



Intense Geomagnetic Storms, its Causes in Interplanetary Magnetic Field and Arising Phase of Solar Cycles 23 & 24

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Abstract: Geomagnetic Storms are disturbances in Earth's magnetosphere caused by solar activities such as solar flares or coronal mass ejection (CMEs). These storms occur when solar wind carrying charged particles and magnetic field, interacts with Earth's magnetic field. Here we have investigated the relationship between cycles 22, 23 and the rising phase of cycle 24. Solar features are, we observed and used to qualitatively characterise intense storms. The results of this paper reviewed specifically provide an estimate of the main source of geomagnetic storms (GMS), which are arising in cycle 22 & 23 and rising phase of cycle 24. We observed that solar cycle 23 was magnetically disturbed with 41.52% of disturbed days against 27.58% for cycle 24 which was magnetically calm with 72.35% of quiet days against 58.64% for cycle 23. The solar cycle 24 proceeded as a low energy cycle with historically lower energy levels of sunspots and geomagnetic activity than that of all previous solar cycles of the space era. Solar cycle 24 presents similar characteristics as solar cycles 12 & 14 which experienced spotless days at solar maxima and have experienced Gleissberg minimum.

Keywords: CMEs, X-ray solar flares, radio bursts, inter-planetary magnetic fields and geomagnetic storms, antagonistic cycle.

Introduction: The Solar activity, solar flares and coronal mass ejections are most energetic solar events in the heliosphere and are widely recognized as being responsible for production of geomagnetic disturbances in geomagnetic fields. Solar flares and CMEs are two major manifestations of eruptive release of energy. Flares are related to small scale magnetic fields. It is now well established that coronal mass ejections (CMEs) are a major cause for large geomagnetic storms. High speed streams (HIS) in corotating interaction regions (CIRs) causes only moderate to weak storms ($-100\text{nT} \leq \text{Dst} \leq 50\text{nT}$). The Earth's main field varies slowly in time and creates a cavity in interplanetary space which is called the geomagnetosphere, where the Earth's magnetic field dominates the magnetic field of solar wind, this is known as interplanetary manifestation which is a continuous stream of energetic particles called "solar wind". This energetic flow interacts with earth's atmosphere modifies the electromagnetic environment of earth (geomagnetic variations, auroras) affecting different technological tools, impacting human life and activity.

The Solar wind is responsible for 91.5% of geomagnetic activity according to some previous investigation Legrand and Simon 1989, 1990; zerbo et al 2013. By investigating the long term evolution of solar and geomagnetic activities showed themselves useful for understanding the dynamics of Earth's

atmosphere. Many Studies have been carried out to understand solar activity and its terrestrial impacts. Legrand and Simon (1989, 1991), Richardson and Cane (2002), Uttara and Amory-Mazaudier (2009), Etal (2011, 2012) have studied solar activity based on various transient variations experienced by the Earth's magnetic field in response to the influence of solar magnetism. It is observed that the close link between variations of solar wind and geomagnetic activity level over several time scales and have outlined the fact that the coupling between the solar wind and the Earth's magnetosphere is the main source of all observed fluctuations in Earth's magnetism, such as geomagnetic storms and auroras.

Brief, Studies Already Done: It is well known that stronger geomagnetic storms are usually due to solar wind disturbances created by interplanetary coronal mass ejections (ICMEs) and their propagation through the interplanetary medium. These investigations about different authors (Gosling et al., 1990; Tsurutani et al., 1992; Vennerstorm, 2001; Gonzalez et al., 2007; Verbanac et al., 2013; Lamy et al., 2019) have investigated CMEs and their properties through several automated catalogs and established that CME occurrence follow solar activity indices/proxies with no time lag. Najra et al (2021) analysed the long term variations of geomagnetic activity and the solar wind magnetosphere coupling during solar cycles 20-24, it is observed that cycles 20 and 24 have had significantly weak energy levels compared to cycles 19,21,22, and 23. In the present study an attempt was carried out to discover particularities in solar wind conditions during the solar cycle 23 and 24, and presented the comparison between the cycles.

METHODOLOGY: Data used in this work were obtained from different sources and cover the solar cycles 23 and 24 (1996-2019). These data were used to investigate the level of solar and geomagnetic activity during both solar cycles over different period of time (day, month, and year) which is used to investigate the specificity of each solar cycle. (1) The IMF-Bz component of the interplanetary magnetic field, the interplanetary electric field (E), the proton density (N), and the Dst (disturbance storm time) index obtained from <http://omniweb.gsfc.nasa.gov/ow.html>. The Polar cap (PC) indices (PCN and PCS) were used from <http://isgi.latmos.ipsl.fr/>. The Dst index, a standard measure of ring current, is used here to identify intense storms ($Dst < -100$ nT) during two solar cycles. The IMF-Bz, electric field E were used to investigate the information of the severity of magnetic storms. PC index were used to investigate the level of energy transferred from solar wind to Earth's magnetosphere. (2) The sunspots number available on the site <http://www.sidc.be/silso/>. We have also counted the number of spotless days during the period 1875 to 2019, to observe its evolution according to the different phases of the solar cycle. (3) The geomagnetic aa index taken from the ISGI website <http://isgi.latmos.ipsl.fr/>. The aa index (planetary measure of magnetic activity based on two antipodal observatories) was used to give an overview of the level of each class of geomagnetic activity. This classification (Quiet, Recurrence, Shock, and fluctuating activities) defined by Legrand and Simon (1989) which is fully described by some authors (Uttara and Amory-Mazaudier, 2009; Zerbo et al., 2012) with extended criterion in Zerbo et al. (2012). This observation allows the identification to extract from two additional classes from the fluctuating activity defined by Legrand and Simon (1989) using a pixel diagram which display the daily average of Aa index as a table over Bartles rotation. These classes of geomagnetic activity are: (1) Quiet activity days which are defined as days when $Aa < 20$. The other classes constitute the disturbed geomagnetic activity classes which occur on days when $Aa \geq 20$ nT (Legrand and Simon, 1989). These classes are distinguished as follows:

(2) Recurrent (stream) activity (RA) is driven by fast solar wind from coronal holes which persist for more than one solar rotation without storms. This class corresponds in the pixel diagrams to days where $Aa > 40$ at the same solar longitude for at least two consecutive solar rotations (Legrand and Simon, 1989).

(3) Shock activity (SA) is driven by CMEs on the Sun which often produces high solar wind speeds. SA is defined to occur on days when SSC are observed and up to 3 days after the shock passage where $A_a > 40$ nT (Legrand and Simon, 1989).

(4) Co-rotating activity: This class is defined as the manifestation of solar winds, stable in co-rotation and having moderate magnetic effects in the vicinity of the terrestrial environment. Under these conditions, the geomagnetic index is such that $20 \text{ nT} \leq A_a < 40 \text{ nT}$. This class is identified by the areas of recurrence without SSC (Zerbo et al., 2012).

(5) Clouds shock activity: This activity includes shock events causing a moderate change in the level of geomagnetic activity. The days selected are the SSC dates whose effect lasts one to three days. Which are corresponding A_a vary from 20 to 40 nT (Zerbo et al., 2012).

(6) Unclear activity (Fluctuating): This is the class of transient and fluctuating events that are not taken into account in the previous classes. Figure 1 shows the pixel diagram for the year 2003 with the different classes of solar activity (Zerbo et al., 2012). Circle represents the data of sudden storms commencement (SSC).

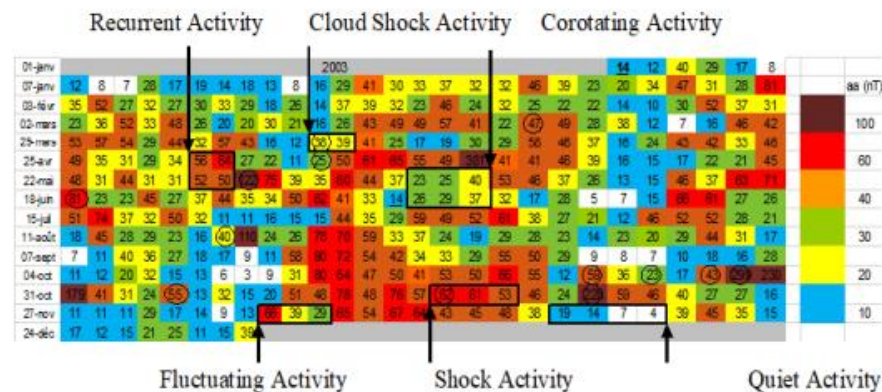


Figure 1. Pixel diagram of the A_a index for the year 2003.
Source: Adopted from Zerbo et al. (2012).

Results and Discussions

Level of geomagnetic activity during the two solar cycles

Figure 2a represents the histograms the occurrence of geomagnetic quiet activity and the sunspots number's profile during the period covered by the study (1996 to 2019). It appears that low solar wind structure remind permanent during the entire period investigated. However, differences in importance can be noticed: the most impressive level of quiet activity is observed when sunspot number reached its minimum values for both solar cycles 23 and 24 (Figure 2). This observation has been established in several studies (Russell et al., 2010; Tsurutani et al., 2011; Richardson and Cane, 2012a, b), where it has been noted that geomagnetic activity during the minimum following solar cycle 23 was exceptionally low, and associated with unusual solar wind conditions, especially low magnetic field strengths, and slow flow velocities. It is also easy to see that quiet days class occurrence is much more important during the whole period of the solar cycle 24 compared to that of solar cycle 23. Moreover, a statistical study of the magnetic quiet day's number shows that solar cycle 24 is the magnetically quieter of the two solar cycles, with 72.35% of quiet days versus 58.64% for solar cycle 23. This observation is in argument with the investigations conducted by Zerbo and Richardson (2015) and Nakagawa et al. (2019) where a significant drop in solar wind parameters has been show during the last

decade. The weak solar polar fields (McComas et al., 2008; Kilpua et al., 2014) may result in fewer low-latitude excursions of coronal polar holes and hence a wider area of slow solar wind. This slow solar wind condition also induces low solar wind pressure. Referring to the strong correlation, between solar wind speed and the geomagnetic aa index, established by Svalgaard (1977), Zerbo and al. (2015), we can see that Earth was under slow solar wind conditions during the solar cycle 24. Figure 2b superimposes the histograms of shock days and sunspot number variation over the past two solar cycles. The notable aspect of this figure is that shock activity does not cover the entire period. The highest level of shock activity is recorded during the maximum phase of sunspot cycle of each solar cycle. Comparing the two solar cycles, it appears that the level of shock activity during solar cycle 23 is much more important than that of solar cycle 24. Moreover, with a statistical study of the level of shock activity for each solar cycle, we get 2.08% shock days during solar cycle 23, compared to 0.8% for cycle 24. Thus, we then deduce that solar cycle 23 was much more disturbed and Earth was under strong shock waves compared to the cycle solar 24. Figure 2 represents the occurrence of the six different classes of geomagnetic activity. The Figure 2c represents the occurrence of the recurrent activity and the profile of sunspots number over the period of our investigation. The morphological analysis of this figure shows that recurrent events reach a maximum level at the descending phase of each solar cycle as reviewed by Legrand and simon (1989), Ouattara and Amory-Mazaudier (2009), and Zerbo et al. (2012, 2013). Thus, comparing the level of recurrence events of the two cycles, we observe that the level of recurrent activity during the solar cycle 23 is greater than that of solar cycle 24 (Figure 2c). A statistical study of the level of recurrence events shows that, during the solar cycle 23 recurrent days represent 3.26% of the global geomagnetic activity against 1.12% for the solar cycle 24. We can then assume that the solar cycle 23 has experienced much more recurrent high streams solar wind condition compared to that of the solar cycle 24. That makes it the most disturbed cycle of both. Figure 2d represents the percentages of occurrence of corotating activity and the temporal evolution of the sunspots number. This activity remains during the entire period of our study but present various levels in time. Over the entire series of data analysed, the level of

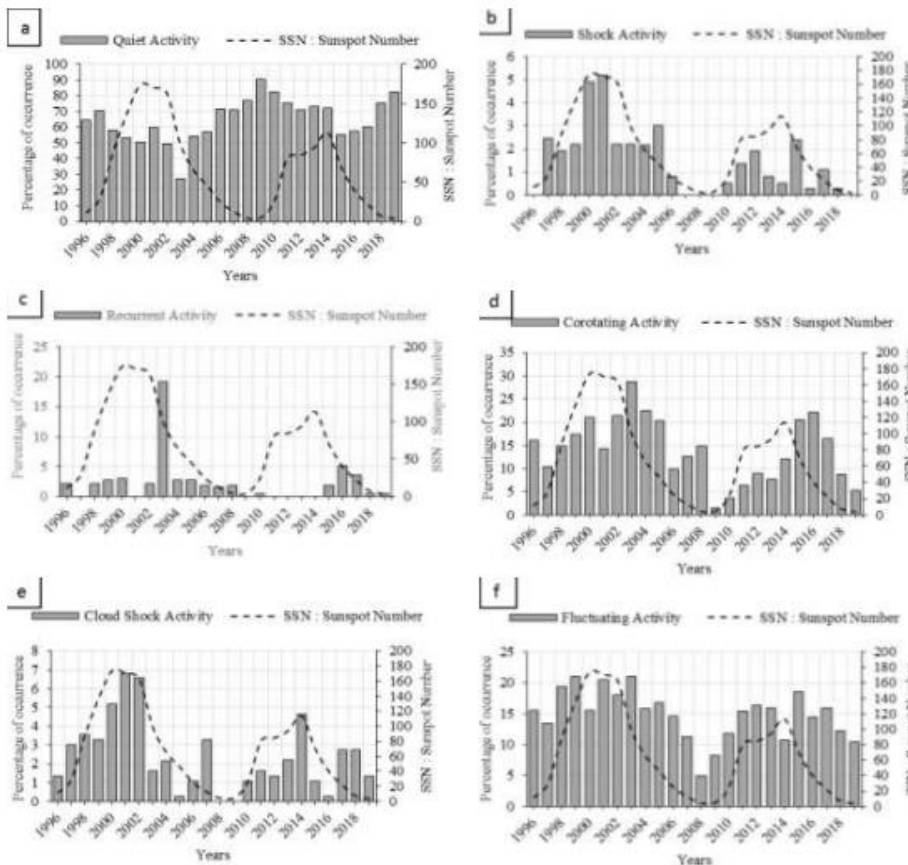


Figure 2. Histogram of the percentages of occurrence geomagnetic activity and sunspot number profile from 1996 to 2019: (a) quiet days; (b) shock activity; (c) recurrent activity; (d) corotating activity; (e) cloud shock activity; (f) fluctuating activity. Source: Koala et al. (2022).

corotating activity is higher on the descending phase of each solar cycle. That is in agreement with conclusion made in Zerbo et al. (2012) on the importance rate of recurrent wind condition into the earth atmosphere. From this figure, it appears that the level of corotating activity is much important during the solar cycle 23 compared to the follower one. With a statistical study we have pointed out that corotating activity represents about 17.22% of geomagnetic activity during the cycle 23 against 10.28% for solar cycle 24. This is agreement with the fact that coronal holes and the co-rotating interaction regions (CIRs) are more geoeffective during the descending phase of the solar cycle as reported in previous studies (Smith and Wolfe, 1976; Sheeley and Harvey, 1981; Burlaga et al., 1978). From this result, we can conclude that the solar cycle 23 has experienced more corotative events from corotating interactive regions compared to solar cycle 24. Figure 2e represents the occurrence of magnetic clouds days and the evolution of the sunspots number during the solar cycles 23 and 24. During this period it is interesting to note that the magnetic clouds activity evolves with the number of sunspots. It reaches its maximum at the same time as sunspots number. It is the geomagnetic responses of solar plasma's sporadic disturbances. From this figure we also notice that the level of magnetic cloud activity during solar cycle 23 is greater than that of solar cycle 24. A statistical study concludes that 2.94% of solar cycle 23's global geomagnetic activity represents cloud activity against 1.74% for solar cycle 24. Figure 2f represents the percentages of occurrence of fluctuating activity and the profile of the sunspots number during the period 1996 to 2019. Fluctuating activity is observed at all the phases of the solar cycle. The permanent fluctuation of the heliosheet (Simon and Legrand, 1989) may explain the observations of these effects through all the solar cycle phases. This figure shares that fluctuations conditions are important during the ascending and decreasing phases of each solar cycle. This may be due to the importance of Sun agitation during these phases of solar cycle characterized by transition between slow and high stream wind conditions

and reciprocally. We can also notice on this figure that, the level of fluctuation during the solar cycle 23 is much more important than that of the solar cycle 24. Additionnal statistical study of the level of fluctuating activity allowed us to point out that fluctuating activity represents 16% geomagnetic activity for solar cycle 23 against 13.64% for solar cycle 24. This indicates that earth was particularly under remarkable fluctuating solar wind conditions during solar cycle 23.

Conclusion

The main objective of the present study is to examine and achieve a better understanding of geomagnetic conditions during two successive solar cycles. The main findings are as follows:

- (1) A decrease in the energy level of solar activity and that of geomagnetic activity during the last decade
- (2) The solar cycle 23 was magnetically disturbed with 41.52% of disturbed days against 27.58% for cycle 24 which was magnetically calm with 72.35% of quiet days against 58.64% for cycle 23.
- (3) The strength of the magnetic field reached a historical low level during solar minimum which follow the solar cycle 23 and remained weak during all the solar cycle 24 phases; extending at the same time the work by Zerbo et al. (2012, 2013) on geomagnetism. Going back in previous works (Zerbo et al., 2015; Owens et al., 2008a, b) and using recent observations, we have observed that the remarkable low in geomagnetic and solar activities level during the deep solar minimum which follow the solar cycle 23 remained over the solar cycle 24 and may help to understand the unusual solar wind conditions.
- (4) The solar cycle 24 proceeded as a low-magnitude cycle with historical lower level of sunspot and geomagnetic activity than that of all previous solar cycles of the space era.
- (5) Solar cycle 24 presents similar characteristics as solar cycles 12 and 14 which experienced spotless days at solar maximum and have experienced Gleissberg minimum.
- (6) The solar activity and solar plasma parameters retain a downward trend since the deep minimum that followed the solar 23, so we can witness in future solar cycles, a period similar to the Gleissberg minimum. With all these observations, we conclude that solar cycle 24 experienced lower magnetic and sunspot level compared to solar cycle 23. So, the two solar appear as two antagonistic magnitude cycles.

Conflict of Interest

The authors have not declared any conflict of interest.

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References

Banerjee A, Amaresh B, Chatterjee TN, Majumdar A (2019). An SOC Approach to Study the Solar Wind-Magnetosphere Energy Coupling. *Earth and Space Science* 6:565-576.
<https://doi.org/10.1029/2018EA000468>

Burlaga LF, Behannon KW, Hansen SF, Pneuman GW, Feldman WC (1978). Sources of magnetic fields in recurrent interplanetary streams. *Journal of Geophysical Research: Space Physics* 83:4177-4185.
<https://doi.org/10.1029/JA083iA09p04177>

Dungey JW (1961). Interplanetary Magnetic Field and the Auroral Zones. *Physical Review Letters* 6:47-48.
<https://doi.org/10.1103/PhysRevLett.6.47>

Gonzalez WD, Tsurutani BT (1987). Criteria of interplanetary parameters causing intense magnetic storms ($Dst < -100$ nT). *Planetary and Space Science* 35:1101-1109.
[https://doi.org/10.1016/0032-0633\(87\)90015-8](https://doi.org/10.1016/0032-0633(87)90015-8)

Hajra R, Marques de Souza Franco A, Echer E, José Alves Bolzan M (2021). Long-Term Variations of the Geomagnetic Activity: A Comparison Between the Strong and Weak Solar Activity Cycles and Implications for the Space Climate. *Journal of Geophysical Research: Space Physics* 126, e2020JA028695.
<https://doi.org/10.1029/2020JA028695>

Ishkov VN (2022). Outcomes and Lessons from Cycle 24—the First Cycle in the Second Epoch of Low Solar Activity. *Astronomy Reports* volume 66:48-63.
<https://doi.org/10.1134/S1063772922020056>

Kakad B, Kakad A, Ramesh DS, Lakhina GS (2019). Diminishing activity of recent solar cycles (22-24) and their impact on geospace. *Journal of Space Weather and Space Climate* 9:A1.
<https://doi.org/10.1051/swsc/2018048>

Kamide Y, Kusano K (2013). Is Something Wrong With the Present Solar Maximum? *Space Weather* 11:140-141.
<https://doi.org/10.1002/swe.20045>

Kilpua EKJ, Luhmann JG, Jian LK, Russell CT, Li Y (2014). Why have geomagnetic storms been so weak during the recent solar minimum and the rising phase of cycle 24? *Journal of Atmospheric and Solar- Terrestrial Physics* 107:12-19.
<https://doi.org/10.1016/j.jastp.2013.11.001>

Nakagawa Y, Nozawa S, Shinbori A (2019). Relationship between the low-latitude coronal hole area, solar wind velocity, and geomagnetic activity during solar cycles 23 and 24. *Earth, Planets and Space* 71:24.
<https://doi.org/10.1186/s40623-019-1005-y>

Troshichev OA, Dolgacheva SA, Sormakov DA (2022). Invariability of relationships between the solar wind electric field EKL and the magnetic activity indices PC, AL and Dst. Journal of Atmospheric and Solar-Terrestrial Physics 235, 105894.

<https://doi.org/10.1016/j.jastp.2022.105894>

Zerbo JL, Richardson JD (2015). The solar wind during current and past solar minima and maxima. Journal of Geophysical Research: Space Physics 120(10):250-10,256.

<https://doi.org/10.1002/2015JA021407>

Zhang J, Richardson IG, Webb DF, Gopalswamy N, Huttunen E, Kasper JC, Nitta NV, Poomvises W, Thompson BJ, Wu CC, Yashiro S, Zhukov AN (2007). Solar and interplanetary sources of major geomagnetic storms ($Dst \leq -100$ nT) during 1996–2005. Journal of Geophysical Research: Space Physics 112(A10).

<https://doi.org/10.1029/2007JA012321>

