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The Study of the Association between the Solar Wind Parameter and Cosmic Ray Intensity to a Severe Geomagnetic Storm ($-350 < \mathrm{Dst} \leq -200$ nT) during Solar Cycles 24 and 25

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Abstract. To shed light on potential differences in the magnetosphere-solar wind coupling processes between both cycles, this study examines the link between solar wind characteristics and the Dst index during Solar Cycles (SCs) 24 and 25. In this study, we look into the correlation between geomagnetic storms and several solar wind parameters (solar wind speed, solar wind plasma temperature, solar wind proton density, and flow pressure), sunspot number, Ey, cosmic ray intensity (CRI) and geomagnetic index Dst for SC 24 (start Dec 2008 to end Dec 2019) and SC 25 (start Dec 2019 to 10th August 2023). With the use of the superposed epoch method (Chree analysis), comparative research has been conducted. Solar wind plasma temperature is a geoeffective parameter for SC 24, according to the findings of the current investigation. Compared to other solar wind parameters, the temperature (0.7) of the solar wind has a stronger link with geomagnetic storms. For SCs 24 and 25, the correlation between Dst and CRI is 0.2 and 0.9, respectively. SC 24 and 25 for Dst and Ey have correlations of -0.5 and -0.9, respectively. These variables are highly correlated. There is a modest link between sunspot number and Dst. Which solar wind parameter increases or causes these severe geomagnetic storms was the primary motivation for this investigation. Such understandings are essential for enhancing our capacity to forecast and mitigate the effects of geomagnetic storms on technological systems and societal infrastructure, as well as our comprehension of the dynamics of space weather.

KEY WORDS: Geomagnetic storms, Sunspot number, Solar wind speed, Sun.

1 Introduction

The electromagnetic and environmental conditions in Earth's space, including the magnetosphere, ionosphere, and thermosphere, are governed by solar activity, which causes space weather. The sun continuously spews out solar wind, which is made up of charged particles or plasma and travels at a fast speed throughout interplanetary space, during space weather events. During a space weather event, fluctuations in the Earth's magnetosphere and ionosphere cause the geomagnetic field to fluctuate over time. Geomagnetic storms (GSs) and substorms, or irregular variations, are caused by currents moving through the magnetosphere [1]. A disruption in the magnetosphere of the Earth typically characterizes GS. Magnetized plasma is constantly flowing from the Sun; when this plasma reaches the Earth's surface, it may be connected to the magnetic field of the planet [2]. The magnetic field of the Earth may be disturbed by solar wind structures that travel into interplanetary space. The most extreme of them are known as geomagnetic storms (GSs) [3–10], also known as geomagnetic disturbances. The physical, technological, and health implications of these storms on space and ground-based systems as well as human activity can vary depending on their intensity [11–15]. There has been a lot of interest in comprehending recent Sun-Earth link events including solar flares, coronal mass ejections (CMEs), and related magnetic storms. Magnetic storms are arguably the most notable and stunning feature of space weather's influence on Earth. There has been geomagnetism for at least 400 years. The study of geomagnetism began with the publication of William Gilbert's De Magnete in 1600 AD. At the beginning of the eighteenth century, Edmund Halley produced the first magnetic field declination map [16]. According to numerous studies [5, 17–20], the magnetic reconnection between the south component of the interplanetary magnetic field (IMF) and the Earth's magnetic field is the primary cause of geomagnetic storms. The Earth's magnetosphere is used as a conduit for the passage of energy and magnetic flux from the solar wind and its structures. According to several studies [4, 10, 21–23], it is thought that the interplanetary coronal mass ejections (ICMEs), which are CMEs that occur between planets, are the primary cause of the most intense storms. These formations have a strong south IMF (Bz) component that can cause strong geomagnetic disruptions. Using so-called geomagnetic indices, they can be measured globally by terrestrial magnetometers dispersed across the surface of the Earth [24]. Each geomagnetic index is measured at different latitudes and typically describes a different physical phenomenon. For instance, the AL and AE indices measure the intensity of the ring current system close to the equator, the Kp index measures disturbances of field-aligned currents at mid-latitudes, and the Dst index measures global auroral electrojet activity at polar regions [25]. A geomagnetic storm is a disturbance of the Earth's magnetic field that results from changes in the IMF. These alterations are to blame for abrupt onsets of geomagnetic activity. GSs are caused by perturbations in the IMF, as noted by Burton, McPherson, and Russell [26] and Tsurutani *et al.* [27]. It has been proposed that the southward-oriented IMF is more geoeffective than the north-oriented one. It is well known that the Dst index is used to gauge the power of GSs and that the southbound Bz component peaks at the same time as Dst [5]. Even though they only provide information about the geomagnetic field's present state, certain studies show how important geomagnetic time series are for predicting. According to the geomagnetic location, Bellanger *et al.* [28] demonstrated that extreme geomagnetic occurrences could be predicted using the hourly mean of the magnetic fluctuations with a lead time of several hours [29]. In Hajra [30], it is found that the smallest magnitude of Solar Cycle 24 is associated with a general fall in energy coupling and a decrease in the frequency of magnetic storms. Planetary indices generally fail to adequately capture the geographically complex and temporally dynamic changes in the geomagnetic field that may take place during a geomagnetic storm because they typically lack the appropriate regional context. Large impulsive geomagnetic field disruptions have been found to pose a threat to power systems nearby [31]. The ionospheric reaction to solar activity is crucial for satellite navigation, radio transmission, radar detection, space weather forecasting, and other systems using ionospheric electromagnetic wave signals [32]. In our analysis, we also examine how dependent GSs are on CRI. According to Thomas *et al.* [33], an ionospheric storm is the ionosphere alteration or reaction to a change in the dynamic features coming from the Sun. The solar system is not the source of cosmic rays, which are radiations with extraordinarily high energy [34]. With energy up to 10^{20} eV, these are the most energetic particles known to have inherent mass. Cosmic rays (CR) are the most difficult to simulate on Earth since they can have energies up to 10^{20} eV and a flux maximum of roughly 1 GeV/n [35]. It is vital to investigate the relationship between CRI changes and geomagnetic conditions. When there are high GS incidence days, CRI briefly decreases with a pattern similar to the Dst [36]. Forbush decreases are characterized by a brief, sharp decline in CRI, followed by a gradual recovery that normally lasts several days [37]. Many scientists started looking for the reason for these declines and their connection to geomagnetic activity after the discovery of FDs [38–41]. According to Barouch and Burlaga [38], it has been proposed that the high-magnetic-field regions in interplanetary space are connected to FDs. According to Zhang and Burlaga [3], floating in the magnetic cloud's strong field does not significantly affect cosmic ray fluctuations. Badruddin *et al.* [42] noted a potential relationship between magnetic clouds and CRI declines, while Kudo *et al.* [43] noted a potential relationship between CRI increases and the geomagnetic disturbance storm-time index (Dst). The global intensity of geomagnetic storms brought on by interactions between the solar wind and the Earth's magnetosphere is gauged using the Dst metric. It sheds light on how the Earth's magnetic field was affected by these occurrences. Geomagnetic storms are disturbances in the magnetosphere of the Earth brought on by fluctuations in the magnetic field and energy of the solar wind. Charged particles are launched into space by solar activity such as coronal mass ejections and solar flares. These particles cause electrical currents to flow in the ionosphere and cause geomagnetic fluctuations when they come into contact with the Earth's magnetic field. CRI and Dst are important variables in space science. While cosmic ray intensity offers insights into the energetic processes of the universe, Dst aids in our understanding of and preparation for space weather events that may have an impact on technology on Earth.

2 Data Analysis and Method

For the analysis, we employed the Chree analysis, also referred to as the superposed epoch technique. Additionally, during the corresponding years, we have calculated the correlation coefficient between several solar and planetary properties. The Moscow Neutron Monitor Station's pressure-corrected hourly mean data of the CRI were used (http://cr0.izmiran.ru/mosc/main.htm). The Dst index, solar wind parameters (solar wind speed, solar wind plasma temperature, solar wind proton density, and flow pressure), sunspot number, and Ey, hourly mean values were obtained from the Omniweb data center (omniweb.gsfc.nasa.gov/form/dx1.html). Dst is utilized in this case as a GS indicator. The variations in the impinging solar wind are what are causing these perturbations in the geomagnetic field. For careful results, the hourly mean average data are chosen. Assuming it to be the trigger day, our gauge for the judgment is $350 < \text{Dst} \leq -200$ nT. Now, the six values mentioned above -1, -2, -3, -4, -5, and -6 hours are taken into account. Similar to the above, a table with a column of information is created for each year, taking into account the six numbers below that are considered to be $+1$, $+2$, $+3$, $+4$, $+5$, $+6$ days. After that, the range of these days' average values (-6 to $+6$) is calculated, and the graph is drawn between two parameters for the corresponding years. Now, in order to determine any potential correlation between these factors, we first determine the correlation coefficient for a year in which we obtain severe storms.

Table 1. Classifies geomagnetic storms. According to Loewe and Prölss's [44] categorization, the Dst classification is used

Storms scale (Dst)	**Dst values**
Moderate	$-100 < \text{Dst} \leq -50$ nT
Strong	$-200 < \text{Dst} \leq -100$ nT
Severe	$-350 < \text{Dst} \leq -200$ nT
Great	$\text{Dst} \leq -350$ nT

3 Results and Discussion

In the current study, during SC 24 and 25, we compare the GS with various solar wind parameters, including solar wind speed, solar wind plasma temperature, solar wind proton density, and flow pressure. We also compare the GS with the SSN, Ey, and CRI. We only got storms for the year 2015 for solar cycle 24 whereas we got severe storms for the year 2023 for solar cycle 25. Three strong storms each year have been recorded by us. Figure 1 depicts the variation of various parameters with Dst for SC 24, while Figure 2 depicts the variation of various parameters with Dst for SC 25. Table 2 provides correlation coefficients for SC 24 and SC 25 different parameters with Dst.

Table 2. The correlation coefficient for Solar Cycles 24 and 25

	Correlation coefficient	
Parameters	**SC 24**	**SC 25**
Solar wind speed	-0.2	0.03
Solar wind plasma temperature	0.7	0.3
Flow pressure	0.08	0.03
Plasma proton density	-0.03	-0.02
CRI	0.2	0.9
Ey	-0.5	-0.9
Sunspot number	0.4	0.3

3.1 Dst variation with solar wind parameters (solar wind speed, solar wind plasma temperature, solar wind proton density, flow pressure, and Ey)

Beginning at the end of the 1950s, experiments on the solar wind carried out by spacecraft beyond the Earth's magnetosphere resulted in many significant discoveries in this field of study [45]. The great majority of the ions in the solar wind are protons, with incredibly small concentrations of alpha particles (He^{++}) and highly ionized heavy ions (such as C, N, O, Ne, Mg, Si, and Fe). Protons move away from the Sun faster than the proton wind when alpha particles and heavy ions flow past them in the field-aligned direction 46 [46–49]. The plasma flow rate abruptly increased while the value of Dst rapidly fell, according to Adebesin [50]. The term "solar wind plasma temperature" describes the thermal energy or temperature of the charged particles (plasma) that the Sun continuously emits and moves around the solar system.

On multiple occasions, Lee *et al.* [51] have demonstrated that variations in the solar wind do not cause substorms. These situations might be brought on by the lack of substorm growth phase development before the potential triggering change, the solar wind changes themselves being intrinsically non-triggering, or the nullifying impact that could happen when numerous solar wind quantity changes are happening simultaneously. A weak correlation between solar wind variation and Dst is also discovered in our investigation. The modest correlation coefficient between the Dst index and solar wind proton density throughout both solar cycles 23 and 24 [52] supports our findings that proton density is not

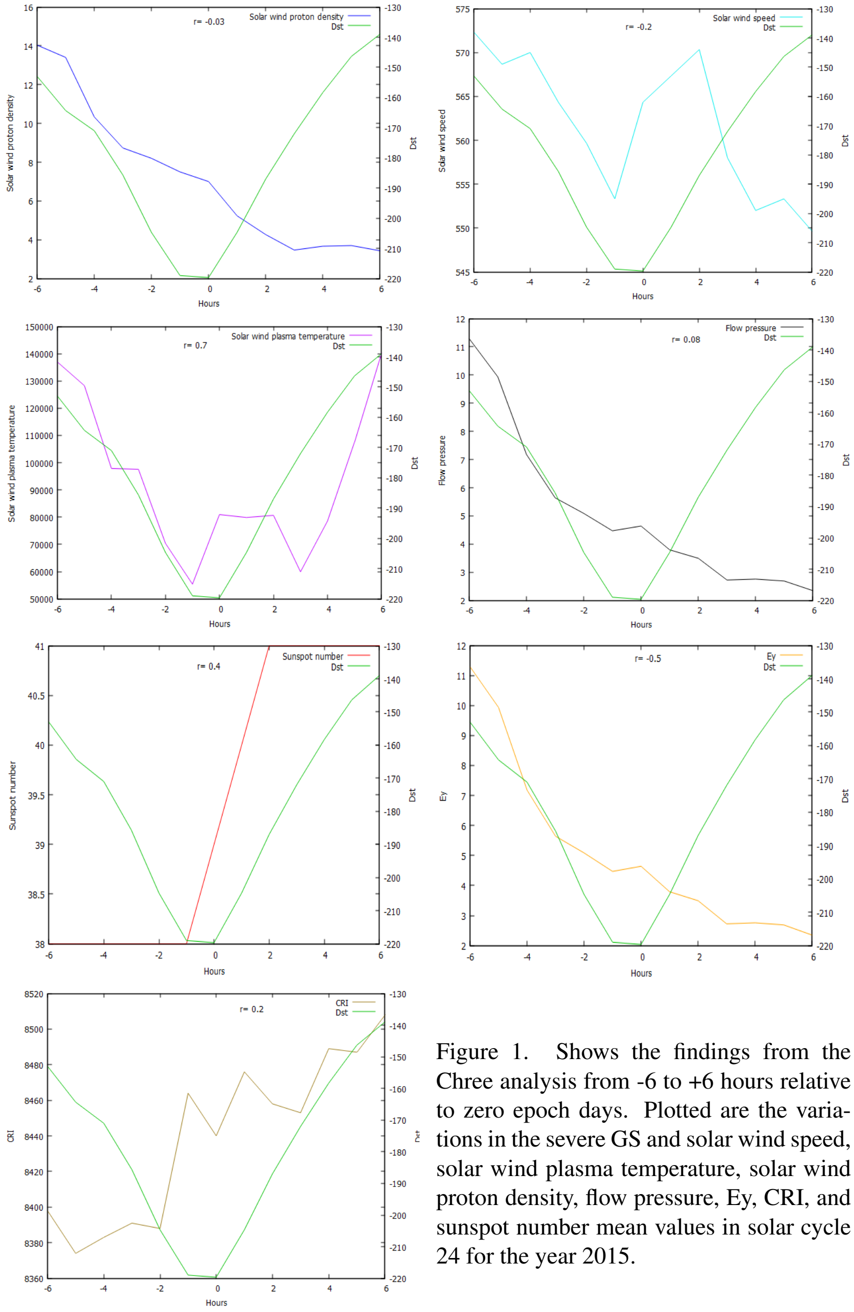

Figure 1. Shows the findings from the Chree analysis from -6 to +6 hours relative to zero epoch days. Plotted are the variations in the severe GS and solar wind speed, solar wind plasma temperature, solar wind proton density, flow pressure, Ey, CRI, and sunspot number mean values in solar cycle 24 for the year 2015.

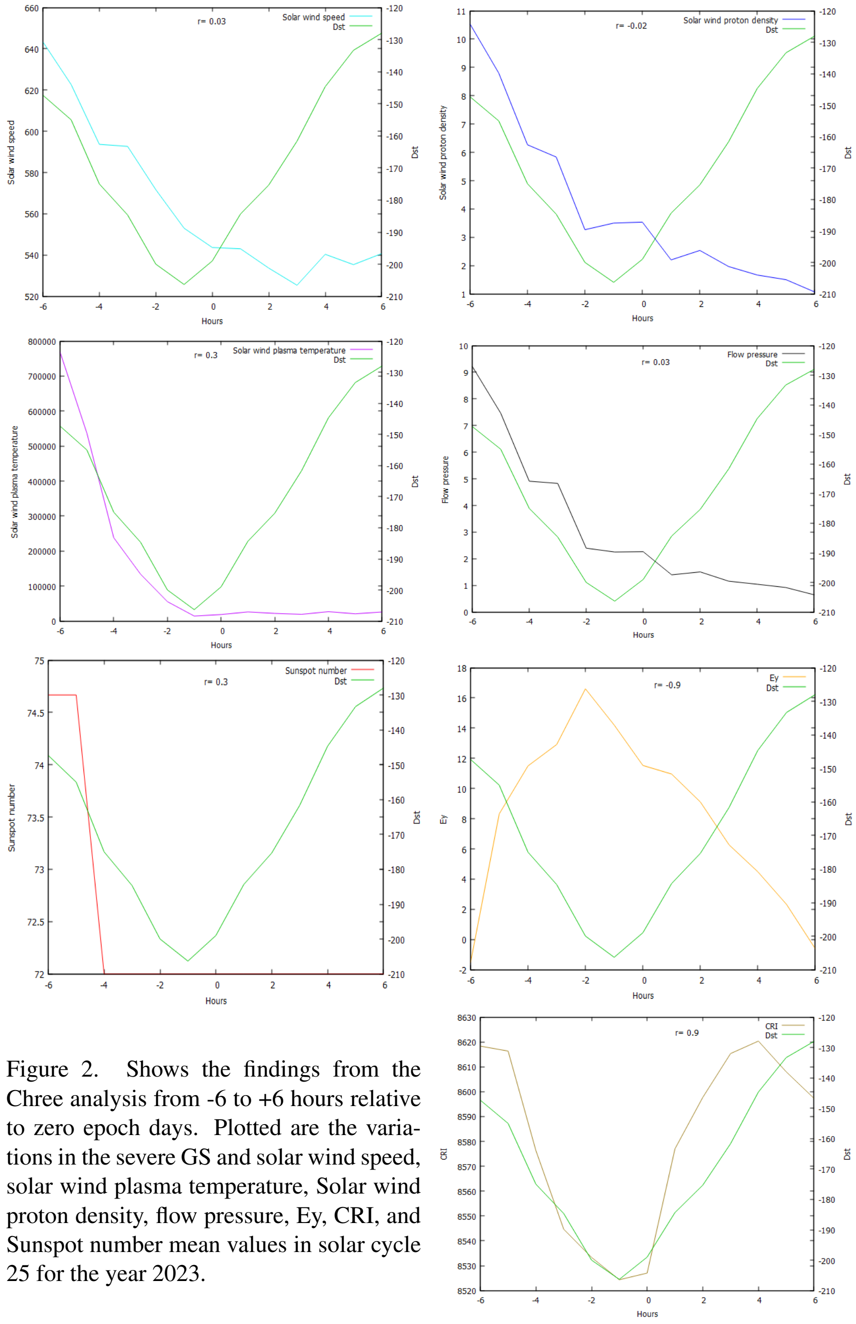

Figure 2. Shows the findings from the Chree analysis from -6 to +6 hours relative to zero epoch days. Plotted are the variations in the severe GS and solar wind speed, solar wind plasma temperature, Solar wind proton density, flow pressure, Ey, CRI, and Sunspot number mean values in solar cycle 25 for the year 2023.

a geoeffective attribute. According to Tian *et al.* [53], the corrected Dst has a correlation coefficient with flow pressure of 0.20, which is consistent with our observation. It was shown that the correlation between Dst and solar wind speed was between 0.58 and 0.57 for magnetic clouds and complex ejecta [54]. According to Mathpal and Prasad [55], the day of the GS is when Ey increases the most. There is no lag in time between these two parameters. The strong and negative correlation ($r = -0.92$) between Ey and GS shows how efficient Ey is at lowering GS. For solar cycle 25, we also discovered a -0.9 connection between Dst and Ey. Dst and Ey have a significant link across the board for both SCs. The primary component influencing geomagnetic activity, Ey, is the electric field, according to Burlaga and Lepping [56]. When Dst achieved its maximum negative value, Ey attained its highest positive value (Figure 2) and had an inverted carbon copy appearance. In solar wind parameters and Dst, we detect a time lag of 6 hours; for Ey and Dst, the time lag is 1 hour (2015) and 2 hours (2023) (Figures 1 and 2). The strength of the solar event, the speed of the solar wind, and the separation between the Sun and Earth all affect how long this delay lasts. It will take some time for the Earth's magnetosphere to respond to an abrupt increase in solar wind speed brought on by a solar storm. During this delay, the Dst index might not immediately reflect the storm's effects. On the other side, as the solar wind speed lowers, there will be a delay between the Earth's magnetic field stabilizing and the Dst index starting to recover. Understanding the lag is essential for forecasting both space weather and the potential geomagnetic impacts of solar storms. It gives us the ability to anticipate when geomagnetic disturbances might occur or when they might subside, which helps us better prepare and take preventative measures. The solar wind effectively transfers energy and momentum to the Earth's magnetosphere when there is no temporal lag. The geomagnetic field is directly impacted by quick changes in solar wind conditions without significant delays or attenuation.

3.2 Dst variation with CRI and SSN

The main factor affecting geomagnetic disruptions is CRI, which also affects space weather. Geomagnetic storms have a significant impact on space weather scenarios, according to Gonzalez *et al.* [18] and Bakare & Chukwuma [54], since they transport more energy from the solar wind/IMF to the magnetosphere, increasing the amount of charged particles in the ring current. According to Mishra and Agarwal [57] and Sharma [58], CMEs are more efficient transitory modulators of CRI. According to Lockwood [59], the FD can be identified by a dramatic decline in CRI over a short period, followed by a slow recovery over several days. According to Mathpal *et al.* [60], there is a strong positive association between CRI and Dst. The CRI drops for the bulk of the time, similar to the Dst index. The positive association between the Dst index and CRI demonstrates that magnetic storms and FDs have similar underlying causes. The strong link between Dst and CRI makes it obvious that 21 and 23 solar cycles have a significant influence on both of these indicators [61]. Shrivastava [62], discovered that the CRI declines when the Dst values are low. Similar to the Dst index, the CRI shows a pattern of sharp decline. The day that GSs occur is when CRI decreases. The CRI and Dst (0.79) index have a strong correlation, showing that a CME can most effectively cause FD when it is nearest to Earth [36]. According to Nagashima and Morishita [63], Davis [64], and Cliver *et al.* [65], the flow of galactic cosmic rays that reach the Earth is significantly influenced by the magnetic activity of the Sun and its evolution in the parameters associated to the processes of the solar corona. The heliospheric magnetic flux has an impact on galactic cosmic rays (GCRs), which are ubiquitous, charged, and energetic particles that originate outside the heliosphere and travel inward from the heliospheric border at about 120 au [66]. Intense magnetic fields are produced during times of extreme solar activity, such as explosions and mass ejections, which is the cause of this phenomenon. Solar flares and coronal mass ejections, however, can briefly enhance cosmic ray counts at neutron monitor stations on Earth. Numerous factors affect how galactic cosmic rays are modulated. For instance, the magnetic field carried by the solar wind can interact with cosmic rays. As the magnetic field of the solar wind reduces the total intensity (particle counts) that reaches the Earth, the intensity of cosmic rays can also be adjusted. The Earth can be exposed to more cosmic rays when the magnetic field of the solar wind is weak [67]. There is a time lag of 5 hours (2015) and 1 hour (2023) (Figures 1 and 2) because the highest CRI decline occurs just before Dst. It could imply a direct or indirect relationship between the strength of cosmic rays and the frequency of geomagnetic storms. The geomagnetic disturbances that can result from variations in cosmic ray intensity are nearly instantly reflected in the Dst index. For the remaining year, there is a delay. The delay may indicate that it takes longer for cosmic ray strength to affect the characteristics of a geomagnetic storm. Changes in cosmic ray intensity could take some time to manifest in the magnetosphere and ionosphere of Earth before affecting geomagnetic activity. A lag could mean that there isn't a direct correlation between the strength of cosmic rays and geomagnetic storm activity. There can be more intermediary processes or components at work. We have not seen a consistent fluctuation in the SSN curve, making it impossible to determine the time delay.

At the start of a new cycle, sunspots will form on the photosphere (surface) of the sun [68]. Galileo's discovery of sunspots marked the beginning of the scientific understanding of the magnetic field that exists on the Sun's surface [68]. The amount of disturbances in the interplanetary medium and magnetospheric-ionospheric system of the planets depends on the number of spots on the surface of the Sun, corona holes, and coronal mass ejection events, as well as the speed of the solar particulate matter emanating from the Sun. The number indicates when the Sun will experience short-term, cyclical high and low activity. The "solar minimum" is the period of the cycle with low sunspot activity, and the "solar maximum" is the period with the highest solar activity. Solar Cycle 24 began with a very low level of activity. The frequency of CMEs (per year) increases or decreases with the number of sunspots, but there are different variations. A. Singh, and K. Patel [69] Sunspot areas and coronal holes, which reflect the Sun's closed and open magnetic field zones, respectively, arise and move about as observational manifestations of solar activity. According to a recent study using information theory, the peak smoot SSN of the following cycle can be influenced by the polar solar magnetic fields from the previous three or more solar cycles [70]. This suggests that the current decrease in the solar magnetic field may have long-term effects on the formation of SSNs. The 'group' sunspot number was explored by Hathaway *et al.* [71], demonstrating its use in highlighting the Sun's activity throughout the solar year [72]. There is no discernible link between SSN and Dst. For Solar Cycles 22 and 24, the correlation coefficient between SSN and Dst is shown to be low, at 0.04 and 0.06, respectively [73]. Our results are in good accord with those of Kharayat *et al.* [36] who reported a low correlation between these two parameters (0.04), but in contrast to the findings of Waheed *et al.* [74] who found a significant correlation between these two parameters (0.7).

4 Conclusions

1. The correlations for SC 24 and 25 for Dst and Ey are -0.5 and -0.9, respectively. Ey and Dst have a high connection. Physically, this association makes sense because, during strong geomagnetic storms (lower Dst values), the ionosphere may be disrupted, changing the electric field. In conclusion, the statement suggests that during solar cycles 24 and 25, Dst and Ey have a significant inverse relationship. According to our understanding of the relationship between solar and geomagnetic events, the Ey tends to be lower when the geomagnetic disturbance (Dst) is greater.
2. The present study shows that the solar wind plasma temperature is a geo-effective parameter for SC 24. The temperature of the solar wind (0.7) has a better correlation with geomagnetic storms than other solar wind parameters. Thus, there is a tendency for the activity of geomagnetic storms to grow in direct proportion to an increase in the solar wind plasma temperature. The solar wind plasma temperature stands out as having the strongest link with geomagnetic storms among the many solar wind properties that were examined. This implies that, for SC 24, solar wind temperature is a better predictor or indication of geomagnetic storm activity than other variables like solar wind parameters. Particles in the solar wind that are hotter have higher kinetic energy. This extra energy can speed up energy transfer processes when they come into contact with the magnetosphere of the Earth, which can cause geomagnetic disturbances. The Earth's magnetosphere may be compressed by a solar wind with a higher temperature, which could result in more powerful geomagnetic interactions. The implication is that, during solar cycle 24, the solar wind temperature is

a crucial variable for comprehending and forecasting geomagnetic storm activity. The Earth-Sun interaction and geomagnetic activity during this particular SC can be better understood by monitoring solar wind plasma temperature, as shown by its strong link with geomagnetic storms.

3. The correlation between the sunspot number and Dst is not very strong. According to the statement, there is a connection between sunspot numbers and geomagnetic activity (Dst), although it is not a particularly significant one. Sunspot counts may not be a reliable indicator of geomagnetic storm activity because solar and geomagnetic elements interact in a complex way to affect geomagnetic storms. To better understand and forecast these phenomena, researchers take a variety of solar and geomagnetic factors into account.
4. The correlation between Dst and CRI for SCs 24 and 25 is 0.2 and 0.9, respectively. CRI and Dst have a strong association in SC 25. A link between CRI and Dst during solar cycle 24 is suggested by a correlation coefficient of 0.2, which is just marginally positive. It indicates that there is some association, but it is not a particularly strong one. This may suggest a weak relationship, if any, between the strength of geomagnetic storms (Dst) and CRI during SC 24. A correlation coefficient of 0.9 implies that CRI and Dst during solar cycle 25 have a very strong positive relationship. This suggests that cosmic ray intensity (CRI) and the potency of Dst are significantly correlated in SC 25. Indicating a significant correlation between the two during this solar cycle, when one parameter rises, the other tends to rise as well. The comparatively modest correlation in SC 24 (correlation coefficient of 0.2) may suggest that variables other than cosmic ray intensity govern the strength of Dst during this cycle. The substantial positive correlation between CRI and Dst in SC 25 (correlation coefficient of 0.9) indicates that there is a close relationship between cosmic ray intensity and geomagnetic storm activity throughout this solar cycle. This may suggest that fluctuations in the strength of cosmic rays are impacted by solar activity, which in turn affects the geomagnetic environment and results in larger or weaker geomagnetic storms.
5. Solar cycle 25 starts from December 2019 to August 10, 2023, while solar cycle 24 from starts December 2008 to the end of December 2019. In our analysis of a severe geomagnetic storm, we discovered that the storm peaked in the year 2015 for solar cycle 24 while it peaked in early 2023 for solar cycle 25.

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