INTERNATIONAL SPACE SCIENCE INSTITUTE

International Team

Effects of Interplanetary Disturbances on the Earth's Atmosphere and Climate

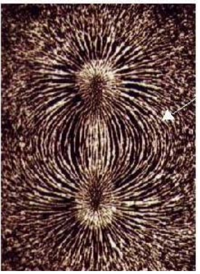
COST Action ES1005

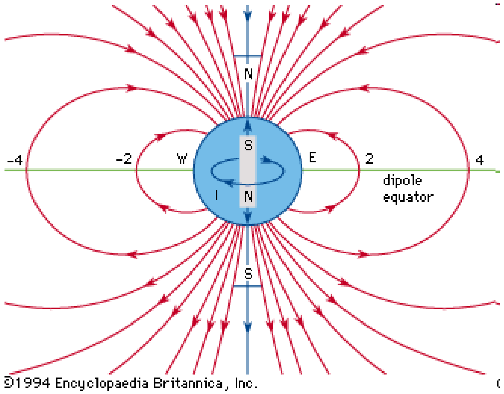
TOSCA - Towards a more complete assessment of the impact of solar variability on the Earth's climate

background

- The Sun is the only significant external energy source in the vicinity of the Earth
- The solar variability is due to the action of solar dynamo
- The solar dynamo transforms two types of solar magnetic fields: poloidal and toroidal
- All geoeffective manifestations of solar activity are related to these two faces of solar magnetism

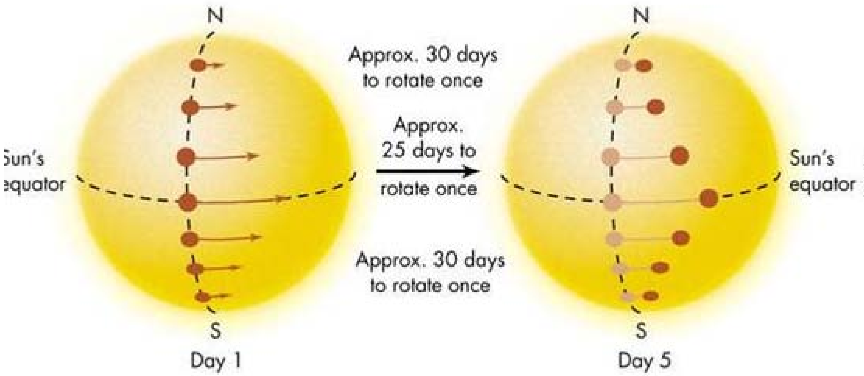
How the solar dynamo operates





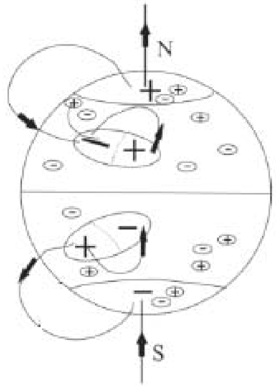
Dipolar, or poloidal magnetic field in sunspot min

poloidal to toroidal field (Ω-effect)

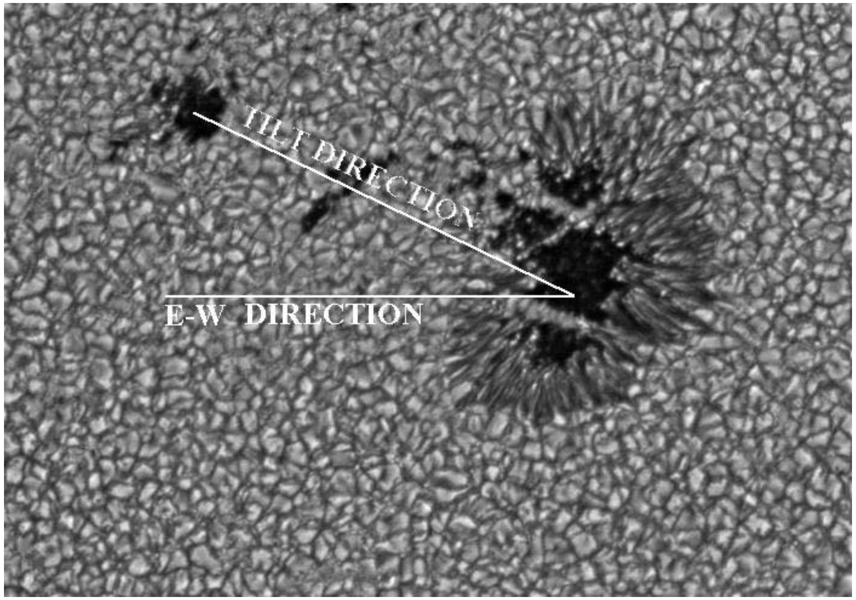


Differential rotation stretches the poloidal field

The buoyant magnetic field tubes rise up, piercing the surface at two spots (sunspots) with opposite magnetic polarities.



Toroidal to poloidal field (α-effect)



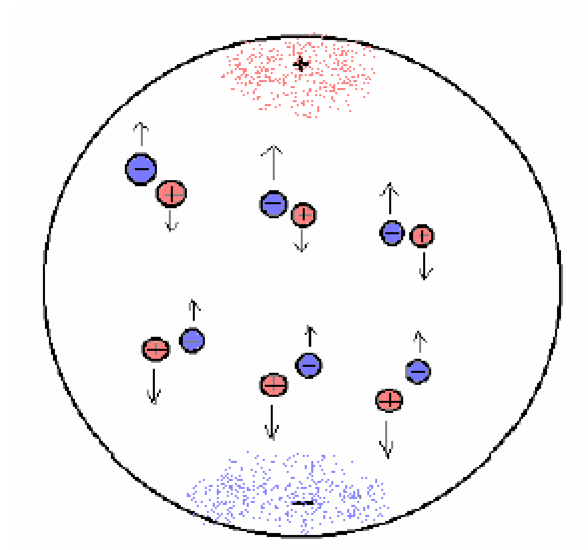
Babkock-Leighton mechanism

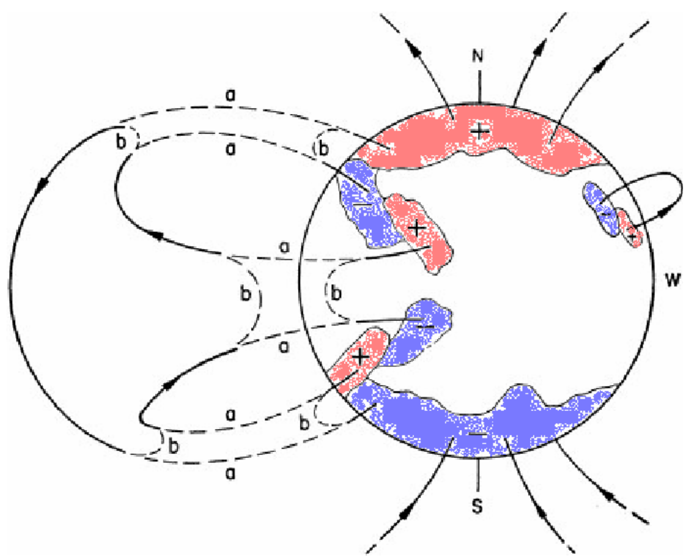
Due to the Coriolis force during the flux tube emergence, the sunspot pairs are tilted to the E-W direction

Late in the sunspot cycle:

leading spots diffuse across the equator

cancel with the opposite polarity leading spots in the other hemisphere.

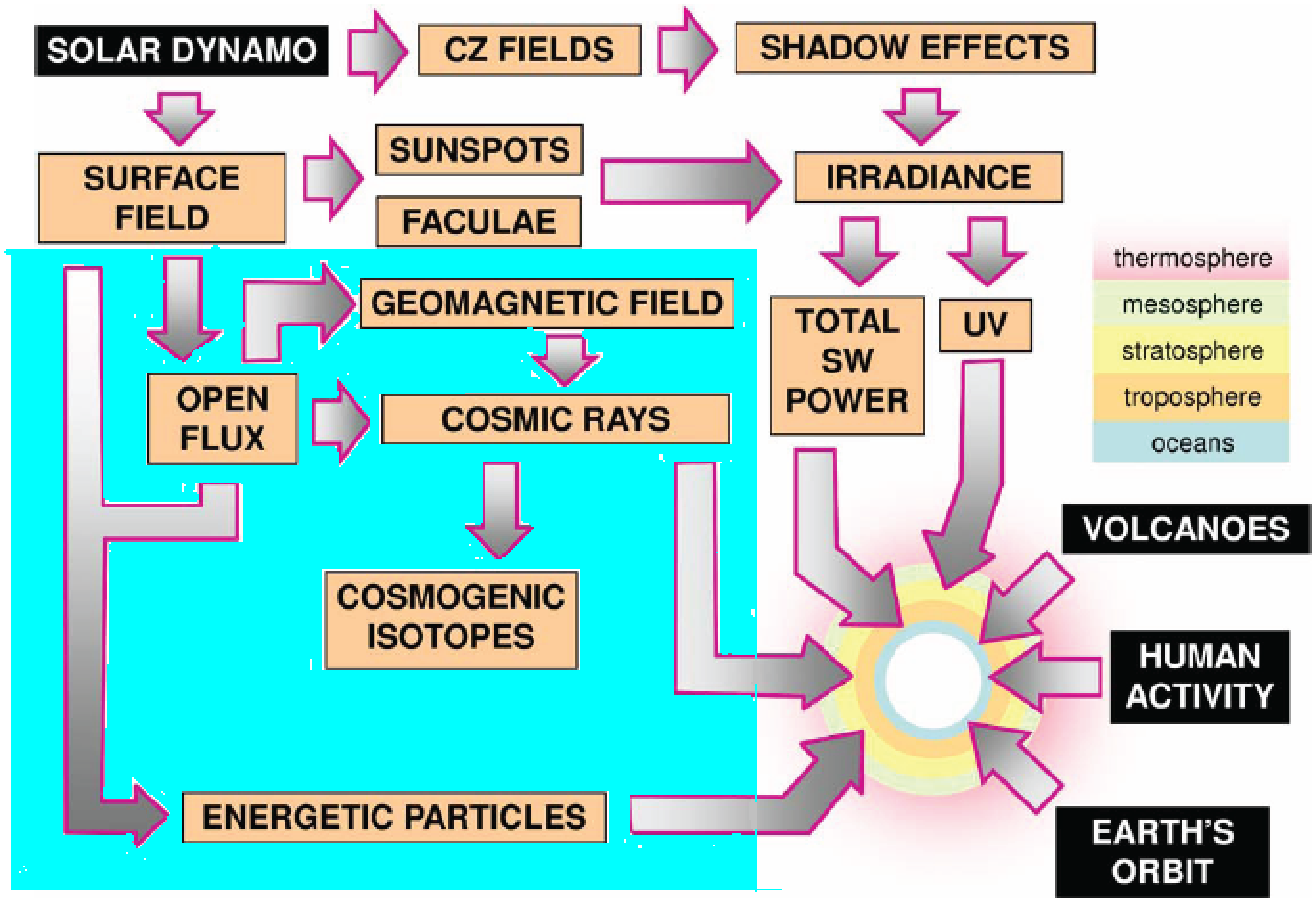




⇒ excess trailing spots flux carried to the poles

- cancels the flux of the previous cycle
- accumulates to form the poloidal field of the next solar cycle with the opposite polarity

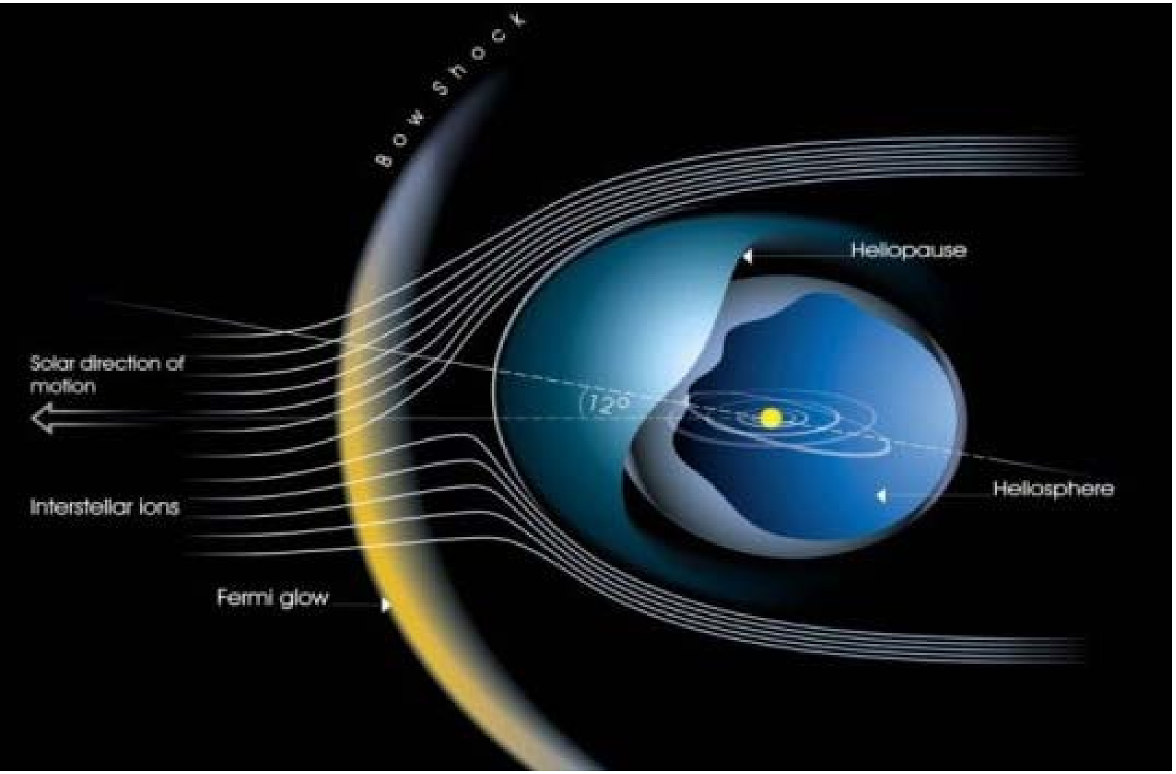
Schematic overview:
climate forcings associated with solar variability



Interplanetary disturbances affecting weather and climate

- Energetic particles (EPP, SPE)
- Coronal mass ejections (CMEs)
- High speed streams (HSS)
- Galactic cosmic rays (GCR)
- Solar wind carrying EP, SP, CMEs, HSS, modulating GCR, carrying solar plasma and magnetic fields

Solar wind – expansion of the solar corona



The solar corona is not in hydrostatic equilibruim

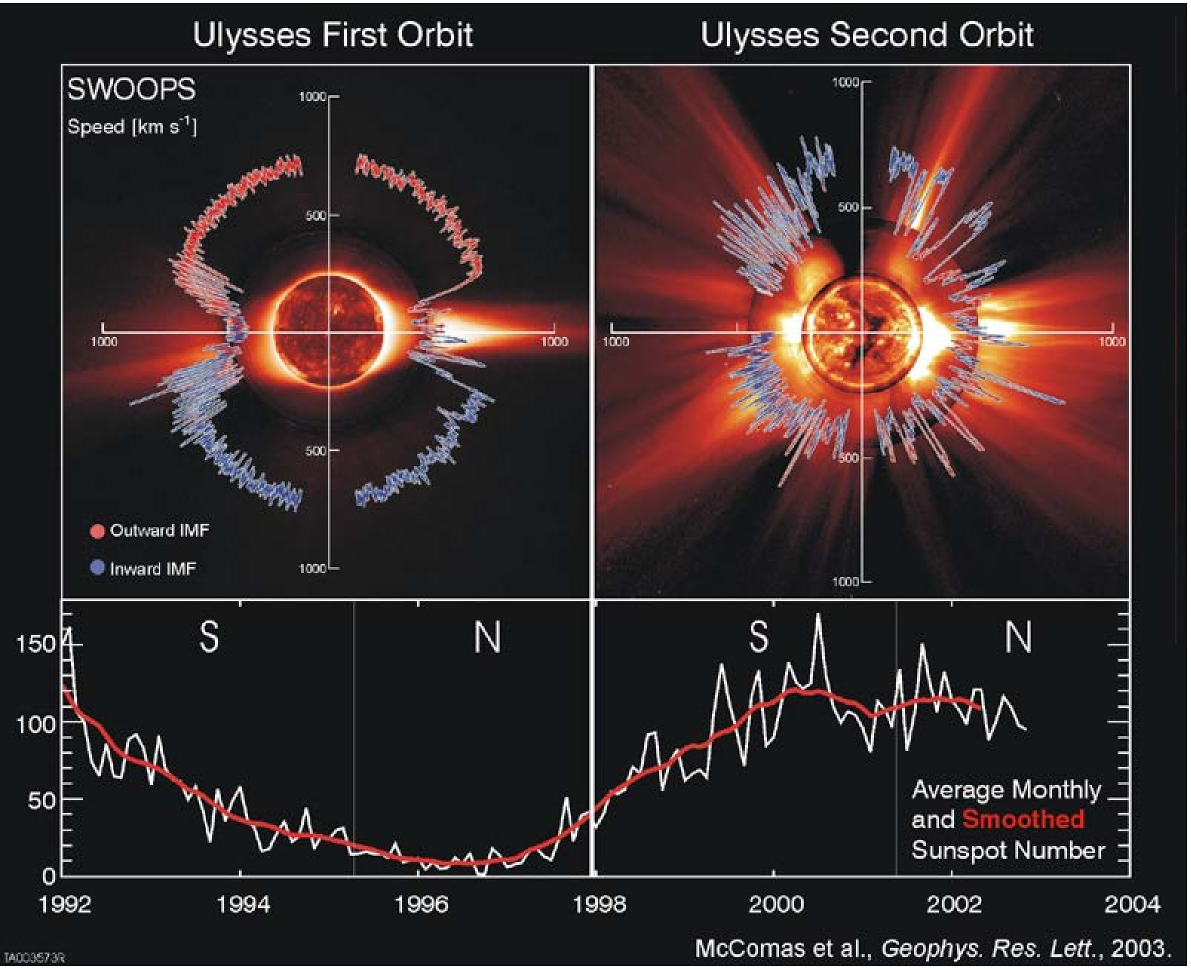
⇒The corona (≡ the solar atmosphere) is expanding until it encounters the interstellar matter

Eugene Parker (1956)

The solar wind carries plasma with embedded magnetic fields to the Earth

The interaction of the solar wind with the Earth's magnetic field leads to geomagnetic disturbances

Solar wind components

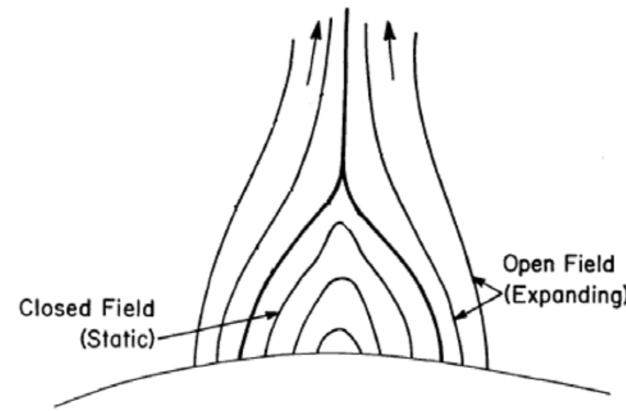


- Slow solar wind
- Quasistationary fast solar wind (HSS)
- Transient solar wind disrurbances (CMEs)

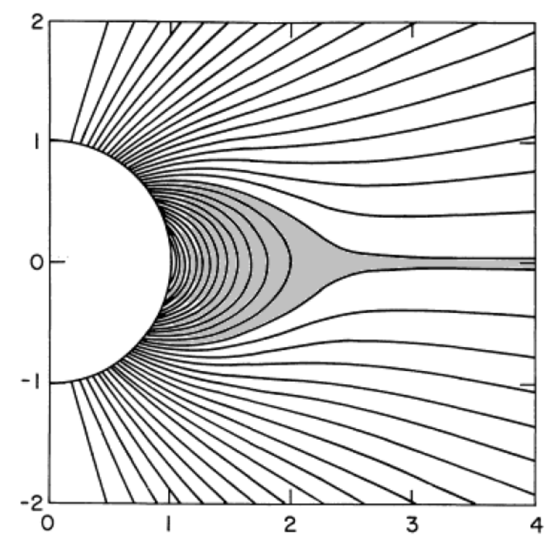
Source of slow solar wind

Classical Parker's (1958) theory:

the solar wind is a continuous outflow of plasma from the Sun due to the lack of hydrostatic equilibrium in the solar corona, leading to its expansion.

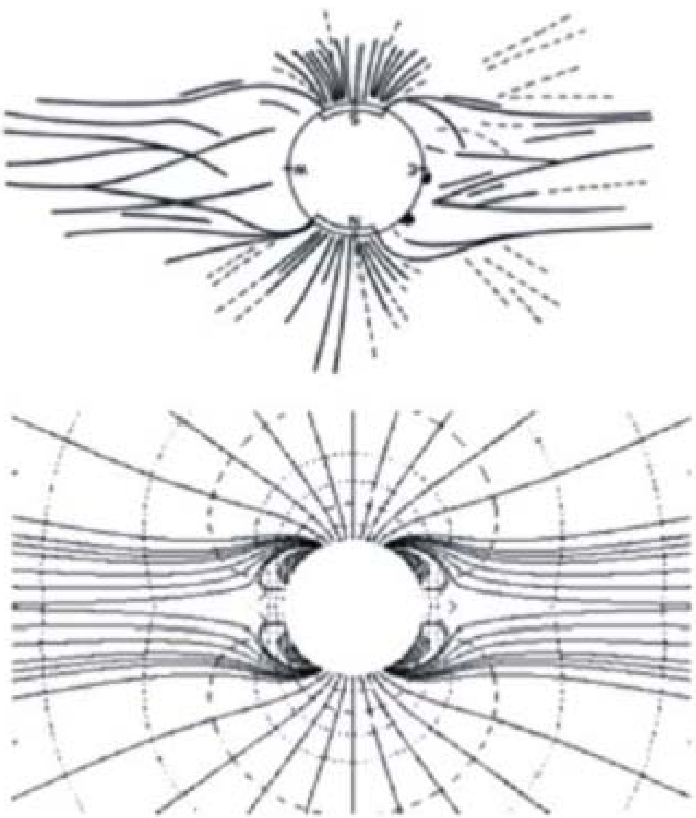


Pneuman and Kopp (1971): gas – magnetic field interaction



⇒ slow solar wind can emanate not from the whole corona but from "helmet" streamers: regions of open magnetic loops with open field lines adjacent to and above the loops

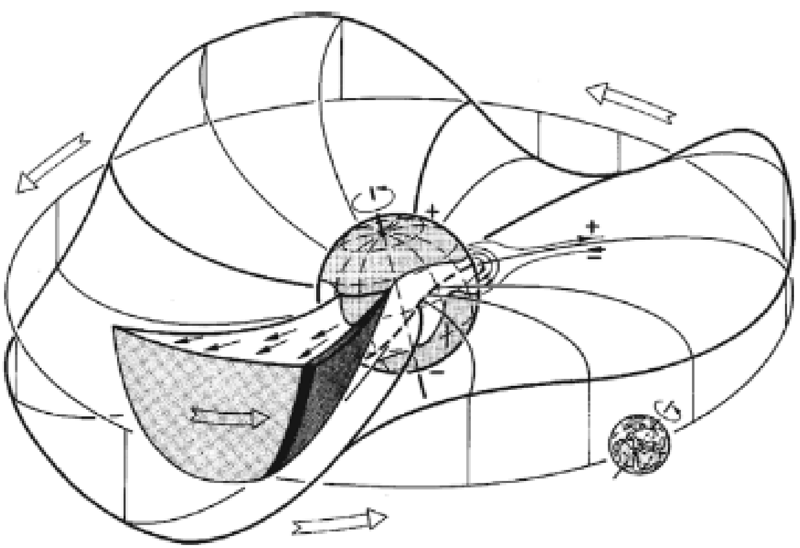
Source of the slow solar wind: the equatorial streamer belt (heliosheet)

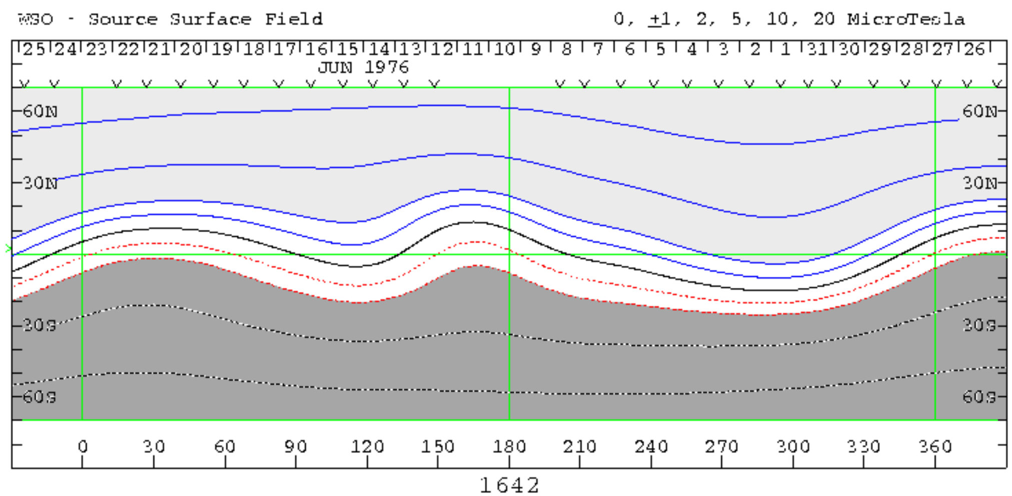


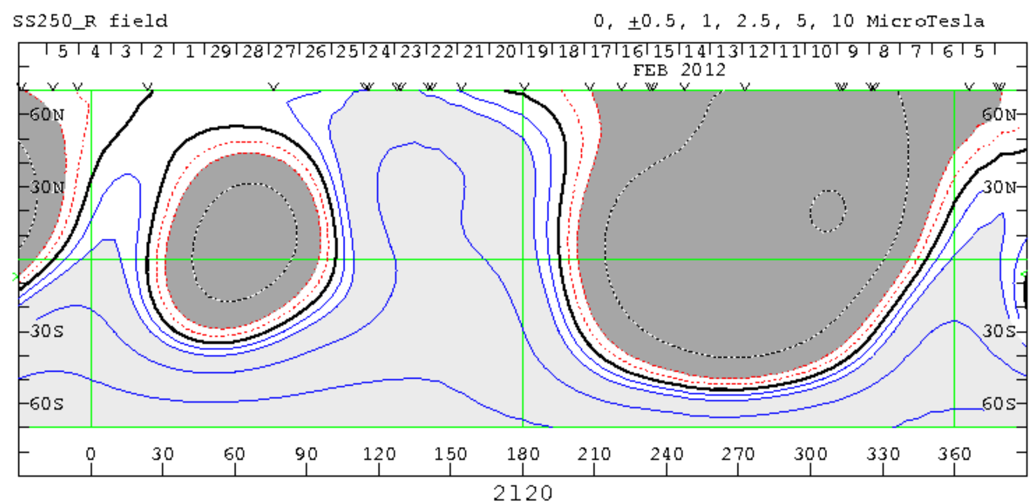
Simon and Legrand (1987)

- The annual number of geomagnetically “quiet” and “very quiet” days is determined by the time the Earth spends in slow solar wind from the equatorial streamer belt

The time the Earth spends in slow solar wind from the equatorial streamer belt depends on the solar cycle phase







Sources of the quasistationary fast solar wind (HSS)
M-regions (Bartels, 1932)

- Maunder (1905) - link to the solar rotation period
- Chree and Stagg (1927) – only the smaller storms are recurrent
- Babcock and Babcock (1955) – M-regions are unipolar magnetic regions
- "Mariner-2" (1967) – high-speed wind recurring at 27 days related to recurrent storms

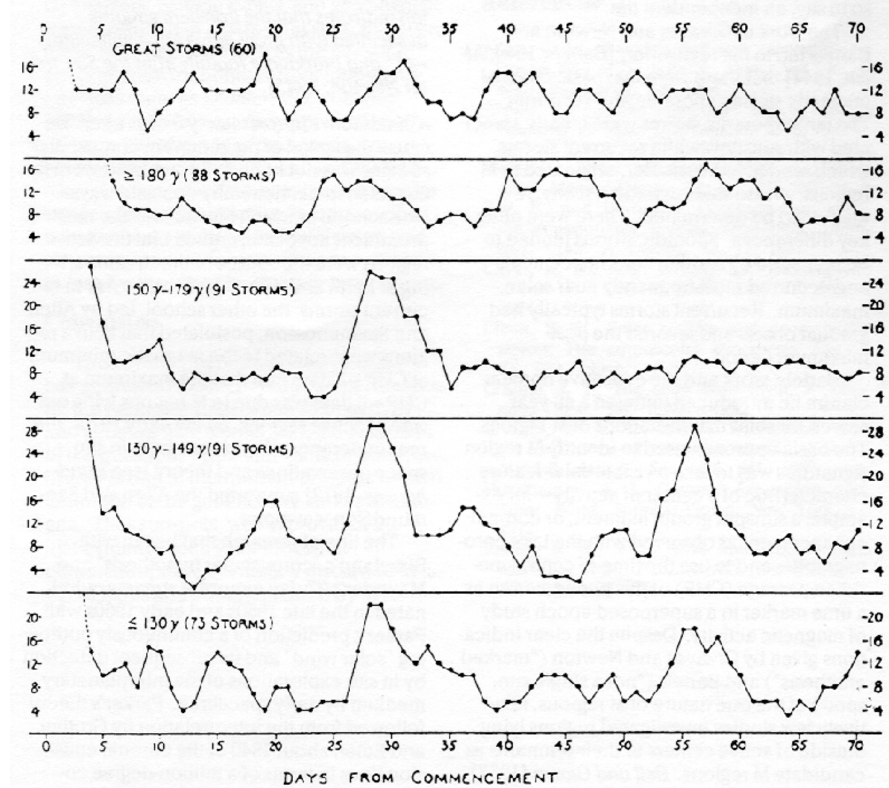
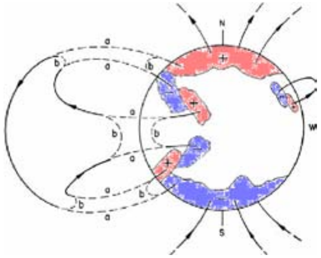


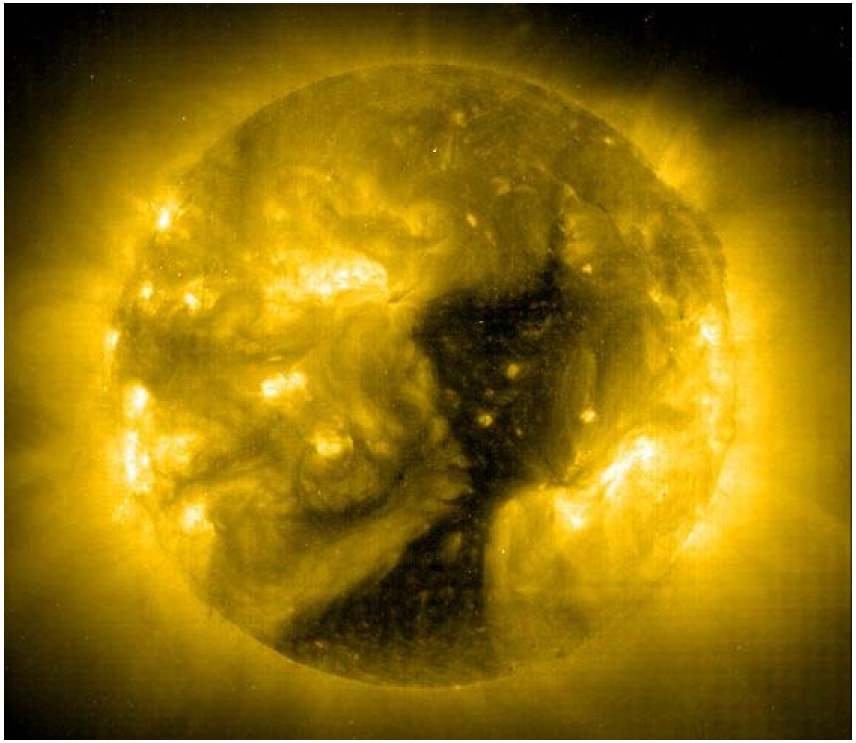
Fig. 1. Figure from Greaves and Newton [1929] showing that the 27-day recurrence property of magnetic storms is mainly a property of the smaller events. The y axis in this superposed epoch analysis gives the percentage of cases in which magnetic storms of any size were observed on given days following storms of the indicated sizes.

The source of high-speed solar wind: coronal holes

- **Unipolar** regions, remnants of sunspot pairs

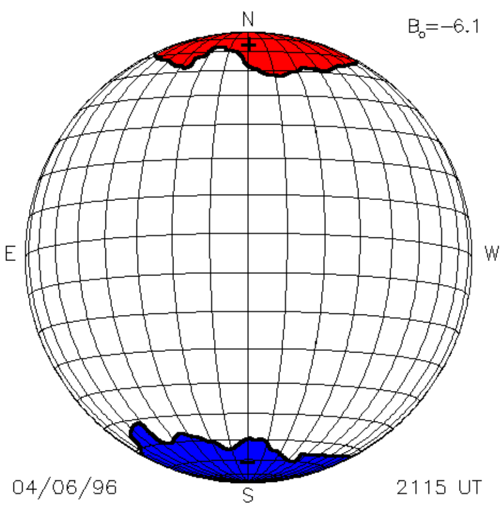


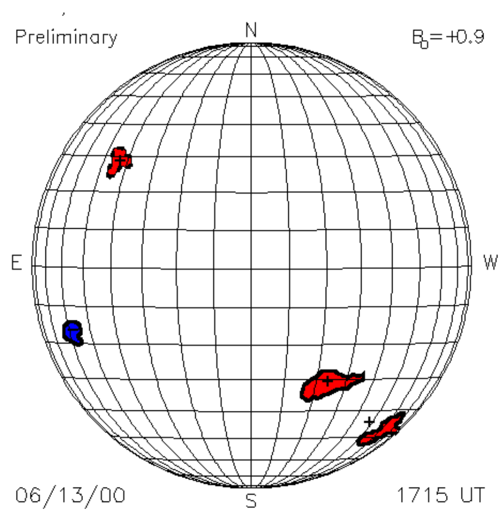
- Areas of **open magnetic field lines**
- Reduced density
  ⇒ dark in X-rays
- Long lived
- Sources of recurrent geomagnetic storms

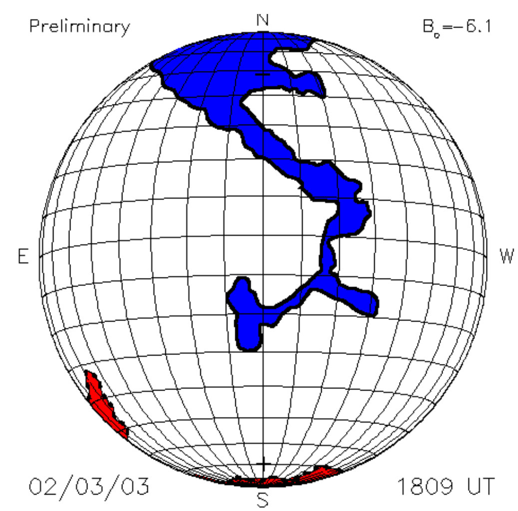


Solar cycle dependence of coronal holes

minimum in sunspot maximum and maximum on sunspot decline phase





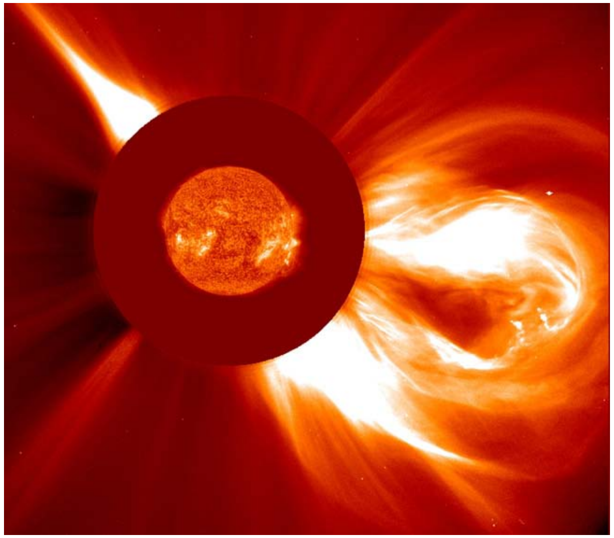


Sunspot min:
large polar coronal holes; no coronal holes at low latitudes

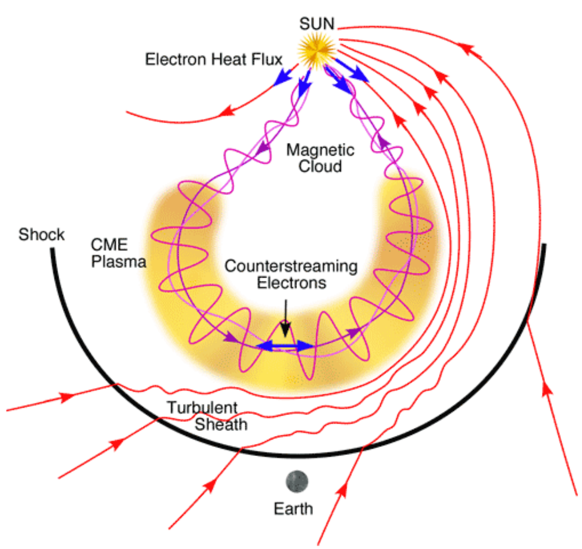
Sunspot max:
small scattered short-living coronal hole at all latitudes

Sunspot decline phase:
big long-lasting holes at all latitudes

Sources of transient solar wind disrurbances:
Coronal Mass Ejections (CMEs)



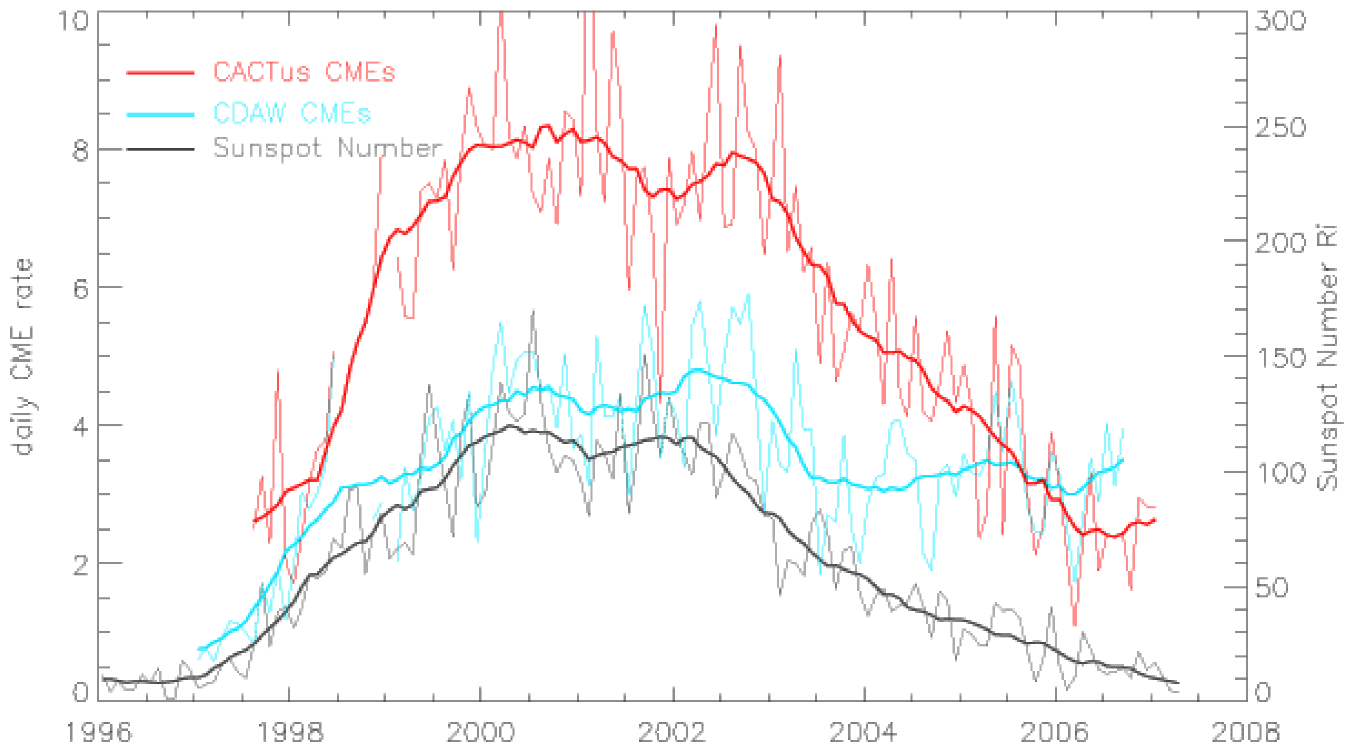
eruption of plasma and embedded magnetic fields from the corona



Coronal mass ejections interact with the Earth's magnetic field and lead to geomagnetic storms

CME formation

CMEs are formed by the same mechanism as sunspots



Max in sunspot max
Min in sunspot min

Effects and solar cycle distribution

Slow solar wind: max in sunspot min

- background geomagnetic activity
- galactic cosmic rays modulation
- solar wind electric field

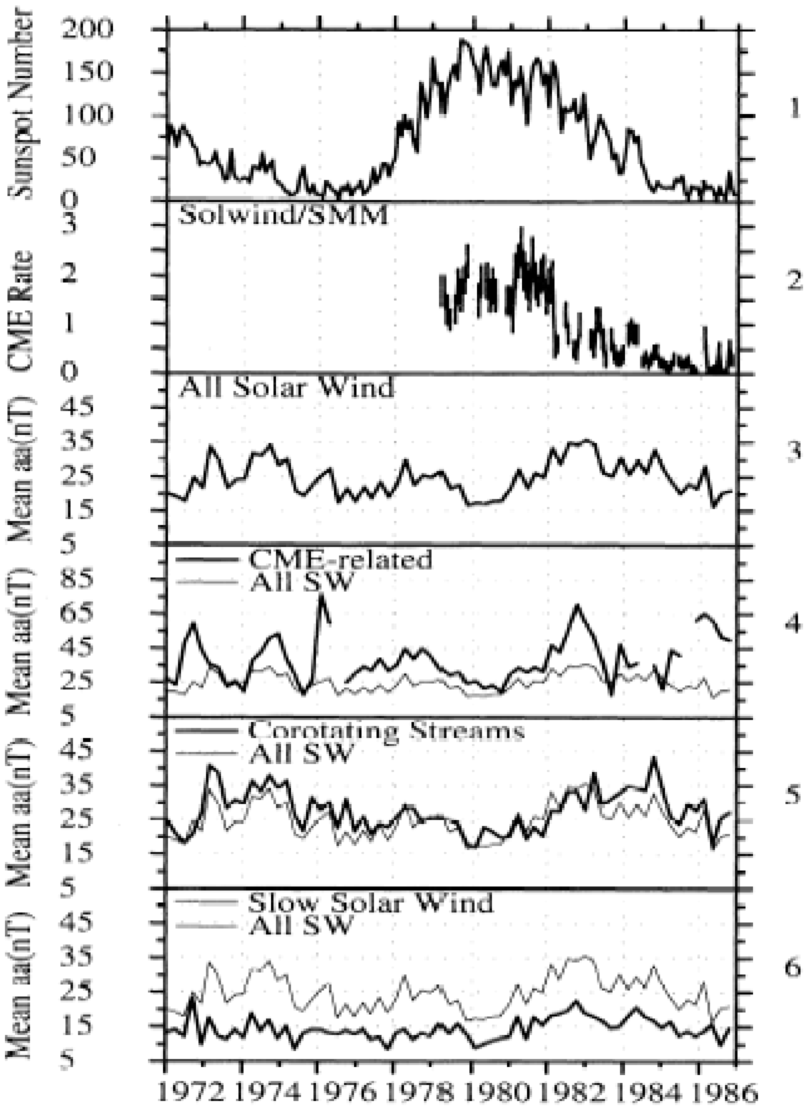
High speed solar wind: max during sunspot declining phase

- recurrent geomagnetic storms
- galactic cosmic rays modulation
- energetic particles precipitation
- solar wind electric field
- solar wind electric field

Coronal mass ejections: max during sunspot max

- Sporadic geomagnetic storms
- galactic cosmic rays modulation
- energetic particles precipitation, solar proton events
- solar wind electric field
- solar wind electric field

Geomagnetic activity sources during the sunspot cycle

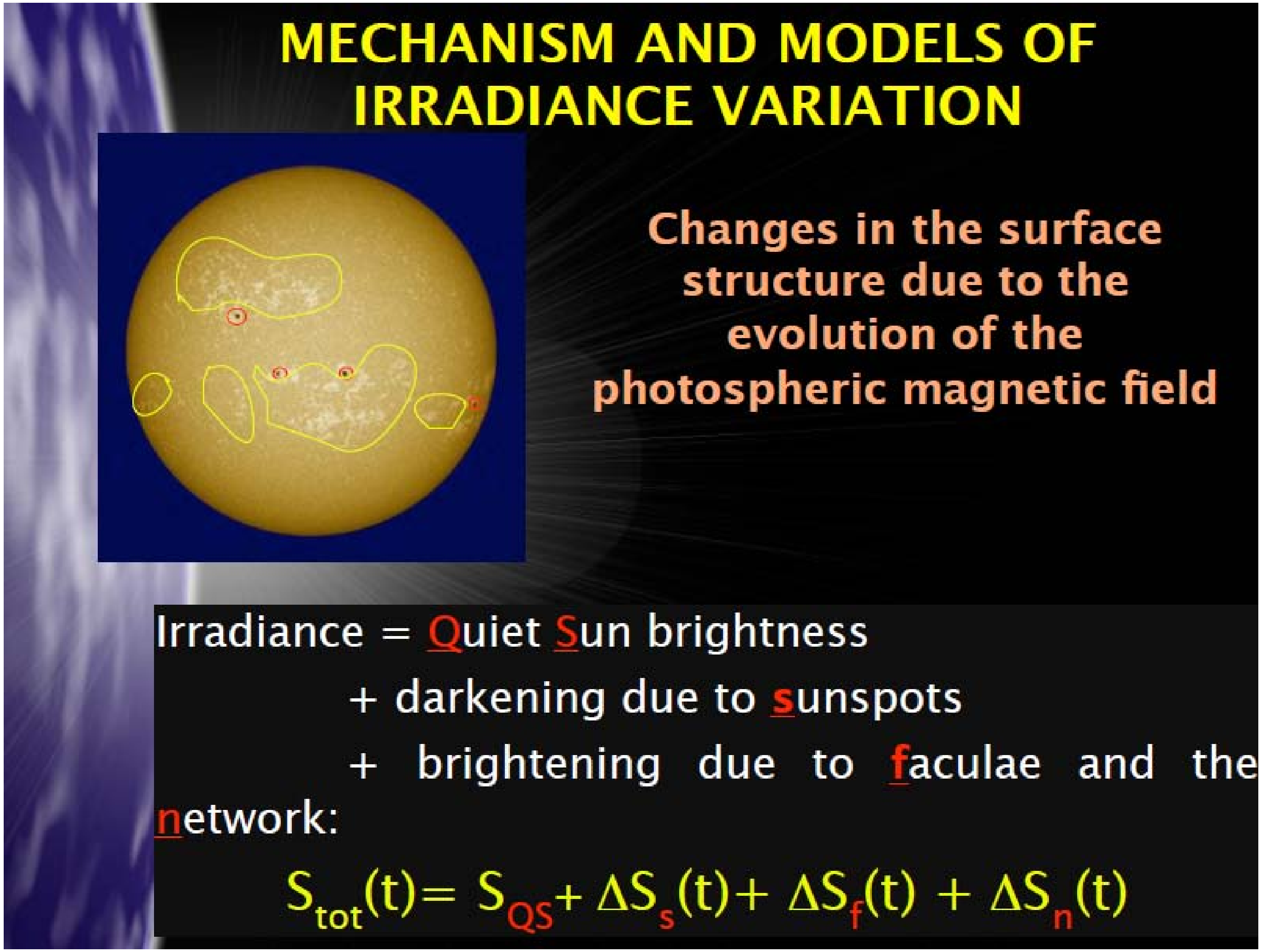


slow solar wind and high speed solar wind provide the main impact to geomagnetic activity in the 11-year sunspot cycle

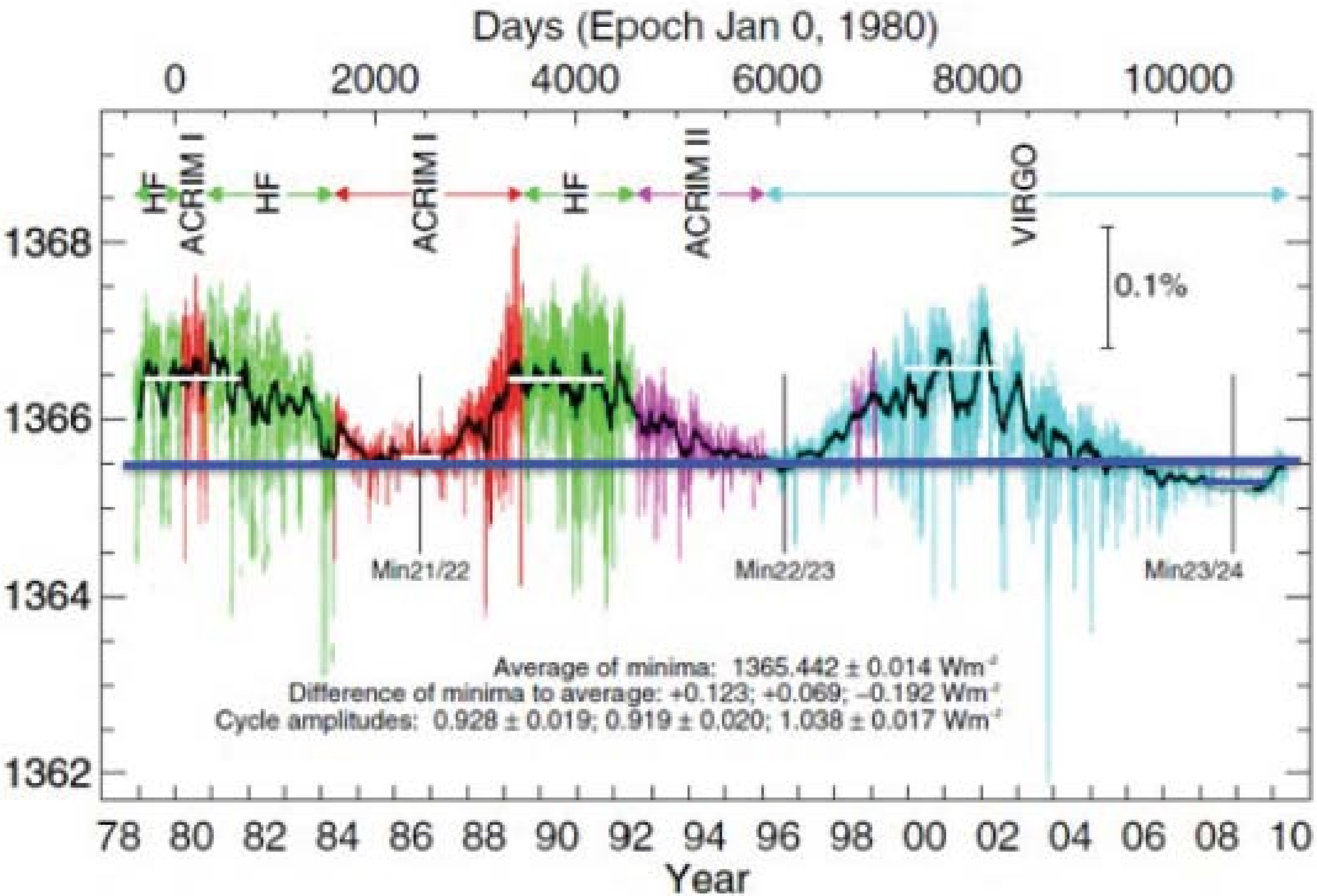
The impact of interplanetary disturbances is NOT proportional to the sunspot number

Richardson, Cliver, Cane (2000)

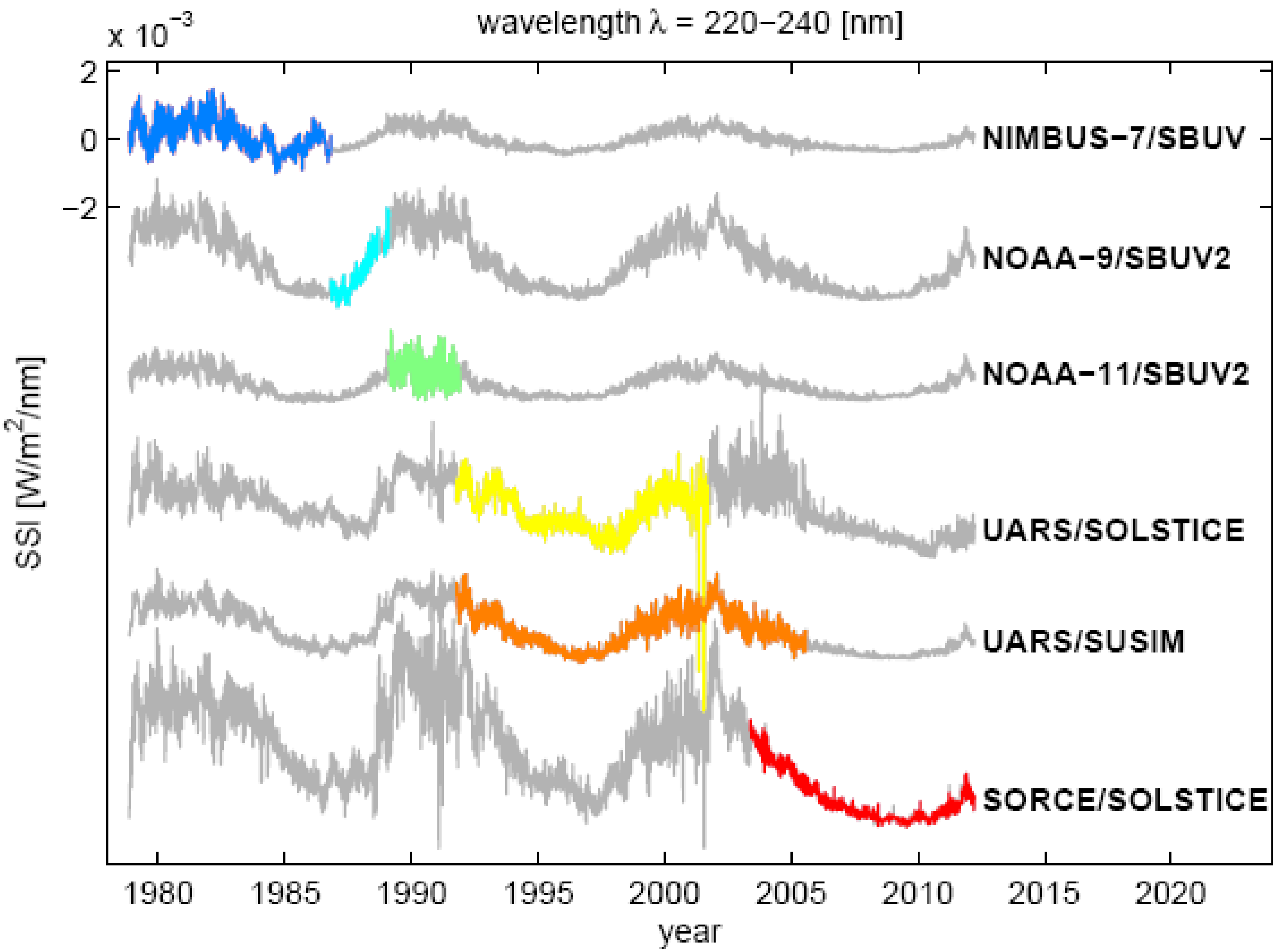
Comparison with solar irradiance



Total solar irradiance follows the sunspot number



Spectral solar irradiance follows the sunspot number



Ermolli et al., 2013

Variations in the sunspot cycle

The two main types of solar drivers of climate (solar irradiance and interplanetary disturbances) have different variations in the sunspot cycle:

- Solar irradiance follows the sunspot number (sunspot-related)
- Interplanetary disturbances do not (non sunspot-related)

Long-term variations

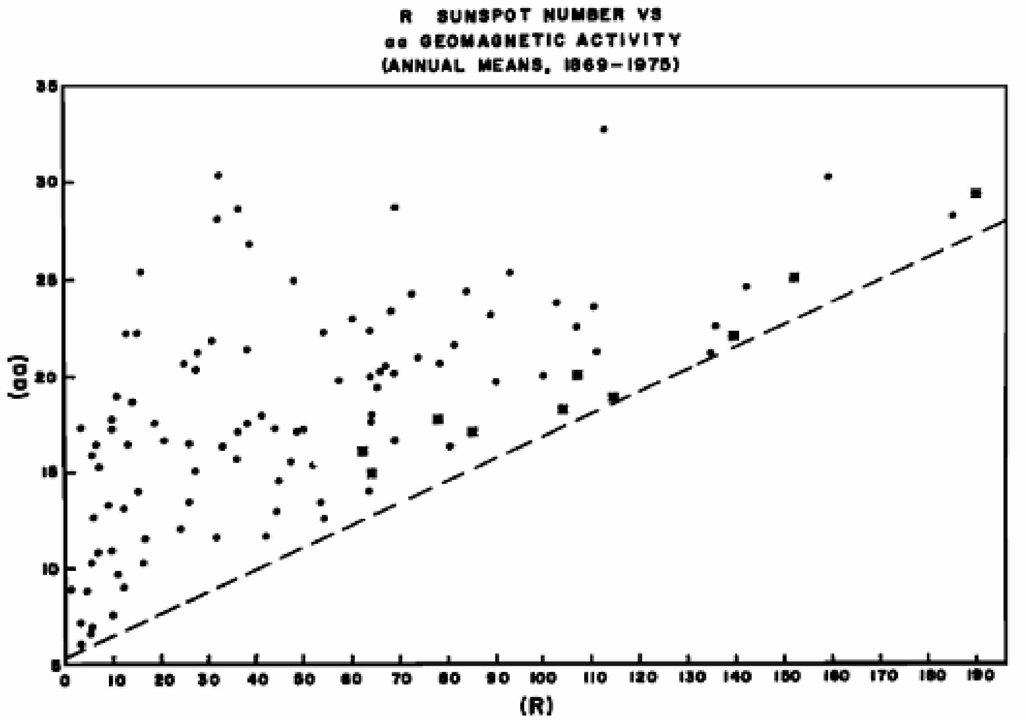
Feynman (1982): two components of geomagnetic activity (sunspot- and non sunspot-related)

$$aa_R = a + b*R$$

the minimum geomagnetic activity at a given number of sunspots = geomagnetic activity due to sunspot-related solar activity

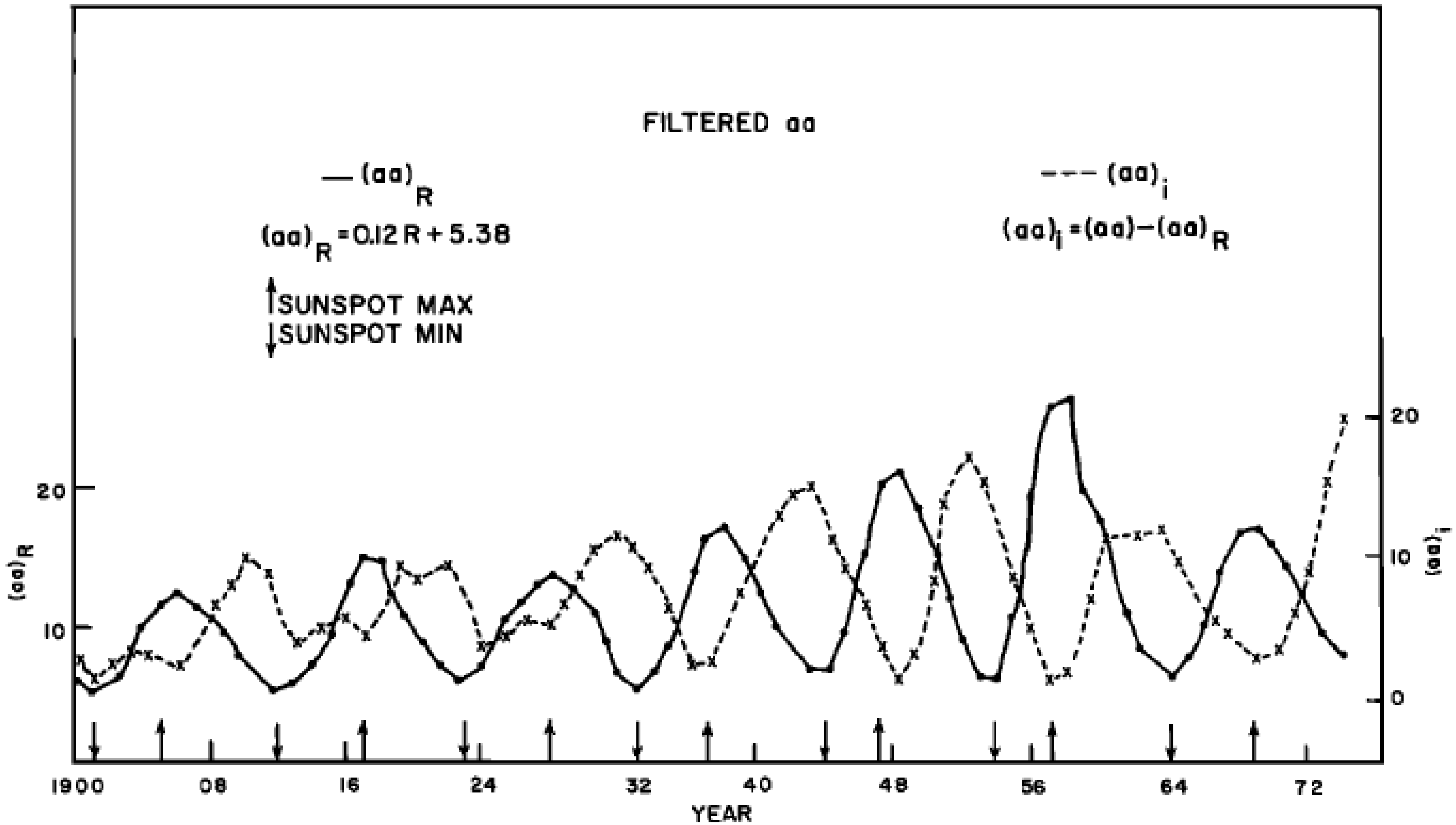
$$aa_P = aa - aa_R$$

geomagnetic activity due to non-sunspot-related solar activity



(Feynman, 1982)

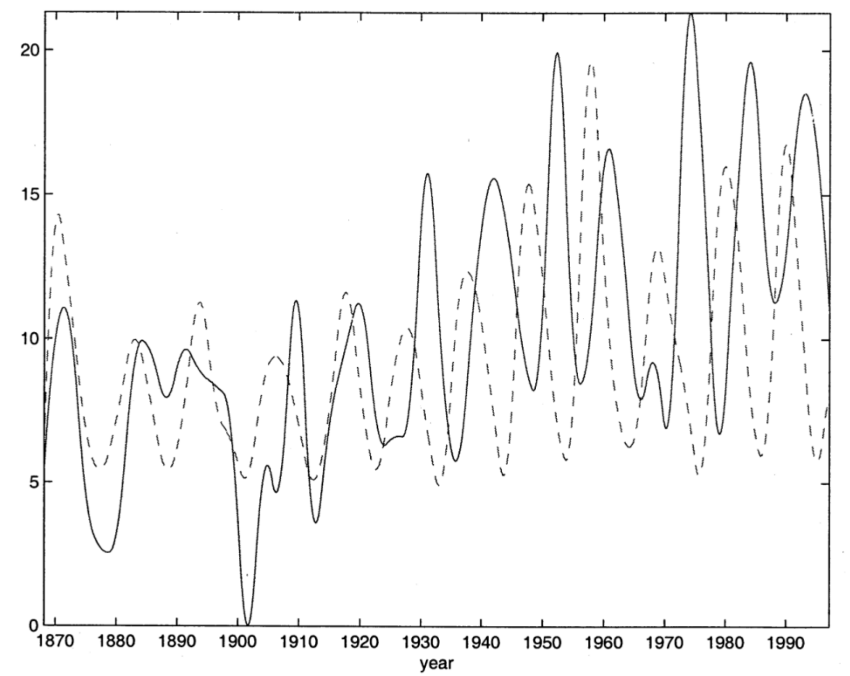
The periodic variations of these two components are **equally strong**, but differing in phase



(Feynman, 1982)

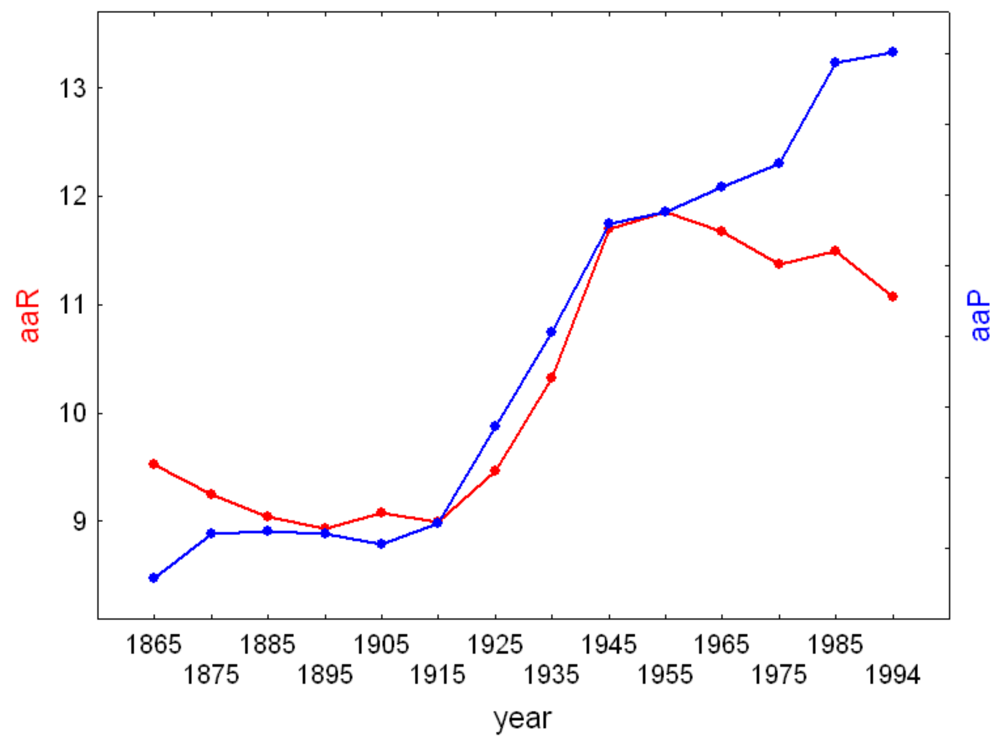
A longer time series: a change in the **relative strength** of the two components?

Filtered (32-month moving averages)



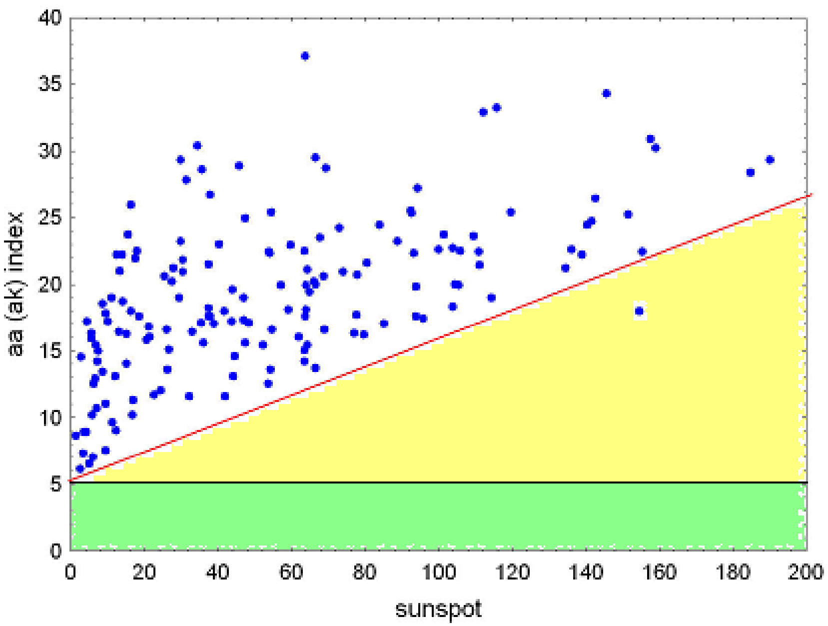
(Ruzmaikin and Feynman, 2001)

Climatic normals (30-year averages with a step of 10 years)



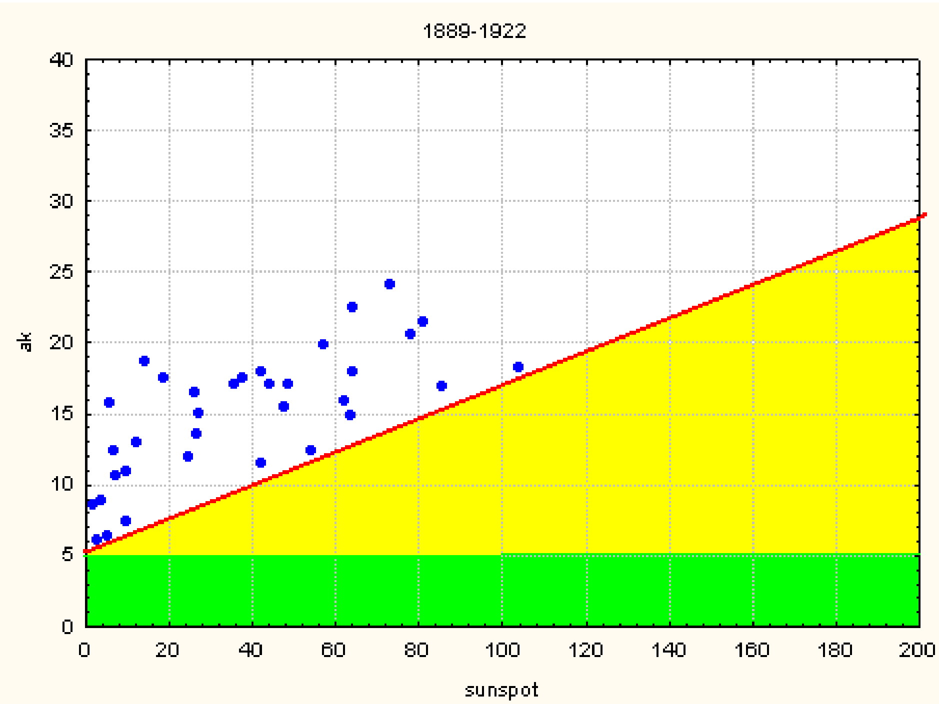
(Georgieva and Kirov, 2007)

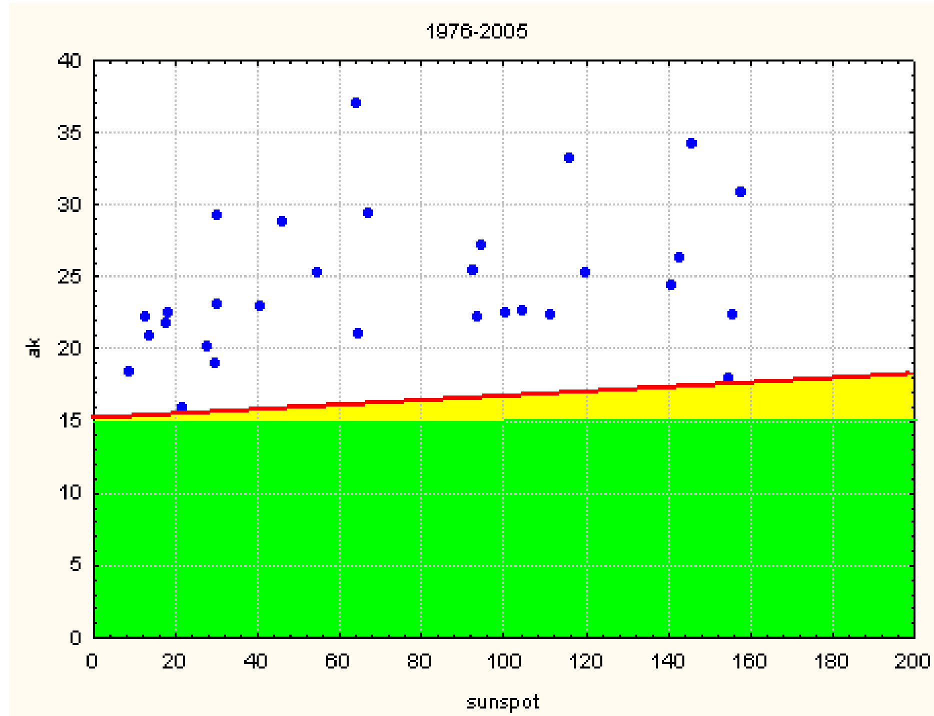
Actually, geomagnetic activity has 3 components corresponding to the 3 types of solar wind



- Floor – background geomagnetic activity due to the slow solar wind
- Sunspot-related geomagnetic activity due to CMEs proportional in number and intensity to the sunspot number
- Additional geomagnetic activity due to high-speed solar wind

Different relative importance of the 3 components of geomagnetic activity in different periods

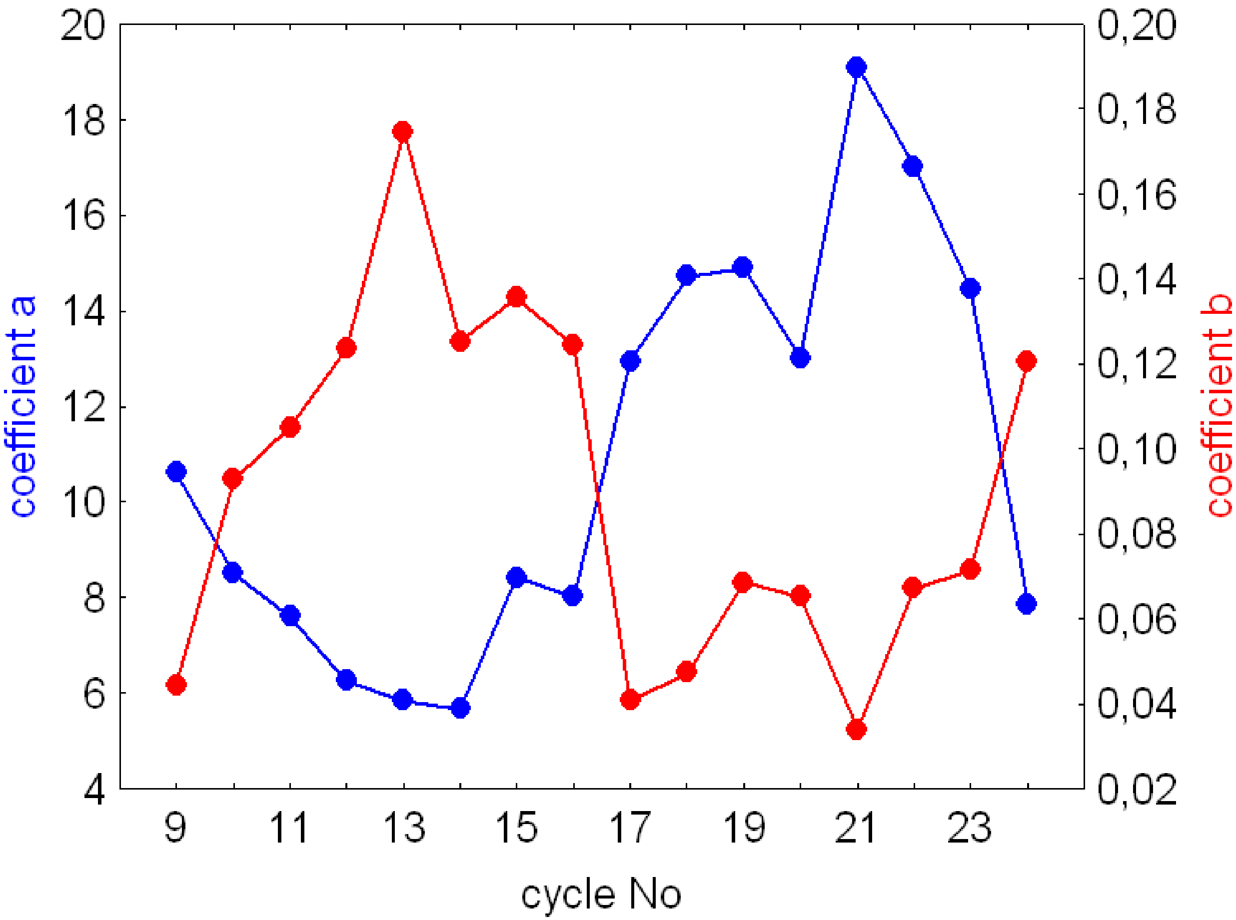


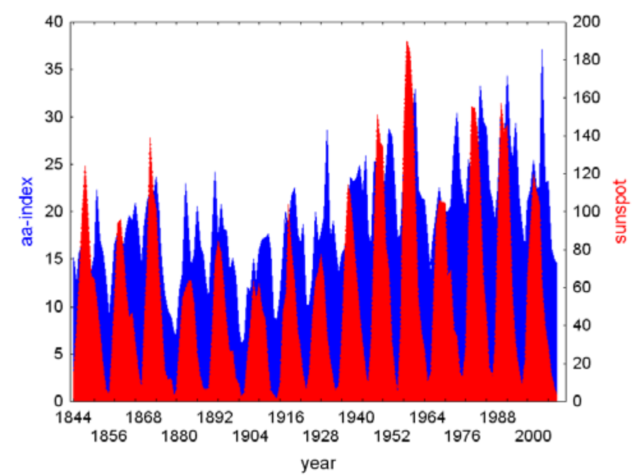


low "floor" of geomagnetic activity
well expressed dependence of geomagnetic activity on sunspot-related solar activity
small impact of non sunspot-related solar activity

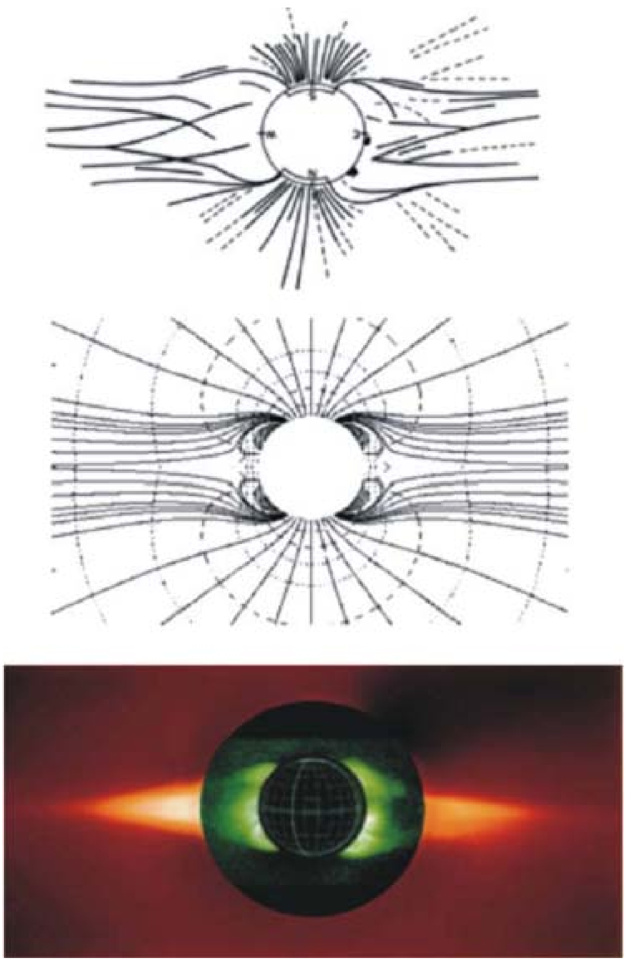
high "floor" of geomagnetic activity
small to vanishing dependence geomagnetic activity on sunspot –related solar activity
high impact of non sunspot-related solar activity

Cyclic variations of the coefficients a and b





Reasons for the variations in floor height

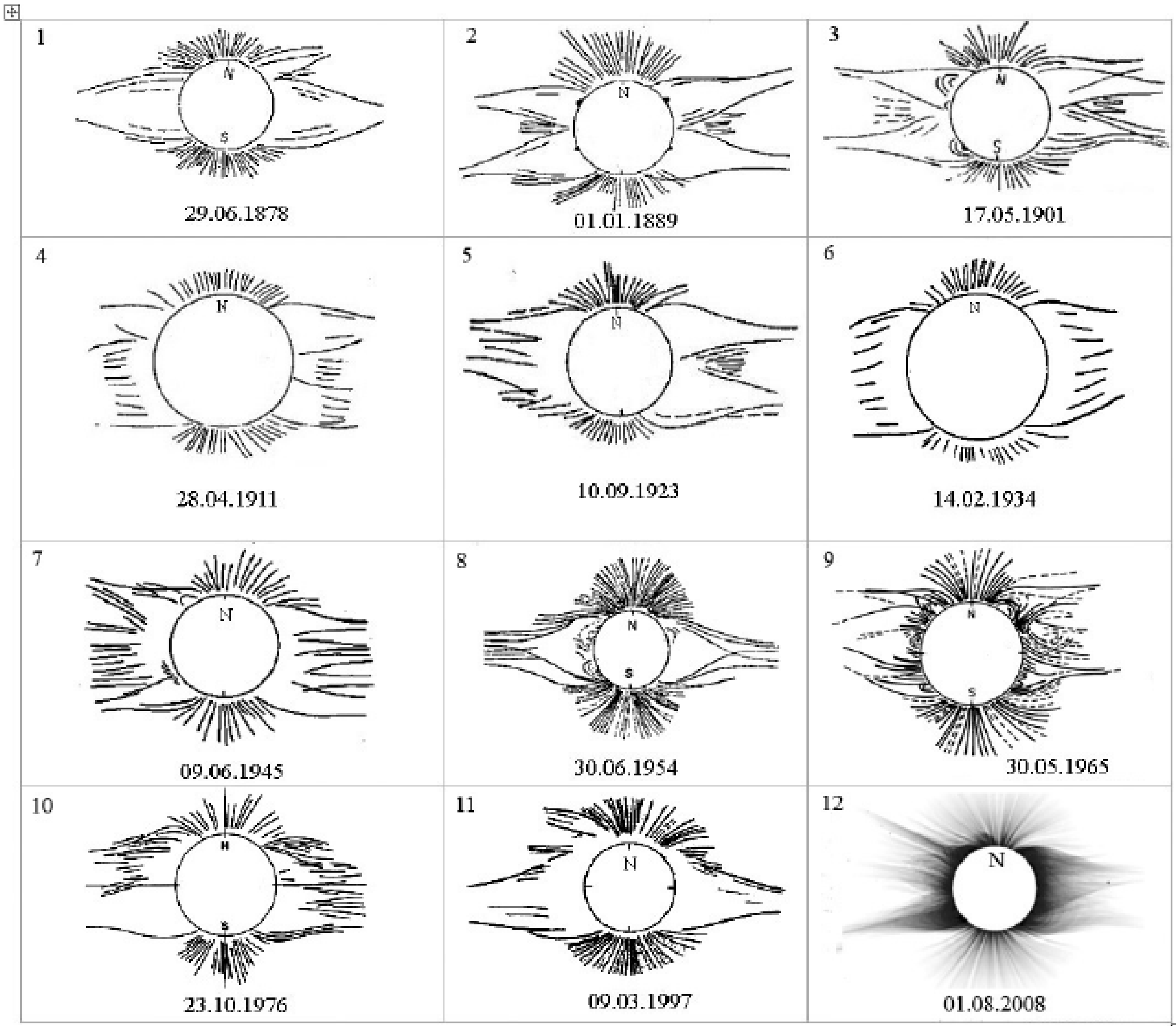


[Simon and Legrand (1987)]

- The annual number of geomagnetically "quiet" and "very quiet" days is determined by the time the Earth spends in slow solar wing from the equatorial streamer belt

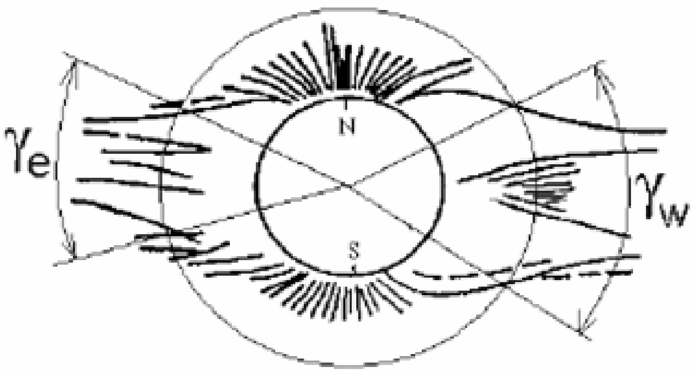
➢ The floor depends on the thickness of the heliosheet

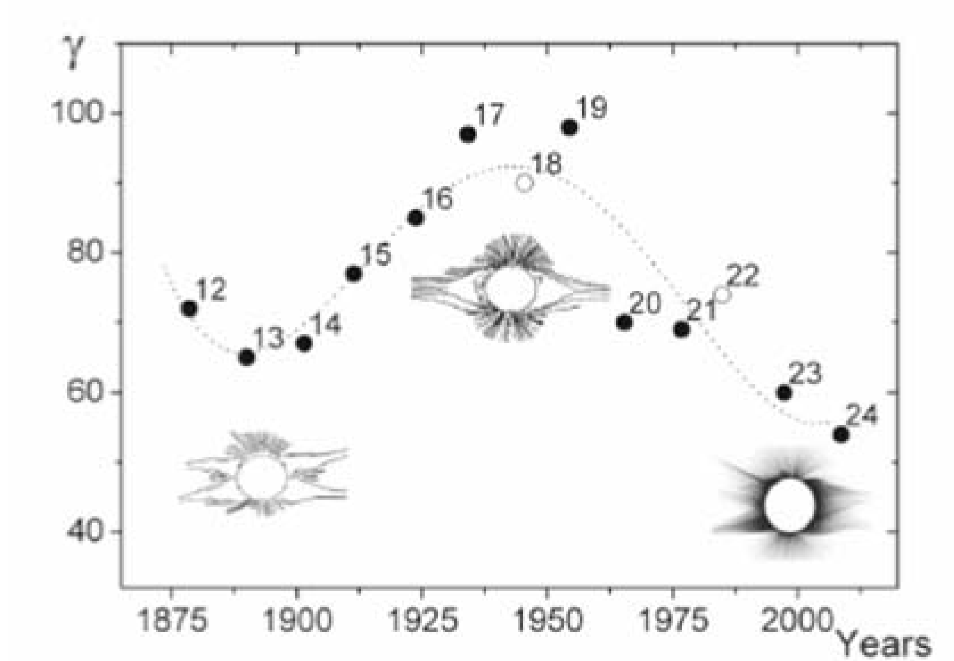
Confirmation: The solar corona during minima



(Tlatov, 2010)

Cyclic variations of the thickness of the heliosheet

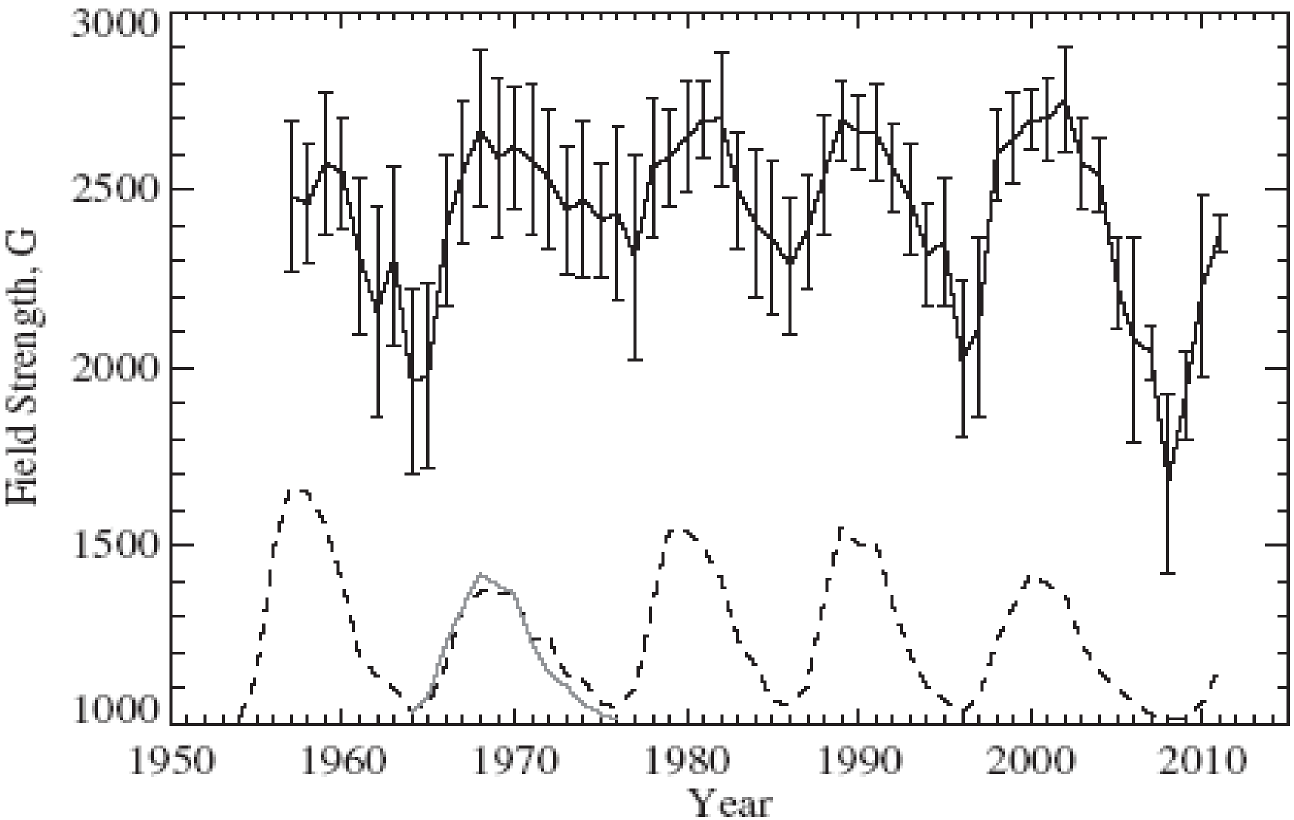




The thickness of the heliosheeth is related to the solar polar field: stronger polar field ⇒ thinner heliosheet ⇒ higher floor

Stronger polar field ⇒ more and more intense high speed solar wind streams

Cycle-to-cycle variations in sunspot magnetic fields



Synoptic data from seven observatories in the former USSR

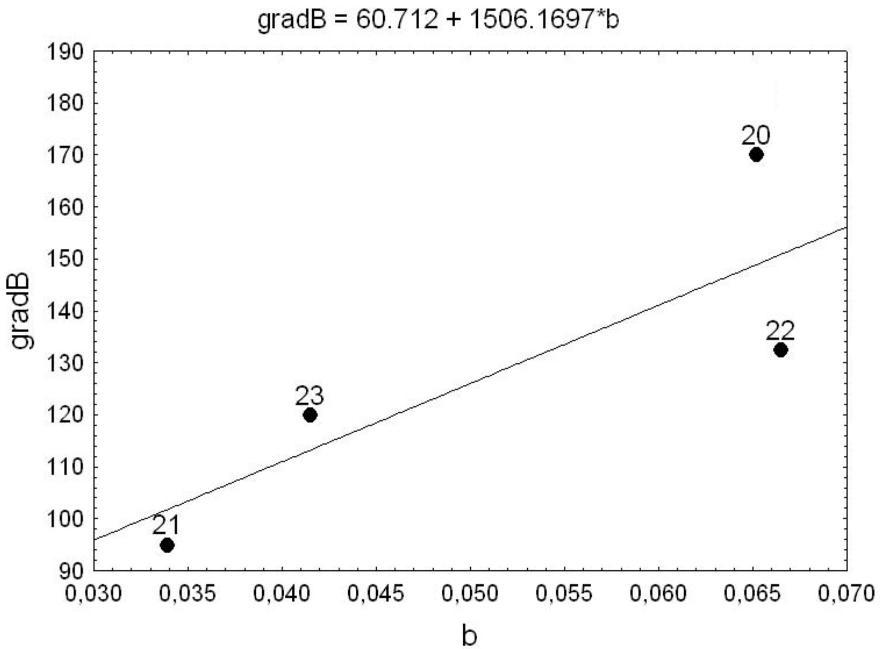
(Pevtsov et al., 2011)

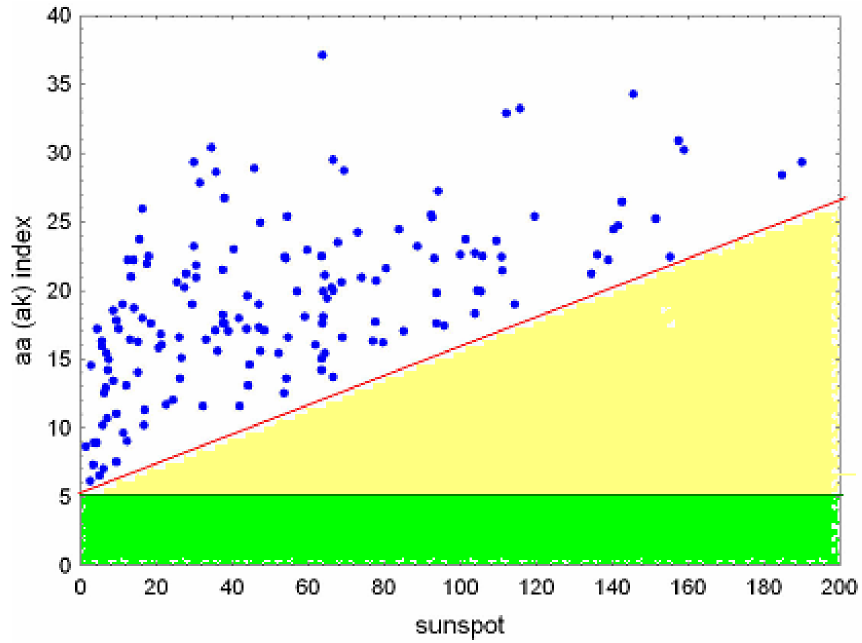
Variations in:

Bmin – sunspot magnetic field in minimum

gradB – rate of increase from min to max

Relation with geomagnetic activity components





The rate of increase of sunspot magnetic field from min to max sunspot number corresponds to the rate of increase of geomagnetic activity with increasing sunspot number (sensitivity of the geomagnetic activity to sunspot-related solar activity)

Long-term variations of electromagnetic and corpuscular solar wind drivers

The two main types of solar drivers of climate (solar irradiance and interplanetary disturbances) have different long-term variations:

- Solar irradiance follows the magnitude of the sunspot number:

- Interplanetary disturbances do not

Effects of the two types of solar activity on the atmosphere

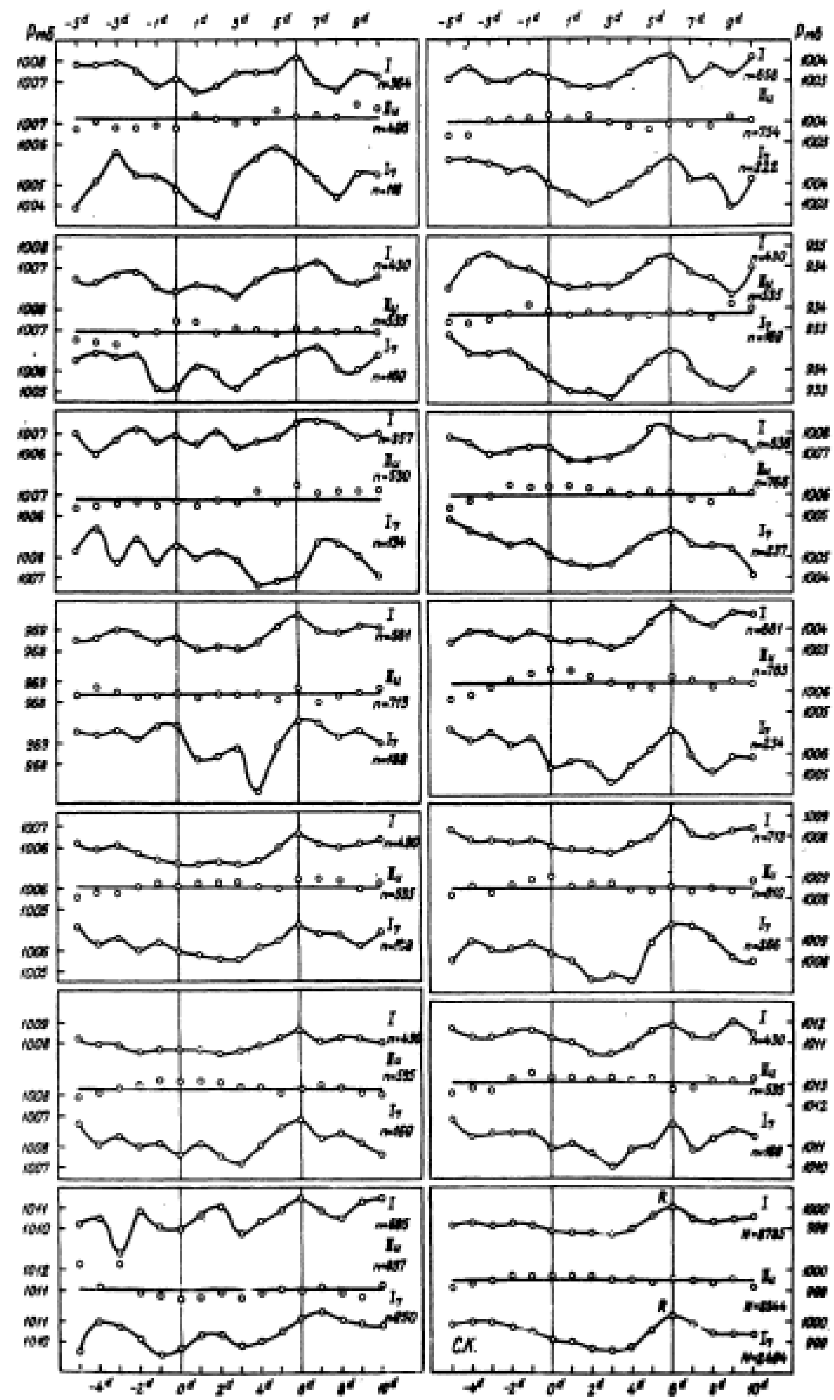
Rubashov (1964)

Corpuscular, rather than electromagnetic, solar emissions are the main solar driver influencing the Earth's atmosphere

The problem is very complex

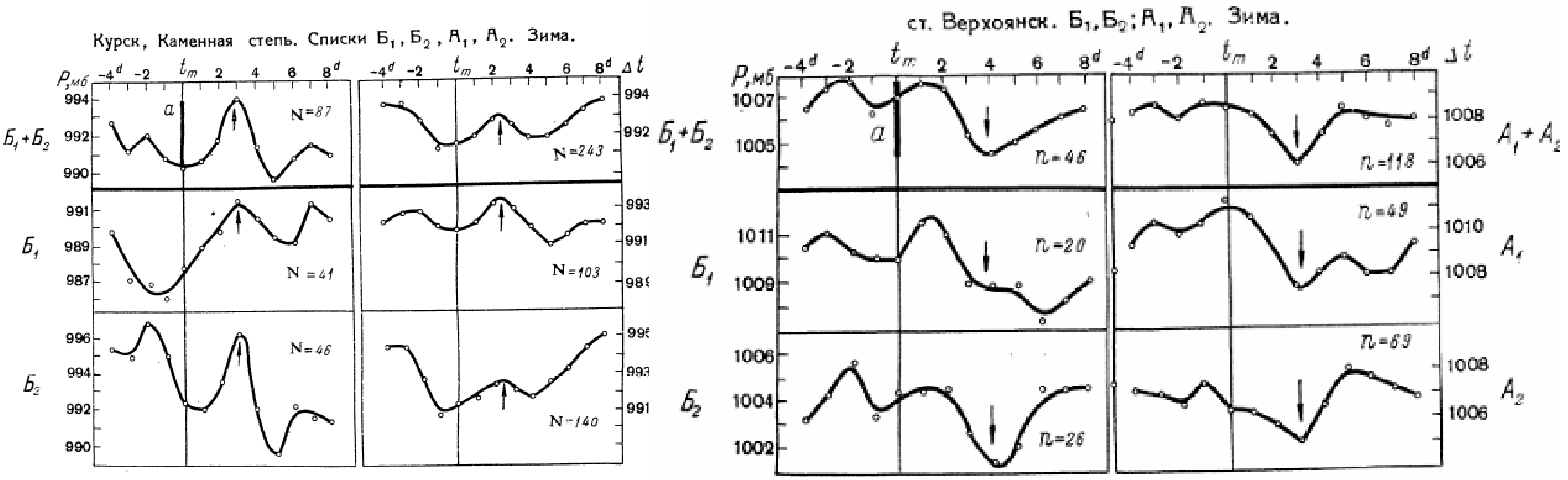
The main reason for the complexity: it is impossible to localize the solar sources of corpuscular emissions

Superposed method analyses use central solar meridian passage of big sunspots as zero days



Mustel (1966) first used days of geomagnetic storms as zero days

Identified 2 types of storms: recurrent (A) and sporadic (Б)



-Sporadic geomagnetic storms are related to stronger surface air pressure patterns than recurrent storms

-Geomagnetic storms further increase the pressure in high pressure stations, and further decrease it in low pressure stations ("law of accentuation")

-Effects depend on season, strongest in winter

-Effects increase with latitude

Confirmation of the "law of accentuation"

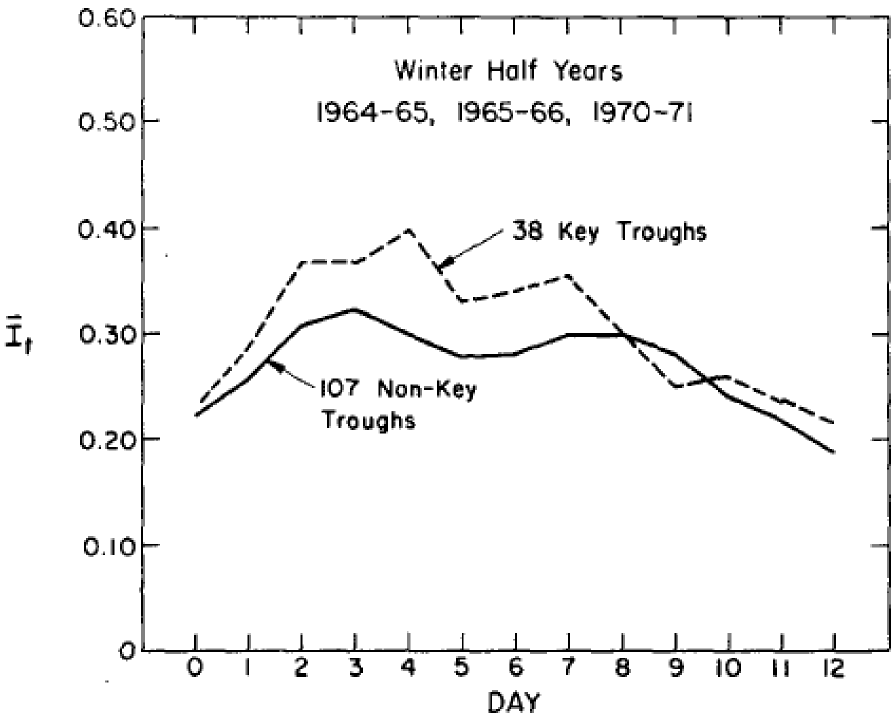


FIG. 2a. Mean trough index I_t vs days after 0-day, for the winters 1964–65, 1965–66, 1970–71.

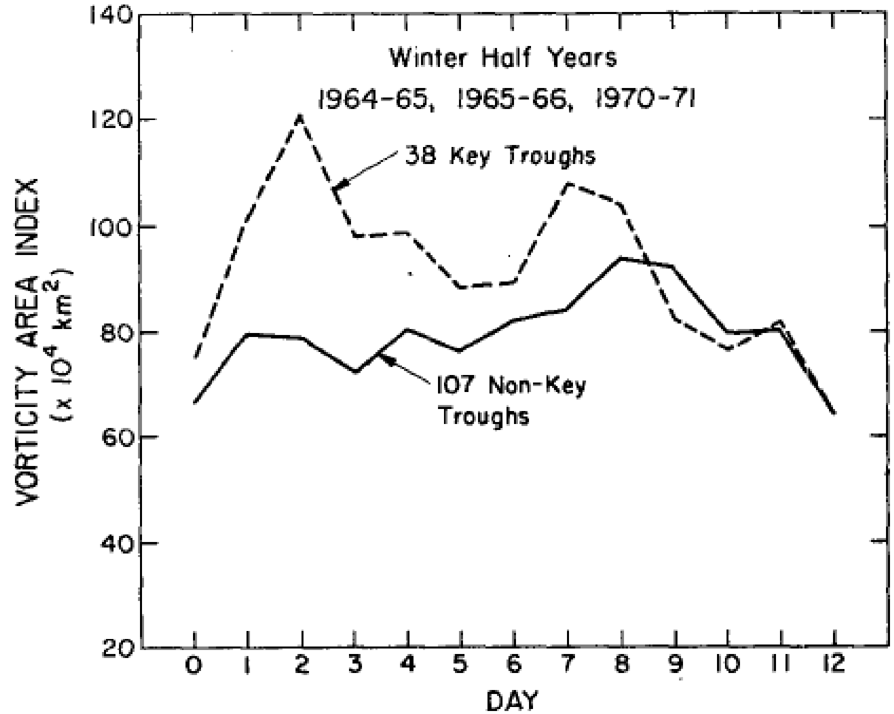
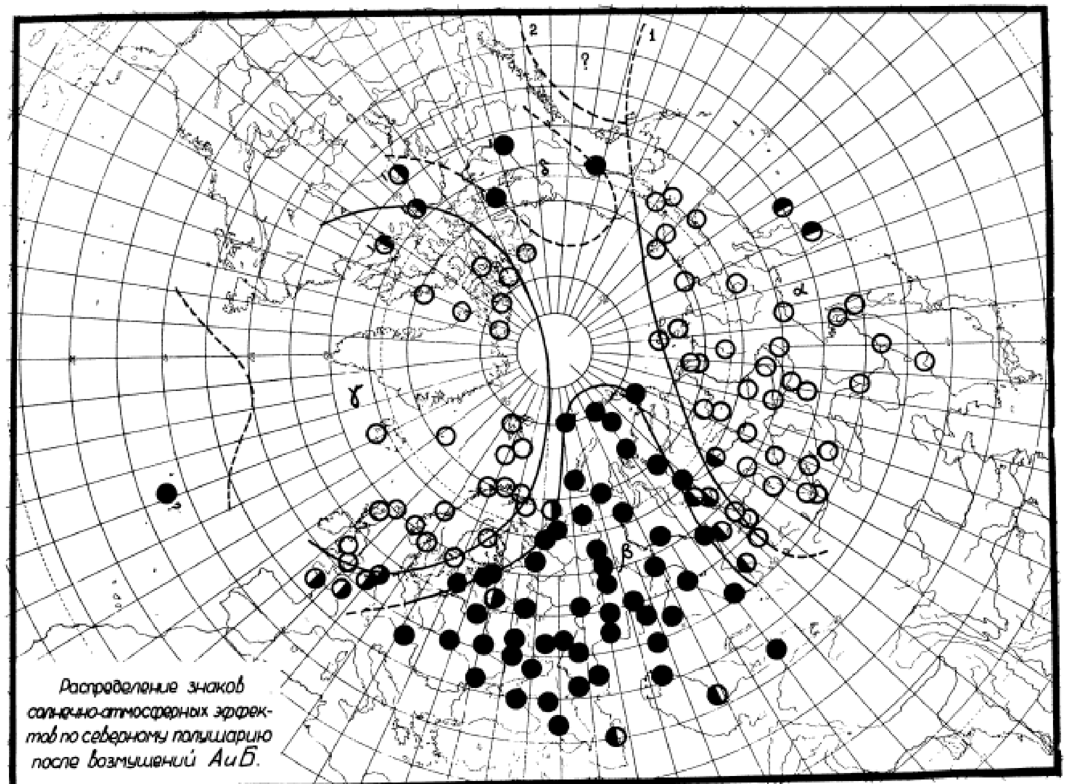


FIG. 2b. Mean vorticity area index vs days after 0-day, for the same years as in Fig. 2a.

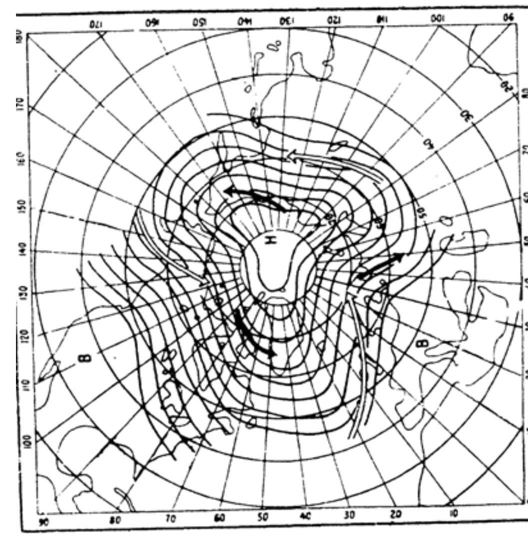
Troughs intensify after geomagnetic storms

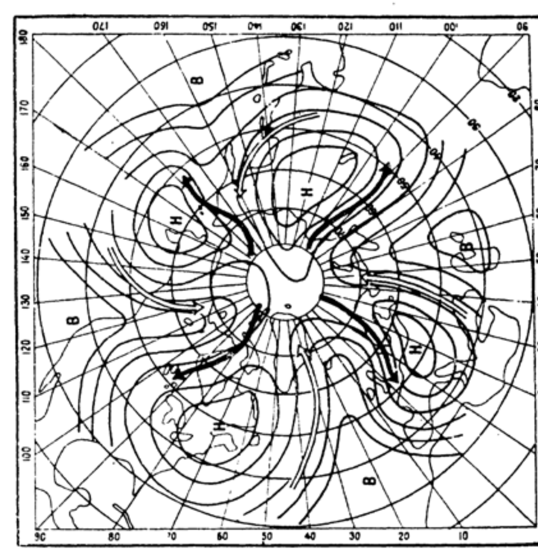
Roberts and Olson, 1973

The penetration of solar corpuscules into the magnetosphere leads to the rise or increase of meridional circulation

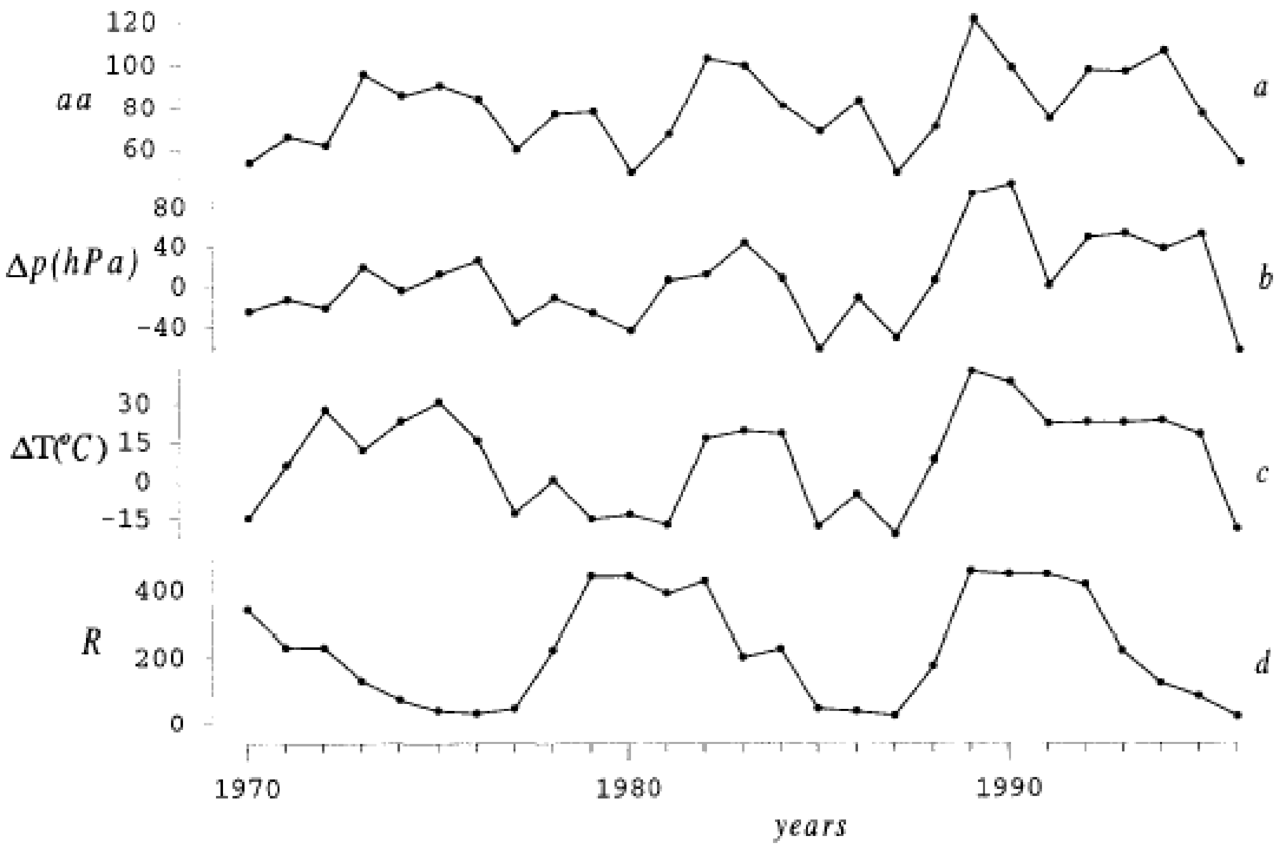


Mustel (1968)



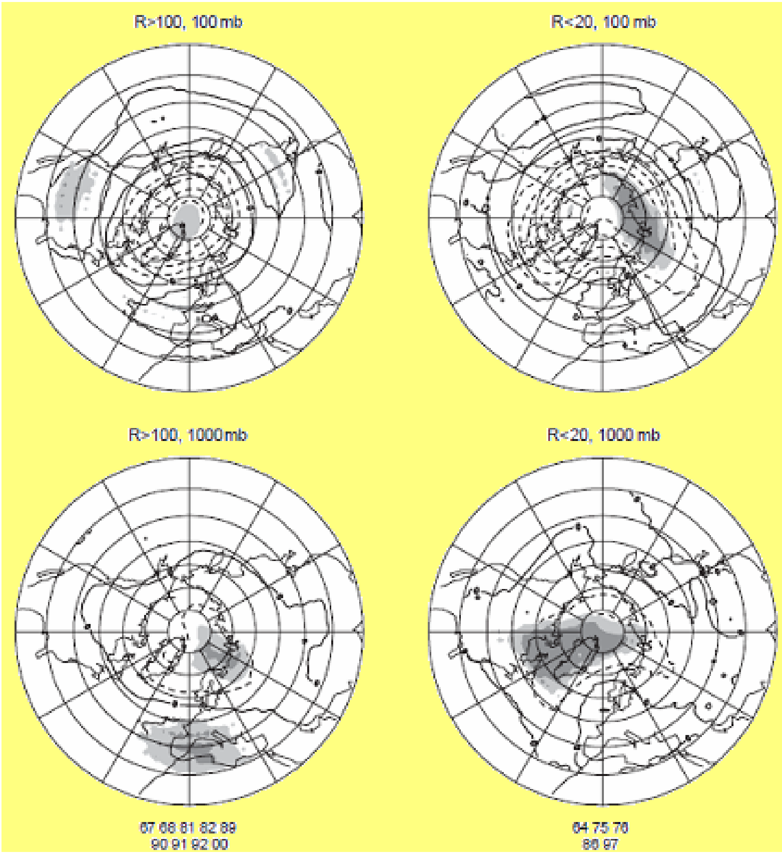


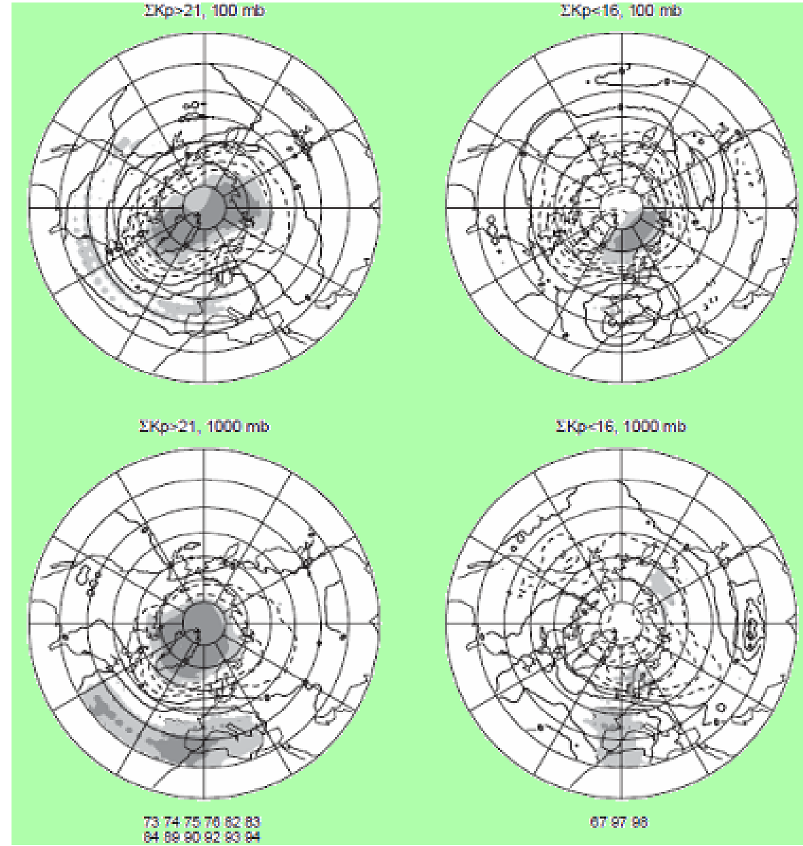
Bucha and Bucha (1998): geomagnetic activity is better correlated with pressure variations and surface air temperature than sunspot number

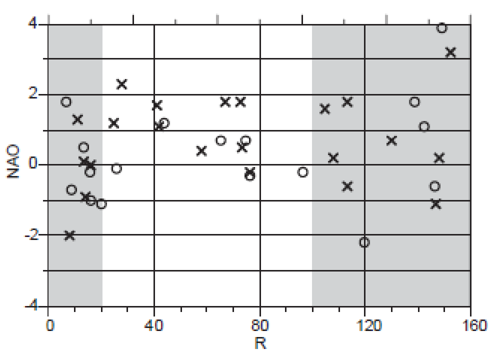


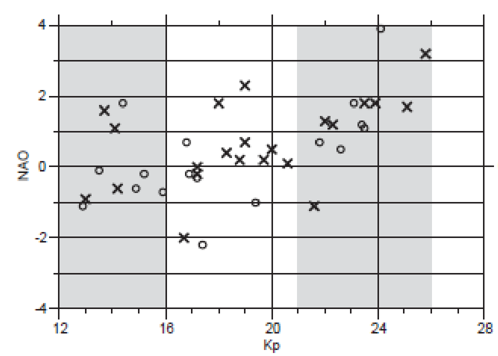
Better correlation with geomagnetic activity

Bochnicek and Hejda, 2005









maximum wind speed at 200 hPa
during geomagnetic storms

Hypothesis:

downward winds following geomagnetic storms are generated at the polar cap of the thermosphere

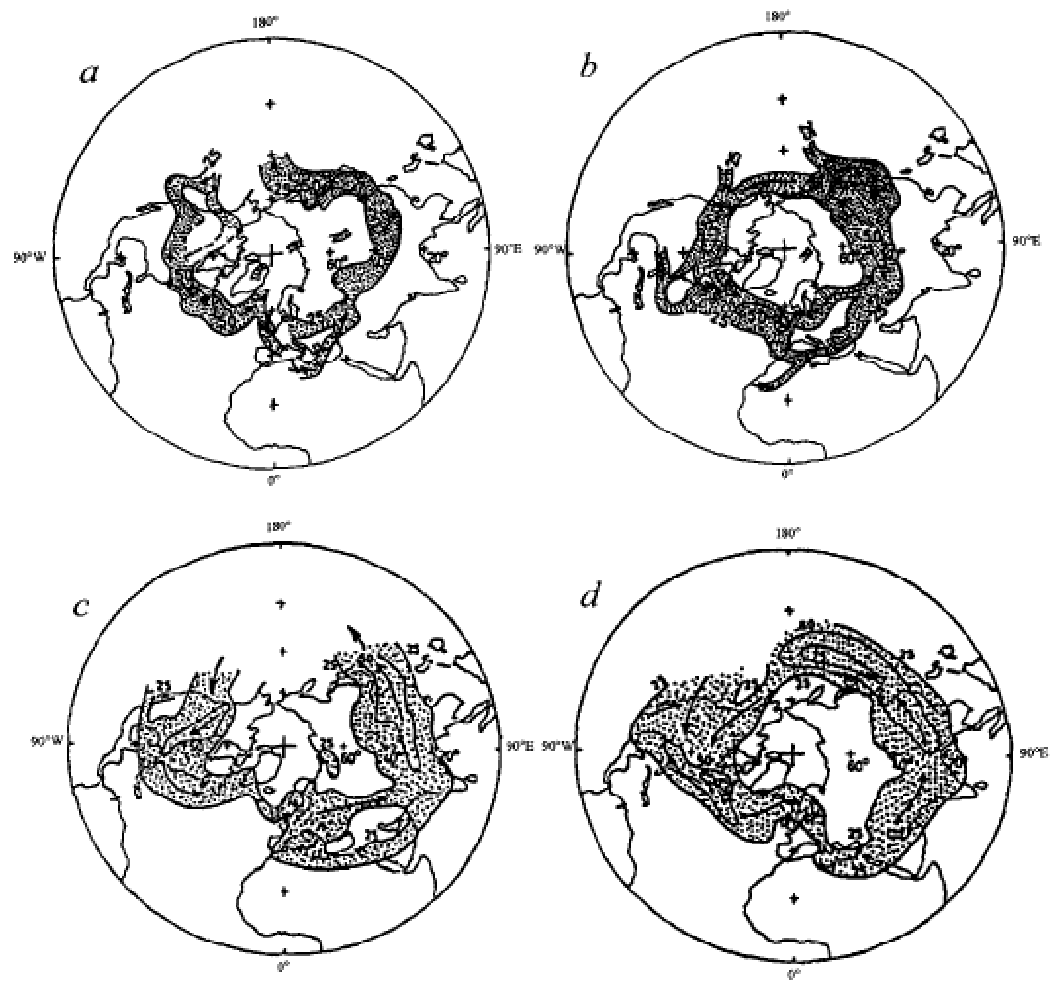
penetrate down to the stratosphere and troposphere

sudden increase of pressure and temperature

intensification of the jet streams

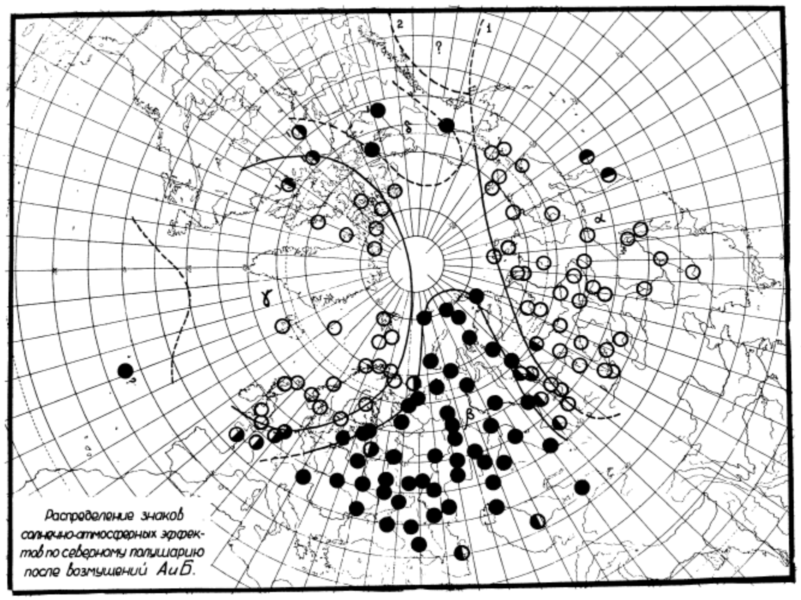
zonalization of the circulation

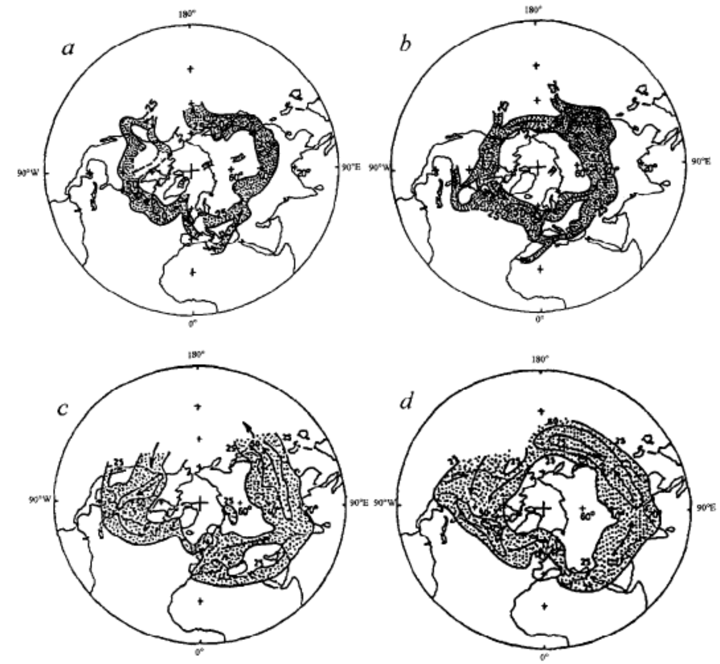
before after



Bucha and Bucha, 1998

Is something wrong?





Mustel (1968):

Geomagnetic activity

⇒ more meridional circulation

1890-1967

Bucha and Bucha (1998):

Geomagnetic activity

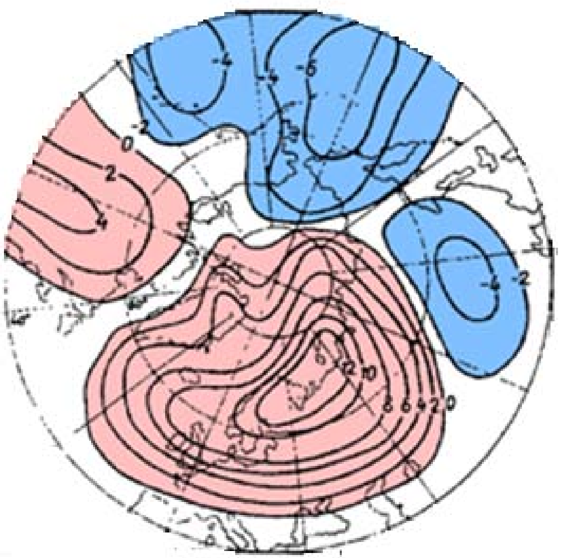
⇒ more zonal circulation

1970-1996

Other results

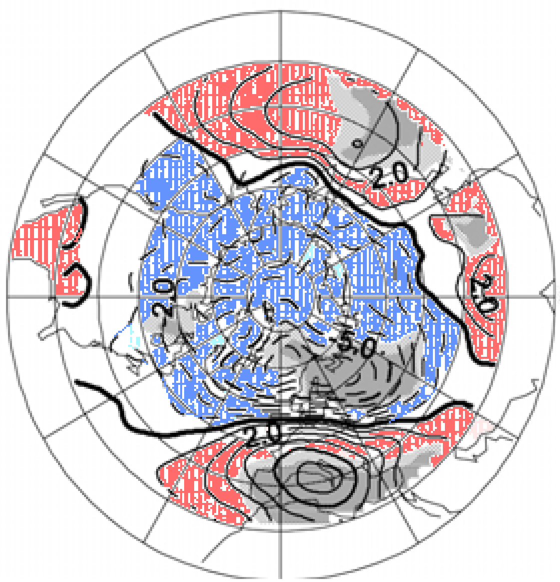
Changes in sea level pressure as a result of solar activity

1890-1966



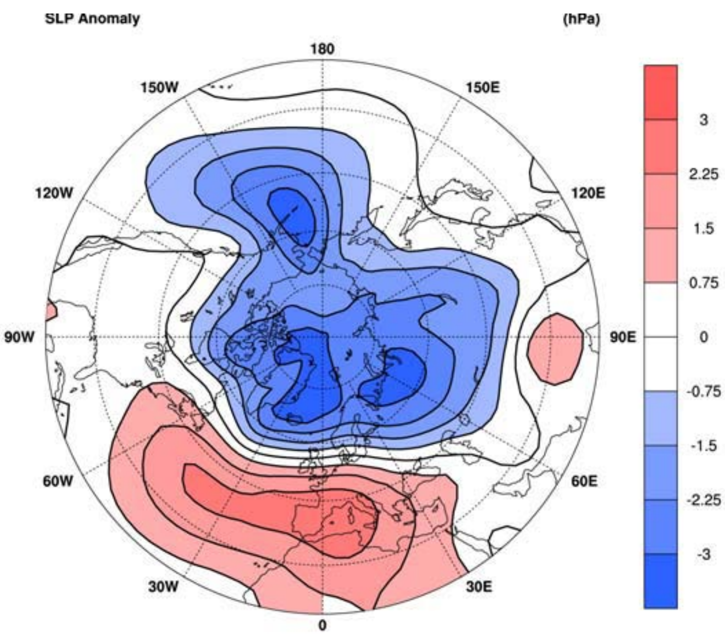
Smirnov and Kononovich, 1996

1952-1999



Bochnicek and Hejda, 2003

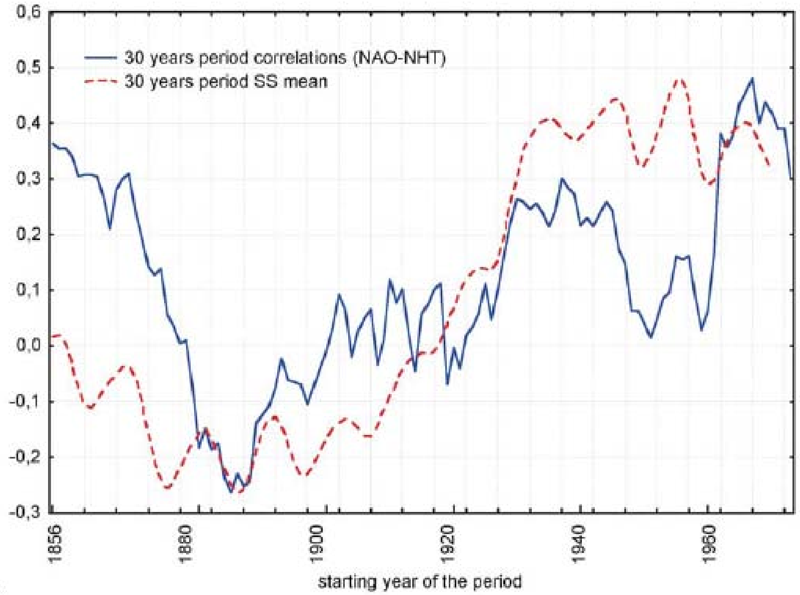
1981-2002



Hurrell (2002)

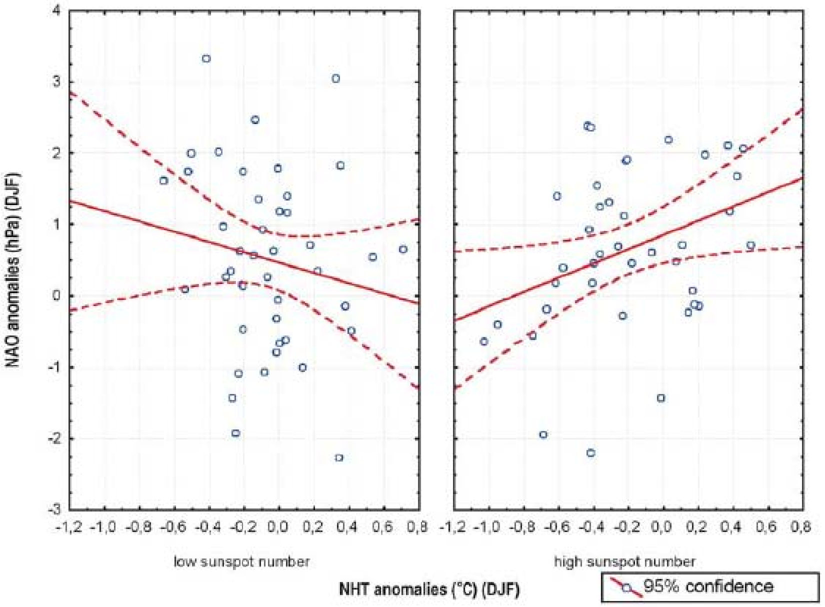
the correlation between NAO and Northern hemisphere temperature also changes

L. Gimeno et al. / Earth and Planetary Science Letters 206 (2003) 15–20



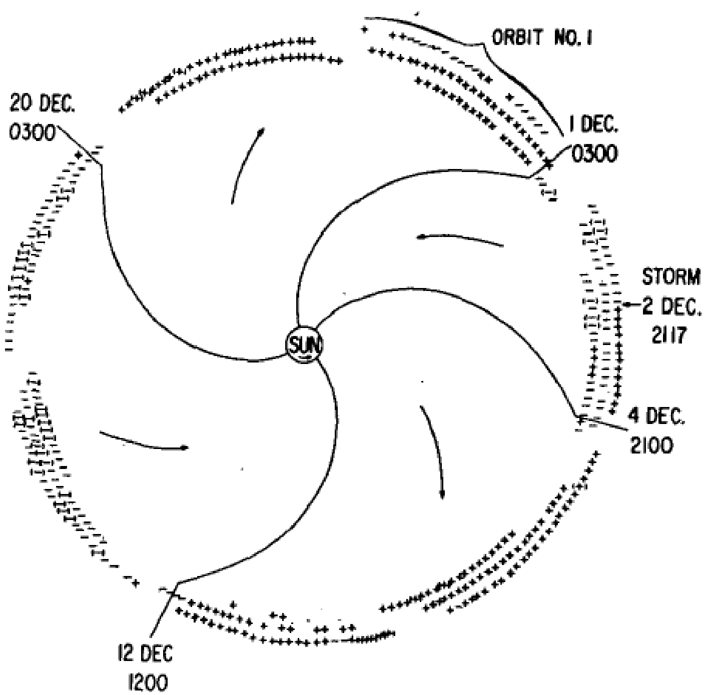
low solar activity

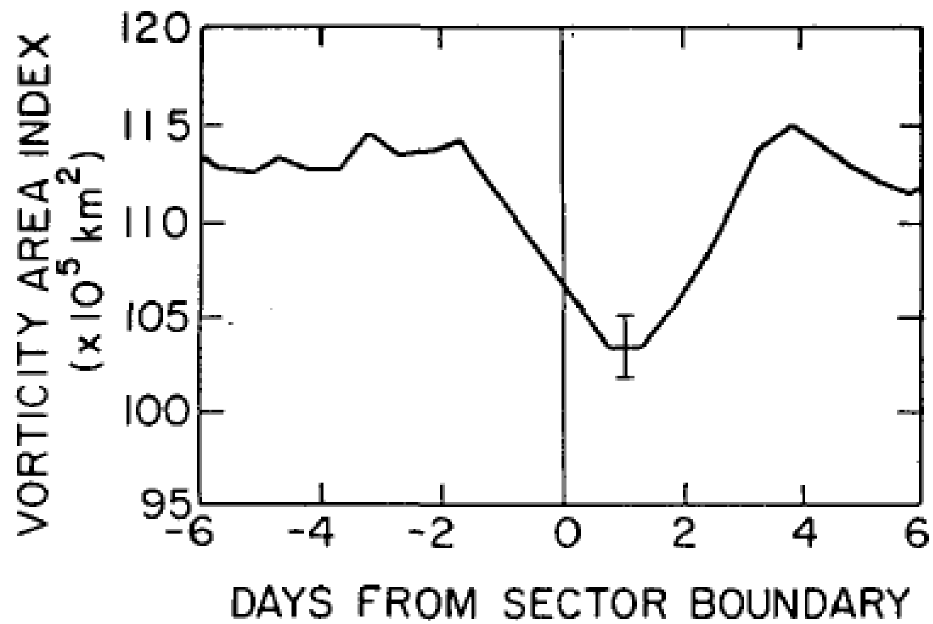
high solar activity



High and positive correlation for high solar activity
Low to negative correlation for low solar activity

Effects of interplanetary sector boundary crossing on atmospheric vorticity area





Vorticity area decreases after interplanetary sector boundary crossing

Wilcox et al., 1974