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On solar wind speed distribution and geomagnetic activity during solar cycle 23 and the early ascending phase of solar cycle 24

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This paper investigates solar wind repartition through four classes of solar events: (1) one class of quiet days (QD) caused by slow solar wind (V< 450 km/s), and three disturbed activities, where V ≥ 450 km/s, (2) recurrent wind (RW), (3) shock wind (SW), (4) fluctuating wind (FW). RW class is characterized by recurrent high solar wind extended on several solar rotations. SW class is caused by CMEs events. FW class is formed with all the un-identified events in the previous well-organized classes. We achieve this classification by using pixel diagram built with solar wind velocity. This includes the sunspot cycle 23 and the early ascending phase of sunspot cycle 24 (2009-2010). Quiet days occurred most frequently during the increasing phase of sunspot cycle (35%), while recurrent wind activity was present at solar maximum around 20% of the time, with the largest occurrence (49%) on the declining phase of the sunspot cycle. The largest percentage of shock wind events (43%) occurs around the maximum phase while fluctuating events stay fairly during the entire sunspot cycle (~27%). We also discuss current ideas about the interaction between solar wind and geomagnetic activity over sunspot cycle 23 and the early ascending phase of sunspot cycle 24.

Key words: Solar wind, geomagnetic activity, solar cycle, sunspot cycle.

INTRODUCTION

Geomagnetic activity may be defined as short-term variation in Earth's magnetic field induced by change in solar magnetic field. Many studies showed the existence of two types of magnetic perturbations. Maunder (1905) investigated recurrent events in geomagnetic activity.

Greaves and Newton (1929) noticed that weak storms

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tend to recur whereas stronger ones occur sporadically. For Bartels (1932) and Bartels et al. (1939), there are two types of geomagnetic storms: the ones that are sporadic, associated with sunspots, and the recurrent storms that are more prominent at low activity levels and often strongest during the declining phase of the cycle. Danilov and Lastovicka (2001) addressed the complexity of geomagnetic events and their variations. The most important phenomenon related to solar wind and high energy investigated by these authors is the magnetic storm, a complex process of solar wind/ magnetospheric origin. The effects of geomagnetic storm are various and the level of ionospheric and atmospheric disturbance depends on altitude. The strongest effects are generally observed on auroral zone (Danilov and Lastovicka, 2001). More recent studies (Legrand and Simon, 1989; Richardson et al., 2000, 2002; Zerbo et al., 2012) show that these perturbations can be organized into quiet, recurrent, shock, and fluctuating/ unclear geomagnetic activity classes. These classes are defined using Bartels 27-days solar rotation based on geomagnetic index aa as a function of time to give the measure of the geoeffectiveness of solar wind events. In pursuance of the strong correlation between the aa index and solar wind established by Svalgaard (1977) and the fact that 91.5% of the time geomagnetic activity is generated by corotating wind sources (Simon and Legrand, 1987), we are investigating in this paper the distribution of solar wind speed through diagrams displaying solar wind speed as a function of time over Bartels rotations and discuss each solar wind structure effects level on geomagnetic activity during sunspot cycle phases.

METHODOLOGY

The daily values of solar wind speed and the sunspot number used for this work are obtained from http://omniweb.gsfc.nasa.gov/ow.html. The homogeneous series of aa index established by Mayaud (1972, 1973) are available per day on http://isgi.latmos.ipsl.fr/. The three hourly variability index aa is derived from two antipodal subauroral observatories to show how solar magnetic field induces changes in Earth atmosphere (Mayaud, 1971). It derives from the average of the K-index. The aa index is like the planetary-scale magnetic index Kp except that it utilizes only two, roughly antipodal, observatories, one in the northern hemisphere and one in the southern hemisphere (Mayaud,1980). The aa index has been continuously calculated since 1868, making it one of the longest historical time series in geophysics (Menvielle and Berthelier, 1991). Recent studies (Svalgaard and Cliver, 2005; Svalgaard et al., 2003; Russell et al., 2010; Lu et al., 2012; Legrand and Simon, 1989; Zerbo et al., 2012, 2013; Richardson et al., 2000), using the aa index, the interdiurnal variability (IDV) index, the inter-hour variability index (IHV), or solar wind indicate the possibility to investigate solar activity throughout geomagnetic indices and solar wind speed variations. In this paper, we used coded-color and display solar wind speed as a function of time during Bartels 27-days rotation to figure out four classes of solar wind repartition during geomagnetic activity. The classification is inspired by the strong correlation between solar wind speed and geomagnetic index (Svalgaard, 1977) and the geomagnetic activity classification (Legrand and Simon, 1989; Richardson et al., 2000, 2002; Richardson and Cane, 2012; Zerbo et al., 2012, 2013); here, quiet days and slow wind limit are fixed as $V < 450$ km/s, with $aa < 20$ nT and $V \geq 450$ km/s for disturbed activities having $aa \geq 20$ nT.

The four solar wind distributions are defined as follows and somewhat described in Zerbo et al. (2013).

(i) Quiet Days (QD) design slow solar wind coming from solar heliosheet and contain the very quiet days without storm activity defined by $V < 350$ km/s (white pixels in the diagram) and quiet days characterized by 350 km/s < V < 450 km/s (blue color in pixel diagram). An example of pixel diagram is shown in Figure 1a.

(ii) Recurrent wind (RW) class is formed by recurrent high solar wind coming from coronal holes and extended on several solar rotations and characterized by $V \geq 550$ km/s (orange, red, and olive red colors in pixel diagram).

(iii) Shock wind (SW) class is formed with days under CMEs (circle on pixel diagram) events and characterized by $V \geq 550$ km/s with one, two, or three days in duration.

(iv) Fluctuating wind (FW) class is formed by days not identified in the previous two well-organized class ($V \geq 450$ km/s).

RESULTS AND DISCUSSION

The temporal occurrence of each type of geomagnetic activity through a solar cycle is well-known and many studies outlining the close link between solar wind and geomagnetic events have been done by several authors (Legrand and Simon, 1989; Ouattara and Mazaudier, 2009; Richardson and Cane, 2012; Zerbo et al., 2012; Holappa et al., 2014). This paper investigates how solar wind different structures impact geomagnetic activity when solar wind reaches the Earth.

Figure 1 is an example of pixel diagram used to show often different solar wind structures induce geomagnetism. Each line of the pixel shows a 27-day rotation, and successive lines are solar rotations. Each number is the daily average of in situ solar wind speed provided by OMNIWEB data base (http://omniweb.gsfc.nasa.gov/ow.html and each circle indicates a day of storm/coronal mass ejection (CME). In this pixel $V < 450$ km/s characterizes quiet or very quiet day and $V \geq 450$ km/s a disturbed day (Legrand and Simon, 1989; Richardson and Cane, 2012; Zerbo et al., 2012). Based on the criterion presented in section 2, we identified the class of quiet day (white and blue colors), the class of recurrent wind (orange, red, olive red colors) with recurrence over several rotations, the class of shock wind characterized by storm effects, and the class of fluctuating wind formed by days where solar wind speed $V \geq 450$ without no recurrence. Figure 1a and b show, respectively, the pixels of the years 2003 and 2009 which are known to be very particular years regarding their geomagnetic activity levels (2003 very active and 2009 very quiet) (Zerbo et al., 2013). Taking a look at Figure 1, one can remark clearly that the year 2003 is dominated by recurrent wind flow most of the time while the year 2009 is under the control of slow wind flow.

Tables 1 and 2 summarized the annual numbers of each type of solar wind structure investigated in our study for these two years. The results shown in Figure 1 and

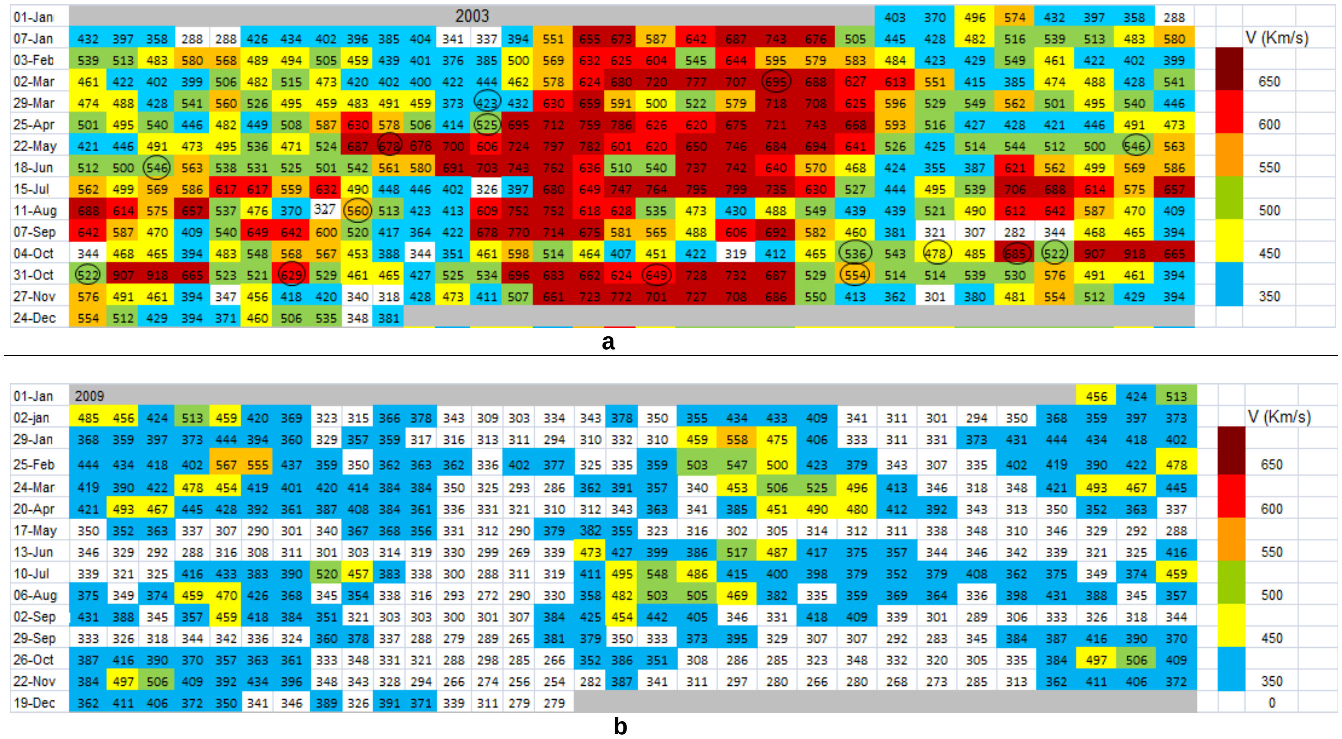

Figure 1. Example of pixel diagram: year 2003 (a), and year 2009 (b). Each line shows a 27 day rotation, successive lines solar rotations, and each number the daily average of solar wind speed. Circle indicates the date of storm/coronal mass ejection (CME).

Table 1. Number of days in each class of solar wind (quiet days, shock wind activity, recurrent high wind and fluctuating wind) during the year 2003.

Classes / year 2003	Number of days
Quiet wind days	97
Recurrent wind	157
Shock wind	13
Fluctuating wind	100

Table 2. The occurrence of solar wind flow classes for 2009.

Classes / year 2009	Number of Days
Quiet wind days	328
Recurrent wind	0
Shock wind	0
Fluctuating wind	37

Tables 1 and 2 indicate the strong correlation between solar wind and geomagnetic activity exposed in older studies (Svalgaard, 1977, Feynman, 1982; Richardson and Cane, 2012).

On our way for understanding how often each solar wind structure induced geomagnetism, we have evaluated the annual level of the different classes. Figure 2 shows their time profiles versus sunspot number evolution for the period of our study. Each type of solar wind structure is observed during the entire period investigated with variations in level. The most impressive quiet days class is recorded in 1997 (80%), and 2009 (85%) when 2003 gets the lowest level (18%). The highest and lowest recurrent wind effects are obtained in 2003 (43%) and in 2009 (0%), respectively. Shock wind highest level occurs in 2000 (12%). Considering now the sunspot number time profile, we can see that quiet days (slow solar wind effects) class is predominant when sunspot number is rising (minimum phase), shock wind is important around the maximum of sunspot number, and the recurrent wind effects are most significant on the declining of sunspot number which lead to the very fast solar wind streams flowing from the coronal hole and inducing severe geomagnetic activity (Legrand and Simon, 1989; Zerbo et al., 2012; Richardson and Cane, 2012) during solar cycle decreasing phase.

Figure 3 presents the occurrences of each type of solar wind structure and show how often the Earth is under each effect during solar cycle phases (minimum, increasing/ ascending, maximum, decreasing/declining). Slow solar wind flows modulate geomagnetism mostly (35%) during the ascending phase of solar cycle while the Earth is under strong recurrent wind effects (49%) on the decreasing phase. During a given sunspot cycle, the

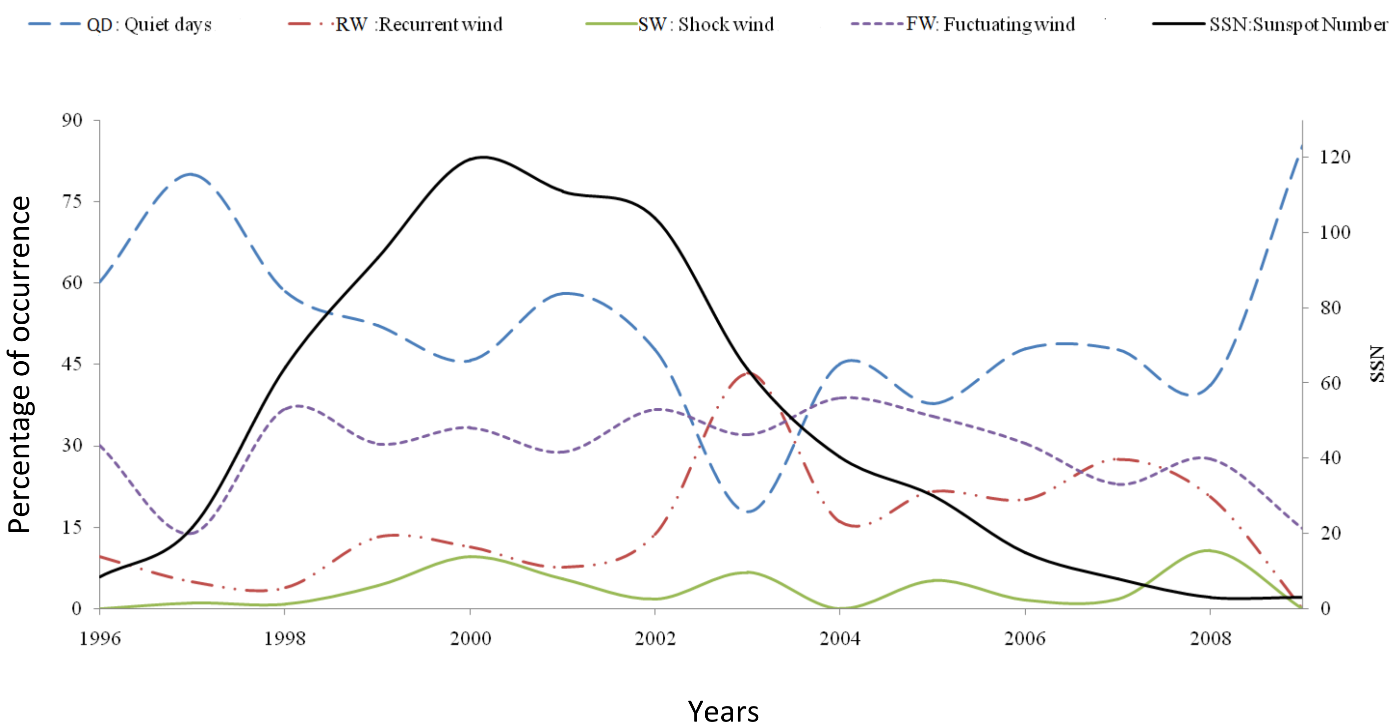

Figure 2. Annual level of quiet days (blue line), recurrent wind (red line), shock wind (green line), fluctuating wind (violet line), and sunspot number (black line).

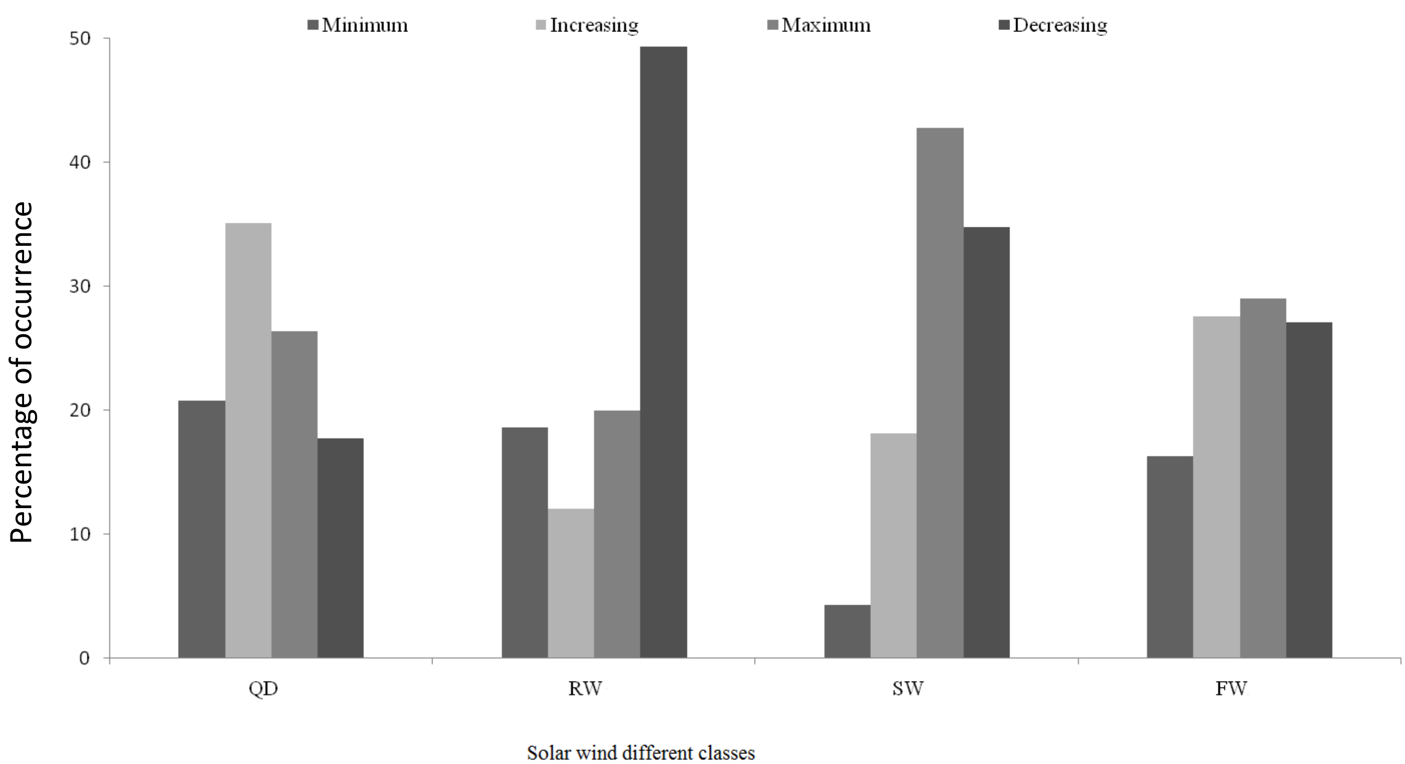

Figure 3. Level of different type of solar wind structure during solar cycle phases (minimum, increasing, maximum, and declining): quiet days (QD), recurrent wind (RW), shock wind (SW), and fluctuating wind (FW).

Table 3. Value of the histogram and giving the occurrence rate of solar wind different structure during sunspot cycle.

Solar wind occurrence	QD quiet days (%)	SW shock wind (%)	RW Recurrent wind (%)	FW fluctuating wind (%)
Minimum phase	21	4	19	16
Increasing phase	35	18	12	28
Maximum phase	26	43	20	29
Decreasing phase	18	35	49	27

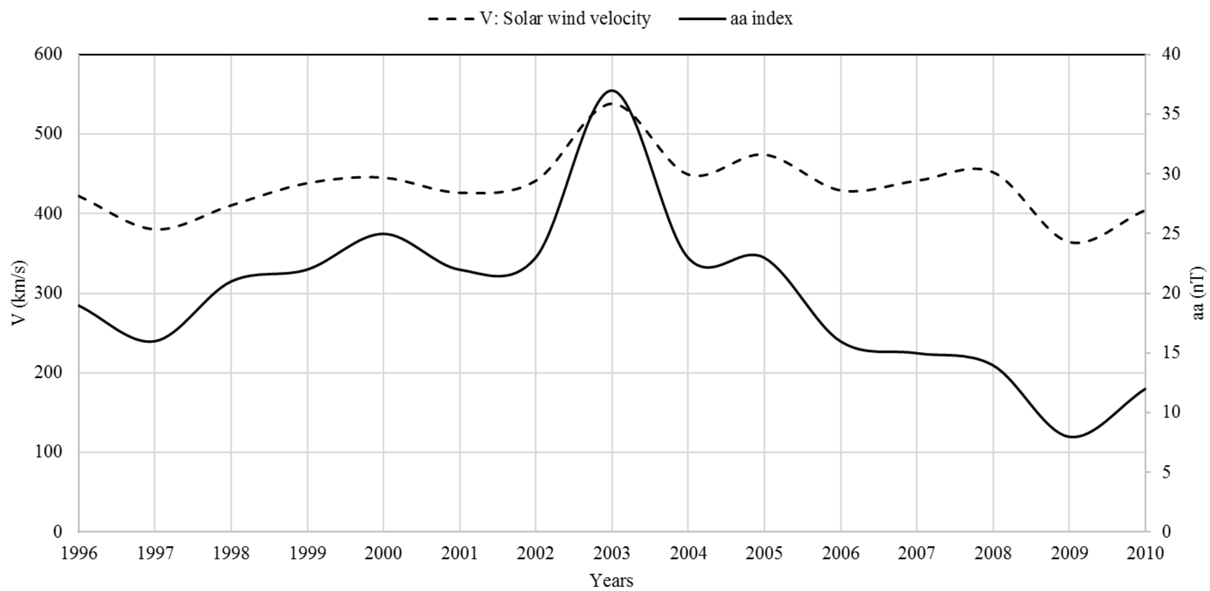

Figure 4. Annual average of aa index versus solar wind speed (V) profiles during solar cycle 23 and the early ascending phase of solar cycle 24: continuous line shows aa time variation and dusk line solar wind profile.

Earth is under the control of major shock winds on the maximum phase. That agrees with the importance of three solar wind structures during solar cycle phases noted previously by Richardson et al. (2000) and Hapgood et al. (1991). The permanent fluctuation of the heliosheet (Simon and Legrand, 1987) may explain the fairly constant level of fluctuating wind effects through all the solar cycle phases. Table 3 summarizes the different values used in Figure 3.

To give an overview of the relationship of solar wind-geomagnetic activity, we investigate the profiles of the geomagnetic index aa versus solar wind speed over solar cycle 23 and the early ascending phase of solar cycle 24. Figure 4 shows this comparison. Continuous line shows the annual average of aa time variation and dotted line, the annual average of solar wind profile. The strong correlation between aa index and solar wind speed V appears clearly and we can see that slow solar wind is closed to low geomagnetic level (1997 and 2009) and high stream solar wind is strongly closed to severe geomagnetic level (2003). This agrees with the ideas that low solar activity and severe solar activity occur mostly on the minimum and declining of solar cycle respectively (Legrand and Simon, 1989; Zerbo et al., 2012; Richardson and Cane, 2012).

Our results make it possible to suggest the following scheme of solar wind structure: (1) strong heating leads to strong dynamo process in solar, (2) solar wind structure induces harmonious geomagnetic activity classification, (3) geoeffectiveness varies with solar wind structure.

Conclusion

We have outline some current ideas about the interaction between solar wind and geomagnetic activity over solar cycle 23 and the early ascending phase of solar cycle 24. We have shown how often different types of solar wind structure impact the Earth magnetic field. The most severe magnetic activity (Legrand and Simon, 1989; Richardson and Cane, 2002:2014; Zerbo et al., 2012, 2013) are driven by two types of solar wind structure: Coronal Mass Ejection (CME) ~ 43%, and High-Speed solar wind streams (HSSs) ~ 49%, respectively at the maximum and declining phase of solar cycle. Major fraction of slow solar wind (~ 82% in 1997; ~ 85% in 2009) is observed during the rising of both sunspot cycles 23 and 24 which leads to the fact that the lowest level of geomagnetic activity is recorded during the rising of solar cycle and show the temporal stability of the recurrent patterns of slow wind following from the sun. The level of fluctuation in solar wind remains fairly important through all the solar cycles phases (16-29%) and may induce the unclear/ fluctuating geomagnetic activity (Legrand and Simon, 1989; Zerbo et al., 2012) and lead to the fluctuation of the heliosheet as discussed by Simon and Legrand (1987).

Conflict of Interests

The authors have not declared any conflict of interests.

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