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Effective polar cap area and multi-station basis for Polar Cap (PC) indices

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Abstract. The PC indices, PCN (North) and PCS (South), are presently derived from geomagnetic observations at Thule in Greenland and Vostok in Antarctica, respectively. The indices are useful for analyses of solar wind-magnetosphere interactions by monitoring the convection of plasma and magnetic fields over the polar caps. For Space Weather warning forecasts the PC indices can be used to predict substorm developments and associated risks for power grid disturbances in the subauroral regions.
In order to provide reliable forecast services based on PC indices, it would be advantageous to have access to independent back-up supplies of index data. The presentation suggests observatories that could provide data for PC index calculations should the primary sources fail due to instrument or communication problems. The alternative index data enhance the credibility of PC index values.

1. PC index basics.

The polar cap horizontal magnetic field variations $\boldsymbol{\Delta F}$ are related to the “Merging” (or ”Geo-effective”) Electric Field, E_M, that controls the global energy input from the Solar Wind (SW) and Interplanetary Magnetic Field (IMF) to the Earth’s Magnetosphere (Kan and Lee, 1979):

$$E_M = V_{SW} \bullet B_T \bullet sin^2(\theta/2) \qquad (1)$$

Where V_{SW} is solar wind velocity, $B_T = (B_Y^2 + B_Z^2)^{1/2}$ is IMF transverse magnetic field component, and $\theta = \arctan(B_Y/B_Z)$ is IMF polar angle with respect to the GSM Z-axis.

The correlation could be substantiated by projecting the vector $\boldsymbol{\Delta F}$ to an “optimum” direction in a polar cap coordinate system fixed with respect to the Sun-Earth direction (the X-axis in the GSM system). The optimum direction is characterized by the angle, φ, between the normal to the equivalent horizontal current (directed opposite of the plasma convection) and the E-W meridian, and varies with local time and season.

ΔF_{PROJ} is now a scalar quantity. A further increase in the correlation is obtained by displacing the projected horizontal variation by an amount, β (intercept), which also varies with local time and season. Hence we are looking for the correlation between the modified polar cap horizontal magnetic field variations ΔF^* (in nT) and the solar wind merging electric field E_M (in mV/m) of the form:

$$\Delta F^* = \Delta F_{PROJ} - \beta = \alpha \bullet E_M \qquad (2)$$

where β (in units of nT) is the baseline shift (“intercept”), while the proportionality constant α is the “slope” (in units of nT/(mV/m)). The parameters are calculated on a statistical basis from cases of measured values through an extended epoch.

From equivalence with E_M the Polar Cap Index PC is now defined by:

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

The PC index is derived from polar geomagnetic activity as a measure of the transpolar convection of plasma ad magnetic fields but could also be considered to be a proxy for the geo-effective electric field E_M measured in mV/m. Further description of the principles of the PC index concept may be found in *Troshichev et al.* (2006). A detailed description of the derivation procedure used in the present work is provided in *Stauning* (2016).

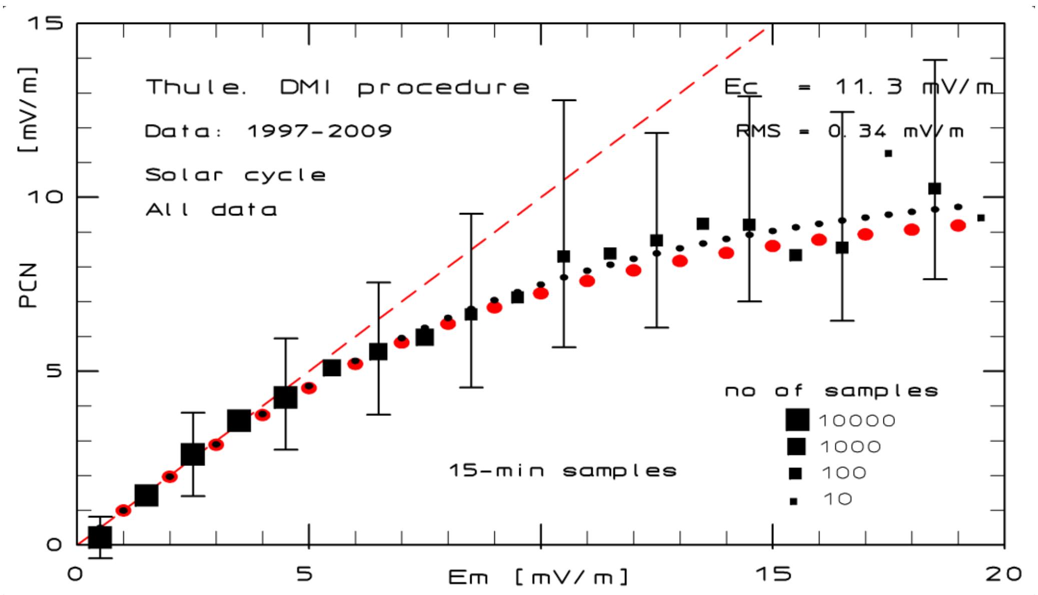
2. PC index quality criteria

In order to judge the applicability of magnetic data from alternative sources for PC index calculations, criteria based on the fundamental definition have been established to assess the quality of PC index series. The calibration parameters, α, β, φ, (cf. Eq. 3) should make the index independent of local time and season. Accordingly, the primary quality test comprises an analysis of whether this goal is accomplished by comparing relations of index values to solar wind electric fields for different selections of data. The relation between E_M and PC index values should remain the same independent of the selection of data sets.

The plots in Fig. 1 display the relations of PCN to E_M for sets of (a) all data, (b) winter nights, and (c) summer days. The black square dots mark averages through units of the merging electric field. The size of the dots indicates the number of samples involved in the average value. The standard deviations are marked by the error bars every other dot. The curve marked by the large red dots is a common reference in all plots derived from the best fit of the form: PC= $E_M /(1+(E_M / E_0)^2)^{½}$ with E_0=10.5 mV/m to samples of PC index values vs. E_M during magnetic storms (*Stauning*, 2012). The curve marked by the small dots indicates the best fit to the displayed average values with E_0 replaced by a variable parameter E_C.

Ideally, the average PC index should equal the merging electric field. However, changes in the size of the magnetosphere (getting smaller at high solar wind intensities) and in the diameter of the polar cap (getting larger at large E_M) as well as further solar wind-magnetosphere interface processes make the PC indices saturate at high E_M levels. The index quality should be judged on the invariability of the relation between PC indices and E_M. Thus, the fit parameter E_C should remain the same through the hours of the day and through the seasons. Winter nights and summer days are considered to represent extreme cases. Hence, these cases are contrasted here in Figs. 1b and 1c.

a.



b. **c.**

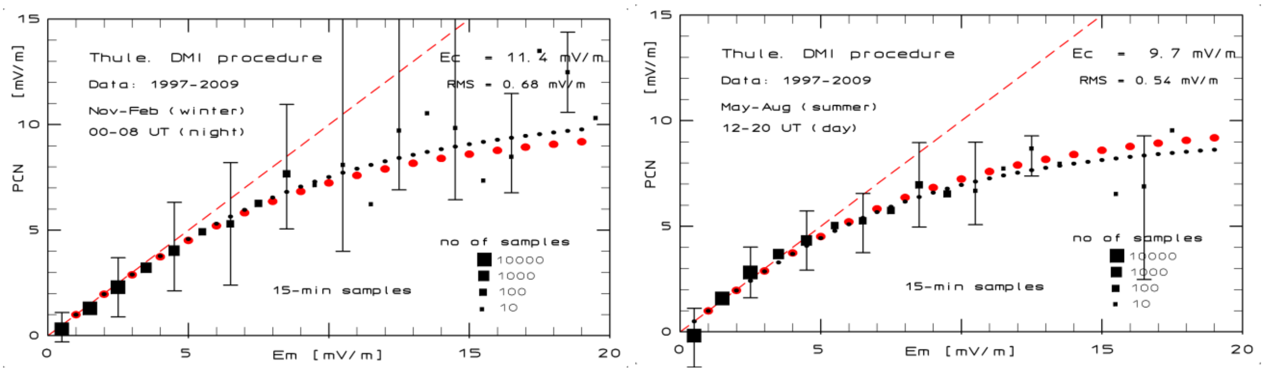


Figure 1. Display of PCN from Thule data vs. E_M for the solar cycle epoch 1997-2009. (a) All data. (b) Winter nights. (c) Summer days. Dashed line indicates equality. Square dots mark averages, while error bars indicate standard deviation within bins. Curve with large red dots show common reference, while curve of smaller dots indicate best fit to the averages.

3. Resolute Bay magnetic data as source for an alternative PCN index.

The index quality test applied to PCN index values derived from a range of stations along the west coast of Greenland have excluded stations with geomagnetic co-latitude above 9 degrees. Thus, alternative locations for PC index observatories in the northern polar cap (Fig. 2) and in Antarctica (Fig. 7) should be located within 9 degree from the northern and southern magnetic poles, respectively. In Canada, Alert, Eureka, and Resolute are located well. However, the quality of the magnetic data from Alert and Eureka is not adequate. Hence, Resolute Bay observatory operated by Geomagnetic Laboratory of Natural Resources, Canada, is the only option for an alternative PCN observatory in Canada.

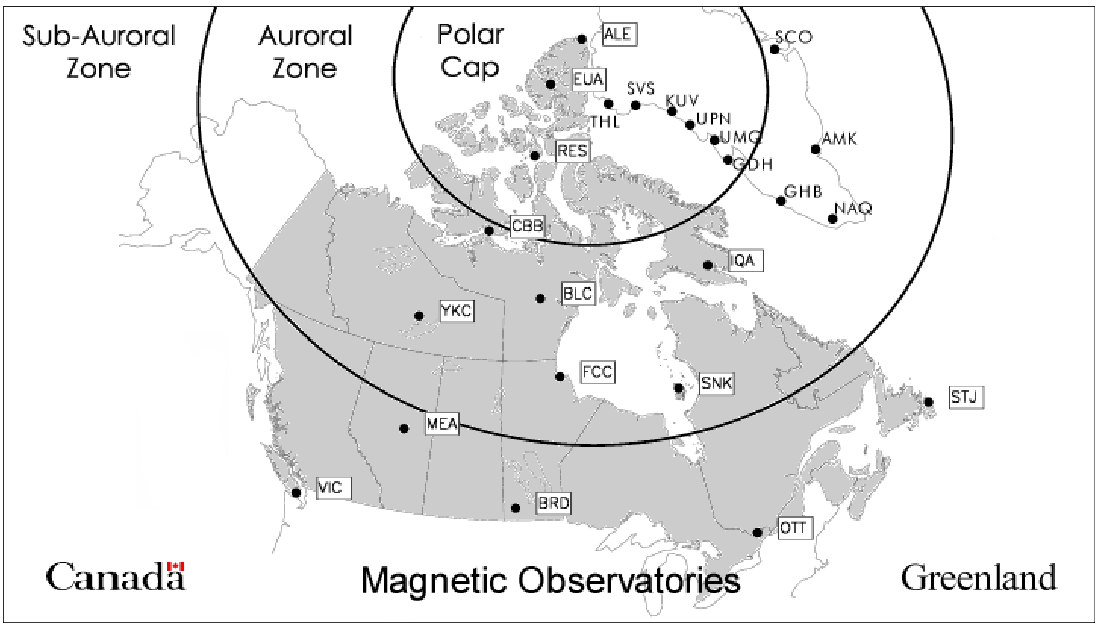


Figure 2. Magnetic observatories in Canada and Greenland. Map from Geomagnetic Laboratory of Natural Resources Canada.

The quality of the magnetic data from the observatory at Resolute Bay is good, and digital data are available since (at least) 1988. Thus, the calculation of PC index parameters may proceed using the same epoch of data (1997-2009) as that used for the standard PCN index based on Thule data.

The index quality test corresponding to the display in Figs. 1a-c is presented in Figs. 3a-c.

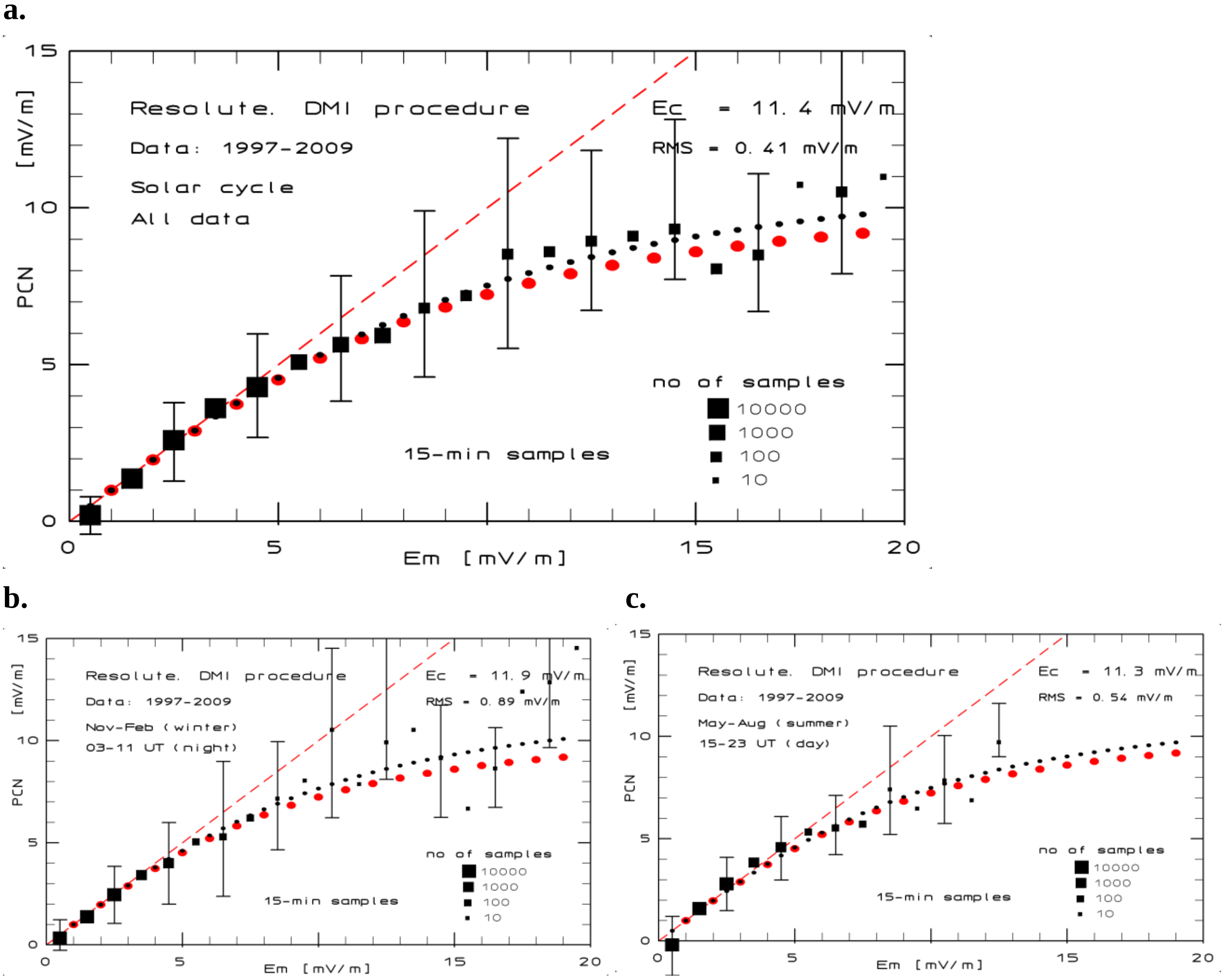


Figure 3. Display in the format of Fig. 1 of PCN based on Resolute data vs. E_M for the solar cycle epoch 1997-2009. (a) All data. (b) Winter nights. (c) Summer days.

Comparing Fig.3 to Fig. 1 shows that the variations in the fit parameter, EC, from winter nights to summer days are less for an index based on Resolute data than for the standard PCN index based on Thule data.

Fig. 4 displays the correlation between PCN index values based on Resolute and Thule data, respectively, through the interval from 1997 to 2009. The dashed line indicates equality. The dots represent averages through each unit of index values, while the sizes of the dots indicate the number of 15-min samples involved. The error bars represent standard deviation. In addition to the total number of samples the listing includes the percentage distribution of samples in the four quadrants of which the two with opposite signs (pn and np) implies anti correlation between samples of the two PCN series. The over-all correlation coefficient is R=0.865.

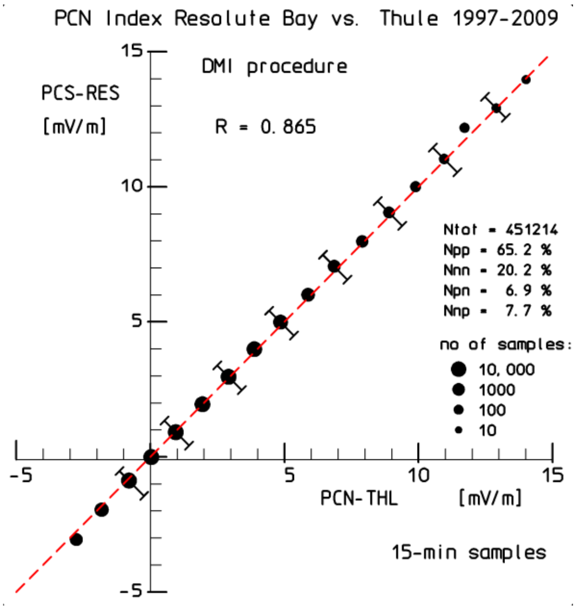


Figure 4. Correlation between PCN values derived from Resolute and Thule data, respectively. The dots present bin averages, while their sizes indicate number of samples involved. Error bars indicate standard deviation. The distribution of samples in each of the four quadrants is listed.

The successful quality test and the close correlation with the standard PCN index based on Thule data show that an alternative PCN index based on Resolute magnetic data is feasible. As an example of PC indices for Space Weather services, the Quebec 13 March 1989 power outage is considered. The PCN index based on local magnetic data from Resolute (blue and magenta lines) could have given around 6 hours of warning starting 01:50 UT as PCN exceeded 10 mV/m ("Alert" level), and including two hours of "Red Alert" with PCN>15 mV/m from 05:40 UT ahead of the event onset at 07:44 UT (02:44 EST) as documented in Fig. 5.

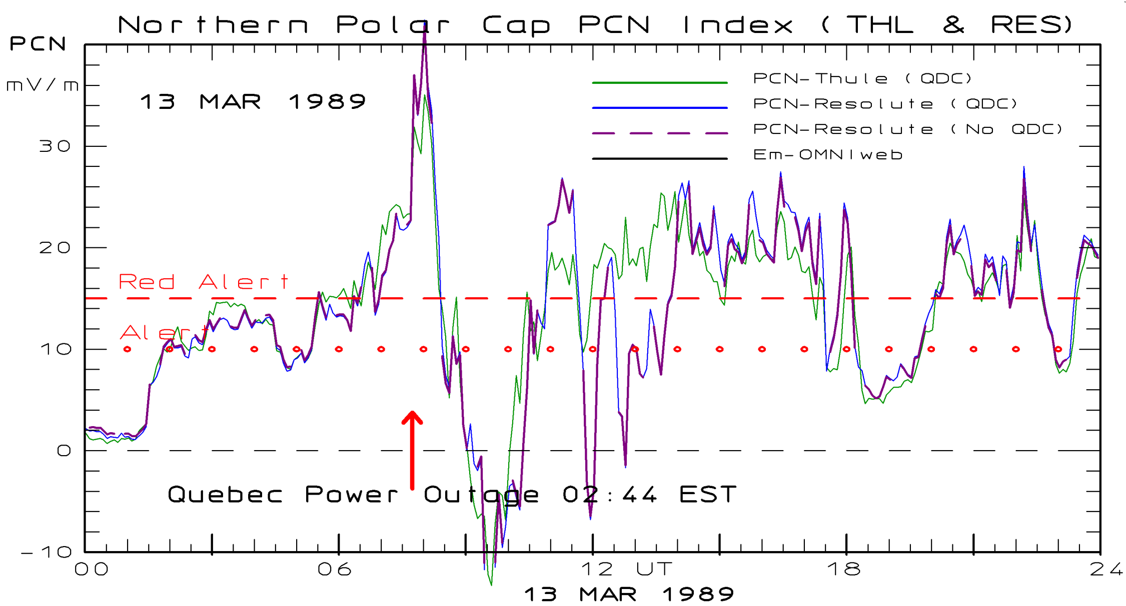


Figure 5. PCN values based on Thule data (green line), and Resolute data (blue line) with full derivation procedure (involving QDC). PCN based on Resolute data (dashed magenta line) with simplified derivation (no QDC involved). Solar wind merging electric field data were not available.

4. Dome-C magnetic data as source for an alternative PCS index.

For the southern polar cap, the magnetic data from the Concordia Dome-C observatory could provide basis for an alternative PCS index. The locations of Dome-C (DMC) close to the CGM magnetic pole, and the standard PCS observatory, Vostok (VOS), are shown in Fig. 6.

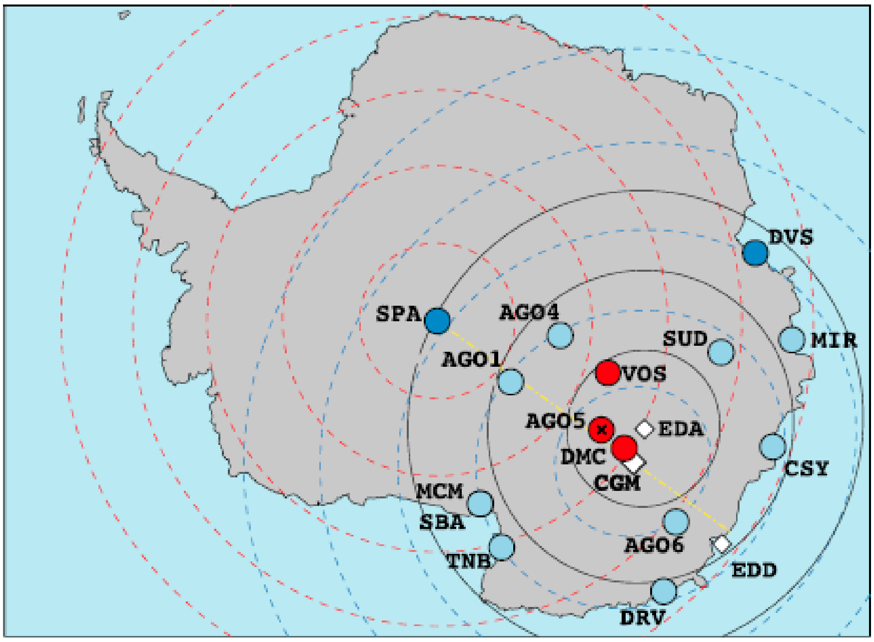
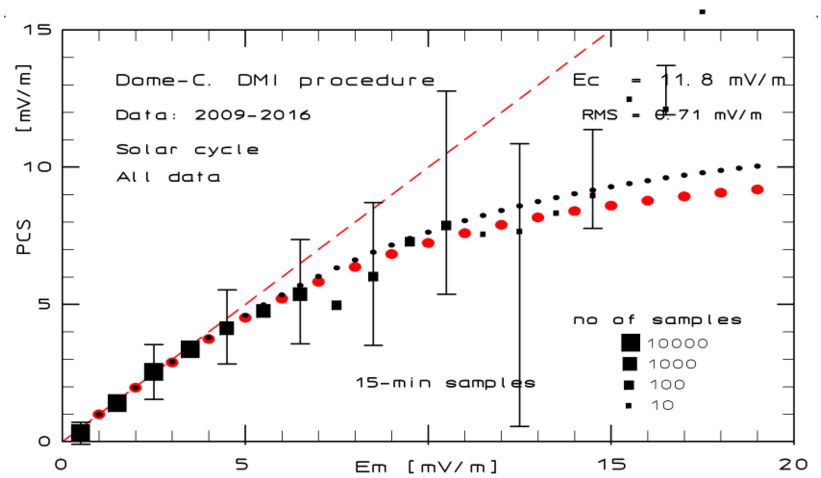


Figure 6. Magnetic observatories in Antarctica. Red dashed circles (centred at SPA) indicate geographic latitude in 5° steps. Blue dashed circles indicate corrected geomagnetic latitude centred at the CGM pole. Full line circles indicate eccentric dipole latitudes centred at the EDA pole. Dome-C (DMC) observatory is located very close to the geomagnetic pole(s). Map from *Urban et al.*, 2016.

Quality test diagrams for a PCS index based on Dome-C magnetic data are shown in Fig. 7a-c. It should be noted that the quality test is rather uncertain due to the lack of strong events during the interval from 2009 to 2016 used here since Dome-C data were not available before 2009.

a.



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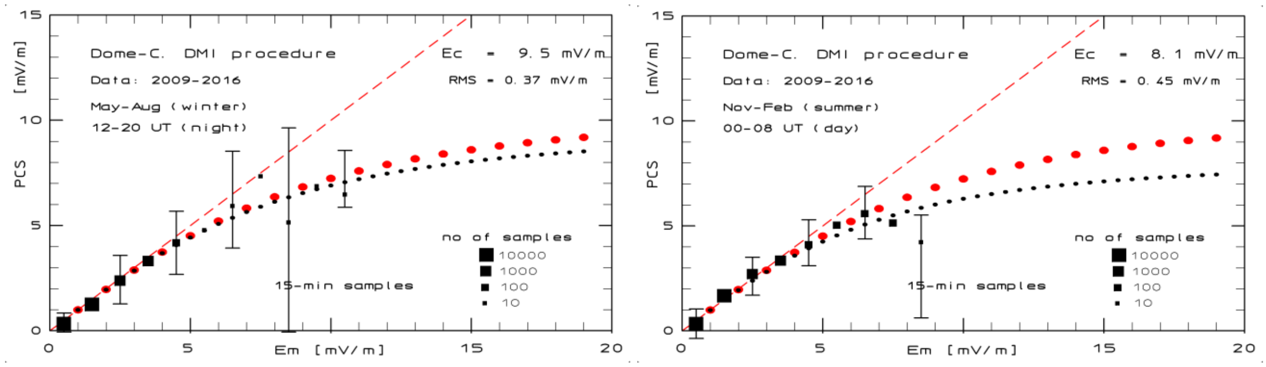

Figure 7. Quality test plot of PCS based on Dome-C magnetic data in the format of Figs. 1 and 3.

Fig. 8 presents the correlation between samples of the PCS index series based on Dome-C and Vostok data, respectively, in the format of Fig. 4. PCS(Vostok) values are around 5% larger than the corresponding PCS(Dome-C) values.

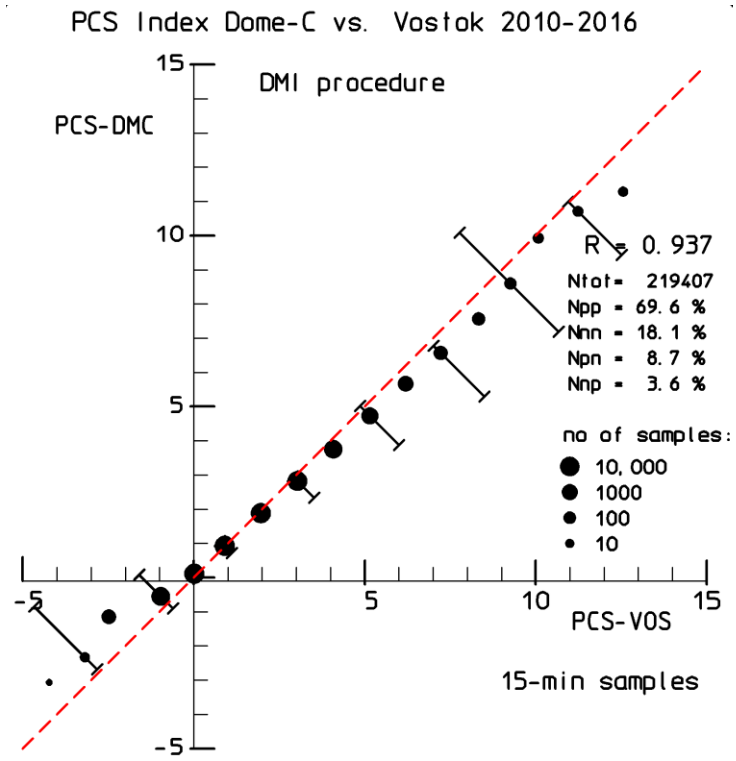

Figure 8. Correlation between PCS derived from Dome-C and Vostok data, respectively.

In spite of the inconclusive quality and correlation tests, the importance of having independent alternative sources of PC index data could be illustrated by considering the PCS index data for 2011. The diagram in Fig. 9 presents Vostok horizontal magnetic field components through 2010-2011. There are several irregularities in the data. One is the jump in base levels on 26 April 2010. Another is the sloping X-component base level through 2011. The effect of the latter is illustrated in the Vostok PCS values in the diagram in Fig. 10 of PCS indices derived from different sources.

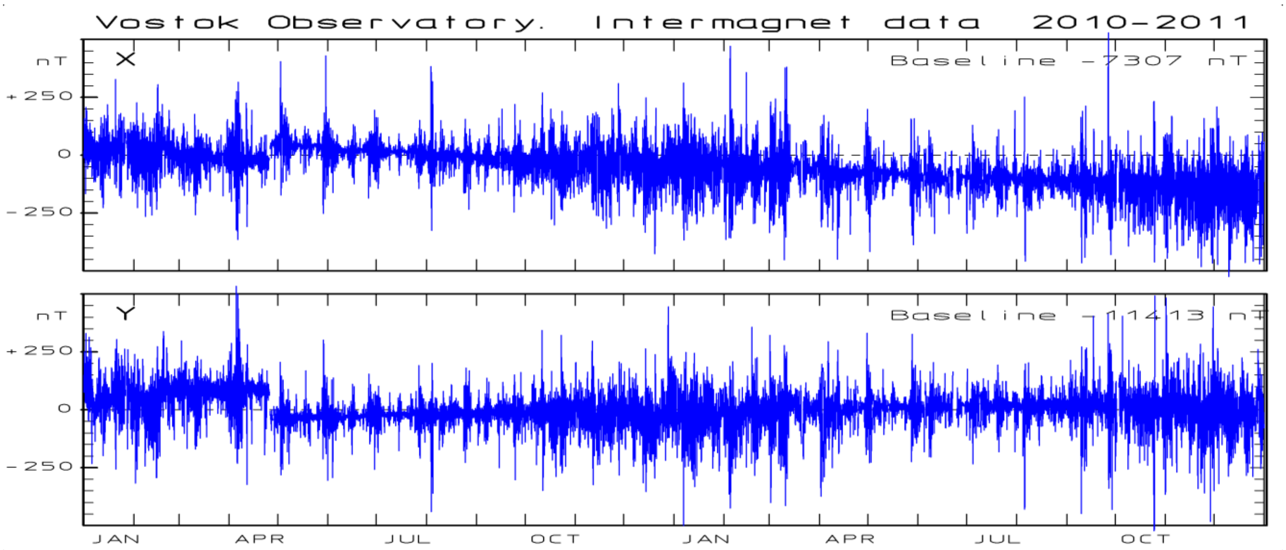

Figure 9. Horizontal components of the magnetic recordings at Vostok through 2010-2011.

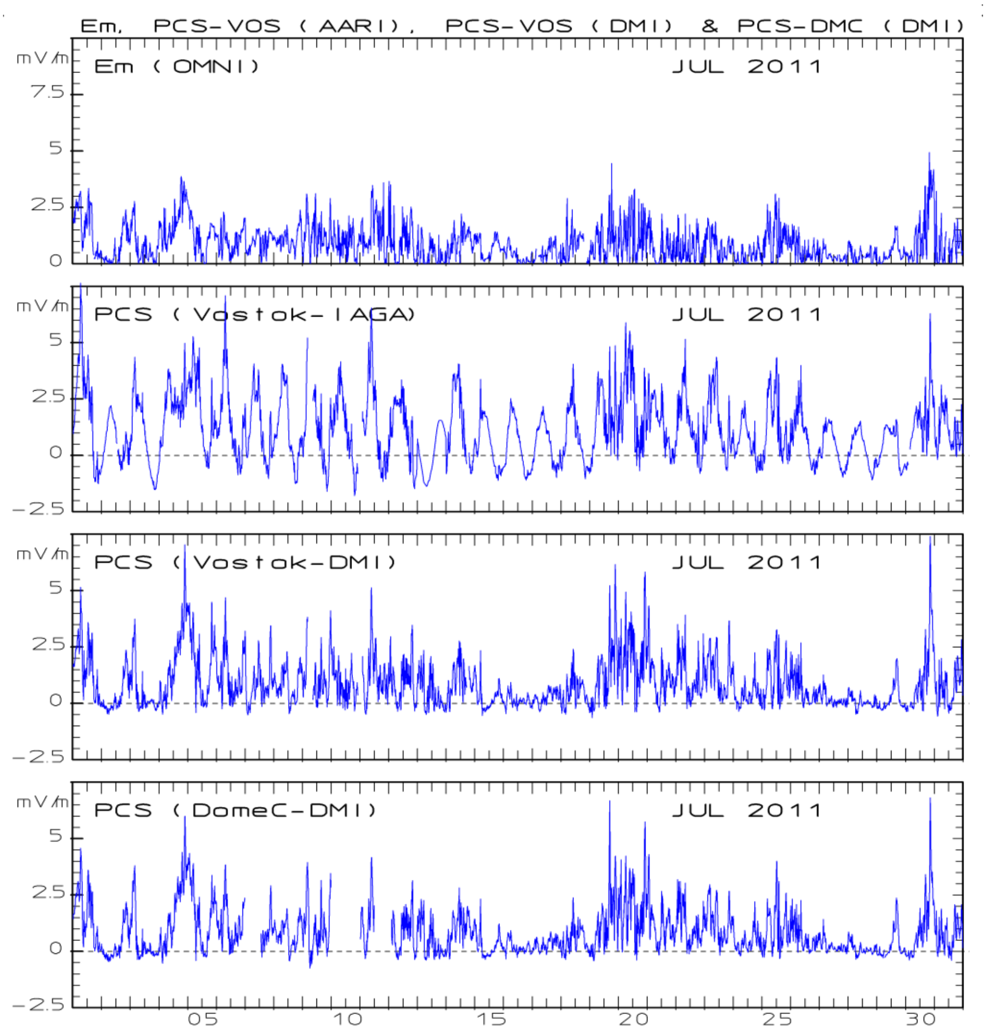

Figure 10. Solar wind merging electric field (top panel) and PCS indices from different sources through July 2011.

The IAGA-endorsed PCS index values in the second panel from the top are strongly corrupted through the month. The daily excursions between -1 and +2 mV/m in the IAGA PCS index (downloaded from http://pcindex.org) are probably caused by poor handling of the base level. The PCS values based on Vostok data but derived by a different procedure (*Stauning*, 2016) and the PCS values based on Dome-C data show good mutual agreement and they also agree well with the merging electric field values in the top field. Corresponding plots from further months have shown that the derivation problem affects the IAGA-endorsed PCS data through most of 2011.

Conclusions

- It is considered mandatory for reliable Space Weather services using the PC indices in their forecasts to have access to alternative data sources for verification and possible back-up of the standard PC index sources.
- For Space Weather forecasts it is recommended to use a simplified PC index derivation procedure that avoids the complicated derivation of a Quiet Day Curve (QDC).
- For the use of PC indices in investigations of solar wind-magnetosphere interactions, it is recommended to contrast the standard PC indices with alternative index values based on independent sources.

References

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Troshichev, O., A. Janzhura, and P. Stauning. Correction to “Unified PCN and PCS indices: Method of calculation, physical sense, and dependence on the IMF azimuthal and northward components”, *J. Geophys. Res.*, **114**, A11202, 2009. doi:10.1029/2009JA014937.