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Space environment (natural and artificial) — Operational estimation of the solar wind energy input into the Earth's magnetosphere by means of the ground-based magnetic polar cap (*PC*) index

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Foreword

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Introduction

The polar cap magnetic activity *PC* index was introduced as a measure of the magnetic activity generated in the Earth's polar caps by interplanetary electric field and is regarded at present as a proxy of the solar wind energy input into the magnetosphere in course of solar wind – magnetosphere coupling.

The *PC* index can be required as input parameter for monitoring and nowcasting the space weather influence on various characteristics of magnetosphere and high-latitude ionosphere.

The *PC* index can be applicable for a variety of engineering and scientific domains and can be used to monitor the state of the magnetosphere and high-latitude ionosphere to solve the problems of navigation, radio-connection and induced currents typical of high-latitude regions during magnetospheric disturbances.

Space environment (natural and artificial) — Operational estimation of the solar wind energy input into the Earth's magnetosphere by means of the ground-based magnetic polar cap (PC) index

1 Scope

This document provides guidelines for specifying the qualitative estimation of the solar wind energy input into the magnetosphere with use of operative ground-based information on the polar cap magnetic activity (*PC* index).

The solar wind energy incoming into the magnetosphere predetermines development of the magnetospheric disturbances: magnetic storms and substorms. Magnetospheric disturbances include a wide range of phenomena and processes directly affecting human activity, such as satellite damage, radiation hazards for astronauts and airline passengers, telecommunication problems, outrages of power and electronic systems, effects in the atmospheric processes, and impact on human health.

This document is intended for on-line monitoring the magnetosphere state and nowcasting the intensity and extent of magnetic disturbances as well as parameters of the high-latitude ionosphere. The method and accuracy of estimating is ascertained by close relationship between the *PC* index and interplanetary electric field (as the most geoeffective solar wind parameter), on the one hand, and between the *PC* index and magnetoshpheric disturbances, on the other hand.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

3.1
solar wind
SW
fully ionized, electrically neutral plasma that carries a magnetic field, *B*, and streams outward from the inner solar corona at all times

3.2
interplanetary electric field
$\boldsymbol{E}_{\mathbf{KL}}$
electric field, affecting the magnetosphere in course of the *solar wind* (3.1) – magnetosphere coupling, calculated according to formula of *Kan and Lee* [1979]

$$E_{KL} = vB_T\sin^2\theta/2$$

where

v is the solar wind speed;

B_T is tangential component of the *interplanetary magnetic field* (3.3);

θ is clock angle between the IMF tangential (B_T) component and the geomagnetic dipole

3.3
interplanetary magnetic field
IMF
magnetic field of solar origin transmitted by *solar wind* (3.1)

3.4
magnetic storm
combination of strong negative geomagnetic disturbances, which are produced over the entire planet by ring currents flowing around the Earth in the inner magnetosphere

Note 1 to entry: The maximal geomagnetic field depression in the equatorial region (estimated by 1-hour *D*st index or 1-min *SymH* index) is regarded as a storm intensity.

Note 2 to entry: Definition inspired by *Chapman and Ferraro,* 1932.

3.5
magnetic substorm
magnetic disturbances typical of the auroral zone

Note 1 to entry: Their distinctive feature is formation of the westward and eastward ionospheric currents (electrojets) and development of corresponding negative and positive magnetic disturbances on the ground surface, which intensity is estimated by the 1-min *AL* and *AU* indices [*Davis and Sugiura,* 1966]. The "substorm" includes a lot of accompanying phenomena in the auroral zone, such as sudden auroral brightening (produced by precipitation of the auroral particles), its poleward expansion, simultaneous sudden increase of the westward electrojet intensity and others.

Note 2 to entry: Definition inspired by *Akasofu,* 1964.

3.6
polar cap magnetic activity
magnetic short-term (minutes or tens of minutes) variations generated in the near-pole region by *interplanetary electric field* (3.2)

Note 1 to entry: Value of the polar cap magnetic activity is estimated by the 1-min *PC* index [*Troshichev et al.*, 1988; *Troshichev,* 2018].

4 Symbols and abbreviated terms

AL	1-min index of intensity of negative magnetic disturbances in the auroral zone
AU	1-min index of intensity of positive magnetic disturbances in the auroral zone
AE	1-min index characterizing the magnetic substorm intensity ($AE = AU-AL$)
B_Y	azimuthal component of the interplanetary magnetic field
B_Z	vertical component of the interplanetary magnetic field
B_{ZS}	southward component of the interplanetary magnetic field
B_T	tangential component of the IMF; $B_T = (B_Z{}^2 + B_Y{}^2)^{1/2}$
DR	ring magnetospheric currents flowing around the Earth

Dst	1-hour index characterizing the magnetic storm intensity
FAC	field-aligned currents (currents in the magnetosphere flowing along field lines)
MLat	geomagnetic latitude
MLon	geomagnetic longitude
QDC	geomagnetic field variations under quiet conditions (quiet daily curve)
PC	1-min index characterizing magnetic activity in the Earth's polar caps
SymH	1-min index characterizing the magnetic storm intensity
SO	substorm sudden onset
UT	universal time
v	solar wind velocity
Θ	clock angle between the IMF tangential component and the geomagnetic dipole

5 General parameters

5.1 Solar wind parameters determining the magnetosphere state

The various combinations of the solar wind parameters, providing the best correlation between the solar wind variations and magnetic activity, were proposed since 2004. About 20 versions of such combinations, referred as coupling functions, have been examined. All of them include the solar wind velocity and the IMF B_{ZS} or B_T components. The comprehensive analysis of *Newell et al.* [2007, 2008] revealed that different coupling functions demonstrate the good correlation with different variables characterizing the magnetosphere state, and the unique coupling function, if it exists, should involve the solar wind velocity, *v*, to the first (or a little higher) power, the tangential IMF component B_T to the first (or a little lower) power, and sine of the IMF clock angle θc to the second (or more) power. One can see that the interplanetary electric field E_{KL} answers to the unique coupling function formula in the best way.

The solar wind parameters determining coupling functions are usually fixed in the Lagrange point L1, at distance of 1,5 million km far upstream of the Earth. This circumstance determines the most serious imperfection of all coupling functions because "estimated" characteristics of the solar wind can be quite distinguished from characteristics of the real solar wind coming into contact with the magnetosphere. Knowledge of the solar wind affecting the magnetosphere in actuality is necessary to monitor the magnetosphere state and to forecast the magnetospheric disturbances.

5.2 Magnetic activity in the polar cap and its relation to the solar wind parameters

A special class of the polar cap magnetic activity, identified by *Obayashi* [1967] as DP2 disturbances, turned out to be closely related to southward IMF [*Nishida*, 1968a, b, 1971; *Troshichev*, 1975]. Statistical analysis of the relationships between the DP2 disturbances and various 5-min coupling functions showed [*Troshichev and Andrezen, 1985*] that the polar cap magnetic activity correlates the best with interplanetary electric field, E_{KL}, determined according to formula of *Kan and Lee* [1979]. Basing on this result, the *PC* index, characterizing the polar cap magnetic activity generated by E_{KL} field, has been elaborated in Arctic and Antarctic Research Institute (AARI, Saint-Petersburg) [*Troshichev and Andrezen, 1985*] and put into practical use in cooperation with the Danish Meteorological Institute (DMI, Copenhagen) [*Troshichev et al.*, 1988]. The 1-min *PC* index is calculated independently by magnetic data from the near-pole stations Qaanaaq in the Northern polar cap (*PCN*) and Vostok in the Southern polar cap (*PCS*) beginning in 1998. The unified method for derivation of the *PC* index was formulated in [*Troshichev et al.*, 2006]. Thorough description of the method is given in [*Troshichev,* 2017].

5.3 The *PC*-index: method of derivation

The unified technique for derivation of the *PCN* and *PCS* indices consists of two separate procedures.

The first procedure is determination of the statistically justified regression coefficients α (slope), β (intersection) and angle φ, defining the relationship between the interplanetary electric field, E_{KL}, and the DP2 magnetic disturbance vector, δF [see Formula (1)]

$$\delta F = \alpha E_{KL} + \beta \quad (1)$$

This procedure includes determination of the quiet daily curve (QDC), as a level of reference, and estimation of value δF in reference to QDC according to Formula (2):

$$\delta F = \delta \mathrm{H} \cdot \sin\varphi \pm \delta \mathrm{D} \cdot \cos\varphi \quad (2)$$

where

δH and δD are deviations of the geomagnetic field horizontal and declination components from QDC at the station;

φ is an angle which determines the δF vector arrangement relative to the ionospheric current system (generated by the E_{KL} field) during the daily rotation of station under this current system.

The regression coefficients α, β and angle φ were determined as values providing the best correlation between δF and E_{KL} for any UT moment (with 5-min solution) of each day of the year, separately for stations Qaanaaq and Vostok. The statistically justified values of α, β and φ were calculated separately for the epochs of the solar maximum (1998-2001) and solar minimum (1997, 2007-2009) and for complete solar cycle (1998-2009). Comparison of results has demonstrated [*Troshichev et al.,* 2011] a close consistency in the parameters α, β and φ obtained for these three solar activity epochs. It means that usage of a proper QDC, as a level of reference for estimation of the polar cap magnetic activity, δF, provides invariance of parameters α, β and φ, defining relationship between the interplanetary electric field, E_{KL}, and the polar cap magnetic activity, δF, irrespective of level of solar activity.

The second procedure is calculation of the *PC* index for any particular moment UT with use of statistically justified coefficients α, β and φ determined in course of the first procedure.

Particular δF values are counted from the QDC, as a level of reference, with use of a special method for on-line derivation of QDC [*Troshichev et al.*, 2006]. The regression coefficients determined above, α and β, ensure allowance for the diurnal and seasonal changes in the δF response to E_{KL} variations. The *PC* value is calculated for any current moment UT with Formula (3):

$$PC_{curr} = \xi (\delta F_{curr} - \beta)/\alpha \quad (3)$$

where ξ is the scale coefficient taken equal to 1 for convenience of comparison of the *PC* and E_{KL} values. As a result, the *PC* index is expressed in mV/m as well as the E_{KL} field.

Being calibrated for interplanetary electric field E_{KL} for each UT moment, the *PCN* and *PCS* indices vary in conformity with E_{KL} and consistent, in general, one with another in their value and behaviour irrespective of UT time, season and point of observation.

5.4 Relationship between the *PC* index and magnetic substorms and storms

The relationship between the *PC* behaviour and magnetic disturbances was examined in detail for different classes of substorms and magnetic storms [*Janzhura et al.,* 2007; *Troshichev and Janzhura*, 2009; *Troshichev et al.*, 2011b, 2012, 2014]. The following results were obtained:

a) magnetic substorms and storms are always preceded by the *PC* index growth;

b) isolated magnetic substorms (occurring against the background of quiet geomagnetic field) generally start when the *PC* index exceeds the level ~1 mV/m;

c) in case of expanded substorms (occurring under disturbed conditions) any sharp rise in the *PC* growth rate can lead to the substorm sudden onset;

d) intensity of magnetic substorms (*AL* index) is linearly related to the *PC* index value;

e) magnetic storms start to develop when the *PC* index steadily (during more than 1 h) exceeds the threshold ~1,5 mV/m, and maximal depression (the magnetic storm intensity) is reached with time delay ΔT = 60 min ± 30 min after the time of maximal PC index;

f) the magnetic storm intensity (Dst_{min}) follows to maximum value of the smoothed *PC* index (PC_{max}), the Dst_{min} and PC_{max} quantities being connected by linear relation: the higher the PC_{max}, the larger is the magnetic storm intensity;

g) storm progression lasts as long as *PC* exceeds the threshold level and begins to decay as soon as the *PC* value displays decline.

The summarizing conclusion was that development of magnetic substorms (disturbances in the auroral zone) and magnetic storms is related to preceding growth of the polar cap magnetic activity (*PC* index), the magnetic disturbances intensity being related to the *PC* index value.

5.5 Relation of the *PC* index to the interplanetary electric field, E_{KL}

Analysis of correlation between the 1-min *PC* index and E_{KL} field [*Troshichev and Sormakov,* 2015, 2019] gave the following statistically justified results:

a) the *PC* index usually strongly follows to changes in the interplanetary electric field, E_{KL}, the high correlation between E_{KL} and *PC* (R > 0,50) is observed in ~80 % of substorms;

b) time delays ΔT in response of *PC* to E_{KL} lie in range from 3 min to 40 min with the pronounced peak at ΔT = 12 min to 20 min, the lowest values ΔT ~ 3 min to 5 minutes being observed in case of extremely sharp rise of the E_{KL} field in course of interplanetary shocks;

c) values of ΔT and efficiency of linkage between *PC* and E_{KL} are determined by the interplanetary electric field growth rate (dE_{KL} / dt);

d) the index of magnetic activity in the winter polar cap (PC_{winter}) demonstrates the better correlation with E_{KL} field than the index in the summer polar cap (PC_{summer}).

5.6 *PC* index as a verifier of the solar wind parameters presented at OMNI website

Monitoring the solar wind parameters during two last decades was performed by measurements in the L1 Lagrange point, located about 1,5 million km upstream of the Earth. These data, presented on the OMNI database (https://omniweb.gsfc.nasa.gov/), are widely available to the community for the research and application purposes. Just OMNI data provided a basis for estimation of the E_{KL} field reduced to magnetopause in the *PC* index derivation method.

In spite of statistically justified correlation between interplanetary electric field, E_{KL}, and polar cap magnetic activity, the correspondence between E_{KL} and *PC* is often violated (breaks down) under disturbed conditions. As analysis of *Troshichev and Sormakov* [2019] showed, the poor (R < 0,50) or negative correlation between "estimated" E_{KL} field and *PC* took place in ~20 % of substorm events, even though these substorms were evidently preceded by the *PC* growth. It implies that "estimated" E_{KL} field did not affect the magnetosphere in course of these events and, consequently, the solar wind fixed far upstream of the Earth did not contact with the magnetosphere. It was shown also [*Troshichev et al.,* 2011b] that "the extraordinary magnetic disturbances", described by *Du et al.* [2008] and *Lee et al.* [2010] as happened under conditions of ineffective northward IMF, were occurred when the *PC* index was in excess of threshold level ~1,5 mV/m.

Therefore, the *PC* index makes it possible to validate the interplanetary electric field affecting the magnetosphere, and verify, in such manner, whether or not the solar wind, whose parameters are given in OMNI dataset, encountered the magnetosphere in reality.

5.7 *PC* index as a proxy of the solar wind energy input into the magnetosphere

The above-outlined results demonstrate that *PC* index responds to variations of the interplanetary electric field, E_{KL}, on the one hand, and predetermines progression and intensity of the magnetospheric disturbances (substorms and magnetic storms), on the other hand. These results indicate convincingly that *PC* index can be regarded as indicator of the solar wind energy entering the magnetosphere. Therein lies the principal distinction of the *PC* index from various coupling functions (which are characteristic of the solar wind arriving to the Lagrange point L1) and from *D*st or *AL* indices (which are characteristics of the energy realized in the magnetosphere in form of magnetic storms and substorm). Taking into account these distinctive features of the *PC* index, the International Association of Geomagnetism and Aeronomy (IAGA) approved *PC* index as a proxy for energy that enters into the magnetosphere during solar wind-magnetosphere coupling (see Annex A).

5.8 *PC* index as a standard for calibration of the magnetospheric disturbances power

Magnetospheric disturbances present a complex of different phenomena and processes occurring in the high-latitude magnetic field and ionosphere. Preliminary results of the *PC* index usage for calibration of the substorm development were obtained for such phenomena as negative and positive deviations of geomagnetic field from the quiet level, precipitation of auroral particles (electrons and ions), auroral absorption of cosmic radioemission, appearance of sporadic ionospheric layers and corresponding changes in the ionospheric critical frequencies, and so on. Maps of spatial–temporal distributions of the auroral absorption calibrated by the *PC* value, presented as an example in Annex B, demonstrate that the *PC* index can be successfully used as a standard for calibration of power of the substorm phenomena.

As for magnetic storms, whose progression is evaluated by *D*st index, the following storm characteristics can be monitored by the *PC* index:

a) start of the ring current formation (related to the *PC* steady rising above the threshold level);

b) dynamics of the ring current (controlled by time evolution of the run-averaged *PC* values);

c) the storm intensity (predetermined by the PC_{max} value in course of preceding 1-hour period);

d) beginning of the recovery phase (related to *PC* steady drop below the threshold level).

6 Availability of the *PC* index

6.1 Production of the *PC* index

A great advantage of the *PC* index application over other methods based on the ground-based or satellite data is a permanent on-line availability of information on the magnetic activity in both northern and southern polar caps and, correspondingly, awareness of the solar wind energy input into the magnetosphere. A special procedure agreed by the Arctic and Antarctic Research Institute (responsible for production of *PCS* index) and Space Institute of the Danish Technical University (responsible for production of *PCN* index, beginning in 2010) 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 and Qaanaaq.

6.2 Access to the *PC* data

The *PCN*/*PCS* indices have two classes for operational use. The quick-look *PCN* and *PCS* indices are updated each 2 to 3 minutes. They are freely available at https://PCindex.org. The quality-controlled indices are published with a 3-month delay. They are available at the same website as the archive *PCN* and *PCS* data for 1997–2018.

PC indices are also presented on the following websites:

https://omniweb.gsfc.nasa.gov/form/omni_min.html

ftp://ftp.space.dtu.dk/WDC/indices/PCn/

https://PCindex.org

http://isgi.unistra.fr/indices_PC.php

ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/RELATED_INDICES/PC_INDEX

https://www.ukssdc.ac.uk/Help/PCI.html

7 Compliance criteria for use of the *PC* index as a calibrator of the magnetospheric disturbance

7.1 Rationale

The principles and scheme of the phenomenon (or process) calibration by the *PC* value should be described concisely and clearly. They should be published as scientific articles in refereed/peer-review international journals and their references should be available to the public. Otherwise, journal-style documents suitable for publication in journals should be accessible to the public.

7.2 Reporting

Results of calibration should be made public for evaluation and application by third parties (e.g. individuals or institutes who are interested in the calibration results).

7.3 Documenting

The following information relating to calibration should be clearly documented or displayed:

a) input:

   1) types of data;

   2) source of data;

   3) time resolution of data;

   4) number of data points;

   5) time of data acquisition.

b) output:

   1) types of calibrated data;

   2) time of calibrated data;

7.4 Publishing

When the results of calibration become available, they should be tested by comparison with independent experimental results. Comparison should include calculating the prediction error, skill score, correlation coefficients, etc.

7.5 Archiving

The results of calibration should be archived and available to the public for evaluation.

Annex A
(informative)

Resolution No. 3 of XXII Scientific Assembly of International Geomagnetism and Aeronomy Association (12th IAGA), Merida, Mexico, August 2013: *PC* index

IAGA,

a) noting that polar cap magnetic activity is not yet described by existing IAGA geomagnetic indices,

b) considering that the Polar Cap (*PC*) index constitutes a quantitative estimate of geomagnetic activity at polar latitudes and serves as a proxy for energy that enters into the magnetosphere during solar wind-magnetosphere coupling,

c) emphasizing that the usefulness of such an index is dependent on having a continuous data series,

d) recognizing that the *PC* index is derived in partnership between the Arctic and Antarctic Research Institute (AARI, Russian Federation) and the National Space Institute, Technical University of Denmark (DTU, Denmark),

e) recommends use of the *PC* index by the international scientific community in its near-real time and definitive forms, and

f) urges that all possible efforts be made to maintain continuous operation of all geomagnetic observatories contributing to the *PC* index.

