TRANSPOLAR IONOSPHERIC CURRENTS DERIVED FROM ØRSTED AND FROM GROUND

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ABSTRACT

Both the Polar Cap (*PC*) geomagnetic index and the current resulting from using Ampère's integral formula on magnetic observations along the orbit of a polar orbiting satellite provides largely a measure of the transpolar ionospheric currents. The intensities of these currents reflect the level of the global geomagnetic disturbances resulting from the interaction of the solar wind with the Earth's magnetosphere. In both cases the currents are proportional to the interplanetary "merging electric field" (*MEF*), which is closely associated with the level of energy transfer from the solar wind to the magnetosphere and upper atmosphere. The two terrestrial magnetic disturbance parameters are described and compared both to solar wind MEF observations and to each other.

1. INTRODUCTION

In the central polar cap the geomagnetic perturbations measured from ground are mainly related to the transverse Hall currents in the ionosphere. A parameter to describe these currents is the Polar Cap (*PC*) index originally introduced in [3] in an attempt to derive the solar wind merging electric field (*MEF*) on basis of available ground-based polar magnetic observations. Systematic calculations of the *PC* index values based on either southern (*PC-S*) or northern (*PC-N*) polar geomagnetic observations have been made at the Arctic and Antarctic Research Institute (AARI) and the Danish Meteorological Institute (DMI), respectively [4].

Several years of data have been used to calculate the best possible statistical correlation between polar magnetic disturbances and solar wind electric fields. From these correlations sets of coefficients to convert the polar cap horizontal magnetic disturbance vector into a proxy for the *MEF* have been derived. In units of mV/m the derived value is the Polar Cap (*PC*) index. The coefficients are constructed to vary with local time and season and with the location of the magnetic observatory in order to make the resulting index independent of such conditions.

The concept of deriving transpolar currents from using Ampère's integral law with magnetic precision measurements conducted from polar orbiting satellites was originally introduced in [2] based on Magsat data. More recent the concept in a modified form was used in [1] using data from the Ørsted satellite. In short the observations have revealed the transpolar Pedersen currents connecting the downward field-aligned current (FAC) to the morning side of the polar cap with the upward FAC emerging from the evening side. It was also shown that these currents are proportional to the solar wind merging (or geo-effective) electric field ($E_M = MEF = V_{SW}\ B_T\ \sin^2(\theta/2)$) taking into account the seasonally varying ionospheric conductivities.

Here we give a brief outline of the new unified procedure for calculation of *PC* index values from ground-based northern and southern polar cap geomagnetic observations and the derivation of transpolar currents from polar orbiting satellite observations. The two quantities are compared to each other and to values of the merging electric field derived from IMP-8 or ACE interplanetary satellite observations. The potential use of these quantities for Space Weather monitoring is noted.

2. POLAR GEOMAGNETIC OBSERVATIONS

Around 95% of the geomagnetic field observed at a ground-based observatory arise from the main field generated within the Earth's fluid core. This part varies on time scales of tens or hundreds of years (secular variations) A further few percent of the total field arises from magnetization (induced and remnant) in the crust. The induced part varies with the main field while the remnant part varies on geological time scales (millions of years). Another few percent of the total field is generated by currents in the upper atmosphere and further out. This fraction shows variations on time scales spanning from fraction of a second to a few years. The large differences in time scales is one of the tools used to separate the different contributions.

The ionospheric and magnetospheric currents causing variations in the geomagnetic field observed near either geomagnetic pole depend to a large degree on the conditions in the solar wind and its embedded interplanetary magnetic field (IMF). Their intensities also depend on location of the observatory as well as local time and season partly because of the changing upper atmospheric ionization depending, among other, on the varying solar illumination and partly on the geomagnetic field morphology relative to the solar wind flow.

A typical example of polar geomagnetic observations, here from Thule, Greenland, located at a corrected geomagnetic (CGM) latitude of 85.30^{O}, is displayed in the top fields of Fig. 1.

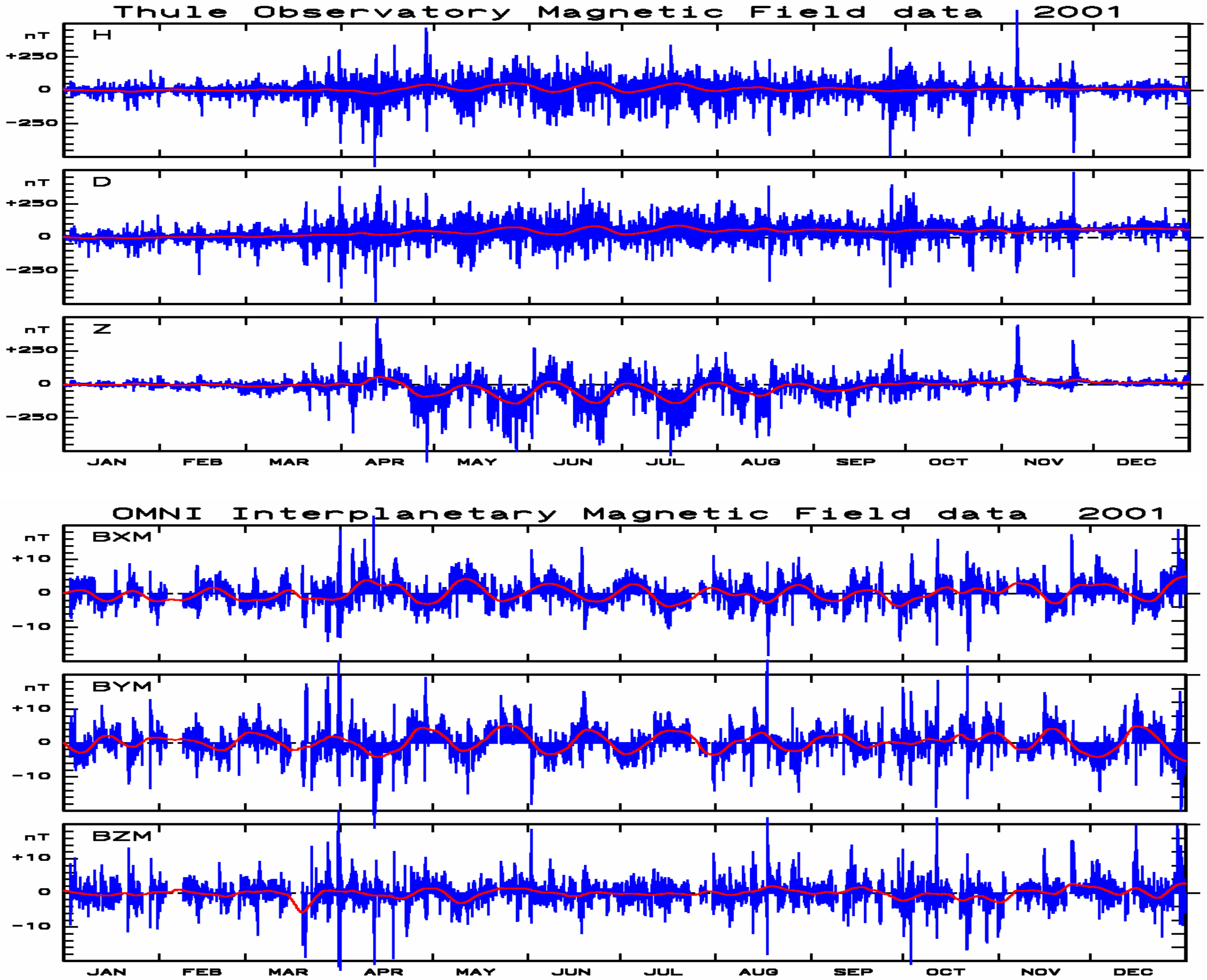

Figure 1. Thule observatory polar magnetic field and OMNI interplanetary magnetic field data. Hourly values 2001.

The blue traces in the three top fields in the diagram show hourly average values of the field resolved in the H-component (geomagnetic North), D-component (East) and Z-component (down) through the year 2001. Interplanetary magnetic field values at the Earth's position, resolved in Geocentric Solar Magnetospheric (GSM) coordinates, derived from the OMNI data base for the same year, 2001, are shown in the bottom fields. The red continuous curves are smoothed averages.

In these data several features are noteworthy:
(i) The three components of the Thule polar magnetic data, particularly the D-component, display significant steady changes through the year. This is the result of secular variations in the main field.
(ii) There is a low-frequency modulation on time scales from one to a few weeks in both the Thule data, seen most distinctly in the Z-component, and in the interplanetary components. This modulation is indicative of the interplanetary sector structure where the preferred field direction is either toward or away from the Sun, the so-called Svalgaard-Manzurov effect.
(iii) Strong high-frequency excursions, here on time scales of one or a few hours, are seen in all three components of the ground-based data as well as in the interplanetary data. In the ground-based data these excursions are strongest during the (northern) summer months occurring at the middle of the diagram. The excursions observed at ground and in space are strongly correlated. This correlation is part of the basis for defining the Polar Cap (*PC*) index.

The highest degree of correlation between polar cap horizontal magnetic field variations ***F*** and various constellations of solar wind parameters is found between ***F*** and the so-called "Merging Electric Field", *MEF*, (or "Geo-effective Electric Field"), E_M.

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

where V_{SW} is the solar wind velocity, B_T is the transverse component of the IMF ($B_T=\sqrt{(B_Y^2+B_Z^2)}$), while θ is the polar angle between the Z-axis of a Geocentric Solar-Magnetospheric (GSM) coordinate system and the transverse IMF component.

A simplified physics-based explanation of this correlation can be given with reference to the schematic representation in Fig. 2 (from GEM Handbook) of the structure, current systems and magnetic fields in the Earth's magnetosphere exposed to the solar wind flow. The solar wind electric field (***E***=***V***x***B***) extends over the Earth's magnetosphere. However, the interaction is strongly enhanced by a southward (θ=180^{O}) IMF since this direction favors merging with the northward, and thus oppositely directed, geomagnetic field at the frontal magnetopause boundary. This explains the construction in Eq. 1 of the geoeffective (merging) electric field.

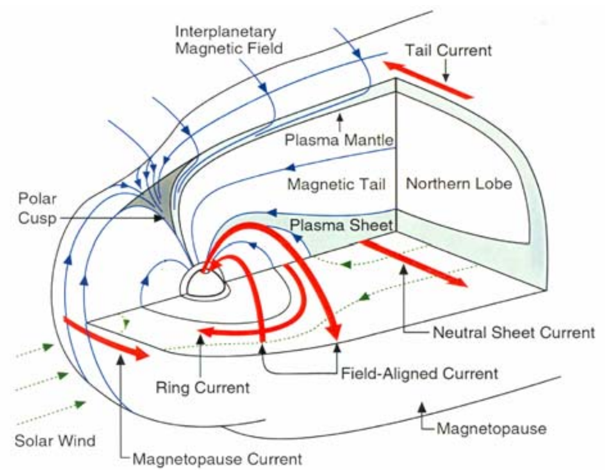

Figure 2. Simplified sketch of magnetospheric structure

This field extending from dawn to dusk drives currents along field lines from the outer magnetospheric regions interfacing the solar wind to the polar ionosphere. The projected ionospheric intensities of such field-aligned currents (FAC) detected from satellites are shown in colour code in Fig. 3 together with the accompanying electric potential distribution for cases where the IMF is directed in the azimuthal directions (θ=-90^{O}, θ=+90^{O}).

The strongly yellow colored region at the morning side at 70^{O} - 80^{O} (geomagnetic) latitude indicate the downward Region 1 (R1) FAC while the strongly blue colored region at the dusk side represents the upward R1 FAC leaving the ionosphere. These two R1 FAC currents are partly connected via dawn-dusk Pedersen currents flowing horizontally in the polar ionosphere. The electric potential distribution, in addition, drives an ionospheric convection largely along equipotential contours. Due to differences in ion and electron mobility, the convection is equivalent to an oppositely directed Hall current system closing within the ionosphere. The magnetic variations measured at ground level are dominated by the contributions from the Hall currents since the contributions from the Pedersen currents are reduced by the contributions from the associated FAC's. The polar magnetic variations are thus related to the solar wind *MEF* through the steps outlined above.

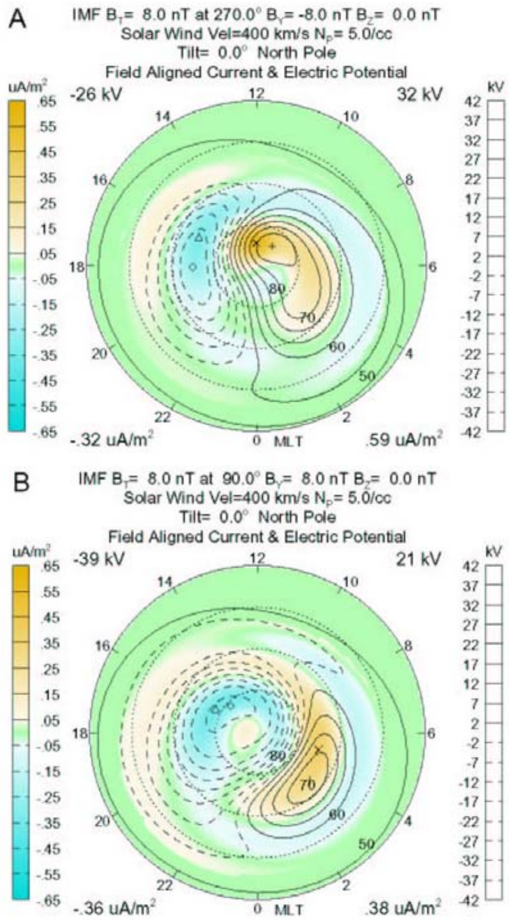

Figure 3. North-polar field-aligned currents and electric potential distribution in typical cases with IMF B_Y>0 (A) and IMF B_Y>0 (B), respectively. [5]

3. PC INDEX CALCULATIONS

We may increase the correlation between the horizontal disturbance vector ***F*** corrected for the quiet daily variations and the *MEF* by projecting ***F*** to a specific direction ("optimum direction"), which in a GSM coordinate system varies slowly with local time and season. A further increase in correlation is obtained by displacing the baseline for the projected horizontal variation F_{PROJ} by ΔF_I ("intercept"), which may also vary slowly with local time and season.

Hence we are looking for the correlation between the modified polar cap horizontal magnetic field variations F* and the solar wind *MEF*, E_M, of the form:

$$F^* = F_{PROJ} - \Delta F_I = S \cdot E_M \qquad (2)$$

where ΔF_I (e.g. in units of nT) is the baseline shift ("intercept") while *S* is the sensitivity ("slope") e.g. in units of nT/(mV/m). The projection angle to the optimum direction is:

$$V_{PROJ} = longitude + UThr \cdot 15^o + opt.angle \qquad (3)$$

Hence we define the dimensionless Polar Cap Index *PC*:

$$PC == S^{-1} \cdot (F_{PROJ} - \Delta F_{BL}) \cdot (1\ mV/m)^{-1} \qquad (4)$$

which is then a proxy for the merging electric field E_M $== (Vsw \cdot B_T \cdot sin^2(\theta/2))$ measured in mV/m.

The scaling parameters have been derived over a span of years using IMP-8 satellite data. The availability of satellite data is illustrated in the top field of Fig.4 while the parameters opt.angle, intersept and slope are displayed in the next lower fields. In these fields there is a section for each month along the horizontal axis. Each section has a time scale from 00 to 24 UT. Hence, the displays illustrate the daily as well as the seasonal variations. The different colors depict data sets calculated for different epochs. Together the data spans 25 years, that is, more than two 11-year solar cycle.

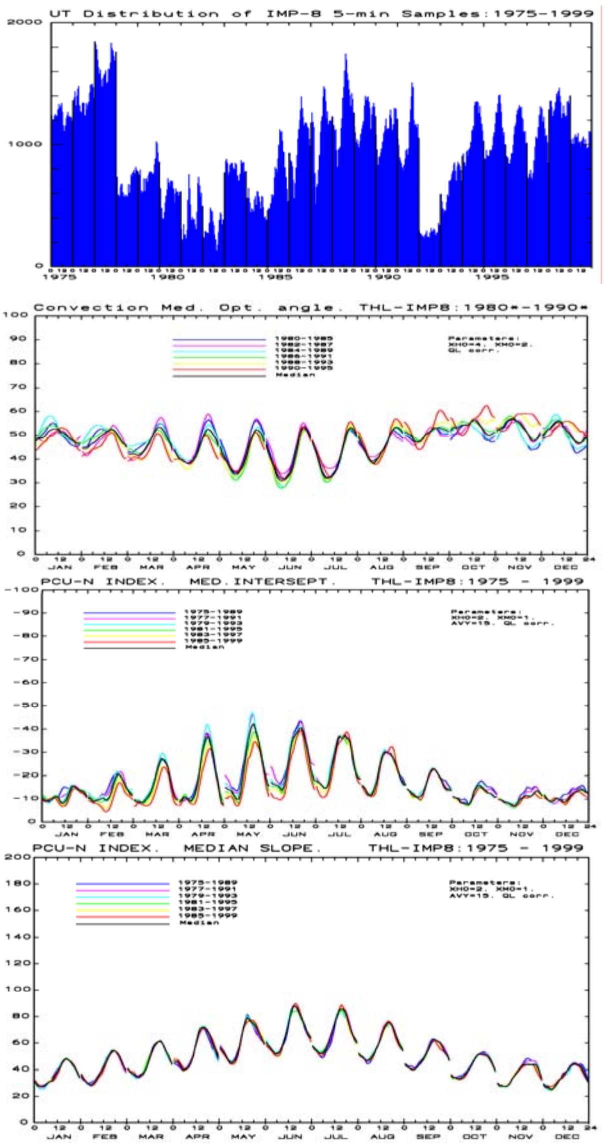

Figure 4. IMP-8 data availablity 1975-2000, optimum angle, intersept and slope for PC-N calculations.

If this procedure works then we may, conversely, derive the solar wind MEF from polar cap magnetic variations. In order to illustrate the correspondence the relation between the two parameters may be shown in a scatter plot. Fig. 5 displays *PC-N* (Thule) vs. E_M (IMP-8, 12Re) for 1995. (5-min averages, E_M delayed 20 min).

The values noted at the plots all refer to the differences between *PC-N* index values and IMP-8 *MEF* values E_M. They are:
S0 : average shift in *PC-N* index values
S1 : average numerical shift in *PC-N*
S2 : RMS shift in *PC-N*

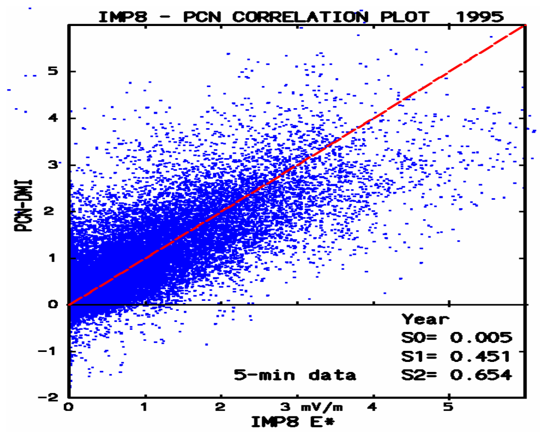

Figure 5. PC-N index vs. IMP-8 merging electric field

Such correlation scatter plots between IMP-8 E_M data and *PC-N* (DMI) values have been made for different seasons. Fig. 6 displays an example where the plots are organised in summer, equinox, winter and all-year sets.

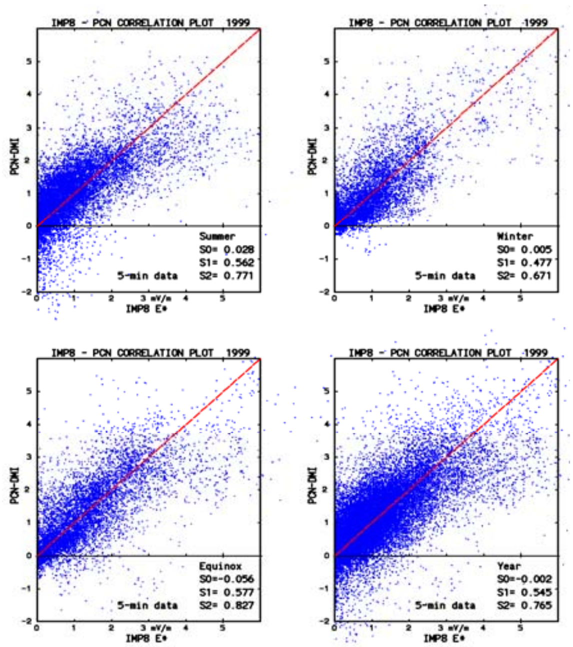

Figure 6. Correlation scatter plots for PC-N vs. E_M for 1999 to display seasonal and solar cycle variations.

4. AMPÈRE'S SEMI-ORBIT INTEGRAL

The current found from Ampère's Integral Law applied to a satellite orbit is the total current *I* trough the surface S delimited by the contour L, i.e.:

$$\mu_o I \; = \; \int_L \boldsymbol{B} \bullet \boldsymbol{dl} \qquad (4)$$

where L = closed contour, $\boldsymbol{dl}$ = differential element of L, $\boldsymbol{B} \bullet \boldsymbol{dl}$ = projection of $\boldsymbol{B}$ on $\boldsymbol{dl}$, I = total current.

The concept is illustrated in Fig. 7. Some of the various current systems which add to produce the geomagnetic field observed at the satellite orbit may be disregarded in the evaluation of the integral in Eq. 4. The currents inside the Earths and currents which close in the ionosphere below the satellite orbit will give no resultant contribution to the integral since they either do not intersect the surface S or they cross S twice but in opposite directions.

Left to consider are currents which have only one leg crossing the surface S while the closing path is outside L, i.e. somewhere in the outer space. The dominant current of this kind is the Region 1 system of currents originating at the flanks of the magnetosphere. These currents flow as R1 FAC down to the morning sector. Here they continue as ionospheric Pedersen currents partly flowing equatorward to feed the Region 2 FAC and partly flowing across the polar cap to feed the upward R1 FAC from the evening sector. The main contribution to the total current through S comes from the transpolar dawn-to-dusk oriented ionospheric currents closing between the downward R1 FAC to the dawn sector and the upward R1 FAC from the dusk sector of the polar ionosphere. This system is illustrated in Fig. 7 for the northern polar cap [1].

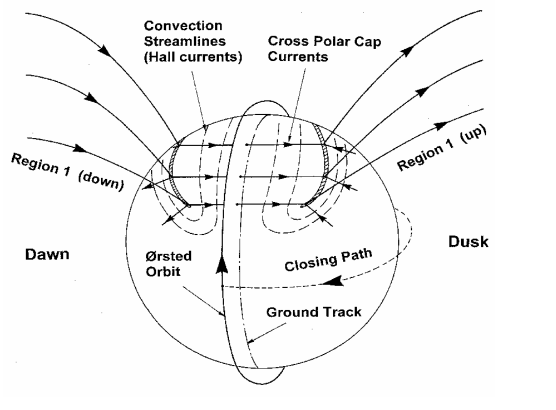

Figure 7. Sketch of satellite orbit and current systems

A major problem when applying Ampère's integral law is the requirement of stationary conditions. All currents need to be steady while the satellite measures the magnetic fields along the orbit during the ~100 min orbital period. Considering the variability imposed by the fluctuating IMF this is an almost prohibitive requirement. In order to relax the conditions we have added a fictitious closing path at low latitudes. Based on statistical results we have derived the approximate magnitude for the possible contributions along this closing path and have found them negligible. Hence we may derive the Ampère's Integral along a semi-orbit and associate it with the transpolar current in one hemisphere only. Since a polar pass lasts for 10-15 min only this procedure relaxes the requirements by almost an order of magnitude and makes the steady-state conditions a reasonably fulfilled approximation.

An example of the derivation of Ampère's semi-orbit integral is shown in Fig. 8. The three upper fields depict three components of the observed magnetic field while the bottom curve depicts the differential contributions B • dl. It is seen that these contributions are of significant magnitude for the 15 minutes polar pass from 05:19 to 05:34 UT only. At lower latitudes the amplitudes are very small and the contributions are insignificant.

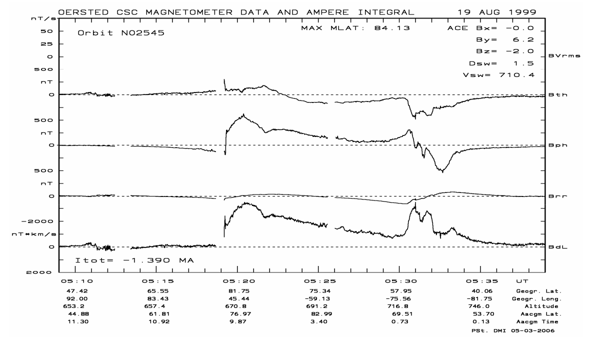

Figure 8. Magnetic field components and contributions to Ampère's integral during an Ørsted polar pass.

Some of the results obtained are presented in Fig. 9.

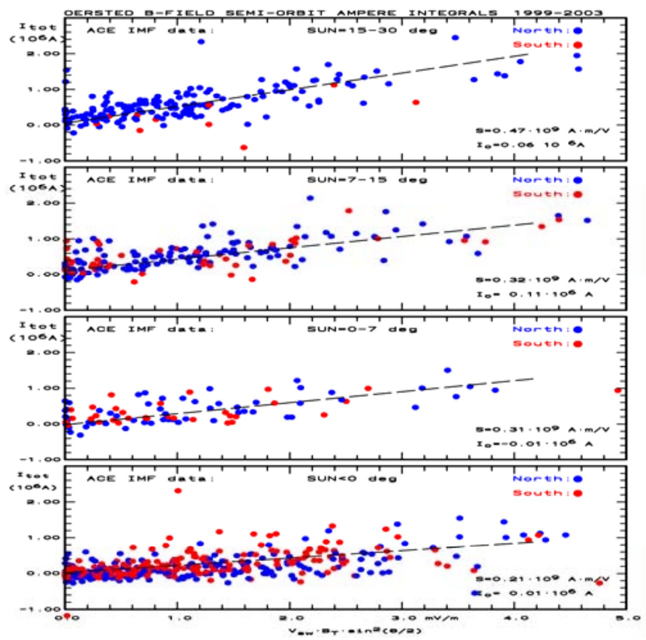

Figure 9. Total hemispheric transpolar currents vs. MEF. Solar horizon angle at the pole is parameter for the fields.

The slope of the line drawn in each field indicates the ratio between transpolar ionospheric currents and the solar wind MEF, i.e. the ionospheric transconductance assuming that the conductance along field lines are much larger. The so defined ionospheric conductance vary in a systematic way with the solar illumination being largest at the top field where the horizon angle is 15-30 degrees (local summer). The conductance is minimum at the bottom field where the Sun is below the horizon (local winter).

Since both the PC index and the current resulting from the Ampère's semi-orbit integral are related to the solar wind MEF then the two terrestrial magnetic disturbance parameters could be expected to be closely correlated to each other. It should be taken into account that the PC index in principle is fully corrected for seasonal effects (see Fig. 6) while the transpolar currents as seen in Fig. 9 varies with solar illumination of the polar cap and thus are strongly dependent on season. However, when considering data from a specific season, the relation is clear. This is shown in Figure 10 for the transpolar current vs. PC-N index. The top field presents data from local summer while the bottom field shows data for local winter. The blue points refer to northern and the red to southern polar passes. The black are averages.

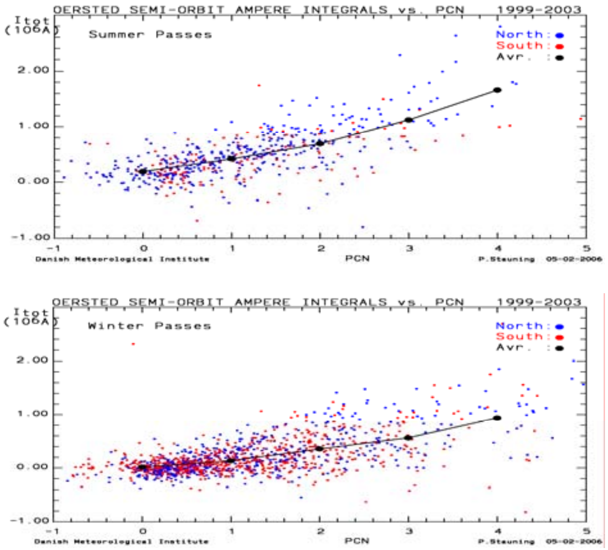

Figure 10. Correlation scatter plot of transpolar current vs. PC-N index values. Top: summer. Bottom: winter.

5. CONCLUSIONS

1. The use of Ørsted geomagnetic observations for calculation of Ampère's integral along the satellite orbit has provided reasonable and consistent results for the total hemispheric dawn-to-dusk ionospheric current intensities encompassed by the semi-orbit. The use of Ørsted high-precision magnetic measurements and an accurate main field model including *Dst*-dependent parameters is of decisive importance.

2. The use of a semi-orbit integration contour supplemented by an equatorial closing path for the Ampère's integral increases the number of available cases and lower the demand on the steadiness of the decisive parameters. The contributions to the integral from the added low-latitude path are found negligible compared to the high-latitude part of the semi-orbit.

3. The relation between the total hemispherical dawn-to-dusk ionospheric current intensities and the geo-effective solar wind merging electric field can be expressed as a transconductance ranging from $0.2 \cdot 10^9$ A·m/V during darkness at the (geomagnetic) polar cap to $0.5 \cdot 10^9$ A·m/V at full illumination where the sun is $15\text{-}30^{\circ}$ above the horizon. The illuminated hemisphere may convey up to three times the dawn-to-dusk currents of the dark hemisphere.

4. The above defined Ampère's semi-orbit integral may provide a versatile space weather parameter, which could be a useful supplement to the Polar Cap (PC) index to indicate solar wind properties and define solar wind influence on geospace current systems. The two parameters may also be used in the selection of undisturbed intervals for modeling of the main field and for a range of further purposes.

6. ACKNOWLEDGMENTS

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7. REFERENCES

1. Stauning, P. and F. Primdahl, First detection of global dawn-dusk ionospheric current intensities using Ampères integral law on Ørsted orbits, *Geophys. Res. Lett.,* 27 (20), 3273-3276, 2000.
2. Suzuki, A. and N. Fukushima, Sunward or anti-sunward electric current in space below the MAGSAT level, *Geophys. Res. Lett*., *9*, 345, 1982.
3. Troshichev, O. A., and V. G. Andrezen, The relationship between interplanetary quantities and magnetic activity in the southern polar cap, *Planet. Space Sci.*, 33, 415, 1985.
4. Troshichev, O. A., V. G. Andrezen, S. Vennerstrøm, and E. Friis-Christensen, Magnetic activity in the polar cap – A new index, *Planet. Space Sci*., 36, 1095, 1988.
5. Weimer, D.R., Maps of ionospheric field-aligned currents as a function of the interplanetary magnetic field derived from Dynamics Explorer 2 data, *J. Geophys. Res.,* 106, 12,889-12,902, 2001.