

THE EVER CHANGING SUN

Solar influence on climate



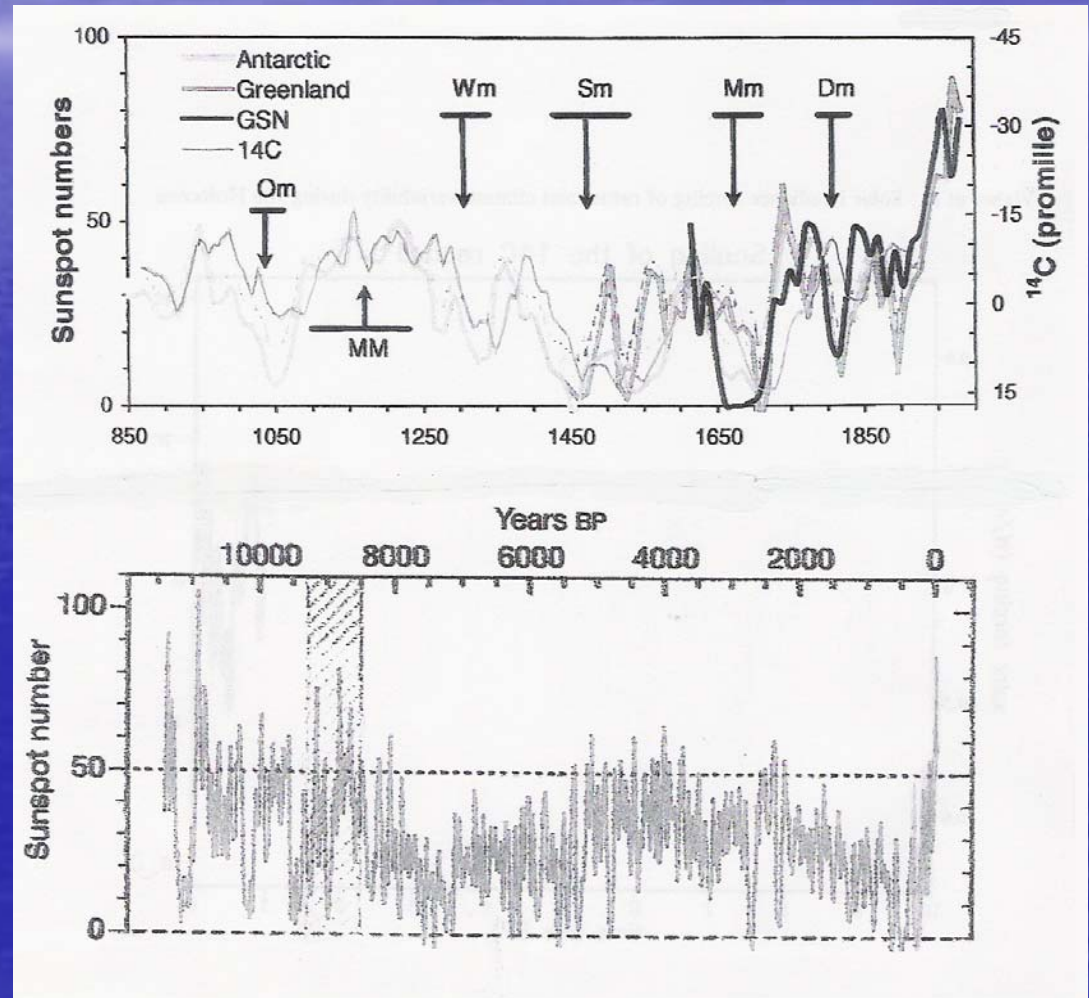
Solar activity during holocene

[ref: Solanki et al.]

Present maximum is highest of past 9 millennia

(as far as plasma ejection from sun is concerned; but note conflicting evidence Antarctic vs. Greenland ice cores)

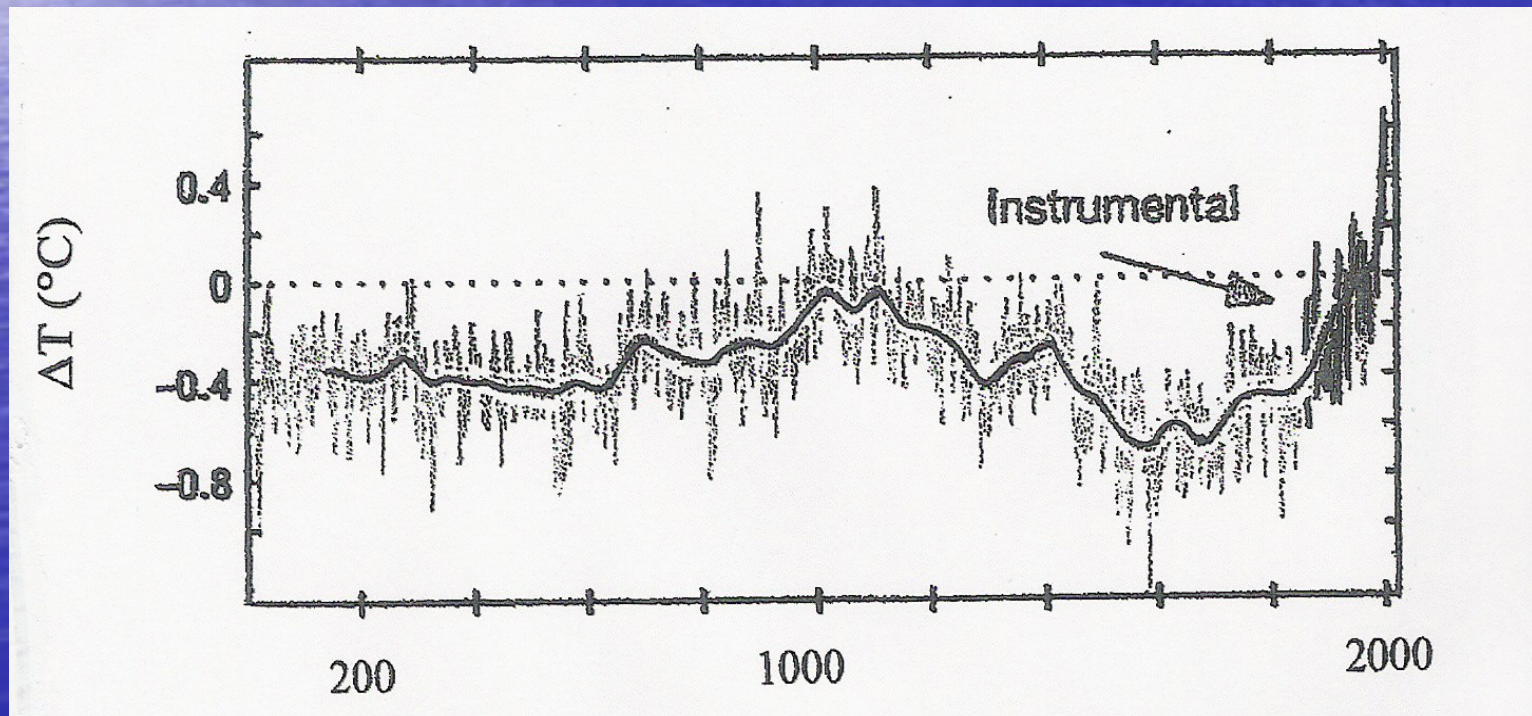
[Solanki et al.; Muscheler et al.]



Northern Hemisphere Temperatures

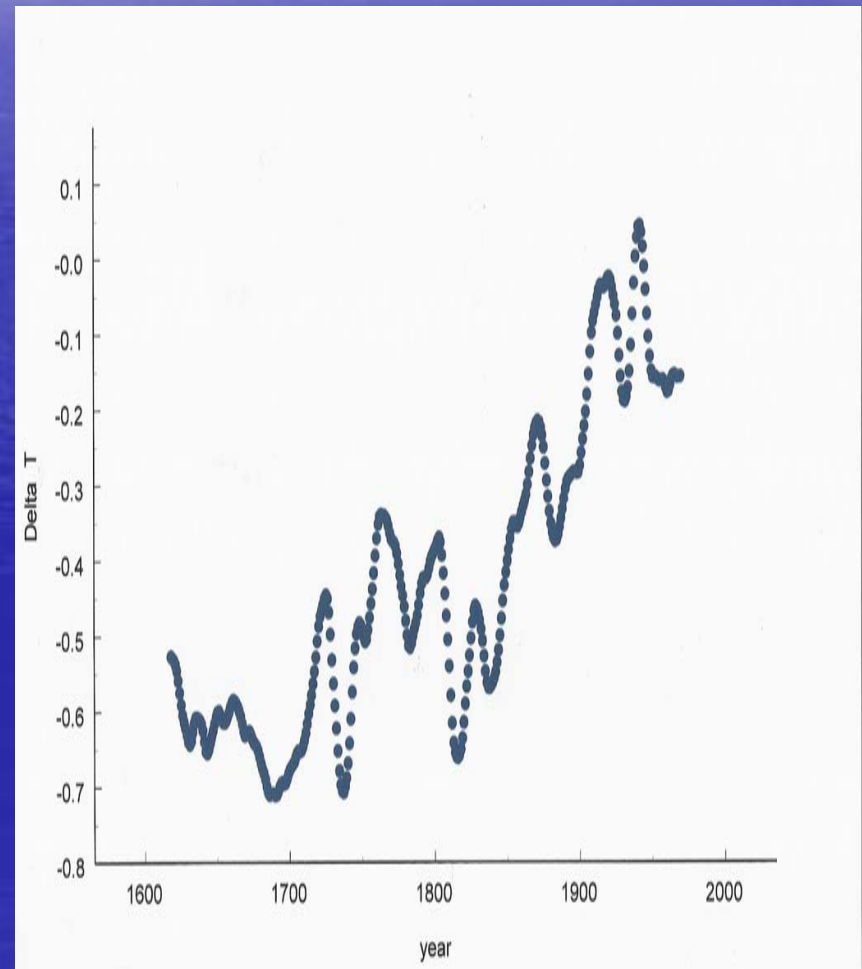
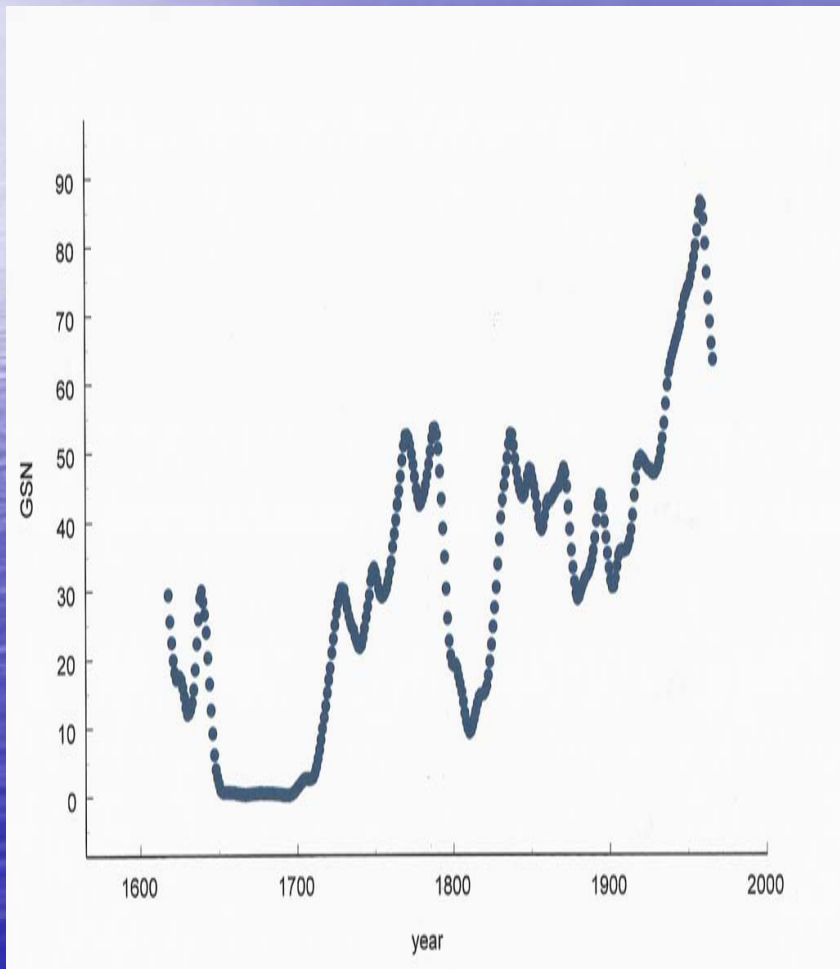
[source: Anders Moberg et al., 2005]

- Medieval maximum (AD 1000 – 1200)
- Broad minimum around 1600 (Little Ice Age)
- Strong 20th century increase



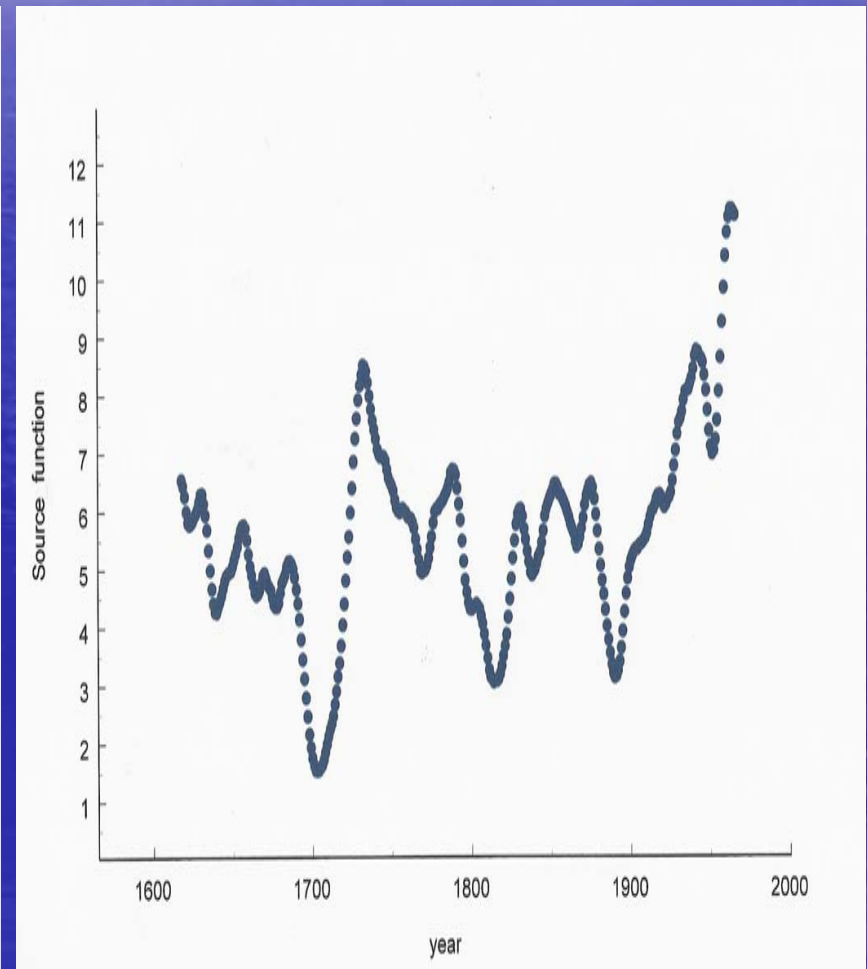
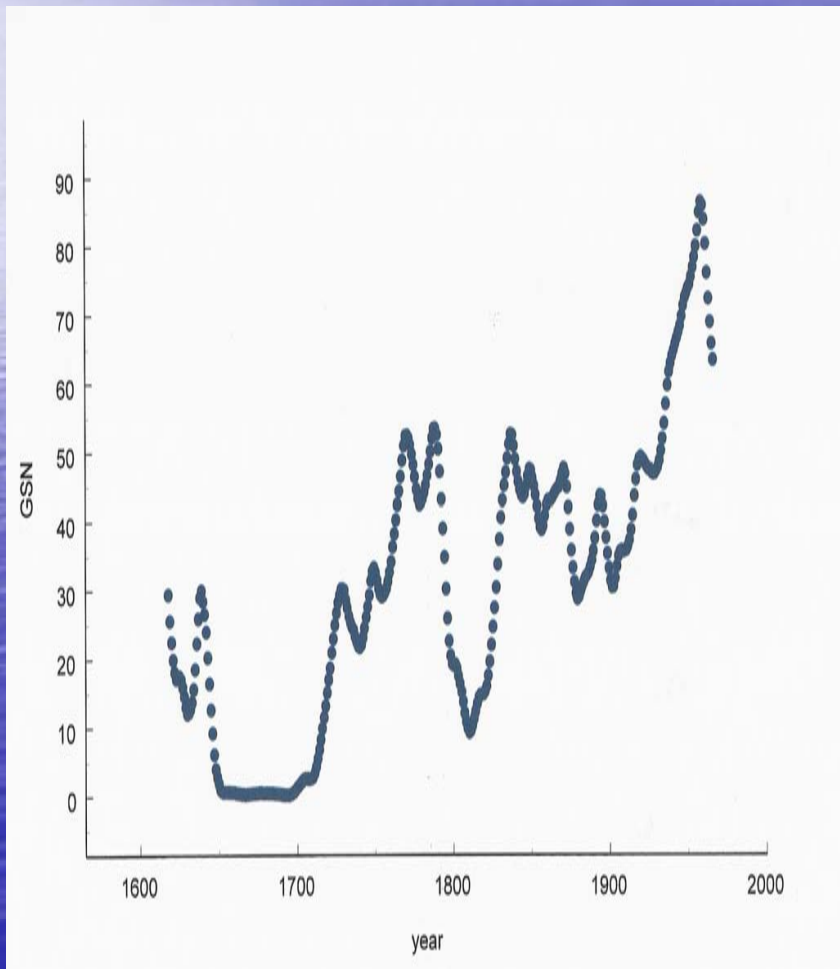
Basic data for the period 1619 – 1964

Smoothed Group Sunspot Number (*left*; ref. Hoyt & Schatten) and smoothed Northern Hemisphere Temperature [ref: Moberg et al.]



Basic data for the period 1619 - 1964

Smoothed Group Sunspot number (*left*) and Source function (= ejected plasma \sim open solar flux) [refs: Hoyt & Schatten for GSN; Usoskin & Solanki for S-function]



Outline of talk

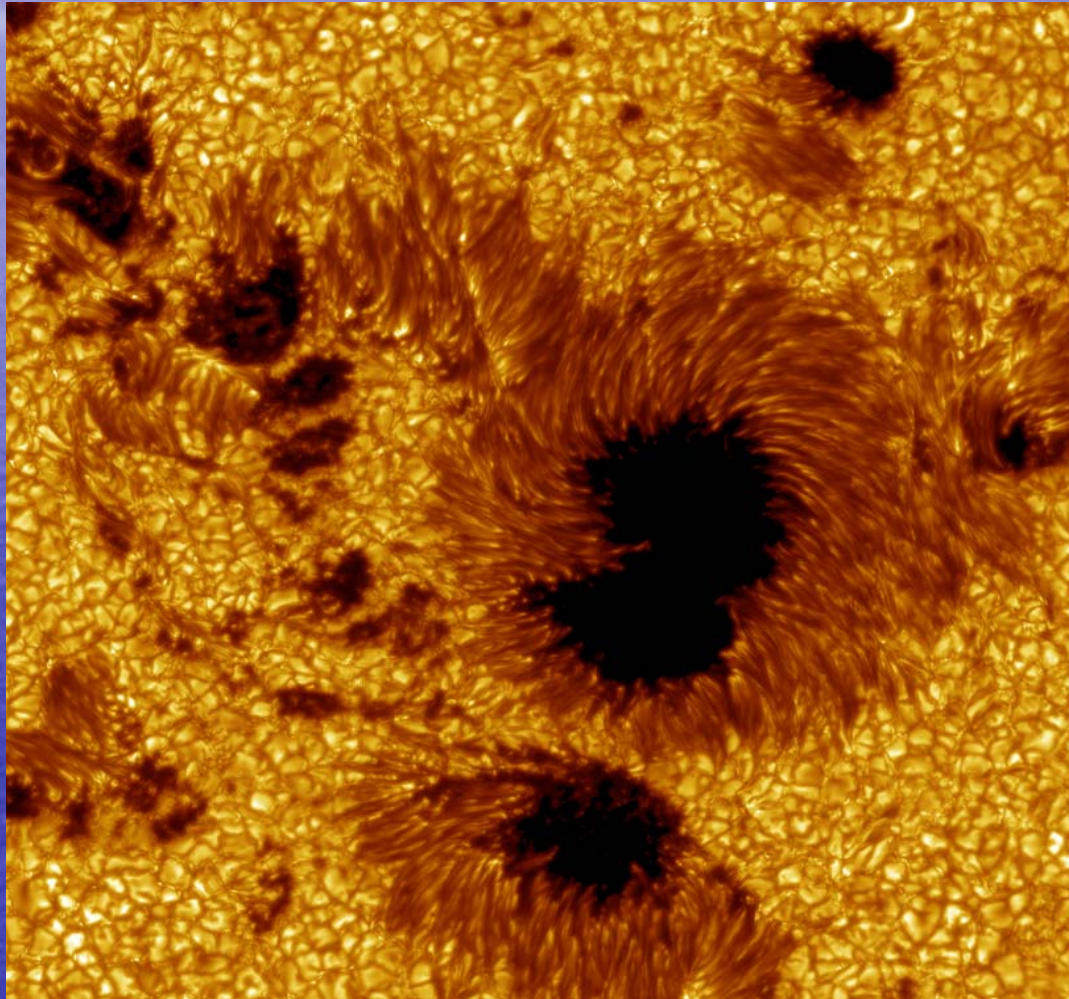
- Two main aspects of solar variability:
 - Active regions around sunspots
 - Coronal plasma ejections of various kinds
- Do these influence tropospheric temperatures and what is the main driver of sun-induced climate change?
- The solar dynamo
- Forecasting solar activity

BASIC SOLAR DATA

Activity Centers and Ejection of
solar plasma

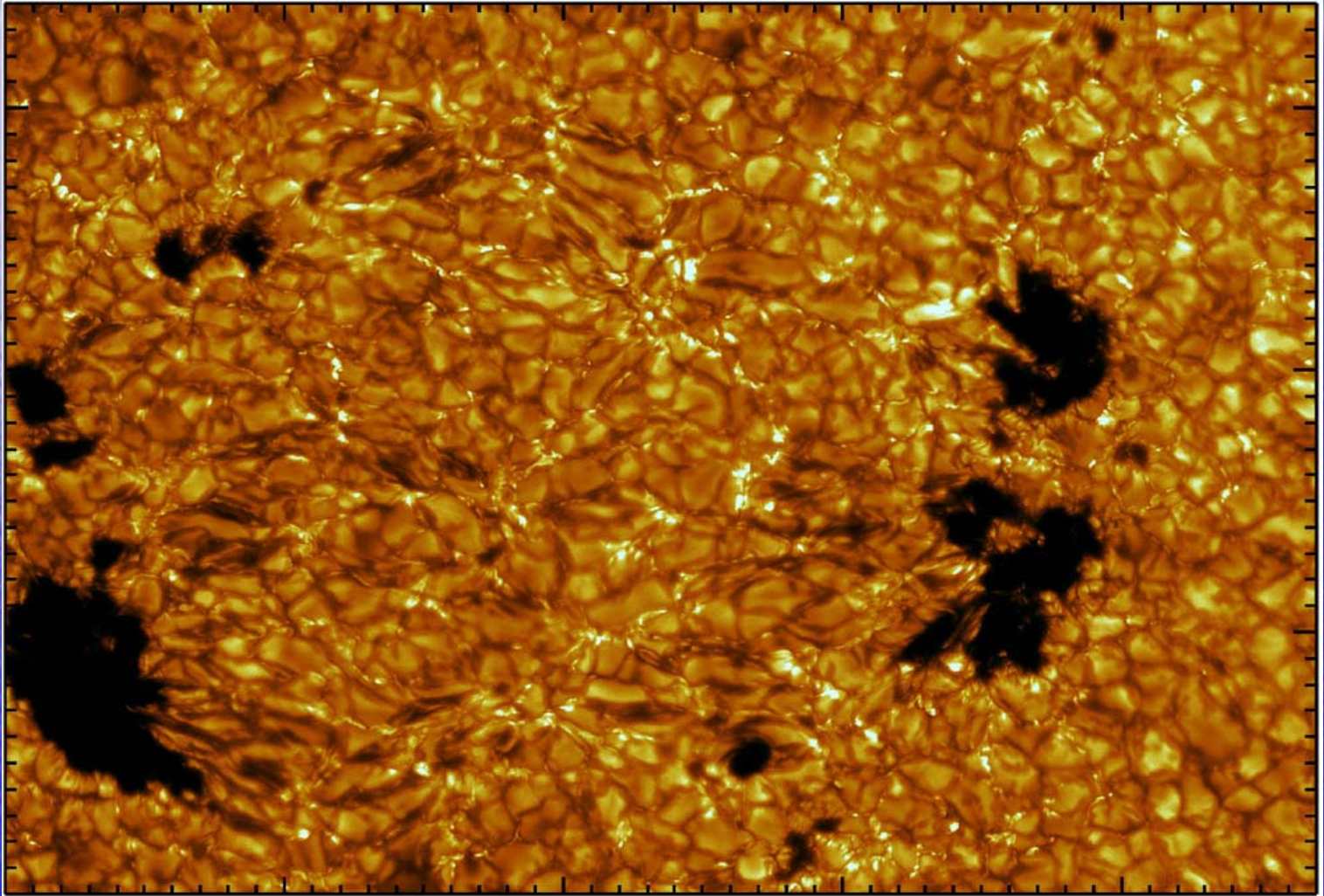
Sunspots and active regions

A sunspot group [DOT observations]



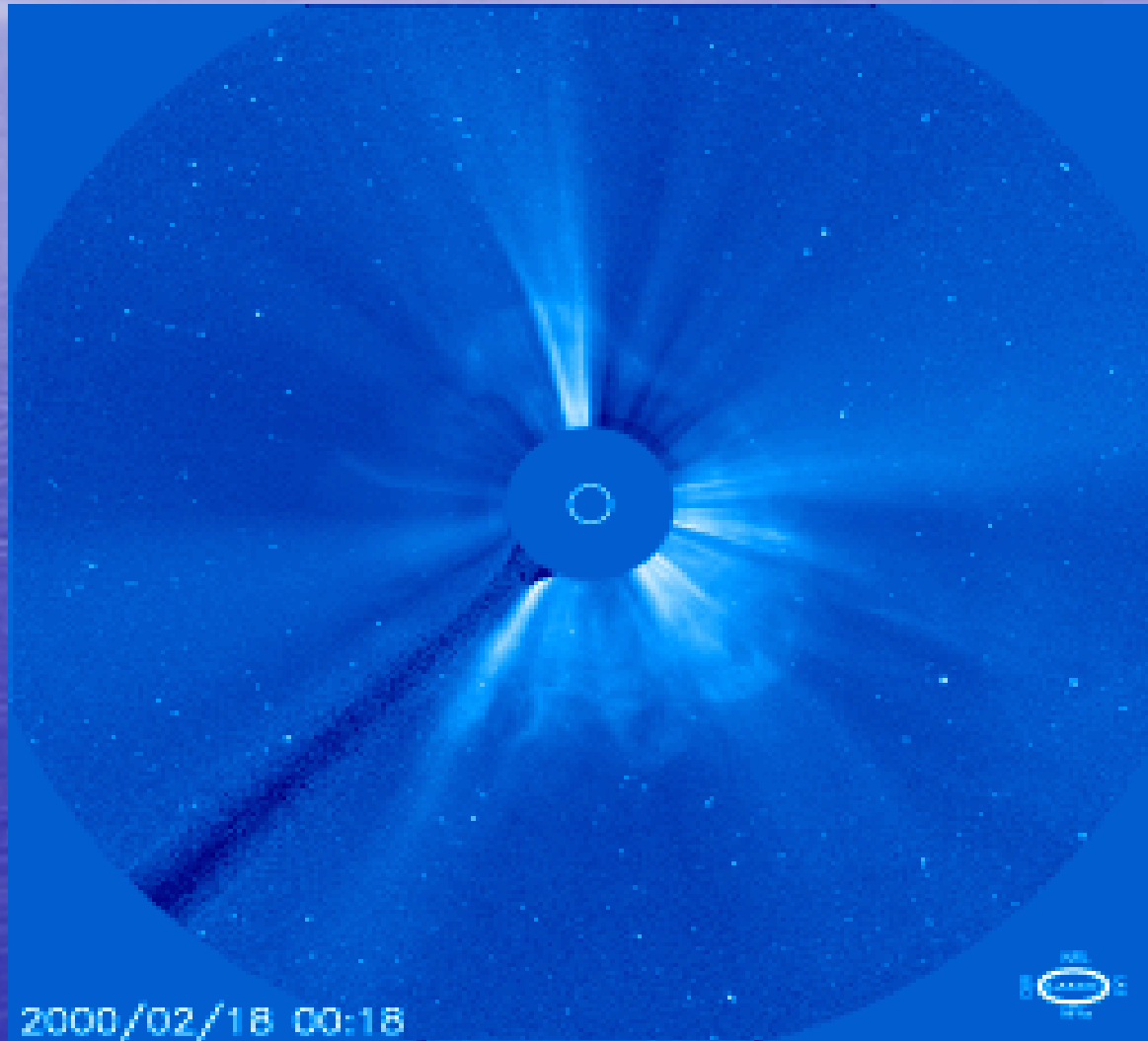
Surrounding facular fields

higher temperatures are located on top of photosphere; emit variable (UV) radiation flux



Coronal mass Ejections

(Lasco on SOHO spacecraft)

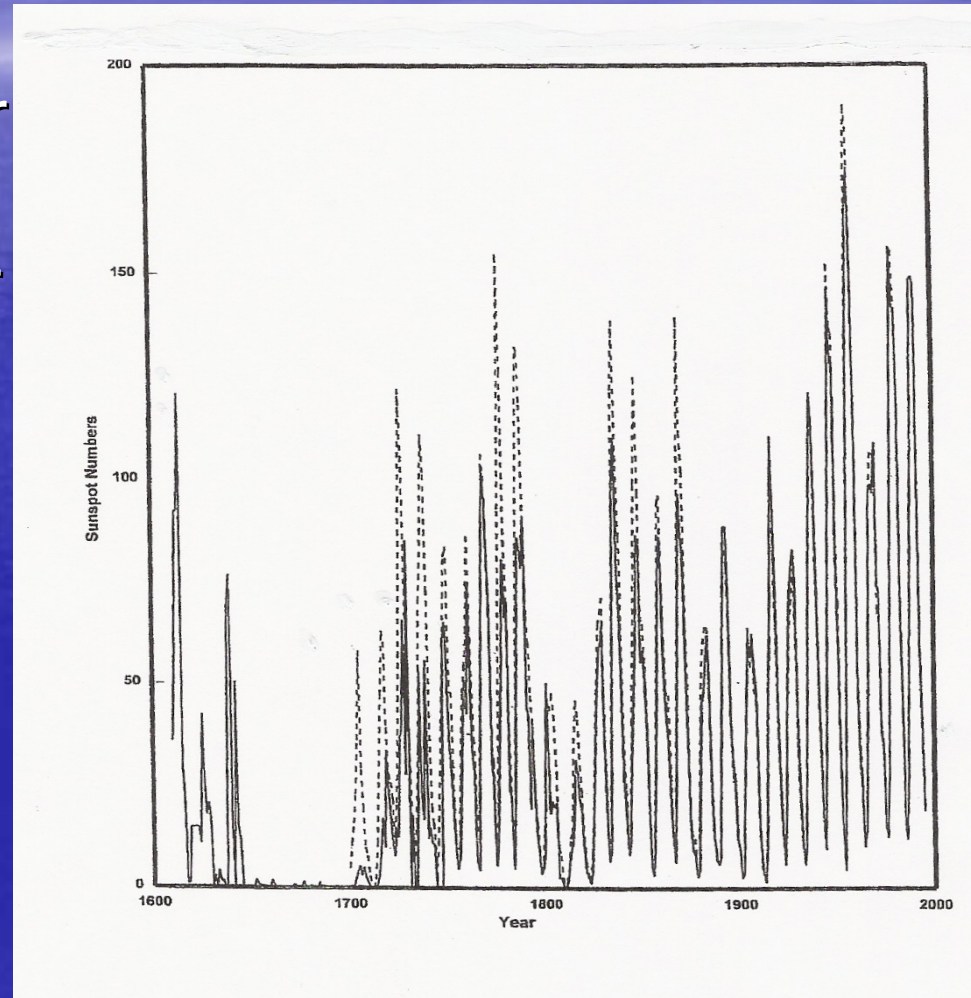


The center of activity

- Sunspots and the surrounding active regions
- Facular fields
- Solar flares and their effects
- Coronal Mass Ejections
- Prominences of various kinds (will not be discussed here)

Sunspot numbers

- R_Z = Zürich sunspot number (dashed)
- R_G = group sunspot number (solid; ref. Hoyt & Schatten)
- Use of R_G advisable
- Maunder minimum from 1652 – 1704
- During MM few spots but normal activity in plasma ejection

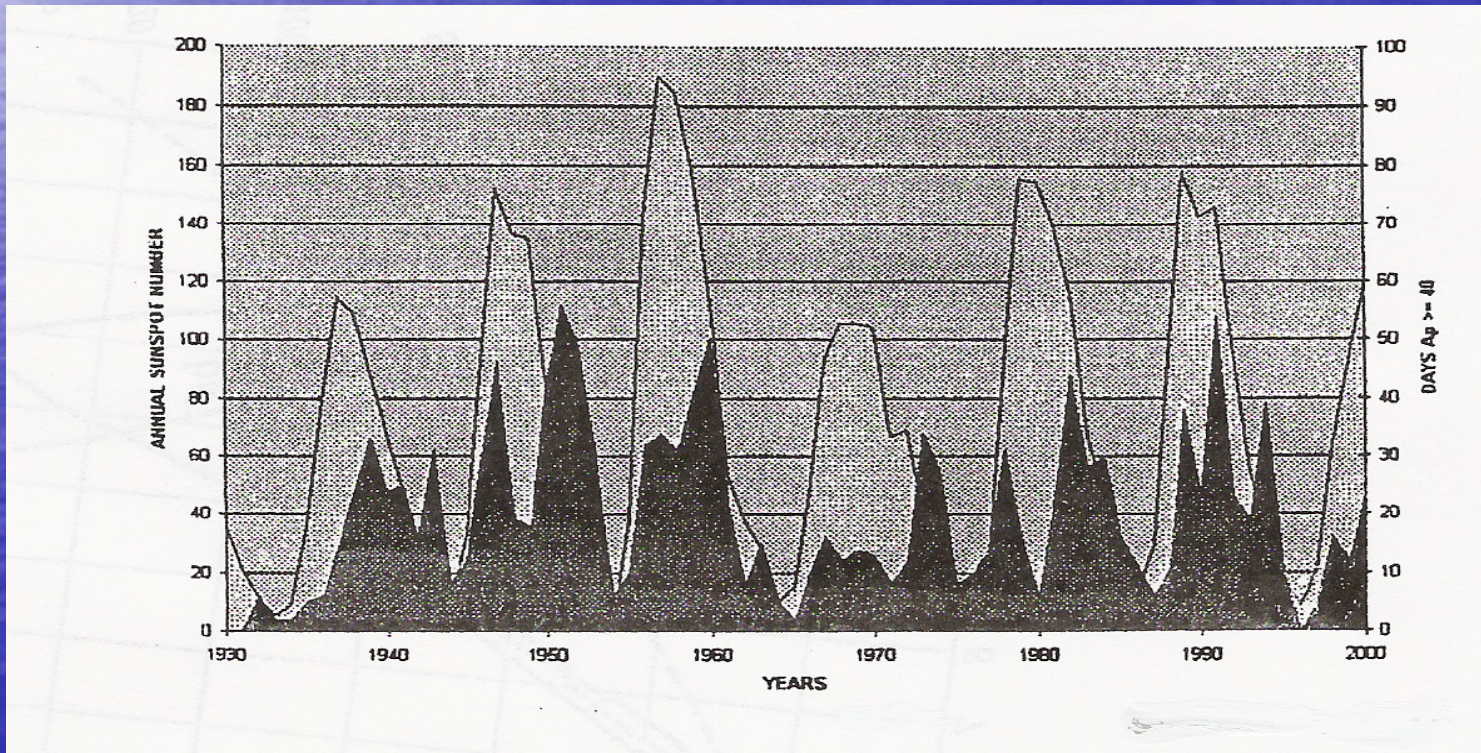


Time delays of various kinds:

- High latitude activity follows or precedes (?) sunspot activity by half a Schwabe cycle
- Gnevyshev Gap: spot activity maxima in the two hemispheres are not simultaneous; delays average a year
- Energetic Emissions Delay: energetic emission follow spot maximum by roughly 1 – 2 yr

The energetic emissions delay

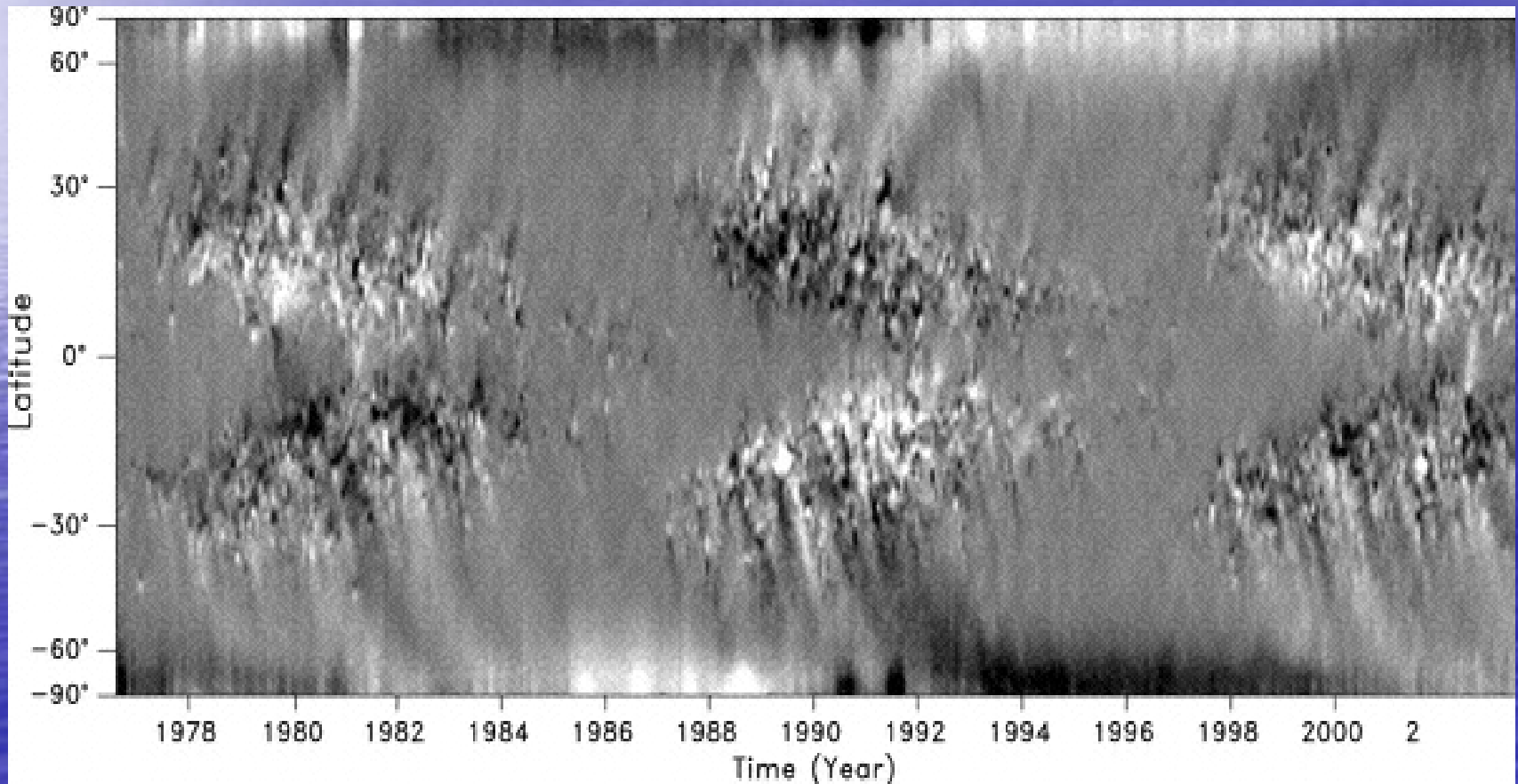
- Energetic emissions such as X or γ -ray flares (black) delayed by about one year with respect to spot numbers (lighter shaded; ref. J. Allen)



Equator-ward and pole-ward drift

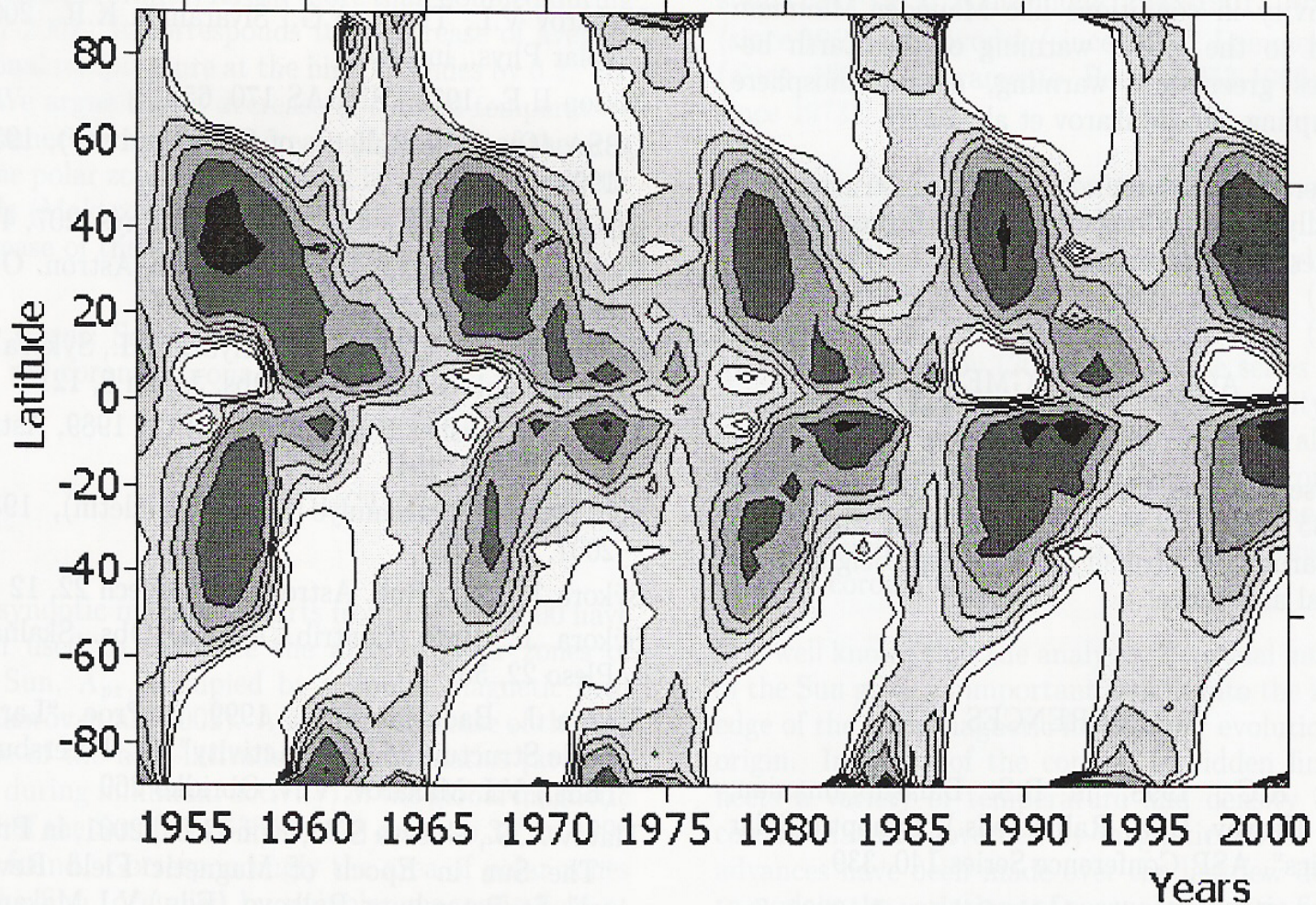
sunspot area and high latitude magnetic fields

[ref: Hathaway)



Variation intensity Green Coronal line

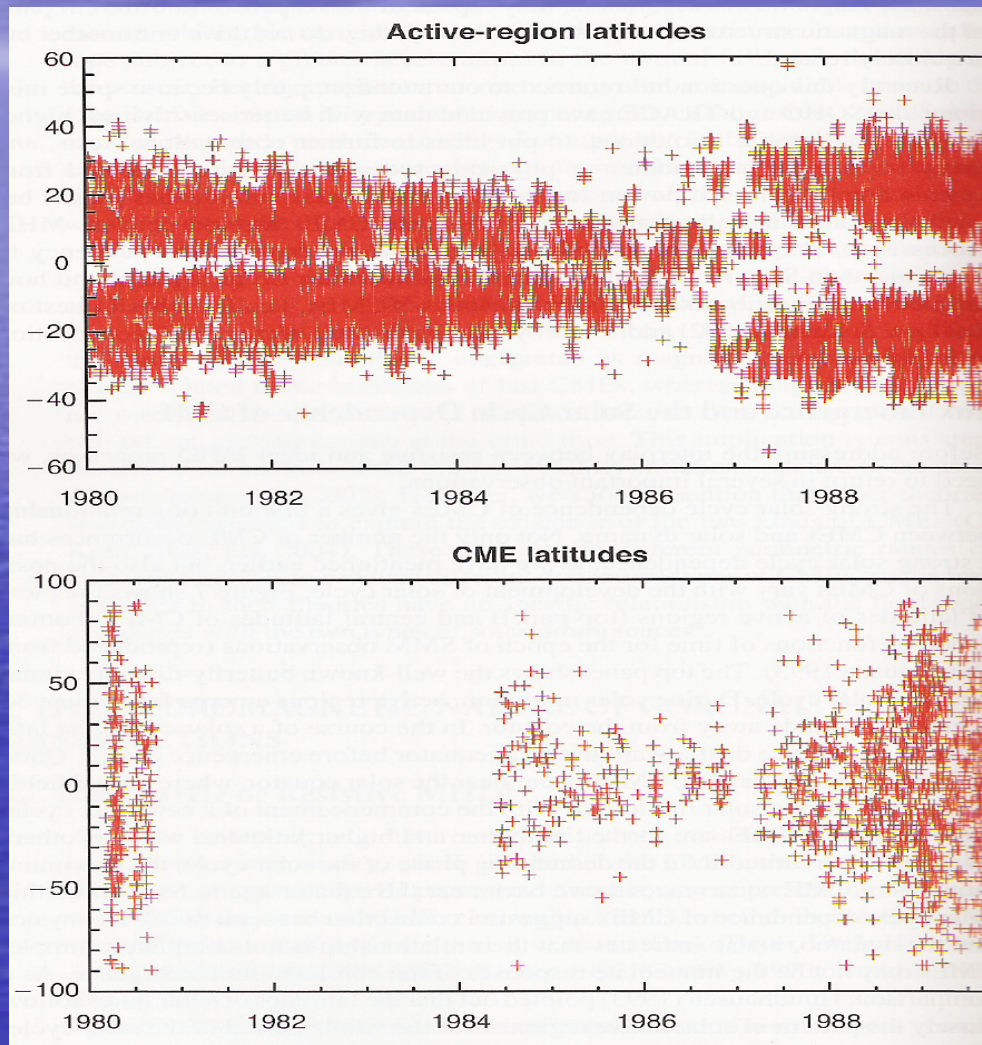
[Green line: 530.3 nm; FeXIV; ref. Makarov et al.]



Plasma ejection

Low- and high-latitude ejections

Latitudes of Active Regions compared with those of plasma ejection [ref: Hundhausen]



Two sources for plasma ejection. Three questions

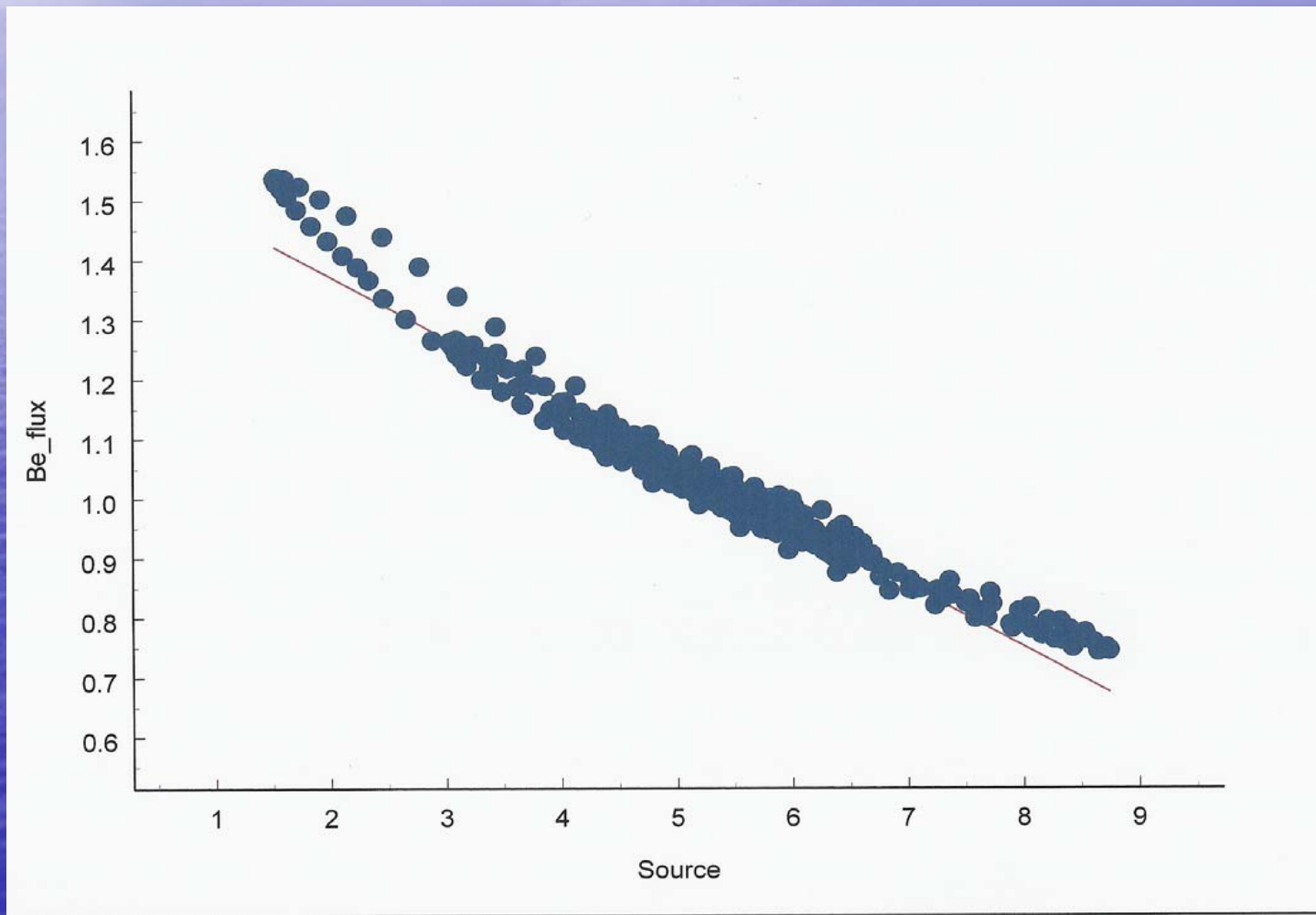
- From Centers of Activity; chiefly Coronal Mass Ejections (latitude below 40°)
 - At higher latitudes: from coronal holes, polar faculae, ephemeral active regions.
 - The totality of all these ejections define the Source Function S (Solanki; Usoskin et al.)
-
- Q1: How is S known?
 - Q2: Relation S – cosmogenic radionuclides deposit rate
 - Q3: Relative contribution of low- and high-latitude sources to S function

Answers to three questions:

- 1. Source function describes strength of open solar flux in Earth environment → modulation of cosmic ray flux → change in deposit of cosmogenic radionuclides (^{14}C , ^{10}Be ...) [refs: Solanki, Usoskin et al.; Beer et al.; Muscheler et al.]
- Hence, source function is derived (via physical theory) from the rate of deposit of cosmogenic radionuclides

2. Relation S-function – ^{10}Be deposit rate

[Ref. De Jager and Usoskin, submitted]



3. High- and low-latitude plasma fluxes

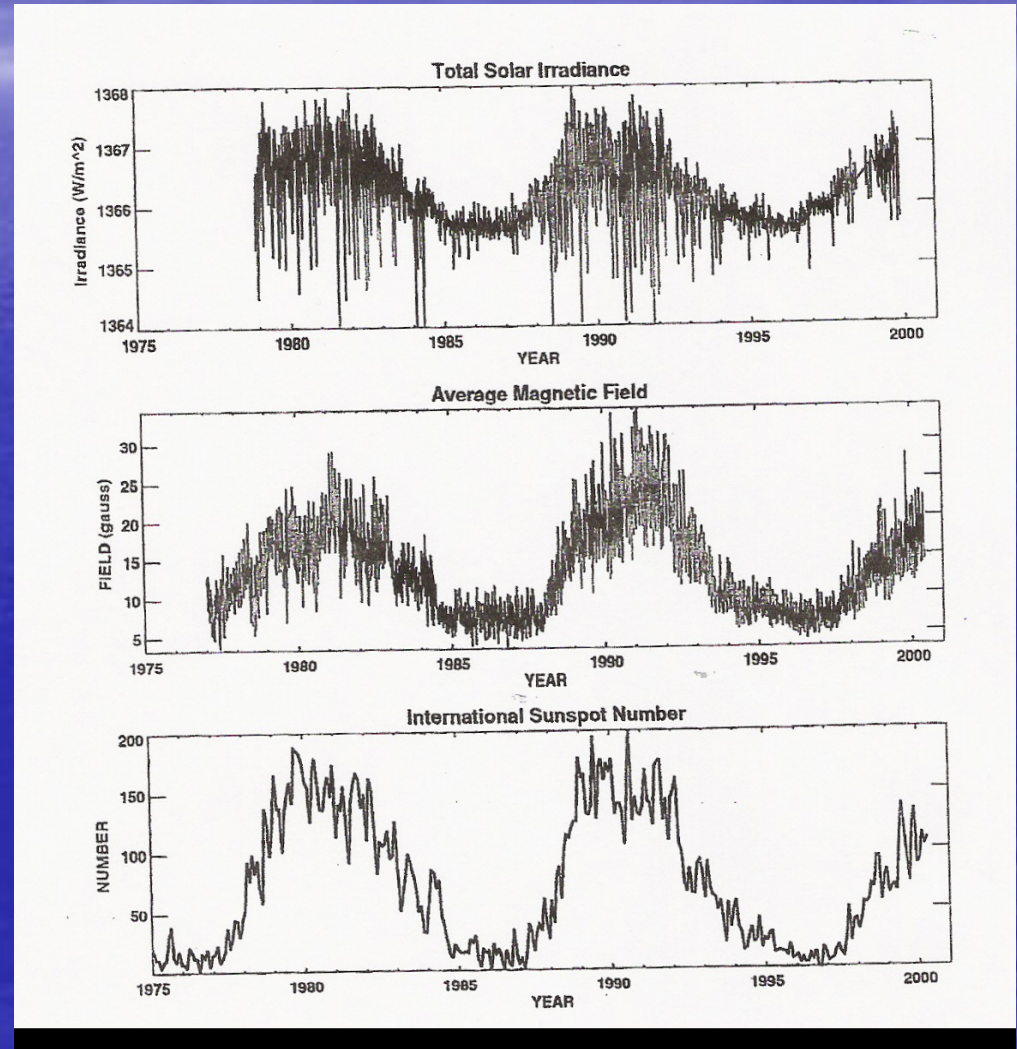
- Average ratio between S-fluxes from low latitudes and high latitudes = 1.2 (= average over 3 cycles; 1967.5 – 1998.5; refs. Wang, Kane, *re.* Wang & Sheeley, 2002; *Cf.* also Shrivastava, 2003: ~ 1.0)
- Note: low latitude ejections (CME's) are from Activity Centers and hence correlate strongly with Sunspot numbers. High latitude ejections are not.

HOW DOES THE SUN INFLUENCE CLIMATE

Irradiance variations *or* cosmic ray
modulation by plasma clouds?

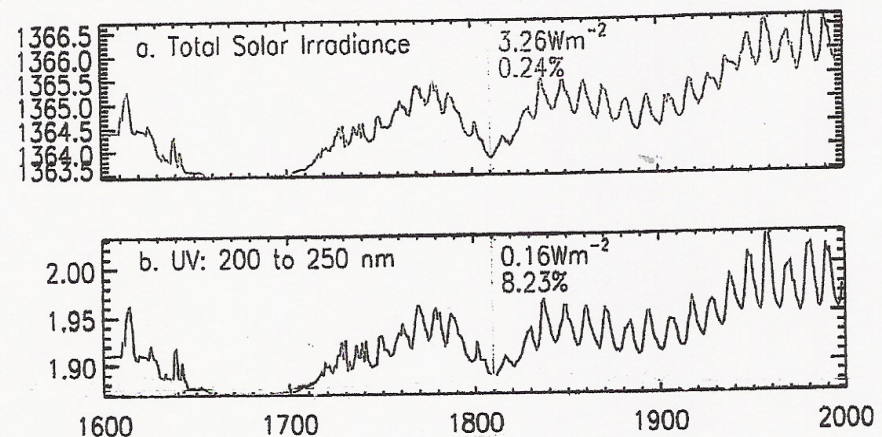
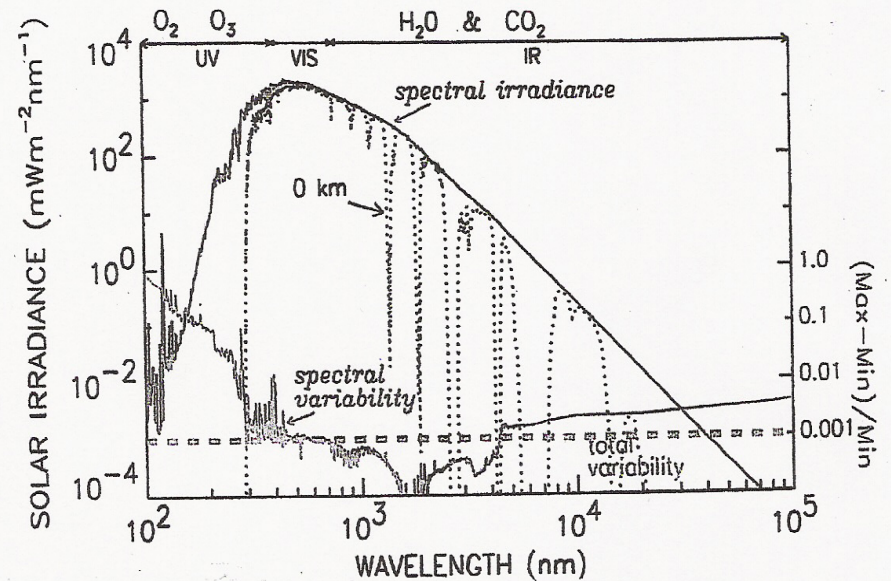
1. Solar irradiance variations

- Less than 0.1% variation during cycle (upper frame)
- Correlated with average magnetic field (middle)
- and sunspot numbers (lower frame)
- Sunspot number R is proxy for irradiance variation
- Gnevyshev Gap (two maxima)



Origin of irradiance variations

- Variations largest in ultraviolet spectrum, less in infrared; little or none in visible [ref Lean, 2000]
- Photospheric emissions (emitted in visual part of spectrum) do not vary
- Origin of variations: low-chromospheric levels of Active Regions
- Sources: scattered magnetic fields ($\sim 50 - 200$ Gauss) in Active Region area



Solar UV emissions are absorbed in terrestrial stratosphere

- Do not reach troposphere
- Hence, in order to affect tropospheric physics some kind of stratosphere – troposphere coupling is needed

2. The other aspect of solar variability; a. low-latitude ejections

- From Active Regions: coronal mass ejections
- CME-mass is 10^{12} to 10^{13} kg
- Speed at Earth distance 200 to 2500 km/sec
- Magnetic fields from CME's carried along into heliosphere contribute for $\sim 54\%$ to 'Open solar flux' (interplanetary magnetic field at Earth distance)

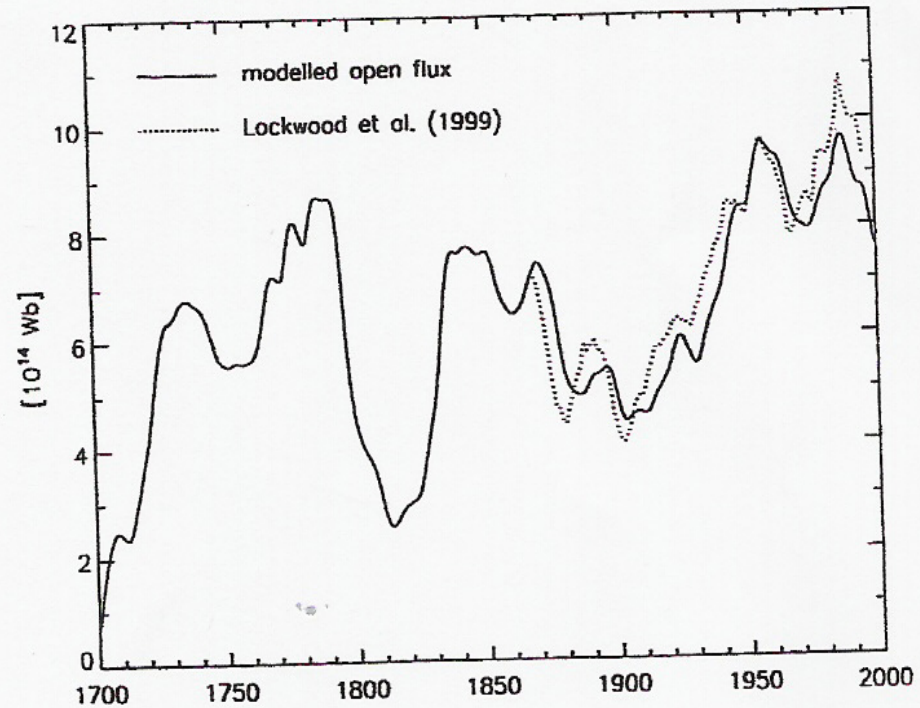
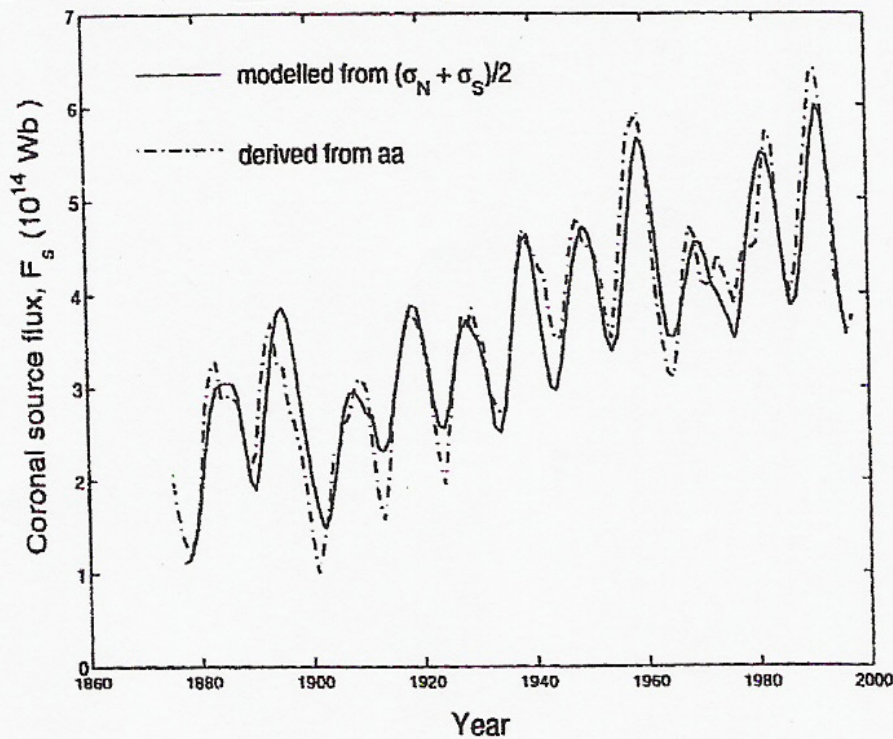
b. High latitude component ($\sim 46\%$)

- Solar wind, mainly high latitude coronal holes; varies during cycle; prominent during minimum
- Other ejection: from high latitude (ephemeral) active regions, polar faculae, structures associated with polar prominence zone
- All abrupt ejections (low- and high-latitude) cause:
- Co-rotating Interaction Regions = interplanetary shocks at collision of solar plasma ejections with earlier emitted slower wind

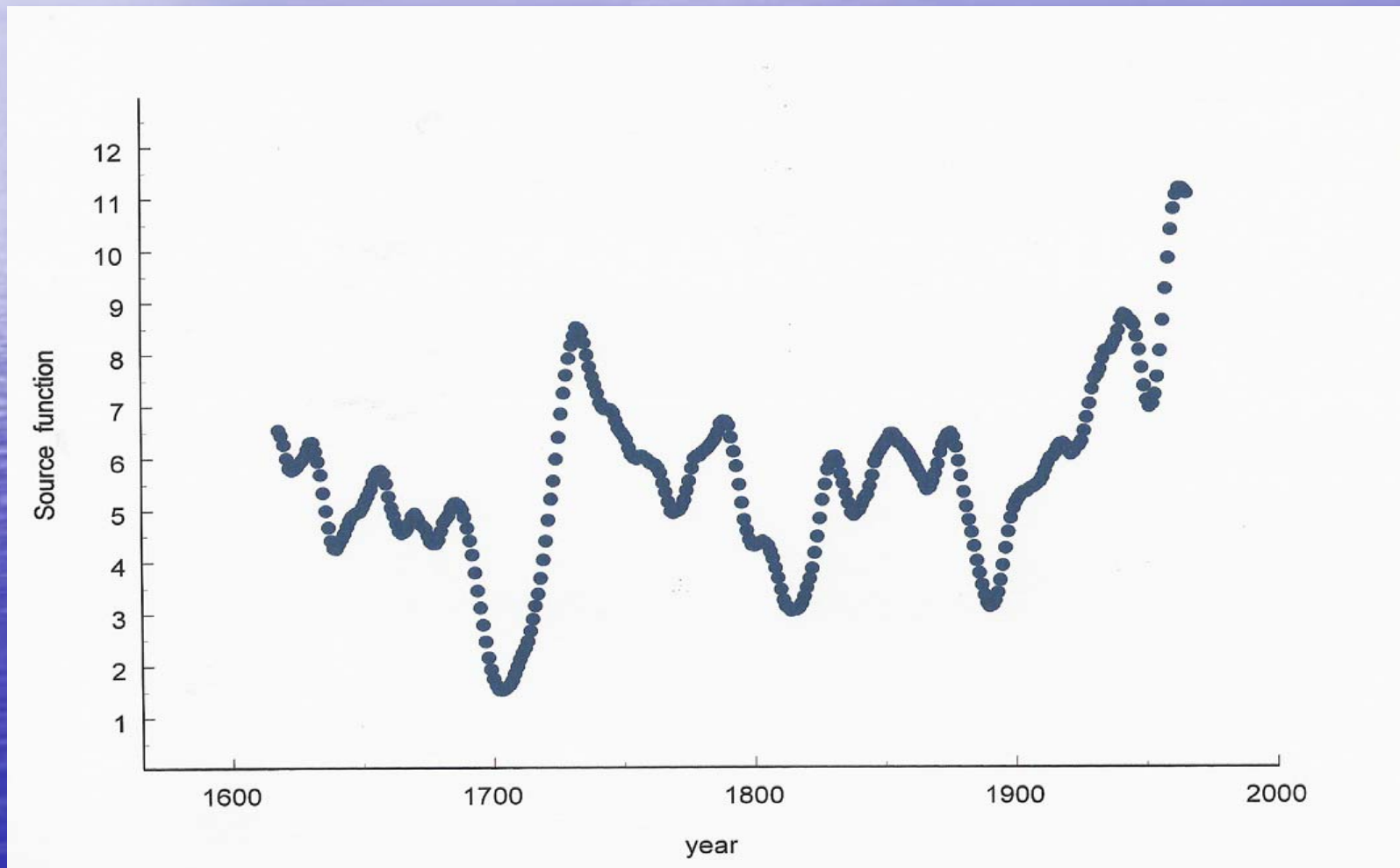
Open solar flux (\sim S-function)

Left: annual data; *Right:* smoothed

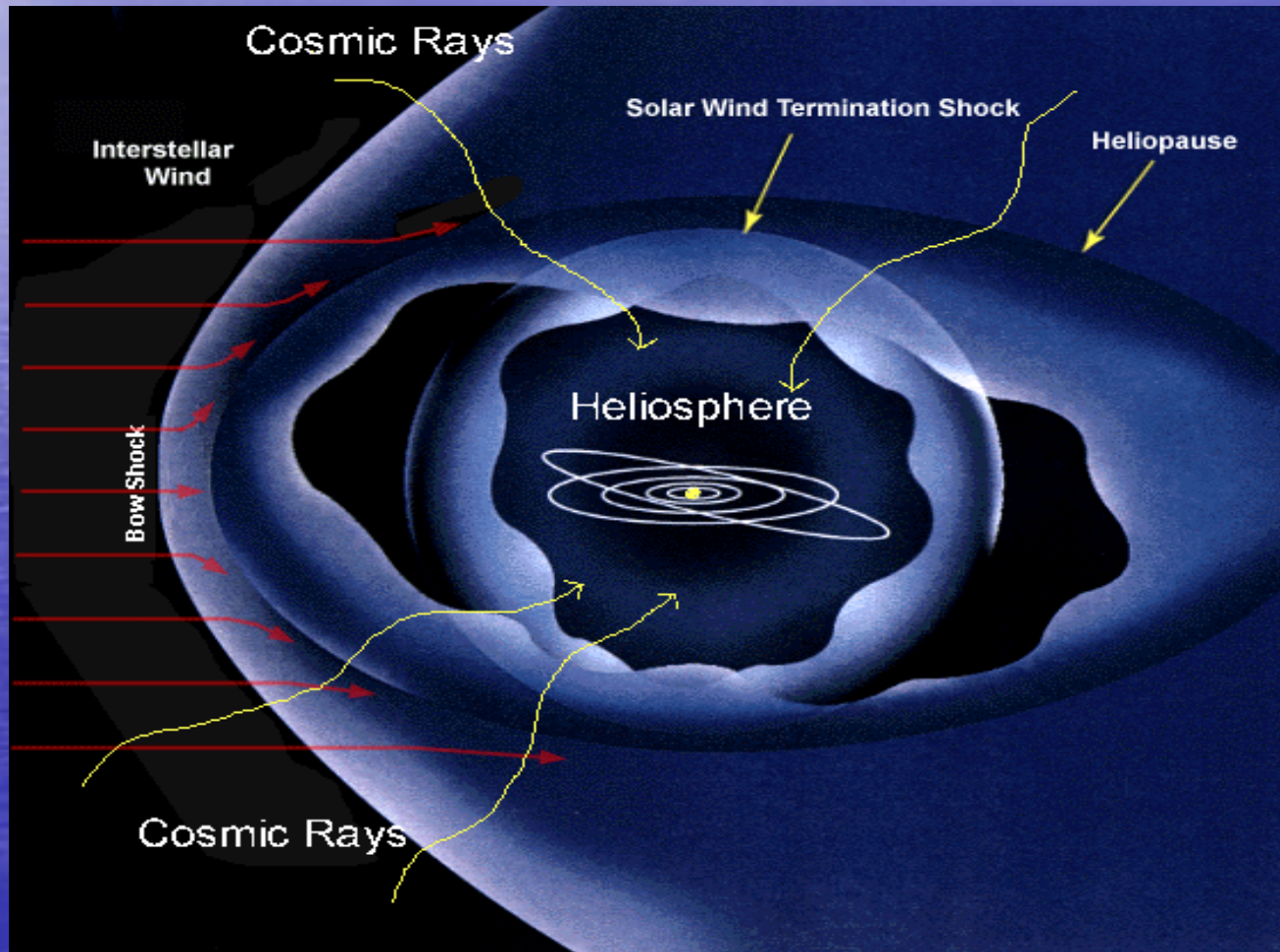
[Refs: Lockwood et al.; Solanki et al.]



Open solar flux again. [Smoothed data from Solanki, Usoskin et al.]

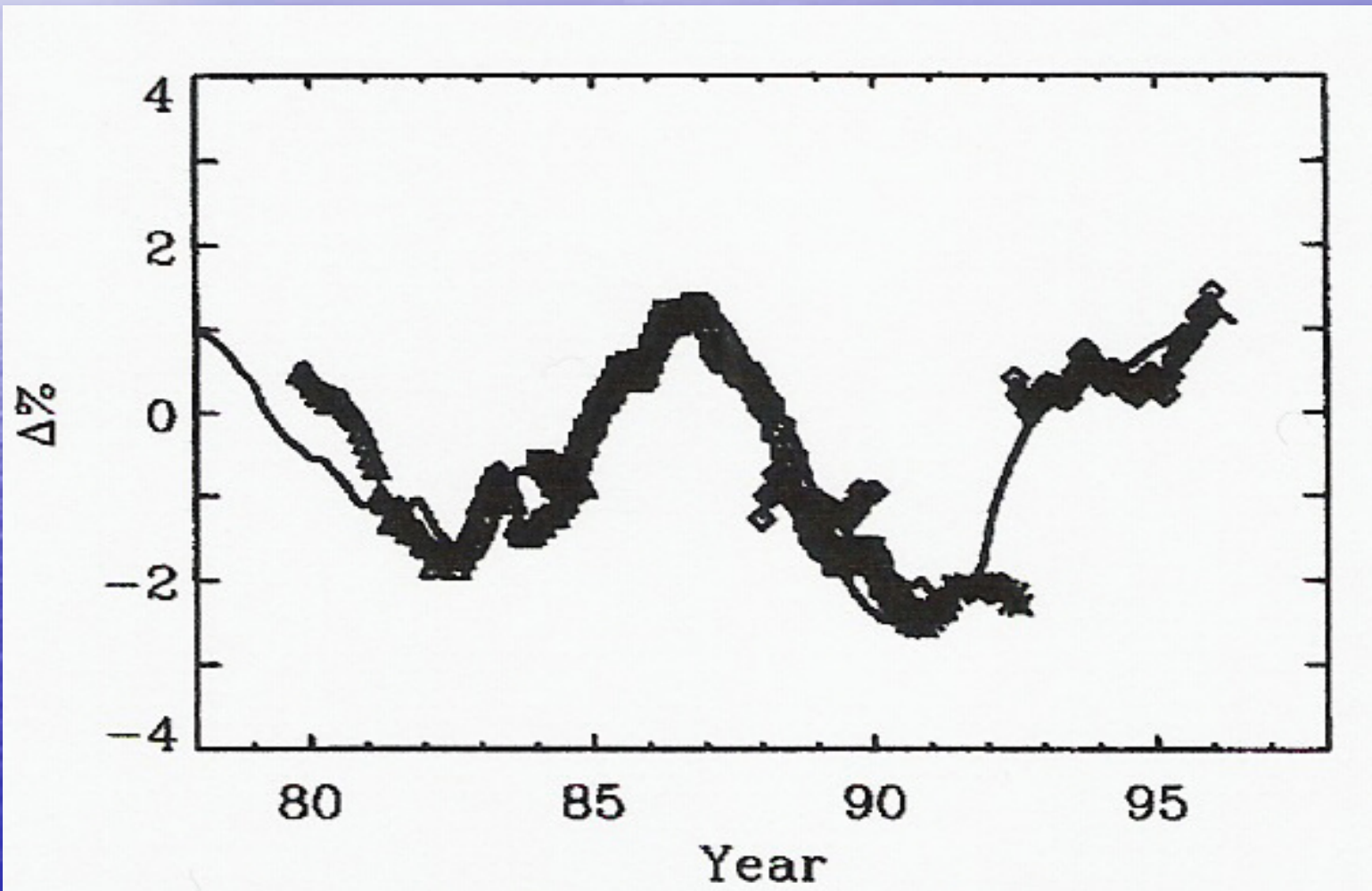


Modulation of cosmic ray flux by magnetic shielding in heliosphere



Cloud coverage variation

parallel to cosmic ray flux [ref Svesnsmark&Friis-Christensen]



Cosmic ray – clouds scenario

Increased solar activity yields:

- Stronger open solar flux; hence
- Larger cosmic ray deflection; causing
- decrease of cosmic ray flux; causing
- Reduced cloud formation; hence
- Increased solar irradiance on Earth and
- Temperature increase

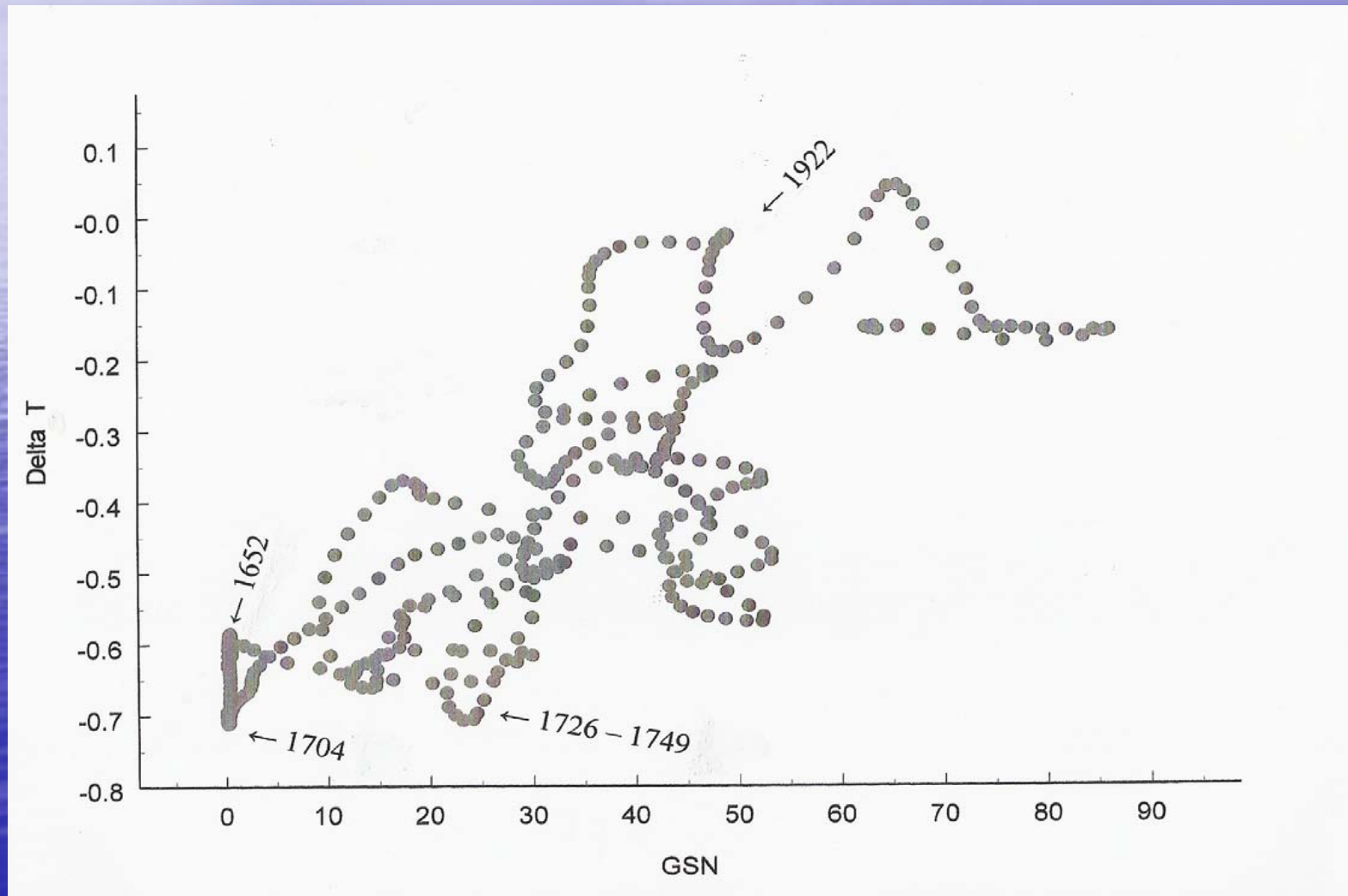
Proxies for cosmic ray activity

- Cosmogenic radionuclides such as ^{10}Be , ^{14}C , etc. are proxies for the cosmic ray flux
- Since observed cosmic ray flux depends on flux of solar ejected magnetized plasma, cosmogenic radionuclides inform us on past solar plasma ejection activity
- Ice cores and sediments offer way to study past history of solar Source Function

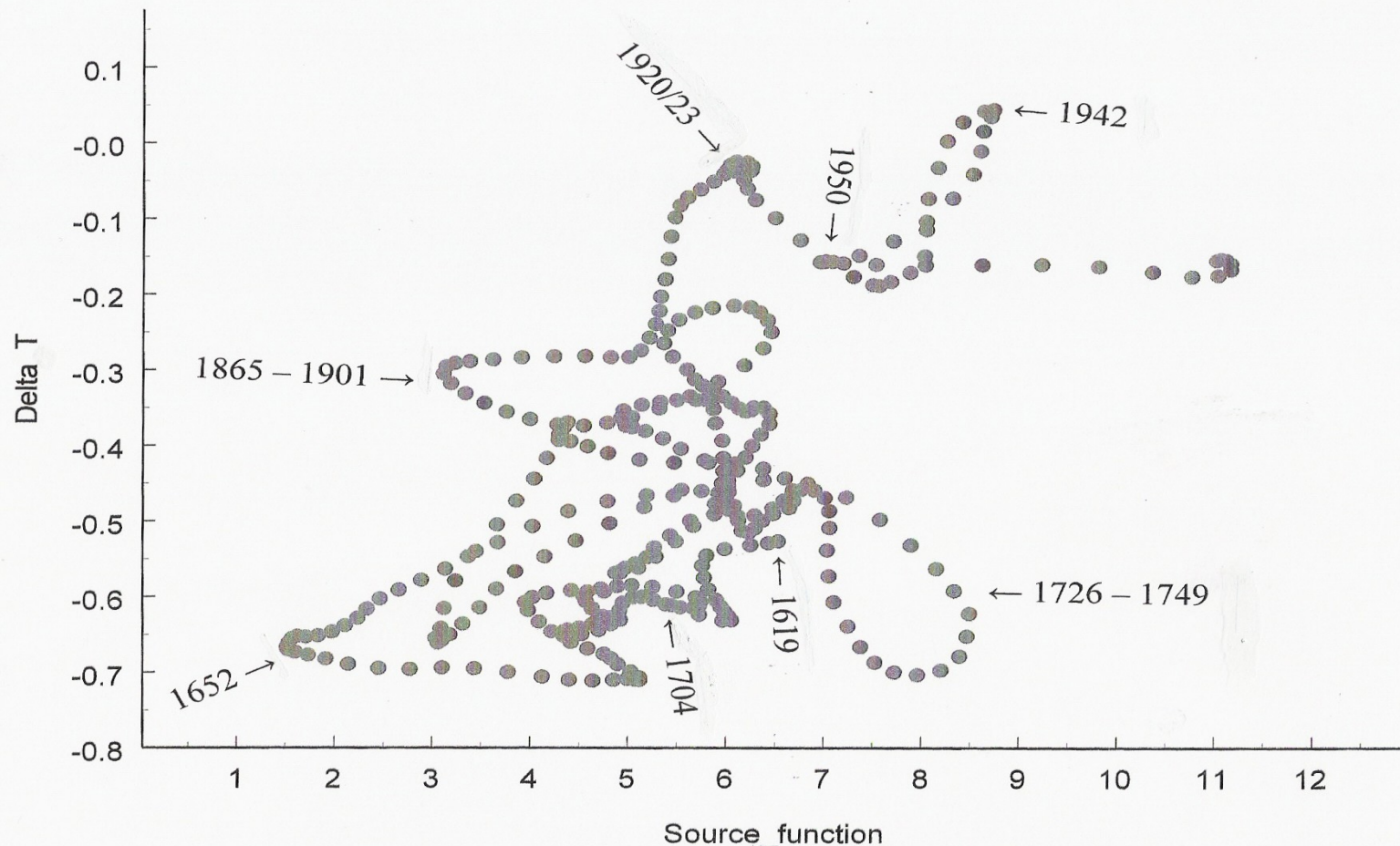
Hence: two possible mechanisms for sun – climate interaction

- Variation of UV radiance, during the solar cycle as well as secular changes
- Variation of cosmic ray flux, due to variable source function (plasma ejection)
- Which of these, or both??

Correlation analysis shows reasonable dependence NH temperatures on Group Sunspot Number (GSN)



But weaker dependence of NH temperatures on Source Function



Full and partial correlation coefficients for R- and S-dependence for various temperature sets [de Jager & Usoskin, submitted]

- | | | | |
|------------------------------|----------------|----------------|-------------------|
| • [Overpeck & Hughen (1997) | $C_{TR} = .60$ | $C_{TS} = .35$ | $P_{T(R)S} = .01$ |
| • Jones et al. (1998) | .55 | .47 | .15 |
| • Mann et al. (1999) | .52 | .50 | .20 |
| • Briffa et al. (2000) | .76 | .48 | .06 |
| • Crowley & Lowery 2000) | .77 | .43 | -.01 |
| • Mann & Jones (2003) | .72 | .54 | .15 |
| • Moberg et al. (2005) | .77 | .43 | .07 |
| • Average: | .67 | .45 | .09 |
- Conclusions: stronger correlation of T with R; partial correlation T-S (=keeping R-correlation fixed) small. T-S correlation is not zero because of the significant S-R correlation (due to CME's from Active Regions).

Hence:

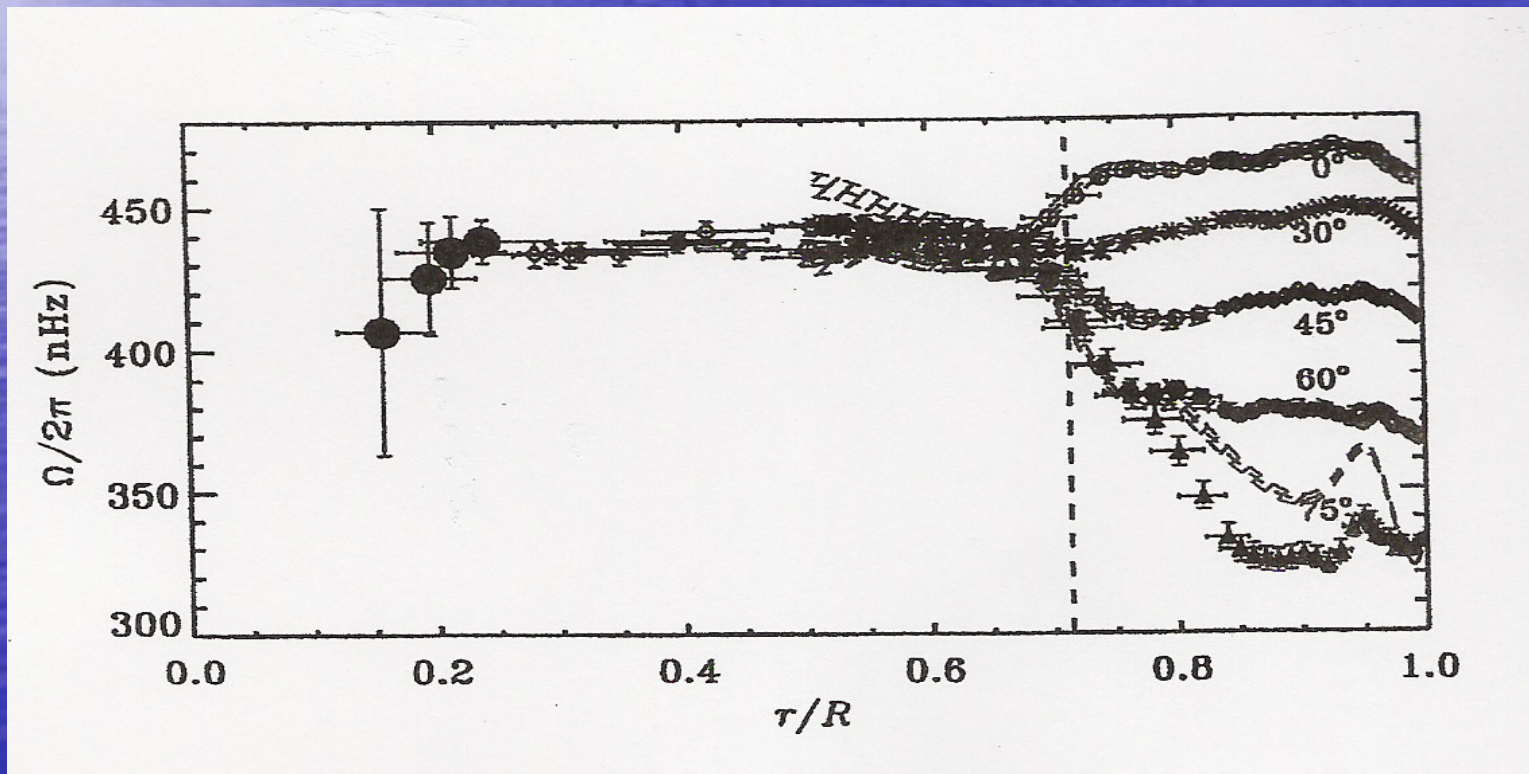
- Sun-related NH temperature variations are coupled to variations in Active Region (UV) radiance rather than to those in open solar flux

THE SOLAR DYNAMO

The engine of solar activity

The sun's internal rotation

- varies with depth and latitude
- *tachocline* at $r/R_{\odot} = 0.69$; strong shearing motions in overshoot layer of convection zone



Tachocline: seat of dynamo; Ω effect

- Shearing motions in existing magnetic fields generate poloidal magnetic fields
- Differential rotation cause toroidal components by stretching and amplifying fields
- Equipartition field strength 10^4 Gauss
- Further amplification till 10^5 Gauss cause kink instability of the fluxes, leading to flux tube detachment and buoyancy
- Rise time is few months; sunspots at surface

Oscillating magnetic field in tachocline

Magnetic field oscillates with period

$$P = \eta / (\pi H^2),$$

where H = storage thickness of field.

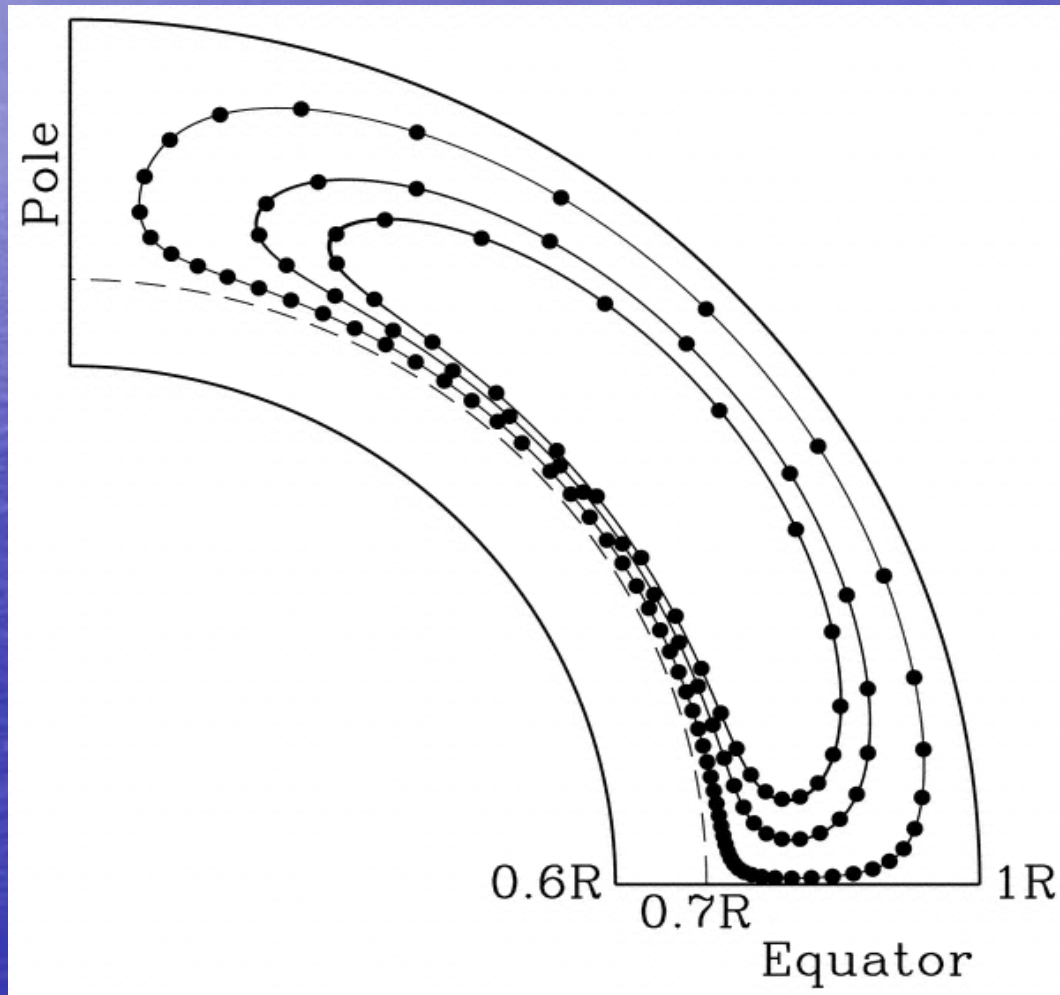
With η (turbulent magnetic diffusivity) = $10^{11} \text{ cm}^2 \text{ s}^{-1}$ and H (thickness tachocline) = $.04R_{\odot}$ we find $P \sim 4 \text{ yr}$

Active longitudes

- Two active longitudes, 180° apart [Neugebauer et al., 2000; Ruzmaikin et al. Usoskin et al., de Toma et al., Caligari et al. Akasofu et al.]
- Non-axis symmetric modes in field, to be represented by two dipoles
- Simple representation: wavelength of periodic oscillation of tachocline is half of solar circumference

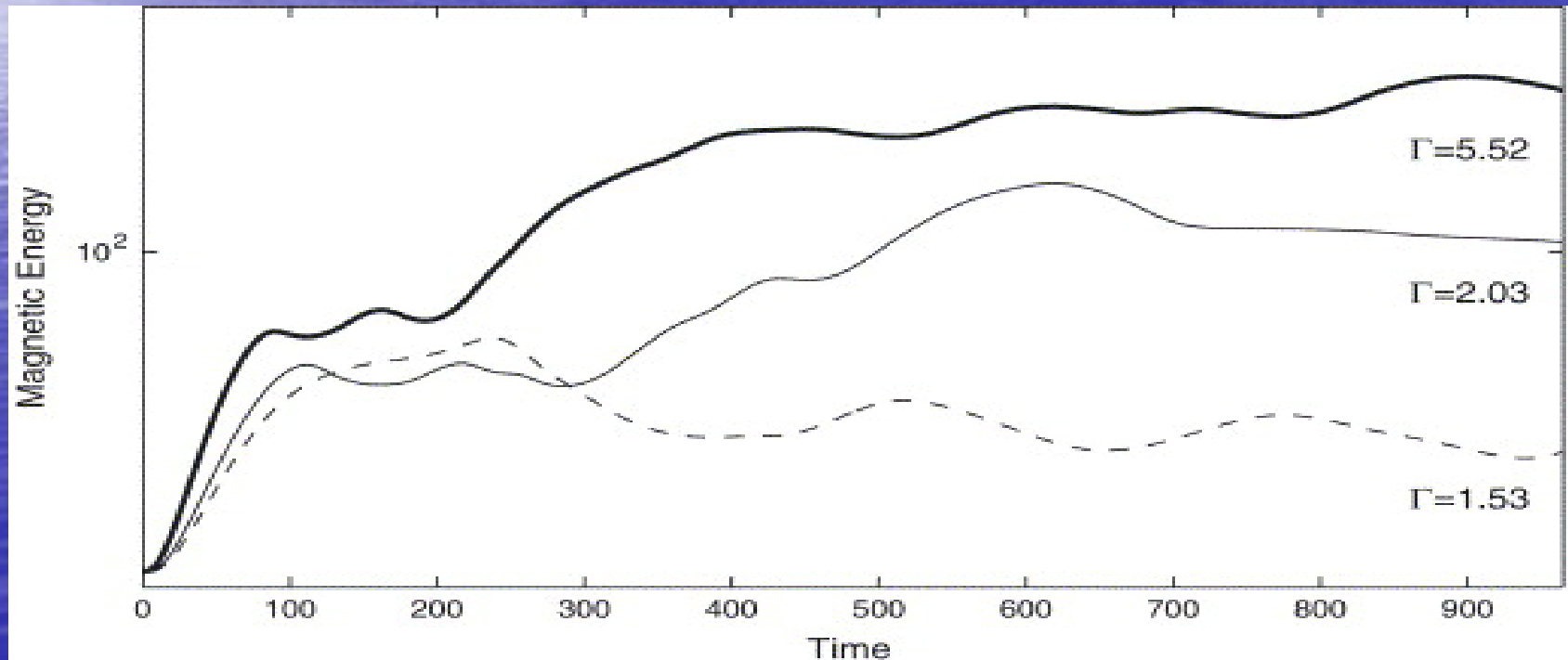
Equator-ward and pole-ward drift demand meridional circulation (~ 1 m/sec)

[Hathaway et al; Dikpati et al., and others]



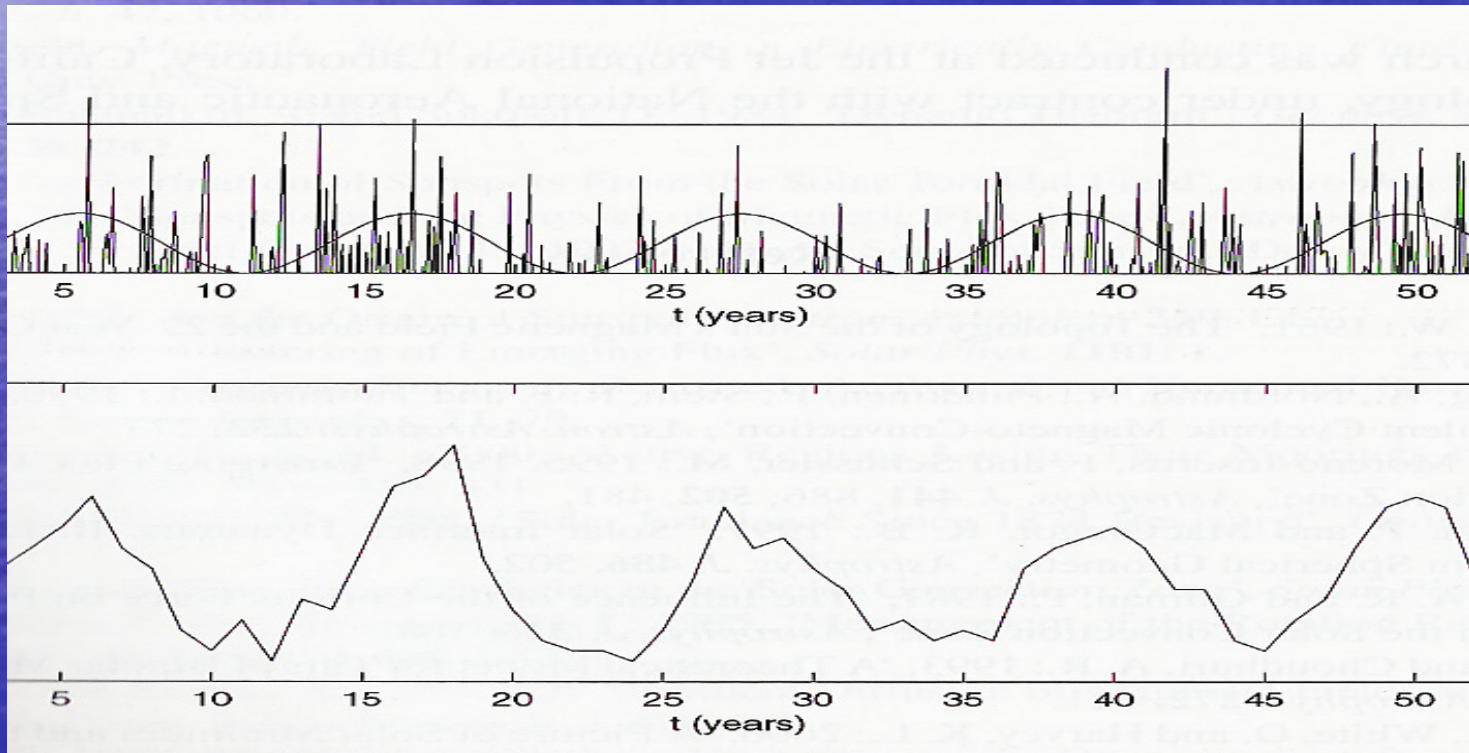
Flux amplification and emergence

- Toroidal stretching amplifies field
- Amplification by factor ~ 100 in \sim one year [Lillo et al. 2005]

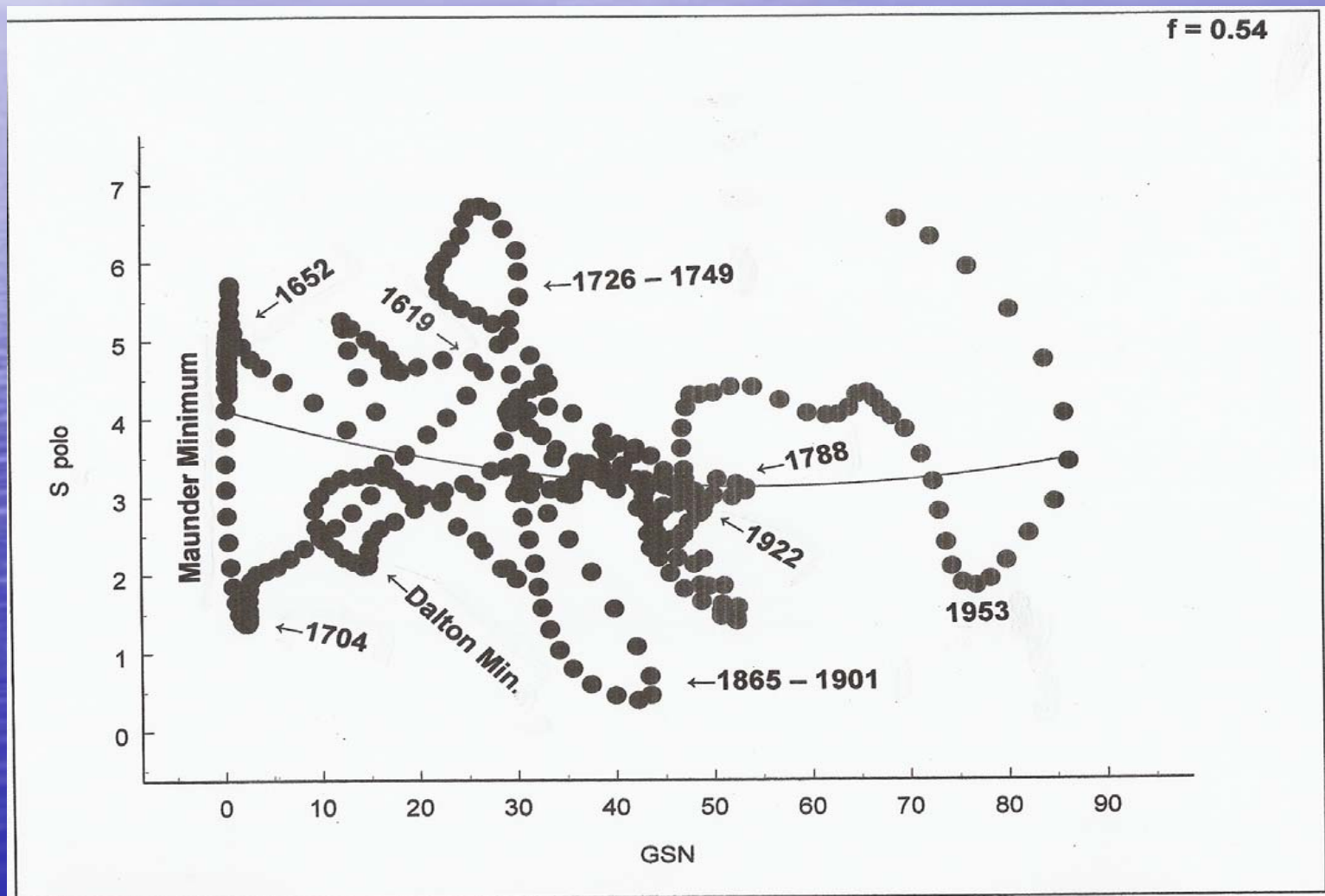


A sunspot cycle hypothesis

- Production of flux tubes: *ongoing process*
- Assume: basic oscillation of tachocline and superimposed randomly appearing unstable loops [Ruzmaikin; Usoskin et al.]



Chaotic dynamo appears in smoothed data
by plotting S_{poloidal} against R (toroidal field) [deJager & Duhaou]



Main conclusion

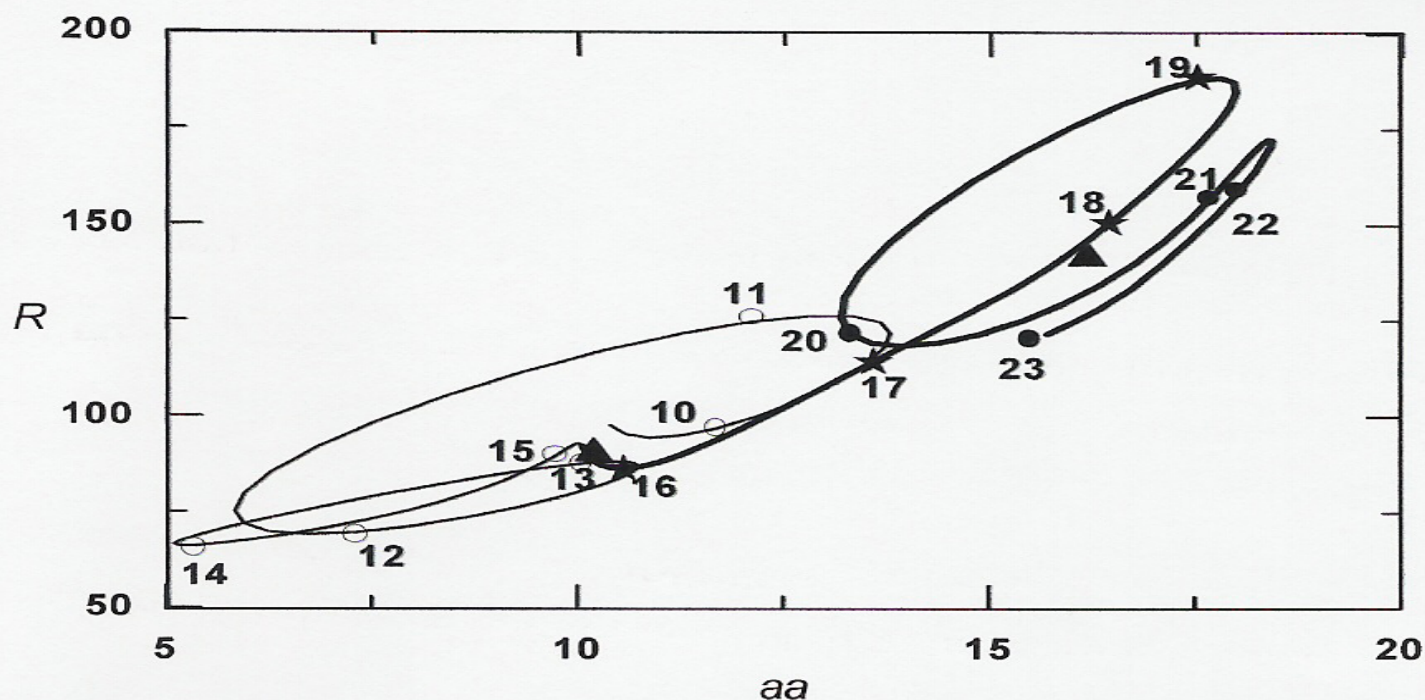
- At time scales of Schwabe cycle or above: high-latitude field is not correlated with toroidal (low-latitude) field
- Best example: Maunder Minimum
- This conclusion has inferences for the origin of high-latitude phenomena
- Note also the quasi-chaotic jumps (*e.g.* 1704, 1922)

The alpha effect

- Weaker fields are lifted but do not reach surface
- 'Explode' in convection zone; are deformed by cyclonic convection, with simultaneous expansion and rotation → the α effect
- When arriving at the surface these fields are chiefly poloidal
- They ascend primarily parallel to solar axis
- Hence appear in higher latitudes

Hysteresis and phase catastrophe

- A plot of R -max (toroidal field) against aa -min (poloidal) shows hysteresis. Another feature: phase catastrophe (1921-'23). [Duhau; Duhau & Chen]



Forecasting solar activity

Is it possible to forecast the behavior of this chaotic system?

Quasi-periodicities

- Five significant (quasi-)periods in solar activity: 11 yrs (Schwabe); 22 yrs (Hale); 1-2 yrs (quasi-biennial, Basilevskaya); 88 yrs (Gleissberg); 205 yrs (De Vries or Suess); 2300 yrs (Hallstatt).
- All quasi-periods are variable and none of them is constant in time. Gleissberg period has even two maxima, interchanging in importance during past centuries
- Phase catastrophes have occurred at least twice: ~ 1788 and ~ 1922

Is forecasting possible?

- Ratio between strengths of poloidal and toroidal fields appear to vary with time; not correlated in intervals \geq Schwabe cycle. Best example: Maunder Minimum.
- Solar dynamo: non-linear system, a quasi periodic engine with the properties of deterministic chaos.
- Its future is unpredictable

SUMMARY OF TALK

- Two aspects of variability: plasma ejection and UV radiance
- NH temperature correlated with variation in UV radiance
- Plasma ejection from low- and high-latitude areas
- Dynamo: seated in tachocline. Main aspect: the toroidal fields. Byproduct: poloidal magnetic fields.
- Toroidal fields generate activity centers; poloidal fields in high latitude magnetic areas
- Dynamo is chaotic and unpredictable system