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

P. Stauning

Danish Meteorological Institute (e-mail: pst@dmi.dk/phone: + 45 39135743)

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., Troschichev 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, \( E_{\text{mer}} \) (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 \( E_{\text{mer}} \) 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, \( E_{\text{mer}} \), that controls the global energy input from the Solar wind to the Earth’s magnetosphere, is defined by (Kan and Lee, 1979):

\[
E_{\text{mer}} = V_{\text{SW}} \cdot B_{z} \cdot \sin(\theta/2)
\]

(1)

The relation between the polar cap horizontal field variations projected to an “optimal direction”, assumed to be perpendicular to the DP2 transpolar plasma convection lines, and the merging electric field, \( E_{\text{mer}} \), has the form:

\[
\Delta B_{\text{TRPC}} = \alpha \cdot E_{\text{mer}} + \beta
\]

(2)

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

From equivalence with \( E_{\text{mer}} \) the Polar Cap Index PC is defined by:

\[
PC = \Delta B_{\text{TRPC}} - \beta \alpha
\]

(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 \( E_{\text{mer}} \) measured in mV/m.

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


OMNI 1977-1980 Peak of cycle Frequent No QDC, BL only

AARI 1998-2001 Peak of cycle Frequent BL and QDC\(^*\)

IAGA 2007-2009 Cycle average Average BL and QDC\(^*\)

DMI 2007-2009 Cycle average Excluded BL and QDC\(^*\)

BL: Base Level. QDC: Quiet Day Curve (Quiet day values not related to \( E_{\text{mer}} \)).

QDC\(^*\): based on running 30 days quiet samples (Jahnthra & Troschichev, 2008).

QDC\(^**\): running 30 days quiet samples + solar wind sector contributions (Jahnthra & Troschichev, 2011).

QDC\(^***\): 40 days solar rotation weighted quiet days (Stauning, 2011).

Saturation effects

Figure 1. Display of PCN in various versions vs. solar wind merging electric field, \( E_{\text{mer}} \) 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 \( E_{\text{mer}} \) bin PCN averages, error bars indicate standard deviation within each other bin. The curve of small dots indicates best fit between the function in Eq. 4 (with variable \( E_{\text{mer}} \)) and the bin average PCN values. The parameters from the fit, \( E_{\text{mer}} \) and the minimum weighted RMS deviation are noted in the plots.

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

\[
PC = E_{\text{mer}}/(1 + (E_{\text{mer}})^2)
\]

(4)

with \( E_{\text{mer}} \) fixed at 10.5 mV/m. The relation was determined as the best fit between PC and \( E_{\text{mer}} \) 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 PC index values versus \( E_{\text{mer}} \).

It is clear that the shape of this curve provides a good representation of the linear relation at small \( E_{\text{mer}} \) values and shows PC saturation effects at larger \( E_{\text{mer}} \) levels. The precise course could be adjusted simply by changing the parameter \( E_{\text{mer}} \) in Eq. 4. The 50% saturation (PCN=0.5) occurs at \( E_{\text{mer}}=3\ E_{\text{mer}} \).

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. \( E_{\text{mer}} \) relate the quality demands listed in Troschichev (2011).

The “OMNI” version (Vennerstrøm, 1991) performs worst with 50% saturation reached at \( E_{\text{mer}}=14.5 \) 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 index more actual. 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 worst with respect to deriving equal saturation properties regardless of time of day and season. They show 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 (\( E_{\text{CP}} \)) relates to the merging electric field (\( E_{\text{mer}} \)) with a factor that depends on the ionospheric conductance, \( \Sigma_\text{I} \), and the Alfvén conductance, \( \Sigma_\text{A} \), in the solar wind:

\[
E_{\text{CP}} = E_{\text{mer}} \cdot (2 \Sigma_\text{I} + 2 \Sigma_\text{A})
\]

Using \( E_{\text{CP}} \) instead of \( E_{\text{mer}} \) 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 in the PCN index values at 15 mV/m and above are thus shown to be due to the solar wind convection inertia, while the invariations in the electric field, which the PC could not follow up to high levels due to inertia in the transpolar plasma convection.

Conclusions

All versions of Polar Cap (PC) indices display saturation effects in their relation to the merging electric field, \( E_{\text{mer}} \) (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 (Troschichev 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, the aspects of the saturation effects are related to the interplay between the solar wind Alfvénic and the solar cap ionospheric conductances.

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