Comparison of substorms near two solar cycle maxima: (1999-2000 and 2012-2013)

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Abstract. We present the comparative analysis of the substorm behavior during two solar cycle maxima. The substorms, observed during the large solar cycle maximum (1999- 2000, with Wp> 100) and during the last maximum (2012-2013 with Wp~60), were studied. The considered substorms were divided into 3 types according to auroral oval dynamic. First type - substorms which are observed only at auroral latitudes ("usual" substorms); second type - substorms which propagate from auroral latitudes (<70º) to polar geomagnetic latitudes (>70º) ("expanded" substorms, according to expanded oval); third type - substorms which are observed only at latitudes above ~70º in the absence of simultaneous geomagnetic disturbances below 70° ("polar" substorms, according to contracted oval). Over 1700 substorm events have been analyzed. The following substorm characteristics have been studied: (i) the seasonal variations, (ii) the latitudinal range of the occurrence, (iii) solar wind and IMF parameters before substorm onset, (iiii) PC-index before substorm onset. Thus, the difference between two solar activity maxima could be seen in the difference of substorm behavior in these periods as well.

Key words: solar cycle, solar wind, substorms, PC-index

Introduction

Magnetospheric substorms have long been in the focus of solar-terrestrial physics; however, up to now they still represent an outstanding unsolved problem. It is noted that although the history of the substorm study is very long, there are only a few large statistical substorm investigations (Borovsky et al., 1993; Tanskanen et al., 2002, 2005; Newell et al., 2001; Frey et al., 2004). Newell et al. (2001) determined 390 substorms events from POLAR UVI, Frey et al. (2004) found more than 2400 substorm events from IMAGE FUV instrument, Tanskanen et al. (2002, 2005) identified more than 5000 substorm events from IMAGE magnetometers network. Traditionally, researchers have been considered all substorms.

In our work we divided all observed substorms into 3 groups according to auroral dynamics. It is known that under normal conditions (moderate disturbance) the auroral oval is located at geomagnetic latitudes (GLAT) of about 65-67° ("normal oval"), under quiet conditions (at B_Z>0) the auroral oval shrinks and moves to higher latitudes (>70° GLAT, "contracted oval"), and in disturbed conditions (increased magnitude of the IMF negative B_Z component), the equatorward boundary of the oval is shifted down to 50° geomagnetic latitude, while its poleward boundary extends to higher latitudes ("expanded oval") (Feldstein and Starkov, 1967). Thus, in our terminology, we call the first type of substorms as "usual" substorms, i.e. substorms which are observed only at auroral latitudes. Similarly to the auroral oval which is called an "expanded" oval, meaning its extension in the disturbed conditions, we will call "expanded" substorms those which start at the auroral zone and then propagate to very high latitudes. We point out that in the maximum phase of "expanded" substorms, the westward electrojet can be observed at very high geomagnetic latitudes (> 75º) (Despirak et al., 2008). The third type of substorms, termed as "polar" substorms, correspond to the contracted oval. They represent isolated bay-like magnetic disturbances, observed at geomagnetic latitudes higher than the location of the typical polarward boundary of the auroral oval (> 70° GLAT) and are not accompanied or preceded by substorm activity at auroral latitudes.

The aim of this work is the comparison of some substorm characteristics of all three types of substorms and the solar wind conditions observed before substorm onsets during two solar cycles maximum: (1999-2000 with Wp>100 and 2012-2013 with Wp~60). It should be noted that details of substorms at the contracted oval ("polar" substorms) and substorms at the enxpanded oval ("expanded" substorms) were considered in a recent paper by Despirak et al. (2014). There are shown many clear examples of the "polar" and "expanded" substorms observed at the IMAGE meridional chain Nurmijarvi - Ny Alesund located at geomagnetic latitudes of 57-75°. Therefore, in this article we will not give examples of "polar" and "expanded" substorms, and focus on the results of the comparison between the different types of substorms during the two maxima of solar activity.

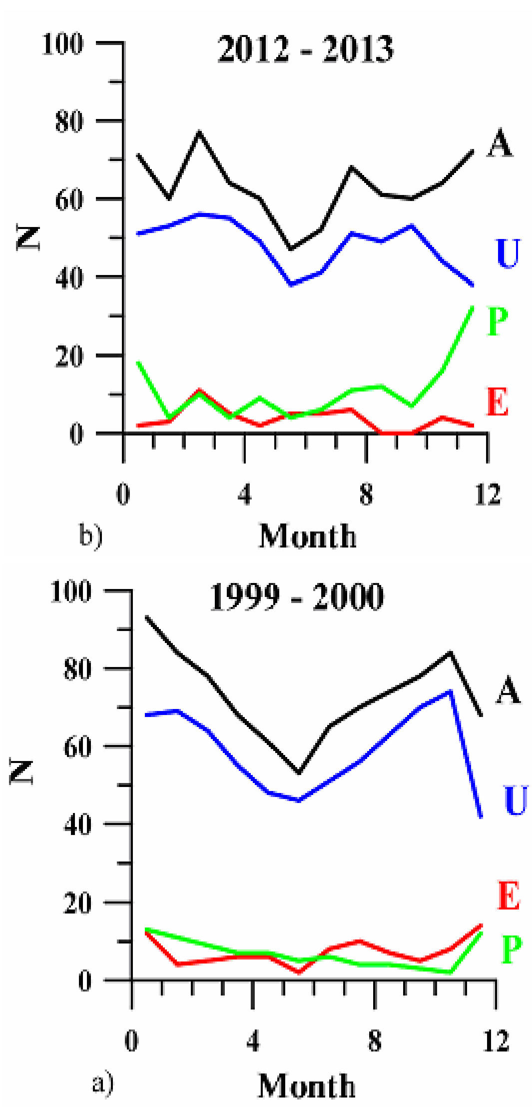

Figure 1 The seasonal variations of the substorm different types during two solar cycle maxima: (*a*) - 1999-2000; (b) -2012-2013. A - all substorms (black), U - "usual" substorms (blue), E - "expanded" substorms (red), P - "polar" substorms (green).

Data

Our analysis was based on the 10-s sampled IMAGE magnetometers data, namely the data from the meridional chain Nurmijarvi - Ny Alesund, and on the 1-min sampled OMNI solar wind and Interplanetary Magnetic Field (IMF) data, measured by Wind spacecraft. Two time intervals, close to the different solar cycle maxima are used. First time interval is the period of 1999-2000, which is close to the large solar cycle maximum with Wp> 100. Second time interval is the period of 2012-2013, which is close to the last solar maximum with Wp~60. There were selected and analyzed over 1700 events of "expanded", "polar" and "usual" substorms in 1999- 2000 and in 2012-2013 years all together.

In Table 1, the number of the analyzed events of all three types of substorms is presented.

Table 1. Number of the selected substorm events for different years

Type of substorm	1999	2000	2012	2013
"usual"	363	320	285	285
"expanded"	62	25	27	18
"polar"	42	39	65	64

Results

a) Seasonal variations of substorm number

We calculated the seasonal variations of the 3 types of substorms, observed in two different solar cycle maxima – 1999-2000 and 2012-2013. The results for 3 different types of substorms: U - "usual" substorms (blue); P - "polar" substorms (green); E - "expanded" substorms (red line); and all substorms A - (black line) are presented in Figure 1. The seasonal variations of substorms observed during 1999-2000 interval are shown in the left panel (*a*), and during 2012-2013 interval, in the right panel (*b*).

It is seen that number of substorms is higher during 1999-2000 period than during 2012-2013 period. It is also seen that the summer minima of the substorms occurrence and its spring and autumn maxima are common to both periods. However, the "polar" substorms behavior is in opposition to the behavior of other types of substorms. The "polar" substorms occurrence showed its maximum in the winter months. We note that the "expanded" substorms maximum is observed in winter 1999-2000, but not in winter 2012-2013.

b) Onset and maximal latitudes of the substorm occurrence

To determine onset and maximal latitudes of substorms, we used the data of the Nurmijarvi – Ny Alesund (NUR–NAL) meridional chain from 56.89° to 75.25° geomagnetic latitudes. It should be noted that the stations are located uneven along latitude, and, correspondingly, the substorm latitude was measured discretely and was determined with different accuracy (the accuracy varies from 0.5° to 1.5° depending on the distance between adjacent stations). Onset and maximal latitudes of all 3 types of substorms were determined. For example, in figure 2, the "usual" substorms onsets and their maximal reaching latitudes are presented. Onset latitudes are marked by the black triangles and maximal latitudes by the red ones. In the picture, there are presented the onsets and maximal latitudes of "usual" substorms during 1999 (right panels), 2000 (middle panels), 2012 (middle panels) and 2013 (left panels). The latitudes were presented as dependences on the Z- component of the Interplanetary Magnetic Field (B_Z) (*a*) and on the X-component of the solar wind velocity (V_X) (*b*). In figure 2, we show the linear approximations for each point. The red line represents the linear approximation of the maximum latitudes, while the black one – of the substorms onset latitudes. There one can see the averaged dependence of the initial and maximum

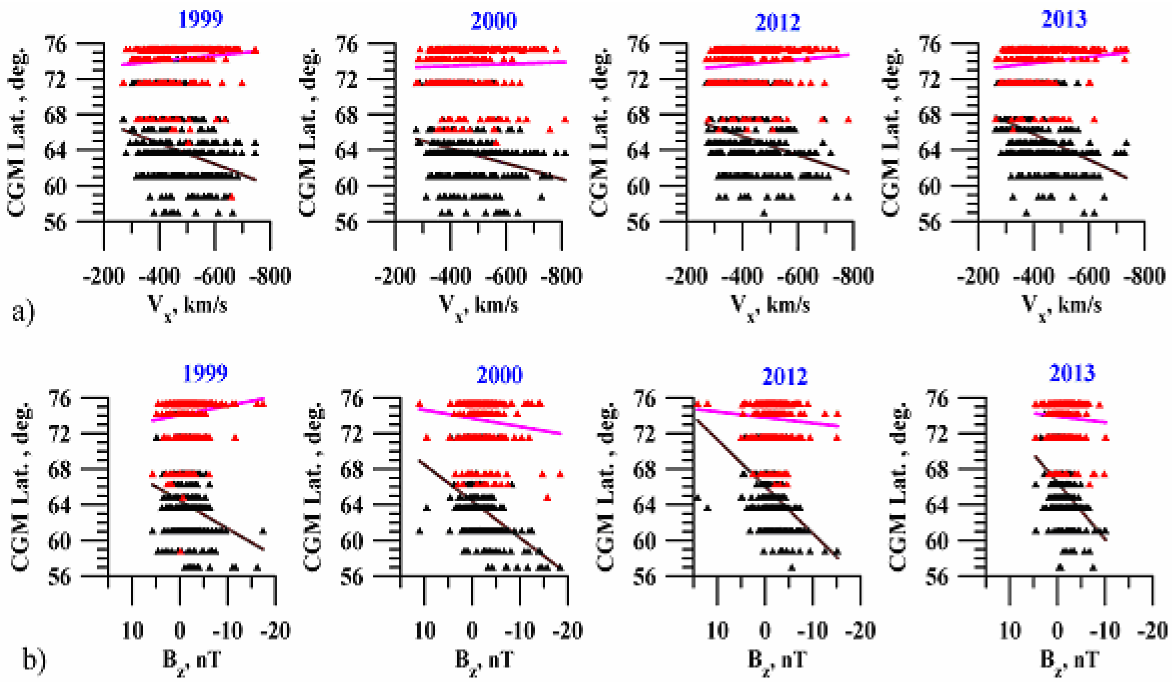

Figure 2 The maximal reaching latitudes of the "usual" substorm onsets, depending on the solar wind velocity (V_X) (*a*) and IMF B_Z (*b*) in 1999, 2000, 2012, and 2013.

latitudes on the IMF BZ (a) and on the solar wind velocity VX (b). So, we may estimate the average latitudinal size of a substorm development. It is seen that, in 1999-2000, the substorm onset latitudes were a little bit lower than the onset latitudes in 2012-2013. It is also shown that the latitudinal sizes of substorms in 1999-2000 were a little bit larger than the substorm latitudinal size during 2012-2013.

c) Solar wind parameters before the onset of substorms

We considered the solar wind and IMF parameters observed before the onset of the three types of substorms. We downloaded the values of the following solar wind parameters: the B_X, B_Y, B_Z components of IMF, V_X component of the solar wind velocity, E_Y component of the interplanetary electric field, temperature (T), density (N) and dynamic pressure (P) of the solar wind. All considered parameters were averaged for 1.5 hours before the substorm onset. The dependences of the IMF B_Z and solar wind dynamic pressure (P) on the V_X component of the solar wind velocity are shown in Figure 3. The observed values before the onset of substorms are separately plotted for the three types of substorms - "usual" (top panels, (*a*)),"expanded" (middle panels, (*b*)) and "polar" (bottom panels, (*c*)) substorms. The years of observation are marked on the figure.

It can be seen that significant differences in distributions of the solar wind parameters (Vx, Bz, P) between substorms during 1999-2000 and substorms during 2012-2013 have been not found. However, there is a big difference between "polar" and "expanded" substorms: the first occur at low solar wind velocity and the second at values of solar wind velocity higher than 500 km/s. It should be noted that we also analyzed the E_Y component values of the solar wind electric field, B_X and B_Y components of the IMF, the solar wind density and temperature before the onset of the substorms in 1999-2000 and 2012-2013 (the pictures are not shown in this paper). No significant differences have been found.

d) PC-index for all three types of substorms

We also downloaded the PC-index values (e.g. Troshichev and Janzhura, 2009) before the onset of the three types of substorms, averaged for a 1.5 hours interval prior to the moment of the substorm onset. Figure 4 shows the histograms of the PC-index values observed before the onset of the "polar" (right top panel, (a)), "expanded" (left top panel, (b)), "usual" (left bottom panel, (c)) and all (right bottom panel, (d)) substorms. The histograms of the PC-index values before substorms for periods 1999-2000 (black lines) and 2012-2013 (blue lines) are shown.

We also calculated averaged values and the standard deviations of all of the PC-index values before the onset of all substorms.

In the Table 2 are presented averaged values and standard deviations of the PC-index.

Table 2. Averaged values and standard deviations of the PC-index

Type of substorm	1999-2000	2012-2013
"expanded" substorms	1.98±0.80	1.59±0.95
"polar" substorms	0.77±0.59	0.52±0.54
"usual" substorms	1.49±0.92	0.95±0.82
all substorms	1.47±0.93	0.91±0.82

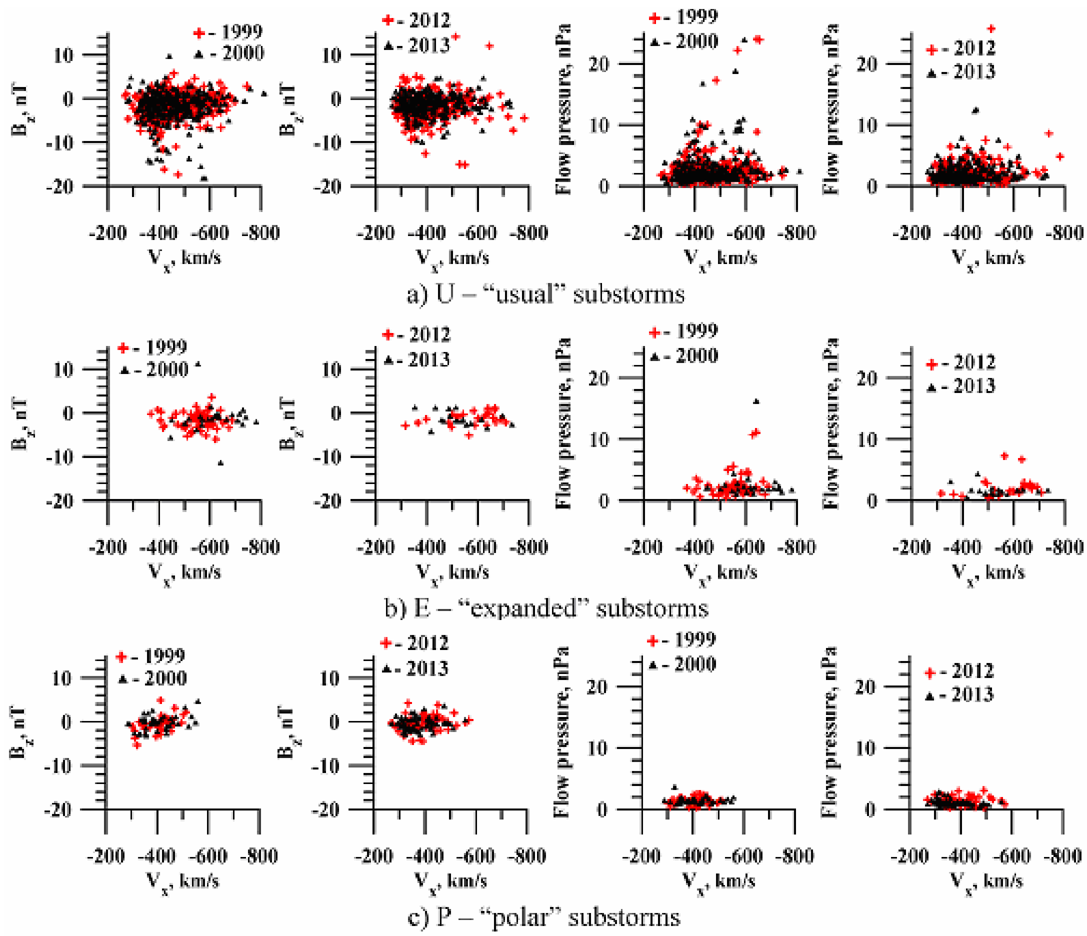

Figure 3 The solar wind and IMF (B_Z, V_X and P) parameters before three types substorm onsets in1999-2000 and 2012-2013: U - "usual" substorms (*a*), E - "expanded" substorms (*b*) and P - "polar substorms (*c*).

It can be seen that the highest PC-index values are observed before the occurrence of the "expanded" substorms, the lowest value of the PC-index before the occurrence of the "polar" substorms, while the "usual" substorms occur at intermediate values of the PC-index. At the same time, the PC-index values were 2.57-3.06 times less for the "polar" substorms than for the "expanded" substorms.

It should be also noted that for the substorms which were observed during the last solar maximum (2012-2013) the PC-index values were 1.3-1.6 times less than for the substorms during the previous solar cycle maximum (1999-2000).

Discussion

We have carried out a comparative analysis of the occurrence conditions for different types of substorms which were observed during two maxima of solar activity, namely during the large solar cycle maximum (1999- 2000, with Wp>100) and during the last maximum (2012-2013 with Wp~60). Three types of substorms, i.e., the "polar", "expanded" and "usual" substorms, were compared with respect to the interplanetary and geomagnetic conditions, namely, the solar wind and IMF parameters and PC-index values before the onset of the three types of substorms.

It is shown that no significant differences in distributions of the solar wind parameters (V_X , B_Z, P) were found between the substorms during 1999-2000 and substorms during 2012-2013. However, if we compare the "polar" substorms and the "expanded" substorms, one can see that the former are observed at low solar wind velocity and the later at higher values of the solar wind velocity. This result has been recently obtained by Despirak et al. (2014), and it is confirmed in this paper for other long-time intervals of observations.

In our opinion, the new interesting result of our study is finding different values of the PC-index before the occurrence of the three types of substorms. It is shown that the highest PC-index values are observed before the "expanded" substorms, the lowest value of the PC-index before the "polar" substorms. The PC-index values are 2.57 - 3.06 times less for the "polar" substorms than for the "expanded" substorms. It should be noted that these two types of substorms are observed at almost identical high geomagnetic latitudes. However, they appear in different situations and for different preceding conditions. It follows that the conditions of these substorms generation are different, i.e., they reflect different processes in the magnetotail or different sources.

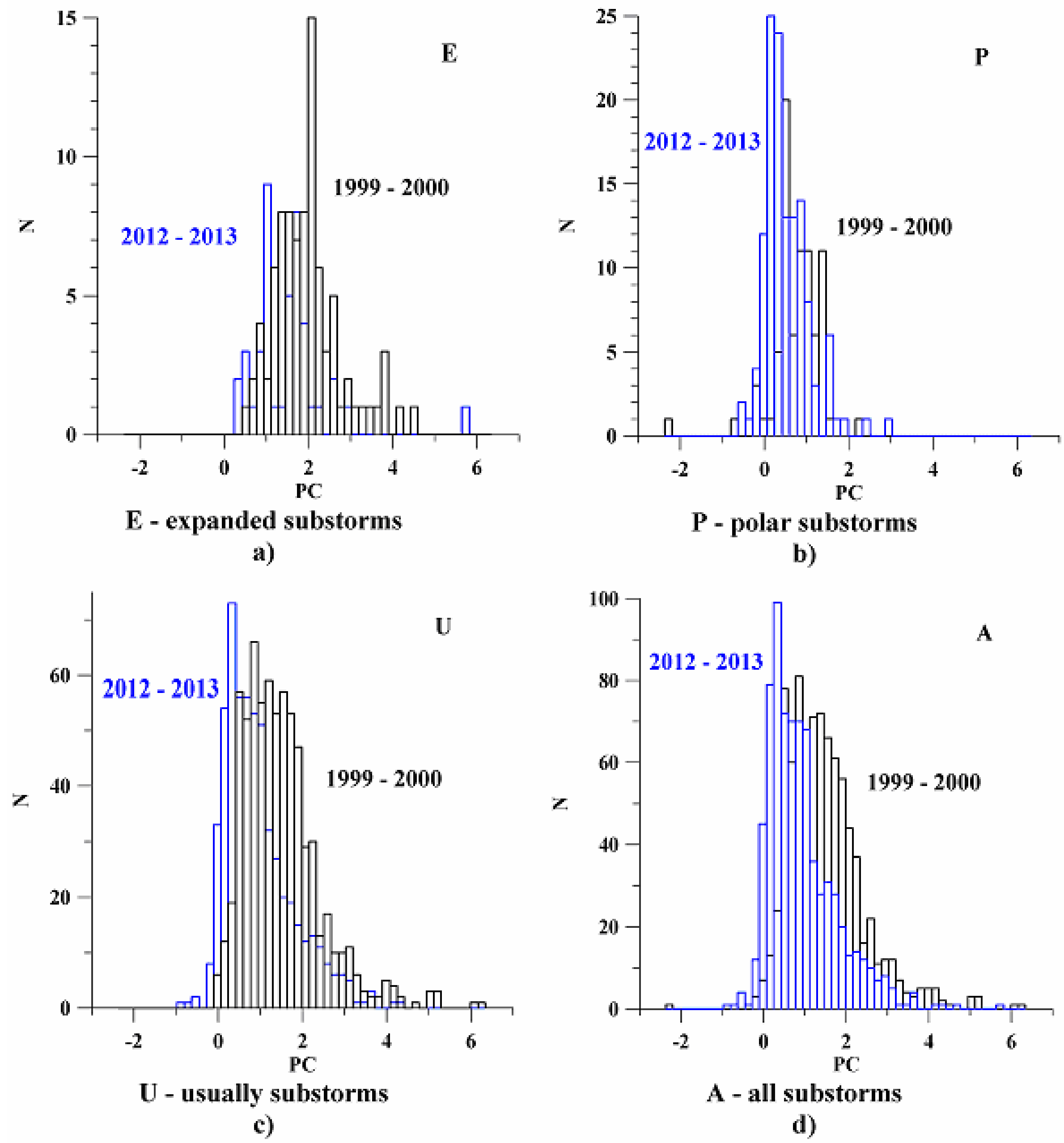

Figure 4 The PC-index distributions (histograms) before 3 types of substorms during two intervals: 1999-2000 and 2012-2013: E - "expanded" substorms (a), P - "polar" substorms (b), U - "usual" substorms (c), A - all substorms (d).

Conclusions

It was found:

1. (i) The substorm number is higher in 1999-2000 than in 2012-2013; (ii) the summer minima of the substorms occurrence and the equinox (spring and autumn) maxima are common to both considered periods; (iii) the "polar" substorms behavior was opposite to other types of substorms behavior. The number of the "polar" substorms has its maximum in the winter months; it is also noted that the "expanded" substorms occurrence maximum was also observed in winter 1999-2000, but it was not observed in winter 2012-2013.
2. The substorms onset latitudes were a little lower in 1999-2000 than in 2012-2013; the substorms latitudinal extent was a little larger in 1999-2000 than in 2012-2013.
3. There were no significant differences of the solar wind parameters (VX, BZ, P) before substorms in 1999-2000 and in 2012-2013.
4. For all three types of substorms which were observed during the last solar maximum (2012-2013) the PC-index values are 1.3- 1.6 times lower than for substorms during the large solar cycle maximum (1999-2000). It is also shown that the PC-index values are 2.57 - 3.06 times lower for the "polar" substorms than for the "expanded" substorms.

Thus, the difference between two solar activity maxima could be seen in the difference of substorm behavior in these periods as well.

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