Transpolar Convection and Magnetospheric Ring Current Relations: Real-Time Applications of the Polar Cap (PC) Indices

Peter Stauning

1Danish Meteorological Institute, Copenhagen, Denmark

Abstract The present study confirms the validity of previously derived relations between the polar cap (PC) indices and the ASY-H and the Dst and SYM-H ring current indices when used in real-time applications. PC indices are here derived in simulated real-time (SRT) versions by using past data only from −40 days up to current time in the construction of the quiet reference levels (QDCs) for the magnetic data. From analyses spanning a decade (2009–2018), equivalent ASY-H index values were derived from a linear relation with SRT PCN (North) and PCS (South) indices combined to form the non-negative PCC indices. For the cases of strong magnetic storms (Dst(peak)< −100 nT), the equivalent ASY-H indices were found to agree well with reported (real) ASY-H index values. The SRT PCC indices, furthermore, have been used in a PC-based source function to derive equivalent values of the total ring current indices Dst (or SYM-H) up to 1 h ahead of time. With integration of the source function throughout a decade (2009–2018) with no attachment to reported Dst values, the SRT equivalent Dst indices display close agreement with real Dst index values. The applied method could be used without modifications to generate PC index values and derived ASY-H and Dst (or SYM-H) index values in real-time space weather applications.

Plain Language Summary Polar Cap (PC) indices are derived from the magnetic variations related to the plasma drift over the polar caps generated by the interaction with the solar wind. The present work believed to be the first of its kind presents applications of PC indices developed in a reliable real-time version. The PC indices may be used to monitor the solar wind electric fields considered responsible for the transfer of solar wind energy to the magnetosphere. The solar wind energy supply power to disturbances such as auroral current systems responsible for upper atmosphere heating and fast magnetic variations that may induce harmful currents in power grids near the auroral regions. The PC indices are used here to derive intensities of the ring currents of oppositely drifting positive and negative ions encircling the Earth near equator at distances of 4–6 earth radii. The present work demonstrates the close relation between polar cap and ring currents and supports the use of real-time PC indices for space weather monitoring.

1. Introduction

The hourly Dst index (Sugiura & Kamei, 1981) and the equivalent 1-min SYM-H index values derived from low-latitude magnetic observations are considered to represent the intensity of the magnetospheric ring current of mirroring ions drifting near equator at distances of 4–6 Earth Radii ($R_E$). A relation between the accumulated kinetic energy of the charged particles encircling the Earth and the Dst* indices (i.e., the Dst indices corrected for magnetopause current [MPC] effects) is provided by the Dessler-Parker-Sckopke relation (Dessler & Parker, 1959; Sckopke, 1966). The ring currents are believed to result from solar wind-magnetosphere interactions. Thus, building the ring currents could be considered to represent the input of energy from the solar wind conveyed by the electric fields extended over the magnetosphere (Burton et al., 1975).

In addition to building the ring currents, the incoming solar wind energy is also used to power further disturbance processes such as polar and auroral magnetic substorm activity that may generate upper atmosphere heating and strong auroral currents which, in turn, generate geomagnetically induced currents.
GICs) in conducting structures on ground. The strongest GIC cases could seriously disturb power grids (Kappenman, 2010; Pulkkinen et al., 2017; Stauning, 2013, 2020a).

Thus, monitoring the energy input from the solar wind to the magnetosphere has strong relevance for operational space weather-related applications. In addition, investigations of the relations between ring current intensities and other solar wind and related geospace parameters may help understanding and modeling the ring currents and enlighten their association with polar cap (PC) plasma convection processes. Both phenomena are essential parts of the structure and dynamics of the magnetosphere in relation to its interaction with the solar wind.

The standard polar cap PCN (North) indices are based on magnetic observations at Qaanaaq (THL) in the northern polar cap, while PCS (South) index values are based on magnetic observations at Vostok in Antarctica. The PC indices are derived from the magnetic variations generated by the transpolar convection of plasma and magnetic fields and scaled to level the Kan and Lee (1979) merging electric field, $E_M$, in the solar wind (e.g., Troshichev et al., 1988). In consequence of their close relations to $E_M$, the PC indices are considered to represent the input of energy from the solar wind.

Thus, one might expect close relations between the ring current intensities, scaled by the partial (asymmetric) and the total (symmetric) 1-min indices ASY-H and SYM-H or the hourly Dst indices, and the PC indices, PCN and PCS. With the two available PC indices, the question arises which one or which combination of the two PC indices is the most representative version. Furthermore, there is also the conceptual problem that the individual (hemispherical) PC indices and also their averages may take large negative values at times without causing the ring current to reverse its direction of revolution, but mostly just causing weakening of its strength.

An effective solution to both problems was found by the introduction of the non-negative polar cap PCC index combination (Stauning, 2007). The PCC indices are derived as the average of positive values of the two hemispherical PC indices disregarding (zero filling) negative values. It has been demonstrated that the PCC indices have a higher degree of correlation with the merging electric fields than either of the individual PC indices or their averages (Stauning, 2012, 2021; Stauning et al., 2008).

Basic models of the magnetospheric convection of plasma and embedded magnetic fields are based on the two-cell convection patterns (DP2) introduced by Dungey (1961). The cross-PC electric fields that generate the transpolar plasma flow are linked to region 1 currents generated at the magnetospheric boundary regions, while the lower-latitude return flows are driven by electric fields linked to region 2 currents extending from the auroral regions to the ring current regime. In the DP2 system, the magnetospheric tail region is loaded by plasma and embedded magnetic fields convected over the PCs from the front to the rear of the magnetosphere. Enhanced plasma pressure and occasional substorm activity in the tail region may cause injection of energetic plasma from the tail to the partial ring current regime at the rear of the ring current region.

Such processes may cause enhancements of the asymmetric (partial) ring currents which are related directly to the transpolar convection and contribute to the building of the symmetric (total) ring currents. The gradual building of the total ring current intensities could be estimated by the integration of a PC index-based source function. The asymmetrical (partial) ring currents scaled by ASY-H indices and symmetrical (total) ring current intensities scaled by Dst or SYM-H involve geomagnetic activity at both PCs conveniently scaled by the PCC indices.

The relations between PC indices and the ring current ASY-H and Dst (or SYM-H) indices have been investigated previously by Stauning et al. (2008), Stauning (2012), and in a recent study by Stauning (2021). The target in the present study is to examine the validity of the established relations based on post-event data for their use in real-time applications. Thus, the PC indices are derived here in simulated real-time (SRT) versions by using past data only with respect to current time in the construction of the undisturbed reference levels named the quiet day curve (QDC). The QDCs are needed for the calculation of the magnetic variations that are subsequently processed with tabulated scaling parameters for deriving PC index values. In real-time applications where the geomagnetic data are currently available, this approach would provide
actual ring current intensity values, including the actual ASY-H indices and gradient values for the Dst (or SYM-H) indices enabling estimates of their values up to 1 h ahead.

2. The Polar Cap Indices, PCN, PCS, and PCC

The magnetic variations providing the basis for the PC indices are related to the transpolar convection of plasma and embedded magnetic fields driven by the interaction of the solar wind with the Earth's magnetosphere. The interaction is controlled by the solar wind merging (or “geo-effective”) electric fields, $E_M$, defined by Equation 1 from the solar wind velocity, $V_{SW}$, and the components $B_Y$ and $B_Z$ of the interplanetary magnetic field (IMF) in its geocentric solar magnetosphere (GSM) representation (Kan & Lee, 1979):

$$E_M = V_{SW} \cdot \sqrt{ \left( B_Y^2 + B_Z^2 \right) } \cdot \sin^2 \left( \theta / 2 \right) \cdot \theta = \arctan \left( B_Y / B_Z \right)$$  \hspace{1cm} (1)

The magnetic variation vectors, $\Delta F$, when projected to an optimum direction considered to be perpendicular to the dominant forward transpolar convection direction, are assumed to be related to the merging electric fields by:

$$\Delta F_{PROJ} = \alpha \cdot E_M + \beta$$  \hspace{1cm} (2)

where the scaling parameters, slope ($\alpha$) and intercept ($\beta$), are derived from an epoch of past data by the regression defined in Equation 2.

Thus, to level with $E_M$, the PC index is defined by Equation 3 using the scaling parameters from Equation 2:

$$PC = \left( \Delta F_{PROJ} - \beta \right) / \alpha \approx E_M$$  \hspace{1cm} (3)

The optimum direction is characterized by its angle ($\varphi$) to the PC dawn-dusk meridian. The angle is found by seeking maximum correlation between the projected magnetic variations and the non-negative merging electric field values. This process also determines the propagation delay from the position where the solar wind parameters are measured to the observatory position in the PC where the effects are recorded. Detailed descriptions of the derivation methods may be found in Stauning et al. (2006) or Stauning (2016).

It is important to realize that the transpolar convection has two basic modes, forward and reverse convection patterns. The forward (day to night) transpolar convection is part of the DP2 two-cell convection patterns with return flows in the auroral regions. DP2 patterns are observed during conditions where IMF is either southward (negative) or just weak. The reverse convection mode is part of the DP3 two-cell convection patterns observed during strong northward (NBZ) IMF conditions. The two modes, DP2 and DP3, have very different relations to solar wind properties and geospace disturbances. Usually, the DP2 forward convection mode has much wider latitudinal and longitudinal patterns and much stronger effects on geomagnetic storm and substorm conditions than the DP3 reverse convection mode.

The estimate of the optimum direction angle is mostly based on DP2 (forward) convection samples since they are more frequent than samples taken during DP3 conditions. Furthermore, the merging electric field values are generally small for northward IMF (NBZ) conditions reducing their effects on the correlation results. Thus, the forward convection conditions generate positive values of the projected magnetic variations and mostly positive values of the derived PC indices since $\alpha$ in Equation 3 is positive and $\beta$ small while the reverse convection conditions, correspondingly, generate negative PC index values.

In the present “DMI2016” PCN and PCS versions (Stauning, 2016), the reverse convection samples are omitted in the regression of Equation 2 used to derive the scaling parameters. In the past, the PCN version developed by Vennerstrøm (1991) and the PCN and PCS versions issued by the Arctic and Antarctic Research Institute (AARI), named AARI#1, AARI#2, AARI#3, and AARI#4 and also the version here named IAGA2014 (Matzka, 2014; Nielsen & Willer, 2019) include forward as well as reverse convection samples in the regression (Equation 2). Thereby, DP2 and DP3 conditions are mixed with the adverse consequences discussed in Stauning (2015, 2018b). The IAGA2014 PC index version was endorsed by the International Association for Geomagnetism and Aeronomy (IAGA) by its resolution no. 3 (IAGA, 2013).
The PCC indices defined in Stauning (2007) are derived by combining non-negative values of the PCN and PCS indices as shown in Equation 4:

\[
PCC = (\text{PCN if } > 0 \text{ or else } 0 + \text{PCS if } > 0 \text{ or else } 0) / 2.
\]

Thus, the PCC indices represent the mean level of forward convection (DP2) intensities in the two PCs taken as an entity. If PCN and PCS indices are invalid or missing, then an error code is substituted in the PCC index series. If one index value is invalid or missing, then the PCC index is given the value of the other index.

3. Deriving PC Indices in Real Time

In an approach using solar rotation weighted (SRW) QDC techniques (Stauning, 2011) in the calculations, the post-event reference levels are estimated from weighted averages of the quietest samples collected at comparable conditions within ±40 days of the day of interest. The weighting gives preference to nearby samples and to samples one solar rotation away where the solar wind and solar UV conditions are most likely to resemble the actual conditions. In the simulated real-time approach (SRT), the quiet samples are collected from the past −40 days only. With previously defined (tabulated) calibration parameters (φ, α, β), access to polar magnetic data in real time, and with the QDC it is now possible to calculate PC index values in real time with good precision and high reliability.

Examples of the QDC reference levels (with the secularly varying base levels subtracted) for Vostok throughout 2015 are displayed in Figures 1a, 1b, 2a, and 2b. Figures (a) display the X-components while figures (b) display the Y-components. Figure 1 displays the full SRW QDC values (±40 days) while Figure 2 displays the SRT HSRW (half solar rotation weighted) QDC values (−40 to 0 days).

In these diagrams, there is a QDC curve for each day of the year. For each month, the daily QDC curves are drawn on top of each other in blue line. For Day 1 (in black line), day 15 (in yellow lines), and for the last day of the month (in red line), the QDCs are re-drawn on top of the other QDCs. Going from the black curves through the yellow ones to the red curves provides an impression of the development of the QDCs throughout the month. Most of the amplitude variability, particularly seen during the summer months, represents IMF \(B_y\)-related effects included in the QDC values. The QDCs derived this way may also accommodate moderate secular variations in the magnetometer base levels as illustrated by the slight sloping of the assembly of curves in Figures 1 and 2. For most months, the differences between the post-event and SRT QDCs are less than 10 nT in each component which corresponds to differences in PC index values of less than 0.5 mV/m.

For the epoch (2009–2018) considered here, PCN and PCS index values have been calculated based on calibration parameters derived from final magnetic data and using QDCs in either SRW versions for post-event (PE) calculations or in HSRW versions for SRT index calculations. Hourly average PCS index values in SRT and PE versions are displayed in Figure 3a for 2015. The differences between the two versions are displayed at the bottom of the diagram. This year on top of 24’th solar activity cycle presents the largest deviations between SRT and PE PC index versions seen throughout the examined epoch.

Usually, the differences between the SRT and PE PC index values are largest in the local summer season where the QDC variability related, among other, to IMF \(B_y\) and NBZ effects, are largest. The effects are seen in the QDC displays in Figures 1 and 2 and also in the PCS indices displayed in Figure 3a. The corresponding displays have also been generated for the PCN and the PCC SRT and PE index versions. The differences between the SRT and PE versions of PCN, PCS, and PCC for 2015 are displayed in Figure 3b.

The large difference values seen at local summer conditions are mitigated when combining the PCN and PCS indices into the PCC index version. Thus, the differences between the SRT and PE PCC values exceed 0.5 mV/m during a few days only (in January and August). For the remaining part of this solar max year (2015), the differences remain safely below 0.5 mV/m. For other years of the present solar cycle, the differences are considerably lower. Further specifications of the differences and correlation between hourly values of the simulated real-time and the post-event values for the PCN, PCS, and PCC indices are provided in Table 1.
The QDC values are derived on an hourly basis. Thus, PC index samples of higher resolution than 1-h reflect the variations in the (common) magnetic data for the SRT and PE versions and would just repeat the differences between the hourly index values.

The number of PCN samples is close to the total number of hours (87,660) within the epoch (2009–2018) which indicates that the supply of data from Qaanaaq (THL) is very stable. The number of PCS samples is somewhat lower because of longer intervals of unavailable Vostok data (particularly in 2012 and 2013). The number of PCC samples is the largest since either of the two PC index values would suffice to provide a PCC value (however of degraded quality).

The present IAGA-recommended “near real-time” PC index versions are not considered reliable as explained in Stauning (2018a, 2020b). The cubic spline-based solar wind sector (SS) terms in the reference level construction (Janzhura & Troshichev, 2011; Troshichev and Janzhura, 2012a) may generate excessive excursions reaching magnetic storm level magnitude at frequently occurring (not necessarily extreme) variations in the IMF $B_Y$ conditions or by short interruptions of the data supply. Moreover, these near real-time indices, which have been issued since February 2014, have never been verified or applied to published works. Recorded series of the “near real-time” PC indices appearing temporarily at the AARI and ISGI websites and precise descriptions of the derivation methods (apart from the SS term) are not available.

Figure 1. Vostok QDC reference levels 2015 by SRW method. (a) X-component and (b) Y-component. QDC, quiet day curve; SRW, solar rotation weighted.
Relations of PCN, PCS, and PCC to the Merging Electric Field

It was demonstrated in Stauning (2007) at the presentation of the PCC index concept that the PCC indices had a higher degree of correlation with the merging electric fields, $E_M$, than either of the individual, PCN or PCS, indices. This feature was confirmed in Stauning et al. (2008) and Stauning (2012). In a recent investigation (Stauning, 2021), the comparison of correlation results was extended to comprise also the plain average, PCA, of PCN and PCS as well as selections of either local winter or summer PC index values (PCW and PCU). Furthermore, the correlation of $E_M$ with a PCS (PCD) index version based on using magnetic data from Dome-C observatory (Chambodut et al., 2009; Di Mauro et al., 2014) was examined. Comparing the correlations between hourly values of $E_M$ and PCC, PCN, and PCS values throughout 2009–2018 are presented in Figure 4a here (see Stauning, 2021). In this figure, the PC indices are based on post-event derivation. The corresponding correlation coefficients derived from simulated real-time PC indices throughout 2009–2018 are displayed in Figure 4b.

4. Relations of PCN, PCS, and PCC to the Merging Electric Field

It was demonstrated in Stauning (2007) at the presentation of the PCC index concept that the PCC indices had a higher degree of correlation with the merging electric fields, $E_M$, than either of the individual, PCN or PCS, indices. This feature was confirmed in Stauning et al. (2008) and Stauning (2012). In a recent investigation (Stauning, 2021), the comparison of correlation results was extended to comprise also the plain average, PCA, of PCN and PCS as well as selections of either local winter or summer PC index values (PCW and PCU). Furthermore, the correlation of $E_M$ with a PCS (PCD) index version based on using magnetic data from Dome-C observatory (Chambodut et al., 2009; Di Mauro et al., 2014) was examined. Comparing the correlations between hourly values of $E_M$ and PCC, PCN, and PCS values throughout 2009–2018 are presented in Figure 4a here (see Stauning, 2021). In this figure, the PC indices are based on post-event derivation. The corresponding correlation coefficients derived from simulated real-time PC indices throughout 2009–2018 are displayed in Figure 4b.

A summary of epoch-average correlation coefficients for the relations between $E_M$ and the various index types in their post-event (PE) and SRT versions are presented in Table 2. It is seen by comparing Figures 4a–4b, as also noted in Table 2, that the real-time PC indices display almost the same correlations with $E_M$ as those found for the post-event values. It is also evident from Figures 4a and 4b and Table 2 that the correlation...
between $E_M$ and PCC or PCCD (PCC using PCD for poor PCS values) is superior to the correlation coefficients obtained with just PCN or PCS indices and also display much less seasonal variation. Thus, applications used to estimate values of the solar wind merging electric field, whether in real-time or post-event situations could take advantage of using the PCC (PCCD) index version instead of the individual PC indices or other combinations or selections.

It might be noted that the PCS indices (here named PCD) based on using data from Dome-C magnetometer provide slightly better correlations with $E_M$ than PCS indices based on data from the standard PC

---

Figure 3. (a) Simulated real-time (SRT) (upper part) and post-event (PE) PCS (middle part) index values based on Vostok magnetic data using common calibration parameters and HSRW and SRW QDC values, respectively. The lower part of the field displays their differences. (b) Differences between SRT (HSRW-based QDCs) and PE (SRW-based QDCs) PCN, PCS, and PCC indices. HSRW, half solar rotation weighted; QDC, quiet day curve; SRW, solar rotation weighted.
observatory, Vostok, whether in post-event or real-time versions. Another observation is the lower correlations of PCN with $E_M$ than found for either of the PCS indices. The main reason being the high NBZ occurrence rate at Qaanaaq compared to Vostok or, in particular, Dome-C.

5. The PC Indices and the Asymmetrical Ring Current Index, ASY-H

The asymmetrical (partial) ring current indices, ASY-H, are provided by Kyoto WDC-C2 (Iyemori et al., 2000) as 1-min values. For the present statistical study, a less detailed time resolution is considered appropriate. Hence, the ASY-H and the polar cap (PCN and PCS) indices have been averaged to form 15-min samples.

### Table 1

| Index type | Samples | SRT mean | PE mean | Mean diff. | Abs diff. | RMS diff. | Correlation |
|------------|---------|----------|---------|------------|-----------|-----------|-------------|
| Unit       | mV/m    | mV/m     | mV/m    | mV/m       | mV/m      | mV/m      |             |
| PCN        | 87,215  | 0.750    | 0.775   | −0.025     | 0.116     | 0.170     | 0.992       |
| PCS        | 80,590  | 0.809    | 0.830   | −0.021     | 0.108     | 0.158     | 0.991       |
| PCC        | 87,394  | 0.873    | 0.879   | −0.006     | 0.060     | 0.092     | 0.997       |

Figure 4. Display of monthly average coefficients for the correlation between hourly values of $E_M$ and PCN (blue line), PCS (red), and PCC (magenta). (a) Post-event PC indices 2009–2018 (similar to Figure 6 of Stauning [2021]). (b) Simulated real-time PC indices 2009–2018.
For the series of indices, the 15-min averaging intervals for the ASY-H indices were shifted with respect to the corresponding intervals for the PC indices to obtain maximum correlation.

The present investigation has considered 4-day intervals of major geomagnetic storms with Dst(peak) < −100 nT occurring between 2009 and 2018 and with the onset occurring on the first day. A complete list of these geomagnetic storm events, times, and amplitudes of their peak intensities (minimum hourly Dst or 15-min SYM-H values) are provided in Appendix A. These values are supplemented by corresponding times and max amplitudes for the PCC indices throughout each storm interval.

Figures 5a and 5b display scatter plots of 15-min ASY-H index values against PCC values derived by post-event (PE) or by simulated real-time (SRT) calculations, respectively. The PCC indices are based on the combination of Qaanaaq PCN and Vostok (or Dome-C observatory for 2012 and 2013) PCS indices. The

| Epoch 2009–2018 | PCCD | PCC | PCN | PCS | PCD |
|-----------------|------|-----|-----|-----|-----|
| Post-event      | 0.753| 0.751| 0.696| 0.722| 0.736|
| Real-time       | 0.749| 0.748| 0.692| 0.720| 0.728|

Table 2. Correlation Coefficients for Relations Between $E_M$ and Various PE or SRT PC Index Versions

Figure 5. (a) Scatter plot of ASY-H against post-event PCC index values for storm events in 2009–2018. The black squares indicate average values and number of 15-min samples within each unit interval in PCC, while the error bars at every other unit interval indicate standard deviation (spread). The red dashed line in Figure 5a is based on the regression in Stauning (2021). (b) Corresponding scatter plot of ASY-H against simulated real-time PCC index values for storm events 2009–2018. The red line is repeated from Figure 5a.
8-min delay noted in the figure was found to provide the least RMS deviation and optimum correlation for samples of the two index series. The samples are represented by their interval average values shown by black squares, sized to present the number of individual samples, and error bars to indicate RMS standard deviation. The error bars are placed in every other square dot to avoid blurring the overall impression.

A linear relation between 15-min samples corresponding to the dashed line in Figure 5a was estimated by least squares regression analyses based on data from the much larger group of storm events from 1992 to 2018 to provide the relation expressed in Equation 5 (from Stauning [2021]):

\[
\text{ASY-H}_{EQ} = 10.9 \times \text{PCC} + 16.1 \text{nT}
\]  

(5)

The validity of Equation 5 in real-time relations is examined by comparing the reported (real) ASY-H values with equivalent ASY-H_{EQ} index values provided by Equation 5 using post-event or simulated real-time PCC index values. The results are summarized in Table 3.

Further details on the relations between ASY-H indices and modeled ASY-H_{EQ} index values based on post-event (PE) PCC indices as well those based on the individual PCN and PCS indices and further possible combinations may be found in Figures 9 and 10 and Tables 2 and 5 of Stauning (2021). The correlation coefficient between the ASY-H and the real-time PCC-based ASY-H_{EQ} index series, although a little smaller than the coefficient for the post-event case, is still considerably larger than the corresponding coefficients for the relation between ASY-H and ASY-H_{EQ} based on post-event PCN, PCS, and PCA (the average of PCN and PCS) indices (see Table 5 in Section 10).

The non-negative PCC index resolves the conceptual dilemma in handling the frequently occurring cases of negative PCN or PCS values since the ASY-H indices rise for increasing positive as well as numerically increasing negative PCN or PCS index values making the relations ambiguous (see Figures 10a–10c of Stauning [2021]). With the PCC indices, whether in real time or post-event versions, the derived ASY-H_{EQ} index values are unambiguously defined, as shown in Figures 5a and 5b.

### 6. The PC Indices and the Symmetrical Ring Current Index, SYM-H

The relations between post-event (PE) or simulated real-time (SRT) PCC indices and SYM-H index values corresponding to those displayed in Figures 5a and 5b for the ASY-H indices are presented in Figures 6a and 6b. For the SYM-H versus PCC relations, contrary to the ASY-H versus PCC relations, it was not possible to define the delay (time shift) within examined 4 h that would provide maximum correlation. Table 3 presents imposed delays (SYM-H after PCC) and derived correlation coefficients for the 4-day magnetic storm events (Dst < −100 nT) with onset on the first day recorded throughout 2009–2018. The implications of the results are discussed in Section 9.

The differences between the SYM-H versus PCC display in Figure 6a for the post-event PCC version and in Figure 6b for the simulated real-time version are hardly discernible. The differences in correlation coefficients at corresponding time shifts (delays) depicted in Table 4 are also quite small.

| PCC version | 0 min | 60 min | 120 min | 180 min | 240 min |
|-------------|-------|--------|---------|---------|---------|
| Post-event  | 0.531 | 0.619  | 0.632   | 0.636   | 0.643   |
| Real-time   | 0.530 | 0.614  | 0.625   | 0.628   | 0.632   |

Note. Magnetic storms 2009–2018.

---

**Table 3**

Summary of Post-Event and Real-Time ASY-H_{EQ} Relations Versus ASY-H (15 Min Samples)

| PCC version | Samples | Mean PCC | Mean ASY-H | Mean ASY-H_{EQ} | Mean error | RMS error | Correlation |
|-------------|---------|----------|------------|-----------------|------------|-----------|-------------|
| Post-event  | 7,349   | 2.07 mV/m| 38.5 nT    | 38.6 nT         | −0.08 nT   | 20.9 nT   | 0.752       |
| Real-time   | 7,349   | 2.16 mV/m| 38.5 nT    | 39.6 nT         | −1.06 nT   | 21.2 nT   | 0.744       |

Note. Magnetic storms 2009–2018.
Examples of Displays of ASY-H and SYM-H During Magnetic Storms

In view of the good correlation between ASY-H and PCC demonstrated in Figures 5a and 5b and Table 3 (Rx(PE) = 0.752, Rx(SRT) = 0.744) for a delay of 8 min and the fair correlation between SYM-H and PCC shown in Figures 6a and 6b and Table 4 (Rx(PE) = 0.619, Rx(SRT) = 0.614) for a delay of 60 min, it might be expected that displays of the indices would show a fair degree of similarity between the real ring current indices and the PCC-based equivalent index values.

The slopes, ASY-H/PCC = 10.9 [nT/(mV/m)] and SYM-H/PCC = −11.5 [nT/(mV/m)], defined from the processing of 98 storm events (Stauning, 2021), have been used here with the simulated real-time PCC index versions to derive equivalent ASY-H\text{EQ} and SYM-H\text{EQ} values for selected magnetic storm events among those used to derive the relations. Examples for the 4-day magnetic storms on March 16–19 and June 22–25, 2015 are displayed in Figures 7a and 7b using the simulated real-time PCC index versions. Whether using post-event or real-time PCC index values actually changes little in the displays.

| Correlation | PCC | PCN | PCS | PCA\text{a} | PCW\text{b} | PCU\text{c} |
|-------------|-----|-----|-----|-------------|-------------|-------------|
| \(E_\text{M}\) | \textbf{0.764} | 0.714 | 0.727 | 0.720 | 0.732 | 0.707 |
| Kp          | \textbf{0.820} | 0.756 | 0.764 | 0.791 | 0.799 | 0.729 |
| ASY-H\text{d} | \textbf{0.743} | 0.702 | 0.679 | 0.716 | 0.700 | 0.683 |

\text{a}Plain average of PCN and PCS. \text{b}Selection of winter hemisphere PC indices. \text{c}Selection of summer hemisphere PC indices. \text{d}Storm events.

Table 5: Post-Event Correlation Coefficients for Epoch 1996–2016 (Table 5 of Stauning, 2021)

Figure 6. (a) Scatter plot of SYM-H against post-event PCC index values for storm events in 2009–2018. The black squares indicate average values and number of 15-min samples within each unit interval in PCC, while the error bars at every other unit interval indicate standard deviation. The red dashed lines are drawn for illustration only. (b) Corresponding scatter plot of SYM-H against simulated real-time PCC index values using the same red dashed line.
Note in Figures 7a and 7b the rather coarse agreement between ASYM-H or SYM-H and their PCC-based equivalent index series. However, the detailed courses of the PCC-based equivalent versions are rather different from those of the real ring current indices. The best agreement is seen in the displays of the ASY-H indices in the upper parts of the fields (black line with dots) and equivalent ASY-H_{EQ} values (red) converted from PCC index values by scaling. The lower parts display real SYM-H (black line with crosses) and Dst indices (magenta line), and equivalent SYM-H_{EQ} index values (blue) converted from PCC by scaling. The triangular symbols mark events of storm sudden commencements (SSCs).

Note in Figures 7a and 7b the rather coarse agreement between ASYM-H or SYM-H and their PCC-based equivalent index series. However, the detailed courses of the PCC-based equivalent versions are rather different from those of the real ring current indices. The best agreement is seen in the displays of the ASY-H indices in the upper parts of the fields (black line with dots vs. red lines), while the PCC-based SYM-H (blue) variations with periods of a few hours are hardly noticeable at all in the smooth real SYM-H (black with crosses) or Dst (magenta) indices in the lower parts. The lack of providing maximum correlation at extended time shift between the real and equivalent SYM-H series demonstrated in Table 4 indicates that the direct relation of PC index values with SYM-H or Dst indices is not meaningful for the strong magnetic storm events (peak Dst < −100 nT) considered here. This suggests that there is little basis for rules connecting peak times and amplitudes between PC and SYM-H or Dst indices like those expressed in Troshichev, Somarkov, et al. (2011), Troshichev and Janzhura (2012a), Troshichev and Sormakov (2018), or in ISO/TR23989:2020.

8. PC Indices in a Source Function for the Total Ring Current Indices, SYM-H and Dst

8.1. The Relation of Post-Event PC Indices to Ring Current Indices

The approach suggested in Stauning et al. (2008) and further developed in Stauning (2012, 2021) has been applied to provide extended examinations of the relations between real-time PC indices and the 1-h Dst
and 1-min SYM-H indices. Thus, the PCC indices are used in a source function to describe the gradient in the Dst indices rather than in correlations with the actual ring current index values. Following Burton et al. (1975), the change in the Dst index with time could be written:

\[
\frac{dDst*}{dt} = Q\left[\frac{ DST*}{nT} \right] - \frac{ DST^*}{nT} \frac{1}{\tau[h]} \]

(6)

where \( DST^* \) is the recorded Dst index values corrected for contributions from MPCs related mostly to the solar wind dynamic pressure. The quantity \( Q \) (in nT/h) is the source term while the last term in Equation 6 is the ring current loss function controlled by the decay time constant, \( \tau \), here measured in hours. For the small actual MPC corrections (~20 nT), the Dst dependent statistical values provided in Jorgensen et al. (2004) have been used here. The decay function in the version provided by Feldstein et al. (1984) uses \( \tau = 5.2 \) h for large disturbances where Dst < −55 nT, and \( \tau = 8.2 \) h for small disturbances where Dst > −55 nT. Now, the relation in Equation 6 may provide derived Dst index values by integrating from known start conditions, once the source term is defined.

From the investigations in Stauning (2021), the source term was defined to become \( Q(nT/h) = -4.5 (nT/h)/\left(mV/m\right) \cdot \text{PCC}(mV/m) \) to provide the best agreement between real and equivalent Dst values for an integration starting from Dst = 0 on January 1, 1992 and proceeding to December 31, 2018 without attachment to the real Dst values. From the same processing, the decay time constants were redefined to become \( \tau = 5.5 \) h for large disturbances where Dst < −52 nT, and \( \tau = 7.0 \) h for small disturbances where Dst > −52 nT. A coarse compensation for PC saturation effects was accomplished by adjustment of PCC amplitudes by adding a linearly rising amount to PCC values in excess of 5 mV/m:

\[
PCC_{eff} = PCC \text{ for } PCC < 5 \text{ mV/m} : PCC_{eff} = PCC + 0.60 \times \left( \text{ PCC} - 5 \right) \text{ for } PCC > 5 \text{ mV/m}
\]

(7)

The overall correlation coefficient for the relation between Dst and the equivalent Dst values was 0.856, the mean difference was −0.01 nT, while the RMS difference was 12.3 nT (Stauning, 2021). The relations from Stauning (2021) derived by using post-event PC index values are applied here using simulated real-time PC indices to replace post-event PC index values in the source function.

### 8.2. Simulated Real-Time Derivation of Ring Current Intensities From PC-Based Source Functions During Magnetic Storm Events

The updated parameters and simulated real-time PC index values were used for integration of the source function in Equation 6 to give simulated real-time equivalent ring current index values where \( Dst_{EQ,SRT} \) would be the hourly average of 1-min SYM-H \( \text{EQ,SRT} \) values. Examples are presented in Figures 8a and 8b where the integration of the source function has started at the real Dst values recorded at the start of the intervals and then allowed to proceed independently throughout the 4 days in each set. This type of processing was used in Stauning (2021) with post-event PCC values. Here, we apply the simulated real-time PC indices. The SYM-H values (green line) in Figures 8a and 8b track the Dst values quite well except for variations in response to the storm sudden commencements (SSCs) (http://isgi.unistra.fr). The SSC events are included in the figures with markings of their times of occurrence and amplitudes by the upward pointing peaks and sizes of the triangular symbols. The correlation between Dst and the simulated real-time (equivalent) Dst values is \( Rx = 0.960 \) for Figure 2a, which is better than the average correlation coefficient for the events of epoch 2009–2018 of 0.846 (cf. Table A1 of Appendix A). For Figure 2b, the correlation coefficient is \( Rx = 0.775 \) making it the worst example in 2015 (cf. Table A1 in Appendix A).

Compared to the initial (post-event) version in Stauning (2021), the use of simulated real-time PC indices has generated very little change in correlation coefficients and other parameters resulting from the calculations such as the mean and rms differences between real and equivalent Dst values.

The reduced range for the QDC derivation from the post-event standard range of ±40 days to just −40 days up to actual time has little effect on the reference levels for the PC indices. Furthermore, contrary to the IAGA-recommended cubic spline-based extrapolation method (see Stauning, 2018a), the QDC values are not strongly dependent on singular values or missing samples and generate reliable reference levels and index values.
Diagrams corresponding to Figures 8a and 8b and a summary table, Table A1, of Dst and SYM-H peak values are provided in Appendix A for all 20 cases of strong magnetic storms with Dst < −100 nT occurring during the decade from 2009 to 2018. For these 20 storm events with peak amplitudes ranging from Dst = −100 to −222 nT, the differences between the real Dst values and the simulated real-time equivalent Dst values could be characterized by the average correlation coefficient, $R_x = 0.846$ (0.840), the mean absolute difference, $D_{abs} = 19.3$ nT (19.7 nT), and the average rms difference, $D_{rms} = 24.3$ nT (24.7 nT). The small magnitudes of the deviations between SRT and PE versions demonstrate that the real-time estimates of Dst are about as valid as the post-event estimates.

8.3. Extended Simulated Real-Time Derivation of Ring Current Intensities

In a further development of the PC-based source function concept, the equivalent simulated real-time Dst indices have been derived for the decadal interval from 2009 to 2018 without attachment to the real Dst index values. The interim results for 2015 are displayed in Figure 9.

The display of $D_{st, SRT}$ based on simulated real-time PCC indices in Figure 9 is almost indistinguishable from the corresponding diagram of $D_{st, PE}$ based on post-event PCC values presented in Figure 15b of Stauning (2021). The post-event and the simulated real-time PCC index values differ by small and randomly
distributed contributions only (cf., Figures 3a and 3b). For a more comprehensive illustration, the Appendix A presents in Figures A3 and A4 further displays throughout 2011–2018 of Dst and values of \( \text{Dst}_{\text{EQ,SRT}} \) calculated from using PCC-based source function and integrated since 2009 without attachment to the real Dst values. For the years 2012–2013 where there are large gaps in Vostok magnetic data, the PCS values were based on using Dome-C data.

These calculations generate Dst gradients in simulated real-time which upon integration provide the Dst indices up one hour ahead. They illustrate the results made possible by calculations of Dst indices from a PCC-based source function with continuous access to magnetic data to provide PCN and PCS indices in real time. The process operates much like the forecast of Dst values (e.g., at space weather centers) based on data arriving from remote spacecraft in the solar wind.

**8.4. Predictability of Ring Current Intensities Derived From Polar Cap Indices**

Generally, the ring current intensities defined by the Dst or SYM-H indices start increasing when the gradient in Equation 6 assumes negative values as the PCC indices rise above zero. The \( \text{Dst}_{\text{EQ}} \) index values continue increasing their negative amplitude as long as the gradient in Equation 6 is negative. They may reach

![Figure 9. Real Dst values (blue line) and simulated real-time \( \text{Dst}_{\text{EQ,SRT}} \) values (magenta line) as the interim result for 2015 derived by integration of the simulated real-time PCC-based source function since 2009 without attachment to real Dst values. The triangular symbols mark events of storm sudden commencements (SSCs).](image-url)
peak minimum value at zero gradients even in cases where the PC indices are still large and rising. The ring current intensities decay when the gradient term in Equation 6 assumes positive values at conditions where the PCC-based source term becomes (numerically) smaller than the decay function term.

An important question is the predictability of the Dst (or SYM-H) values. The good agreement between real and simulated real-time Dst values ensures that the PCC-based expression in Equation 6 provides the actual Dst gradient. Thus, the Dst value could be estimated one hour ahead of its present value with fair precision.

It is believed that running a reliable operational estimate of ring current intensities one hour ahead could be a useful supplement to predictions of Dst values from space data derived from satellites such as the ACE satellite in the solar wind (e.g., Lundstedt et al., 2002; O’Brien and McPherron, 2000).

Considering the data collection from remote polar observatories in the harsh arctic environment, the reliability might be enhanced by establishing access to polar magnetic data from multiple sources (Stauning, 2018b). Thus, data from Resolute Bay (RES) might substitute for data from the standard observatory, Qaanaaq, for PCN values, while data from Dome-C could be substituted for data from the standard observatory, Vostok, for PCS values. The scaling coefficients should be taken from observatory-specific tables. The reference levels should be derived using the HSRW QDC scheme. Specifications of the on-line real-time derivation of PC index values are provided in the appendix to Stauning (2018c).

With the small contributions to the ring current indices from MPCs fixed at 20 nT, then the Dst (or SYM-H) indices could be derived with slightly reduced accuracy from the simplified version of Equation 6 shown in Equation 8, using the modified parameters from Stauning (2021):

\[
\frac{d(D_{st}^*)}{d\tau} = \text{grad}D \times PCC_{eff} \times D_{st}^* / \tau
\]

where, \(D_{st}^* = Dst - 20 \text{ nT}\), \(\text{grad}D = -4.5 \text{ nT/(mV/m)}\), \(PCC_{eff} = PCC\) if \(PCC < 5 \text{ mV/m}\) or \(PCC_{eff} = PCC + 0.6 \times (PCC - 5)\) if \(PCC > 5 \text{ mV/m}\), \(\tau = 5.5 \text{ h}\) if \(Dst < -52 \text{ nT}\) or \(\tau = 7.0 \text{ h}\) if \(Dst > -52 \text{ nT}\).

The integration of Equation 8 could be conducted in steps of one or a few (up to 5) minutes.

9. Discussions

Investigations aiming at deriving intensities of the solar wind merging electric field, \(E_M\) (Kan & Lee, 1979), from PC indices (e.g., Gao et al., 2012; Troshichev and Andrezen, 1985; Troshichev & Lukianova, 2002; Troshichev & Sormakov, 2015, 2018, 2019; Troshichev, Podorozhina, et al., 2011) might take advantage of the improved correlation available with the PCC indices over the individual PCN or PCS indices or other possible combinations such as their plain averages or the summer or winter PC index selection. The PCC approach solves the conceptual problem of having two at times quite different index values available for estimates of the energy arriving to the magnetosphere from the impinging solar wind. Using the PCC indices also avoids negative PC index values which could definitely not substitute for the non-negative merging electric field values.

Previous investigations have attempted to link ring current intensities to further observable solar wind or geospace parameters. The approach by Burton et al. (1975), which has provided basis for the method applied here, used the Y-component of the solar wind electric field to estimate ring current intensities defined by the Dst indices.

Including further solar wind parameters and using neural network technique, the work by O’Brien and McPherron (2000) have analyzed ring current dynamics aiming at forecasting the development of equivalent ring current indices Dst in real time based on ACE measurements at the L1 libration orbit. In a similar approach, Lundstedt et al. (2002) applied neural network for operational forecasts of the Dst indices from solar wind parameters without attachment to recorded Dst values. These comprehensive approaches have provided valuable insight in the role of various solar wind parameters and the processes responsible for the solar wind-magnetosphere interactions.

Stepanova et al. (2005) developed procedures for the prediction of Dst variations 1 h ahead from PC indices. The neural network in different versions used three sets of input parameters: 24 previous hourly averages of 1-min polar cap PCN indices, 24 previous hourly PCN standard deviation values, and 24 previous Dst values. The two versions based exclusively on PC indices appeared to saturate early at a predicted Dst level.
of around 75 nT even for cases of observed Dst values up to 120 nT. The third version attached also to the previous 24 real Dst values performed better reaching predicted values 1 h ahead close to the observed Dst indices with standard deviations on the order of 15 nT judged from their Figure 2.

Further reports on the relations between polar cap and ring current indices have been published by Troshichev, Somarkov, et al. (2011), Troshichev et al. (2014), Troshichev and Janzhura (2012a), Troshichev and Sormakov (2018), and in ISO Report TR23989 (ISO, 2020). These reports attempt to link total ring current indices, Dst or SYM-H, directly with the PC indices. However, in spite of the expressed importance for real-time space weather applications, none of the quoted publications actually used real-time (or simulated real-time) PC indices in their presentations although IAGA-recommended “near real-time” PCN and PCS indices have been displayed since February 2014 at the AARI website http://pcindex.org and also for recent years at the web portal http://isgi.unistra.fr of the International Service for Geomagnetic Indices (ISGI) supported by IAGA. Recorded “near real-time” PC index series have not been made available to the community.

10. Summary

10.1. Correlation of PC Indices With Solar Wind Merging Electric Field Intensities

It has been demonstrated here (Figure 4) that the non-negative combination, PCC, of the PCN and PCS indices have closer relations to the merging electric field, \( E_M \), in the solar wind with considerably higher correlation coefficients than either of the individual PC indices and further possible combinations.

The naming of the combined PCN and PCS indices, “PCC” index (Equation 4), enables a well-defined distinguishing between this index combination and other possible combinations or selections of PCN and PCS indices often just named “PC index.” Thus from published works:

Troshichev, Somarkov, et al. (2011): selection of local summer PC index values (PCU).
Troshichev, Podorozhkina, et al. (2011): PCN indices.
Troshichev and Janzhura (2012b): selections of local winter (PCW) and summer (PCU) indices.
Troshichev et al. (2012): PCN, PCS, local summer (PCU), and local winter (PCW) PC selections.
Troshichev et al. (2014): PCN and PCS. PC index version used in statistics is not defined.
Troshichev and Sormakov (2015, 2018): Average of PCN and PCS (PCA).

A more comprehensive analysis of the relations between \( E_M \) and various PC index series including the plain average of PCN and PCS and the selection of summer or winter PC indices and also the correlation with the \( Kp \) indices and the partial ring current indices, ASY-H, is provided in Stauning (2021). Table 5 from this study is quoted in Table 5 here. The correlation coefficients for epoch 1996–2016 noted in Table 5 agree well with those estimated here in the post-event version for epoch 2009–2018 as noted in Tables 2 and 3.

Thus, the present study confirms that PCC indices are superior over the hemispherical PC indices or further index combinations in applications involving the \( E_M \) parameter in the solar wind or global geomagnetic disturbances such as magnetospheric substorms and ring current developments because of their response to magnetic activity in both PCs and the adequate handling of negative PC index values.

However, the unipolar PCN or PCS indices could still be the better choice for studying relations to geomagnetic phenomena confined predominantly to the individual PCs, such as upper atmosphere auroral heating and reverse plasma convection during NBZ conditions.

10.2. Direct Correlation of PC Indices With 1-Min SYM-H and ASYM-H Indices

For the relations between the PC indices and the SYM-H and ASYM-H indices, there are coarse agreement between their averages taken over 6–12 h. For the more detailed variations on scales of one or a few hours, the ASY-H indices still to some extent show changes similar to the variations seen in the PC indices while the SYM-H (and Dst) indices display almost no response similar to the PC index variations. Thus, the ASY-H indices display some of the features seen in the PC indices while the direct correlation of PC indices with
SYM-H indices appears not to be meaningful. This result is expected since the total ring currents result from the integration (summation) of differential PC-related contributions.

10.3. Relations of PC Indices to Dst or Hourly Averages of SYM-H

It has been demonstrated that integration of a source function based on the non-negative PCC index combination (Equation 4), may provide equivalent Dst or SYM-H values that rather closely agree with observed (real) index values in real-time applications (Figures 7a, 7b, and 8). The PC-based source function may provide the actual Dst gradient in real-time which would then define the total ring current intensities (described by Dst or SYM-H indices) up to one hour ahead. The neural network-based techniques may provide important information on the relations between geomagnetic storms and solar wind conditions. It appears that this technique may provide forecasts of ring current intensities about 1 h ahead of the arrival of processed spacecraft data from satellites in the solar wind. However, the simple and reliable PC indices may provide a worthwhile supplement to space data based estimates of geomagnetic storm developments.

11. Conclusions

1. The “DMI2016” derivation methods used to calculate PC index values whether post-event or in real time are accurate and reliable and also well documented. The SRW QDC method described and applied here generates robust values of the reference level needed for calculations of PC indices and provides seamless transitions from real-time to post-event versions.
2. As suggested by previous studies (e.g., Stauning, 2021), the PC indices, particularly in the non-negative PCC index combination, have close relations with the merging electric fields \( E_M \) in the impinging solar wind assumed to control the input of energy from the solar wind to the magnetosphere. The provision of reliable PCC indices in real time as enabled by the methods presented here makes these indices particularly useful for space weather monitoring.
3. The partial ring current intensities characterized by the ASY-H indices relate directly to the PC indices whether in post-event or real-time versions with the closest correlation observed with the PCC index version over the individual PCN or PCS indices or further combinations. The total ring current intensities characterized by the Dst and SYM-H indices relate to the integration of a PCC index-based differential source function being the same for post-event and real-time applications.
4. The equivalent total ring currents intensities whether in real-time or post-event versions start rising as the PCC-based differential source function assumes negative values when either or both PCN and PCS indices are positive. They start decaying when the source function assumes positive values in the balance between contributions derived from the PC indices and the exponential decay function. The decay may start at any PC index level even at increasing PC index values.
5. For geomagnetic storm events, the integration of the PCC-based ring current source function in its real-time version may provide useful indications of ring current developments up to 1 h beyond actual time.
6. It was confirmed that the example integration of the PCC-based source function throughout the decade from 2009 to 2018 by using simulated real-time PC index values had generated equivalent Dst index values very close to the real Dst indices. The example demonstrates the potential application of PCC indices in space weather surveillance by enabling current monitoring of ring current intensities and providing estimates of their development one hour ahead.
7. The close relations between the partial and total ring current indices and their equivalent counterparts derived from the PC indices confirm the view that the PC indices represent the input of energy from the solar wind to the Earth’s magnetosphere and are valuable assets for space weather applications, particularly in their real-time dual hemisphere PCC index versions.

Appendix A

Diagrams and Table of Related Dst and PCC Indices for Storm Events 2009–2018

Corresponding Dst, Dst_{EQchemy}, and PCC_{SRT} indices for 4-day strong (Dst(peak) < −100 nT) geomagnetic storm events are displayed in Figures A1a–A1j and A2a–A2j. The PC index series was derived with the −40 to 0 days HSRW real-time QDC version.
Figure A1. Examples of published (real) Dst (black line, dots) and equivalent Dst\textsubscript{EQ,SRT} (magenta, crosses) values in the format like Figures 8a and 8b calculated from using the simulated real-time PCC\textsubscript{SRT} indices (magenta line) in the source function. Occurrence time and amplitudes of storm sudden commencements (SSCs) indicated by pointing and size of triangular symbols.
Figure A2. Examples of published (real) Dst (black line, dots), equivalent Dst_{EQ,SRT} (magenta, crosses), and simulated real-time PCC_{SRT} (magenta).
Figure A3. Real Dst values (blue line) and simulated real-time Dst_{EQ,SRT} values (magenta line) as the interim result for 2011–2014 derived by integration of the simulated real-time PCC_{SRT}-based source function since 2009 without attachment to real (published) Dst values. Occurrence time and amplitudes of storm sudden commencements (SSCs) are indicated by triangular symbols.
Figure A4. Real Dst values (blue line) and simulated real-time Dst_{EQ,SRT} values (magenta line) as the interim result for 2015–2018 derived by integration of the simulated real-time PCC_{SRT}-based source function since 2009 without attachment to real (published) Dst values.
The examples in Figures A1a–A1j and A2a–A2j comprise all 4-day intervals of strong magnetic storm events with \( Dst(peak) < -100 \text{ nT} \) occurring between 2009 and 2018 regardless of the actual correlation between \( Dst \) and \( Dst_{E_{EQ}} \). Essential characteristics of the individual events are depicted in Table A1.

**Data Availability Statement**

PCN and PCS index series derived by the IAGA-endorsed procedures are available through AARI and ISGI websites. Archived PCN and PCS data and SSC information used in the study were downloaded from [http://isgi.unistra.fr](http://isgi.unistra.fr) web portal in January 2020 unless otherwise noted. The website, [http://pcindex.org](http://pcindex.org), holds PCN and PCS index coefficients and includes the descriptive document “Polar Cap (PC) Index” (Troschichev, 2011). Geomagnetic data from Qaanaaq, Vostok, and Dome-C observatories were downloaded from the INTERMAGNET data service web portal at [http://intermagnet.org](http://intermagnet.org). Ring current indices, \( Dst \), SYM-H, and ASY-H were downloaded from the web portal for World Data Centre WDC-C2 in Kyoto at [http://swd-cwww.kugi.kyoto-u.ac.jp/dstdir/index.html](http://swd-cwww.kugi.kyoto-u.ac.jp/dstdir/index.html). Spacecraft data needed to generate the merging electric field values were downloaded from the OMNIWeb service portal [http://omniweb.gsfc.nasa.gov](http://omniweb.gsfc.nasa.gov). SSC data were downloaded from the ISGI data service portal [http://isgi.unistra.fr](http://isgi.unistra.fr). The magnetic observatory in Qaanaaq is managed by the Danish Meteorological Institute, while the magnetometer instruments are 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 (France) and Istituto Nazionale di Geofisica e Vulcanologia (Italy). The “DMI2016” PC index version is documented in the report SR-16-22 (Stauning, 2016) available at the website http://www.dmi.dk/fileadmin/user_upload/Rapporter/TR/2016/SR-16-22-PCIndex.pdf.

Acknowledgments
The staffs at the observatories in Qaanaaq (Thule), Vostok, and Dome-C, and their supporting institutes are gratefully acknowledged for providing high-quality geomagnetic data for this study. The provision of space data from the IMP, ACE, Wind, and Geotail missions and the management of data by the OMNIWeb service, the supply of geomagnetic data from the INTERMAGNET data service center, and the excellent performance of the ISG1 and AARI PC index portals are greatly appreciated. The efforts from the geomagnetic observations in the collection of data for the Dst, SYM, and ASY indices and the processing at WDC-C2 in Kyoto are most gratefully acknowledged. The author gratefully acknowledges the collaboration and many rewarding discussions in the past with Drs. O. A. Troshichev and A. S. Janzhura at the Arctic and Antarctic Research Institute in St. Petersburg, Russia.

References

Burton, R. K., McPherron, R. L., & Russell, C. T. (1975). An empirical relationship between interplanetary conditions and Dst. Journal of Geophysical Research, 80, 4204–4214. https://doi.org/10.1029/JA080i031p04204

Chambodut, A., Di Mauro, D., Schott, J. J., Bordais, P., Agnoletto, L., & Di Fede, P. (2009). Three years continuous record of the Earth’s magnetic field at Concordia station (Dome-C, Antarctica). Annals of Geophysics, 52, 15–24. https://doi.org/10.4401/ag-4569

Dessler, A. J., & Parker, E. N. (1959). Hydromagnetic theory of geomagnetic storms. Journal of Geophysical Research, 64, 2239–2252. https://doi.org/10.1029/1JZ064i02p02239

DiMauro, D., Caffarella, L., Lepidi, S., Pietrolungo, M., Alfonsi, L., & Chambodut, A. (2014). Geomagnetic polar observatories: The role of Concordia station at Dome C, Antarctica. Annals of Geophysics, 57(6), G0656. https://doi.org/10.4401/ag-6605

Dungey, J. W. (1961). Interplanetary magnetic field and the aural zones. Physical Review Letters, 6, 47–48. https://doi.org/10.1103/PhysRevLett.6.47

Feldstein, Y. I., Pisarsky, V. Y., Rudneva, N. M., & Grafe, A. (1984). Ring current simulation in connection with interplanetary space conditions. Planetary and Space Science, 32, 975–984. https://doi.org/10.1016/0032-0633(84)90054-0

Gao, Y., Kivelson, M. G., & Walker, R. J. (2012). The linear dependence of polar cap index on its controlling factors in the solar wind and magnetotail. Journal of Geophysical Research, 117(A5). https://doi.org/10.1029/2011JA017229

IAGA. (2013). Resolution no. 3. Retrieved from http://www.iaga-aiga.org/resolutions

ISO. (2020). Space environment (natural and artificial) – Operational estimation of the solar wind energy input into the Earth’s magnetosphere by means of the ground-based polar cap (PC) index. (ISO Technical Report ISO/TR/23989-2020). International Organization for Standardization. Retrieved from https://www.iso.org/standard/77565.html

Iyemori, T., Araki, T., Kamei, T., & Takeda, M. (2000). Mid-latitude geomagnetic indices “ASY” and “SYM” for 1999. In T. Iyemori (Ed.), Geomagnetic indices homepage. WDC-C2 for Geomagnetism. Kyoto University. Retrieved from http://wdc.kugi.kyoto-u.ac.jp/wdc/Sec3.html

Janzhura, A. S., & Troshichev, O. A. (2011). Identification of the IMF sector structure in near-real-time by ground magnetic data. Annales Geophysicae, 29, 1491–1500. https://doi.org/10.5194/angeo-29-1491-2011

Jorgensen, A. M., Spence, H. E., Hughes, W. J., & Singer, H. J. (2004). A statistical study of the ring current. Journal of Geophysical Research, 109, A11204. https://doi.org/10.1029/2003JA010090

Kan, J. R., & Lee, L. C. (1979). Energy coupling function and solar wind-magnetosphere dynamo. Geophysical Research Letter, 6(7), 577–580. https://doi.org/10.1029/GL006i007p00577

Kappenman, J. (2010). Geomagnetic storms and their impact on the U.S. power grid. Metatech Report, Meta-R-319, 197.

Lundstedt, H., Gleinher, H., & Winitto, P. (2002). Operational forecasts of the geomagnetic Dst index. Geophysical Research Letters, 29(24), 218–221. https://doi.org/10.1029/2002GL016151

Matska, J. (2014). PC_index_description_main_document_incl_Appendix_A.pdf. Available at DTU Space web portal. https://doi.org/10.11581/DTU/90000057

Nielsen, J. B., & Willer, A. N. (2019). Restructuring and harmonizing the code used to calculate the Definitive Polar Cap Index. Report from DTU space. Retrieved from https://tinyurl.com/x3c3g65

O’Brien, T. P., & McPherron, R. L. (2000). Forecasting the ring current index Dst in real time. Journal of Atmospheric and Solar-Terrestrial Physics, 62, 1295–1299. https://doi.org/10.1016/S1364-6826(00)00702-9

Pulkkinen, A., Bernabeu, E., Thomson, A., Viljanen, A., Pirjola, R., Botelier, D., et al. (2017). Geomagnetically induced currents: Science, engineering, and applications readiness. Space Weather, 15, 828–856. https://doi.org/10.1002/2016SW001501

Sckopke, N. (1966). A general relation between the energy of trapped particles and the disturbance field near the Earth. Journal of Geophysical Research, 71, 3125–3130. https://doi.org/10.1029/JZ071i010p03125

Stauning, P. (2007). A new index for the interplanetary merging electric field and the global geomagnetic activity: Application of the unified Polar Cap (PCN and PCS) indices. AGU Space Weather, 5, S09001. https://doi.org/10.1029/2007SW000311

Stauning, P. (2011). Determination of the quiet daily geomagnetic variations for polar regions. Journal of Atmospheric and Solar-Terrestrial Physics, 73(16), 2314–2330. https://doi.org/10.1016/j.jastp.2011.07.004

Stauning, P. (2012). In M. Lazar (Ed.), The Polar Cap (PC) Indices: Relations to Solar Wind and Global Disturbances, Exploring the Solar Wind. InTech Publ. ISBN: 978-953-51-0339-4. https://doi.org/10.5772/37539

Stauning, P. (2013). Power grid disturbances and polar cap index during geomagnetic storms. Journal of Space Weather and Space Climate, 3, A22. https://doi.org/10.1051/swsc/2013044

Stauning, P. (2015). A critical note on the IAGA-endorsed Polar Cap index procedure: Effects of solar wind sector structure and reverse polar convection. Annales Geophysics, 33, 1443–1455. https://doi.org/10.5194/angeo-33-1443-2015

Stauning, P. (2016). The Polar Cap (PC) Index: Derivation procedures and quality control. DMI Scientific Report, 33, 1443–1455. https://doi.org/10.5194/angeo-33-1443-2015

Stauning, P. (2018a). A critical note on the IAGA-endorsed Polar Cap (PC) indices: Excessive excursions in the real-time index values. Annales Geophysics, 36, 621–631. https://doi.org/10.5194/angeo-36-621-2018

Stauning, P. (2018b). Multi-station basis for Polar Cap (PC) indices: Ensuring credibility and operational reliability. Journal of Space Weather and Space Climate, 8, A07. https://doi.org/10.1051/swsc/2017036

Stauning, P. (2018c). Reliable Polar Cap (PC) indices for space weather monitoring and forecast. Journal of Space Weather and Space Climate, 8, A49. https://doi.org/10.1051/swsc/2018031

Stauning, P. (2020a). Using PC indices to predict violent GIC events threatening power grids. Journal of Space Weather and Space Climate, 10, A3. https://doi.org/10.1051/swsc/2020004

Stauning, P. (2020b). Using PC indices to predict violent GIC events threatening power grids. Journal of Space Weather and Space Climate, 10, A3. https://doi.org/10.1051/swsc/2020004
Stauning, P. (2020b). The Polar Cap (PC) index: Invalid index series and a different approach. *Space Weather*, 16, e2020SW002442. https://doi.org/10.1029/2020SW002442

Stauning, P. (2021). The Polar Cap (PC) index combination, PCC: Relations to solar wind properties and global magnetic disturbances. *Journal of Space Weather and Space Climate*, 11, 2021. https://doi.org/10.1051/swsc/2020074

Stauning, P., Troshichev, O. A., & Janzhura, A. S. (2012). Polar Cap (PC) index. Unified PC-N (North) index procedures and quality. *DML Scientific Report*, SR-06-04 (revised 2007 version). Retrieved from http://www.dmi.dk/fileadmin/Rapporter/SR/sr06-04.pdf

Stauning, P., Troshichev, O. A., & Janzhura, A. S. (2018). PC index as a proxy of the solar wind energy that entered into the magnetosphere: 3. Development of magnetic storms. *Journal of Atmospheric and Solar-Terrestrial Physics*, 180, 6521–6540. https://doi.org/10.1016/j.jastp.2017.10.012

Stauning, P., Troshichev, O. A., & Janzhura, A. S. (2019). PC index as a proxy of the solar wind energy that entered into the magnetosphere: (5) Verification of the solar wind parameters presented at OMNI website. *Journal of Atmospheric and Solar-Terrestrial Physics*, 196, 105147. https://doi.org/10.1016/j.jastp.2019.105147

Vennerstrøm, S. (1991). *The geomagnetic activity index PC*. (PhD Thesis, Scientific Report 91-3) (p. 105). Danish Meteorological Institute. Retrieved from https://www.dmi.dk/fileadmin/user_upload/Rapporter/8R/1991/sr91-3.pdf