Saturation of Polar Cap (PC) indices during strong solar wind conditions

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Abstract.

The Polar Cap (PC) indices, PCN (north) and PCS (South) are derived from geomagnetic variations measured at Qaanaaq (Thule) and Vostok, respectively (e.g., *Troshichev et al*., 2006). The magnetic variations, to a large degree, relate to the transpolar plasma convection driven by the cross-polar cap potential (CPCP) generated by the interaction of the solar wind with the Earth's magnetosphere. In the derivation of scaling coefficients, the PC index values, on the average, should equal the merging electric field, E_M (*Kan and Lee*, 1979).

For actual PC index values, the equality between average index and electric field values extend up to around 5 mV/m. Beyond that level, reaching index values that for Space Weather applications are most important, the relation between PC index and E_M field values indicates saturation effects.

The PC index saturation results from (i) saturation of the CPCP fields compared to the impinging solar wind electric fields, (ii) convection inertia reducing the response to sudden high electric field values, and (iii) the PC index derivation method. The relative importance of the three potential sources of PC index saturation are discussed.

PC index basics. The "merging" (or "Geo-effective") electric field, E_M, that controls the global energy input from the Solar wind to the Earth's magnetosphere, is defined by (Kan and Lee, 1979):

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

$B_T = (B_Y^2 + B_Z^2)^{1/2}$: IMF transverse magnetic field component

$\theta = \arctan(B_Y/B_Z)$: IMF polar angle with respect to the GSM Z-axis

The rrelation between the polar cap horizontal magnetic field variations projected to an "optimal direction", assumed to be perpendicular to the DP2 transpolar plasma flow, and the merging electric field, E_M, has the form:

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

where β (e.g. in units of nT) is the baseline shift ("intercept"), while the proportionality constant α is the "slope" (e.g. in units of nT/(mV/m)). The calibration 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 defined by:

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

The PC index is a measure of the polar geomagnetic activity scaled to suppress daily and seasonal sensitivity variations to become a consistent global magnetic activity parameter as well as a proxy for the merging (geo-effective) electric field E_M measured in mV/m

Figures 1a-1h (from *Stauning*, 2018) illustrate saturation effects in four widely used PC index versions: OMNI (*Vennerstrøm*, 1991), AARI (*Troshichev et al*., 2006), IAGA-endorsed (*Troshichev* 2011), and DMI (*Stauning*, 2016).

Version	Epoch scaling	Solar activity	Reverse convection	Reference level
OMNI	1977-1980	Peak of cycle	Frequent	No QDC, BL only
AARI	1998-2001	Peak of cycle	Frequent	BL and QDC*
IAGA	1997-2009	Cycle average	Average	BL and QDC**
DMI	1997-2009	Cycle average	Excluded	BL and QDC***

BL: Base Level. QDC: Quiet Day Curve (Quiet daily variation not related to E_{KL})

QDC* : based on running 30 days quiet samples (*Janzhura & Troshichev*, 2008)

QDC** : running 30 days quiet samples + solar wind sector contribution (*Janzhura & Troshichev*, 2011)

QDC***: 40 days solar rotation weighted quiet samples (*Stauning*, 2011)

Saturation effects

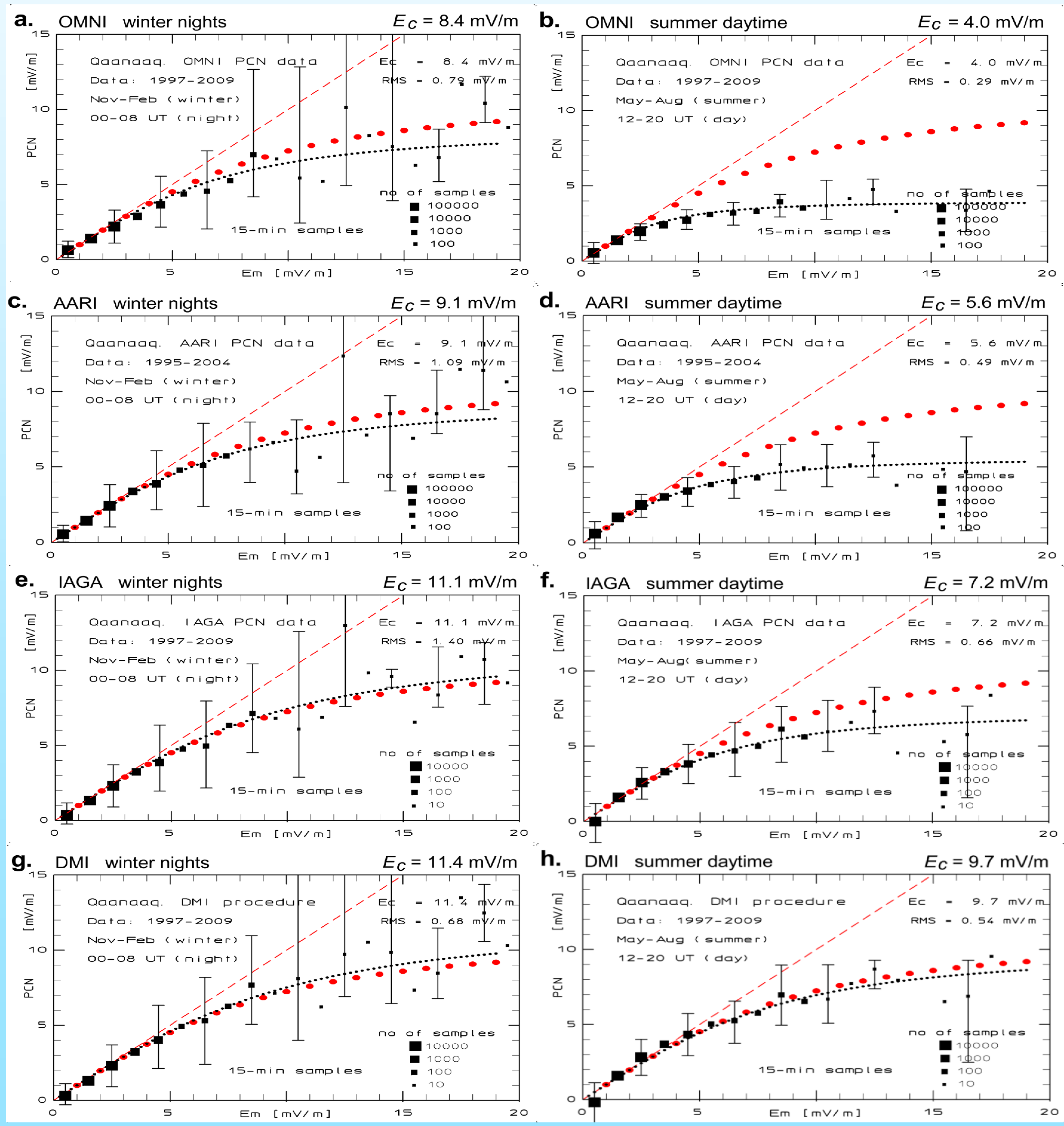
Figure 1. Display of PCN in various versions vs. solar wind merging electric field, E_M, for the solar cycle epoch 1997-2009. The left diagrams of Fig. 1 present PCN values for local night time during winter seasons, while the right diagrams display index values for local daytime during summer seasons.

Dashed red lines indicates equality. Square dots mark E_M bin PCN averages, error bars indicate standard deviation within every other bin. The curve of small dots indicates best fit between the function in Eq. 4 (with variable E_C) and the bin average PCN values. The parameters from the fit, E_C and the minimum weighted RMS deviation are noted in the plots.

The curve of large red dots in Fig. 1 indicates the functional relation:

$$PC = E_M/(1 + (E_M/E_C)^2)^{1/2} \qquad (4)$$

with E_C fixed at 10.5 mV/m. The relation was determined as the best fit between PC and E_M for magnetic storm cases during 1995-2005 (*Stauning*, 2012) and is used here to provide a common reference (not a target) to ease visual comparisons of various displays of PC index values versus E_M. It is clear that the shape of this curve provides a good representation of the linear relation at small E_M values and shows PC saturation effects at larger E_M levels. The precise course could be adjusted simply by changing the parameter E_C in Eq. 4. The 50% saturation (PCN=0.5·E_M) occurs at $E_M=\sqrt{3}\cdot E_C$.



Saturation effects in different PC index versions

The diagrams of Fig.1 clearly indicate saturation of the PC indices in all versions. Furthermore, the daily and seasonal differences between the courses of PC vs. E_M violate the quality demands listed in *Troshichev* (2011).

The "OMNI" version (*Vennerstrøm*, 1991) performs worst with 50% saturation reached at E_M=14.5 mV/m in winter nights and already at 7 mV/m during summer daytime cases. The epoch of data (1977-1980) used for derivation of calibration parameters in this version has the highest relative amount of reverse convection cases, which increases the slope and makes the intercept more negative. According to Eq. 3, the large slope values reduce the PC index values at high activity levels where the intercept contributions are relatively small.

The "DMI" version (*Stauning*, 2016), where the reverse convection events are omitted in the calculation of calibration parameters, performs best with respect to giving equal saturation properties regardless of time of day and season, and with a 50% saturation value at ~19 mV/m. The "AARI" and "IAGA" versions perform in-between. Thus, the saturation effects relate to the PC index version.

Saturation in cross polar cap potentials

A further cause of relative PC index reduction at high solar wind intensities is the saturation of the cross polar cap potential (CPCP). The CPCP is generated by the large scale interaction of the solar wind with the Earth's magnetosphere and drives the transpolar convection that in turn generates the magnetic variations reflected in the PC indices. In the *Kivelson and Ridley* (2008) model, the cross polar cap electric field (E_{KR}) relates to the merging electric field (E_M) with a factor that depends on the ionospheric conductance, Σ_P, and the Alfvén conductance, Σ_A, in the solar wind:

$$E_{KR} = E_M \cdot 2 \cdot \Sigma_A/(\Sigma_P + \Sigma_A) \qquad (5)$$

Using E_{KR} instead of E_M in the relations between the PC indices and the driving electric field largely removes the saturation effects in the DMI version as shown in Fig. 2. The depressions of the PCN index values at E_{KR}>13 mV/m were looked at individually. They relate to spiky variations in the electric field, which the PC could not follow up to high levels due to inertia in the transpolar plasma convection.

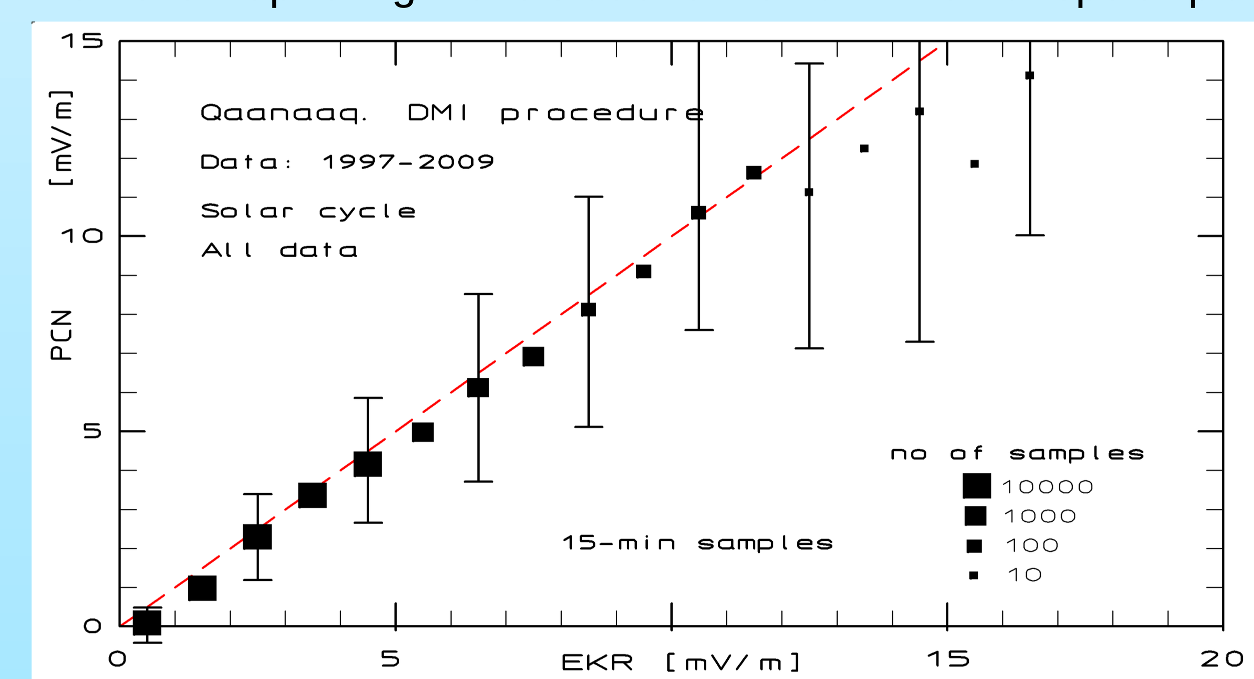


Fig. 2 Relations between PCN and *Kivelson-Ridley* (2008) cross polar cap electric field.

Conclusions

- All versions of Polar Cap (PC) indices display saturation effects in their relation to the merging electric field, E_M (*Kan and Lee*, 1979).
- The saturation effects are strongest in the OMNI version (*Vennerstrøm*, 1991) that also display the largest local time and seasonal variations.
- Compared to the OMNI, the AARI (*Troshichev et al*., 2006), and the IAGA-endorsed (*Troshichev*, 2011) PC versions, the DMI indices (*Stauning*, 2016) have the smallest saturation effects and least local time and seasonal variations.
- Polar Cap (PC) indices in the DMI version relate linearly to the cross polar cap electric fields in the *Kivelson and Ridley* (2008) model up to values of 13 mV/m. Beyond that level, saturation effects are mainly caused by convection inertia.
- Parts of the saturation effects are related to the interplay between the solar wind Alfvénic and the polar cap ionospheric conductances.