Geoeffectiveness of solar events during the solar cycles 23 and 24.

Somaïla KOALA[1*], Issamaïl KI [1], Jean Louis ZERBO [1,2]

Abstract

In this study, we analyzed the geoeffectiveness of quiet and shocks solar events during the solar cycles 23 and 24. It appears that solar cycle 24 is magnetically quiet compared to solar cycle 23. Shock events are more geoeffective during the solar cycle 23 compared to the solar cycle 24. A statistical analysis of solar events shows that the different types of shocks do not have the same occurrences. During the solar cycle 23, 20%, 68% and 64% of the shocks of one day, two and three days respectively have been geoeffective. However during the solar cycle 24, 18%, 28% and 47% of one-day, two-day, and three-day shocks respectively have been geoeffective. This low geoeffectiveness of the shocks observed during solar cycle 24 is due to the weak solar winds recorded during this period. One-day shocks appear to be less geoeffective compared to two-day and three-day shocks due to the important rate of speed below 550 km/s.

Keywords: Solar activity, geomagnetic activity, solar events, solar cycle, geoeffectiveness.

Introduction

The disturbances observed in the near-Earth environment are attributed to the various variations of the Sun such as solar activity and solar events such as interplanetary shocks, coronal mass ejections (CMEs), high-velocity corotating fluxes from coronal holes, and interface regions/interaction flows. Disturbed interplanetary conditions lead to geomagnetic disturbances and geomagnetic storms (Gonzalez *et al.,* 1994). The study of the variability of solar activity and solar events is extremely important today because of the large number of technologies that our society depends on. The study of the geoeffectiveness of these structures has been the subject of several studies. Among these studies, we have the work of Echer and Gonzalez (2004), which focused on the statistical analysis of the geoeffectiveness of several interplanetary structures, during the period 1973-2001; in terms of Dst index response. (Alves *et al.,* 2006) studied the effects of 727 corotating interaction regions (CIR) on the magnetosphere from 1964 to 2003 by classifying the magnitude of the magnetic storm into three levels according to the value of the Dst index. They observed that 33% of the corotating interaction regions (CIR) induced moderate/intense magnetic activity ($Dst < -50$ nT). (Wang *et al.,* 2002)

[1]Laboratoire de Matériaux, d'Héliophysique et Environnement (La.M.H.E), ED/ST, Université Nazi BONI, 01 BP 1091, Bobo- Dioulasso, Burkina Faso

[2]Unité de Formation et de Recherche en Sciences Exactes et Appliquées (UFR/SEA), Université Nazi BONI, 01 BP 1091, Bobo- Dioulasso, Burkina Faso

*Corresponding author: ismaelkoala@yahoo.com

analyzed 132 coronal mass ejections (CMEs) observed by SOHO from 1997 and 2000 that were directed towards the earth. They found that 45% of these coronal mass ejections (CME) caused storms with Kp > 5. Legrand and Simon (1989) using a century series of the geomagnetic index aa, and the relationship between the index aa and solar wind speed, associated the value of aa with different interplanetary structures: transient flows/shocks, corotating, fluctuating and quiet levels. They observed that for 67% of the days the geomagnetic activity was calm, for 17.5% of the day was fluctuating activity, for 8.5% of day it was shock activity, and for 7% of the day activity was fluvial. (Richardson *et al.*, 2000) determined the contributions of structures related to coronal mass ejections (CMEs), corotating high-velocity flows and slow solar wind to mean levels of geomagnetic activity, as measured by the aa index, during the period 1972–1986. They found that at solar maximum, transient structures following coronal mass ejections contribute about 50% of the average aa, with the remaining activity contributed by corotating interaction regions (CIRs) (about 33%) and the slow solar wind (about 20%). At solar minimum, the average aa is dominated by corotating interaction regions (CIR) (~70%), with slow solar wind contributing (~20%) and transient structures following coronal mass ejections with 10%. (Yermolaev *et al.*, 2005) conducted a comprehensive review of the geoeffectiveness of coronal mass ejections and flares. In this work, we analyze the geoeffectiveness of solar events during solar cycles 23 and 24, using the classification of solar and geomagnetic activity established by Legrand and Simon (1989) and the levels of intensity of geomagnetic activity of shocks using the Dst criteria (Gonzalez et al., 1994).

1. Data and methodology

The data used in this work are: (1) the dates of Sudden Storms Commencement (SSC), the daily average values of the geomagnetic index Aa (http://isgi.latmos.ispl.fr/) and the solar wind speed (http://omniweb.gsfc.nasa.gov/ow.html), to identify respectively the days of shocks due to coronal mass ejections and the different classes of solar and geomagnetic activity (Legrand and Simon, 1989) over the period 1996-2019; (2) Daily averages of the Dst index (http://omniweb.gsfc.nasa.gov/ow.html), to identify shock geomagnetic activity intensity levels.

Through the pixel diagram and the geomagnetic activity classification criteria established by (Legrand and Simon, 1989; Ouattara and Amory, 2009) and improved by (Zerbo et al., 2012), we identified the shock days. The days of shocks correspond to the circles on the pixel diagram with a value of the index Aa≥ 40 nT, and of the solar wind with a speed V ≥550 km/s (Figure 1). Quiet days correspond to values of Aa <20 nT and wind speeds V<450 km/s (Figure 1). We have also identified the values of the Dst index corresponding to the days of Shock, which effect lasts one day called "One-day shock", two days called "two-day shock", three days called "three-day shock" (Figure

1). Using the geomagnetic activity intensity level classification established by (Gonzalez *et al.*, 1994) (Table I), we calculated the percentages of geomagnetic activity levels for each type of Shock. Figure 1 presents an example of a pixel of the Aa index and the solar wind.

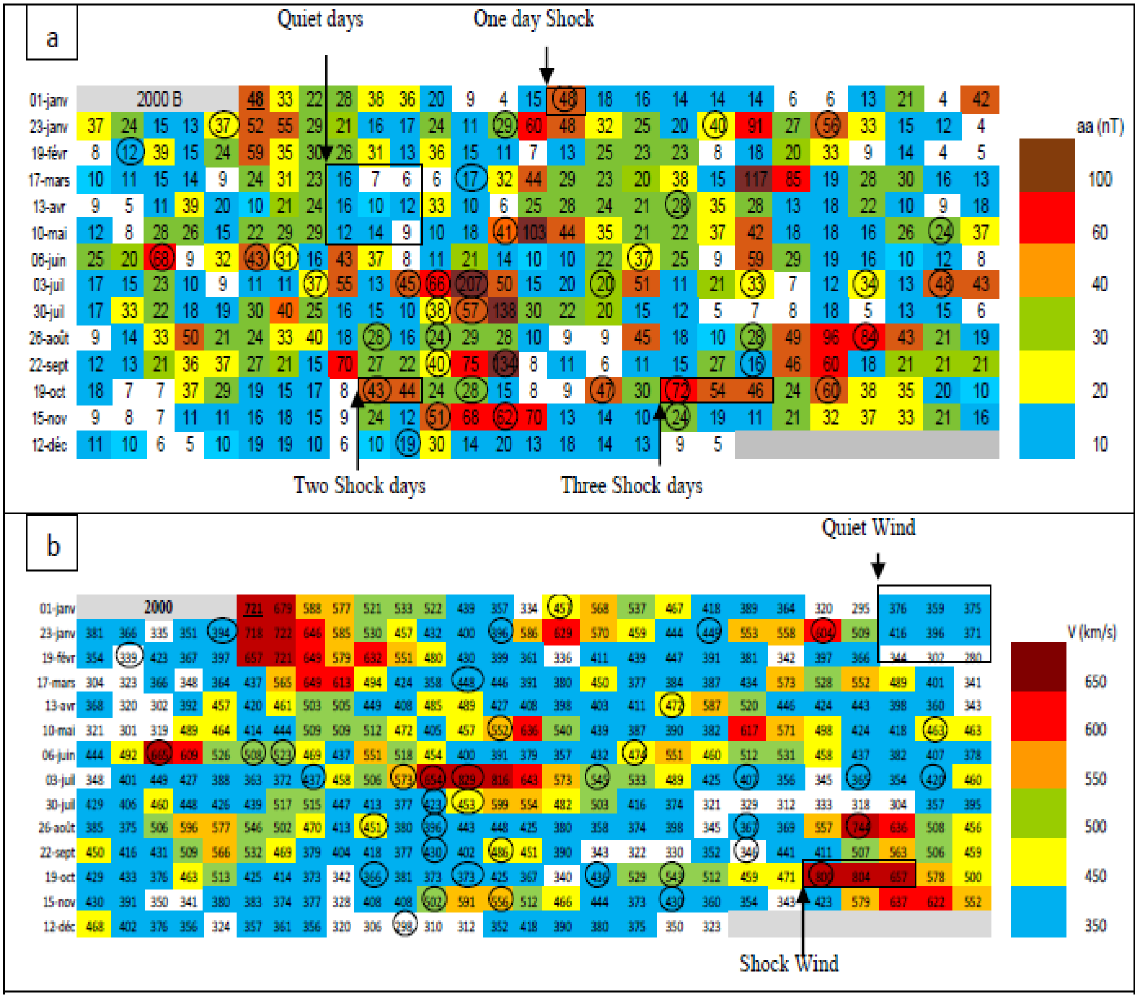

Figure 1: Pixel diagrams of year 2000 : geomagnetic index Aa (a) and solar wind speed (b).

Table I. Classification of intensity levels of geomagnetic activity according to the Dst criterion (Gonzalez et al., 1994)

Geomagnetic activity level	**Dst**
Intense	$Dst \leq -100$ nT
Moderate	-100 nT $< Dst \leq -50$ nT
Low	-50 nT $< Dst \leq -30$ nT
Calm	$Dst > -30$ nT

2. Results and discussion

In this paragraph, we analyze the data of the different indices of solar and geomagnetic activity from 1996 to 2019 to compare the geoeffectiveness of solar events during the last two solar cycles (solar cycles 23 and 24).

2.1. Level of solar and geomagnetic activity

Figure 2.a presents the percentages of quiet and solar wind shock days during solar cycles 23 and 24. This figure shows that the maximum of quiet days is recorded at the phase minimum of each cycle except solar cycle 24 which recorded significant percentages of quiet days at the maximum phase (2013 and 2014). This result shows an unusual behavior of the solar dynamo during solar cycle 24, distinguishing it at the same time from previous cycles. Figure 2.b presents the percentages of solar wind shock days. This figure indicates that the days of shock are more important during the maximum phase of the solar cycle. Moreover, we observe that the days of shock are more important during solar cycle 23 compared to solar cycle 24.

Figure 3.a shows the histogram of occurrences of quiet and shock day activity during solar cycles 23 and 24. The highest occurrences of quiet days during each cycle, are recorded during the minimum of solar cycle phase, with the exception of solar cycle 24, which presents significant values during its maximum phase (2013 and 2014). Solar cycle 24 exhibits an unusual influence of solar activity in the near-Earth environment. In addition, the year 2009 recorded the highest number of quiet days for the past two decades. From a magnetic calm perspective, we can say that solar cycle 24 has been the calmest since 1995.

Figure 3.b presents the percentages of shock days during cycles 23 and 24. This figure shows that the maximum shocks are recorded during the maximum phase (2000, 2001) of solar cycle 23. Exceptionally, the shock maximum of solar cycle 24 is observed at the descending phase (2015). Moreover, we notice that the percentages of shock days during solar cycle 23 is significant compared to solar cycle 24.

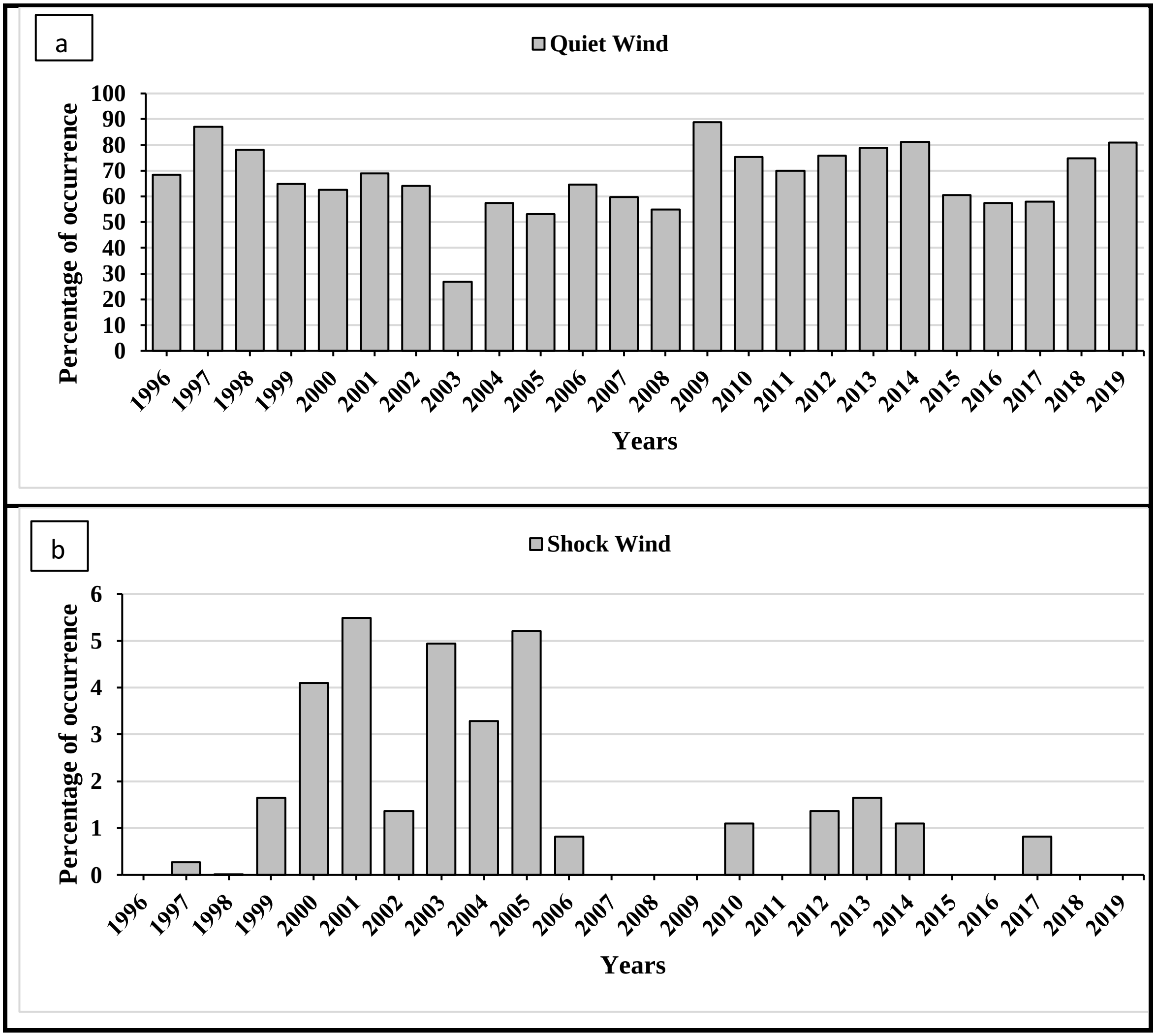

Figure 2: Occurrence of quiet (a) and shock (b) solar wind days during solar cycles 23 and 24.

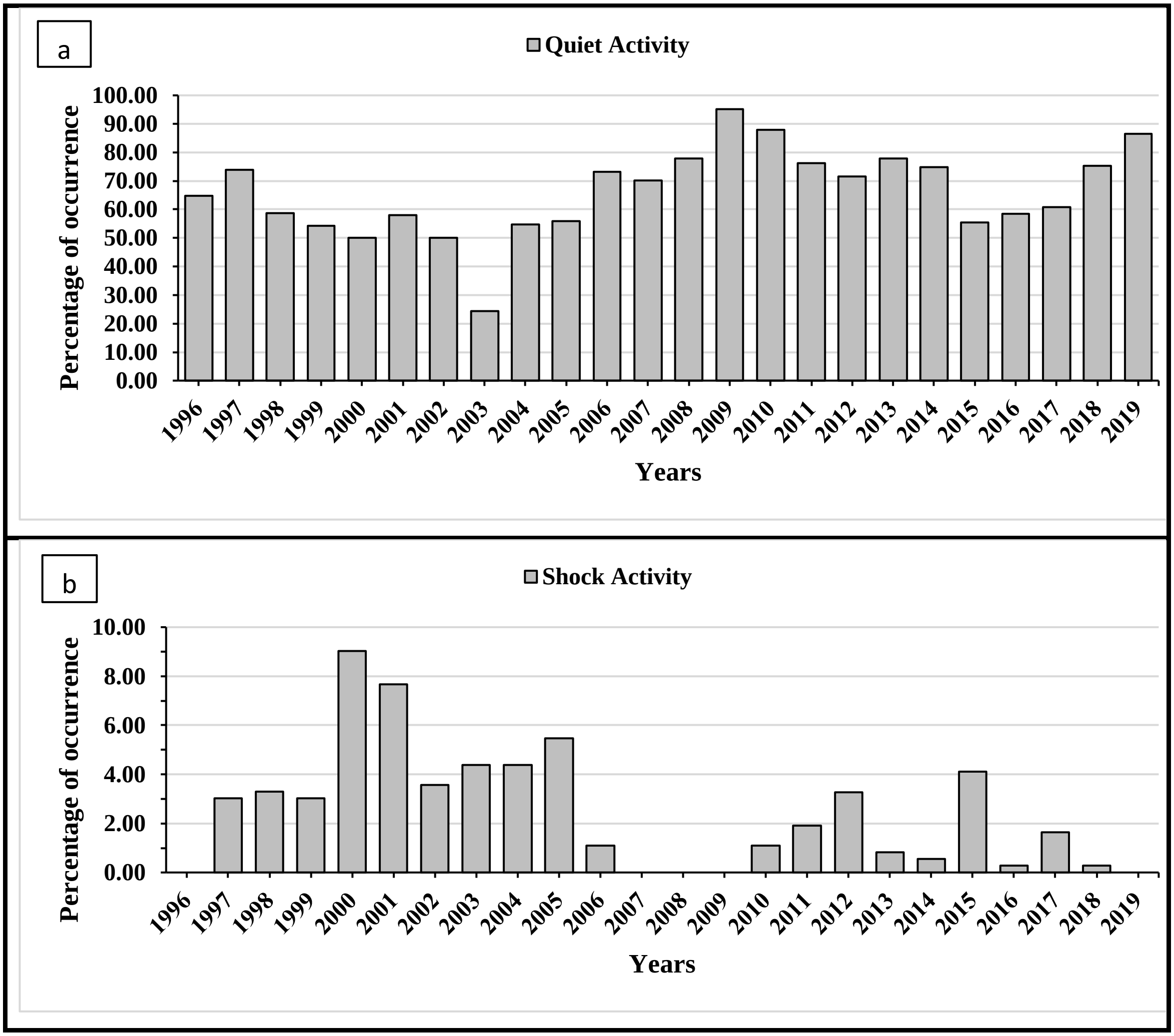

Figure 3: Occurrence of quiet (a) and shock (b) days of the Aa index during solar cycles 23 and 24.

Comparing Figures 2 and 3, i.e. the quiet and shock day activity of geomagnetic index Aa and solar wind respectively, it appears that geomagnetic index Aa expresses the field response terrestrial magnetic to that of the interplanetary medium conveyed by the solar wind. We observe an unusual behavior of the solar activity, therefore of the geomagnetic activity during the solar cycle 24. It records a significant rate of quiet days during the maximum between 2013 and 2014. In addition, the pattern of distributions (occurrences) of quiet days and shocks is similar to the speeds of the solar wind and the geomagnetic index Aa thus showing the geoeffectiveness of the wind and the solar events (coronal mass ejections) which accompany it. These observations are correlate with several studies (Russel *et al.*, 2010 ; Tsurutani *et al.*, 2011 ; Richardson and Cane, 2012a) ; Richardson and Cane, 2012b ; Zerbo and Richardson, 2015) which have shown that the geomagnetic activity during the minimum following the solar cycle 23 was unusually weak, and associated with unusual solar wind conditions, particularly low magnetic field strengths unprecedented in the space age, and slow flow velocities. Also according to (Echer *et al.,* 2006), the dominant interplanetary phenomena around solar maximum are interplanetary coronal mass ejections (ICME). This explains the significant rate of shocks observed around the maximum of each solar cycle. By a simple comparison between the two solar cycles and the occurrences of solar wind and geomagnetic index Aa, we can say from our investigations presented above that the solar wind was very geoeffective during solar cycle 23 compared to the solar cycle 24. Low solar activity leads to low geoeffectiveness of solar events.

2.2. Intensity levels of geomagnetic activity during shock events.

Figure 4 presents the pie diagram of geomagnetic activity intensity levels during one-day shocks on solar cycles 23 and 24. We counted a total of 71 one-day shocks in the two cycles: 49 during solar cycle 23 and 22 during solar cycle 24. We observed that nearly 80% of one-day shocks induce calm/weak geomagnetic activity during the two solar cycles. Also 14% of one-day shocks produce moderate geomagnetic activity during solar cycle 23 while 18% during solar cycle 24. 6% of one-day shocks produce intense geomagnetic activity during solar cycle 23 against 0% during solar cycle 24.

Figure 5 shows the pie diagram of geomagnetic activity intensity levels during two-day shocks during solar cycles 23 and 24. There are a total of 70 two-day shocks: 56 during solar cycles 23 and 14 at solar cycle 24. Solar cycle 23 records 21% and 11% calm and weak geomagnetic activity respectively compared to 43% and 29% during solar cycle 24. There are also 41% and 27% of two-day shocks induced respectively moderate and intense geomagnetic activity during solar cycle 23; compared to 21% and 7% respectively during solar cycle 24. This means that the two-day shocks were more geoeffective during solar cycle 23 compared to solar cycle 24.

Figure 6 shows the pie diagram of geomagnetic activity intensity levels during the three-day shocks during solar cycles 23 and 24. There are a total of 76 three-day shocks: 61 in solar cycle 23; and 15 in solar cycle 24. In this figure, the three-day shocks produced 18% calm and weak geomagnetic activity, respectively, compared to 7% and 46% during solar cycle 24. We also observe that 39% and 25 % of three-day shocks produced moderate and intense geomagnetic activity, respectively, compared to 40% and 7% during solar cycle 24.

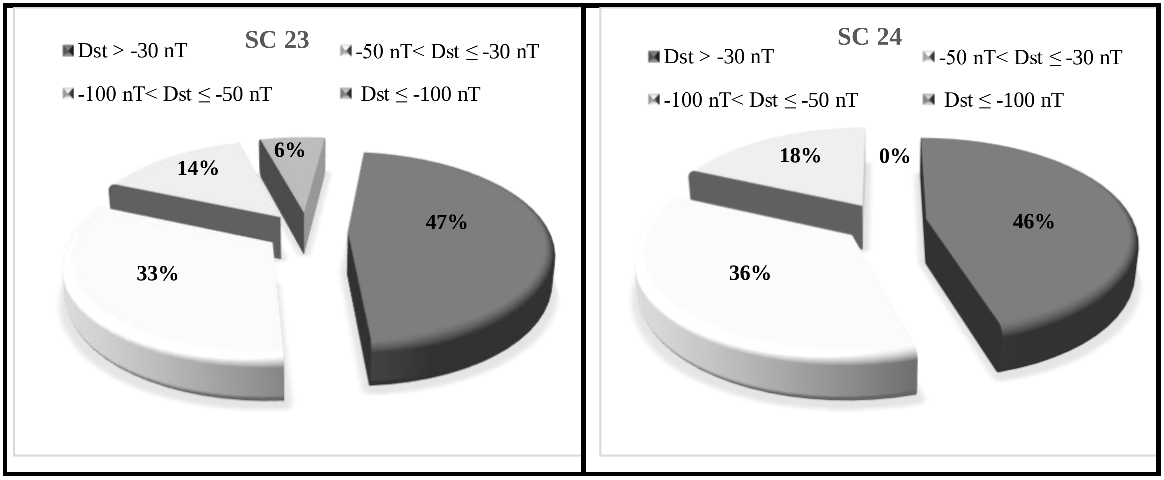

Figure 4: Pie diagram of intensity levels of geomagnetic activity of one day shocks during solar cycles 23 and 24

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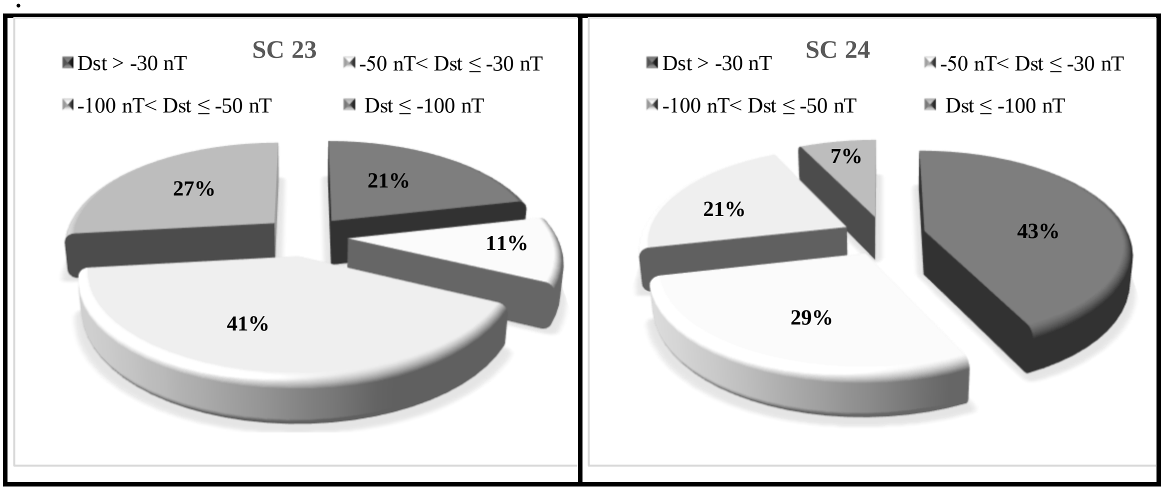

Figure 5: Pie diagram of intensity levels of geomagnetic activity of two-day shocks during solar cycles 23 and 24.

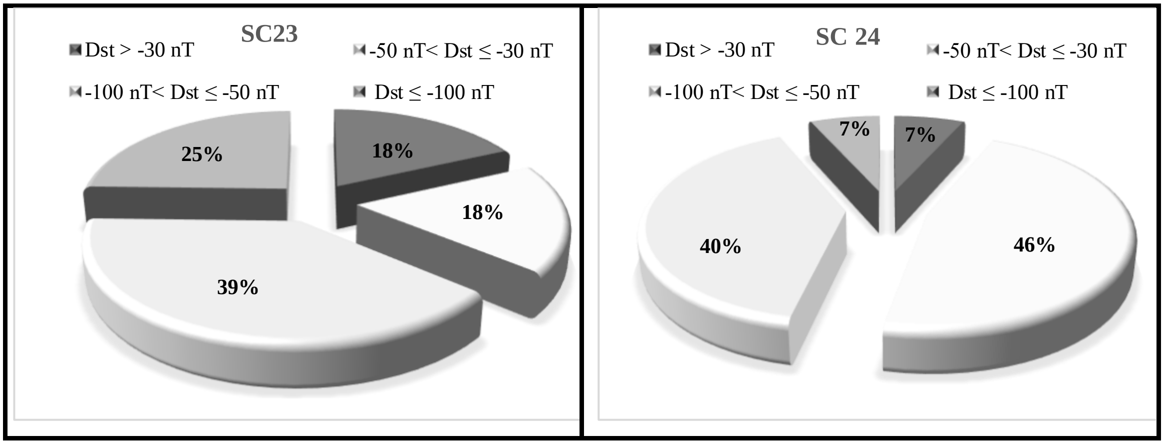

Figure 6: Pie diagram of intensity levels of geomagnetic activity of three-day shocks during solar cycles 23 and 24.

Analysis of figures 4, 5 and 6 shows that 20% of one-day shocks were geoeffective during solar cycle 23 against 18% during solar cycle 24, i.e. followed by a storm moderate or intense. 68% of two-day shocks were geoeffective during solar cycle 23 versus 28% during solar cycle 24. 64% of three-day shocks were geoeffective during solar cycle 23 versus 47% during solar cycle solar 24. Generally, we observe that the shocks of one day were less geoeffective compared to the two and three days. We also analyzed the solar wind speeds associated with shocks. Respectively 65.3% and 77.27% of the one-day shocks had a speed lower than 550 km/s during solar cycles 23 and 24. During the two-day shocks 44.64% and 57.14% of the speeds were lower than 550 km/s during solar cycles 23 and 24 respectively. Three-day shocks recorded 41% and 26.66% of velocities below 550 km/s during solar cycles 23 and 24 respectively. One-day shocks are less geoeffective due to low shock wind rate (V ≥550km/s). According to several previous studies (e.g. Gosling *et al.*, 1991 ; Tsurutani and Gonzalez, 1997 ; Zhang *et al.*, 2007 ; Echer *et al.*, 2008) intense geomagnetic storms (Dst ≤ 100 nT) are mainly associated with the passage of ICMEs and their upstream sheaths, or corotating high-velocity streams. Solar events and intensity levels of geomagnetic activity were less geoeffective during solar cycle 24 due to the low magnetic activity and low velocities observed. According to the work of (Gopalswamy *et al.*, 2015) and (Watari, 2017), geomagnetic activity was lower in solar cycle 24 than that in solar cycle 23. Also (Gopalswamy *et al.*, 2015) reported that the number of magnetic storms was low due to the expansion of the coronal mass ejections (CMEs) due to the decrease in solar wind density by 1 AU from 2008 to 2013. (Nakagawa *et al.*, 2019), by analyzing the relationships between the coronal hole areas and solar wind speed, showed that the solar wind speeds for solar cycle 24 were lower than those for solar cycle 23.

Conclusion

In this work, we studied the geoeffectiveness of solar events and the intensity level of geomagnetic activity of shocks during solar cycles 23 and 24. It appears from our study that the solar cycle 24 was magnetically quiet compared to solar cycle 23. Shock events were very geoeffective during solar cycle 23 compared to solar cycle 24. Low geoeffectiveness shocks during solar cycle 24 are caused by weak solar winds. We also observe that one-day shocks are less geoeffective compared to two-day and three-day shocks, because of the high wind rate below 550 km/s.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests

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