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Correlation Analysis of Key Parameters Associated with Solar Activity and Geomagnetic Disturbances throughout 2023

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Abstract

Solar activity and geomagnetic disturbances are intricately linked phenomena with potentially disruptive impacts on space-based and ground-based technological systems. This study presents a comprehensive correlation analysis of key parameters associated with solar activity and geomagnetic storms throughout 2023, aimed at elucidating their interrelationships. The parameters investigated include the Disturbance Storm Time (Dst) index, intensities of C-class and B-class solar flares, sunspot numbers (SSN), and the 10.7 cm solar radio flux. Employing Pearson's correlation analysis, a robust statistical technique, the research quantifies the strength and direction of associations between these variables. The findings reveal positive correlations between the Dst index and C-class flare intensity (r = 0.1458), sunspot numbers (r = 0.2360), and the 10.7 cm solar radio flux (r = 0.3441), implying that increased solar activity corresponds to more intense geomagnetic disturbances. Conversely, a negative correlation is observed between the Dst index and B-class flare intensity (r = -0.3740). Strong positive correlations are also identified between sunspot numbers and C-class (r = 0.4278) and B-class (r = 0.5879) flare intensities, as well as the 10.7 cm solar radio flux (r = 0.8425). The results contribute to a deeper understanding of the Sun-Earth connection and have significant implications for space weather forecasting, risk assessment, and the development of mitigation strategies against adverse space weather events.

Keywords: 10.7 cm solar radio flux, sunspot numbers (SSN), Disturbance Storm Time (Dst), solar flares (SF)

1. INTRODUCTION

Solar activity exhibits dynamic and complex behavior, driven by phenomena such as sunspots, solar flares, and coronal mass ejections (CMEs). These manifestations of solar activity can significantly perturb the Earth's magnetosphere, leading to geomagnetic storms and disturbances. Geomagnetic storms have far-reaching consequences, including disruptions to communication and navigation systems, damage to spacecraft electronics, and potential impacts on power grids (Pulkkinen et al., 2005; Baker et al., 2008; Eastwood et al., 2017). Consequently, understanding the intricate relationships between various indicators of solar activity and the intensity of geomagnetic disturbances is crucial for space weather forecasting, risk assessment, and mitigating the adverse effects of these events (Hapgood, 2011; Knipp, 2011). Numerous studies have investigated the correlations between solar activity parameters and geomagnetic indices, yielding valuable insights into the underlying physical processes (Gonzalez et al., 1994; Tsurutani et al., 1995; Gopalswamy et al., 2007). For example, a recent study by Meena et al. (2022) analysed coronal mass ejections (CMEs) and solar flares during solar cycle 24. They found that CME events were moderately correlated with M-class solar flares but not with B-class or C-class flares. Additionally, CMEs showed a moderate positive correlation with X-class solar flares. Meena et al. concluded that CMEs are not primarily responsible for interplanetary phenomena, and other activities like flares and energetic particles may also contribute to interplanetary disturbances. Another study by Vaswani et al. (2022) examined geomagnetic storms in association with solar activities during 2010-2020. They found a strong positive correlation between the Dst index of geomagnetic storms and the flux of X-class solar flares, but no correlation with the linear speed of CMEs. The authors suggested that CMEs are not the main cause of geomagnetic storms during the studied period, and X-class flares played a more significant role in driving these disturbances.

Furthermore, Meena et al. (2024) analysed the ionospheric responses to solar flares during moderately high solar activity in January 2023. They observed enhancements and broadening of the atomic oxygen (O+) layer, increases in molecular ions like NO+ and O2+ at higher altitudes, and temporary depletions of lighter ions such as H+ and He+ around 500 km altitude. These ionospheric changes corresponded with the timing of M-class and X-class solar flares, indicating the complex interactions between solar emissions and Earth's upper atmosphere. However, many previous studies have focused on specific aspects or employed limited datasets, leaving room for a more comprehensive analysis encompassing multiple key variables over an extended period. This study presents a comprehensive correlation analysis of multiple parameters associated with solar activity and geomagnetic disturbances throughout the year 2023 The principal variables investigated include the Disturbance Storm Time (Dst) index, a widely used quantitative measure of geomagnetic storm intensity (Sugiura, 1964; Rostoker, 1972); the intensity of C-class and B-class solar flares, intense bursts of electromagnetic radiation and energetic particles from the Sun's surface (Fletcher et al., 2011); sunspot numbers (SSN), which serve as a proxy for overall solar activity (Hathaway, 2015); and the 10.7 cm solar radio flux, another well-established indicator of solar activity related to the presence of active regions and sunspots on the solar surface (Tapping, 2013).

By employing Pearson's correlation analysis, a robust statistical technique for quantifying the degree of linear association between variables (Rodgers and Nicewander, 1988), this research aims to unveil the intricate relationships between these parameters. The correlation coefficients obtained from this analysis provide a quantitative measure of the strength and direction of the associations, enabling a deeper understanding of the underlying physical processes governing solar activity and its impact on the Earth's magnetic field. The findings of this study have significant implications for space weather forecasting, risk assessment for space-based and ground-based technological systems, and advancing our fundamental knowledge of the Sun-

Earth connection. By elucidating the correlations between solar activity indicators and geomagnetic disturbances, this research contributes to the development of more accurate prediction models and the implementation of appropriate mitigation strategies to minimize the adverse effects of space weather events on critical infrastructure and operations.

2. DATA AND METHODOLOGY

This study utilized data sourced from reliable sources, encompassing a comprehensive set of measurements and observations related to solar activity and geomagnetic disturbances throughout the year 2023. The key variables analyzed in this research include:

2.1 Dst Index: Measured in nanoTeslas (nT), the Dst index serves as a crucial indicator of geomagnetic storm intensity. It quantifies variations in the horizontal component of the Earth's magnetic field, with more negative values indicating stronger geomagnetic disturbances (Sugiura, 1964; Rostoker, 1972).

2.2 Intensity of C-class and B-class Solar Flares: Solar flares, intense bursts of electromagnetic radiation and energetic particles from the Sun's surface, were analyzed. The intensity of these flares is measured in watts per square meter (W/m^2), with higher values indicating more intense flare events (Fletcher et al., 2011).

2.3 Sunspot Numbers (SSN): Sunspots, temporary dark regions on the Sun's surface, serve as a proxy for solar activity. Higher sunspot numbers generally correspond to periods of increased solar activity (Hathaway, 2015).

2.4 10.7 cm Solar Radio Flux: Measured in solar flux units (sfu), the 10.7 cm solar radio flux is another key indicator of solar activity. It represents the intensity of radio emissions from the Sun at a wavelength of 10.7 cm, strongly influenced by the presence of sunspots and other active regions on the solar surface (Tapping, 2013).

The data for these variables were obtained from reputable sources, such as the World Data Center for Geomagnetism (Dst index), the Space Weather Prediction Center (solar flare intensities), the Solar Influences Data Analysis Center (sunspot numbers), and the National Research Council of Canada (10.7 cm solar radio flux).

2.5 Pearson's Correlation Analysis

To investigate the relationships between these variables, this study employed Pearson's correlation analysis, a robust statistical technique for quantifying the degree of linear association between variables (Rodgers and Nicewander, 1988). The correlation coefficient (r) serves as a quantifiable measure of their association, ranging from -1 to +1. A correlation coefficient near -1 suggests a strong negative relationship, implying that as one variable increases, the other decreases. Conversely, a value close to +1 indicates a strong positive relationship, signifying that an increase in one variable corresponds to an increase in the other. When r = 0, there is no linear correlation between the variables.

The correlation coefficient (r) for two variables, a and b, is calculated using the following formula:

$$r = \frac{n(\Sigma ab) - (\Sigma a)(\Sigma b)}{\sqrt{[n\Sigma a2 - (\Sigma a)2][n\Sigma b2 - (\Sigma b)2]}}$$

The following correlations were investigated:

- Relationship between the Dst index and the intensity of C-class solar flares
- Relationship between the Dst index and the intensity of B-class solar flares

- Correlation between the Dst index and sunspot numbers (SSN)
- Correlation between the Dst index and the 10.7 cm solar radio flux
- Correlation between the intensity of C-class solar flares and sunspot numbers (SSN)
- Correlation between the intensity of B-class solar flares and sunspot numbers (SSN)
- Correlation between the intensity of C-class solar flares and the 10.7 cm solar radio flux
- Correlation between the intensity of B-class solar flares and the 10.7 cm solar radio flux
- Correlation between sunspot numbers (SSN) and the 10.7 cm solar radio flux

By conducting a comprehensive correlation analysis, this research aims to unravel the intricate relationships between these variables, shedding light on the underlying physical processes governing solar activity and its impact on the Earth's magnetic field.

3. RESULTS AND DISCUSSION

The results of the correlation analyses are presented below, accompanied by detailed discussions and interpretations of the findings. The corresponding correlation coefficients (r) are provided for each relationship investigated.

3.1 Relationship between the Dst index and the intensity of C-class solar flares: r = 0.1458

The scatter plot in Figure 1 illustrates the positive correlation between the Dst index and the intensity of C-class solar flares, with a correlation coefficient (r) of 0.1458. This indicates a direct, albeit weak, relationship between the two variables. The data suggest that higher intensities of C-class solar flares are associated with more intense geomagnetic disturbances, as measured by the Dst index. The physical explanation for this relationship lies in the fact that solar flares, including C-class events, are often accompanied by coronal mass ejections (CMEs) and high-energy particle streams. When these energetic particles and CMEs interact with the Earth's magnetosphere, they can cause disturbances and compression of the magnetic field, leading to more negative Dst index values, which are indicative of geomagnetic storms.

It is important to note that while the correlation is positive, the relatively low value of r suggests that the intensity of C-class flares alone may not be a strong predictor of geomagnetic storm intensity. Other factors, such as the location and orientation of the flare on the solar disk, the speed and density of the associated CME, and the background conditions of the interplanetary medium, can also play significant roles in determining the severity of geomagnetic disturbances.

3.2 Relationship between the Dst index and the intensity of B-class solar flares: r = -0.3740

The scatter plot in Figure 2 illustrates the negative correlation between the Dst index and the intensity of B-class solar flares, with a correlation coefficient (r) of -0.3740. This suggests an inverse relationship between the two variables, indicating that higher intensities of B-class solar flares are associated with lower geomagnetic disturbance levels, as indicated by less negative Dst index values.

This result may seem counterintuitive at first glance, but it is essential to consider the context of B-class flares within the broader spectrum of solar activity. B-class flares are relatively small and less energetic compared to larger flare classes, such as M-class and X-class events. Consequently, they may not always be accompanied by significant coronal mass ejections (CMEs) or high-energy particle streams capable of triggering intense geomagnetic disturbances. During periods of elevated B-class flare activity, the overall solar activity levels may be relatively low, with fewer large-scale CMEs and energetic particle events impacting the Earth's magnetosphere. This could result in a weaker compression of the magnetic field and, consequently, less negative Dst index values However, it is crucial to interpret this negative correlation with caution, as it may be influenced by factors not accounted for in this study, such as the specific timing and location of the B-class flares relative to the Earth's position, as well as the interplay with other solar activity phenomena.

3.3 Correlation between the Dst index and sunspot numbers (SSN): r = 0.2360

The scatter plot in Figure 3 illustrates the positive correlation between the Dst index and sunspot numbers (SSN), with a correlation coefficient (r) of 0.2360. This indicates a direct relationship, where higher sunspot numbers are associated with more intense geomagnetic disturbances, as measured by more negative Dst index values.

Sunspots are widely recognized as indicators of overall solar activity, with higher sunspot numbers generally corresponding to periods of increased solar activity, including the occurrence of solar flares, coronal mass ejections (CMEs), and energetic particle events. These phenomena can interact with the Earth's magnetosphere, leading to geomagnetic disturbances and more negative Dst index values. The positive correlation observed in this study is consistent with the well-established understanding that periods of elevated solar activity, marked by higher sunspot numbers, tend to coincide with an increased likelihood of geomagnetic storms. However, it is important to note that the relatively low value of r suggests that sunspot numbers alone may not be a strong predictor of geomagnetic storm intensity, as other factors, such as the specific characteristics and orientations of active regions on the Sun, also play significant roles.

3.4 Correlation between the Dst index and the 10.7 cm solar radio flux: r = 0.3441

The scatter plot in Figure 4 illustrates the positive correlation between the Dst index and the 10.7 cm solar radio flux, with a correlation coefficient (r) of 0.3441. This indicates a direct relationship, where higher levels of the 10.7 cm solar radio flux are associated with more intense geomagnetic disturbances, as measured by more negative Dst index values. The 10.7 cm solar radio flux is a well-established proxy for solar activity, particularly related to the presence of active regions and sunspots on the solar surface. Higher levels of the 10.7 cm solar radio flux are generally indicative of increased solar activity, including the occurrence of solar flares, coronal mass ejections (CMEs), and energetic particle events.

The positive correlation observed in this study is consistent with the expectation that periods of elevated solar activity, as indicated by higher 10.7 cm solar radio flux levels, are more likely to be accompanied by geomagnetic disturbances. The energetic particles and CMEs associated with active regions on the Sun can interact with the Earth's magnetosphere, leading to compression of the magnetic field and more negative Dst index values. While the correlation is positive, the moderate value of r suggests that the 10.7 cm solar radio flux alone may not be a strong predictor of geomagnetic storm intensity, as other factors, such as the specific characteristics and orientations of active regions, as well as the interplanetary medium conditions, can also influence the severity of geomagnetic disturbances.

3.5 Correlation between the intensity of C-class solar flares and sunspot numbers (SSN): r = 0.4278

The scatter plot in Figure 5 illustrates the positive correlation between the intensity of C-class solar flares and sunspot numbers (SSN), with a correlation coefficient (r) of 0.4278. This indicates a direct relationship, where higher sunspot numbers are associated with higher intensities of C-class solar flares. This finding is consistent with the understanding that sunspots and active regions on the Sun are the primary sources of solar flares, including C-class events. Periods of increased solar activity, characterized by higher sunspot numbers, typically correspond to an increased likelihood of observing more intense solar flare events. The positive correlation observed in this study suggests that sunspot numbers can serve as a useful proxy for predicting the intensity of C-class solar flares. However, it is important to note that the moderate value of r indicates that other factors, such as the complexity and magnetic field configurations of active regions, also play a role in determining the intensity of solar flares.

3.6 Correlation between the intensity of B-class solar flares and sunspot numbers (SSN): r = 0.5879

The scatter plot in Figure 6 illustrates the positive correlation between the intensity of B-class solar flares and sunspot numbers (SSN), with a correlation coefficient (r) of 0.5879. This indicates a direct relationship, where higher sunspot numbers are associated with higher intensities of B-class solar flares. This finding aligns with the relationship observed for C-class flares and is consistent with the expectation that periods of increased solar activity, as indicated by higher sunspot numbers, are more likely to produce more intense solar flare events, including B-class flares.

The positive correlation observed in this study suggests that sunspot numbers can serve as a useful proxy for predicting the intensity of B-class solar flares. However, it is important to note that the moderate value of r indicates that other factors, such as the complexity and magnetic field configurations of active regions, also contribute to determining the intensity of solar flares.

3.7 Correlation between the intensity of C-class solar flares and the 10.7 cm solar radio flux: r = 0.4583

The scatter plot in Figure 7 illustrates the positive correlation between the intensity of C-class solar flares and the 10.7 cm solar radio flux, with a correlation coefficient (r) of 0.4583. This indicates a direct relationship, where higher levels of the 10.7 cm solar radio flux are associated with higher intensities of C-class solar flares. This finding is consistent with the understanding that the 10.7 cm solar radio flux is a proxy for solar activity, particularly related to the presence of active regions and sunspots on the solar surface. These active regions are known to be the primary sources of solar flares, including C-class events.

The positive correlation observed in this study suggests that the 10.7 cm solar radio flux can serve as a useful predictor of the intensity of C-class solar flares.

However, it is important to note that the moderate value of r indicates that other factors, such as the complexity and magnetic field configurations of active regions, also contribute to determining the intensity of solar flares.

3.8 Correlation between the intensity of B-class solar flares and the 10.7 cm solar radio flux: r = 0.5879

The scatter plot in Figure 8 illustrates the positive correlation between the intensity of B-class solar flares and the 10.7 cm solar radio flux, with a correlation coefficient (r) of 0.5879. This indicates a direct relationship, where higher levels of the 10.7 cm solar radio flux are associated with higher intensities of B-class solar flares. Similar to the relationship observed for C-class flares, this finding is consistent with the expectation that higher levels of the 10.7 cm solar radio flux, indicative of increased solar activity and the presence of active regions, are more likely to be accompanied by more intense solar flare events, including B-class flares.

The positive correlation observed in this study suggests that the 10.7 cm solar radio flux can serve as a useful predictor of the intensity of B-class solar flares. However, it is important to note that the moderate value of r indicates that other factors, such as the complexity and magnetic field configurations of active regions, also contribute to determining the intensity of solar flares.

3.9 Correlation between sunspot numbers (SSN) and the 10.7 cm solar radio flux: r = 0.8425

The scatter plot in Figure 9 illustrates the correlation between sunspot numbers (SSN) and the 10.7 cm solar radio flux, with a correlation coefficient (r) of 0.8425. This indicates a strong positive correlation between the two variables, where higher sunspot numbers are associated with higher levels of the 10.7 cm solar radio flux.

This strong correlation is expected, as sunspot numbers are a well-established indicator of solar activity, and the 10.7 cm solar radio flux is a proxy for solar activity related to the presence of active regions and sunspots on the solar surface. Higher sunspot numbers correspond to increased solar activity, which is typically accompanied by higher levels of the 10.7 cm solar radio flux. The strong positive correlation suggests that the 10.7 cm solar radio flux can serve as a reliable proxy for monitoring solar activity, as indicated by sunspot numbers. However, it is important to note that while the correlation is strong, other factors, such as the specific characteristics of active regions and their magnetic field configurations, can also influence both sunspot numbers and the 10.7 cm solar radio flux.

CONCLUSION

This study presents a comprehensive correlation analysis of key parameters associated with solar activity and geomagnetic storms throughout 2023. The findings reveal positive correlations between the Disturbance Storm Time (Dst) index, a measure of geomagnetic storm intensity, and the intensity of C-class solar flares (r = 0.1458), sunspot numbers (r = 0.2360), and the 10.7 cm solar radio flux (r = 0.3441). These positive correlations indicate that increased solar activity, as represented by higher values of these parameters, corresponds to more intense geomagnetic disturbances. Conversely, a negative correlation is observed between the Dst index and the intensity of B-class solar flares (r = -0.3740), suggesting that higher B-class flare intensities are associated with lower geomagnetic disturbance levels. Strong positive correlations are also identified between sunspot numbers and the intensity of C-class (r = 0.4278) and B-class (r = 0.5879) solar flares, as well as the 10.7 cm solar radio flux (r = 0.8425). These correlations indicate that higher sunspot numbers are linked to more intense solar flares and higher levels of the 10.7 cm solar radio flux, which are proxies for solar activity.

The results contribute to a deeper understanding of the Sun-Earth connection and have significant implications for space weather forecasting, risk assessment, and the development of mitigation strategies against adverse space weather events. The findings highlight the importance of considering multiple parameters and their interrelationships in predicting and mitigating the impacts of geomagnetic disturbances on space-based and ground-based technological systems.

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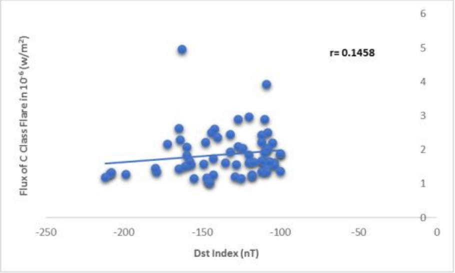

Figure 1: Relationship between Geomagnetic Disturbance and C-Class Flare Intensity.

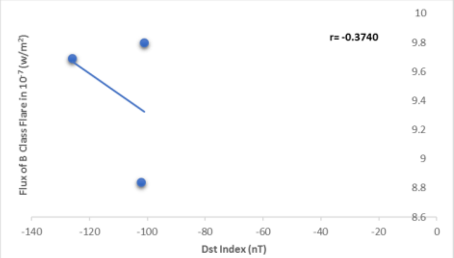

Figure 2: Relationship between the Dst Index and the Occurrence of B-Class Solar Flares in 2023.

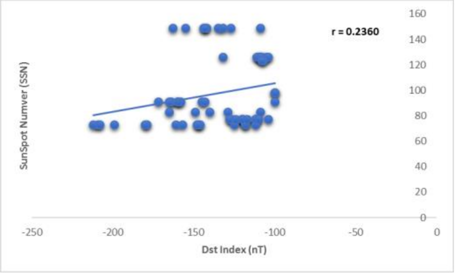

Figure 3: Correlation between Dst Index and Sunspot Number (SSN) for 2023 (r = 0.2360).

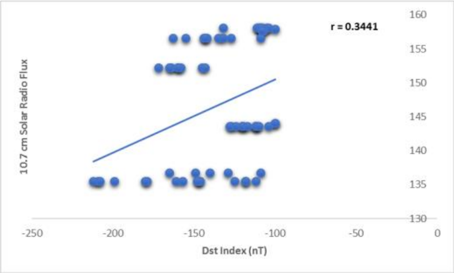

Figure 4: Correlation between Dst Index and 10.7 cm Solar Radio Flux for 2023 (r = 0.3441).

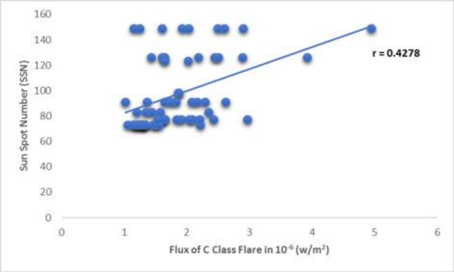

Figure 5: Comparison of Solar Flare Flux of C-Class Events in 2023 with the Sunspot Number (SSN).

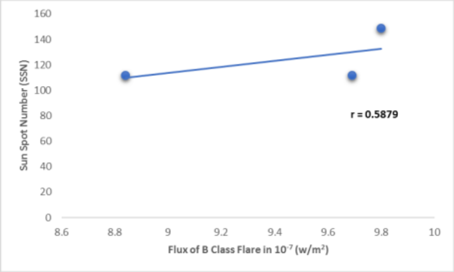

Figure 6: Relationship between the Flux of B-Class Solar Flares and the 10.7 cm Solar Radio Flux in 2023.

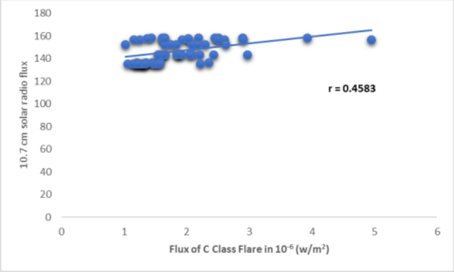

Figure7: Flux of C-Class Solar Flares compared to 10.7 cm Solar Radio Flux in 2023

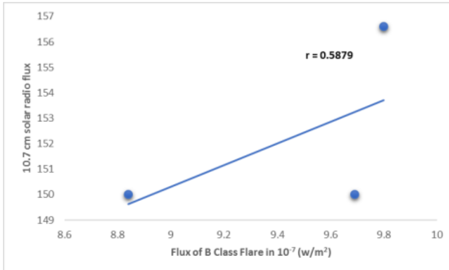

Figure8: Flux of B-Class Solar Flares vs. 10.7 cm Solar Radio Flux in 2023.

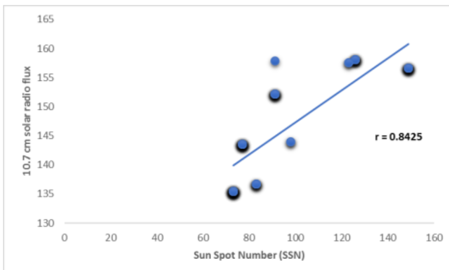

Figure 9: shows the correlation between the Sunspot Number (SSN) and the 10.7 cm Solar Radio Flux for the year 2023.