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The polar cap (PC) index: PCS version based on Dome-C data

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Abstract
The standard Polar Cap (PC) indices, PCN (North) based on magnetic data from Qaanaaq in Greenland and PCS (South) based on data from Vostok in Antarctica, have been submitted from the Arctic and Antarctic Research Institute (AARI) in St. Petersburg, Russia, the Danish Meteorological Institute (DMI), and the Danish Space Research Institute (DTU Space) in different versions. In order to consolidate PCS indices based on Vostok data or replace poor or missing index data, derivation procedures have been developed to generate alternative PCS index values based on data from Dome Concordia (Dome-C) magnetic observations from epoch 2009-2020 of solar cycle 24. The reference levels and calibration parameters needed for calculations of Dome-C-based PCS values in post-event and real-time versions are defined and explained in the present work. Assessments of the new PCS index have shown its unprecedented high relevance. Part of the methods used here such as the quiet reference level construction and the correlation and regression procedures used for calculations of scaling parameters deviate from corresponding features considered inadequate of the IAGA-endorsed PC index derivation methods.

Description in plain text.
The polar cap (PC) indices are derived from magnetic variations measured in the central northern and southern polar caps. They represent the coupling between the solar wind and the magnetosphere providing power to space weather disturbances such as strong electric currents in the polar ionosphere. These currents may in turn generate upper atmosphere heating which may disturb satellite orbits and induce electric currents and voltages in conducting structures at ground level. During the strong events the geomagnetically induced currents (GIC) may cause power line failures in important subauroral power grids. The geomagnetic disturbance level is conveniently monitored through the PC indices. However, due to the harsh Arctic and Antarctic environments, measurements or transmissions of magnetic data may be impeded. Thus, alternative PC index sources are needed to ensure reliable space weather monitoring. The present work defines and describes an alternative PCS (South) index based on measurements from the Antarctic Dome Concordia observatory to supplement the standard PCS observatory at Vostok.

1. Introduction.

Dungey (1961) formulated the concept of magnetic merging processes taking place at the front of the magnetosphere between the Interplanetary Magnetic Field (IMF), when southward oriented, and the geomagnetic field, followed by the draping of the combined solar and geomagnetic fields and associated ionized plasma over the poles creating an elongated magnetospheric structure. In the extended magnetospheric tail region the geomagnetic field would reconnect releasing the solar magnetic fields. The restored geomagnetic field would then be convected sunward at lower latitudes to resume merging with the solar wind field at the front of the magnetosphere.

The high-latitude antisunward ionospheric and magnetospheric plasma drift across the polar cap and the return flow in the sunward motion along dawn and dusk auroral latitudes generate the two-cell "forward convection" patterns, now termed DP2 (Polar Disturbance type 2). Later, Dungey (1963) extended his model to include cases where IMF is northward (NBZ conditions), which in stronger cases would reverse the convection patterns in the central polar cap and generate sunward transpolar plasma flow (DP3) possibly inside a residual two-cell forward convection system. Although many details have been added later, these solar wind-magnetosphere interaction models still prevail now, 60 years later. The strictly southward or northward IMF directions in the idealized models have been extended to all IMF directions while retaining the basic features of northward vs. southward IMF orientation.

The present versions of the Polar Cap (PC) index are based on the formulation by Troshichev et al. (1988) for the version developed at the Arctic and Antarctic Research Institute (AARI). The new idea was the scaling on a statistical basis of the ground magnetic variations to the merging electric field, E_M, in the solar wind (Kan and Lee, 1979) in order to make the PC indices independent of local ionospheric properties and their daily and seasonal variations. Furthermore, for the scaling of PC index values they used components of the magnetic variations in an "optimal direction" assumed being perpendicular to the average DP2 transpolar convection in order to make the new index focused on solar wind-magnetosphere interactions.

The standard Polar Cap (PC) indices, PCN (North) and PCS (South) are derived from polar magnetic variations recorded at Qaanaaq (Thule) in Greenland and Vostok in Antarctica, respectively. The formulation of derivation procedures has taken three directions related to the contributions by Vennerstrøm (1991), Troshichev et al. (2006), and Stauning et al. (2006). The PCN and PCS versions developed at the Danish Meteorological Institute (DMI) by Stauning et al. (2006) and Stauning (2016) are modifications of the Troshichev et al (2006) index versions. The Vennerstrøm (1991) version was abandoned in 2015. A comprehensive description of different PC index versions is available in Stauning (2013b)

The PCN and PCS indices have been used in various versions and combinations in studies of the relations between polar cap disturbances and further activity parameters such as solar wind electric fields and magnetospheric storm and substorm indices. Thus, single-pole PC indices, particularly PCN indices, have been used widely, but also averages of PCN and PCS indices and seasonal selections (summer or winter) of indices have been used, occasionally just named "PC index", in scientific contributions.

For the relations between single-pole PC indices and solar wind conditions or global magnetic disturbances there are two conceptual problems. One is the choice between the two available hemispherical indices to be used in such relations. The other is the interpretation of negative index values which could not relate directly to the inherently positive E_M values. The combination of non-negative values of PCN and PCS indices introduced by Stauning (2007) and named PCC index have helped solving both problems and underlines the need for alternative PC index data sources to ensure availability of both PCN and PCS indices.

The present contribution presents the potential source for PCS index values in the magnetic data from Dome Concordia (Dome-C) observatory in Antarctica (Chambodut et al., 2009; Di Mauro et al., 2014) in order to enhance the reliability and availability of PCC indices to be used for solar-terrestrial sciences as well as for space weather monitoring applications. The suggestion to use data from Dome-C for an alternative PCS index was initially forwarded in Stauning (2018b). The description of the Dome-C-based PCS indices and the definition of reference levels and scaling parameters are very similar to the corresponding definitions and descriptions of Qaanaaq (THL)-based PCN indices or Vostok-based PCS indices available in Stauning (2016). An extended description of the index derivation methods beyond the present work may be found in the associated Supporting Information (SI) file where the disagreements with features of the methodologies endorsed by the International Association for Geomagnetism and Aeronomy (IAGA) are also discussed. Such discussions may also be found, among others, in Stauning (2013a, 2015, 2018a, 2020 and 2021a,b).

2. Basic principles for calculation of Polar Cap indices.

The transpolar (noon to midnight) convection of plasma and magnetic fields driven by the interaction of the solar wind with the magnetosphere is associated with electric (equivalent Hall-type) currents in the upper atmosphere in opposite directions of the flow. These currents, in turn, induce magnetic variations at ground level (Troshichev et al., 1988, 2006; Vennerstrøm, 1991) from which the Polar Cap (PC) indices are derived.

The steps in the calculations of PC indices may be found elsewhere, for instance in Troshichev et al. (2006) or Stauning (2006, 2016, 2018b,c, 2020). They are summarized here for convenience and further specified in the associated SI file. In order to focus on solar wind effects, the horizontal magnetic variations, $\Delta\boldsymbol{F} = \boldsymbol{F} - \boldsymbol{F}_{RL}$, of the recorded horizontal magnetic field vector series, $\boldsymbol{F}$, with respect to an undisturbed reference level, $\boldsymbol{F}_{RL}$, are projected to an "optimum direction" in space to provide the projected variations, ΔF_{PROJ}. The optimum direction is assumed perpendicular to the DP2 transpolar convection-related sunward currents and characterized by its angle, φ, with the dawn-dusk meridian.

An important parameter for the interaction between the solar wind and the magnetosphere is the solar wind merging electric field, E_M, (also termed E_{KL}; also named "coupling function") formulated by Kan and Lee (1979):

$$E_M = V_{SW} \cdot (B_Y^2 + B_Z^2)^{½} \cdot \sin^2(\theta/2) \quad : \quad \theta = \arctan(B_Y/B_Z) \qquad (1)$$

where V_{SW} is the solar wind velocity, B_Y and B_Z are Geocentric Solar-Magnetosphere (GSM) components of the Interplanetary Magnetic Field (IMF), while θ is the polar angle of the transverse IMF vector. The merging electric field is supposed to control the rate of merging (coupling) between solar wind and geospace magnetic fields at the front of the magnetosphere and thereby in control of the input of solar wind energy to the Earth's magnetosphere.

In consequence, the projected polar cap magnetic disturbances, ΔF_{PROJ}, are assumed being proportional to E_M:

$$\Delta F_{PROJ} = \alpha \cdot E_M + \beta \qquad (2)$$

where α is the slope and β the intercept parameter named from a graphical display of the relation.

The Polar Cap (PC) index is now defined by equivalence with E_M in the inverse relation of Eq. 2, i.e.:

$$PC = (\Delta F_{PROJ} - \beta)/\alpha \quad (\approx E_M) \tag{3}$$

With the relation in Eq. 3, the ΔF_{PROJ} scalar values are scaled to make the PC index equal (on the average) to values of E_M in the solar wind. The scaling of the polar cap magnetic disturbances to a quantity in the solar wind removes (in principle) the dependence on the daily and seasonally varying ionospheric conductivities and other local conditions such as the location of the measuring polar magnetic observatory.

3. Handling of geomagnetic observations.

The magnetic data used for the standard PCN indices are collected from Qaanaaq observatory in Greenland operated by the Danish Meteorological Institute (DMI) while the Danish Space Research Institute (DTU Space) operates the magnetic instruments and takes care of the data collection and processing. Data for the standard PCS indices are collected from Vostok observatory operated by the Arctic and Antarctic Research Institute (AARI) in St. Petersburg while data for en alternative PCS index are collected from the French-Italian Dome Concordia (Dome-C) observatory. Characteristics of the three locations including essential geomagnetic parameters based on the NASA VITMO application for 2021 are specified in Table 1.

Table 1. Geographic and geomagnetic parameters at 100 km of altitude for selected stations.

Observatory	Station	Latitude	Longitude	CGMlat	CGMlon	LT=00	MLT=00
Name	Acr.	Deg.	Deg.	Deg.	Deg.	UThrs	UThrs
Qaanaaq	THL	77.47	290.77	83.86	23.86	4.62	3.60
Dome-C	DMC	-75.25	124.17	-89.31	44.52	15.72	1.77
Vostok	VOS	-78.46	106.84	-84.04	56.64	16.88	0.95

The magnetic data are carefully examined prior to their use in PC index calculations. It is of major importance that the base level values are correctly adjusted. In order to disclose possible problems, the monthly average X- and Y-component values are inspected. These values are derived as the means of measured values for all hours of the 5 quietest (QQ) days each month defined by the International Service for Geomagnetic Indices (ISGI). Figs. 1a,b display the average values for the observed X and Y components from Qaanaaq (THL) and Vostok (VOS).

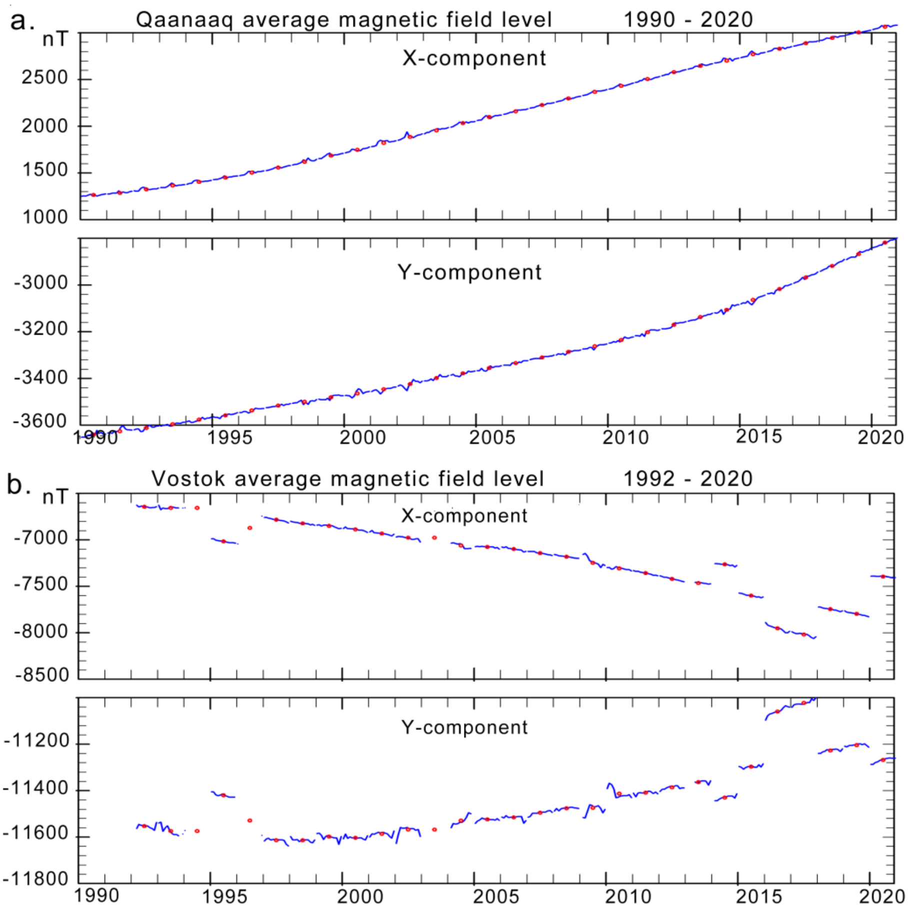

Fig. 1. Monthly (blue line) and yearly (red dots) average X- and Y-component values compiled throughout all hours of the 5 quietest days each month (http://isgi.unistra.fr). (a) Qaanaaq (THL). (b) Vostok (VOS). (data from https://intermagnet.org).

It is evident from Fig. 1b that the definition of proper baseline values for Vostok present challenges. The base levels need comprehensive adjustments to remove irregular base level changes and retain secular variations only. Such adjustments are described (to some length) in Stauning (2016). The problem and possible base level corrections are not discussed at all in available reports from the IAGA-endorsed PC index providers at AARI and the Danish Space Research Institute, DTU Space, (e.g., Troshichev, 2011, 2017; Troshichev and Janzhura, 2012; Matzka, 2014). The base level problems and occasional missing data supply from Vostok observatory underline the need for alternative PCS index sources.

Corresponding data from Dome-C observatory are displayed in Fig. 2a. In these data there are obvious base level problems during 2016-2017. However, for Dome-C data the adjustments are simple and the data quality is otherwise good. The monthly and yearly average data values after level correction are displayed in Fig. 2b.

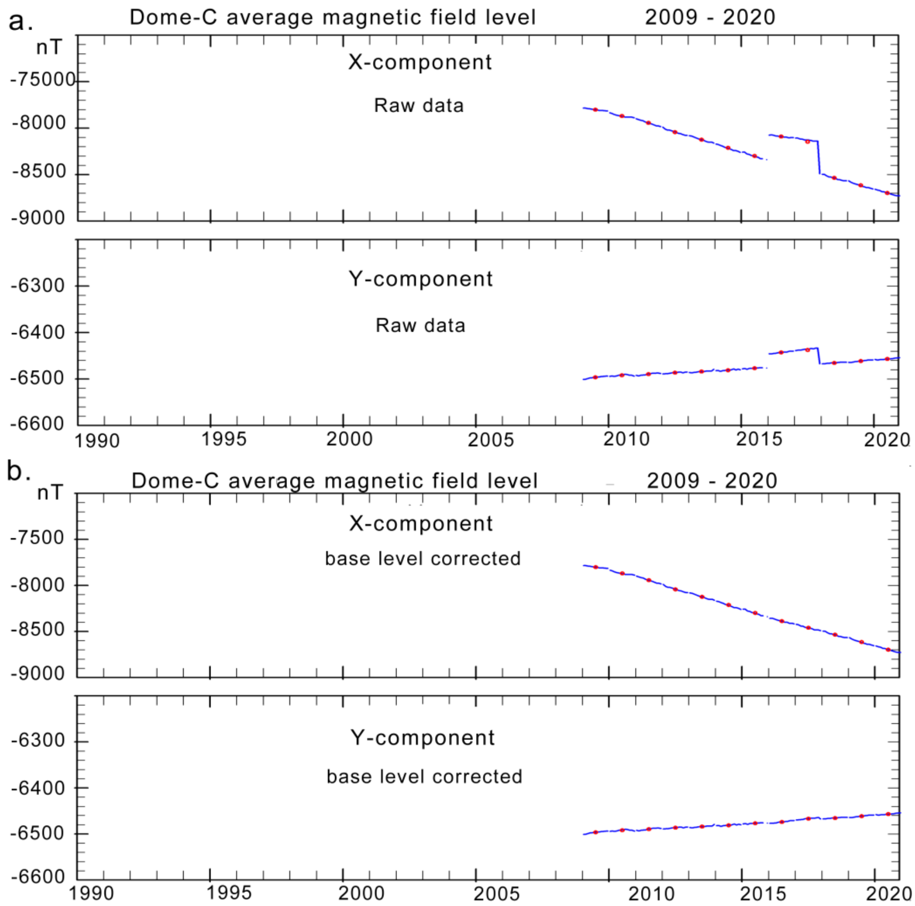

Fig. 2. Monthly (blue line) and yearly (red dots) average X- and Y-component values compiled throughout all hours of the 5 quietest days each month. (a) Dome-C measurements (data from https://intermagnet.org). (b) Dome-C data with base level corrections.

4. Reference level (QDC) for PC index calculations in the SRW version.

The definition of reference levels, $\boldsymbol{F}_{RL}$, to be used for calculations of the polar magnetic variations needed for PC index calculations differs among the PC index versions. In the version developed at AARI, the varying level on "*extremely quiescent days*" (Troshichev et al., 2006) was used as the data reference level. This level could be considered built from a quiet day curve (QDC), $\boldsymbol{F}_{QDC}$, added on top of the base level, $\boldsymbol{F}_{BL}$. Thus, in vector formulation:

$$\boldsymbol{F}_{RL} = \boldsymbol{F}_{BL} + \boldsymbol{F}_{QDC} \quad (4)$$

Extremely quiescent days are particularly rare at polar latitudes. Therefore, the concept was broadened to imply the generation of QDC values from quiet segments of nearby days within 30 days at a time (Troshichev et al, 2006; Janzhura and Troshichev, 2008). The use of an interval close to the solar rotation period (~27.4 days) with equal weight on each day's quiet samples removes most solar rotation effects from the QDCs.

The definition of the reference level is one of the issues that distinguish the PC index version presented in Stauning (2016) and used in the present work from the IAGA-endorsed PC index versions. The reference level construction used here (Eq. 4) is based on the formulation in

Troshichev et al. (2006) but uses the "solar rotation weighted" (SRW) QDC construction published in Stauning (2011) instead of the 30-days equal weight QDC methods detailed in Janzhura and Troshichev (2008) or the version with the added solar sector (SS) term detailed in Janzhura and Troshichev (2011), Matzka and Troshichev (2014), and Nielsen and Willer (2019).

As formulated in Stauning (2011, 2020), the essential point for the SRW method is deriving the reference level from quiet samples collected on nearby days at conditions otherwise as close as possible to those prevailing at the day of interest. Weight functions are defined to optimize the effects on the QDCs with respect to sample separation and solar rotation (see details in the SI file). For each hour of the day, observed hourly average values at corresponding hours within an extended interval (±40 days) are multiplied by the relevant weights, added and then divided by the sum of weights to provide hourly QDC value. Subsequently, the hourly QDC values are smoothed to remove irregular fluctuations and interpolated to provide any more detailed resolution as required. The derived QDCs are routinely displayed in yearly plots for each component like the example shown in Fig. 3.

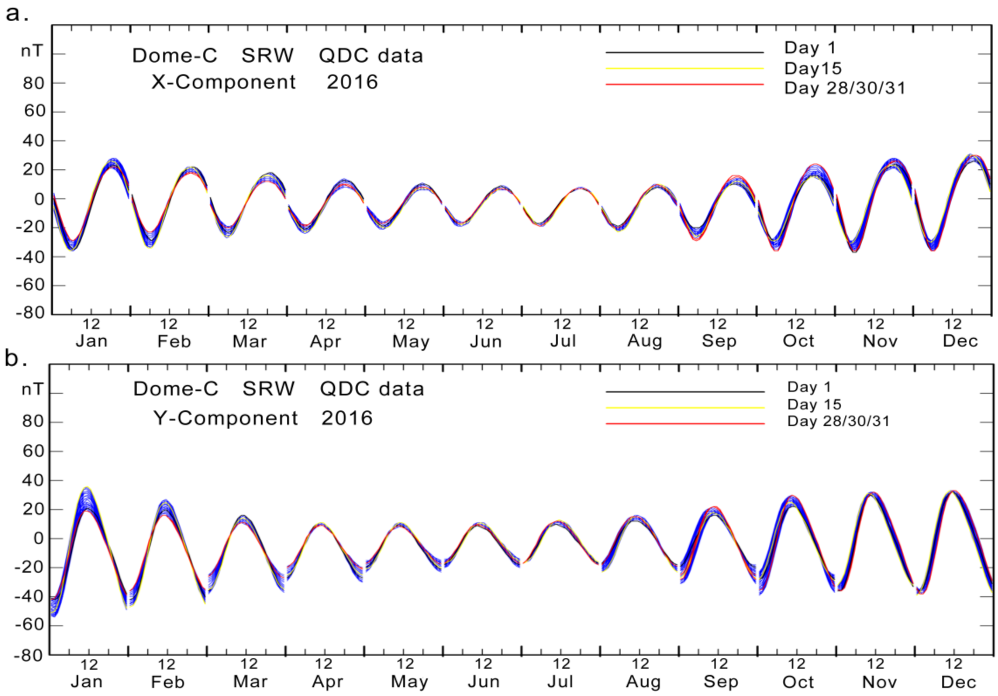

Fig. 3. One year's (2016) QDC values for Dome-C (DMC). The monthly assemblies of daily QDCs are displayed in blue lines. The QDC values on day 1, 15, and the last day of the month are superposed in black, yellow, and red lines, respectively. (a) X-component. (b) Y-component.

In these diagrams for the magnetic data from Dome-C (DMC) there is a QDC curve for each day of the year. For one month at a time, the daily QDC curves are drawn on top of each other in blue line. For day 1 (in black line), day 15 (yellow), and last day of the month (in red line) the QDCs are re-drawn on top of the other QDCs. Going from the black through the yellow to the red curves provides an impression of the development of the QDCs throughout the month. The seasonal variations are very distinct with amplitude maxima at local summer. Most of the additional variability in the QDCs is caused by the IMF B_Y–related solar sector effects which are taken into account this way.

The weighting over ±40 days makes the determination of the final QDC fairly insensitive to intervals of missing data. Thus, the weighting technique allows calculations of real-time QDCs with reduced accuracy from past data collected within -40 to 0 days (actual time) by simply ignoring the not yet available post-event samples without changing the ±40 days' calculation scheme. As further data arrive, then the QDCs could be gradually improved to be completed after passing +40 days with respect to the day of interest. Thus, there are seamless transitions between real-time and post-event QDC values.

5. Optimum angle calculations.

At the correlation studies by Stauning (2016) using 5-min samples, the best correlations between OMNI Bow Shock Nose (BSN) values of E_M and Qaanaaq ground-based ΔF_{PROJ} data series were obtained for delays close to 20 min.

With the delay fixed, the optimum direction angles are now derived by the method defined in Stauning (2016). For each calendar month and each UT hour of the day and with steps of 10° in the optimum direction angle through all possible directions, the disturbance vectors, $\Delta\boldsymbol{F}$**,** are projected to the optimum direction while the correlations between the projected magnetic disturbances and the solar wind merging electric fields are calculated using textbook's product-momentum formula.

Among the calculated values of the correlation coefficients derived through all steps in optimum direction angle, the maximum value is found. Based on the direction angle for this maximum value along with the angles for the preceding and the following values of the correlation coefficient, a parabolic function is then adapted to determine the precise values of the optimum direction angle at the top of the parabola and the corresponding maximum correlation coefficient for the calendar month and UT hour in question.

In order to make the values generally representative some averaging and smoothing is necessary. In the present version, the values are exposed to bivariate Gaussian smoothing over months and UT hours by weighted averaging. The exponents used in the smoothing weight functions characterize the degree of smoothing and are stored with the derived optimum direction values. The resulting mean hourly optimum angles for cases without QDC adjustments and excluding NBZ reverse convection samples (blue line), with QDC and without NBZ samples (magenta line with dots), and with QDC and including NBZ samples (red line) are displayed for each calendar month in Fig. 4

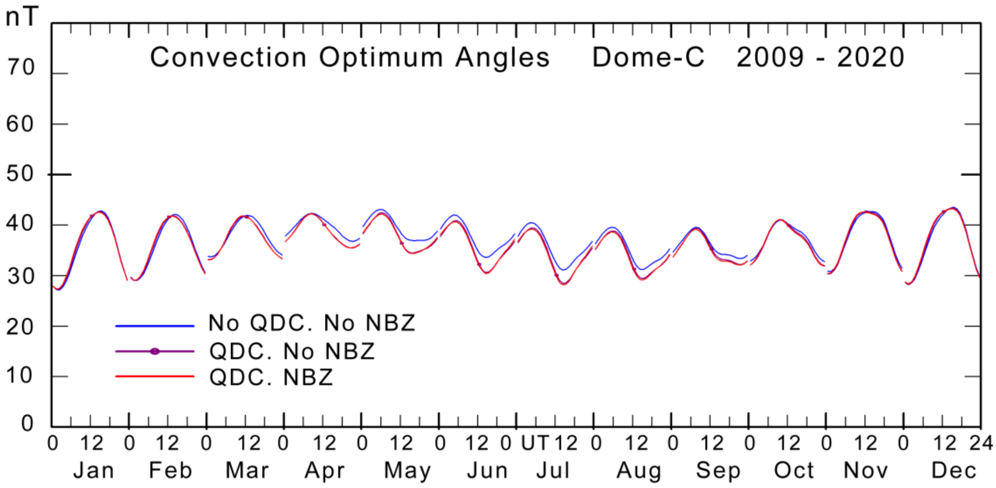

Fig. 4. Monthly mean daily variation in optimum angles for Dome-C for each month of the year. Angles have been derived by using DMI2016 methods without QDC adjustments and without NBZ samples (blue line), with QDC and without NBZ (magenta), with QDC and with NBZ samples (red).

6. Calculations of slope and intercept

Recalling that we are searching for proxy values based on polar magnetic disturbances to represent the solar wind "merging” electric field ($E_M = E_{KL} = V_{SW} B_T \sin^2(\theta/2)$), the general assumption is that there is a (statistical) linear relation between the polar magnetic variations, ΔF_{PROJ}, and the solar wind electric field, E_M, and that this relation can be inverted and used to define a polar cap (PC) index by equivalence (cf. Eqs. 1-3). Contrary to the calculation of the optimum direction, the QDC issue has considerable importance for the calculations of slope and intercepts parameters.

To solve for the coefficients in the linear relation ($\Delta F_{PROJ} = \alpha\ E_M + \beta$), standard least squares regression is applied on a comprehensive and representative data base. For each calendar month the hourly values of α and β are formed by processing all 5-min values of E_M (t-20 min) and corresponding ΔF_{PROJ} (t) throughout that hour of all days of the month and all years of the selected epoch.

In order to avoid reverse convection cases in the data base used for calculations of PC index coefficients, it is required for each sample that IMF B_Z < | IMF B_Y | + 3.0 nT. This condition excludes cases where strong northward B_Z is the dominant IMF component. A further condition imposed on the selection of data requires that the projected magnetic variation, ΔF_{PROJ}, is larger than the value corresponding to PC = -2 mV/m (≈ -50 nT). This condition ensures that cases with strong reverse convection, which may continue for a while after the driving northward IMF parameter has been reduced or has changed polarity, are also omitted.

The raw (non-smoothed) values of the slopes and intercept coefficients are exposed to bivariate Gaussian smoothing over months and UT hours by weighted averaging (Stauning, 2016). The resulting slope and intercept values for epoch 2009-2020 are presented in Fig. 5 in the format corresponding to Fig. 4. Each of the 12 monthly sections presents the mean hourly variation in the parameters for the (calendar) month. The monthly mean hourly values of the slopes and intercepts are converted into series of hourly values for each (calendar) day of the year by Gaussian bivariate weight function interpolation. For finer resolutions, e.g., 5-min or 1-min samples, a simple parabolic or linear interpolation is used. (Stauning, 2016).

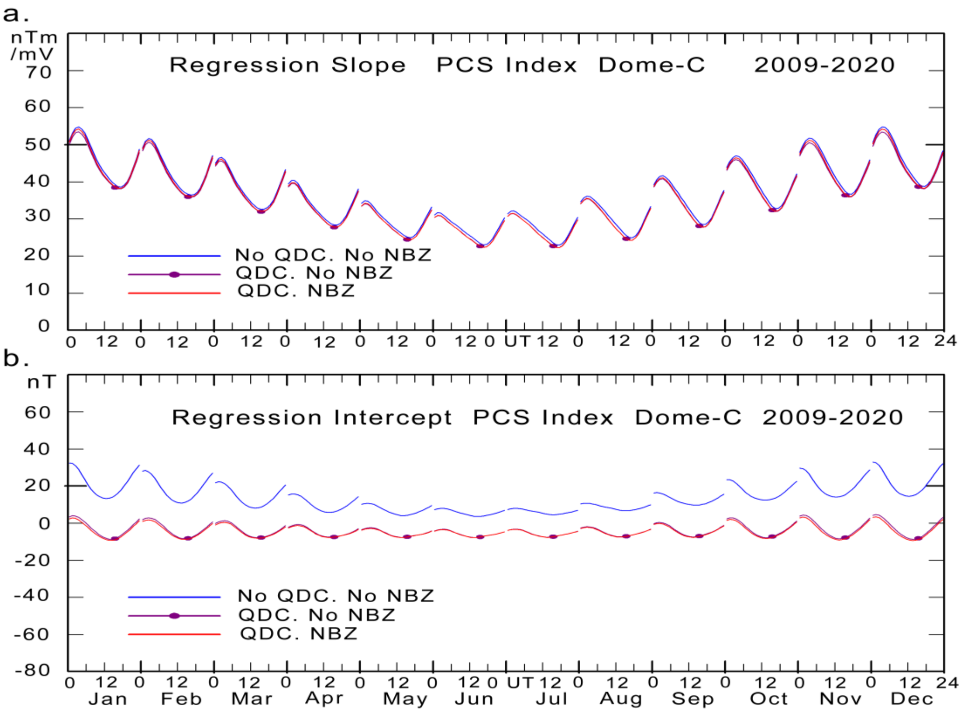

Fig. 5. PCS slope and intercept values derived by regression of ΔF_{PROJ} on E_M with data from Dome-C (DMC) for epoch 2009-2020. Data processed without QDC involvement and without NBZ samples are displayed in blue line; data with QDC and without NBZ samples in magenta line with dots; data with QDC and including NBZ samples in red line.

It is seen from Fig. 5 that the slope values are little affected whether the data are handled with or without QDC. The intercept values without QDC involvement (blue line) are increased by an amount representing the projected QDC contribution while including the NBZ samples (red line) has no significant effects on slope or intercept. Due to its proximity to the magnetic pole the amount and the intensities of reverse convection events are minimal at Dome-C which makes the station an ideal location for supply of data for PCS calculations. The calibration parameters are not invariant to general changes in solar activity or to secular variations in the local polar magnetic configuration, but they are kept invariant over years unless a new index version is implemented.

7. Calculation of PC index values post event and in real time.

With the DMI methods (Stauning, 2016), detailed in the SI file, the scaling parameters, (φ, α, β), are derived as monthly mean hourly values and then interpolated to provide tables at finer resolution as required. With the optimum angle values displayed in Figs. 4, the slope and intercept values displayed in Fig. 5, and the QDC values derived by the solar rotation weighted (SRW) method described in the SI file, it is now possible to calculate PCS index values vs. UT time and date. The magnetic variations are derived from the observed values by subtracting base line and QDC values.

The projection angle for the projection of the horizontal magnetic variation vector, (ΔF_X, ΔF_Y), in the (rotating) observatory frame at longitude, λ, to the optimum direction, φ, in space is defined by:

$$V_{PROJ} = \text{Longitude}(\lambda) + \text{UTh}\cdot 15° + \text{optimum direction angle}(\varphi) \quad (5)$$

using the tabulated optimum angles (φ) while UTh is the UT time at the observatory in hours.

Thus, the projected magnetic variations could be expressed by:

$$\Delta F_{PROJ} = \Delta F_X\cdot\sin(V_{PROJ}) \pm \Delta F_Y\cdot\cos(V_{PROJ}) \;:\; \text{(+ for southern, - for northern hemisphere)} \quad (6)$$

The slope and intercept values, α and β are fetched from their tabulated values to be used in Eq. 3 defining PC index values (PC = (ΔF_{PROJ}–β)/α)

For real-time applications the critical issue is defining the undisturbed reference level. For the present approach the QDC values are derived by the (half interval) HSRW method using quiet samples collected from past data only during the interval from -40 to 0 days (see SI file). A detailed description of methods for current calculations of QDC values and PC indices in real-time may be found in the appendix to Stauning (2018c).

8. Assessments of PC index quality.

For a geophysical index offered to the international scientific community and important space weather services, the quality of the post event (definitive) as well as the real-time (prompt) index values is of utmost importance. In spite of this (seemingly) obvious ascertainment, little efforts have been provided on this issue at past and present PC index versions.

The main quality principles were formulated in Troshichev et al. (1988).

"- PC index in any UT time should be determined by the polar cap magnetic disturbance value related to influence of the geoeffective solar wind, and therefore

- the magnetic disturbance vector δF should be counted from level of the quiet geomagnetic field to eliminate variations unrelated to the solar wind fluctuations;

- PC index should correspond to the value of the interplanetary electric field E_{KL} (E_M) impacting the magnetosphere, irrespective of UT time, season and point of observation."

The reference levels advocated here are by their definition (cf. section 5) based on quiet (the quietest) geomagnetic samples and thus they comply with the quality requirements.

The correlations between 15-min average values of Dome-C-based PCS index values (PCD) and values of the merging electric field shifted by 20 min are displayed in Fig. 6. The quarterly mean correlation coefficients between 15-min E_M values and PCS values based on Dome-C data are displayed in heavy magenta line while the corresponding correlation coefficients for Vostok-based PCS values are displayed in red line and the coefficients for Qaanaaq (THL)-based PCN values are shown in blue line.

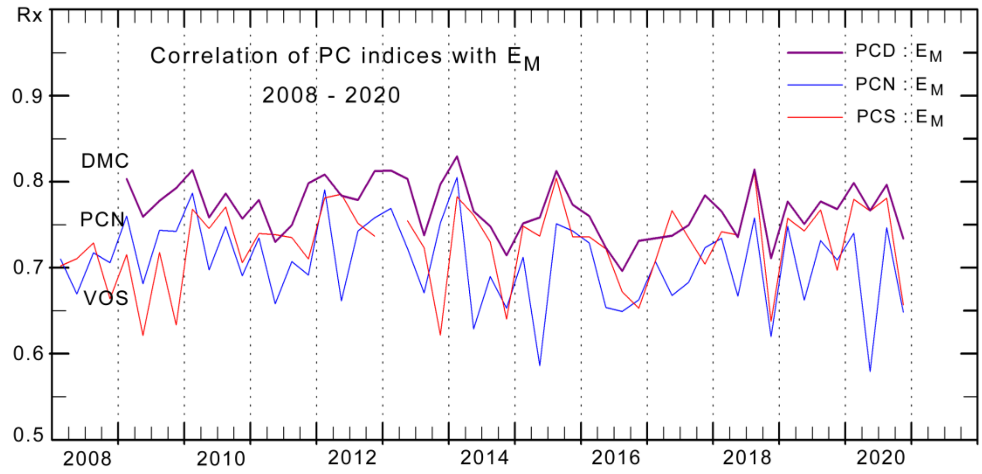

Fig. 6. Quarterly means of coefficients for the correlation between 15-min averages of the merging electric field, E_M, and Dome-C-based PCS values (PCD) in heavy magenta line and corresponding coefficients for Vostok-based PCS values (red line) and Qaanaaq-based PCN values (blue line).

With a single exception in 2017, the correlation between 15-min E_M and Dome-C based PCS values seen in Fig. 6 is higher – at times much higher – than the correlation between E_M and the Vostok-based PCS values and consistently much higher than the correlation between E_M and the Qaanaaq (THL)-based PCN values throughout the epoch (2009-2020).

The seasonal variations in the correlation between E_M and the PC indices are displayed in Fig. 7 by the monthly mean correlation coefficients for 15-min samples averaged over the epoch 2009-2020. The line types are the same as those used in Fig. 6. The order of southern months has been rearranged to make seasons match.

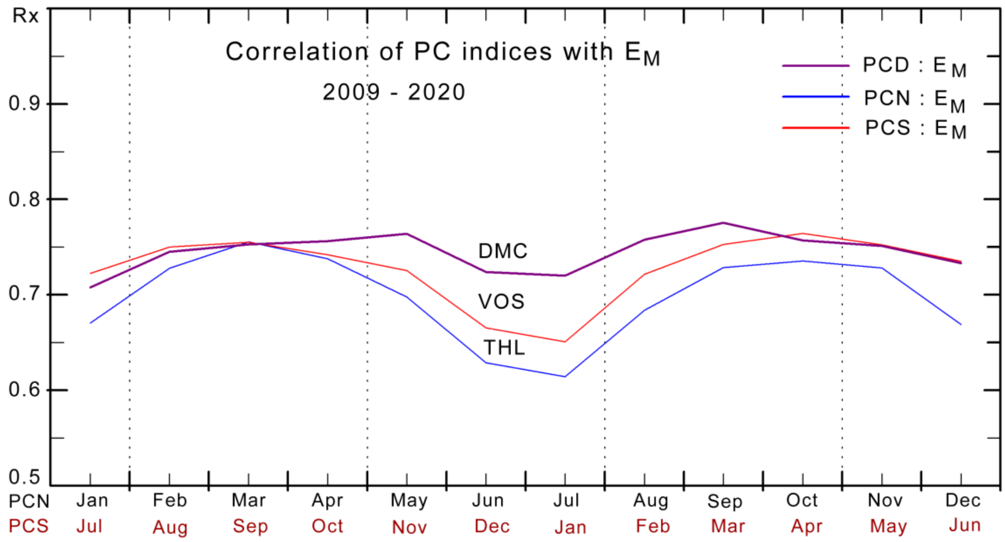

Fig. 7. Monthly means of coefficients for the correlation between 15-min averages of E_M and Dome-C-based PCS values (PCD) in heavy magenta line. Corresponding coefficients for Vostok-based PCS values in red line and Qaanaaq-based PCN values in blue line. The order of southern months has been rearranged.

It is seen from Fig. 7 that the coefficients for the correlation between E_M and PCS values based on Dome-C data are close to the corresponding values for PCS indices based on Vostok data throughout the local winter months (April-September) but much higher at local summer (October-March). The correlation coefficients between E_M and Qaanaaq-based PCN index values are much lower than either E_M - PCS correlations during most of the year.

The main reason for the low correlations during local summer months is the increased occurrence frequencies and enhanced intensities of reverse convection events compared to conditions at (local) winter. In terms of location, such reverse convection events are particularly frequent and intense midway between the Cusp region at the dayside and the geomagnetic pole. Thus, they are less frequent and intense at Vostok compared to Qaanaaq and furthermore less frequent at Dome-C compared to Vostok due to the closer proximity to the (southern) geomagnetic pole (cf. Table 1).

9. Examples of Dome-C-based PCS indices.

The availability of magnetic observations and the derivation of calibration parameters from Dome Concordia data are important for reliable investigations of space weather effects by providing back-up for the PCS index values particularly in cases where the harsh arctic environment may inhibit supply of data from Vostok or invalidate data quality. Correspondingly, the supply of data for PCN index values might be consolidated by using alternative sources of magnetic data such as Resolute Bay (RES) in Canada or Thule Air Base (TAB) in Greenland (Stauning, 2018b). An example of PCN and PCS values compiled from these sources is displayed in Fig.8 for the strong magnetic storm (Dst(min) = -222 nT) on 16-19 March 2015.

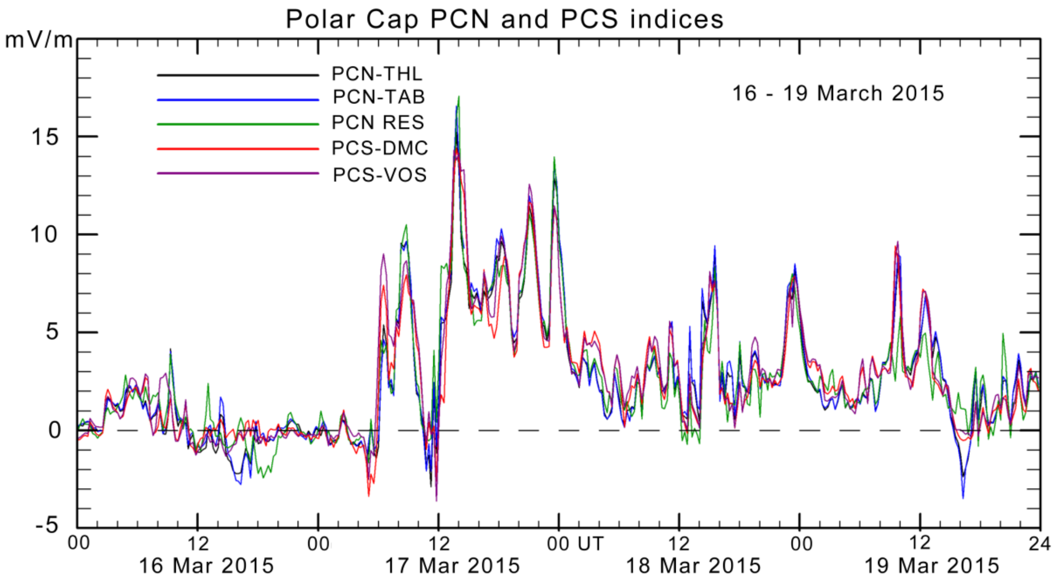

Fig. 8. Example of PCN and PCS values calculated in the "DMI2016" index versions for 4 days, 16-19 March 2015, of a strong magnetic storm event (Dst(min) = -222 nT).

It is evident from Fig. 8 that the main polar convection parameters such as the PCC indices (Stauning, 2007, 2012, 2021c, 2021d; Stauning et al., 2008) which need available PCN as well as

PCS indices could be restored with high confidence from the abundance of index sources even in the absence of a single data source.

In the strong and complex magnetic storm on 23-26 July 2015 (Dst(min) = -204 nT), the Qaanaaq-based PCN indices have been combined with the Vostok-based PCS indices to form the PCC indices displayed in blue line while the Thule AB-based PCN indices have been combined with the Dome-C-based PCS indices to form alternative PCC indices shown in red line. The PCN and PCS indices could be combined differently to form the dual-pole PCC indices.

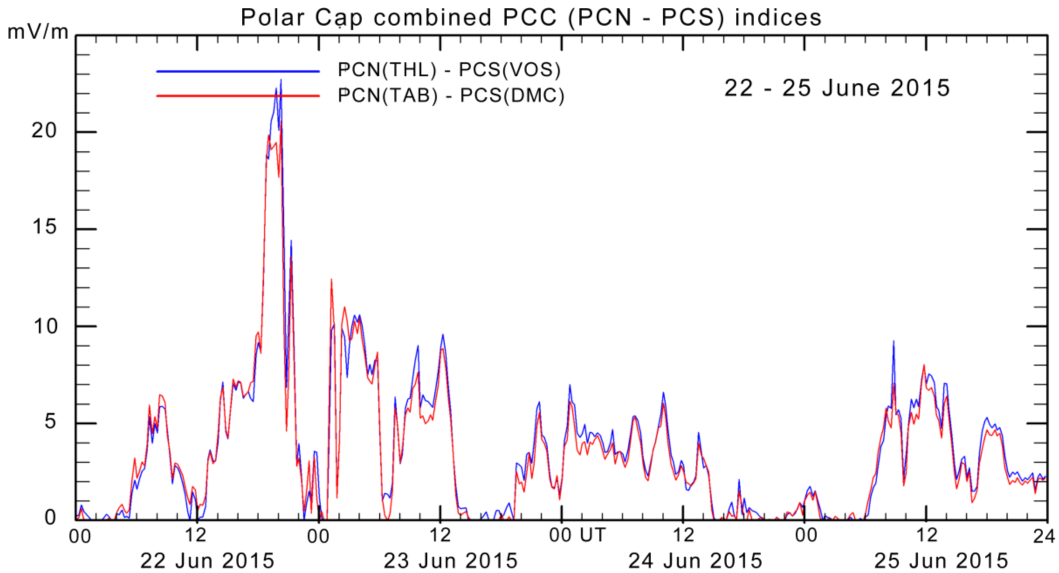

Fig. 9. Polar Cap combined (PCC) indices formed from PCN(Qaanaaq) and PCS(Vostok) indices in blue line. Alternative PCC indices formed from PCN(Thule AB) and PCS(Dome-C) in red line.

The differences between the two alternative PCC indices are just a small fraction of their amplitudes such that either version would suffice for most space weather applications such as estimates of the solar wind energy input or ring current enhancements (Stauning, 2012, 2021a,c).

Furthermore, for space weather monitoring as well as for scientific investigations of solar wind-magnetosphere interactions, the double variety of index versions would provide an insurance against faulty interpretation of the situation relying on invalid data from any single source.

10. Invalid IAGA-supported PCS indices

In spite of IAGA support through forming the "Index Endorsement Criteria" (2009) and the PC index endorsement by Resolution #3 (2013) and furthermore the involvement in the International Service for Geomagnetic Indices (ISGI), the "official" PC index series are poorly documented and not reliable.

One issue is the reference level construction (Janzhura and Troshichev, 2011; Troshichev and Janzhura, 2012) that may cause unfounded changes in the reference level during several days around any particularly strong disturbance event or cause considerable changes in the night-time reference level from daytime cusp-related disturbances (see Stauning, 2013a, 2015, and 2020). Another issue is the statistical handling where the non-linear processing (smoothing) of fluctuating scaling parameters based on small initial batches of data samples generate systematic errors as documented in Stauning (2021b). A further issue is the mixing of DP2 (forward convection) and

DP3 (reverse convection) samples in the calculations of scaling parameters (see Stauning, 2015). A particularly alarming issue is the lack of verification of methods and control of the PC index series offered to the scientific community.

A striking example of invalid PCS index values is displayed in Fig. 10 with indices for 27-30 June 2011 for Qaanaaq (THL), Vostok (VOS) and Dome-C (DMC) in the versions (DMI) defined in the present work and PCN and PCS index values in the IAGA-supported versions.

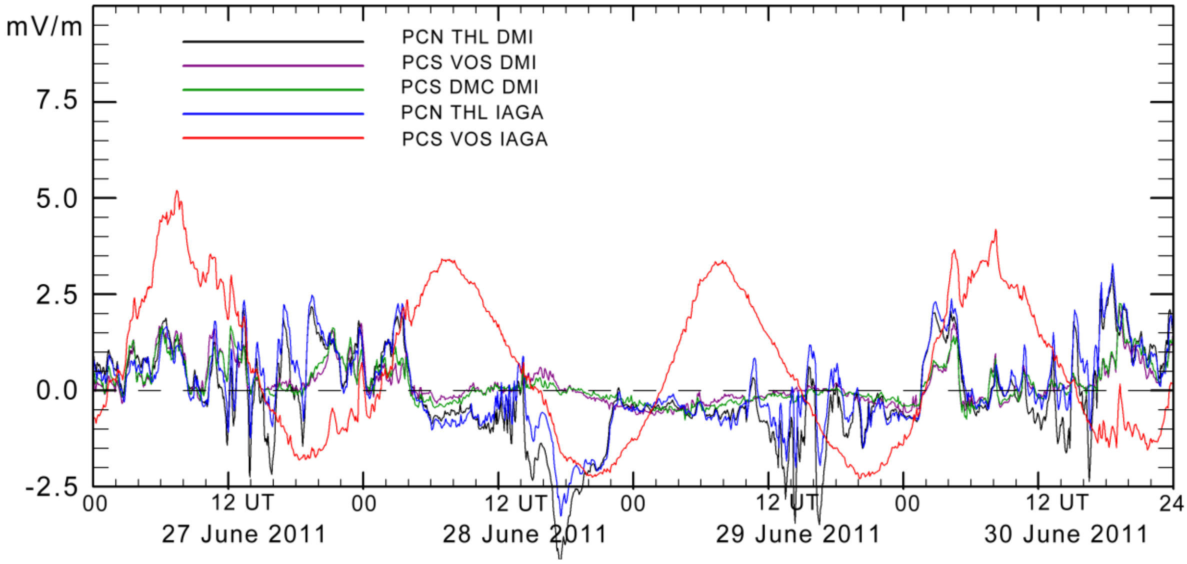

Fig. 10. PCN and PCS index values for 27-30 June 2011 in DMI2016 versions based on data from Qaanaaq (THL) in black line, from Vostok (magenta), and from Dome-C (green). PCN and PCS index values in IAGA-supported versions based on data from Qaanaaq (blue line) and Vostok (red line).

It is seen that the daily excursions between -2 and +4 mV/m (magnetic storm level) in the IAGA PCS values (red line) must be in error when compared to the other index values recorded on these rather quiet days. In passing it might be noted that the Vostok-based PCS indices (magenta line) agree well with the Dome-C-based PCS index values (green) in the DMI versions.

The PCN and PCS index values in the IAGA-supported versions (blue and red lines) were downloaded in September 2021 from the "final" version link at the AARI web site https://pcindex.org and confirmed by the identical index data downloaded also in September 2021 from the IAGA-supported ISGI web service at (http://isgi.unistra.fr .

Corresponding features are seen in Fig. 11 holding PC index data for 15-18 December 2011. It is obvious that the daily excursions between -1 and +3 mV/m in the IAGA PCS values (red line) must be in error when compared to the other index values recorded on these very quiet days.

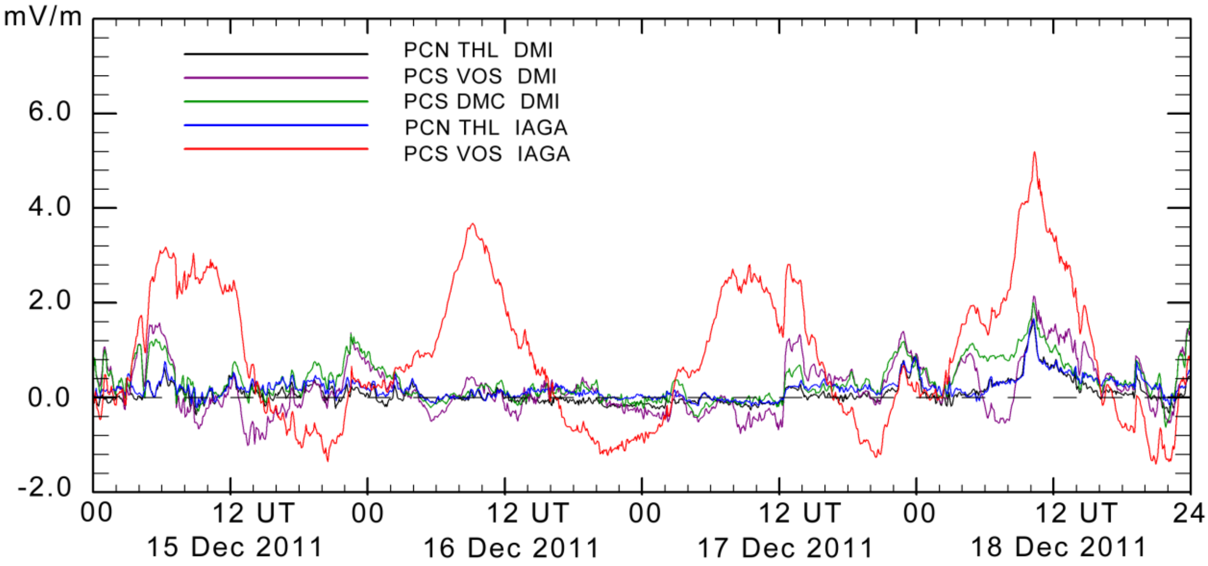

Fig. 11. PCN and PCS index values for 15-18 December 2011 in DMI2016 versions (DMI) based on data from Qaanaaq (THL) in black line, from Vostok (magenta), and from Dome-C (green). PCN and PCS index values in IAGA-supported versions based on data from Qaanaaq (blue line) and Vostok (red line).

The diagram in Fig. 11 was initially presented in Stauning (2020 and 2021c) but has now been redrawn with PCN and PCS index values in the IAGA-supported versions downloaded in September 2021 from the "final" versions link at the AARI web site https://pcindex.org and (again) confirmed by the identical index data from the IAGA-supported ISGI web service at (http://isgi.unistra.fr .

The Vostok data from this interval (from https://intermagnet.org) are good (cf. Fig. 1). Thus, the excessive values in the IAGA PCS data must rely on failures in the processing software which have been in use since the IAGA endorsement by Resolution #3 in 2013.

Similar excessive PCS index values published by AARI and ISGI web services were displayed in Fig. 8 of Stauning (2018b) and the failures reported to the index providers and to IAGA. There were no responses from the index providers. In the reply from 21 May 2018 from IAGA EC the concerns over the invalid PCS index values were dismissed. However, these erroneous PCS index data have been used in a number of publications since 2013 up to now (2021), among others, in those issued from AARI, which now add to the 40 devaluated publications listed in Stauning (2021b) that have used PC indices in versions now known being invalid.

Conclusions

Due to its close proximity to the (southern) geomagnetic pole, the occurrence frequency and the intensity of disturbing reverse convection events (NBZ conditions) as well as the amount of interfering substorm activity are at very low levels at the Antarctic research station Dome Concordia (Dome-C) making the location ideal for supply of basic magnetic data for PC indices.

- The characteristics of the PCS indices derived from data from Dome-C have shown that these data have an unprecedented close relation to the merging electric field, E_M, in the impinging solar wind.

- It is strongly recommended that available Dome-C data (since 2009) are processed to form alternative PCS index values made available to provide substitutes for missing or poor PCS values based on data from the standard observatory, Vostok.

- Alternative Dome-C-based PCS index values may form reassuring validation when agreeing with the standard PCS indices based on Vostok magnetic data or provide motivation for critical examination of data and processing procedures in cases of disagreements.

- It is suggested that efforts are invested in making data from Dome-C available in real-time and that processing procedures like those presented here are established to generate real-time Polar Cap (PCS) indices for space weather monitoring.

- The present work (including its SI file) provides coherent definitions and detailed descriptions of all steps involved in the generation of Polar Cap (PC) index scaling parameters and index values in their post-event and real-time versions.

- It is disappointing that IAGA upon endorsing the current "official" PC index versions by its Resolution #3 (2013) has failed to request comprehensive documentation of derivation procedures, proper validation of methods, and effective quality control of published index series supplied to the international scientific community.

Data availability:

Near real-time (prompt) PC index values and archived PCN and PCS index series derived by the IAGA-endorsed procedures are available through AARI and ISGI web sites. Archived PCN and PCS data used in the paper were downloaded from the "final" version link at https://pcindex.org and from http://isgi.unistra.fr in September 2021 unless otherwise noted.

Space data from the WIND, ACE, and GeoTail missions for deriving E_M and IMF B_Y values have been obtained from OMNIweb space data service at https://omniweb.gsfc.nasa.gov .

Geomagnetic data from Qaanaaq, Vostok and Dome-C were provided from the INTERMAGNET data service web portal at https://intermagnet.org .

The observatory in Qaanaaq is managed by the Danish Meteorological Institute, while the magnetometer there is operated by DTU Space, Denmark. The Vostok observatory is operated by the Arctic and Antarctic Research Institute in St. Petersburg, Russia. The Dome-C observatory is managed by Ecole et Observatoire des Sciences de la Terre (https://eost.unistra.fr) (France) and Istituto Nazionale di Geofisica e Vulcanologia (https://ingv.it) (Italy).

The "DMI2016" PC index version is documented in the report DMI SR-16-22 (Stauning, 2016) available at the web site: https://www.dmi.dk/fileadmin/user_upload/Rapporter/TR/2016/SR-16-22-PCindex.pdf

Details of the Dome-C-based PCS index definitions and derivation methods are provided in the accompanying Supporting Information file.

Conflict of interest

The author declares that he has no conflict of interests related to the present submission.

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