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Different origins of magnetic disturbances during substorm growth and expansion phases and insufficiency of the *AL* index as their sole measure

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Abstract. The paper examines the relationship between the PC index, characterizing the solar wind energy input into the magnetosphere, and the *AL* index, characterizing the magnetic substorm intensity for the expansion phase of isolated substorms recorded in 1998–2017. Magnetic disturbances in the course of the expansion phase are produced by the DP11 current system with a powerful westward electrojet disposed in the midnight auroral zone. It is generally accepted that this electrojet is generated by the "substorm current wedge" system of field-aligned currents (SCW FAC) providing closure of the magnetotail plasma sheet currents through the auroral ionosphere. As this takes place, magnetic disturbances in the course of the substorm growth phase are produced by the DP12 current system with westward and eastward electrojets located, correspondingly, in the morning and evening sectors of the auroral zone, with the electrojets generated by the R1/R2 FAC system operating in the inner (closed) magnetosphere. The intensity of R1 currents is determined by the "coupling function" E_{KL}, which represents the optimal combination of all geoeffective solar wind parameters affecting the magnetosphere. The DP2 magnetic disturbances generated by the R1 FAC system in polar caps forms the basis for estimating the *PC* index, which strongly follows the E_{KL} field changes and correlates well with the development of magnetic substorms. Analyses performed in AARI revealed the principally distinctive character of the relationships between the *PC* index and *AL* index in the course of the substorm growth (DP12 disturbances) and explosive (DP11 disturbances) phases. The DP12 disturbances, generated by FAC systems in the closed magnetosphere, are developed in strong relation to the *PC* index. The DP11 disturbances, generated by the SCW FAC system, related to the magnetotail plasma sheet, show quite irregular character of relationship between the *PC* and *AL* values: the sudden jumps of the substorm intensity (*ALpeaks*) might occur, time and again, at any value of the *PC* index and with quite different delay times relative to sudden substorm onset. It means that the processes in the tail plasma sheet, leading to the formation of a "substorm current wedge" are determined by the state of the magnetotail plasma sheet itself. The solar wind influence (evaluated by the *PC* index) affects but does not control the processes in the magnetotail, unlike those in the inner magnetosphere. It should be noted in this connection that the intensity of magnetic DP12 and DP11 disturbances, observed in the course of the substorm growth and explosive phases, is estimated by a single *AL* index, in spite of the different origin of these disturbances (R1/R2 and SCW FAC systems). It is necessary to employ two separate indices characterizing DP12 and DP11 disturbances in order to allow for the effects of the solar wind on the processes in the inner magnetosphere and in the magnetotail.

Keywords: magnetic activity in polar caps, magnetospheric field-aligned currents, magnetic substorms, *PC* index, solar wind parameters, solar wind — magnetosphere interaction, substorm growth and expansive phasesc

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Introduction

Specific magnetic disturbances occurring in high latitudes in the course of intense aurora were first identified by Birkeland [1] as a "polar elementary storm". Later a close relationship of the "polar storms" to magnetic storms (magnetic disturbances extending over the whole planet) was revealed [2] and the term "substorm" was introduced to denote magnetic disturbances observed in the auroral zone [3, 4]. The magnetic substorm features are usually depicted through "equivalent current systems", i.e. systems of conventional electric currents flowing in the polar ionosphere, whose spatial distribution and intensity ensure the really observed allocation of magnetic disturbances (the horizontal H/D, or X/Y components) at the ground surface. According to [3], an equivalent current system of a powerful magnetic substorm (DP1) consists of intense westward currents (westward electrojet) in the morning and night sectors of the auroral zone and closing currents in the polar cap and in the subauroral latitudes (Fig. 1*a*). In the case of a moderate substorm an eastward electrojet was observed in the evening auroral zone. As the following study [5] showed, the DP1 current system represents a superposition of two separate systems: DP12 system typical of the growth and recovery substorm phases, with westward and eastward electrojets in the morning and evening sectors (Fig. 1*b*), and DP11 system typical of the expansion (explosive) substorm phase, with an intense westward electrojet in the night sector (Fig. 1*c*). The intensity of the westward and eastward electrojets (*AL* and *AU* indices) is estimated by the value of negative and positive magnetic disturbances recorded in the auroral zone.

Weaker magnetic disturbances, independent of magnetic substorms, were revealed in the polar caps. The main one is the DP2 disturbance [6–8], represented by two-vortices current system with focuses in the morning and evening sectors on the pole-ward edge of the auroral zone and sunward-directed currents in the near-pole region. The DP2 current system is available continuously, irrespective of the time and season, with the current intensity increasing under conditions of the southward interplanetary magnetic field (IMF) [6, 7, 9, 10] and high solar wind velocity [10, 11].

The physical mechanisms responsible for the substorms and polar cap magnetic disturbances came to light when transverse magnetic deviations in the magnetosphere were revealed in the course of spacecraft experiments [12–17]. It became evident that the ground magnetic disturbances are related to various systems of the magnetospheric field-aligned currents (FAC). The main FAC system is the Region 1 (R1) system, with the currents flowing into the ionosphere on the dawn side and out of the ionosphere on the dusk side of the poleward edge of the auroral zone. The R1 FAC system operates constantly, irrespective of the season and IMF polarity, with the current intensity increasing under conditions of the southward IMF.

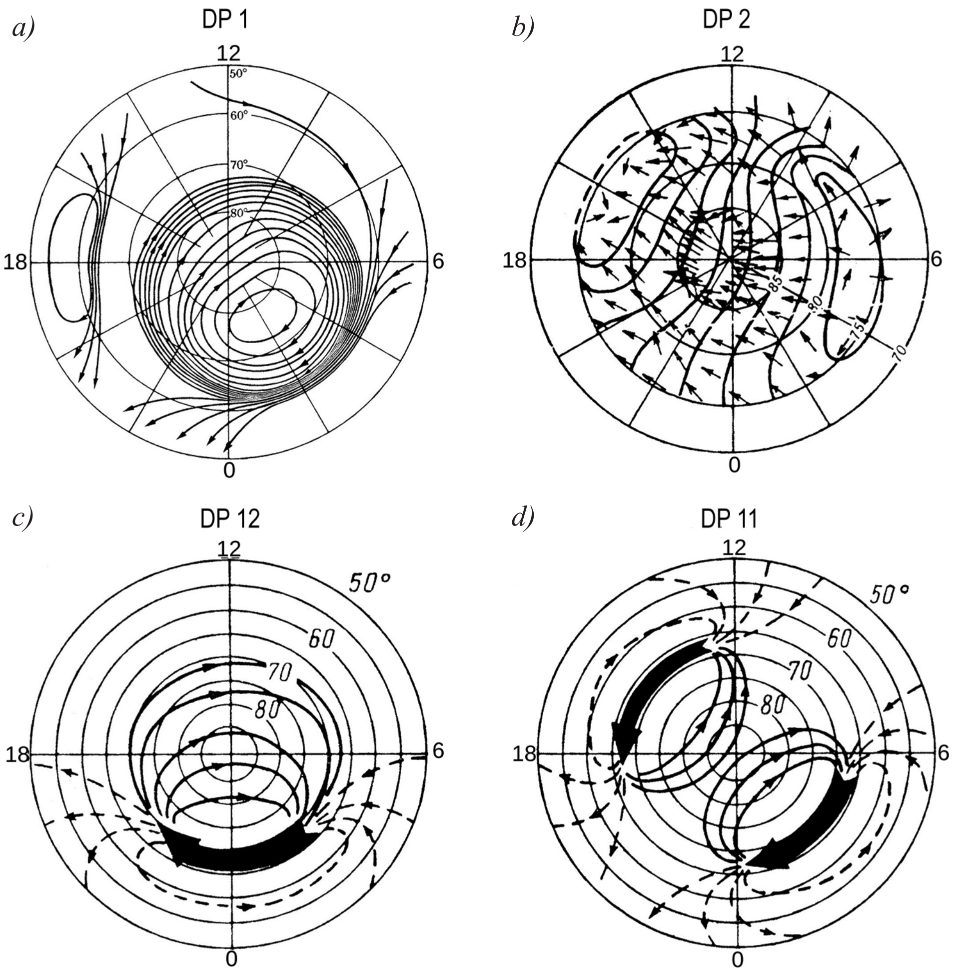

Fig. 1. Equivalent current systems of magnetic disturbances: (*a*) magnetic substorm DP1 [3], (*b*) polar cap DP2 disturbance [9], the substorm growth and expansion phase disturbances DP12 (*c*) and DP11(*d*) [5]

Рис. 1. Эквивалентные токовые системы высокоширотных магнитных возмущений: (*a*) магнитная суббуря DP1 [3], (*b*) DP2 магнитное возмущение в полярной шапке [9], возмущения на фазе роста DP12 (*c*) и на взрывной фазе DP11 (*d*) суббури [5]

Model calculations of ionospheric electric fields and currents generated by the field-aligned currents were performed [18, 19] using experimental data on field-aligned currents and ionospheric conductivity in the polar cap. The results of the model calculations demonstrated full agreement with “equivalent current systems” obtained in [9, 10] based on the data of the ground magnetic observations, indicating that “equivalent systems” represent the real ionospheric current systems generated by field-aligned currents in the well-conducting polar ionosphere. Conclusion was made [20] that the field-aligned currents are responsible for the generation of magnetic activity in the polar cap and auroral

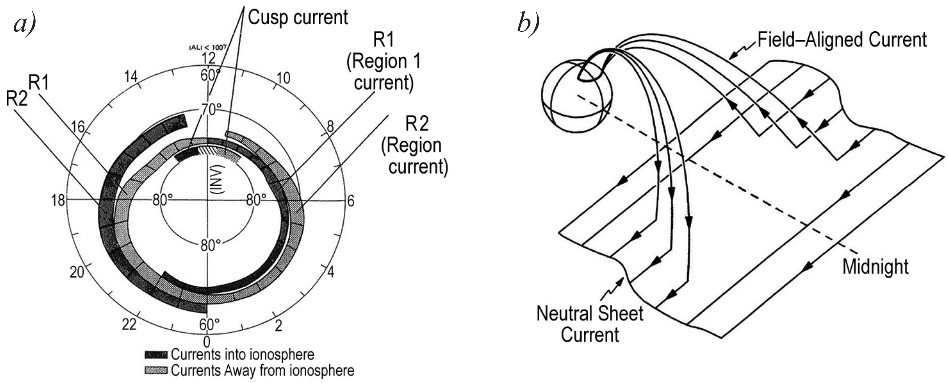

Fig. 2. Pattern of (*a*) field-aligned currents derived from spacecraft data [14] and (*b*) the substorm current wedge short-circuiting the neutral sheet current in the magnetotail [26]

Рис. 2. Системы продольных токов (*a*) R1 и R2, действующие в замкнутой магнитосфере [14], и (*b*) суббуревой токовый клин (SCW), связывающий токи в хвосте магнитосферы с ионосферой [26]

zone. The results [18, 19] were confirmed afterwards in more detailed and complicated analyses [21–24].

The substorm expansion phase (jump of the westward electrojet intensity in the night auroral zone) is related to the action of a specific "substorm current wedge" (SCW) FAC system [25], which includes plasma sheet currents in the magnetotail, a westward electrojet in the night auroral zone, and connecting field-aligned "Birkeland currents". It was suggested [26] that the solar wind energy, which is not directly dissipated via auroral electrojets in the course of the growth phase, is stored as a consequence of magnetosphere convection, in the tail magnetosphere in the form of magnetic energy by enhancing the neutral sheet — tail current circuit. After the storage period (substrorm growth phase) the magnetic tension is suddenly released by short-closing the neutral sheet current through the midnight auroral ionosphere by means of Birkeland currents (Fig. 2*b*) marking a sudden substorm onset (SO).

Given that the DP2 disturbances increase is invariably followed by substorm development, it was suggested [27] that the polar cap magnetic activity can be used as an indicator of the magnetosphere state. Analysis of relationships between the DP2 disturbances, evaluated based on the data of magnetic observations at the near-pole station Vostok (Antarctic), and various "coupling functions" proposed for the description of relationships between the solar wind parameters and magnetic disturbances, showed [28] that the DP2 disturbances correlate the best ($R = 0.80$) with the coupling function $E_{KL} = V_{SW}\,(B_Z^2 + B_Y^2)^{1/2} sin^2(\Theta/2)$ proposed by Kan and Lee [29], where V_{SW} is the solar wind velocity, B_Y and B_Z are the IMF components, Θ is the angle between the geomagnetic dipole and transverse IMF component $B_T = (B_Z^2 + B_Y^2)^{1/2}$. This result is indicative of the E_{KL} function as an optimal combination of the geoeffective solar wind parameters ensuring the highest intensity of the R1 field-aligned currents generating DP2 disturbances. As a consequence, the polar cap magnetic activity index *PC* began to be used in AARI in collaboration with the Danish Meteorological Institute (DMI) [30]. The *PC* index

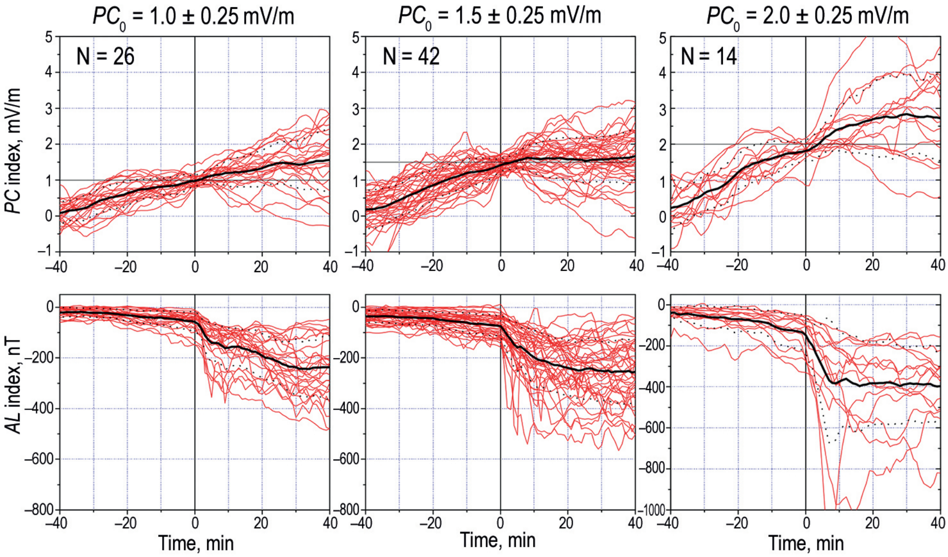

Fig. 3. Behavior of the *PC* and *AL* indices in the course of isolated substorms with the *PC* growth period ΔT = 20-45 min for 3 levels of *PC* value at the moment of a sudden substorm sudden (PC_0): 1.0 mV/m, 1.5 mV/m and 2.0 mV/m [36]

Рис. 3. Поведение *PC* и *AL* индексов в ходе изолированных магнитных суббурь с периодом роста *PC* индекса ΔT от 20 до 45 мин, для 3 уровней величины *PC* индекса в момент начала суббури (PC_0): 1,0 мВ/м, 1,5 мВ/м и 2,0 мВ/м [36]

is calculated based on the data of magnetic observations at the Thule observatory in Greenland (*PCN* index) and at Vostok in the Antarctic (*PCS* index). The following studies showed a close relationship between the 15-min *PC* and auroral elecrtrojet indices [31–33]. Basing on these results the International Association of Geomagnetism and Aeronomy (IAGA) endorsed the *PC* index as a proxy for the energy that enters into the magnetosphere during the solar wind — magnetosphere coupling [34, 35].

Transition to the 1-min scale of indices revealed a distinction in the behavior of the *PC* and *AL* indices in the course of the substorm growth and expansion phases. Whereas the relationship between the 1-min *PC* and *AL* indices at the growth phase remains mainly the same for various substorms, the relationship at the expansion phase changes from one substorm to another. Fig. 3 [Troshichev et al. [36] shows, as an example, the relationship between the *PC* and *AL* indices in the course of isolated substorms (thin red lines) for three levels of the PC_0 index at the moment of a substorm onset (T=0), which are marked in the graphs by a vertical line, with the mean *PC* and *AL* values represented by thick solid lines. One can see that the *AL* index before SO increases in good agreement with the *PC* growth, whereas the relationships between the corresponding *PC* and *AL* indices after SO can be quite different: from full agreement to independence. To clarify this issue, a comprehensive analysis of the relationships between the *PC* and *AL* indices in the course of the substorm expansion phase was carried out for isolated magnetic substorms recorded over 20 years (1998–2017). The results of the analysis are presented in this paper.

Method of analysis

To identify the substorm event, the same criteria were used as in study [36]: (1) the magnetic disturbance event was regarded as a substorm if the SO amplitude (*AL* decrease value) within 15 minutes was more than 100 nT, (2) only isolated disturbances were examined, which arise on the background of quiet conditions ($AL \leq 200$ nT) lasting one hour or more prior to SO. Thereafter these substorms were separated into different categories in accordance with the relationship between the *AL* and *PC* indices in the course of the substorm. The *PC* index in the winter polar cap (*PCwinter*) index was taken for examination with regard to results demonstrating that the correlation between the *AL* and *PCwinter* indices is always better than that between the *AL* and *PCsummer* indices. The index *PCmean* = (*PCwinter* + *PCsummer*)/2 was used for the equinox season.

The following quantities have been evaluated for each individual substorm:

PCmax — maximal value of the *PC* index in the course of a substorm expansion phase;

ALcorr — corresponding value of the *AL* index at the moment of *PCmax*;

Alpeak — amplitude of the *AL* index maximal jump during a substorm expansion phase; in the case of some jumps with an equal amplitude, the central of them is taken as *Alpeak*; if the *AL* maximal jump is recorded a few minutes after the *PCmax* moment, just this *AL* jump was taken as *Alpeak*; in the case of the *AL* index increase without jumps in the course of an expansion phase, the *Alpeak* index was regarded as unavailable;

DTmax — time interval between SO and *PCmax* moments in the course of a substorm expansion phase;

DTpeak — time interval between SO and *PCpeak* moments in the course of a substorm expansion phase.

Results of analysis

Different types of relationships between PC and AL indices

Magnetic disturbances observed over the period 1998–2017 have been examined and substorms satisfying the criteria indicated above ($N = 820$) have been identified. These substorms were divided into 7 categories shown below, according to particularities of the relationship between the *PC* and *AL* indices in the course of each individual substorm. Typical examples of these categories are presented in Fig. 4–10, where the vertical black line marks the substorm sudden onset time T_0, whereas the horizontal red line denotes the appropriate value of the *PC* index at this moment (“*PC* critical level”). It could be noted that this critical level usually lies in the range of *PC* from ~0.5 to 1.5 mV/m, in full agreement with the results [36]. It should be born in mind that the division of substorms into these categories is conditional to some extent since in many cases the real substorms demonstrate signatures of different categories concurrently. In such a case the most representative signature was taken into account for categorization.

“*PC*-concerted” substorms (N = 49) are disturbances with *AL* increase going on in good agreement with the *PC* gradual growth (Fig. 4); the intervals with the *PC* growth slowing-down are accompanied by the *AL* rise fall-dawn. The substorm intensity reaches maximum simultaneously with the PC index (“*PCmax* moment”) and thereupon decreases. As this takes place, changes in the *AL* index can outstrip or delay for a few minutes relative to the *PC* index changes (Fig. 4*a*). Usually, the substorm intensity is higher for events with a larger “PC_0 critical level”.

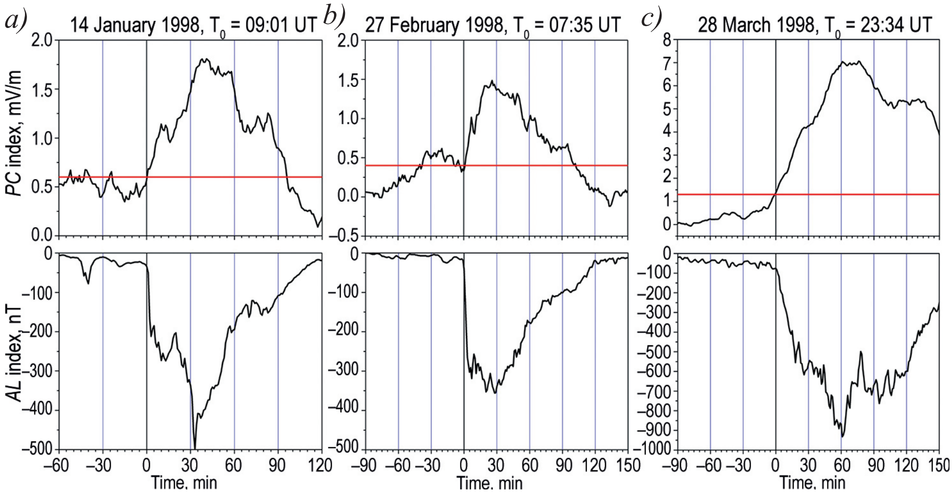

Fig. 4. Changes of the *PC* and *AL* indices in the course of “*PC* – concerted ” substorms

Рис. 4. Изменения *PC* и *AL* индексов в ходе «согласованных с *PC*» суббурь

“*PC*-followed” substorms ($N = 330$) are disturbances with one or more *ALpeaks* of different or approximately equal intensity, which are observed during the rise of the *PC* index and its presence at the top (Fig. 5). In the case of a “delayed” substorm (Fig. 5*a*), *ALpeaks* continue to appear after the *PCmax* moment and a maximal intensity of the substorm can be reached during the *PC* drop. In the case of “advanced” substorms (Fig. 5*b*, *c*), the *ALpeaks* are observed before the *PCmax* moment and substorm intensity falls simultaneously with the *PC* index decrease or previously. The relationship between the *PCmax* and *ALpeak* values changes from one substorm to another, with the substorm intensity related to the *PC* critical level.

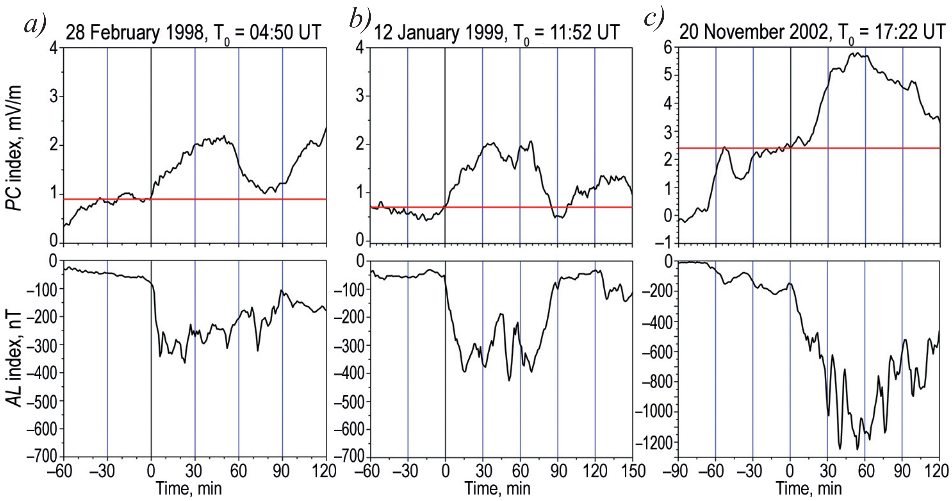

Fig. 5. Changes of the *PC* and *AL* indices in the course of “*PC* – followed” substorms

Рис. 5. Изменения *PC* и *AL* индексов в ходе суббурь, «следующих изменениям *PC* индекса»

“SO-peaked” substorms (N = 58) are a specific variety of *PC*-accompanied substorms, where the first extremely high *Alpeak* arises just at the SO moment (Fig. 6). In this case the relationship between the *PC* and *AL* values can be strongly changed even in the course of one individual substorm (see Fig. 6*a*, *b*, *c*). Sometimes the first *Alpeak* turns out to be the main peak during the substorm but usually it is followed by other peaks. Again, the intensity of substorms is higher for events with a larger *PC* critical level.

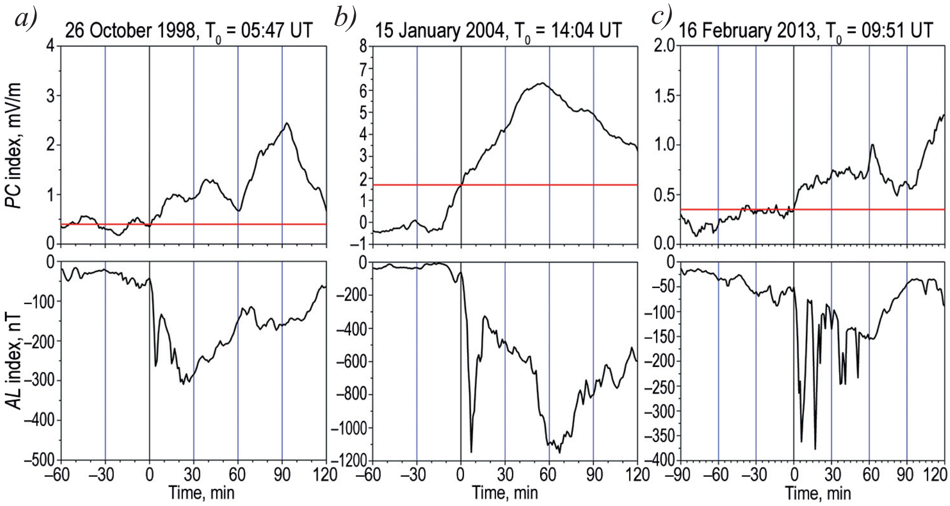

Fig. 6. Changes of the *PC* and *AL* indices in the course of “SO-peaked” substorms

Рис. 6. Изменения *PC* и *AL* индексов в ходе суббурь с максимумом интенсивности в начале суббури

“*PC*-reversed” substorms (N = 99) are another variety of “*PC*-followed substorms (Fig. 7) starting in a way that is evidently related to the “*PC* reverse” transformation, when the *PC* index suddenly changes from drop down to jump up. The substorm beginning is stimulated even by an insignificant *PC* reverse in the course of the *PC* index increase (Fig. 7*b*) or decrease (Fig. 7*c*), as well as when the *PC* index stays more or less invariable for a long period of time. The substorm can be initiated also when the PC_0 is negative if the *PC* reverse amplitude and rate are great (Fig. 7*a*). It is reasonable to suggest that the *PC* reverse is always conducive to the development of a substorm, but the start of a substorm is actually determined by the total state of the system.

“*PC*-fluctuated” substorms (N = 127) are disturbances related to *PC* index regular fluctuations, such as “*PC*-waved” alternations with a period of more than 20 minutes, or “*PC*-oscillated” alternations with periods shorter than 15 minutes. In the case of **“*PC*-waved”** substorms, the disturbance usually starts with an onset of the second (or third) wave of the *PC* index increase, continues for about one hour and finishes thereupon (Fig. 8*a*), the *PC* values lie in the range from 0 to 3 mV/m. The intensity of “*PC*-waved” substorms (*ALmax* magnitude) can reach the value ~ –350 nT, depending mainly on the *PC* critical level. **“*PC*-oscillated”** substorms present a total response of magnetic activity to short-period alternations of *PC*, without any evident relationship of the substorm onset to the *PC* index growth or decrease (Fig. 8*b*). Usually, short *PC* oscillations are observed against the background of long *PC*-waved alternations (Fig. 8*c*). In these cases, the relationship between the *PC* and *AL* index remains identical to that for pure “*PC*-waved” or for “*PC*-oscillated” substorms depending on the amplitude of *PC* index waves and oscillations, the substorm intensity (*AL* index) is changed in the range from ~ –200 nT to –400 nT.

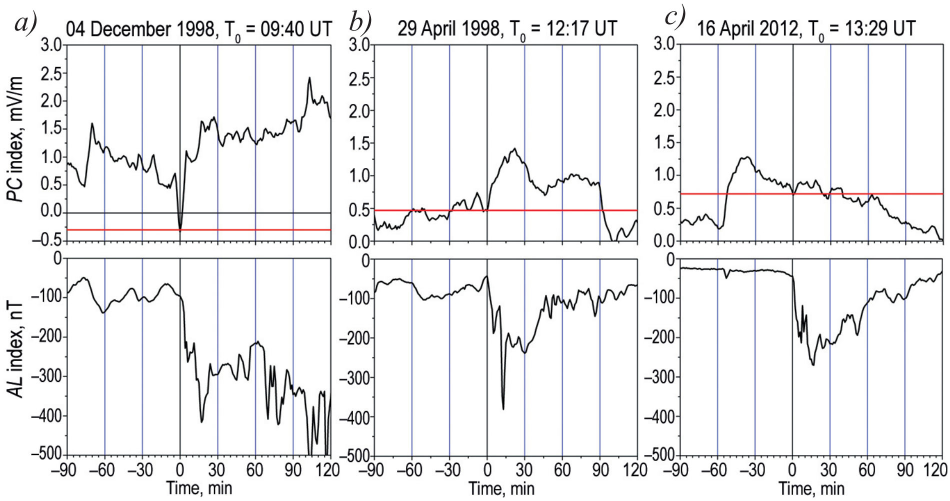

Fig. 7. Changes of the *PC* and *AL* indices in the course of "*PC*-reversed" substorms

Рис. 7. Изменения *PC* и *AL* индексов в ходе суббурь, связанных с реверсом *PC* индекса

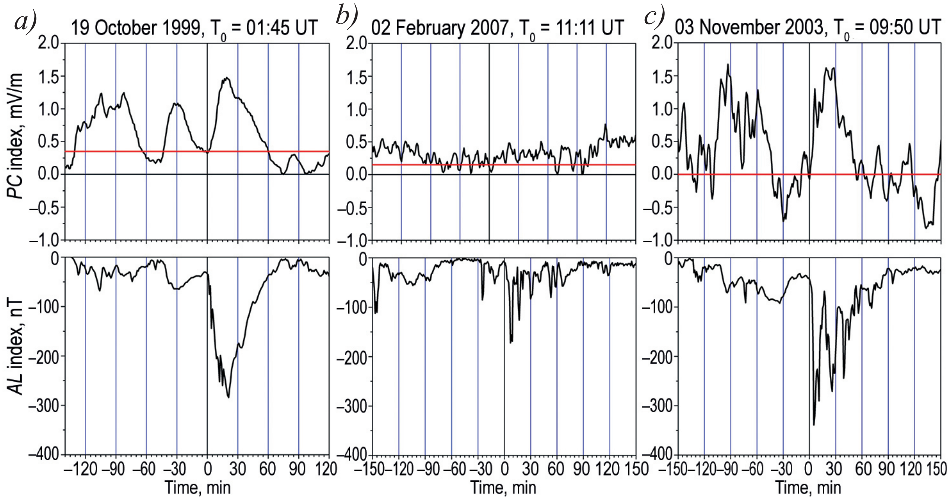

Fig. 8. Changes of the *PC* and *AL* indices in the course of "*PC*-fluctuated" substorms: waived (*a*), oscillated (*b*) and combined (*c*) alterations of the *PC* index

Рис. 8. Изменения *PC* и *AL* индексов в ходе суббурь, «связанных с колебательными изменениями величины *PC* индекса»: волны (*a*), осцилляции (*b*), комбинированные (*c*)

"*PC*-fluctuated" substorms appear to be associated with the effect of the *PC*-fluctuated pack passage, rather than the effect of the separate *PC* index growth. Although "*PC*-fluctuated" substorms usually start at the beginning of the corresponding pack, sometimes they are observed in relation to the pack maximum or after this maximum, with the substorm intensity being rather limited. Situation changes if the *PC* index fluctuations occur against the background of gradual *PC* index increase. Fig. 9 gives examples of "*PC*-increase/fluctuated" substorms (N=134) that developed with the *PC* value increase in the case of waived (*a*), oscillated (*b*) and combined (*c*) alternations of the *PC* index. One can see that the relationship between the *PC* and *AL* values in such a case becomes similar to that for "accompanying" substorms, and the substorm intensity is significantly increased.

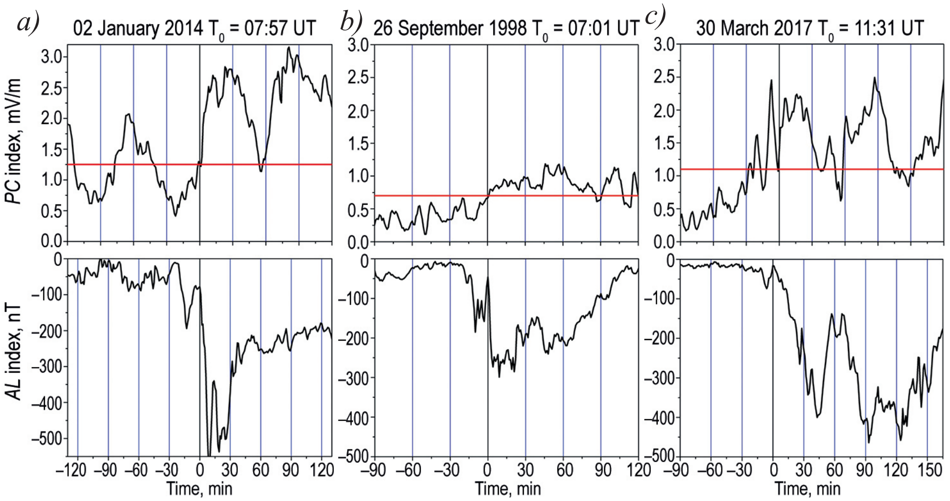

Fig. 9. Changes of the *PC* and *AL* indices in the course of “*PC*-increase/fluctuated” substorms occurring against the background of the *PC* gradual growth in the case of waived (*a*), oscillated (*b*) and combined (*c*) *PC* alterations.

Рис. 9. Изменения *PC* и *AL* индексов в ходе суббурь, «связанных с колебательными изменениями величины *PC* индекса на фоне постепенного роста *PC* индекса»: (*a*) волны, (*b*) осцилляции, (*c*) комбинированные изменения *PC* индекса

“Unrelated” substorms ($N = 23$) are disturbances that start in the absence of distinct *PC* index changes at the moment of a sudden substorm onset (Fig. 10). Substorm can start with the *PC* index unvarying (*a*), or decreasing (*b*), or irregularly changin (*c*). This category of magnetic disturbances, few in number, implies the possibility of substorm development even under conditions of ineffective solar wind impact on the magnetosphere.

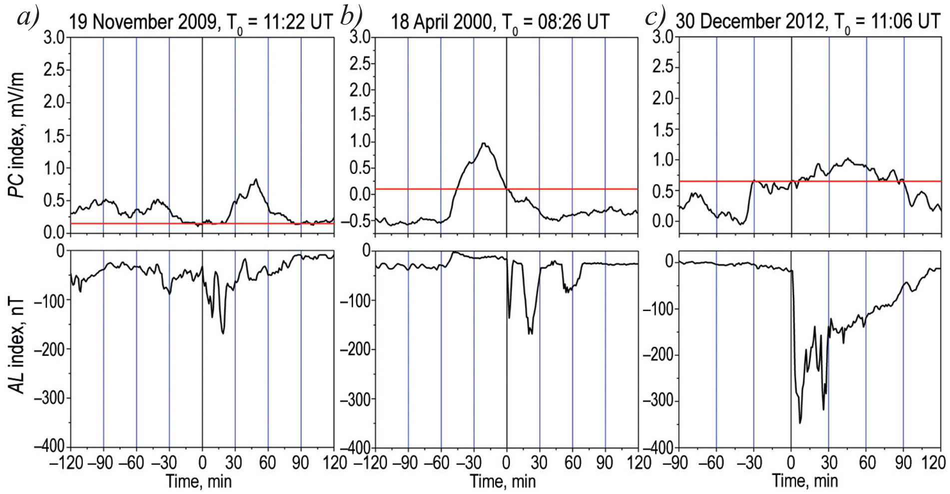

Fig. 10. Changes of the *PC* and *AL* indices in the course of “*PC*-unrelated” substorms occurring in the absence of distinct *PC* index signatures related to the substorm sudden onset

Рис. 10. Изменения *PC* и *AL* индексов в ходе суббурь, не связанных с вариациями *PC* индекса

Statistically justified relationship between the *PC* and *AL* indices

Statistical analysis of relationships between the values of the *PC* and *AL* indices has been performed for all the categories of substorms ("*PC*-concerted", "*PC*-followed", "SO-peaked", "*PC*-reversed", "*PC*-increase/fluctuated"), which demonstrated an evident relationship of the substorm progression to the *PC* index growth in the course of the expansion phase. Fig. 11 shows an example of relationship between the *PCmax*

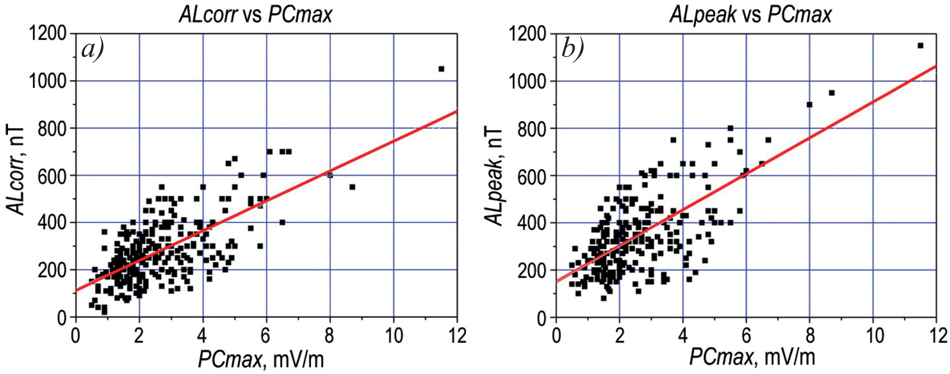

Fig. 11. Relationship between the substorm intensity parameters *ALcorr* (*a*) and *ALpeak* (*b*) and maximal value of the *PC* index (*PCmax*) in the case of "*PC*-followed" substorms

Рис. 11. Зависимость параметров интенсивности суббури *ALcorr* (*a*) и *ALpeak* (*b*) от максимальной величины *PC* индекса (*PCmax*) в случае суббурь, «следующих изменениям *PC* индекса»

Table 1

Parameters of linear relationship between the substorm intensity (*ALcorr*) and *PCmax* value (*ALcorr* = $\beta_0 + \beta_1 \cdot PCmax$)

Таблица 1

Параметры линейной связи между параметрами *ALcorr* и *PCmax*

Category of substorm	Indicator	Interception β_0	Slope β_1	Correlation *R*	Number
Concerted	*ALcorr*	147	87	0.90	49
Followed	*ALcorr*	111	66	0.70	330
SO-peaked	*ALcorr*	78	75	0.80	58
PC-reversed	*ALcorr*	123	57	0.71	99
PC-increase/waived	*ALcorr*	92	78	0.67	65
PC-increase/oscillated	*ALcorr*	57	96	0.57	69

Table 2

Parameters of linear relationship between the substorm intensity (*ALpeak*) and *PCmax* value (*ALpeak* = $\beta_0 + \beta_1 \cdot PCmax$)

Таблица 2

Параметры линейной связи между параметрами *ALpeak* и *PCmax*

Category of substorm	Indicator	Interception β_0	Slope β_1	Correlation *R*	Number
Followed	*ALpeak*	150	76	0.70	298
PC-reversed	*ALpeak*	160	76	0.72	86
PC-increase/waived	*ALpeak*	123	106	0.73	59
PC-increase/oscillated	*ALpeak*	116	119	0.73	65

values and the substorm intensity quantities *ALpeak* and *ALcorr* in the case of the category of "*PC*-followed" substorms, large in number. Both quantities, *ALpeak* and *ALcorr*, are linearly related to the *PCmax* value with the coefficient of correlation R = 0.70. Similar results were obtained for other categories of substorms (Tables 1 and 2). Thus, the majority of the isolated magnetic substorms (~82 %) demonstrate linear linkage between the *PC* index value and the substorm intensity in the course of the substorm expansion phase. The best correlation between *PCmax* and ALcorr (R = 0.899) is observed in the case of "*PC*-concerted" substorms, which demonstrate consistency between *PC* and *AL* indices alternation. Note that the high correlation between the *AL* and *PC* indices (R = 83) is typical of the DP12 disturbances during the substorm growth phase [36]. The lowest correlation between *PCmax* and *ALcorr* in the course of the expansion phase is observed for "*PC*- increase/waived" substorms (R = 0.67) and "*PC*-increase/oscillated" substorms (R = 0.57), related to the combined effect of *PC* index increase and passage of the *PC*- fluctuated packs. The remaining 18% are "*PC*-fluctuated" substorms, which exhibit the *PC*-fluctuated pack passage effect.

On the other hand, the results of the analysis indicate that maximal *AL* values (*ALpeaks*) can be recorded at any moment in the course of the substorm expansion phase: just at the SO moment T_0, during the whole interval between the moments of *PCmax* and T_0, at the *PCmax* moment and after it. It implies that the delay time of the *ALpeaks* accomplishment relative to the SO moment is not related to the values of *ALpeaks* or *PCmax*. To verify this supposition, we examined the statistically justified relationship between the time intervals DT(*ALpeak*) (time duration from moment T_0 to moment of *ALpeak*) and the values *ALpeak* and *PCmax*. The results of the analysis, presented in Fig. 12 for the category of "followed" substorms demonstrate that the moment of the *Alpeak* appearance (characterized by intervals DT(*ALpeak*)) is not related either to the *PCmax* value (R = 0.23) or to the *ALpeak* value (R = 0.38). The same results have been obtained for other substorm categories. It implies that substorm power bursts (*ALpeaks*), related to the "substorm current wedge" FAC system action, are most likely controlled by the current state (steady or unsteady) of the neutral sheet current circuit in the magnetosphere tail.

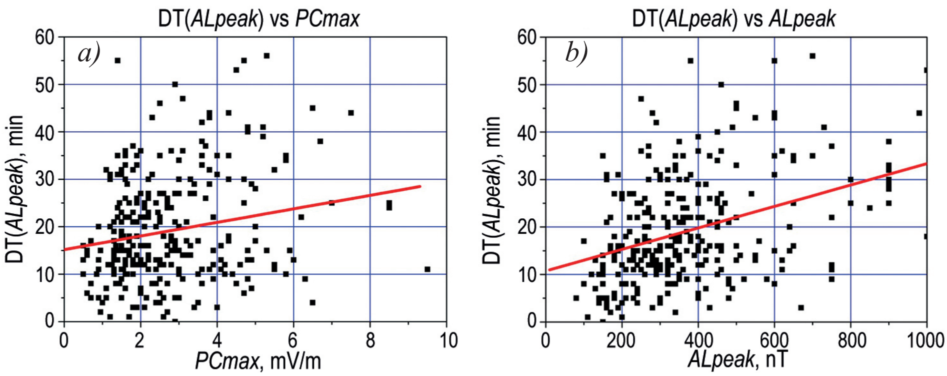

Fig. 12. Relationship between the duration of DT(*ALpeak*) intervals and values *PCmax* (*a*) and *ALpeak* (*b*) in the case of "*PC*-followed" substorms

Рис. 12. Связь между длительностью интервала DT(*ALpeak*) и величинами *PCmax* (*a*) и *ALpeak* (*b*) в ходе суббурь, «следующих изменениям *PC* индекса»

Discussion

It should be borne in mind that the *PC* index is regarded in this study as an indicator of the solar wind influence on the magnetosphere, in conformity with the IAGA resolutions [34, 35]. The results of the analysis indicate that the response of the substorm activity (*AL* index) to the *PC* index growth is quite different in the course of preliminary and expansion substorm phases. Indeed, the substorm activity during the preliminary phase (i. e. DP12 disturbances, produced by R2 field-aligned currents acting in the morning and evening sectors of the inner magnetosphere) closely follows the *PC* growth, whereas the sudden jumps of the *AL* maximum value (*ALpeaks*) during the expansion phase (i. e. DP11 disturbances, produced by the SCW FAC system) are observed at any value of the *PC* index, time and again, with quite different delay times relative to the sudden substorm onset (SO). It means that jumps of substorm intensity (*ALpeaks*) in the course of the expansion phase occur regardless of the substorm duration and *PCmax* value, although the *ALpeak* values demonstrate, like *ALcorr* values, linkage with the *PC* index. In other words, the substorm intensity is related to the *PC* value, but the substorm progression is not in line with the *PC* index dynamics. This experimental fact implies that the formation of the substorm current wedge (SCW) is controlled first of all by the state (steady or unsteady) of the magnetotail plasma sheet itself, with the solar wind influence being favourable for the increase of instability.

Mechanisms of instability in the magnetotail plasma sheet are not established. It may be suggested that several phenomena and processes giving rise to instability can operate in the magnetotail irrespective of the solar wind impact (manifested by the *PC* index). Only the synthesis of these processes determines the magnetotail plasma sheet state (stability or instability) and its reaction to the solar wind influence. It appears evident that “*PC*-concerted” substorms occur when the magnetotail plasma sheet is in a sufficiently stable state and Birkeland currents can grow gradually, in response to the solar wind influence (i.e. to *PC* growth), the maximums of *PC* and *AL* values are attained simultaneously, without appearance of any remarkable ALpeak (see Fig. 4). Conversely, the appearance of *ALpeak* immediately after the substorm onset (Fig. 6) implies that the magnetotail plasma sheet was near the critical level of instability and the increase in the solar wind impact (i. e. the *PC* index growth) promoted instantaneous destruction of the plasma sheet current system and the formation of an appropriate powerful SCW FAC system. “*PC*-unrelated” substorms (Fig. 10), displaying substorm development in the absence of the required solar wind impact on the magnetosphere, are indicative of the crucial instability of the magnetotail plasma sheet in this case.

It should me noted that this point of view on the magnetotail processes is not consistent with the concept of Dungey [37], where processes in the magnetotail are regarded as a constituent of the total magnetospheric convection system. Indeed, only “*PC*-concerted” substorms (~6 %) can be considered as related to the united system of convection in the entire magnetosphere. All the other substorms demonstrate that DP11 disturbances, related to the SCW FAC system, start irrespective of DP12 disturbances, related to R1/R2 FAC systems operating in the closed magnetosphere. As this takes place, generation of R1/R2 FAC systems is successfully explained in the framework of Tverskoy’s concept [38, 39], as a result of a continuous formation of plasma pressure gradients within the magnetosphere under the uninterrupted influence of the solar wind.

Thus, the magnetic substorm intensity and dynamics are determined by two independent FAC structures. The R2 FAC system, acting within the closed magnetosphere, is responsible for DP12 disturbances typical of the preliminary substorm phase, whereas the SCW FAC system, acting in the magnetotail, is responsible for DP11 disturbances typical of the explosive phase. These FAC systems are distinct not only by their disposition, but also by quite a different response to the solar wind influence (represented by the *PC* index). However, the product of their separate action is estimated by a single *AL* index, characterizing the substorm activity as a whole. Note that the same peculiarity is provided by SML and SMU indices (SuperMAG auroral electrojet indices) [40], which are analogues to AL and AU indices, although they are calculated by data of measurements at magnetic stations (N > 100) located at geomagnetic latitudes Θ > 50°. It is necessary to separate magnetic effects related to processes in the inner magnetosphere from those related to processes in the magnetotail. It is suggested two different indices of magnetic activity be used, which should be evaluated based on data of magnetic observations in the morning/ evening sectors of the auroral zone (DP12 disturbances) and data of observations in the midnight sector of the auroral zone (DP11 disturbances).

Conclusions

Magnetic substorm DP1 disturbances represent a superposition of DP12 and DP11 disturbances typical of the growth and explosive phases of a substorm. DP12 disturbances, with westward and eastward electojets, located in the morning and evening sectors of the auroral ionosphere, are generated by the R2 FAC system acting in the inner (closed) magnetosphere, whereas DP11 disturbances, with a powerful westward electrojet in the midnight auroral ionosphere, are generated by the SCW FAC system related to the magnetotail plasma sheet. As this takes place, the substorm power is evaluated by a single AL index characterizing the intensity of negative magnetic disturbances observed in the auroral zone irrespective of their disposition and origin.

The formation and development of the R2 FAC system (and DP12 disturbances) is closely related to the growth of the *PC* index, which characterizes the efficiency of the solar wind impact on the magnetoshere. The intensity of the SCW FAC system (and DP11 disturbances as a whole) is also correlated with the *PC* index, but temporal characteristics of the magnetic activity in the course of DP11 disturbances (*ALpeak* number, their dynamics and time delays relative to the substorm onset) are not related to the *PC* alternations. It means that the formation and development of the SCW FAC system, linked with the magnetotail plasma sheet, is controlled by processes in the plasma sheet itself. Therefore, the acting *AL* index is a summary indicator of two separate phenomena operating in different parts of the magnetosphere.

It is necessary to use two different indices of magnetic activity instead of a single *AL* index. The first of them, evaluated by data of magnetic observations in the morning and evening sectors of the auroral zone, should characterize the intensity of DP12 disturbances produced by the R2 FAC system acting in the closed magnetosphere. The second index, evaluated by data of magnetic observations in the midnight auroral zone, should characterize the intensity of DP11 disturbances produced by the SCW FAC system determined by processes in the magnetotail.

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Различная природа магнитных возмущений, наблюдаемых в ходе фазы роста и экспансии магнитной суббури, и неэффективность *AL* индекса как единого критерия их интенсивности (расширенный реферат)

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Согласно данным спутниковых измерений, в магнитосфере действует несколько систем текущих вдоль силовых линий геомагнитного поля (продольных) электрических токов (FAC). Основной является R1 FAC система, постоянно действующая на приполюсной границе аврорального овала, т. е. в замкнутой магнитосфере. Мощность токов в R1 системе определяется «функцией взаимодействия» (полем) E_{KL}, которое представляет оптимальную комбинацию всех геоэффективных параметров солнечного ветра, действующих на магнитосферу. R1 FAC система генерирует в полярных шапках DP2 магнитные возмущения, которые являются основой для расчета *PC* индекса магнитной активности. Критические изменения поля E_{KL} приводят к развитию магнитосферных возмущений (магнитных бурь и суббурь), которые хорошо коррелируют с вариациями *PC* индекса. Поэтому *PC* индекс рассматривается в настоящее время как показатель поступающей в магнитосферу энергии солнечного ветра (IAGA Resolutions, 2013, 2021). Развитие начальной фазы суббури (фазы роста) обусловлено действием системы R2 FAC, которая формируется на экваториальной границе авроральной зоны в условиях повышенных вторжений авроральных частиц, с продольными токами, втекающими в полярную ионосферу в утреннем секторе и вытекающими из ионосферы в вечернем секторе. Как результат, на начальной фазе суббури в полярной ионосфере формируется DP12 система ионосферных токов, основными элементами которой являются западный и восточный электроджеты в утреннем и вечернем секторах авроральной зоны. Развитие взрывной фазы суббури (фазы экспансии) связано с формированием «токового клина суббури» (substorm current wedge, SCW) — специфической системы продольных токов, которая обеспечивает замыкание токов, текущих в плазменном слое хвоста магнитосферы через авроральную ионосферу. SCW FAC система, включающая продольные токи, втекающие в авроральную ионосферу в послеполуночные часы, и токи, вытекающие из ионосферы в предполуночные часы, генерирует систему ионосферных токов DP11, с мощным западным электроджетом в ночном секторе авроральной зоны.

В работе представлены результаты анализа, который показывает принципиально различный характер протекания DP12 и DP11 возмущений, фиксируемых, соответственно, в ходе

предварительной и взрывной фаз суббури. DP12 возмущения, генерируемые R1/R2 системой, действующей во внутренней магнитосфере, развиваются в строгом соответствии с ходом *PC* индекса, т. е. с силой воздействия солнечного ветра на магнитосферу (поле E_{KL}). Наоборот, DP11 возмущения, генерируемые SCW FAC системой, связанной с плазменным слоем хвоста магнитосферы, демонстрируют иррегулярный характер соотношений между величинами *PC* и *AL* в ходе взрывной фазы: внезапные усиления интенсивности суббури (*ALpeaks*) могут происходить неоднократно, при любой величине *PC* индекса и при совершенно различном времени задержки (ΔT) максимума суббури относительно внезапного начала взрывной фазы суббури. В результате анализа соотношений между *PC* и *AL* индексами в ходе взрывной фазы было выделено 7 категорий развития суббурь: суббури “*PC*-concerted”, интенсивность которых растет и уменьшается в полном согласии с вариациями *PC* индекса; суббури “*PC*-followed”, демонстрирующие нерегулярные всплески интенсивности (*ALpeaks*) в период роста и максимума *PC* индекса; суббури “SO-peaked”, достигающие максимальной интенсивности сразу после внезапного начала взрывной фазы; суббури “*PC*-reversed”, связанные с резким кратковременным падением и последующим ростом величины *PC* индекса; суббури “*PC*-fluctuated”, связанные с флуктуациями величины *PC* индекса с периодом T > 20 мин (волны) и T < ~15 мин (осцилляции); суббури “*PC*-increase/fluctuated”, связанные с флуктуациями величины *PC* индекса, происходящими на фоне постепенного роста величины *PC*, и, наконец, суббури “*PC*-unrelated”, происходящие вне очевидной связи с изменениями *PC* индекса. Эти особенности в развитии взрывной фазы свидетельствуют о том, что процессы в плазменном слое хвоста магнитосферы, определяющие формирование «токового клина», контролируются состоянием (стабильным или неустойчивым) самого плазменного слоя. То есть воздействие солнечного ветра (оцениваемое *PC* индексом) не определяет развитие процессов в плазменном слое, в отличие от процессов во внутренней магнитосфере. При этом следует отметить, что интенсивность DP12 и DP11 возмущений, наблюдаемых в ходе предварительной и взрывной фазы, оценивается одним и тем же *AL* индексом, несмотря на то что эти возмущения генерируются разными R1/R2 и SCW FAC системами и связаны с процессами, происходящими в различных частях магнитосферы. Необходимо ввести в практику два разных индекса магнитной активности, характеризующих интенсивность DP12 and DP11 возмущения, что позволит разделить и диагностировать эффекты воздействия солнечного ветра на процессы во внутренней магнитосфере и в плазменном слое хвоста магнитосферы.