Solar–geomagnetic activity and Aa indices toward a standard classification

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Solar– geomagnetic activity and Aa indices toward a standard classification

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Legrand and Simon [1989. Solar cycle and geomagnetic activity: a review for geophysicists. Part I. The contributions to geomagnetic activity of shock waves and of the solar wind. Annales Geophysicae 7(6), 565–578] classified one century (1868–1978) of geomagnetic activity, using the Mayaud's Aa index, in four classes related to solar activity: (1) the magnetic quiet activity due to slow solar wind flowing around the magnetosphere, (2) the recurrent activity related to high wind speed solar wind, (3) the fluctuating activity related to fluctuating solar wind and (4) the shock activity due to shock events (CME). In this paper, we use this classification to analyse the solar–geomagnetic activity from 1978 to 2005. We found that during the last three decades the level of geomagnetic quiet activity estimated by Aa indices is decreasing: 2003 is the year of the smallest level of quiet geomagnetic activity since 1868. We compare Legrand and Simon's classification with new in situ solar wind data [Richardson, I.G., Cliver, E.W., Cane, H.V., 2000. Sources of geomagnetic activity over the solar cycle: relative importance of coronal mass ejections, high-speed streams, and slow solar wind. Journal of Geophysical research 105(A8), 18,200–18,213; Richardson, I.G., Cane, H.V., 2002. Sources of geomagnetic activity during nearly three solar cycles (1972–2000). Journal of Geophysical Research 107(A8), 1187] and find a rather good agreement. The differences are only due to minor definitions of the extent of the classes. An attempt is made at defining a more precise standard classification of solar phenomena and at defining time scales of these to understand more precisely the geomagnetic signatures of solar activity.

1. Introduction

Since several centuries Geophysicists observed the Earth's magnetic field and in some observatories over the world, continuous records of the Earth's magnetic field exist since more than one century and a half. The observed transient variations of the Earth's magnetic field exhibit a daily regular part Sq/S_R (S_R is the regular variation of the Earth magnetic field) resulting mainly from the circulation of ionospheric electric currents in the dynamo layer (Stewart, 1882; Chapman and Bartels, 1940; Mayaud, 1965a, b).

Sometime an irregular variation is superimposed on the regular variation of the Earth's magnetic field. This irregular part is interpreted as the result of electric currents flowing in ionosphere and magnetosphere during magnetic storms (Humboldt, 1808; Chapman and Ferraro, 1931; Mayaud, 1965c; Cole, 1966; Fukushima and Kamide, 1973). Two main physical processes were proposed to explain the interaction between the solar wind and the magnetosphere: (1) the viscous interaction (Axford and

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Hines, 1961) and (2) the reconnection (Dungey, 1961). Both mechanisms produce electric fields transmitted from magnetosphere to ionosphere (Nishida, 1978). Kuznetsova et al. (2006) show that solar electric field participates also to the interconnection process during geomagnetic activities. The UT and annual variations of geomagnetic activity are due to the same variations of solar electric field.

Irregular variations of the Earth's magnetic field integrate many sources of electric current in the Earth's environment and are difficult to analyse. This fact led geophysicists to establish various geomagnetic indices (Bartels, 1932, 1949, 1957; Mayaud, 1980) in order to help understanding the geomagnetic activity. One of these indices is the Aa index computed by Mayaud (1971, 1972, 1973) for one century 1868–1978. This index based on records from two antipodal stations, gives an estimation of the geomagnetic activity at daily, monthly or annual time scales. This index is currently used by many scientists as a reference for geomagnetic activity. Some authors analysed the Aa index to characterize the harmonics components, which periods are annual, semi annual, 10–11 years, 5, 2 years, etc. (Delouis and Mayaud, 1975; Mayaud, 1975, 1977c; Courtillot et al., 1977; Prestes et al., 2006). Other authors characterized the different signatures of the solar activity in terms of Aa index. Legrand and Simon (1989) found that the Aa index exhibits a dual structure related to the two components of the magnetic solar field: the sunspot solar component and the dipolar solar component (Simon and Legrand, 1989, 1990). Later on Echer et al. (2004) confirmed this result. Legrand and Simon (1981, 1989) classified the Aa index in four geomagnetic classes related to solar phenomena and solar cycles for the whole period 1868–1978.

In this paper, we used Legrand and Simon' classification to analyse the last three decades of Aa indices. Mayaud's Aa indice is used in this study not only because the goal of this study is to continue the work of Legrand and Simon, which is stopped at 1980, but also Menvielle and Berthelier (1991) show that this index can give only a rough estimate of the planetary activity.

Section 2 recalls the dependence of the geomagnetic index on solar activity following Legrand and Simon's criteria. Section 3 presents the analysis of the Aa indices for the three last decades. Section 4 compares the results obtained with Legrand and Simon's method with new in situ solar data (Richardson et al., 2000; Richardson and Cane, 2002). Then in Section 5, we discuss the results and propose for the future to work on a new standard classification of solar and geomagnetic activity.

2. Old classification of geomagnetic activity from Legrand and Simon

Legrand and Simon (1989) analysed the centennial series of the Aa indices and classified these data in four classes of geomagnetic activity: (1) magnetic quiet days activity, (2) recurrent (stream) activity, (3) fluctuating activity and (4) shock activity (CME).

In order to determine the different classes of geomagnetic activity, they used a pixel diagram as shown on Fig. 1.

A pixel diagram helps to select the geomagnetic data as a function of the solar activity as described by solar rotation (27 days).

Each pixel diagram has 31 rows corresponding to the maximum day of the month. To obtain the 31 rows the first four rows have been repeated at the end. The diagram is started by reading from the third row and finished at the 29th row. The corresponding day of the third row has been mentioned on the left of the diagram and the corresponding year on the top of the diagram.

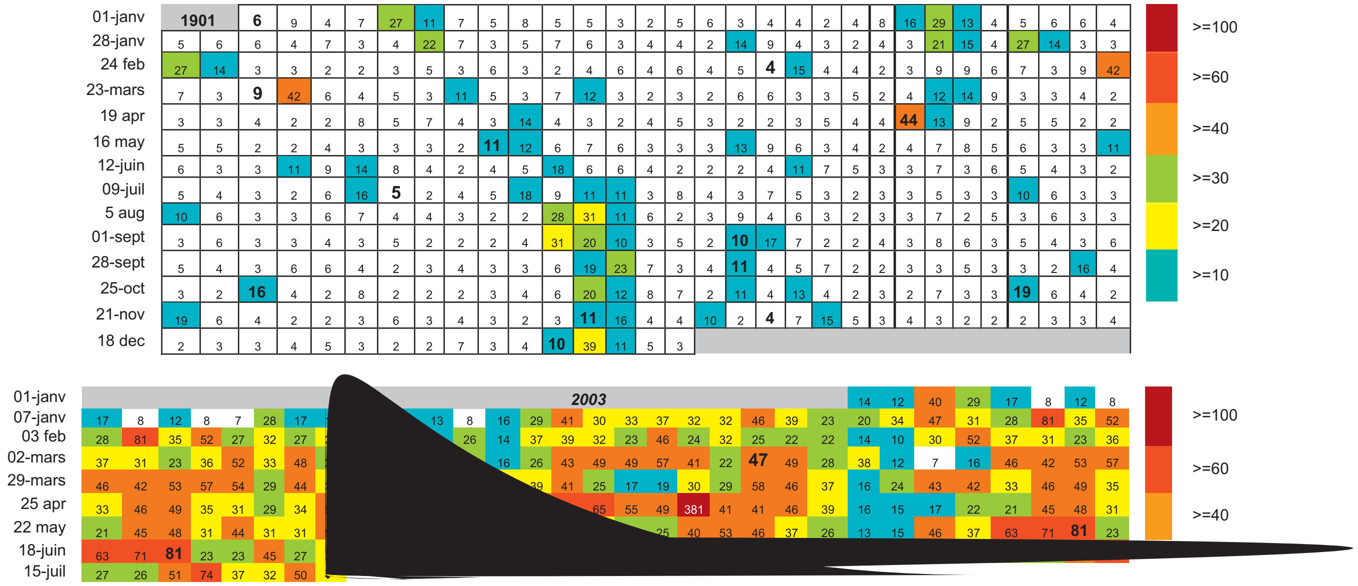
Pixel diagrams have been made for the whole values of Aa since 1868, year after year until 2006. The picture obtained gives the continuum description of the geomagnetic activity as a function of solar activity. For the continuum, it becomes impossible to make a pixel diagram for 1 year without comparing the year before the desired year. The picture gives the date of the SSCs, which are indicated by the thick black value of Aa for the corresponding day. Shock event is estimated by taking account 2 or 3 disturbed days after SSC date. Shock event activity thus defined includes all of the different SSC class level such as S or R.

Fig. 1 is a pixel diagram of 1901 and 2003 years extracted from the grid given by the whole Aa from 1868 to 2006.

On this figure the value of the daily Aa index is plotted in a Bartels diagram, the dates of SSC are quoted (thick black numbers design the daily Aa numbers for the SSC days and thin black numbers correspond to the daily Aa numbers for the days without SSC). A colour code helps us to identify quiet days activity and each class of disturbed activity (see Fig. 1).

The pixel diagram of Fig. 1 shows a very quiet magnetic year 1901 and a very magnetic disturbed year 2003. In 2003, there are few very quiet days ($Aa < 10\,nT$—white) and quiet days ($10\,nT < Aa < 20\,nT$—blue). There are four periods of very strong Aa ($Aa > 100\,nT$), in May, August, October and November. This annual variation of very strong Aa is in phase with Legrand and Simon (1989) study. Thus, according to this study, monthly distribution of the geomagnetic activity and monthly number of severe storms ($Aa < 100\,nT$) between 1868 and 1980 show seasonal evolution. Maxima are situated on one hand, between February and April with a peak in this interval at March and on the other hand, between August and September with a peak in September. Minima are situated at June and December. With such diagram we have a global view of the geomagnetic activity over a year. Many studies explain such variations (Berthelier, 1976; Green, 1984; Silverman, 1986). First, equinoctial mechanism postulates that it is due to the varying inclination of the Earth's dipole to the Earth–Sun line. This mechanism contributes for 45% to the shock events (Legrand and Simon, 1989).

Second, axial mechanism takes into account of the seasonal variation of the Earth heliolatitude, which is a consequence of the tilt of the solar axis on the ecliptic plane. This contributed to 15% of shock events. There is also a mechanism suggested by Russell and McPherron



01-janv	**1901**		**6**	9	4	7	27	11	7	5	8	5	5	3	2	5	6	3	4	4	2	4	8	16	29	13	4	5	6	6	4
28-janv	5	6	6	4	7	3	4	22	7	3	5	7	6	3	4	4	2	14	9	4	3	2	4	3	21	15	4	27	14	3	3
24 feb	27	14	3	3	2	2	3	5	3	6	3	2	4	6	4	6	4	5	**4**	15	4	4	2	3	9	9	6	7	3	9	42
23-mars	7	3	**9**	42	6	4	5	3	11	5	3	7	12	3	2	3	2	6	6	3	3	5	2	4	12	14	9	3	3	4	2
19 apr	3	3	4	2	2	8	5	7	4	3	14	4	3	2	4	5	3	2	2	3	5	4	4	**44**	13	9	2	5	5	2	2
16 may	5	5	2	2	4	3	3	3	2	**11**	12	6	7	6	3	3	3	13	9	6	3	4	2	4	7	8	5	6	3	3	11
12-juin	6	3	3	11	9	14	8	4	2	4	5	18	6	6	4	2	2	2	4	11	7	5	3	3	7	3	6	5	4	3	2
09-juil	5	4	3	2	6	16	**5**	2	4	5	18	9	11	11	3	8	4	3	7	5	3	2	3	3	5	3	3	10	6	3	3
5 aug	10	6	3	3	6	7	4	4	3	2	2	28	31	11	6	2	3	9	4	6	3	2	3	3	7	2	5	3	6	3	3
01-sept	3	6	3	3	4	3	5	2	2	2	4	31	20	10	3	5	2	**10**	17	7	2	2	4	3	8	6	3	5	4	3	6
28-sept	5	4	3	6	6	4	2	3	4	3	3	6	19	23	7	3	4	**11**	4	5	7	2	2	3	3	5	3	3	2	16	4
25-oct	3	2	**16**	4	2	8	2	2	2	3	4	6	20	12	8	7	2	11	4	13	4	2	3	2	7	3	3	**19**	6	4	2
21-nov	19	6	4	2	2	3	6	3	4	3	2	3	**11**	16	4	4	10	2	**4**	7	15	5	3	4	3	2	2	2	3	3	4
18 dec	2	3	3	4	5	3	2	2	7	3	4	**10**	39	11	5	3															

01-janv																***2003***								14	12	40	29	17	8	12	8
07-janv	17	8	12	8	7	28	17	[illegible]	[illegible]	[illegible]	13	8	16	29	41	30	33	37	32	32	46	39	23	20	34	47	31	28	81	35	52
03 feb	28	81	35	52	27	32	27	[illegible]	[illegible]	[illegible]	[illegible]	26	14	37	39	32	23	46	24	32	25	22	22	14	10	30	52	37	31	23	36
02-mars	37	31	23	36	52	33	48	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	16	26	43	49	49	57	41	22	**47**	49	28	38	12	7	16	46	42	53	57
29-mars	46	42	53	57	54	29	44	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	39	41	25	17	19	30	29	58	46	37	16	24	43	42	33	46	49	35
25 apr	33	46	49	35	31	29	34	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	65	55	49	381	41	41	46	39	16	15	17	22	21	45	48	31
22 may	21	45	48	31	44	31	31	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	25	40	53	46	37	26	13	15	46	37	63	71	**81**	23
18-juin	63	71	**81**	23	23	45	27	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
15-juil	27	26	51	74	37	32	50	[illegible]																							

(1973), which contains both equinoctial and axial elements. In fact, the seasonal evolution marked by the observation of the lowest Aa in July and December for the year 2003 (Fig. 1) is generally present in our pixel diagrams started from 1868 to 2005. Some exceptions can be seen (e.g. years from 1984 to 1989, 1991, 1992). But regarding monthly values we observe like Legrand and Simon the same evolution from 1868 to 2005. Our study points out that it is possible to observe seasonal effect of severe storms by using only daily values of Aa.

Legrand and Simon (1989) based their classification on two facts: (1) the contribution of shock wave to geomagnetic activity and (2) the strong correlation between the Aa index and the solar wind (Svalgaard, 1977). They classified the solar wind speed in three classes (low speed, fluctuating and high speed) and derived the following geomagnetic classes:

(a) one class is defined as days with $\mathrm{Aa} < 20\,\mathrm{nT}$, this class corresponds to the slow-speed solar wind ($v < 450\,\mathrm{km/s}$) flowing continuously past the magnetosphere;
(b) three classes concern disturbed geomagnetic activity ($\mathrm{Aa} > = 20\,\mathrm{nT}$); they follow morphological features of the solar phenomena:
   - ○ recurrent (stream) activity: it presents a continuing evolution during one solar rotation as well as during the following solar rotation. There is no SSC during the main phase. This class corresponds to high-speed solar wind,
   - ○ transient activity: it is composed of two components, a first one related to very active spots on the solar disc (shock activity) and the second one due to the existence of fluctuating solar wind jets,
   - ○ shock activity class: determined by the special storms, which arise by random bursts and without a recurrence of 27 days during 2, 3 or 4 rotations,
   - ○ fluctuating activity, determined by subtracting from the disturbed activity ($\mathrm{Aa} > = 20\,\mathrm{nT}$) the shock activity and the recurrent activity. This class corresponds to fluctuating solar wind.

Each class of activity determines solar wind structure and expresses solar magnetic field topology behaviour. Thus, physically different classes differ from others. Here, the key role is attributed to daily Aa value for determining the class of activity not to the summarised daily Aa values. The latter value is used to determine only the whole level of each class of activity.

3. Analysis of the three last decades of Aa indices

Following the classification described in Section 2, the Aa index can be expressed as:

$$\mathrm{Aa} = \mathrm{Aa(quiet)} + \mathrm{Aa(disturbed)}$$

$$\mathrm{Aa(disturbed)} = \mathrm{Aa(recurrent)} + \mathrm{Aa(shock)} + \mathrm{Aa(fluctuating)}$$

Each year is characterized by four components:

$$\mathrm{Aa} = \mathrm{Aa}_\mathrm{q} + \mathrm{Aa}_\mathrm{r} + \mathrm{Aa}_\mathrm{s} + \mathrm{Aa}_\mathrm{f}$$

Aa_q (ΣAa (quiet)) is the sum of the daily Aa indices for all the day with $\mathrm{Aa} < 20\,\mathrm{nT}$, Aa_r is the sum of the daily Aa indices of days with recurrent activity (ΣAa (recurrent))…

With this classification we obtain for each year a level of geomagnetic activity for four categories of solar phenomena.

On Fig. 2 is plotted the evolution of the various kinds of solar–geomagnetic activity classes for the period 1868–2006: the Aa_s, the shock activity (panel a), the Aa_q, the quiet magnetic activity (panel b) the Aa_r, the recurrent activity (panel c) and the Aa_f the fluctuating (panel d). The values of the different classes of activity for the period 1868–1978 are from Legrand and Simon (1989). In the present paper, we analyse the last three decades. In Fig. 2, we indicate sunspot maximum (M) by black squares and sunspot minimum (m) by black triangles.

Fig. 2a for the shock activity does not present any significant feature during the three decades. We can just mention that the maxima of shock activity occurred between 1930 and 1960. This observation is closely correlated with Legrand and Simon (1981) study. In fact, according to these authors severe storms ($\mathrm{Aa} > 100\,\mathrm{nT}$) grouped between year of sunspot maximum minus one ($M-1$) and year of sunspot maximum plus four ($M+4$) for 88% of them. This last result is also shown by Fig. 2a where one can locate shock maximum in the interval between $M-1$ and $M+4$ with 85% of probability, and 79% of probability at sunspot maximum. Thus, the annual shock event activity is correlated to sunspot cycle activity. During solar cycle, the later is correlated to the sum of shock event activity (Legrand and Simon, 1989).

Fig. 2b shows that the fluctuations of class 'Aa_q' have gained much intensity since 1950. Table 1 gives the years

Table 1
Years with the smaller quiet magnetic activity for the period 1868–2005

1868–2005			
Year	Annual Aa < 2000	Year	Annual Aa < 1800
1901	1840	1930	1571
1902	1980	1959	1689
1930	1571	1960	1687
1943	1967	1974	1521
1951	1804	1982	1411
1952	1809	1983	1696
1956	1950	1984	1795
1957	1991	1991	1739
1958	1954	2003	1207
1959	1689		
1960	1687		
1973	1903		
1974	1521		
1982	1411		
1983	1696		
1984	1795		
1991	1739		
1993	1989		
1994	1901		
2003	1207		

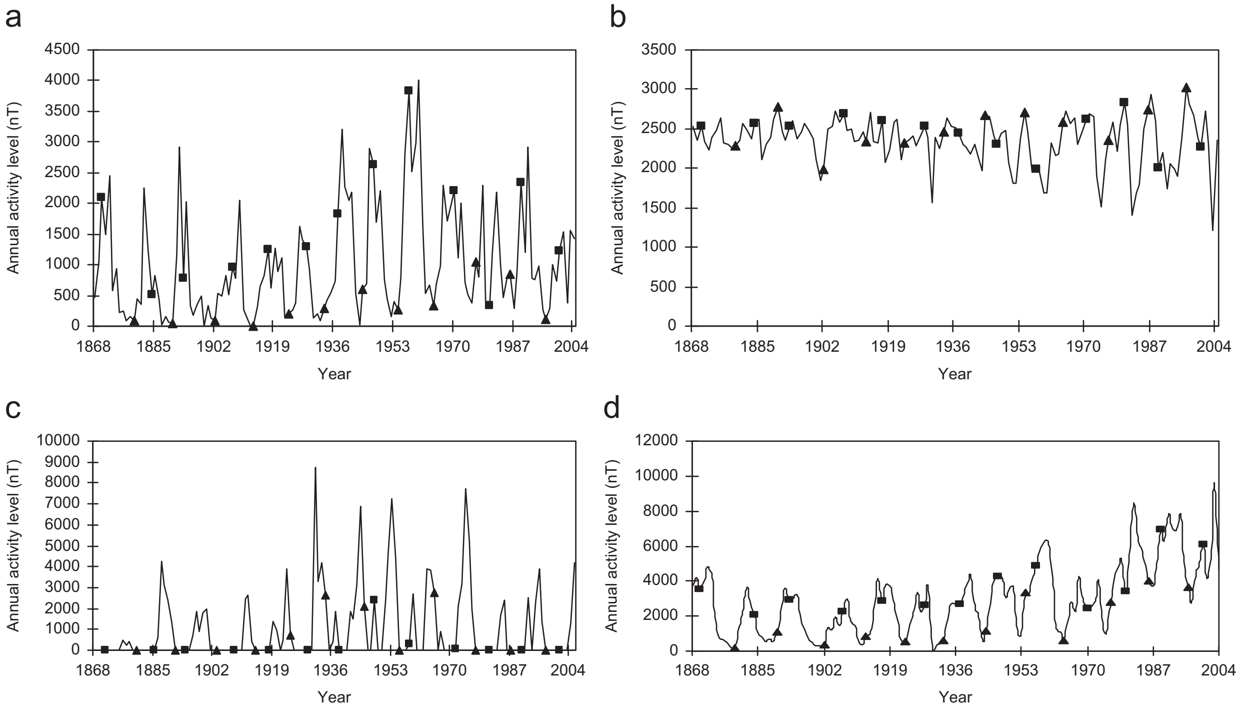


Fig. 2. Time variation from 1868 to 2004 of the four geomagnetic activity classes, related to solar activity, defined by Legrand and Simon (1989). The panel (a) corresponds to the shock activity and the panel (b) to quiet magnetic days ($\mathrm{Aa} < 20\,\mathrm{nT}$).The panel (c) highlights the recurrent activity and the panel (d) the fluctuating activity. Sunspot maximum (M) is labelled black squares while its minimum is indicated by black triangles.

with the smaller values of class "Aaq" since 1868. It shows that the years with smallest amplitude in the class 'Aa_q'<2000 nT are in majority (16/20) after 1950. If we consider 'Aa_q'<1800 nT, it is the same observation: 8 over 9 years are after 1950. The smallest value of 'Aa_q' since 1868 occurred in 2003. Such observation must be due to the persistence of solar polar wind stream during several Bartels rotation for this year.

The annual activity level trend obtained by 11 years running mean for quiet days ($Aa<20$ nT) and very quiet days ($Aa<13$ nT) shows that the trend of quiet days activity is fairly constant and is situated above 2000 nT but this of very quiet days is decreased and situated between 800 nT (year, 1983) and 1750 nT (year 1888) (Ouattara et al., 2008). As the majority of years after 1950 have their annual quiet activity level between 800 and 1750 nT, Table 1 illustrates the increase of the geomagnetic activity. One can notice that minimum and maximum of 50% quiet days activity occurred at sunspot minimum and 50% at sunspot maximum. This yearly activity is not correlated to sunspot activity but Legrand and Simon (1989) show that from $m-4$ to $M+2$ the sum of quiet days activity is inversely proportional to sunspot activity.

Fig. 2c for the recurrent activity shows that the recurrent (stream) activity observed during the two last decades is similar to the recurrent activity observed during the period 1955–1965 and before 1920. Maximum of this activity neither occurred at sunspot maximum nor at sunspot minimum. There is no correlation of yearly recurrent activity to sunspot cycle; but for the activity at equinox, the sum during 4 years interval is closely correlated to sunspot activity (Legrand and Simon, 1989).

On Fig. 2d related to the class 'Aa_f', we observe an increase of the fluctuating activity during the last four or five decades. The year with the highest maximum in fluctuating activity is 2003. This result is a consequence of the decrease of very quiet days: the fluctuating class including all the cases that are not related to the three other classes. The analysis of the Fig. 2d shows that fluctuating activity minimum often occurred at sunspot minimum (~79%) during the same time. It is the same occurrence for the maximum. Yearly fluctuating activity level is fairly correlated to sunspot cycle activity. The same correlation was observed by Legrand and Simon (1989) during a full cycle.

From the analysis of Fig. 2, it emerges that the increasing geomagnetic activity is due to the fluctuating activity. Maximum of sunspot is dominated by shock and fluctuating activities.

On Figs. 3a–c is plotted the percentage of level activity of the four classes: diagram a corresponds to the period 1868–1978, diagram b to the period from 1979 until now and diagram c to the whole period 1868–2005. The percentages of activity level of each class expressed by piegrams (Figs. 3a–c) highlight their average contribution to the whole geomagnetic activity level.

Analyse of Fig. 3 will be done by comparing diagrams a and b on one hand, and a and c on the other. Only percentages of SSC events, quiet days and recurrent activities will be analysed. Comparison between diagrams a and b shows the decrease of these activities: SSC activity (−1%), recurrent activity (−5%), quiet days activity (−6%). By comparing the decreasing of the percentages of the three activities one can conclude that for the last decades there is strong decrease of the intensity level of the stream (recurrent) activity: −5%, and the quiet magnetic activity: −6%.

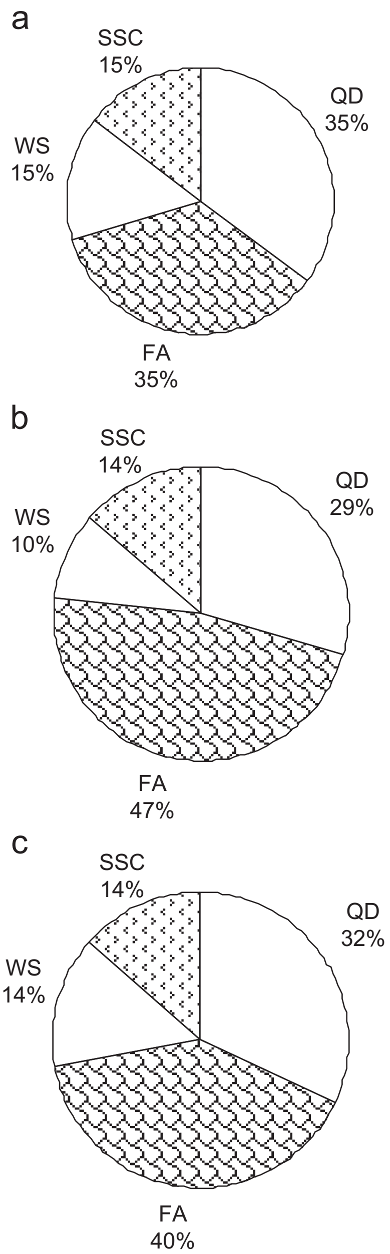


Fig. 3. Percentage of each geomagnetic class magnetic quiet days (QD), the shock activity (SSC), the recurrent activity (WS) and the fluctuant activity (FA). The panel (a) is for the period 1868–1978 (analysed by Legrand and Simon, 1989), the panel (b) for the period 1979–2004 and the panel (c) for the period 1868–2004.

Comparison between diagrams a and c shows that for the whole period 1868–2005, the quiet activity decreased by −3%, the fluctuating activity increased by +5% and shock activity was constant. For that, only the quiet activity is decreasing and constitutes the strong one. It is clear that the Aa index highlights a decrease of the level of quiet magnetic activity during the last three decades.

The sole remarkable feature during the three last decades is the strong decrease of the number of quiet days and as a consequence the increase of the number of disturbed days and geomagnetic activity (Mursula et al., 2004; Mursula and Martini, 2006). Moreover, Ouattara et al. (2008) on one hand show that the strong decreasing of quiet days ($Aa<20$ nT) number is a consequence of those of very quiet days ($Aa<13$ nT), and on the other hand that the activity level of quiet days is fairly constant and very quiet days decreased during the time. The latter corresponds to a change in the coronal solar magnetic field.

The increase of disturbed days during the last decades is not only due to the decrease of quiet days activity but also results to the increase of solar wind velocity and the IMF. Indeed, Kuznetsova and Tsirulnik (2008) show that these parameters increase: by 55% for solar wind velocity and by 45% for IMF.

It is important to note that the different percentage during the period 1868–1978 (SSC activity (−1%), recurrent activity (−5%), quiet days activity (−6%)) and for the period 1868–2005 (quiet days activity decreased by −3%, fluctuating activity increased by +5% and shock activity was constant) depend on solar magnetic field topology for quiet days, fluctuating and recurrent activities depend on sunspot activity for shock activity while 55% of solar wind velocity and 45% of IMF highlight the strength of solar magnetic field.

4. Aa indices and in situ measurement

4.1. Aa indices and in situ measurement for the year 2003—classification of Legrand and Simon

In this section, we will analyse for the year 2003 the estimation of shock activity given by the Aa indices and by in situ solar wind data. In Table 2, we give the classification of Legrand and Simon (1985) concerning the effects of wind and of shock activities on the solar wind parameters.

Table 2
Characteristics of solar wind and shock activities following Legrand and Simon (1989)

	Solar wind activity	Shock activity
IMF	Increases but less than the shock activity effect	Increases but more than the wind activity effect
Solar wind density	Increases	Increases
Solar wind speed	Increases after the increase of solar wind density	Abrupt increasing simultaneous with solar wind density increase
Solar wind temperature	Increases	Increases

In the pixel diagram (Fig. 1), we select the days corresponding to the above solar activities by considering the date of SSC and the value of Aa. The days, with Aa values superior or equal to 100, marked by SSCs or not, are chosen. The days marked by SSCs and situated in the orange, red or olive red colour areas are retained.

According to Legrand criteria, the days with $Aa>=100$ nT without SSC are affected by the wind activity. The days, characterised by recurrent SSC on two, three or four Bartels rotations, are also affected by wind activity. The rest of the days retained are under shock activity.

By respecting the above classification, Table 3 gives the dates and the Aa values for the days characterized by shock activity or wind activity.

For the illustration, we have extracted some days of shock activity and wind activity.

For the chosen days

- 29 May with $Aa=122$ nT. This shock activity starts with an SSC and lasts 2 days (29 and 30 May);
- 29 October with $Aa=299$ nT. This shock activity starts with an SSC, and lasts 3 days (29–31 October);
- 20 November with $Aa=228$ nT, the shock activity starts with an SSC, and lasts 1 day (20 November).

For the chosen days, the fluctuating wind stream activity corresponds to:

- 11 May with $Aa=381$ nT;
- 24 May with $Aa=53$ nT;
- 15 November with $Aa=62$ nT.

One can notice that even if the value of Aa on 11 May is very high. Especially, this day contributes to fluctuating activity; this is, because there is no SSC event on 11 May. Such result exhibits that only the knowing of the Aa value is not sufficient to determine the class activity of the day. It is necessary to add to this parameter the date of the SSC event.

Table 3 sets up together for the year 2003 the shock events and the wind activity signatures observed on

Table 3
Dates and the Aa values of the days characterized by shock activity or wind activity

Months of year 2003	Aa values (nT)	
	Shock activity	Wind activity
20 March		47
11 May		381
24 May		53
29 May	122	
30 May	75	
18 June	81	
17 August	40	
29 October	299	
30 October	230	
31 October	179	
4 November	55	
15 November		62
20 November	228	

Aa index. The whole value of this table is taken from Fig. 1. For example to determine the value of Aa for 11 May, we start our reading by third row and sixth line. The corresponding values of Aa and date of the day are, respectively 49 nT and 25 April. In sixth line, from left (third row with Aa = 49 nT) to right the Aa value of 11 May corresponds to the Aa value of 19th row (i.e. 381 nT).

By taking Aa values of year 2003 (Fig. 1) only two values of Aa > 100 nT (11 May: 381 nT and November (20: 228 nT) are rejected. The 11 May value is rejected because of the absence of SSC event and November is rejected for recurrent SSC event: first SSC event occurs on 24 October with Aa = 59 nT and the second SSC event after one Bartels rotation on 20 November during the second Bartels rotation.

The other values of Aa > 100 nT contribute to SSC events:

- 29 May with Aa = 122 nT; this shock event takes into account the day of 30 May with Aa = 75 nT;
- 18 August with Aa = 110 nT; this shock event starts on 17 August with Aa = 40 nT day of SSC event and finishes at 18 August with Aa = 110 nT;
- 29, 30 and 31 October with, respectively, Aa values 299, 230 and 179 nT. This shock starts at 29 October and finishes at 31 October.

Figs. 4–6 present solar wind measurements for May, October and November 2003. Fig. 4 corresponds to solar wind parameters measured on board spacecraft ACE during May 2003, the four curves of Fig. 4a correspond to the magnetic field. Respectively, from top to bottom the total amplitude and the X, Y and Z components. The three curves of Fig. 4b are the proton speed, the proton density and the proton temperature.

Graphs given by Figs. 4–6 are taken from ACE plotted database, which gives for recent years IMF total amplitude and components, and solar wind plasma parameters. To characterize shock event, only solar wind plasma and total amplitude of IMF are used (Legrand, 1984; Legrand and Simon, 1989; Simon and Legrand, 1990). As the components of IMF are plotted together with its total amplitude, impacts of shock event on these are just mentioned (the validity of coordinate system is out the aim of this paper).

Figs. 5 and 6 are similar to Fig. 4 for the months October and November 2003.

In Fig. 4a, we observe an increase of the IMF amplitude due to the shock event of 29 May. On 11 May, there is no shock signature in the IMF parameters. In Fig. 4b, for 29 May due to the shock wave, the proton speed and the proton density increase and proton temperature decrease. Such a signature is not observed on 11 May. In Fig. 5a, on 29 October, date of the shock event, all the IMF components increase as well as the proton speed, density and temperature. In Fig. 6, we observe the increase of all parameters of the IMF and of the solar wind during the passage of the shock wave.

Comparison of the results obtained by the analysis of the Figs. 4–6 with Legrand criteria (Table 2) shows that Legrand and Simon really found in the Aa index the signature of the shock solar class of activity. IMF is the best indicator of the shock activity. It is interesting that the Aa index series starts in 1868, while systematic measurements of the solar wind parameters on board spacecrafts started 40 years ago.

4.2. *Aa indices and in situ measurement from 1972 to 1986 and from 1972 to 2000 (Richardson's classification)*

Richardson et al. (2000) determined the contribution of the different types of geomagnetic activity from 1972 to 1986. In their work, they assumed four classes for the solar wind: (1) slow solar wind values to $V < 400$ km/h, (2) CME-related structures (shocks/post shock flow, ejecta), (3) co-rotating solar wind streams from coronal holes and associated corotating interactions regions and (4) unclear solar sources.

They distinguish the part of co-rotating streams contributing ~70% outside of solar maximum and ~30% at solar maximum, the part of CMEs during the years around solar maximum is ~50% and <10% out of the maximum. The slow solar wind contribution is evaluated as ~20% throughout the solar cycle, including solar maxima. They have noticed contribution of "unclear" solar sources of geomagnetic activities. The above percentages do not include the part of the "unclear" solar sources of geomagnetic activities.

Richardson and Cane (2002) pursue their classification (Richardson et al., 2000) for determining the different types of structure related to geomagnetic activity from 1972 to 2000. In their work, without considering the part of the "unclear" solar sources of geomagnetic activities, they obtain for the high-speed streams two-thirds of long-term Aa averages at solar minimum, while at solar maximum, structures associated with transients (i.e. interplanetary coronal mass ejections (CMEs), shocks, and postshock flows) make the largest contribution (~50%).

For the solar cycle averages high-speed streams account for ~48%, CME-related structures, ~32%, and slow solar wind ~19% of Aa.

4.3. *Validation of the method of Legrand and Simon*

To compare Legrand and Simon estimation with in situ measurement on the one hand from 1972 to 1986 and on the other hand from 1972 to 2000, it is necessary to determine the contribution of the three classes of activities by Legrand and Simon method with Richardson's criteria. For this, using the solar wind parameters for year 2003, we obtain that ~89% of Aa values are less than 15 nT for $V < 400$ km/s. The criterium of Richardson's classification to determine the slow solar wind condition is Aa < 15 nT.

The co-rotating solar wind streams part in Aa is determined by using following conditions:

- Class of recurrent (stream) activity from coronal holes: it presents a continuing evolution during one solar rotation as well as during the following rotation. There is no SSC during the main phase. This class corresponds

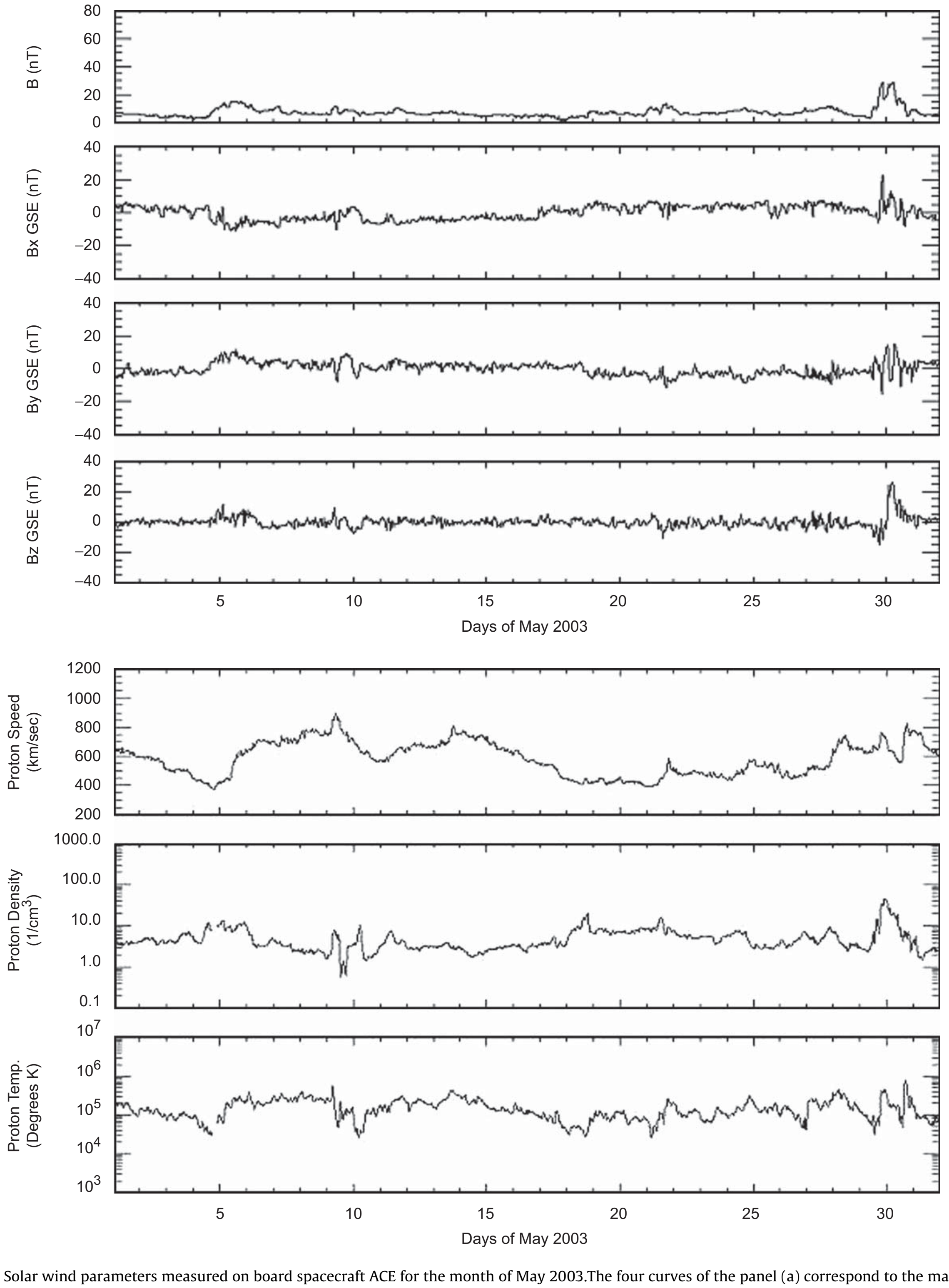


Fig. 4. Solar wind parameters measured on board spacecraft ACE for the month of May 2003.The four curves of the panel (a) correspond to the magnetic field, respectively from the top to the bottom the total amplitude and the *X*, *Y* and *Z* components. The three curves of the panel (b) are, respectively the proton speed, the proton density and the proton temperature.

to high-speed solar wind. In the pixel diagram, this condition corresponds to $\mathrm{Aa} > 40\,\mathrm{nT}$ with, $40 < = \mathrm{Aa} < 60$: orange colour, $60 < = \mathrm{Aa} < 100$: red colour;

- Class of associated co-rotating interactions regions activity determined by recurrent yellow colour: $30 < = \mathrm{Aa} < 40$.

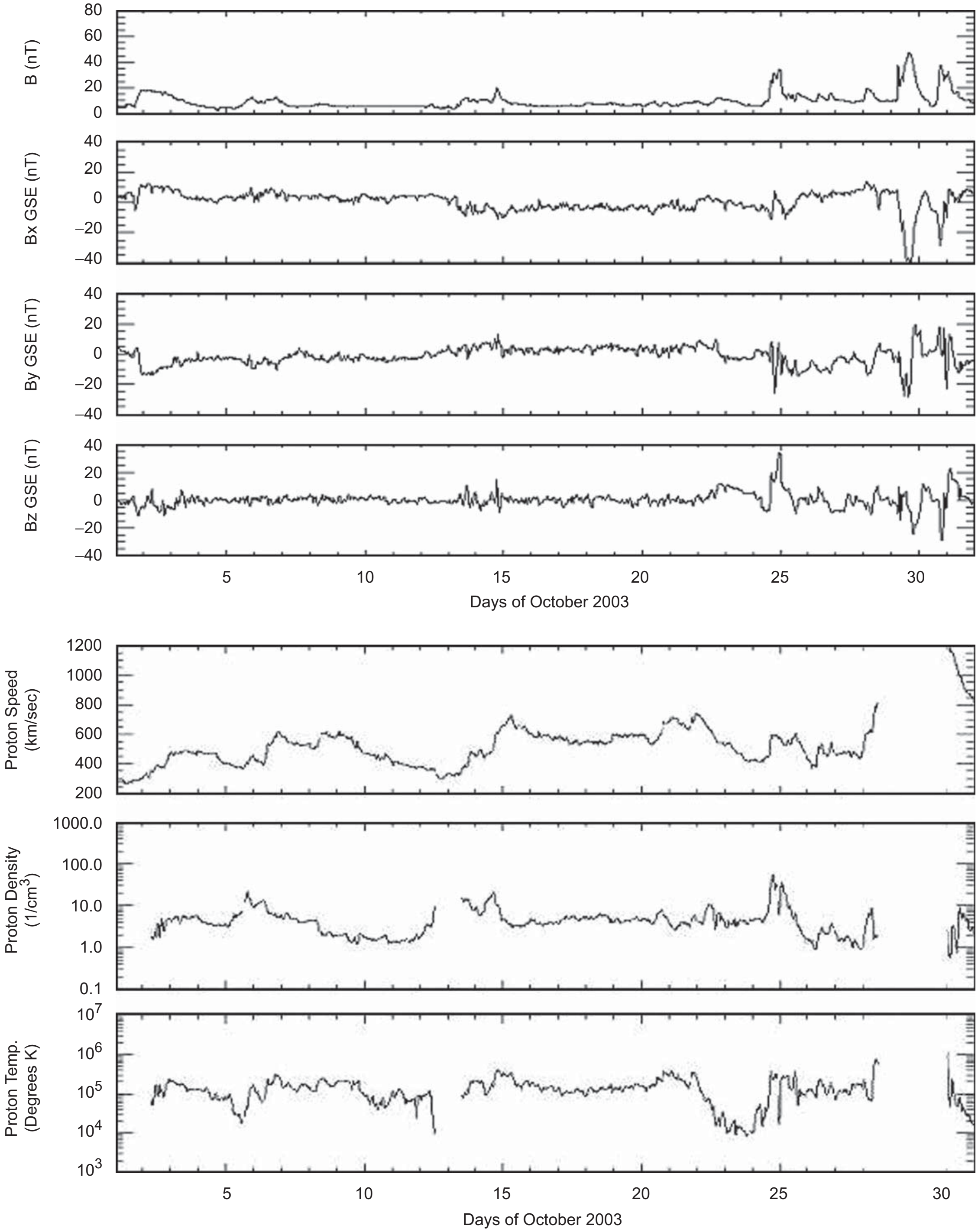


Fig. 5. Similar to Fig. 4 for the month of October 2003.

The CME-related structures are determined by using:

- ICMEs activity (Legrand class of shock activity): determined by the selection of storms, which arise by random burst and without a recurrence of 27 days during 2, 3 or 4 rotations.
- Transient forward shocks generated ahead of fast ICMEs and related postshock flows determined by isolated Aa > 40 nT (orange, red and alive red colours) without SSC.

Applying the above conditions to the pixel diagrams from 1972 to 2000 permitted us to obtain Figs. 7 and 8.

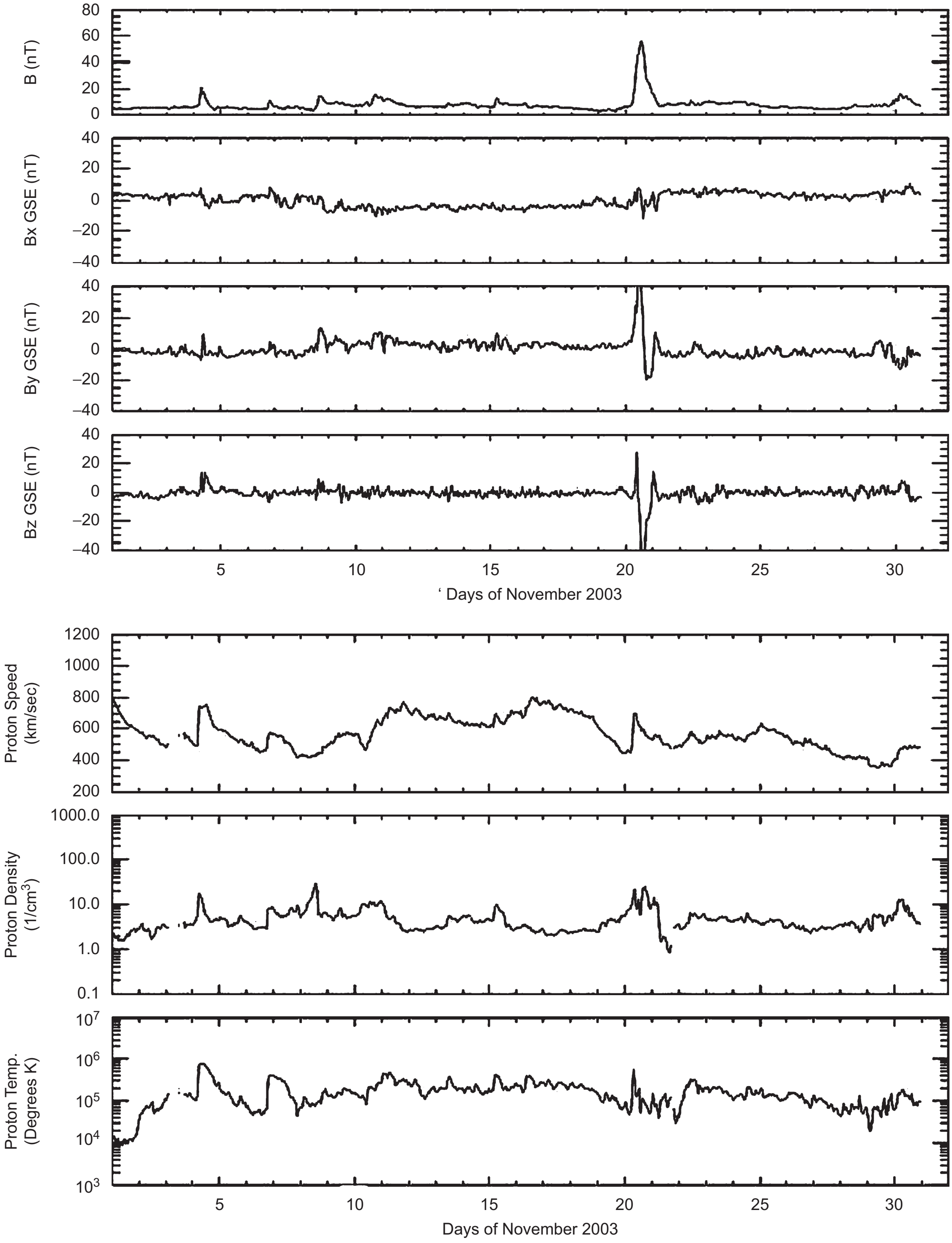


Fig. 6. Similar to Fig. 4 for the month of November 2003.

Fig. 7 corresponds for the period of 1972–1986 and Fig. 8 to the period 1972–2000. In Fig. 7 and 8, the percentage of fluctuating activity is not considered to allow comparison with Richardson's results (Richardson et al., 2000; Richardson and Cane, 2002).

Fig. 7a shows that the CME-related structures part in Aa at solar maximum is 51% (values nearer of Richardson et al., 2000: ~50%), the slow solar wind 19% (value nearer of Richardson et al., 2000: ~20%) the co-rotating wind streams 30% (same value as Richardson et al., 2000 value).

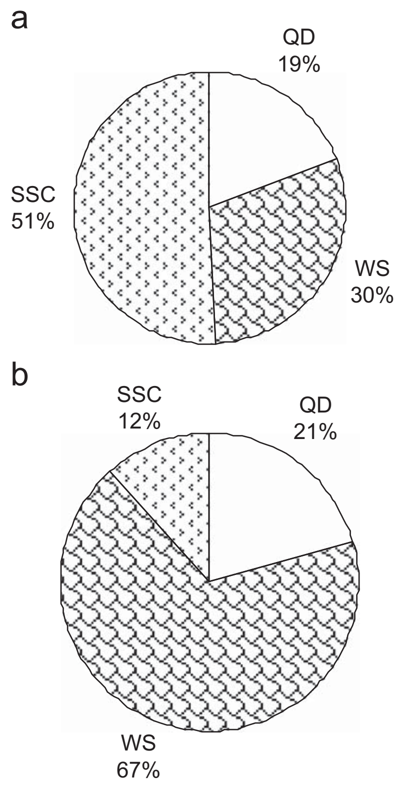


Fig. 7. Percentage of the different classes of solar activity, by applying the Richardson's criteria to pixel diagram of daily value of Aa indice for the period 1972–1986, (a) solar maximum and (b) solar minimum.

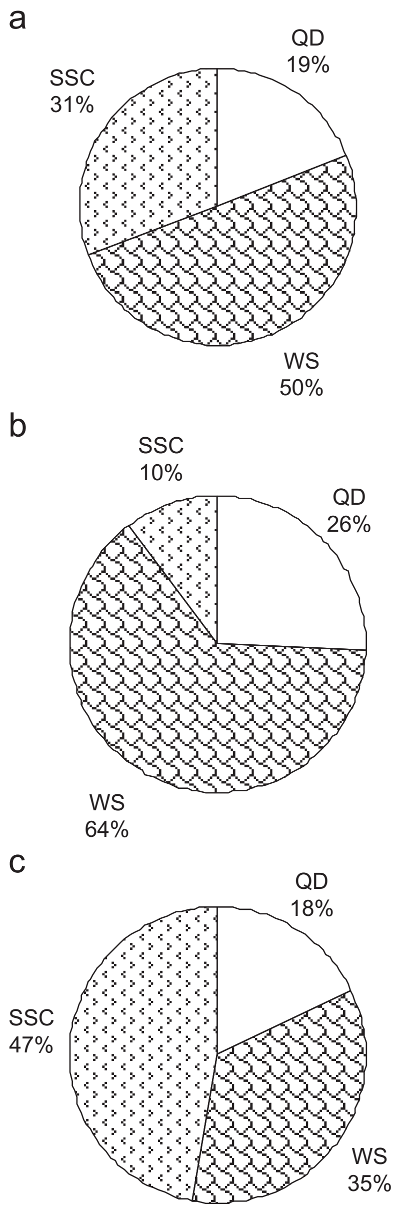


Fig. 8. Percentage of the different classes of solar activity, by applying the Richardson's criteria to pixel diagram of daily value of Aa indice for the period 1972 to 2000, panel (a) solar cycle averages, panel (b) solar minimum, panel (c) solar maximum.

In Fig. 7b, the co-rotating wind streams part is 67% (value nearer of Richardson et al., 2000: ~70%) CME-related structures 12% (value nearer of Richardson et al., 2000: ~10%), slow solar wind 21% not far from ~20% of Richardson et al. (2000).

Fig. 8 exhibits the percentage of the three classes from 1972 to 2000 by using pixel diagrams. In Fig. 8a, we observe that for the solar cycle averages high-speed streams account for 50% (value nearer of ~48% of Richardson and Cane, 2002), the CME-related structures, 31% not far from ~32% of Richardson and Cane, 2002), the slow solar wind, 19% same value as Richardson and Cane (2002).

Fig. 8b shows that at solar minimum the high-speed stream part is estimated to be 64% not far from two-thirds (~67%) as in Richardson and Cane (2002) value. The contribution of CMEs-related structures is 10%, same value of Richardson et al. At solar minimum, slow solar wind accounts for 26% not far from ~20% of Richardson and Cane (2002).

Fig. 8c structure associated with transients (shock) accounts for 47%, not far from ~50% of Richardson and Cane (2002). Co-rotating streams account for 35%; this value is near this ~30% of Richardson et al.

5. Discussion and conclusion

In this paper, we have analysed the last 30 years of geomagnetic activity by using the classification of Legrand and Simon (1989) for determining the different classes of solar sources of geomagnetic activity. We analysed the Richardson et al. (2000), Richardson and Cane (2002) estimation of solar sources of geomagnetic activity based on solar wind parameters and compared it to the estimation of Legrand and Simon (1989). These two approaches are based on four classes: slow solar wind, co-rotating streams, CME-related structures and fluctuating or "unclear" activity, but they use slightly different criteria to make the classification. Legrand and Simon method is more restrictive to identify co-rotating streams and CME-related structures and Richardson et al. criteria qualify more strictly the slow solar wind effect ($V<400$ km/s for Richardson et al. and $V<=450$ km/s for Legrand and Simon). Thus, even if the above methods give four classes of solar sources of geomagnetic activity, their definition differs for the different classes.

By taking into account to the above classifications Legrand and Simon method rejects upper boundary values of Aa ($30\,\text{nT}<\text{Aa}<=40\,\text{nT}$) to fluctuating activity and Richardson et al. criteria rejects the inferior boundary values of Aa ($15\,\text{nT}<=\text{Aa}<20\,\text{nT}$) to fluctuating activity. Slow solar wind activity is determined by fairly very quiet days activity ($\text{Aa}<15\,\text{nT}$) and co-rotating streams activity at least by the recurrence of moderately disturbed days activity (recurrence of $40<\text{Aa}<100\,\text{nT}$).

In this paper, we applied Richardson et al. criteria to the Legrand and Simon's pixel diagrams. We show that the best concordance exists between results obtained from pixel diagrams and results issued from the in situ measurements: this fact is important as it shows that solar–geomagnetic activity must be analysed at a daily time scale or even hourly time scale with the geomagnetic index.

So, it seems necessary:

- to unify the criteria for determining the classes of solar sources of geomagnetic activity. This should better define the "unclear" source of geomagnetic activity. It could be possible to improve the definition of the fluctuating class of activity;
- to work at smaller time scales than the Sun Carrington rotation;
- to define more classes for the solar wind activity and solar phenomena;
- to consider temporal changes of orientation of the IMF and the solar wind velocity (V) vectors relative to the geomagnetic moment (connected mainly with annual and daily motions of the Earth).

It is interesting to use the old magnetic datasets as they give the time history of the Sun in their records and it is important to connect the new in situ solar data to geomagnetic data so as to really understand the impact of solar phenomena on the Earth's geomagnetic field.

All this work has be done in the frame of scientific projects as International Heliophysical Year (IHY) or Climate and Weather in the Sun Earth System (CAWSES).

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