A cosmic ray - cloud link and cloud observations

STRUKTURNI I INVESTICIJSKI FONDOVI

PoKRet

SOLSTEL

ESF HUMAN RESOURCES DEVELOPMENT

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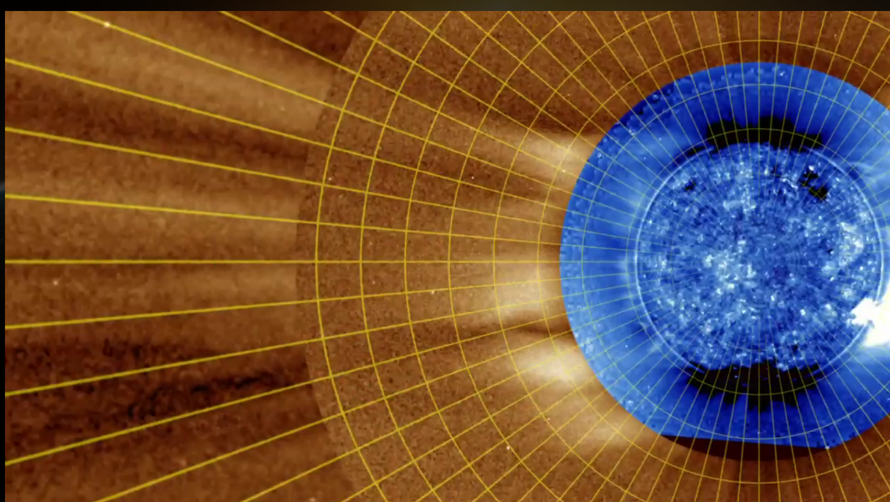
Lecture outline

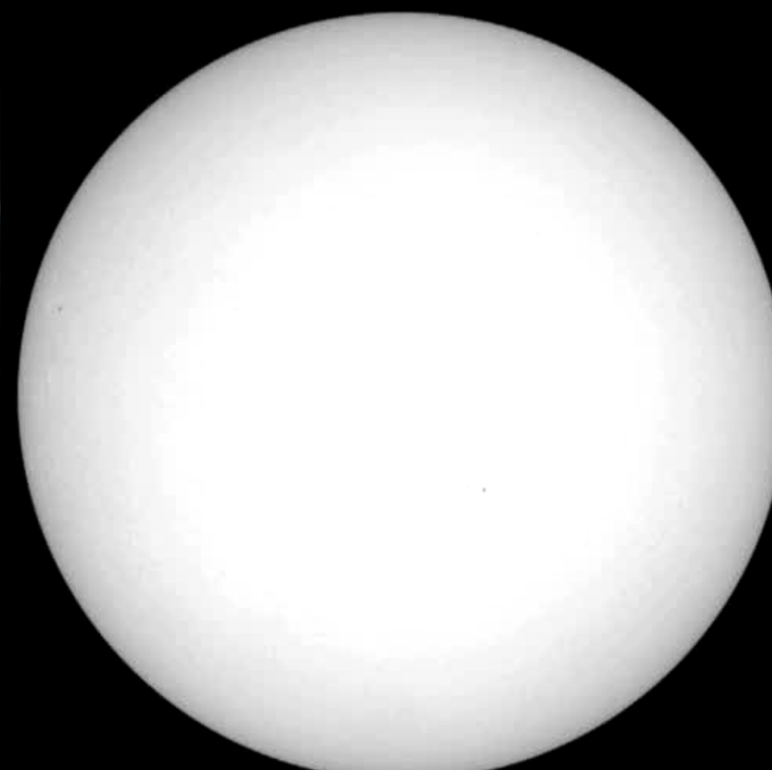
- Introduction (about the Sun, solar activity phenomena)
- Solar cycle and its origin
- Cosmic rays (solar modulation, influences on Earth)
- Solar activity and climate (cosmogenic radionuclides)
- Hypothesized mechanisms linking solar activity to the climate
- "Clean-air" mechanism linking cosmic rays and clouds
- Observations of clouds and studies testing CR-cloud hypotesis
- Experimental and modeling results
- Conclusions

Influence of solar variability on the Earth's climate requires knowledge of

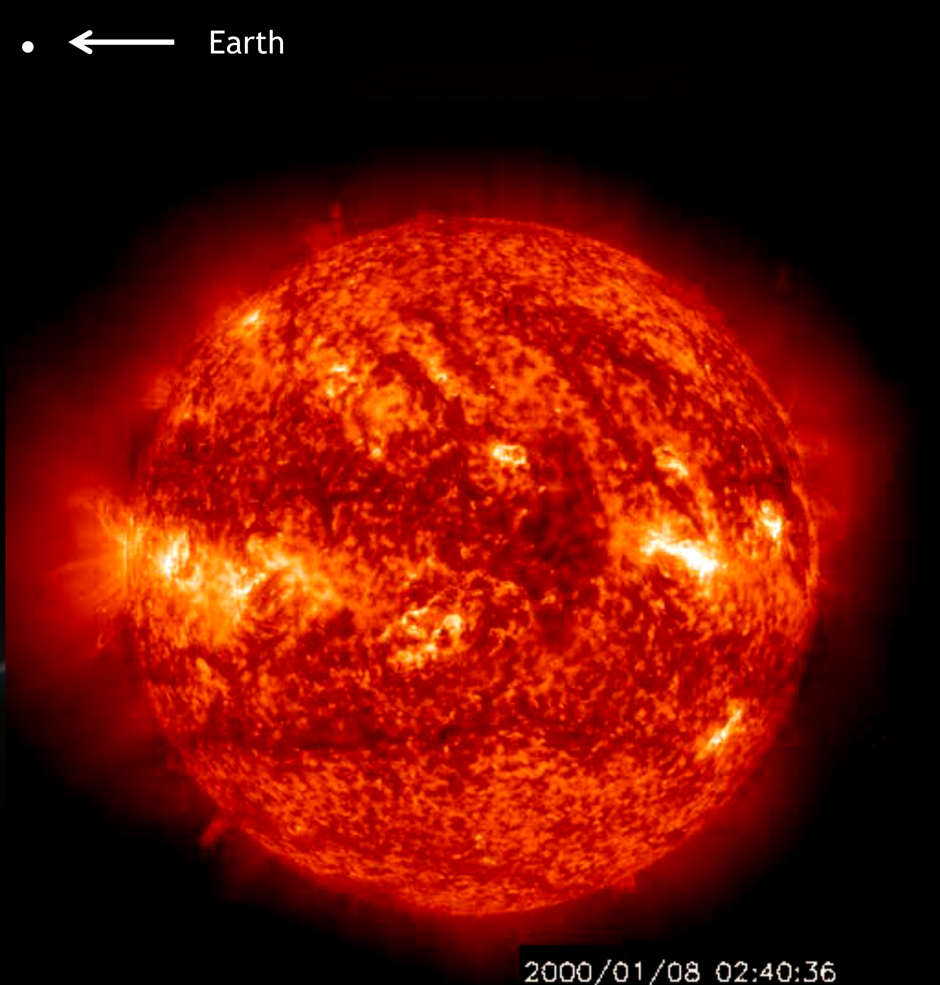
1. Short- and long-term solar variability
2. Solar-terrestrial interactions
3. Mechanisms determining the response of the Earth's climate system to these interactions

Rind, 2002





About the Sun



- **diameter**: 1 392 000 km
  (109x Earth)

- **mass**: 2 x 10^{30} kg
  (333 000x Earth)

- **g** = 274 m/s^2 (28x Earth)

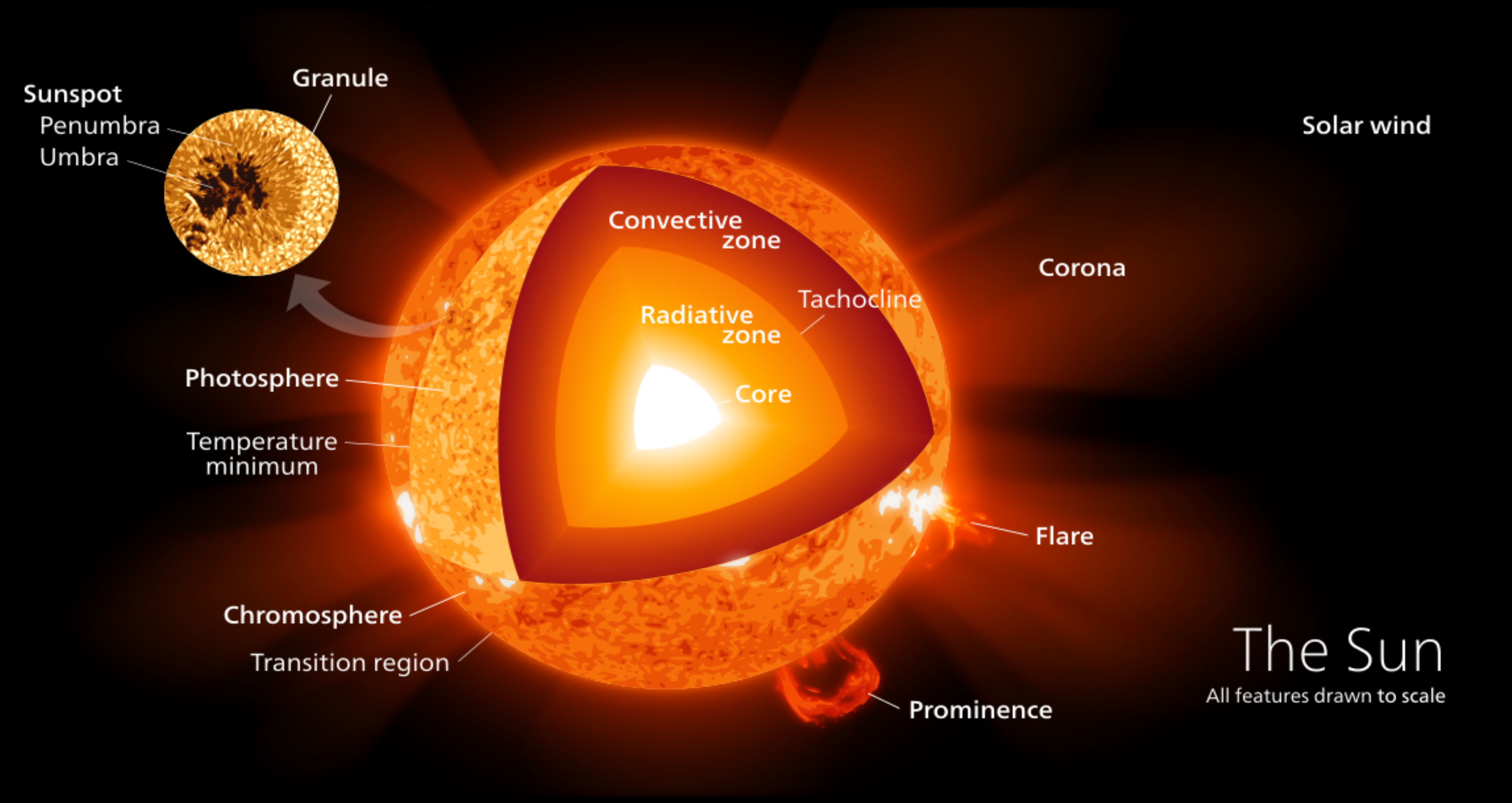
- **distance**: 150 000 000 km
  (1 astronomical unit,
  8 min 19 s with light speed)

- **core temperature**: 15 700 000 K
- **surface temperature**: 5 780K

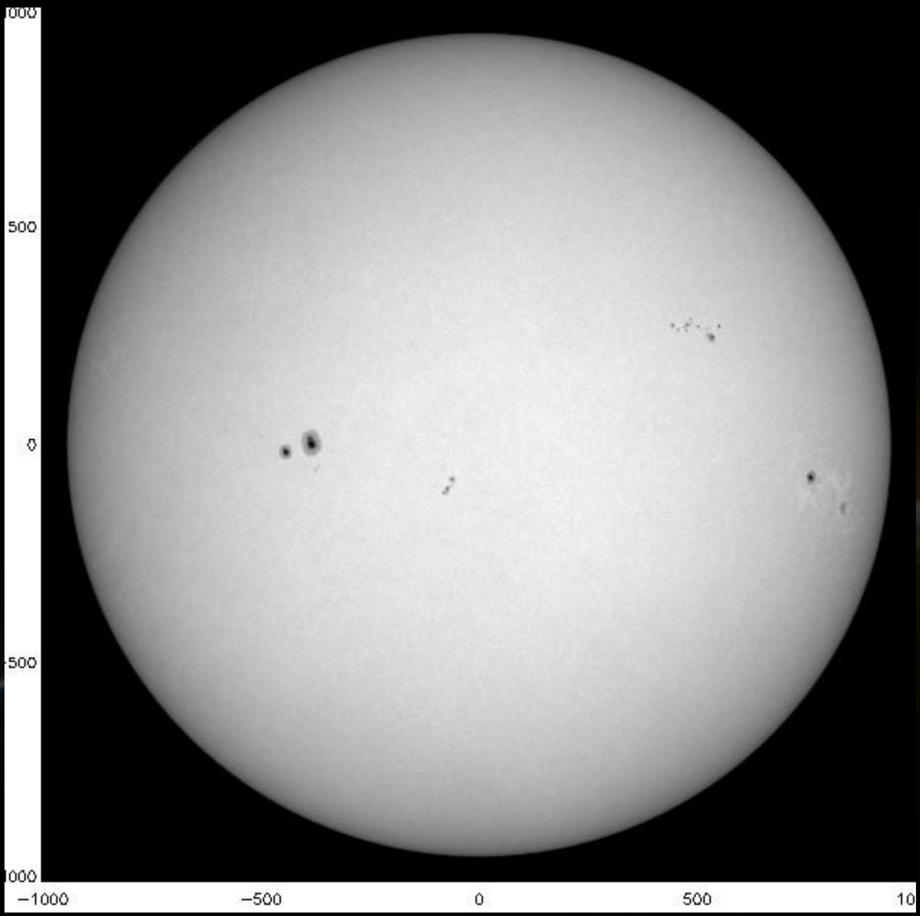
- 70% hydrogen, 28% helium, 2% heavier elements

- **age**: 4.6 billion years

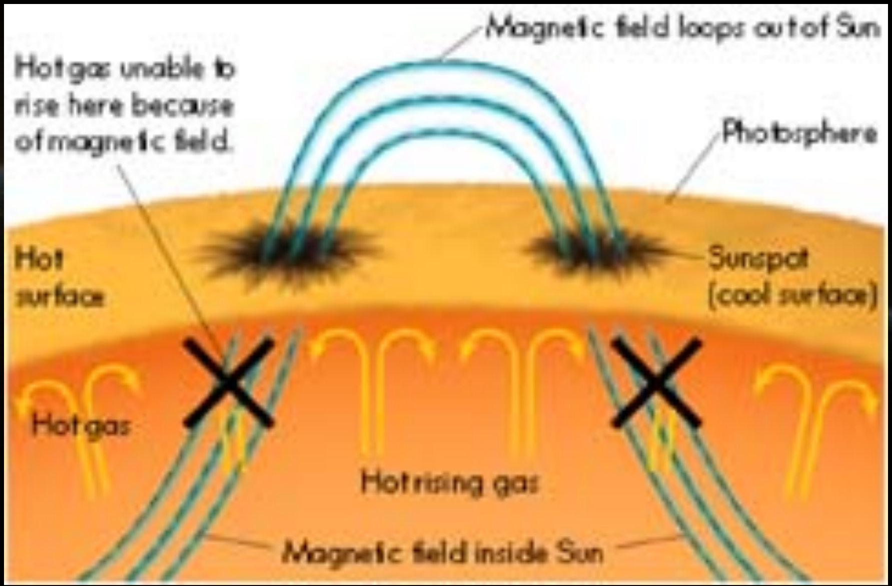
Structure of the Sun



Sunspots



- Regions of strong magnetic field concentrations that hinder energy transport from below (convection)
- cooler than their surrounding (with temperatures 4000 – 5000 K)

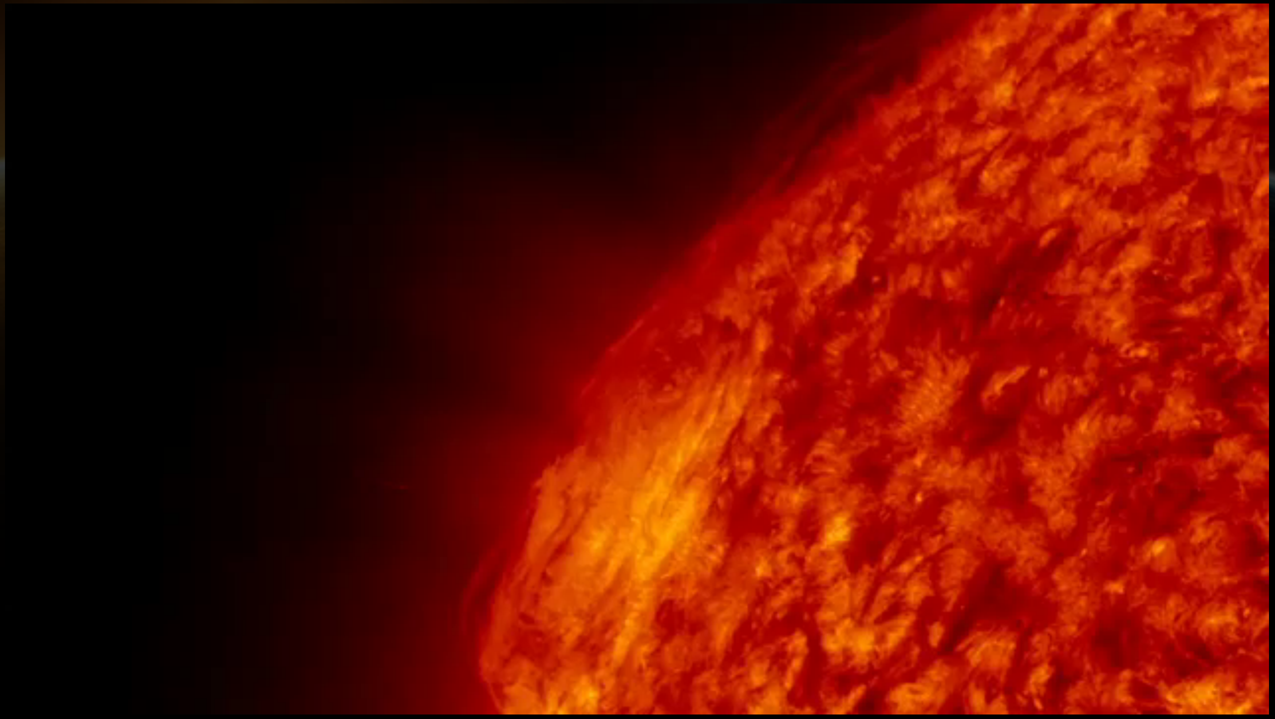


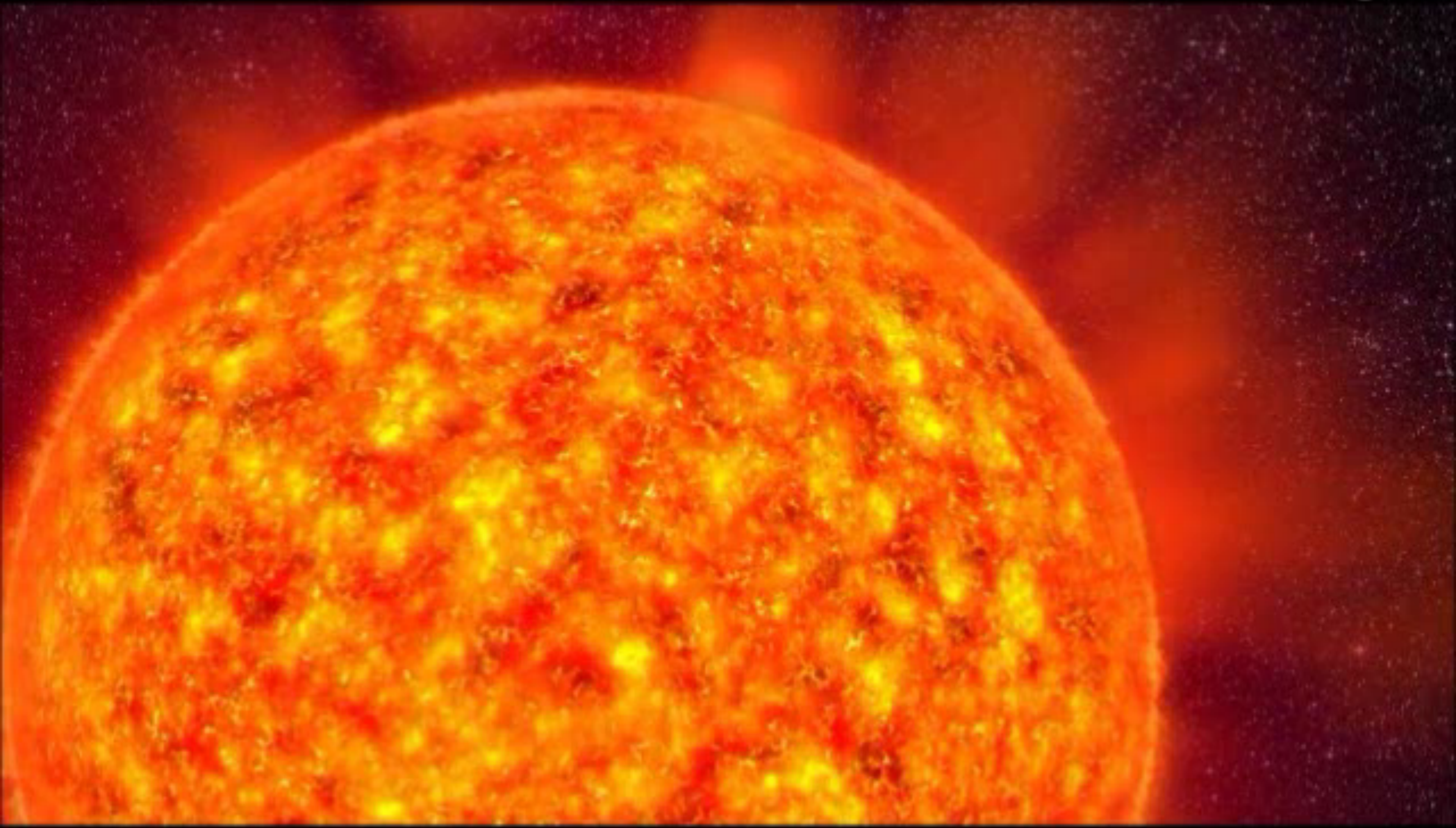
- Photosphere is structured by a network of granulation cells (consequence of mass motions from the convection zone)
- Granules have a diameter of about 1000km and lifetime of 10min

Disturbances on the Sun

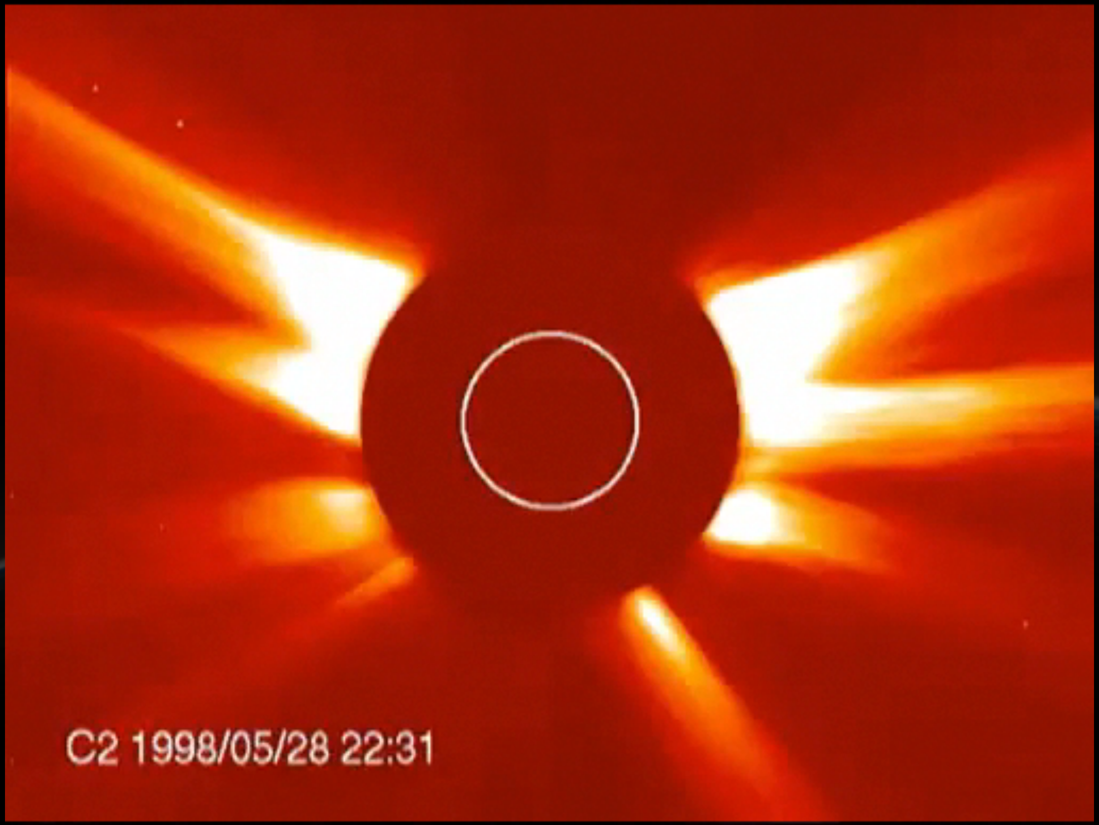
- **Promineces (filaments)** – large gaseous features from cooler and denser plasma captured by solar magnetic field, extend from chromosphere to corona
- **Flares** – short and bright plasma eruptions in the chromosphere due to magnetic reconfiguration of solar magnetic field (reconnection), release huge amounts of energy (~160 000 000 000 megatons TNT), last from minutes to hours
- **Coronal mass ejections (CME)** – magnetized plasma clouds expelled from the Sun (speeds up to 3000 km/s), often associated with flares and eruptive prominences

Prominence
30.3.2010





Solar wind

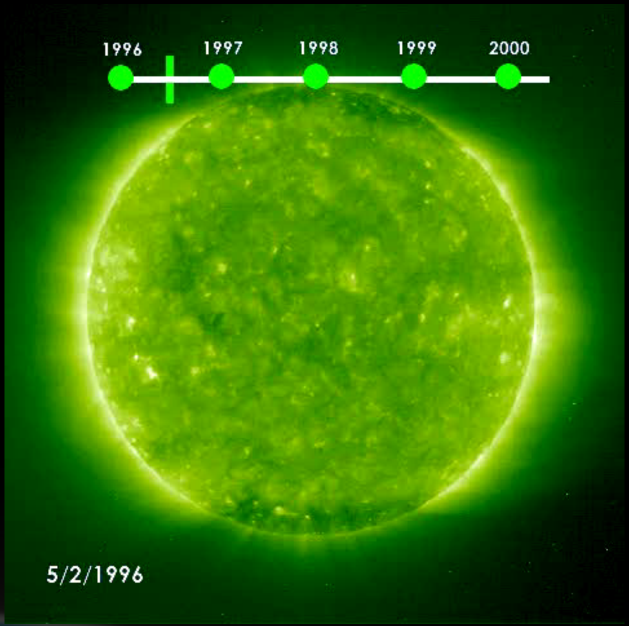


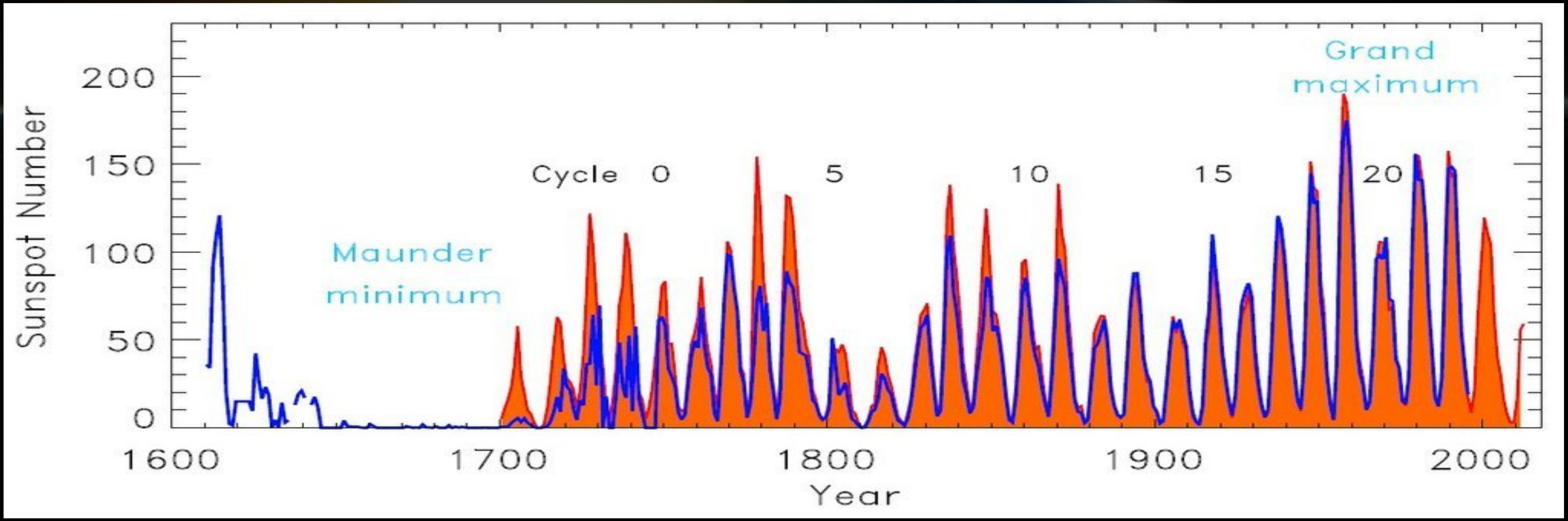
- Stream of charged particles (protons and electrons) released from the Sun (corona) with speeds in range from 300 to 800 km/s
- Fast solar wind streams originate in coronal holes (open-field regions)
- Solar wind particles carry the magnetic field form the Sun – interplanetary magentic field (IMF)
- also influences the geomagnetic field of Earth (geomagnetic storms)

Solar cycle

• 11 year solar cycle (Schwabe)

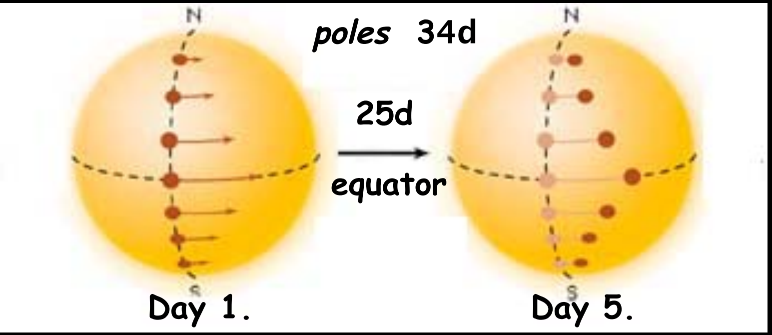
• other known cycles: 22 years (Hale, solar magnetic field reversal), 87 years (Gleissberg), 210 years (Suess), 2300 years (Hallstatt)…

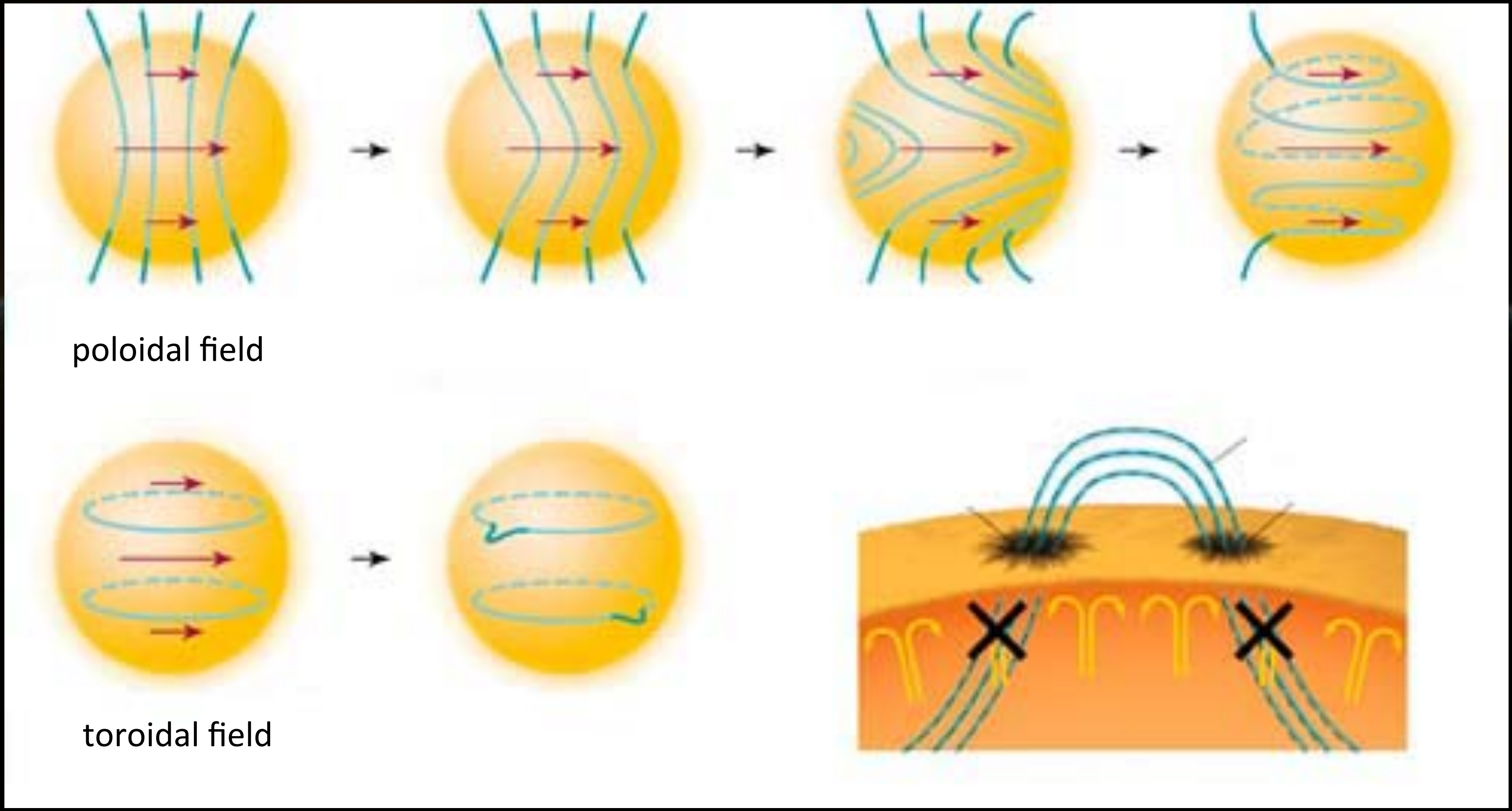




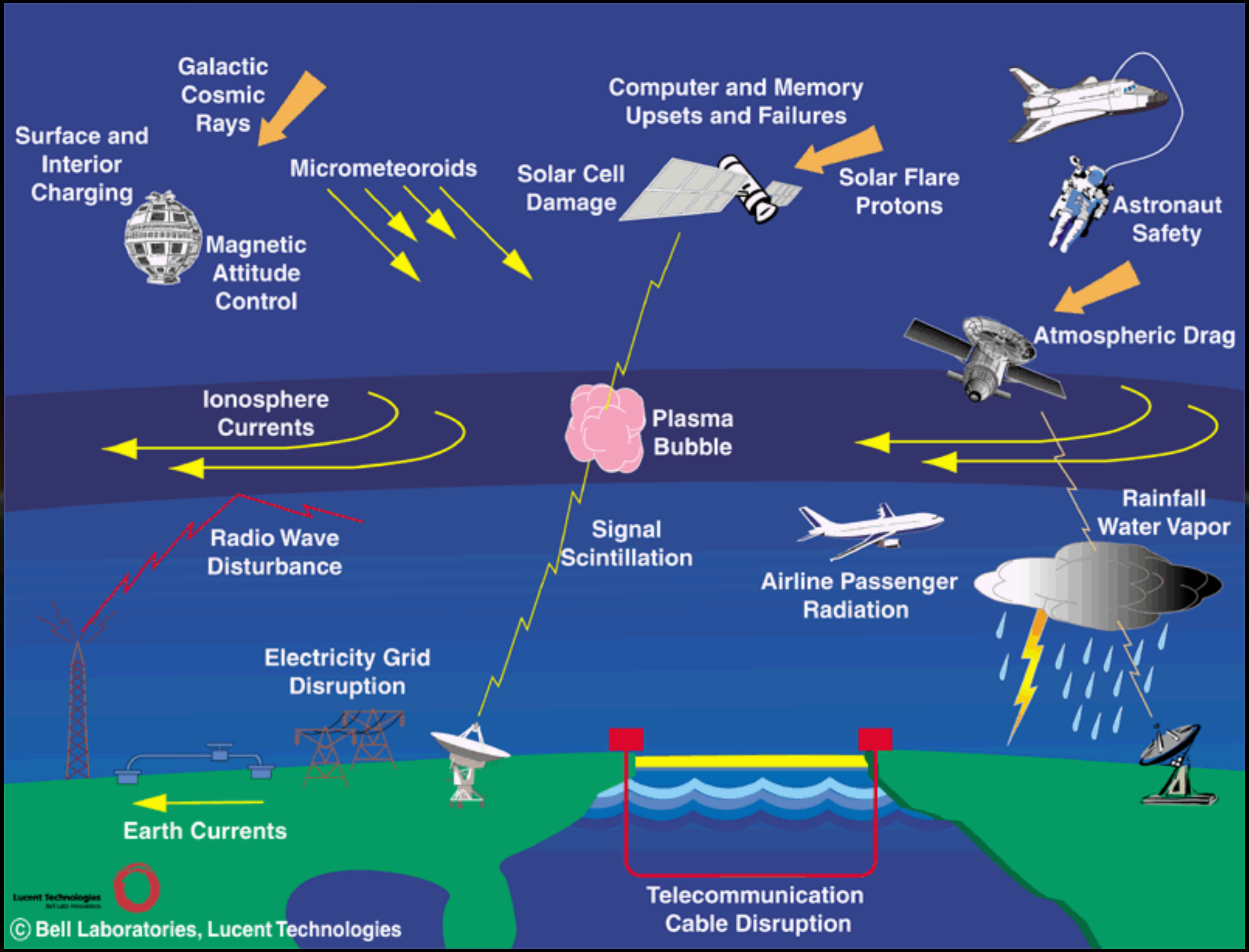
Origin of solar cycle

Solar differential rotation: equator rotates faster (25 days) than poles (34 days), magnetic field gets twisted and streched (from poloidal to toroidal field).



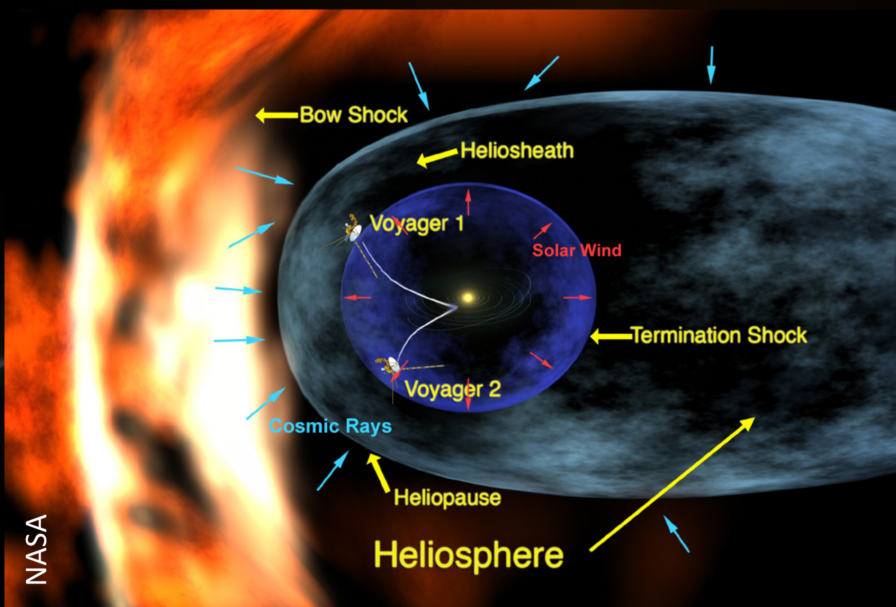


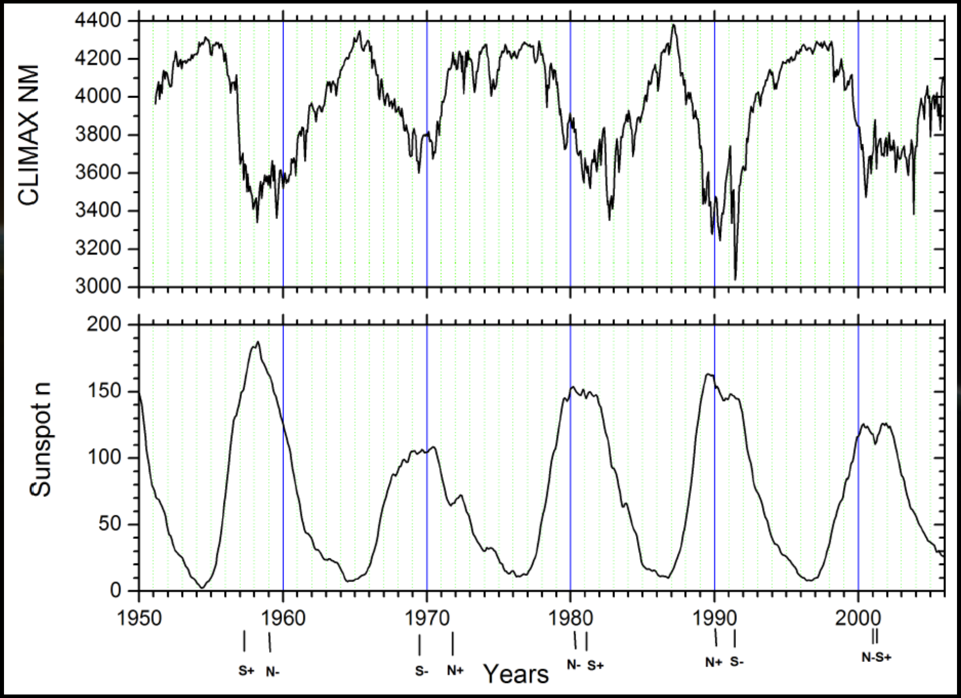
Solar influences on Earth
space weather



Solar activity modulates cosmic rays

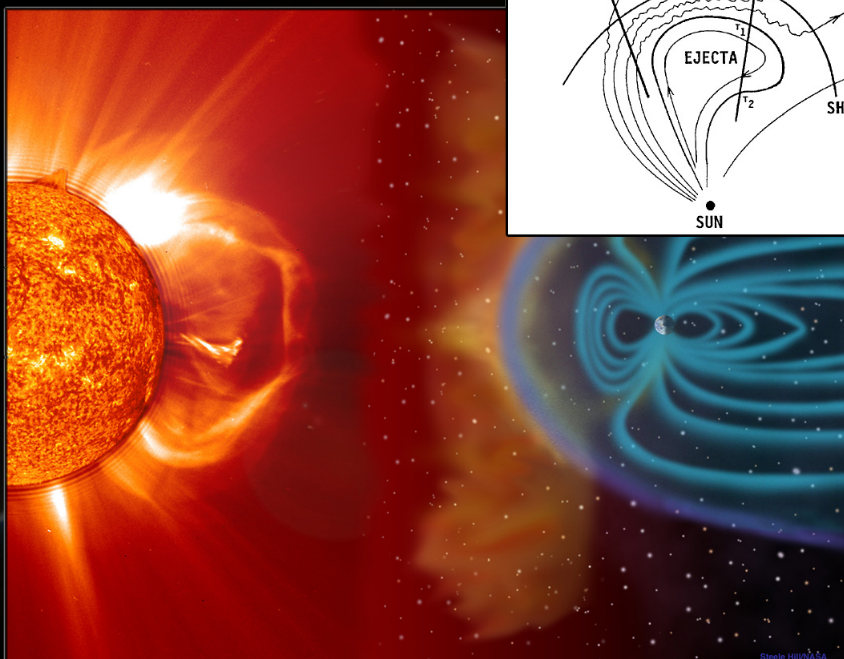
- Cosmic rays (CR) consist of high-energy particles (mainly protons)
- CR flux of low energy particles is greater than flux of high energy particles ($E^{-\gamma}$)
- Particles with less energy are more influenced by the Sun

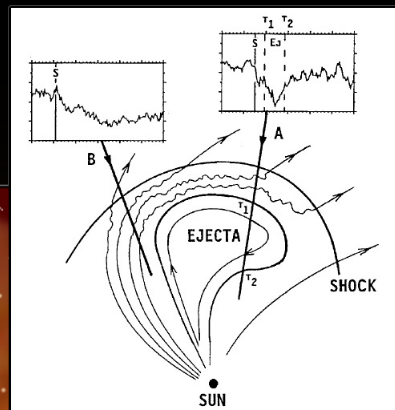




ICME & CIR influence the cosmic rays

Interplanetary coronal mass ejections (ICME)

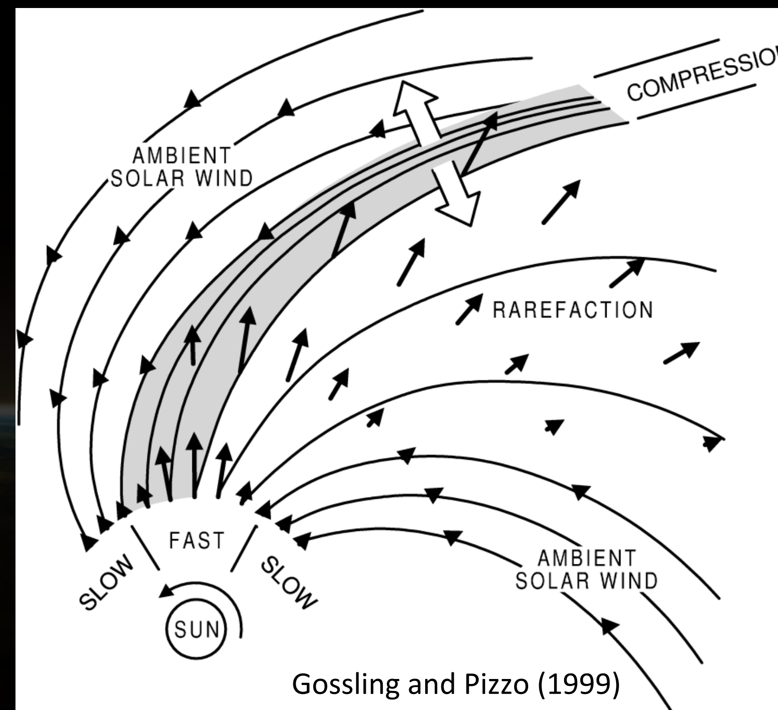




Cane (2000)

- **Forbush decreases (Fd)** – sudden reductions in cosmic ray flux with duration from few days to more than one week, strongest Fd may have reduction in cosmic rays > 10%

Corotating interactive regions (CIR)



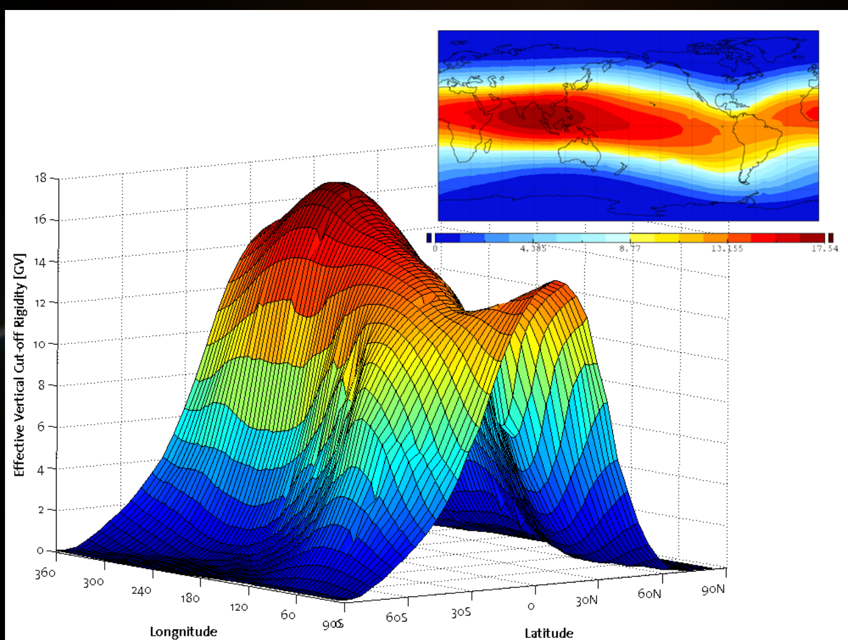
Gossling and Pizzo (1999)

- Most pronounced during the time of low solar activity
- CIRs produce smaller reductions in cosmic ray flux (0.5% to 2%).

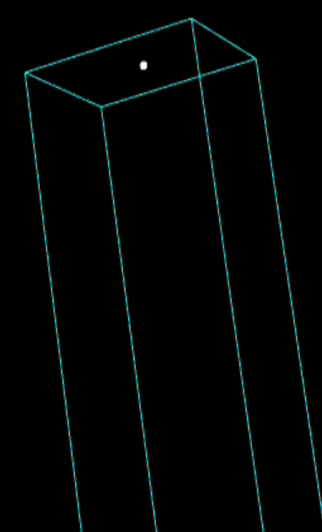
Cosmic ray flux on Earth depends on

- Solar magnetic field and Solar wind
- Geomagnetic field (vertical cutoff rigidity)
- Earth's atmosphere

Example of vertical cutoff rigidity for 20 km altitude, 19.3.1991. 00:00h



Cosmic ray showers (cascade) → ionization in the atmosphere

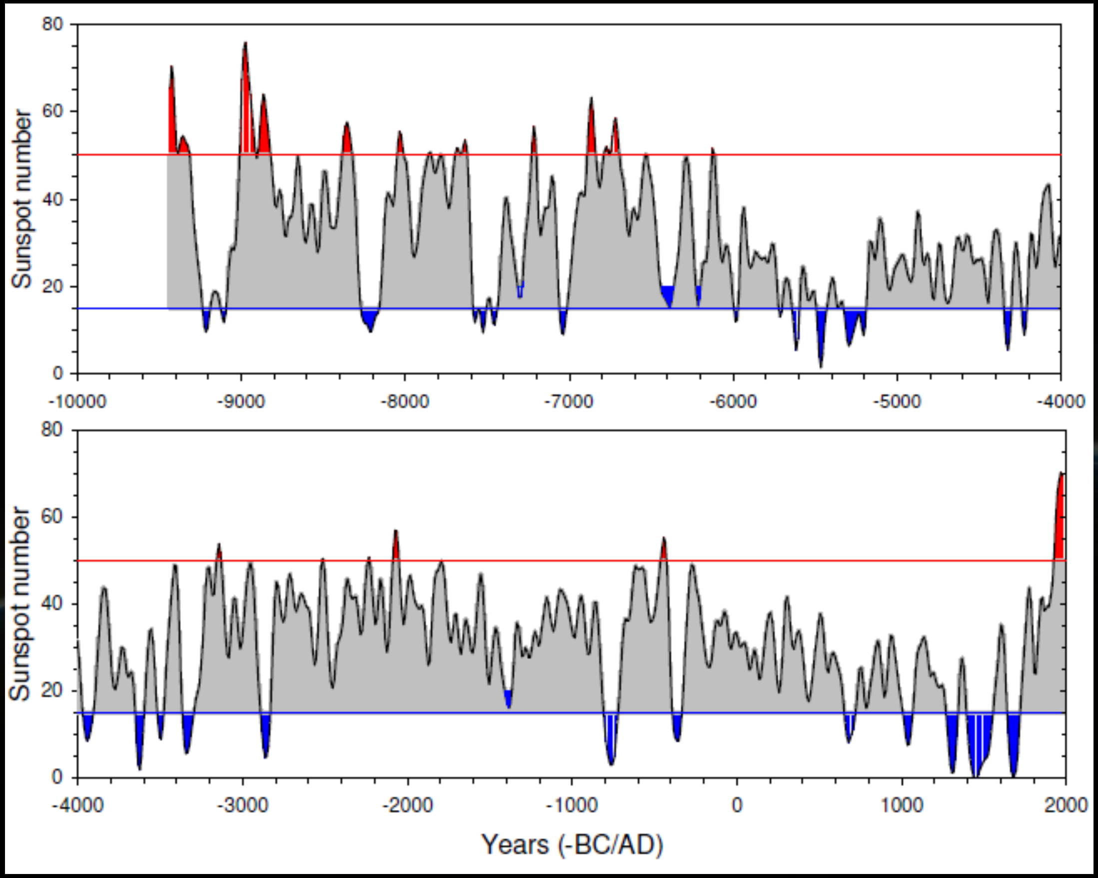


Solar activity and climate in the past

- Global temperature changes in the past show a coincidence with the major changes in the solar activity (based on sunspot, ^{10}Be and ^{14}C isotope measurements), however there are exceptions due to other climate forcings and oscillations
- Little ice age period (16^{th} to 19^{th} century) corresponds to the periods of low solar activity (e.g. Eddy, 1976).

Pieter Bruegel
the Elder
(1565 g.)

Cosmogenic radionuclides allow to reconstruct solar activity thousands of years in the past



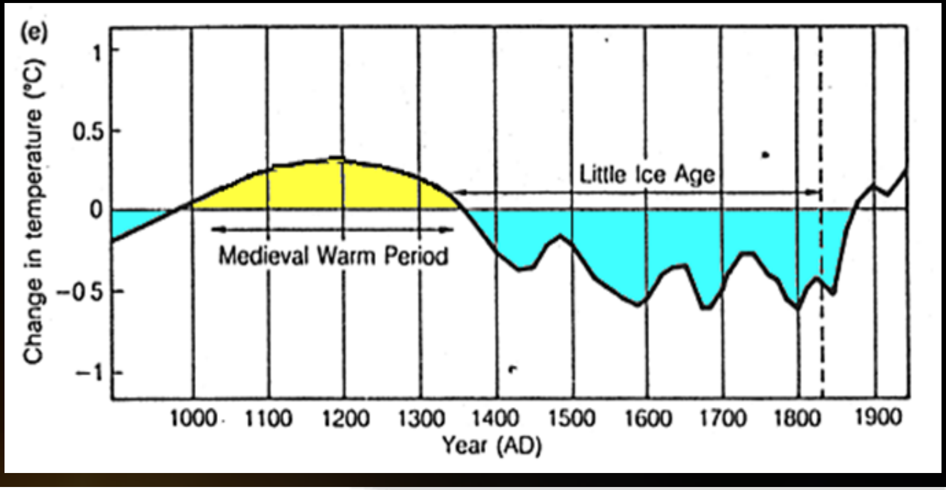
Usoskin, 2007

- ^{14}C and ^{10}Be are produced by cosmic rays in the Earth's atmosphere and stored in natural archives (ice, trees, sediments)
- Proxies for solar activity

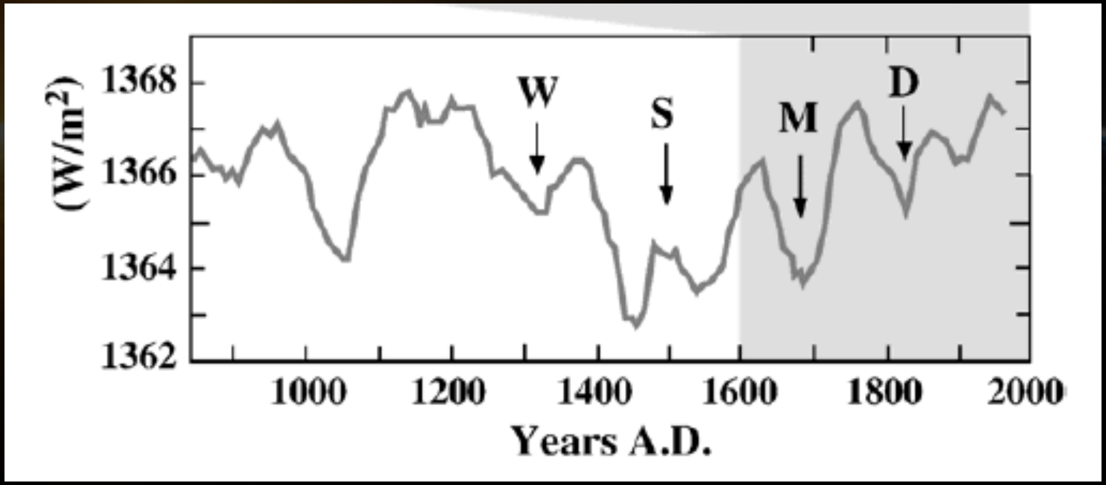
Drilling of ice cores to obtain ^{10}Be measurements

Solar activity and climate

Global temperature



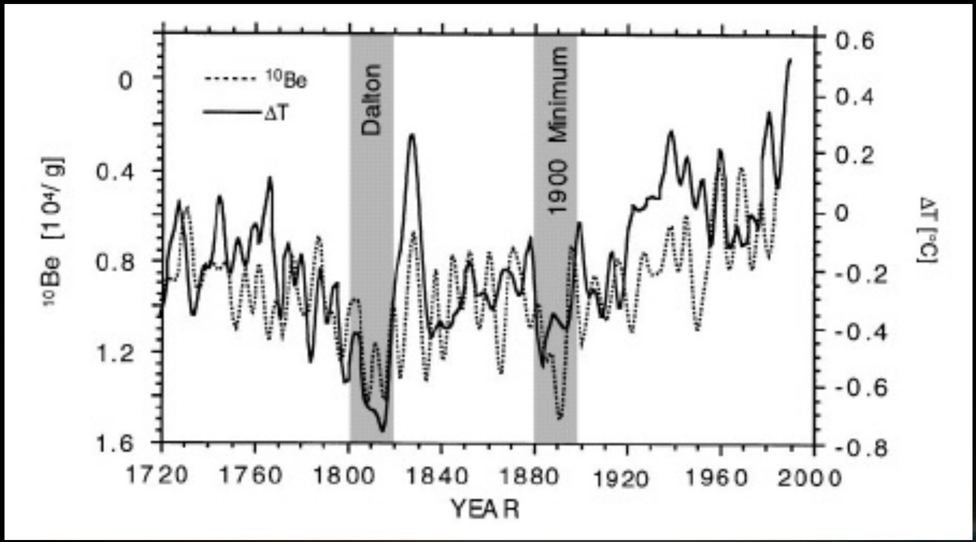
Solar activity



Solar irradiance reconstruction (based on ^{10}Be measurements in ice), Bard et. al. 2000

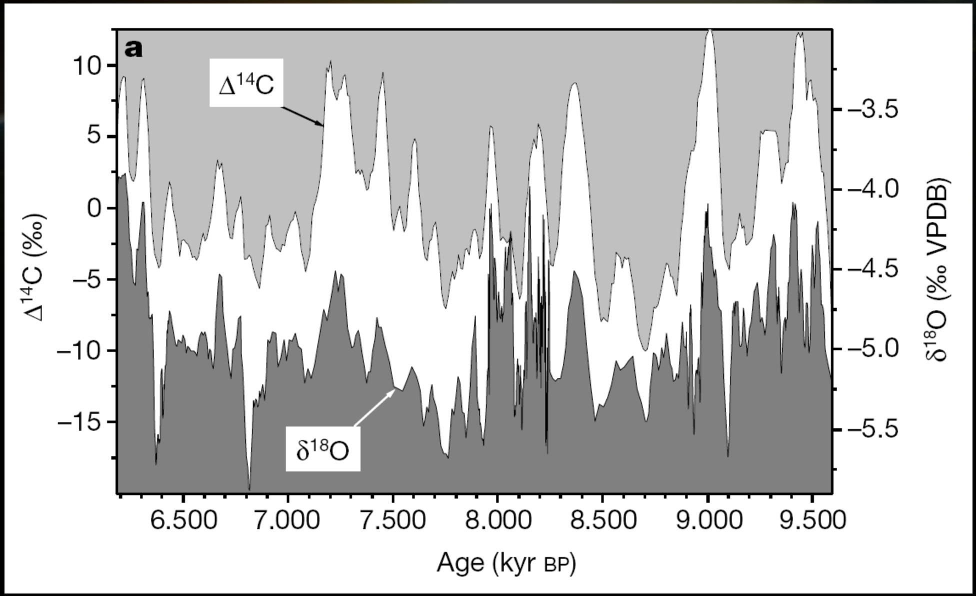
Solar Minimums: Wolf (W), Spörer (S), Maunder (M), Dalton (D)

Solar activity and climate



Solar activity and temperature

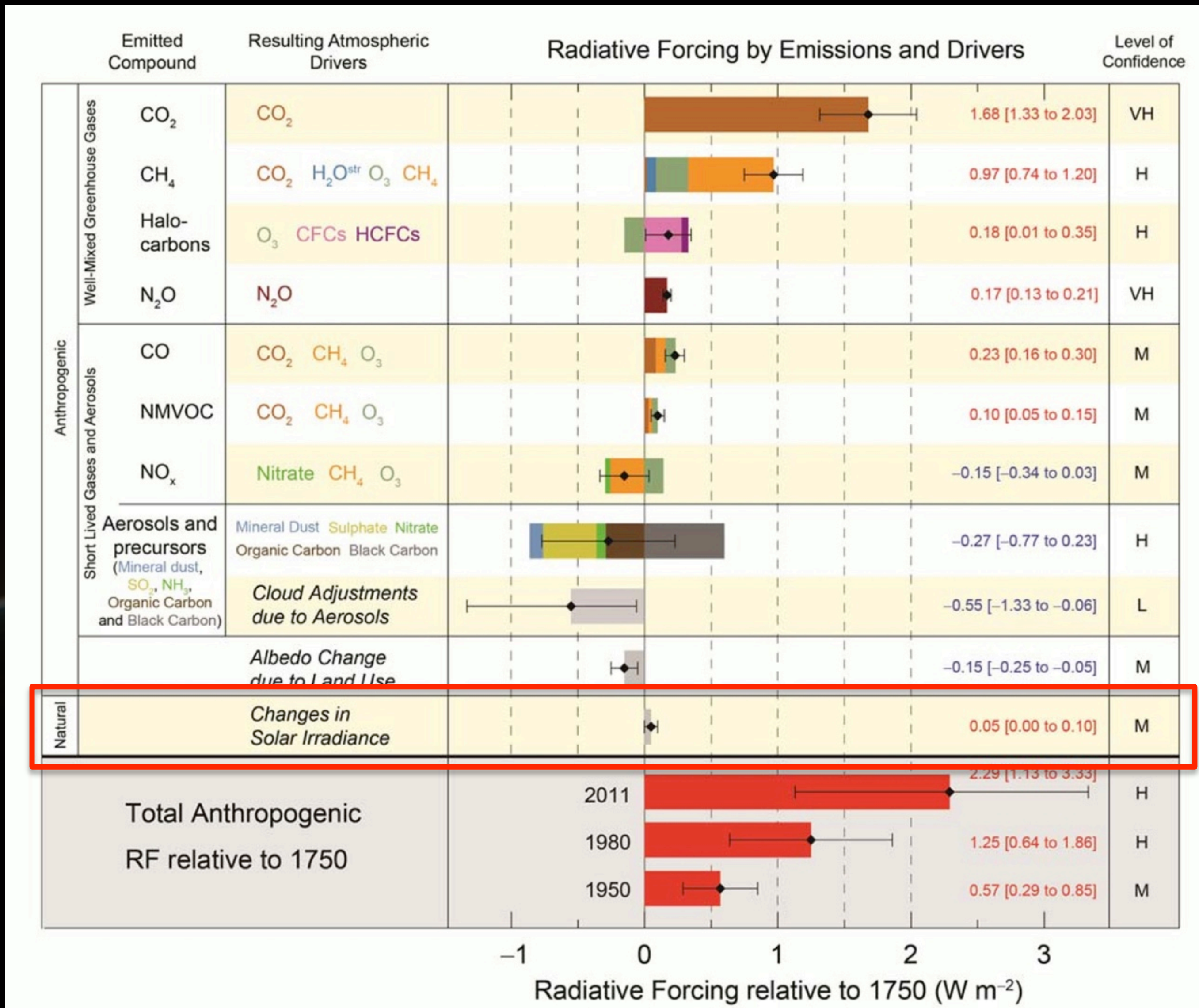
Beer et. al. 2000



Solar activity and precipitation

Neff et al. 2001, measurements from Oman caves (stalagmites)

According to IPCC solar influences on climate are minor



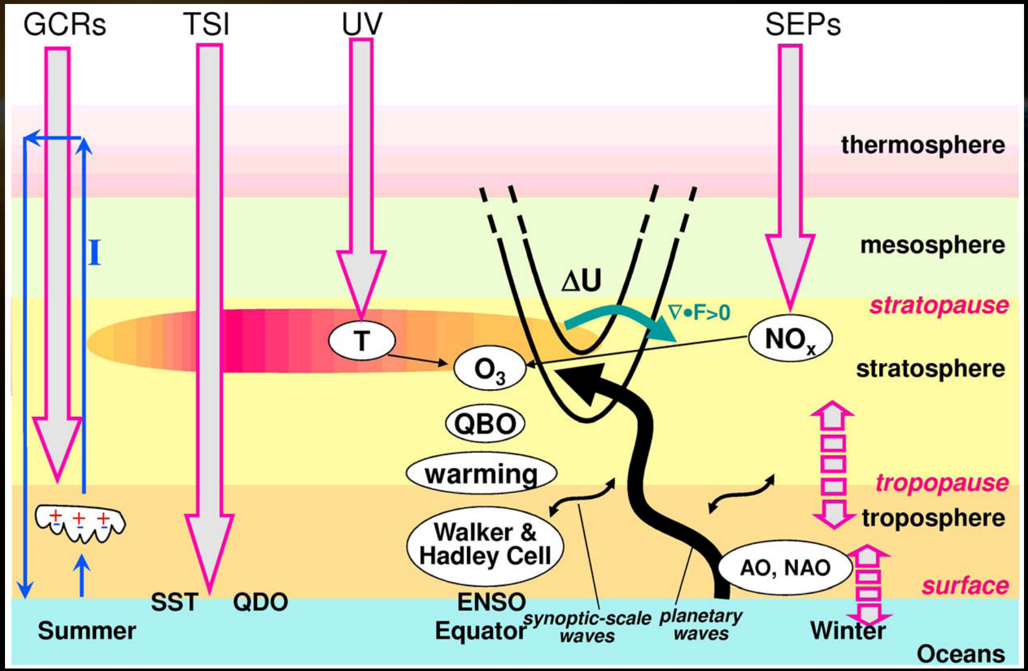
IPCC AR5 (2014)

Solar (natural) radiative forcing is **very small** (0.05 W m^{-2}) compared to CO_2 radiative forcing (1.68 W m^{-2})

Mechanisms of solar influence on climate are still debated and poorly understood

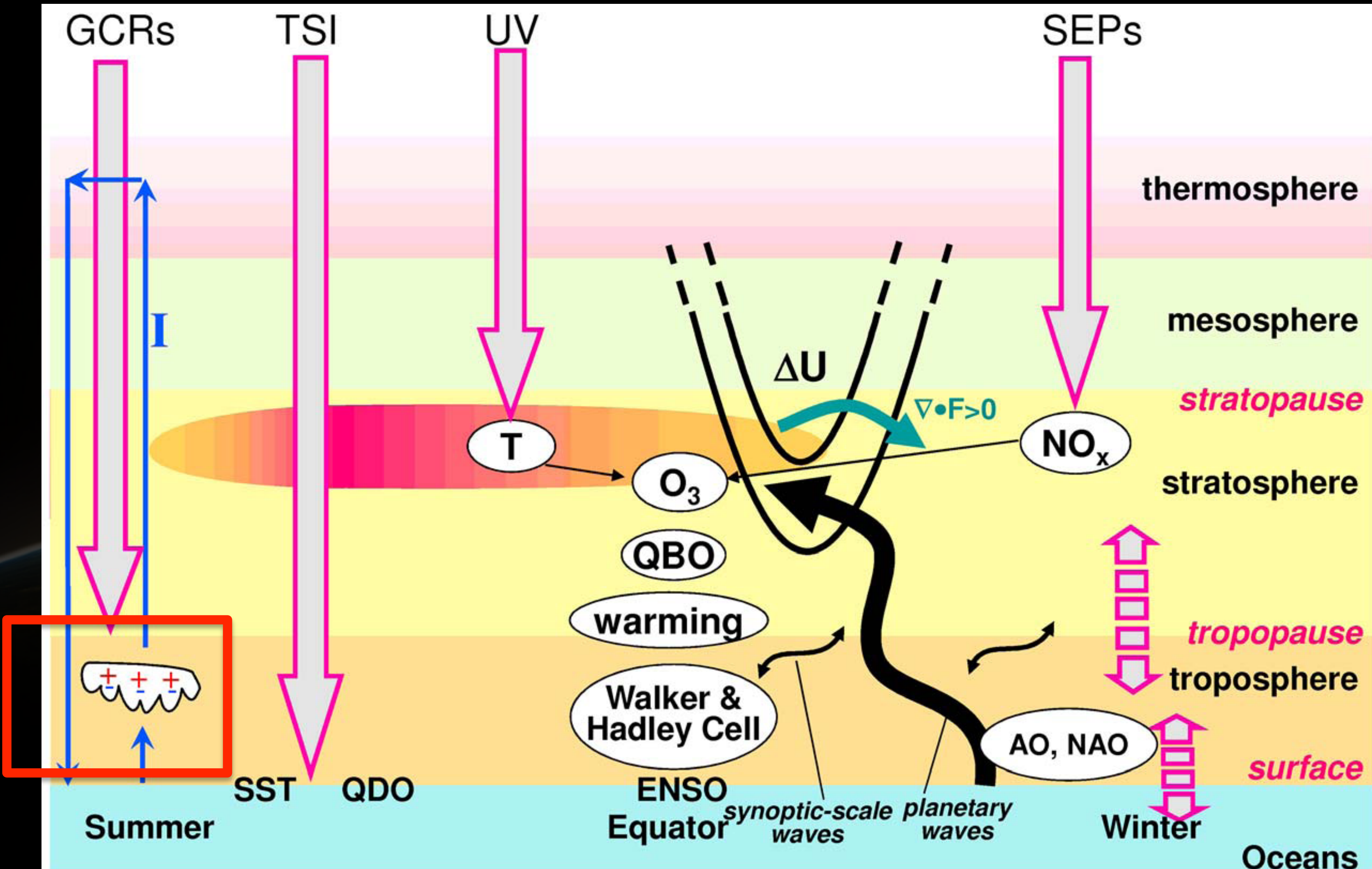
Mechanisms of solar influences on climate

- **Total solar irradiance (TSI)** → sea surface temperature (SST) → modifications of synoptic circulation patterns (Meehl et al., 2009)
- **Ultraviolet (UV)** spectral irradiance → ozone - stratospheric temperatures (Austin et al., 2008) → may impact large scale tropospheric variability via dynamic stratosphere-troposphere couplings (Haigh, 1996)
- **Solar proton events (SEP)** → atmospheric chemistry → ozone
- Galactic cosmic ray (GCR) flux → cloud amount and properties



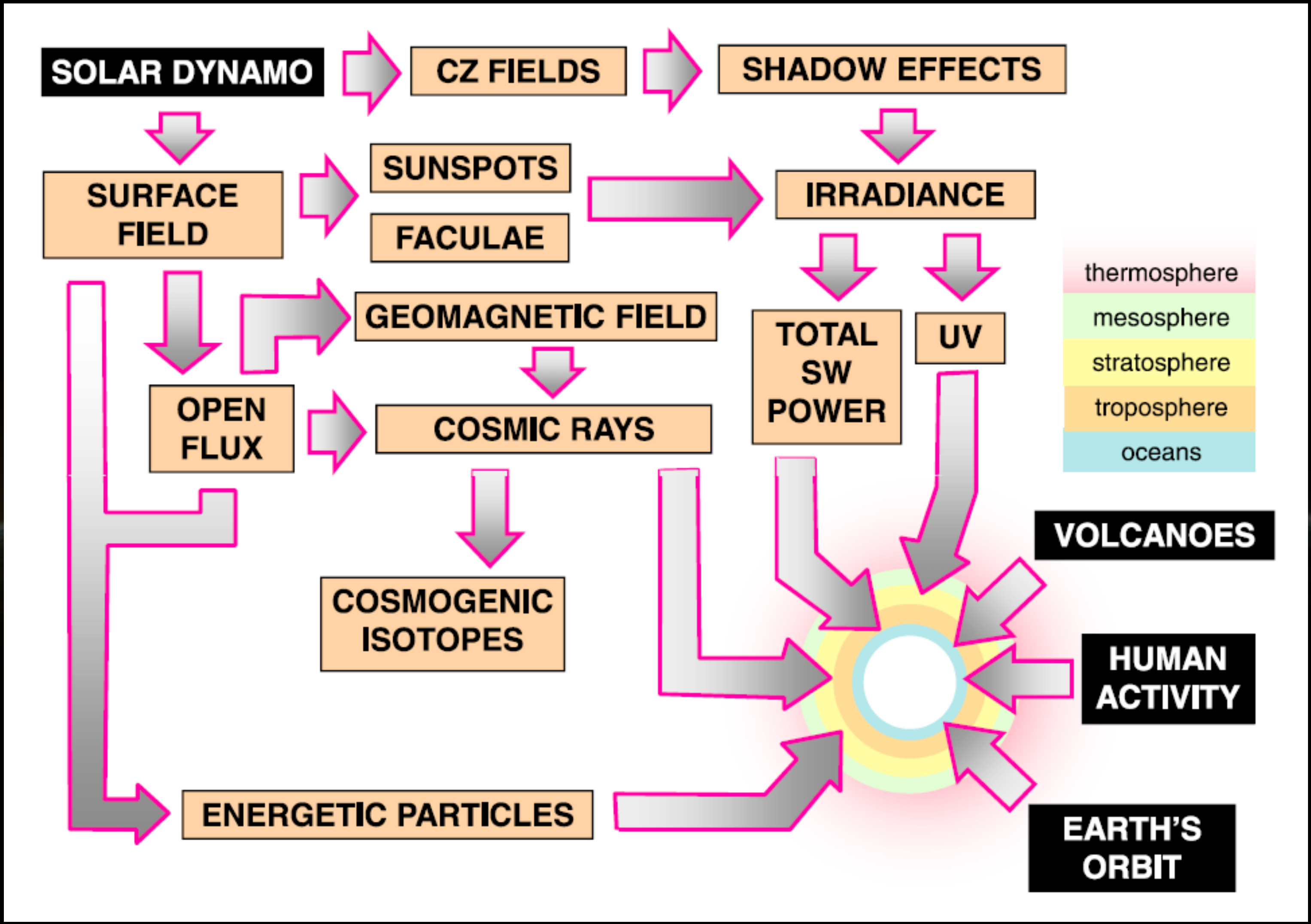
Kodera and Kuroda (2002)

Mechanisms of solar influences on climate



Kodera & Kuroda , 2002

Schematic overview showing various climate forcings of the Earth's atmosphere



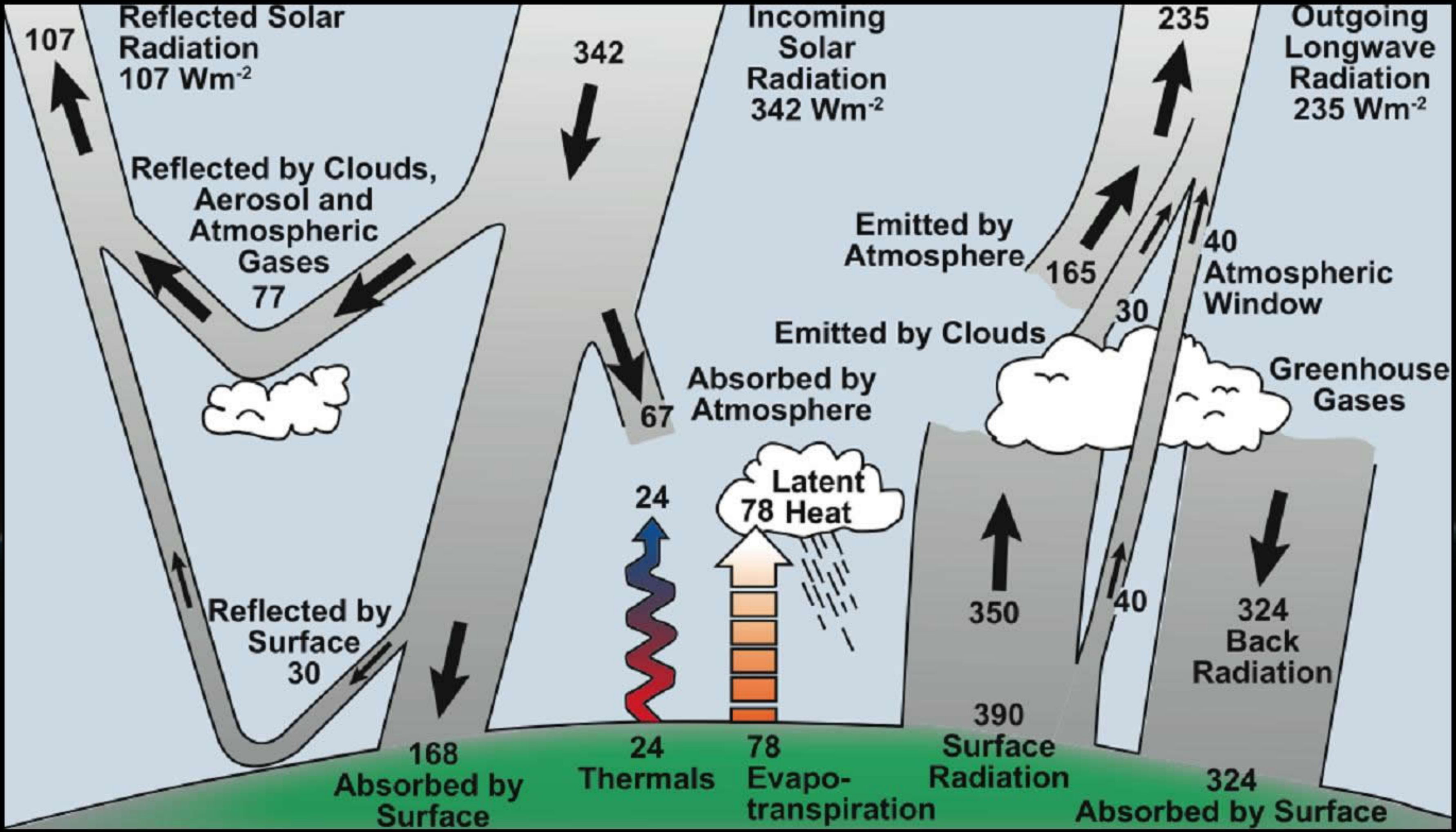
Amplification mechanisms!?

Cosmic ray shower (cascade)

Cosmic ray total energy flux on earth is **10^9 times smaller** than solar irradiation (~ 10^{-5} W/m^2).

How such small energy can influence our climate system?

Earth's radiative balance and clouds



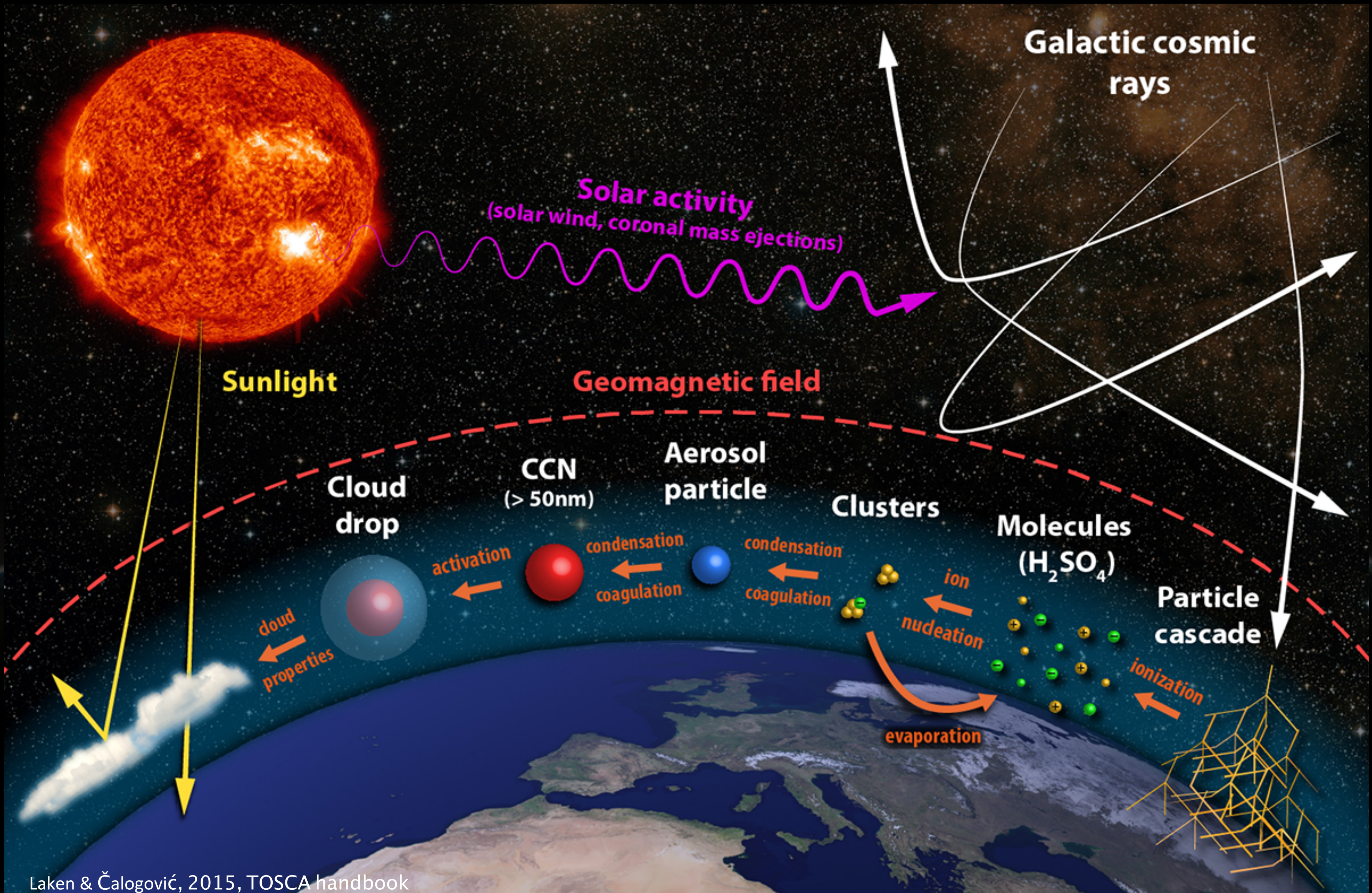
Houghton et al., 1996

Proposed amplification mechanisms for GCR-cloud link

(a) **Ion-mediated nucleation (”clean air” mechanism)**: atmospheric ions produced by the cosmic ray flux alter the nucleation and growth of aerosols (condensation nuclei, CN) upon which cloud droplets form (CR-CN-cloud hypothesis) - Dickinson, 1975; Yu and Turco, 2000.

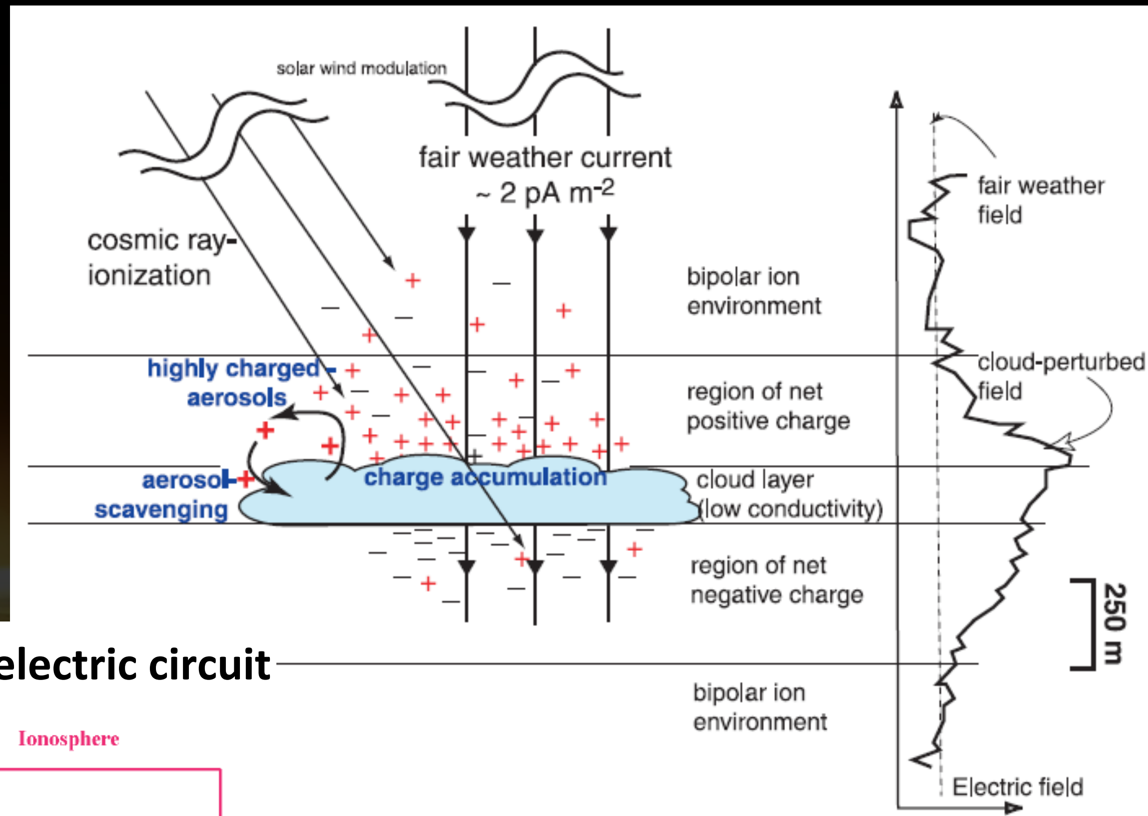
(b) **”Near cloud” mechanism:** operates via global atmospheric electric circuit modulated by cosmic ray flux → changes in the cloud microphysics (current density-cloud hypothesis) - Tinsley, 1996; 2000.

“Clear-air” mechanism



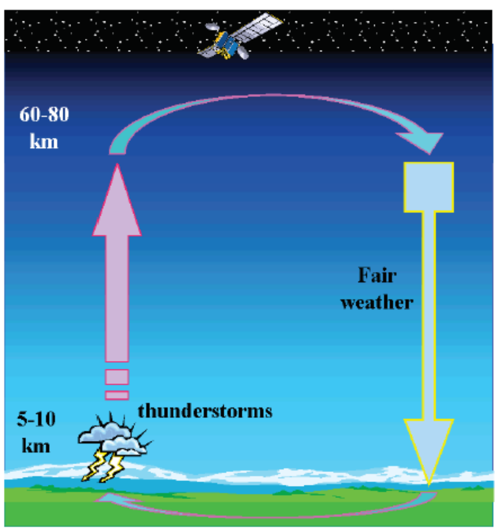
“Near-cloud” mechanism

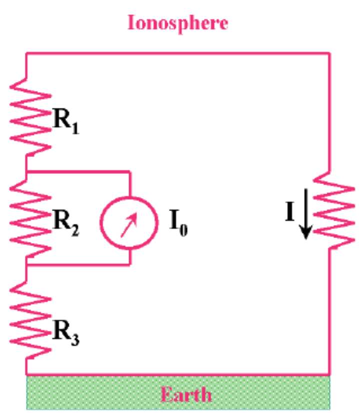
Charges at cloud boundaries and its attachment to aerosols and cloud droplets impact the microphysics of clouds – cloud droplet formation, droplet-to-droplet collision efficiency, droplet-to-aerosol particle collisions and so-called electroprotection and electroscavenging processes.



Carslaw, Harrison et al., 2002

Global electric circuit



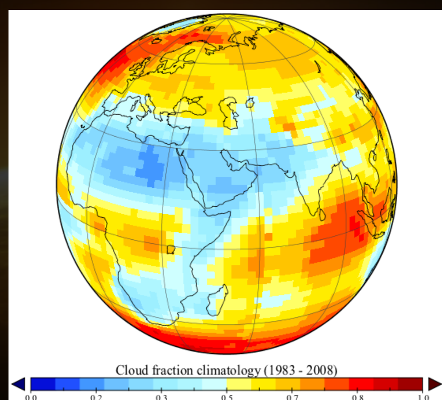


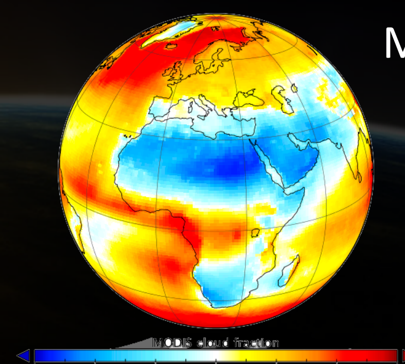
Makino and Ogawa, 1984

Cloud datasets

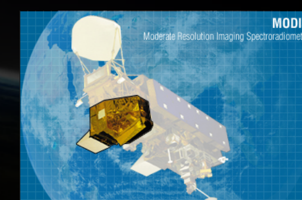
ISCCP (International Satellite Cloud Climatology Project)

- D1 dataset (from 1983), intercalibrated radiance measurements from a fleet of polar and geostationary satellites
- temporal resolution: 3h (IR data)
- spatial resolution: 2.5° x2.5° (280 x 280km^2)
- distinguishes clouds at different altitude levels: e.g. high (>6.5km), middle (3.2 – 6.5km) and low (0 – 3.2km)





MODIS



MODIS (MODerate Resolution Imaging Spectroradiometer)

- views in 36 channels from Visible to thermal IR, on board two polar orbiting satellites Aqua, and Terra, operational since 2000
- temporal resolution: 12h, spatial resolution: 1° x 1°

The hypothesized link between cosmic ray flux and cloud cover

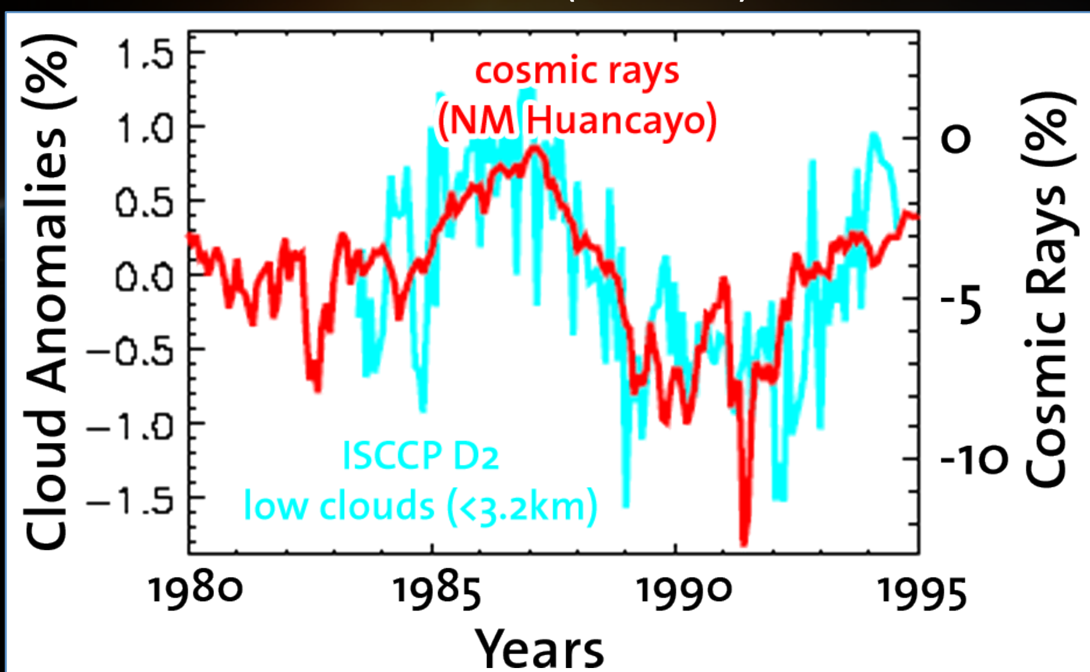
Long-term studies

Svensmark and Friis-Chistensen (1997)

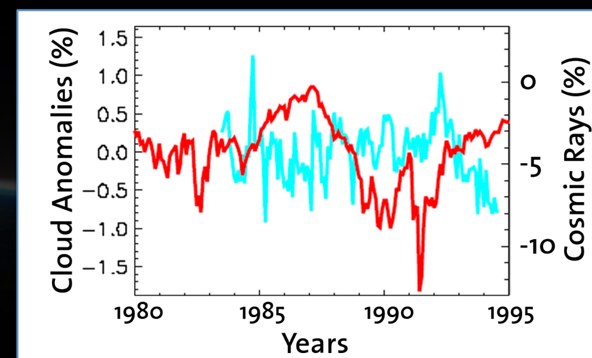
- analyzed one solar cycle and reported that global cloud cover changed in phase with the GCR flux by 2-3% → radiative forcing (0.8 – 1.7 W/m^2) comparable with greenhouse gases forcing

Marsh and Svensmark, 2000

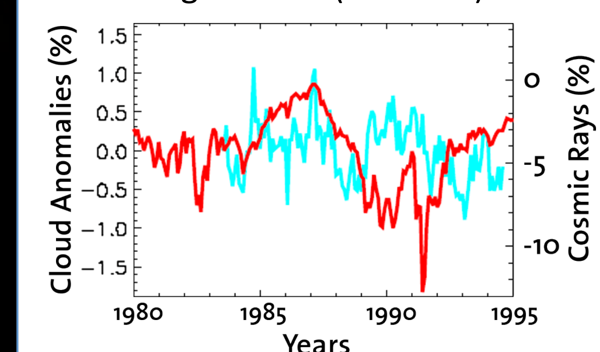
low clouds (0-3.2km)



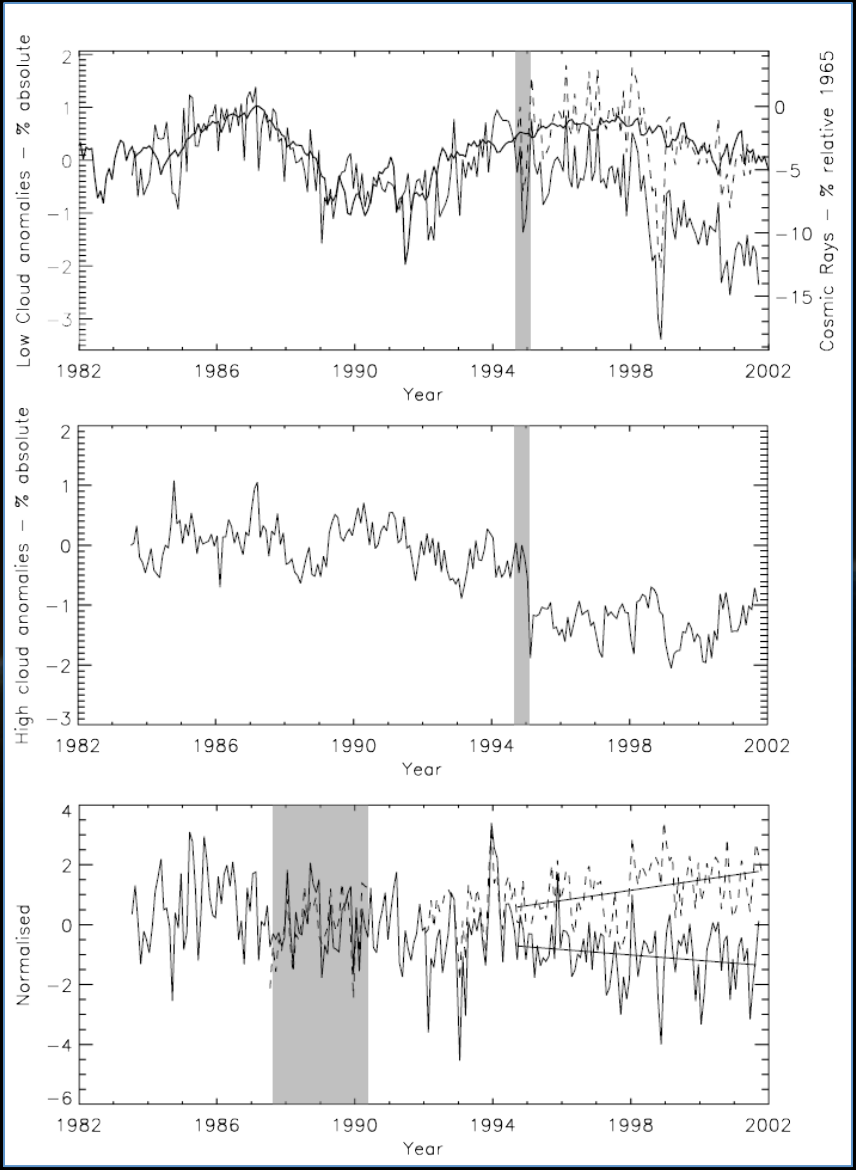
middle clouds (3.2 - 6.5 km)



high clouds (> 6.5 km)



Marsh and Svensmark, 2003



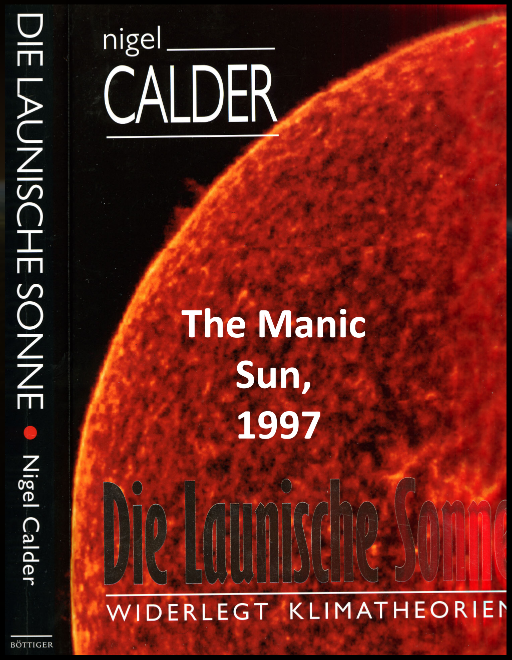
- After year **1995** there is **no correlation** anymore between cosmic rays and clouds
- Marsh and Svensmark, 2003 tried to correct ISCCP cloud dataset **on their own**

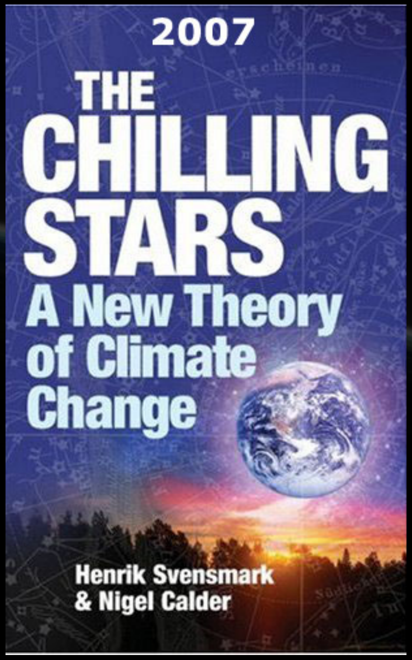
Many critics for a found correlation…

…and heavy debates in the scientific community: *e.g. Kernthaler et al.*, 1999; Wagner, 2001; Udelhofen & Cess,2001; Sun & Bradley, 2002; *Laut*, 2003; *Kristjansson et al.*, 2002, 2004, 2008; *Sloan and Wolfendale*, 2008…

However…

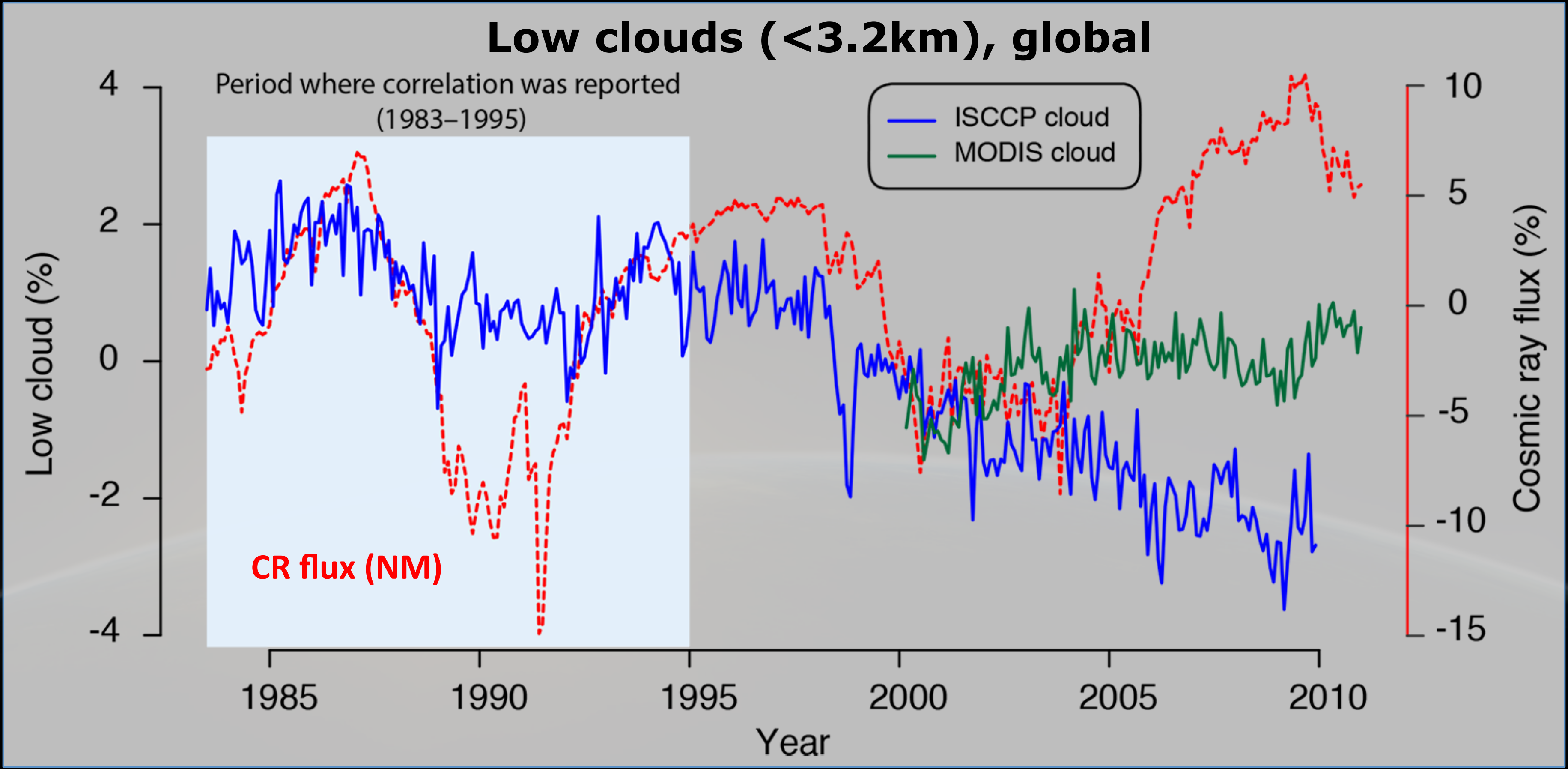
- …danish group ignored majority of this critics and gave basis for **”Cosmoclimatology”** hypothesis (Svensmark, 2007) - Earth’s climate is solar-driven with minor human contribution to recent climate change.
- Various groups and climate sceptics used these arguments – eg. Nongovermental Panel on Climate Change, NIPCC (Idso and Singer, 2009)





These (incorrect) arguments are still used today!

Long-term cloud data doesn't support GCR-cloud link



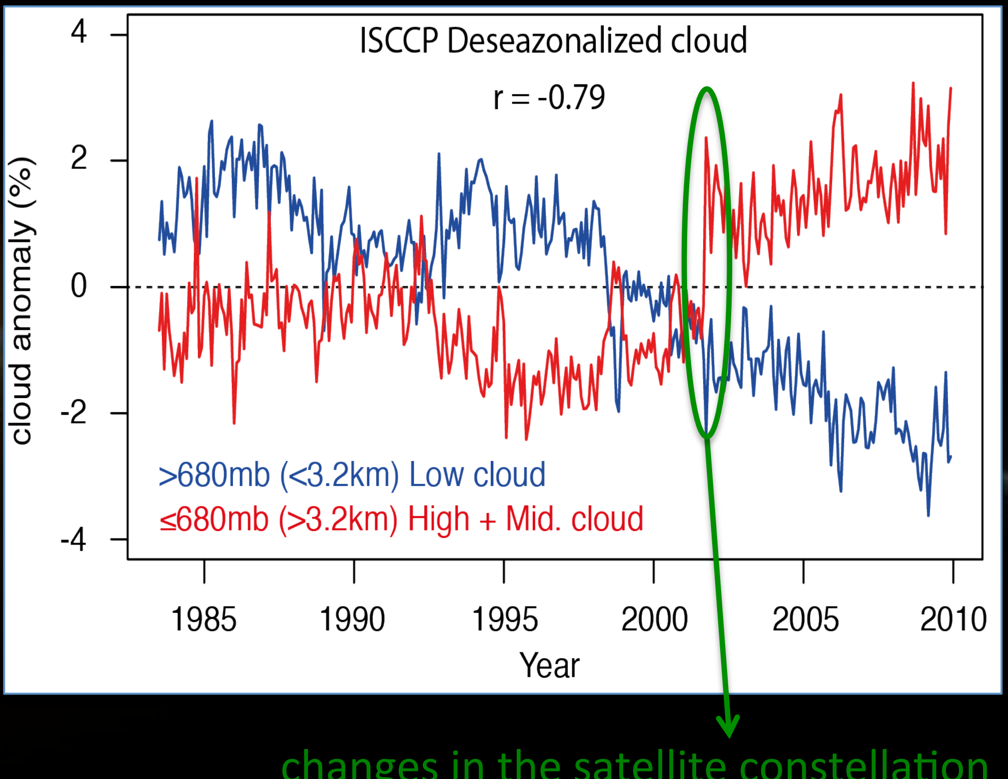
- Correlation only in low (<3.2km) ISCCP cloud (1983–1995)
- High correlation from 12-month smoothed data (df=4)
- Low (non-significant) correlation from unsmoothed data

Laken, Pallé, Čalogović & Dunne, 2012, SWSC

Artificial anti-correlation exists between low and high/middle troposphere cloud

- Low cloud obscured by overlying cloud (**measurements are non-cloud penetrating**).
- Number of geostationary satellites increased over time → artificial drop in low cloud
- Errors in identifying cloud height can contribute to shifts between low and high cloud.
- Satellite cloud issues well known: e.g. Hughes, 1984; Minnis, 1989, Tian & Curry, 1989; Rozendall et al. 1995; Loeb & Davies, 1996; Salby & Callaghan, 1997, Campbell, 2004

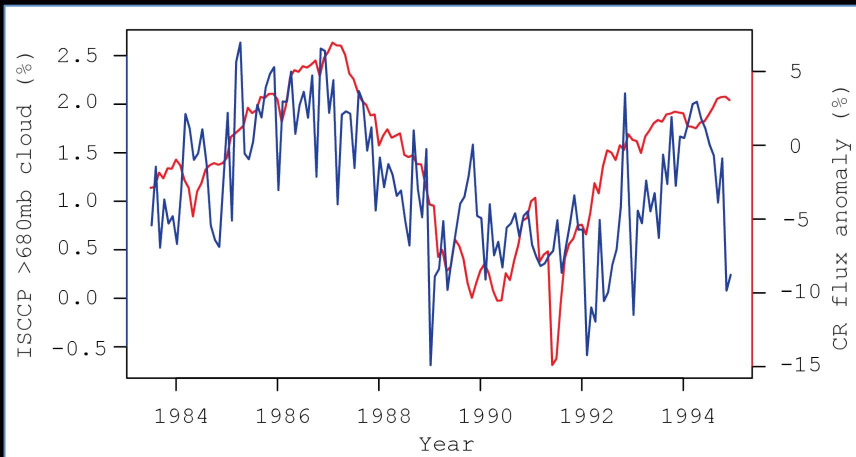
Evidence for CR – cloud link is based on low level clouds:
these data are not reliable!

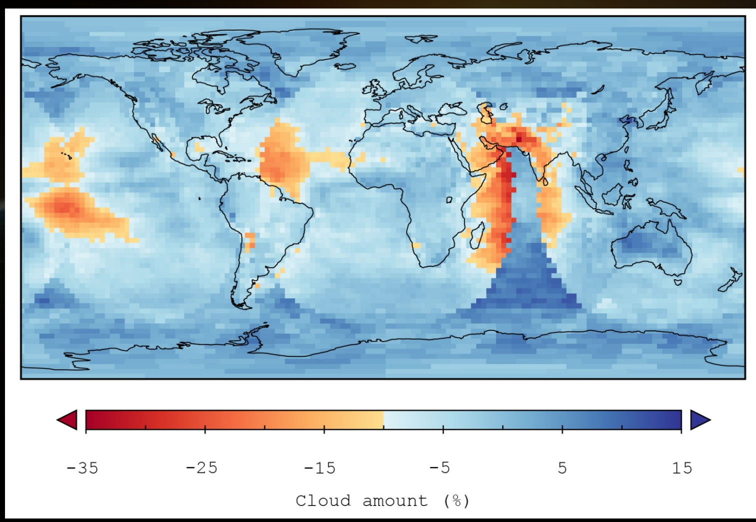


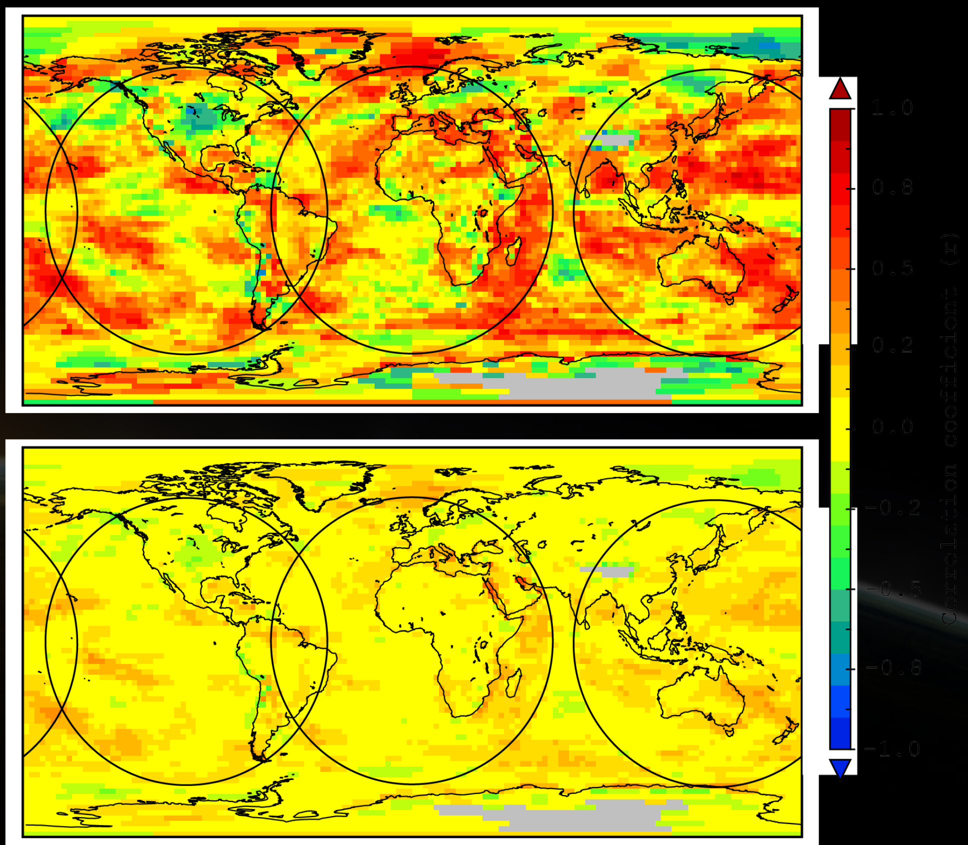
Laken, Pallé, Čalogović & Dunne, 2012, SWSC

Many additional problems of long-term analysis (e.g. signal attribution - ENSO, volcanic eruptions...)

Correlations between CR flux and clouds are artificial



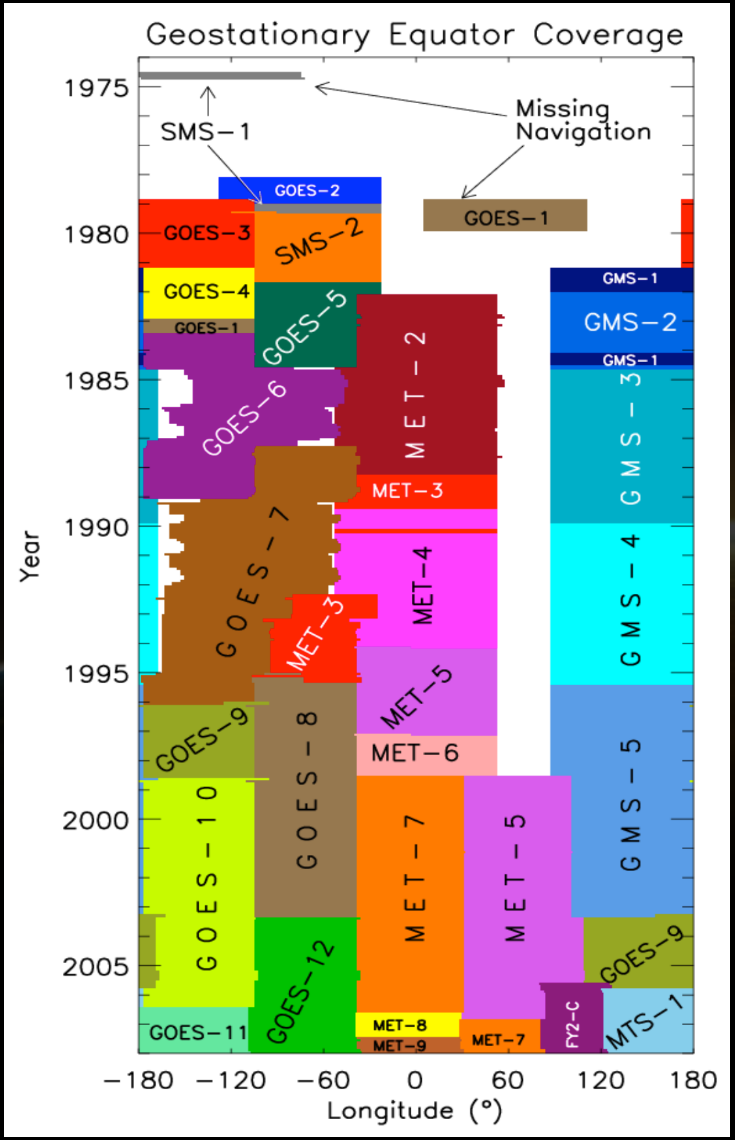


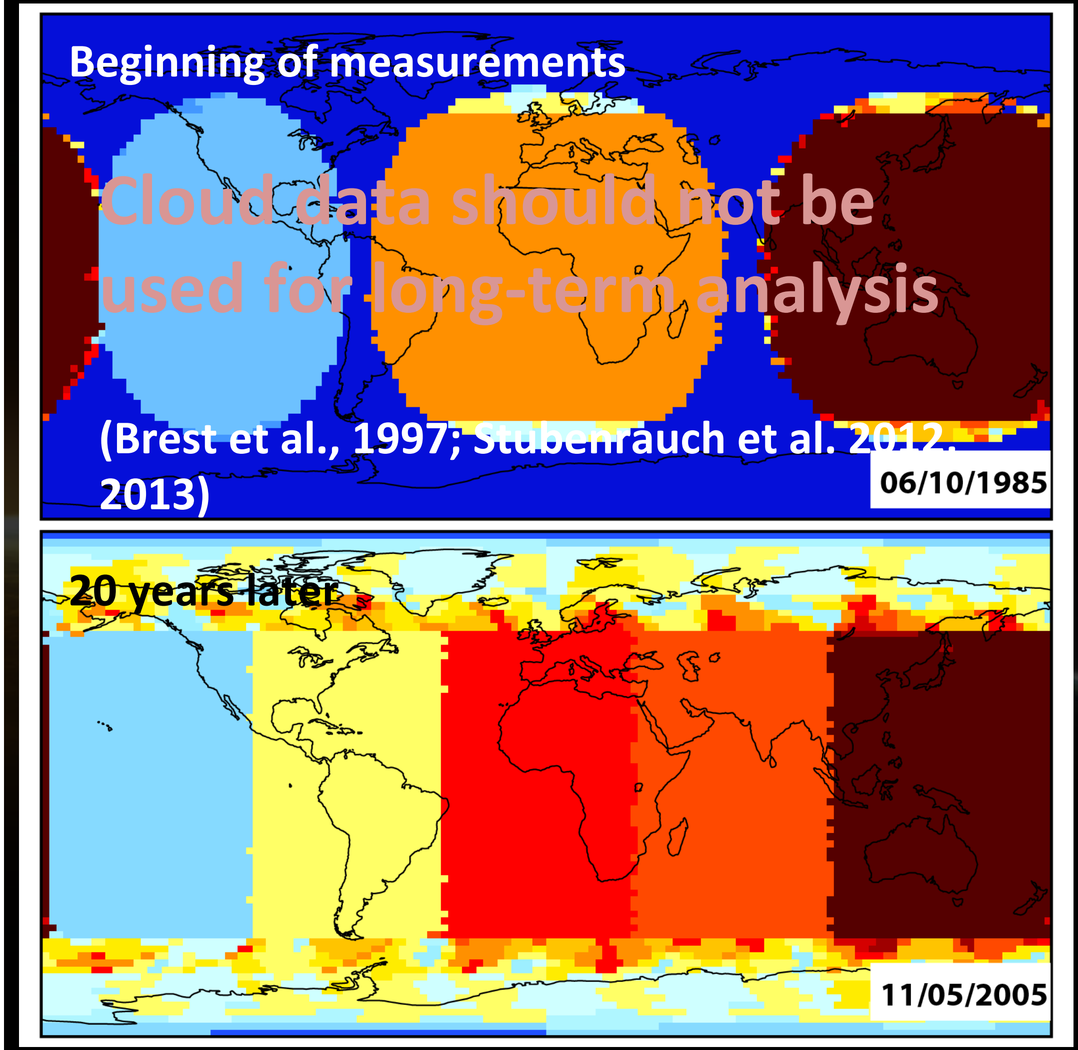


Laken, Pallé, Čalogović i Dunne, 2012, SWSC

If linear trends in CR and cloud data are removed correlation becomes weak

Timeline of geostationary satellite operation at equator over ISCCP observation period





CERN CLOUD experiment

- **C**osmics **L**eaving **OU**tdoor **D**roplets

Laboratory experiment with a special cloud chamber to study the possible link between galactic cosmic rays and cloud formation.

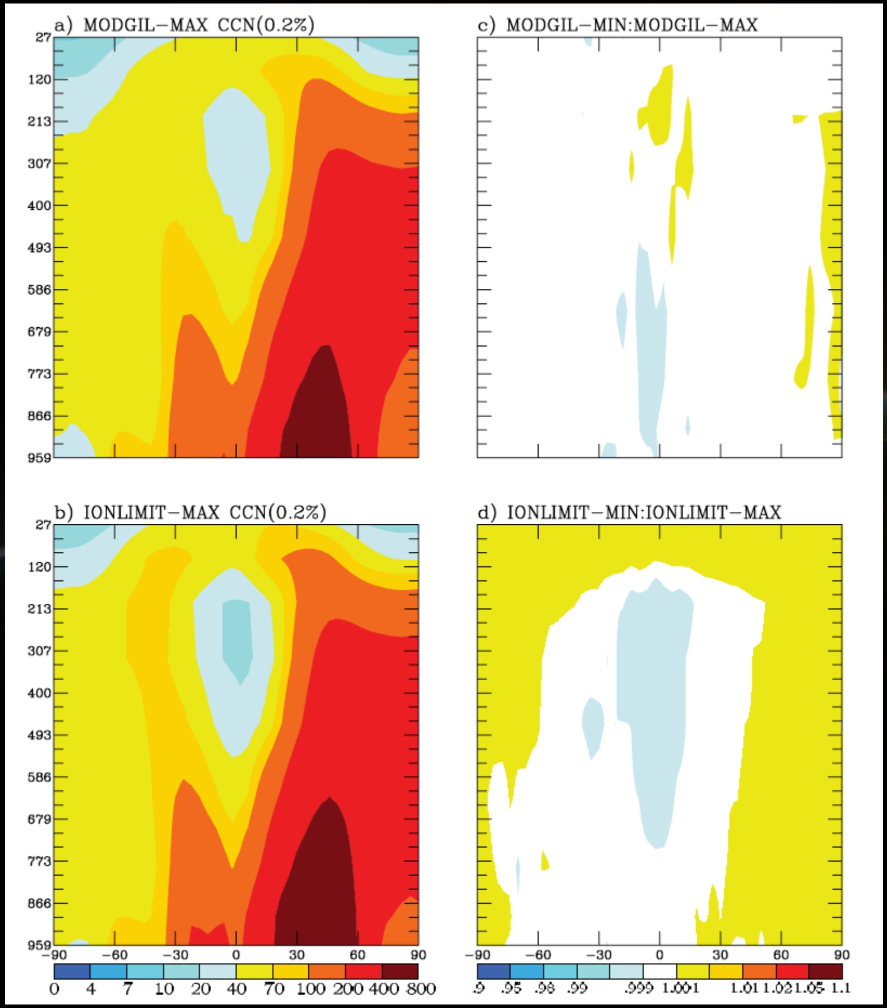
- **Ion-induced aerosol nucleation 10x faster than binary homogeneous nucleation**
- Nucleation in presence of ammonia → **100 do 1000x** faster than ion-induced nucleation
- Nucleation with acid-amines → **1000x** faster than nucleation with ammonia (explains observed particle formation rates in the atmosphere)

Almeida et al., 2013, Nature

Model studies show minor impact to alter CCN populations

CCN concentrations during solar max

Difference (solar max – solar min)

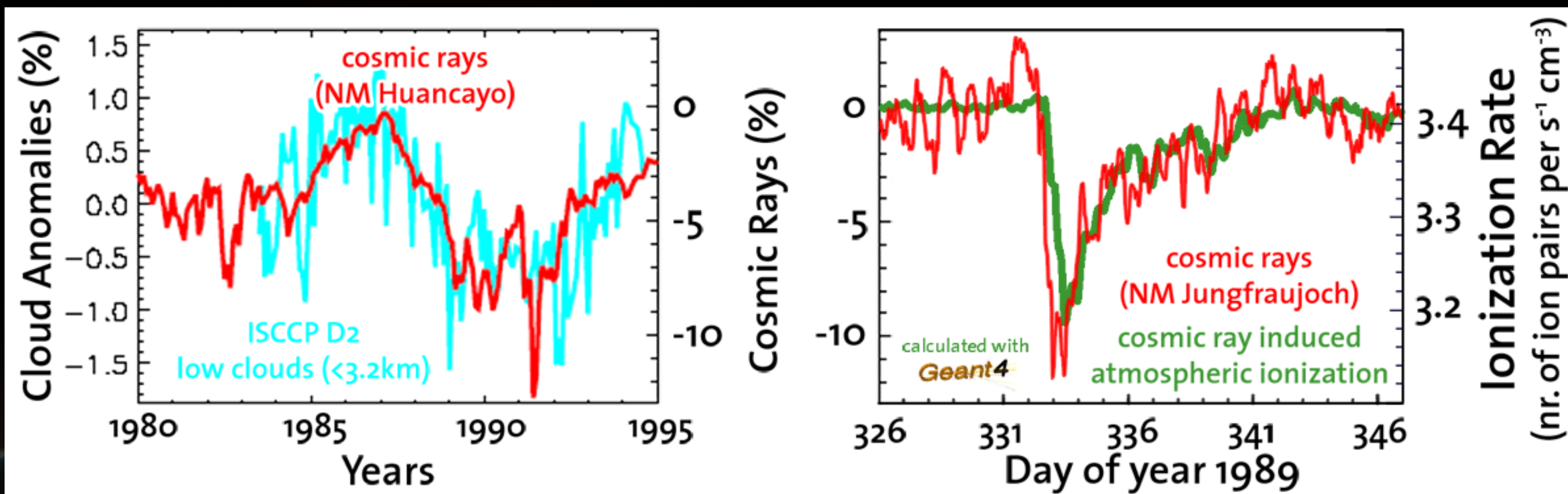


Pierce and Adams, 2009

- Used general circulation model (GCM) with aerosol microphysics (TOMAS)
- Changes in the nucleation rate due to cosmic rays (ion-induced nucleation) are very small
- Ionisation increases growth od small particles, but these particles remain at small sizes for long time – unlikely to survive and grow to CCN sizes.
- Model calculations show change of approx. 0.2% for aerosols >80 nm in diameter over the solar cycle

Short-term studies - opportunity to test GCR-cloud hypothesis

• Short-term changes in cosmic rays (Forbush decreases) are comparable to variations during the solar cycle.

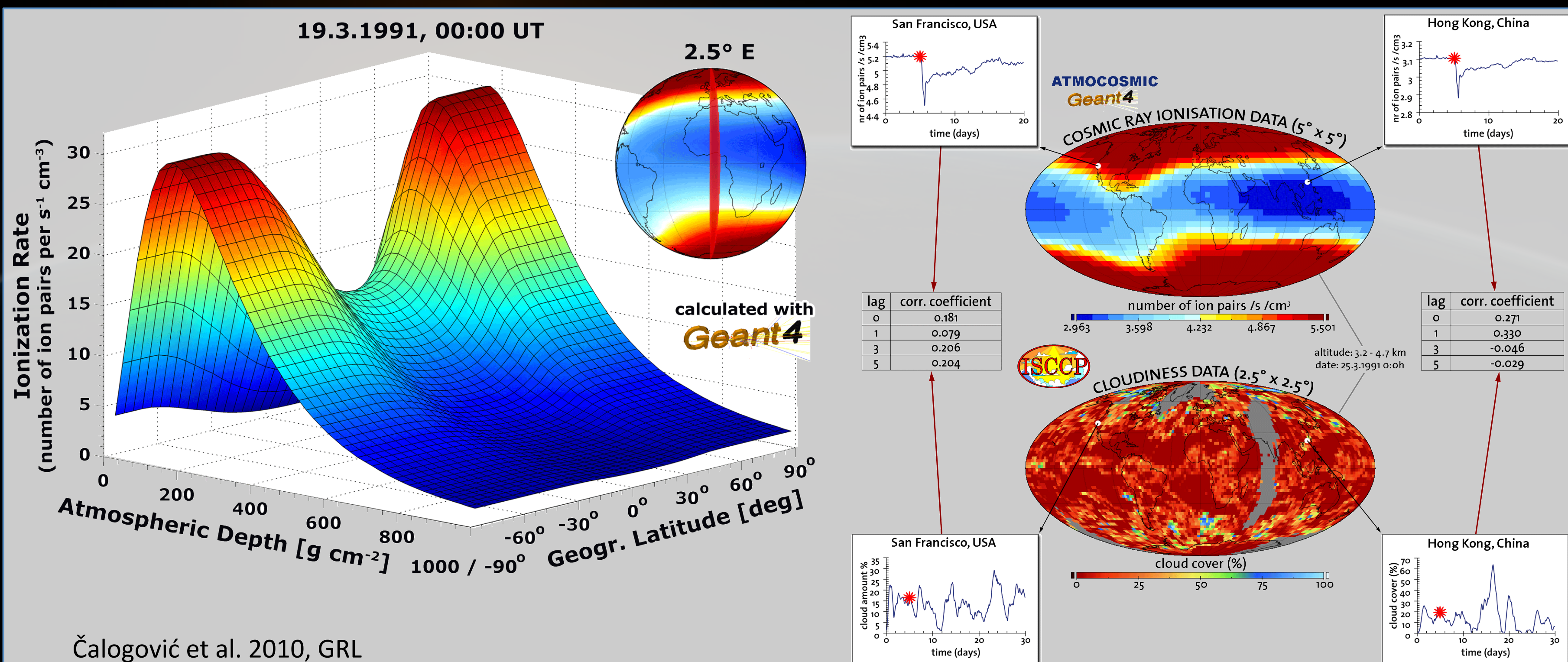


• **Advantages**: some important unwanted factors that influence long-therm studies are removed (ENSO, vulcanic eruptions, satellite calibration errors)

• **Disadvantages**: Meteorological variability (noise) in clouds has to be **reduced** to be able to detect the solar-related changes (signal), **limited** number of high-magnitude Forbush decreases (several pro cycle)

Analysis of ISCCP cloud cover during 6 biggest Forbush decreases (1989-1998)

- Forbush events with decreases in CR flux > 9 %
- calculated cosmic ray induced ionization rate (GEANT4, 2.5°x2.5°)
- independent correlation analysis of all grid cells for each lag (10 days)
- in total 8.6 milion correlations calculated



San Francisco, USA:

lag	corr. coefficient
0	0.181
1	0.079
3	0.206
5	0.204

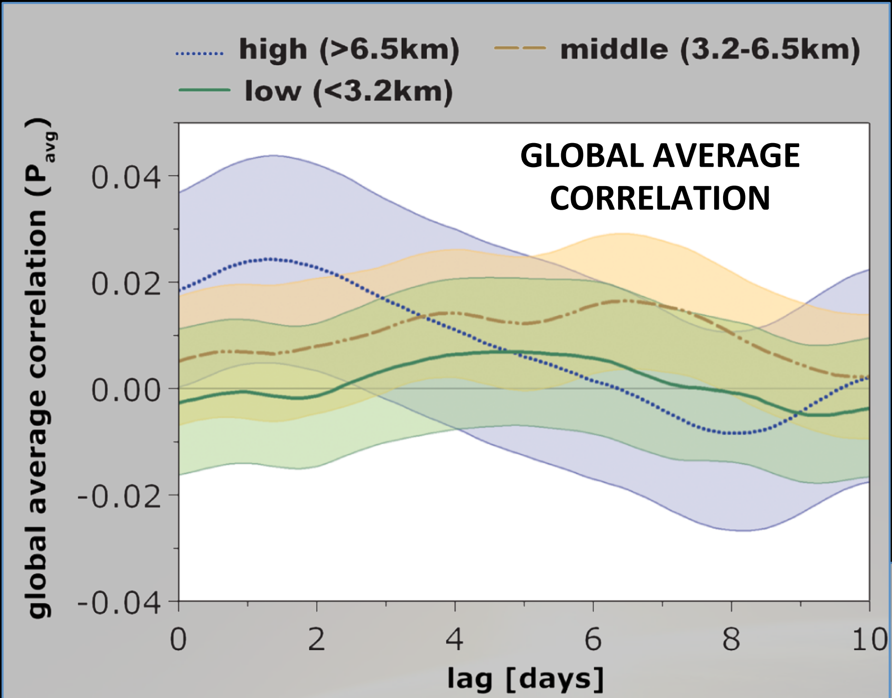
Hong Kong, China:

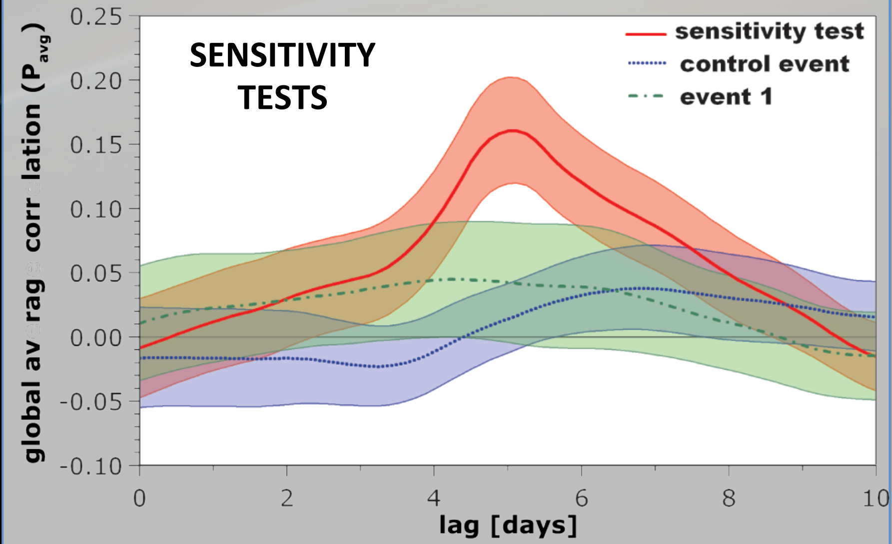
lag	corr. coefficient
0	0.271
1	0.330
3	-0.046
5	-0.029

Čalogović et al. 2010, GRL

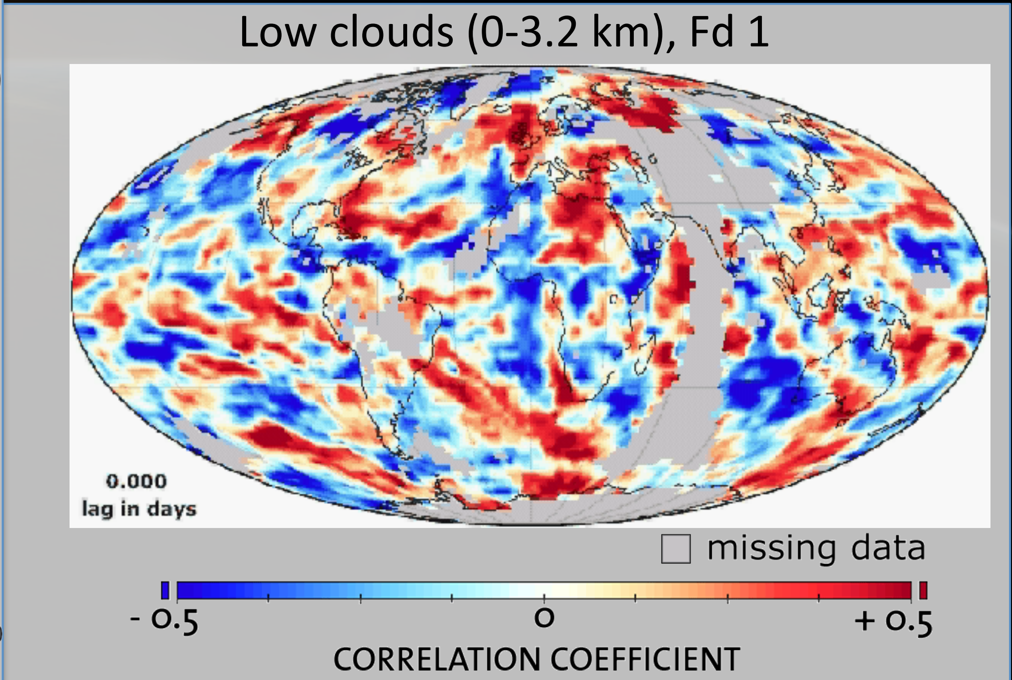
Results

Čalogović et al., 2010, GRL





- No siginificant corrleations found in all 6 Forbush events together, in analysis of individual events or cloud layers (low, middle, high cloud cover)
- No significant diferences for obtained correlations in different areas (low and high latitudes, land, oceans)
- Method is enough sensitive to detect global cloud changes



There are numerous issues that may affect the results of long-term solar-terrestrial studies

- Satellite cloud estimates are fraught with limitations and calibration errors, meaning long-term analysis is problematic at best, and, as in the case of commonly used ISCCP data, is fundamentally flawed.
- Co-variance of solar-related parameters (UV, TSI, CR flux, solar wind) make signal attribution difficult.
- Climate variability (eg. ENSO) and volcanic activity, operating over time-scales similar to the solar cycle, make disambiguating causes of cloud cover change difficult (**signal attribution**).

Some of these issues already discussed by Pittock (1978, 1979)

Conclusions

- Solar-terrestrial studies are often compromised by the difficulties of statistical analysis of autocorrelated data – inappropriate statistical tests can produce **false-positives**.
- Quality of satellite cloud measurements and proper signal attribution makes long-term studies difficult to perform.
- **No compelling evidence** using the satellite cloud data (ISCCP, MODIS) to support a wide-spread cosmic ray-cloud connection.
- Experimental data (CLOUD) and model calculations for “clean-air” mechanism doesn’t show very strong impact of cosmic rays on clouds.
- However, if cosmic ray-cloud relationship is second order (small and dynamic changes to cloud cover over certain regions - may be the case with “near-cloud mechanism”) then it may be very difficult to detect it with currently available techniques and datasets.
- Cosmic rays doesn’t influence the **global** cloud cover and it is not a major factor in climate change or global warming! (opposite to believing of climate sceptics)

Thank you for your attention!

We acknowledge the support of Croatian Science Foundation under the project 6212 „**Solar and Stellar Variability**“ and of European social fond under the project “**PoKRet**”.