No increase of the interplanetary electric field since 1926

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[1] The long-term variation of the interplanetary electric field is inferred back to 1926 from a correlation analysis with the magnetograms recorded at Godhavn and Thule, two polar cap geomagnetic observatories. The method is reliable because of the large dependence of the magnetic perturbation on the cross-polar cap electric field, i.e., the penetration and mapping of the interplanetary electric field into the magnetosphere-ionosphere system. This dependence is isolated by minimizing *Sq* and the Svalgaard-Mansurov effect. Both appear when an observatory moves closer to the polar cap boundary and are found to be a minimum in a direction almost perpendicular to the magnetic north. Strictly speaking, no secular trend in the solar wind-magnetosphere large-scale coupling is indicated for the past 77 years. This suggests that there is no secular trend in the interplanetary electric field and by inference in the Sun's open magnetic flux and in the solar wind speed. The method is independent of the *aa* geomagnetic index and the sunspot cycle characteristics. *INDEX TERMS:* 1650 Global Change: Solar variability; 1555 Geomagnetism and Paleomagnetism: Time variations—diurnal to secular; 2134 Interplanetary Physics: Interplanetary magnetic fields; 2475 Ionosphere: Polar cap ionosphere; 2776 Magnetospheric Physics: Polar cap phenomena; *KEYWORDS:* solar variability, IMF, polar cap, aa index

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1. Introduction

[2] Owing to its implications for both terrestrial and space climatology, the long-term (decades and beyond) solar variability has been intensely debated since *Lockwood et al.* [1999] reported a doubling of the Sun's open magnetic flux during the 20th century, including a 40% increase since the 1960s during the space era. Although the approximate twofold increase in the heliospheric field has been reproduced through a simple model by *Solanki et al.* [2000], several studies based on direct measurements found no long-term trend in the second half of the century. Using photospheric field observations from three observatories, *Arge et al.* [2002] find no evidence for an increase in the solar open flux since 1976. Using measurements of the mean magnetic field of the Sun as a star at four observatories, *Kotov and Kotova* [2001] found no increase since 1968. Using in situ observations of the interplanetary magnetic field (IMF) and the cosmic ray record, *Richardson et al.* [2002] detect no increase in the cycle averages of IMF strength since 1954. Although these observations disprove the reported increase after ~1955, they do not necessarily contradict *Lockwood et al.*'s [1999] main result. The latter is based on the *aa* geomagnetic index, which exhibited a remarkable secular rise during the last century, and it appears that the bulk of the rise was completed by ~1955. However, the calibration of the *aa* index has been questioned [*Svalgaard et al.*, 2004; L. Svalgaard and E. W. Cliver, Long-term variation of geomagnetic activity: 1. The IHV index, submitted to *Journal of Geophysical Research*, 2004, hereinafter referred to as Svalgaard and Cliver, submitted reference, 2004]. Clearly, an independent estimate of the IMF strength before 1955 not based on *aa* is needed.

[3] As a first step, we evaluate the long-term variation of the product *BV* of the solar wind speed, *V*, and the IMF strength, *B*. Our method exploits high-latitude ground magnetograms and has the advantage of being *aa*-independent. It principally rests on the long series of magnetograms recorded at Thule (Qaanaaq) and Godhavn (Qeqertarsuaq), both in Greenland.

[4] For polar cap stations like Thule (section 3), the diurnal variation of the horizontal magnetic components is particularly simple, amounting to a nearly sinusoidal wave with a magnitude controlled jointly by ionospheric conductivity and by the cross-polar cap electric potential. Because the latter is determined by the solar wind-magnetosphere coupling, a strong correlation between the sinusoid magnitude and observed *BV* for the 1964–2001 space era is found and applied back to 1947. For stations like Godhavn that are closer to the polar cap boundary (section 4), additional magnetic perturbations are observed when the station rotates closer to the auroral

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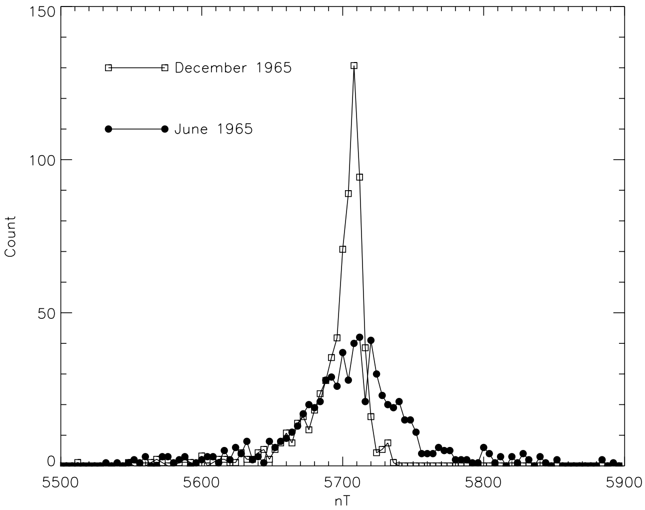

Figure 1. Monthly distributions of the northward component at Godhavn for June and December 1965.

oval. As we shall see, it is possible to identify a direction along which these perturbations are minimized. This allows the magnitude of the sinusoidal variation to be determined. The strong correlation between the so-determined magnitude and observed BV for the 1964–2001 epoch suggests applying it confidently back to 1926 (section 5).

2. Internal Magnetic Field

[5] Hourly values of the geomagnetic field have been used for this study. Data discontinuities have been determined and corrected by plotting their monthly distribution and identifying jumps. They are related either to the move of a station, like in 1976 for Godhavn, or to clerical errors, like for the Z component at Godhavn in the polar year 1932–1933.

[6] Magnetic field observations are the sum of the main field of internal origin and the field resulting from electric currents flowing in space. To isolate the field of external origin, an accurate determination of the internal magnetic field for any day of 1926–2002 is required. The International Geomagnetic Reference Field/Definitive Geomagnetic Reference Field (IGRF/DGRF) model gives the field of internal origin for 1940–2005 only, and local particularities are not included. To get a truly local main field, a property of high-latitude stations is exploited: monthly distributions of the field are found to be sharply peaked during winter months (Figure 1). This winter minimal variability (i.e., the small standard deviation) is explained by the daytime ionospheric conductivity, which remains at the low nighttime levels in winter. January and December peaks are then confidently identified with the main field and used to define its secular variation. Comparison with IGRF shows identical secular variation but with a systematic shift in the field magnitude at Godhavn (+240, −270, +780 nT for the northward, eastward, and vertical components, respectively). This local anomaly is caused by the rather magnetic basaltic bedrock. Daily values of the main field are finally obtained by interpolation and subtracted from the observed hourly values for the present study.

3. Thule Magnetograms

[7] With a corrected geomagnetic (CGM) [*Gustafsson et al.*, 1992] latitude of about 85° in 2000, Thule (THL) is a station very close to the magnetic pole that has been operating almost continuously since 1947. Figure 2 shows the 1990 average horizontal magnetic daily disturbance observed at THL once the main field is removed. The two horizontal components are in local geomagnetic coordinates. They both describe a sinusoid due to a polar cap current sheet rotating overhead. This is a constant feature of THL observations that exhibits a solar cycle dependence, as indicated in Figure 3 by the northward component during the 1956–2002 epoch. The Hall current sheet is part of a well-known current system determined by the cross-polar cap electric potential, Φ_{PC}. The current system also comprises the auroral electrojets and their associated field-aligned currents [e.g., *Hughes and Rostoker*, 1979]. Historically, the term DP2 has also been used to identify the system. The cross-polar cap electric field is primarily controlled by the IMF strength as well as by the solar wind dynamic pressure. It corresponds to the penetration of the large-scale interplanetary electric field, $-\boldsymbol{V} \times \boldsymbol{B}$, to ionospheric altitudes. It is then reasonable to investigate, in a statistical sense, the relationship between BV and the Sinusoidal Diurnal Variation (SDV) magnitude.

[8] A correlation between yearly averages, canceling any seasonal dependence, is performed. Data from 1964 to 2001 are considered and selected as follows. The hourly field magnitude average from the OMNI dataset is used as a measure of the IMF strength. For each day we determine a daily average BV and a SDV magnitude. To get an average BV, at least one hourly mean value is required. To ensure a proper SDV magnitude measurement, we require that all the 24 hourly values are available. We select the days for which both BV and SDV magnitude are available. The yearly

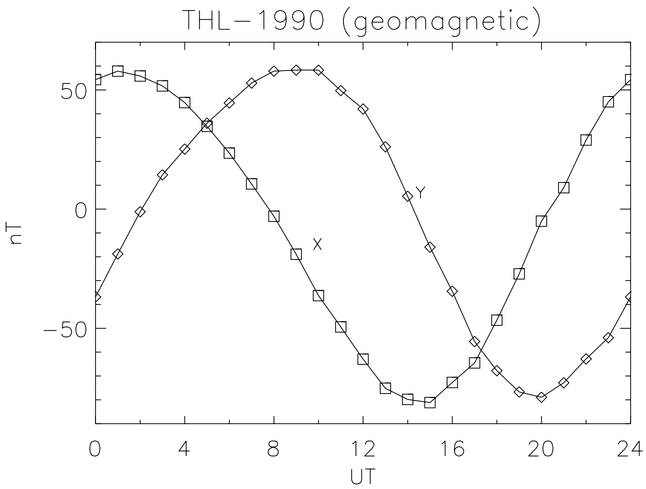

Figure 2. The 1990 average of the horizontal magnetic disturbance observed at Thule. X and Y are the northward and eastward components, respectively, in geomagnetic coordinates.

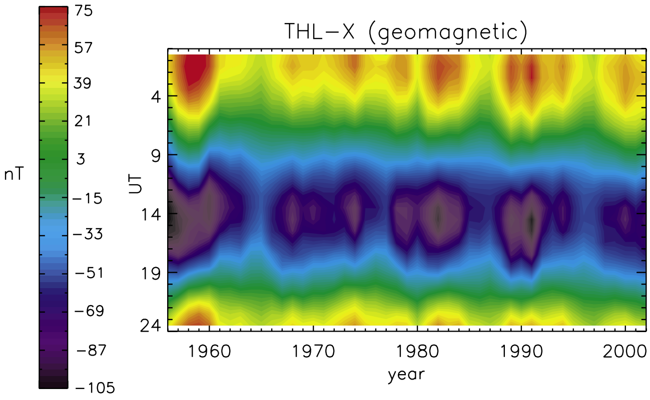

Figure 3. Yearly average of the daily variation of the northward (geomagnetic coordinates) magnetic disturbance at Thule from 1956 to 2002.

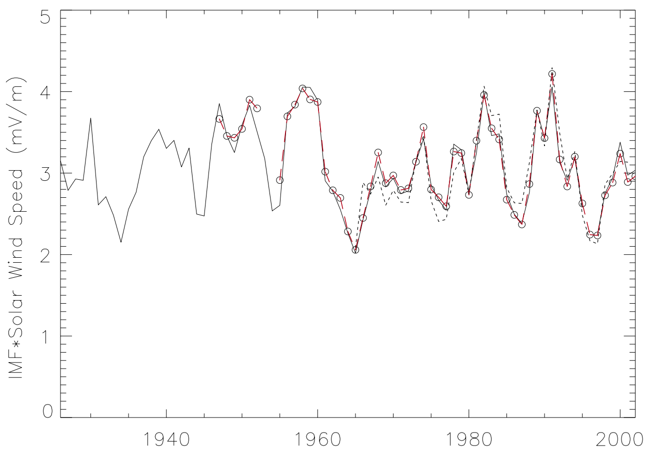

Figure 5. Yearly averaged *BV* inferred from the magnitude of all available diurnal variation at THL (long-dash red line with circles, 1947–2002), at GDH (solid line, 1926–2002), and measured from all available interplanetary near-Earth data (dash line, 1965–2001).

averages are then computed and a correlation analysis is performed. The results are shown in Figure 4, and it yields

$$\langle BV \rangle [\mathrm{mV/m}] = 0.351 + 0.0221\ SDV[\mathrm{nT}]. \quad (1)$$

Since the correlation is strong ($R^2 = 0.88$), the linear relation in equation (1) can be applied back to 1947, when observations started at THL. Figure 5 shows the *BV* reconstruction. Note that there has been no observation at THL between 16 October 1952 (day 252) and 1 September 1955 (day 244). The years 1953 and 1954 cannot provide any results, but averages from the partial 1952 and 1955 are scaled to represent a full year. The scaling factors are determined from all the full years between 1947 and 2002. The SDV magnitudes averaged over days 1–252 (244–365) are compared with the yearly average. A scaling factor of 0.90 (1.25) is found for 1952 (1955). Before discussing the results, we turn to the Godhavn observatory, which has been in operation since 1926.

4. Godhavn

4.1. Magnetogram Characteristics

[9] With a CGM latitude around 76°, Godhavn (GDH) is inside the polar cap but also closer to its boundary than THL is. Because of this particular location, supplementary magnetic perturbations appear on top of the SDV. This is clearly visible in Figure 6, which depict the yearly average variation of the northward component at GDH for the interval 1926–2000. The sinusoidal variation is clearly visible. The ellipse drawn in Figure 6 indicates the additional perturbations centered on local noon (~1400 UT). They have been attributed to the *Sq* perturbation and the Svalgaard-Mansurov effect.

[10] The *Sq* current flows in the sunlit part of the ionosphere and is produced by dynamo action (see reviews by *Wagner et al.* [1980] and *Richmond* [1995]). Driven by the neutral wind, it is not modulated by IMF. The Svalgaard-Mansurov effect [e.g., *Nishida*, 1978; *Wilcox*, 1972] is caused by the azimuthal component of IMF [*Friis-Christensen et al.*, 1972]. It is seen as an increase (decrease) of the horizontal field around the noon meridian for an east-west (west-east) IMF [e.g., *Svalgaard*, 1973]. It has been related to a *DPY* current located in the dayside cleft. The *DPY* currents have been identified as an extension across noon of the electrojets

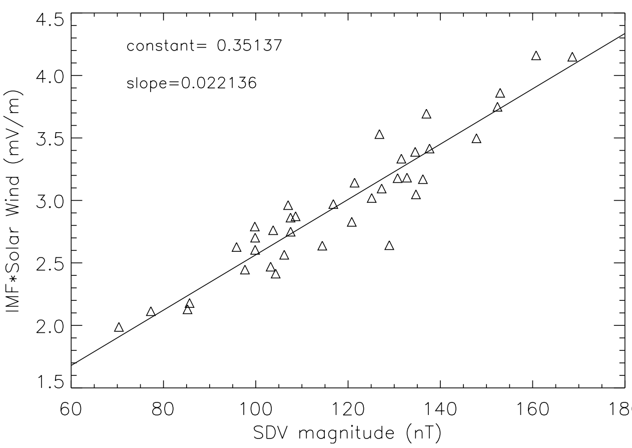

Figure 4. Correlation analysis between the SDV magnitude observed at Thule and *BV*.

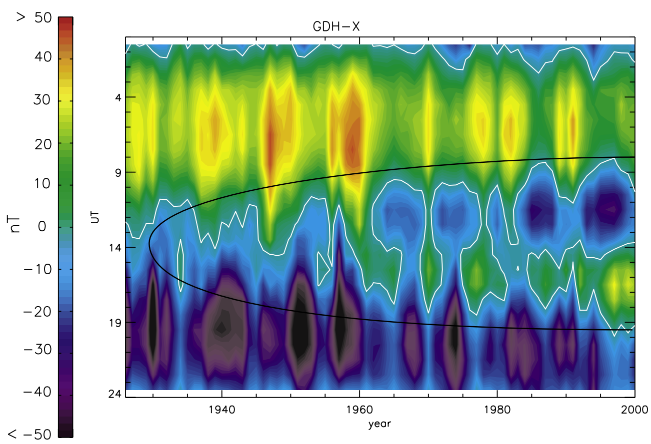

Figure 6. Yearly average of the diurnal variation of the northward component at GDH. The white line shows the zero level. The ellipse indicates growing influence of *Sq*/*DPY*.

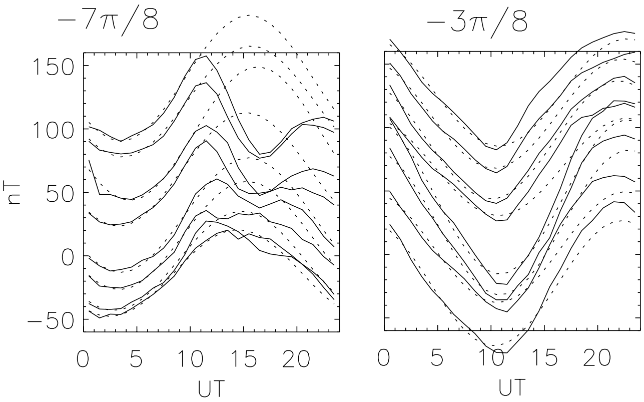

Figure 7. Solid line shows the yearly average daily variation at GDH along two directions in the geomagnetic frame. The directions are defined by the rotation angle (indicated on top of the plots) from magnetic north. Eight 10-years-separated years are shown, with different baseline shifts for readability. Dashed line shows the sinusoidal fit.

(i.e., of the DP2 system) in studies of geomagnetic observations [*Belehaki and Rostoker*, 1996] and in models of high-latitude electric potentials [*Weimer*, 1999].

[11] It is important to notice the increasing magnitude of the *Sq* disturbance and the Svalgaard-Mansurov effect with time in Figure 6. It reflects the decrease of GDH geomagnetic latitude; around local noon, GDH is closer in 2000 to the *DPY* current located in the dayside cleft and to the dayside *Sq* vortex than it was in 1926. In other words, GDH is becoming an auroral station. Caution is then required when applying finding from space-age data to presatellite data.

[12] To repeat the correlation analysis done with THL, we now need to suppress the combined *Sq*/*DPY*. *Sq* models exist but are not accurate enough for Godhavn latitude [*Campbell et al.*, 1989]. As for the *DPY* system, its dependence on IMF-By precludes its determination, since IMF is a variable and not a parameter in our problem. For lack of model, it is possible to strongly minimize *Sq* and *DPY* by exploring their geometric properties.

4.2. Minimizing *Sq* and *DPY*

[13] We shall employ local geomagnetic components. As with THL, the direction to the northern magnetic pole is determined by the yearly averaged declination and used to convert geographic components to local geomagnetic ones. We further investigate changes of components by a series of rotations around the local normal to the ground. Since the SDV is produced by rotation under an equivalent current sheet, it is featured along any direction. On the contrary, the daytime *Sq*/*DPY* couple tends to favor one direction, along which its effect is maximum.

[14] By fitting a sinusoidal function on the (yearly average) nighttime data and extrapolating it to the entire 24 hours, it is possible to model the SDV and estimate the deviation from this model caused by *Sq*/*DPY* for a given direction. Eight examples are illustrated in Figure 7, along two directions corresponding to one large and one small deviation. For each yearly average magnetic daily perturbation, the deviation is computed as the root-mean-square difference between observations and the model. The deviation is averaged over the years 1926 to 2000. This average deviation is now computed rotating the direction through a full circle. It varies from a maximum of 23 nT down to a minimum of 6.5 nT, which is obtained in a direction rotated by $-81.45°$ ($\pm 0.23°$) from geomagnetic north.

[15] Along this direction, the average magnitude of the daily variation is about 110 nT. A 6.5 nT average deviation represents a residual *Sq*/*DPY* effect, i.e., an uncertainty on SDV magnitude estimate, of 6%.

4.3. Latitudinal Dependence of SDV Magnitude

[16] Along this direction, the SDV varies only slightly with latitude. To demonstrate this, eight observatories with a geomagnetic latitude larger than 70° have been selected: Narsarsuaq, Baker Lake, Hornsund, Cambridge Bay (CBB), Godhavn, Resolute Bay, Alert, and Thule. Using data from 1990–2000 to cover a solar cycle, the SDV magnitude is calculated as the difference between the maximum and the minimum values of the diurnal variation along the direction that minimizes *Sq*/*DPY*. Figure 8 shows the resulting latitudinal dependences in both geomagnetic and CGM coordinates. Above 75° there is hardly any latitudinal variation. The CGM latitude of GDH has been between 77.89° (1945) and 75.68° (2000) according to the IGRF/DGRF model. We estimate the CGM latitude for GDH to have been between 77° and 79° in 1926, in any case, closer to the pole. Referring to Figure 8, we conclude that the changing geomagnetic latitude of GDH over time since 1926 did not significantly influence the SDV magnitude.

5. *BV* Reconstruction Back to 1926: Discussion

[17] In this section the data selection procedure used above to analyze THL observations is repeated with GDH. The correlation between the diurnal variation

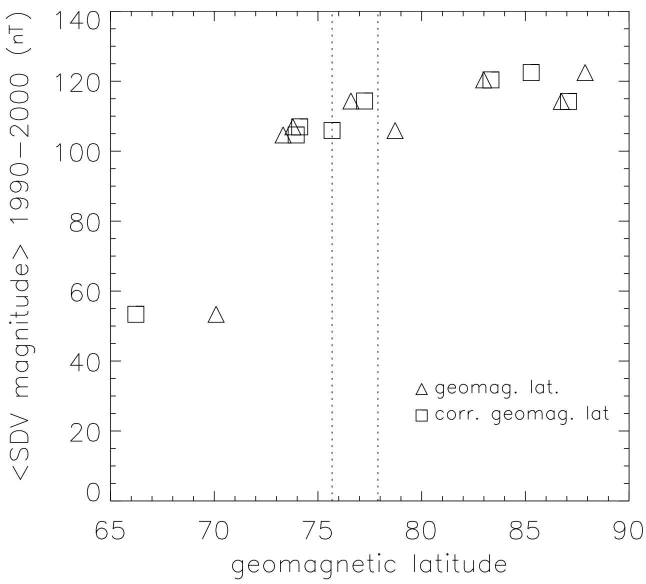

Figure 8. Latitudinal dependence of the 1990–2000 average SDV magnitude. Both CGM (squares) and geomagnetic (triangles) latitudes are used. The two vertical dashed lines show GDH CGM latitude in 1945 (77°89) and 2000 (75°68).

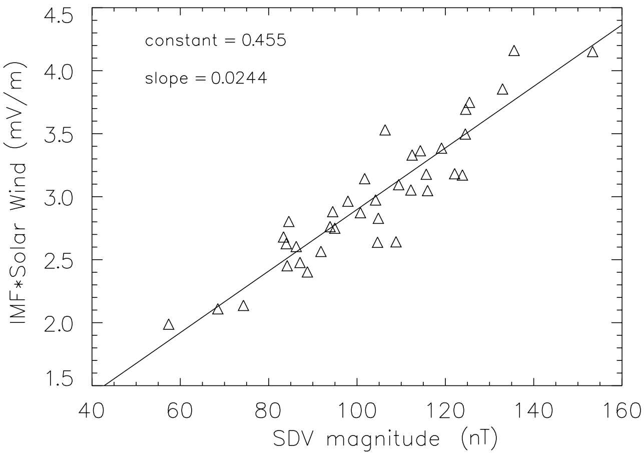

Figure 9. Correlation analysis between the magnitude of the diurnal magnetic variation at GDH and *BV*.

magnitude and *BV* is investigated along the direction where *Sq*/*DPY* is minimal. Figure 9 shows the regression fit. A high linear correlation is apparent with

$$BV(\mathrm{mV/m}) = 0.455 + 0.0244\ SDV(\mathrm{nT}) \tag{2}$$

and a squared correlation coefficient $R^2 = 0.85$. Since the sensitivity to the proximity of the polar cap boundary has been drastically reduced by measuring the diurnal variation magnitude along the direction where *Sq*/*DPY* is minimal, the product *BV* can be inferred back to 1926 by applying the above relation to the long time series of GDH data. The yearly average reconstruction from 1926 to 2002 is compared with space-age observations in Figure 5. The 1947–2002 reconstruction obtained from THL magnetic records is also featured to substantiate our findings. The two reconstructed series strongly correlate when they overlap ($R^2 = 0.97$).

[18] At first sight, no long-term trend is present. By simply applying a best linear fit on the 1926–2002 reconstructed series, a decrease of about 2% over 77 years is found. Since 1926 is in the rising phase of the solar cycle and 2002 is in the descending phase, we recalculate the trend over 1926–1999 (i.e., between midrising phases); a −0.5 % decrease is obtained after application of an 11-year running average to reduce the sunspot cycle dependence. Between years of solar maximum, 1928 and 2000, the 11-year average series shows a decrease of −2%.

[19] Several possible sources of uncertainty exist. Changes of instrument, known to modify the scaling of the *K* index [*Clilverd et al.*, 2002], do not affect the nominal measure of the geomagnetic field and then SDV. The SDV magnitude features a negligible latitudinal dependence within the polar cap (Figure 8), but it is measured with a ±6% uncertainty due to some residual *Sq*/*DPY*. Changes in ionospheric conductivity and the Earth's dipole tilt influence the solar wind-magnetosphere-ionosphere coupling, but the effects of these changes in the 20th century have been shown to be small on the geomagnetic activity [*Stamper et al.*, 1999; *Clilverd et al.*, 2002]. Together, these small uncertainties allow us to conclude that there is no evidence for a significant secular trend in *BV* and probably in *B* and *V*.

[20] The reader may question our choice of *BV*, since the interplanetary electric field magnitude is $E_\mathrm{I} = VB_T\sin(\theta)$, where $B_T = (B_Y^2 + B_Z^2)^{1/2}$ and θ is the IMF clock angle in the Y_{GSM}, Z_{GSM} plane. Moreover, numerous studies have used the effective interplanetary electric field $E_{kl} = VB_T\sin^2(\theta/2)$ to demonstrate a correlation between Φ_{PC} and interplanetary parameters [e.g., *Weimer*, 1995]. The correlation of these electric fields with SDV magnitude has also been investigated, and both cases give results very similar to, but not better than, the one obtained with *BV*. This emphasizes the statistical nature of our study. Using *BV* is as justified as using E_I or E_{kl} if it leads to a strong correlation. Our approach is supported by the SuperDARN observations used by *Shepherd et al.* [2002]. They show that internal and coupling processes between the magnetosphere and ionosphere are necessary to describe the nonlinear relationship between the solar wind-IMF parameters and the instantaneous Φ_{PC}. Neither E_I or E_{kl} nor *BV* can totally describe the involved physics.

[21] Our result, no long-term trend in *BV*, is in agreement with and extends back to 1926 those of *Arge et al.* [2002], *Kotov and Kotova* [2001], and *Richardson et al.* [2002]. On the other hand, *Lockwood et al.* [1999] have suggested that *B* has risen by a factor of 2 and *V* by a factor of 1.15 since 1901, for a combined change of *BV* by a factor of 2.3, a 130% increase. Their study was based on the *aa* index. Roughly half of the increase they reported occurs during the 1901–1925 period, when *aa* rises steeply by 42%. The other half of the increase from 1926 to 2000 is absent from our reconstructed series (the rate of change in the 11-year average *aa* series is +28% (+26%) over the 1926–1999 (1928–2000) interval). This discrepancy may be explained by the possibility that *aa* is in error before 1957, as has already been suggested by *Svalgaard et al.* [2004] and Svalgaard and Cliver (submitted reference, 2004). Note that this does not contradict *Clilverd et al.* [2002], who indirectly examine the quality of *aa* through a comparison of $K = 0$ occurrences at different stations but do not scrutinize the determination of the *K* index itself. Combined with the fact that the bulk of the rise occurred before ~1955, it yields a spurious doubling of the IMF over the last 100 years.

[22] Finally, note that cosmic ray observations compare well with our *BV*, although their relationship is poorly understood [*Parhi et al.*, 2002]. Both series feature a short-term increase between sunspot minima of 1933 and 1954 [*Neher et al.*, 1953] and no long-term variation from 1937 to 2000 [*Stozhkov*, 2002].

6. Conclusion

[23] We have inferred *BV* back to 1926 from a correlation with the magnitude of the diurnal variation of the horizontal magnetic field at Godhavn. The combined effect of *Sq* and *DPY* on the diurnal variation depends strongly on latitude and is minimized by examining the variation along a direction almost perpendicular to the direction to geomagnetic north. Along this direction and using eight geomagnetic observatories, the magnetic perturbation magnitude is found to be essentially constant within the polar cap. This constancy, along the small effect of changes in ionospheric conductivity and the Earth's dipole during the past century, validates the application of correlation results to presatellite

data. Strictly speaking, we find no evidence for a long-term trend in BV and therefore in the interplanetary electric field $-\boldsymbol{V} \times \boldsymbol{B}$. By inference, no increase in the solar open magnetic flux is suggested.

[24] The method presented here has the prime advantage of being independent of *aa*. Since *aa* is the basis of the *Lockwood et al.* [1999] divergent finding, it suggests that *aa* is not uniformly calibrated.

[25] **Acknowledgments.** We are grateful to the NASA National Space Science Data Center for providing the OMNI dataset and to the World Data Center in Kyoto for providing the geomagnetic data. This work was supported by the Air Force Office of Scientific Research under grant F49620-02-1-0345.

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