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Solar wind:
Long-term evolution and effects in the near-Earth space and climate

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Topics

Solar activity and solar dynamo

Dominant drivers of geomagnetic activity: ICMEs and HSS/CIRs

Variation of SW properties at 1 AU

Solar wind and/from geomagnetic activity

- Solar wind – magnetosphere interaction
- New methods to study GA-SW relationship
- Centennial occurrence of HSS and its solar implications

Energetic particle fluxes

HSS as a cause to Winter NAO

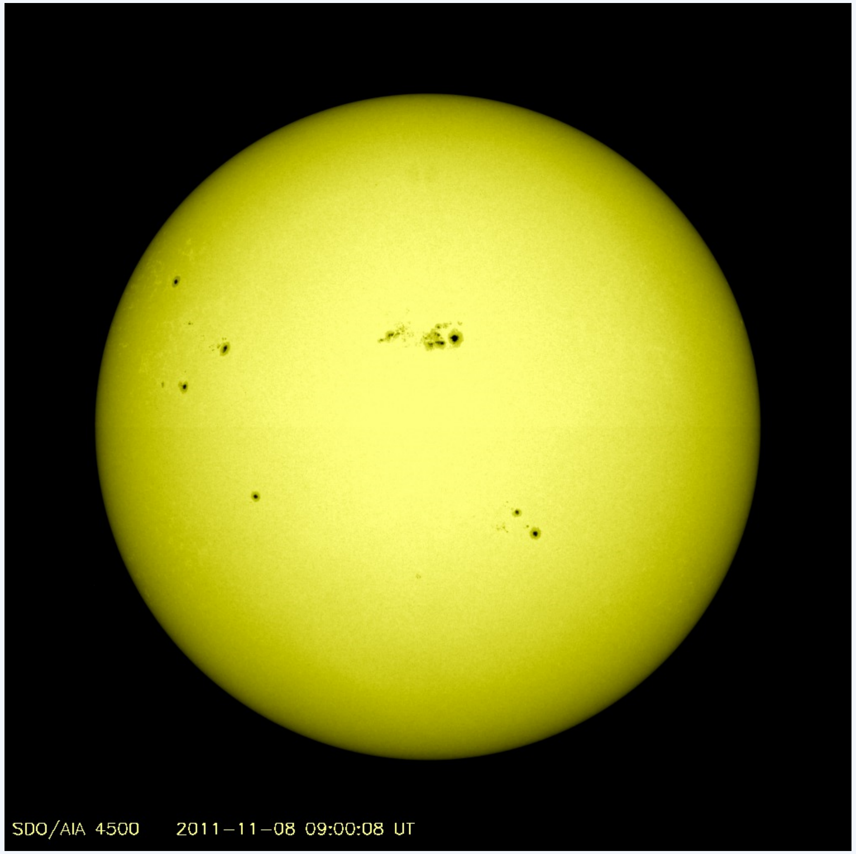
(Hemispheric asymmetry of SW and HMF)

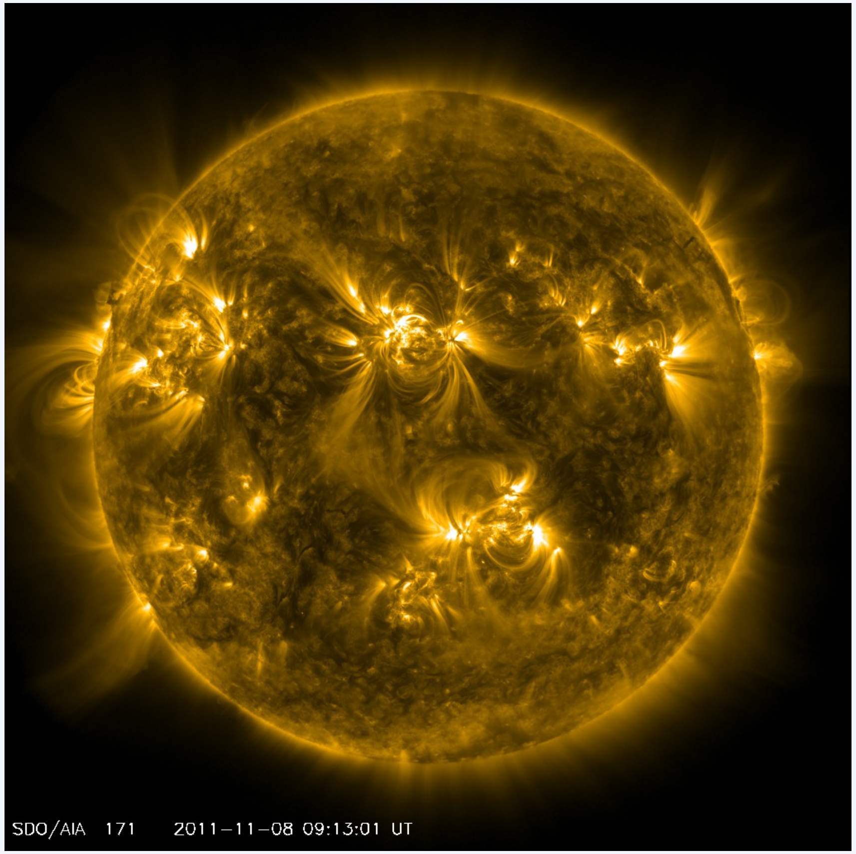
Solar activity ad solar dynamo

Sun as a magnetic star

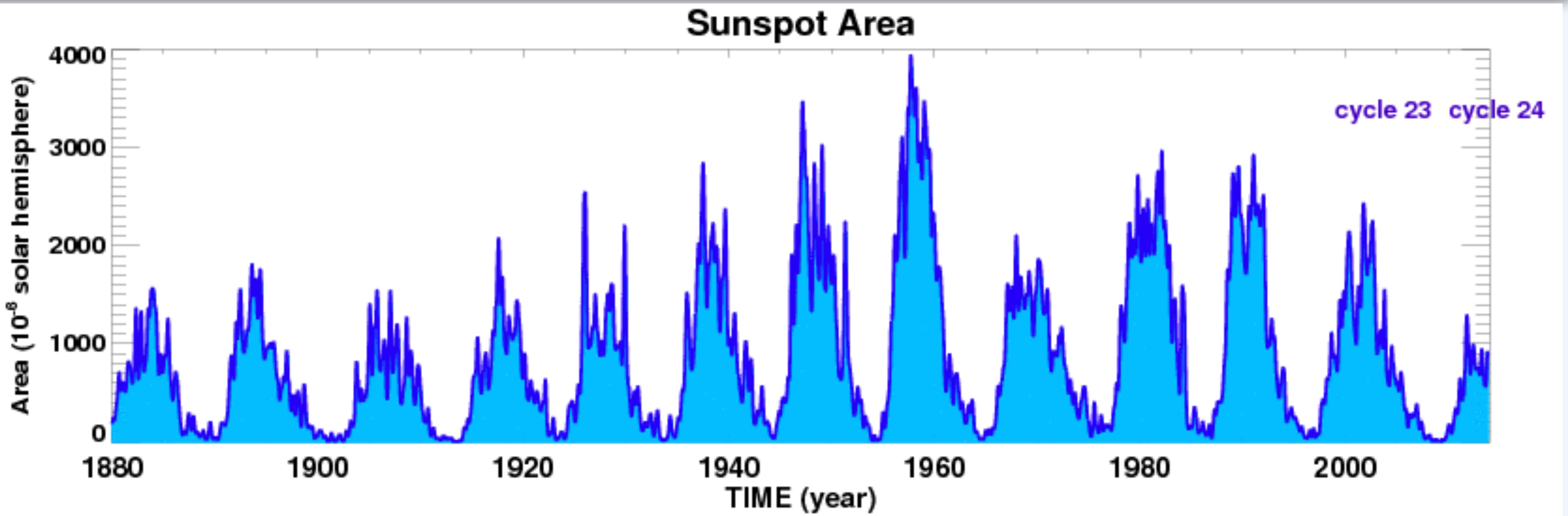
Sun is a magnetically active star.

Sunspots are connected to magnetic active regions and are indicators of magnetic activity in the Sun.





Sunspot activity since 1880



Activity maximum during solar cycle 19 in 1957.
Grand modern Maximum (GMM)

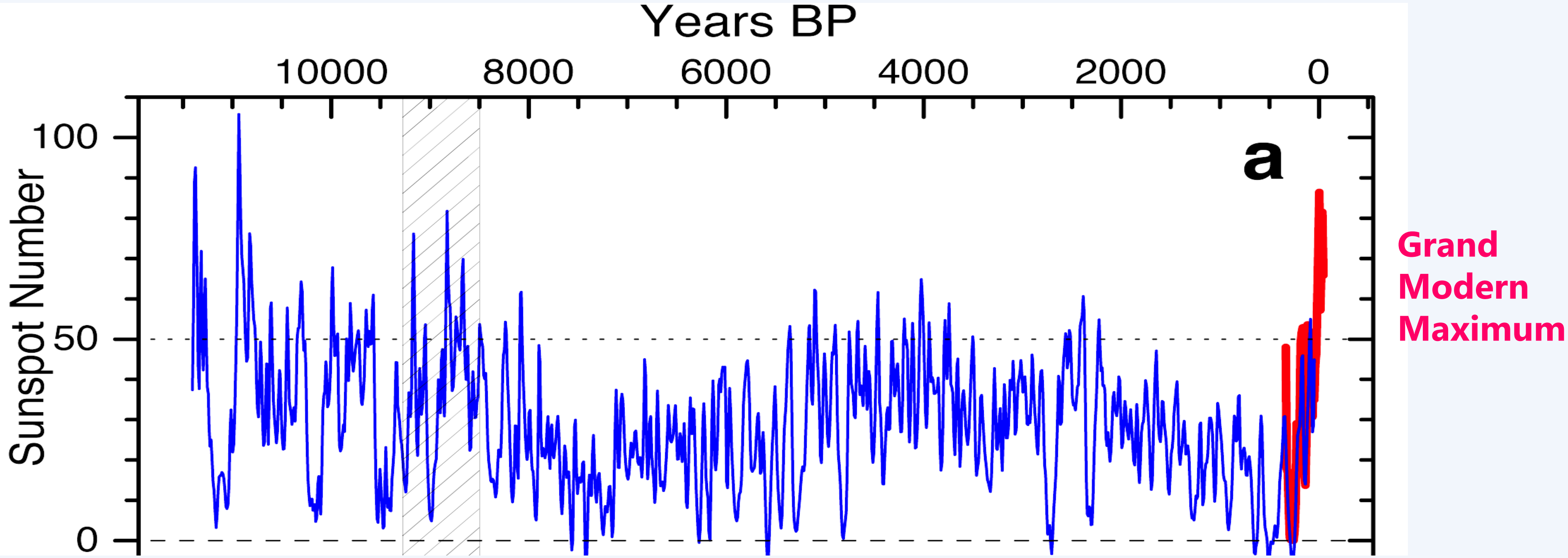
Long and low minimum between cycles 23 and 24
Cycle 24 will remain lowest in at least 100 years

Solar activity during Holocene

Solar activity during GMM was greatest for at least a few thousand years.

There have been more active periods during some 3000 years after the Ice Age, last some 9000 years ago.

Solar activity is very variable. Great minima and maxima last only 5-10 solar cycles.

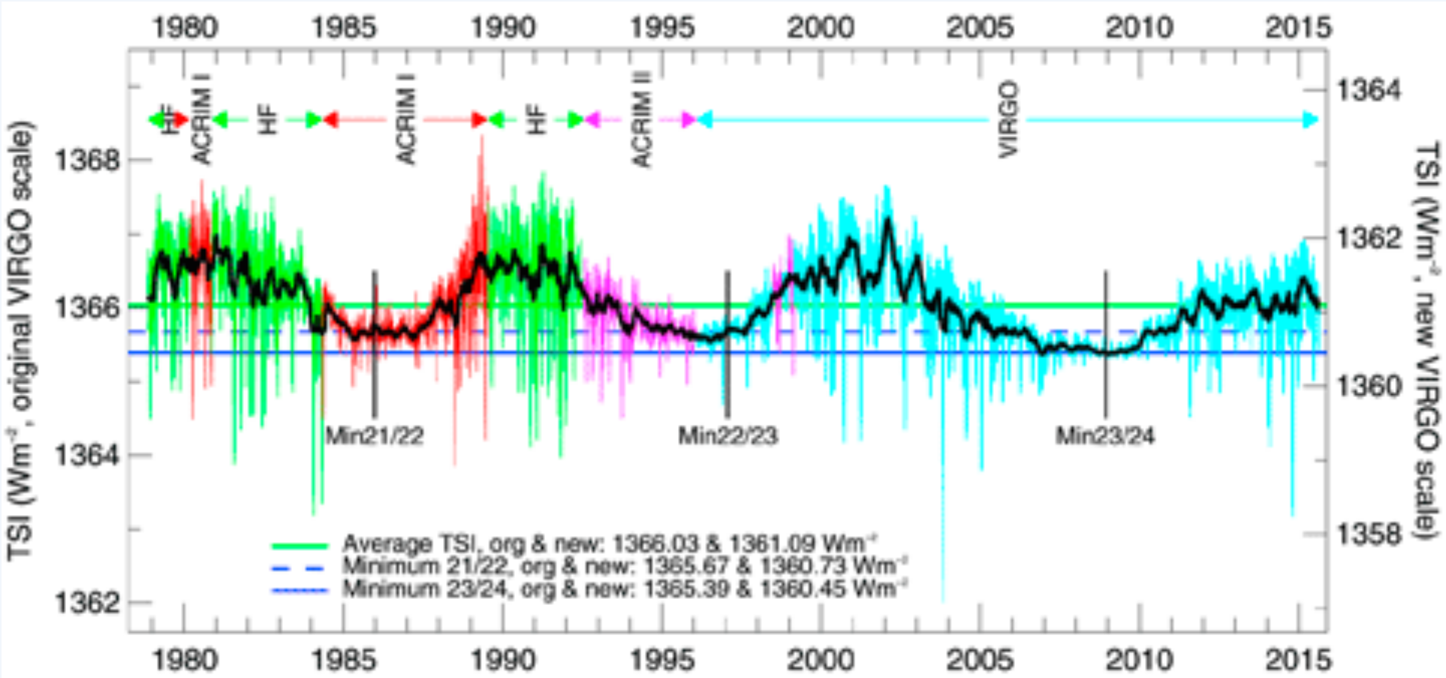


Sunspots as indicators

Sunspots are indicators not only of surface magnetic fields, but of important global changes in solar convection layer that cause great changes in the whole heliosphere.

For example, the total solar irradiance (TSI) varies with sunspot cycle by about 0.1%.

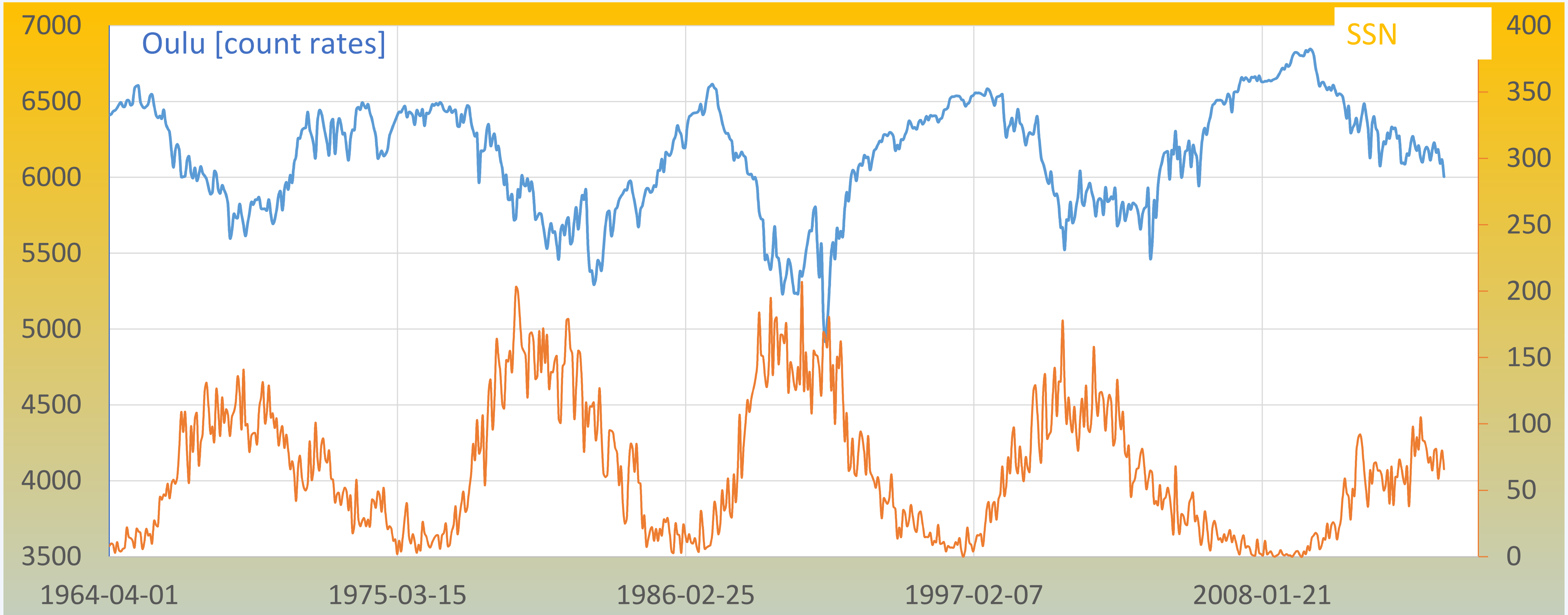
TSI in SC24 maximum will remain lower than during the maxima of all previous cycles covered.



Sunspots vs Oulu NM

All time high in GCR flux in 2009.

GCR flux during SC24 is well above normal solar max levels.

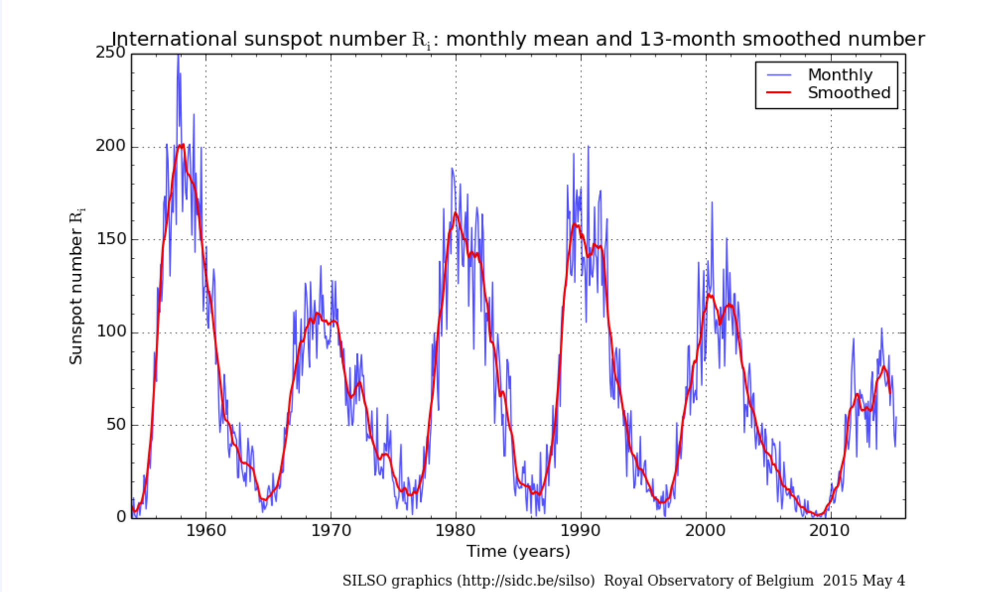


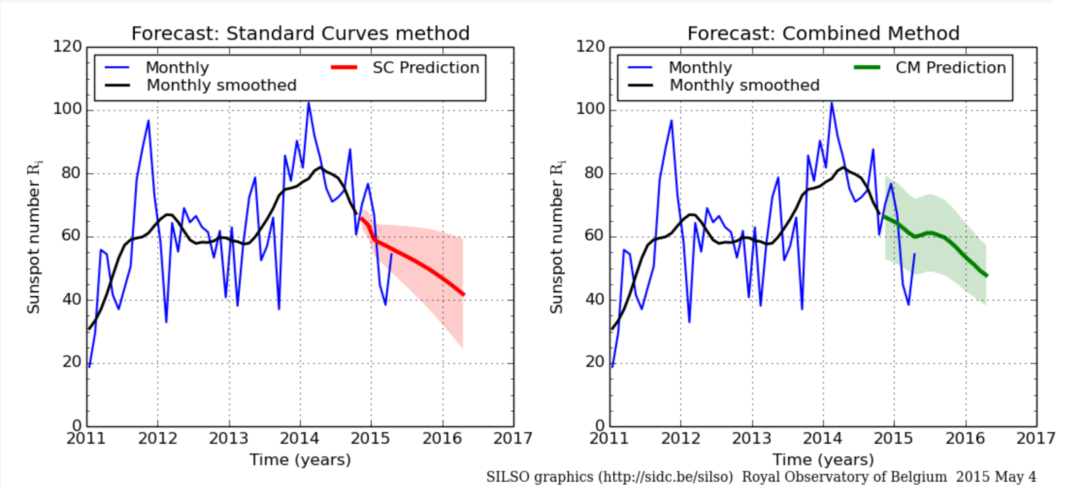
Solar activity since 1950

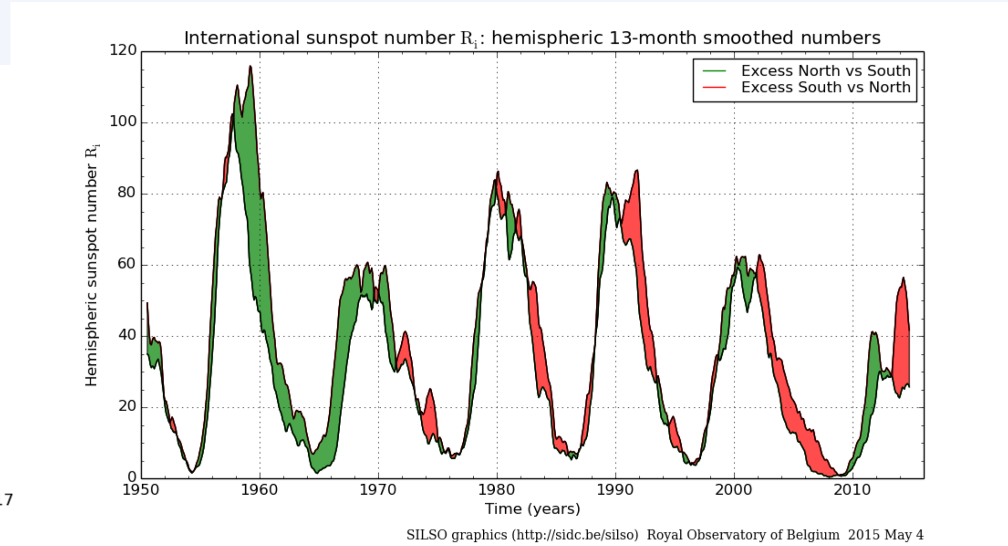
GMM is over !

Cycle 24 is over and remains lowest since SC14 (110 years)

Cycle 24 was very asymmetric





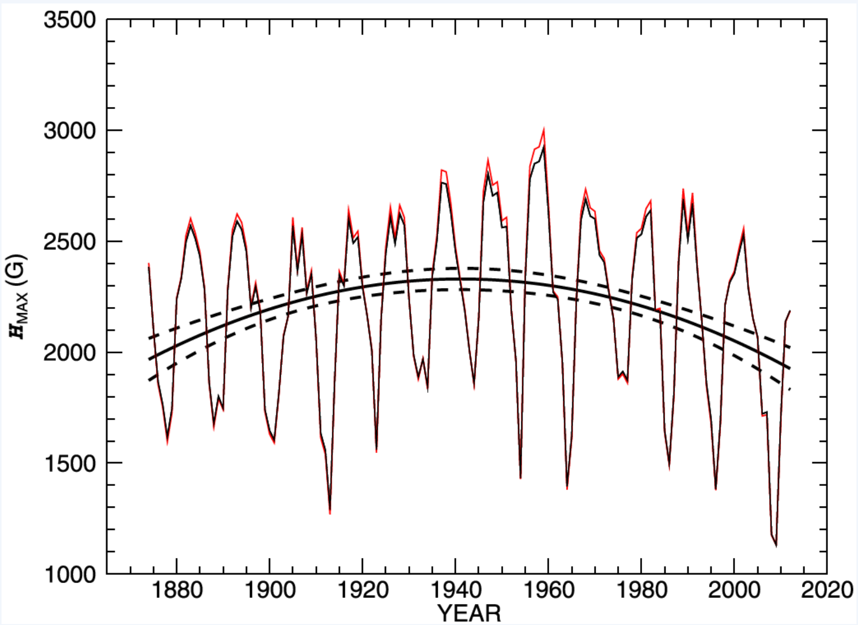


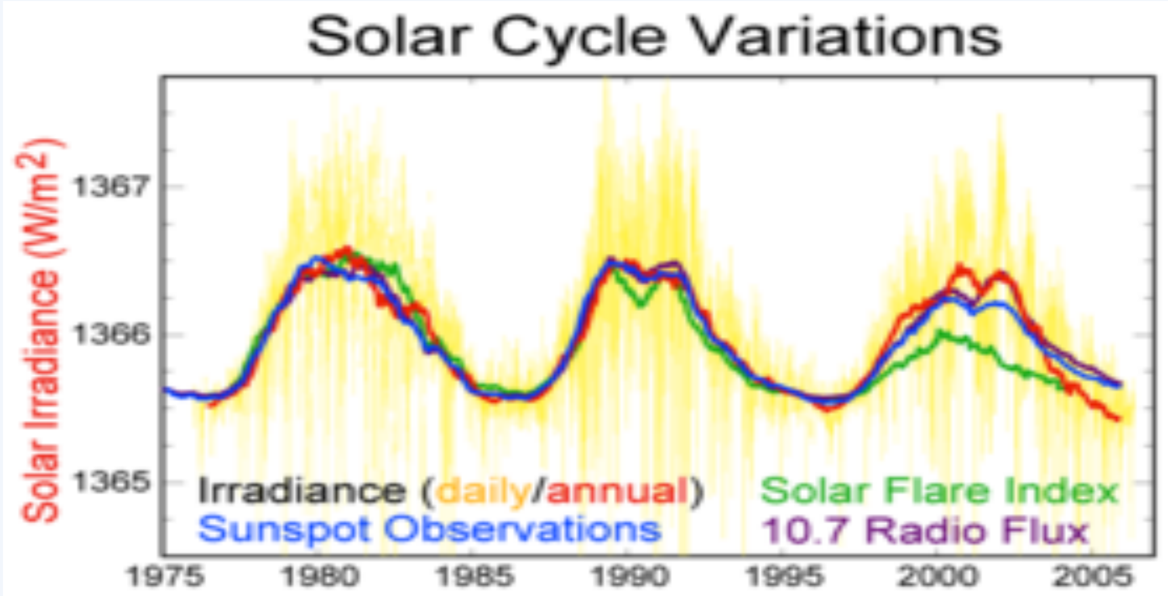
Unprecedented change going on

Currently, the magnetic strength of spots is decreasing and the temperature is rising

⇒ Smallest spots disappear

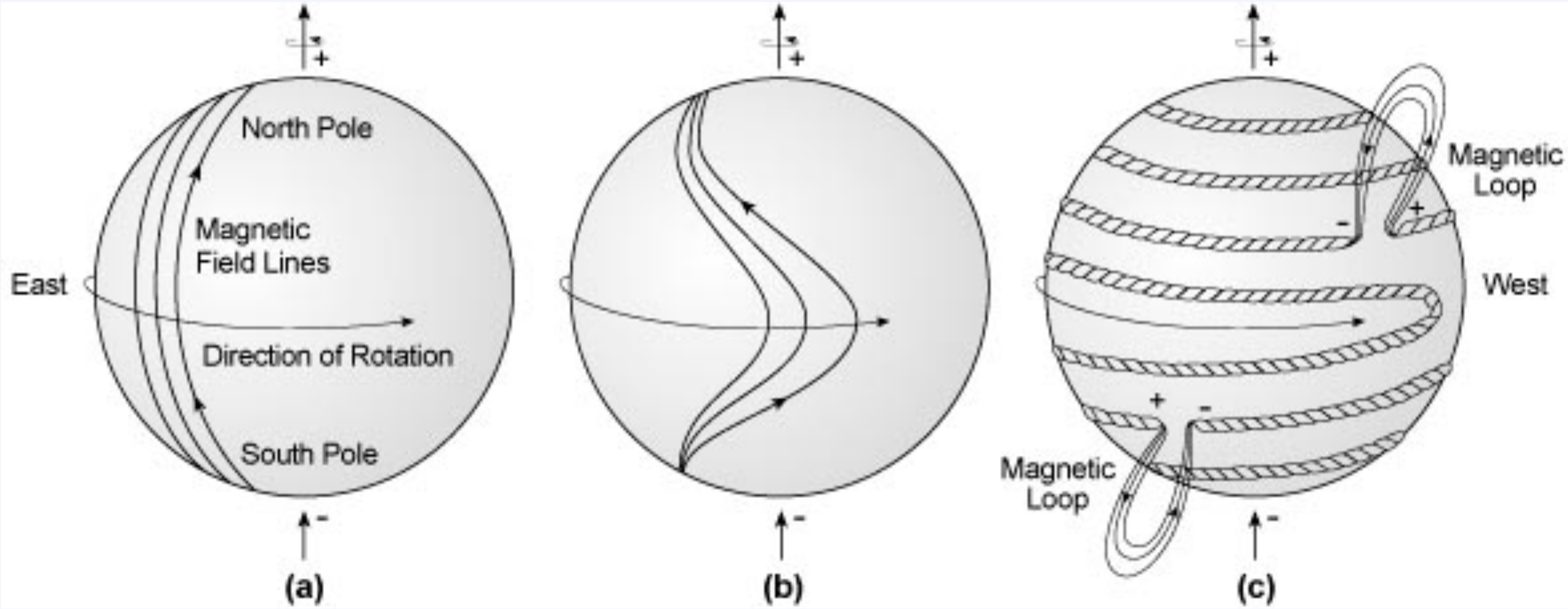
GMM decline ?





The mutual relations between sunspots and several other solar activity parameters (F10.7, flares, TSI,...) have changed during SC23 from what they used to be for several decades earlier.

Solar dynamo: Poloidal to toroidal (min to max)

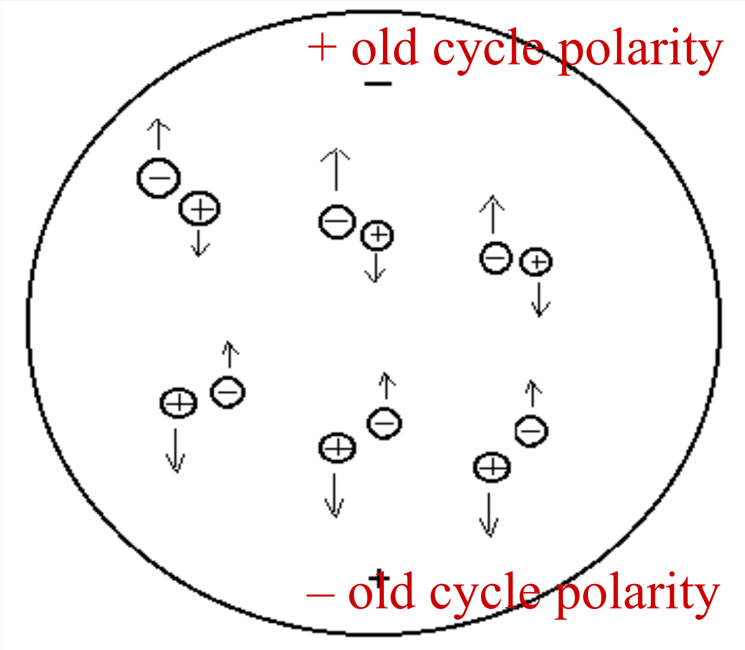


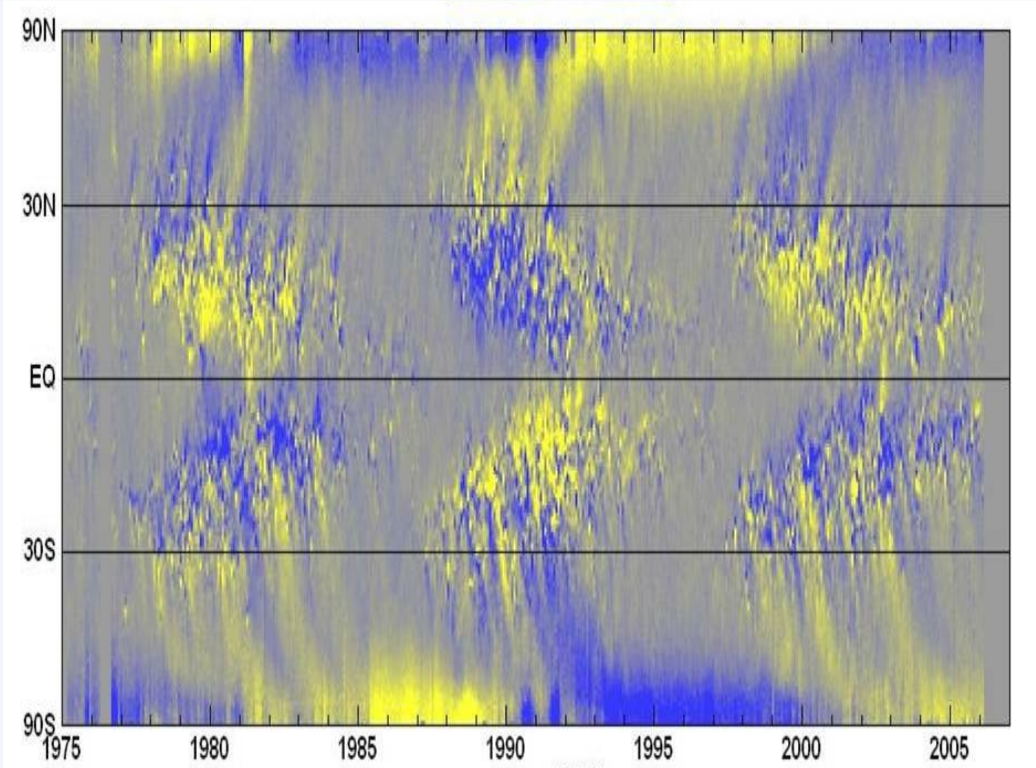
Poloidal field
Solar minimum

Toroidal Field
Sunspot maximum

Differential rotation stretches a pre-existing poloidal field in the direction of rotation and creates a toroidal component (Parker 1955).

Solar dynamo: Toroidal to poloidal (max to min)

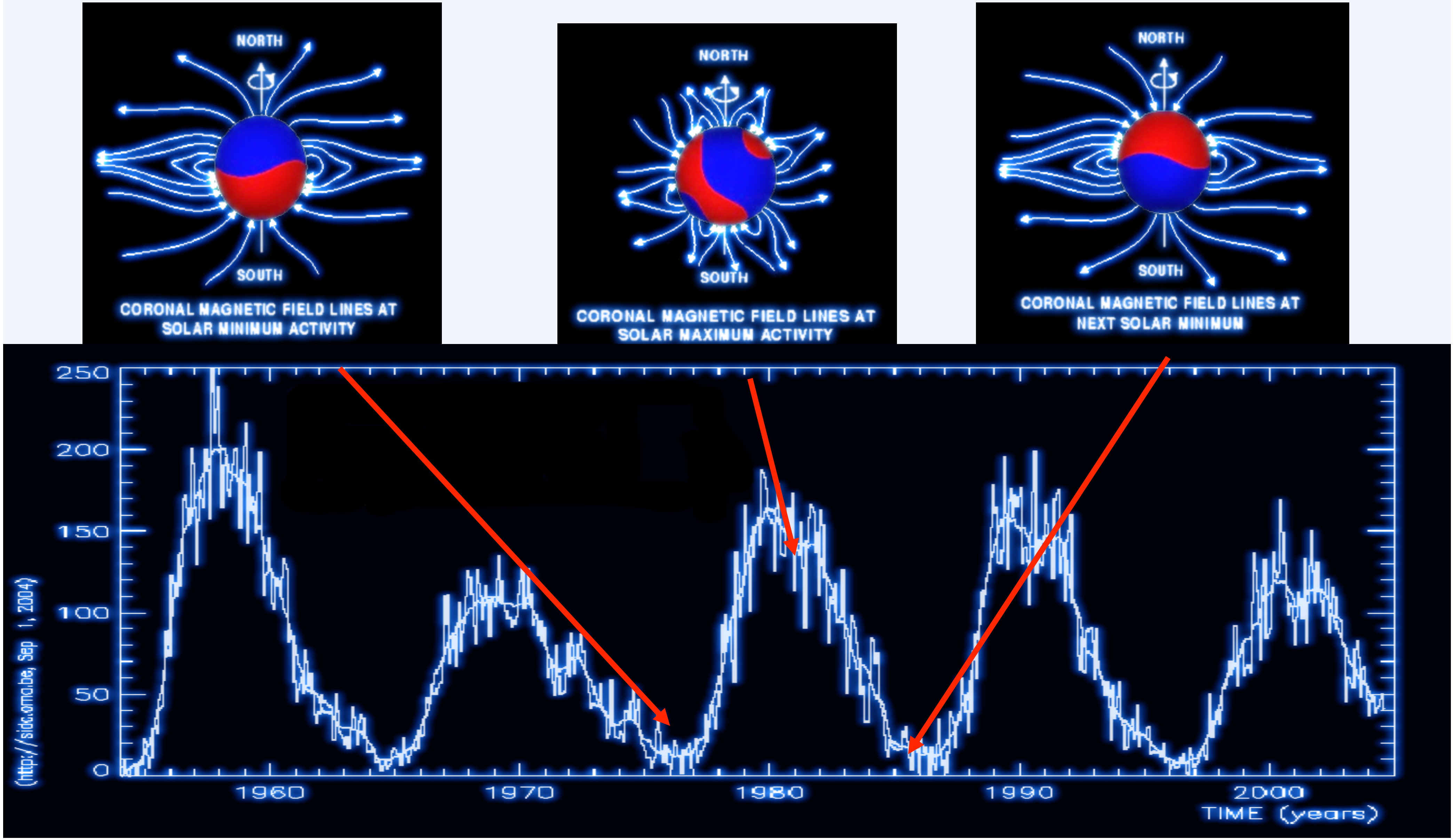




Babcock and Leighton: Tilted sunspot pairs decay and convect in opposite directions, leading to equator, trailing to pole to form the poloidal field of new cycle and polarity.

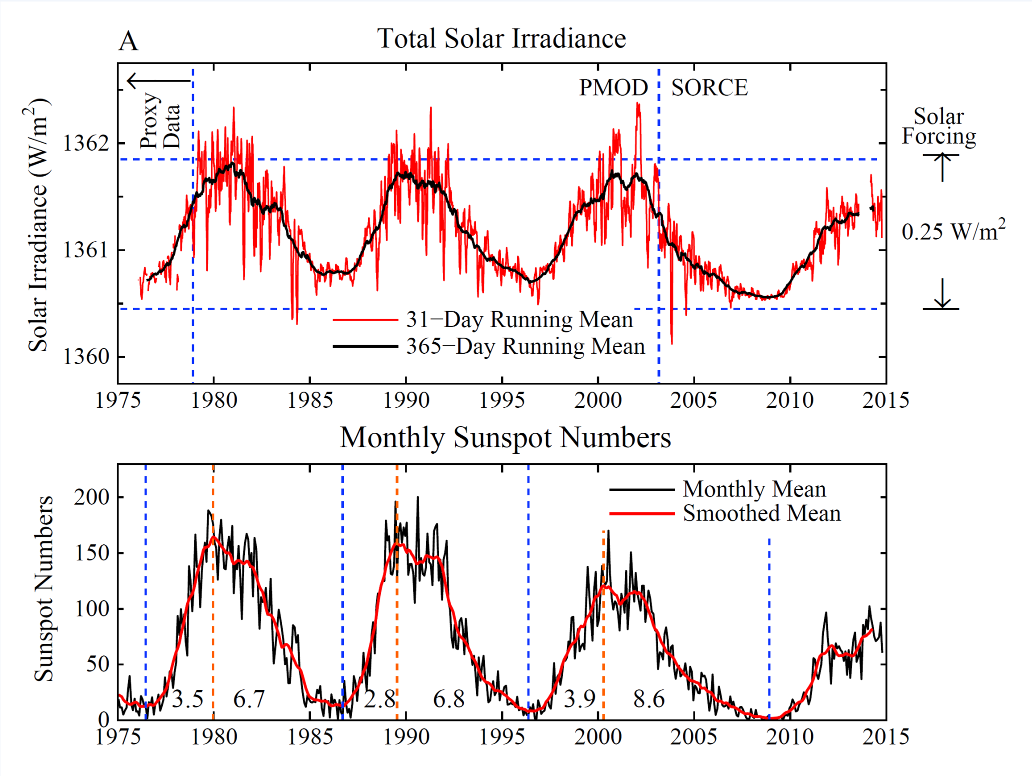
Many recent models are based on the B-L idea.

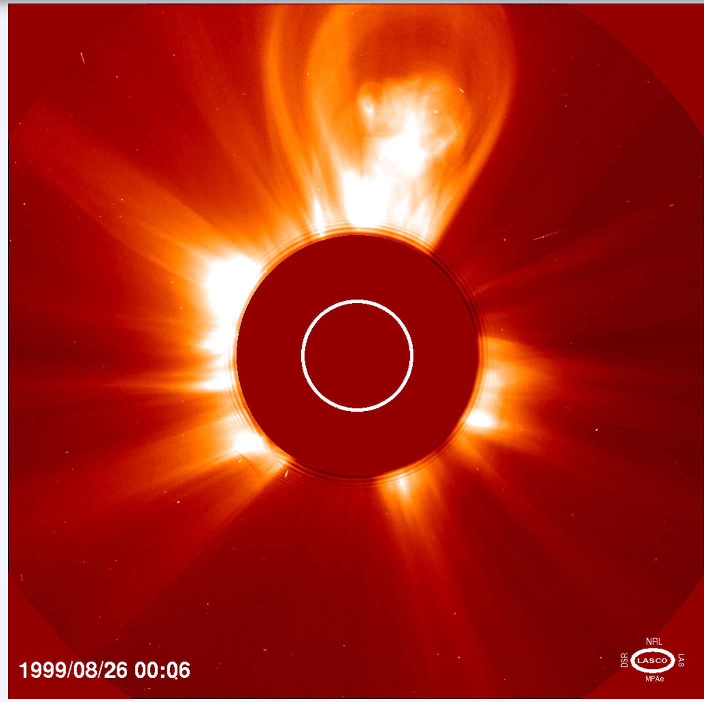
Hale 22-year magnetic polarity cycle



Toroidal phase: Sunspots, CMEs, TSI…

Toroidal phase: Maximum of sunspots and active regions like flares and CMEs (coronal mass ejections) that cause greatest geomagnetic storms.





Toroidal phase:
Increased total and spectral irradiance
=> Obviously important for Earth !

Two active phases (NOT ONE!)

Toroidal phase: many sunspots and other active regions

Obviously important for Earth !

Poloidal phase: few sunspots and few active regions

Unimportant for Earth ?

NO !

Solar poloidal phase

Directly measured only since 1970s (cf. toroidal phase since 1610)

Why is the poloidal phase of solar dynamo (solar cycle) important ?

Effects:

It has significant, independent effects in the heliosphere that affect the Earth's space environment, neutral atmosphere and climate

Theory:

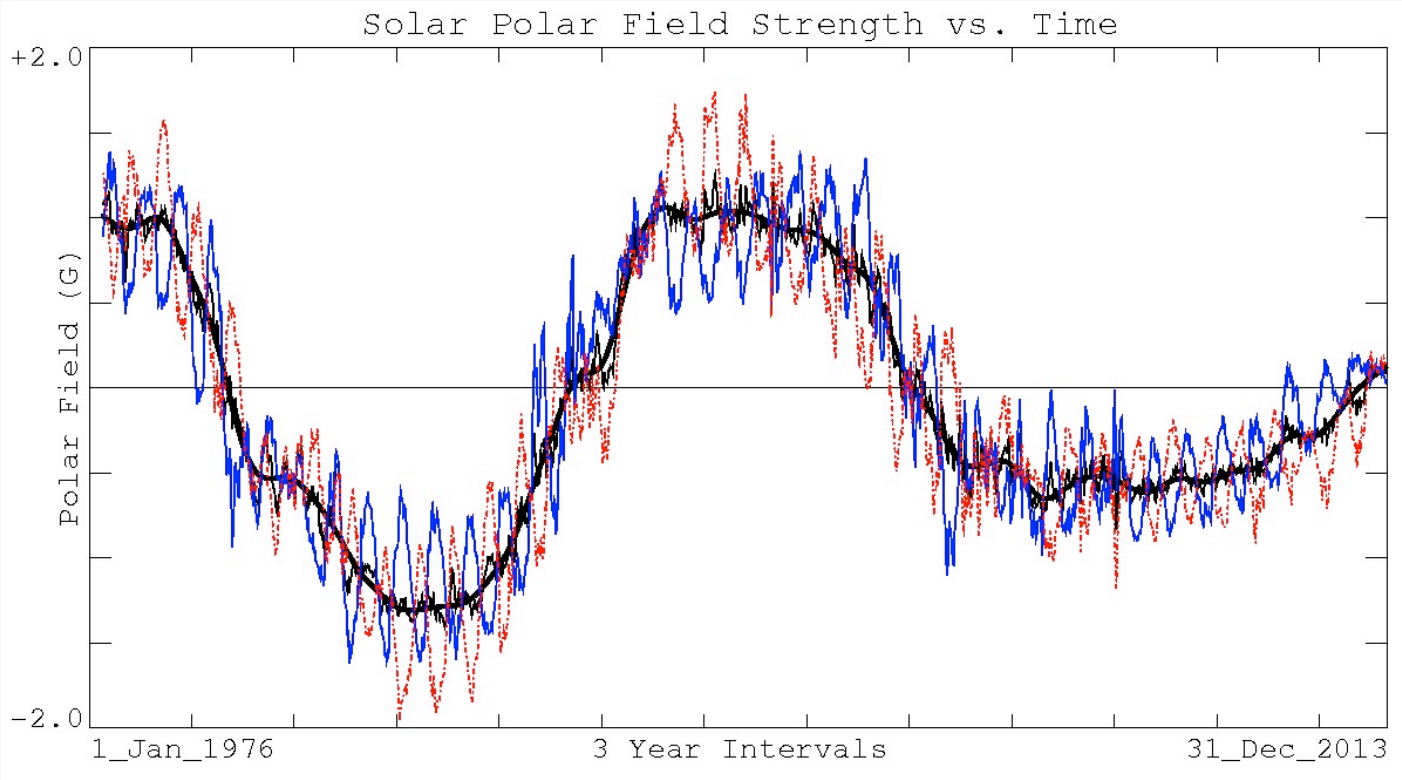
Needs to be better known for a better understanding of the dynamo and the long-term variation of solar activity

Polar fields: WSO observations

Direct measurements of solar polar field only since 1970s

Polar field decreases since 1980s. Large drop from 1990s to 2000s

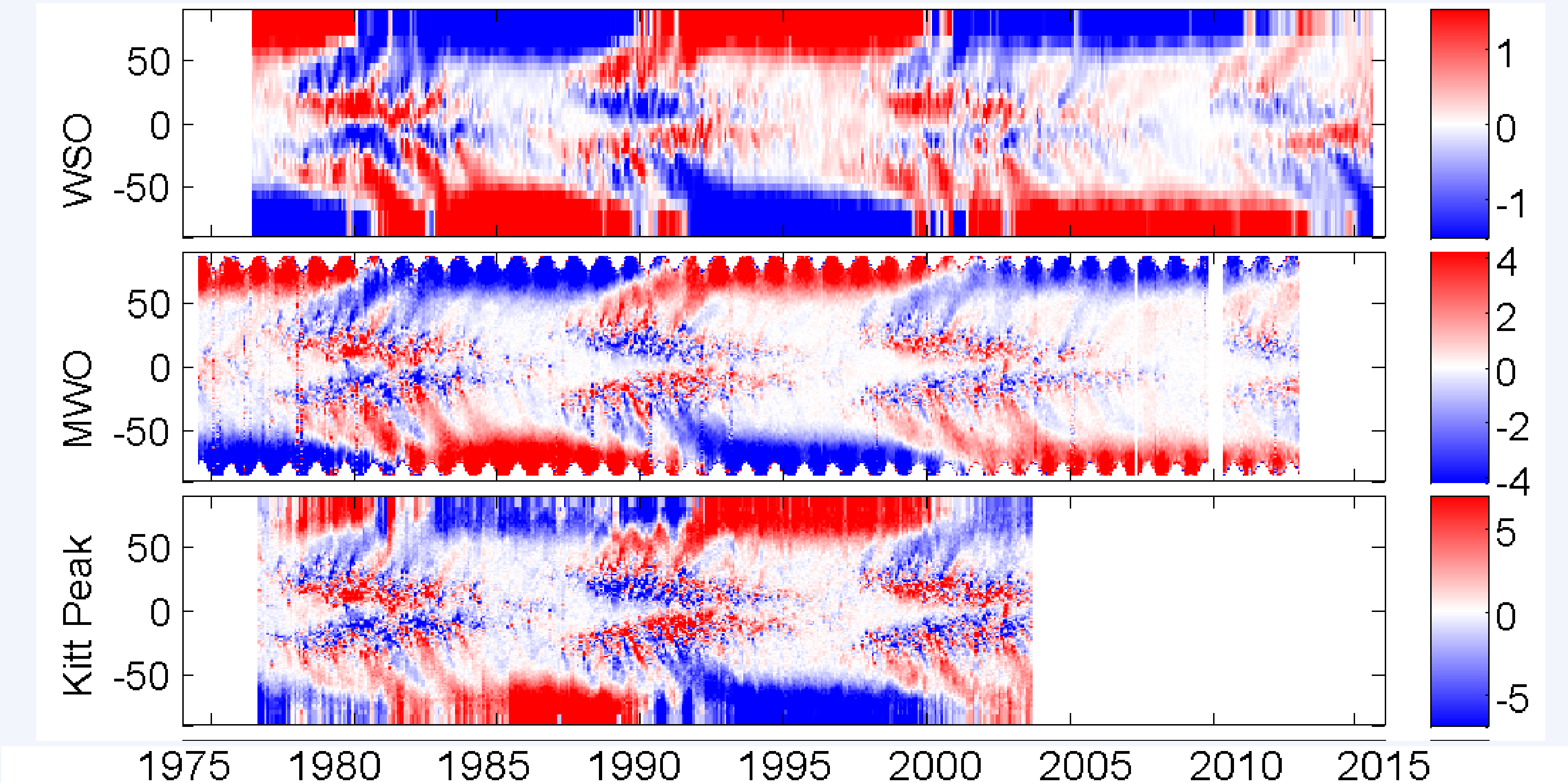
Southern field stronger than northern in 1970s, 1980s, 1990s: Bashful ballerina



Photospheric fields: WSO, MWO, KP

Measurements of solar photospheric fields at the three longest observing stations.

Occasional large differences between the stations, esp. at high latitudes.



Why is poloidal phase important ?

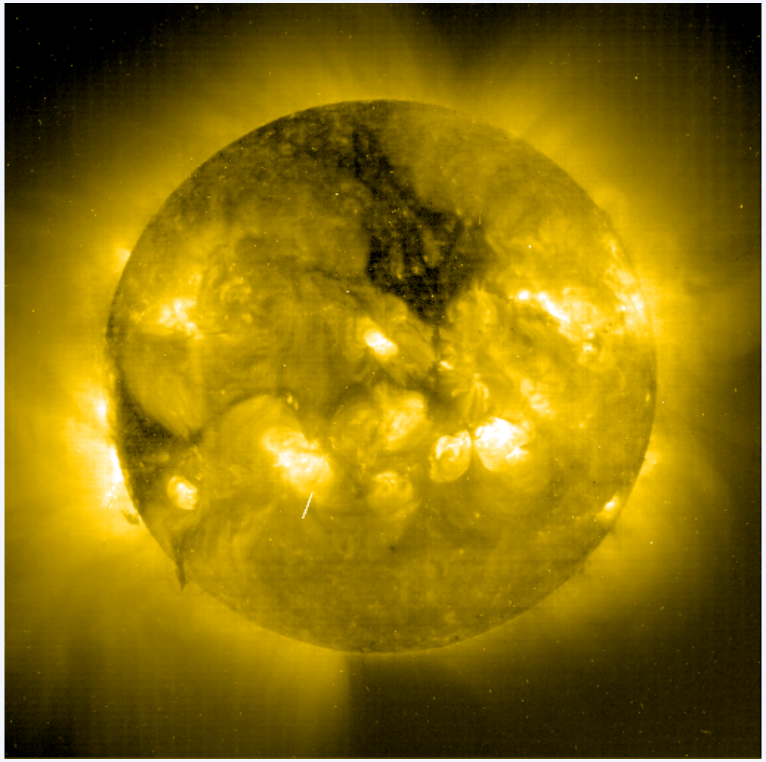
During the poloidal phase there are unipolar (one pole only) magnetic fields at the solar poles.

Unipolar field => No magnetic loops
=> Solar wind (SW) can easily escape:
high-speed solar wind stream (HSS)

=> Corona looks empty: coronal holes

Solar wind has a much higher speed (about 750-800 km/s) from large polar coronal holes.

These form corotating interaction regions (CIR) with the preceding slow solar wind.

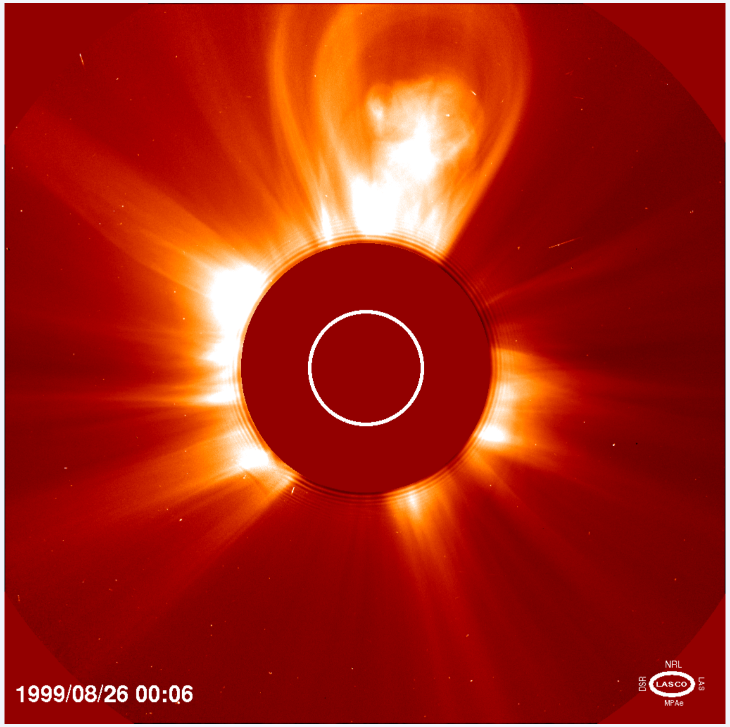


Dominant drivers of geomagnetic activity: CMEs and HSS/CIRs

Drivers of geomagnetic activity: CMEs

Coronal Mass Ejections (CME)

- large bursts of coronal mass
- sporadic
- related to active solar magnetic regions
- maximize at maxima of sunspot cycles
- cause the largest storms



- cause massive dayside reconnection
- intensity and extend the auroral oval to lower latitudes

ICME structure

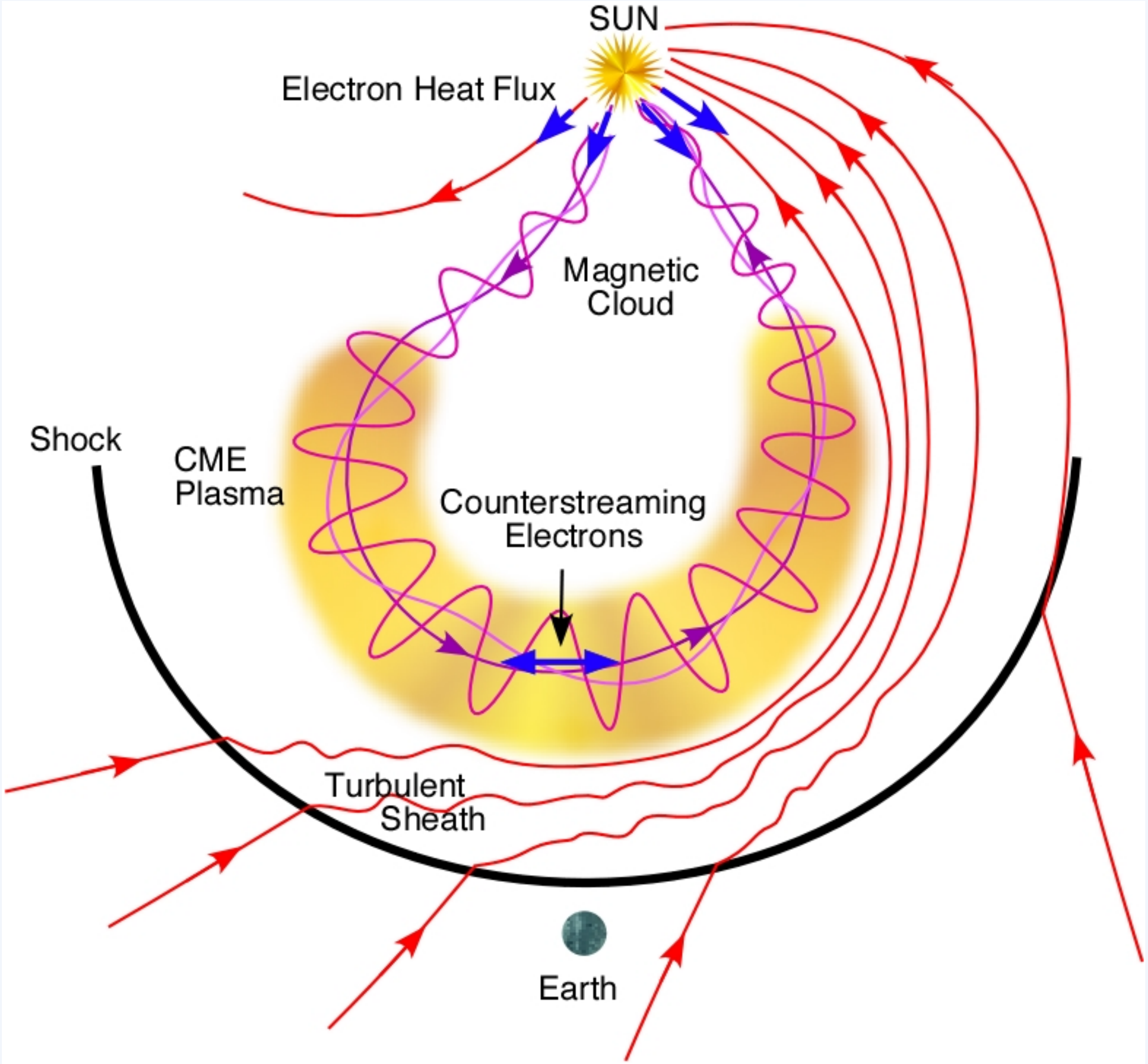
Interplanetary Coronal Mass Ejection (ICME)

- Often a clear flux tube magnetic field structure (magnetic cloud)

- Cool dense plasma

- Often counterstreaming electrons

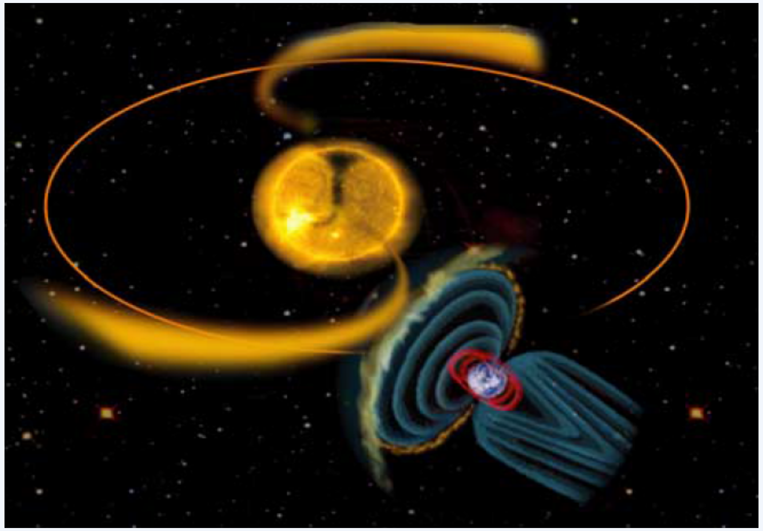
- Shock and turbulent sheath ahead of ICME core

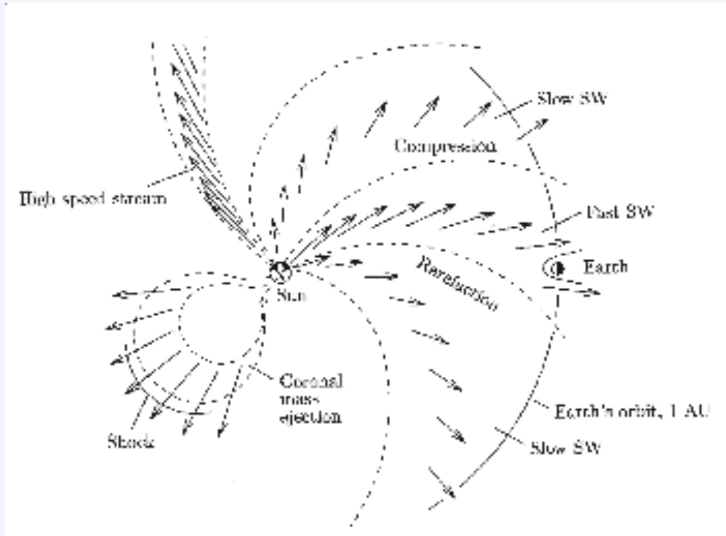


Drivers of geomagnetic activity: HSS/CIR

HSS/CIR

- interaction regions of fast and slow solar wind
- repeat with solar rotation in multiples of 27 days
- sometimes 2-4 CIRs per rotation (sub-harmonics of rotation: 27/2, 27/3,…)
- related to coronal inactive regions (coronal holes)
- maximize at declining phase of sunspot cycles
- cause many intermediate storms
- mainly widen and intensify the auroral oval



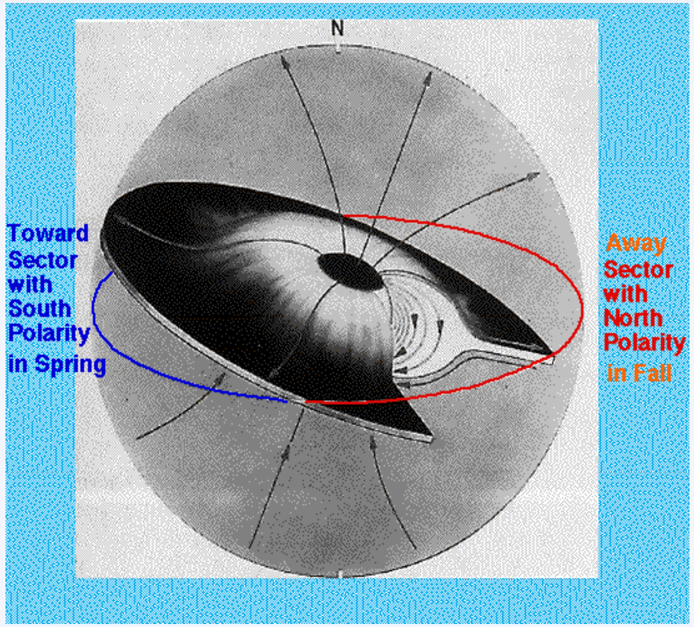


Variation of SW properties at 1 AU

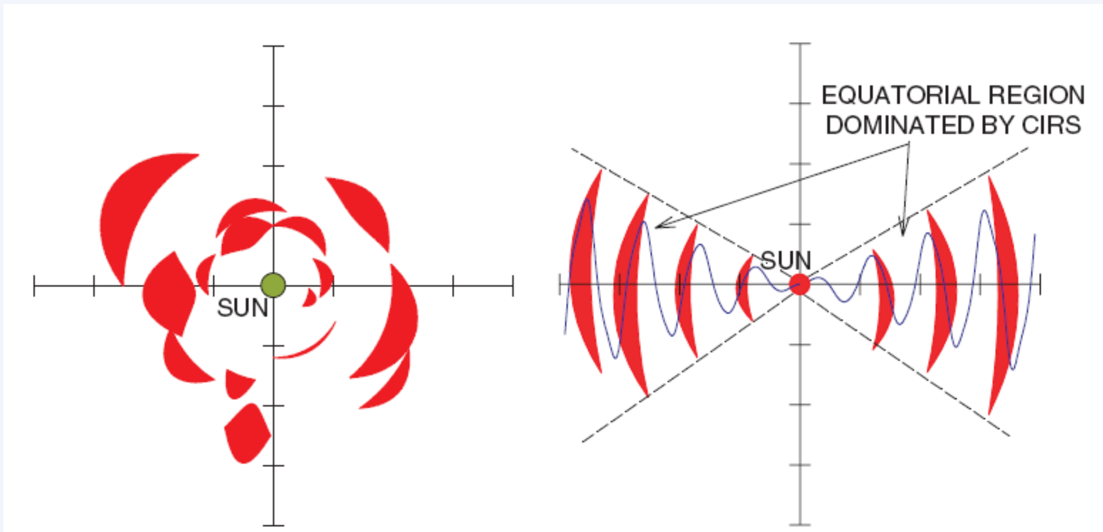
Basic setting of location at 1 AU

Thanks to the 7.2° tilt angle between the solar rotation axis and the ecliptic plane, the Earth covers a range of ±7.2° of heliographic latitudes.

Highest northern (southern) latitude in Sep 5 (Mar 5).



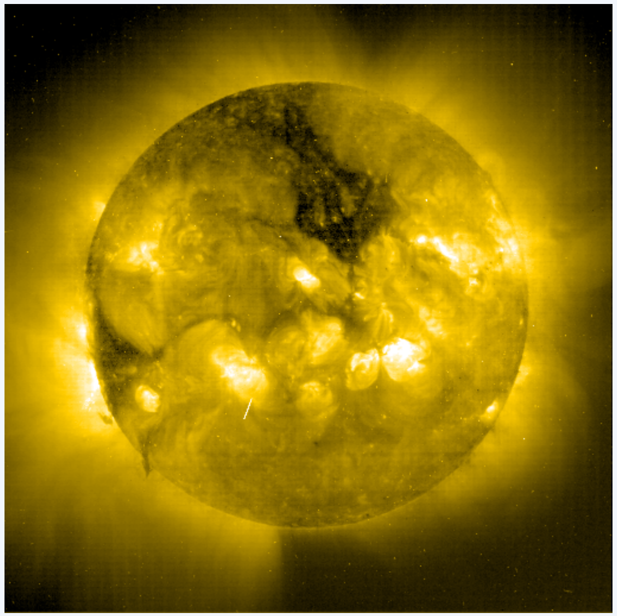
However, the streamer belt of slow wind (≈heliospheric current sheet) is always thicker than this latitude range, so we get short snapshots of pure fast wind of only 2-3 days.

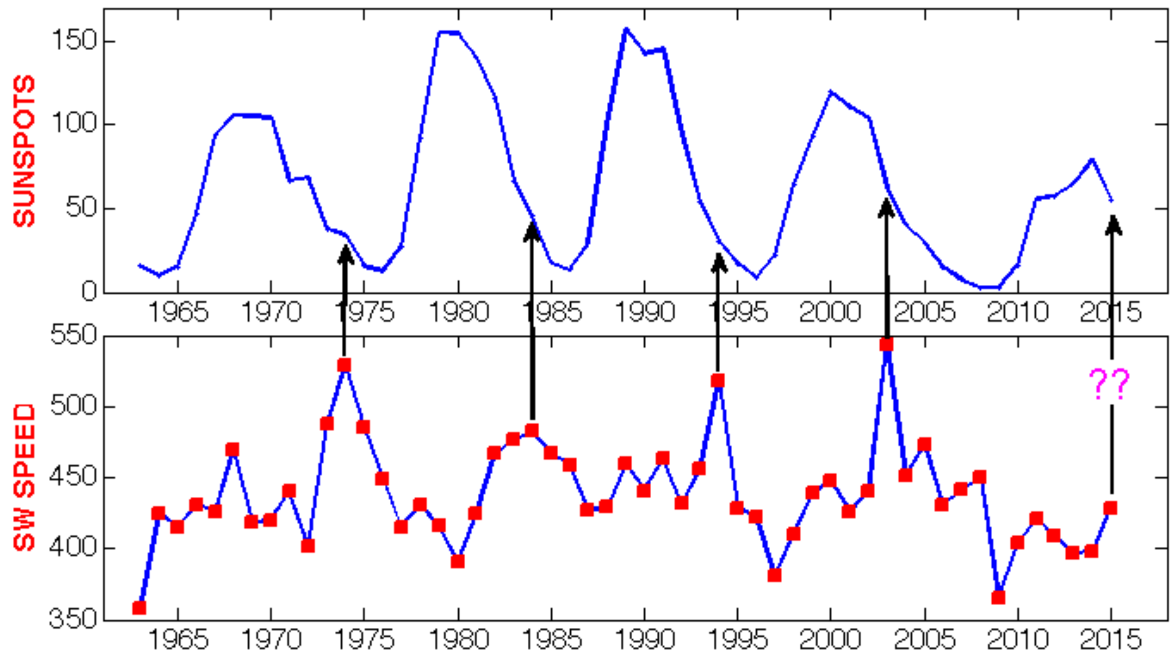


Solar cycle variation of SW speed at 1AU

Solar wind speed has maximum in the descending phase of solar cycle due to high speed streams emanating from coronal holes, most typically polar coronal holes with equatorial extensions.

In many cycles, these cause the highest peak in geomagnetic activity.





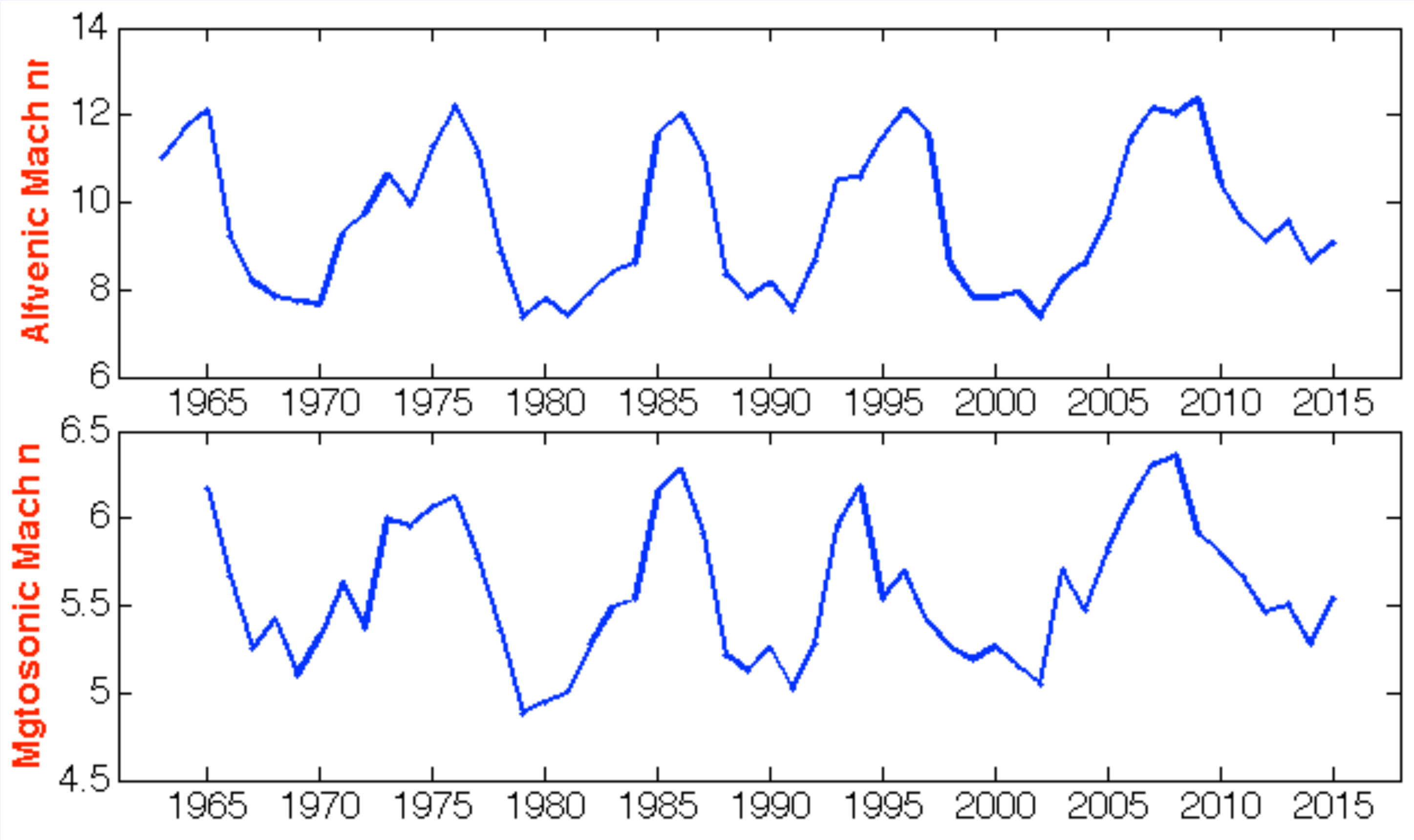
Mach numbers at 1 AU

Systematic solar cycle variation in both Mach numbers (Ma or QI also used as SSN proxy).
Mach number maxima at sunspot minima (large Vsw, small B), minima around sunspot maxima (small Vsw, large B).

Abnormally large Mach numbers in SC 24!
May affect shock formation.

Ma = Vsw/Va

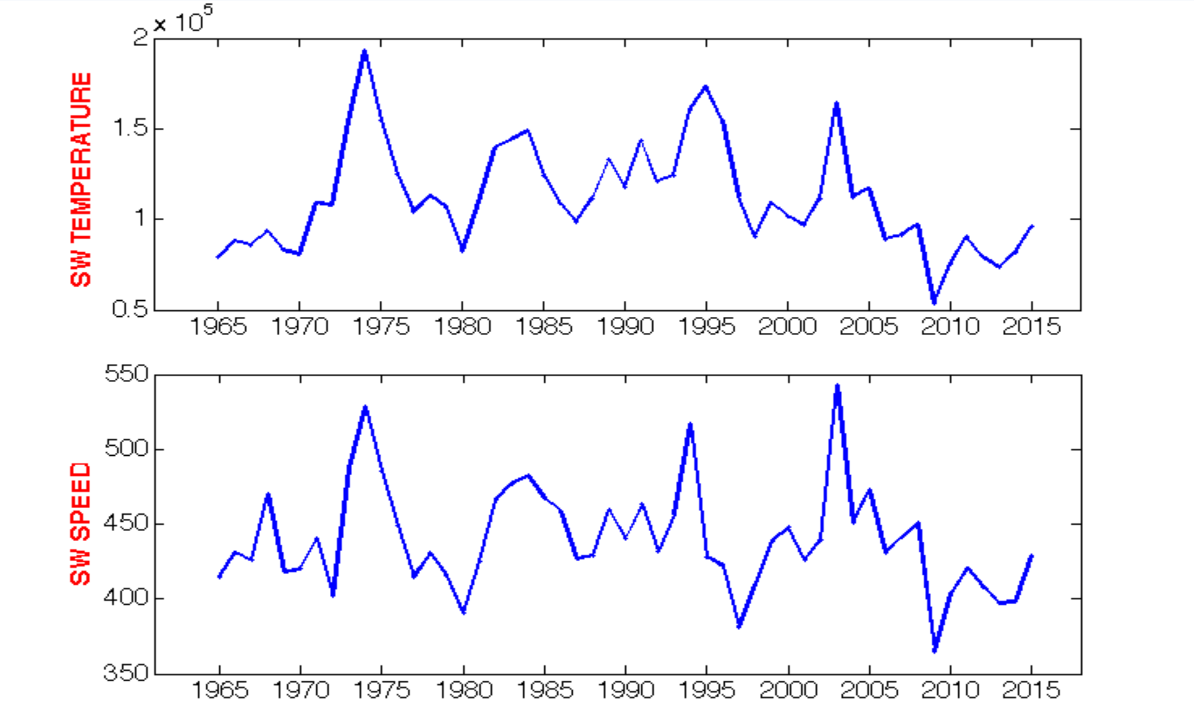
Mms=Vsw/Vms = Vsw/sqrt(Va^2+Vs^2)



Annual SW temperature at 1AU

Fast SW is also hot!

This is somewhat surprising since fast speed arises from lower corona with lower temperature (lower O^{+7}/O^{+6} and other fractionization ratios).



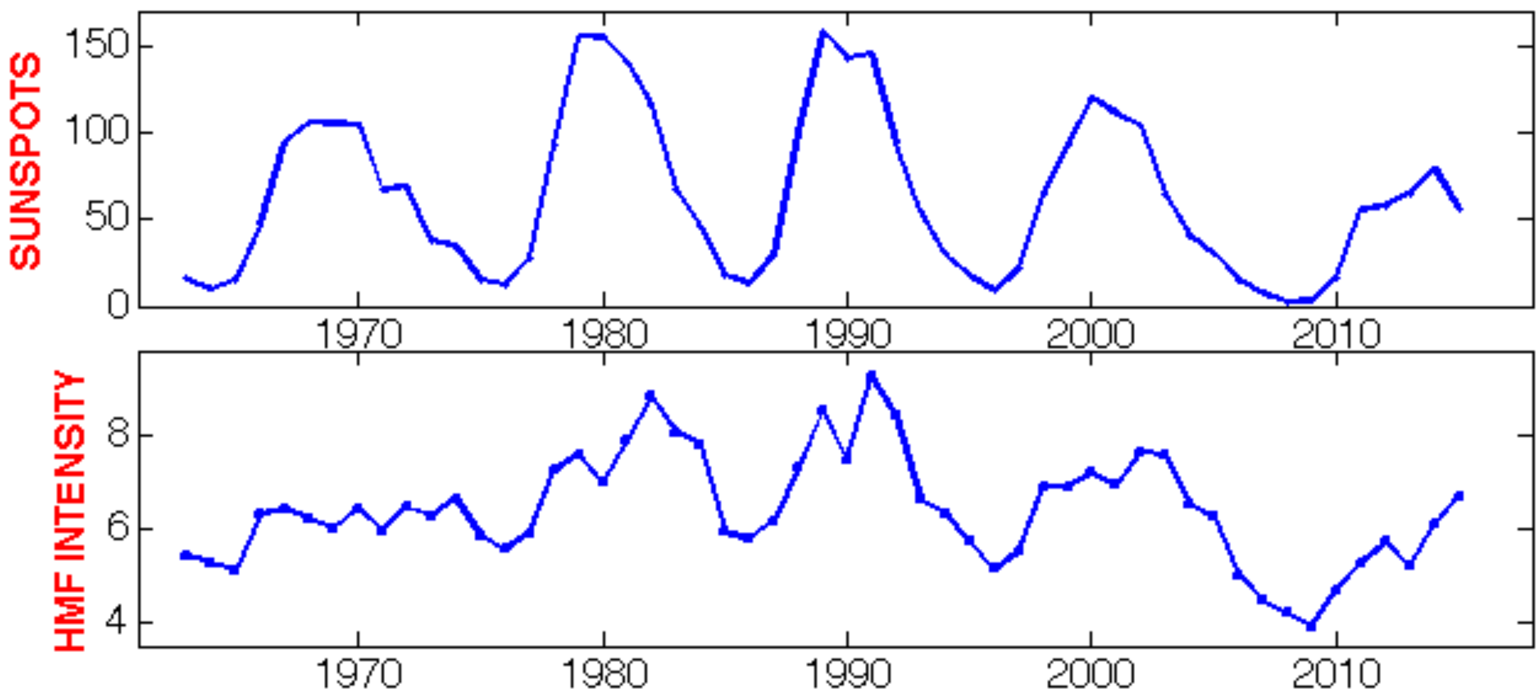
High similarity with Vsw at solar cycle time scales.

Annual HMF intensity at 1 AU

HMF maxima 1-3 years after sunspot maxima.

Higher sunspot cycles produce stronger HMF.

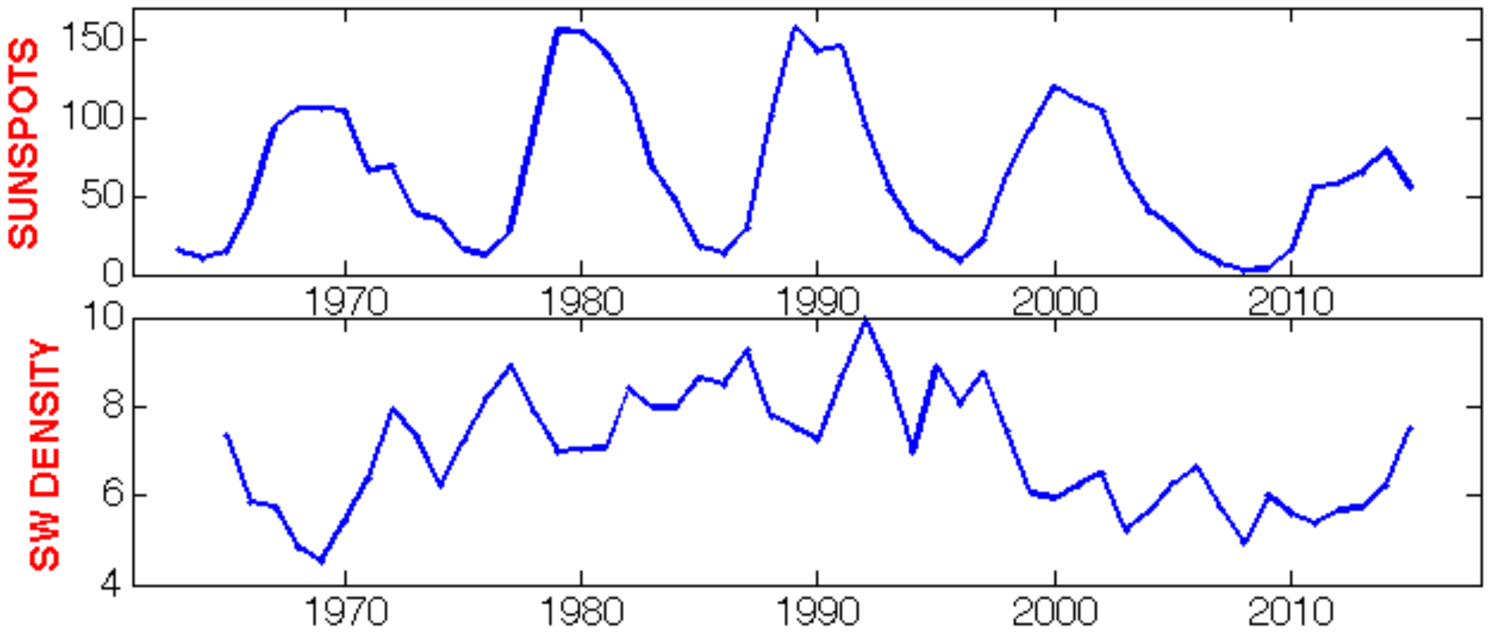
Strong decline from SC22 to SC24.



Annual SW density at 1 AU

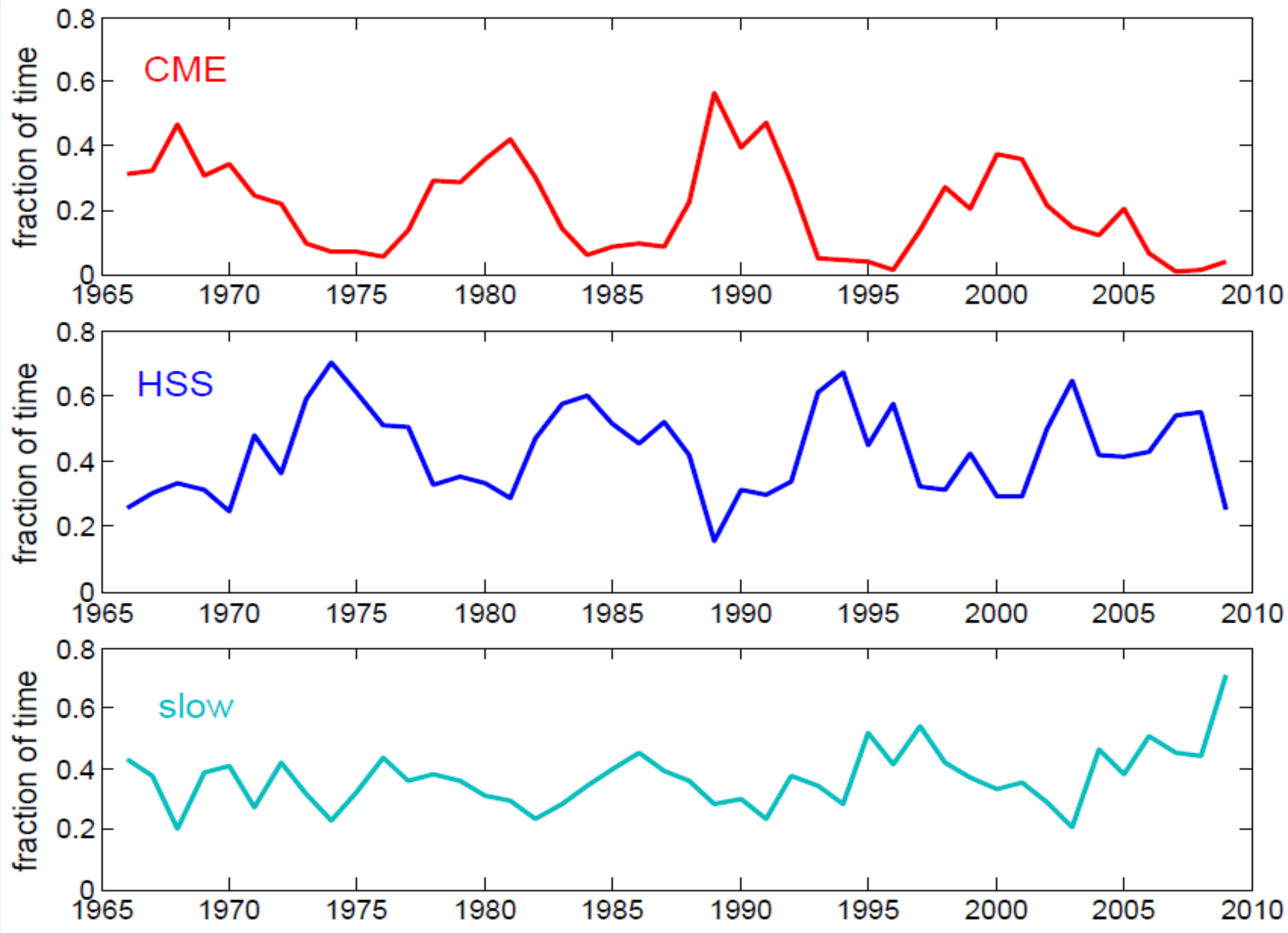
No clear solar cycle variation in SW density.
(Rather, typically 2-3 peaks per cycle).

Weak sunspot activity produces less dense SW.
Increasing trend since SC22, but SC24 not exceptionally low.



Different solar wind types at 1AU

Annual fractions of the different SW drivers according to the list by I.G. Richardson (SWSC, 2012)



CMEs follow the sunspot cycle fairly well.

HSS maximizes in the declining phase.

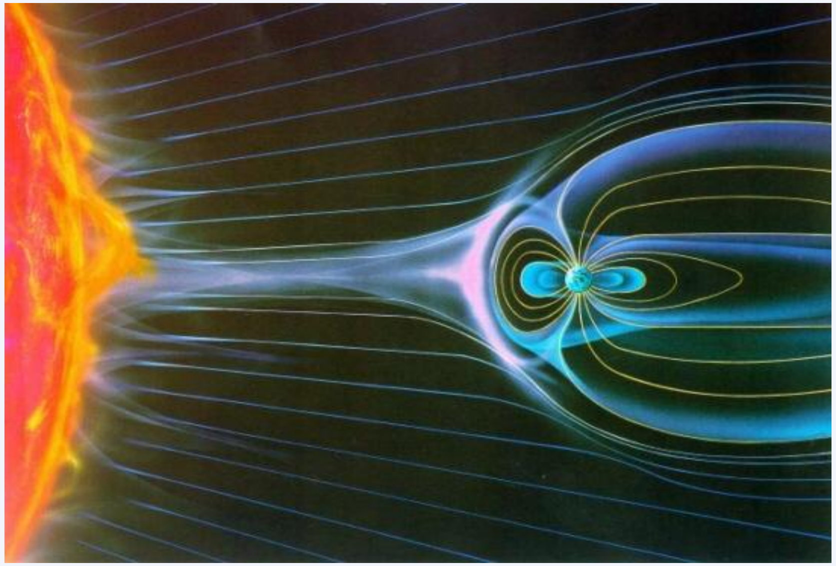
Slow SW maximizes at sunspot minimum.

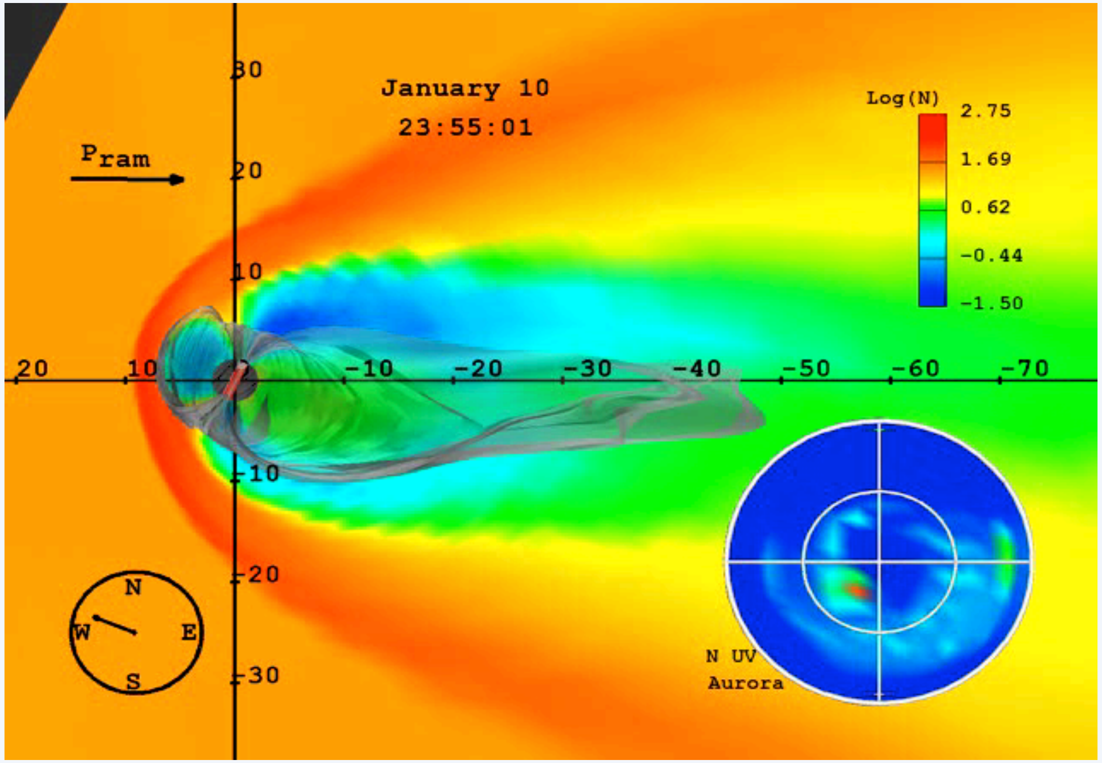
SW and/from GA

Solar wind-Earth interaction

Solar wind interacts with the Earth´s magnetic field and makes it to form a cometary structure, the magnetosphere.

Magnetosphere is in a constantly disturbed state
=> geomagnetic activity

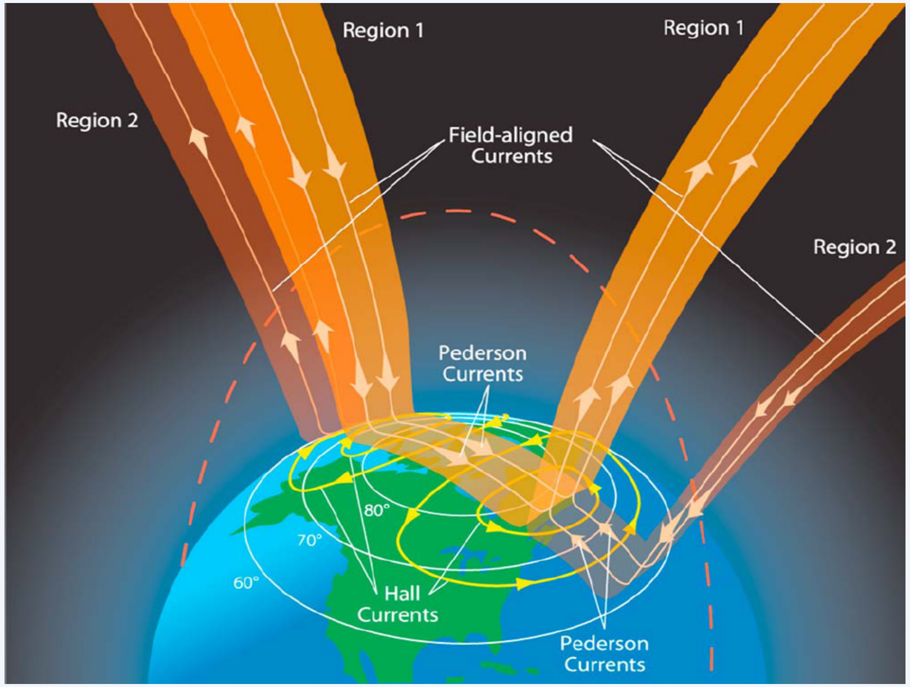




Monitoring SW by geomagnetic activity

Systematic geomagnetic measurements have been made for over 170 years

Short-term variations in geomagnetic measurements (geomagnetic activity) provides a unique possibility to extract information about the solar wind structures (HSSs and CMEs) and parameters before the era of direct satellite measurements.



Solar wind effects are more directly reflected upon the auroral oval.

GA is quantified by different geomagnetic indices calculated from ground magnetic observations at different latitudes (e.g., AE, Kp/Ap, Dst).

How to separate CME and HSS effects?

Earlier (Svalgaard, Lockwood etc) method:

Extract long-term SW and HMF by using two different indices of GA that have different dependence on Vsw and HMF.

New methods:

1. Purify geomagnetic activity from CMEs by using only stations that are most sensitive to HSS/CIR (and using Z-component instead of H).
These are at the poleward boundary of the auroral zone.

2. Use systematic differences in local GA at different latitudes to separate HSS vs CME effects.

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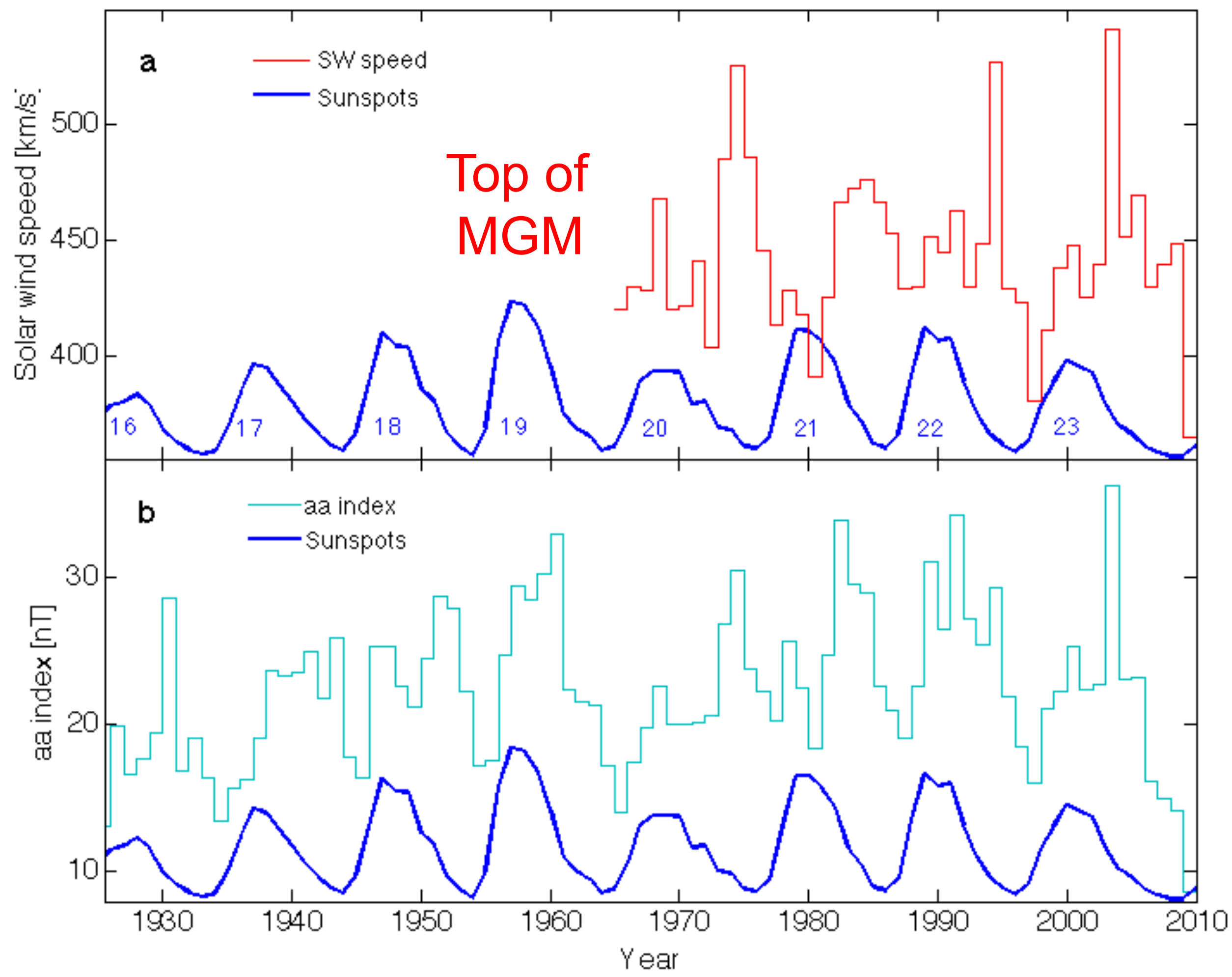
Method 1:
Z-component at polar cap station

Solar wind speed, aa index, SSN

Geomagnetic activity (as normally defined; at mid-latitudes) depicts a clearly different evolution than SW speed for most solar cycles.

GA maximum is often earlier than SW speed.

This is due to CME contribution to GA.

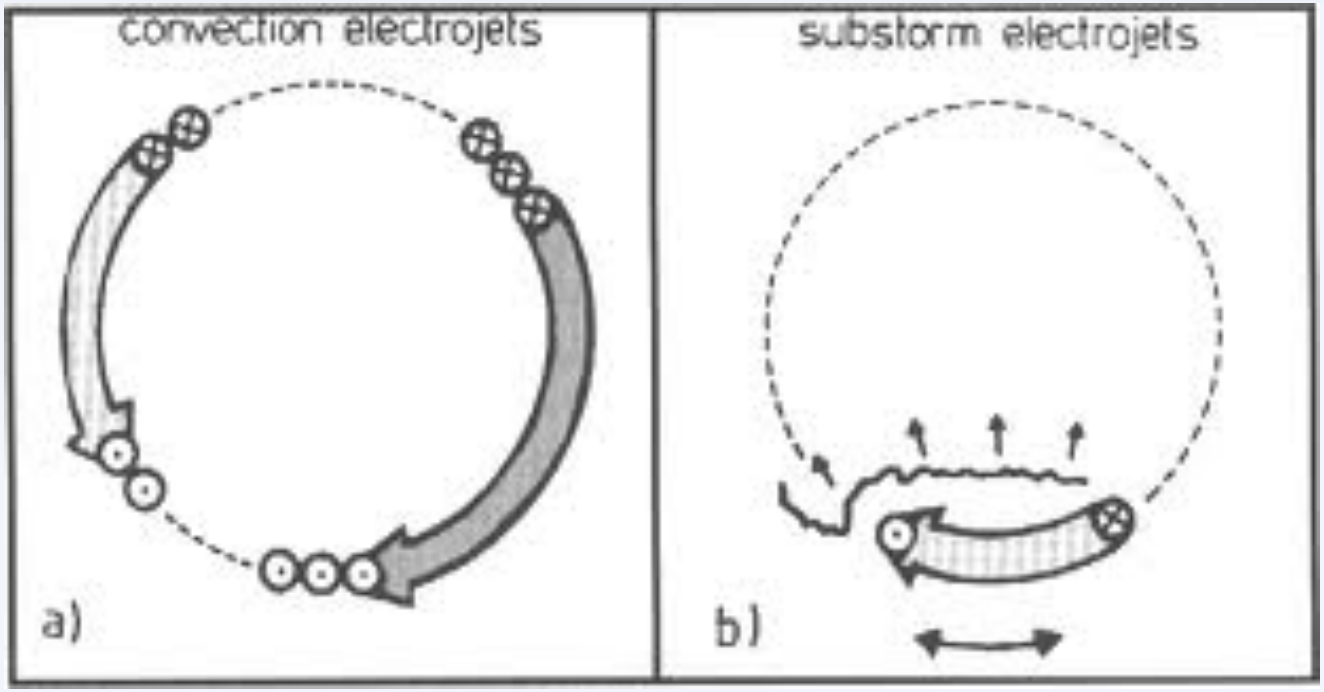


Auroral electrojets

Westward electrojet (WEJ) dominates in the midnight to post-midnight sector

Eastward electrojet (EEJ) dominates in the afternoon sector

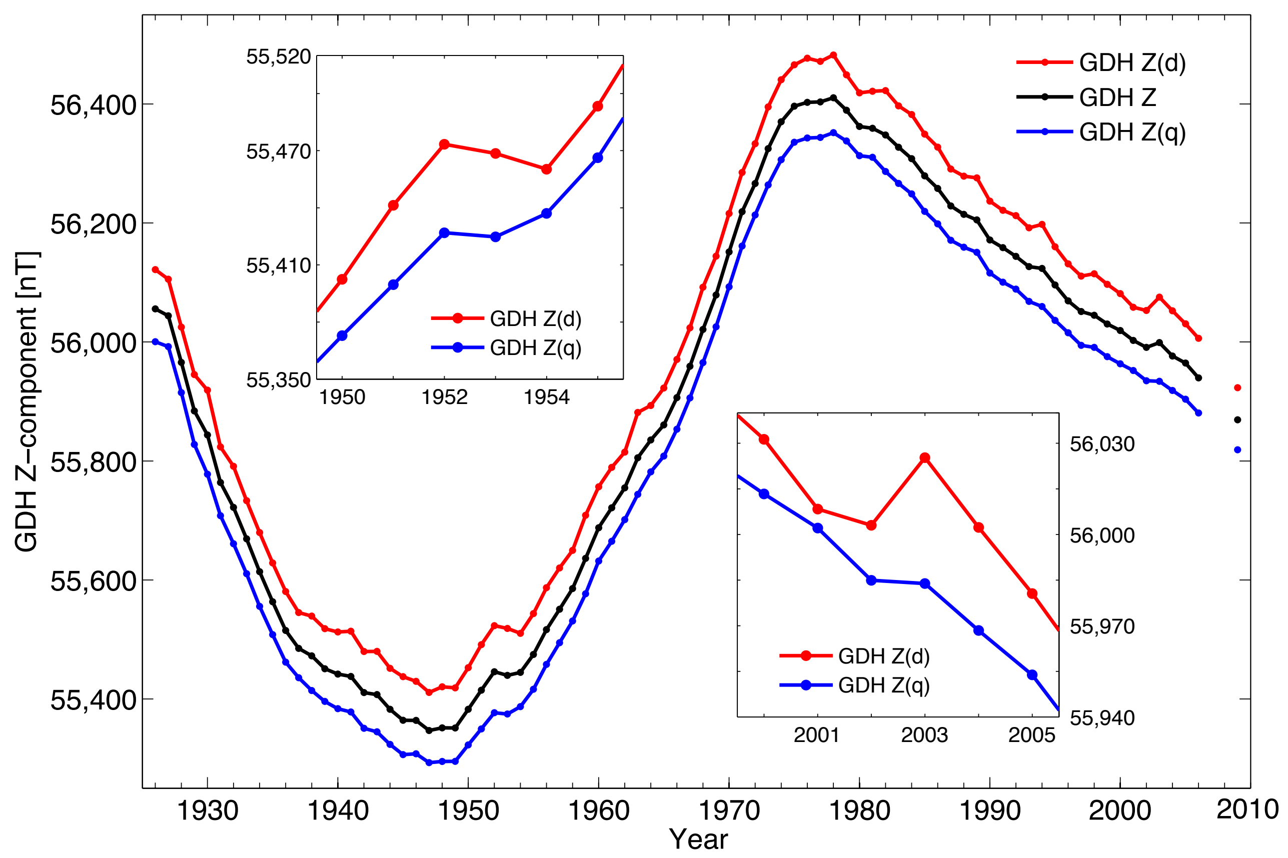
During substorms WEJ extends westwards towards the evening sector (substorm electrojet



Annual means of magnetic Z-component at GDH

During years of high solar wind speed, there are positive deflections in annual means of Z-component at Godhavn (GDH), just inside polar cap.

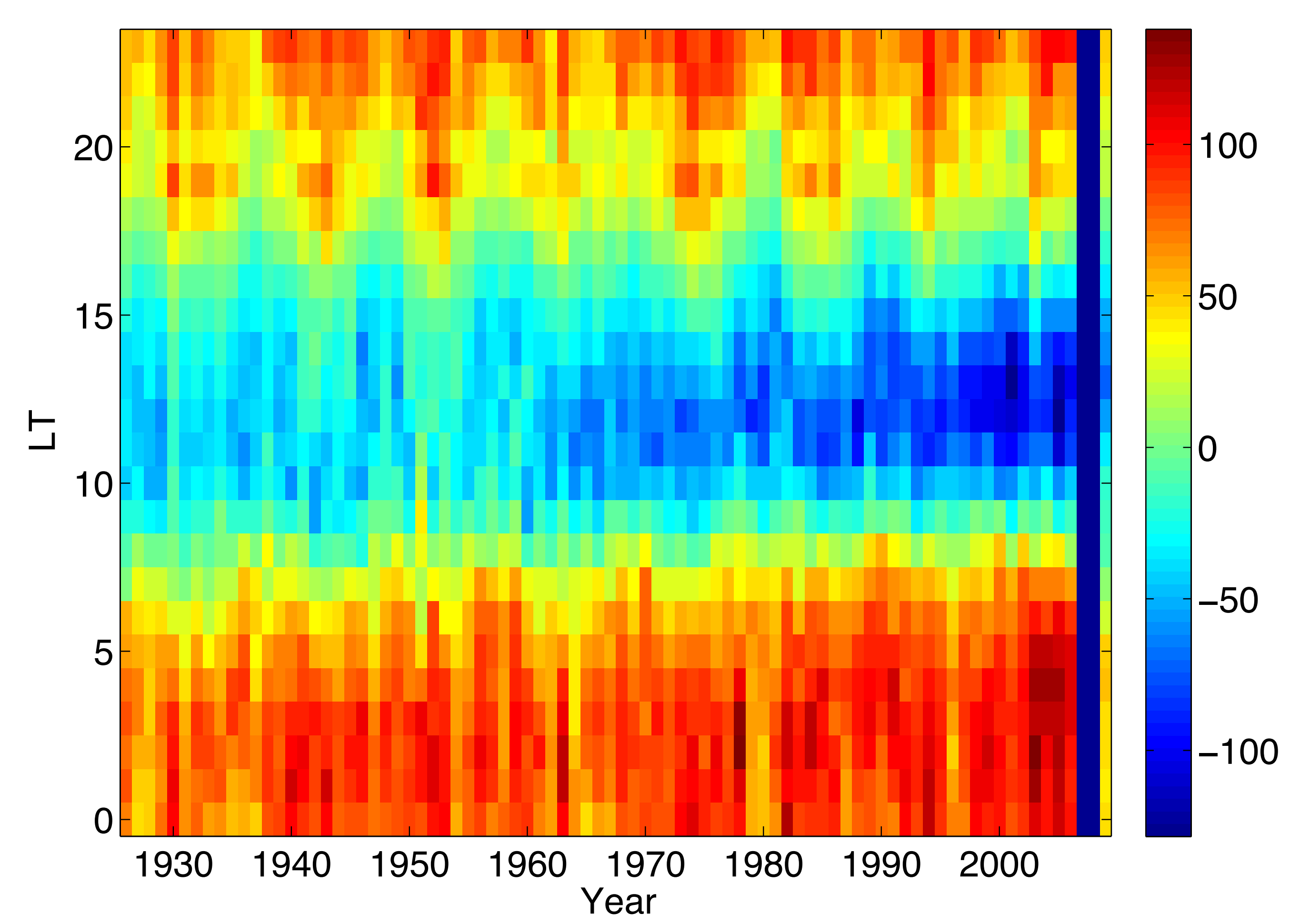
The effect is strongest in 1952 and 2003 and other strong HSS years.



Local time variation of GDH $\Delta Z = Z(d) - Z(q)$

During HSS years the westward electrojet (red region) expands in LT covering most of the day.

Due to the secular variation of the Earth's magnetic field, there is a secular evolution in the observations of electrojet intensities. However, this does not affect much to ΔZ since both electrojets enhance roughly equally.



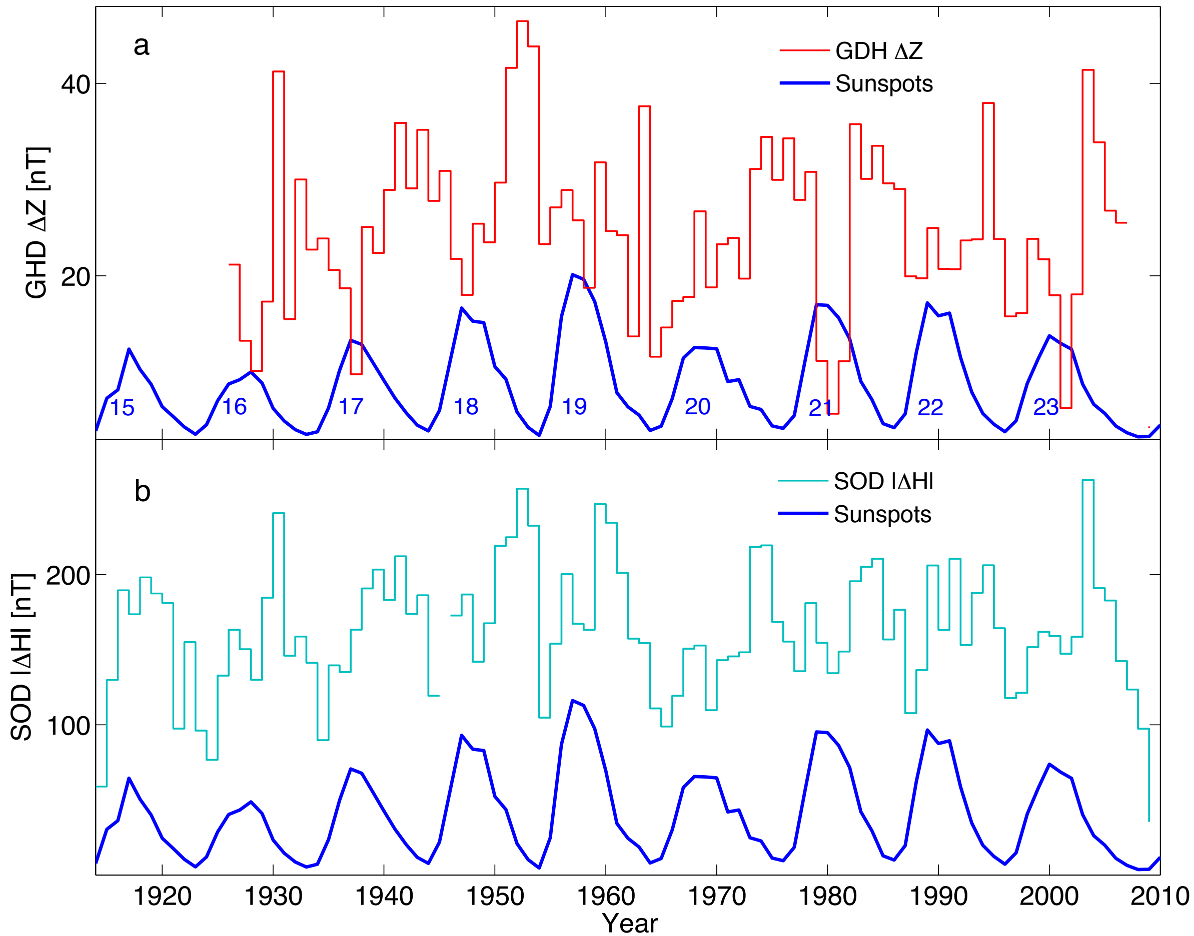
GDH ΔZ and SOD ΔH

Annual values of GDH ΔZ quantify the effect of HSSs on the Z component.

YEAR 1952 shows the strongest HSSs

Also SOD ΔH = |H(d) – H(q)| in the night time sector (21-03 LT) give **the same maximum.**

In this LT sector, the HSS effect has relatively larger contribution.

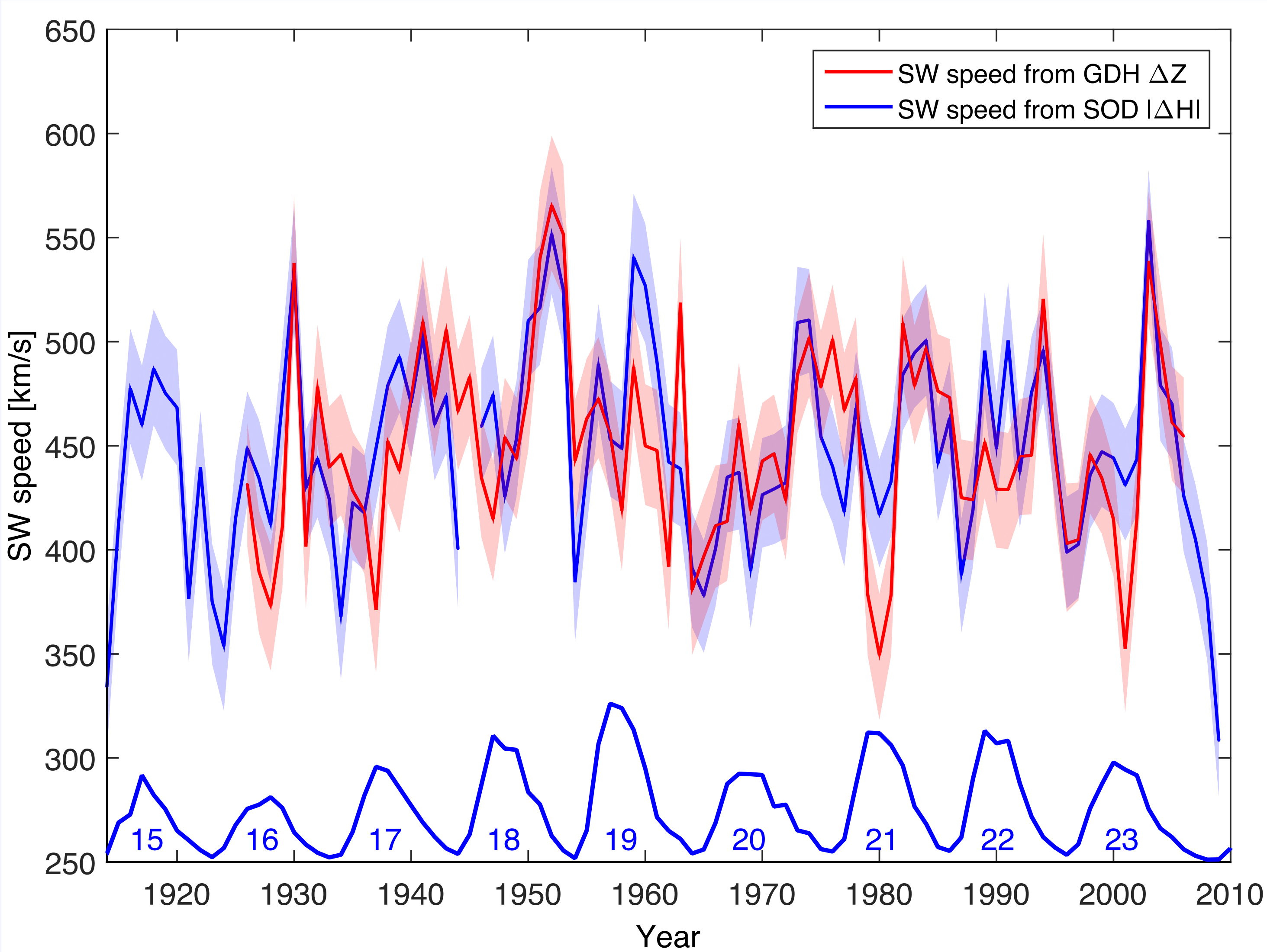


Finding HSS for the last century

Yearly mean solar wind speeds since 1914, as obtained from geomagnetic activity at polar (GDH) and high-latitude (SOD) stations.

Highest SW speeds were found during solar cycle 18, just before the highest sunspot cycle 19.

This proves the validity of the solar dynamo (Ω-effect), for the first time for this most dramatic period of solar activity.



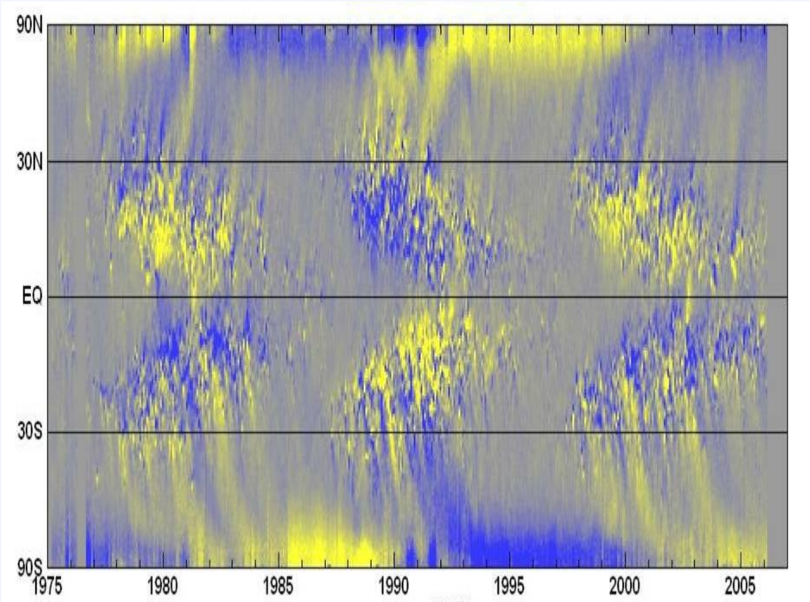
Mursula et al. ApJ, 2015

Other conclusions

HSS period exists during declining phase of each cycle 16-23, both before and after GMM maximum

In 5 out of 8 cycles this period causes a maximum during one year only.
In 2 cycles lower HSS levels are found during a few years.

Interpretation: One main activation of the solar dipole tilt = coronal hole extension = solar excursion phase lasting for about 5 rotations causes the strongest HSS period.



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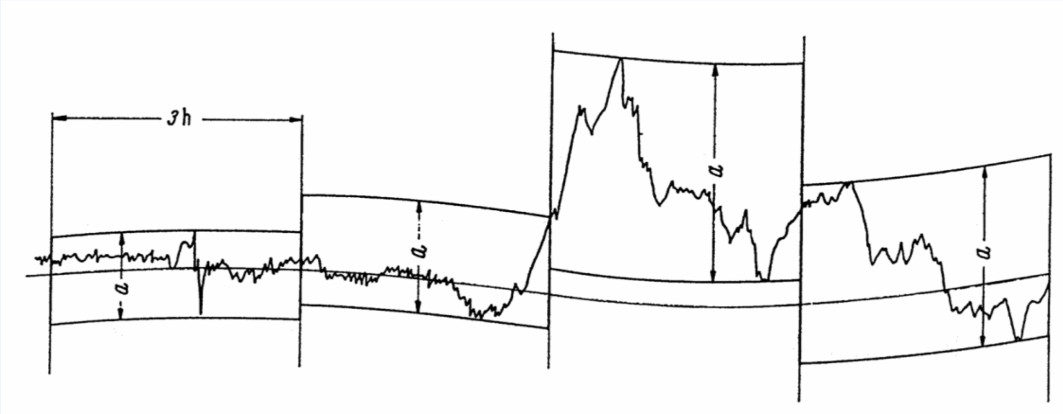
Method2:
Annual fractions of high speed streams from local geomagnetic activity using principal component analysis

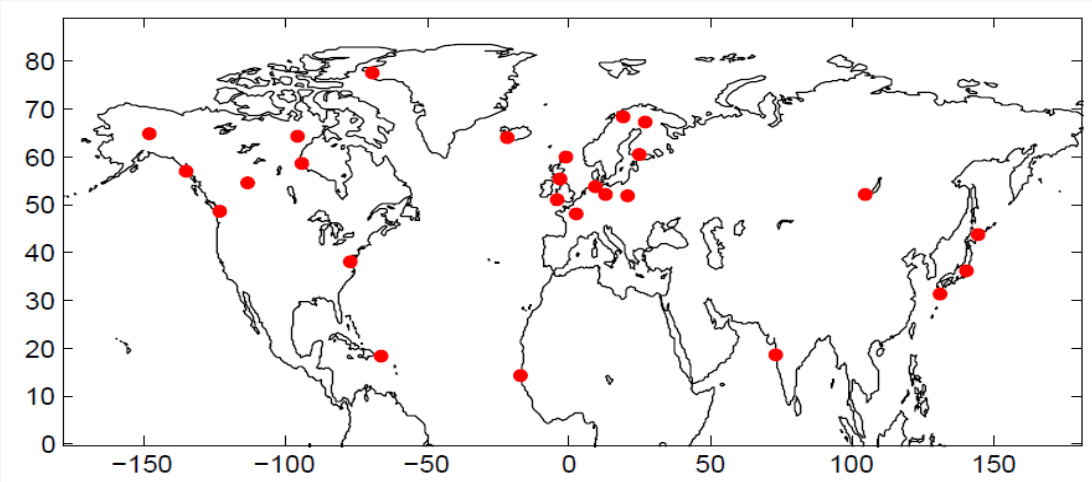
A_h indices from several magnetic stations

We use A_h indices [*Mursula and Martini, 2007*] from 26 stations between 1966-2009

A_h index measures the range of magnetic disturbances in 3 h intervals.

Stations cover a wide range of latitudes.

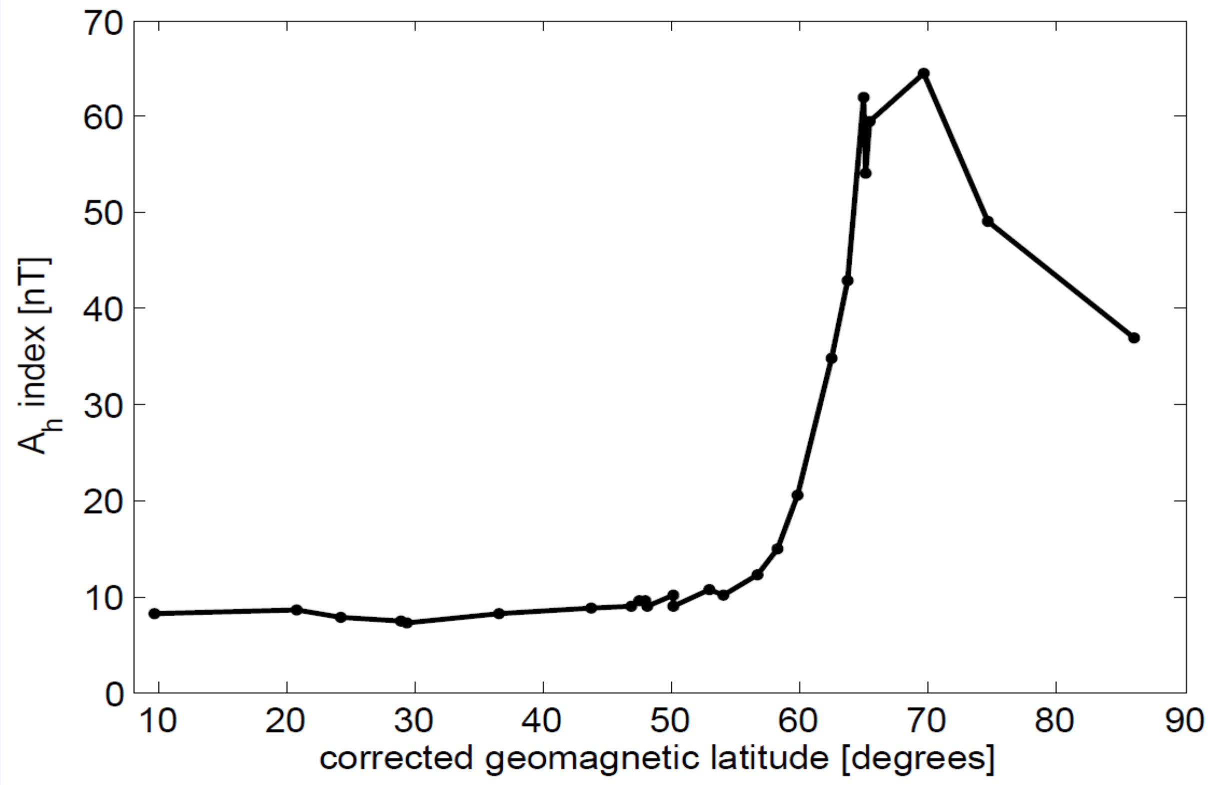




Average latitudinal distribution

Average level of geomagnetic activity at auroral latitudes is almost 10 times greater than at low latitudes!

=> We use standardized Ah indices (zero mean and unit variance)

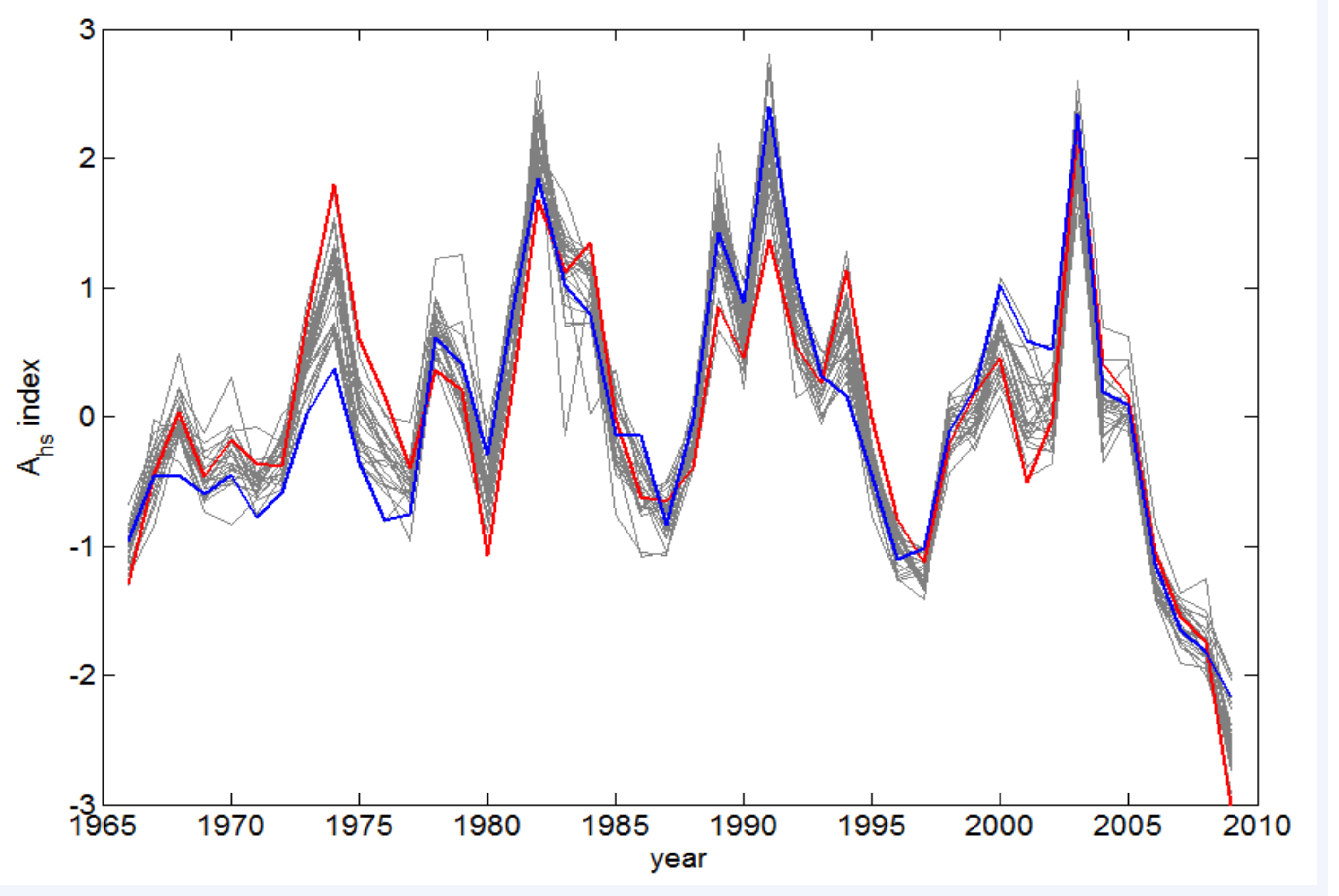


Standardized A_h indices of different stations

Roughly the same solar cycle variation of geomagnetic activity

Small differences between, e.g., low latitude (blue curve) and high latitude (red curve) indices.

What information is contained in these differences and how to extract it?



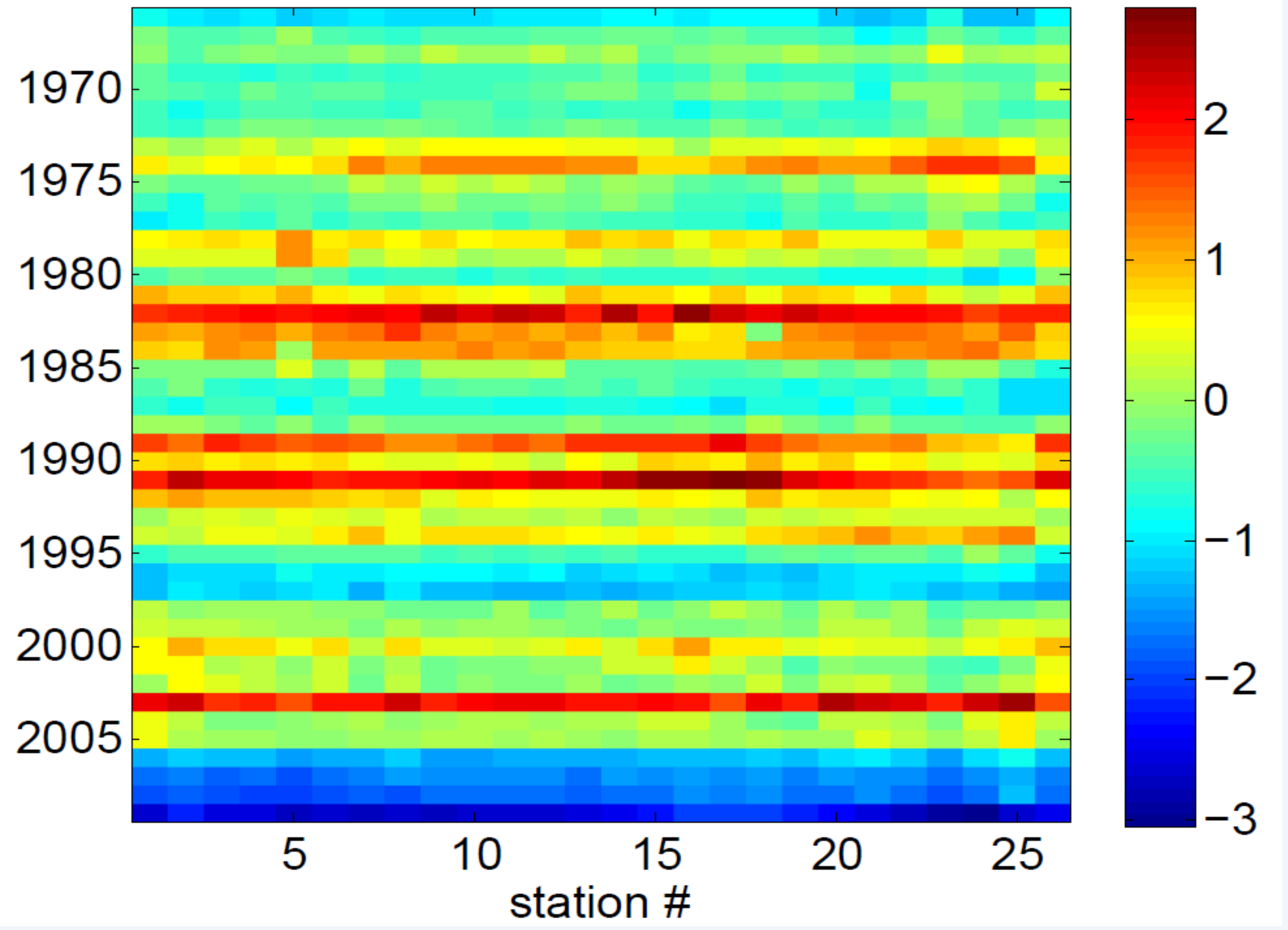
Annual averages of Ah indices in 1966-2009.

Principal component analysis for A_h indices

Standardized indices show **roughly the same solar cycle variation of geomagnetic activity**

⇒ Only few first principal components needed to describe the data.

Two leading principal components explain > 97% of the variance in the data.

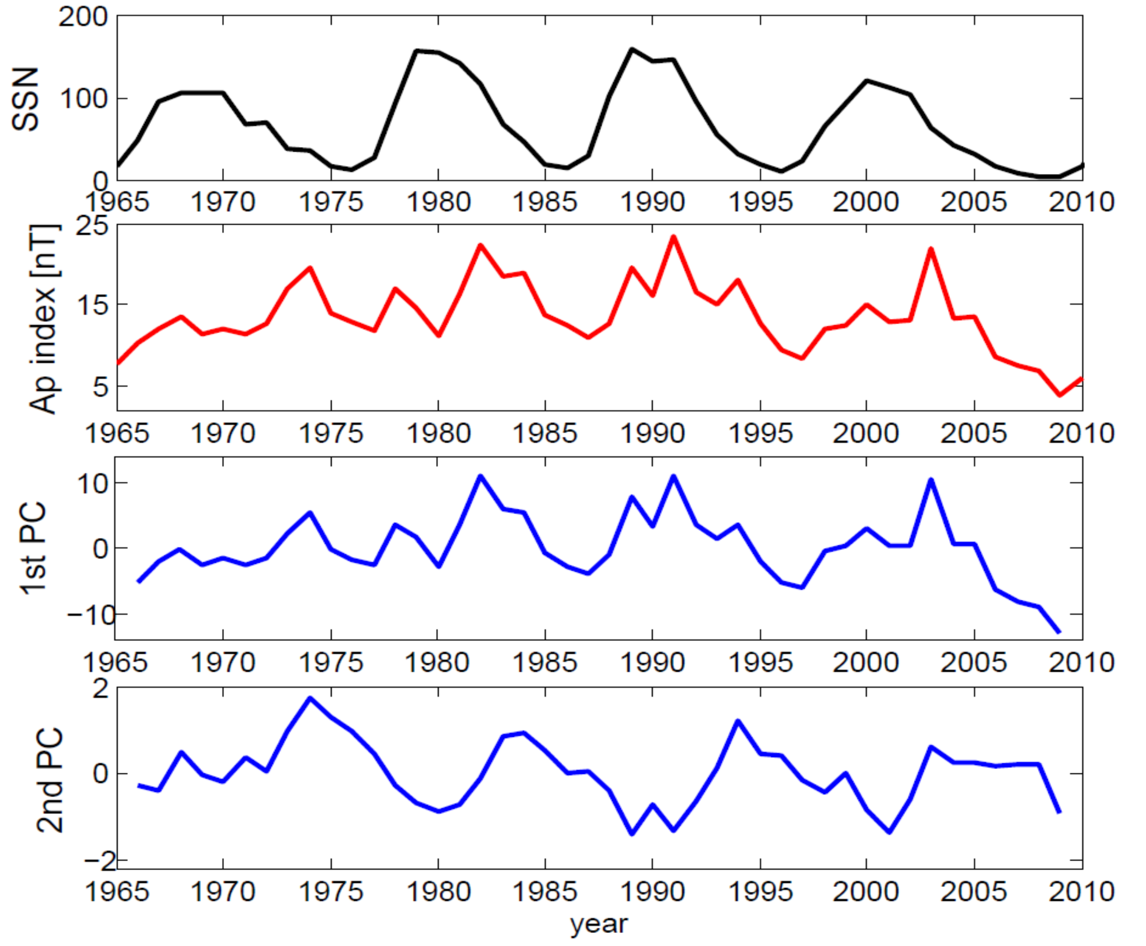


Two first principal components

1st PC correlates almost perfectly with the Ap index representing globally averaged geomagnetic activity.

2nd PC shows maxima in the declining phase phase of the solar cycle.

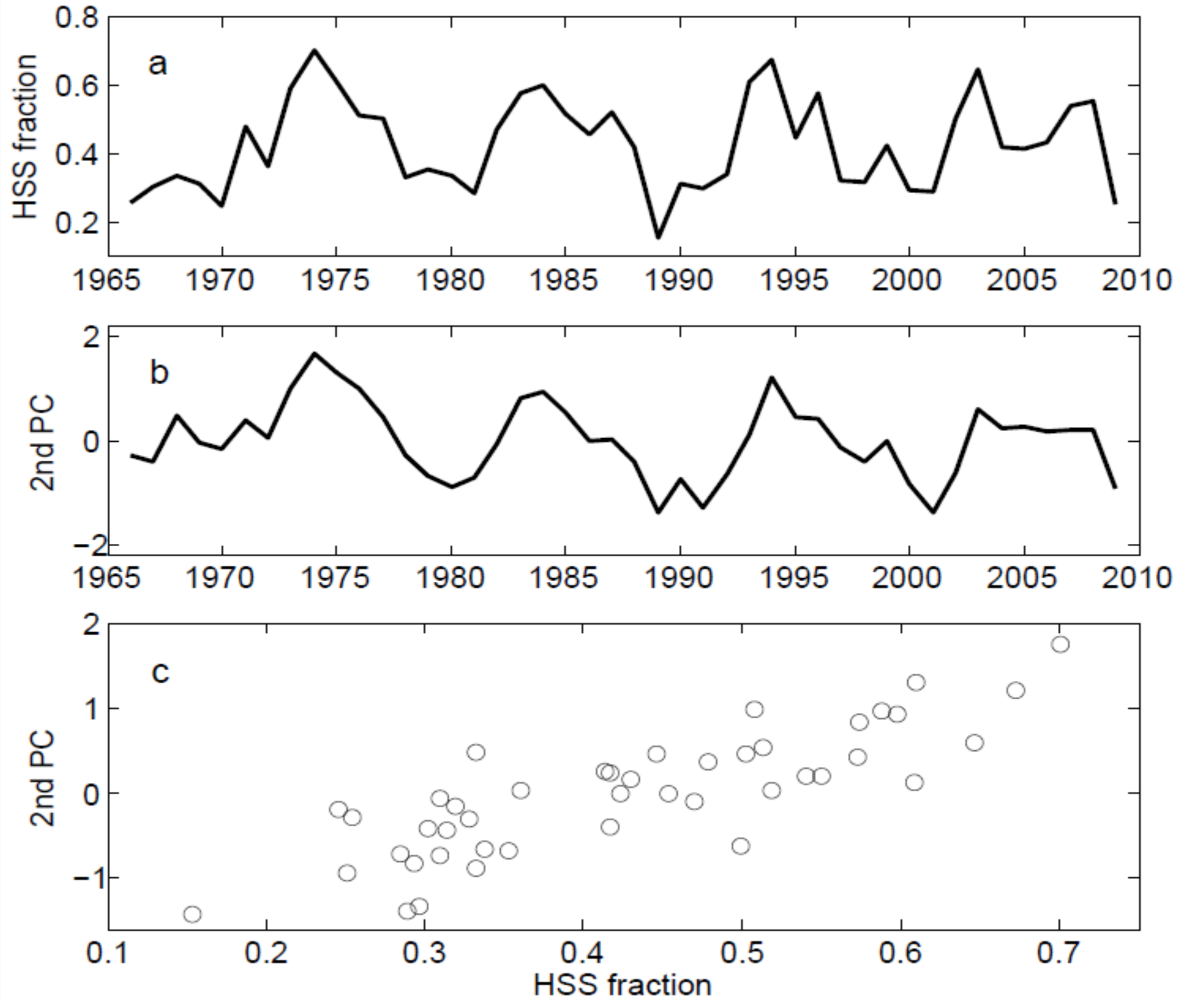
➔ 2nd PC is related to high speed streams?



2nd PC and HSS fraction

Very high correlation between the 2nd PC and the yearly time fraction of HSSs (cc = 0.83, p = 1.1·10-11)

Also high anticorrelation with the CMEs fraction (cc = -0.79)

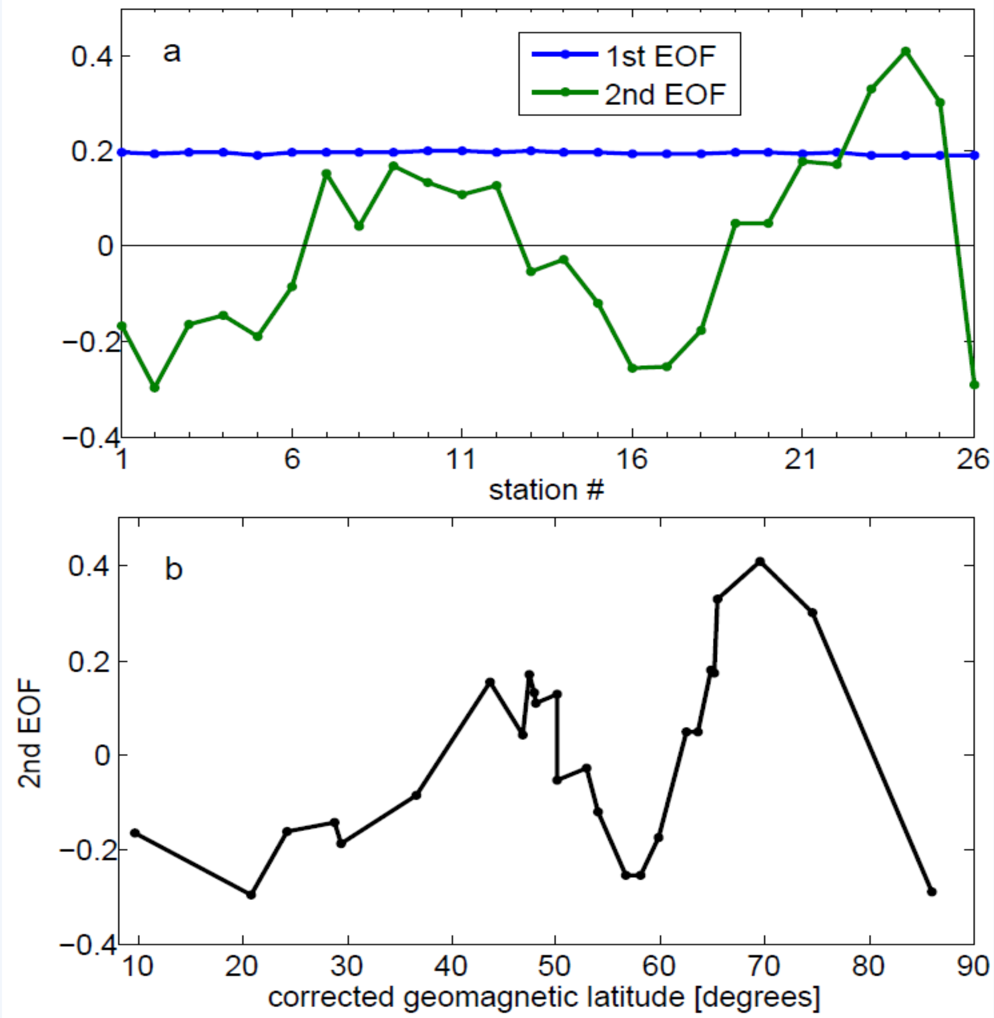


Empirical orthogonal functions

Empirical Orthogonal Functions (EOF) describe how the effect of the corresponding principal component is spread to different stations.

- 1st PC contributes with the same weight in all stations
  ➔ 1st PC represents the average of the 26 Ah indices.

- 2nd PC contributes with different weights to individual stations
  ➔ Differences between stations are mainly due to 2nd PC.

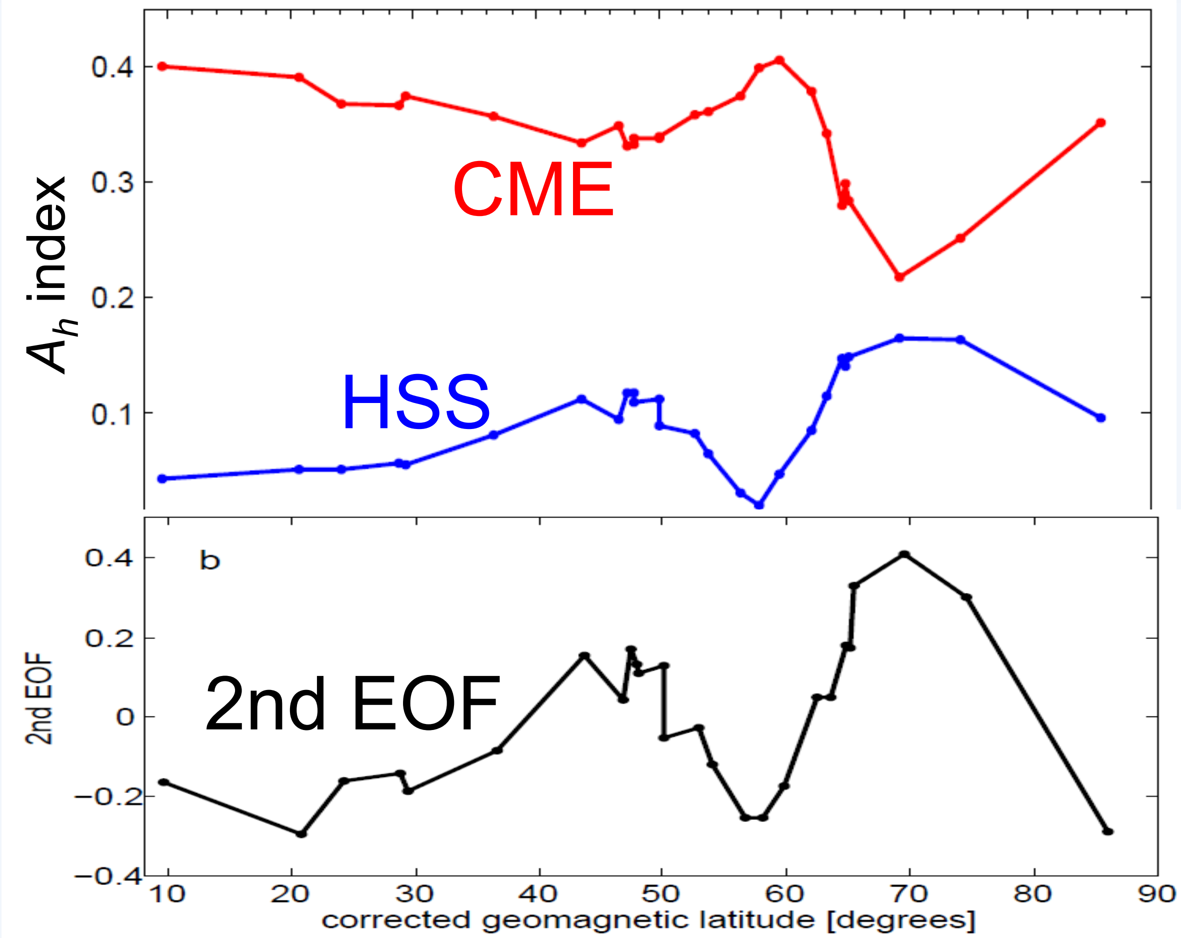


Average A_h indices during different SW types

The latitudinal distribution of the standardized A_h indices during HSSs is strikingly similar with the 2nd EOF!

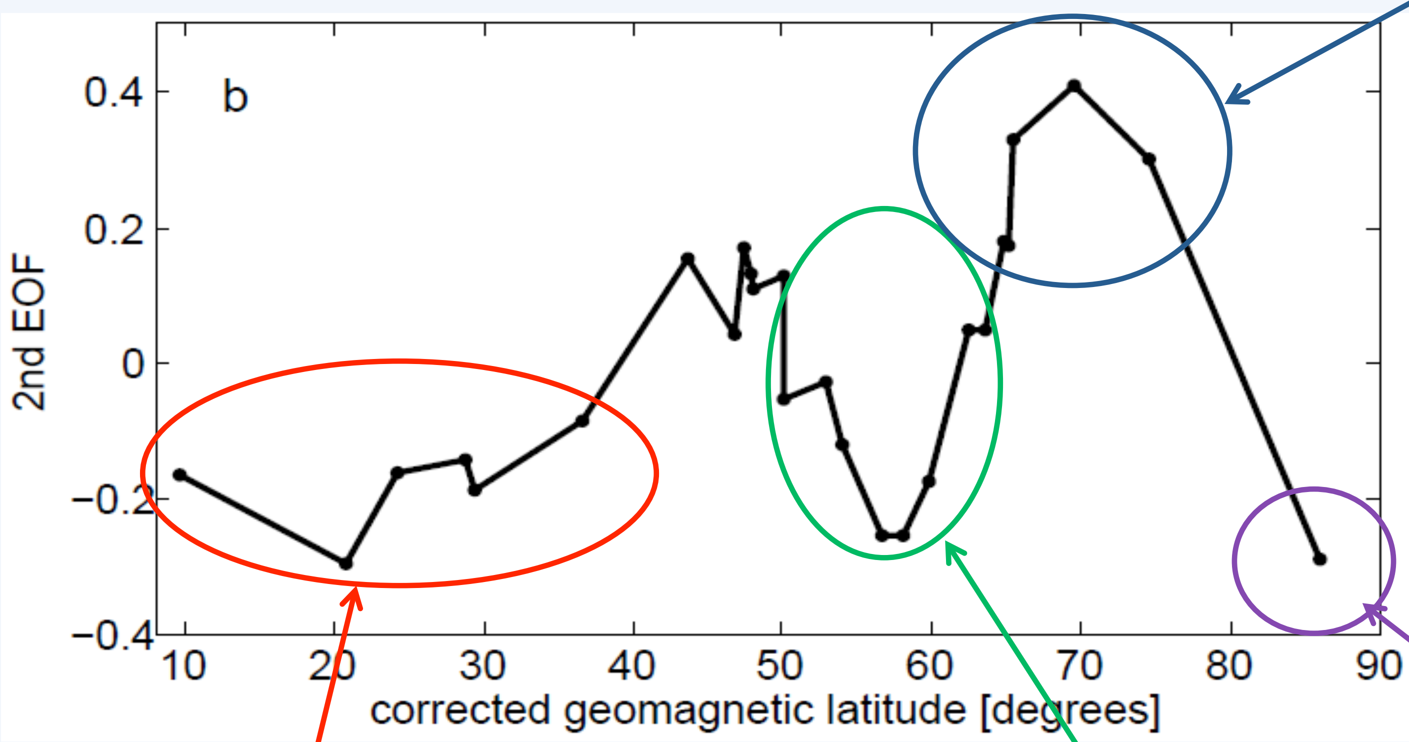
The distribution during CMEs is almost the mirror image of the distribution during HSSs.

- When PC2 is positive the distribution of Ah indices resembles the HSS related distribution
- When PC2 is negative the distribution of Ah indices resembles the CME related distribution



2nd PC describes the relative contribution of HSSs in the distribution of Ah indices!

Understanding the 2nd EOF



2nd EOF is maximized at auroral latitudes because substorm activity is dominated by HSSs at yearly timescale [e.g. *Tanskanen et al., GRL* 2005]

2nd EOF is negative at low latitudes because of relatively strong contribution of the ring current (stronger during CMEs than during HSSs).

Extension of CME effect in latitude.

Polar cap station measures DP2 current which is stronger during CMEs than HSSs

A_{hs} distribution during CME and HSS substorms

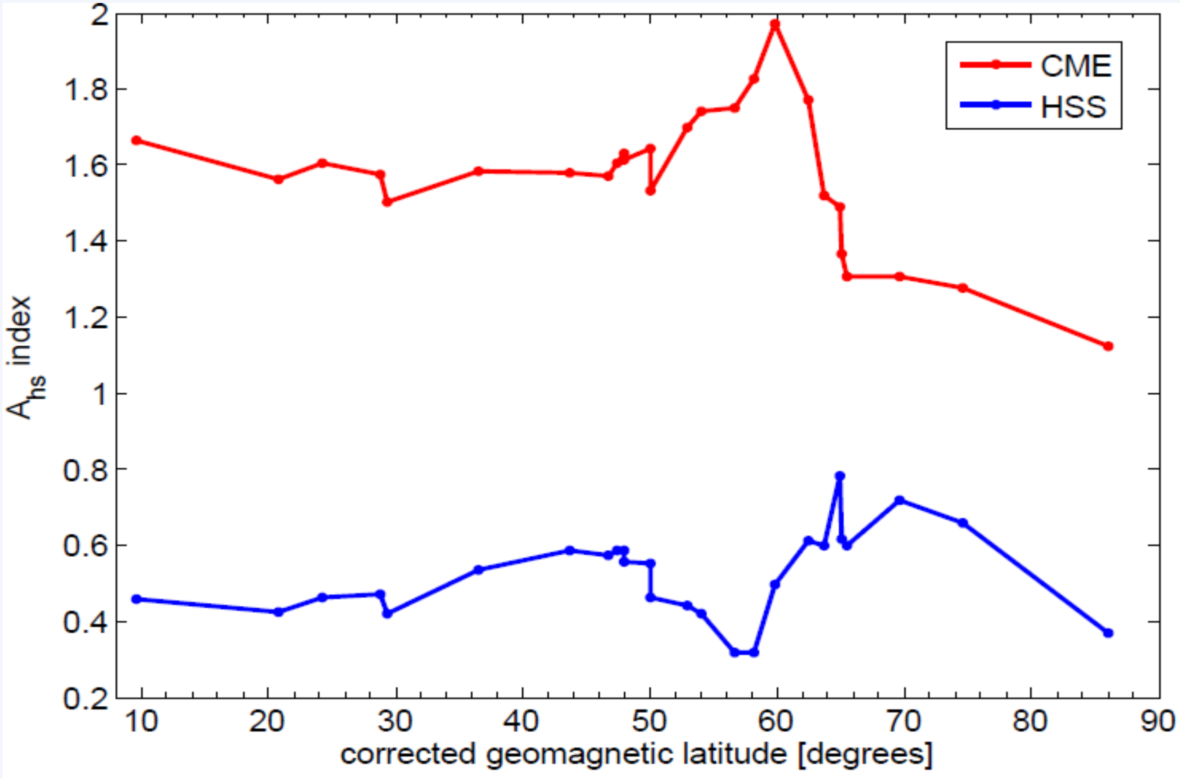
Effects of CME-related substorms extend to lower latitudes than effects of HSS substorms.

=> Relative effect of CME substorms is largest at subauroral latitudes.

This explains the subauroral minimum in the 2nd EOF.

List of substorm onsets identified by the SuperMAG magnetometer network:

http://supermag.uib.no/



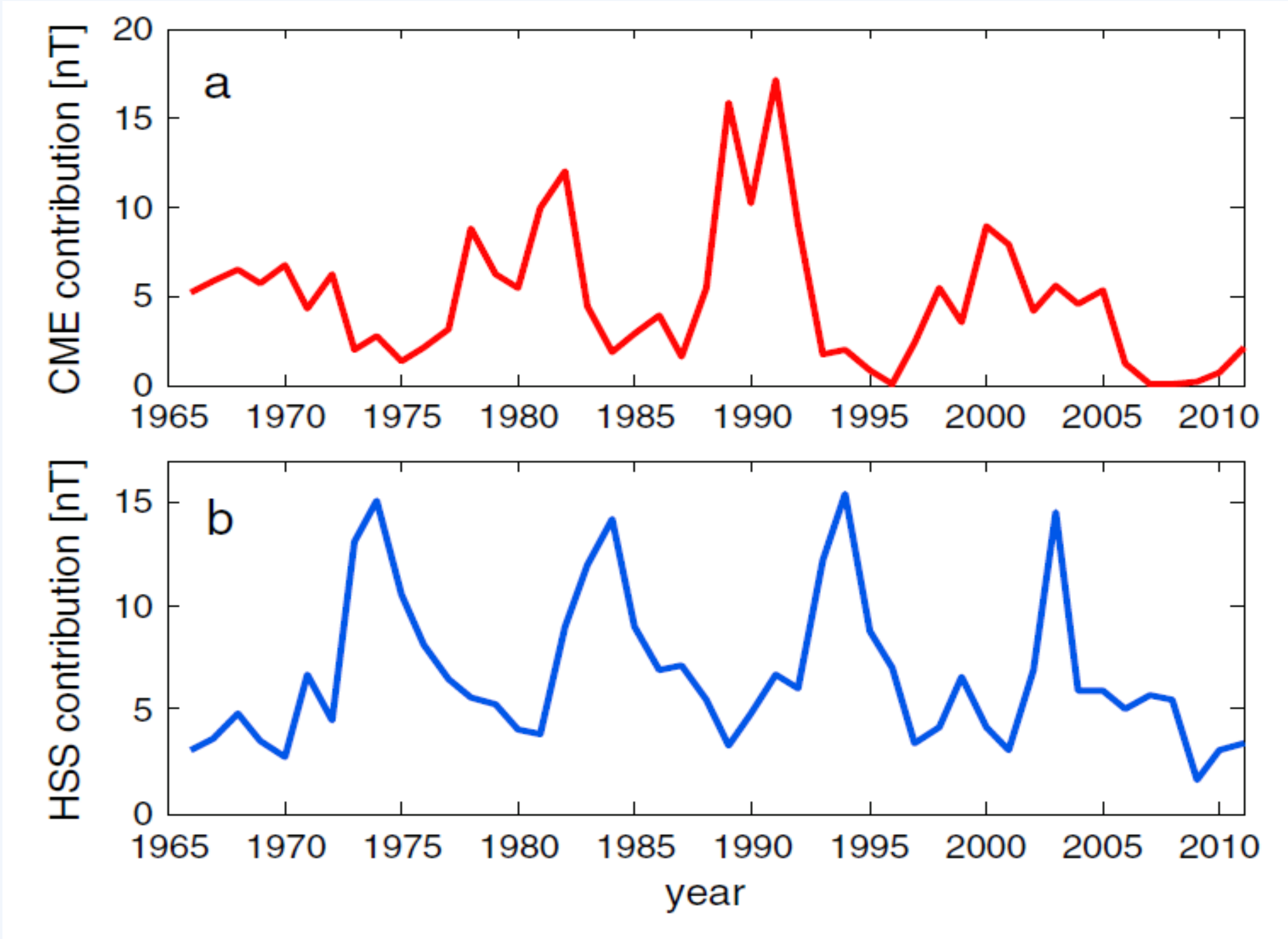
Averages of Ahs indices during CME-substorms and HSS-substorms in 1980-2009. (8083 CME and 16734 HSS substorms)

CME and HSS contributions to GA

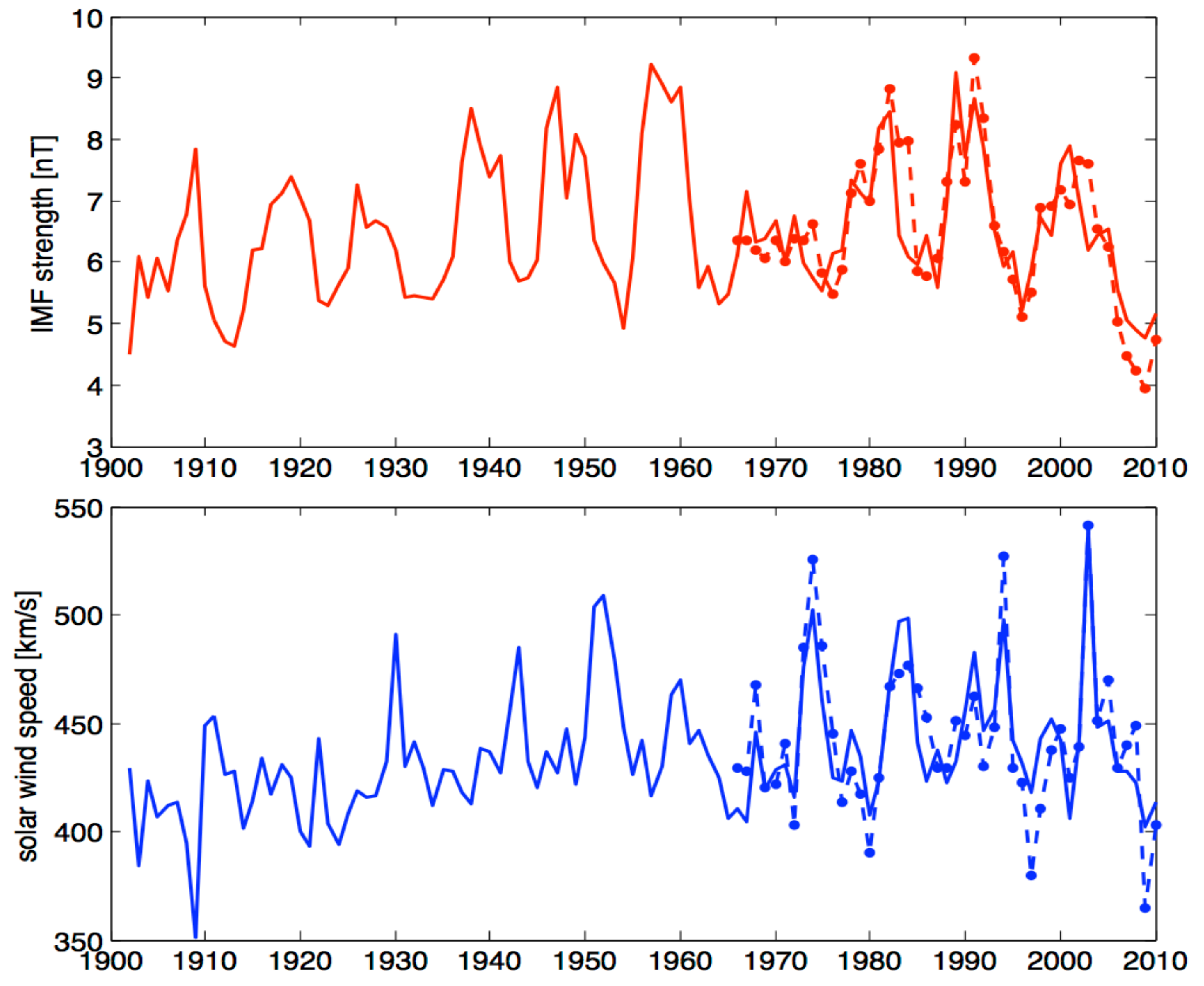
Contribution = (fraction of stream type) x (average effect to geomagnetic activity during stream)

CME contribution dominates around solar maxima, but also seems to be high during the early declining phase.

HSS contribution is typically largest and peaks in the late declining phase.



Centennial SW speed and HMF



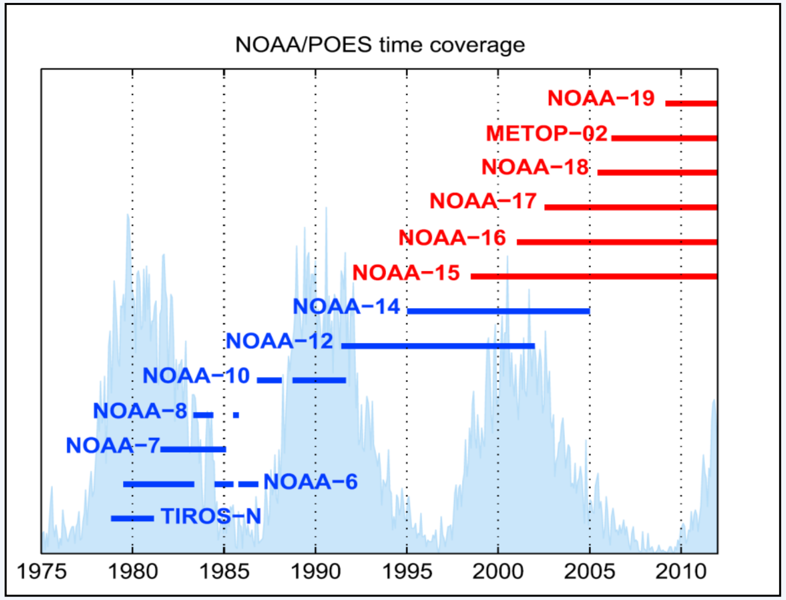
Solar wind speed and HMF strength since 1900.

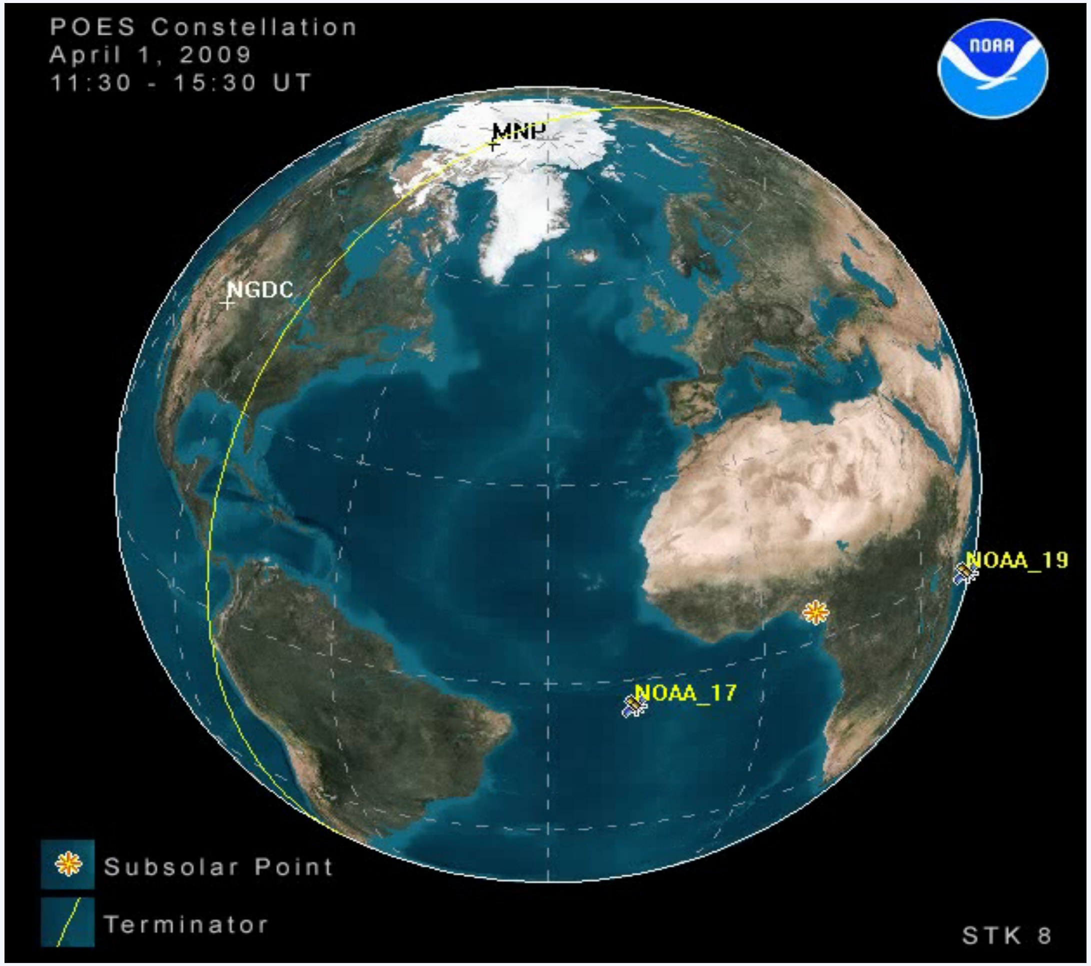
HMF strength maximizes during SC19, in agreement with goog correlation with sunspots.

SW speed maximum during SC18 is verified.

Energetic particle fluxes

NOAA/POES measurements





NOAA/POES s/c MEPED instrument measurements have recently been recalibrated and corrected for radiation damage, electronics problems and detector differences.

Corrections/Calibrations

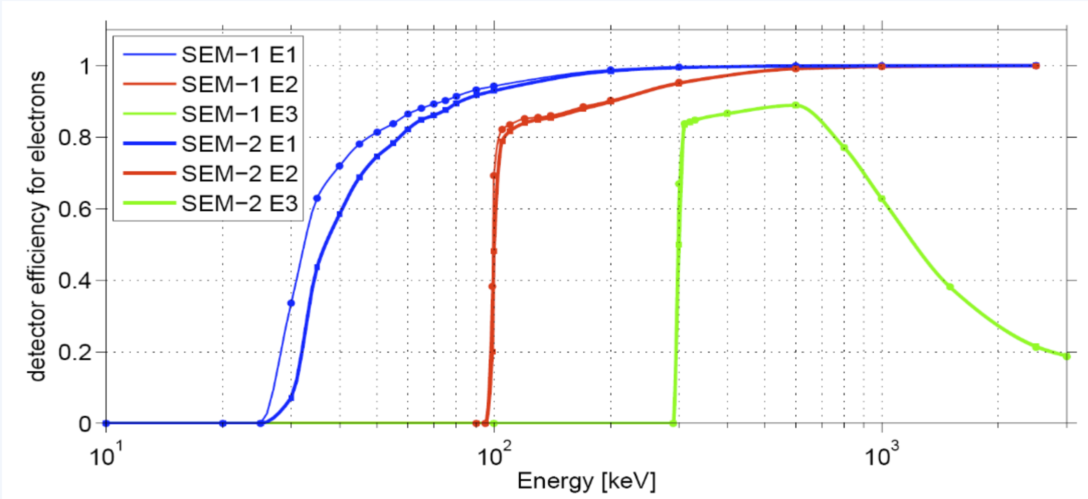
Estimating the detector aging effects (radiation damage, noise effects)

Cross-contamination (electron instrument also measures protons)

Non-ideal instrument efficiencies

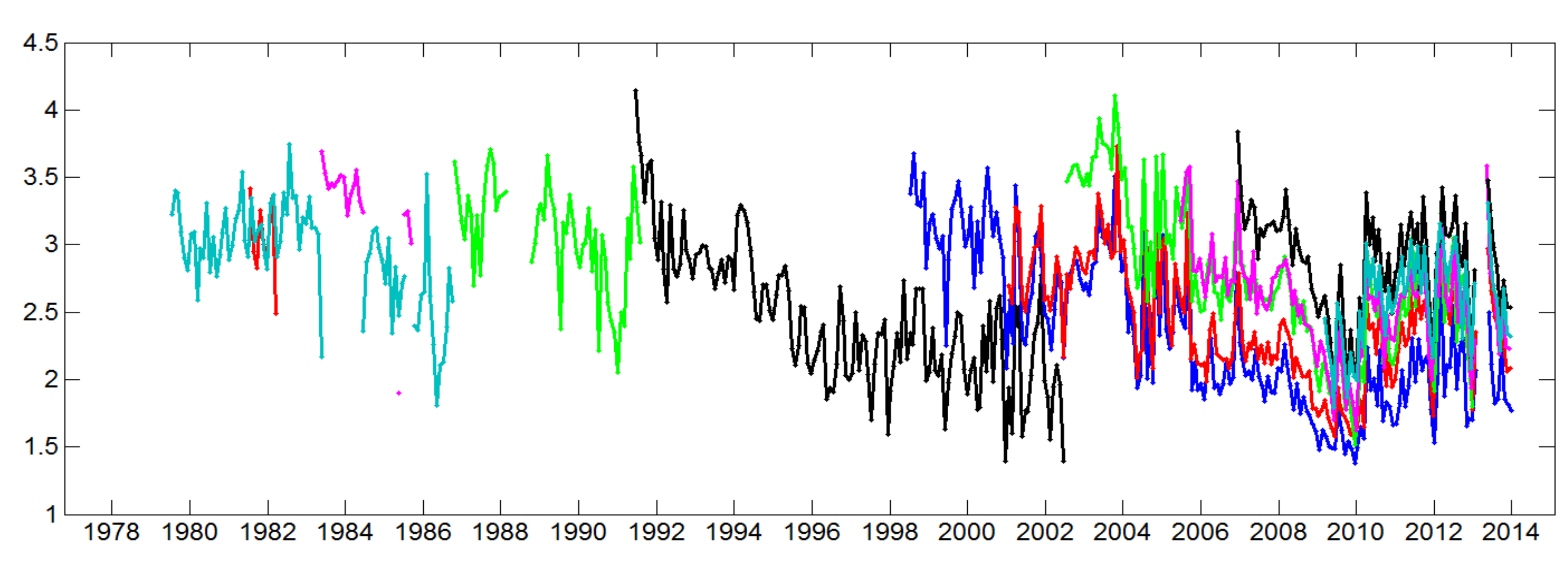
Differences in instrument construction in different satellites

Our dataset is the only dataset that corrects all these issues in the NOAA/POES data!



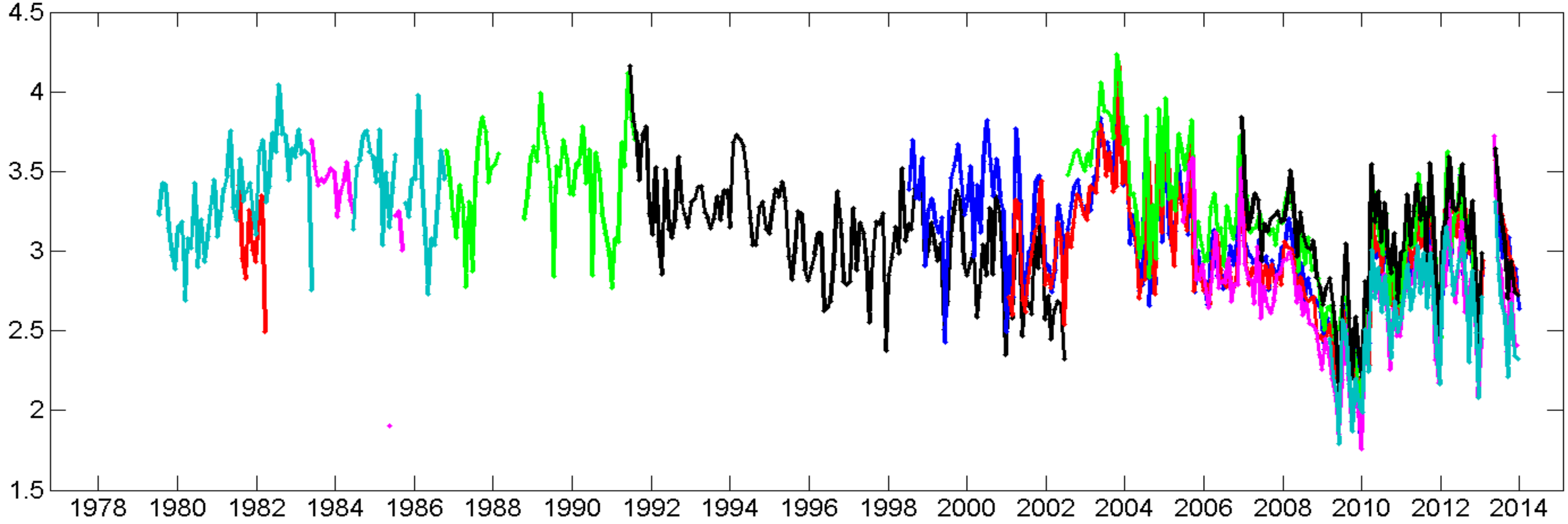
Example of modeled instrument response curves for two instrument versions

Example: **uncorrected** proton flux



Steady decrease in each individual satellite ➔ degradation of instrument
Large spread between simultaneous satellites

Example: **corrected** proton flux



Continuous series from different satellites. Satellite differences greatly reduced.

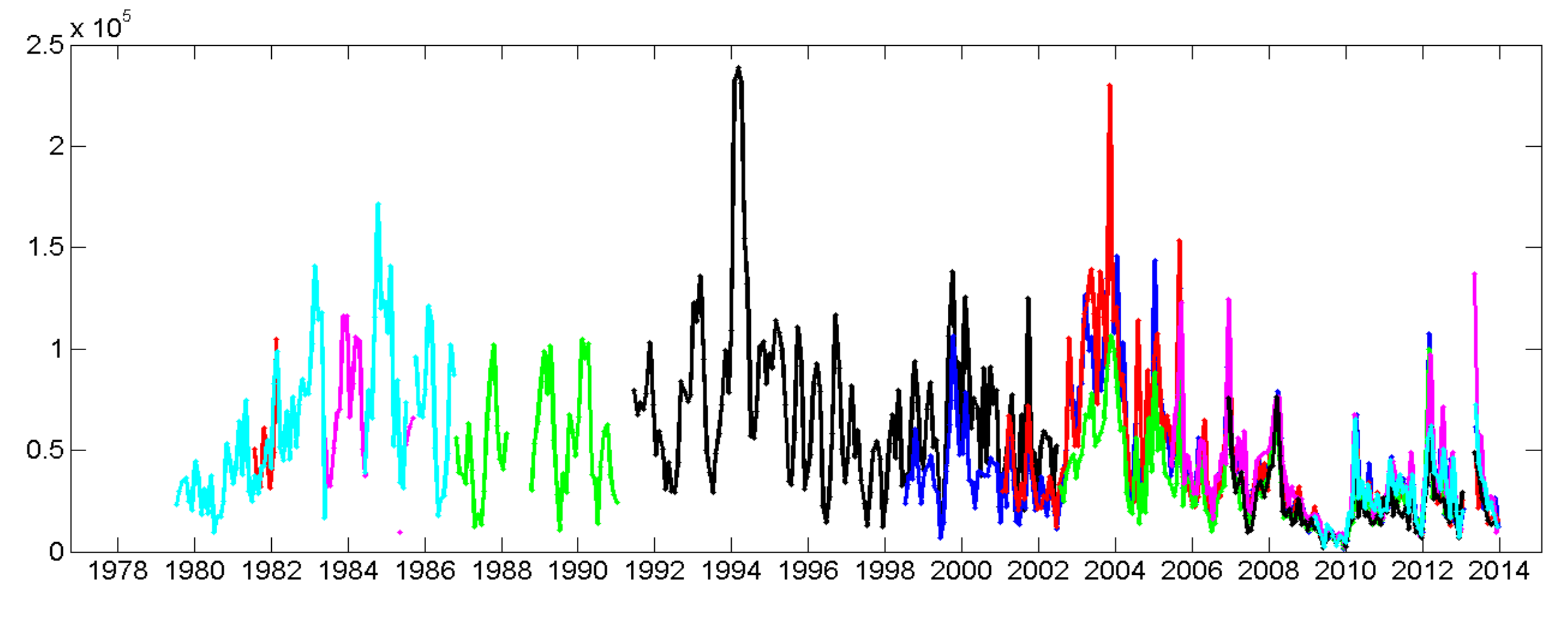
Corrected fluxes maximize in the declining phase of the cycle, verifying the connection to HSSs.

Minimum in 2009 found to be uniquely low.

T. Asikainen, K. Mursula, J. Geophys. Res., 117, A09204, 16 pages, 2012

Corrected electron fluxes

SEM-1 instruments — SEM-2 instruments



EEP flux follows the solar cycle variation of solar wind speed.

Maxima in the declining phase.

All time minimum in 2009. (SC24 may stay lower than other cycles)

T. Asikainen, K. Mursula, J. Geophys. Res.(A), 118, 6500–6510, 2013

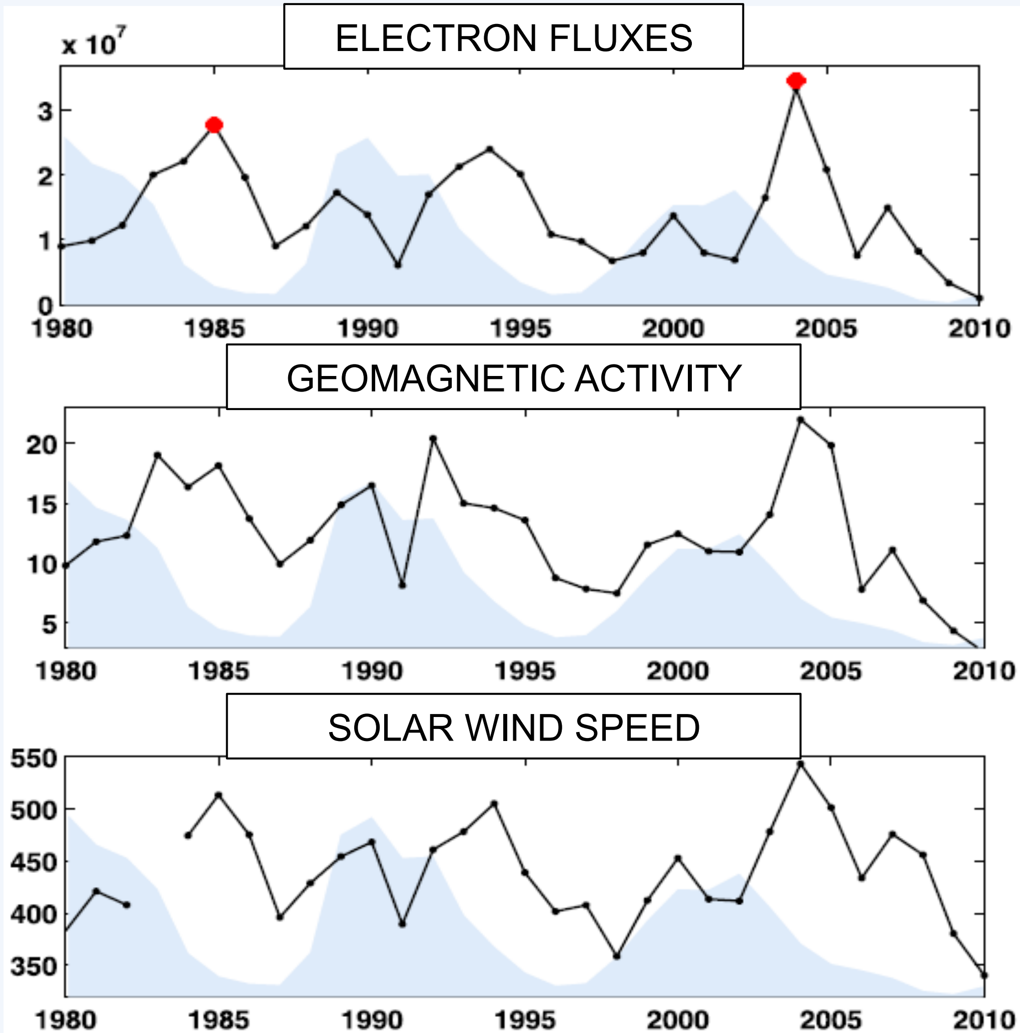
EEP, Ap, Vsw

Electrons between 30-100 keV (D1 channel) precipitate down to 75-90 km.

EEP peaks in the declining phase of the solar cycle

EEP correlates somewhat better with solar wind speed than with geomagnetic activity

(NOTE: EEP are slightly more energetic than typical auroral electrons)



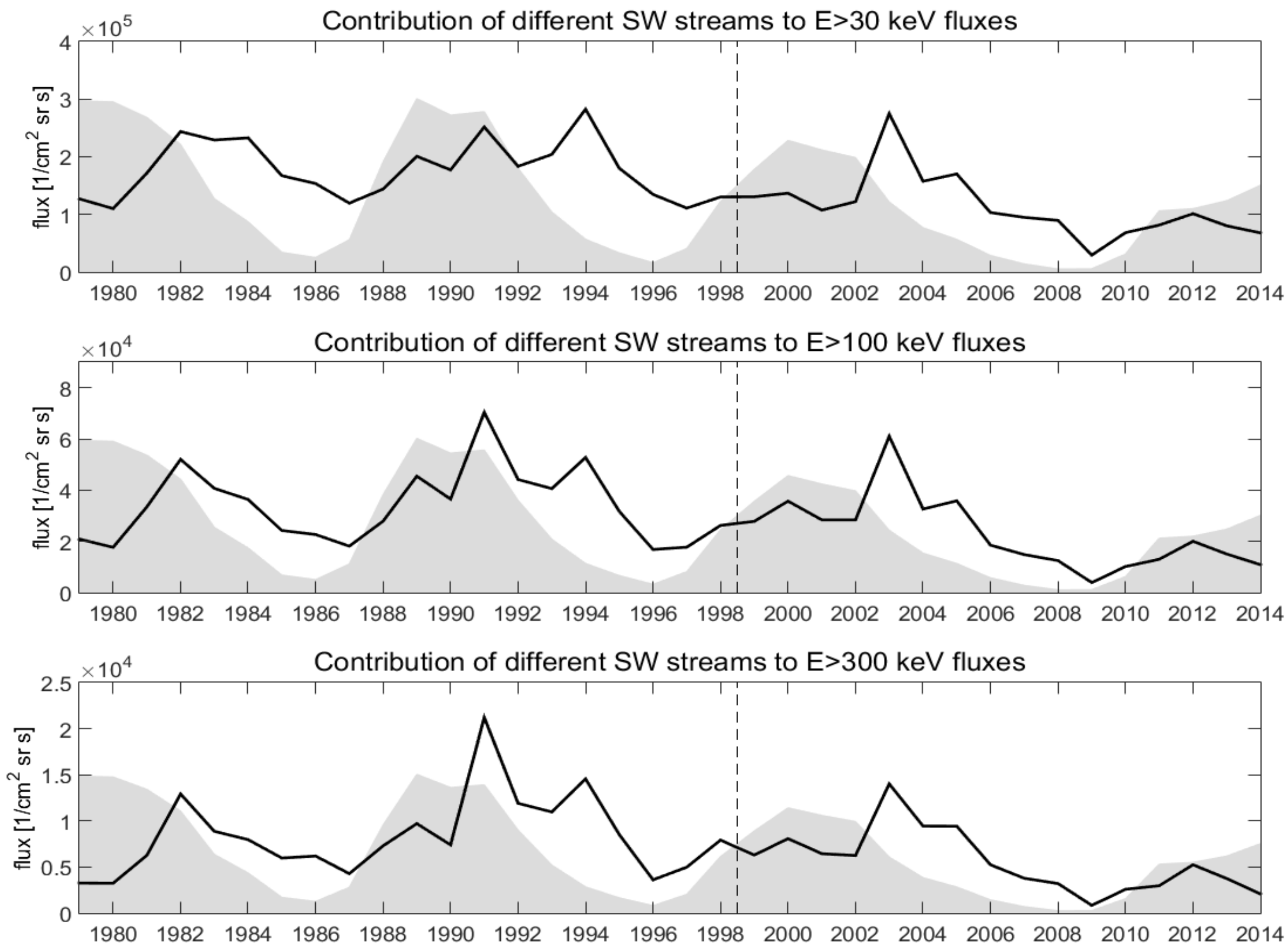
EEP: 3 MEPED channels

Electrons of >30keV measured by NOAA satellites since 1978

Fluxes now corrected to form a reliable homogeneous series

Energetic electron precipitation (EEP) peaks in the declining solar cycle phase.

Slight differences in relative peak heights in different energies.

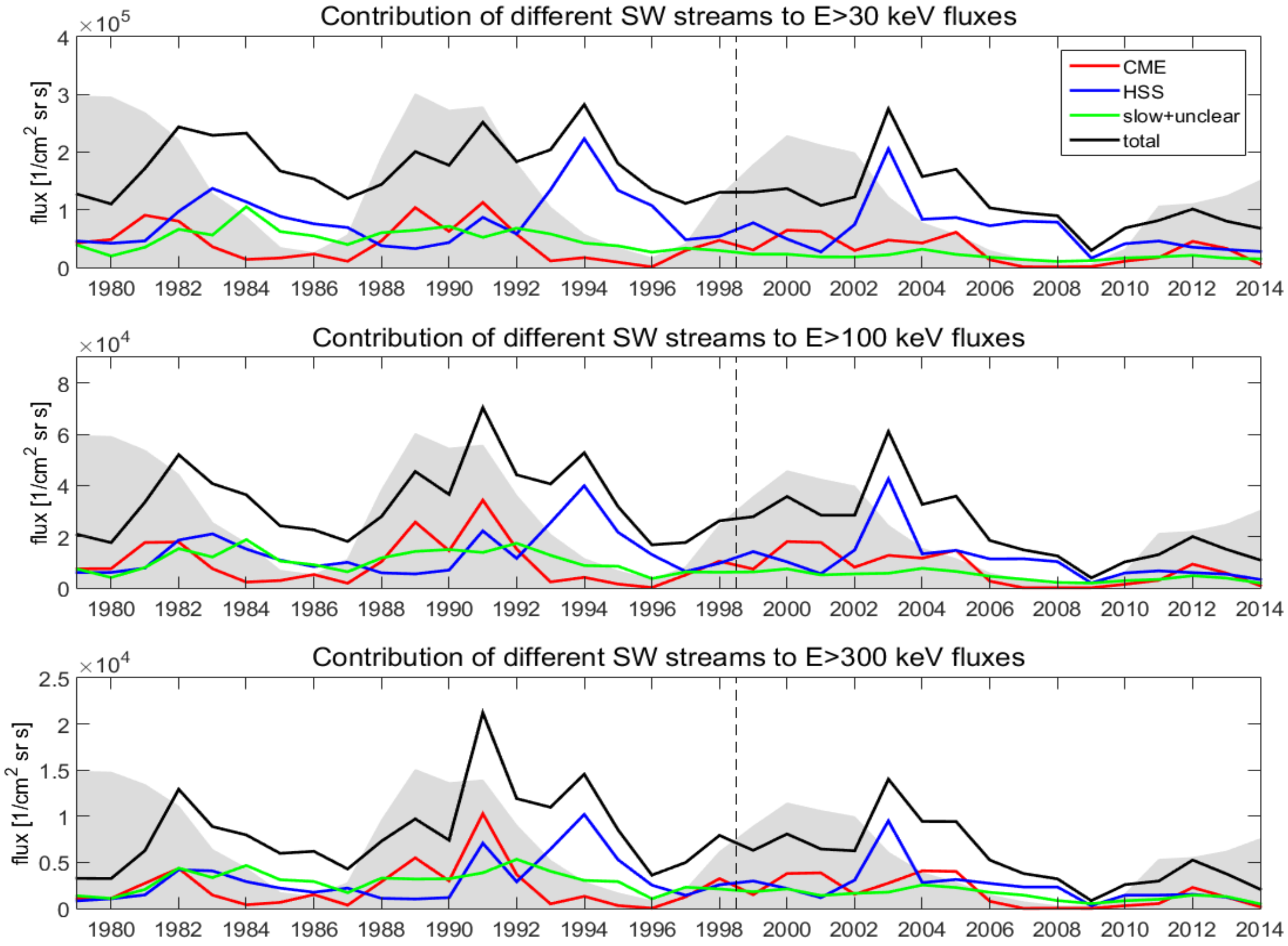


Contribution of different drivers to EEP

Contribution = (fraction of stream type) x (average flux during stream)

HSS contribution is typically largest and peaks in the late declining phase.

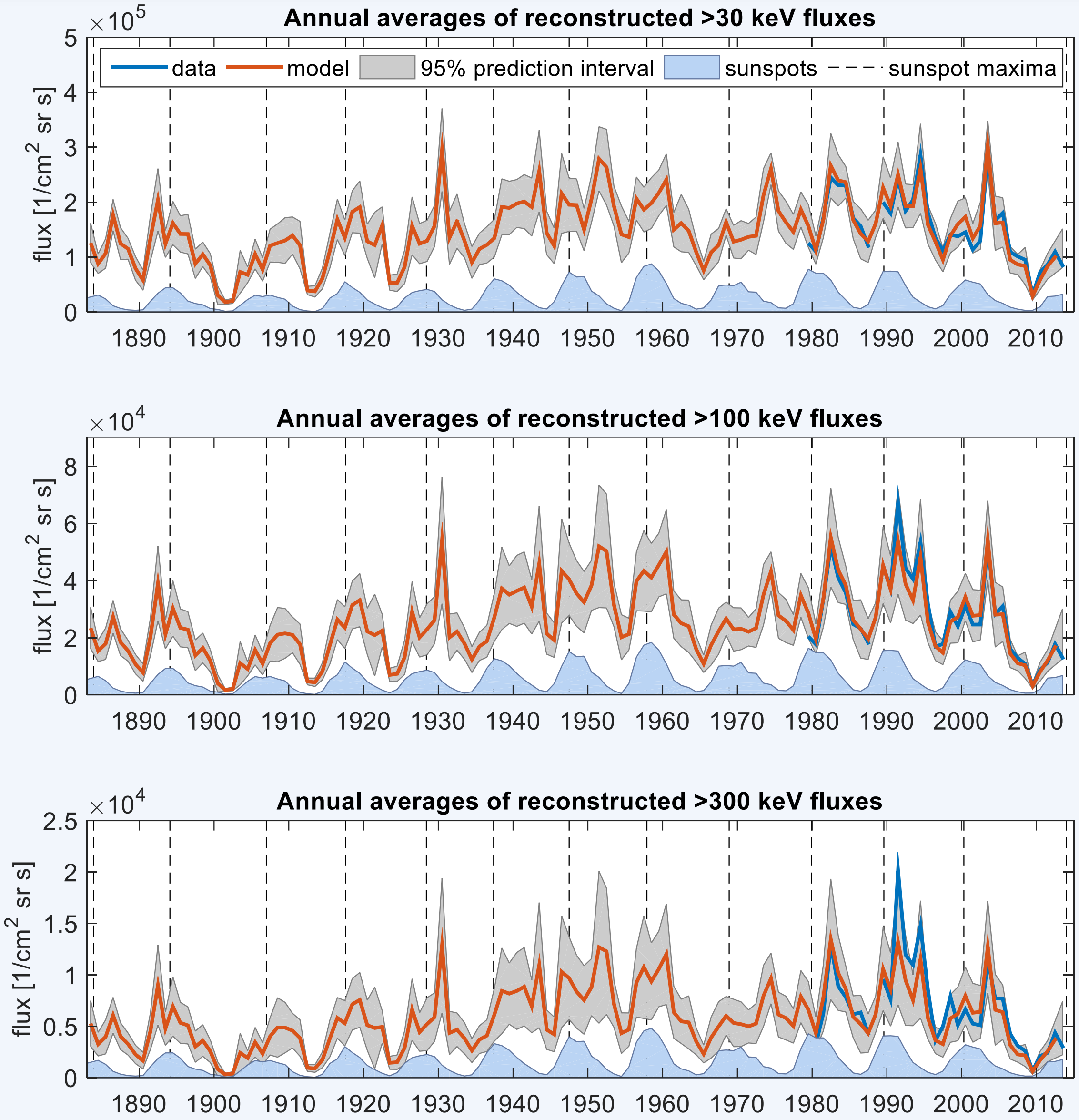
CME contribution dominates around solar maxima, but also seems to be high during the early declining phase.



Centennial EEP

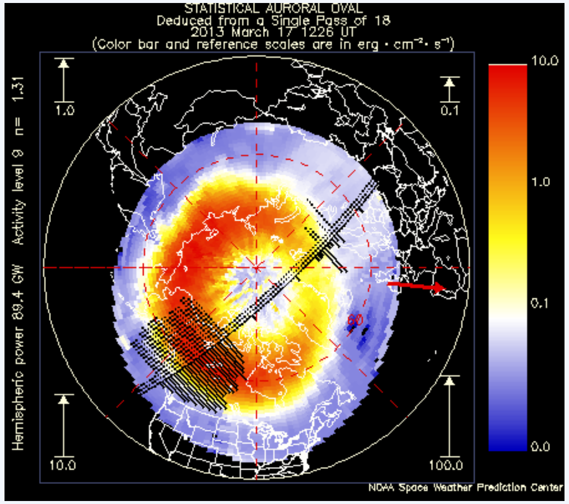
Modeled energetic particle fluxes using geomagnetic activity indices.

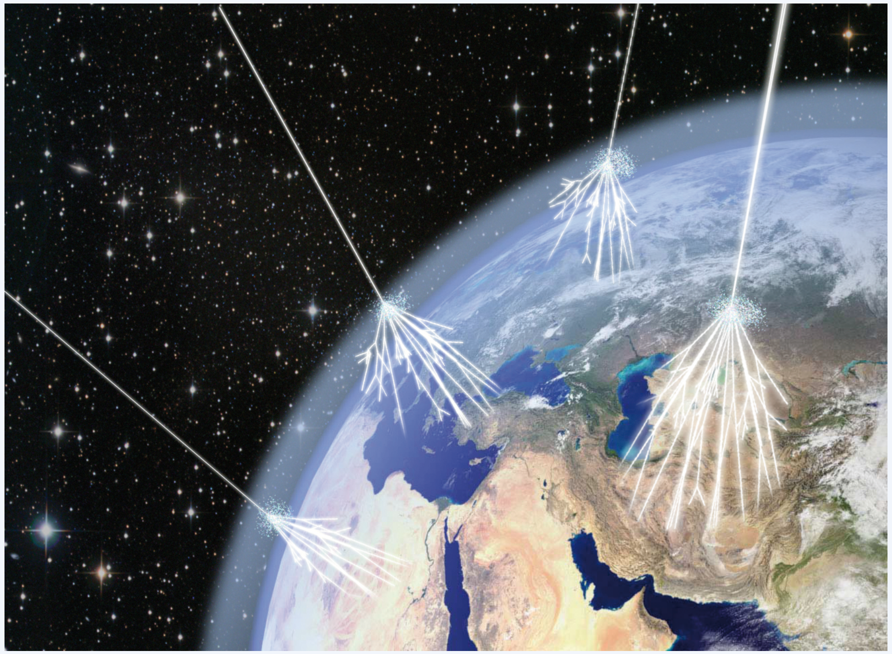
(Work under progress)

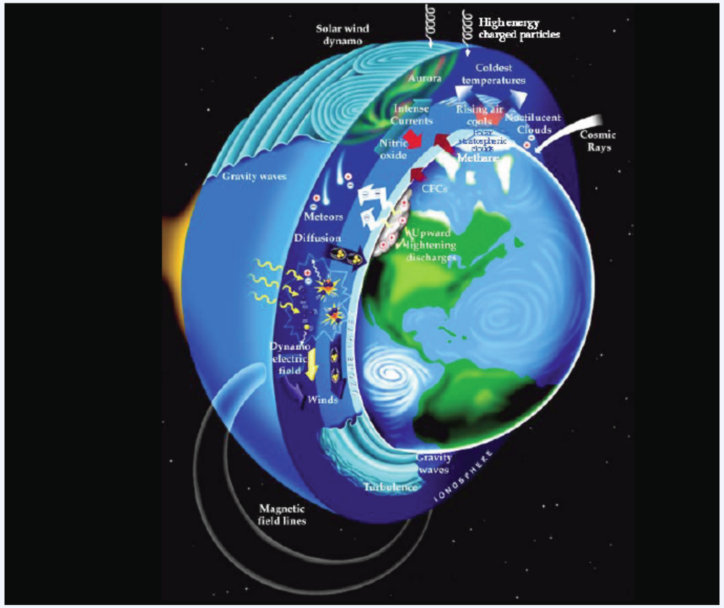


Energetic particle effects

- Energetic particles change atmospheric ionization and affect atmospheric chemistry.
- These changes may affect atmospheric thermal balance and circulation dynamics and may even couple to climate.







Atmospheric effects

Precipitation causes atmospheric ionization

➔ Changes in atmospheric chemistry, e.g., O_3 loss

➔ Changes in atmospheric dynamics ➔ Climate effects

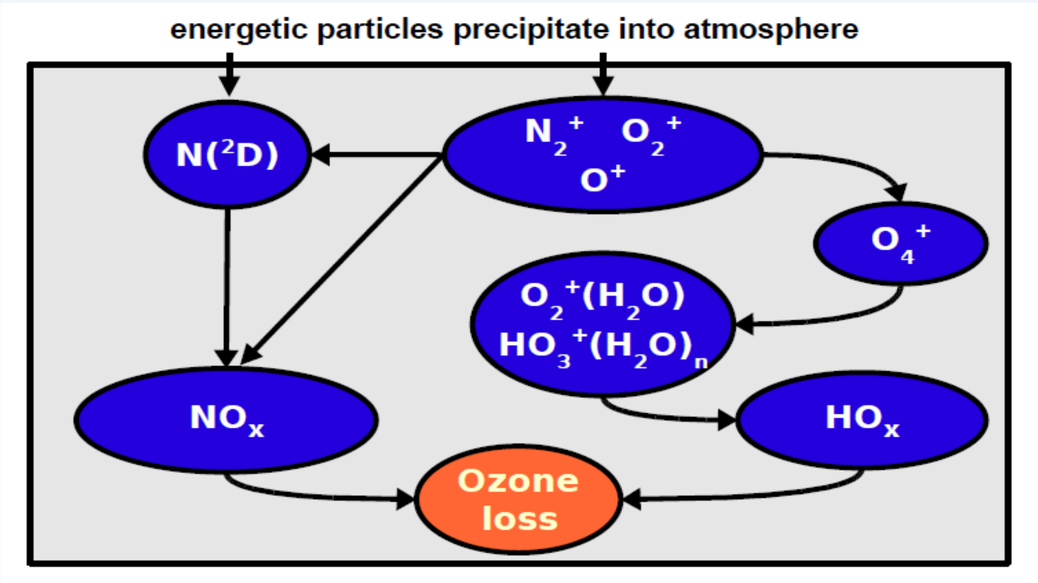
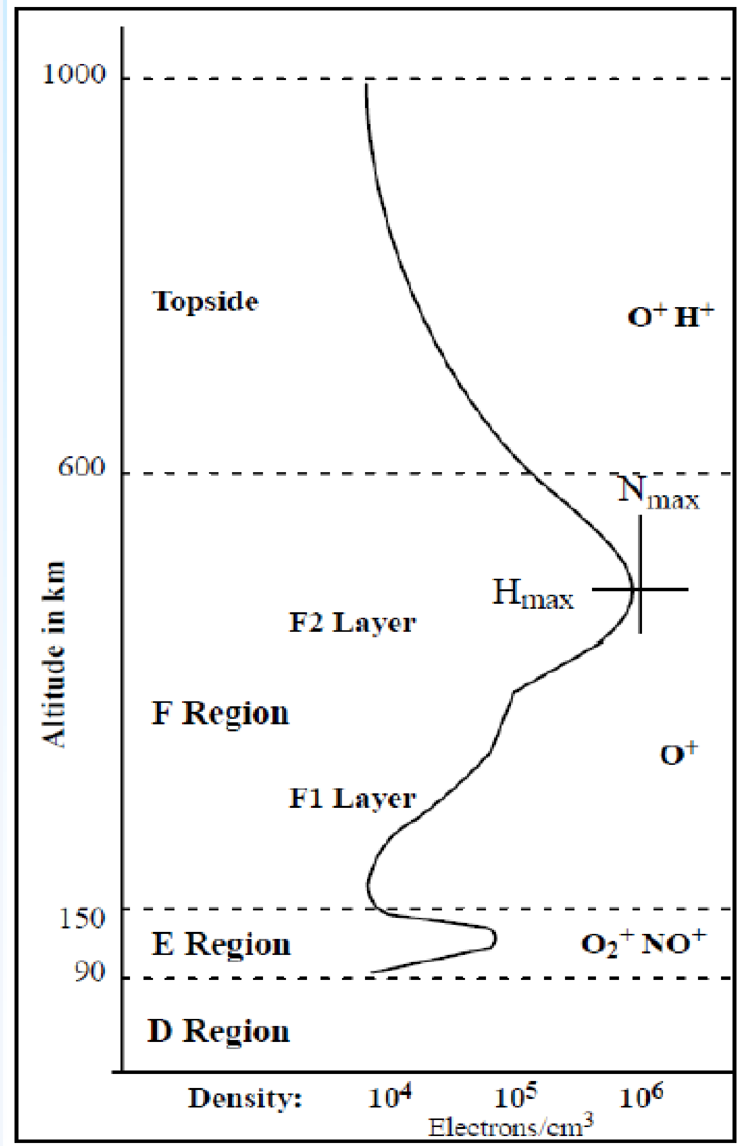
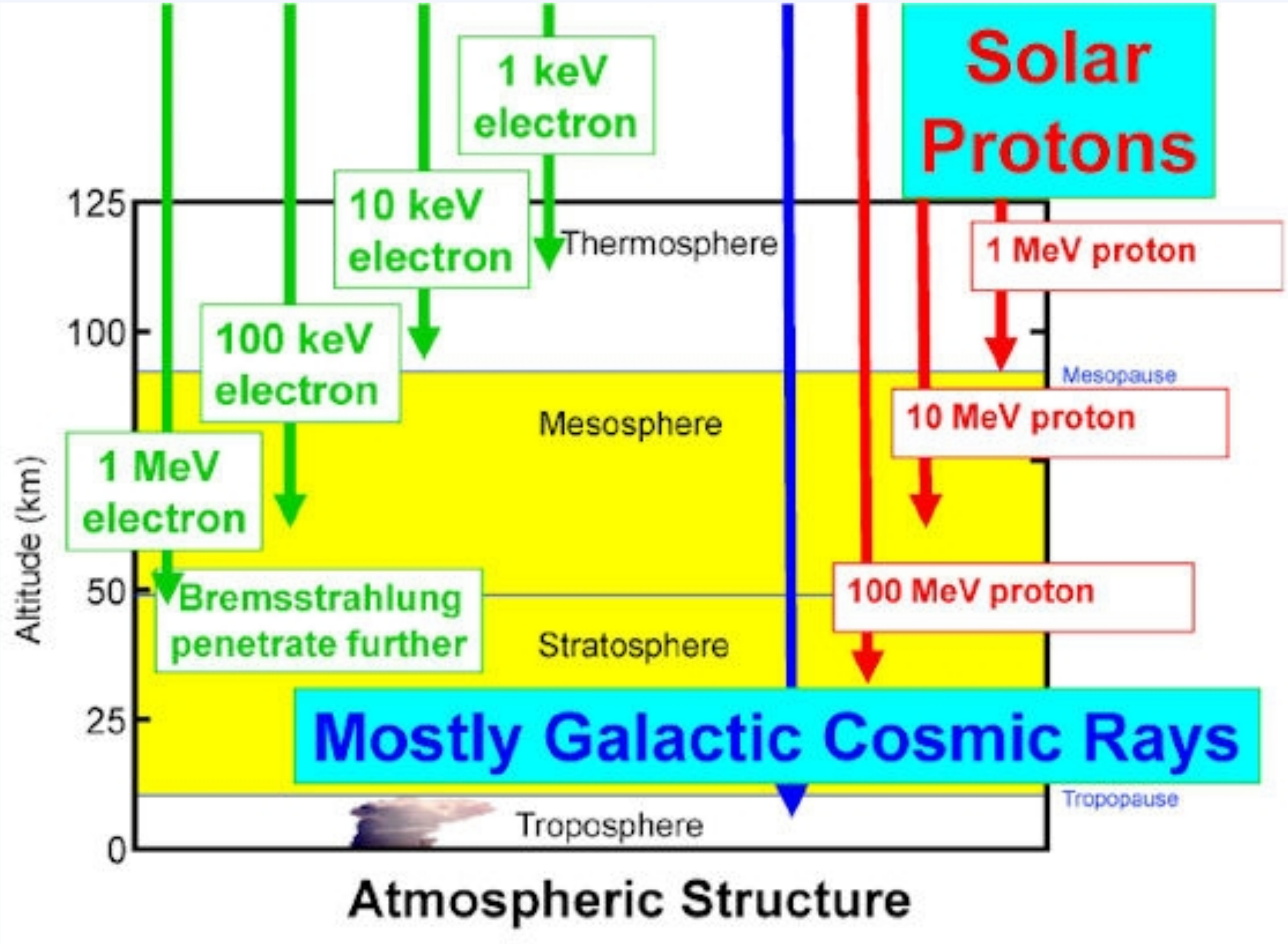


Figure courtesy of P.T. Verronen, FMI



Precipitation height vs. energy



SW and NAO

CONTEXT

Study the appearance of the NAO pattern in correlation between tropospheric high-latitude Winter temperatures and energetic particle fluxes

Use recently recalibrated homogeneous EEP fluxes during the last 35 years

Study QBO phase dependence

Study the occurrence of NAO pattern in different sunpot cycle phases over 130 years

Conclusion:
High-speed SW streams are a major cause to winter NAO via EEP

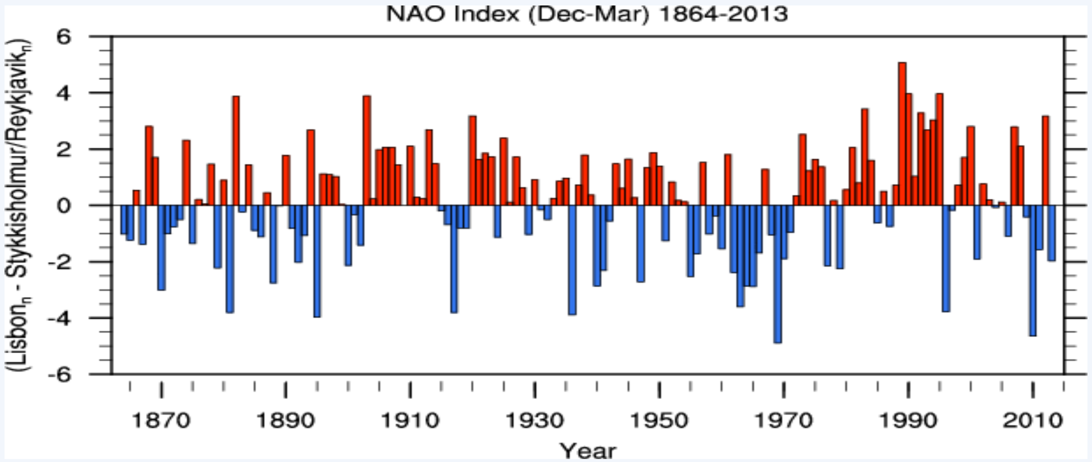
V. Maliniemi, T. Asikainen, K. Mursula and A. Seppälä, JGR (Atmos), 118, 6302-6310, 2013

V. Maliniemi, T. Asikainen and K. Mursula, JGR (Atmos), 119, 2014.

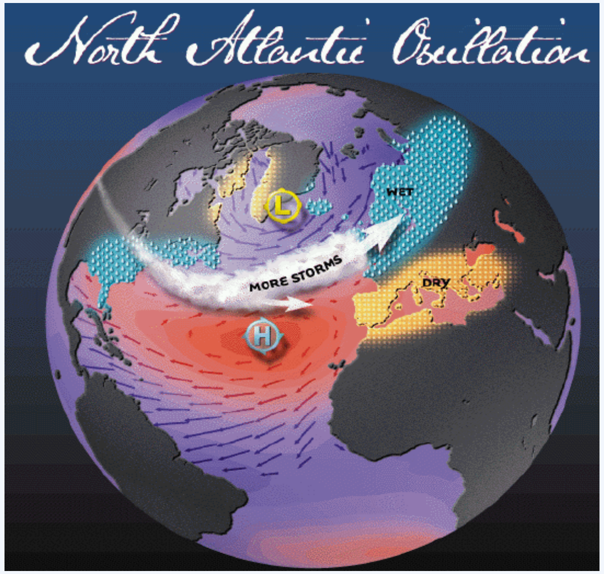
North Atlantic oscillation (NAO)

- Fluctuation of sea-level pressure difference between Iceland and Azores/Iberia

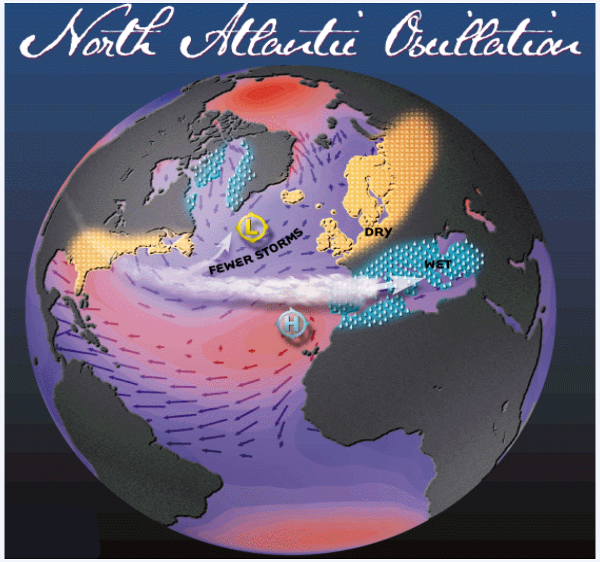
- NAO+ (positive phase of NAO)
  - ✓ Stronger pressure gradient => Increased meridional circulation
  - ✓ Warm & wet winters in Northern Eurasia and US east coast
- NAO- (negative phase of NAO)
  - ✓ Weaker pressure gradient => Reduced meridional circulation
  - ✓ Dry & cold winters in Northern Eurasia and US east coast



NAO+

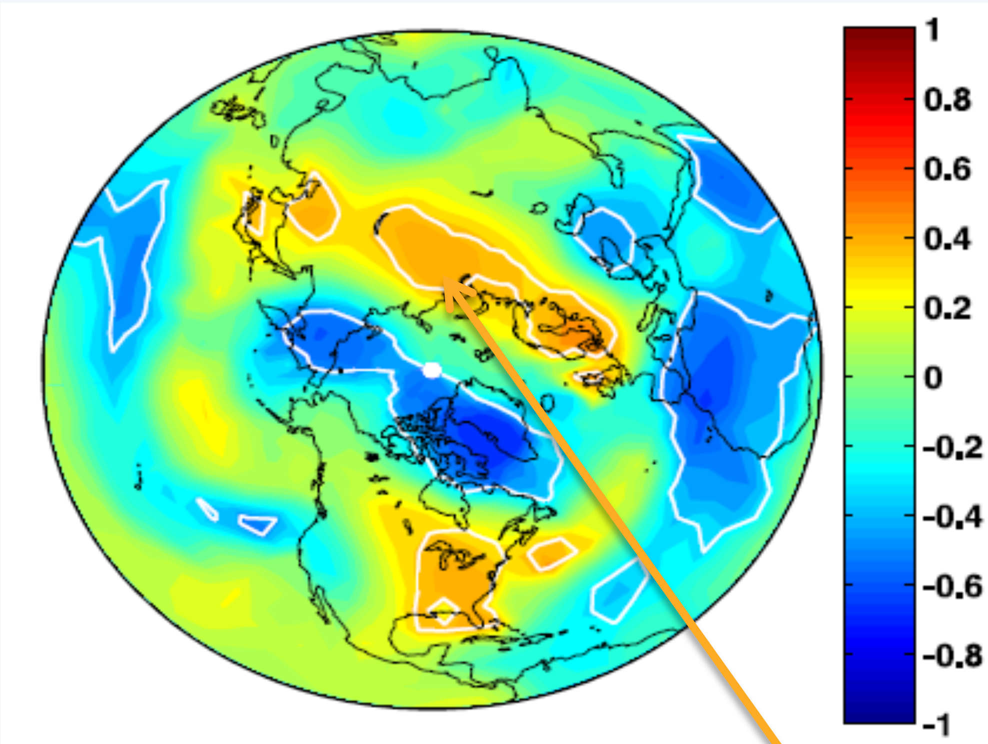


NAO-

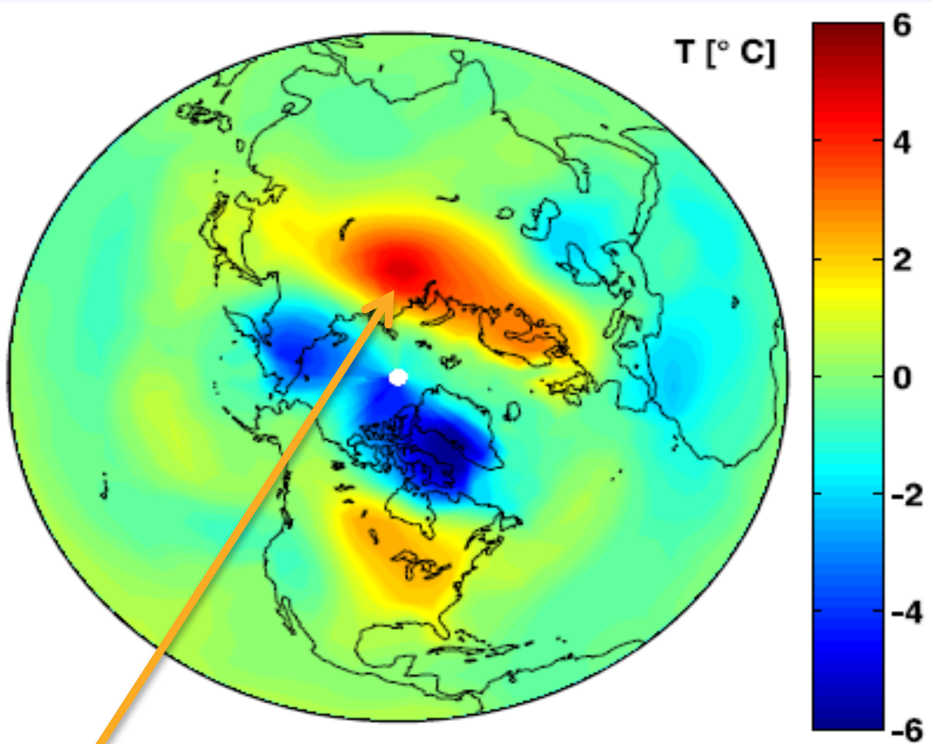


NAO and winter SAT (1980-2010)

Correlation

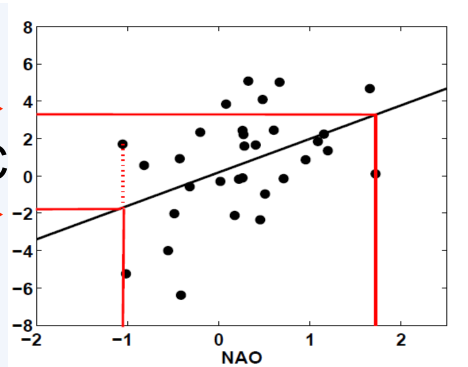


Range of SAT variation



cc=0.45

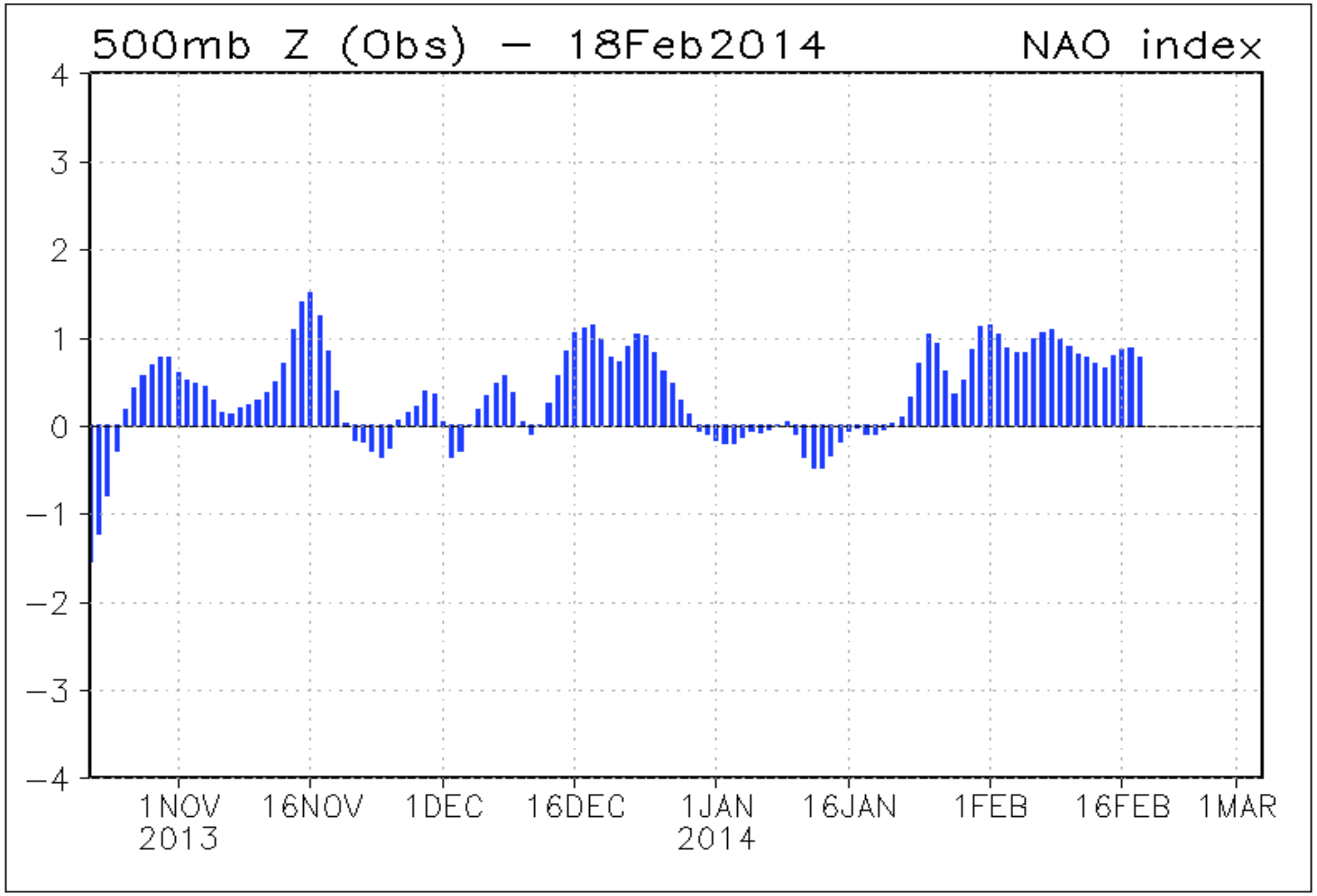
ΔT=5.0°C



Positive NAO pattern:
Warmer in North Eurasia,
colder in Greenland & N. Canada

Daily NAO index and melting of snow in Finland in Winter 2014

Very low snow levels in most of Finland inWinter 2014:
Two events of snowfall and snow melting



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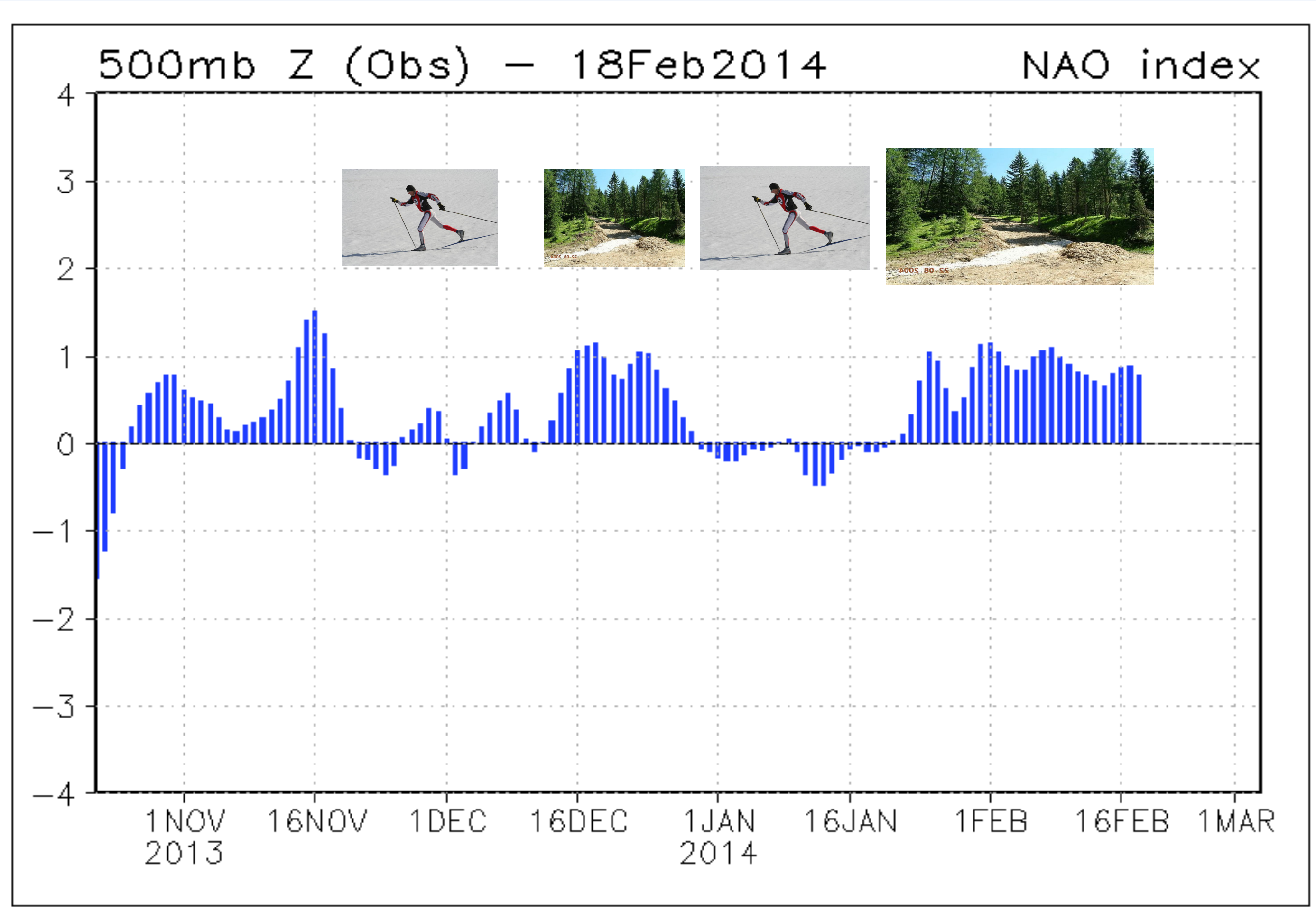


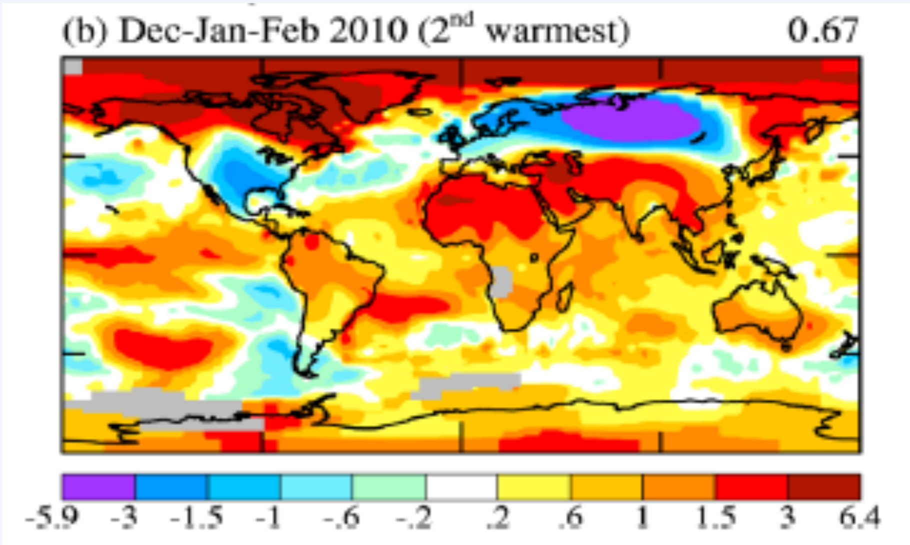
Surface air temperature (SAT) anomalies

We use NASA/GISS temperature record

Monthly geographic maps of temperature anomalies (relative to 1951-1980 base period) since 1880.

Constructed from ground station records, from analysis of sea surface temperatures for 1880-1981 and from satellite measurements of sea surface temperature from 1982 onwards.

We construct average winter temperature maps (Nov, Dec, Jan)



Hansen et al. (2010), Rev. Geophys

Polar vortex

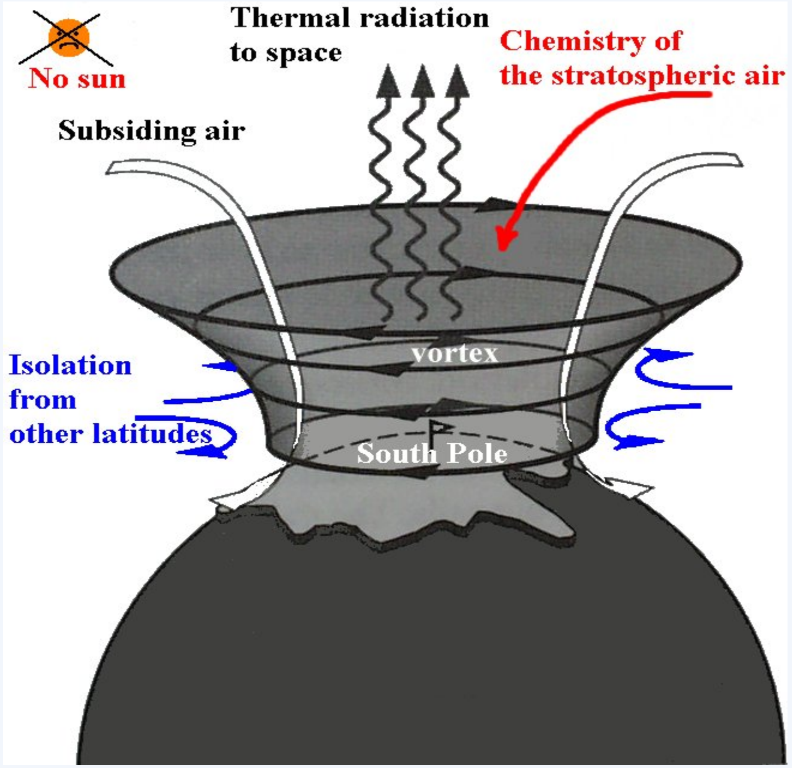
Forms during winter around the cold polar air mass.

Winds circulate counterclockwise around the low pressure center forming westerly zonal wind.

Polar vortex isolates the air within it from the surroundings

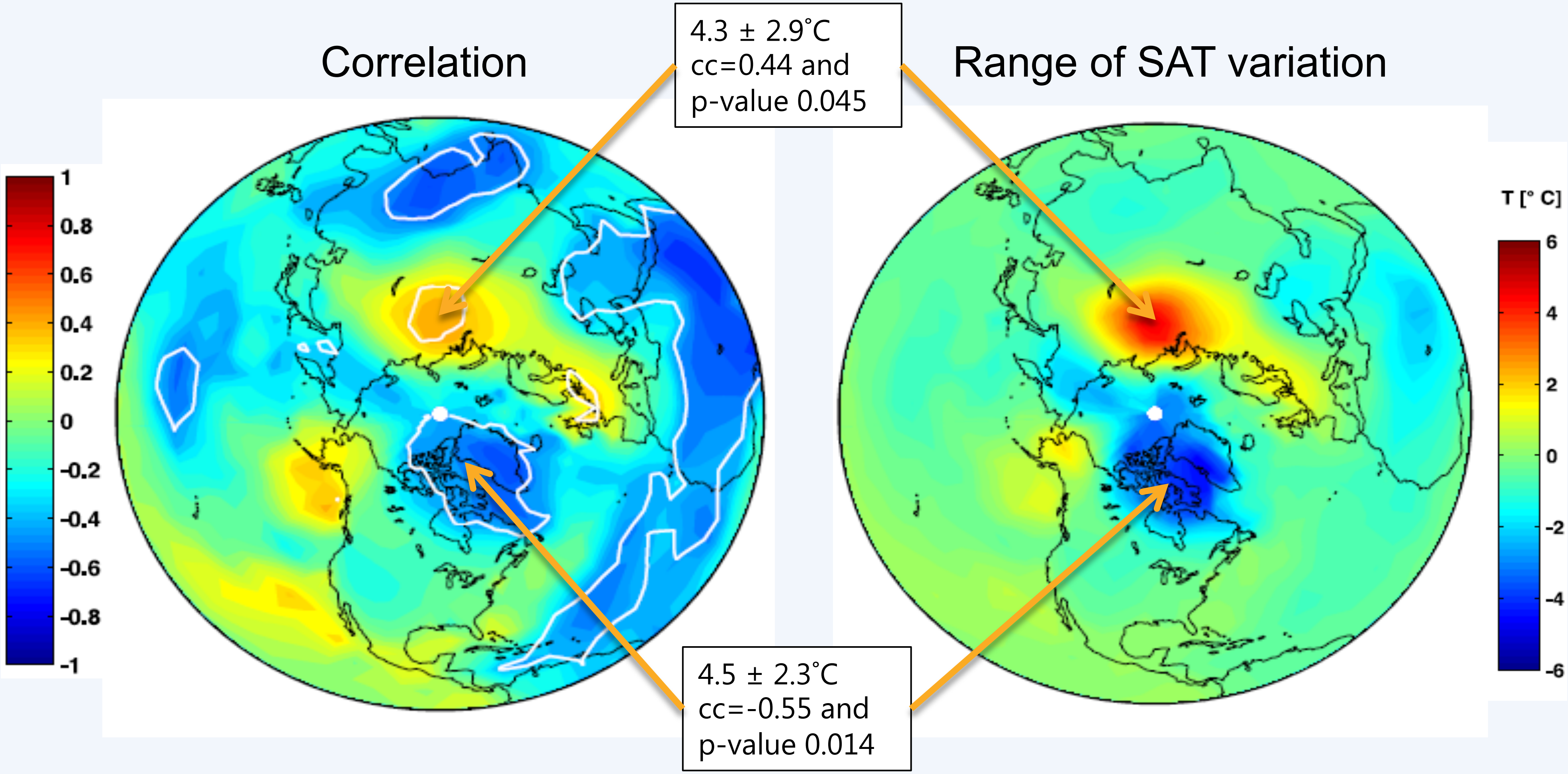
➔ Allows certain important chemical effects operate more effectively in the absence of sunlight in the isolated polar air

Sudden stratospheric warmings change the overall circulation and slow down the polar vortex (typically in Spring).



Polar vortex connects to NAO on ground

SAT and EEP (1980-2010)

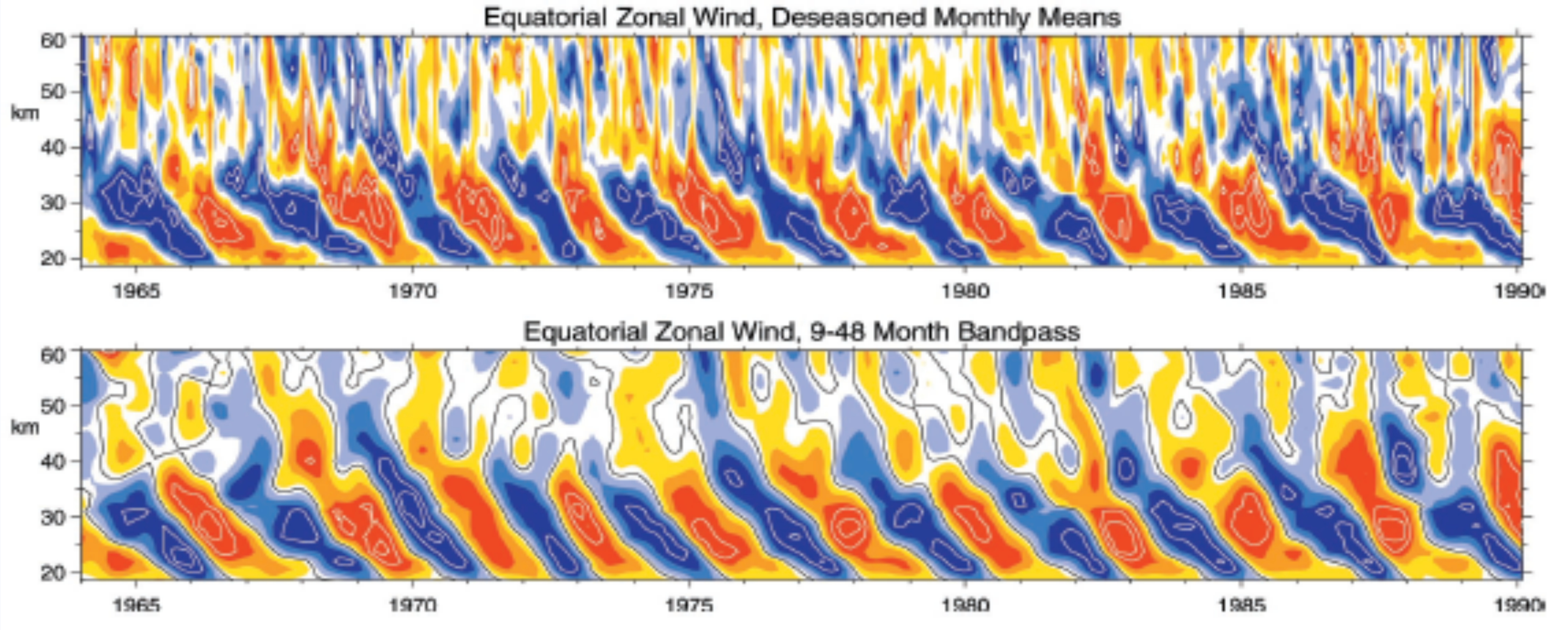


Correlation between EEP fluxes and SAT produces the NAO pattern.

Quasi-biennial oscillation (QBO)

About 28-month oscillation of equatorial stratospheric zonal wind

Affects the strength of the polar vortex

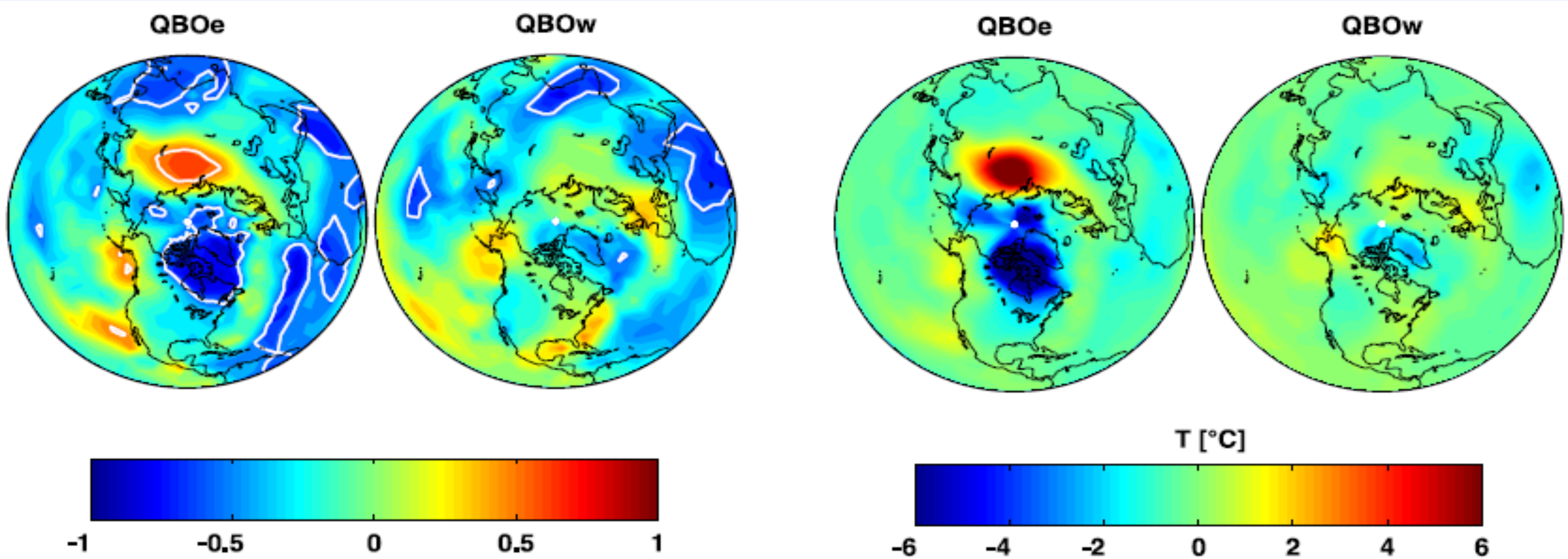


Baldwin et al. (2001), Rev. Geophys.

QBO phase separation

We divided the data into Easterly and Westerly QBO phases

EPP effect on NAO is only visible during Easterly QBO



ACADEMY
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UNIVERSITY of OULU
OULUN YLIOPISTO

FINNISH METEOROLOGICAL
INSTITUTE

Aalto University

Centennial study:
Separate sunspot cycle into phases

Solar cycle phases

We study the connection between NAO and wintertime surface temperatures over 1880-2009

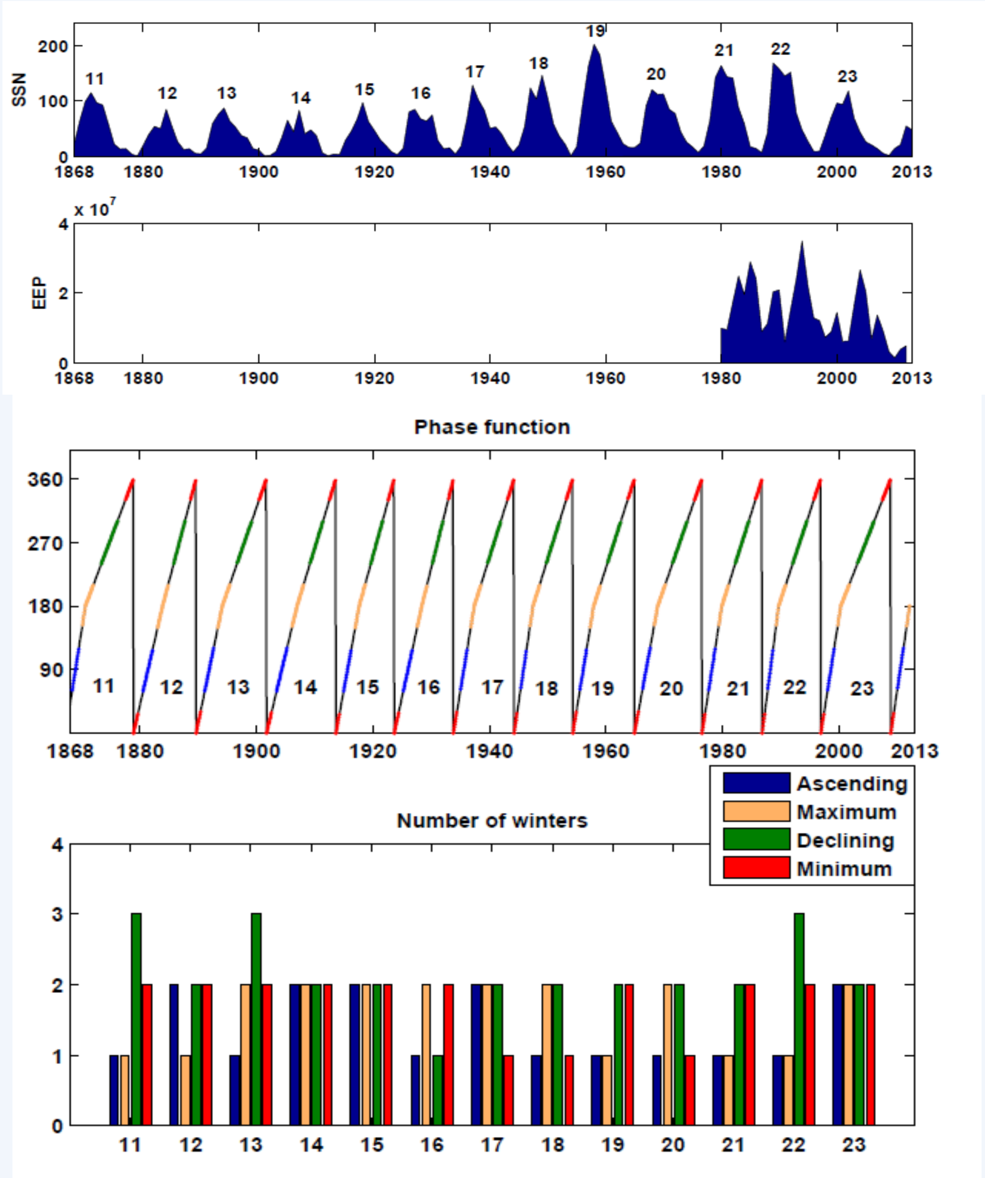
BUT: No direct EEP observations !

We separate the data to different phases of the sunspot cycle

Four separate phases with a 60° wide window in the phase function (ascending phase centered at 90°, maximum at 180°, declining at 270° and minimum at 360°/0°).

In total:

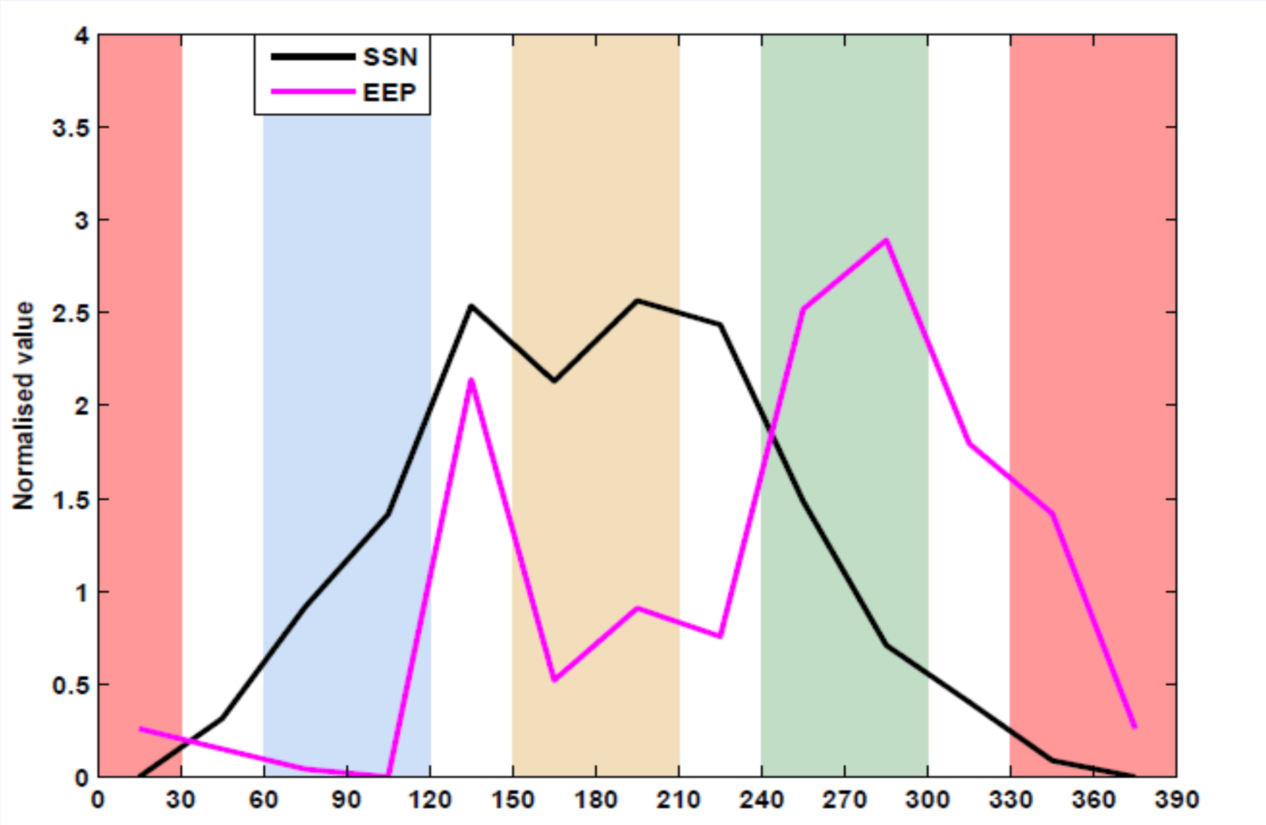
- Ascending phase: 18 winters
- Maximum phase: 21 winters
- Declining phase: 28 winters
- Minimum phase: 23 winters



Solar cycle phases

Four cycle phases denoted as vertical stripes of different colour.

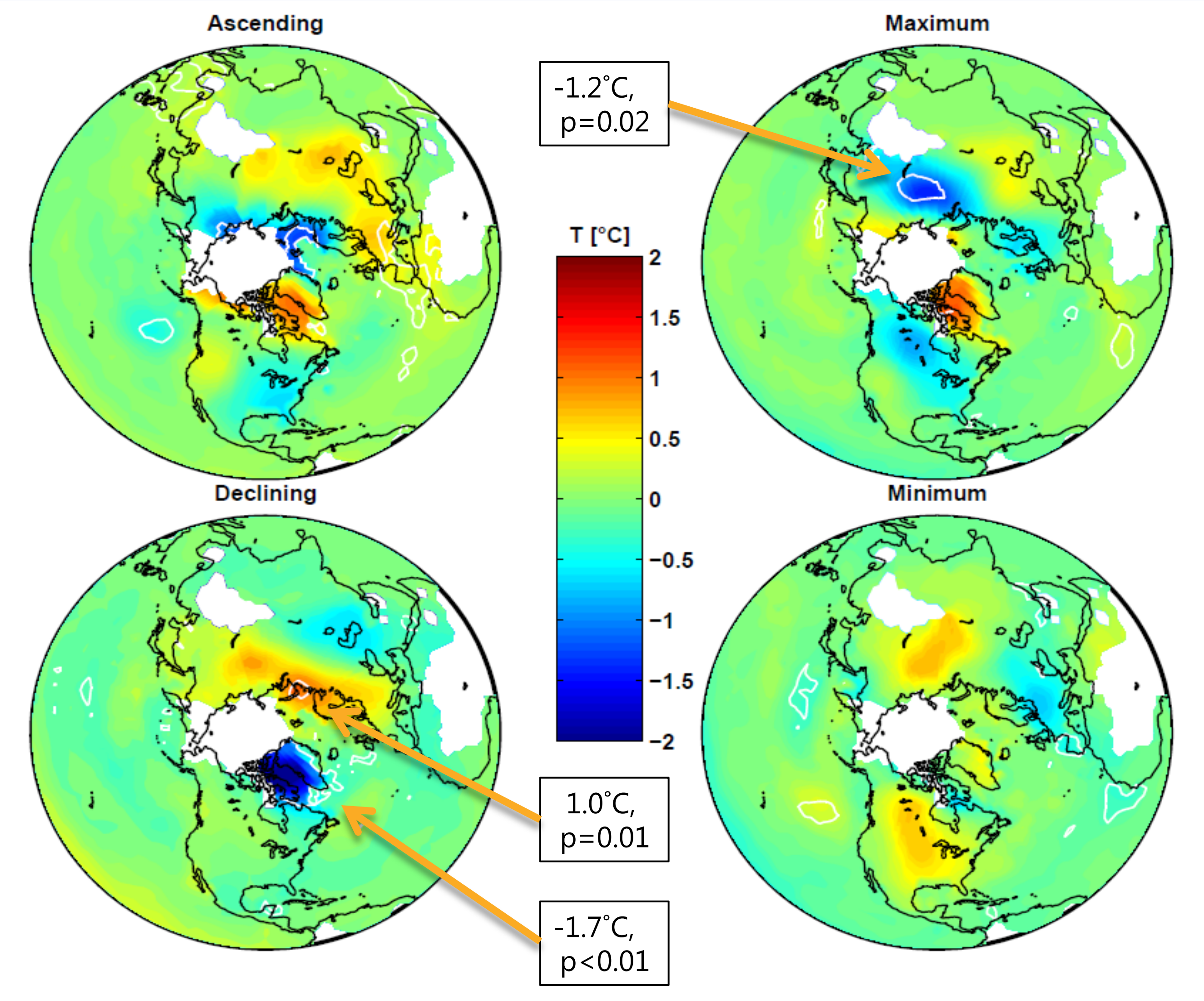
Lines show mean sunspot cycle and EEP flux variation with maximum in the declining phase of the solar cycle.



Winter temperature anomalies during the four cycle phases (1880-2009)

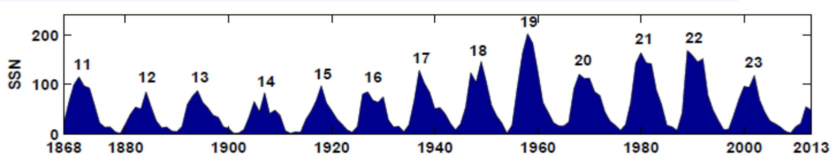
Temperature pattern in the declining phase greatly resembles the temperature pattern during positive NAO.

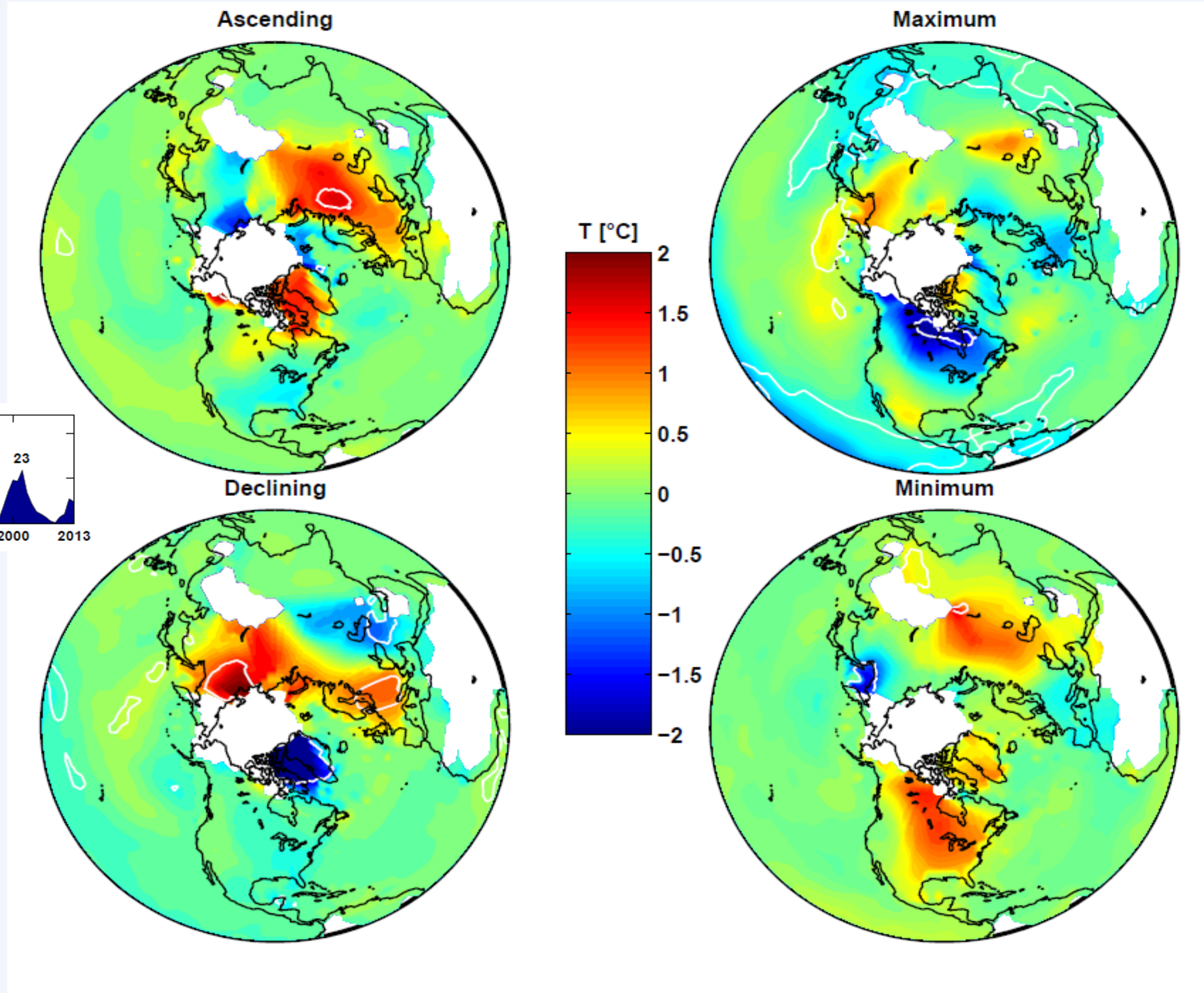
Field signifigance test yields a statistically significant result only in the declining phase (less than 70% in other phases)



Temperature anomalies during weak cycles 12-15 (1880-1925)

This relation is also true during the weak sunspot cycles 12-15.



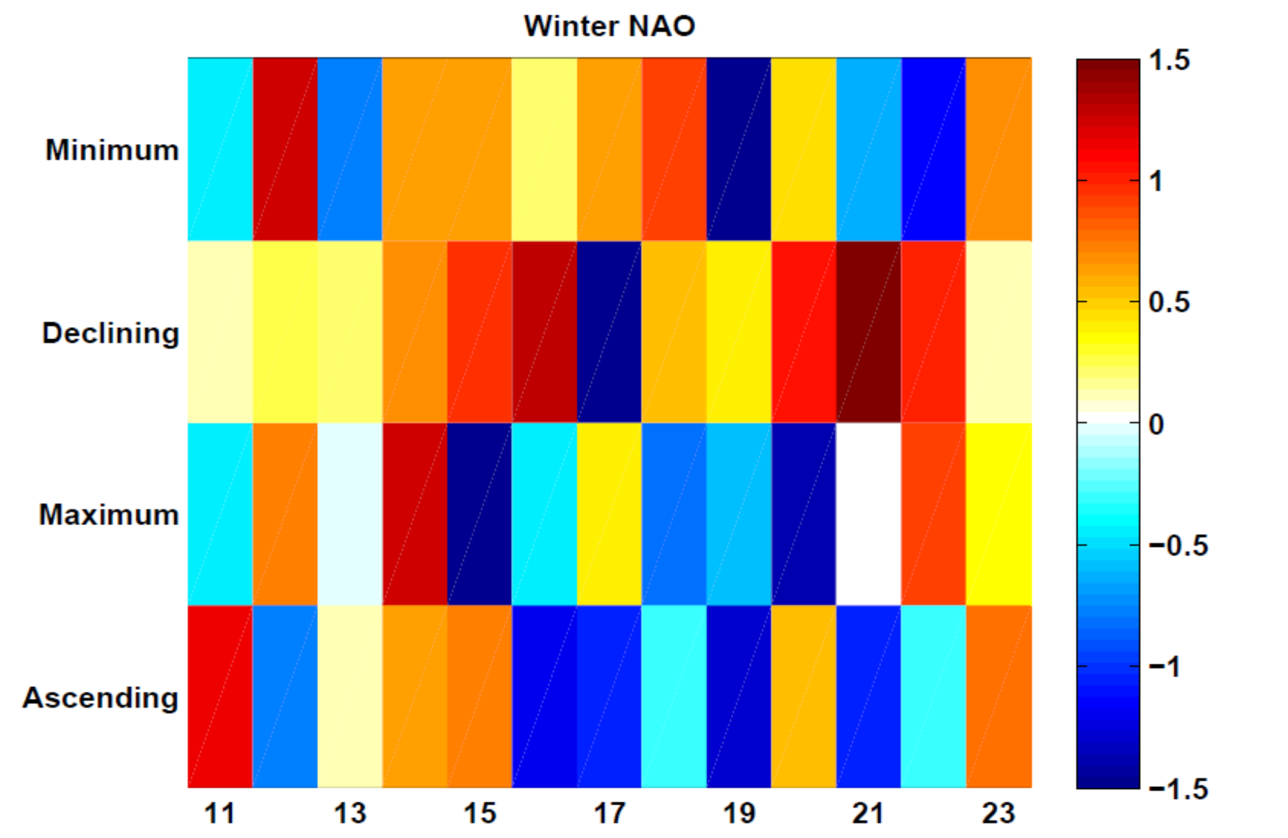


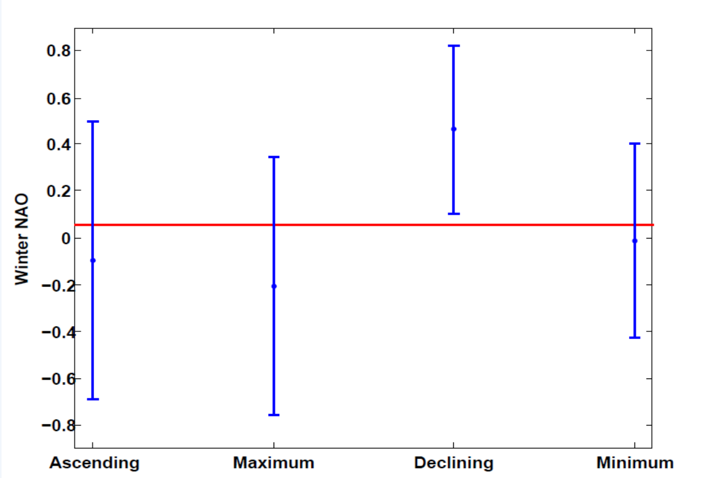
Field significance 93% in the declining phase (less than 70% in other phases)

NAO during different cycle phases (1880-2009)

Only the declining phase systematically produces positive NAO

Wintertime NAO is significantly different (positive) from the long term mean only in the declining phase.

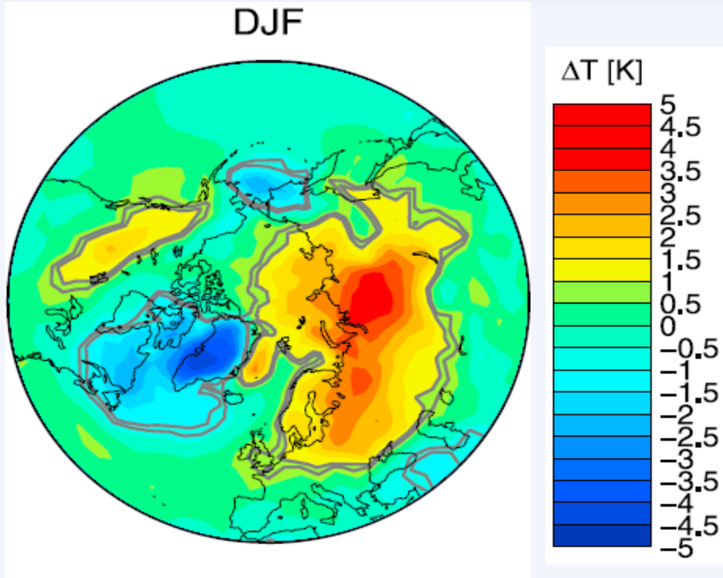




Particle effects on winter NAO

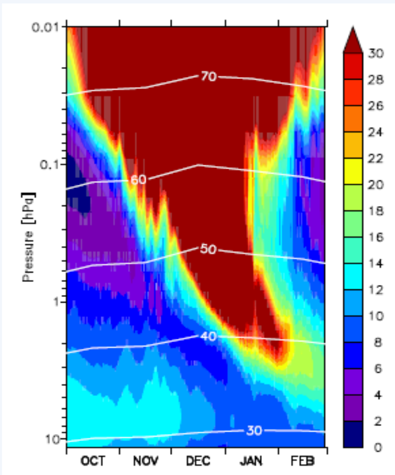
- Connection between EEP fluxes and winter time tropospheric conditions

- Particle precipitation into MLT region
  ➔ Enhancement of NO_x and Ho_x
  ➔ Ozone destruction
    ➔ radiative cooling of stratosphere
    ➔ Increased meridional gradients&circulation
    ➔ positive NAO and stronger polar vortex
    ➔ Faster descent of NO_x
  ➔ More ozone destruction (FEEDBACK LOOP)

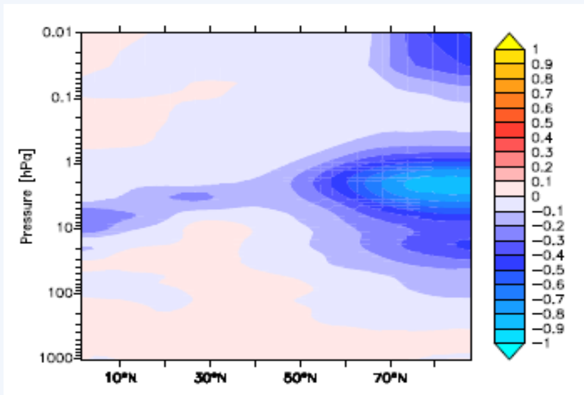


Seppälä et al. (2009), JGR

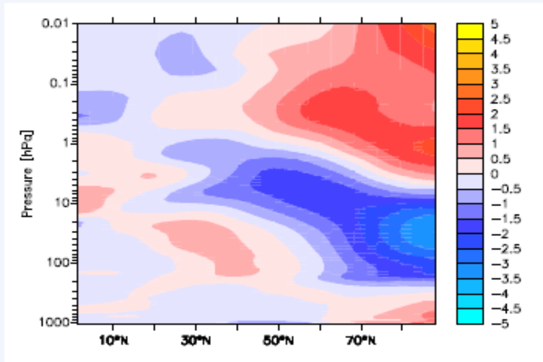
NO_X



O_3

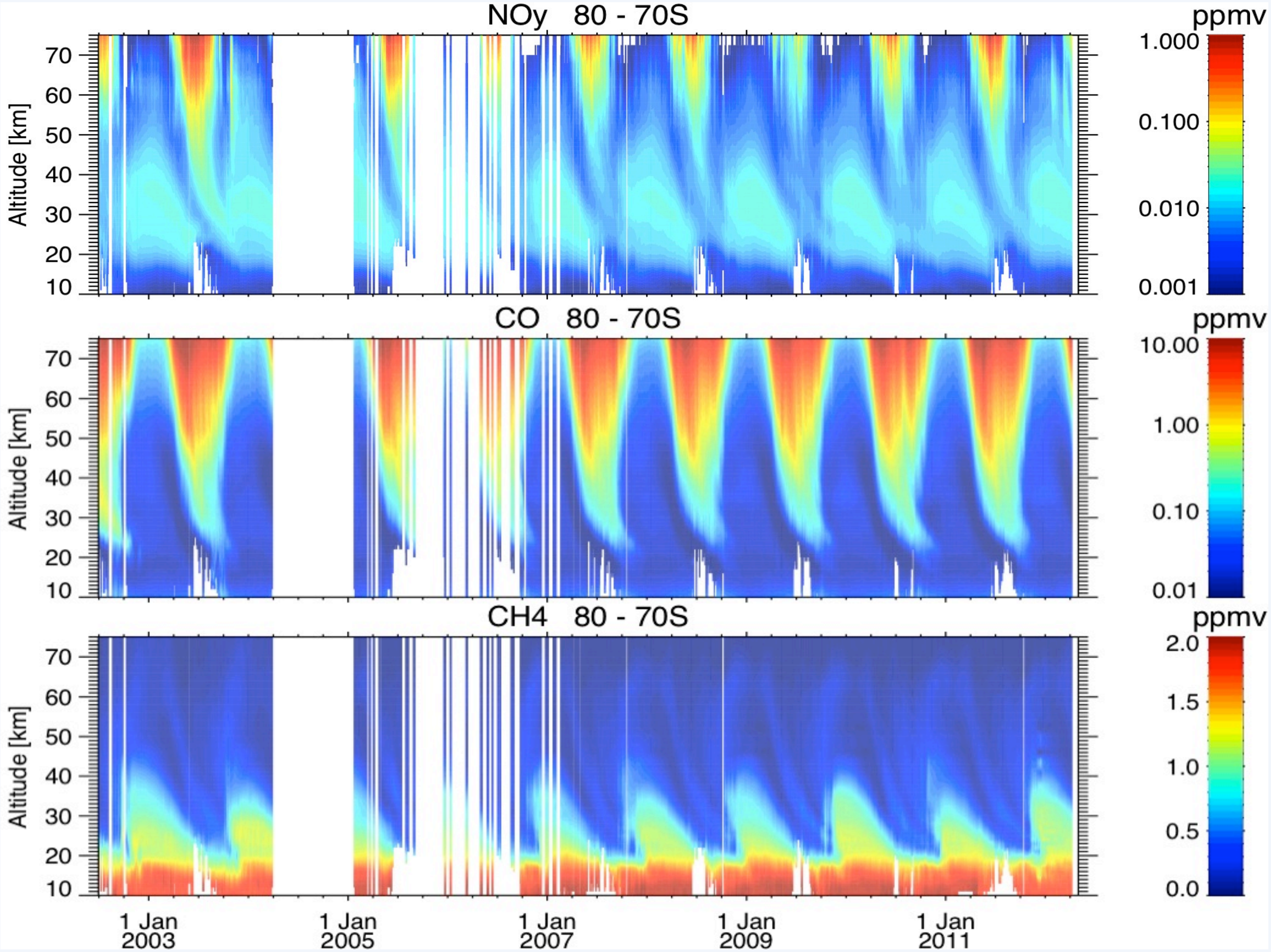


ΔT



Baumgaertner et al. (2011), ACP

NOy, CO and CH4 molecules



NOy-molecules are produced in the upper atmosphere by particle precipitation.

They are seen to descend to stratosphere within the polar vortex.

They destroy ozone in the PV boundary.

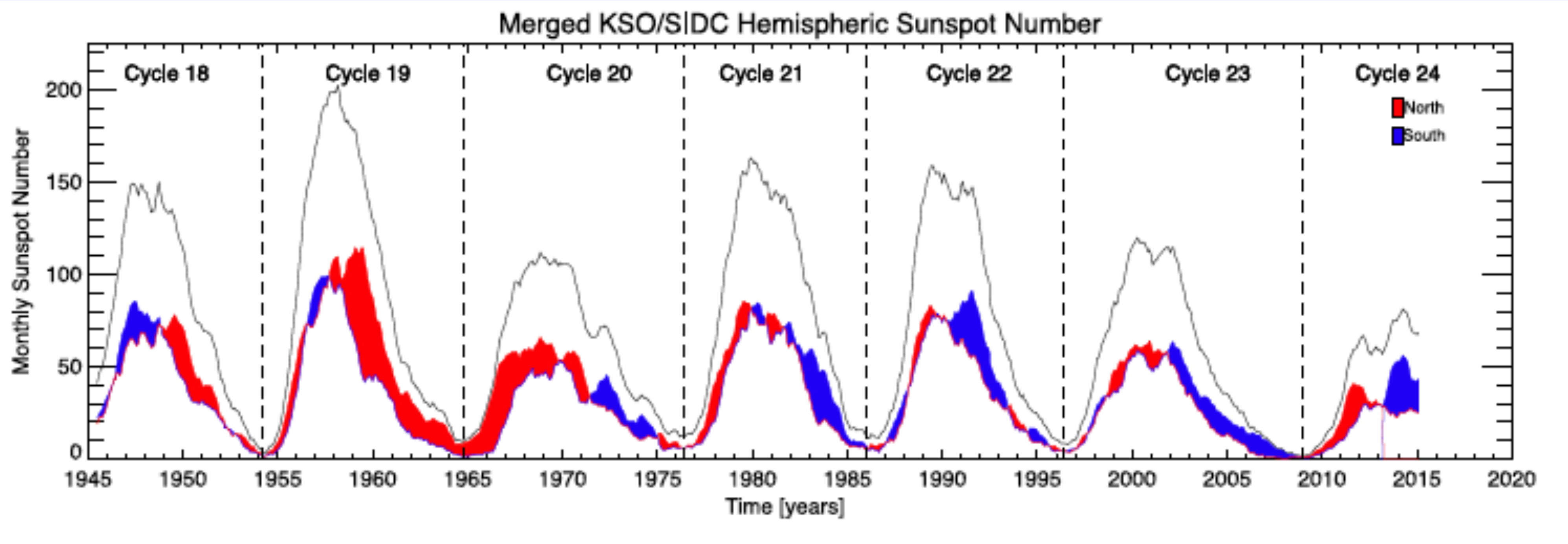
Note weak descend in 2009 !

Hemispheric asymmetries

Hemispheric asymmetry in sunspots

Sunspot activity is known to be north-south asymmetric
- Northern and southern hemispheres are connected but not tightly
- Polar fields develop slightly differently in the two hemispheres

Some systematic pattern suggested, at least for recent cycles.



Asymmetry in the heliosphere

Heliospheric current sheet (HCS) is the heliospheric magnetic equator that separates the two magnetic hemispheres (HMF sectors).

Because of its wavy structure, HCS is also called the ballerina skirt.

In the solar corona HCS appears as the neutral line.

HCS is found to be southward shifted by about 2 degrees during roughly three years in the declining phase (the so called bashful ballerina phenomenon).

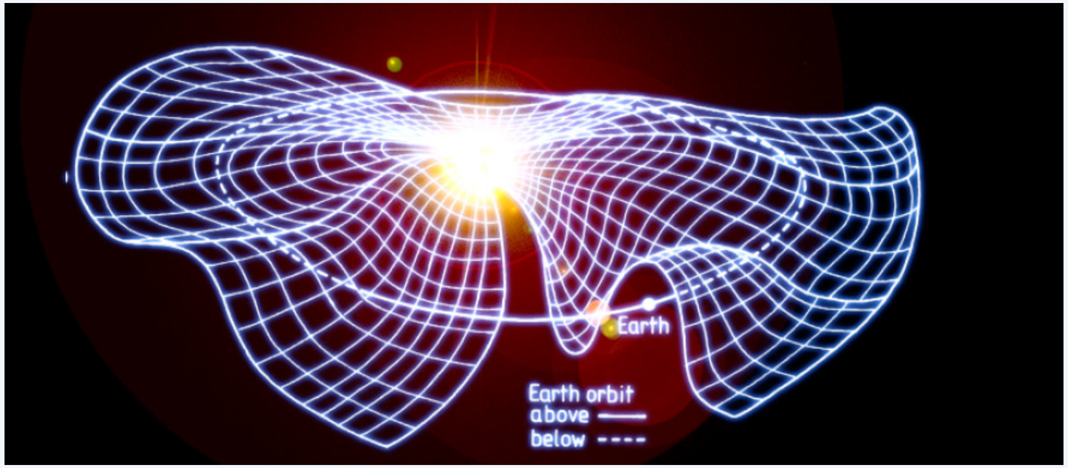
By now verified by several data sets and different methods: OMNI, WSO/MWO/KP, Ulysses, Pioneers, Voyagers,..

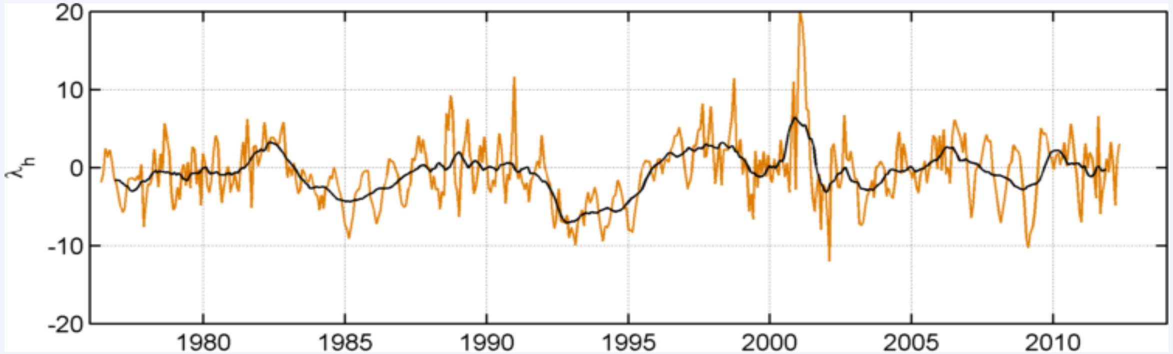
Asymmetry extends over very wide radial distances (probably the whole heliosphere)

Mursula and Hiltula, 2003

Bashful ballerina

HCS is southward coned by about 2 degrees during 3 years in the declining phase of solar cycle: Bashful ballerina





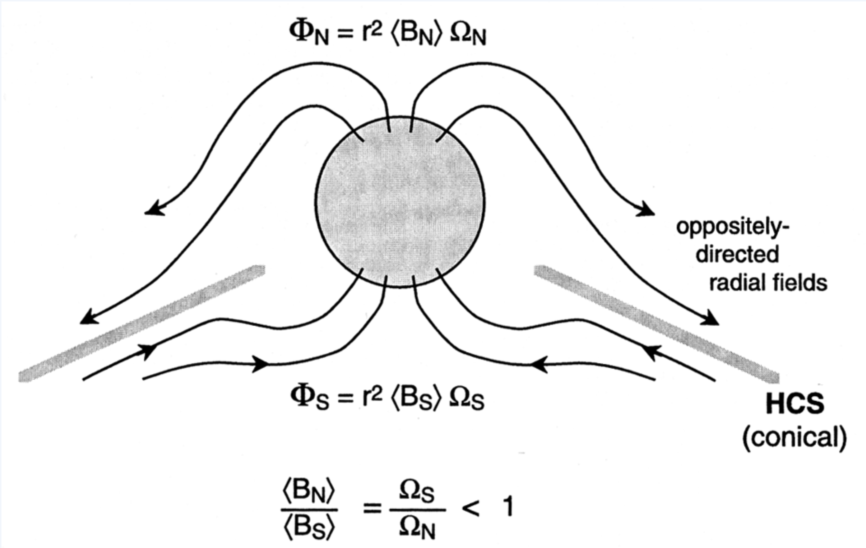
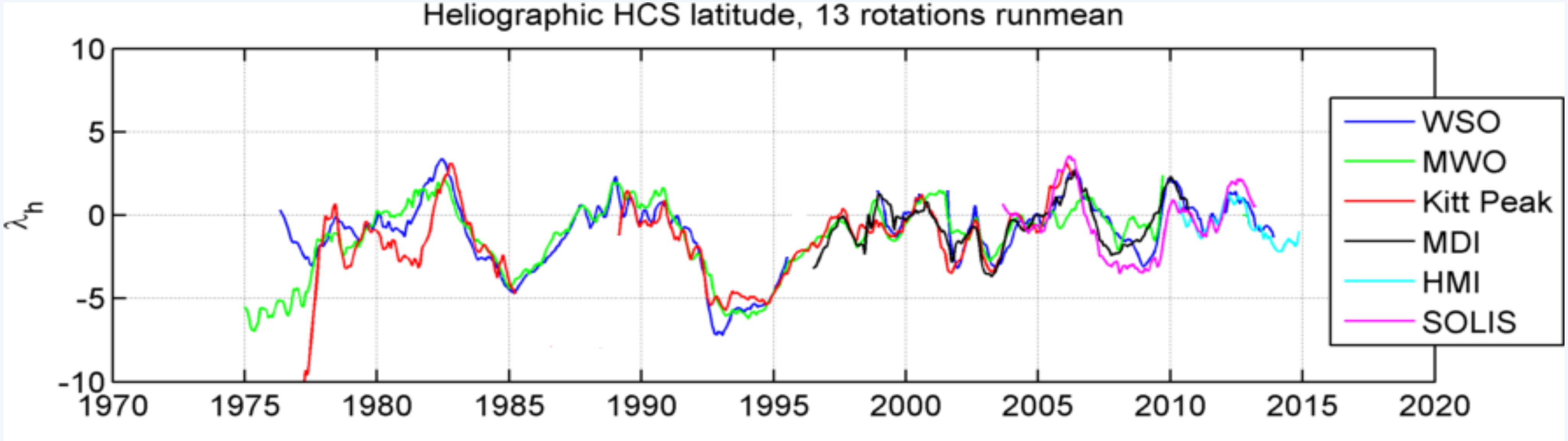


Figure: Smith et al., ApJ, 2000

HCS shift acc to solar observations



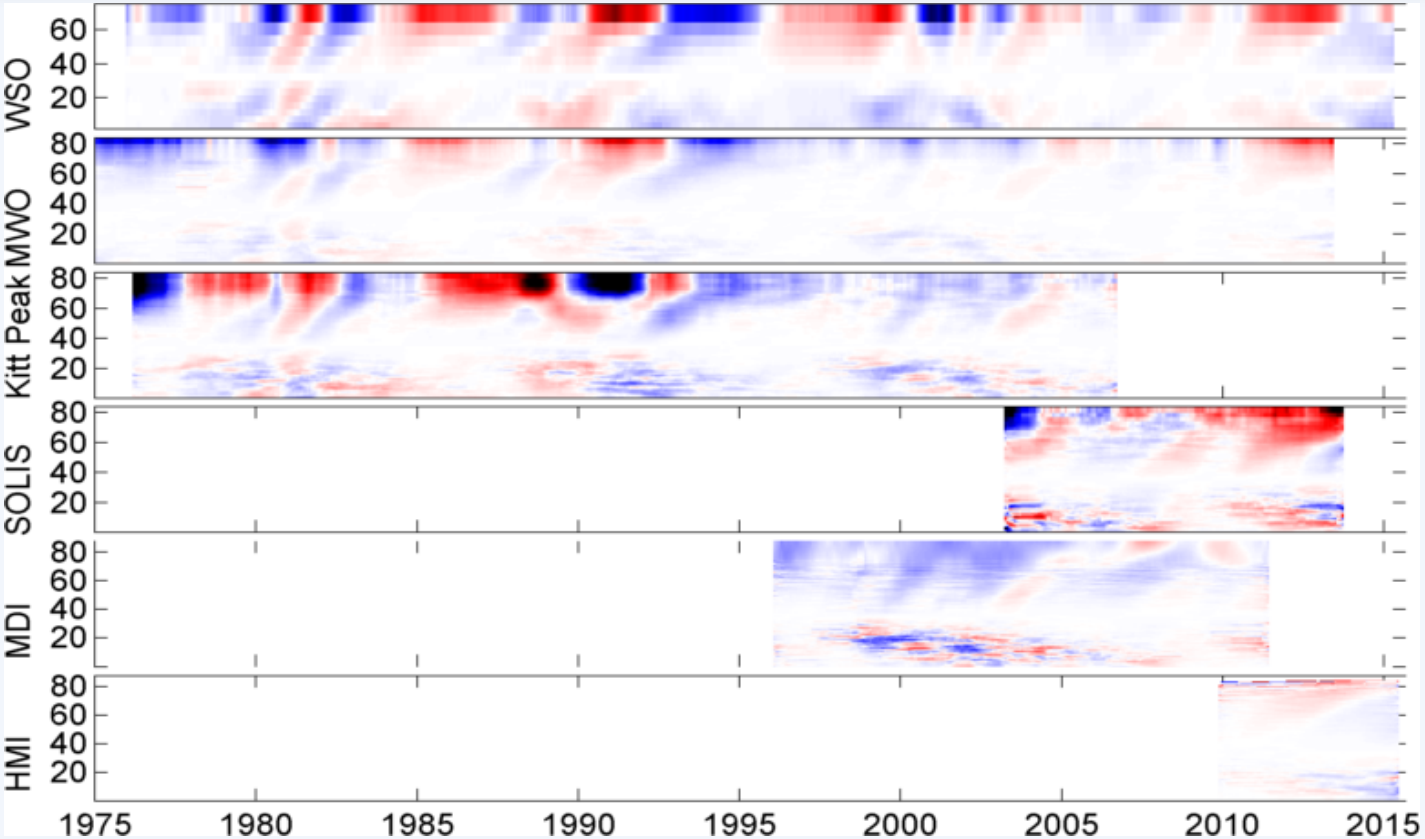
13-rotation mean latitudes of HCS in heliographic coordinates.

A very consistent agreement between the 6 data sets.

Southward shifted HCS during the declining to minimum phase of solar cycles (20), 21, 22 and 23.

Shift shows weaker and less systematic at 1 AU during cycle 23.

Quadrupole term due to polar field asymmetry



Shift is caused mainly by the quadrupole term g_2^0 of field harmonic expansion.

g_2^0-term relates to polar field N-S asymmetry, which arises from N-S asymmetric surges of flux drifting toward poles

Possible causes: Asymmetric flux generation, asymmetric meridional transport,..

Radial profile of radial field: HMF-WSO comparison

According to Maxwell equations (divergenceless magnetic field, or no magnetic monopoles), the radial magnetic field should behave like

$$B_r = B_0 \left(\frac{r_0}{r}\right)^n$$

with n = 2.

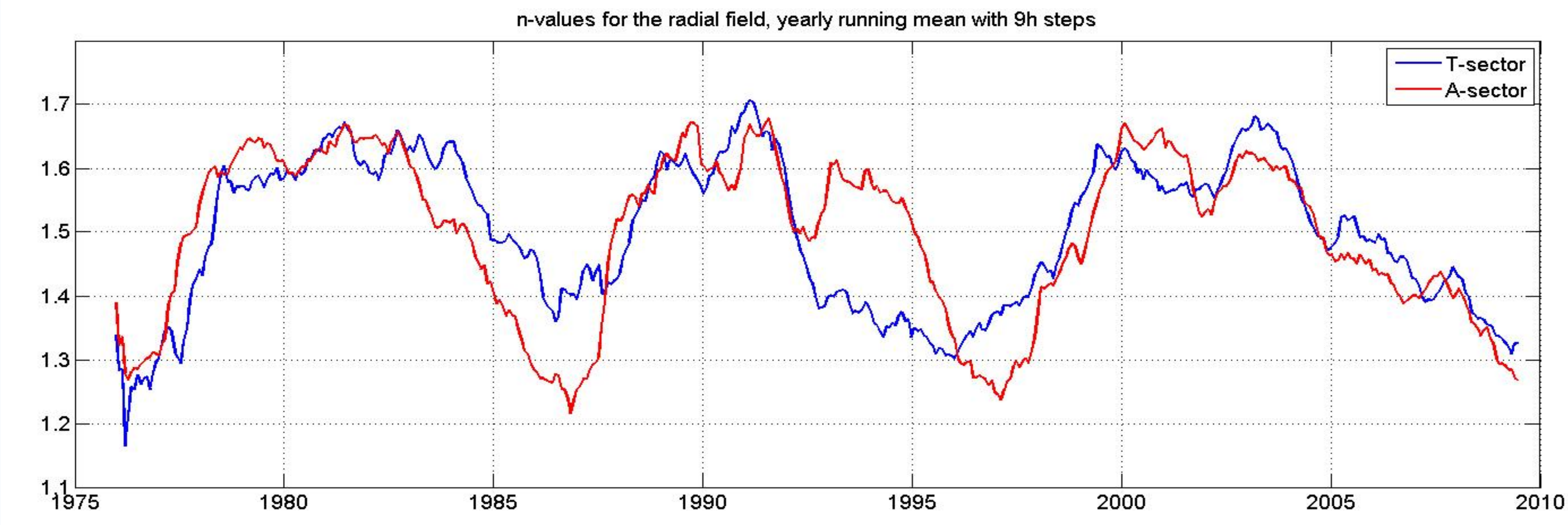
However, in WSO-OMNI comparison, the effective value of n is smaller than 2 because source fields close to HCS have excessively weak field values due to PFSS model.

The value of n is also solar cycle dependent.

- During solar maxima, because of large tilt, most source regions are at fairly high heliomagnetic latitudes (further from HCS), leading to a better match.

- During minima, because of small tilt, most source regions are located close to HCS, leading to a worse match (and smaller n).

Radial profile of radial field: HMF-WSO comparison



- n varies strongly with solar cycle because of variable HCS proximity.
- During the Ballerina times n is larger for the northern hemisphere field because magnetic equator is shifted south and the northern footpoint is located further away from HCS. This is clearly valid for SC 21 and 22.

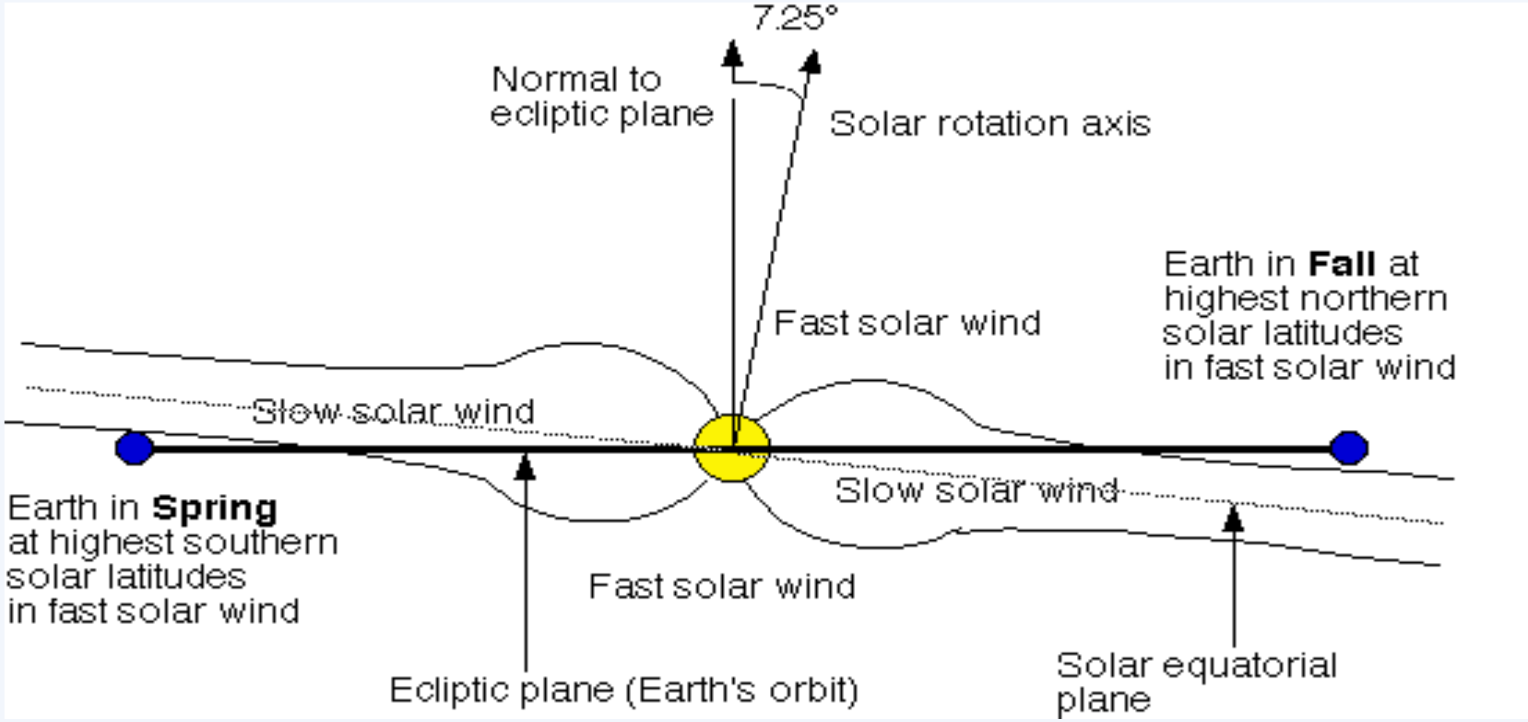
- During SC 23 minimum n is large because of the large dipole tilt.
- During SC 23 Ballerina is also bashful but less than in earlier minima.

Solar wind: Seasonal variation and its asymmetry

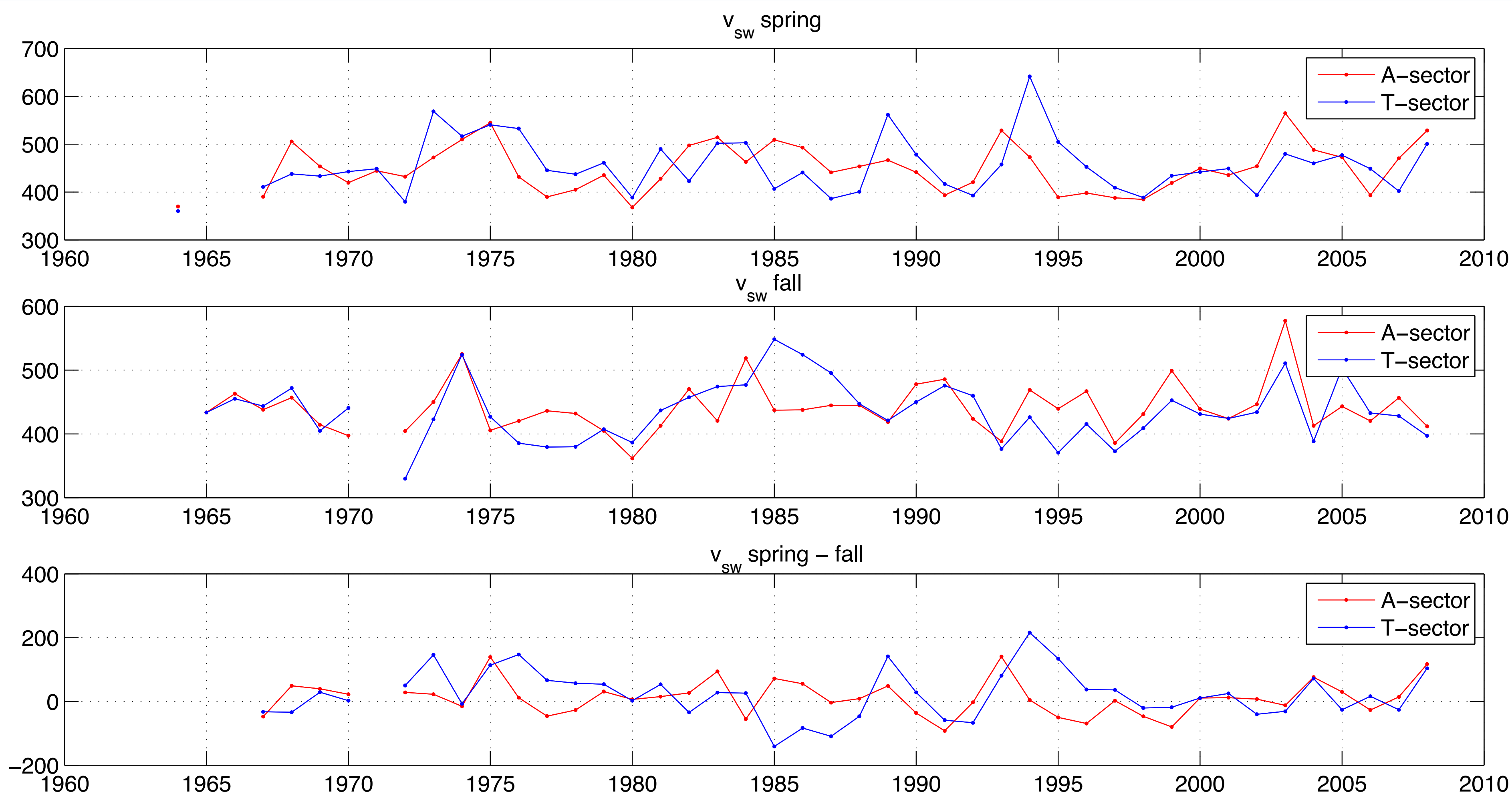
Rotation axis of the Sun is 7.25˚ tilted to the normal of the ecliptic plane.

The Earth reaches its highest northern (southern) heliographic 7.25˚ latitude in Fall (Spring).

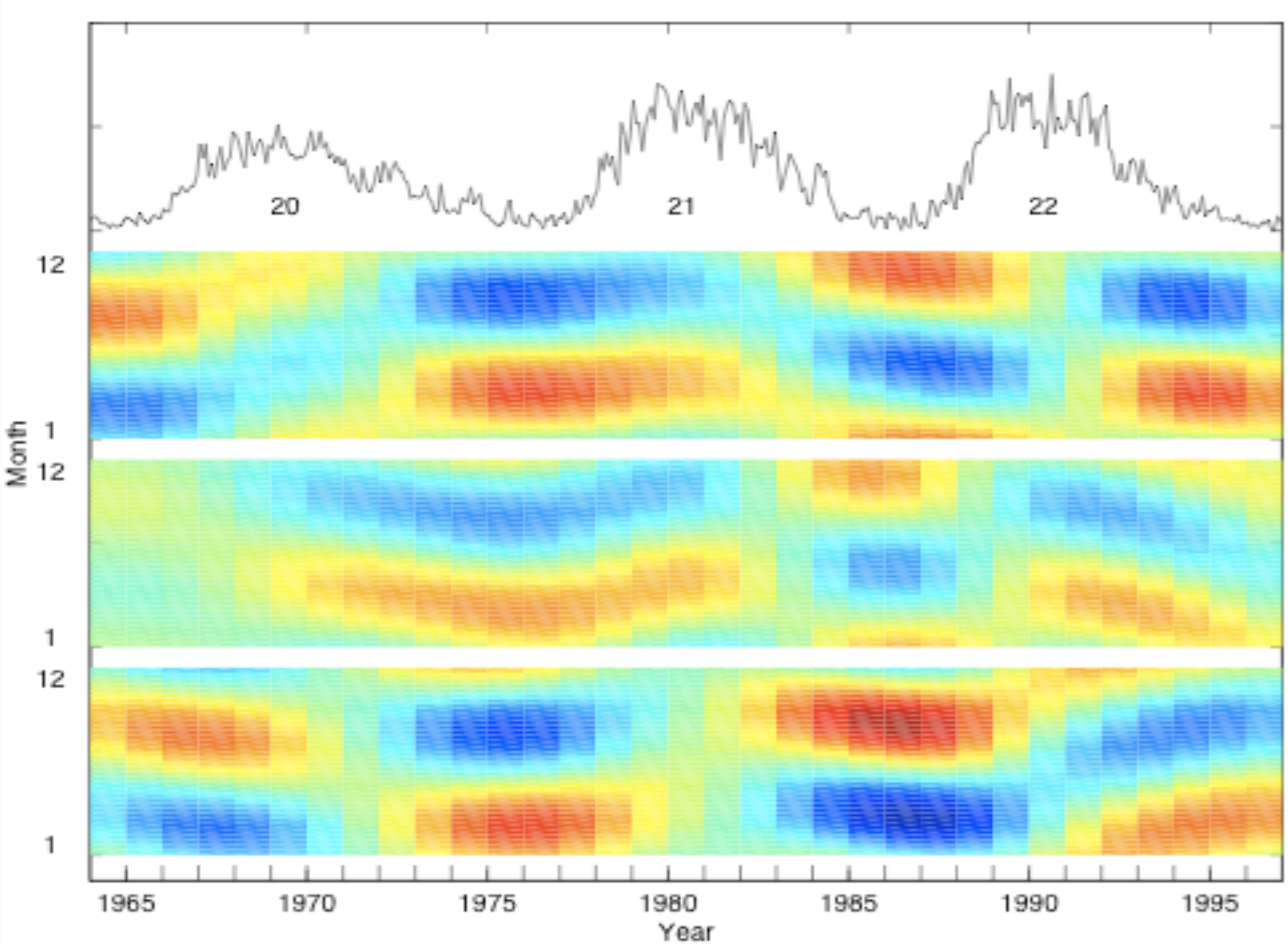
Slow solar wind concentrated around solar equator, fast SW at high latitudes.



Vsw in Spring and Fall: T + A separately



Annual variation in GA and solar wind speed



Annual variation in SW speed, geomagnetic activity (Kp index) and HMF sector component in color coding.

Phase of the annual variation changes from one solar minimum to another.

Solar hemispheric asymmetry: negative polarity hemisphere emits faster wind. Streamer belt is N-S asymmetric.

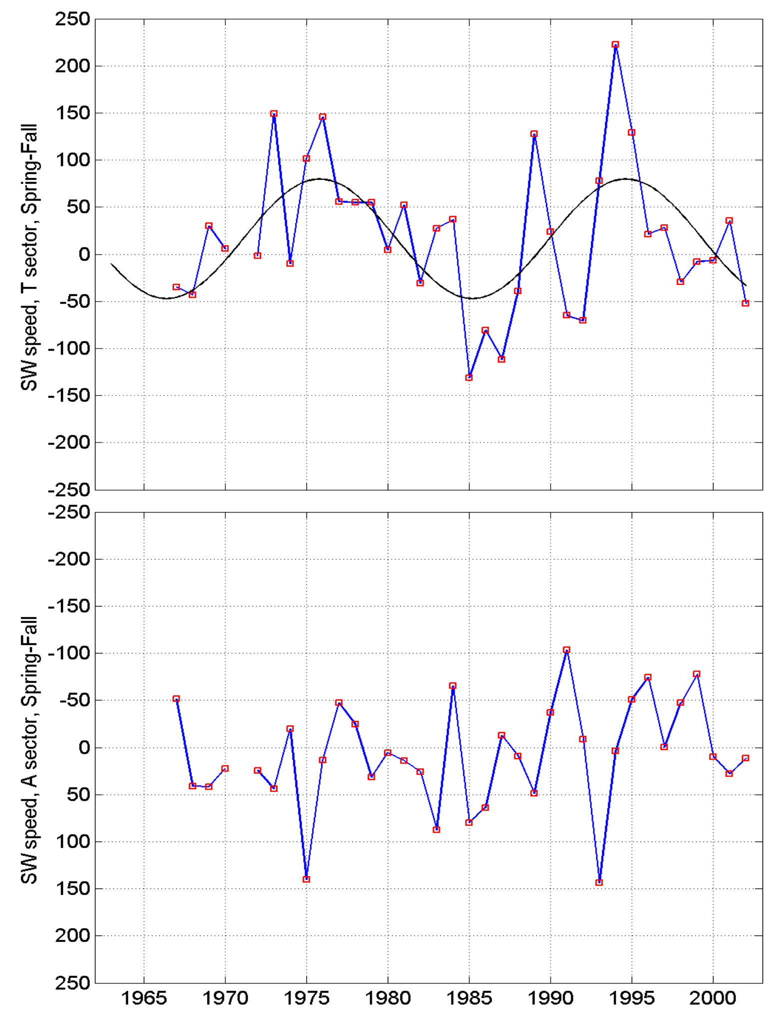
Zieger and Mursula, GRL, 25, p. 841, 1998.

Interpretation: Streamer belt asymmetry

Variation of SW speed with latitude is much larger in the southern magnetic hemisphere (T sector) than in the northern magnetic hemisphere (A sector).

This implies a strong north-south asymmetry in the Sun related to the 22-year magnetic cycle.

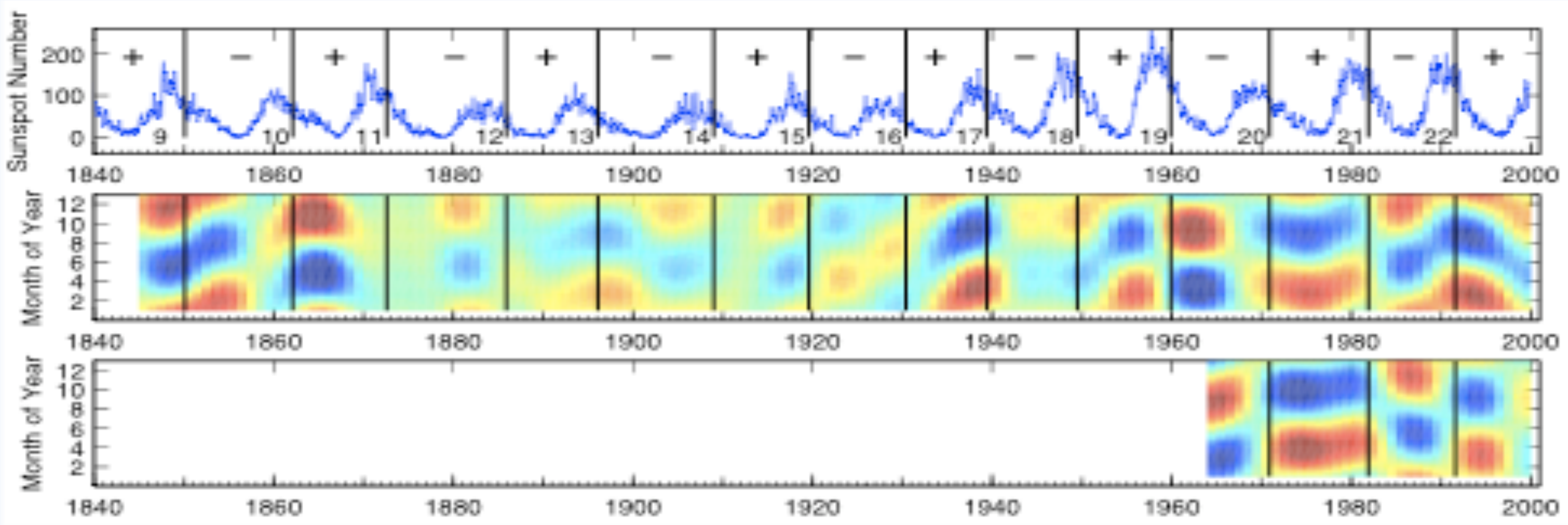
The SW speed distribution is effectively shifted towards the northern magnetic hemisphere.



Streamer belt north-south asymmetry

Long-term SB asymmetry

We have used a band pass filter in order to extract the annual variation in the extended aa index (Nevanlinna and Kataja, 1993) which covers nearly 160 years.



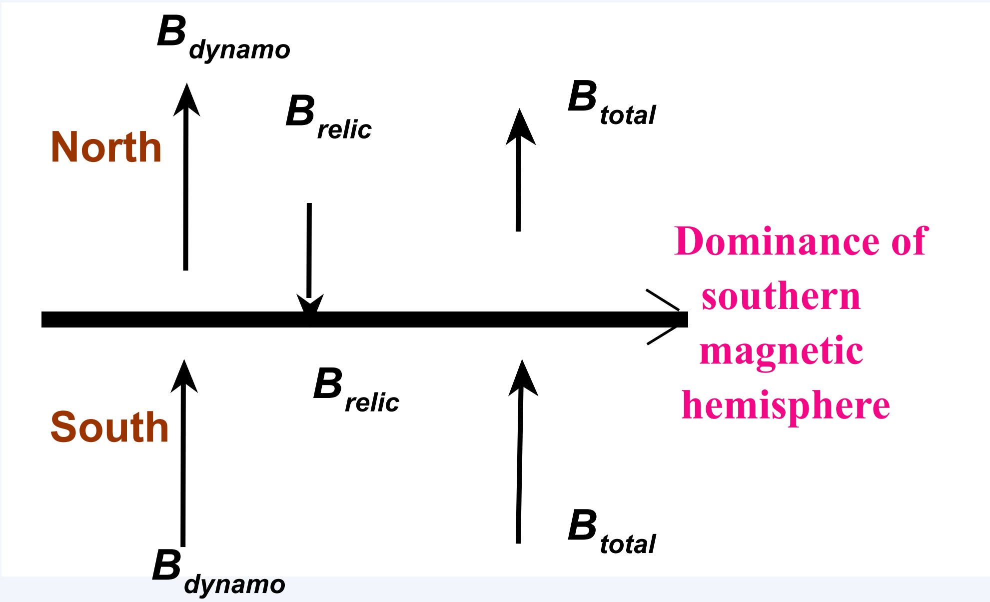
Streamer belt (and most likely also HCS) north-south asymmetry is oscillating in time with a period of about 200-250 years.

Hemispheric asymetry may relate to the 210-year deVries cycle known in cosmogenic isotopes.
Two Gleissberg cycles make one asymmetry cycle (like two Schwabe cycles make one Hale cycle)

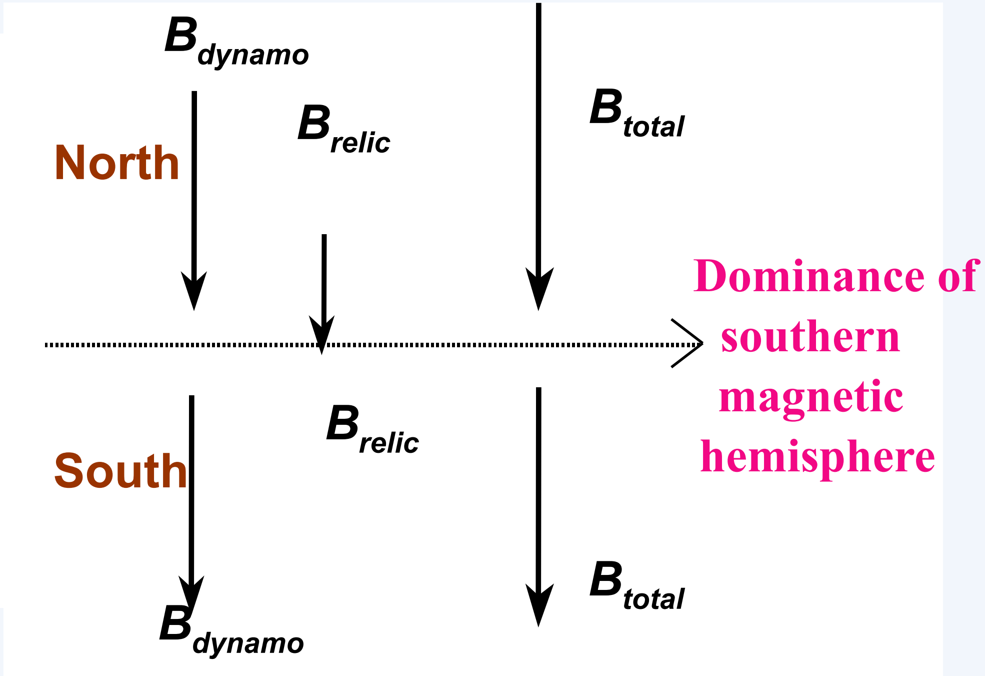
K. Mursula, and B. Zieger, Geophys. Res. Lett., 28, 95-98, 2001.

Relic field effect

Positive polarity cycle:



Negative polarity cycle:



Scheme of the effect of arelic field dislocated above the equator for positive and negative polarity cycles.

Conclusions on solar dynamo

The decay of GMM since about 2000 depicts interestingly different behavior from the previous 40-50 years of highly active Sun.

- Long-lasting low-latitude coronal hole appears and modifies the evolution of the solar magnetic fields and coronal holes (and SW).

Detailed new information can be extracted about the ascending phase of GMM from new methods of studying geomagnetic activity.

- HSS occurrence has a maximum in early 1950s, is the declining phase of the cycle 18, preceding the highest cycle 19 (max of MGM)

This result supports solar dynamo theory.

- Only one excursion phase (CH extension) per cycle hemisphere, lasting for roughly half a year.

Conclusions on solar N-S asymmetry

The Sun has systematic hemispheric asymmetries.

The HCS has been southward shifted for about 3 years in the declining to minimum phase of each cycle at least during the last 80 years
(Bashful ballerina)

There may a long-term oscillation of about 200-250 years (maybe the deVries/ Suess cycle) in this hemispheric asymmetry.
Possible relation to Gleissberg cycle.
Asymmetry should reverse during the next 1-3 cycles
(No more Bashful, but..?)

This asymmetry has tangible effects in the near-Earth space environment and can be used – to some extent – for long-term forecasting of space weather events.

Conclusions on SW-GA

A network of local geomagnetic indices can provide detailed, quantitative information on the occurrence and relative importance of the two main solar wind structures (HSSs and ICMEs).

PC analysis gives interesting information about the laitudinal distribution of geomagnetic activity caused by ICMEs and HSS/CIRs.

We now have the possibility to reconstruct the fraction of high speed streams for the past 100 years.

We also can soon construct the centennial evolution of energetic partice fluxes.

Conclusions on HSS climate effects

Northern Hemisphere winter surface temperatures and associated NAO variability are positively correlated with energetic electron precipitation.

This connection is strongly dependent on the QBO phase (easterly QBO).

For the last 130 years (12 solar cycles) the temperature pattern during the declining phase resembles the pattern associated with positive NAO phase

This indicates that the chemical changes caused by EEP can have a significant effect on regional winter time climate in the Northern Hemisphere

Also other possible mechanisms related to HSS may exist.

The long-term effects of EEP will be studied in more detail with the estimated centennial particle precipitation.

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Thanks to

Timo Asikainen, Lauri Holappa, Renata Lukianova, Ville Maliniemi..

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