

ФИЗИКА АТМОСФЕРЫ И ГИДРОСФЕРЫ

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PC INDEX AS A PROXY OF THE SOLAR WIND ENERGY THAT ENTERED INTO THE MAGNETOSPHERE (SUMMARY)

O.A. TROSHICHEV, D.A. SORMAKOV*

*State Scientific Center of the Russian Federation Arctic and Antarctic Research Institute,
St. Petersburg, Russia*

**olegtr@aari.ru*

РС ИНДЕКС КАК ПОКАЗАТЕЛЬ ЭНЕРГИИ СОЛНЕЧНОГО ВЕТРА, ПОСТУПАЮЩЕЙ В МАГНИТОСФЕРУ (ИТОГИ)

O.A. ТРОШИЧЕВ, Д.А. СОРМАКОВ*

*ГНЦ РФ Арктический и антарктический научно-исследовательский институт,
Санкт-Петербург, Россия*

**olegtr@aari.ru*

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Summary

The paper includes a short review of advantages of the *PC* index which is a characteristic of the magnetic activity in the polar caps in the northern (*PCN*) and southern (*PCS*) hemispheres. It is demonstrated that the *PC* index properly responds to variations of the geoeffective interplanetary electric field E_{KL} coupling with the magnetosphere, on the one side, and predetermined the development of magnetospheric disturbances (magnetic storms and substorms), on the other side. These experimental results formed the physical backgrounds for concept that the ground-based *PC* index characterizes the solar wind energy input into the magnetosphere. It is shown that problem of random discordances in behavior and value of the *PCN* and *PCS* indices during the summer/winter seasons is easily solved by choosing the *PC* index in the winter polar cap (*PCwinter*) as the best characteristic of the polar cap magnetic activity. At present the *PC* index is successfully applied to

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validate the utility of SW data presented at OMNI website (i.e. to verify whether or not the solar wind, measured in the Lagrange point, encountered the magnetosphere in reality). A special procedure agreed by the Arctic and Antarctic Research Institute (responsible for production of PCS index) and DTU Space (responsible for production of PCN index) ensures the calculation of the 1-min PC indices in quasi-real time based on data of magnetic observations at the polar cap stations Vostok (Antarctic) and Qaanaaq (Greenland).

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Ключевые слова: импульсы динамического давления, индекс магнитной активности, ионосфера, солнечный ветер, магнитосфера, магнитные бури и суббури, межпланетное электрическое поле, мониторинг и наукастинг, показатель энергии, полярные шапки, продольные электрические токи.

Дается краткий обзор достижений, полученных при использовании индексов магнитной активности в северной (PCN) и южной (PCS) полярных шапках. Показано, что PC индекс четко отвечает на вариации геоэффективного межпланетного электрического поля E_{KL} , взаимодействующего с магнитосферой, с одной стороны, и является предвестником магнитосферных возмущений (магнитных бурь и суббурь), с другой стороны. Эти экспериментальные факты послужили основой представления о PC индексе как характеристике энергии солнечного ветра, поступающей в магнитосферу. Показано, что проблема случайных расхождений в поведении и величине PCN и PCS индексов в сезоны зима/лето решается выбором PC индекса в зимней шапке (PCwinter) как наиболее адекватной характеристики магнитной активности. В настоящее время PC индекс успешно применяется при оценке пригодности данных сайта OMNI о параметрах солнечного ветра (т.е. для проверки реальности контакта с магнитосферой солнечного ветра, измеренного в точке либрации). Специальная процедура, согласованная Арктическим и антарктическим НИИ (который ответствен за производство PCS индекса) и Датским техническим университетом (который ответствен за производство PCN индекса), обеспечивает расчет в реальном времени 1-мин PC индекса по данным магнитных наблюдений на полярных станциях Восток (Антарктика) и Туле (Гренландия).

1. INTRODUCTION

At all times the Sun radiates in space a fully ionized, electrically neutral plasma, which was named as solar wind (SW). The solar wind carries a magnetic field B of solar origin named as Interplanetary Magnetic Field (IMF). Under action of solar wind and IMF the Earth's magnetic field is confined to "magnetosphere", the limited region in space, where the plasma processes are guided by geomagnetic field. The state of magnetosphere is strongly controlled by the solar wind energy incoming into the magnetosphere in course of the solar wind — magnetosphere coupling. Different combinations of the solar wind parameters, mainly the solar wind velocity (V_{sw}) and the vertical (B_{zs}) or tangential (B_r) IMF components, were repeatedly examined to reveal the "coupling function" — the optimal combination providing the best correlation between the solar wind changes and the magnetosphere disturbances development. The comprehensive analyses [1, 2] revealed that (1) different coupling functions demonstrate the best correlation with different variables characterizing the magnetosphere state, and (2) the unique coupling function, if it exists, must involve the solar wind velocity V_{sw} to the first (or a little higher) power, transverse IMF component B_r to the first (or a little lower) power, and $\sin \theta c$ to the second (or more) power (θc is clock angle between B_r and the geomagnetic dipole).

The solar wind parameters determining the coupling functions are fixed on board ACE spacecraft in the point of Lagrange L1, at distance of 1.5 million km far upstream of the Earth. This circumstance defines the most serious imperfection of all coupling functions

because the “estimated” characteristics of solar wind can be quite distinguished from characteristics of real solar wind coming into contact with the magnetosphere. Knowledge of the real solar wind impacting magnetosphere is necessary to monitor the magnetosphere state and to forecast the magnetospheric disturbances, which strongly affect many aspect of human activity. The PC index is intended to estimate the solar wind energy input into the Earth’s magnetosphere in actuality.

The PC index has been introduced [3, 4] to characterize the polar cap DP2 disturbances [5] produced in polar caps by southward IMF [6–9]. As results [9] showed, DP2 disturbances are generated by the magnetospheric field-aligned currents (FAC) in Region 1. As measurements at satellites demonstrated [10–13], the R1 FAC system with currents strongly dependent on IMF, which flow into ionosphere in the dawn sector and flow out of the ionosphere in the dusk sector, is permanently presented on poleward boundary of the auroral oval, the R2 FAC system with opposite directed currents is located on the equatorward boundary of the oval.

Statistical analysis of the relationships between the DP2 disturbances and various coupling functions showed [3] that the polar cap magnetic activity correlates the best with interplanetary electric field E_{KL} determined according to formula of Kan and Lee [14]

$$E_{KL} = V_{sw} \cdot (By^2 + Bz^2)^{1/2} \sin^2\theta/2 \quad (1)$$

where By and Bz are the azimuthal and vertical IMF components and θ is clock angle between the geomagnetic dipole and the IMF tangential component $B_T = (By^2 + Bz^2)^{1/2}$. Based on this result, the PC index, characterizing the polar cap magnetic activity generated by the EKL field, has been elaborated in the Arctic and Antarctic Research Institute (AARI, St. Petersburg) [3] and put into the practical use in cooperation with, first, the Danish Meteorological Institute (DMI, Copenhagen) [4] and now the National Space Institute, Technical University of Denmark (DTU Space, Copenhagen). The 1-min PC index is calculated independently by magnetic data from near-pole stations Qaanaaq (Thule) in the Northern hemisphere (PCN) and Vostok in the Southern hemisphere (PCS) beginning in 1998. The unified method for derivation of the PC index was formulated in [15].

This paper summarizes the results of long-standing researches of relationships between the PC index and such solar wind characteristics as interplanetary electric field and dynamic pressure impulses, on the one side, and between the PC index and magnetospheric disturbances (magnetic storms and substorms), on the other side. The aim of the paper is to demonstrate that the PC index can serve as reliable indicator of the solar wind energy, incoming into the Earth’s magnetosphere, and can be used in this charge to monitor the current state of magnetosphere and to verify whether or not the solar wind, whose parameters were measured in the Lagrange point, encounters the magnetosphere in reality.

2. PC INDEX: METHOD OF DERIVATION

The unified technique for derivation of the PCN and PCS indices [15] consists of two separate procedures. In course of the first procedure the statistically justified regression coefficients α (slope), β (intersection) and angle φ , defining relationship between the interplanetary electric field E_{KL} and the DP2 magnetic disturbance vector δF , have been determined for each UT moment of each day of the year, basing on 1-min data of geomagnetic measurements at stations Thule and Vostok and E_{KL} data. Analysis carried out separately for epoch of the maximum solar activity (1998–2001), epoch of the minimum activity (1997, 2007–2009) and for the complete solar cycle (1998–2009)

has demonstrated [16] a close consistency of parameters α , β and φ for these different epochs of solar activity, if the proper choice of the quiet daily variation (QDC), as a level of reference for estimation of the polar cap magnetic activity, is made. The statistically justified coefficients α , β and φ , ensuring allowance for the diurnal and seasonal changes of δF response to E_{KL} variations, are used in everyday practice for calculation of PC_{inst} index for any instant moment UT

$$PC_{inst} = \xi (\delta F_{inst} - \beta) / \alpha \quad (2)$$

where δF_{inst} is value of the DP2 magnetic disturbance in this moment, ξ is the scale coefficient taken equal to 1 for convenience of comparison of the PC index with E_{KL} field (mV/m). Being calibrated for interplanetary electric field E_{KL} the PCN and PCS indices vary in conformity with E_{KL} and consistent, in general, one with another in their value and behavior irrespective of UT time and point of observation. Thorough description of method of the PC index derivation is given in [15, 16].

3. RELATIONSHIP BETWEEN PC INDEX AND MAGNETIC SUBSTORMS

3.1. PC index and substorm development

The name “magnetic substorm” was given to magnetic disturbances occurring in the auroral zone [17]. Their distinctive feature is formation of the westward and eastward ionospheric currents (electrojets) and development of corresponding strong negative and positive magnetic disturbances, which intensity is described by the 1-min AL and AU indices [18]. The “substorm” includes a lot of accompanying phenomena in the auroral zone, such as sudden auroral brightening (produced by the auroral particle precipitation), its poleward expansion, simultaneous sudden increase of westward electrojet intensity and others.

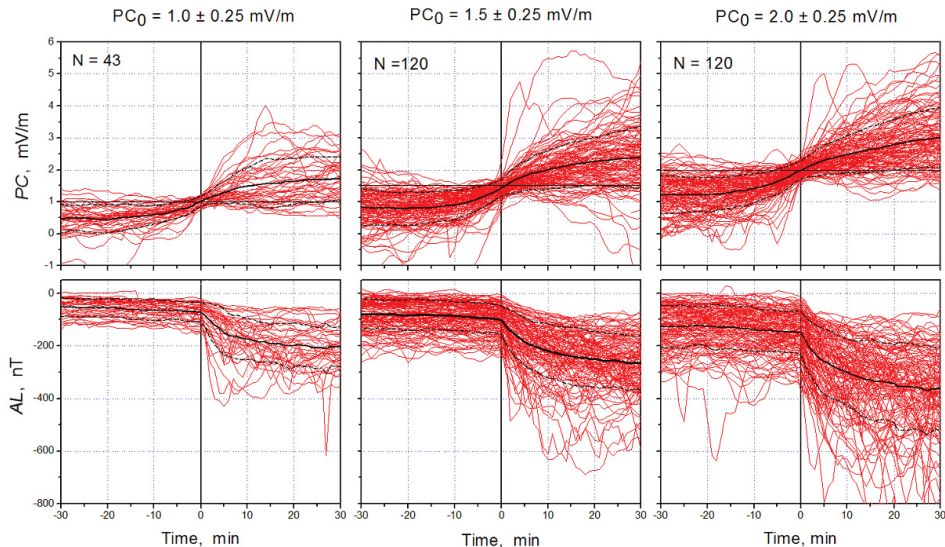


Fig. 1. Time evolution of PC and AL indices in course of magnetic substorms divided into groups according to value of PC at moment of the substorm sudden onset [19]

Рис. 1. Временной ход PC и AL индексов во время развития магнитной суббури. Суббури разделены на три группы в соответствии с величиной PC в момент внезапного начала суббури [19]

Relationship between the *PC* behavior and magnetic disturbances was examined in detail for different types of substorms in [16, 19]. Figure 1 shows, as example, time evolution of *PC* and *AL* indices in course of isolated substorms observed in epoch of the solar maximum (1998–2001), the value of *PC* in the winter hemisphere (*PCN* or *PCS*) being chosen for the analysis [19]. Substorms were divided into groups according to value of *PC* at moment of substorm sudden onset (SO) taken as a reference date ($T = 0$). Thin red lines represent a run of *PC* and *AL* in course of individual events. Thick black line represents variation of mean *PC* and *AL* values for each group. The following consequences were made:

- Development of magnetospheric substorms is always preceded by growth of the *PC* index.
- The substorm sudden onset (SO) is associated, as a rule, with the distinct *PC* value growth occurring in range of 0–10 min ahead of SO.
- If *PC* remains unchanged, the substorm does not begin till moment of the *PC* sharp growth.
- Occurrence of substorms SO reaches maximum (> 75 %) under values of $PC = 1\text{--}2$ mV/m, irrespective of the substorm growth phase duration and type of substorm.
- The *PC* growth rate is not affected by the substorm sudden onset.

The summarizing conclusion was that development and intensity of magnetic disturbances in the auroral zone is controlled by the *PC* index level [19].

3.2. Relation of *PC* index to magnetospheric field-aligned currents

Relationship between the field-aligned currents and the *PC* index was examined [20] basing on data of SWARM satellites. The Swarm mission includes three satellites, two of them, Swarm A and Swarm C, being flown side by side separated by 1.4° in longitude, at an altitude of about 460 km. Owing to orbital configurations three Swarm satellites covered all sectors of the auroral zone through 2014 year and provided information on field-aligned currents features in different FAC patterns. Method of estimation of the FAC density by data of Swarm measurements is described in [21, 22]. The R1 and R2 currents observed by SWARM satellites in dawn ($06 \text{ MLT} \pm 4\text{h}$), dusk ($18 \text{ MLT} \pm 4\text{h}$), noon ($12 \text{ MLT} \pm 2\text{h}$) and midnight ($00 \text{ MLT} \pm 2\text{h}$) sectors of the auroral zone were examined. The downwards currents (flowing into ionosphere) and upwards currents (flowing out of the ionosphere) were regarded, as positive and negative currents, correspondingly.

With aim to reveal a regular relationship between the R1 and R2 FAC intensities and the *PC* index in course of substorm development, the examination was restricted to growth phase of isolated substorms started against the background of magnetic quiescence. The data of Swarm satellites showed that the field-aligned currents in the morning sector of the auroral zone are always downwards (flowing into the ionosphere) in Region 1 and always upwards (flowing out of the ionosphere) in Region 2. The field-aligned currents in the evening sector of the zone are always upwards in Region 1 and downwards in Region 2. The field-aligned currents in the noon and midnight sectors in both R1 and R2 FAC systems can be positive as well as negative, the downwards currents in Region 2 being related to upward currents in Region 1, and vice versa.

Results of the analysis showed (Figure 2) that intensity of the field-aligned currents in Region 1 and Region 2 are well correlated ($R \sim 0.75$), the R1 FAC intensity being nearly