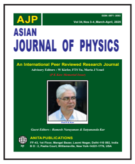

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Sunspot number, solar radio flux, and disturbance storm time index: An interrelationship and implication for space weather forecasting

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Dedicated to Prof P K Kaw

In the present work, we have examined the interrelationships between key solar activity indicators, namely the sunspot number, solar radio flux, and Disturbance Storm Time (DST) index. These parameters play crucial roles in characterizing solar variability and its effect on the Earth's magnetosphere and ionosphere. Understanding the correlations and interactions is essential for improving space weather forecasting capabilities. Present study reviews existing literature on the subject, highlighting the significance of each parameter, their historical trends, and their impact on space weather phenomena such as geomagnetic storm and solar radiation storms. Additionally, the paper discusses the methodologies for analysing and predicting these parameters, including statistical models and machine learning techniques. By elucidating the connections between sunspot number, solar radio flux, and the Dst index, this work contributes to the advancement of space weather prediction and mitigation strategies.

Keywords: Sunspot Number, Solar Radio Flux, Disturbance Storm Time, Space Weather Forecasting.

1 Introduction

Solar activity indicators are fundamental measures of the Sun's dynamic behavior, offering valuable insights into its cyclic and non-cyclic variations [1-3]. These indicators include parameters such as the sunspot number, solar radio flux, and the Disturbance Storm Time (Dst) index. Understanding their fluctuations and interrelationships is crucial for predicting and mitigating the effects of space weather on technological systems and human activities both in space and on Earth [4,5] and for understanding the origin of solar cycle variabilities [6].

Solar activity exhibits periodic changes on various timescales, ranging from short-term fluctuations to long-term cycles. The most prominent cyclic variation is the 11-year solar cycle, characterized by the rise and fall of sunspot activity [7]. The sunspot number, which measures the quantity and distribution of sunspots on the solar surface, serves as a primary indicator of solar magnetic activity. A higher sunspot number signifies increased magnetic disturbances on the Sun, often resulting in heightened solar activity, such as solar flares, coronal mass ejections (CMEs), and solar radiation storms. These phenomena can significantly influence space weather by impacting Earth's magnetosphere and ionosphere, leading to disruptions in satellite communications, navigation systems, and even power grids. Consequently, monitoring the sunspot number is crucial for predicting and mitigating the potential effects of solar activity on our technological infrastructure [8,9].

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The study of geomagnetic activity through indices has significantly advanced solar-terrestrial science. Geomagnetic storms are created when the Earth's magnetic field captures ionized particles carried by the solar wind due to coronal mass ejections or coronal holes at the Sun [10,11]. Long-term geomagnetic data recorded at the Earth's surface have enabled researchers to characterize the Sun-Earth interaction even before the space era. Studies of the long-term evolution of solar activity, such as those by Kuklin (1976), highlight the 22-year Hale cycle, which is related to the Sun's magnetic field and its changing polarity [12,3]. Additionally, the Gleissberg cycle, also known as the "80-90-year cycle", manifests as a modulation of the amplitude and frequency of the 11-year solar cycle, though its physical significance remains unclear. Numerous studies have examined the long-term evolution of geomagnetic activity and its relationship with solar variability, including works by Feynman & Crooker (1978), Svalgaard (1978), Cliver *et al* (1996), and many others. For instance, Lockwood *et al* (1999), building on the work of Stamper *et al* (1999), analyzed the solar causes of increased geomagnetic activity observed in the aa index since 1900 and concluded that this rise was due to an increase in the interplanetary magnetic field, reflecting a doubling of the solar open flux [14].

Solar radio flux, another important indicator, measures the intensity of radio emissions from the Sun, particularly in the microwave and radio wavelength ranges [15]. Solar radio flux is taken from F10.7 which is often expressed in sfu or solar radio flux units. These emissions are closely linked to solar magnetic activity and provide real-time information about solar flares and eruptive events. Monitoring variations in solar radio flux is crucial for assessing the potential impacts of solar events on communication and navigation systems, as well as satellite operations. The solar F10.7 cm record extends back to 1947, and is the longest direct record of solar activity available, other than sunspot-related quantities [16,4].

The **Dst index**, derived from continuous measurements of variations in Earth's magnetic field, is a key tool used to quantify the strength of **geomagnetic storms** triggered by disturbances in the solar wind. These storms occur when the solar wind interacts with Earth's magnetosphere, a process that enhances the flow of energy into the **ionosphere** and generates significant disturbances in the planet's magnetic field. As the solar wind's charged particles are transferred to Earth's magnetosphere, they intensify the **ring current**, causing the magnetic field to weaken, which is directly reflected by a drop in the Dst index. The Dst index effectively serves as a proxy for measuring the intensity of these geomagnetic disturbances, with lower Dst values indicating more severe storms. By providing detailed, real-time data on the magnitude of geomagnetic activity, the Dst index plays a critical role in **space weather forecasting,** offering essential alerts to protect technological systems like satellites, GPS, communication networks, and power grids from potential damage caused by these solar-driven events [17,18].

Understanding solar variability and its effects on space weather is essential for a wide range of technological applications, including satellite communications, GPS navigation, power grid operations, and astronaut safety. Space weather events can cause disruptions in satellite operations, communication blackouts, increased radiation exposure for astronauts and airline passengers, and potential damage to power grid infrastructure. By comprehensively studying solar activity indicators and their interrelationships, researchers and forecasters can improve the accuracy and reliability of space weather predictions, enabling better preparedness and mitigation strategies for both spaceborne and terrestrial systems [19,20].

2 Result and discussion

This styudy examines three solar cycles, spanning from January 1996 to June 2024, providing a comprehensive analysis of solar activity over this extended period. It emphasizes the important role of solar cycles, which typically last around 11 years, in the Sun-Earth connection. Solar activity has a significant impact on space weather, with geomagnetic storms closely correlating with the rise and fall of solar activity.

Table 1. Gives the yearly average Solar Radio Flux (F10.6), Sunspot numbers and No. of occurrences of geomagnetic storm during the period from 1996 to 2024.

Year	No. of Dst Occurred	Solar Radio Flux	Sunspot number
1996	6	72.0	12
1997	19	80.9	29
1998	22	118.1	88
1999	17	153.9	136
2000	31	180.0	174
2001	19	181.1	170
2002	18	179.4	164
2003	25	128.4	99
2004	10	106.8	65
2005	17	91.7	46
2006	10	80.0	25
2007	4	73.1	13
2008	4	69.0	4
2009	1	70.5	5
2010	8	80.0	25
2011	12	73.1	81
2012	23	69.0	85
2013	22	122.7	94
2014	13	145.9	113
2015	27	117.7	70
2016	20	88.7	40
2017	16	77.3	22
2018	7	69.9	7
2019	6	69.7	4
2020	3	73.7	9
2021	9	81.6	30
2022	18	125.0	83
2023	23	159.7	125
2024	8	188.2	155

Initially, we analyzed the yearly average sunspot numbers during solar cycles 23, 24, and the rising phase of solar cycle 25, covering the period from 1996 to 2024. In solar cycle 23, the peak sunspot number occurred in 2000, reaching 174. In solar cycle 24, the peak value was recorded in 2014 at 113, and during the rising phase of solar cycle 25, the peak is projected to occur in 2024 with a value of 155.

Additionally, we studied the yearly average solar radio flux (F10.7) over the same period, covering three peak values corresponding to the three solar cycles. In solar cycle 23, the peak flux was observed in 2001 at 181.0sfu, while in solar cycle 24, the peak occurred in 2014 with a value of 145.9sfu. In the rising phase of solar cycle 25, the peak is expected to reach 188.2sfu in 2024.

In the present study, we analyzed the Dst index from the Omni Web Data Explorer to identify the occurrences of geomagnetic storms using various criteria during solar cycles 23, 24, and the rising phase of solar cycle 25. For our statistical assessment, we observed a total of 420 geomagnetic storms during the period from 1996 to 2024. Among these, we categorized the storms as moderate, intense, and severe based on the Dst index threshold of ≤ –50 nT. Specifically, we found that 299 were moderate storms, 84 were intense, and 10 were classified as severe geomagnetic storms.

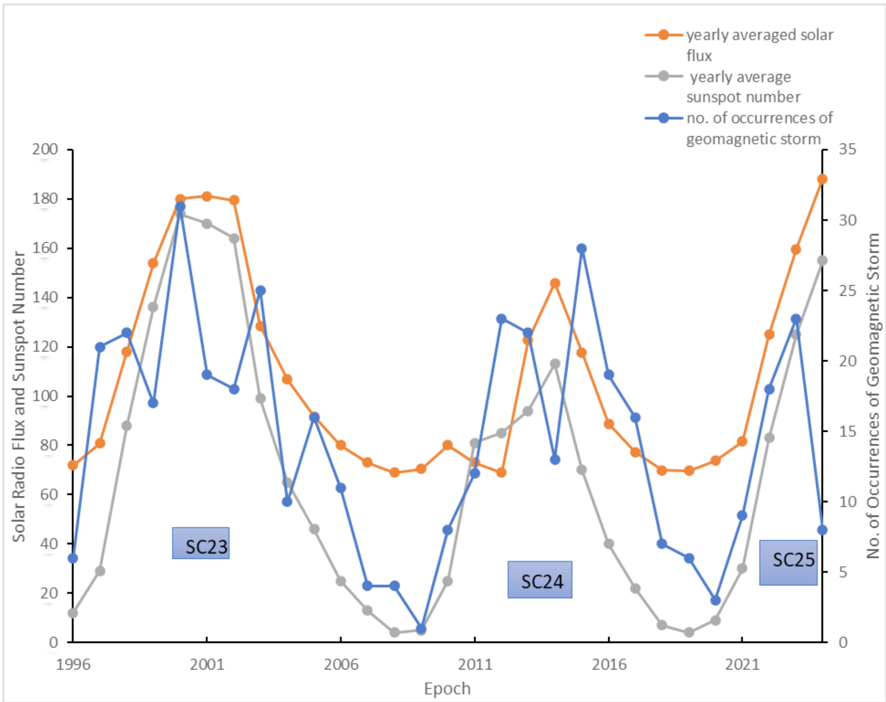

Fig 1. The correlation between the three parameters of three solar cycles i.e., Solar radio flux, sunspot number and the occurrences of the geomagnetic storm.

Figure 1 explains the following points:

SC23 (1996–2008): Shows a strong peak in solar activity around 2000, as indicated by high values of both solar radio flux and sunspot numbers. The number of Dst occurrences also peaks during this period, indicating a higher frequency of geomagnetic storms.

SC24 (2008–2019): The peak in solar activity is less pronounced compared to SC23, with both solar flux and sunspot numbers showing lower maximum values around 2014. Correspondingly, the number of Dst occurrences also appears lower.

SC25 (2019–2024): The current cycle shows an upward trend in solar activity, with solar flux and sunspot numbers increasing, and Dst occurrences starting to rise.

Between each solar cycle, there are periods of low solar activity (solar minimum). The most significant drop-in activity can be seen around 2008, which marks the transition from SC23 to SC24.

From the Fig 1, we can conclude that the rising phase of solar cycle 25 is closely aligned with the behavior observed in solar cycle 23, suggesting similar patterns of solar activity. In contrast, solar cycle 24 stands out as being distinct from both cycles, exhibiting lower solar activity overall. Based on this comparison, it can be inferred that solar cycle 25 may follow a trajectory similar to that of solar cycle 23.

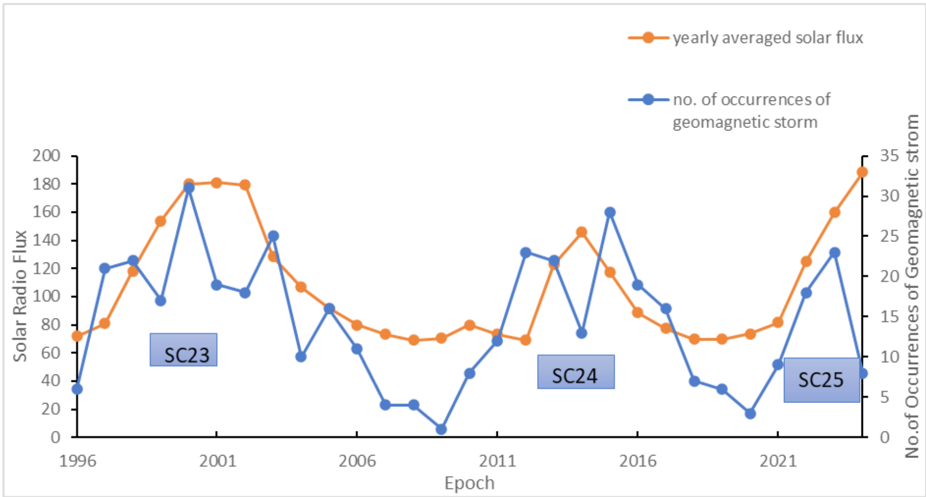

Fig 2. Comparison between the **yearly averaged solar radio flux** with the **number of occurrences of geomagnetic storms** from 1996 to 2024, covering **solar cycles 23, 24** and the rising phase of **solar cycle 25.**

The graph i.e., Fig 2 illustrates the cyclical nature of solar activity and its direct impact on geomagnetic storm occurrences. As solar radio flux increases, geomagnetic storm occurrences tend to rise, indicating a clear link between solar activity and geomagnetic disturbances on Earth. SC25 shows early signs of mimicking the behavior of SC23, suggesting that the upcoming peak in solar activity may bring a higher frequency of geomagnetic storms, similar to the intense activity seen during SC23.

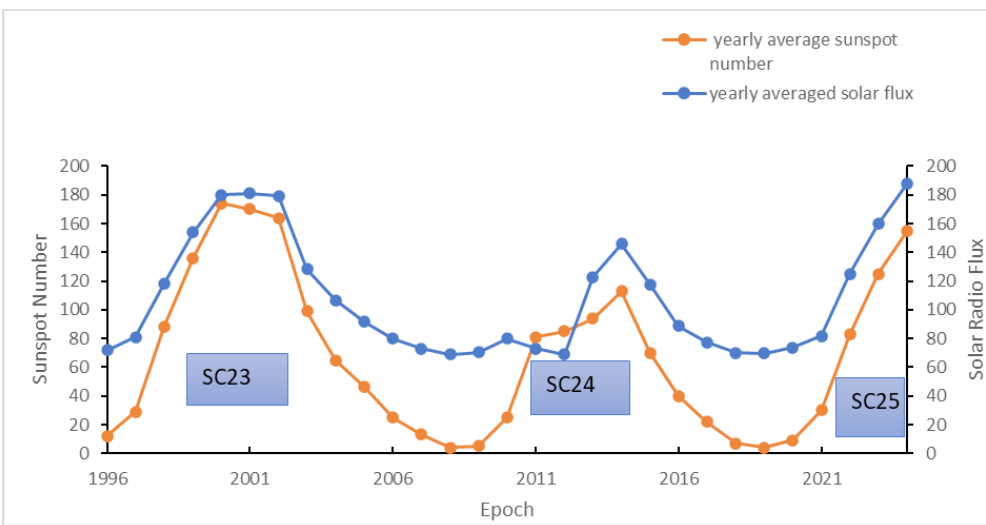

Fig 3. Comparison between the **yearly averaged sunspot number** and **yearly averaged solar radio flux** from 1996 to 2024, encompassing solar cycles 23, 24 and rising phase of solar cycle 25.

The graph i.e., Fig 3 demonstrates the cyclical nature of solar activity, with peaks in both sunspot numbers and solar radio flux during the maximum phases of each solar cycle. Solar cycle 24 stands out as being weaker than the adjacent cycles, while solar cycle 25 is on track to reach or exceed the levels of solar activity observed during solar cycle 23. This strong rise in solar activity during SC25 is crucial for understanding its potential impact on space weather and geomagnetic disturbances.

The graph i.e., Fig 4 highlights the relationship between solar activity (as indicated by sunspot numbers) and geomagnetic storm occurrences. Solar cycles 23 and 25 show a strong correlation between increased sunspot numbers and geomagnetic storms, while solar cycle 24 stands out as a period of reduced activity. The rising phase of solar cycle 25 suggests that it could experience solar activity levels similar to those seen in solar cycle 23, which may lead to an increase in geomagnetic storm occurrences in the coming years.

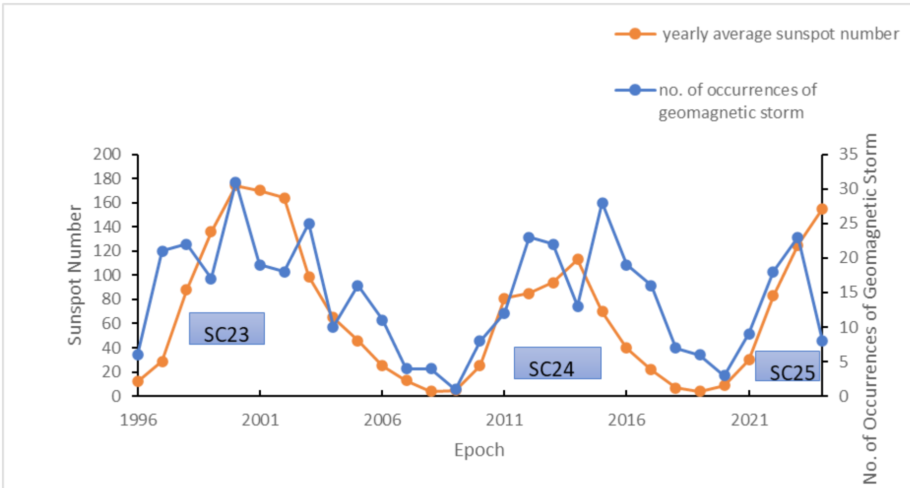

Fig 4. Comparison between the yearly averaged sunspot number and the number of occurrences of geomagnetic storms from 1996 to 2024, covering solar cycles 23, 24 and the rising phase of solar cycle 25.

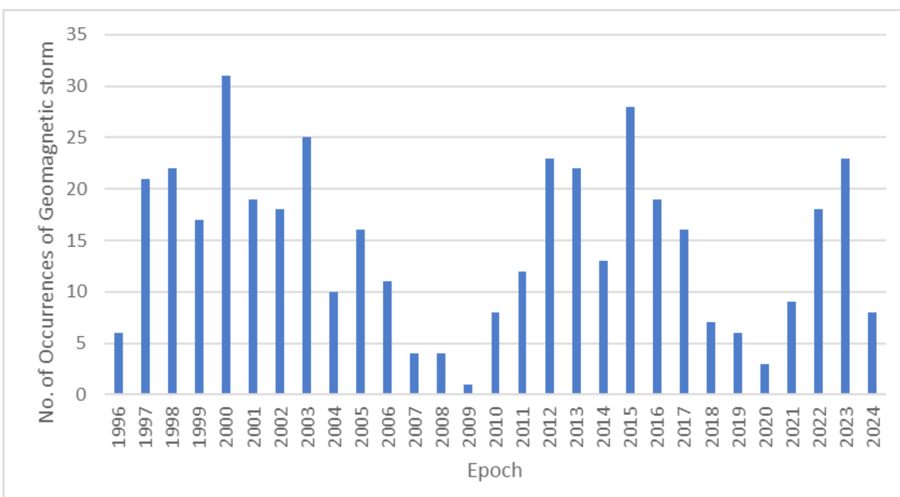

Fig 5. The chart depicts the no. of occurrences of geomagnetic storms from the year 1996 to 2024.

The three charts i.e., Fig 5, Fig 6 and Fig 7 together illustrate the interconnectedness between solar activity indicators, such as solar flux and sunspot numbers, and the occurrences of geomagnetic storms. The peaks in solar flux and sunspot numbers align with periods of heightened geomagnetic storm occurrences. Solar Cycle 25 is exhibiting patterns similar to those of Solar Cycle 23, suggesting that the coming years may experience heightened solar activity and corresponding geomagnetic disturbances, compared to the weaker Solar Cycle 24. This reinforces the importance of understanding solar cycles for better forecasting of geomagnetic storms, which have significant impacts on Earth's technological infrastructure.

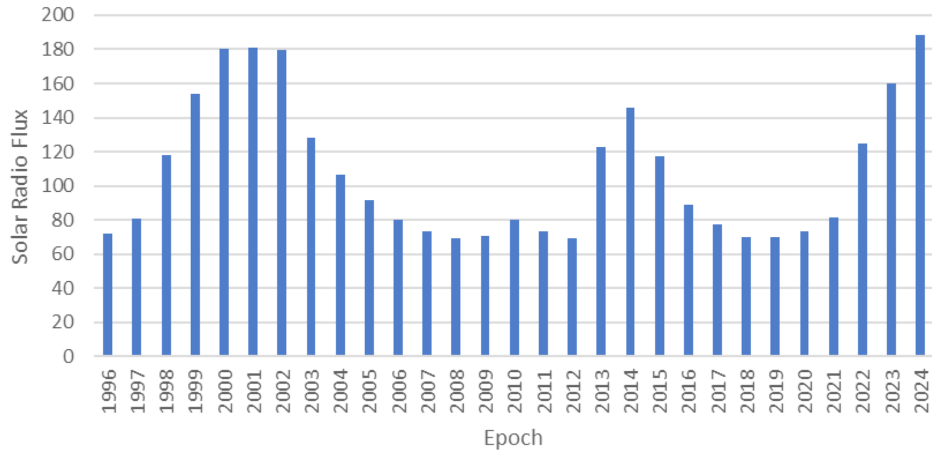

Fig 6. Chart depicts the yearly averaged solar radio flux from the year 1996 to 2024.

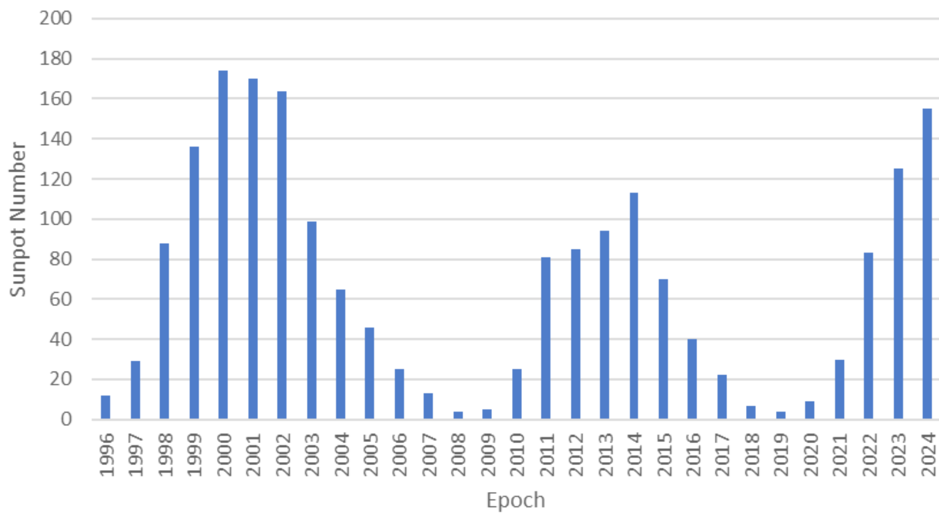

Fig 7. Chart depicts the yearly averaged sunspot number from the year 1996 to 2024.

During 2009–2019, 193 geomagnetic storms were identified, with strong positive correlations observed between yearly average sunspot numbers and geomagnetic storms (0.76) and between solar radio flux and geomagnetic storms (0.74). The correlation between sunspot numbers and solar radio flux was exceptionally high at 0.99, indicating a strong link between these solar activity indicators during this period [4].

In contrast, the extended analysis for 1996–2024 identified 420 geomagnetic storms but revealed weaker correlations. The relationship between yearly average sunspot numbers and geomagnetic storms was 0.63, while solar radio flux and geomagnetic storms had a correlation of 0.52. However, the correlation between sunspot numbers and solar radio flux remained strong at 0.93. These findings suggest that while solar activity strongly influences geomagnetic storm occurrences, the strength of these correlations varies across time periods. The 2009–2019 data exhibited higher correlation values, possibly due to specific phases of solar cycle activity or reduced data variability, whereas the broader 1996–2024 dataset showed more moderate relationships.

Result

After analyzing and observing solar activities and geomagnetic field disturbances from 1996 to 2024, we identified a total of 420 geomagnetic storms. The data suggests a clear dependence between solar activity—such as sunspot number and solar radio flux—and the occurrence of geomagnetic storms. Specifically, the study revealed a positive correlation of 0.63 between the yearly average sunspot number and geomagnetic storm occurrences, a positive correlation of 0.52 between yearly average solar radio flux and storm occurrences, and a strong correlation of 0.93 between sunspot number and solar radio flux.

3 Conclusion

This paper has examined the interrelationships between key solar activity indicators—sunspot number, solar radio flux, and the Disturbance Storm Time (Dst) index—highlighting their vital roles in understanding solar variability and its impacts on Earth's magnetosphere and ionosphere. These parameters are not only central to characterizing solar activity but also crucial for enhancing space weather forecasting capabilities. By reviewing the historical trends and significance of these indicators, we have emphasized their influence on major space weather phenomena such as geomagnetic storms and solar radiation storms.

Our analysis of various methodologies, including traditional statistical models and emerging machine learning techniques, provides a comprehensive approach to predicting solar activity. By elucidating the correlations and interactions between sunspot numbers, solar radio flux, and the Dst index, we have found the correlation between radio flux and sunspot numbers strong while the correlation factors for other parameters (e.g., solar wind speed or geomagnetic activity indices) are weaker, with values of 0.63 and 0.52. This lower correlation might be attributed to the anomalous behavior of Solar Cycle 24 (SC-24). SC-24 was relatively weak compared to other recent solar cycles, showing lower peak sunspot numbers and different solar activity patterns. These anomalies could reduce the consistency of relationships typically observed between solar activity indicators. This study offers new insights into solar-terrestrial interactions. These findings have the potential to improve the accuracy of space weather predictions, thereby aiding in the development of more effective mitigation strategies to minimize the impact of solar events on critical technological infrastructure.

In conclusion, this study contributes to the broader understanding of space weather science by advancing our knowledge of how solar activity indicators interact with geomagnetic events. As solar variability continues to pose challenges for Earth's technological systems, this work serves as a step forward in the ongoing effort to enhance space weather forecasting and safeguard modern technology from the adverse effects of solar activity.

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