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Statistical Analysis and Characterisation of Geomagnetic Storm Occurrence and its Dependent on Solar Cycle, Season, and Time during Solar Cycles 21 – 24

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ABSTRACT

Geomagnetic storms (GMSs) are global phenomenon that is useful in understanding the dynamics of the solar-terrestrial environment. In this study, we attempt to investigate potential connections between sunspot number (SSN), GMSs, phases of solar cycle, and Universal Time (UT) hour for storm occurrence during the recent four solar cycles; in order to study the interconnectivity between solar and geomagnetic activity. This is due to the fact that GMS occurrence may proceed the appearance of sunspot. We employed SSN to characterize solar cycle conditions and disturbance storm time (Dst) index to characterise storms. The total GMSs observed were identified using minimum Dst value and were analyzed statistically. Results revealed that SSN and the frequency of occurrence of GMSs varied from solar cycle to solar cycle; however, the observed GMSs followed the phases of solar cycle. Furthermore, we observed increased GMSs during equinoctial conditions compared to other seasons as well as higher probability of occurrence of great storms (Dst ≤ -350 nT) at about 21 – 8 UT in equinoxes. This depicts possible time for occurrence of great storms. This study has provided scientific insight which could be employed by atmospheric, space, and solar scientists.

Keywords: Sunspot number, Dst Index, Geomagnetic storm occurrence, Solar cycle, Solar activity

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1. INTRODUCTION

Geomagnetic storms (GMSs) are global phenomenon that is useful in understanding the dynamics of solar-terrestrial environment. It is a worldwide temporary disturbance of the Earth's magnetic field due to abnormal conditions in the interplanetary magnetic field (IMF) and solar wind plasma emission (Parashar *et al*., 2011). Geomagnetic storms affect communication systems, satellites, spacecraft operation, geophysical exploration, power grid, and other technological systems. Thus, GMSs affect both space and ground-based technologies (Wu *et al*. 2016; Joshua *et al*. 2018; Reyes *et al*. 2021).

The origin of GMSs, the connection between GMSs and solar activity, the role of Coronal Mass Ejections (CMEs) and magnetic clouds in solar wind leading to the development of storms, as well as the interplanetary magnetic field orientation, have been discussed extensively by several researchers (Gonzalez *et al*. 1994; Wu *et al*. 2016; Al-Feadh and Al-Ramdhan, 2019; Doha and Wathiq, 2019). Detailed information can be gotten from these papers.

According to Reyes *et al*. (2021), the disturbance storm time (Dst) index is a measure of geomagnetic activity, which is used as an indicator to identify storm occurrence and severity. For instance, disturbed storm time, Dst = 0 and Dst ≤ -50 nT depict no deviation from the quiet condition and large storm, respectively (Rathore et al., 2012). Based on minimum Dst value, GMSs are generally classified into moderate, M (-100 < Dst ≤ -50 nT), intense, I (-200 < Dst ≤ -100 nT), severe, S (-350 < Dst ≤ -200 nT), and great, G (Dst ≤ -350 nT) storms, respectively (Rathore *et al*. 2012; Wu 2016; Shadrina 2017). Many scholars such as Parashar et al. (2011), Rathore *et al*. (2012), and Doha and Wathiq (2019) have employed Dst index to study GMSs.

One of the most spectacular phenomena of solar activity is CMEs, originating from the solar corona. However, halo CMEs have great impacts on the Earth, thereby causing GMSs (Rathore *et al*., 2012). Solar activity varies periodically for about 11 years, called solar cycle. Each cycle, however, has specific features and characteristics. In studying solar activity, SSN is mostly used as an index of solar activity. Sunspots are transient phenomena lasting from a few days to some months. It is useful in understanding the dynamics of solar and geomagnetic disturbances (Audu and Okeke, 2019).

It has been reported that GMS occurrence proceed the appearance of sunspot (Joshua et al., 2018). In this research, we attempt to investigate potential connections between sunspot number (SSN), GMSs, phases of solar cycle, and Universal Time (UT) hour for storm occurrence during the recent four solar cycles; in order to study the interconnectivity between solar and geomagnetic activity.

Several works have been carried out on GMSs, employing indices such as Dst and Kp (Dal Lago *et al*., 2004; Rathore *et al*., 2012; Rathore *et al*., 2014; Shadrina, 2017; Christian, 2018; Joshua *et al*., 2018; Al-Feadh and Al-Ramdhan, 2019; Audu *et al*., 2024) and significant results have been reported. Many researchers have also studied the possible causes of GMSs (Wu *et al*., 2016). Despite these works on GMSs, there is need for further studies due to the impacts of storm stated earlier. Thus, the findings of this study will provide scientific insight that will be useful to space, atmospheric, and solar scientists, among others.

2. SOURCES OF DATA AND METHOD OF DATA ANALYSIS

Data of Dst index with hourly resolution and monthly mean daily SSN, provided by the World Data Center Kyoto, Japan, were obtained from the website of the Omni Web (www.omniweb.gsfc.nasa.gov) (World Data Center for Geomagnetism, 2015). The period under study is solar cycles 21 - 24 (1976 - 2019). Table 1 shows features of solar cycles 21 - 24. The data were analyzed as follows:

I. Descriptive statistics was employed in computing the averages of SSN from the monthly mean daily values.
II. Yearly mean SSN was then computed from the monthly mean daily values.
III. The minimum Dst value was used as an indicator to identify storm occurrence during the main phase of GMS from the high-resolution hourly Dst data for each month of the year in each solar cycle.
IV. The identify storms in (III) were classified into storms categories stated earlier and counted for each month.
V. Subsequently, the total storms per year in each solar cycle were then computed from (IV).
VI. The yearly variations of SSN and the total number of GMSs were then compared for each solar cycle.
VII. Finally, the total numbers of moderate, intense, severe, and great storms per year for solar cycles 21 - 24 were compared.

Table 1. Interesting features and parameters of solar cycles 21 – 24 (Joshua *et al.*, 2018)

Solar cycles	Date of cycle start	Date of cycle end	Date of cycle maximum	Date of cycle minimum	Maximum sunspot number	Length (Years)
Cycle 21	1976-03	1986-09	1979	1976	232.9	10.5
Cycle 22	1986-09	1996-08	1989	1986	212.5	9.9
Cycle 23	1996-08	2008-12	2000	1996	180.3	12.3
Cycle 24	2008-12	2019-12	2014	2008	81.8	11.0

3. RESULTS AND DISCUSSION

3.1 Yearly Variation of SSN, total storms, and Classification of GMSs during Cycles 21 - 24

Figure 1a presents the averages of sunspot number and number of storm days per year during Cycle 21. It could be observed that SSN and GMSs followed the same phases of the solar cycle. The year 1979 is the maximum year of solar cycle 21 when SSN is maxima, whereas 1976 is the solar minimum year. This depicts that the occurrence of GMSs generally increases with an increase in solar cycle, however, the frequency decreases near the solar minimum. It is pertinent to note that, though 1979 was the solar maxima year, the highest storm was however observed in 1978, whereas the least storm was recorded in 1976 which is the solar minimum year.

It is pertinent to note that storms were more prominent during the descending phase (1980 – 1986) than in the ascending phase (1976 – 1978). In Figure 1b, moderate and intense storms were the most frequently occurring storms as they were recorded in all the years.

On the other hand, severe storms were observed in all the years except 1977, 1980, 1984, and 1985 while great storms were not observed in solar cycle 21.

In Figure 2a, the highest storm was recorded in 1989 which is the maximum phase of solar cycle 22 when SSN is maxima. The descending phase recorded more storms than the ascending phase of the solar cycle. From Figure 2b, moderate storms were recorded in all the years; intense storms were also recorded in all the years except 1987. Severe storms were observed in 1989 – 1992 and 1994, while great storms were recorded in 1989 and 1991 only. The year 1989 is the maxima of solar cycle 22 and it was when severe and great storms were first recorded in cycle 22. This depicts that severe and great storms were observed at solar maximum and the descending phase of the cycle.

It is evident from Figure 3a, that the variation of SSN followed the phases of the solar cycle. The year 2000 is the maximum year of solar cycle 23 when SSN is maxima, the highest storm was observed in the same year. Also, more storms were observed during the descending phase (2001 – 2008) than in the ascending phase (1997 – 1999). In Figure 3b, moderate storms were recorded in all the years. Intense and severe storms were also recorded in all the years (except 2007 and 2008) and (1997, 2002 - 2004 2006 - 2008) respectively. Great storms were observed in 2001, 2003, and 2004 only. It is interesting to note that solar maximum of solar cycle 23 was recorded in the year 2000; however, great storms were not recorded in this year. Great storms were, however, observed during the descending phase of the solar cycle.

From Figure 4a, it is seen that the variation of SSN followed the phases of the solar cycle. The year 2014 is the maximum year of solar cycle 24, however, GMSs tend to peak in 2015 which is not the solar maximum year. That is, during the descending phase of the solar cycle. Figure 4b presents the average number of storm days per year based on storm classification during cycle 24. Moderate storms were the frequently occurring storms as they were recorded in all the years. Intense storms were observed in all the years except in 2009, 2010, and 2019 while severe storms were only recorded in 2015 when the highest storm was observed. Great storms were not recorded in solar cycle 24. This may depict the weak nature of the solar cycle 24. This is in line with the result of Reyes *et al*. (2021) and Sawadogo *et al*. (2022).

3.2 Frequency of GMSs Occurrence in each Solar Cycle

The frequency of GMSs occurrence in each solar cycle during cycles 21 – 24 is shown in Table 2. It could be observed that the total storms recorded in cycles 21 – 24 were 207, 179, 205, and 116 respectively. These were classified as follows: for cycle 21, the 207 storms were classified as moderate (70.53 %), intense (23.67 %), and severe storms (5.79 %). For cycle 22, we observed moderate (61.45 %), intense (31.84 %), severe (5.59 %), and great storms (1.12 %). In cycle 23, we recorded moderate (66.82 %), intense (25.85 %), severe (5.36 %), and great storms (1.95 %), while for cycle 24, we observed moderate (80.17 %), intense (18.10 %), and severe storms (1.72 %) respectively.

This reveals that among the classes of storms considered, moderate storms were the frequently occurring and dominant storms as they accounted for about 62.22 – 80.17 %, whereas great storms were the least occurring storms as they accounted for about 1.12 – 1.95 % of the observed storms respectively.

It is interesting to note that even though moderate storms occurred frequently, they may last for a relatively short time and may be associated with less energetic particles. Thus, they may be less harmful as compared to severe and great storms that do not occur frequently but are very dangerous, due to their time scale and the associated energetic particles (Kevser, 2021).

It is evident from Table 2 that from solar cycles 21 – 24 considered in this study, solar cycle 24 has the highest moderate storms (80.17 %) with few severe storms (1.72 %) and no great storms. This indicates the weak nature of cycle 24 as one of the weakest solar cycles on record (Reyes et al. 2021). We tend to suggest that for every weak solar cycle, they are higher probability of occurrence of moderate storms as compared to other classes of large storms (Dst ≤ -50 nT).

To further investigate the interconnectivity between solar and geomagnetic activity, we performed Pearson correlation analysis between SSN and number of storms for each solar cycle at 0.05 significant level. The correlation coefficient, r for solar cycles 21, 22, 23, and 24 are 0.58, 0.89, 0.79, and 0.78 respectively. This depicts strong and positive relationship between solar and geomagnetic activity, consistency with earlier reports. The value of the correlation coefficient, r however, differs from solar cycle to solar cycle. This implies that the strength of the relationship varied from one solar cycle to another. This may be due to the fact that each solar cycle may have unique features and characteristics.

3.3 Statistical Characteristics of Storms during Solar Cycles 21 - 24

Statistical characteristics of storms in each solar cycle were determined using descriptive statistics, and the observed statistical parameters are presented in Table 3. It could be observed that the mean, minimum, and maximum storms observed during cycles 21 – 24 ranges from 9.67 - 17.25, 3.00 – 13.00, and 14.00 – 27.00, while standard deviation (StDev) and variance are 2.31 – 4.42 and 5.45 – 19.53 respectively. To check the distribution of storms in each solar cycle, skewness and kurtosis analysis were performed. Negative skewness was observed in cycles 21, 22, and 24. This depicts storms distribution with an asymmetric long tail to the left, while positive skewness observed in cycle 23 depicts storm distribution with an asymmetric long tail to the right. The observed positive and negative skewness show the asymmetry nature of the distribution of storms around the mean. Similarly, negative kurtosis was observed in all the solar cycles considered except cycle 23, indicating flat distribution of storms in these cycles; while the positive kurtosis in cycle 23 depicts peak distribution of storms. The observed variation in the statistical parameters indicates that the frequency and distribution of storm occurrence varied from one solar cycle to another.

3.4 Frequency and Time of Occurrence of Great Storms during Solar Cycles 22 and 23

Among the categories of storms, the frequency and time of occurrence of great storms (Dst ≤ -350 nT); which may have received little or no attention by earlier studies, were considered. This is due to the severe impacts of great storms (Wu et al., 2016). Figure 5 presents the frequency and time of occurrence of great storms for the period under study. It could be observed that great storms were only observed during solar cycles 22 and 23. Thus, no great storms were recorded during cycles 21 and 24.

The great storms recorded in cycle 22 were observed on March 13 – 14th (72 – 73rd days) 1989 at 21 – 3 UT and November 9th (313th days) 1991 at 1 – 2 UT. Similarly, for cycle 23, great storms were recorded on March 31st (90th days) 2001 at 7 – 8 UT, October 30th (304th days) 2003 at 22 – 23 UT, and November 8th (313th days) 2004 at 5 – 6 UT respectively. This depicts that great storms probably occur at about 21 – 8 UT. This confirmed the findings of Gonzalez et al. (1994) who reported that the formation of ring currents which depict the strength of GMSs are due to the drifting of ions and electrons from midnight towards dusk and dawn respectively due to magnetic field gradient. Besides, great storms were observed to last for few hours (Figure 5) within the threshold of about 1 – 3 hours recommended for storm occurrence by Gonzalez et al. (1994). This observation on the frequency and time of occurrence of great storms may probably serve as a guide to space scientists on modeling, forecasting, as well as in observing occurrence of great storms.

Furthermore, great storms were recorded during equinoctial conditions (March, October, and November) which are in spring and autumn seasons. This suggests that great storms probably occur in equinoctial conditions. It has been reported that GMSs are numerous during equinox conditions: spring (March, April, and May) and autumn (September, October, and November) as compared to solstice conditions: summer (June, July, and August) and winter (December, January, and February) (Audu *et al.,* 2024). Thus, we tend to suggest that besides the increase of GMSs during equinoctial conditions reported earlier, our findings depict higher occurrence of great storms during equinoctial conditions.

From the foregoing, variation of SSN and the occurrence of GMSs differ from solar cycle to solar cycle; however, GMSs followed the phases of the solar cycle. We also observed that GMSs can occur at any time during the solar cycle, but the classes of GMSs observed may depend on the phases of the solar cycle. Our observation further indicates that most of the storms occurred during solar maximum and declining phase of solar cycle, due to increase in solar activity during this period, which is in conformity to previous studies. This is clear evidence that the intensity and severity of GMSs are controlled by solar activity (Watari, 2017).

Based on the classification of storms, it could be observed that the frequently occurring storms are moderate storms, as they were observed in all solar cycles irrespective of the phases of the cycle. However, the total number of storms depends on the phases of solar cycle. On the other hand, the least occurring storms were great storms. Great storms were observed during solar maximum and declining phase of solar cycle. Severe storms were mostly observed during this period too. This could be attributed to the sources of the GMSs. According to Kevser *et al*. (2021), GMSs are generally classified into (I) CMEs driven storms which are due to explosive release of energetic particles from the sun and they occur during solar maximum, and (II) Streams Interaction Region (SIR) storms, which are mostly associated with high-speed streams in the co-rotational interaction region. SIR storms are due to persistent coronal holes developed on the sun's surface and are normally observed during the descending phase of solar cycle. This possibly explained the increase in storm occurrence observed in this study during solar maximum and the declining phase of the solar cycle.

The results of this study have contributed significantly to the earlier reports on GMSs by other scholars (Dal Lago *et al*., 2004; Rathore *et al*., 2014; Doha and Wathiq, 2019; Mandea and Chambodut, 2020). Furthermore, based on the classification of GMSs (moderate, intense, severe, and great storms) using the minimum Dst value, we found the least and the most frequently occurring storms, the seasons, and hours for possible occurrence of great storms.

The findings of this research have shown the month, season, time, as well as the phases of the solar cycle to expect higher probability and frequency of storm occurrence. This may help space scientists to know the period and the classes of storms that may probably occur. The implication is that astronauts and other space scientists may possibly avert the impacts of storms while exploring the space. This study has therefore provided scientific insight that will be useful to space, atmospheric, and solar scientists, in modeling, forecasting, as well as in observing GMSs. Thus, we hereby recommend similar and further studies for solar cycle 25.

Table 2. Frequency and occurrence of GMSs for each solar cycle

Solar Cycles	**Classification of Geomagnetic Storms (GMSs)**								**Total GMs**
	Moderate (M)		**Intense (I)**		**Severe (S)**		**Great (G)**		
	Total	%	Total	**%**	Total	**%**	Total	%	
Cycle 21	146	70.53	49	23.67	12	5.79	-	-	207
Cycle 22	110	61.45	57	31.84	10	5.59	2	1.12	179
Cycle 23	137	66.82	53	25.85	11	5.36	4.0	1.95	205
Cycle 24	93	80.17	21	18.10	2	1.72	-	-	116

Table 3. Descriptive statistics of storm frequency and distribution during cycles 21 – 24

Statistics	**Cycle 21**	**Cycle 22**	**Cycle 23**	**Cycle 24**
Mean	17.25	14.91	17.08	9.67
StDev	2.73	2.31	4.42	3.39
Minimum	13.00	11.00	11.00	3.00
Variance	7.47	5.35	19.53	11.51
Maximum	20.00	18.00	27.00	14.00
Skewness	-0.47	-0.09	0.92	-0.65
Kurtosis	-1.37	-1.23	1.12	-0.14

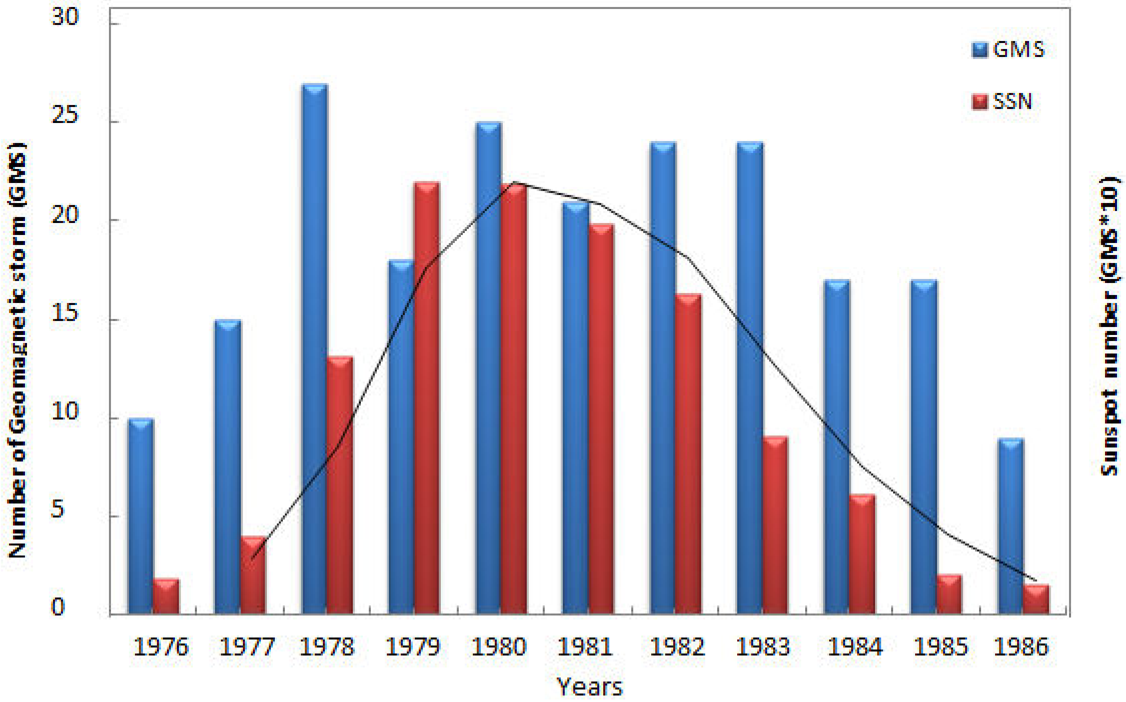

Figure 1a. Averages of sunspot number and number of storm days per year during Cycle 21

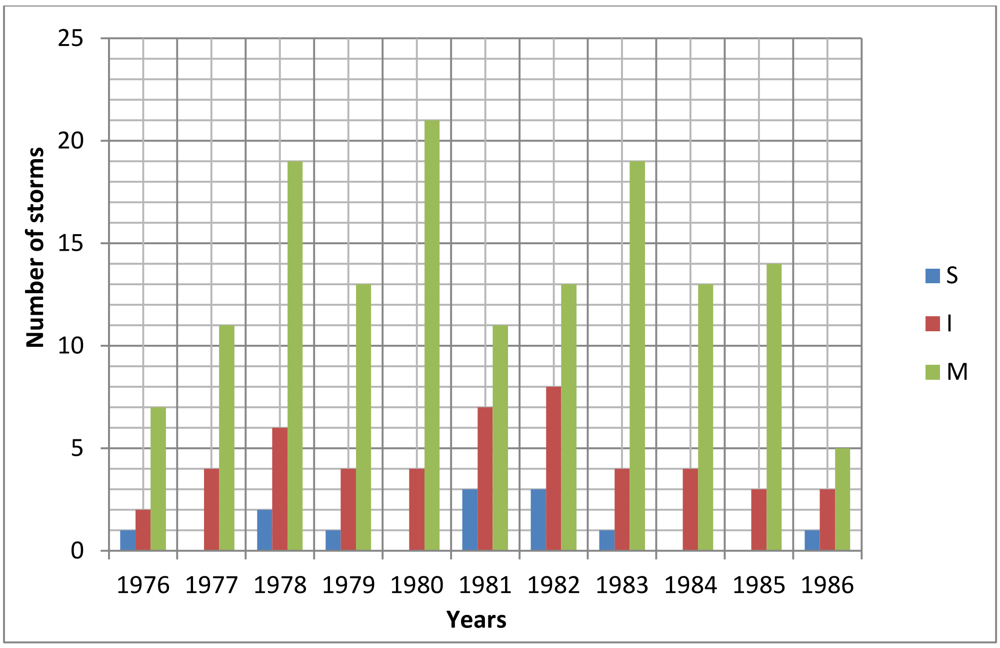

Figure 1b. Average number of storms per year based on storms' classification during Cycle 21

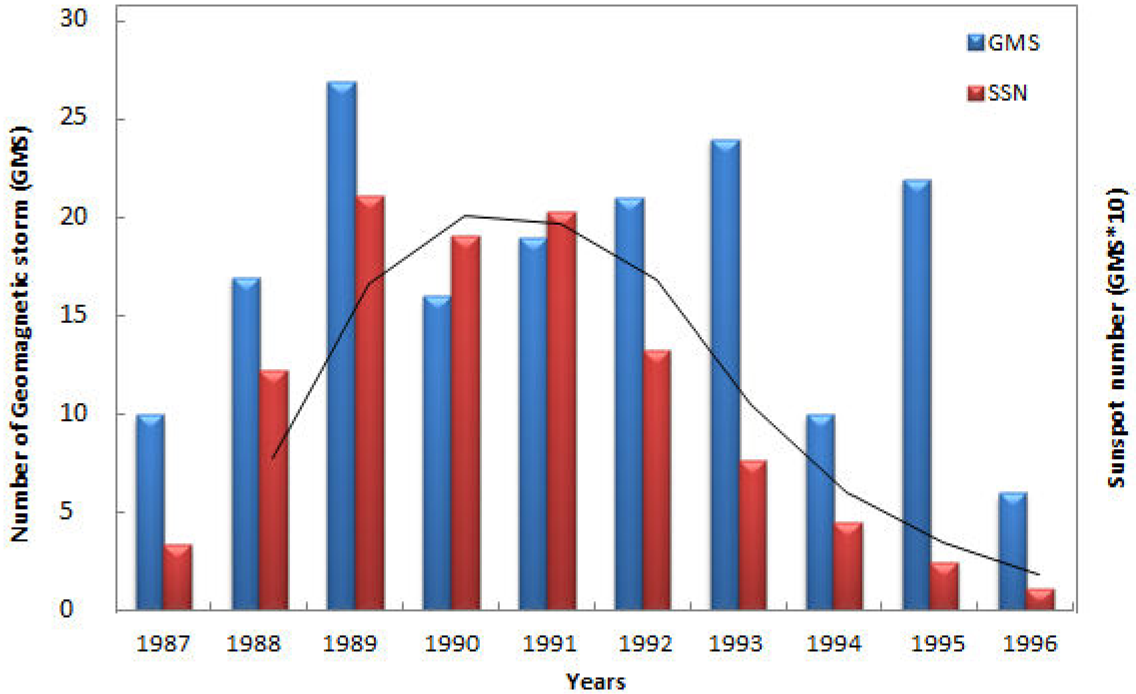

Figure 2a. Averages of sunspot s number and number of storm days per year during Cycle 22

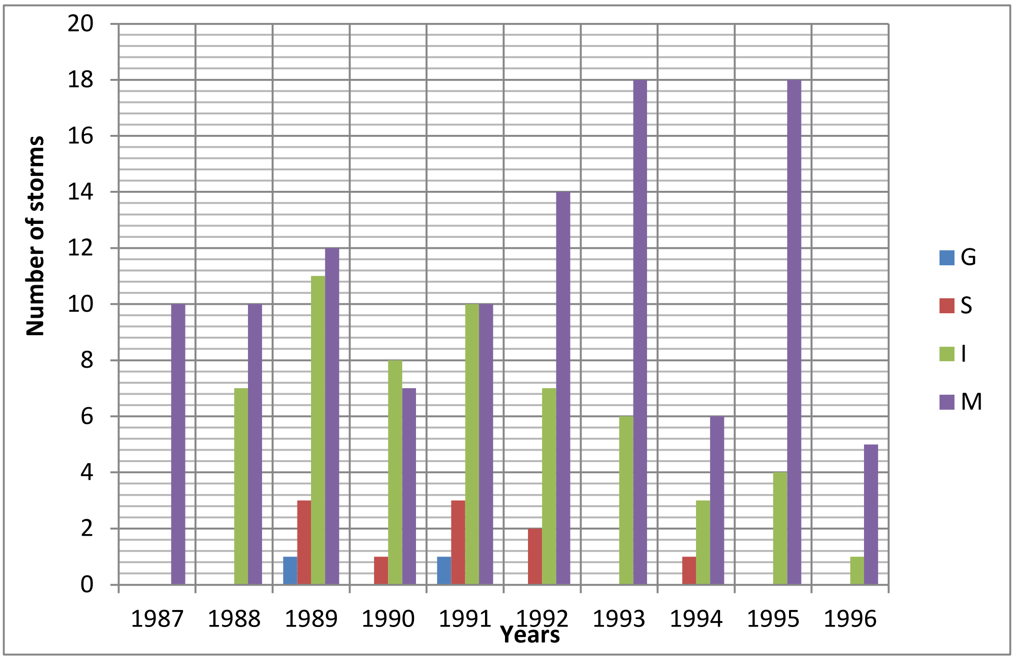

Figure 2b. Average number of storms per year based on storms classification during Cycle 22

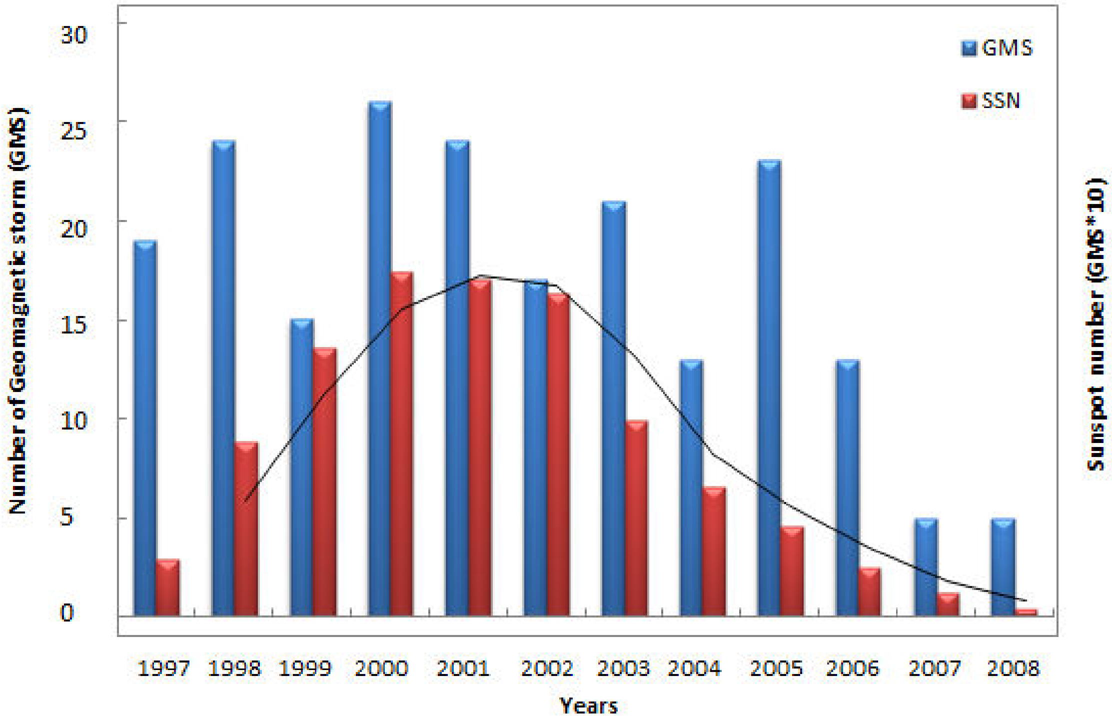

Figure 3a. Averages of sunspot number and number of storm days per year during Cycle 23

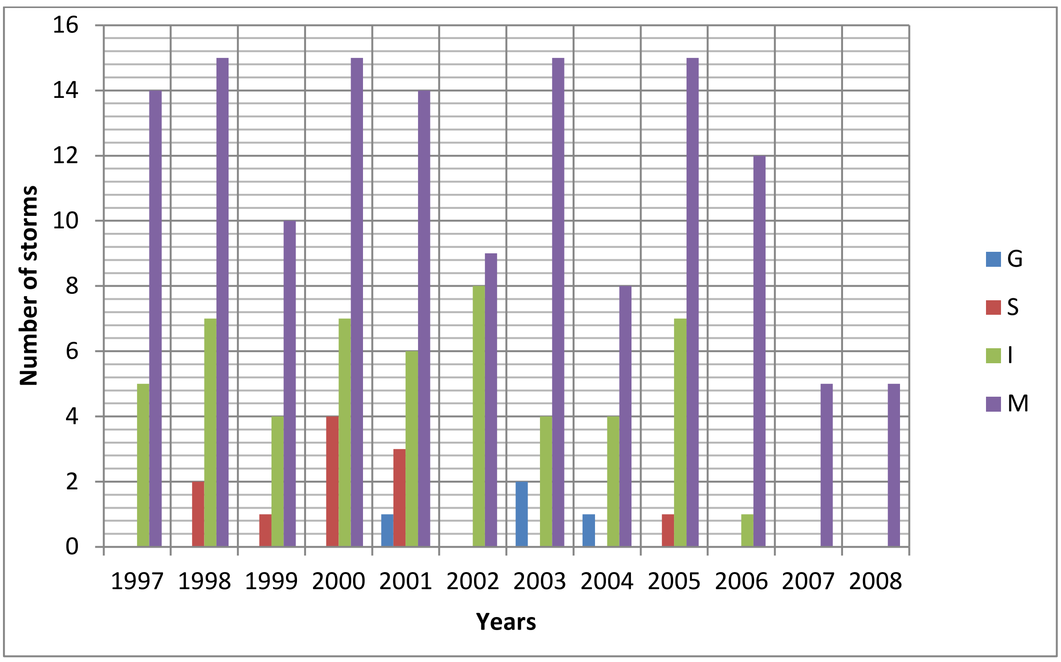

Figure 3b. Average number of storms per year based on storms classification during Cycle 23

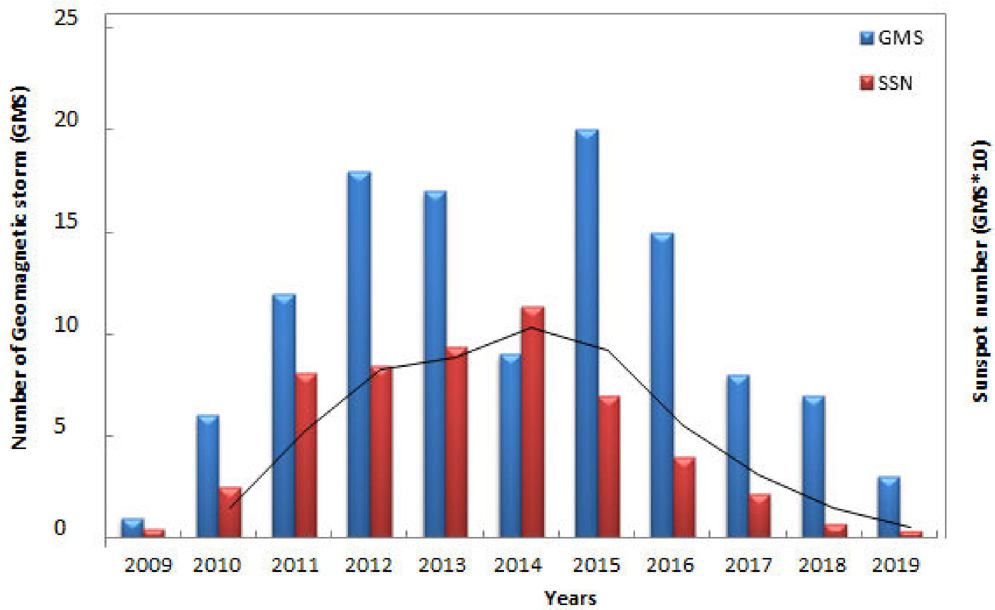

Figure 4a. Averages of sunspot number and number of storm days per year during Cycle 24

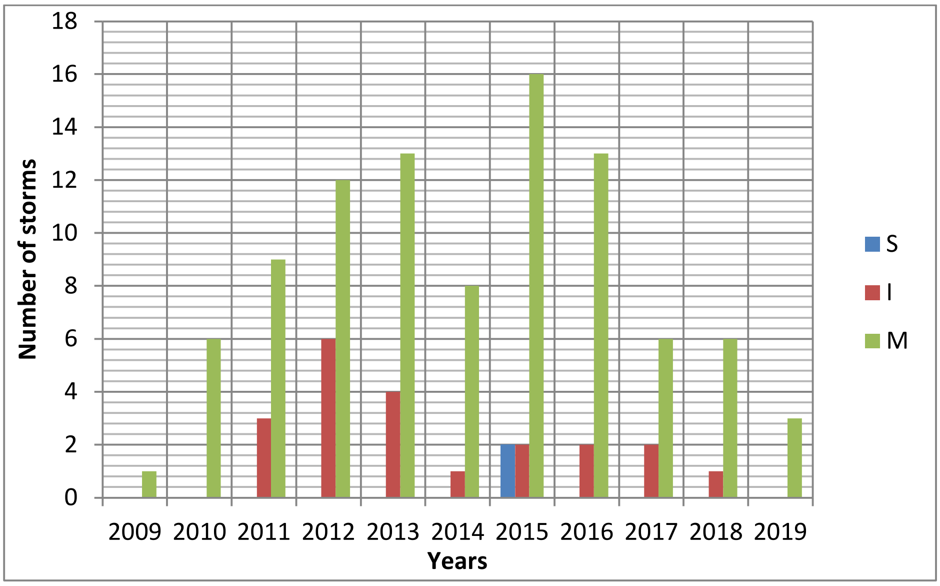

Figure 4b. Average number of storms per year based on storm classification during Cycle 24

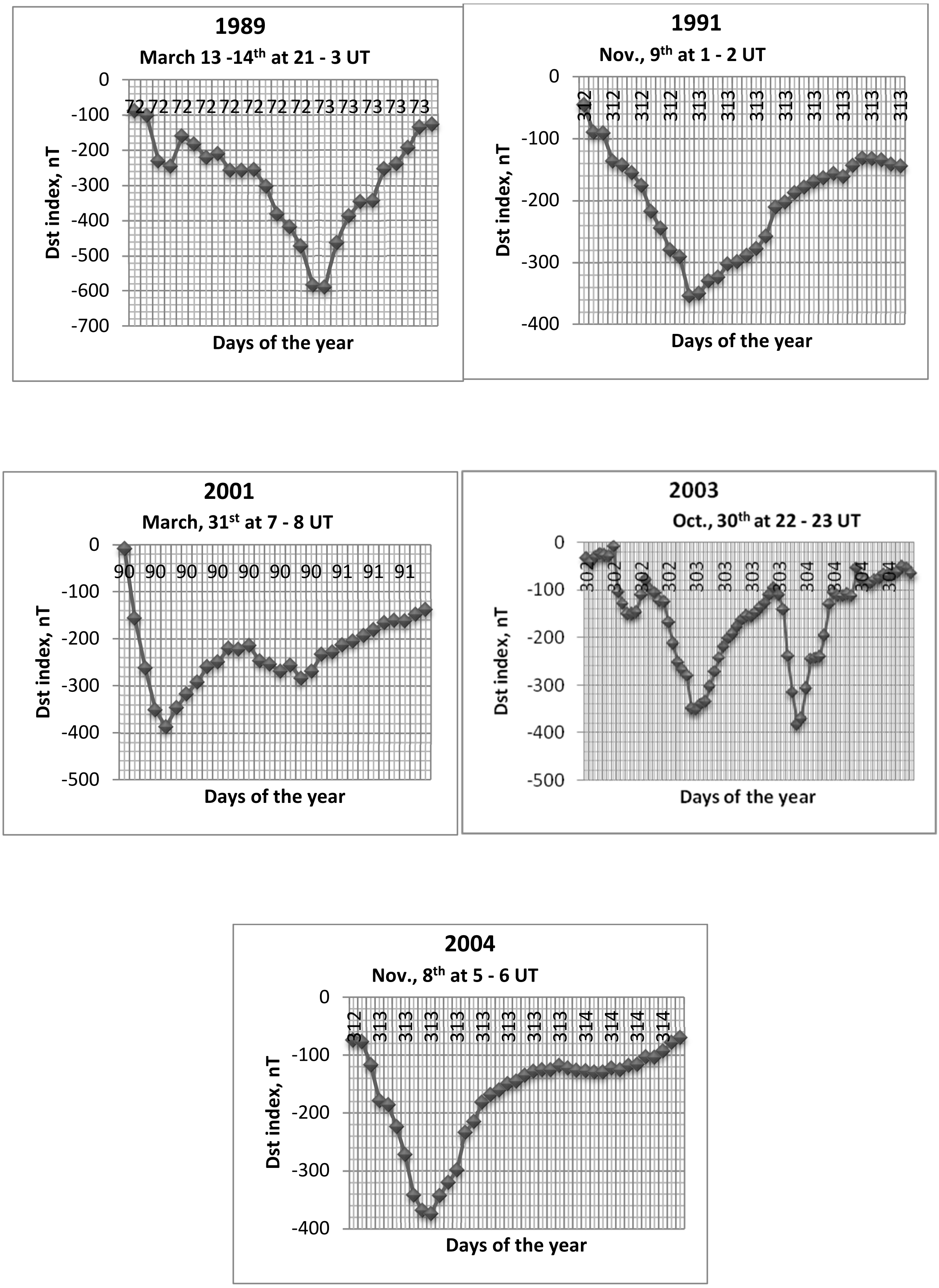

Figure 5. Frequency and time of occurrence of great storm during solar cycles 22 and 23

3. CONCLUSIONS

This work investigates potential connections between sunspot number, geomagnetic storms, phases of solar cycle and Universal Time (UT) hour for occurrence of geomagnetic storms (GMSs). The total GMSs observed during solar cycles 21 - 24 (1976 - 2019) were identified using minimum Dst value. These were classified into moderate, intense, severe, and great storms and were analyzed. The following conclusions are drawn from this study:

I. SSN and the frequency of occurrence of GMSs varied from solar cycle to solar cycle.
II. The frequency of occurrence of GMSs during solar cycles 21 – 24 are: moderate (62.22 – 80.17 %), intense (23.67 - 18.10 %), severe (5.79 – 1.72 %), and great storms (1.12 – 1.95 %).
III. The result of storm occurrence during cycle 24 suggests that for every weak cycle, they are higher probability of occurrence of moderate storms as compared to other classes of large storms (Dst ≤ -50 nT).
IV. Besides the increase of GMSs during equinoctial conditions reported by earlier scholars, our result depicts higher probability of occurrence of great storms (Dst ≤ -350 nT) during this period.We observed great storms at about 21 – 8 UT during equinoctial conditions only, depicting possible time for occurrence of great storms. This confirmed the findings of Gonzalez et al. (1994).
V. The observed duration for occurrence of great storm is in conformity with the threshold of about 1 – 3 hours recommended for storm occurrence by Gonzalez *et al*. (1994).
VI. The result of the correlation analysis depicts connection between solar and geomagnetic activity, however, the observed interconnectivity varied from one solar cycle to another due to the unique features and characteristics of each solar cycle.

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