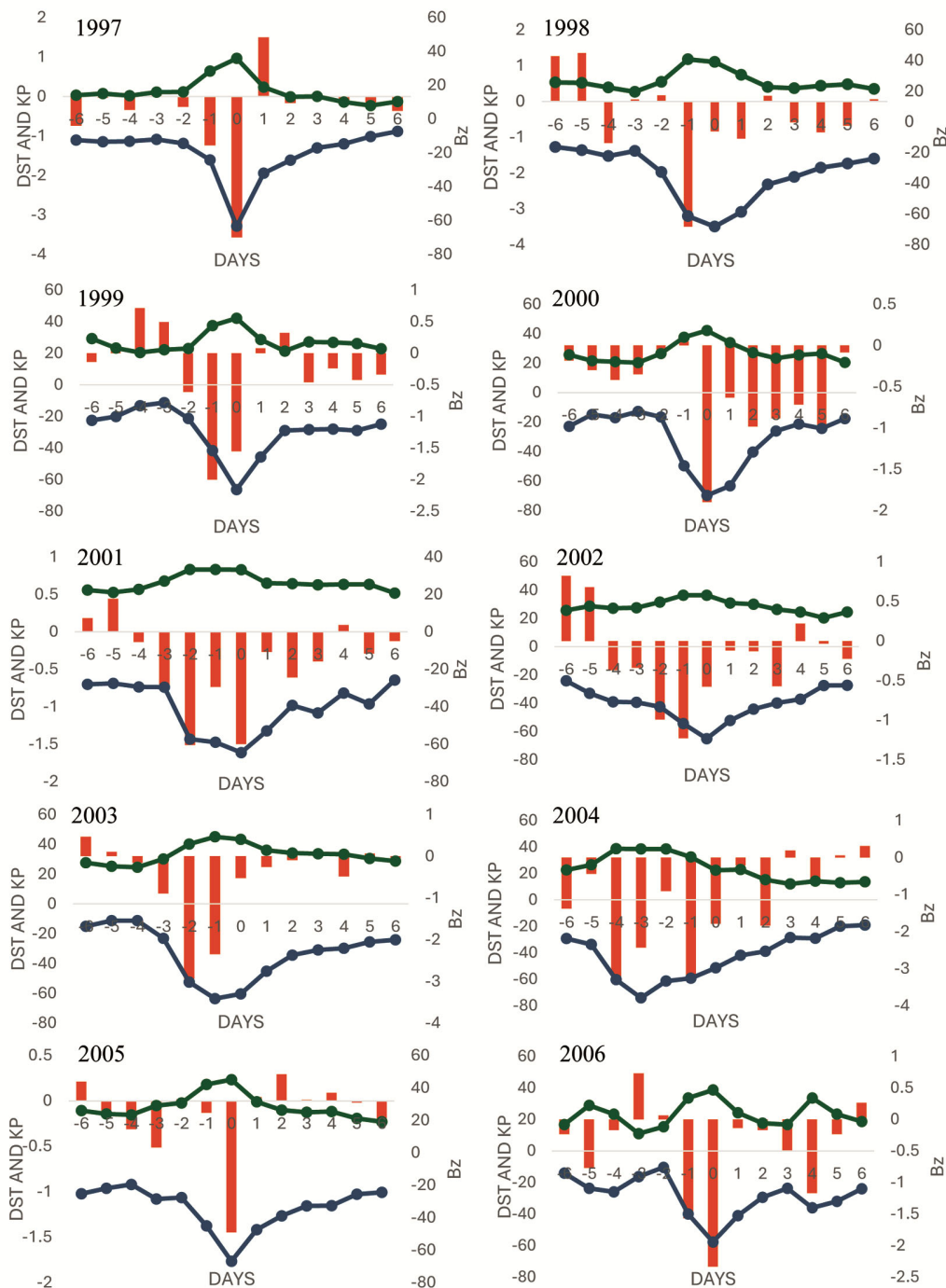


Fig. 3 — Chree analysis results from -6 days to +6 days with respect to the occurrence day of the GS (zero epoch day). To study the patterns of Dst, Kp index and Bz, the variation of their mean values is plotted for solar cycles 23, 24 and 25 (Contd.)

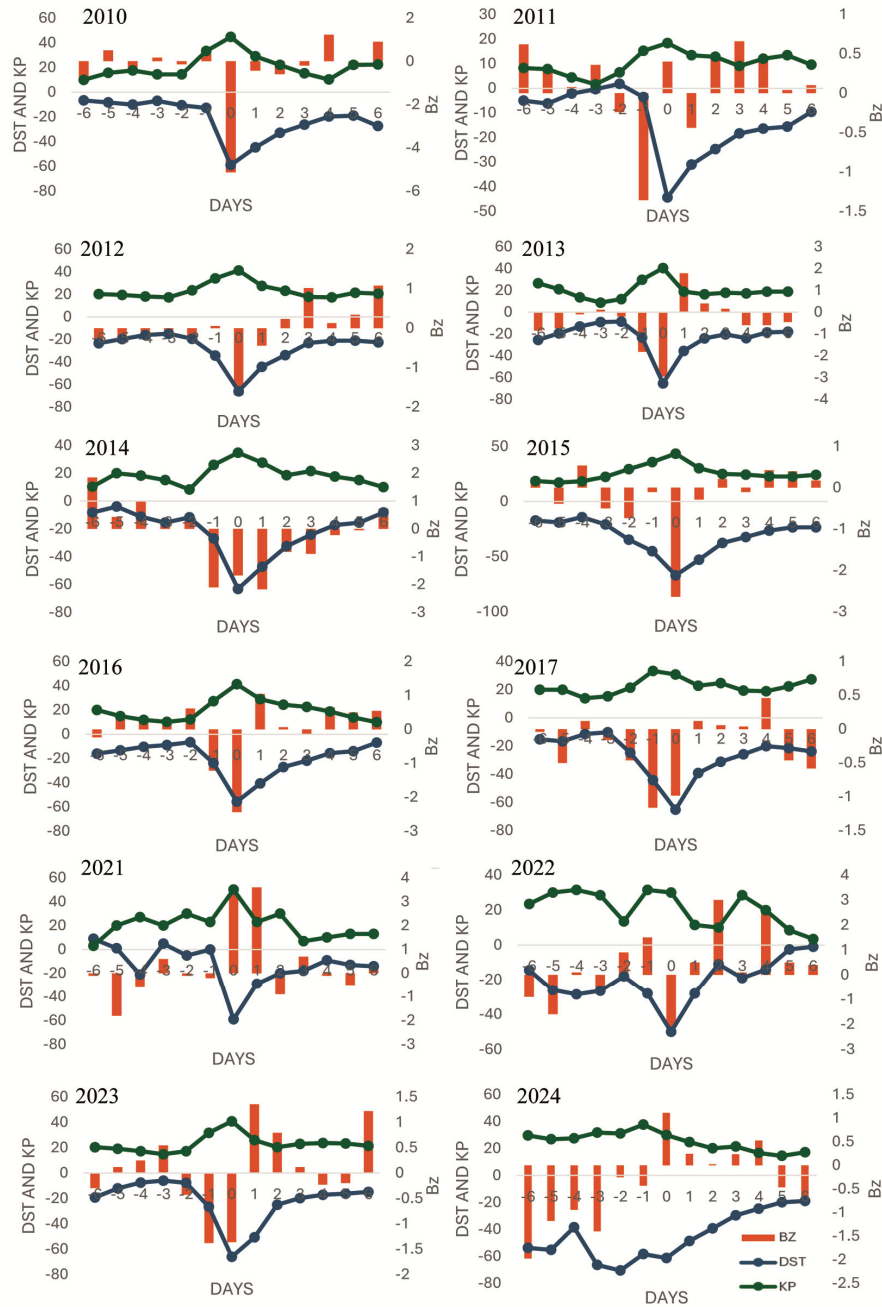


Fig. 3 — Chree analysis results from -6 days to $+6$ days with respect to the occurrence day of the GS (zero epoch day). To study the patterns of Dst, Kp index and Bz, the variation of their mean values is plotted for solar cycles 23, 24 and 25

coincide with Bz and Kp maxima. Also, the average correlation coefficient between IMF Bz and Dst for three SCs is 0.55, and the correlation coefficient between IMF Bz and Kp is -0.46, which suggests that Dst and IMF (Bz) are directly related and Kp is anticorrelated to Bz. For the years 1998, 1999, 2002, 2003, 2011 and 2017, the Dst became minimum after a lag of one day compared to the IMF B_z value; this delay is mainly due to the magnetospheric delay

response time, since the solar energy first interacts with the magnetotail, after which it intensifies the ring current. For the starting phase of SC 25, the Dst minima occur after Bz turned southward (-ve) to northward (+ve). This finding supports previous studies²⁵ who identify Bz as a primary key driver of space weather disturbances. Negative Bz enhances geomagnetic activity, leading to stronger storms (more negative Dst values).

3.4 Dst and Kp Index with VBz

After finding the relation between Dst and Kp with solar wind speed and IMF Bz, the variation in Dst and Kp values with the product of VBz also investigated, the product of V and Bz is important since it produces an electric field ($E_{sw} = V_{sw} \times B_{sw}$) which swaps the ionized particle (coming towards the Earth's magnetosphere from the Sun with solar wind or CMEs) away towards the polar region which later produce auroras, also due to that the geomagnetic activities are intensified when this product become more negative it act as a fuel gauge for GS. The study

revealed that the product of V and Bz plays an important role in the occurrence of GS and the Kp index. Figure 4 shows that for most of the years of SC 23, 24 and 25, the product of VBz is minimum corresponding to the occurrence day of G.S, with an average correlation of (0.61). Kp index shows an inverse relation with VBz; the peak value of Kp index coincides with VBz minima with a correlation coefficient (-0.63). These findings strengthen the previous research²⁶ who reported a similar kind of variations, the average correlation between these parameters for SC 23, 24 and 25 is higher as

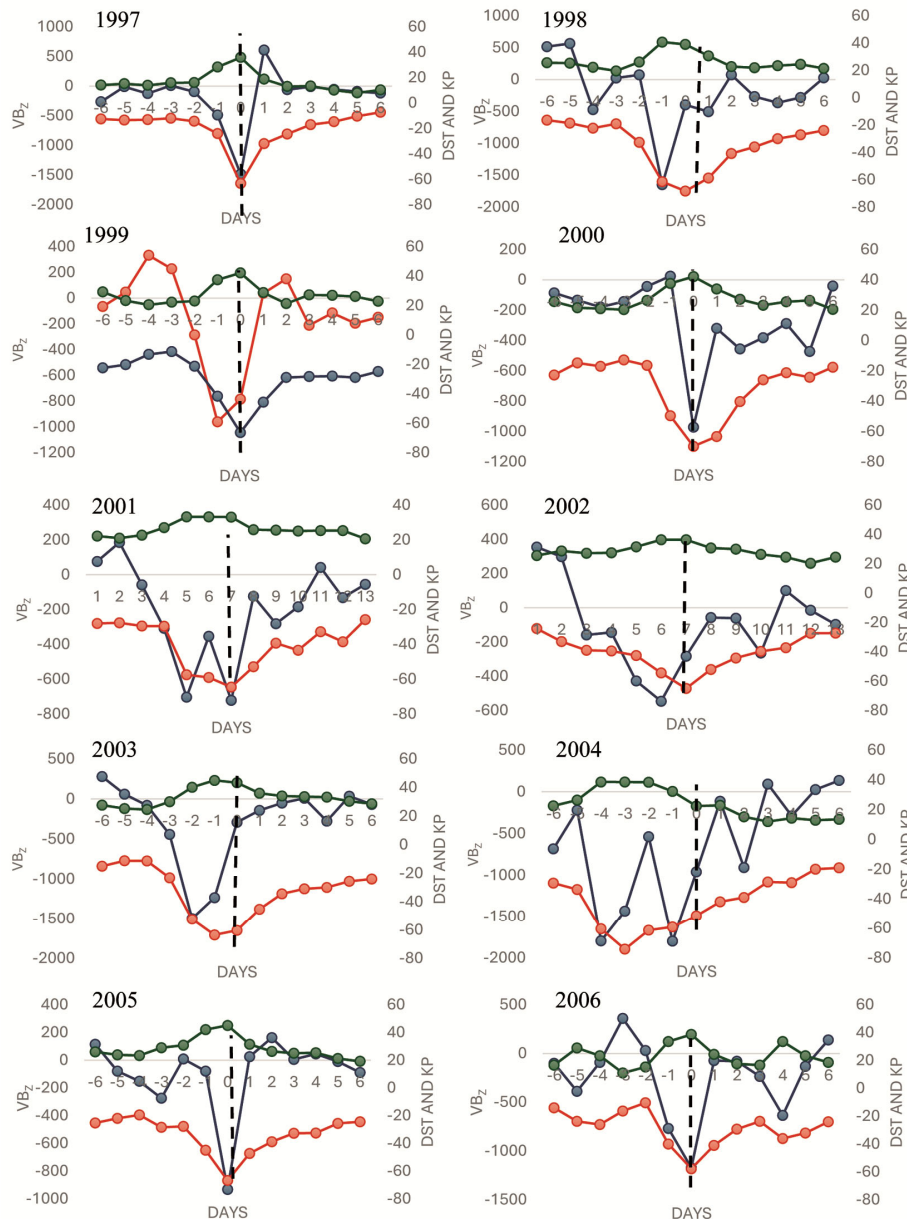


Fig. 4 — Chree analysis results from -6 days to +6 days with respect to the occurrence day of the GS (zero epoch day). To study the pattern of Dst, Kp index and VBz, the variation of their mean values is plotted for solar cycles 23, 24 and 25 (Contd.)

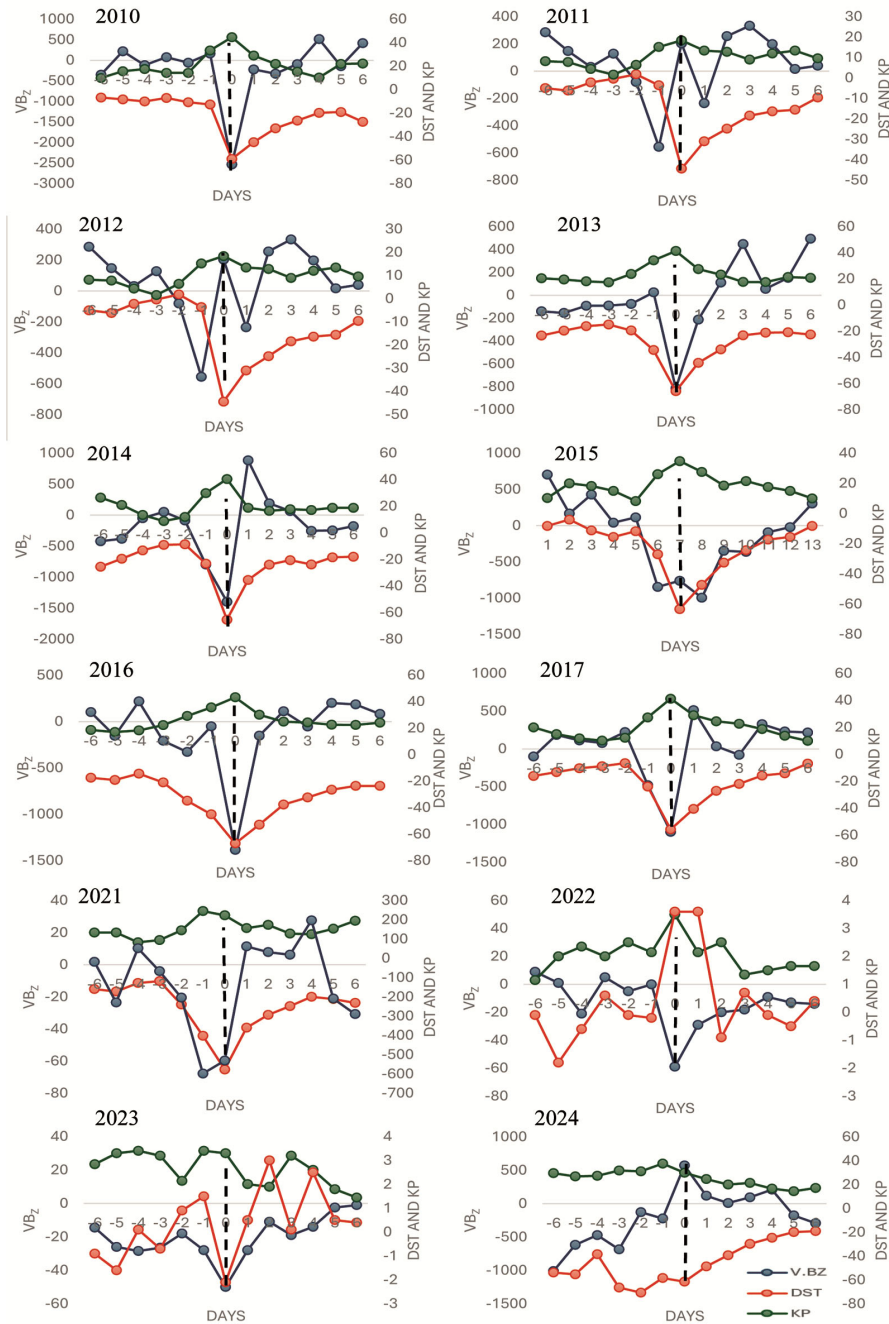


Fig. 4 — Chree analysis results from -6 days to +6 days with respect to the occurrence day of the GS (zero epoch day). To study the pattern of Dst, Kp index and VBz, the variation of their mean values is plotted for solar cycles 23, 24 and 25

compared to V or Bz alone (Table 1). Based on these findings, it was observed that the product of V and Bz is a highly geoeffective parameter, which supports the earlier findings²⁷.

4 Conclusion

- i It found that the Kp index is more sensitive to short-term fluctuations in Earth’s magnetospheric conditions, while Dst is

responsible for large-scale low-altitude geomagnetic storms.

- ii For the three consecutive solar cycles, the product of solar wind speed (V) and IMF Bz consistently shows very high geoeffectiveness in driving geomagnetic disturbances, as indicated by variations in the Dst and Kp index values.

- iii The average value of the correlation coefficient between the Kp index and Dst is approximately (-0.8), which indicates correspond to high Kp index value corresponds to a more negative Dst, with a lag of one to two days for a few years.
- iv During solar maxima, the minimum value of IMF (Bz) coincides with a high Kp index value and the Dst minima occur simultaneously with Bz minima for most of the years. The average correlation between IMF Bz and Dst index is approximately 0.55, while between IMF Bz and Kp is -0.46.
- v The Kp index shows a positive correlation with solar wind speed V (.40) also when solar wind speed increases, geomagnetic activities also increase, which reflected by high value of Kp index, which make Kp index a reliable indicator of solar wind driven geomagnetic disturbances, also value of Dst index become more negative correspond to high solar wind speed with an average correlation coefficient (-0.53).
- vi Dst and Kp indices are closely correlated with VBz; for most of the years, peaks of Dst minima and VBz minima coincide, while Kp index peaks inversely with VBz. The value of the correlation coefficient between VBz and Dst is 0.61, and between VBz and the Kp index is -0.63, which is higher than V or Bz alone.
- vii Solar cycle 25 shows a resemblance in terms of frequent geomagnetic storms occurrence, suggesting a potentially solar-active solar period ahead.
- viii For the years 1997, 2007, 2008, 2009, 2018, 2019 and 2020, no geomagnetic storm was observed in the intensity range ($-100 \text{ nT} < \text{Dst} \leq -50 \text{ nT}$), since these are the year's corresponding to solar minimum, so the solar activities are comparatively low.

References

- 1 Bame S J, Asbridge J R, Feldman W C & Gosling J T, *Geophys Res Lett*, 2 (11) (1975) 441.
- 2 Antichos S, Mikic Z, Titov V S, Linello R & Linker J A, *Astrophys J*, 731 (2) (2011) 112.
- 3 Krieger A S, Timothy A F & Roelof E C, *Solar Phys*, 29 (1973) 505.
- 4 Webb D F & Howard T A, *Living Review Solar Phys*, 9 (2012) 3.
- 5 Akasofu S, *Planet Space Sci*, 12 (4) (1964) 272.
- 6 Antichos S, Joselyn J A, Kamide, Y, Kroehl H W, Rostoker G, Tsurutani B T & Vasyliunas V M, *J Geophys Res*, 99 (A4) (1994) 5771.
- 7 Gonzalez, W D, Echer E, Clua-Gonzalez & Tsurutani B, *Geophys Res Lett*, 34 (2007) L06101.
- 8 Wang C B, Chao J K & Lin, *J Geophys Res*, 108 (2003) 1341.
- 9 Zhang J, Richardson I G, Webb D F, Gopalswamy N, Huttunen, Kasper J C, Nitta N V, Poomvises W, Thompson B J, Wu C C & Yashiro S, *Geophys Res*, 112 (2007) A10102.
- 10 Richardson I G, Cliver E W & Cane H V, *J Geophys Res*, 1005 (A8) (2000) 18203.
- 11 Badruddin A & Falak Z *Astrophys Space Sci*, 361 (2016) 253.
- 12 Kharayat H, Prasad L & Mathpal R, *Sol Phys*, 291 (2016) 603.
- 13 Pokharia M, Prasad L & Bhoj C, *Sol Phys*, 293 (2018) 126.
- 14 Tang T, Guo R, Shi Q, Park J S, Ma X, Zhao J, Zhou X, Zhang H, Yan L, Tian A, Bai S, Zhou Y, Degeling A W, Xiao, Y & Zong Q, *Astrophys J Suppl Ser*, 280 (2025) 2.
- 15 Wing S, Johnson J R, Jen J, Meng C I, Sibeck D G, Bechtold K, Freeman J, Costello K, Balikhin M & Takahashi M, *J Geophys Res*, A4 (2005) 110.
- 16 Prasad L & Garia S, Bhatt *Int J Phys Appl*, 5 (2) (2013) 77.
- 17 Heybatli I, Arikan O & Arikan F, *Signal, Image Video Process*, 19 (2025) 128.
- 18 Cummer S A, Lu G, Briggs M S, Connaughton V, Xiong S, Fishman G J & Dwyer J R, *Geophys Res Lett*, 38 (2011) 14810.
- 19 Matzka J, Stolle C, Yamazaki Y, Bronkalla O & Morschhauser A, *Space Weather*, 19 (5) (2021) 5.
- 20 Borovsky J E & Denton M H, *J Geophys Res; Space Phys*, 111(A7) (2006) A07S08.
- 21 Turner N E, Baker D N, Puikkinen, T I & McPherron R L, *J Geophys Res*, 105 (A12) (2000) 27089.
- 22 Dungey J W, *Phys Review Lett*, 6 (2) (1961) 47.
- 23 Burton R K, McPherron R L & Russell C T, *J Geophys Res*, 80 (1975) 31.
- 24 Rathore B S, Gupta D C & Parashar K K, *Int J Geosci*, 5 (13) (2014) 1602.
- 25 Arnoldy R L, *J Geophys Res*, 76 (1971) 22.
- 26 Gonzalez W D, Gonzalez, Dal Lago, Tsurutani, Arballo J K, Lakhina G K, Buti B, Ho C M & Wu S T, *Geophys Res Lett*, 25 (6) (1998) 963.
- 27 Patel B D, Joshi B & Cho K S, *Sol Phys*, 297 (2022) 139.