

Physics-based Long-term Geomagnetic Indices

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A Geomagnetic Index aims to be a summary of certain aspects of the very complicated phenomenon of geomagnetic activity. Ideally, a given geomagnetic index should:

1. Monitor a single class of geomagnetic variations stemming from a definite physical cause. In reality, complex phenomena have several simultaneous, interacting, and hard to separate causes, so we have to accept the concept of a class of related or co-operating causes being monitored.
2. Be simple to derive without requiring elaborate empirical conversion tables or model-dependent fitting procedures.
3. Be reproducible by automatic means using available observational data.

When it was discovered (long ago) that the geomagnetic field measured at a point on the Earth's surface not only had a secular variation but also varied slightly on time scales from seconds to years, it was also noted that these variations showed a "regular irregularity and irregular regularity" that frustrated interpretation and explanation. Even today, we do not know for sure the causes of some of the "regular" variations, *e.g.* the semiannual/universal time variation and the annual variation.

Today we would characterize geomagnetic activity as those variations that result from the interaction between the solar wind and the magnetosphere:

1. Compression and confinement of the Earth's magnetic field, and
2. Transferring flux to the magnetotail by magnetic reconnection.

When (and afterwards) the stressed magnetosphere gives way and relaxes to lower energy state, electric currents flow. Their magnetic effects we call geomagnetic activity and we try to characterize the phenomenon by indices.

These are thus the physical “inputs” to the system:

1. The interplanetary magnetic (B) flux per unit time and area, $F = B V$
2. The solar wind momentum ($n V$) flux per unit time and area, $P = (n V) V$
3. The angles between the Earth’s magnetic field and the IMF direction (α) and flow direction (ψ)
4. The time scale of interest (hours to days) and the variability within that.

We’ll start with an analysis of a well-established activity index: the *am*-index defined by Mayaud, and then transition to our own *IHV*-index covering a much longer time interval.

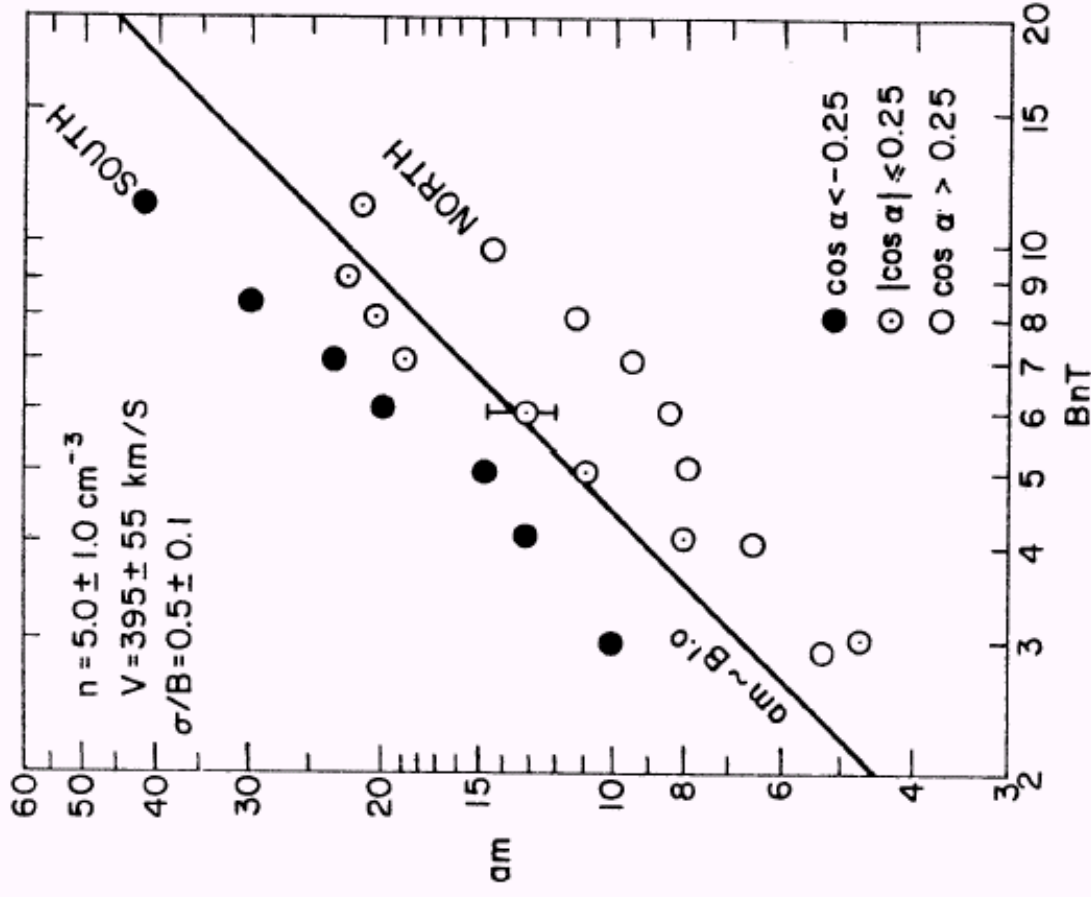
A common technique in laboratory physics is to keep all variables nearly constant except one and investigate the effect of varying only that one. We can simulate this approach by selecting subsets of the vast dataset available.

We first vary only the IMF field strength:

The am -index seems to vary with the first power of B both for Northward ($\cos \alpha > 0$) and for Southward ($\cos \alpha < 0$) merging angles.

Repeating the analysis for other (narrow) intervals of solar wind speed V gives essentially the same result.

This suggests that we can eliminate the influence of BV by dividing am by BV . We shall often use the abbreviation V_0 for $V/100$ km/s. The ‘ \sim ’ symbol in this talk means ‘equal to’ within a constant.

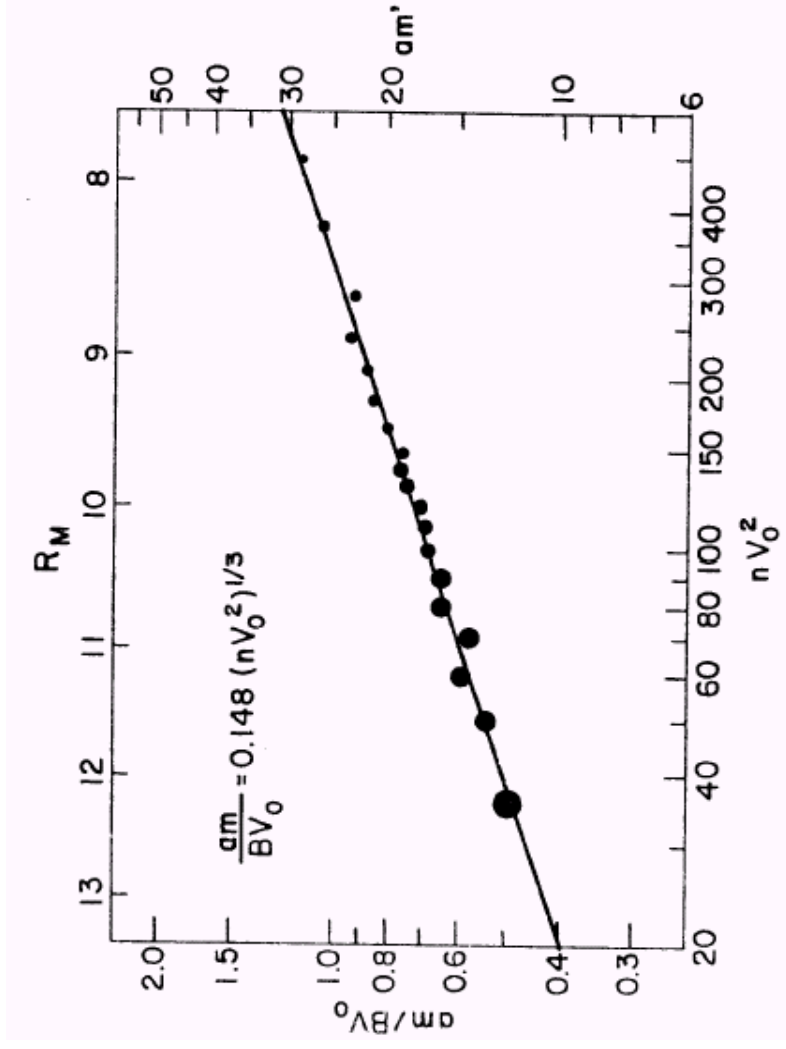


Here we investigate how activity (reduced by BV_0) depends on the momentum flux, nV_0^2 .

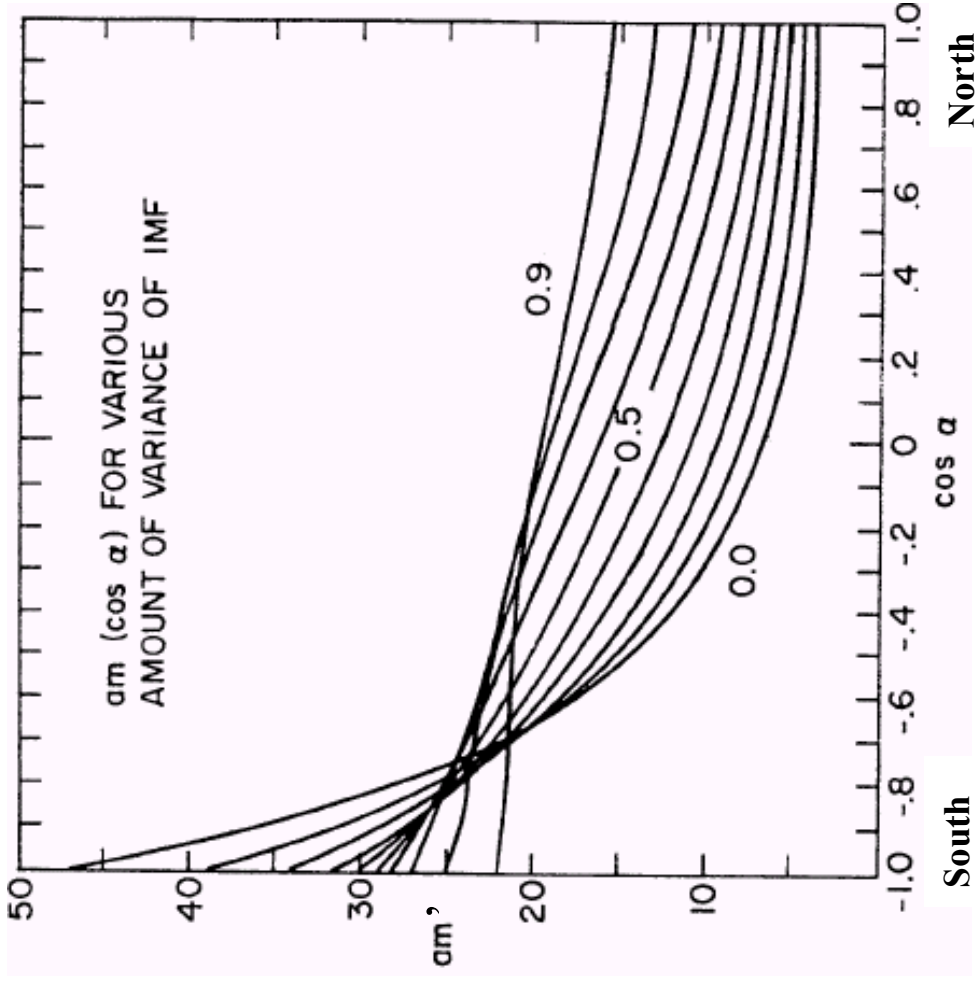
It appears we can eliminate the influence of the solar wind momentum flux by dividing by the cube-root of nV_0^2 :

$$am' = am \left(\frac{\langle BV \rangle}{BV} \right) \cdot \left(\frac{\langle nV^2 \rangle}{nV^2} \right)^{1/3}$$

where $\langle \dots \rangle$ denotes the average value.



The am -index is a three-hour index (we have assigned the same value to each of the three hours when comparing to the hourly-averaged solar wind data) and during that interval the IMF can vary significantly (mostly in direction).

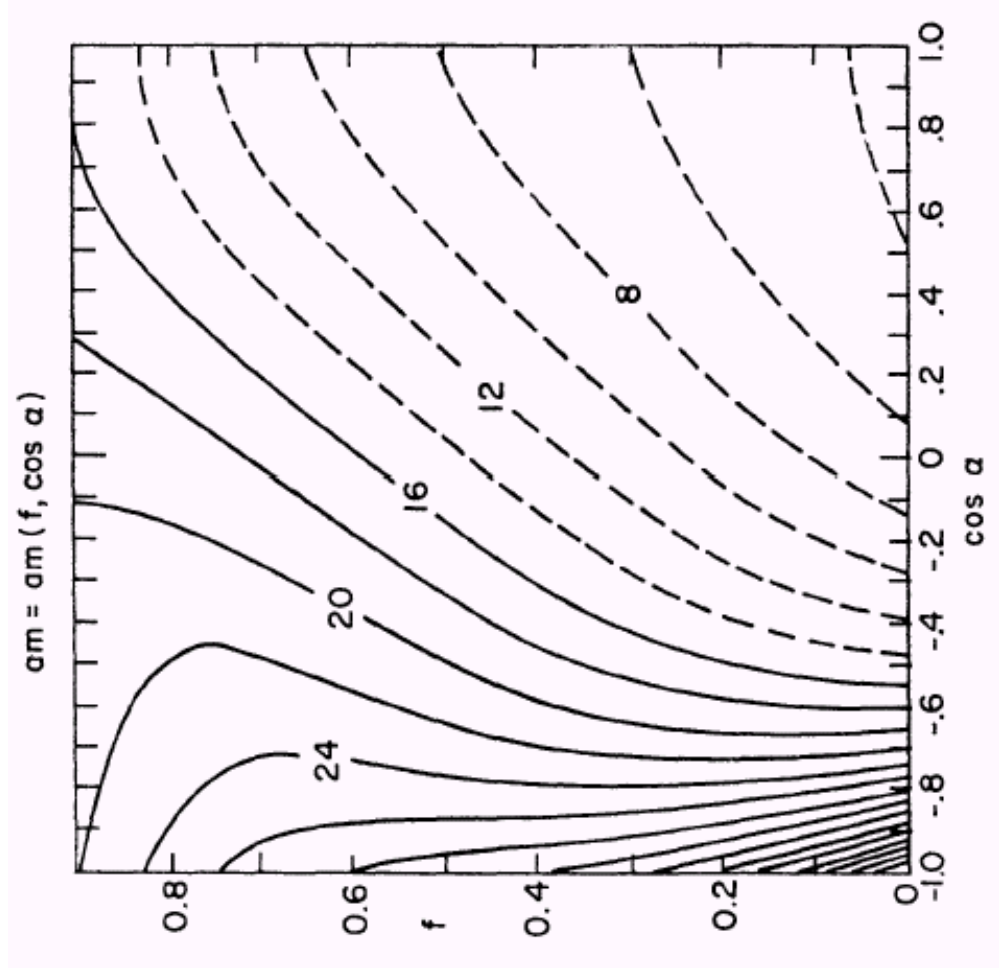


We express the variability of the IMF by the ratio

$$f = (\sigma_{\text{BX}}^2 + \sigma_{\text{BY}}^2 + \sigma_{\text{BZ}}^2)^{1/2} / B$$

The efficiency of the coupling between the solar wind and the magnetosphere depends on the merging angle α , but also critically on the variability, f .

When $f = 1$, there is no real dependence on α as the field varies randomly within the time interval, but for $f = 0$, there is a strong effect of the steady southward fields ($\cos \alpha < 0$).



The coupling function of f and $\cos\alpha$ looks this (left) and can be modeled by an exponential

$$q(f, \cos\alpha) \sim \exp[-p_4(f, \cos\alpha)]$$

where p_4 is a fourth-order polynomial fit to f and $\cos\alpha$. This relationship is, of course, purely empirical and aims only at a (as it turns out, fairly accurate) *description* of the dependence.

We can then write

$$am \sim BV (nV^2)^{1/3} q(f, \cos\alpha)$$

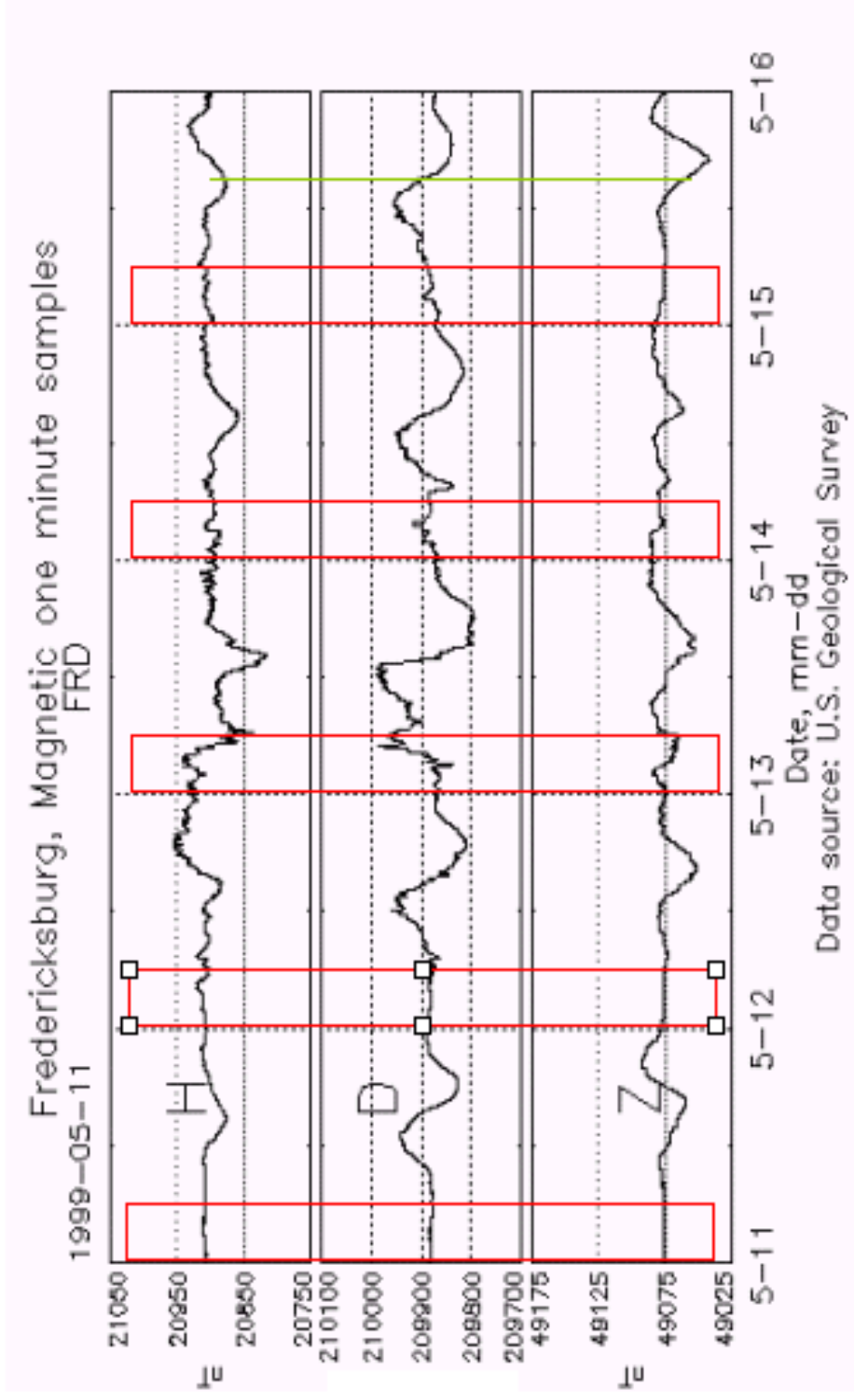
With this relationship we can now *calculate* am from solar wind parameters:

The analysis described above (resulting in the left panel) was actually carried out 30 years ago using the first solar cycle's worth of interplanetary data. Our recent analysis of three additional cycles fully confirms the early results (right panel). The panels show computed and observed am -values for individual three-hour intervals through six Bartels rotations each (~ 400 rotations apart). The scale is logarithmic to show that the fit is equally good for both high and low values, except for the very lowest values of am , which are very difficult to measure. These are systematically measured to be too low by perhaps 5 nT. Adding 5 nT to am would fix this and not impact the fit for large values of am .

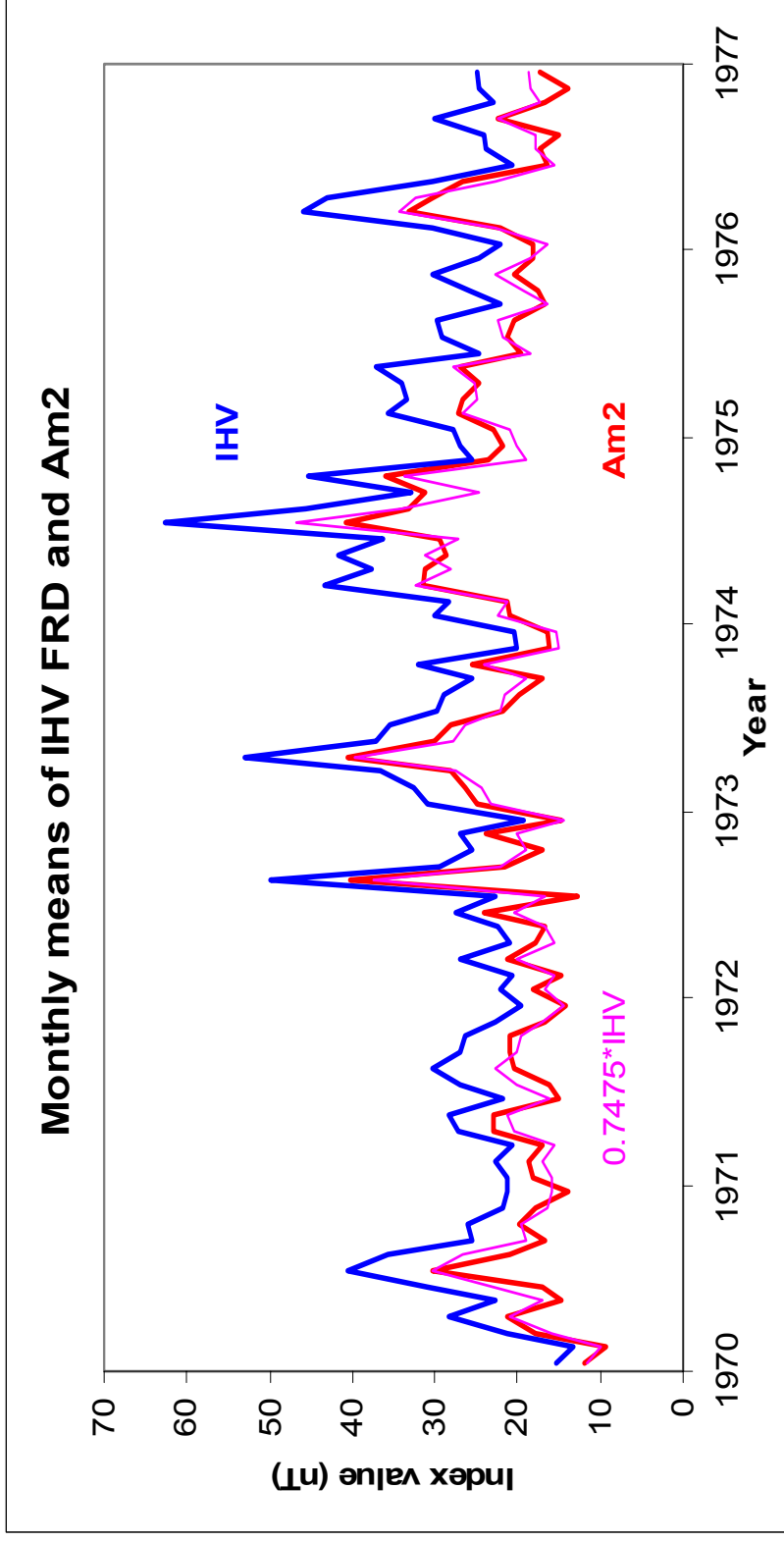
For averages over months or years, $\langle \cos\alpha \rangle$ is to first order constant, but $\langle f \rangle$ is not. At times with high solar wind speed, f is higher too, increasing the coupling efficiency. The net result is that the expression $am \sim Bn^{1/3}V^{5/3}$, that is valid for individual three-hour intervals, for longer-term averages acquires a slightly higher exponent for V , namely $V^{6/3} = V^2$. Noting that longer-term averages of $n^{1/3}$ do not vary much, we finally end with the expectation that $am \sim BV^2$ for averages over months or more, and this is indeed what we find. There is thus a quantitative physical basis for the am -index (and other such range indices).

A problem with the *am*-index is that it only goes back to 1959. Similar indices (*ap* and *aa*) go back further but have uncertain (or wrong) calibrations and cannot be reproduced. The main (actually the only) difficulty with these indices (or their equivalent K-indices) is the identification and removal of the (“irregularly” varying) regular diurnal variation. We attempt to sidestep this difficulty by only using data from the nighttime and define the Inter-Hour Variability index (*IHV*) as the sum of the six *unsigned* differences between hourly (mean) values of a geomagnetic element for the seven-hour interval centered on local midnight (for this talk we use the H-component).

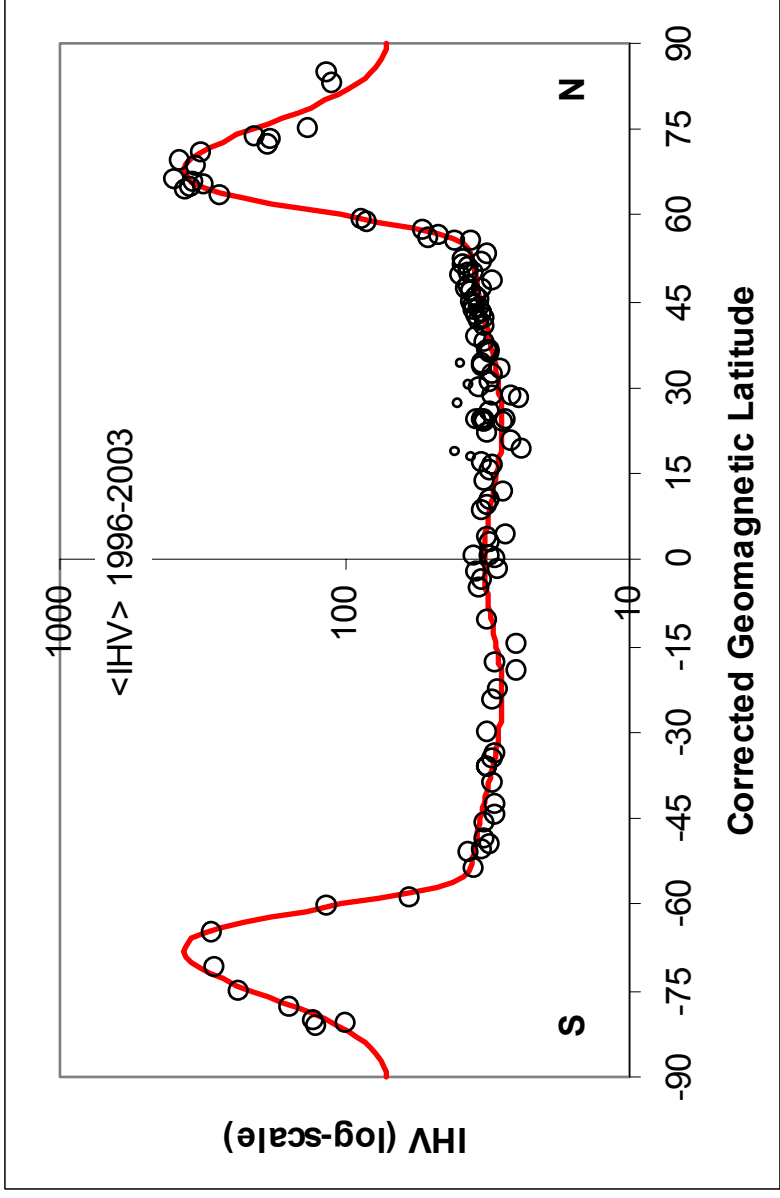
The *IHV*-index can be automatically derived from “yearbook” data, which go back to the 1840s. There is a technical matter having to do with the difference between hourly values (instantaneous on the hour mark) and hourly means (mean values over an hour usually centered on the half-hour mark). The latter were introduced by A. Schmidt with the 1905 Potsdam yearbook. Mean values have lower variance and thus lower *IHV*-values. This effect can reach 60%, but can easily be corrected for, once identified in the data.



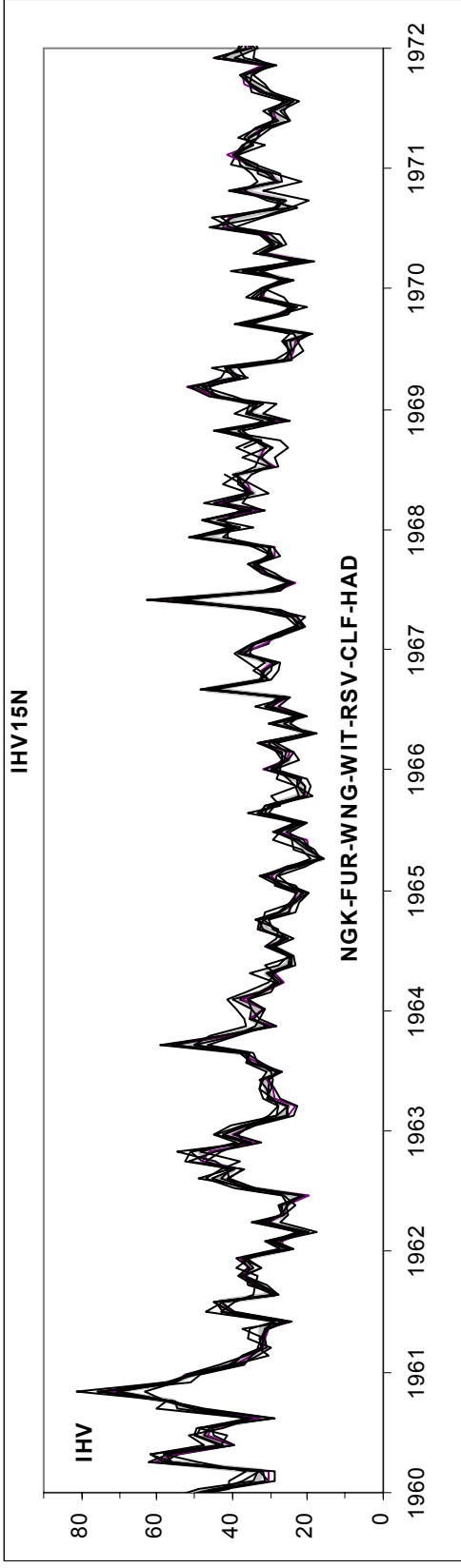
Here is a sequence of magnetograms from Fredericksburg (USA). The red boxes outline the intervals used for calculation of *IHV*.



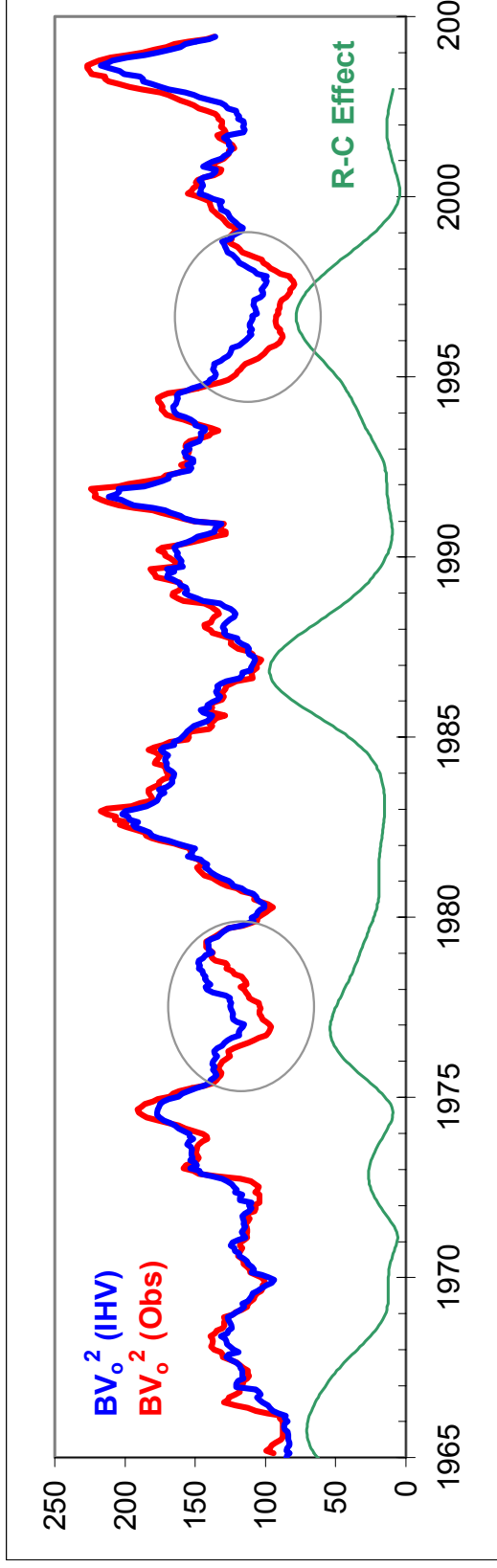
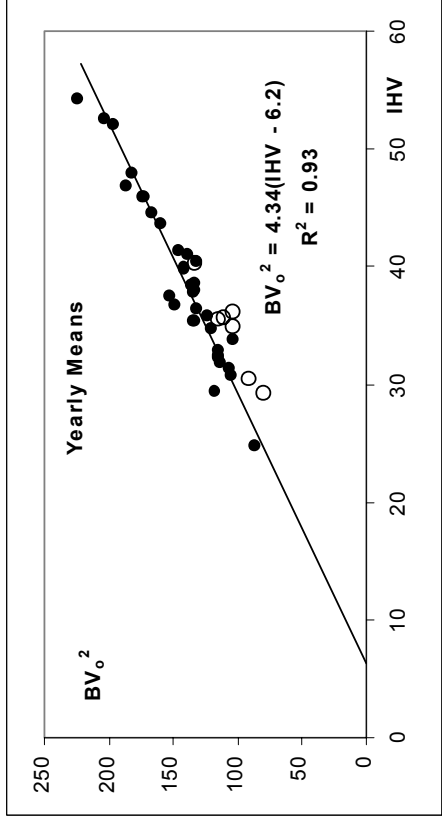
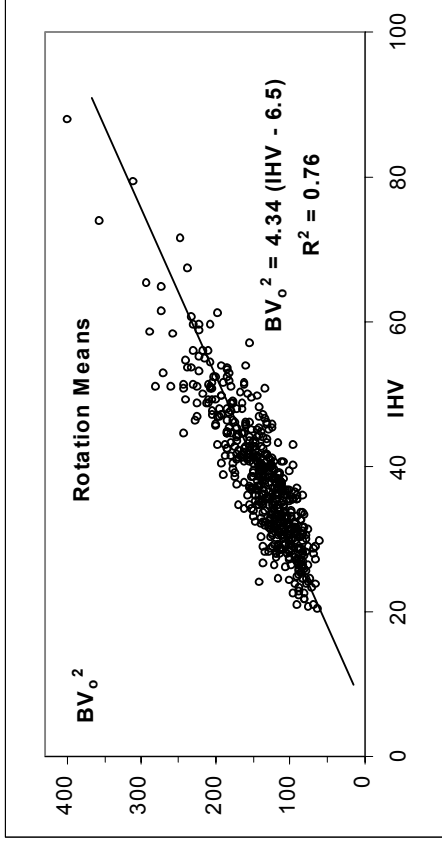
Monthly means of *IHV* for FRD (blue) compared to monthly means of simultaneous *am* values (thick red curve). The thin pink curve is simply $0.7475 \cdot IHV$ and matches the *am*-curve well, suggesting the use of *IHV* as a proxy for *am*.



IHV is a *subauroral* zone index (less than 55° corrected geomagnetic latitude) just like *am*. Here is the average *IHV* for all stations with data in the WDCs during 1996-2003 as a function of corrected geomagnetic latitude.



We saw that even a single station (FRD) is enough to obtain a reliable IHV proxy for am . To get a global index, we divide the globe into six longitude sectors with each a northern and southern latitude part and combine available stations (normalized to NGK) into an index for each sector. Above is a result, Bartels rotation averages for the European sector during years 1960-1971. Averaging all sectors gives us a global composite IHV -index. Because the am -index varies with BV^2 , we expect IHV to do the same, and so it does:

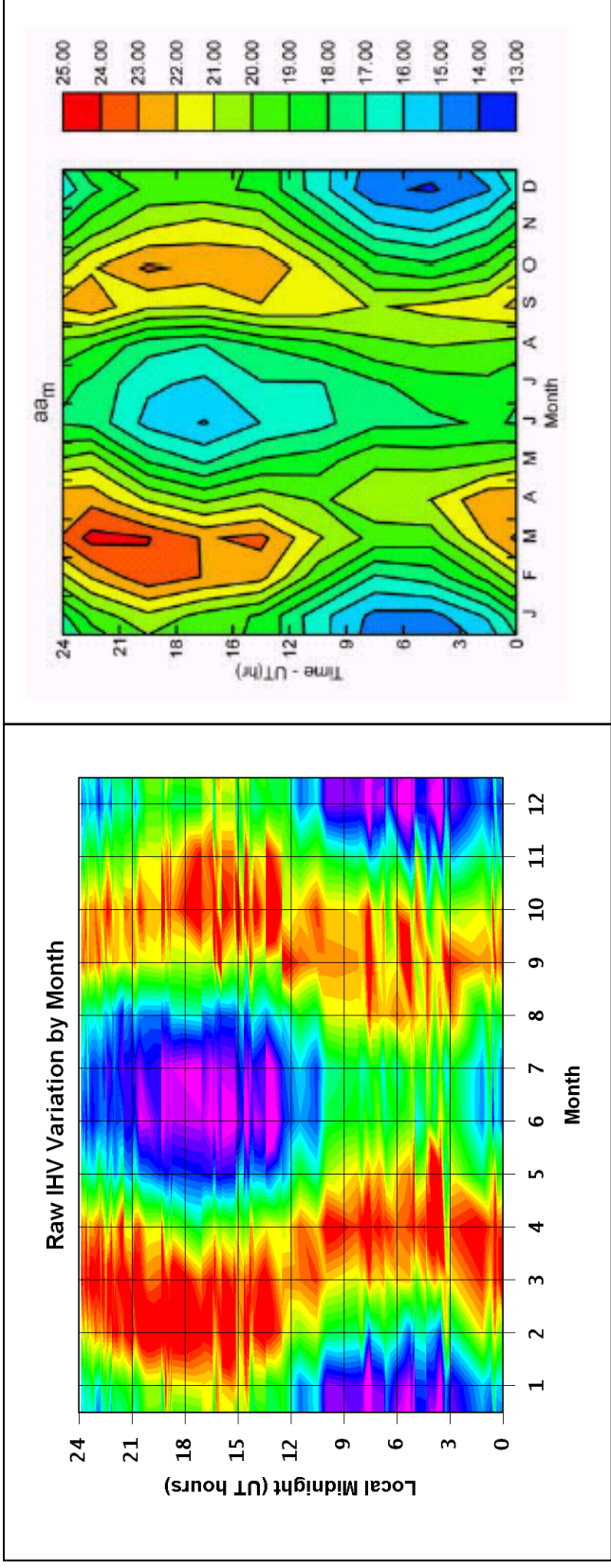


Comparison of computed and observed BV_o^2 (running 13-rotation means).

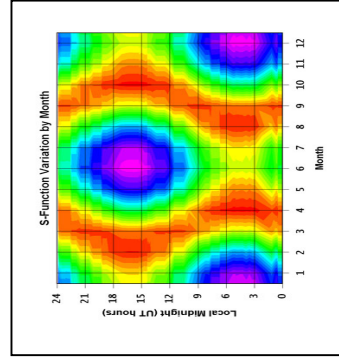
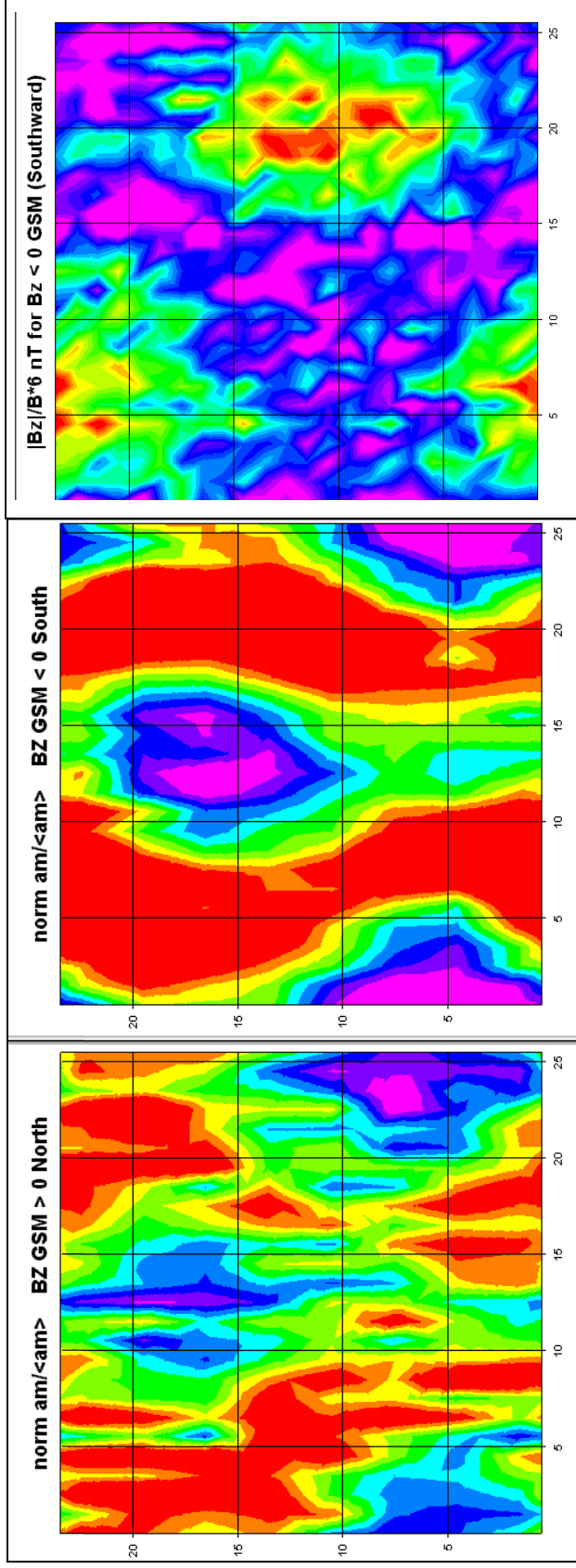
We had turned the correlations around calculating solar wind parameters from geomagnetic activity instead of activity from solar wind parameters. This allows us to estimate solar wind and interplanetary physical quantities using the Earth's magnetosphere as the measuring device. As you can see, we do a very good job.

There are a couple of areas of less agreement (marked with circles). We actually understand the reason for these. There is a 22-year cycle in geomagnetic activity partly caused by a combination of two effects. The Russell-McPherron effect causes opposite annual variations of southward IMF for the two polarities of the IMF. During the minimum and rising phases of the solar cycle there is an imbalance between the occurrence of the two polarities (the Rosenberg-Coleman effect). Because the solar polar fields show a 22-year cycle, the combination of these two effects results in geomagnetic activity being higher every other cycle when the R-C effect is present. The green line shows the size of the R-C effect (in arbitrary units) derived from the observed IMF polarity.

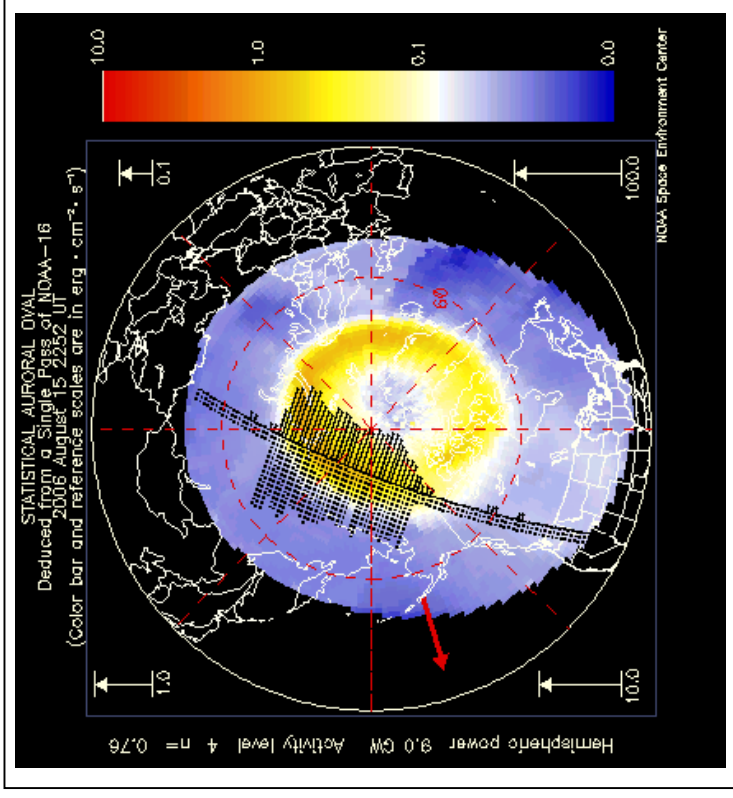
We leave these second-order discrepancies in the *IHV*-index with the knowledge that they exist.



Both am and (raw) IHV show a dependence on the tilt angle of the Earth's dipole towards the solar wind direction (ψ): $am \sim S(\psi) = (1+3 \cos^2 \psi)^{-2/3}$. Since the dipole axis is inclined 11° to the rotation axis, this dependence, involving the dipole field strength at the subsolar point, introduces an undesirable dependence on longitude. We eliminate this by dividing IHV by the function $S(\psi)$. In this way, IHV -values from stations at different longitudes can be directly combined.



The ψ -dependence is a true *modulation* of existing activity. It does not depend on the direction of the IMF (Northwards or Southwards fields). Nor has it any similarity with the variation of the Southward component (the famous Russell-McPherron effect). On the left we show the variation of $S(\psi)$ function. This modulation is removed from IHV.

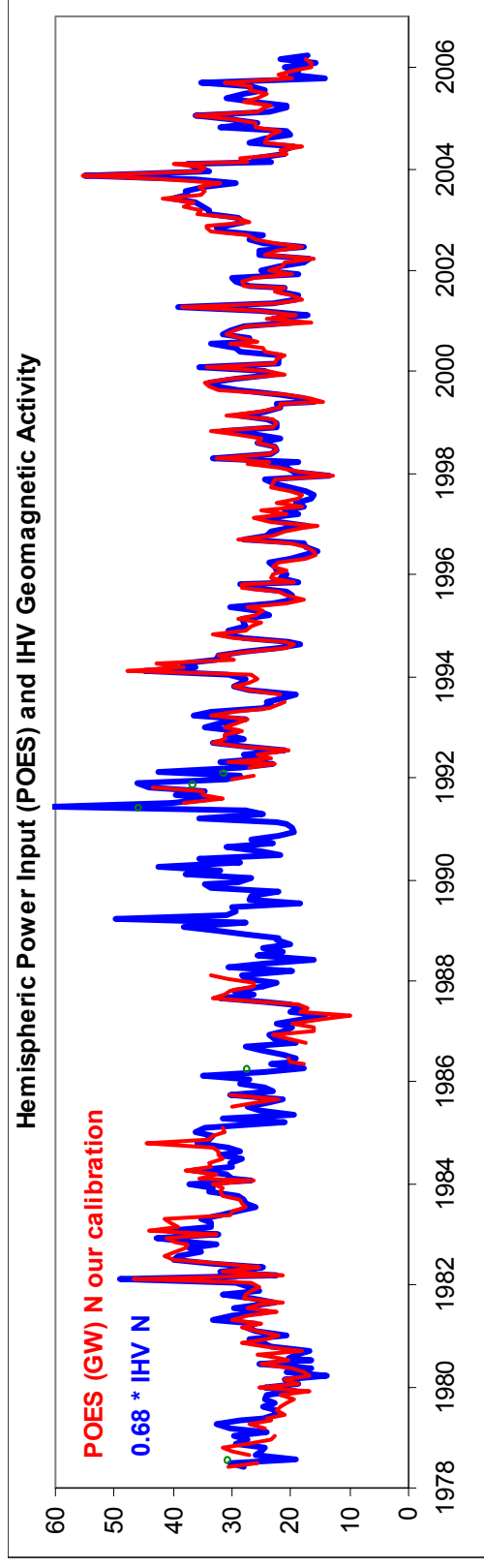
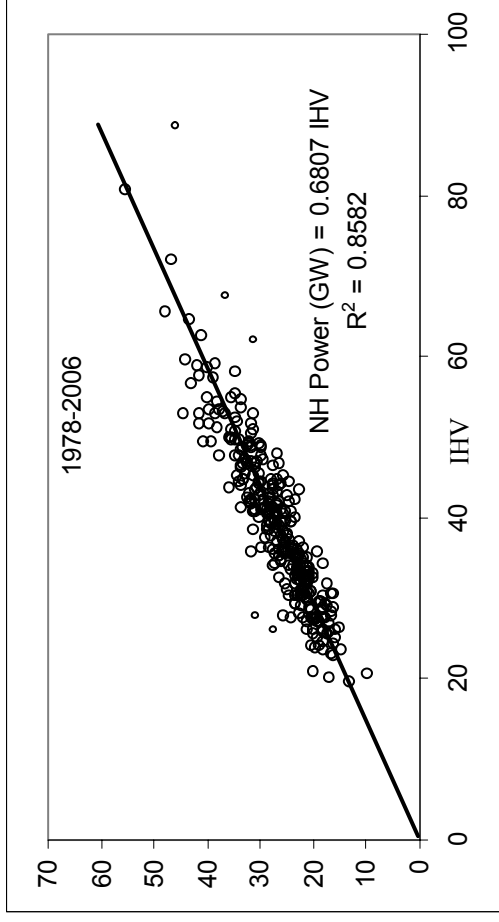


As the stressed magnetosphere gives way, particles are accelerated and precipitate into the upper atmosphere over the polar regions where the energy thus deposited can be directly measured by polar-orbiting satellites (POES).

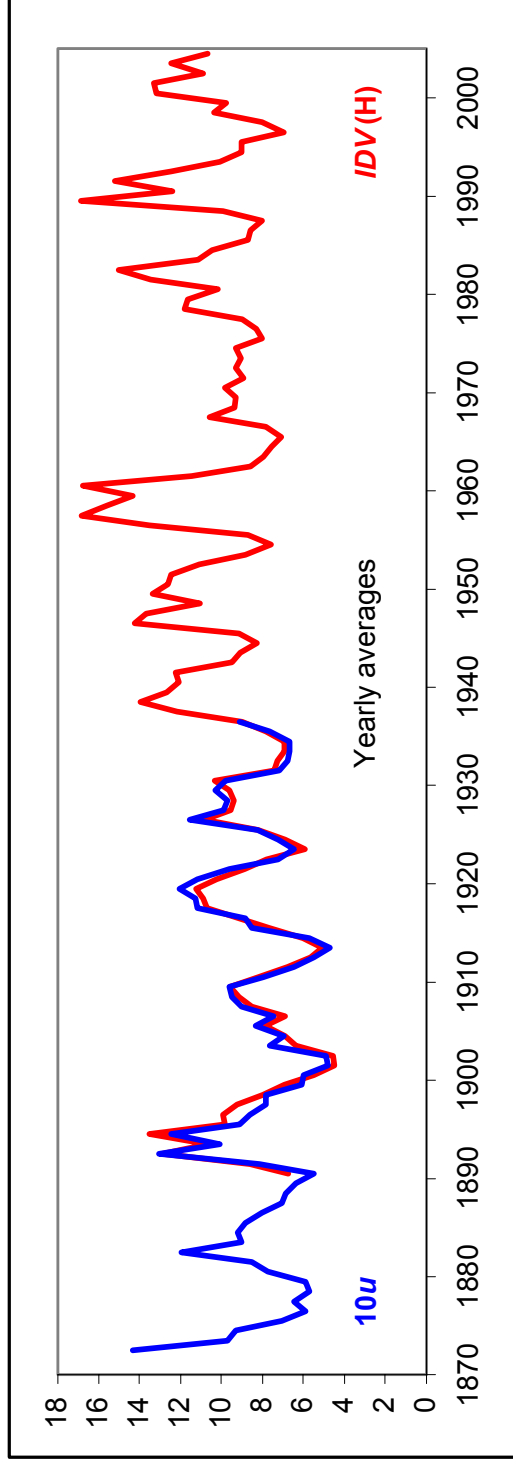
From the satellite data the total energy input (in Gigawatt) to each hemisphere can be estimated. Such estimates exist back to 1978.

It turns out that the *IHV*-index is proportional to the Hemispheric Power input, giving a direct physical interpretation of *IHV*.

Here is the correlation of rotation means of the hemispheric power input and the *IHV*-index. And a comparison between the observed and calculated power since the start of the satellite measurements:

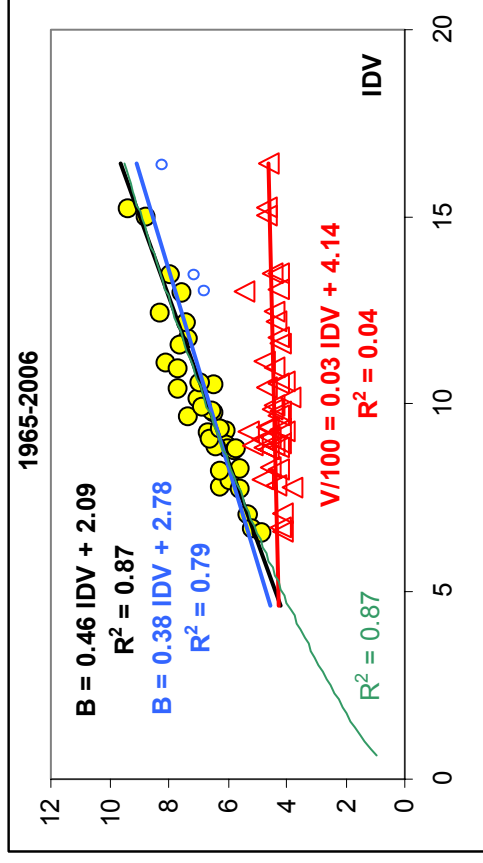


The *IHV*-index captures activity on a time scale of hours. How about on a time scale of days? Bartels defined his μ -measure as the monthly (or yearly) mean of the unsigned differences between the mean values of the H-component on two successive days. We found that you get essentially the same result using the mean over the whole day, a few hours, or only one hour. Our Interdiurnal Variability index (*IDV*) is then simply the μ -measure (in nT, not the original 10 nT units) using only one hour (preferably the midnight hour if available):



Note that μ and *IDV* did not register the strong high-speed streams in 1930, 1952, 1974, 1994, and 2003. This (1930) was a deadly blow to the μ -measure.

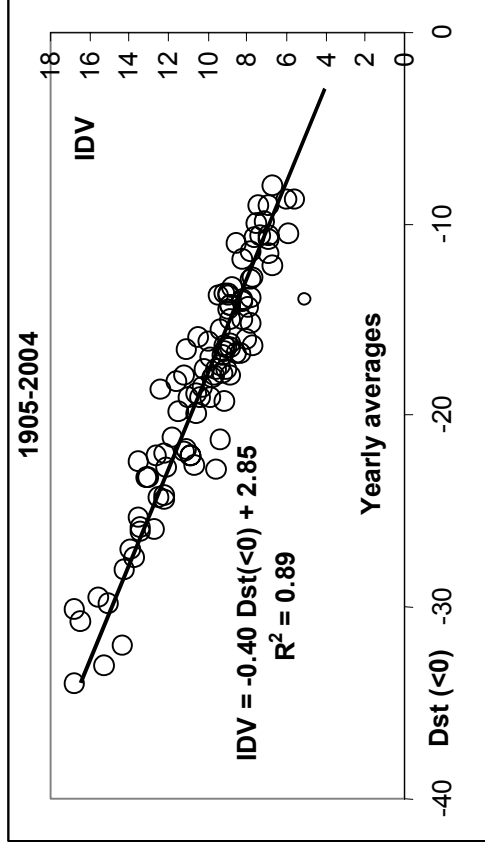
What is the *IDV*-index then measuring? Here we plot yearly averages of *B* and *V* against *IDV*:



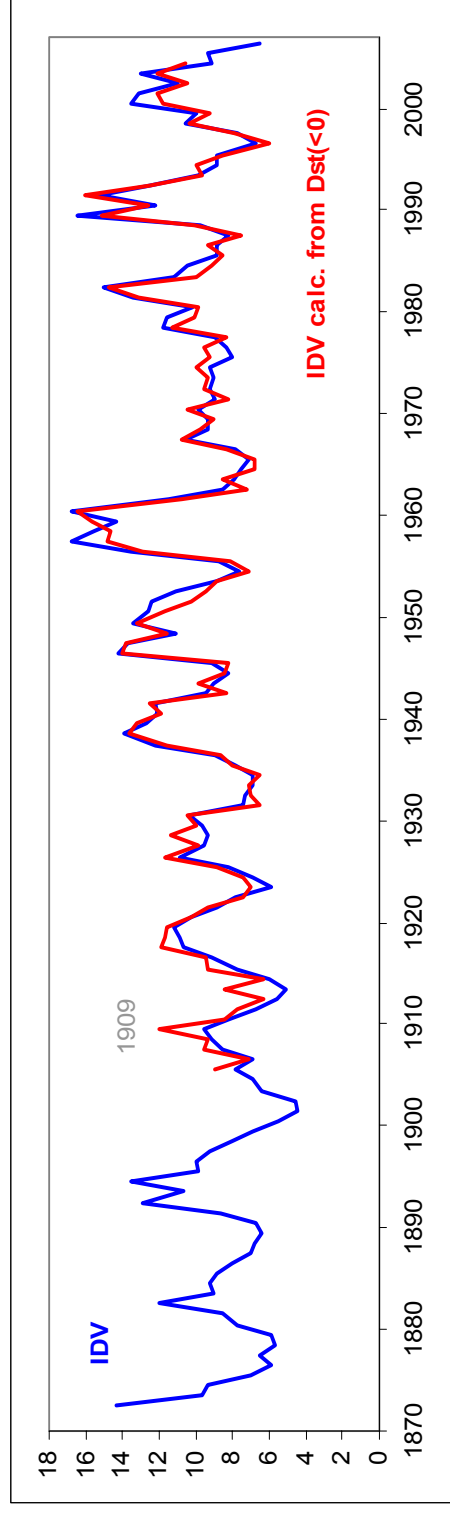
There is indeed no correlation with *V*. There is a robust correlation with *B* (with or without a few outliers - blue circles). Various fits (linear, power law) do not really differ over the range of the data.

Coronal Mass Ejections (CMEs) add (closed) magnetic flux to the IMF and also compress the ambient IMF. The resulting strong magnetic fields of CMEs hitting the Earth create magnetic storms, feeding energy into the inner magnetosphere (“ring current”). The *Dst*-index is aimed at describing this same phenomenon, but only the negative contribution to *Dst* on the nightside is effectively involved. We therefore expect (negative) *Dst* and *IDV* to be strongly related, and they are:

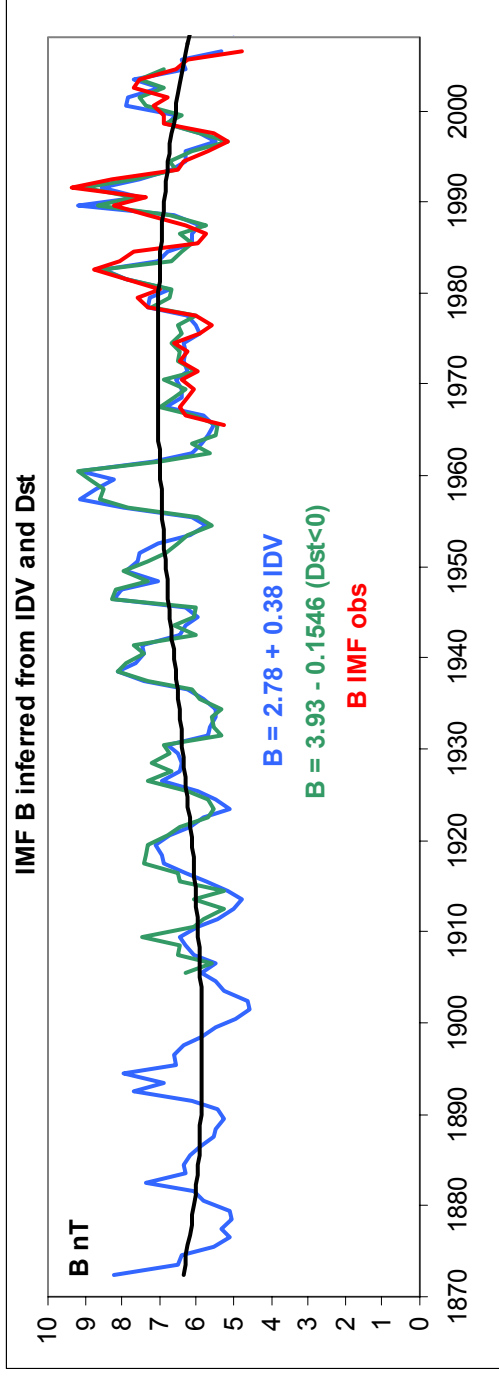
We used a derivation of Dst by J. Love back to 1905. Similar results are obtained with the Dst series by Mursula *et al.* (to 1932) or with the “official” Dst series (to 1957). The very simple-to-derive IDV series compares favorably with the more elaborate $Dst(<0)$.



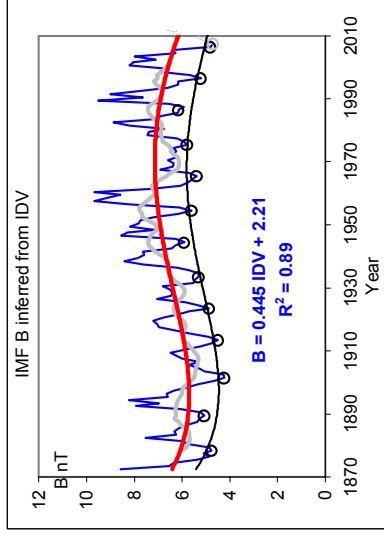
Here are both time series (IDV and IDV calculated from $Dst(<0)$):



Using regressions of IDV and $Dst(<0)$ on IMF B we can directly estimate B back to 1872:

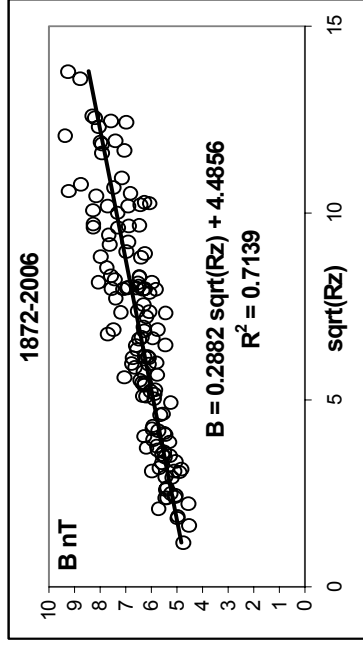
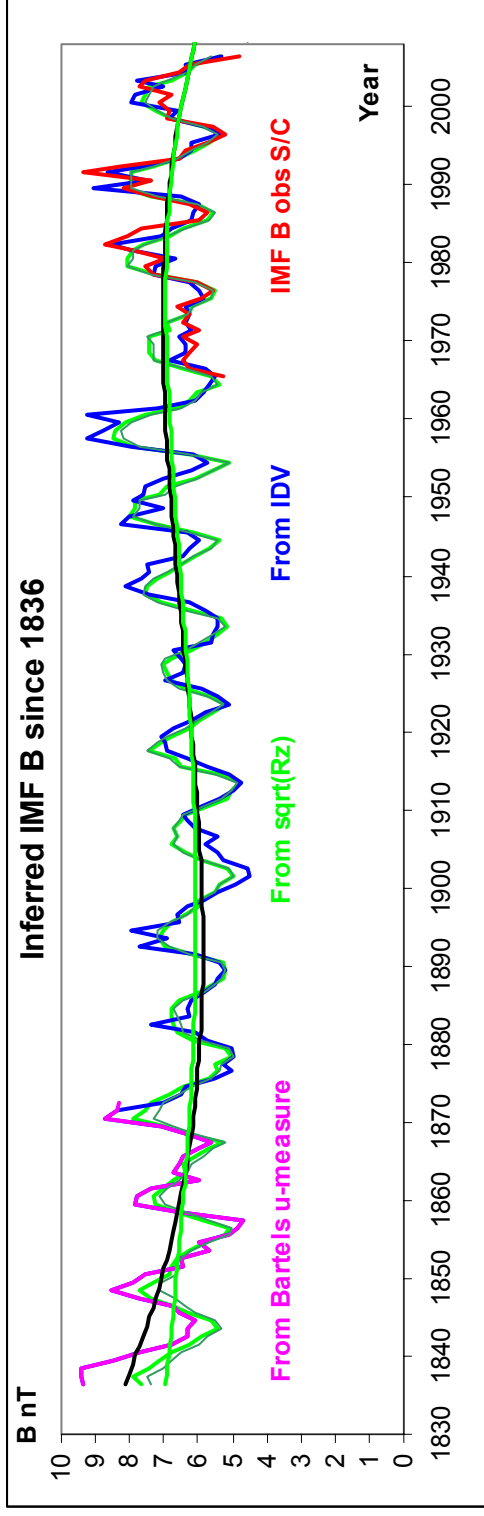


There is a hint of a ≈ 100 -year Gleissberg-type cycle.

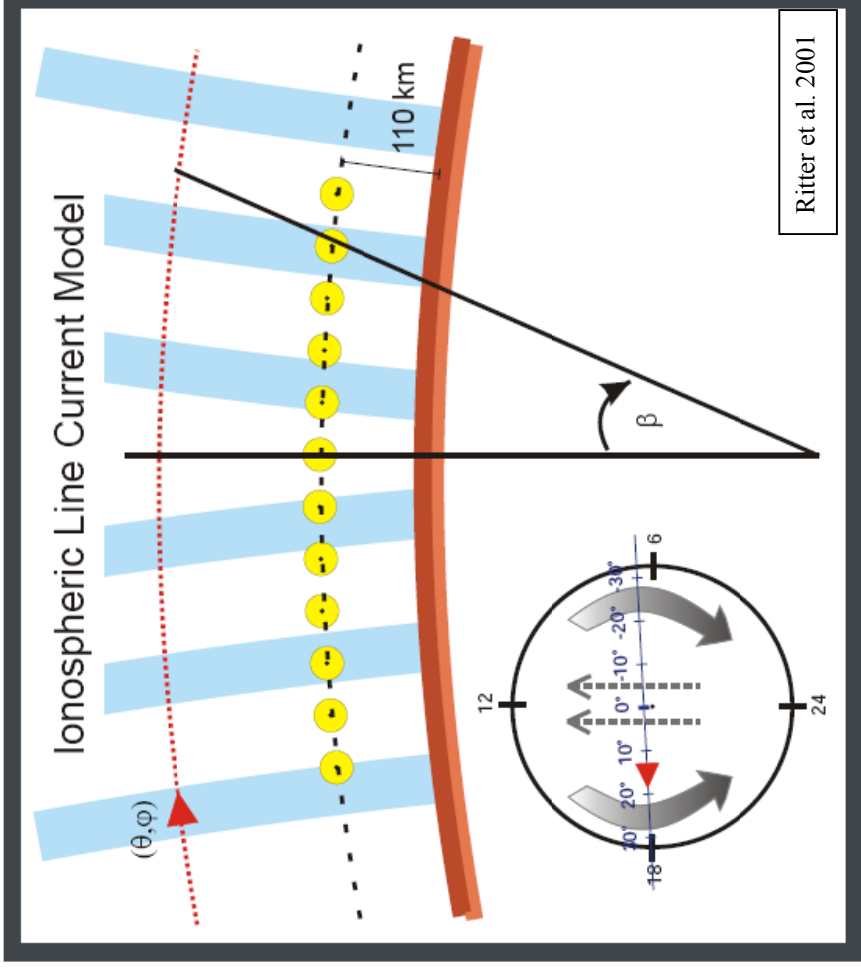


The smooth curve is a 4th-order polynomial fit. One can also just fit the values at solar minima (to eliminate most solar activity) with essentially the same result. We may be approaching another minimum in the Gleissberg cycle. The IMF B for 2006 (so far) is the lowest in the last 94 years.

Can we go further back in time? Bartels had determined the u -measure from 1836 on, but with less confidence before 1872. Here is what we get if we infer IDV (and then B) from u back to 1836:



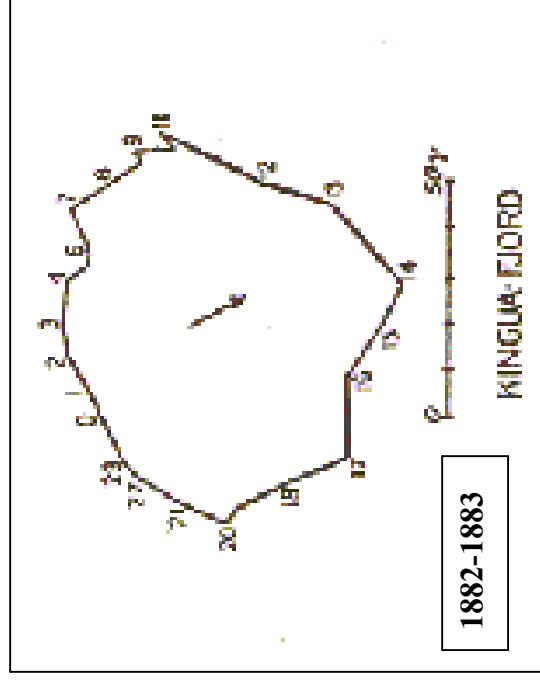
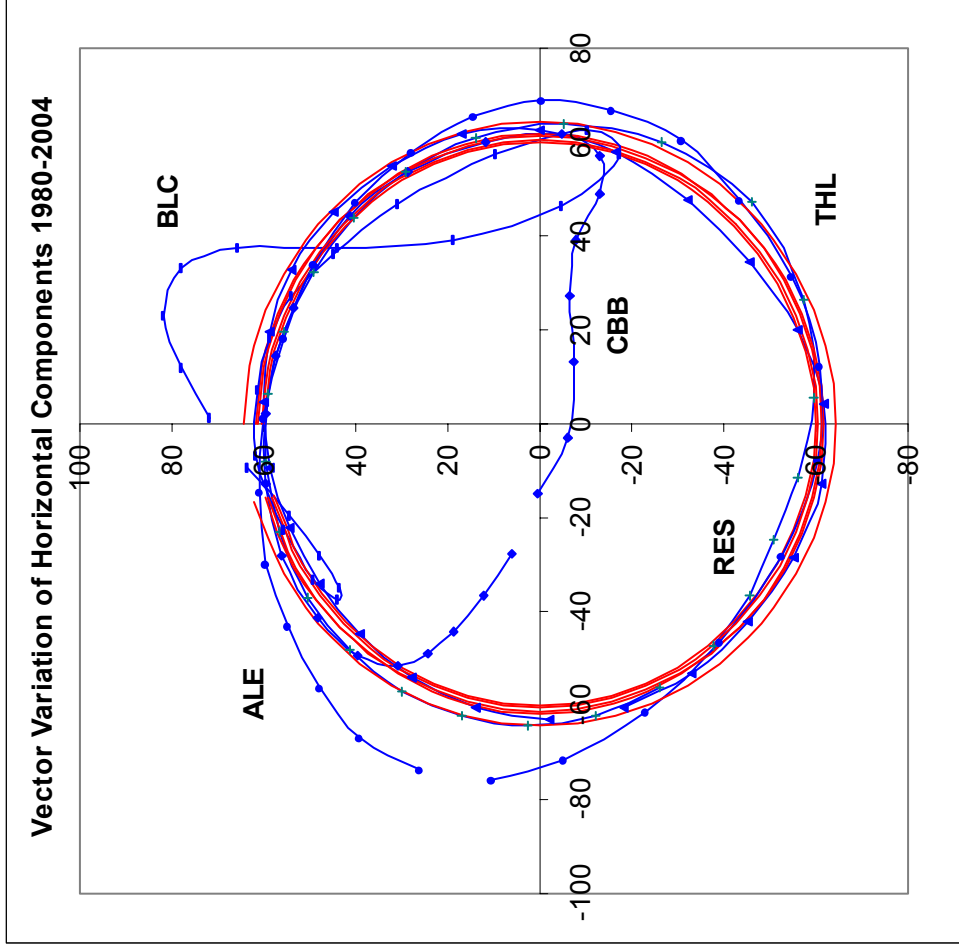
Since there is also a good correlation between B and the square root of the sunspot number (left), we can infer B from Rz as well and compare with B inferred from u . Before about 1850, either u is too large or Rz is too small. Something to investigate!



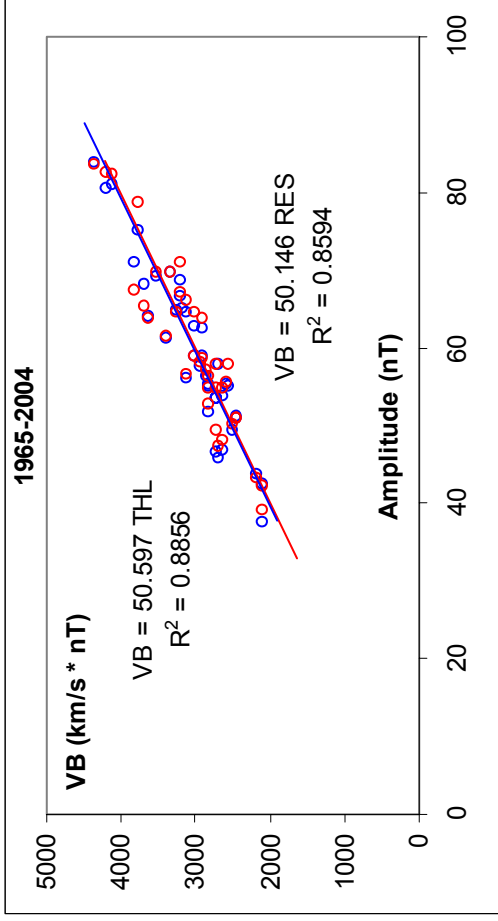
Ritter et al. 2001

Across the Earth's polar caps flows a current in the ionosphere. This is a Hall current basically flowing towards the sun. The Earth rotates under this current causing the magnetic effect of the current to rotate once in 24 hours. This rotating daily effect is readily (and has been since 1883) observed at polar cap magnetic observatories.

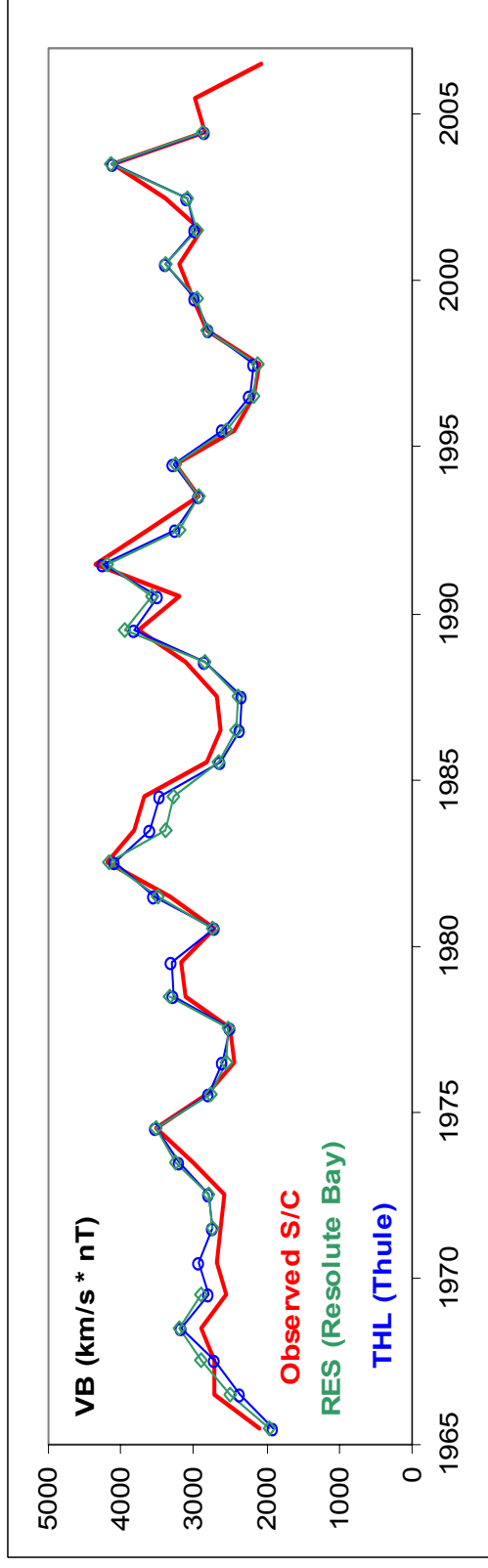
The current derives from the Polar Cap Electric Potential which is basically the electric field ($E = V \times B$) in the solar wind mapped down to the ionosphere.



The radius of the circle traced out by variation of horizontal components is a measure of the polar cap potential. For stations near the polar cap boundary the circle is only partial.



Here we show for each year of 1965-2004 how the average radius depends on the product of B and V for Thule (THL) and Resolute Bay (RES). The radius of the circular variation is the same for all stations in the cap. We can then estimate BV :

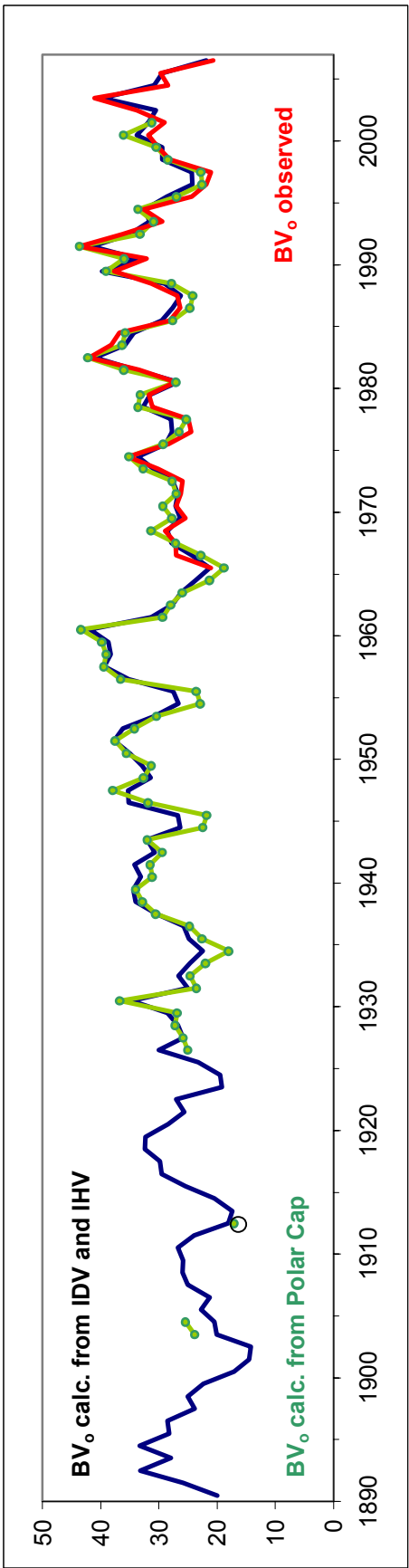
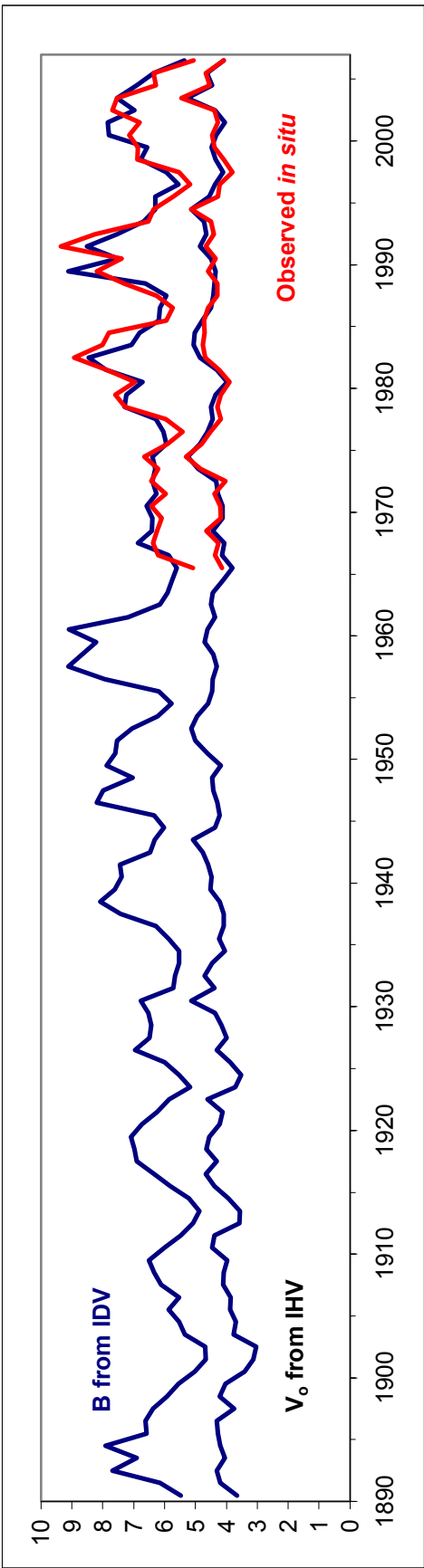


We now have three independent ways of estimating solar wind and IMF parameters:

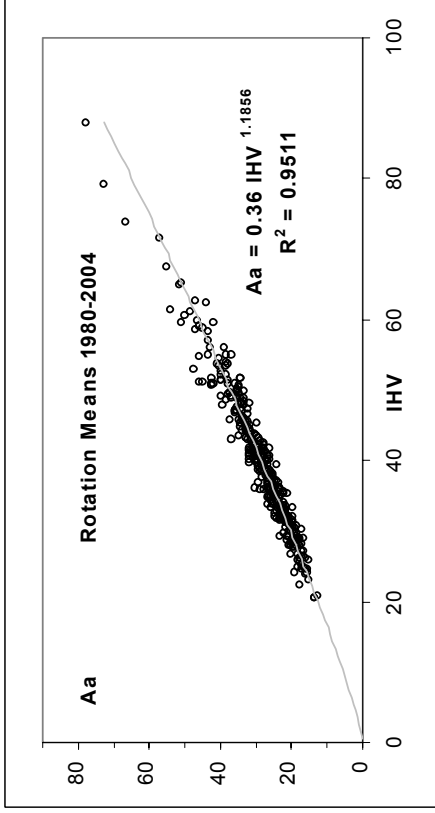
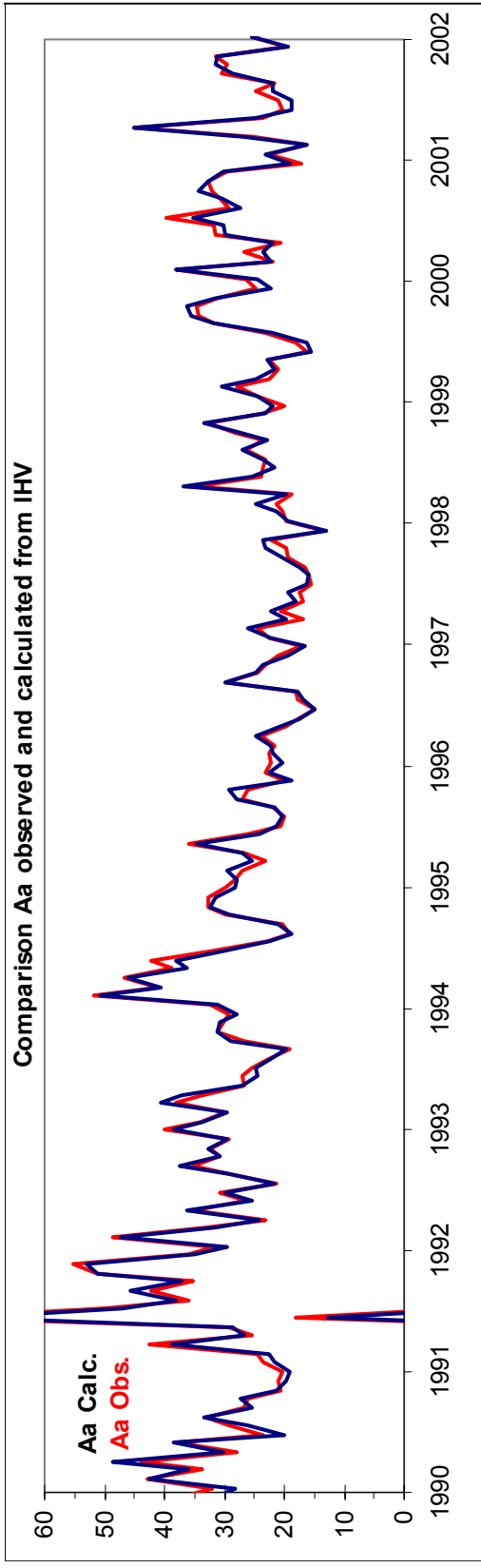
1. The *IHV*-index, estimating BV^2
2. The *IDV*-index, estimating B
3. Polar Cap Potential index, estimating BV

These indices are readily computed from simple hourly means (or values) for which we have measurements stretching back well into the 19th century.

We can thus estimate $V = \sqrt{[(BV^2) / B]}$ and use that value to calculate BV for comparison with the estimated BV . The agreement is encouraging. There are several second-order effects (22-year cycle, solar cycle variations of ionospheric conductivity, secular decrease of Earth's dipole moment, records going off-scale, etc) that can be compensated for, but the overall picture seems clear already:

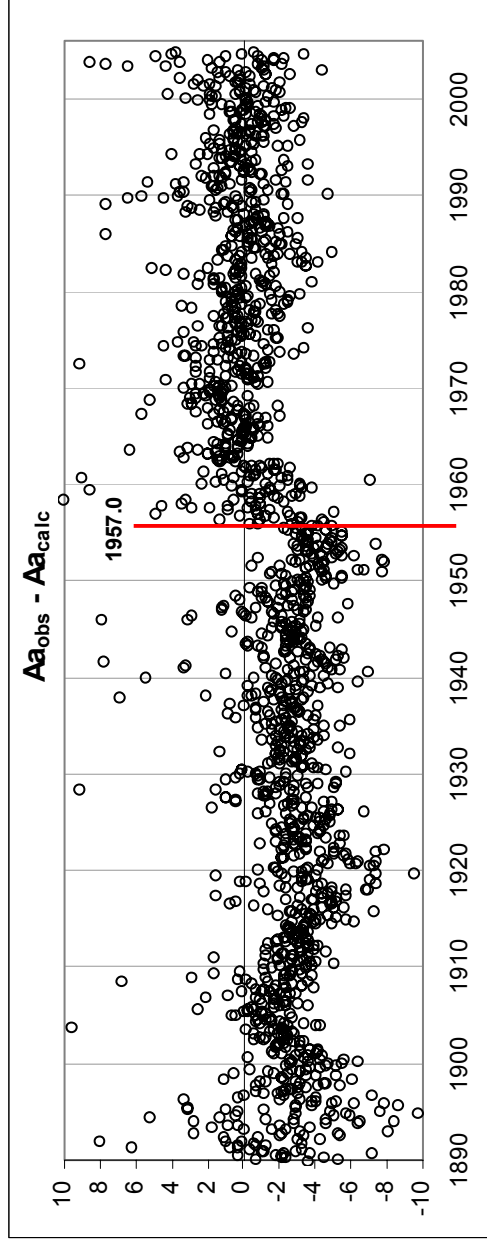


We can even use the *IHV*-index as a check on the long-term stability of the *aa*-index. Regressing *aa* versus *IHV* for recent times we find excellent agreement:



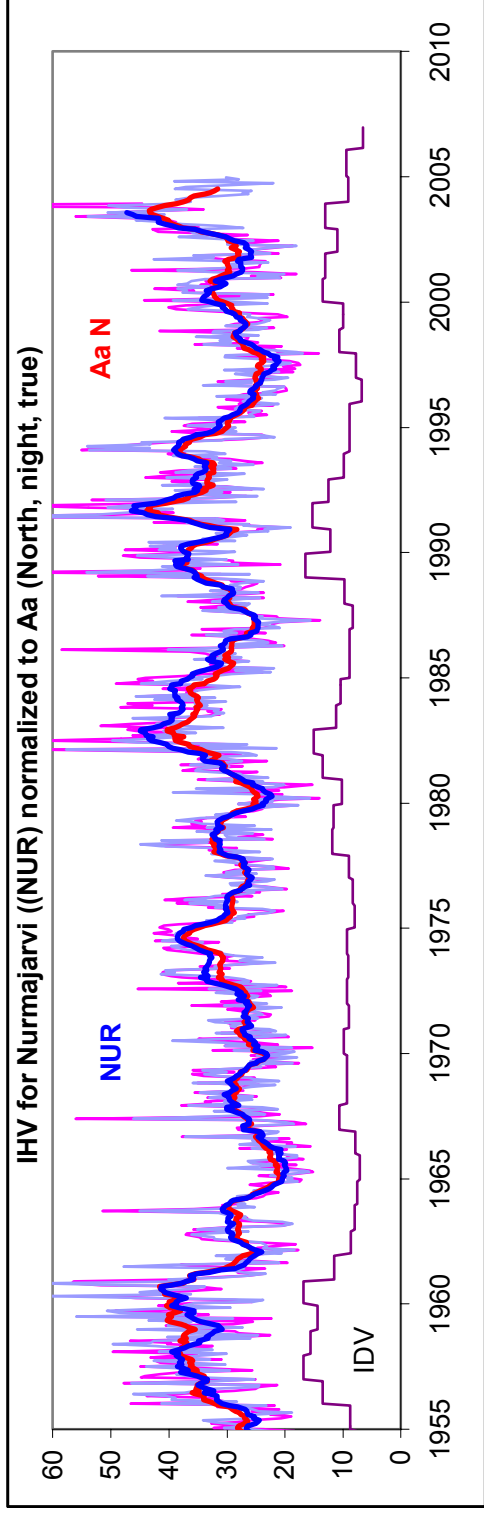
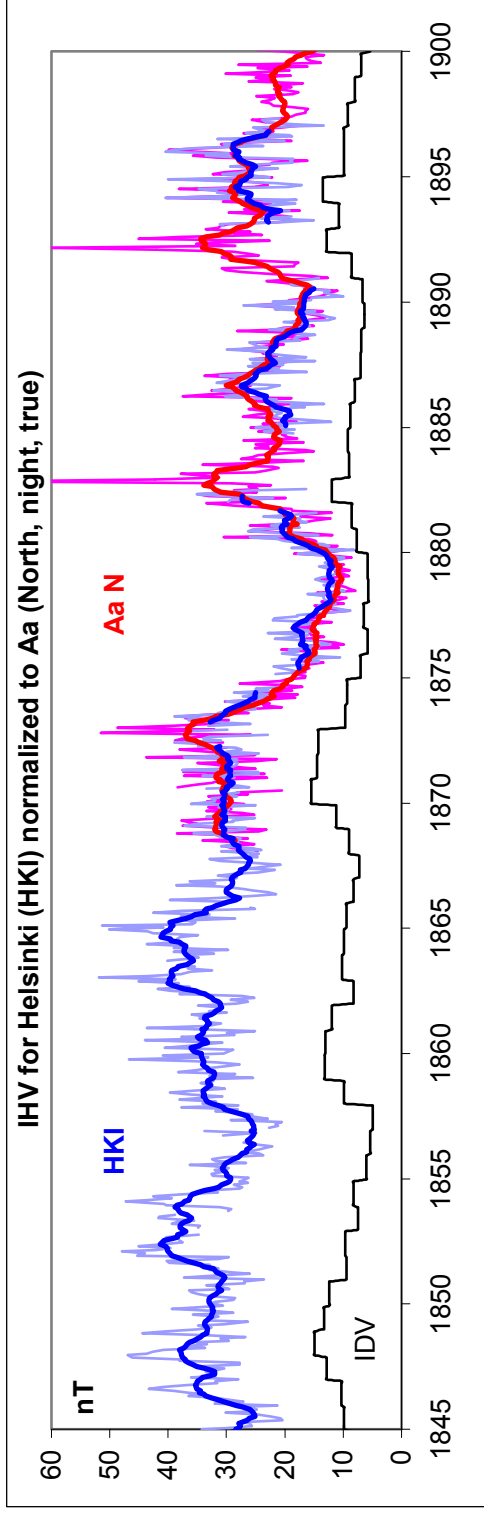
We can then apply the same technique for earlier data, and for the *ap*-index as well. For the *ap*-index, the agreement between *IHV* and calculated *ap* is good back to 1932, but not so for the *aa*-index:

Here is the difference between observed and calculated Bartels rotation averages of the *aa*-index since 1890. Note the marked discontinuity at the beginning of the year 1957:



It would seem that the *aa*-index is in need of a recalibration.

The analyses and results presented in this talk underscore the immense value of old geomagnetic records. An effort should be made to preserve that legacy and to bring the data into electronic form.



Here is an example of what can be done using Helsinki back to 1844.

Conclusion

By constructing geomagnetic indices that are directly related to separate physical conditions in Geospace we bring investigations of the long-term behavior of these conditions onto a firm physical basis and remove much of the speculative character of our inferences about Space Climate. At the same time we are able to bring the historical record of geomagnetic measurements to bear on the issues of Space Climate in ways our predecessors could not dream of, but would certainly much appreciate and delight in.

The End

Extended Summary

A geomagnetic index aims to be a summary of certain aspects of the very complex phenomenon of geomagnetic activity. Many geomagnetic indices have been proposed and used over the years. As so strongly emphasized already by J. Bartels and re-iterated by P.N. Mayaud, a given geomagnetic index should monitor a single class of geomagnetic variations stemming from a definite physical cause. There are many indices for which this goal is not reached (e.g. the classical daily range indices and the modern Dst index). Preferably, an index should be simple to derive without requiring elaborate empirical conversion or adjustment tables and be reproducible by automatic means. Many indices do not meet these criteria (e.g. the Kp, am, and PC indices). There has been a tendency to increase the time-resolution of the indices (e.g. from hours to minutes). Little is gained by this: the summary aspects are overwhelmed by the vastly increased data volume which typically is available for a much shorter time interval, several additional phenomena intrude (e.g. micropulsations), and time- and length scales often no longer match the scales for the physical causes to be monitored. Certain phenomena occur chiefly on the dayside of the magnetosphere (e.g. solar flare effects, the 'regular' solar quiet-time thermal wind and tide effects, sudden storm

commencements, the Svalgaard- Mansurov effect) and have physical causes distinct from the 'classical' geomagnetic activity that peaks near midnight.

We discuss new geomagnetic indices based on nighttime data only, thus avoiding (rather than attempting to solve by ad-hoc methods) the problem of 'mixing-in' of the daytime effects. Using stations distributed in longitude, continuous coverage in Universal Time is obtained:

1) The Inter-Hour-Variability (IHV-) index is defined as the sum of the six unsigned differences between seven successive of hourly means (of the H-component of the geomagnetic field) over an interval centered on local midnight for stations equatorwards of 55 degrees corrected geomagnetic latitude (CGML). The IHV-index has been shown to be a close proxy for a single physical quantity, namely the power flux, HP [measured in GigaWatt], carried into the Earth's upper atmosphere by precipitating auroral charged particles. HP is routinely measured by NOAA/TIROS and DMSP satellites (since 1978). The IHV (or HP) index is proportional to the product of the cube-root of the solar wind momentum flux, $(nV^2)^{1/3}$, intercepted by the magnetosphere and of the flux of reconnected solar wind magnetic fields, BV. Physically, IHV is a measure of the quantity $n^{1/3} * B * V^{5/3} * q$, where q is a geometric factor varying with the angle between B and the Earth's magnetic dipole. For constant density $n^{1/3}$ and longer-term averages over angles, IHV depends on $BV^{5/3}$, or approximately BV^2 . The effective

power of V in this relationship depends slightly on the interval over which IHV is averaged (typically one month to a year). The IHV-index for a given station stands on its own, but for construction of a global index can be corrected for UT-effects and station location and normalized to the NGK station. The IHV-index has, so far, been derived back to 1883, with further extension possible, once existing 19-century observatory yearbook data become electronically available.

2) The Inter-Day-Variability (IDV-) index is defined as the unsigned difference between the hourly means for two successive days (of the H-component of the geomagnetic field) for the hour following local midnight for stations equatorwards of 51 degrees CGML. The IDV-index has been shown to be a close proxy for the energy content of the ring current which in turn is controlled by the open flux in the magnetotail, ultimately depending on IMF B. The negative part of the Dst-index (or Dst derived from night-time data only) is, if one includes the ~ 25 nT 'quiet-time' component, simply proportional to B. The IDV-index for a given station stands on its own, but for construction of a global index can be corrected for station located and normalized to NGK. The IDV-index is a modern version of Bartels' classical u-measure and is available back to 1872 with further extension possible.

3) The solar wind electric field, $V \times B$, maps down to an electric potential across the Earth's polar caps giving rise to an ionospheric Hall current that is

directed towards the sun as the Earth turns under it. The magnetic effect of this current has been measured (with some early data gaps, of course) back to the First Polar Year (1883) and can be calibrated with modern data to allow determination of the product BV .

Collectively, these three indices give us an over-determined system for extracting the long-term variation over the past ~ 120 years of B and V . The analysis so far indicates that the variation of B can be described as a constant value (~ 4.5 nT) plus a component varying with the square-root of the sunspot number. Because the latter seems to exhibit a ~ 100 year Gleissberg cycle, B does as well. The solar wind speed, V , seems to have increased linearly by 15% over the last 120 years and thus not to follow the Gleissberg cycle.

The IHV-index fords a way to check to calibration of other long-term geomagnetic indices. We find that that the Ap-index tracks the variation of IHV, but that the aa-index is systematically too low (3-5 nT) before 1957.