The Polar Cap (PC) Index: Invalid Index Series and a Different Approach

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Abstract The Polar Cap (PC) indices are derived from the magnetic variations generated by the transpolar convection of magnetospheric plasma and embedded magnetic fields driven by the interaction with the solar wind. The PC indices are potentially very useful for space weather monitoring and forecasts and for related research. However, this study suggests that the PC index series in the near-real-time and final published versions endorsed by the International Association for Geomagnetism and Aeronomy (IAGA) are invalid and unreliable. Both versions include solar wind sector (SWS) effects in the calculation of the reference levels from which magnetic disturbances are measured. The SWS effects are caused by current systems in the dayside Cusp region related to the Y-component, BY, of the interplanetary magnetic field (IMF). However, the IAGA-endorsed handling of SWS effects may generate unfounded PC index changes of up to 4 mV/m at the nightside away from the Cusp. For the real-time PCN and PCS indices, the cubic spline-based reference level construction may cause additional unjustified index excursions of more than 3 mV/m with respect to the corresponding final index values. Noting that PC index values above 2 mV/m indicate geomagnetic storm conditions, such unjustified contributions invalidate the PC index series and prove the IAGA-endorsed derivation methods erroneous. Alternative derivation methods are shown to provide more consistent index reference levels for both final and real-time PC indices, to reduce their unfounded excursions, and to significantly increase their reliability.

1. Introduction

The Polar Cap (PC) indices, PCN (North) and PCS (South), are based on magnetic data recorded at the central polar cap observatories in Qaanaaq (Thule) in Greenland and Vostok in Antarctica, respectively. The PC index concept was developed through the pioneering works of Troshichev and Andrezen (1985) and Troshichev et al. (1988). Further PC index developments were made by Vennerstrøm et al. (1991). A fundamental description of the PC index derivation methods and their physical meaning was published by Troshichev et al. (2006).

To derive PC index values, magnetic variations related to the transpolar convection of plasma and magnetic fields are calibrated to equal values of the merging electric field (Kan & Lee, 1979) in the undisturbed solar wind. Thus, the PC indices represent the merging processes between the solar wind magnetic fields extending from the Sun and the terrestrial magnetic fields at the front of the magnetosphere and could be considered representative of the energy input from the solar wind. This energy may be temporarily stored in the magnetospheric tail configuration to be dissipated in processes such as auroral substorms, upper atmosphere heating, and ring current enhancements.

Final (postevent) PCN and PCS index series have been used to investigate relations between interplanetary parameters and polar cap magnetic disturbances (e.g., Huang, 2005; Troshichev & Lukianova, 2002) and the electric potentials in the polar cap ionosphere (e.g., Nagatsuma, 2002; Ridley & Kihn, 2004; Troshichev et al., 2000).

The relations between the polar cap indices and auroral activity were studied, among others, by Troshichev and Andrezen (1985), Vennerstrøm et al. (1991), Vassiliadis et al. (1996), Liou et al. (2003), and Huang (2005). The relations between positive and negative PC index values and Joule heating of the atmosphere were investigated by Chun et al. (1999, 2002). Most investigations have given correlation coefficients ranging between 0.6 and 0.8 between polar cap index values and parameters characterizing auroral activity.
In substorm studies, Janzhura et al. (2007) have used the PC indices to predict the duration of the growth phase in substorm developments. For isolated events, they estimated that substorm onset would occur as the PC index level reached ~2 mV/m. From investigations of a large number of substorms, Troshichev et al. (2014) concluded that substorm onset was likely to happen when the PC index starting from a low level exceeded 1.5 ± 0.5 mV/m.

In studies of geomagnetic storms by Stauning et al. (2008) and Stauning (2012), the PC indices have been used in source functions to predict the development of ring current intensities characterized by Dst index values. Troshichev and Sormakov (2017) have used PC indices to predict the maximum geomagnetic storm intensities (Dst minima).

An important application of real-time PC indices is the forecast of strong substorms that may threaten power grids through their geomagnetically induced current (GIC) effects (e.g., Kappenman, 2010; Pulkkinen et al., 2017). An investigation of GIC-related high voltage power line disturbances in Scandinavia (Stauning, 2013c) has demonstrated that the PC index values most often remained at a high level for more than 2–3 hr up to the power line cuts. The lengthy pre-event intervals are most likely needed for enabling the merging processes at the front of the magnetosphere and subsequent transpolar convection characterized by the PC index to load the tail configuration with enough energy to generate violent substorm events. The intense merging processes may also be necessary for making the polar cap expand enough to enable substorm activity reaching subauroral latitudes where important power grids reside. According to these investigations, PC index levels above 10 mV/m maintained through more than 1 hr should cause alert for subauroral power grids (Stauning, 2020).

In the past, a diversity of PC index versions have been in play at the above-mentioned (and many further) investigations (Stauning, 2013a), which seriously reduce their scientific value. Thus, much effort has been invested in attempts to generate commonly accepted PC index versions (e.g., Stauning et al., 2006; Troshichev et al., 2006). On the basis of the documentation provided in Matzka (2014), new PC index versions were adopted by IAGA by its Resolution no. 3 (2013) with the text:

IAGA, noting that polar cap magnetic activity is not yet described by existing IAGA geomagnetic indices, considering that the Polar Cap (PC) index constitutes a quantitative estimate of geomagnetic activity at polar latitudes and serves as a proxy for energy that enters into the magnetosphere during solar wind-magnetosphere coupling, emphasising that the usefulness of such an index is dependent on having a continuous data series, recognising that the PC index is derived in partnership between the Arctic and Antarctic Research Institute (AARI, Russian Federation) and the National Space Institute, Technical University of Denmark (DTU, Denmark) recommends use of the PC index by the international scientific community in its near-real-time and definitive forms, and urges that all possible efforts be made to maintain continuous operation of all geomagnetic observatories contributing to the PC index.

Thus, the IAGA recommendations comprise both the final and the near-real-time versions of PCN and PCS indices. Until the final values could be issued, the indices may be available in provisional versions. At present, the PCN indices are distributed in all versions, while the PCS indices are distributed in their near-real-time and provisional versions only. The indices are distributed from the web portals http://pcindex.org operated by AARI and http://isgi.unistra.fr operated by the International Service for Geomagnetic Indices (ISGI).

However, as shall be demonstrated, the near-real-time values as well as the final PC index series are invalidated by the questionable handling of solar wind sector effects in reference level calculations. In brief, the IAGA-endorsed PC index series, whether postevent (“final”) or near-real time, are invalid since the reference level construction based on daily median values may generate IMF B_y-related, unjustified (false) index contributions as shown in sections 3 and 4.

The near-real-time PCN and PCS indices (in addition) are unreliable since excessive excursions compared to their postevent values may occur at unfortunate IMF B_y variations and at previous irregularities in the data supply as demonstrated in section 5. Section 6 presents a different approach that circumvents the invalidation features of the IAGA-endorsed methodology. It is followed by discussions in section 7 and conclusions.
The unreliable features in the near-real-time indices are mainly consequences of the invalid reference level handling principles (see Section A of the Supporting Information). In addition, the PCS index series is unreliable since large inexplicable unjustified index contributions appear (see Section B of the Supporting Information).

2. Calculation of Polar Cap Indices

The transpolar (noon to midnight) convection of plasma and magnetic fields driven by the interaction of the solar wind with the magnetosphere generates electric (Hall) currents in the upper atmosphere. These currents, in turn, induce magnetic variations at ground level (Troshichev et al., 1988, 2006; Vennerstrøm, 1991). For derivation of PC indices from the recorded horizontal magnetic field vector series, $F$, the horizontal magnetic variations, $\Delta F = F - F_{RL}$, with respect to an undisturbed reference level ($RL$), $F_{RL}$, are projected to a direction in space assumed to be perpendicular to the transpolar convection-related currents in order to focus on solar wind effects. The optimum direction is characterized by its angle, $\varphi$, to the E-W direction. Next, $\Delta F_{PROJ}$ values are scaled to make the PC index equal on the average to the solar wind merging electric field, $E_M$ (Kan & Lee, 1979). Thus,

$$PC = (\Delta F_{PROJ} - \beta)/\alpha \approx E_M.$$ (1)

The optimum angle, $\varphi$, and the propagation delay, $\tau$, between the reference location for the solar wind data and the location for related effects at the polar cap are both estimated from searching the optimum correlation between $E_M$ and $\Delta F_{PROJ}$. The calibration constants, the slope, $\alpha$, and the intercept, $\beta$, are found by linear regression between $\Delta F_{PROJ}$ and $E_M$ through an extended epoch of past data.

3. PC Index Reference Level

For the reference level from which polar magnetic disturbances are measured, different concepts have been used. In the version developed by Vennerstrøm et al. (1991), just the secularly varying base level, $F_{BL}$, was used. This level does not reflect the daily magnetic variations during undisturbed conditions. However, the calibration parameters, notably the intercept coefficient, reflect the undisturbed daily variation averaged over the epoch used for the regression (Vennerstrøm, 1991).

$$F_{RL} = F_{BL}.$$ (2)

In the version developed at the Arctic and Antarctic Research Institute (AARI) in St. Petersburg, Russia, the varying level on "extremely quiescent days" (Troshichev et al., 2006) was used as the PC index reference level. This level could be considered built from a quiet day curve (QDC), $F_{QDC}$, added on top of the base level, $F_{BL}$. Thus, in vector formulation (AARI, Troshichev et al., 2006),

$$F_{BL} = F_{BL} + F_{QDC}.$$ (3)

Extremely quiescent days are rare particularly at polar latitudes. Therefore, the concept was broadened to imply the generation of QDC values from quiet segments of nearby days. The QDC calculations are detailed in Janzhura and Troshichev (2008) (hereinafter J&T2008): From the recordings during 30 days at a time, the variability in the 1-min samples within each 20-min section of recorded data is used to decide whether the section is quiet enough to let the average value be included in the construction of an initial QDC by superposition of quiet samples. The particular day for the QDC is determined by the relative amounts of quiet samples and usually positioned at the middle of the considered interval. The 30-day interval is then shifted forward and the QDC calculations repeated to be referred to another (or eventually the same) day. Finally, from the sequence of initial 30-day QDCs, the final QDCs for any of the days are found by smoothing interpolation. It should be noted that the choice of using the 30-day interval at a time implies evening out possible solar wind sector (SWS)-related effects which may have cyclic variations with the 27.4-day solar rotation. (The notation “SWS” is used here instead of “SS” used elsewhere).

In order to handle the SWS-related variations, $F_{SWS}$, caused mainly by the effects from the Y-component, IMF $B_Y$, of the interplanetary magnetic field (IMF), on the convection patterns, it was suggested by
Menvielle et al. (2011) that the reference level should be constructed from using a particular solar wind sector term, $F_{SWS}$, added to the base level and the regular QDC.

$$F_{RL} = F_{BL} + F_{QDC} + F_{SWS},$$  \hspace{1cm} (4)

It should be noted that this concept marks an infringement of the QDC definition in Troshichev et al. (2006) by introducing a reference level contribution, $F_{SWS}$, which is not necessarily quiet. There is no validation of this concept given in Menvielle et al. (2011).

The SWS concept is further specified in Janzhura and Troshichev (2011) (hereinafter J&T2011). At the interaction between the solar wind and the magnetosphere, as explained in J&T2011, the IMF BV components generate field-aligned currents (FAC) and associated horizontal currents in the Cusp region near local noon at 75–80° geomagnetic latitude. In p. 1492 of J&T2011, they state that “the QDC level displays long-term changes, which are determined by the sector structure.” Further, they state “Thus, if we are going to analyze the polar cap magnetic activity produced by the IMF fluctuations related to disturbed solar wind, we have to exclude first the sector structure effect.”

One implication of their statement is that the IMF BV component when varying slowly (few days to 2 weeks) is not affecting the polar magnetic disturbance levels. The issue has not been properly validated and the implication might be incorrect. The second issue, which shall be discussed to some extent here, is whether the applied data handling techniques actually remove the sector structure effects or just (as will be shown) generate inconsistent features and odd results. In J&T2011, the sector structure effects are derived from daily median values of the recorded polar magnetic field components that vary with the IMF BV component in the solar wind. In the postevent version, the SWS terms are derived from daily median values smoothed over 7 days with the day of interest at the middle. In the near-real-time version, the actual day's SWS value is derived by cubic spline-based extrapolation of past daily median values. The regular 30-day QDC, $F_{QDC,SWS}$, is derived from the recorded data less the SWS effect (Janzhura & Troshichev, 2011). Thus, $F_{RL} = F_{BL} + F_{SWS} + F_{QDC}$.  \hspace{1cm} (5)

For the IAGA-endorsed version (Matzka, 2014), the base level in the AARI version in Equation 3 (Troshichev et al., 2006) is replaced by a median-based level, $F_{M}$. The modified QDC term, $F_{QDC,SWS}$, is derived from the data series, $F$, less the $F_{M}$ values (IAGA, Matzka, 2014).

$$F_{RL} = F_{M} + F_{QDC,SWS} = F_{BL} + F_{SWS} + F_{QDC}. $$  \hspace{1cm} (6)

Actually, this is the same concept as the one defined in J&T2011 except that the secular variations are now included in the median values (Nielsen & Willer, 2019) instead of being included in the base line values. Thus, the IAGA concept could be discussed on the basis of the J&T2011 publication, which—so far—holds the only existing presentation of the QDC and SWS properties issued from the providers of the IAGA-endorsed PC indices. The SWS concept has been discussed in Stauning (2013b, 2015, 2018a, 2018b, 2018c).

### 4. Reference Levels for PC Index Calculations in the IAGA-Endorsed Postevent (Final) Version

The IMF BV-related variations in the daily course of the polar magnetic field components are important for calculations of the reference level for PC index calculations. It should be noted that the local time 24-hr cycle represents the daily course in the observatory position relative to the Cusp region located close to local noon at magnetic latitudes a few degrees equatorward of Qaanaaq latitude.

Like noted at p. 1492 in J&T2011, “the azimuthal IMF component controls the BY FAC (field-aligned current) system observed in the day-time cusp region during the summer season.” Thus, the anticipated IMF BV-related effects on the convection patterns should maximize near noon and be reduced near midnight when the observatory location is farthest away from the Cusp. For Qaanaaq data, this tendency is seen most clearly in displays of the H- (or Y-) component variations.
The interval from days 145 to 245 of 2001 is discussed in J&T2011 and therefore selected for a closer examination of data and derived values here. Figure 5b of J&T2011 displays the average daily variations in the H-components (all samples) recorded at Qaanaaq during the summer months, May–August, of 2001 for different levels of IMF BY. For the same data interval, Figure 1 here displays the corresponding IMF BY-related daily variations for the quietest days only. Values of the IMF BY component are derived from OMNIweb interplanetary satellite data service (http://omniweb.gsfc.nasa.gov).

The results in Figure 1 are largely the same as those of Figure 5b in J&T2011. Local midnight at Qaanaaq is at around 04:00 UT, noon at 16:00 UT. It is seen in both diagrams that the variations with IMF BY are small during the night while the daytime values, and thus the amplitude in the daily variations, depend strongly on the IMF BY level. Standard deviations for all three curves range from ±30 nT at night to ±60 nT at daytime.

With the variations in the QDC values with IMF BY displayed in Figure 1 during the months centered on 1 July and corresponding displays centered at different dates, the QDC values throughout the selected interval could be constructed. The resulting QDCs taking the seasonal as well as the IMF BY-related variations into account are displayed by the curve in heavy red line superimposed on the observed values of the H-component for days 145–245 of 2001 shown in Figure 2. Values of IMF BY smoothed corresponding to Figures 6 and 7 of J&T2011 are displayed by the lower curve with reference to the right scale. The upper envelope of the QDC values presents the night H-component values and varies little with IMF BY while the lower envelope, which presents the midday QDC values, varies strongly with IMF BY in agreement with the display in Figure 1. These QDCs could be considered to represent idealized QDC levels for the summer season of year 2001.

For the IAGA-endorsed postevent (final) PC index version, Figure 3 displays the construction of the reference levels. The upper three fields are based on interim values derived from PCN index calculations and supplied from the PCN index provider at DTU Space. For reference, the bottom curve (f) displays smoothed values of the IMF BY component (same as those displayed in Figure 2).

The upper curve (a) in Figure 3 displays the 30-day QDCSWS values for the Qaanaaq H-component derived according to the method defined in J&T2008 but based on recorded quiet data less the SWS terms. The next lower curve (b) displays the SWS terms derived as the differences (cf. Equation 6) between the 7-day smoothed daily median values and the secularly varying base line values interpolated...
between the yearly defined values (also supplied from DTU Space). The 0-nT dotted line represents base line values varying between 3895 nT on day 145 and 3899 nT on day 245.

The next lower curve (c) displays the resulting H-component reference level formed as the sum of the $H_{\text{SWS}}$ and $H_{\text{QDC.SWS}}$ values (cf. Equation 5). The horizontal dashed line across this curve (c) presents the uppermost level (3940 nT) of the mean H-component values in Figure 1 (or Figure 5 of J&T2011). Curve (c) is an almost exact replica of the H-component reference curve displayed in heavy line in Figure 1 of J&T2011 for which the caption states “the quiet daily curve (QDC) characterizing the daily variation of the quiet geomagnetic field.” However, there are serious problems with this choice of reference level:

1. Contrary to the caption for Figure 1 of J&T2011, the reference level is not “quiet” being composed from the sum of a quiet part and a median-based part that varies with the disturbance level.
2. The daily variations in the components imposed by the reference level construction are not in agreement with observed daily variations during corresponding conditions.
3. The upper envelope which represents night values of the daily variations in the H-component varies strongly with the varying IMF $B_Y$ level contrary to night values in Figure 1 (or Figure 5 of J&T2011). Some of the night reference values exceed considerably the uppermost statistical average values for corresponding IMF $B_Y$ conditions whether based on all data (Figure 5 of J&T2011) or just quiet values (Figure 1 here).
4. The amplitudes in the daily variation display seasonal variations only and do not vary with the IMF $B_Y$ level contrary to the strong amplitude variations seen in Figure 1 (or Figure 5 of J&T2011). For June (days 152–181) of 2001, the amplitudes in the daily reference level variations remain at approximately 100 nT,
while in Figure 1, the amplitudes vary with the relevant IMF $B_y$ levels ($-3$ to $+4$ nT) between approximately 50 and 150 nT.

5. Using the reference levels from Figure 3 and the corresponding levels for the D-component at index calculations generates peculiar daily variations in the SWS-related contributions to the PCN index. The SWS term, $F_{SWS}$, is a vector rotating with the Earth and must be projected to the optimum direction in space to derive its contribution to the PC index. During 24 hr, the projected term varies between positive (+) and negative (−) values; the maximum amplitudes are reached at two locations, one at daytime, the other at night, when the $F_{SWS}$ direction is parallel (or antiparallel) to the optimum direction. According to Equation 1, the effect on the PC index is $\Delta P_{C_{SWS}} = F_{SWS,PROJ}/\alpha$. The slope values, $\alpha$, are around two times larger at day than at night (cf. coefficient tables at http://pcindex.org). Thus, with the present calculation scheme, the nighttime $\Delta P_{C_{SWS}}$, inevitably, will be around twice the daytime contributions although the IMF $B_y$-related SWS effects caused by current systems at the Cusp region near noon in local time (Iijima & Potemra, 1976; Wilhelms et al., 1972) should maximize there and be minimal at night. This obvious conflict was addressed in Stauning (2013b and 2015).

Using both the H- and the D-components (or the X- and Y-components) of the data supplied from DTU Space enables specific calculations of the SWS effects on the PCN indices. The calibration parameters $(\varphi, \alpha, \beta)$ published at http://pcindex.org by the index providers have been used in the calculation of the contributions. The result for a selected day, 22 June 2001, is shown in Figure 4.

The display in Figure 4 based on the data supplied from DTU Space is very close to the results presented in Figure 4 of Stauning (2015) based on the data presented in J&T2011. The most controversial feature is the (numerical) maximum in the IMF $B_y$-related SWS contributions to the PCN index values at night with a depression of 2.5 mV/m at 06:00 UT near local midnight (04:00 UT). At this time, the THL observatory is farthest away from the Cusp region where the IMF $B_y$-related effects originate. The contribution is small at local noon (16:00 UT) where the observatory is closest to the Cusp region. The largest positive contribution of 1.5 mV/m is seen at 18:20 UT, a few hours past local noon.

A basic error in the method is the implied assumption that an SWS term calculated from daily median values can be applied throughout the whole day to remove SWS effects disregarding the variations of the IMF $B_y$-related solar wind sector effects with the varying observatory position in the polar cap. Thus, like concluded in Stauning (2015) from the corresponding display, the nightside PC index contributions shown in Figure 4 are unjustified (false) being generated mainly by the median-based reference level construction.

The example calculations displayed in Figure 4 were based on the case presented in J&T2011 with a smoothed IMF $B_y$ value of 4 nT, which is not uncommon. Unjustified SWS contributions of 3–4 mV/m could be expected for the stronger cases (larger IMF $B_y$). Such magnitudes are around twice the onset level of around 2 mV/m for magnetic storm or substorm activity (e.g., Troshichev et al., 2014). Further details on the case may be found in Section A of the Supporting Information.
5. Reference Levels for PC Index Calculations in the IAGA-Endorsed Near-Real-Time Version

For real-time calculations of PC index values, which is an important issue for space weather monitoring and forecasting, the 7-day smoothing of median values used for the final version is no longer applicable. Instead, a cubic spline extrapolation method specified in J&T2011 is applied to derive the actual SWS terms from past median values. The method uses 3-day average median values calculated every other day of the past 9 days to derive cubic spline polynomials, which are subsequently extended forward to define the actual SWS value. Based on data from the examined interval of June 2001, the method is illustrated in Figure 5 for 7–17 June using the terminology and rules from J&T2011. This figure simulate real-time operations as a way to explore problems with current techniques and in further examples used to demonstrate what may be a better technique.

Figure 5 demonstrates the cubic spline construction for deriving the SWS term on 16 June 2001. The 3-day median values (green dots) named according to the J&T2011 procedure as r1 (13–15), r2 (11–13), r3 (9–11), and r4 (7–9 June) are marked by black dots superimposed on the green ones. The natural cubic spline polynomials have been derived from these four points and define the curve in black line connecting the points. With the slope defined at the last point (14 June), the cubic spline construction is extended tangentially to 16 June where the resulting HSWS value (103 nT) is marked by a large black dot.

The dots (red) connected by a red line display the HSWS values derived the same way for further days within the interval from 7 to 16 June using past data only. The 3-day median values on 15, 16, and 17 June connected by the green dashed line segments were not available at the simulated real-time construction of HSWS for 16 June. They have been added to the figure for illustration of the “take-off” effects of the cubic spline extrapolation construction that generates the large deviation of the extrapolated SWS values compared to the postevent smoothed values (cf. Figures 3 and 6). This is an inherent effect when using the devised “near-real-time” method from J&T2011 to calculate solar sector effects. A similar figure for a different interval may be seen in Stauning (2018c).

The simulated real-time HSWS values for 7–16 June 2001 displayed in Figure 5 along with the corresponding HSWS values calculated the same way for the remainder of the days 145–245 of 2001 have been inserted as the jagged curve (d) in Figure 3. It should be noted that these values differ from the values presented by the smooth HSS curve in Figure 6 of J&T2011, which appear, contrary to their statements in p. 1496, to be derived from smoothed median values like the nearly identical values (from DTU Space) displayed by the June section of curve (b) in Figure 3. (an extended examination is available in Section A of the Supporting Information).

According to the principles for real-time PC index calculations defined in J&T2008, the 30-day QDC should be derived by adjusting the most recent 30-day QDC using the seasonal trend from last year’s QDCs. Since the QDCs in the formulation of J&T2011 (or Matzka, 2014) are derived from observed data less the SWS terms there is an obvious flaw in the arguments since the SWS-conditions are not necessarily the same at corresponding dates in different years.

Taking a shortcut by assuming that the actual near-real-time HQDC.SWS values are the same as the final HQDC.SWS values displayed by curve (a) of Figure 3 results in the simulated real-time H-component reference level displayed by curve (e) in Figure 3. The corresponding process would provide the simulated D-component real-time values. It is clear from comparing the reference levels defined for the final version (curve c of Figure 3) with those of the near-real-time version (curve e) that PCN values calculated by the near-real-time method must differ considerably from index values derived by the postevent method. The differences in PCN values are calculated from applying the procedure outlined in section 2 to the difference vector \( F_{DF} = (H_{SWS,RT} - H_{SWS,FIN}, D_{SWS,RT} - D_{SWS,FIN}) \) defined from the terms displayed in Figure 6. The
resulting effects on the differences between simulated real-time and postevent (final) PCN values throughout June 2001 are displayed in the bottom panel of Figure 6. The differences of up to 2.84 mV/m have been calculated from the final (smoothed) and the simulated real-time cubic spline extrapolated SWS vectors using consolidated calibration parameters (http://pcindex.org). The calculated examples agree well with results obtained from occasional downloads of near-real-time PCN and PCS values compared to the same index series downloaded at much later times. Differences of up to 3.09 mV/m for PCN (Stauning, 2018c) and up to 3.67 mV/m for PCS (Stauning, 2018a) were found in the examples displayed in Figure 7. Such differences related to using cubic spline extrapolated values instead of smoothed values of SWS terms may come on top of the unjustified SWS contributions discussed in section 4. The examples in Figure 7, furthermore, indicate that the SWS effects, which generate large index differences by their different handling in the near-real-time and postevent versions, are equally strong at the Northern and Southern Polar Caps. This result is contrary to the statement of the opposite in pp. 1492–1493 of J&T2011 where SWS effects are considered negligible for PCS values derived on the basis of magnetic data from Vostok on the Antarctic ice cap.

In Figure 7, the real-time values are those seen at the end of the traces termed "prompt." The remaining parts of the prompt traces are "postevent" values where the approximation to the "final" values is thought to be gradually improved as more postevent data become available from dates up to the download time.

Figure 6. From the top: Solar wind merging electric field (blue line, left scale) and IMF BY component (red line, right scale), $H_{SW}$ (simulated real-time) in magenta line and $H_{SW}$ (final) in black line, $D_{SW}$ (real time) and $D_{SW}$ (final), and (in bottom panel) differences between simulated real-time and final PCN values. Peak differences are noted.
However, the largest excursions, 3.09 mV/m in PCN and −3.67 mV/m in PCS, are seen at dates prior to the real-time days. Details of the IAGA-endorsed calculation methods are not available for further examination of this issue.

6. Reference Levels for PC Index Calculations in the DMI Version

In the DMI PC index version (Stauning, 2016), the definition of the “solar rotation weighted” (SRW) reference level construction published in Stauning (2011) returns to the statements in Troshichev et al. (2006) with the vector formulation in Equation 3 and to the methods outlined in J&T2008. The essential point for the SRW method is deriving the reference level from quiet samples collected at conditions otherwise as close as possible to those prevailing at the day of interest. The factors of primary importance are as follows:

1. Sample “quietness”;
2. Separation of date of samples from QDC date;
3. Solar wind conditions (particularly IMF BY and VSW);
4. Solar UV and X-ray illumination (based on solar radio flux F10.7 values).

For these factors, weight functions are defined. For each hour of the day, observed hourly average values at corresponding hours within an extended interval (+40 days) are multiplied by the relevant weights, added, and then divided by the sum of weights to provide the hourly QDC value. Subsequently, the hourly QDC values are smoothed to remove irregular fluctuations and interpolated to provide any more detailed resolution as required.

The weight function for sample quietness is determined from the variability of 1-min data values within the hour much like the technique used by J&T2008. Two parameters are calculated on a vector basis. One is the maximum time derivative used to indicate the smoothness within the sample hour. The other is the average variance to define the slope of data values. Both parameters need to take small values for the hourly sample to be considered “quiet” (flat and featureless display).

For an estimate of further weight functions, the factors of importance were subjected to an autocorrelation analysis versus separation between the date of interest and the dates of the samples to be included in the construction of the QDC values.
Details of the autocorrelation are provided in Stauning (2011). The main results were, as expected, high autocorrelation values at nearby dates and also high values at dates displaced one full solar rotation of 27.4 days from the day of interest. On these days the solar illumination and the solar wind conditions were similar on a statistical basis to the prevailing conditions on the day of interest. In between, at half a solar rotation, mixed autocorrelation results were found. In some cases, a local maximum was seen indicating the occurrence of four-sector solar wind structures. In most cases, the autocorrelation function had a deep minimum at half a solar rotation period when the opposite face of the Sun is pointing toward the Earth and the solar wind sector effect, most likely, is in the opposite direction (two-sector structure) or weak (multisector structure) (cf. Figure 6 of Stauning, 2013a).

The final weight factors for sample separation have a central maximum holding 50% of the total weights and two secondary maxima at a solar rotation period (27.4 days) before and after the QDC day holding weights corresponding to 25% of the total weight each. The total span of samples included in the QDC construction is set to ±40 days to encompass all three weight maxima. The separation weight factors are precalculated (see Stauning, 2011).

As data are collected, the quietness weight factors can be calculated promptly for each hour of recordings along with the hourly averages of each component. The three values are stored. The quietness weight factors are common for the two horizontal components and independent on their representation in (X,Y) or (H,D) coordinates.

Thus, at any time after 80 days of data collection, the relevant final QDC could be calculated for any day more than 40 days in the past. The hourly component averages and their quietness weight factors are fetched from their stored values and their separation weight factors are found from the tabulated values. For each hour of the day, the hourly average component values within ±40 days are multiplied by the weight factors and summed up. The products of weight factors are summed up. The sum of weighted component hourly average values is divided by the sum of weights to define the hourly QDC value.
The weighting technique allows calculations of real-time QDCs with reduced accuracy by simply ignoring missing samples without changing the calculation scheme. The DMI SRW method is illustrated in Figure 8 in a format similar to Figure 3 with smoothed values of IMF $B_y$ displayed by the bottom curve (d). The uppermost curve (a) displays $H_{QDC}$ values derived by weighting the samples collected at corresponding hours over ±40 days with their “quietness” factors only disregarding the solar rotation weight factors. Curve (b) displays postevent (final) solar rotation-weighted $H_{QDC}$ values. The next lower curve (c) displays simulated real-time $H_{QDC}$ values derived by using the SRW calculation scheme but including pre-event samples only (half solar rotation weighting, HSRW).

The upper envelope (night values) of the SRW QDC reference values in curve (b) displays small variations with IMF $B_y$ while the lower envelope (midday values) and the amplitudes in the daily variation display much stronger variations with IMF $B_y$ as anticipated from the features seen in Figures 1 and 2 here (and Figure 5 of J&T2011). The final QDCs in curve (b) should be compared to the reference levels in curve (c) in Figure 3. The simulated real-time QDCs in curve (c) in Figure 8 based on using past data only (−40 to 0 days) display more irregular variations than the QDCs based on the full amount (±40 days) as could be expected. However, the real-time reference QDCs in curve (c) in Figure 8 should be contrasted to the jagged real-time reference levels displayed by curve (e) in Figure 3. The horizontal dashed lines across the two middle fields present the uppermost level of average H-component values in Figure 1 (like those drawn in

**Figure 9.** Example of differences between simulated real-time and final PCN values derived by using HSRW QDCs on past data from days −40 to the present day only and SRW QDC using the full ±40 days sampling interval.
It is seen that the QDC reference values here—contrary to the reference levels displayed in Figure 3—remain below the uppermost level of statistical mean values for the relevant IMF BY ranges.

An example of the relations between postevent (final) and real-time PCN index values is depicted in Figure 9 using data from the previously selected interval spanning days 145–245 of year 2001.

The differences displayed in the bottom field of Figure 9 should be contrasted to those displayed at the bottom field of Figure 6 on the same scale. It is seen that the differences between calculated real-time and postevent PCN index values have been reduced considerably.

In Figure 7, the prompt index values were downloaded from the web portal http://pcindex.org in near-real time, while the postevent (final) index values were downloaded at a much later time. For further comparisons of IAGA-endorsed methods with the present DMI calculation scheme, Figure 10 presents for the same dates the simulated real-time values of PCN and PCS, which have been constructed from past data using HSRW QDC values on pre-event data only, while the postevent (final) PCN and PCS values have been derived by using the full ±40 days SRW-QDCs.

Comparing the differences between prompt and postevent PC index values in Figure 10 with those displayed in Figure 7 demonstrates the strongly reduced differences obtained by using the HSRW QDC derivation scheme instead of the IAGA-endorsed cubic spline extrapolation method.

An example of both the reduced differences between simulated real-time and final PC index values and the increased robustness to missing data with the DMI method compared to the IAGA-endorsed method is shown in Figure 11 from Stauning (2018c). The calculations are based on Qaanaaq (THL) data from 2015, which were exposed to irregular recordings at the end of July.

PCN index values could not (of course) be calculated where data are missing. The reference levels in the IAGA-endorsed versions are strongly affected by the missing or corrupted median values throughout intervals extending beyond the sections of missing data. The “IAGA PCN differences” of up to more than 4 mV/m in Figure 11 have been calculated from solar sector terms derived by using the procedure defined in J&T2011.

For space weather applications, the risk of false PC index values caused by missing data throughout parts of the days, which may cause large displacements of their median values, is probably still more important than...
missing index data. In an example discussed in Stauning (2018c), where data were made unavailable for 12 hr, the postevent PC index values were changed significantly throughout 13 days centered at the disturbed day. The near-real-time indices were changed throughout 8 days after the disturbance by up to 4 mV/m occurring 2 days after the 12-hr interval of unavailable data. Such amounts may falsely indicate (or hide) strong magnetic storm conditions without warnings.

In Figure 11, the “DMI PCN differences” between simulated real-time and final PCN index values in the versions based on the SRW techniques remain small (below 0.5 mV/m) and almost unaffected by intervals of missing data. In addition, and of prime importance for the potential use of real-time PC indices in space weather monitoring, the SRW-based QDC method (Stauning, 2011), as evident from Figure 11, is far more robust to data supply irregularities than the cubic spline-based forward extrapolation technique (J&T2011) that depends critically on the completeness of data samples.

The application of the DMI methods defined in Stauning (2016), to derive real-time and final PC index values from polar magnetic data assumed currently available, is detailed in the appendix of Stauning (2018c). In order to enhance the reliability of using PC indices for space weather applications, relevant magnetic data might be obtained for qualified PCN and PCS calculations from further observatories in the central Polar Regions like Resolute Bay and Dome C beyond the standard observatories, Qaanaaq and Vostok. Section B of the Supporting Information provides examples where PCS indices derived from Dome C magnetic data have helped to disclose serious errors in the published PCS data series. These errors are indicative of further problems in the PC index calculation methods used by the index provider at AARI.

7. Discussions

It should be stressed that the median-based reference levels used in the IAGA-endorsed versions are not quiet levels and thus differ from previous real or verbal definitions of the PC index reference level in publications included those listed as supporting references in the IAGA endorsement documentation written by Matzka (2014) (e.g., Janzhura & Troshichev, 2008, 2011; Troshichev, 2011; Troshichev et al., 2006; Troshichev & Janzhura, 2012a, 2012b). Even at the web portal (http://isgi.unistra.fr) of the International Service of Geomagnetic Indices (ISGI), the PC index definition states (incorrectly) that index values are derived from deviations from the quiet level. The use of a specific solar sector term in the PC index reference levels originating in Equation 8.3 of Menvielle et al. (2011) and further specified to become the median-based term in Janzhura and Troshichev (2011) has never been validated in publications.
A main objection against the IAGA-endorsed reference level construction is the resulting local time variation in IMF $B_\gamma$-related effects seen in the H-QDC component in Figure 3c or in the effects on the PCN index values seen in Figure 4. In both cases, the IMF $B_\gamma$-related effects contrary to anticipated principles maximize at local night when the observatory is farthest apart from the Cusp region where the IMF $B_\gamma$-related effects originate.

It is not, of course, questioned here that the IMF $B_\gamma$ conditions significantly affect the polar convection patterns and related magnetic variations. However, for the median-based reference level construction, the assumption that slowly varying IMF $B_\gamma$ levels would not affect geomagnetic disturbance conditions has never been validated and may be incorrect in the complicated interplay between the IMF $B_\gamma$- and $B_Z$-related effects.

A fundamental error in the IAGA-endorsed reference level derivation method is the implied assumption that SWS terms calculated from daily median values could be applied to remove solar wind sector effects throughout the whole day disregarding the variations in the IMF $B_\gamma$-related effects with the varying observatory position in the polar cap. The real IMF $B_\gamma$-related SWS effects on the PC indices could even be opposite of the constructed effects resulting from using reference level values derived by the median-based method.

IMF $B_\gamma$ variations may cause large changes in the dayside H-component (cf. Figure 1) which, in turn, should generate corresponding large variations in the PC index values (cf. Equation 1). The changes in the nightside H-components are small (Figure 1), which should imply small variations in the PC index values there. However, the reference level construction based on daily median values generates the same reference level change day and night (cf. Equation 6). On top, the PC index variations at the nightside are amplified by the smaller slope values compared to the dayside which further enhances the risk of generating unjustified PC index contributions at the nightside (cf. Figure 4). The dayside PC index variations, on the other hand, might be underestimated. This fundamental failure in the reference level handling invalidates the IAGA-endorsed PC index series whether in the postevent or in the near-real-time version.

The example PCN calculations displayed in Figure 4 with unjustified PC index contributions of up to 2.5 mV/m at midnight were based on the case presented in J&T2011 with a smoothed IMF $B_\gamma$ value of 4 nT, which is not uncommon. Unjustified SWS contributions of up to 4 mV/m could be expected for the stronger cases (larger IMF $B_\gamma$). Such magnitudes are around twice the onset level of around 2 mV/m for magnetic storm or substorm activity (e.g., Troshichev et al., 2014), which definitely makes the IAGA-endorsed “final” PCN indices unsuitable for scientific applications.

For the PCS indices, corresponding problems with the postevent reference levels may exist in spite of the statement in p. 1492–1493 of J&T2011 that SWS effects are negligible at Vostok on the Antarctic ice cap. It has not been possible to obtain a description of the present PCS calculation methods from the index provider (AARI) or from the index publisher (ISGI) for further examination of this issue.

For the real-time PCN and PCS indices, the excessive excursions in the cubic-spline extrapolated reference levels may generate unfounded differences between near-real-time and postevent index values of more than 4 mV/m. Such excursions with magnitudes at magnetic storm levels make the near-real-time IAGA-recommended PC indices unreliable and thus unsuitable for space weather monitoring and related research. Their strong vulnerability to intervals of incomplete data with the maximum adverse effects appearing 2 days after the occurrence of data irregularities is an additional invalidating feature to be considered.

It has not been possible to obtain descriptions of the real-time PCN and PCS calculation methods from the index provider (AARI) or from the index publisher (ISGI). It has also not been possible to obtain archived recordings of near-real-time PCN and PCS indices provided to the community through the AARI web portal http://pcindex.org and the ISGI web site http://isgi.unistra.fr for further examination of the quality of the near-real-time index data they deliver.

The concerns over the inconsistent index derivation methods and lack of documentation have been forwarded to the IAGA Executive Committee, the Index Task Force, and the Working Group representatives, and also to the PC index providers at AARI and DTU Space with suggestions for thorough analyses of PC
index calculation methods. The specific concerns have not been responded to and the suggestions for further analyses of the index derivation methods have been rejected so far. I hope the present document shall change this attitude.

8. Conclusions

1. The PC indices in their real-time versions have the potential to become very important tools for space weather monitoring and forecasts and in their final versions important for space weather-related research. However, the present study indicates that the published PCN and PCS index series are invalid.

2. The published series of (nominally) final PCN index values calculated by the methods endorsed by IAGA may include unjustified contributions of up to 4 mV/m just due to the handling of IMF $B_Y$-related solar wind sector effects in the reference level construction. An example case gave unjustified contributions of up to 2.5 mV/m (magnetic storm level) to PCN index values. Such unjustified contributions make the “final” PCN index series invalid.

3. The series of simulated real-time PCN and PCS index values calculated by the methods endorsed by IAGA may display considerable differences with respect to their corresponding postevent values. An example case using the referenced calculation procedures to the letter gave differences of up to 2.8 mV/m for a moderate event. Further examples of calculations of effects have given differences of more than 4 mV/m. At occasional downloads of near-real-time index values and comparison to later downloads of final values, differences of up to 3.7 mV/m have been documented in cases not particularly extreme.

4. The IAGA- endorsed near-real-time index calculation method based on cubic spline extrapolation of past median values is extremely vulnerable to irregularities in the data supply. An example of 12 hr of missing data gave unfounded excursions of up to 4 mV/m 2 days later. Such excursions may falsely indicate (or hide) strong magnetic storm conditions making the IAGA-recommended near-real-time indices highly unreliable and thus unsuitable for space weather applications.

5. It is suggested that IAGA initiates a careful evaluation of present index series and index derivation methods and ensures that full documentation of the presently applied index calculation procedures is made available in agreement with its Criteria for endorsement of indices by IAGA, sec.2 (2009). Presently, there is no available documentation of PCS index derivation procedures or of the near-real-time PCN and PCS calculation methods.

6. On the basis of the problems reported here, IAGA might consider encouraging developments of improved PC index calculation methods. The present study has demonstrated that alternative more accurate and reliable methods are available.

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Conflict of interest

I have no conflict of interests.

Data Availability Statement

Near-real-time (prompt) PC index values and archived PCN and PCS index series derived by the IAGA-endorsed procedures are available through AARI and ISGI web sites. Archived PCN and PCS data used in the paper were downloaded from http://pcindex.org on 15 November 2019 unless otherwise noted. The website, furthermore, holds PCN and PCS index coefficients, whereas QDC and SWS values are not included. The web site includes the document “Polar Cap (PC) Index” (Troshichev, 2011). It is presently not known (in spite of requests) whether the near-real-time PC index suppliers (AARI and ISGI) retain copies of the published values. If not available from the index suppliers, then values of occasionally downloaded values held by the author could be delivered, for instance, in their original (zip-encoded) formats to a data repository or included in a data supplement. Data for deriving $E_M$ and IMF $B_Y$ values have been obtained from OMNIweb space data service (http://omniweb.gsfc.nasa.gov). Geomagnetic data from Qaanaaq, Vostok, and Dome-C were supplied from the INTERMAGNET data service web portal (http://
intermagnet.org). The observatory in Qaanaaq is managed by the Danish Meteorological Institute, while the magnetometer there is 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 “DMI” PC index version is documented in the report SR-16-22 (Stauning, 2016) available online (http://www.dmi.dk/fileadmin/user_upload/Rapport/TR/2016/SR-16-22-PCindex.pdf).

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