Vol. 17(3), pp. 57-66, October-December, 2022
DOI: 10.5897/IJPS2022.4998
Article Number: 4A39F8869748
ISSN: 1992-1950
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International Journal of Physical Sciences

Full Length Research Paper

Solar wind and geomagnetic activity during two antagonist solar cycles: Comparative study between the solar cycles 23 and 24

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Received 29 June, 2022; Accepted 1 September, 2022

To better understand the geomagnetic conditions and the particularities of solar cycles 23 and 24, we present analysis from morphological variations of solar and geomagnetic activities parameters IMF-Bz, the interplanetary electric field (E), the proton density (N), Dst (disturbance storm time), Polar cap (PC) indices (PCN and PCS), and geomagnetic activity index aa. The occurrences of the different classes of geomagnetic activity established by Zerbo et al. (2012), through the daily averages of the Aa index are also presented for the period 1996-2019 covering the solar cycle 23 and 24. This investigation reveals: (1) a decrease in solar activity and geomagnetic activity during the last decade; (2) the solar cycle 23 was a magnetically disturbed solar cycle with 41.52% disturbed days versus 72.35% very quiet conditions for the solar cycle 24; (3) the most important numbers of intense and severe storm or magnetic substorm conditions (E, PC index, Dst < -100 nT) are recorded during the solar cycle 23; (4) solar cycle 24 presents similar characteristics as solar cycles 12 and 14 and has also experienced spotless days at its maximum phase; (5) solar cycle 24 experienced low solar activity compared to solar cycle 23. The two solar cycles can be qualified as antagonistic cycles.

Key words: Solar cycle, storms, solar activity, geomagnetic activity, antagonist cycle.

INTRODUCTION

It is well-Know that variabilities in Sun are closely associated to the intensity of its magnetic field and induce dynamo process. These changes in solar magnetic field structure are responsible of instabilities observed in the interplanetary medium. The main factor of this interplanetary manisfestation is continuously streams of energetic particles called "solar wind" emits from the Sun into the interplanetary environment. This energetic flow interacts with Earth atnompshere, modifies the electromagnetic environment of the Earth *(*geomagnetic

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variations, auroras), affects different technological tools and impacts 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). So investigating the long-term evolution of solar and geomagnetic activities showed themselves useful for understanding the dynamics of Earth atmosphere. Many studies have been carried out to understand solar activity and its terrestrial impacts. Legrand and Simon (1989, 1991), Richardson and Cane (2002), Ouattara and Amory-Mazaudier (2009), and Zerbo et al (2011, 2012) have studied solar activity based on the various transient variations experienced by the Earth's magnetic field in response to the influence of solar magnetism. They showed the close link between variation of solar wind parameters and geomagnetic activity level over several time scales and have out lighed 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. Dungey (1961) and Gonzalez et al. (1994) investigated the basic mechanism of energy transfer from the solar wind to the Earth's magnetosphere and lead it to the magnetic reconnection governed by the interaction between the interplanetary magnetic field southward component and the Earth's magnetic field.

From past and recent studies (Gosling et al., 1990; Tsurutani et al., 1992; Vennerstroem, 2001; Gonzalez et al., 2007; Verbanac et al., 2013) it is well known that stronger geomagnetic storms are usually due to solar wind disturbances created by interplanetary coronal mass ejections (ICME) and their propagation through the interplanetary medium. Lamy et al. (2019) have investigated CME and their properties through several automated catalogs and established that CME occurrence follow solar activity indices/proxies with no time lag. Hajra et al. (2021) analyzed the long-term variations of geomagnetic activity and the solar wind-magnetosphere coupling during solar cycles 20-24, they showed that cycles 20 and 24 have recorded significantly weak energetic level compared to cycles 19, 21, 22 and 23. Using solar wind parameters, Zerbo and Richardson (2015), Kamide and Kusano (2013), and Watari et al. (2017) have out lighted a significant drop in solar wind parameters after the deep mimimum that followed the solar cycle 23. Zerbo et al. (2013) investigated the long-term change in solar wind, showed that extreme conditions in solar plasma and it associated geomagnetic responses (recurrent streams, low and high geomagnetic responses) are linked to solar dynamo process.

Nakagawa et al. (2019) analyzed variations in solar wind parameters and geomagnetic indices for solar cycles 23 and 24 and showed that a drop in AE and IMF variation from solar cycle 23 to solar cycle 24.

The present study is an attempt to discover particularities in solar wind conditions during the solar cycles 23 and 24 and present how much they could be different for both solar cycles.

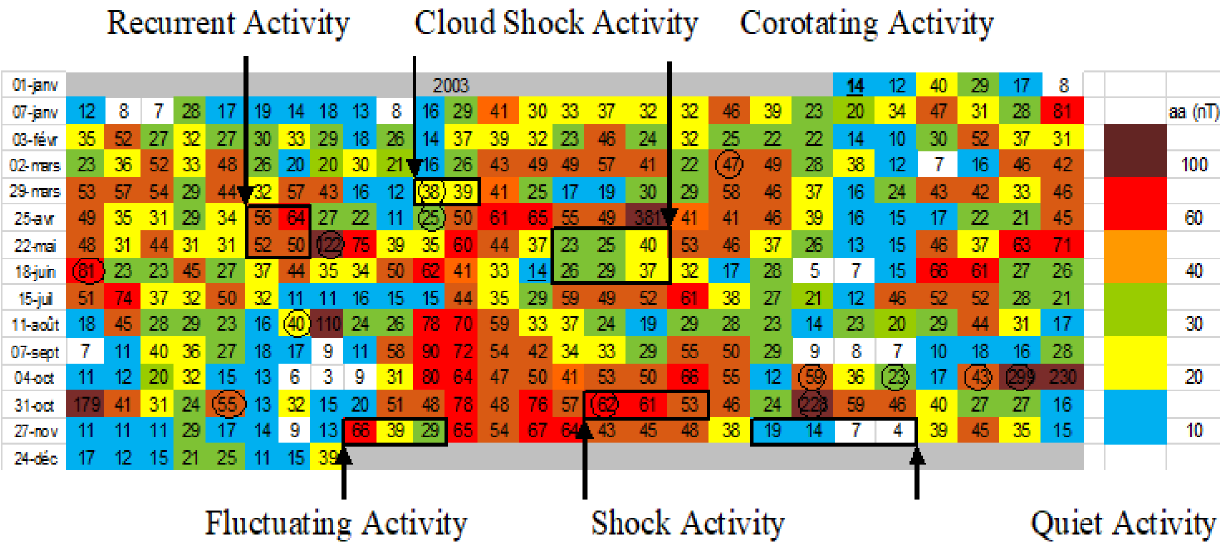
METHODOLOGY

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 taken 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 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 gomagnetic actvivity. This classification (Quiet, Recurrence, Shock, and fluctuationg activities) defined by Legrand and Simon (1989) is fully described by some authors (Ouattara and Amory-Mazaudier, 2009; Zerbo et al., 2012) with extended criterion in Zerbo et al. (2012). This extension 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 are defined as days when Aa < 20. The other classes constitute the disturbed geomagnetic activity classes which occur on days when Aa ≥ 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 Aa > 40 nT (Legrand and Simon, 1989).
(4) Corotating activity: This class is defined as the manifestation of solar winds, stable in corotation and having moderate magnetic effects in the vicinity of the terrestrial environment. Under these conditions, the geomagnetic index is such that 20 nT ≤ Aa < 40 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. And the corresponding Aa vary from 20 to 40 nT (Zerbo et al., 2012);



01-janv											2003											14	12	40	29	17	8
07-janv	12	8	7	28	17	19	14	18	13	8	16	29	41	30	33	37	32	32	46	39	23	20	34	47	31	28	81
03-févr	35	52	27	32	27	30	33	29	18	26	14	37	39	32	23	46	24	32	25	22	22	14	10	30	52	37	31
02-mars	23	36	52	33	48	26	20	20	30	21	16	26	43	49	49	57	41	22	㊼	49	28	38	12	7	16	46	42
29-mars	53	57	54	29	44	32	57	43	16	12	㊳	39	41	25	17	19	30	29	58	46	37	16	24	43	42	33	46
25-avr	49	35	31	29	34	56	64	27	22	11	㉕	50	61	65	55	49	381	41	41	46	39	16	15	17	22	21	45
22-mai	48	31	44	31	31	52	50	(122)	75	39	35	60	44	37	23	25	40	53	46	37	26	13	15	46	37	63	71
18-juin	(81)	23	23	45	27	37	44	35	34	50	62	41	33	14	26	29	37	32	17	28	5	7	15	66	61	27	26
15-juil	51	74	37	32	50	32	11	11	16	15	15	44	35	29	59	49	52	61	38	27	21	12	46	52	52	28	21
11-août	18	45	28	29	23	16	㊵	110	24	26	78	70	59	33	37	24	19	29	28	23	14	23	20	29	44	31	17
07-sept	7	11	40	36	27	18	17	9	11	58	90	72	54	42	34	33	29	55	50	29	9	8	7	10	18	16	28
04-oct	11	12	20	32	15	13	6	3	9	31	80	64	47	50	41	53	50	66	55	12	(59)	36	㉓	17	㊸	(299)	230
31-oct	179	41	31	24	(55)	13	32	15	20	51	48	78	48	76	57	(62)	61	53	46	24	(223)	59	46	40	27	27	16
27-nov	11	11	11	29	17	14	9	13	66	39	29	65	54	67	64	43	45	48	38	19	14	7	4	39	45	35	15
24-déc	17	12	15	21	25	11	15	39																			

Figure 1. Pixel diagram of the Aa index for the year 2003. Source: Adopted from 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).

To compare the two solar cycles we counted the number of days of each class of activity and then calculated the percentages of annual occurrences for each solar cycle. These results allowed us to plot the histograms of the percentages of occurrences coupled with the temporal evolution curve of sunspots number for each class of activity.

RESULTS AND DISCUSSION

Level of geomagnetic activity during the two solar cycles

Figure 2a presents 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 quiets 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 then argue 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 particularity on this figure is that the entire period is not overed with shock activity. 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 presents the occurrence of the six different classes of geomagnetic

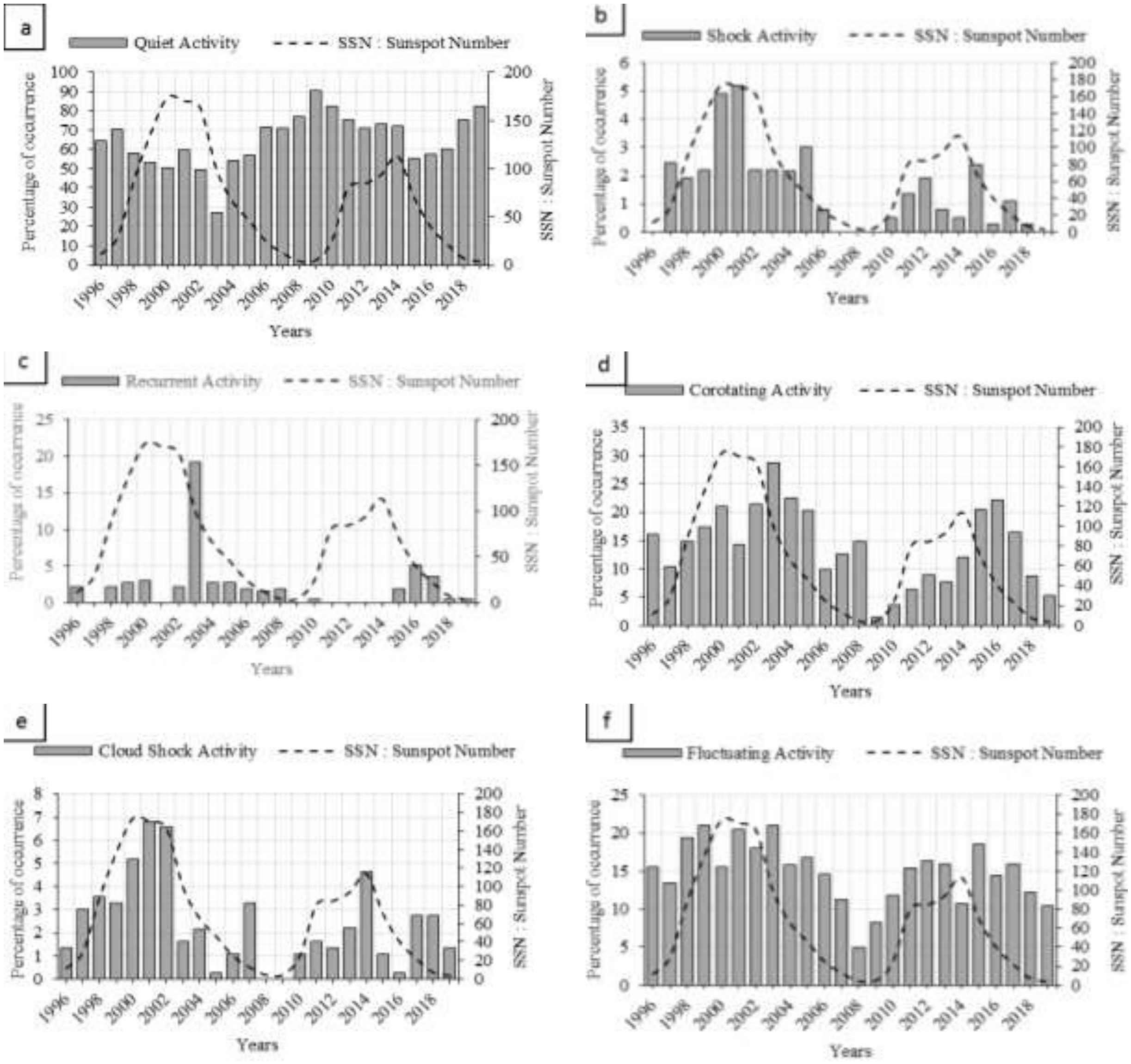


Figure 2. Histogram of the percentages of occurrence geomagnetic activity and sunspot number profile from 1996 to 2019: (a) quiet days; (b) shock activity; (c) recurrent activity; (d) corotating activity; (e) claud shock activity; (f) fluctuating activity.
Source: Koala et al. (2022).

activity

The Figure 2c presents 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 geomagntic 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 presents 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 analyzed, the level of 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 say that the solar cycle 23 has experienced more corotative events from corotating interactive regions compared to solar cycle 24.

Figure 2e presents 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 can also notice that the level of magnetic cloud activity during solar cycle 23 is greater than that of solar cycle 24. A statistical study lets us conclude that 2.94% of solar cycle 23's global geomagnetic activity represents cloud activity against 1.74% for solar cycle 24. That implies that Earth environment was under important sporadic disturbances during solar cycle 23.

Figure 2f presents 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 phases of the solar cycle but with difference in importance. 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 also teaches that fluctuations conditions are important during the ascending and decreasing phases of each solar cycle. This can 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 implies that earth was particulary under remarkable fluctuating solar wind conditions during solar cycle 23.

Solar wind and geomagnetic activity parameters during the period 1996-2019

To give an overview of the relationship solar wind-geomagnetic activity, we have investigated the profiles of the annual average of geomagnetic index aa and solar wind parameters (Aa, E, Bz, PC index, N).

Figure 3 presents the profiles of solar activity parameters. The panels teach on annual variation of: (a) IMF- Bz component, (b) the interplanetary electric field, (c) the PCN index, (d) the PCS index and (e) the proton density during the period 1996 to 2019. All the figures show fluctuations in solar activity parameters with remarkable peaks for both solar cycles 23 and 24. In Figure 3a, it is easy to see important number of negative Bz values, recorded, respectively in 1996 (-0.1 nT), 1997 (-0.1 nT), 2001 (-0.1 nT), 2003 (-0.2 nT), 2012 (-0.2 nT), 2013 (-0.2 nT), 2017 (-0.1 nT) and in 2018 (-0.1 nT). This implies important solar wind energy' transfer to the Earth's magnetosphere during this periods through the magnetic reconnection process (Dungey, 1961; Akasofu, 1981). Additional observation show the stability of the annual means around 0 nT between 1998 and 2000 and between 2005 and 2009 corresponding, respectively to the ascending and decreasing phase of the solar cycle 23. The opposite phenomenon is observed for the solar cycle 24. The much important numbers of Bz <0 were recorded during the solar cycle 24. This observation shows that large storms ocured during solar cycle 24 compared to solar cycle 23. Figure 3b shows that the interplanetary electric field E varies continuously over the different phases of the solar cycle, with a small fluctuation at the minimum phase of each solar cycle. From this figure, we can notice that the greatest annual averages of the electric field are observed in 1996 (0.12 mV/m), 1997 (0.12 mV/m), 2004 (0.1 mV/m), 2012 (0.12 mV/ m), 2015 (0.07 mV/m) and in 2017 (0.09 mV/m). The weakest negative annual averages of the electric field are recorded in 2002 (-0.07 mV/m), 2014 (-0.12 mV/m), with a long negative fluctuation during the period 2006 to 2011. This period covers the deep minimum which followed solar cycle 23. According to Ohtani et al. (2010), where it is shown that the electric field tends is strong in the inner magnetosphere when the geomagnetic activity is high, we can say that Earth was under most dirburbed solar wind conditions during the solar cycle 23. This funding is in argument with inestigations made by Watari et al. (2017) and Nakagawa et al. (2019) where it is reported that geomagnetic activity and the electric field strength were exceptional weak during the solar cycle 23. From Figure 3c, we can observe a fairly stable evolution of the annual averages of the PCN index, respectively around 1.2 mV/m between 1998 and 2001 and around 1 mV/m between 2015 and 2017. There are also significant peaks of the PCN index, respectively in 2003, 2005 and 2012. We can also notice that 2003 recorded the highest value of the PCN index (1.3 mV/m) and 2009, the lowest value of the PCN index (0.5 mV/m). There is also a decrease in the amplitude of the annual averages of the PCN index after the deep minimum of solar cycle 23. In Figure 3d, we observe a discontinuity during the year 2003. This discontinuity is linked to a lack of data during this period. The PCS index fluctuates much more than

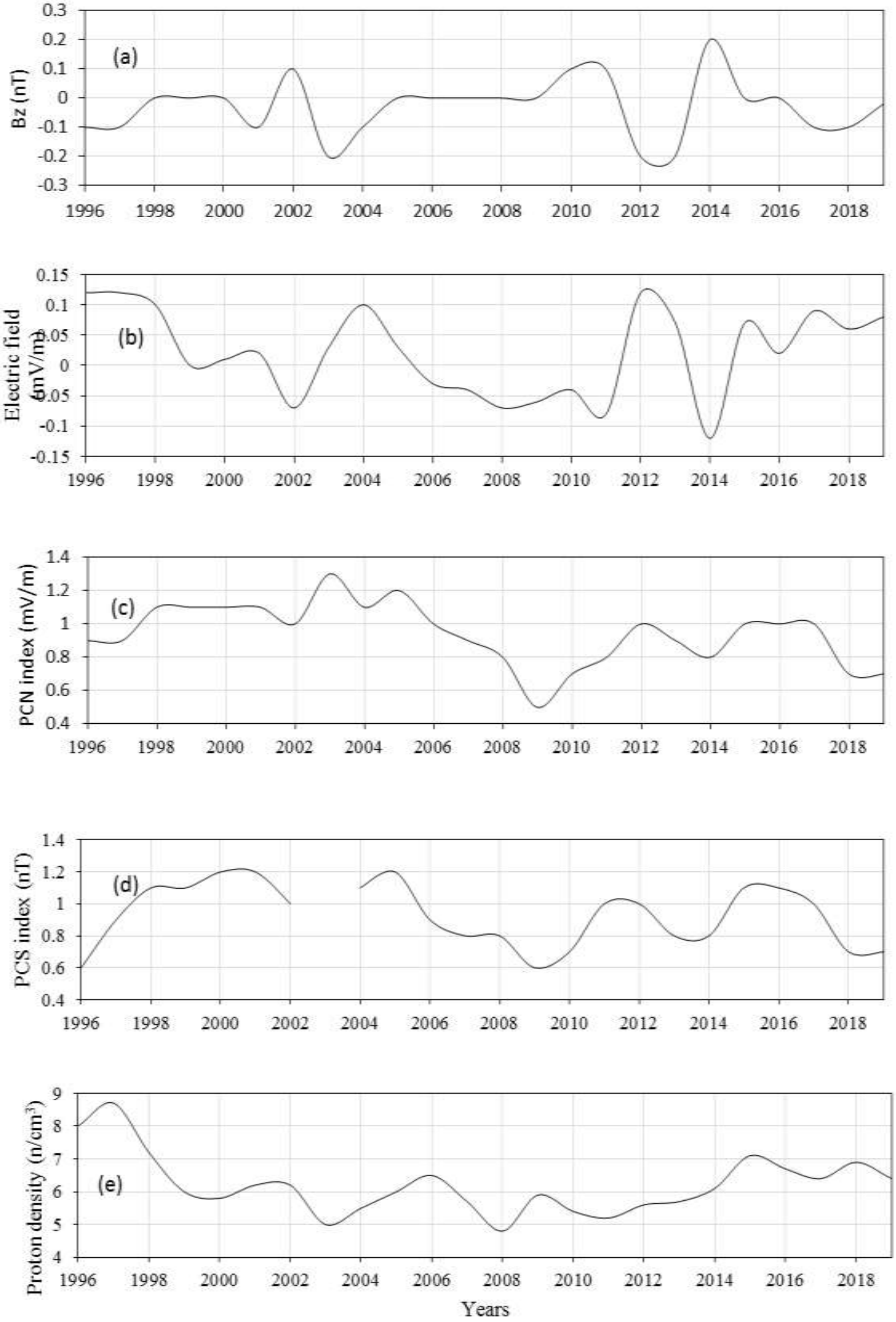


Figure 3. Profile of the annual average, (a) Bz component of the interplanetary magnetic field, (b) electric field, (c) PCN index, (d) PCS index and (e) proton density during the period 1996 to 2019.
Source: Koala et al. (2022).

the PCN index (Figure 3c). The peaks of the PCS index are recorded, respectively in 2001 (1.2 mV/m), 2005 (1.2 mV/m), 2012 (1 mV/m) and 2016 (1.1 mV/m). The lowest annual average values of the PCS index were recorded during the years 1996 (0.6 mV/m), 2009 (0.6 mV/m), 2010 (0.7 mV/m), 2014 (0.8 mV/m), 2018 (0.7 mV/m) and 2019 (0.7 mV/m). In addition, one can see a decrease in the amplitude of the annual averages of the PCS index after the solar minimum of solar cycle 23 as in PCN. Since the PC index measure that strength of solar wind energy that enters the magnetosphere and indicates storm or magnetic substorm conditions (Troshichev et al., 1988, 2014), we can argue from Figure 3c and 3d that Earth magnetosphere was under inportant input solar energy during the solar cycle 23 in both hemisphere North and South. Figure 3e shows that the annual averages of the proton density vary a lot during the period covered by study with annual averages remaining low for a long period (2007 to 2014), before rising again after the solar maximum of solar cycle 24 (2014). However, it is important to notice that the highest amplitude of the proton density was recorded during year 1997. A comparative study of all the previous profiles allow to remark that when the annual average values of the interplanetary electric field are high, the values of Bz are low. We can clearly observe that when we superimpose Figures 3a and 3b: the maxima in the profile of the interplanetary electric field coincide with the lowest values of IMF-Bz component (Bz <0) of the interplanetary magnetic field characteristic of strong storms magnetic conitions. The resurgence of violent magnetic storms observed in the Earth's environment is therefore highly dependent on the interplanetary magnetic field and therefore on the intensity of solar activity. During geomagnetic storms, the electric field is strong. These observations are in agreement with the work of Gonzalez et al. (1994) who showed that geomagnetic storms are well known to be developed in response to enhanced solar wind energy input into the magnetosphere, which is associated with southerly intervals of Bz (Bz < 0) and intense interplanetary electric fields. That leads to enhanced reconnection with the magnetosphere (Dungey, 1961). The main interplanetary cause of geomagnetic storms is the presence of a southerly interplanetary magnetic field (IMF) in the solar wind (Gonzalez and Tsurutani, 1987; Tsurutani et al., 1988; Gonzalez et al., 1994; Echer et al., 2005). The southward interplanetary magnetic field (Bz < 0) allows magnetic reconnection and energy transfer from the solar wind to the Earth's magnetosphere. Indeed, the magnetosphere responds to the increased reconnection on the day side with cycles of loading and unloading of the flux in the magneto-tail, that is, by generating trains of substorms, and the development of an intense convection and electric currents in the polar ionosphere. This enhanced diurnal reconnection has the immediate effect of increasing the size of the polar cap, while tail reconnection associated with substorms causes the polar cap to contract. During geomagnetic storms, however, a general expansion of the polar cap and auroral oval is observed (Vennerstrom et al., 2016). This result is clearly observed on Figure 3b, 3, and 3, the peaks of the indices PCN and PCS coincide with the peaks of the electric field. These observations show that during geomagnetic storms the electric field and the PCN and PCS indices are important. Testifying to that the PC index hint about the geo-efficient interplanetary electric field from the polar magnetic observations available on the ground (Troshichev and Andrezen, 1985) and the fact that relationships between the electric field, PC index, and the magnetic disturbance Dst remained valid in course of 23rd and 24th solar cycles and, therefore (Troshichev et al., 2022) Figure 4 presents the profiles of the sunspots number and the spotless days during the period 1875 - 2019. This figure shows a fairly good anti-correlation between the two parameters. The maxima of the sunspots number correspond to the lowest number of the spotless days and vice versa. Especially, this figure shows that during the solar maxima, spotless days have been observed only during the solar cycles 12, 14 and 24. These observations show that the behavior of solar cycles 24, represents a return to that observed during solar cycles 12 and 14 as reported by Wilson (2017) when analyzing the number of spotless days in relation to the timing and size of the minimum sunspot cycle. This increase in spotless day’s number from solar cycle 23 to solar cycle 24 may suggest a weak in internal pressure produced by the solar dynamo and associated physical phenomenon during the solar cycle 24. That implies higher solar activity which increases the solar wind as well as coronal mass ejections (Bharati Kakad et al., 2018; Adrija Banerjee et al., 2019) and associated geomagnetic phenomenon (geomagnetic storms or auroral disturbances) during the solar cycle 23 compared to solar cycle 24.

Table 1 summaries the number of intense storms (Dst <-100 nT: Gonzalez et al., 1994), the maximum of spotless days and their occurrence rates during the solar cycles 23 and 24.

From this table, it appears that the number of intense geomagnetic storms (Dst < -100 nT) was more significant during solar cycle 23 compared to solar cycle 24. These observations are in agreement with several studies (Zhang et al. 2007; Echer et al. 2008) where, comparing the rising phases of solar cycles 23 and 24, it is shown that there were 10 intense storms and no severe storms in the first 4 years of the cycle 24, compared to 21 intense storms and 4 severe storms during the same period of cycle 23. Based on detailed statistical study of geomagnetic storms (Dst < −100 nT) of solar cycle 23, Gonzalez et al. (2007) have reported on intense storms and their associated solar sources and showed that the most common structures leading to the development of an intense storm are magnetic clouds (MC), coronal

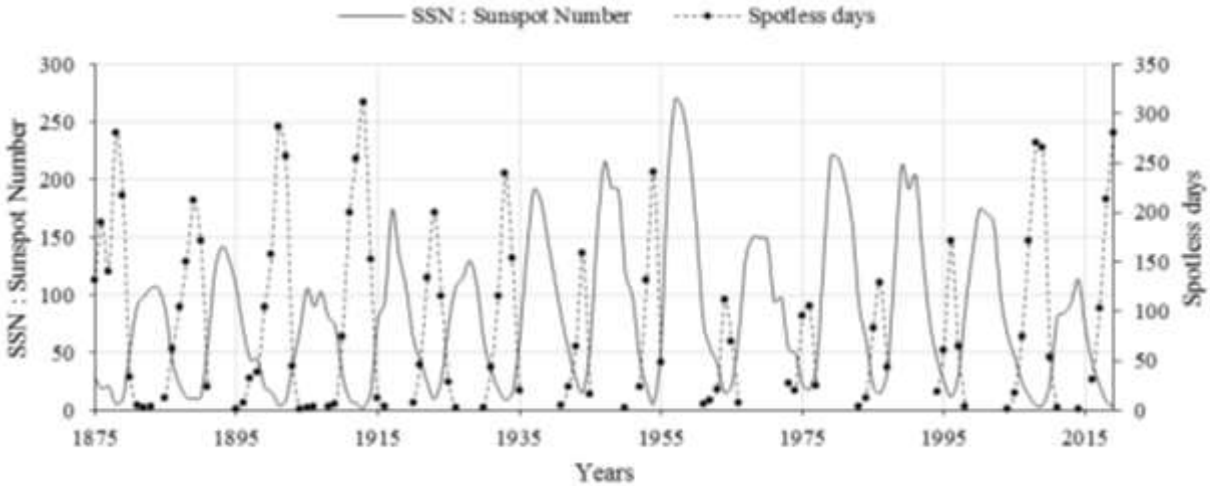


Figure 4. Profile of the sunspots number and the spotless days during the period 1875 to 2019.
Source: Koala et al. (2022).

Table 1. Number of intense geomagnetic storms (Dst < −100 nT) during solar cycles 23 and 24.

Solar cycle	Cycle 23	Cycle 24
Number of storm	124	28
Maximum spotless days	270 (2008)	280 (2019)
Occurrence spotless days	16.27	23.59

Source: Koala et al. (2022)

mass ejection (CMEs), and high-speed solar wind. The drop in these solar plasma conditions lead to a calm geomagnetic condition on Earth. Then, it appears that solar cycle 23 was most disturbed with important input energy into Earth atmosphere compared to solar cycle 23. This extend the investigations of Richardson (2013) who found that the primary contributor to the drop in geomagnetic activity levels in the rise phase of cycle 24 could be the 20% fewer (86 vs. 106) coronal interplanetary coronal mass ejections (ICME) on Earth compared to cycle 23. The low activity during solar cycle 24 is linked to several parameters such as, the low solar wind pressure after the solar minimum that followed solar cycle 23, the low sunspots number, the low number of intense geomagnetic storms, and the length of the deep minimum that followed solar cycle 23. The fluctuation observed in all the aforementioned indices indicate the level of geomagnetic disturbances and the drop in the amplitude of the solar and geomagnetic parameters from solar cycle 23 to solar cycle 24 which is characterized by magnetically weak conditions. This decrease in the amplitude of the solar and geomagnetic parameters can be partially explained by several reasons reviewed in Zerbo et al. (2013) where it showed that solar cycle 23 was one of the longest cycles since 1847 with impressive high solar wind conditions followed by a long solar minimum. Another characteristic of the solar cycles 23 and 24 is the occurrence of the sunspots number: the maximum of the sunspots number during solar cycle 24 was 113 and occurred in April 2014 when the maximum of the solar cycle 23 is extended over a period of four years (1999-2002) with a peak of 174 sunspots obtained during the year 2000. So we can think that the physical phenomena such as: magnetic buoyancy, magneto convection, reconnection, and magnetic torsion (Mark CM Cheung and Hiroaki Isobe, 2014) were much strong during the solar cycle 23. This finding is in argument with results reported by Ishkov (2022) showing that the solar cycle 24 proceeded as a low-magnitude cycle with historical lower level of sunspot and flare activity than that of all previous solar cycles of the space era.

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:

(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 queit 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 can showed 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) Higher intense and severe storm or magnetic substorm conditions (E, PC index, Dst) during the solar cycle 23 compared to cycle 24.

(6) Solar cycle 24 presents similar characteristics as solar cycles 12 and 14 which experienced spotless days at solar maximum and have experienced Gleissberg minimum.

(7) 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 of all these observations, we can say 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 INTERESTS

The authors have not declared any conflict of interests.

ACKNOWLEDGEMENTS

The authors thank the reviewers for their detailed and insightful comments and constructive suggestions. They thank all providers of data used (OMNIweb from NASA Goddard Space Flight Center to provide solar wind data; Royal Observatory of Belgium for providing sunspot number; ISGI for providing polar cap and geomagnetic aa indices).

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