XIII IAGA Observatory Workshop

Golden, 17 June, 2008

Observatory Data: a 170-year Sun-Earth Connection

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Abstract: The discovery of the sunspot cycle and the first results of the 'Magnetic Crusade' together made it clear that solar and geomagnetic activity are intimately related and that observing one is learning about the other [both ways]. Understanding of this magnificent relationship had to await more than a century of progress in both physics and observations, and only in the last few decades have we achieved the elucidation that in the middle of the 19th Century was so fervently hoped for: The lack of rapid progress so frustrated the observers [and their funding agencies] that many observatories were shut down or had operations severely curtailed, because as von Humboldt remarked in vol. 4 of his *Cosmos*: "they have yielded so little return in proportion to the labor that had gone into collecting the material". The confirmation by spacecraft measurements of what workers in solar-terrestrial relations had so long suspected namely that a solar wind connects the magnetic regimes of the Sun and the Earth has finally brought about an understanding of one half of the relationship [activity] while the discovery of the ionosphere and measurements of solar ultraviolet and X-ray emissions have brought understanding of the other half [regular diurnal variation]. We now have a quantitative understanding of these phenomena [although the microphysics is still debated] allowing us to model quantitatively the geomagnetic response to solar and interplanetary conditions. The immense complexity of geomagnetic variations becomes tractable by the introduction of suitable geomagnetic *indices* on a variety of time scales. Because different indices respond to different combinations of solar wind parameters we can invert the response and determine solar wind speed and density and interplanetary magnetic field strength from simple hourly mean values as far back as these are available, as we will show in this talk. In addition, the understanding of the ionospheric response to solar Far UltraViolet, allows us to infer FUV in the past as well, with the possibility of checking [and correcting] the sunspot number and calculating the Total Solar Irradiance. As geomagnetic variations have been monitored for ~170 years with [for this purpose] constant calibration, we have a data set of immense value for understanding long-term changes in the Sun. We argue that all efforts must be expended to preserve and digitize these national and scientific treasure troves.

In Memoriam: Emil Kring Lauridsen

The Central Problem of Geomagnetic Variations

The geomagnetic record shows a mixture of signatures from different physical processes: the regular daily variation (1), irregular short duration [1-3 hours] variations (2), and 'storms' typically lasting a day or more (3). Geomagnetic *indices* have been devised to characterize and quantify these three types [ignoring special effects like pulsations, eclipse effects, etc]. An experienced observer can usually distinguish the various types from the general character of the curves and from hers/his knowledge of the *typical* variations at the observatory. Various computer algorithms more or less successfully attempt to supplant the need for a human, experienced observer, but in any case the *high-frequency* part of the record is the necessary ingredient in the process:
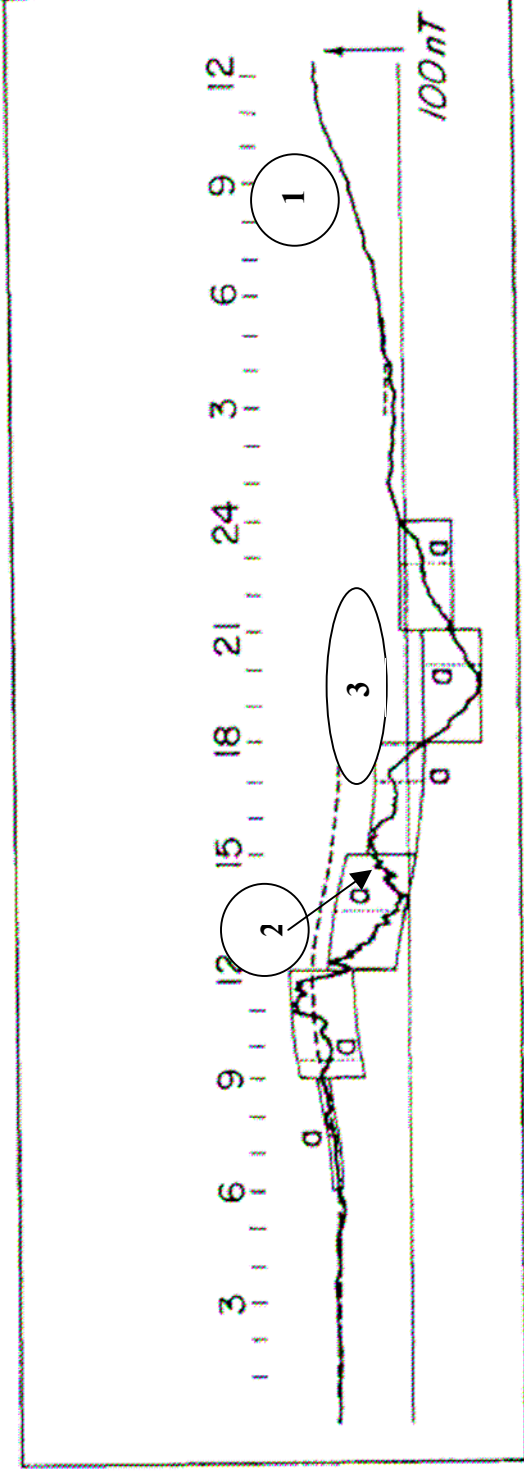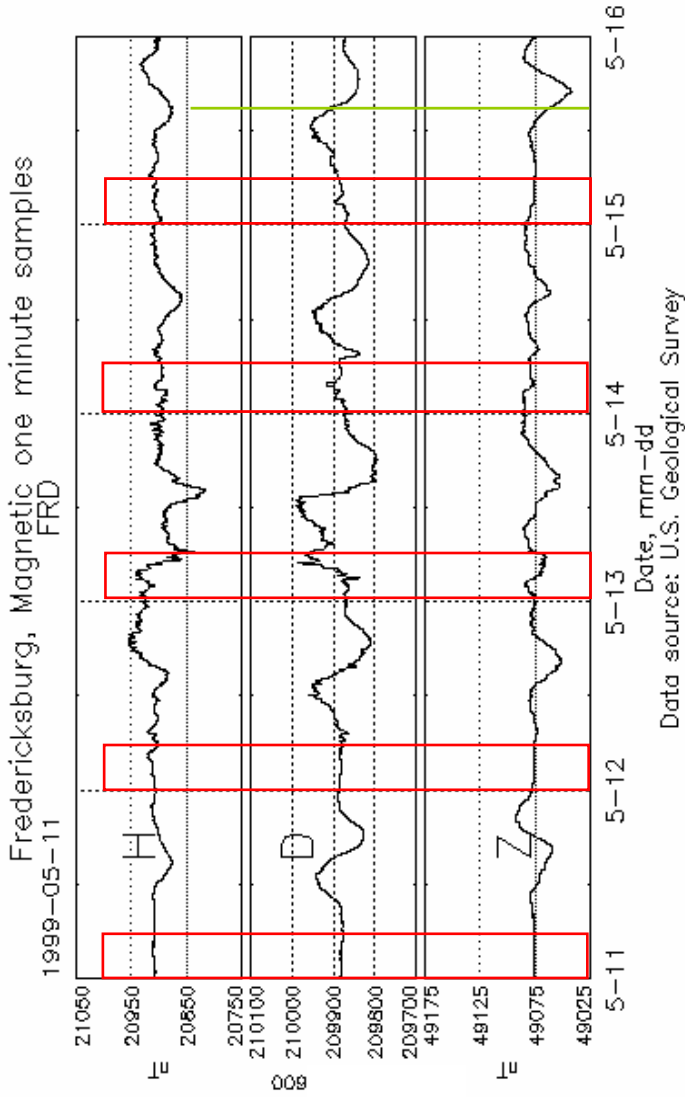
The Difficulty with the Regular Daily Variation

Recognizing and quantifying the regular daily variation, what Mayaud called S_R, is the main problem. The amplitude of this variation varies from day to day; near the focus of the current system, even the type of the variation changes from day to day. In deriving both the Dst index and the K range index, S_R must be recognized and removed. We all know the problems associated with that, with the insufficiency of using the '5 Quiet Days' as the basis for determining S_R, with the error of using an average 'iron curve', etc. The pattern-recognition capabilities of the experienced observer can not be transferred to successors.

Long-Term Geomagnetic Indices

Mayaud's heroic construction of the **aa-index** (back to 1868) is unlikely to be duplicated. The international cooperation and effort that are providing us with the **ap** (1932-), **am** (1959-), and **Dst** (1957-) indices cannot be replicated or extended into the past. It is difficult to gauge the long-term stability of the calibration of the range indices. The vast collection of 19th century **yearbook** data seems useless to many people to the point where the data is not being preserved or digitized for modern processing methods.

In this talk, I'll show how these problems can be overcome and provide a rationale for the preservation and digitization of the yearbook data.

IHV-index: Use of Night Hours Only

Fredericksburg, Magnetic one minute samples
FRD
1999-05-11

Date, mm-dd
Data source: U.S. Geological Survey

Red boxes: Local night.

IHV-index (InterHourly Variability): sum of the six *absolute* differences between hourly values of any of the geomagnetic components [initially for H] for the seven hours spanning local midnight [falling within the 4th hour].
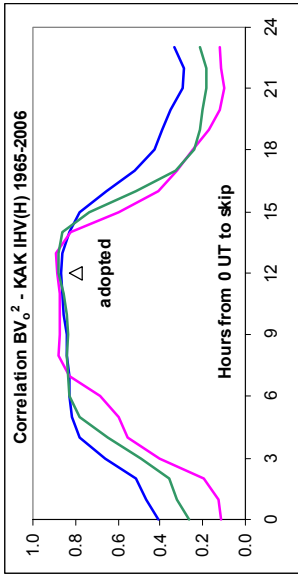
In practice, we determine the *number of hours to skip* from 0^h UT, before beginning to sum the following six hourly absolute differences. Local midnight is also the time where the correlation with interplanetary parameters BV^2 maximizes.

Correlation BV_o^2 - KAK IHV(H) 1965-2006

adopted

Hours from 0 UT to skip

IHV is Strongly Correlated with the Am-index
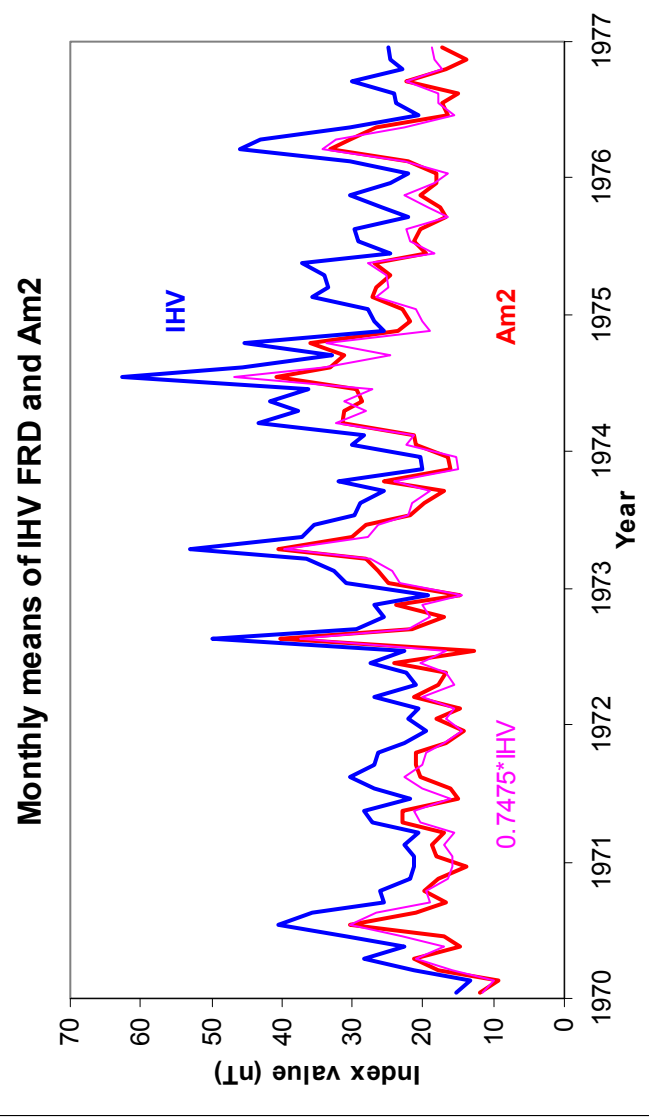
There is a strong correlation between *IHV* [blue] and the *am*-index [red]. For monthly means for FRD we can calculate *am* from *IHV*:

$$am_{calculated} = 0.7475\ IHV.$$

The calculated *am*-index [pink] is a good proxy for *am* using the same six-hour interval [00-06 UT] as was used in the calculation of *IHV*.

Using several stations at different longitudes a global composite *IHV* can now be constructed. The correlation with *am* is very high, which means that we can construct the *am*-index as far back as we can get *IHV*.

Monthly means of IHV FRD and Am2
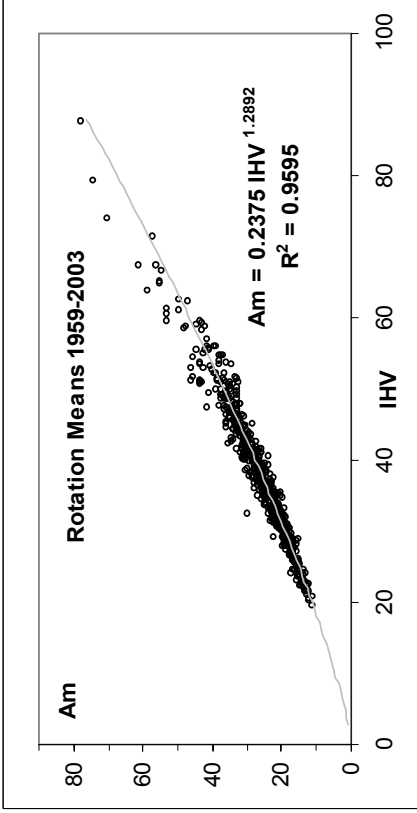
The Am index correlated with Composite IHV index for the interval 1959-2003 on a time scale of Bartels 27-day rotations.

Rotation Means 1959-2003

$$Am = 0.2375\ IHV^{1.2892}$$
$$R^2 = 0.9595$$

Variation of IHV with Latitude
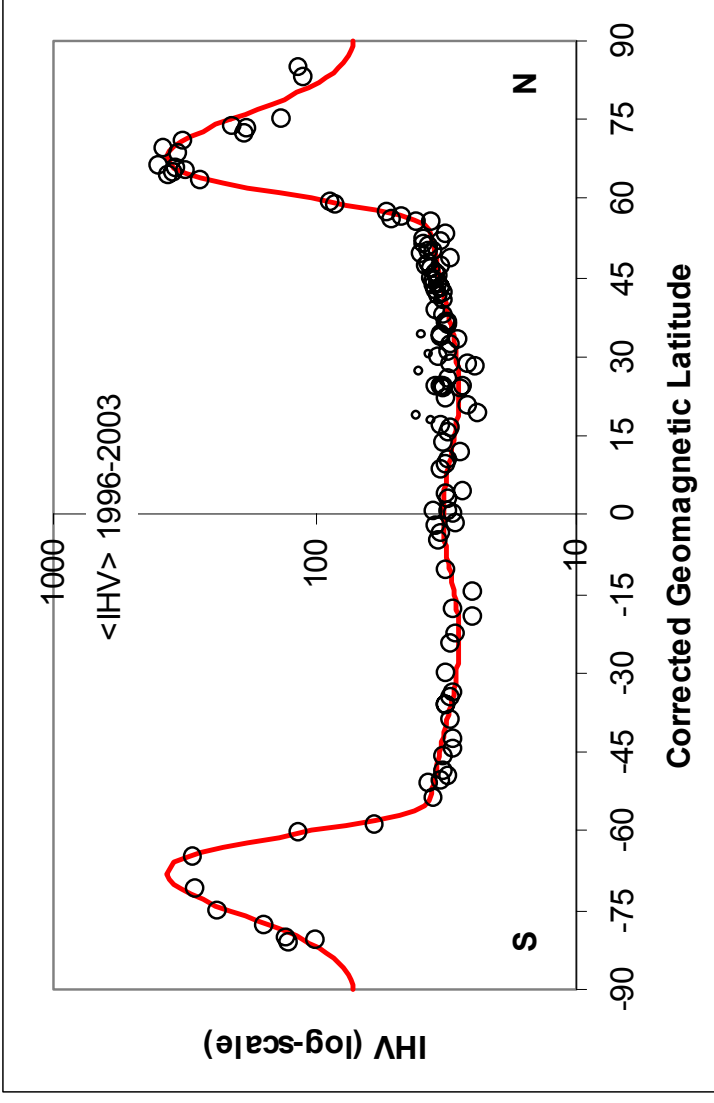
For *all* (~120) stations that had [essentially complete] data during 1996-2003, we calculated the average IHV over that interval and plotted it against corrected geomagnetic latitude. The auroral zones are clearly visible and we *limit* ourselves now to stations below 55° corrected geomagnetic latitude, for which the variation with latitude is slight.
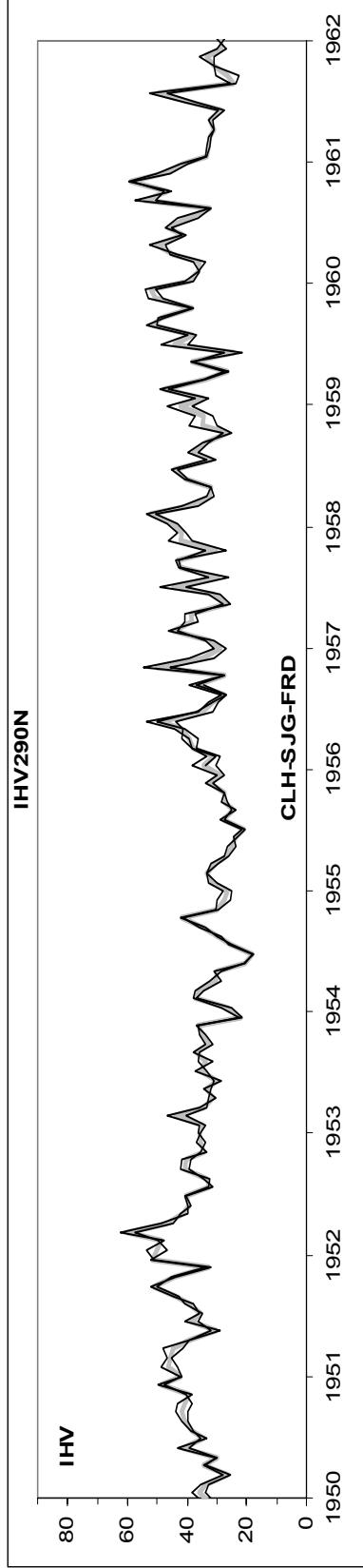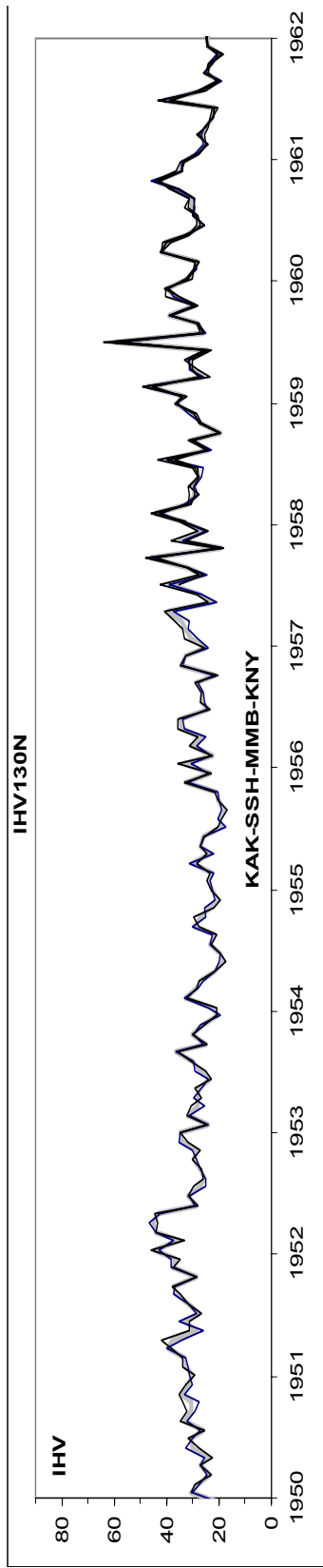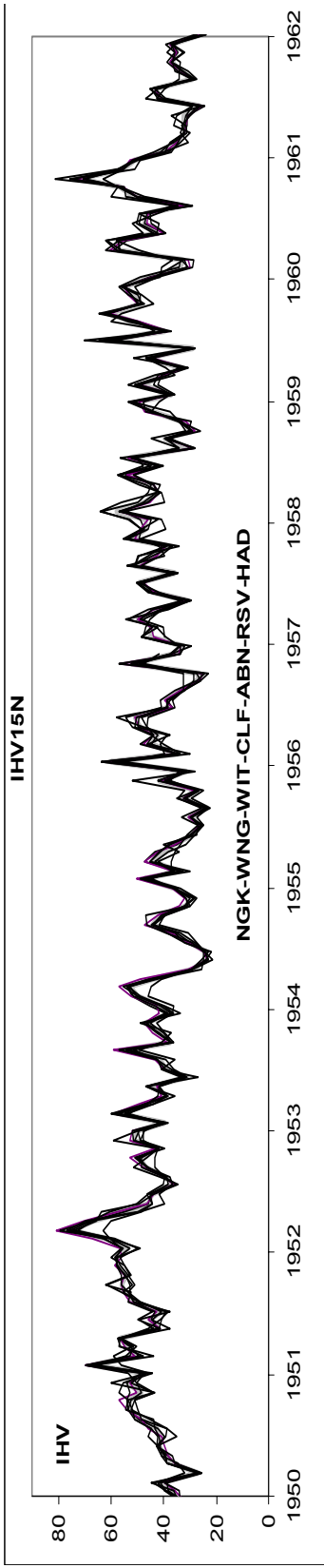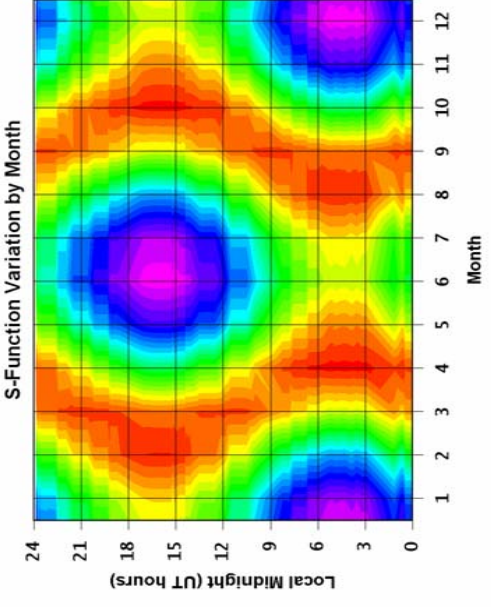
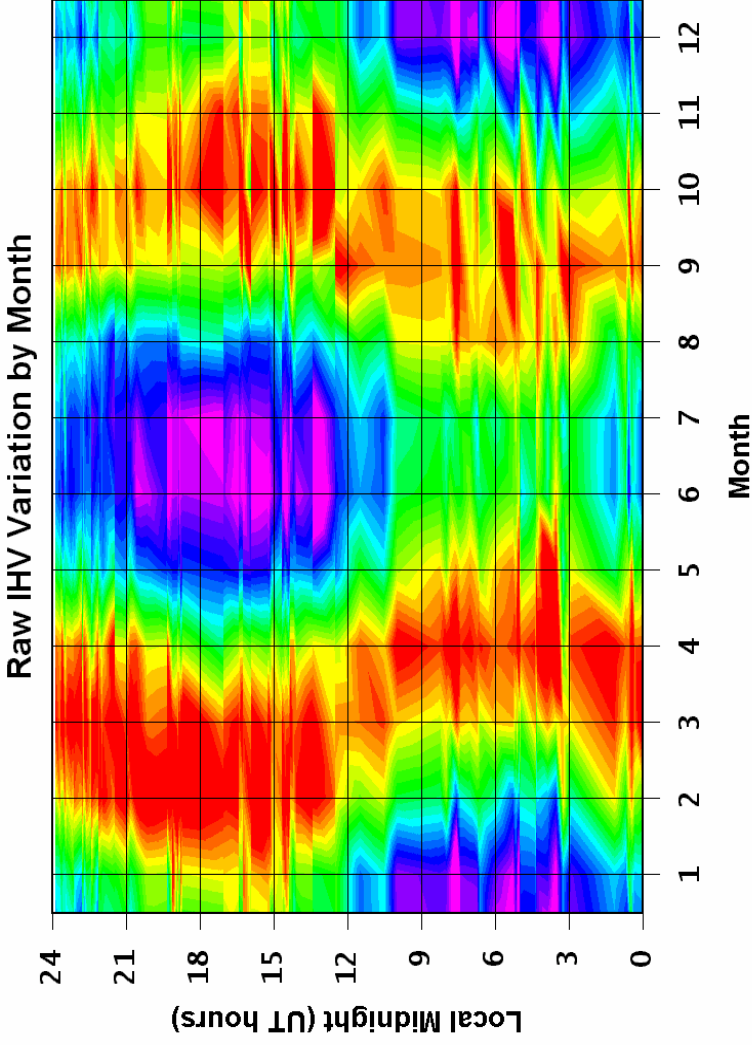# Stations Used for Construction of IHV-index
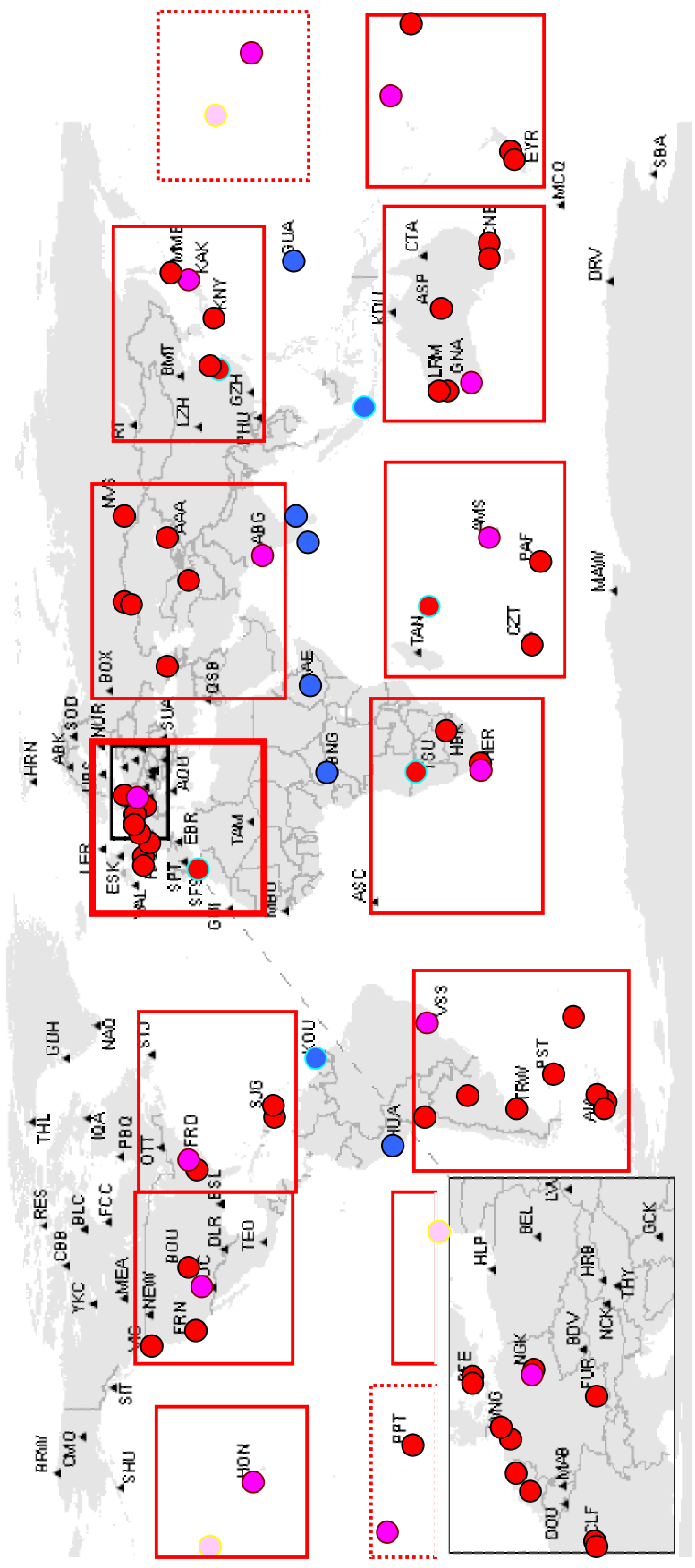
We use 12 independent longitude [and North/South] "boxes" plus an Equatorial band [blue station symbols]. For each box, a *reference* station is shown in pink. All other stations in the box are normalized to the reference station and the average is computed for the box. Finally, each box is normalized to the European box [Ref: Niemegk].

Composite Box IHV-indices

IHV15N

IHV

NGK-WNG-WIT-CLF-ABN-RSV-HAD

IHV130N

IHV

KAK-SSH-MMB-KNY

IHV290N

IHV

CLH-SJG-FRD

Semiannual Variation of (Raw) IHV

Raw IHV Variation by Month

S-Function Variation by Month

$$S(\Psi) = 1/(1 + 3 \cos^2(\Psi))^{2/3}$$
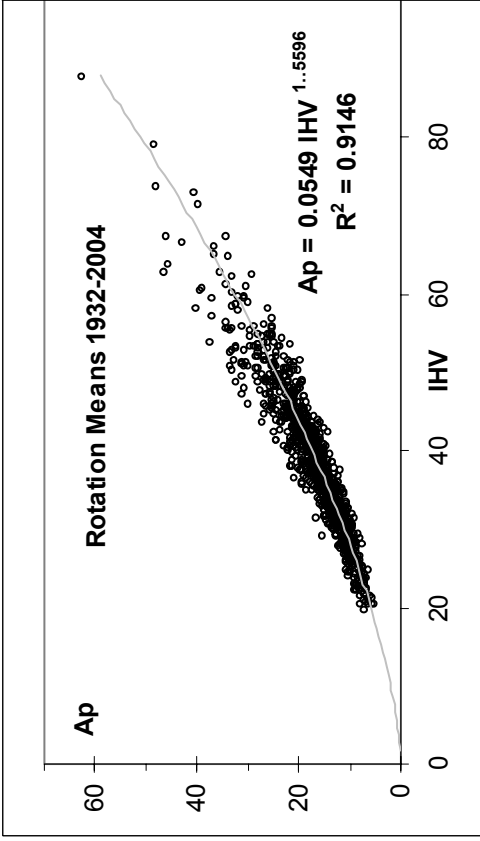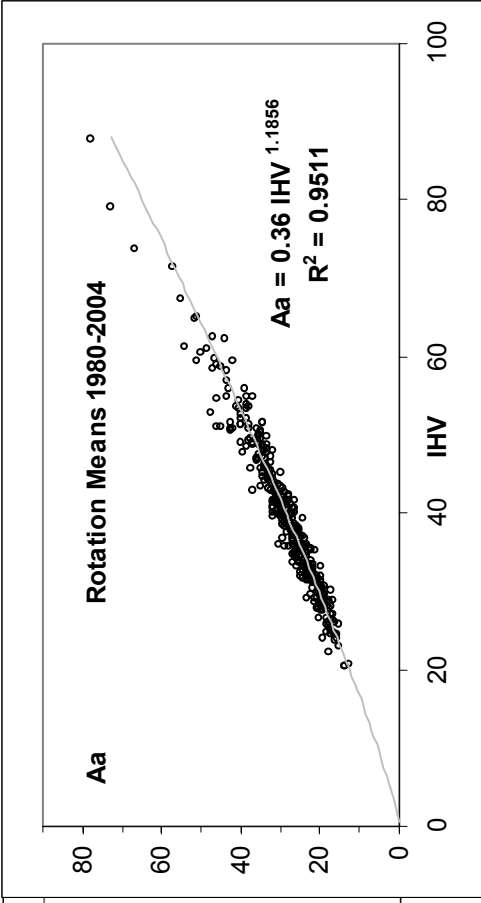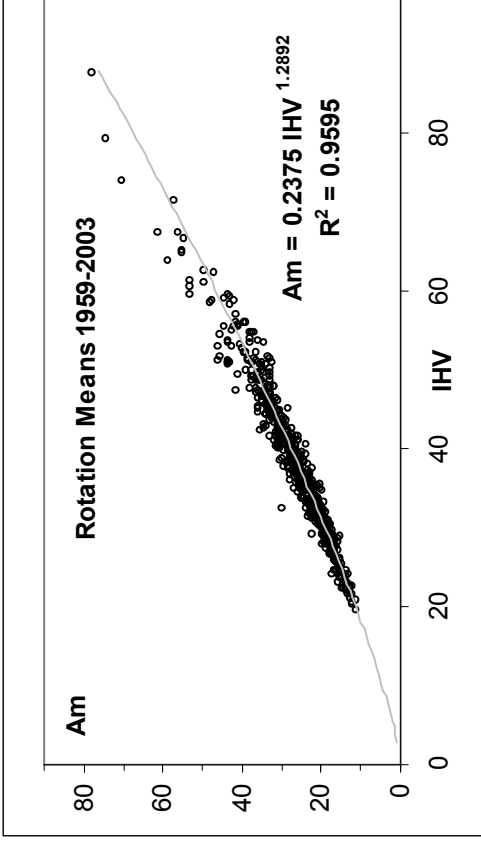Ψ is 'dipole tilt' against the solar wind direction.

IHV exhibits the 'usual' equinoctial semiannual variation. We plot here the seasonal variation of IHV for all stations [during 1996-2003] below 55° corr. geomagnetic latitude as a function of the Universal Time of local midnight for each station. This variation is well described by the 'S'-function of the Earth's dipole tilt, Ψ, against the solar wind direction. We remove this purely terrestrial effect simply by dividing the raw IHV for each station by the S-function for that station.
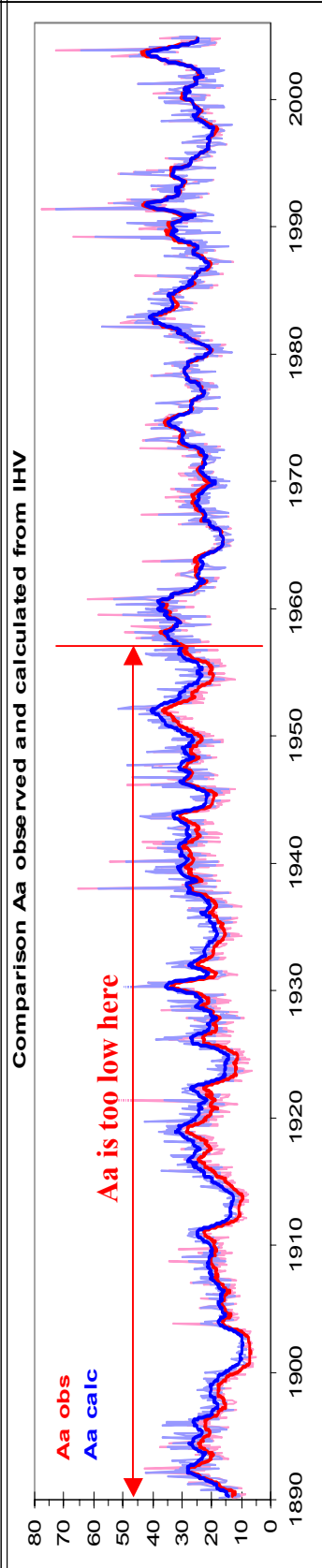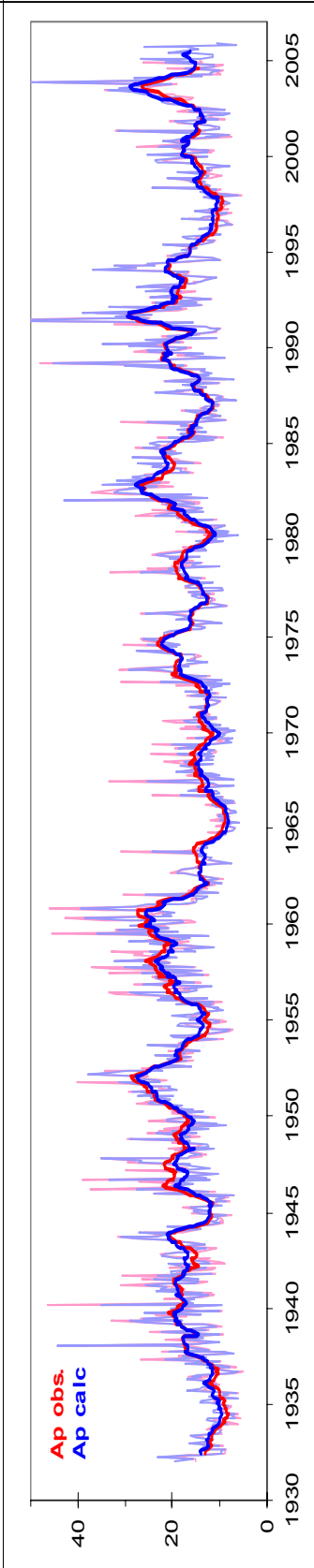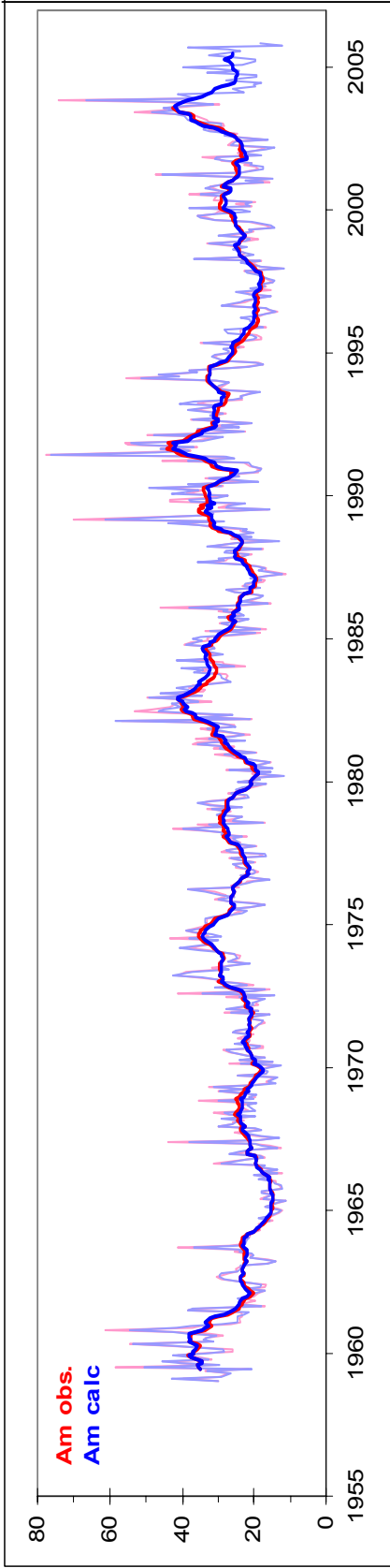
Composite Global IHV-index
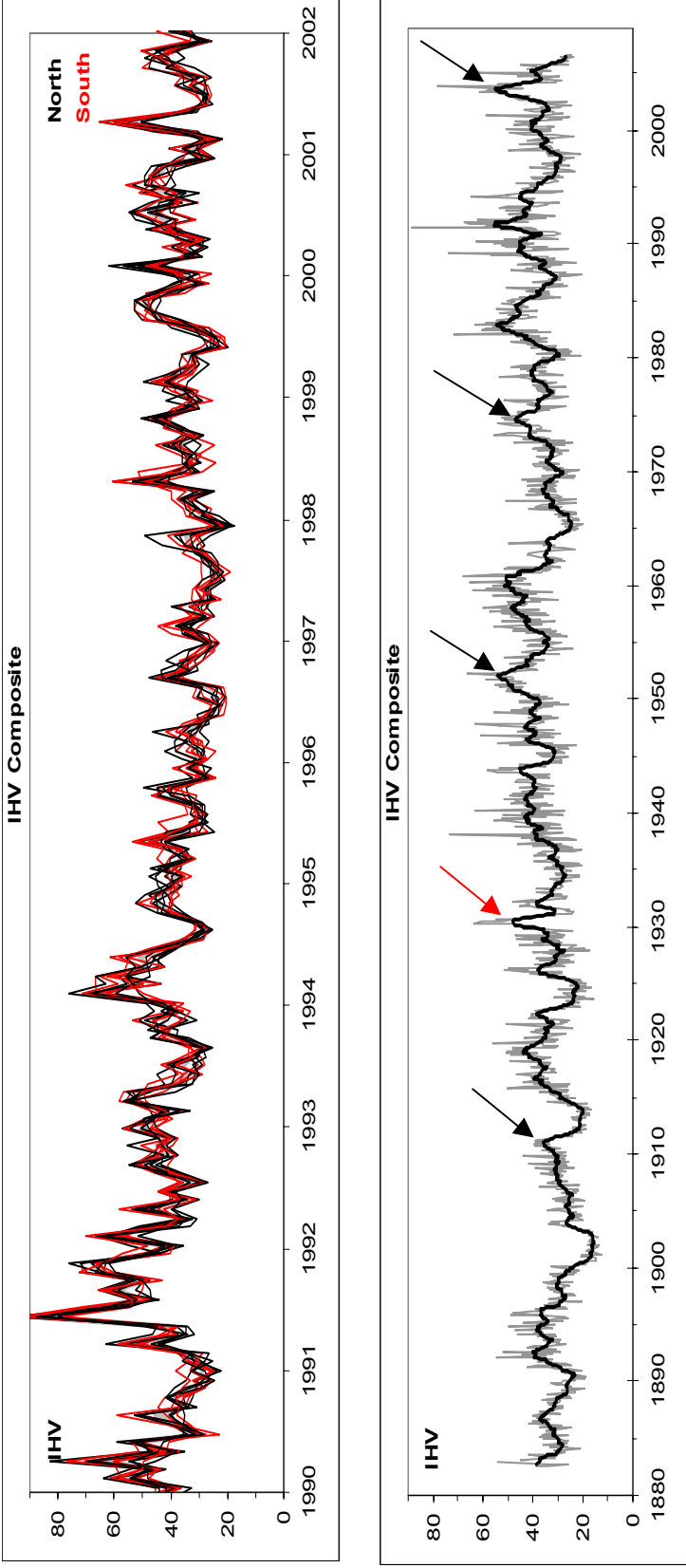
By averaging [with equal weight] all the normalized 'box' composites we arrive at a *global* composite IHV-index that covers all UT hours. The graphs show Bartels 27-day rotation averages [with a 13-rotation running mean]. Note that there is no clear seasonal difference between North and South. Arrows show years with strong high-speed streams.
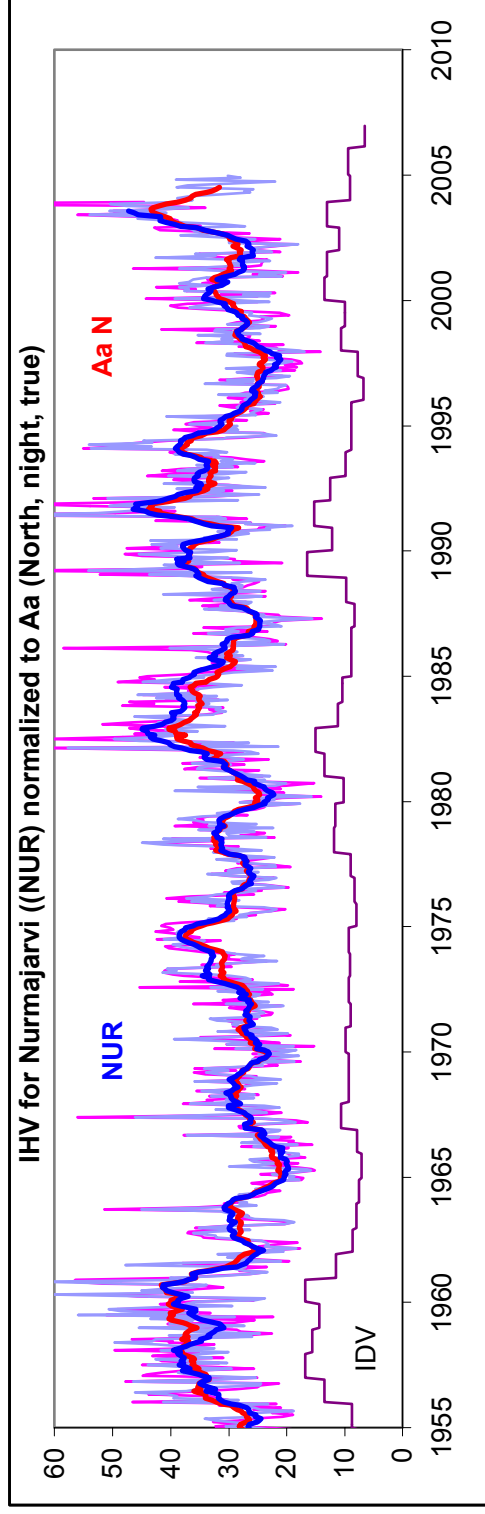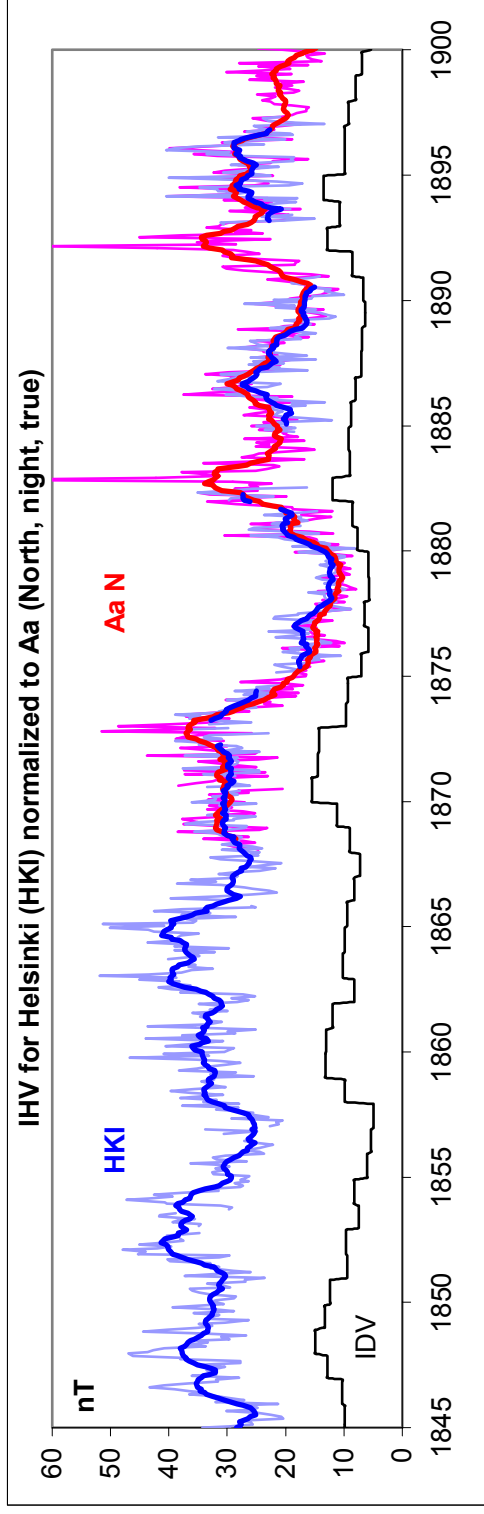
Comparison with Amplitude Indices

Am

Rotation Means 1959-2003

$Am = 0.2375\ IHV^{1.2892}$
$R^2 = 0.9595$

IHV

Aa

Rotation Means 1980-2004

$Aa = 0.36\ IHV^{1.1856}$
$R^2 = 0.9511$

IHV

Ap

Rotation Means 1932-2004

$Ap = 0.0549\ IHV^{1..5596}$
$R^2 = 0.9146$

IHV

The relationships are slightly non-linear [most so for the *Ap*-index]. For the *Aa*-index we have chosen the time since 1980 where there has been no change in stations [and, hopefully, in procedures and calibration].

We can now use these empirical relations to *calculate* the classical amplitude indices for comparison with *IHV*:

It would seem that the *aa*-index is in need of a recalibration before 1957.

IHV for Helsinki (HKI) normalized to Aa (North, night, true)

IHV for Nurmajarvi ((NUR) normalized to Aa (North, night, true)

Here is an example of what can be done using Helsinki back to 1844. [using a preliminarily corrected *aa*-index]

Physical Meaning of IHV (and am, aa, ap)

Geomagnetic activity as given by the three-hour *am*-index has been found [Svalgaard 1978] to depend on solar wind parameters and the geometry of their interaction with the Earth as this:

[Momentum, Reconnection, Modulations]

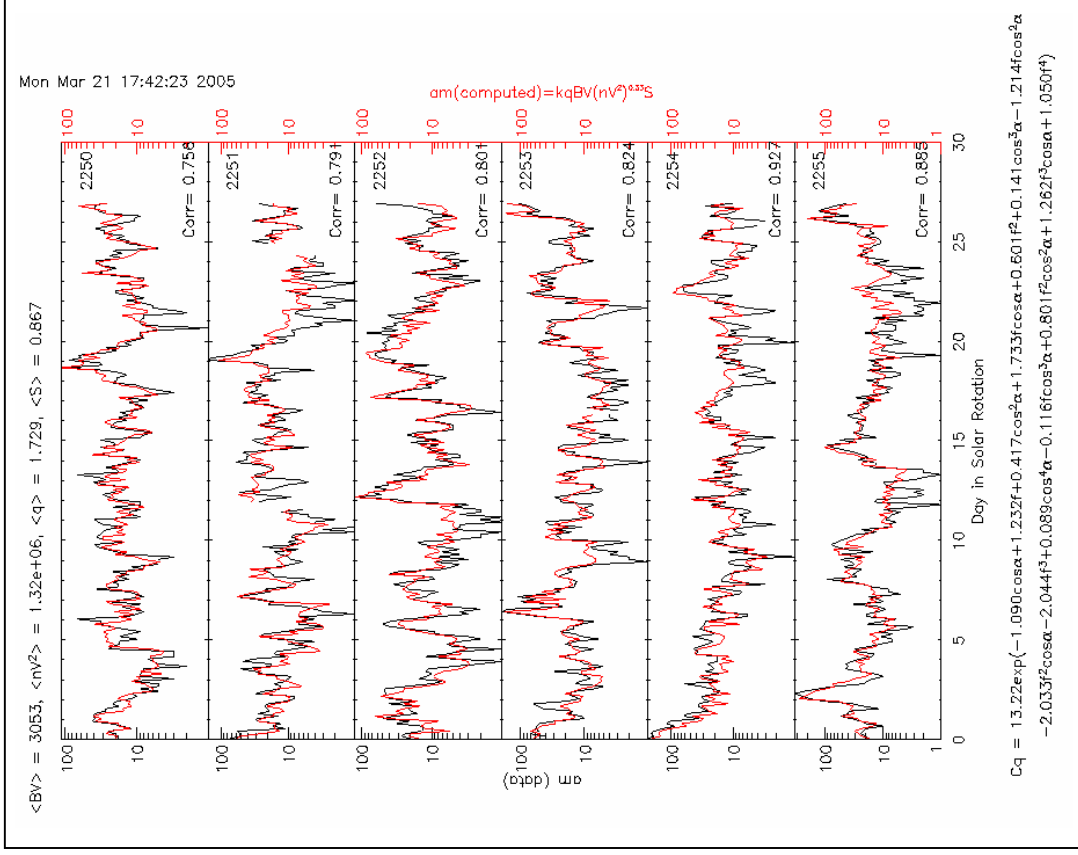$$am = k\,(nV^2)^{1/3}\,(BV)\,q(\alpha,f)\,S(\Psi)$$

B = Interplanetary Magnetic Field strength
V = Solar Wind Speed
q = function of angle α between IMF and Earth's magnetic field
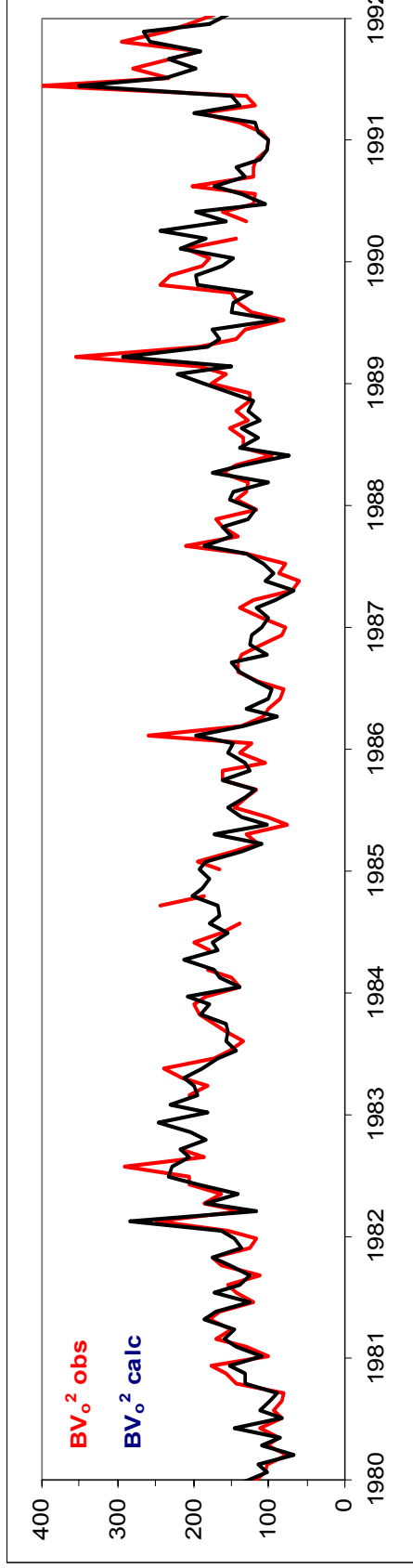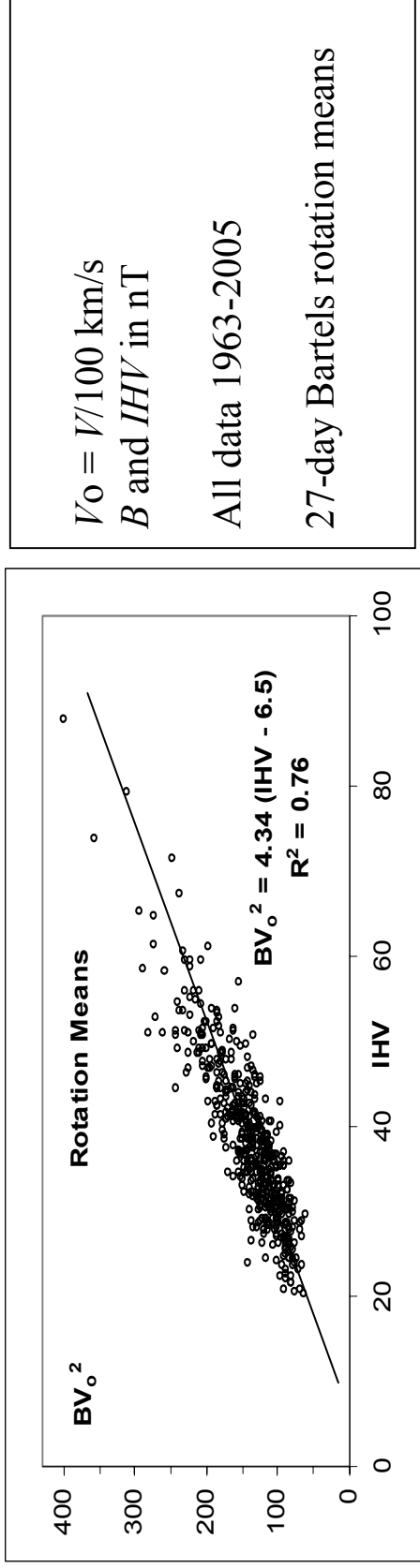f = variability = $\sqrt{(\sigma_{Bx}^2 + \sigma_{By}^2 + \sigma_{Bz}^2)}/\sigma_B$

Here we show how very good the fit is for individual three-hour intervals [red curves = calculated; note the log-scale]. Only for very small values of *am* [<5 nT] where *am* is almost impossible to measure correctly do we have a persistent discrepancy: *am*, or rather *Km*, is too low. K = 0 is always a problem.

Mon Mar 21 17:42:23 2005

$am(\text{computed}) = kqBV(nV^2)^{0.33}S$

$\langle BV \rangle$ = 3053, $\langle nV^2 \rangle$ = 1.32e+06, $\langle q \rangle$ = 1.729, $\langle S \rangle$ = 0.867

2250 Corr= 0.758
2251 Corr= 0.791
2252 Corr= 0.801
2253 Corr= 0.824
2254 Corr= 0.927
2255 Corr= 0.885

am (data)

Day in Solar Rotation

$Cq = 13.22\exp(-1.090\cos\alpha + 1.232f + 0.417\cos^2\alpha + 1.733f\cos\alpha + 0.601f^2 + 0.141\cos^3\alpha - 1.214f\cos^2\alpha - 2.033f^2\cos\alpha - 2.044f^3 + 0.089\cos^4\alpha - 0.116f\cos^3\alpha + 0.801f^2\cos^2\alpha + 1.262f^3\cos\alpha + 1.050f^4)$

For intervals longer than three hours the variables are weakly correlated and the relation becomes slightly modified to $am \sim BV^2$. We would therefore expect a similar relationship for IHV. This is indeed what is observed:

$V_o = V/100$ km/s
B and IHV in nT

All data 1963-2005

27-day Bartels rotation means

Rotation Means

$BV_o^2 = 4.34 \, (IHV - 6.5)$
$R^2 = 0.76$

BV_o^2

IHV

BV_o^2 obs
BV_o^2 calc

And here is a sample of how well the calculated values match the observed. IHV is thus a good proxy for BV^2. It is somewhat remarkable that am [conceived long ago] also is.

Power Input to the Ionosphere

During geomagnetic activity, magnetospheric 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:

27-Day Averages of Calibrated Hp
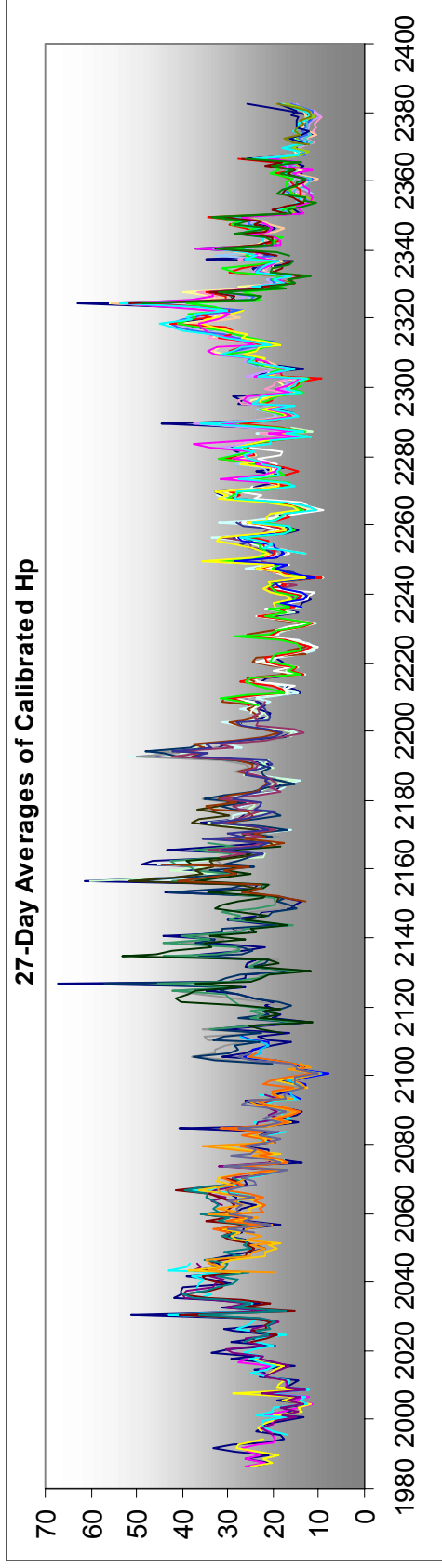
Different colors denote the different satellites used. The abscissa is Bartels rotation numbers from the year 1978 to the present. There is some ongoing discussion about the correct calibration of Hp. The above is my own.
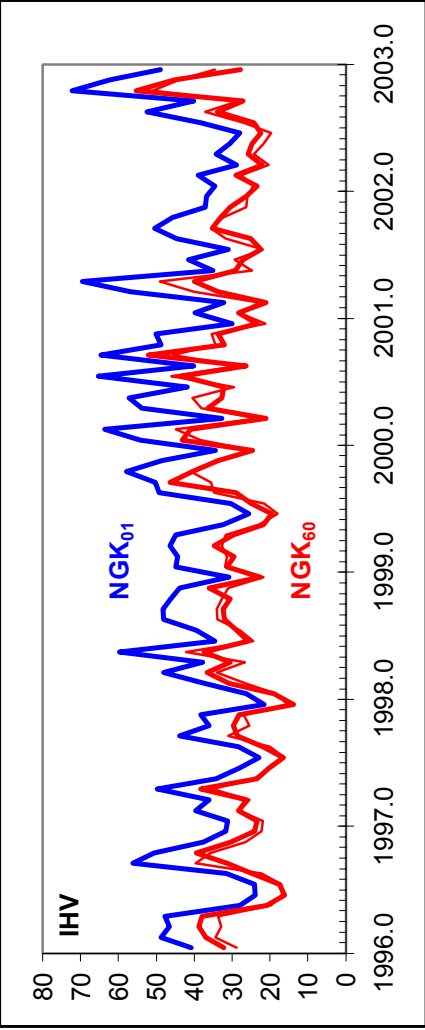
IHV is directly proportional to the power input (*Hp*) to the upper atmosphere:


Relation between Hp and IHV

Hp = 0.6029 IHV
R^2 = 0.8859
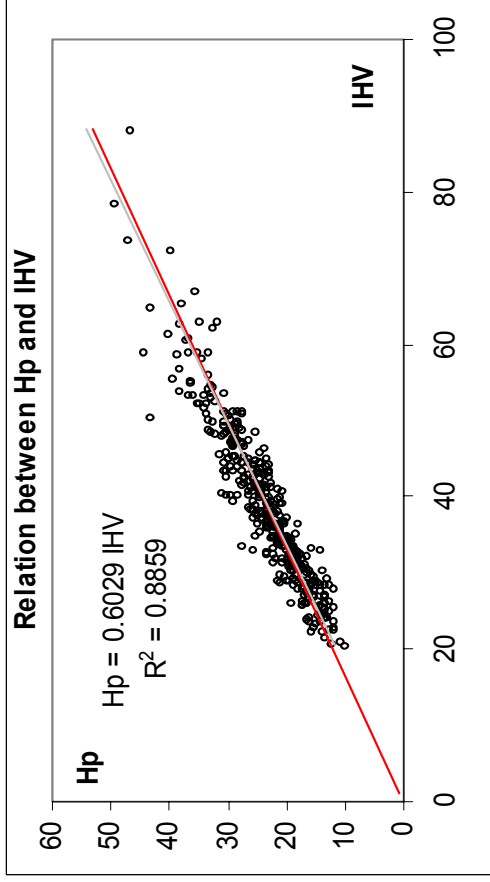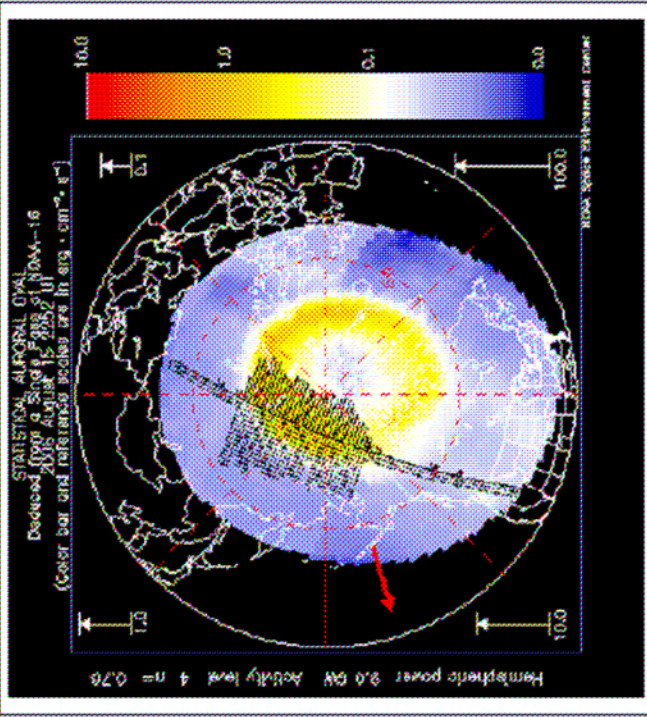
27-Day Averages of (Scaled) am, Hp, and IHV

am
Hp
IHV
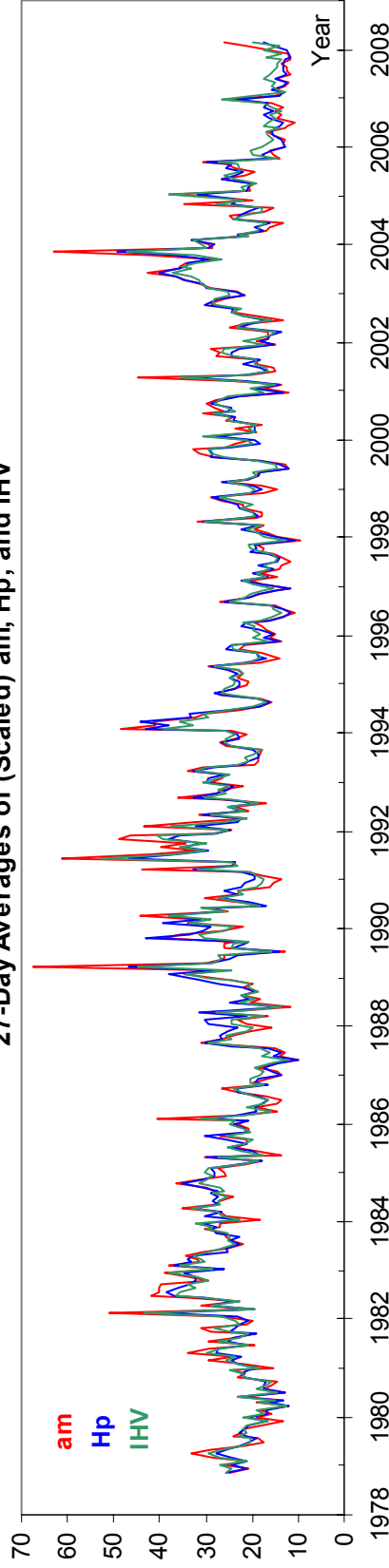
# Correcting IHV from Hourly *Values* to the Level of Hourly *Means*

Starting in 1905 Adolf Schmidt began to use Hourly Means instead of the Hourly point values that had traditionally been reported in yearbooks. And soon most observatories adopted the new practice. [Some waited long, e.g. the French who held out to 1972, before making the switch]. The instantaneous values read once every hour have larger variance which results in larger *IHV*. This is easily corrected for, e.g. by calculating *IHV* from hourly means [from the 60 one-minute values] and from hourly point values and comparing the two *IHV*s. All early observatory data must be so corrected.

$$NGK_{60} = 0.7065\, NGK_{01}$$
$$R^2 = 0.8052$$
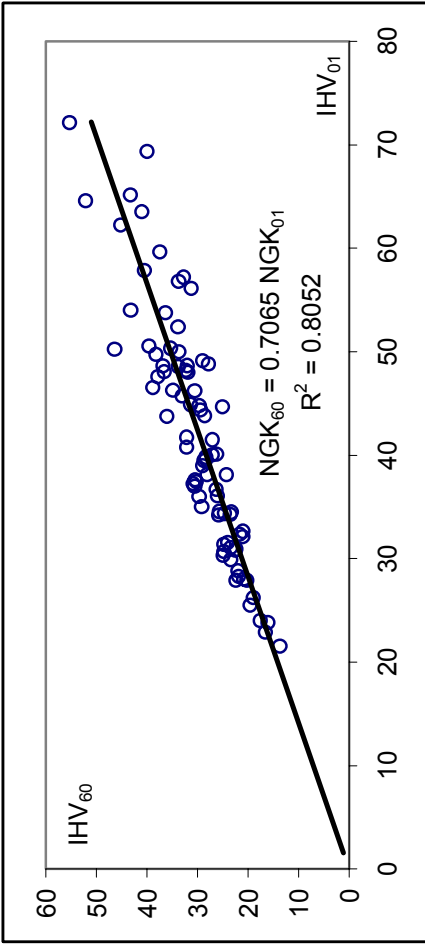
The thin red curve is the blue [*IHV* from one-minute values] multiplied by the slope of the correlation plot. The thick red curve is *IHV* from the published hourly *means*.
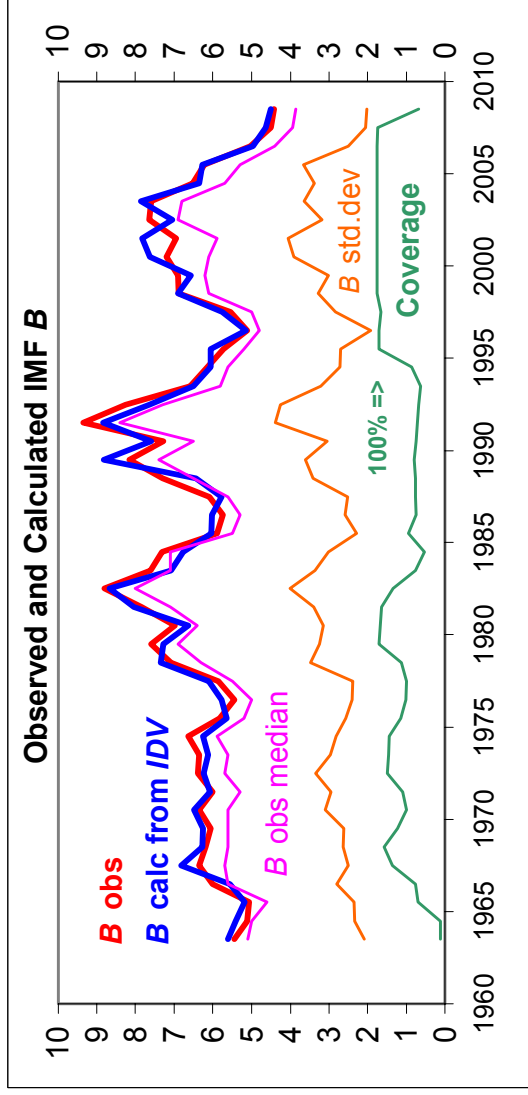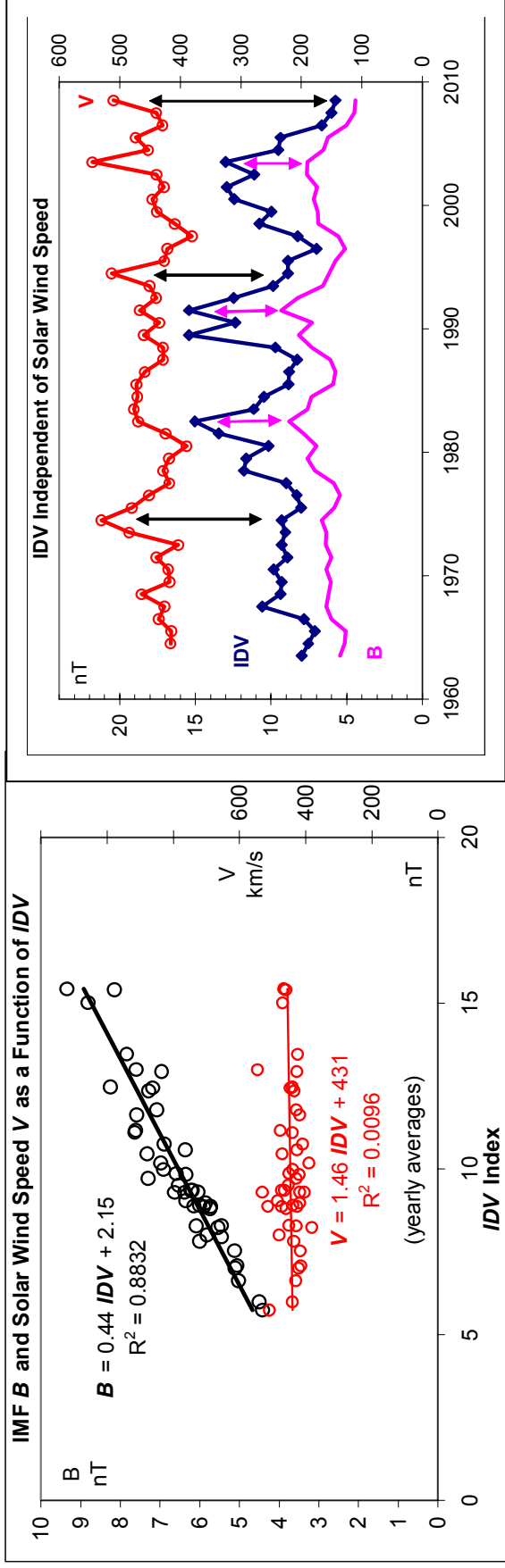
The IDV-Index, a Modern Version of Bartels' *u*-measure

The *IHV*-index captures activity on a time scale of hours. How about on a time scale of days? Julius Bartels defined his *u*-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 average *u*-measure (in nT, not the original 10 nT units) using only one hour (preferably the midnight hour if available) for as many stations as possible below 51° corr. geomagnetic latitude:
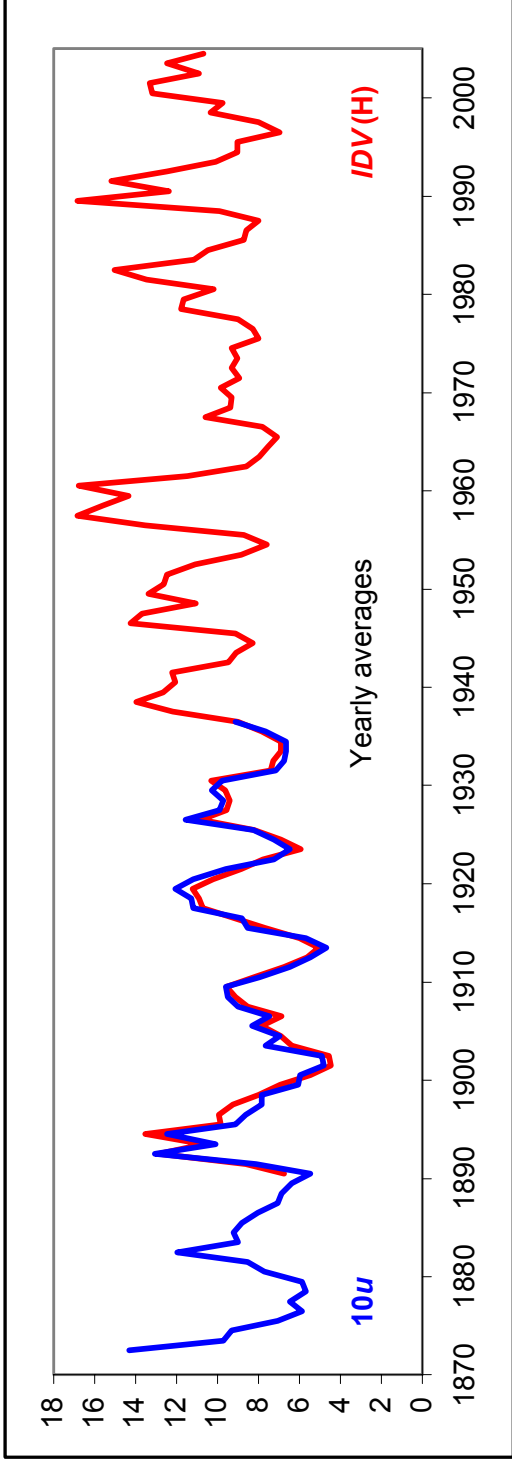
Note that *u* and *IDV* did not register the strong high-speed streams in 1910, 1930, 1952, 1974, 1994, and 2003. This (especially 1930) was a deadly blow to the *u*-measure.

What is the *IDV*-index Measuring? IMF Strength !

IDV Independent of Solar Wind Speed

IMF *B* and Solar Wind Speed *V* as a Function of *IDV*

B = 0.44 *IDV* + 2.15
R² = 0.8832

V = 1.46 *IDV* + 431
R² = 0.0096

(yearly averages)

IDV Index

IDV does not 'see' the high-speed solar wind. But there is a robust correlation with the IMF magnitude, *B*. So instead of the *u*-measure being a failure, its modern equivalent [*IDV*] has a very useful property: response to *B* only.

Observed and Calculated IMF *B*

B obs
B calc from *IDV*
B obs median
B std.dev
Coverage
100% =>

IDV measures the same as the Negative part of Dst Index

Coronal Mass Ejections (CMEs) add (closed) magnetic flux to the IMF. 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:
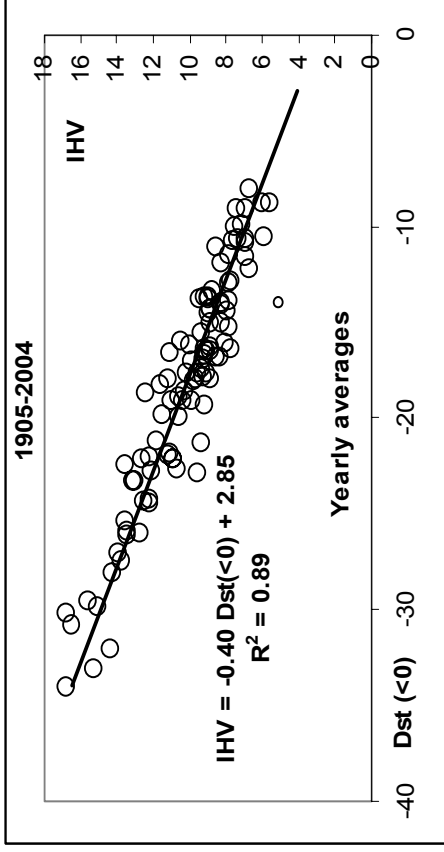
We used a derivation of *Dst* by J. Love back to 1905. Similar results are obtained with the *Dst* series by Mursula *et al.* (to 1932) or with the "official" *Dst* series (to 1957). The very simple-to-derive *IDV* series compares favorably with the much more elaborate *Dst*(<0).

1905-2004

IHV

IHV = -0.40 Dst(<0) + 2.85
R^2 = 0.89

Dst (<0)

Yearly averages
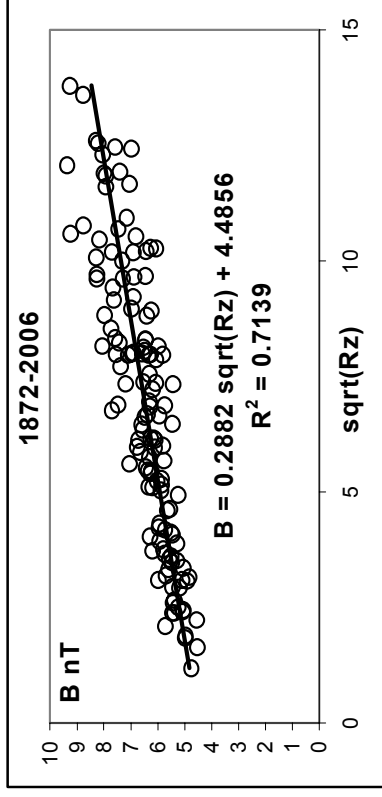
Since there is also a good correlation between *B* and the square root of the sunspot number (left), we can infer *B* from *Rz* as well.

1872-2006

B nT

B = 0.2882 sqrt(Rz) + 4.4856
R^2 = 0.7139

sqrt(Rz)

Here are both time series (*IDV* and *IDV* calculated from *Dst* (<0)):
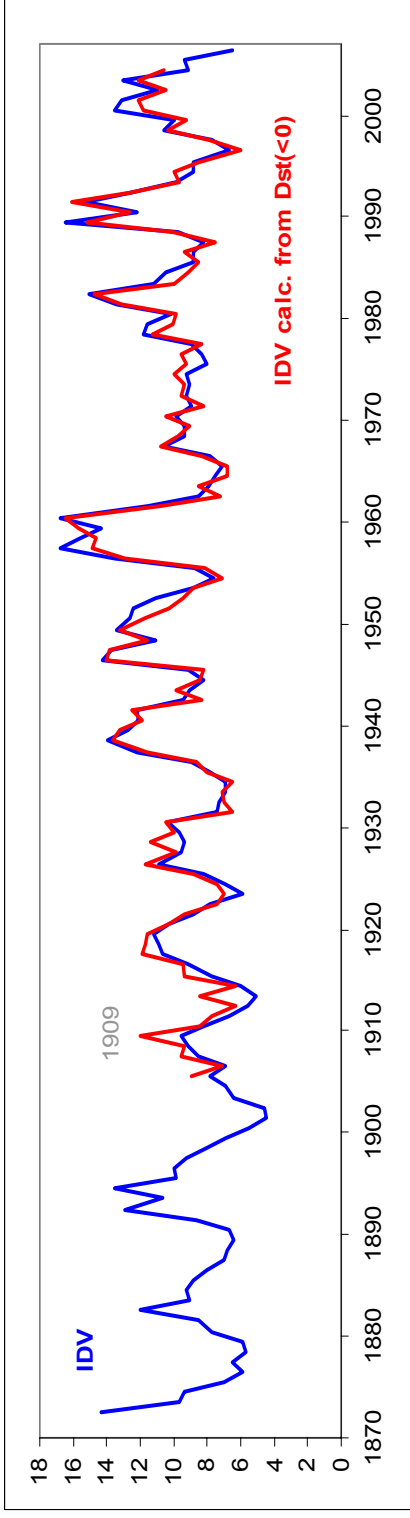
Using regressions of *IDV* and *Dst* (<0) on IMF *B* we can directly estimate *B* back to 1872:
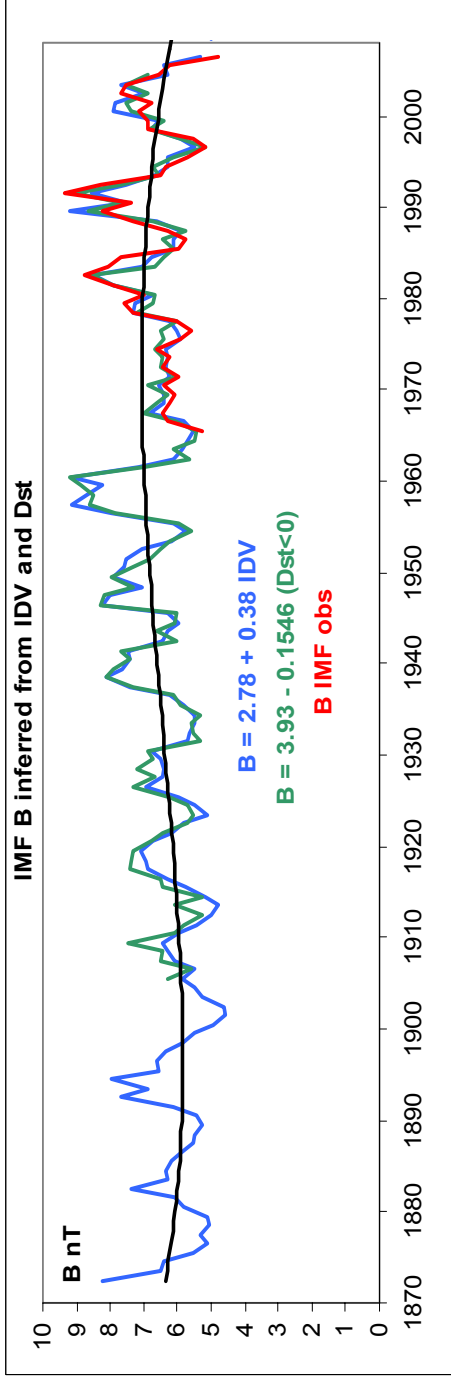
Can we go further back in time? Bartels had determined the *u*-measure from 1836 on, but with less confidence before 1872. Here is what we get if we infer *IDV* (and then *B*) from *u* back to 1836:

Inferred IMF B since 1836

From Bartels u-measure

From sqrt(Rz)

From IDV

IMF B obs S/C
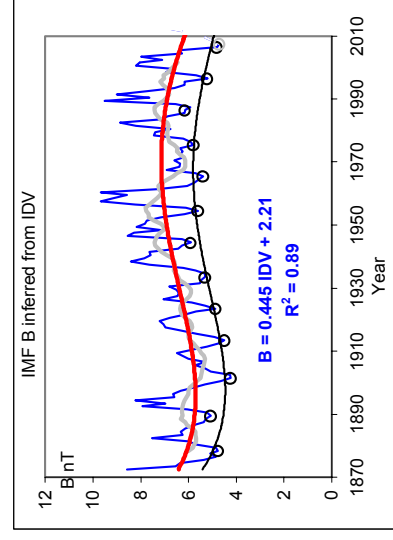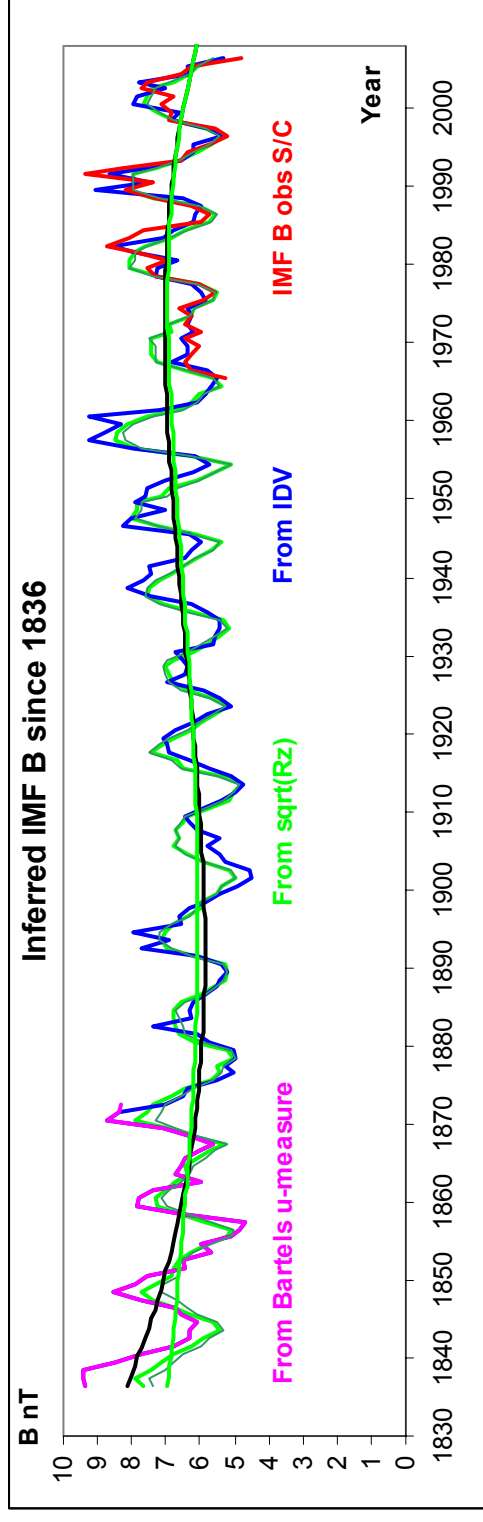
The smooth curve is a 4th-order polynomial fit. One can also just fit the values at solar minima (to eliminate most solar activity) with essentially the same result. We may be approaching another minimum in the Gleissberg cycle. The IMF *B* for 2008 (so far) is the lowest in the last 107 years.

IMF B inferred from IDV

B = 0.445 IDV + 2.21
R^2 = 0.89

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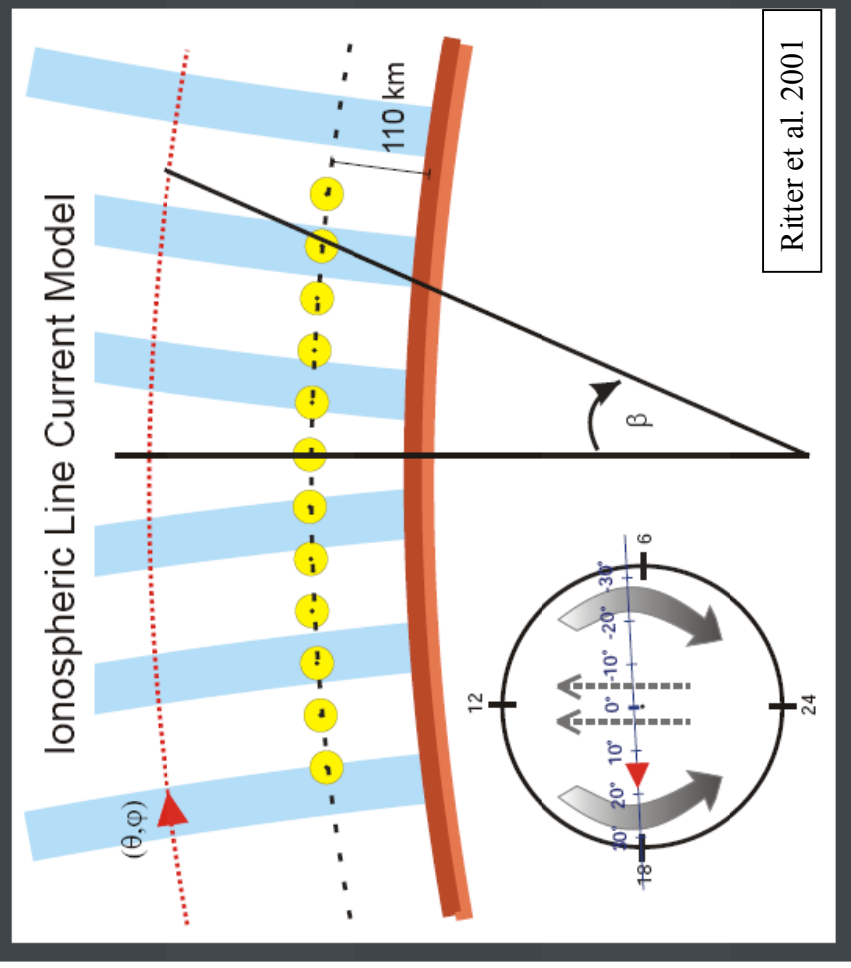
Across the Earth's polar caps flows a current in the ionosphere. This is a Hall current basically flowing towards the sun. The Earth rotates under this current causing the magnetic effect of the current to rotate once in 24 hours. This rotating daily effect is readily (and has been since 1883) observed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

Ritter et al. 2001

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.
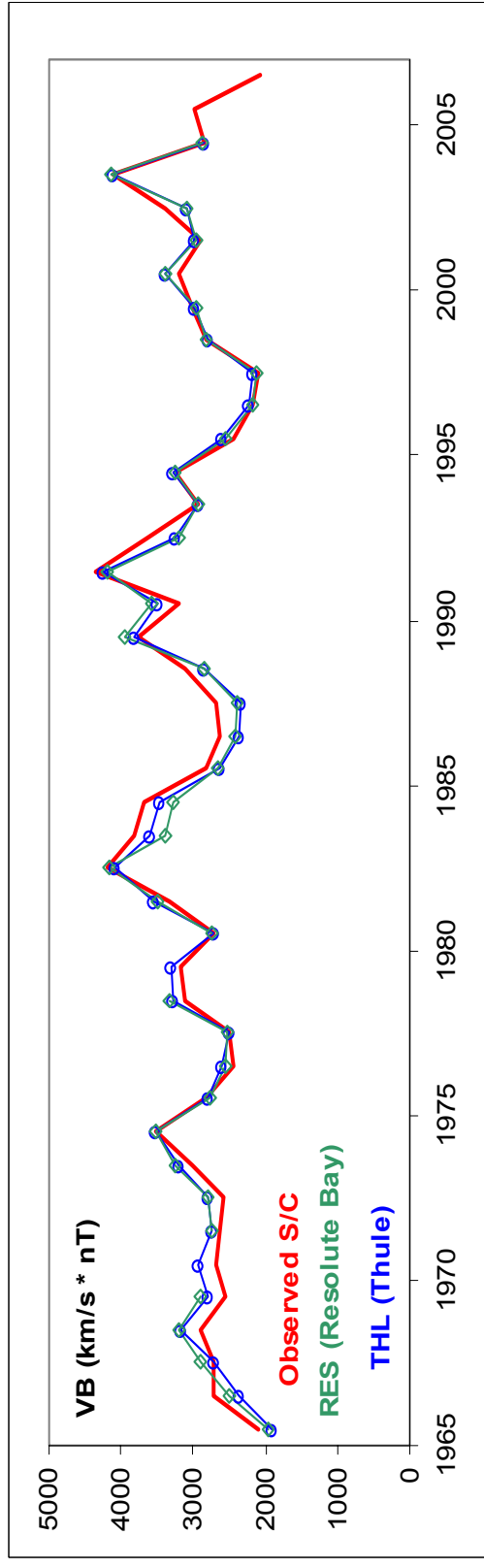
1882-1883

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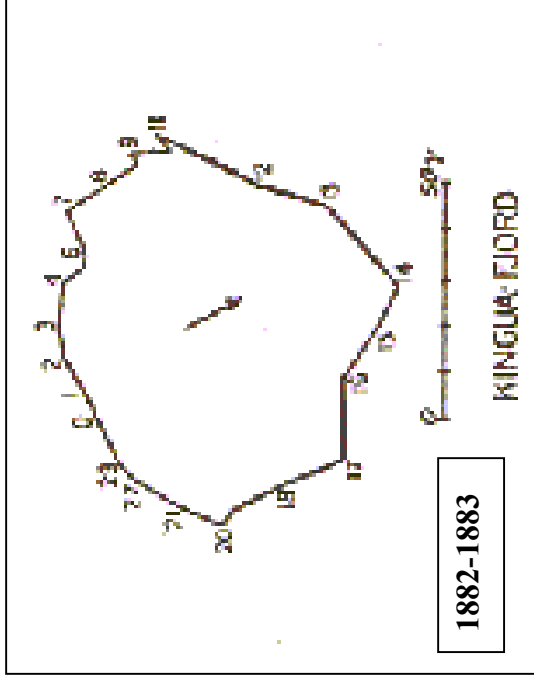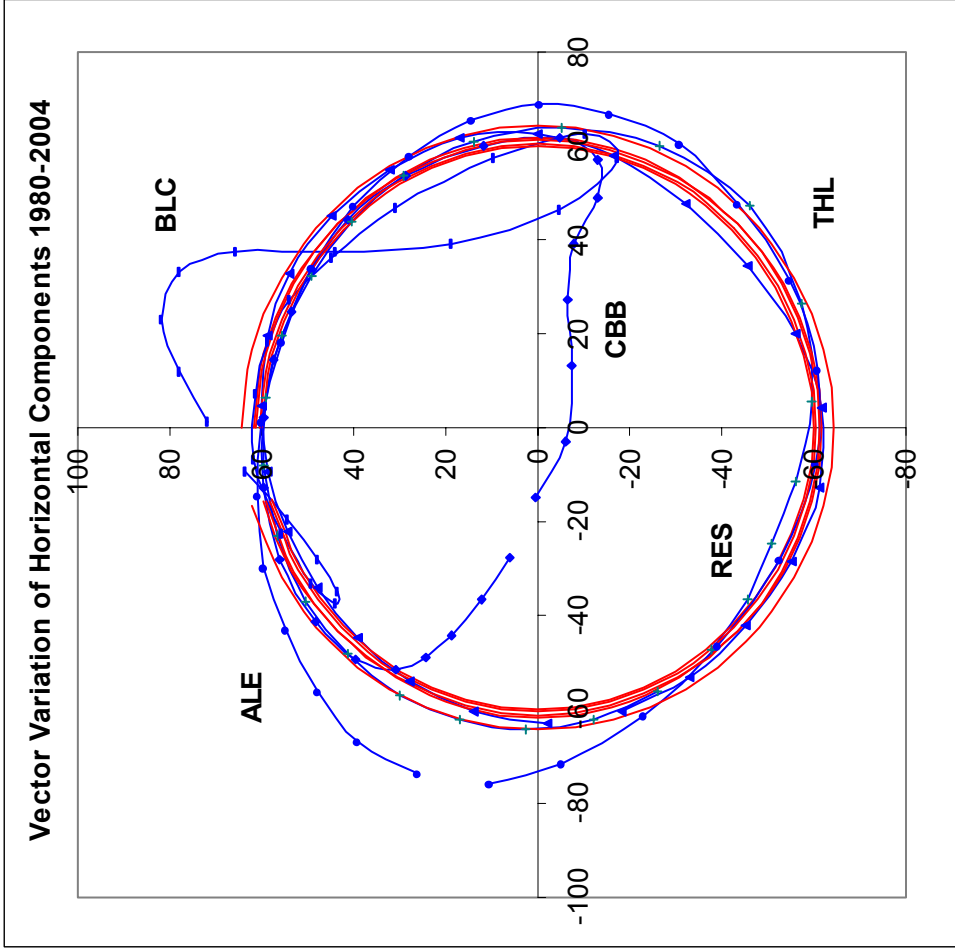
The radius of the circle traced out by variation of horizontal components is a measure of the polar cap potential. For stations near the polar cap boundary the circle is only partial.

Vector Variation of Horizontal Components 1980-2004

BLC

THL

CBB

RES

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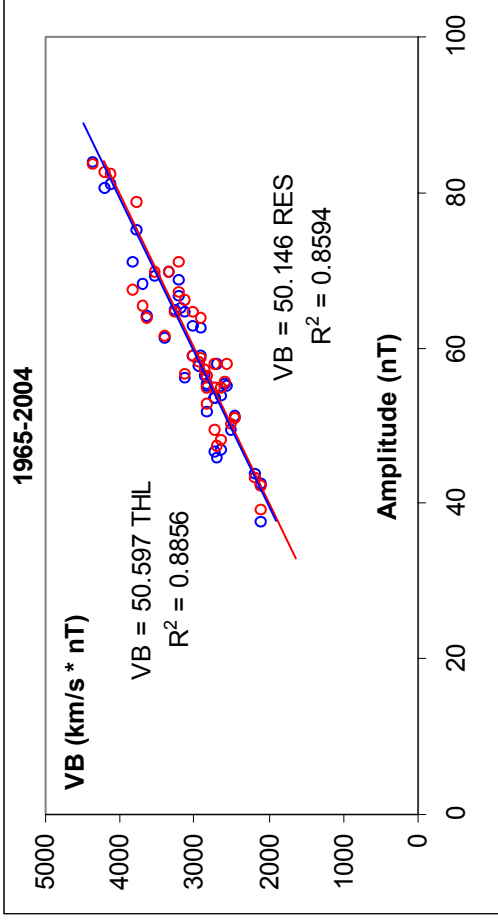
Here we show for each year of 1965-2004 how the average radius depends on the product of B and V for Thule (THL) and Resolute Bay (RES). The radius of the circular variation is the same for all stations in the cap.
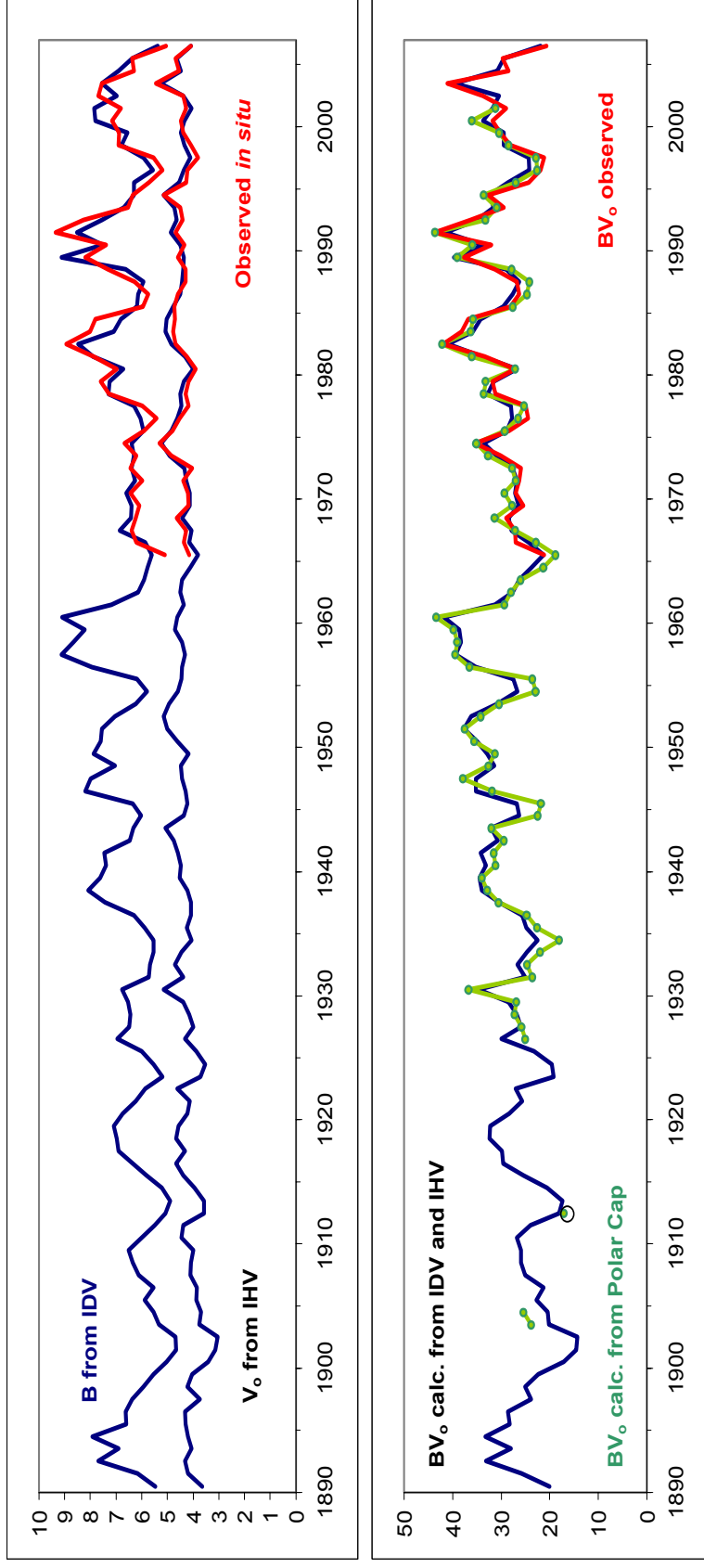
We can then estimate BV:

1965-2004

VB (km/s * nT)

VB = 50.597 THL
$R^2 = 0.8856$

VB = 50.146 RES
$R^2 = 0.8594$

Amplitude (nT)

VB (km/s * nT)

Observed S/C
RES (Resolute Bay)
THL (Thule)

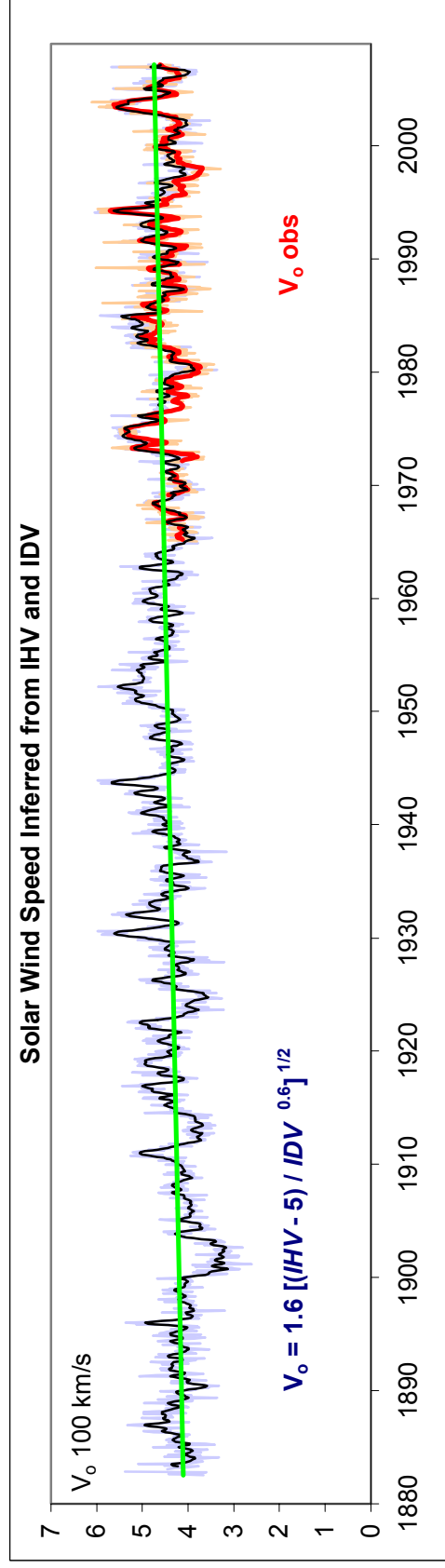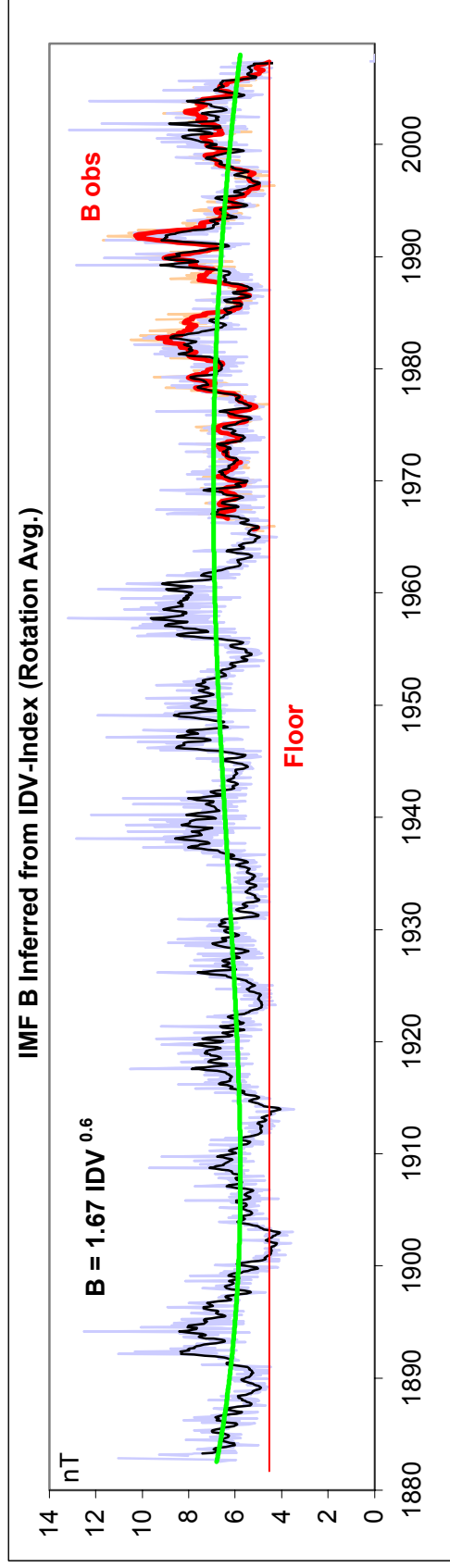We now have three independent ways of estimating solar wind and IMF parameters:

An Over-determined System:

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.
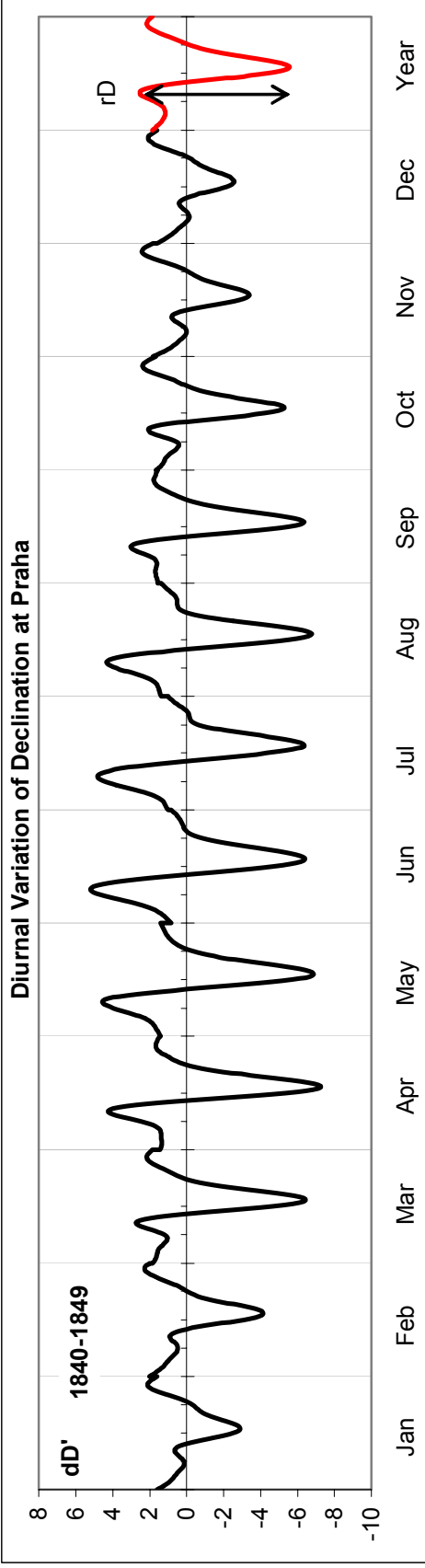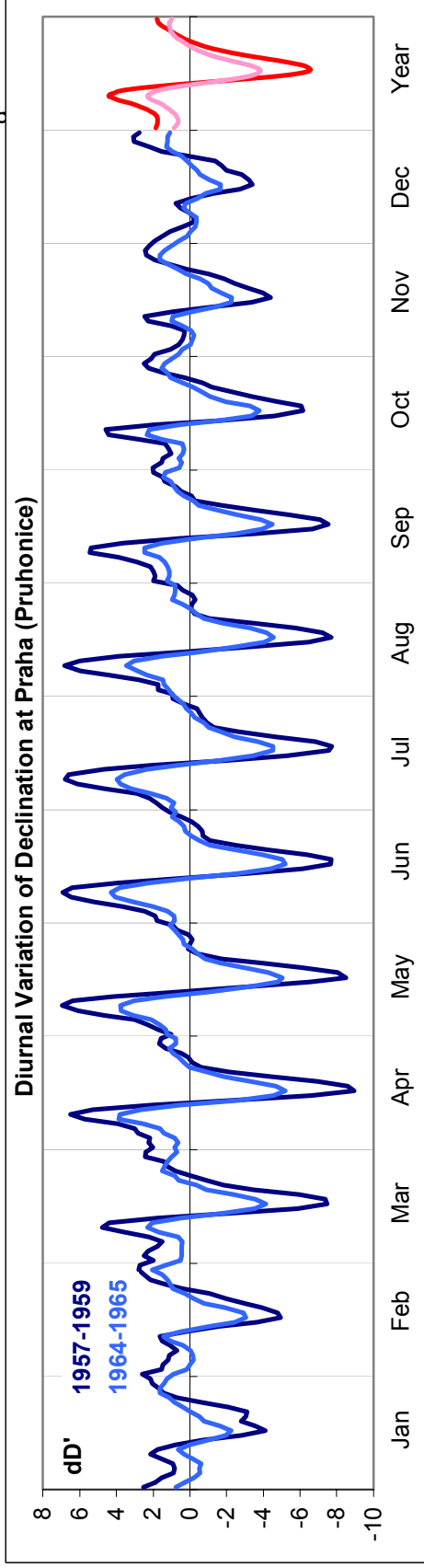
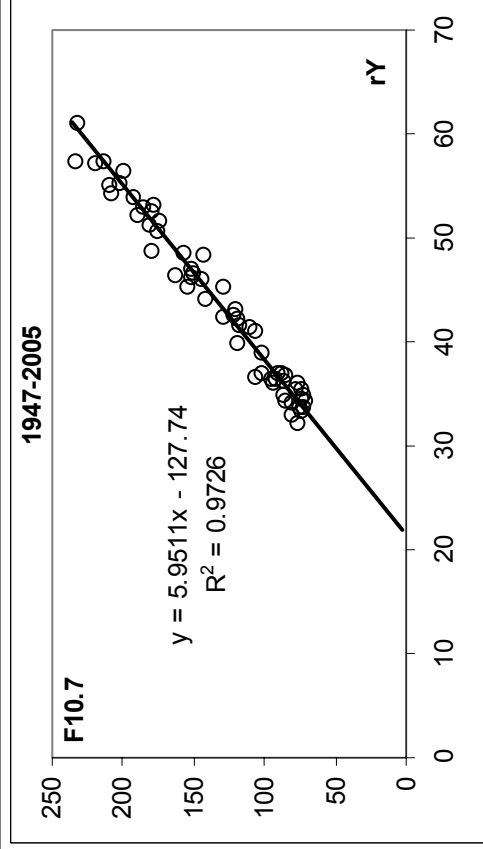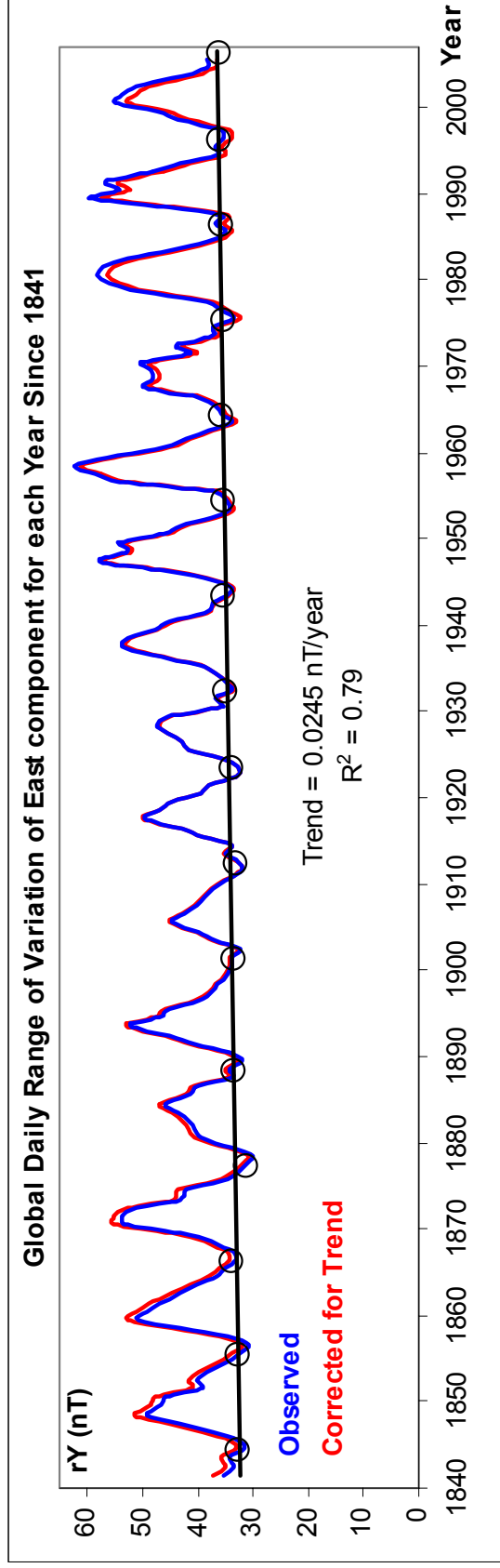We can even do the analysis for a time scale of solar rotations:

IMF B Inferred from IDV-Index (Rotation Avg.)

nT

B = 1.67 IDV $^{0.6}$

B obs

Floor

Solar Wind Speed Inferred from IHV and IDV

V_o 100 km/s

V_o = 1.6 [(IHV - 5) / IDV $^{0.6}$] $^{1/2}$

V_o obs

Note the 'floor' under which IMF B does not seem to fall.

Using the Dayside Data

Diurnal Variation of Declination at Praha (Pruhonice)

dD'

1957-1959
1964-1965

Jan   Feb   Mar   Apr   May   Jun   Jul   Aug   Sep   Oct   Nov   Dec   Year

Diurnal Variation of Declination at Praha

dD'

1840-1849

rD

Jan   Feb   Mar   Apr   May   Jun   Jul   Aug   Sep   Oct   Nov   Dec   Year

The Declination can be converted to the East component using $Y = H \sin (D)$.

Using several stations we can construct a composite series of the amplitude, *rY*, of the daily variation of *Y*:

Global Daily Range of Variation of East component for each Year Since 1841

Trend = 0.0245 nT/year
$R^2 = 0.79$

Observed
Corrected for Trend

rY (nT)

Year

It is well-known that the strength of the S_R current system is a sensitive function of the conductivity of the ionosphere which in turn can be well-described by the 10.7 cm solar radio flux. So, we can translate *rY* directly into an equivalent f10.7 flux:

1947-2005

F10.7

$y = 5.9511x - 127.74$
$R^2 = 0.9726$

rY
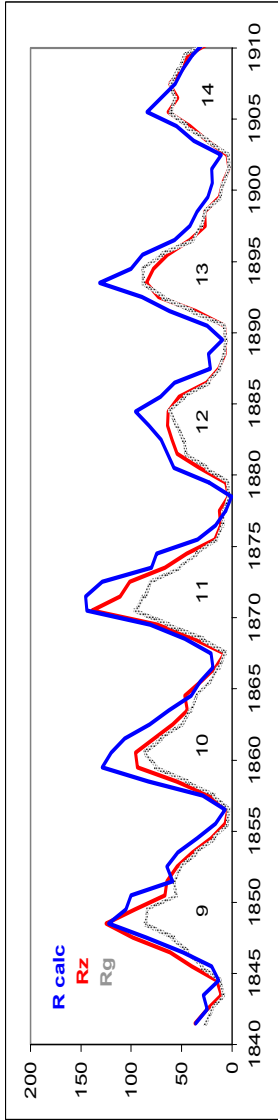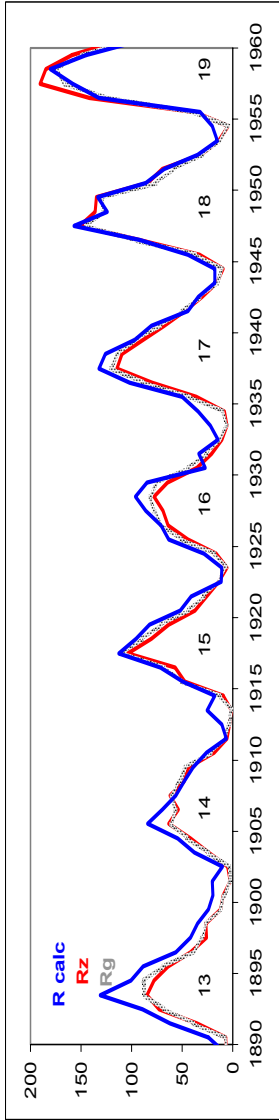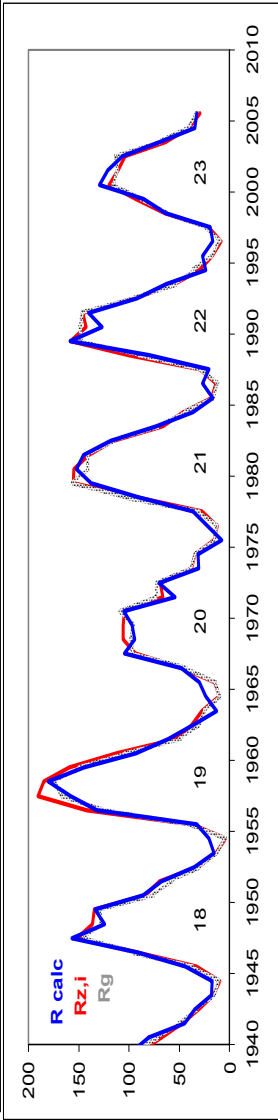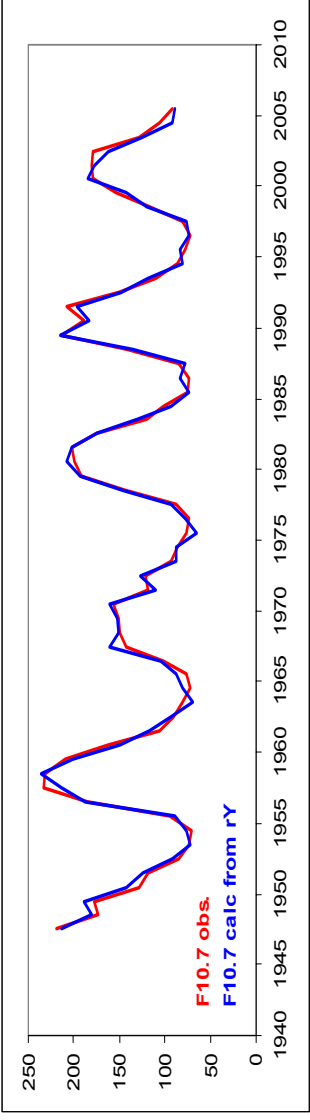
Because the f10.7 radio flux depends on the sunspot number we can turn the calculated f10.7 flux into an equivalent sunspot number and discover that there are indications that the calibration of even the venerable sunspot number before ~1947 is questionable.

This is ongoing work and the conclusions are still preliminary.

Conclusions

1: The hourly values in yearbooks are an extremely valuable data source that allows us to calibrate our long-term geomagnetic and solar indices as far back as the geomagnetic record reaches.

2: By combinations of newly derived geomagnetic indices we can infer the physical properties of the solar wind in the past.

3: Every effort should be expended to preserve and digitize the treasure trove of 19th century hourly data.