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Geoeffectiveness of the inner magnetosphere under the impact of fast solar wind currents: Case of solar cycles 20 to 23

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Earth's magnetosphere is a magnetic shield that protects the Earth from the energetic emissions of the high-speed Solar Wind (HSSW). We perform a statistical analysis of the response of Earth's magnetosphere inner part under the impact of HSSW over 40 years of data encompassing solar cycles 20-23. With misidentified events or events interacting with interplanetary coronal mass ejections (ICMEs) removed, only 23552 events were identified. The results we obtained show that more than 85% of the events recorded from 1964 to 2009 are generated by coronal holes (CHs). Almost all observations were confined between 250-800 km/s and show a unimodal distribution per solar cycle: (1) 93% of the solar wind (SW) velocities are on the order of 567.77 ± 2.46 km/s for solar cycle 20, (2) 81% of the SW velocities are worth 524.30 ± 2.69 km/s for cycle 21, (3) 92% of the SW velocities progress to 565.15 ± 2.72 km/s for cycle 22, and (4) 75% of the SW velocities show a value on the order of 530.38 ± 2.22 km/s for cycle 23. Furthermore, our analysis shows a lower electron density at the beginning of the cycle (48%) than at the end of the solar cycle (52%). Thus HSSWs are more frequent at the end of solar cycles, while the magnetospheric electric field (EM) instead shows dominant features during the upward phase of odd cycles and the downward phase of even cycles. Therefore, the stability of the inner magnetosphere is more significant during the decline of solar cycles.

Key words: High-speed solar winds, magnetospheric electric field, interplanetary coronal mass ejections.

INTRODUCTION

Space weather refers to solar phenomena and environments that can affect the operation and reliability of space and ground-based systems and services, or even threaten human health (Schwenn, 2006; Belisheva et al., 2019; Abdullrahman and Marwa, 2020; Hapgood et al., 2021). All of these disturbances have socio-economic

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consequences whose cost can only be properly assessed with an accurate knowledge of climate variability. The phenomena representing one of the key factors of perturbations of the solar environment are the coronal holes (CHs). It is generally accepted that HSSWs originates from CHs and associated corotating interaction regions (Krieger et al., 1973; Sheeley et al., 1976; McComas et al., 1998; Richardson et al., 2000; McGregor et al., 2011b; Zerbo et al., 2012). Structure of the solar wind (SW) evolves as it flows outward through the heliosphere away from Sun. Through corotation of polar CHs associated with the "open" magnetic flow or through solar flare activity, HSSWs are created (Poletto, 2013; Owens et al., 2017). Ejected from the Sun and traveling through interplanetary space, HSSWs carry highly energetic particles; resulting in an increase in the mean interplanetary magnetic field (IMF). SW interacts with the CMI Bi and generates a $V_{SW} \times$ Bi electric field that crosses the magnetosphere. The latter interacts with the Earth's magnetic field and generates a force that controls the convective motion of the magnetospheric plasma. E_M field thus plays a very important role on the dynamics of the Earth's magnetosphere. Indeed, according to Baumjohann et al. (1985), part of the E_M field is driven by the ionospheric dynamo. Matsui (2003) showed that the magnetospheric source contributes at least 30% of the electric field, while the ionospheric dynamo contributes at least 25%. In addition, numerous quiet-time studies of the characteristics of environmental changes in the magnetospheric plasma due to HSSW have been performed (Harvey and Sheeley, 1978; Sheeley and Harvey, 1981; Verbanac et al., 2011a, b). However, the overall variation in the energy potential of HSSWs in magnetically perturbed periods (Aa ≥ 20 nT) remains unknown, and the response of this solar-phase variability on E_M field for cycles 20 to 23 is not yet clarified.

To quantify the study of solar winds, a consistent definition of what is meant by HSSW is needed. Indeed, many definitions have been proposed for HSSW over time. According to Bame et al. (1976) and Gosling et al. (1976), a HSSW is an observed variation in SW velocity, with an increase in velocity of at least 150 km/s within a five-day interval. Broussard et al. (1978) described it as a flow with a velocity greater than 500 km/s averaged over one day. In addition, Lindblad and Lundstedt (1981) defined it as a flow defined over a period during which the difference in velocity between the lowest value on 03 h and the highest on 03 h of the following day, is greater than 100 km/s and it lasts at least two days. Later, according to Mavromichalaki et al. (1988), and Mavromichalaki and Vassilaki (1998), HSSW is a flow defined over a period in which the difference between highest and average velocity of the plasma immediately preceding and following the flow, is greater than 100 km/s over an interval of at least two days. And finally, Intriligator (1973, 1977), Richardson and Hilary (2012), Zerbo et al. (2012), Villarreal et al. (2014) and Despirak et al. (2019) described it as a rapid increase in SW flux with a peak velocity greater than or equal to 450 km/s on average. The latter definition would be used in the present study because, we believe, it mostly covers the limit imposed according to other authors. A typical example of the velocity variation of the whole solar wind for the year 1994 is shown in Figure 1.

Year 1994 is chosen because of the frequent occurrence of intense activity (Tanskanen et al., 2005; Reeves et al., 2011). In this Figure 1, SW velocities beyond the horizontal plot (blue plot) are greater than or equal to 450 km/s day. We note that more than 80% of the SW velocities for year 1994 coincide with the definition of a HSSW given earlier. This article discusses this topic, in particular the effect of long-term HSSW variability on the E_M field. In this manuscript, we will examine the geoeffectiveness of the Earth's magnetosphere during daytime magnetic reconnection in the face of intense HSSW fluctuations. The main reason for studying long-term HSSWs is that they are a potential hazard to the Earth and to space systems.

Many studies have shown that the solar flux is strongly dependent on the long-term solar cycle and activity (Joshi et al., 2011; Zerbo et al., 2013; Elena et al., 2013; Shinichi, 2017). Indeed, according to Snyder et al. (1963) and Svalgaard (1977), geomagnetic activity depends on the parameters of the SW, in particular its velocity. Thus, several authors have grouped geomagnetic activity into four standard classes (Ouattara et al., 2009; Du, 2011) based on the former classification made by other authors (Legrand and Simon, 1981, 1989; Simon and Legrand, 1989; Richardson et al., 2000, 2002). Later, Ouattara et al. (2009) and Zerbo et al. (2012) reported a new extension of the standard classification by scrutinizing with new solar wind conditions, the global classification established by Legrand and Simon (1981, 1989). This new extension allowed Zerbo et al. (2012) to clearly identify about 80% of the geomagnetic activity today, compared to 60% identified by Legrand and Simon (1981, 1989). In this study, the new extension of Zerbo et al. (2012) will be used and we will restrict ourselves to magnetically disturbed periods, which are characterized by geomagnetic indices Aa ≥ 20 nT (Ouattara et al., 2009; Zerbo et al., 2012).

DATA AND METHODOLOGY

Data set

In this paper, various spatial datasets available in the public domain were used. Hourly observations of SW parameters compiled by the scientific community and available via the OMNIWeb link «http://omniweb.gsfc.nasa.gov/form/dx1.html» are used to obtain information relating to the frozen electric field (Ey) in SWs and the velocity of these SWs. To examine the geomagnetic indices (Aa) evaluated by 03 h resolution, data available on «http://isgi.unistra.fr/» were used to obtain relative information on

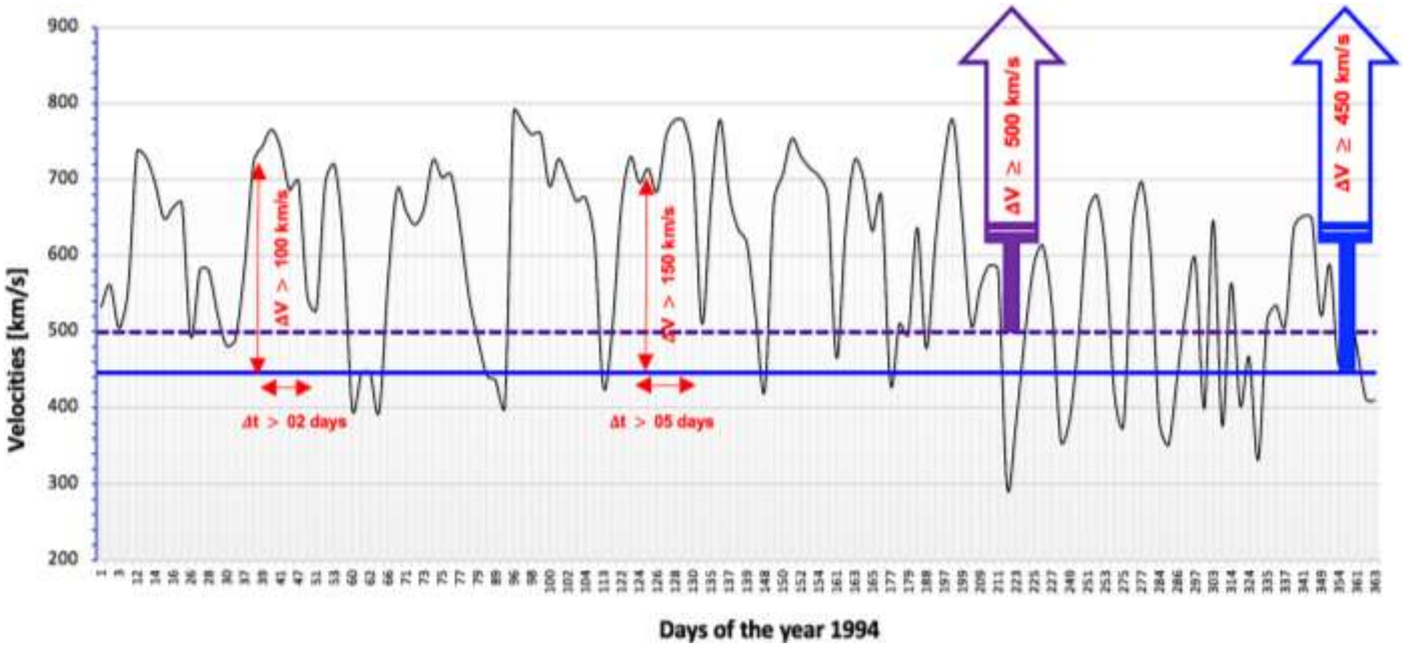

Figure 1. Evolution of solar wind velocities during the disturbed days of 1994.

Table 1. Characteristics of solar cycles 20-23.

Cycle	Period	Start/end	Duration (year)	Rising phase	Downward phase
Cycle 20	1964-1976	August 1964 / March 1976	11.7	1966-1968	1971-1974
Cycle 21	1976-1986	March 1976 / September 1986	10.3	1977-1978	1983-1986
Cycle 22	1986-1996	September 1986 / May 1996	9.7	1987	1992-1995
Cycle 23	1996-2009	May 1996 / January 2009	12.6	1997-1999	2003-2005

magnetically disturbed days from 1964-2009 period. It is important to note that no reliable information on the structure of the Ey field in the SW was available for the first half of the year 1964. For this study, based on the Wolf numbers (Rz) available at «http://sidc.oma.be/sunspot-data/», the exact start/end periods of the ascending and descending phases of the four solar cycles 20-23 studied via the link «http://users.telenet.be/j.janssens/Engzonnecyclus.html#Overzicht» have been summarized in Table 1.

Approach

We analyze continuous data over the range 1964-2009 only for disturbed periods, which are identified by geomagnetic indices Aa ≥ 20 nT. According to Legrand and Simon (1989), Richardson and Hilary (2012), Zerbo et al. (2012) and Despirak et al. (2018), these periods represent the manifestation class of HSSW. First, we remove all unreliable information from the solar flux velocities Vsw and the hourly Ey field into this flux over the long 45-year period. Note that the Ey field is in most cases, the dominant factor that determines the structures of the high latitude E_M field as well as the magnetospheric convection processes associated with it. Thus, component of the total electric field related to the corotation of the Earth, will be neglected in this article. After filtering, Ey field [mV/m] is used to determine E_M field [mV/m] using the relation of Wu et al. (1981), later validated by Revah and Bauer (1982):

$$E_M = 0.13E_y + 0.09 \quad (1)$$

Secondly, annual average values of the E_M and V_{sw} parameters are estimated. These averages remove the periodicities associated with shorter time scales. The use of average values in this study compensates for the effects of day-to-day variability of the Sun's activity in the proxies used. Since, the objective in this paper is to study the global variations of HSSW and their impact on the E_M field during perturbed periods, it would be reasonable to use average parameters for an overall view.

Furthermore, to check our data for a significant difference per solar cycle in the velocity distribution of HSSW and E_M field, recourse was made to the Kolmogorov - Smirnov (KS) test «http://www.physics.csbsju.edu/stats/KS-test.html». KS test statistic measures the largest D_{ks} distance between empirical distribution function of the processed data and hypothesized distribution (Stephens, 1992). It is important to note that KS test is a non-parametric goodness-of-fit test that is widely used in statistical studies. KS test gives a 95% confidence interval for true means against a fixed 5% risk of error (Wilks, 2011; Jesper, 2014). Based on the number of data points, the statistical value D_{ks} varies, which is the maximum difference between the cumulative distributions of two selected data sets. The critical values D_α (Equation 2) with n,

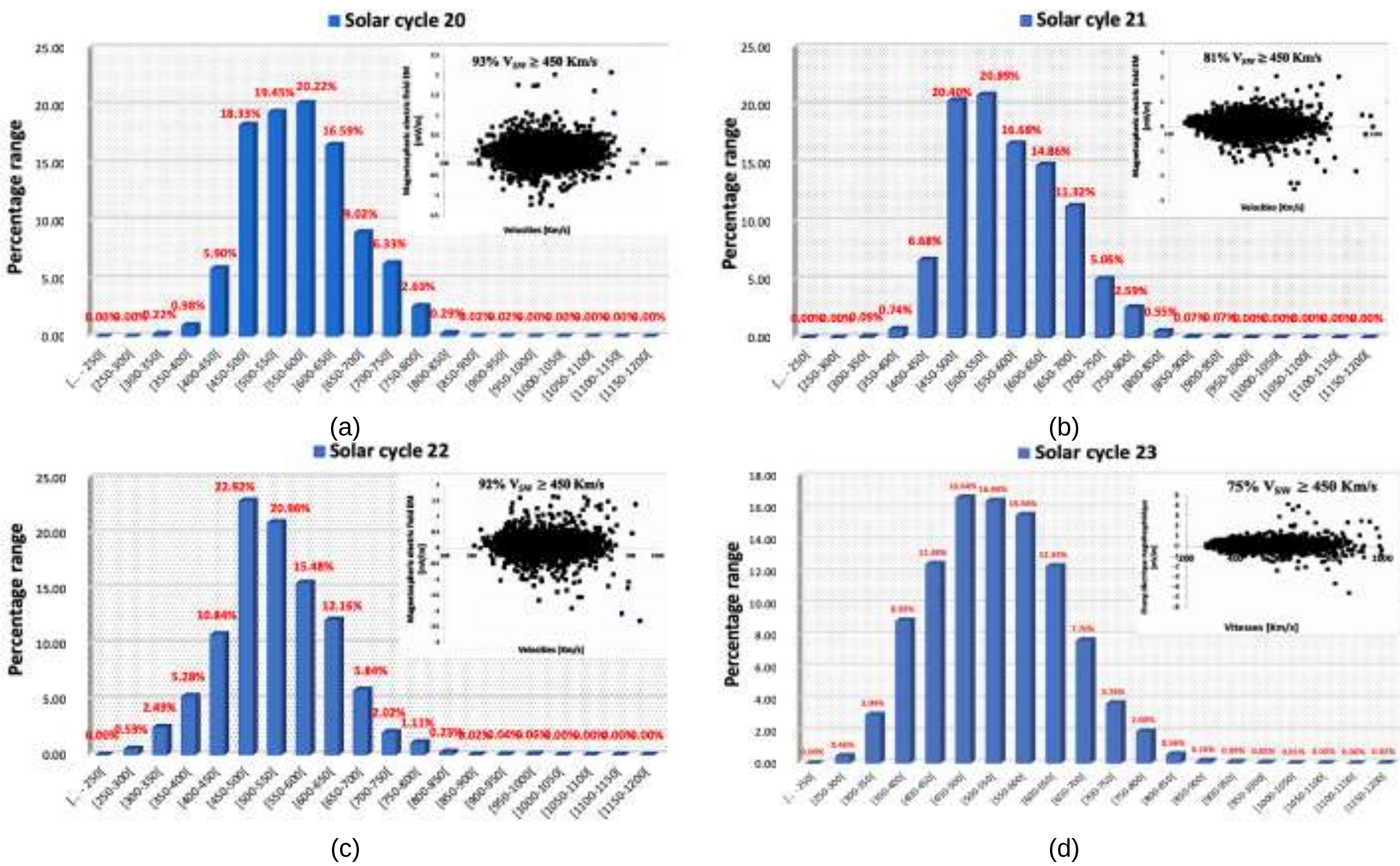

Figure 2. Distribution of HSSW velocities in disturbed activity class.

the number of events, indicate whether the selected data, differ significantly (Gabriel, 2014).

$$D_\alpha = \frac{0.886}{\sqrt{n}} \quad (2)$$

If D_α is greater than D_{ks}, the null hypothesis of no difference between the data sets is rejected (Lilliefors, 1967; Crutcher, 1975; Ruppert, 2004; Steinskog et al., 2007; Vlček and Huth, 2009; Wilks, 2011).

RESULTS AND DISCUSSION

Distribution of high-speed solar winds

Figure 2 shows the statistical distribution of HSSWs during magnetically perturbed periods for all solar cycles 20-23. Panels (a), (b), (c), and (d) represent the statistical distribution of all solar winds for solar cycles 20, 21, 22, and 23, respectively. The analysis of all these panels shows that more than 99% of the solar wind velocities are in the range 250-800 km/s, which is identified by several authors (McGregor et al., 2011a; Villarreal et al., 2014; Rotter et al., 2015). However, according to Figure 2, not all HSSWs have a peak velocity ≥ 450 km/s, as pointed out by several publications (Intriligator, 1973, 1977; Richardson and Hilary, 2012; Zerbo et al., 2012; Villarreal et al., 2014; Despirak et al., 2018). Indeed, examination of panels (a), (b), (c), and (d) in Figure 2 shows that at least 93, 81, 92 and 75% of the SW velocities blowing on disturbed days, respectively, are greater than or equal to 450 km/s. We note that the even cycles (20 and 22) have a high rate of occurrence of HSSW compared to the odd cycles (21 and 23). From this analysis, it is therefore clear that high-speed solar flux is the main contributor at about 85% to the SW solar averages during magnetically disturbed periods. This contribution is in very good agreement with the work of Legrand and Simon (1989), Lindblad (1990), Richardson et al. (2000), Zerbo et al. (2012) and Bharati et al. (2019) in which, SW velocity limit is set to characterize the period of magnetically disturbed days.

Our statistical study shows us to what extent, distributions of HSSWs during perturbed periods are not all similar for the four solar cycles or at least for the interval considered, whatever the solar flux variation (Zerbo et al., 2012; Bharati et al., 2019). Despite the smaller changes in HSSWs from one solar cycle to the

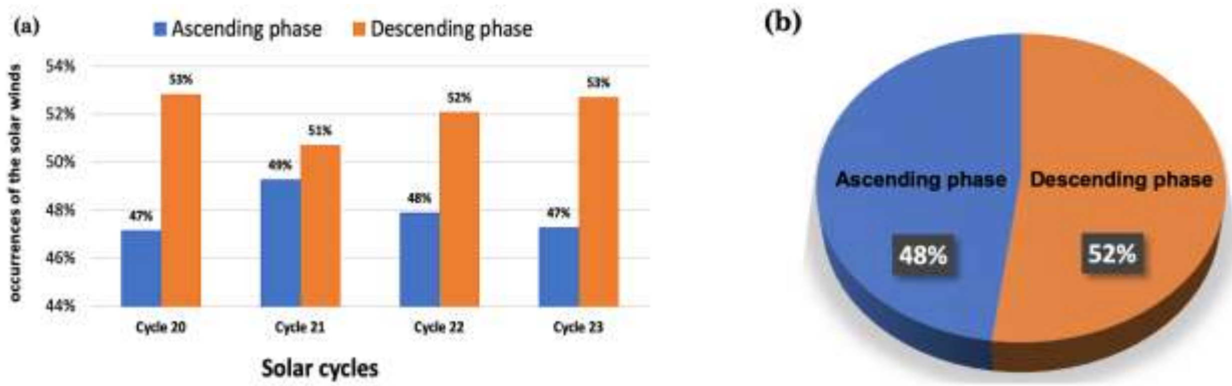

Figure 3. Velocity distribution of HSSW in disturbed periods during the ascending and descending phases of solar cycles 20-23.

next in magnetically perturbed periods; overall, their average variations during the rise and fall of solar phases follow closely. Indeed, according to Figure 3(b), the average velocities of HSSWs corresponding to the ascending and descending phases of the four solar cycles studied are of the order of 48 and 52% respectively of the total flux. In fact, Figure 3(a) shows dominant features during the descent phase: average velocities increase, reaching their highest values. These results are in very good agreement with the work of several authors (Bame et al., 1976; Gazis, 1996; Richardson et al., 2002; Luhmann et al., 2009; Jacob et al., 2020). The peak velocities of solar cycles 20 to 23 obtained during the ascending phases are respectively 541.90, 546.20, 546.67 and 516.95 km/s against 598.04, 557.96, 599.78 and 576.48 km/s for the descending phase. These peaks would be related to several coronal holes (CHs) which are known to generate high-speed solar flows (Lindblad, 1990; Echer et al., 2004). The dominant characteristics of the velocities at the end of the solar cycle suggest that the mass transport towards the Earth intensifies in this period. Consequently, the internal magnetosphere becomes unstable at the end of the solar cycle than at the beginning during magnetically disturbed periods. On the one hand, this result is in good agreement with the simulations of stable magnetospheric convection made by Pulkkinen et al. (2007); and on the other hand, by many other authors (Phillips et al., 1995; Ebert et al., 2009). In addition, during the descending phases of solar cycles, HSSWs velocities are so great that "bow shocks" could form whenever they are forced to travel around the planets of the solar system. Such bow shocks will also form around airplanes, rockets, or the space shuttle when these vehicles travel faster than the speed of sound through the atmosphere.

It is important to note that during the ascending phase, corotating flows have average speeds (Vsw) between 450 and 500 km/s, while they are above 500 km/s during the descending phase. Since the strength of a solar flux is generally characterized by stable magnetospheric convection events, we estimate that there are a significant number of magnetic storms at the end of the solar cycle than at the beginning. Such events at the end of the solar cycle, suggested that the Earth's environment, and perhaps even the Sun, are sources of disruptions and failures in new technologies such as wireless communications and power systems on a local and geographical scale. These notable features are corroborated by the work of Ouattara (2015), Kaboré and Ouattara (2018), and Despirak et al. (2018) where the storms were named "expanded substorms" for Vsw > 500 km/s and "polar substorms" for Vsw < 500 km/s. The increase in HSSW velocities at the end of the solar cycle noted in this paper, makes the outer layers of the plasmasphere convectively unstable and consequently, able to generate many irregularities in the plasmapause region. This aspect of trends is justified by the fact that electron fluxes are seasonally dependent. Indeed, Yeeram (2020) proved that electron fluxes are relatively low during the ascending phases of solar cycles and high during the descending phase. Our results are consistent with this argument when the corresponding periods are compared.

Magnetospheric response in perturbed periods

For a better understanding of the impact of HSSWs on the E_M field during the ascending and descending phases of solar cycles, we have plotted histograms of E_M field for the class of magnetically disturbed periods in Figure 4a. It appears that even cycles (20 and 22) exhibit dominant characteristics of the E_M field during the descending phase. On the other hand, odd solar cycles (21 and 23) show rather a high proportion of the E_M field during the ascending solar phase. The notable features observed during the even cycles may be due to the fluctuations and large amplitudes recorded in these cycles.

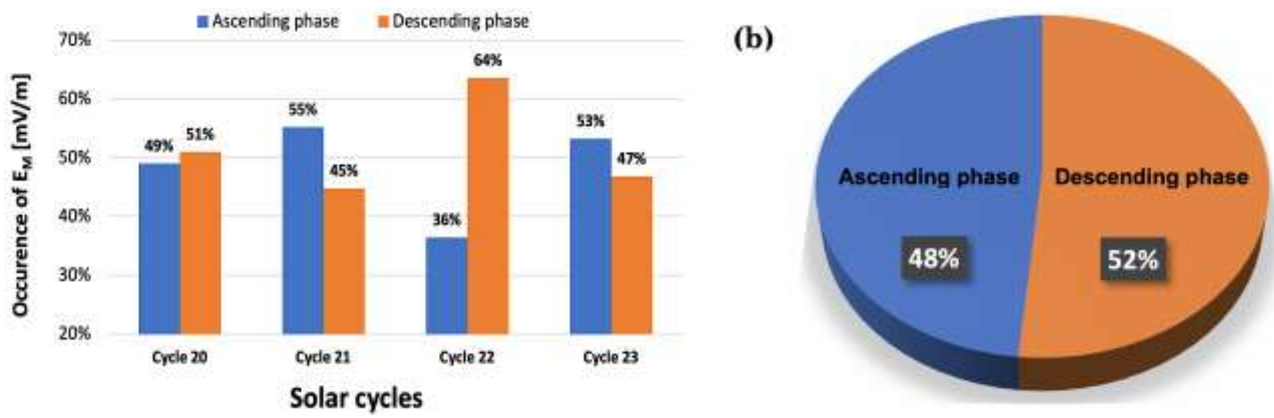

Figure 4. Distribution of E_M in disturbed periods during the ascending and descending phases of solar cycles 20-23.

Table 2. Occurrences and T-test of E_M field during disturbed days of solar cycles 20-23.

Phase	Occurrence (%)		T−test			
	E_M	HSSW	Cycle 20	Cycle 21	Cycle 22	Cycle 23
Ascending	48	48	0.036	0.0034	0.0086	0.011
Descending	52	52				

In order to conclude whether or not the two means of the magnetospheric electric field come from the same population during the ascending and descending solar phases, we performed a T-test. The significance levels of the E_M field, recorded in Table 2, are all satisfactory ($p < 0.05$), so we prove the satisfaction of our results. The results of the T-test confirm once again that the averages of the E_M field come from the same type of sample analyzed.

Examination of columns 2 and 3 of Table 2 tells us that HSSW and E_M field constantly evolve in phase for all the solar cycles studied. This is justified by the similarity of the distributions observed in Figures 3b and 4b. However, special attention is given to the rather large occurrence of the E_M field observed during the downward phase of solar cycle 22 (Figure 4a). Indeed, solar cycle 22 reveals the existence of typical abrupt variations of the E_M field and of large amplitudes of HSSWs. This contribution is corroborated by the work of Inza et al. (2022).

In addition, the study of solar wind particles, and particularly HSSW, are very complex random phenomena. Thus, the distribution of solar flux velocities is made more useful through statistical methods. For this reason, the probabilities of HSSW velocities can be estimated using probability distributions. Since we have only considered magnetically perturbed days in this paper, we do not expect much change in HSSW averages. An accurate determination of the probability distribution of the average HSSW velocities is very important for assessing the solar wind energy potential of a given solar phase/cycle. Instead of computing a full distribution over the features to approximate an underlying process, we will restrict ourselves to the distribution of the properties of these features over a finite number of points for 1964-2009 period. Thus, analysis of the long data set of HSSW particles by the KS test gives very satisfactory results. Indeed, the D_{ks} statistical values are all greater than or equal to the critical values D_α for both solar quantities. Particular attention is paid to the critical D_α values, which are all below the fixed risk of error (5%). These arguments show the consistency of the selected data sets, and therefore, indicate that the velocity distributions of HSSW and E_M field are similar over 03-h cadences. However, for even solar cycles, the statistical values of HSSW are higher than those of E_M field, while the opposite is found for odd cycles. The differences between even and odd cycles have in the Sun, a very random character. According to Durney (2000) and Takalo (2021), these differences are related to the amplitudes and/or Gnevyshev gaps (GG) between the ascending and descending phases of the solar cycles. One could estimate that the D_{ks} statistical values are related to the nature of the solar cycles and the size of the samples. The results of KS test are given in Table 3.

Moreover, when it comes to determining the practical significance of a set of processed data, confidence intervals are generally more useful than tests (Nick et al., 2003; Jean-Baptist et al., 2009; Ranstam, 2012). In the

Table 3. KS test results from solar cycles 20-23 for magnetically disturbed days.

Cycle	Number of events (n)	Confidence interval		Margins of error		D_{ks}		D_{α}
		HSSW [km/s]	E_M [mV/m]	HSSW [km/s]	E_M [mV/m]	HSSW	E_M	
Cycle 20	5100	565.31−570.22	0.095−0.107	± 2.46	± 0.006	0.052	0.038	0.012
Cycle 21	4695	521.61 −526.99	0.096−0.113	± 2.69	± 0.008	0.039	0.079	0.013
Cycle 22	4328	562.44−567.87	0.094−0.110	± 2.72	± 0.007	0.145	0.081	0.014
Cycle 23	9429	528.16−532.60	0.109−0.120	± 2.22	± 0.005	0.029	0.087	0.009

case of comparing two population means of solar winds, it is important to construct a confidence interval and conclude that there is an effect of practical significance only if all differences in that interval are small enough. According to Ruppert (2004), if the difference in the confidence interval is high, then the information is less accurate. Therefore, a lower confidence interval is more likely to return the correct value. In this manuscript, the difference in confidence intervals for HSSWs, although small, is greater (2.22 to 2.72 km/s) than for E_M fields (0.005 to 0.008 mV/m) as can be observed in columns 5 and 6 of Table 3. We could therefore conclude with a 95% confidence level that there is no significant difference for the processed data set. The difference in the margins of error between our two populations is probably due to the size of the samples analyzed. Indeed, the E_M field values are relatively small compared to the HSSW values. It is therefore clear that the confidence intervals are strongly influenced by the sample size. This analysis is corroborated by the results of Tukur (2008).

Conclusion

Various examples of perturbed events and their effect on the inner magnetosphere discussed here, with particular emphasis on the changes associated with the progression of solar cycles 20-23 to the averages of the geomagnetic indices (Aa), have been realized for the period extending from 1964 to 2009. Stable currents of large amplitudes (from peak to trough greater than or equal to 450 km/s) were most often observed during the years of descending phases: about 570.22 km/s in 1974 (cycle 20), about 526.99 km/s in 1986 (cycle 21), about 567.87 km/s in 1994 (cycle 22), and about 532.60 km/s in 2003 (cycle 23). This aspect of solar flux velocity variation is reflected in the 5-95% range of velocity values listed in column 3 of Table 3. The results by means of the statistical tests (T-test, KS test and 95% confidence interval) which we arrived at indicate a better distribution of the selected data. However, these results are more significant for the E_M field than for the HSSW. Moreover, the statistical analysis of the energetic particles in the solar flux confirms that about 85% of the SW represents the main contributor to HSSWs during magnetically disturbed periods. The presence of dominant HSSW features at the end of the solar cycle significantly affects the stability of the day-side inner magnetosphere. Across the 20-23 solar cycles, HSSW and E_M field recorded a small contribution (48%) during the ascending phase compared to 52% of solar averages during the descending phase of solar cycles. These results support the hypothesis that HSSW and E_M quantities controlling the state of the inner magnetosphere, evolve in phase during the ascending and descending phases of solar cycles. Despite the obvious importance of the E_M field on a large scale, their observation is very difficult because of its very complex spatial and temporal structure and its low variability in space and time. Of the solar cycles studied, even cycles (20 and 22) showed dominant E_M field characteristics during the descending phase while the odd cycles (21 and 23) rather showed a high proportion of E_M field during their ascending phases. In addition to the threat to spacecraft systems posed by characteristic dominants, the radiative environment of space also poses risks to the health and safety of astronauts. Appropriate measures must therefore be pursued to minimize astronaut exposure to HSSW particle emissions during geomagnetic storms and solar energy.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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