Solar variability influences on climate and cosmic ray – cloud link

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About me

- Studied Environmental Sciences at ETH Zürich, specialization in the field of Physics and Atmosphere
- PhD in Geophysics (*Influence of solar activity on Earth's space environment and climate*), University of Zagreb
- Postdoc at Faculty of Geodesy, University of Zagreb

Research

- Impact of solar variability on Earth's climate (cosmic ray-cloud link)
- Solar-terrestrial physics - propagation of solar wind disturbances (CME, CIR) and their space weather effects (geomagnetic storms, Forbush decreases)
- Solar observations - double solar telescope on Hvar (H-α, white light)

About Hvar Observatory

• Established in 1972. (based on agreement between the Faculty of Geodesy at Zagreb University and the Astronomical Institute of the Czechoslovak Academy of Sciences).

• Group for Solar Physics (5 people):
- space weather, eruptive processes (CME)
- activity cycle, rotation, convection
- solar activity & climate

• Group for Stellar Physics (3 people):
- variable stars
- Be stars

• Instruments:
- double solar telescope (chromosphere, photosphere)
- 65 cm photometric telescope
- 1 m multi-purpose telescope


Hvar double solar telescope

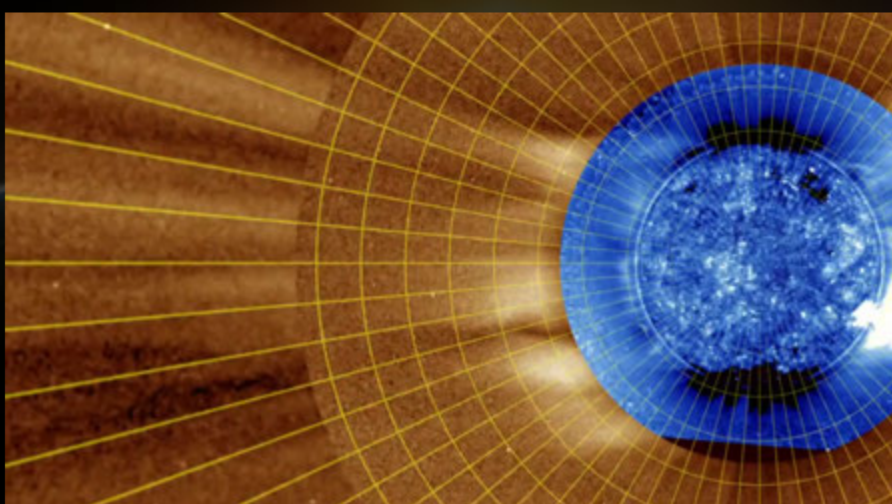

1m telescope

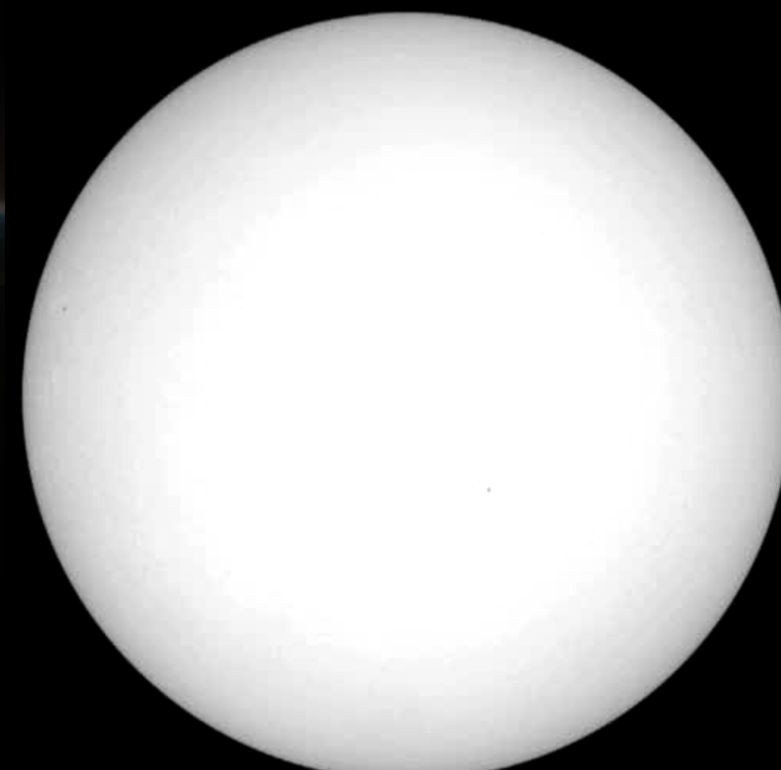

65cm telescope

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



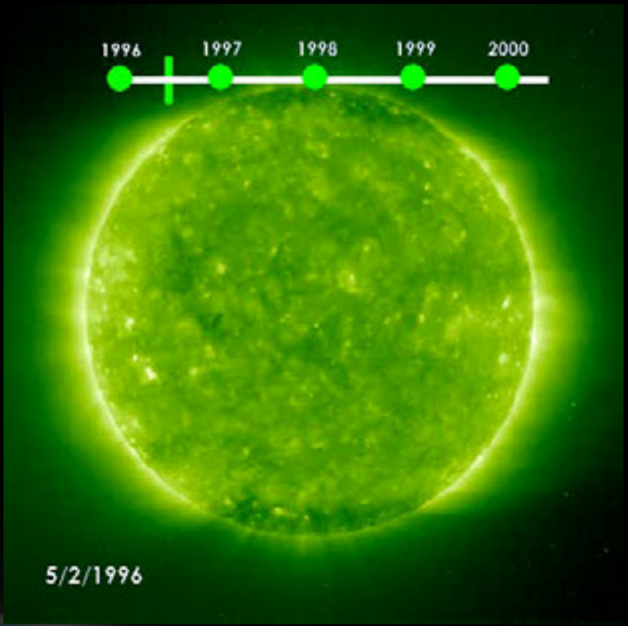


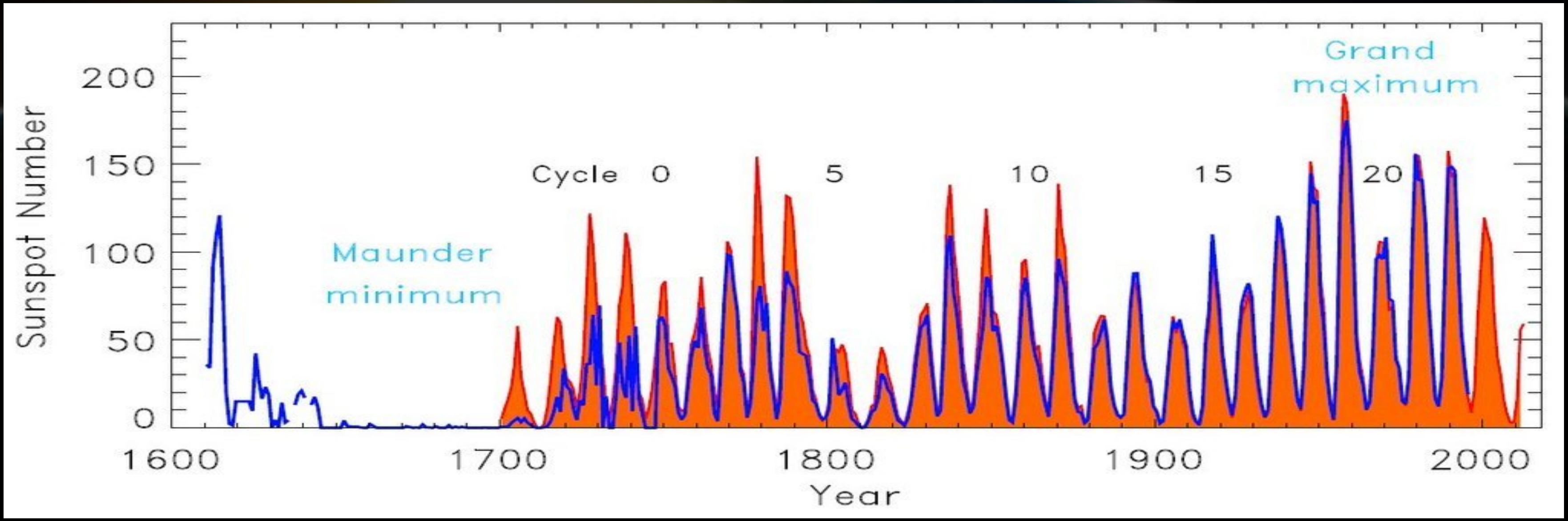
Solar cycles

- 11 year solar cycle (Schwabe)
- 22 years (Hale, solar mag. field reversal)

<u>Long-term cycles</u>

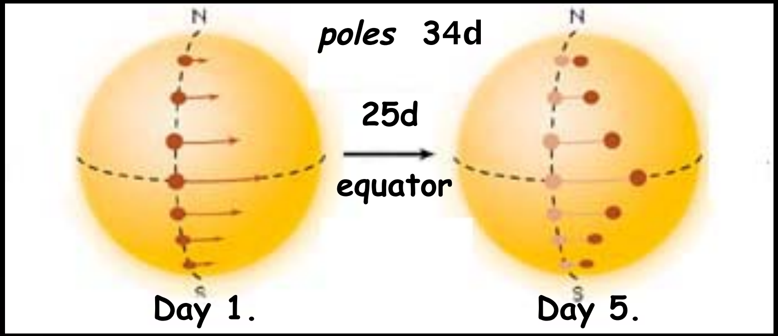
- 87 years (Gleissberg)
- 210 years (De Vries)
- 2300 years (Hallstatt)





Origin of solar cycle

- Solar differential rotation: equator rotates faster (25 days) than poles (34 days)

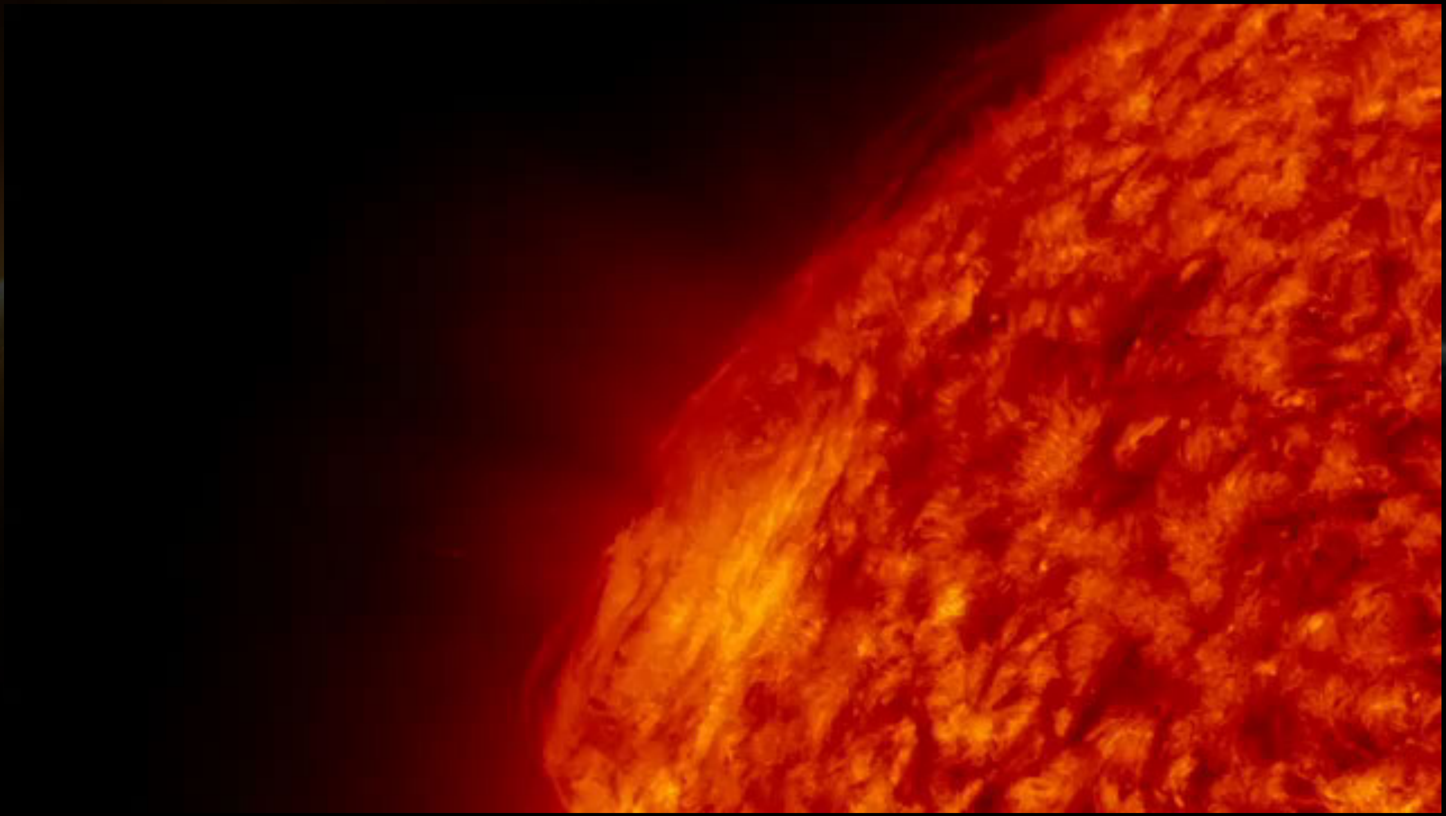


- Magnetic field gets twisted and streched (from poloidal to toroidal field).
- The energy stored in the magnetic field is released during the solar cycle → disturbances on the Sun and in the heliosphere (e.g. flares, prominences, CME)

Promineces (filaments)

- Large gaseous features from cooler and denser plasma captured by solar magnetic field
- Extend from chromosphere to corona
- May erupt and rise to coronal mass ejections (CME)

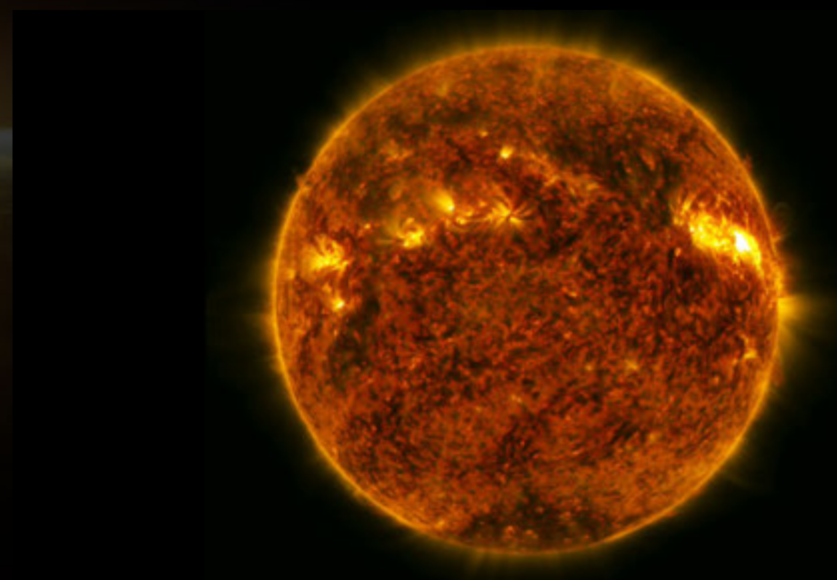
Erupting prominence 30.3.2010, Solar Dynamics Observatory (SDO)



Solar flares

- Short and bright plasma eruptions in the chromosphere due to magnetic reconfiguration of solar magnetic field (reconnection)
- Release huge amounts of energy (10^9 Mt of TNT), last from min to hr
- Often followed by CME, may also produce the solar proton events (SEP)

M3.0 and X1.1 flares in AR 12087 observed by Hvar Solar Telescope, 11.06.2014



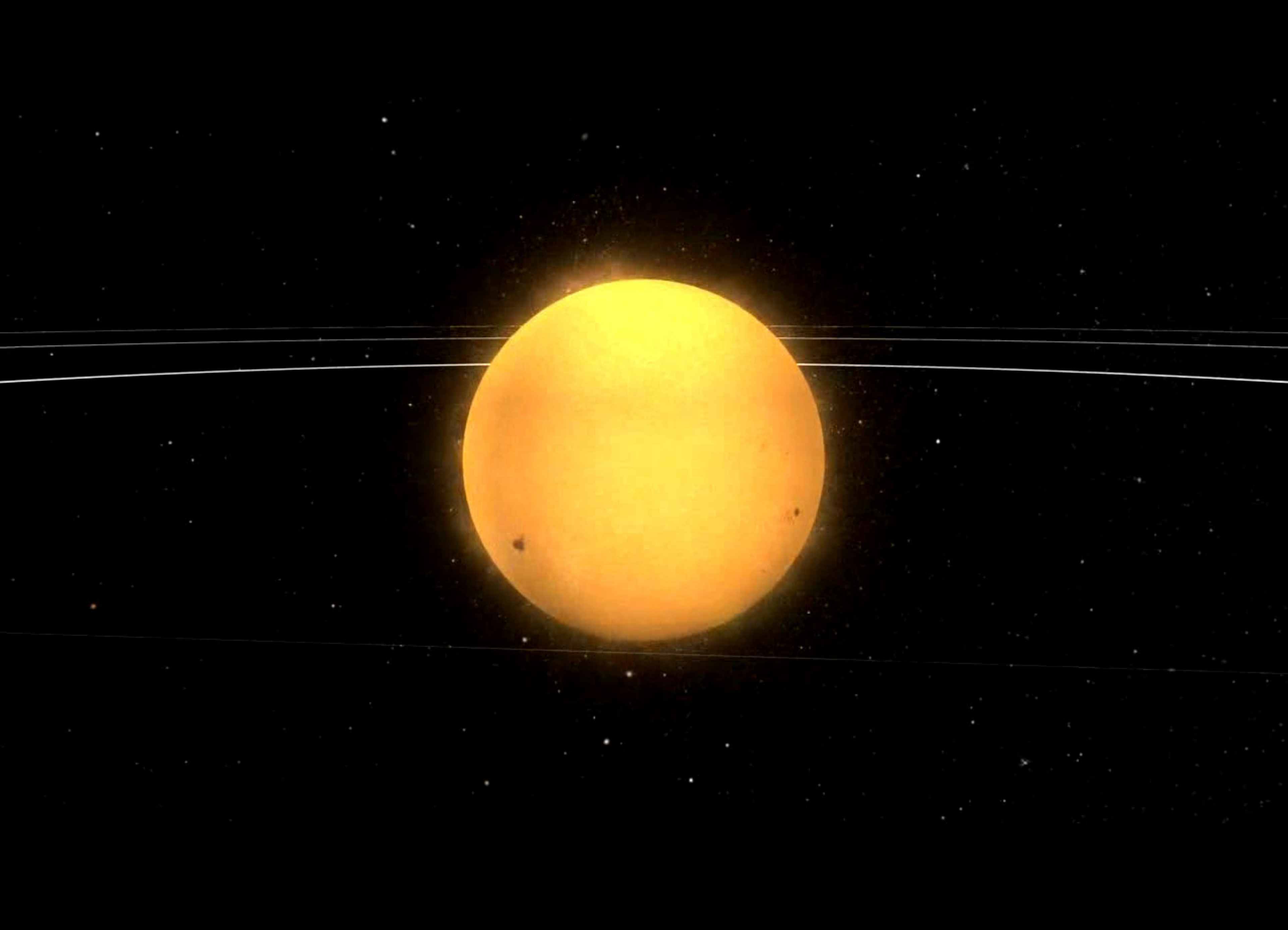
M6.7 flare in AR 12529 on 17.04.2016, SDO

Coronal Mass Ejections (CME)

- Magnetized plasma clouds expelled from the Sun (speeds from 200 to 3000 km/s)
- Often associated with flares and eruptive prominences (active regions)
- Connected with magnetic reconnection – releases stored energy in mag. field
- Often cause severe geomagnetic storms on Earth

Magnetic reconnection and liftoff

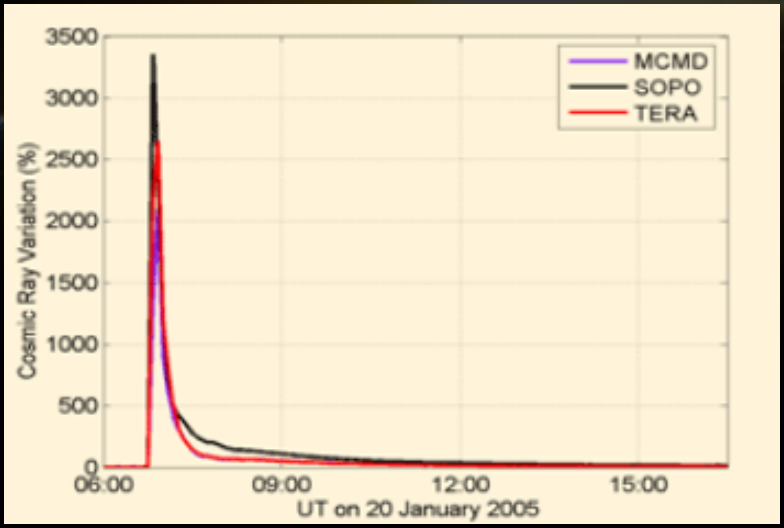
CMEs influence the geomagnetic field and the atmosphere



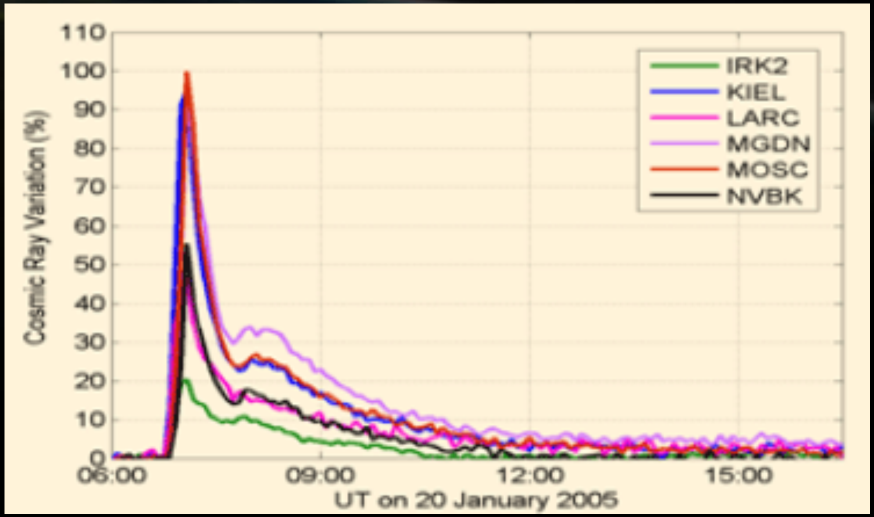
Solar Energetic Particle (SEP) events

- Originate mostly from solar flares
- CME shocks can also produce SEP
- Energies up to few GeV
- Flux on Earth can increase by few hundred percent for short time (hours) during SEP - **ground level enhancement** (GLE)

GLE event on 20 January 2005 (neutron monitor measurements)



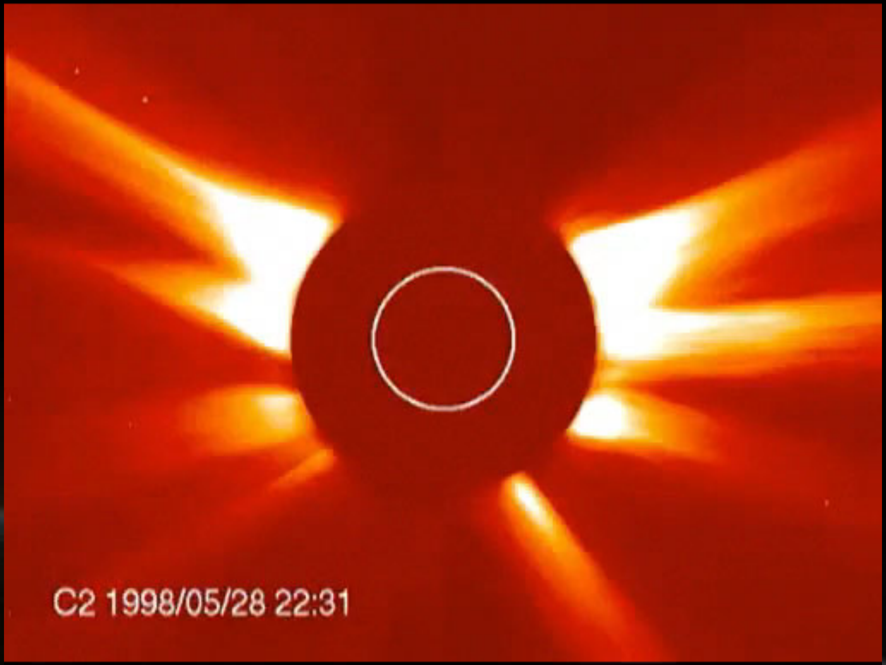
High latitudes



Middle latitudes

Solar wind

- Stream of charged particles (protons and electrons) released from the Sun (corona) with speeds in range from 300 to 800 km/s
- Solar wind particles carry the magnetic field form the Sun – interplanetary magentic field (IMF)

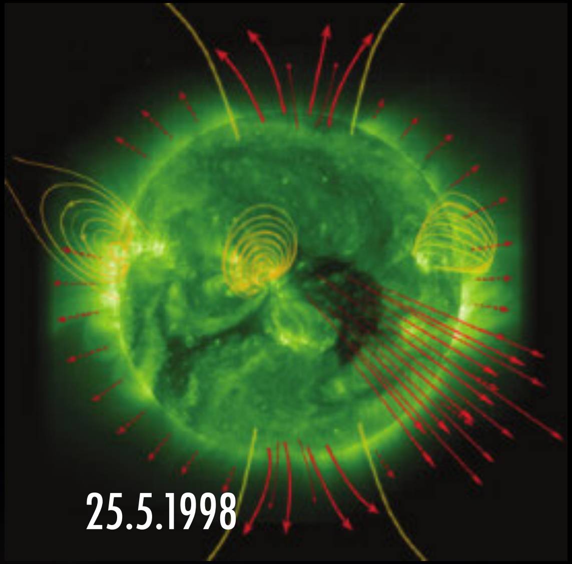


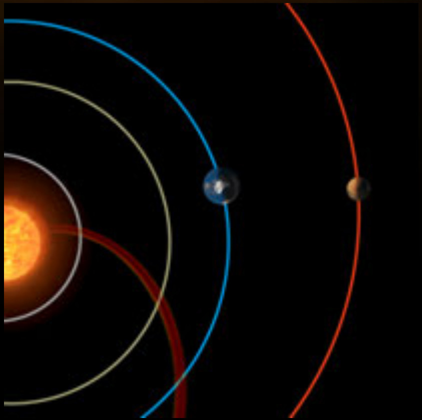
- Solar wind influences the geomagnetic field of Earth (geomagnetic storms)

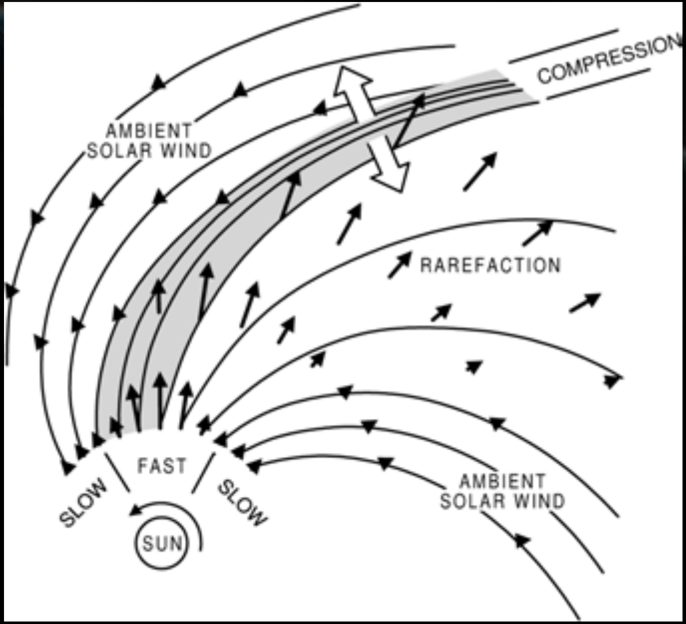
Corotating Interaction Regions (CIR)

- Fast solar wind streams originate in coronal holes (open-field regions) - **High speed streams (HSS)**

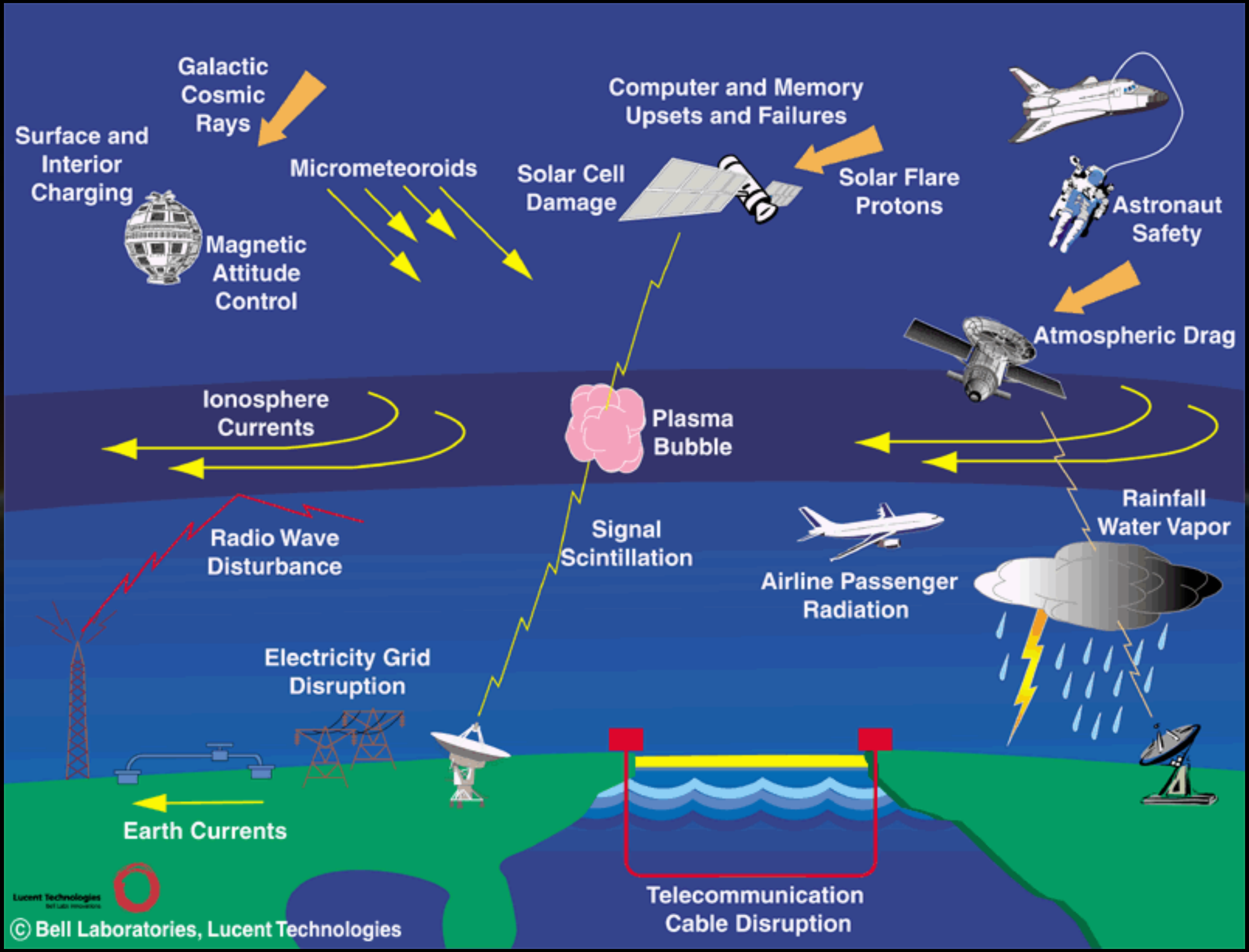
- When fast solar wind streams interact with slow streams, they produce **Corotating Interaction Regions (CIR)** - enhanced mag. field
- Most pronounced during the time of low solar activity (absence of CME)
- CIRs produce also geomagnetic storms and smaller reductions in cosmic ray flux (0.5% to 2%).





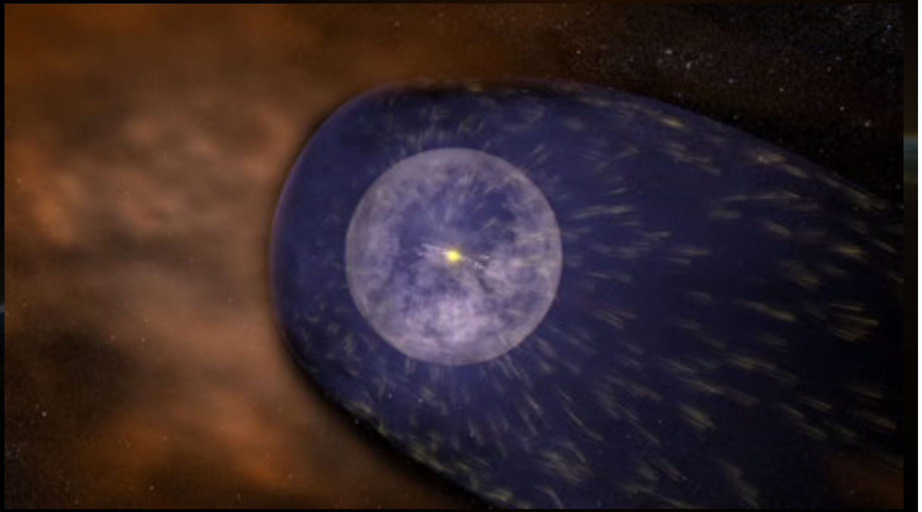


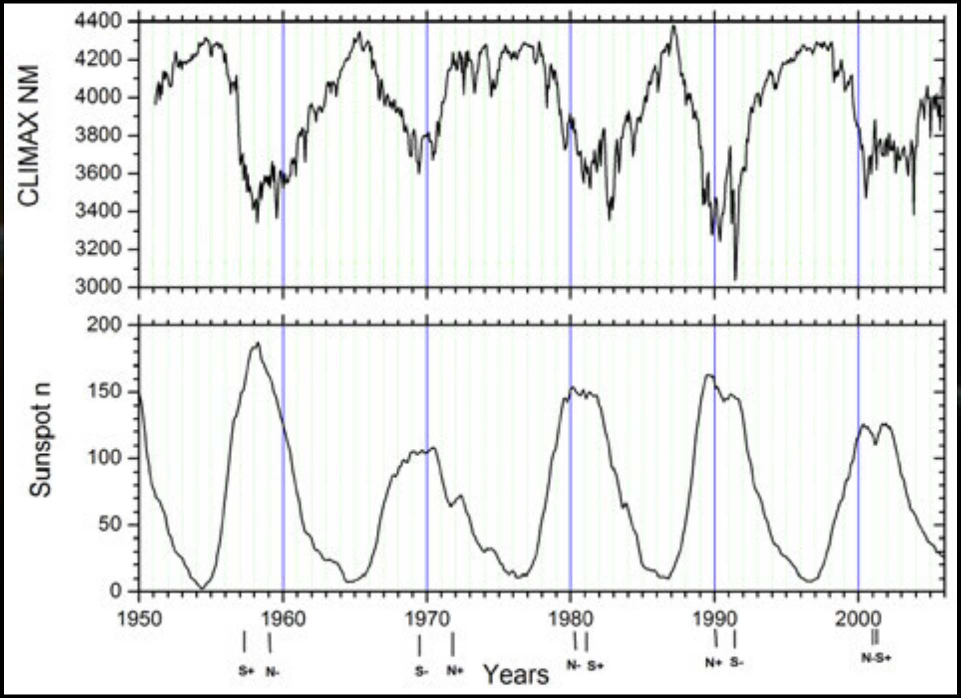
Solar influences on Earth
Space Weather



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

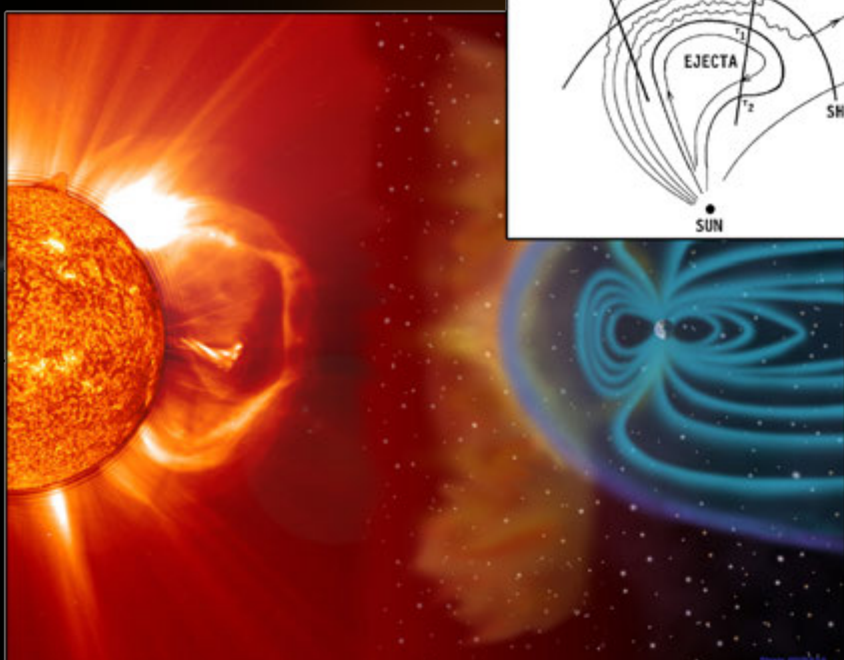


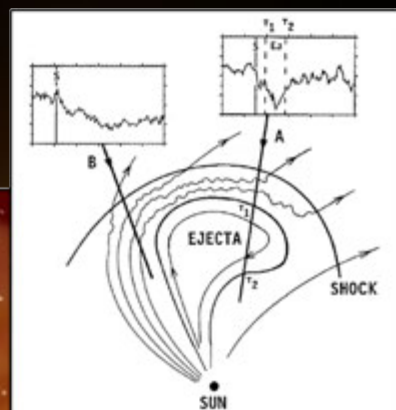


CMEs modulate the cosmic ray flux

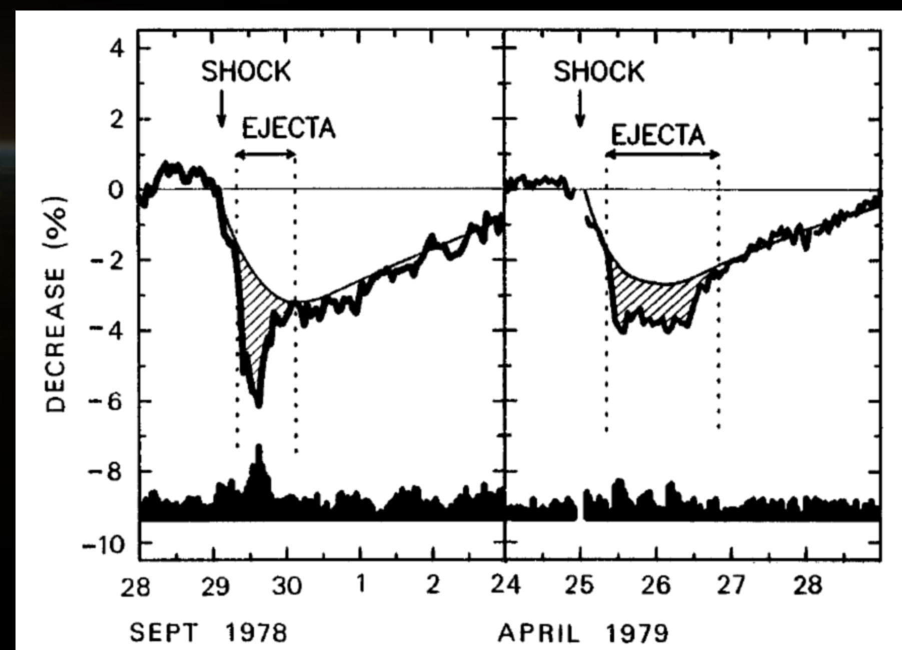
- **Forbush decreases (Fd)** – sudden reductions in cosmic ray flux with duration from few days to more than one week, strongest Fd may have reduction in cosmic rays > 10%

Interplanetary coronal mass ejections (ICME)





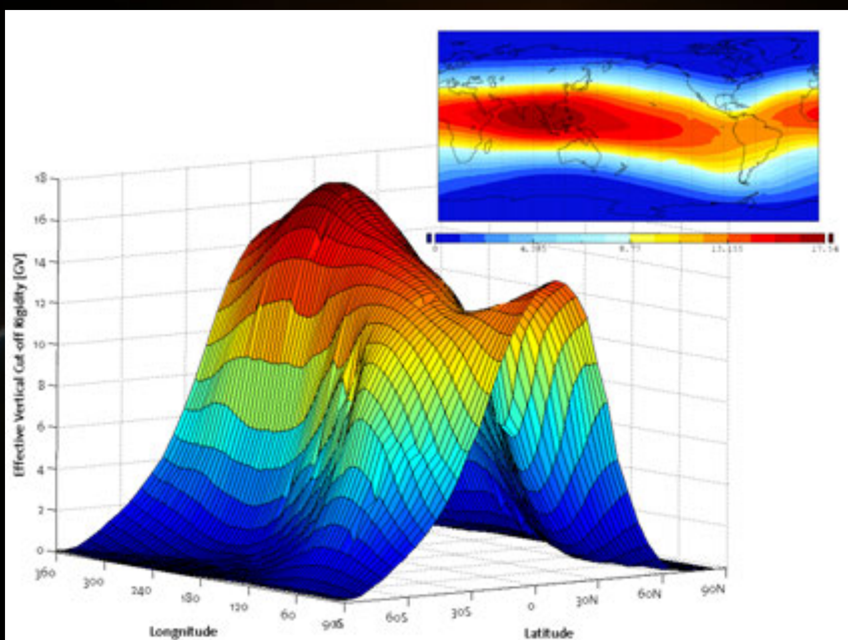
Cane (2000)



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



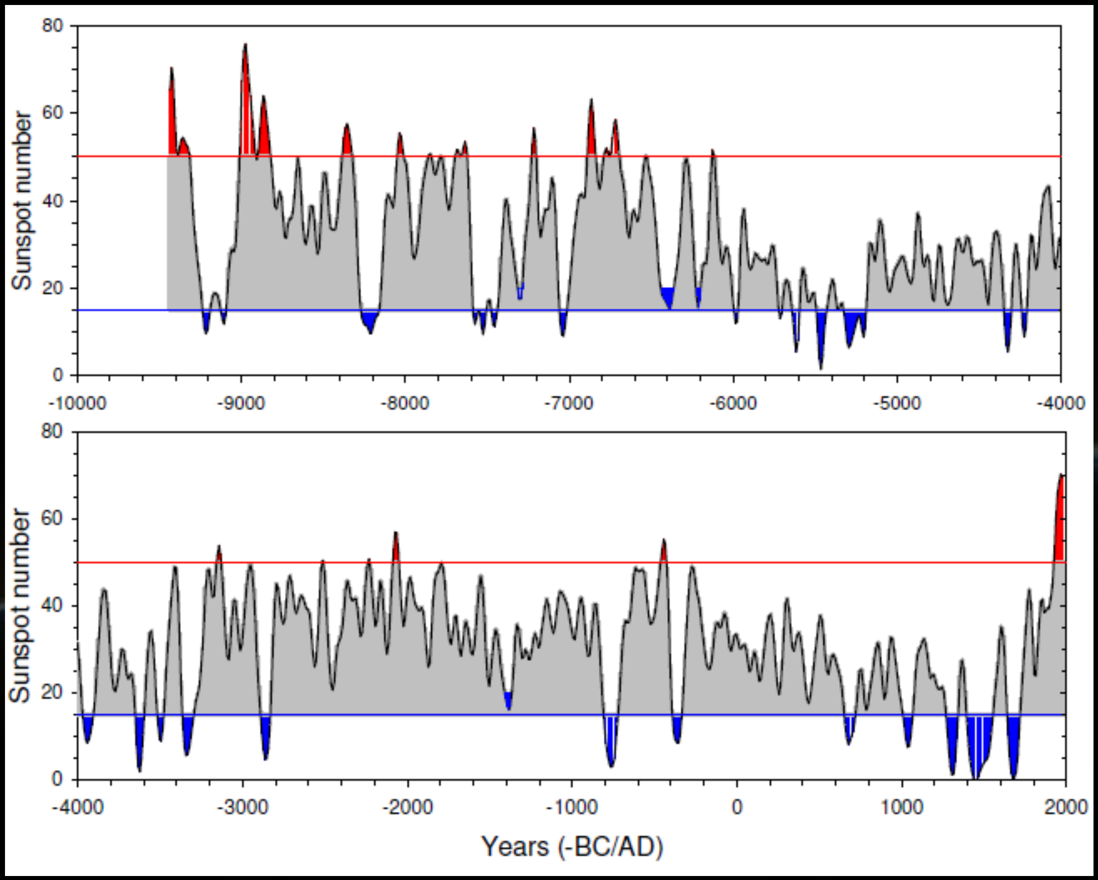
Cosmic ray showers (cascade) → ionization in the atmosphere

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 (16th to 19th 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



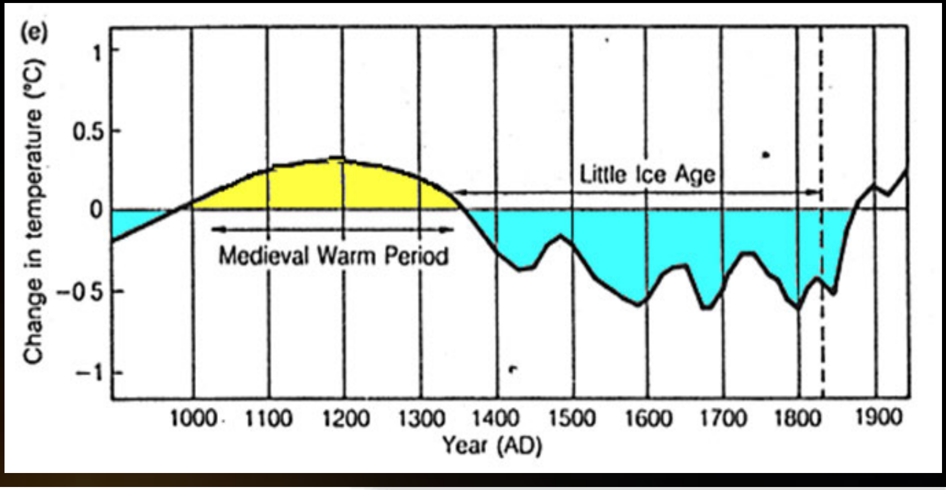
Usoskin, 2007

- ^{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

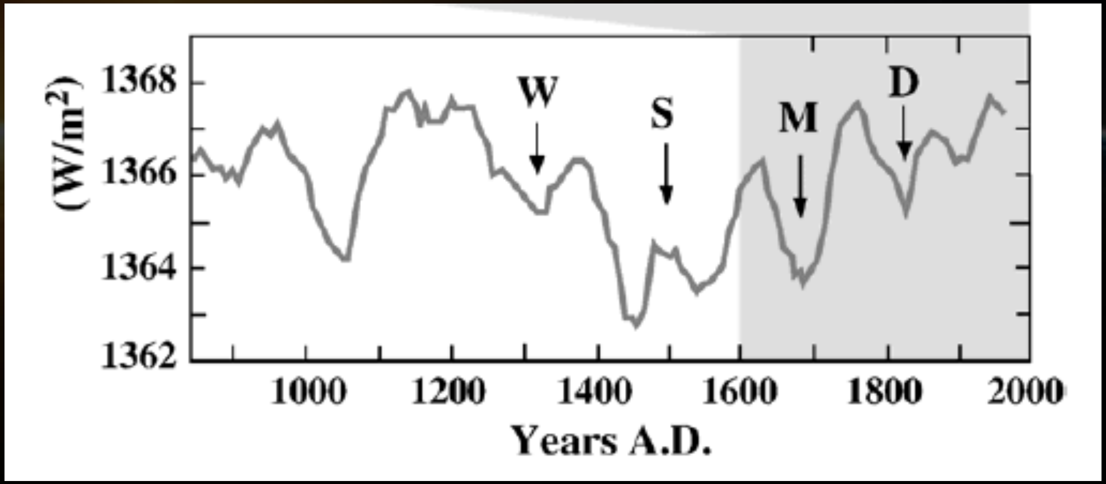
Drilling of ice cores to obtain ^{10}Be measurements

Solar activity and climate

Global temperature



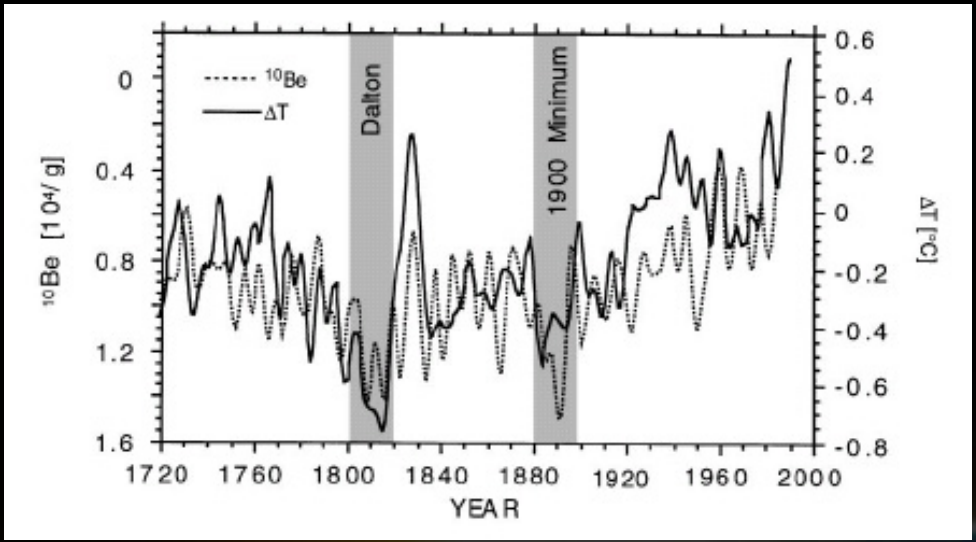
Solar activity



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

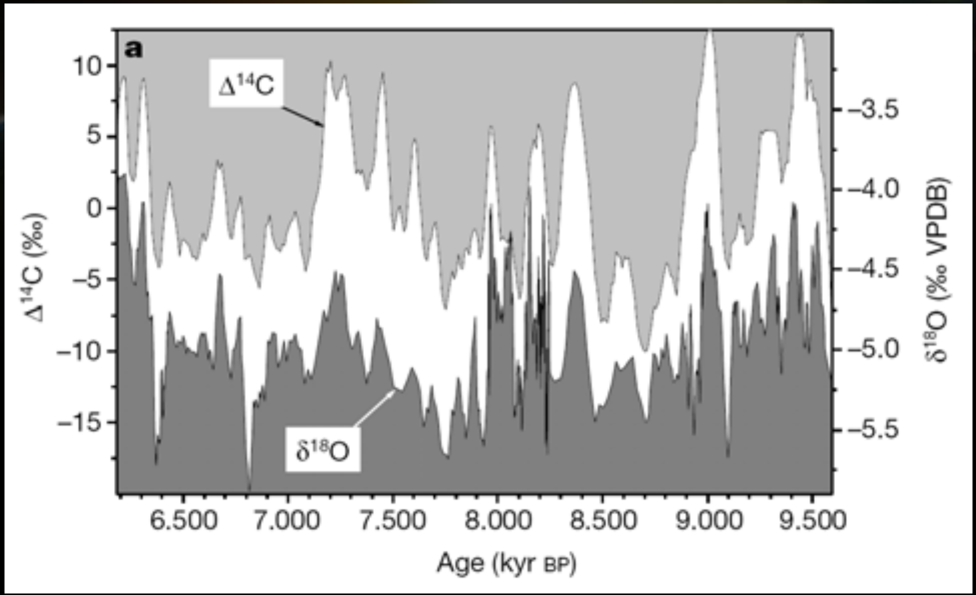
Solar Minimums: Wolf (W), Spörer (S), Maunder (M), Dalton (D)

Solar activity and climate



Solar activity and temperature

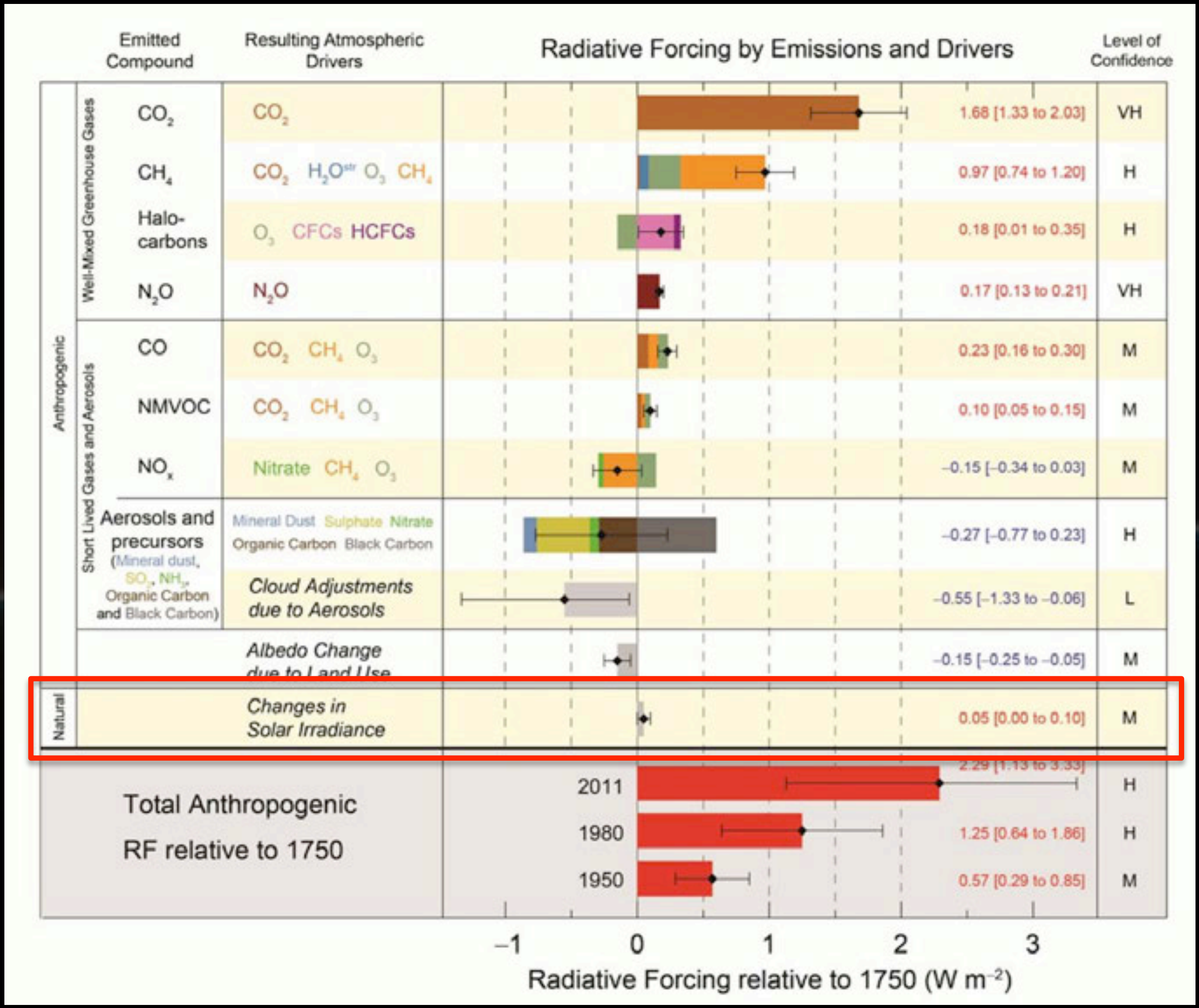
Beer et. al. 2000



Solar activity and precipitation

Neff et al. 2001, measurements from Oman caves (stalagmites) Solar activity modulates the the Indian monsoon circulation

According to IPCC solar influences on climate are minor

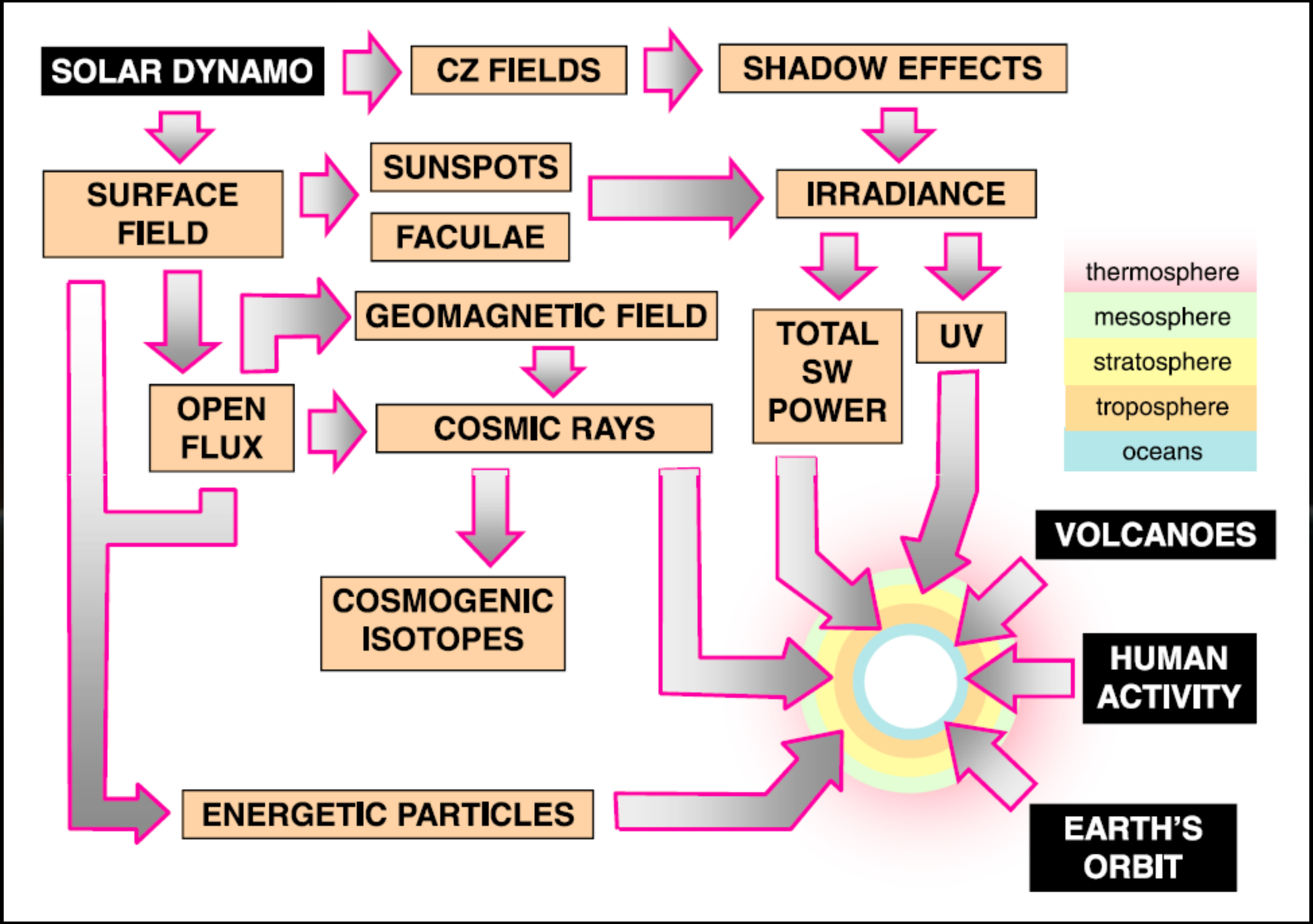


IPCC AR5 (2014)

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

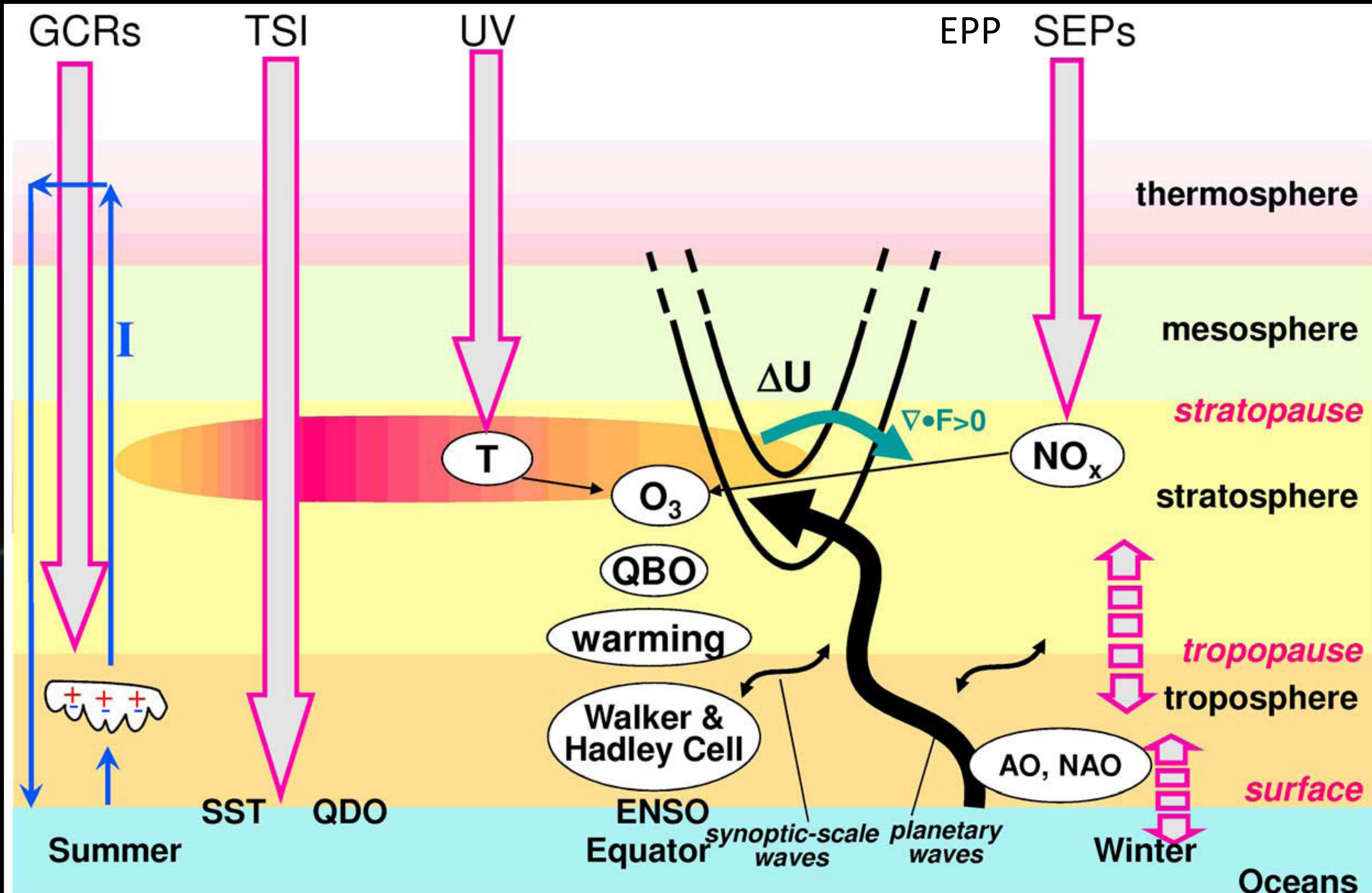
Mechanisms of solar influence on climate are still debated and poorly understood

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



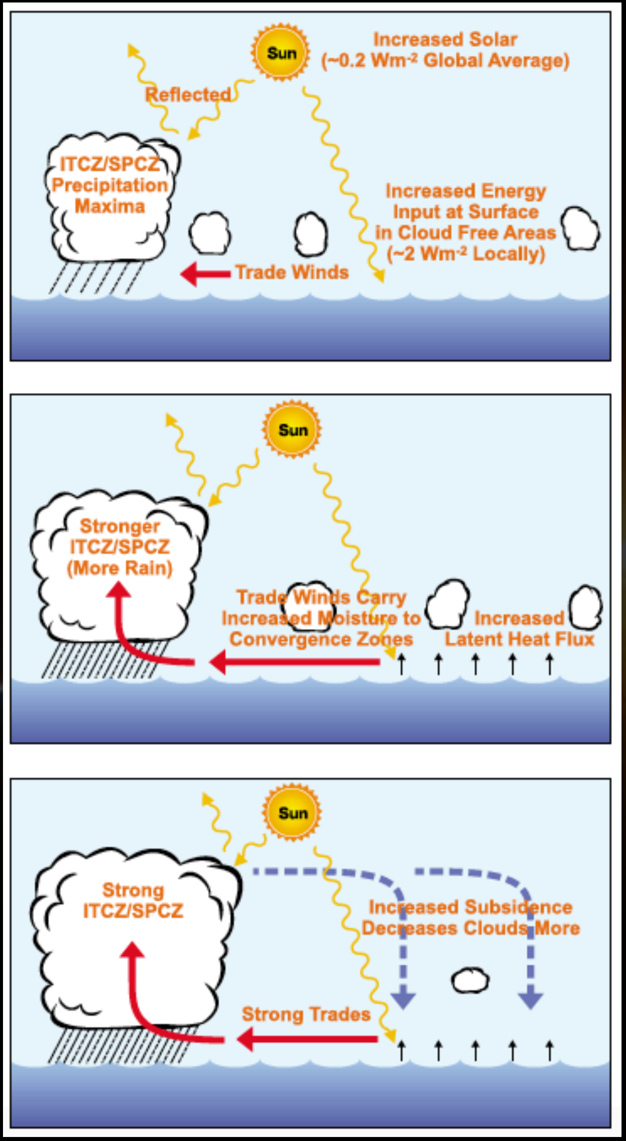
Gray et al., 2010

Mechanisms of solar influences on climate



Kodera & Kuroda , 2002

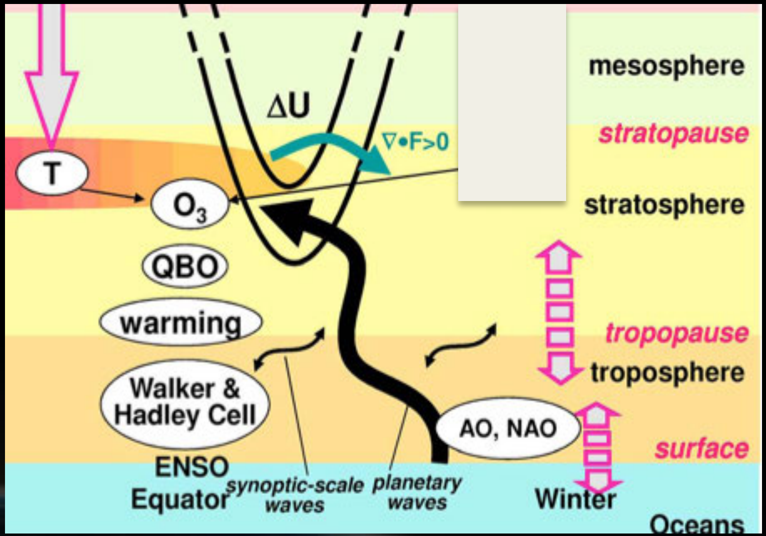
TSI variations
"Bottom-up" mechanism

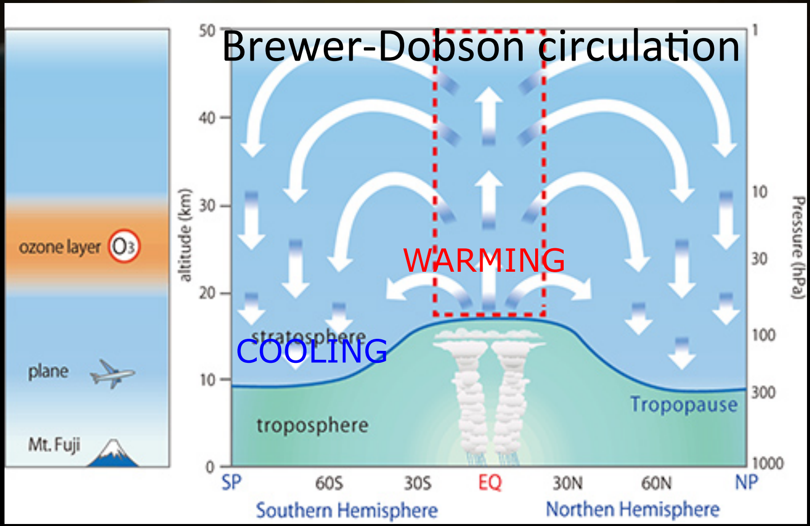


- About 1 Wm^{-2} variation in TSI corresponds to only 0.07 K temperature change at Earth's surface, however observations indicate larger climate variations (amplifying mechanisms/ feedbacks)
- **Total solar irradiance (TSI)** → sea surface temperature (SST) → increased evaporation → intensifies precipitation and upward vertical motions → stronger trade winds → enhances the tropical subsidence that reduces clouds and increases solar forcing at SST (positive feedback) → modification of synoptic circulation patterns (Meehl et al., 2008, 2009)
- Influence on climate internal variations like ENSO (La Nina conditions align with peaks in 11 year solar cycle forcing, lagged El Nino conditions 1-2 years later)

UV variations
“Top-down” mechanisms

- **Ultraviolet (UV)** spectral irradiance → ozone and stratospheric temperature variations (Haigh, 1996; Austin et al., 2008) → changes in the zonal wind → changes in the planetary wave interactions (determine mid-latitude weather, modification of Brewer-Dobson circulation – positive feedback)

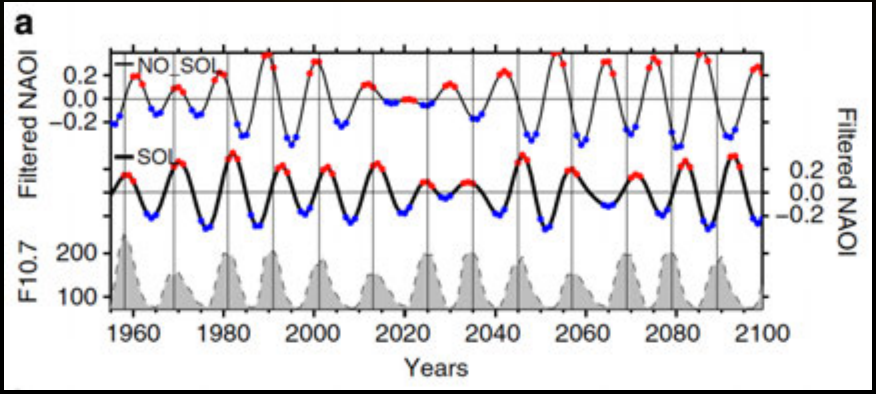


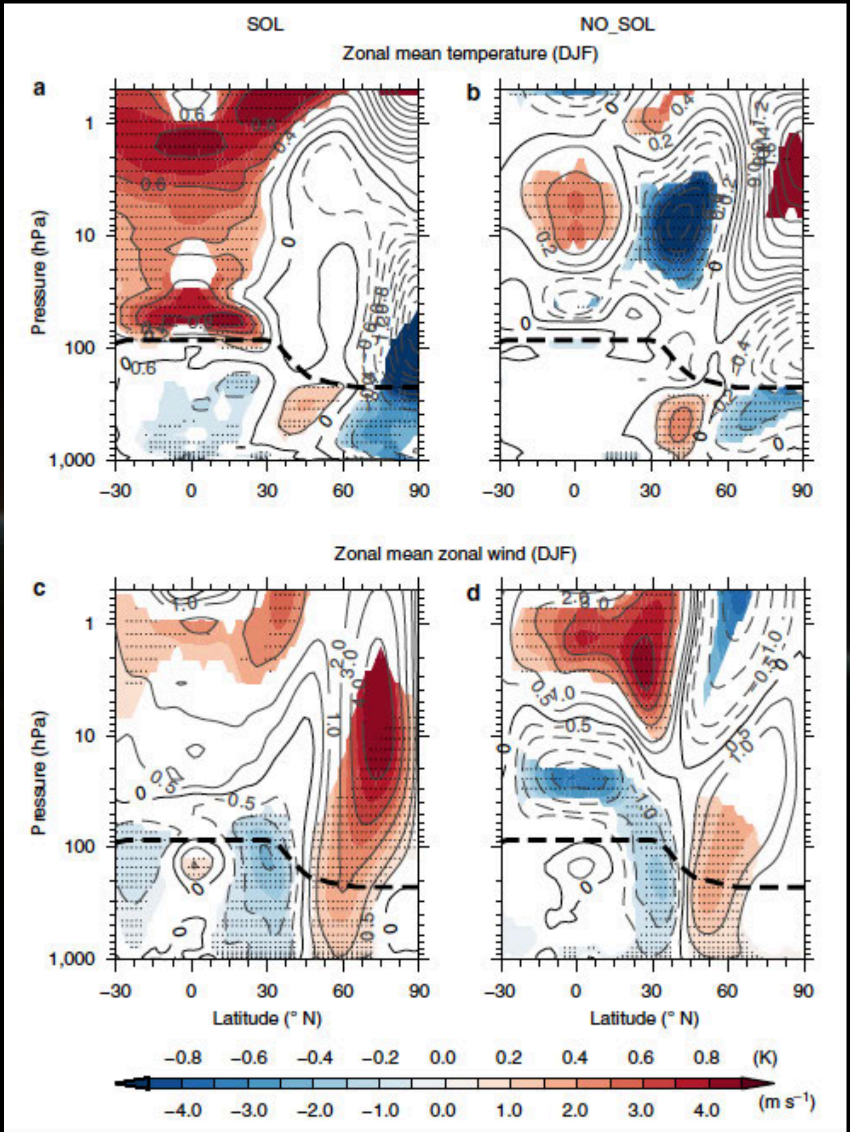


- During 11y solar cycle max years Brewer-Dobson circulation is weaker, polar vortex less disturbed, polar lower stratosphere colder
- in solar cycle min years is vice versa

UV variations
"Top-down" mechanisms

- Stratosphere-Troposhpere Coupling: wind anomalies move poleward and downward and grow in amplitude with time (Kodera and Kuroda, 2002), changes in extratropical modes of variability (NAM & SAM), interaction of B-D circulation with Hadley circulation
- <u>Synchronization of solar signal with 1-2 year lagged NAO variability </u>(or other climate internal variations like AO, ENSO)
- Both bottom-up and top-down mechanisms may work together to increase response in the atmosphere

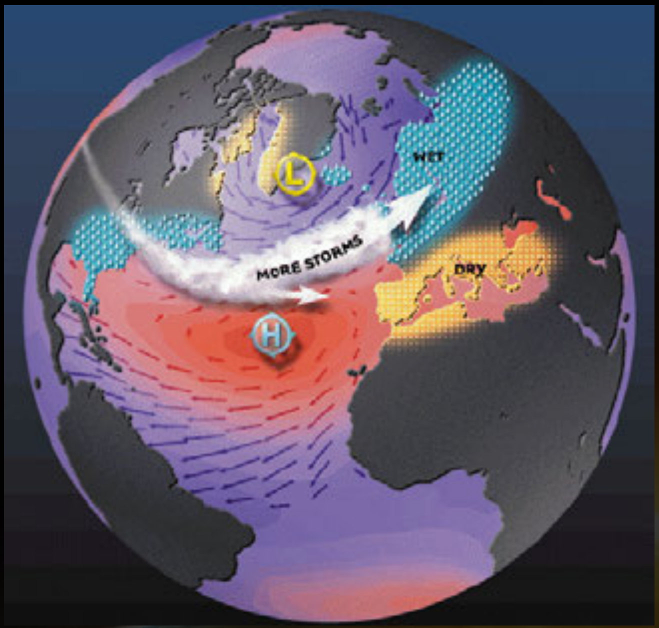




Thieblemont et al, 2015

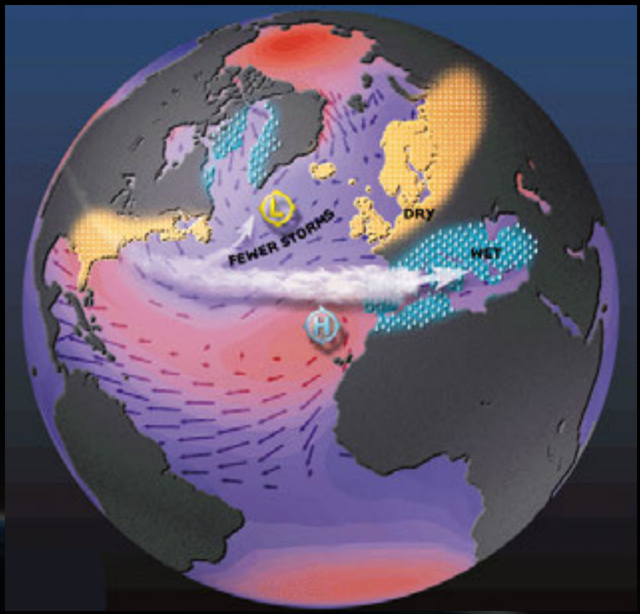
North Atlantic Oscillation (NAO) index

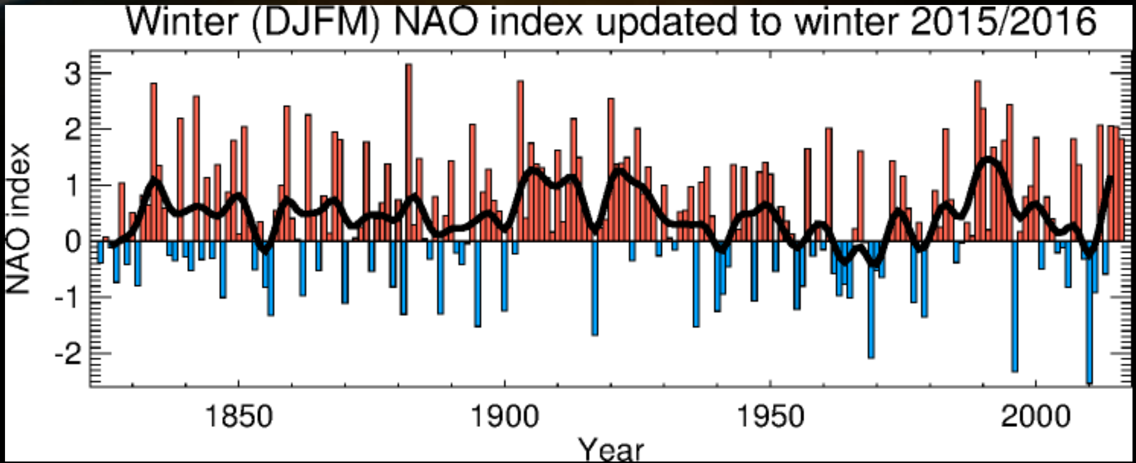
Positive NAO



- Frequent and stronger winter storms over Atlantic on northerly track
- Warm and wet winters in northern Europe an US, dry (cold) winters in Mediterranean
- SC max years coincide with NAO+

Negative NAO



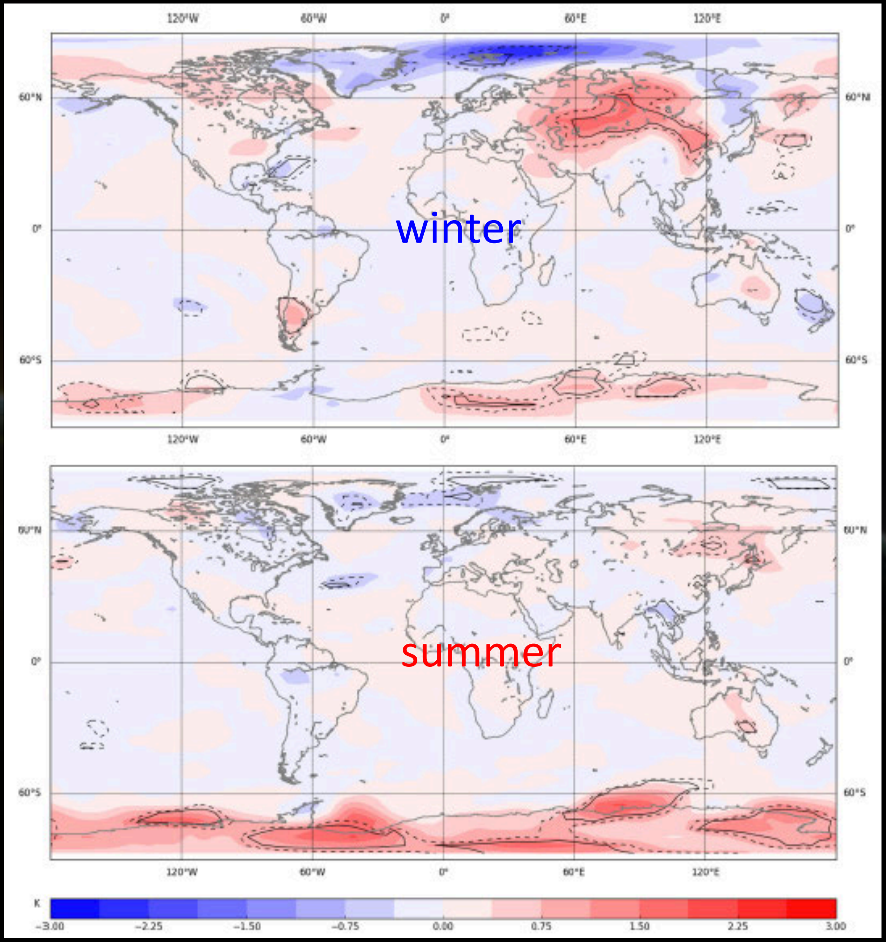


- Fewer and weaker winter storms crossing on a more west-east pathway
- Warm and wet winters in Mediterranean and cold in northern Europe, US

Energetic particle fluxes (EPP)

- **EPP (including electrons) and solar proton events (SEP)** → ionization → produce chemical constituents NO_x, HO_x → depletion of ozone at polar regions → changes in zonal wind (polar night jet) and temperature in polar vortex regions (polar night)

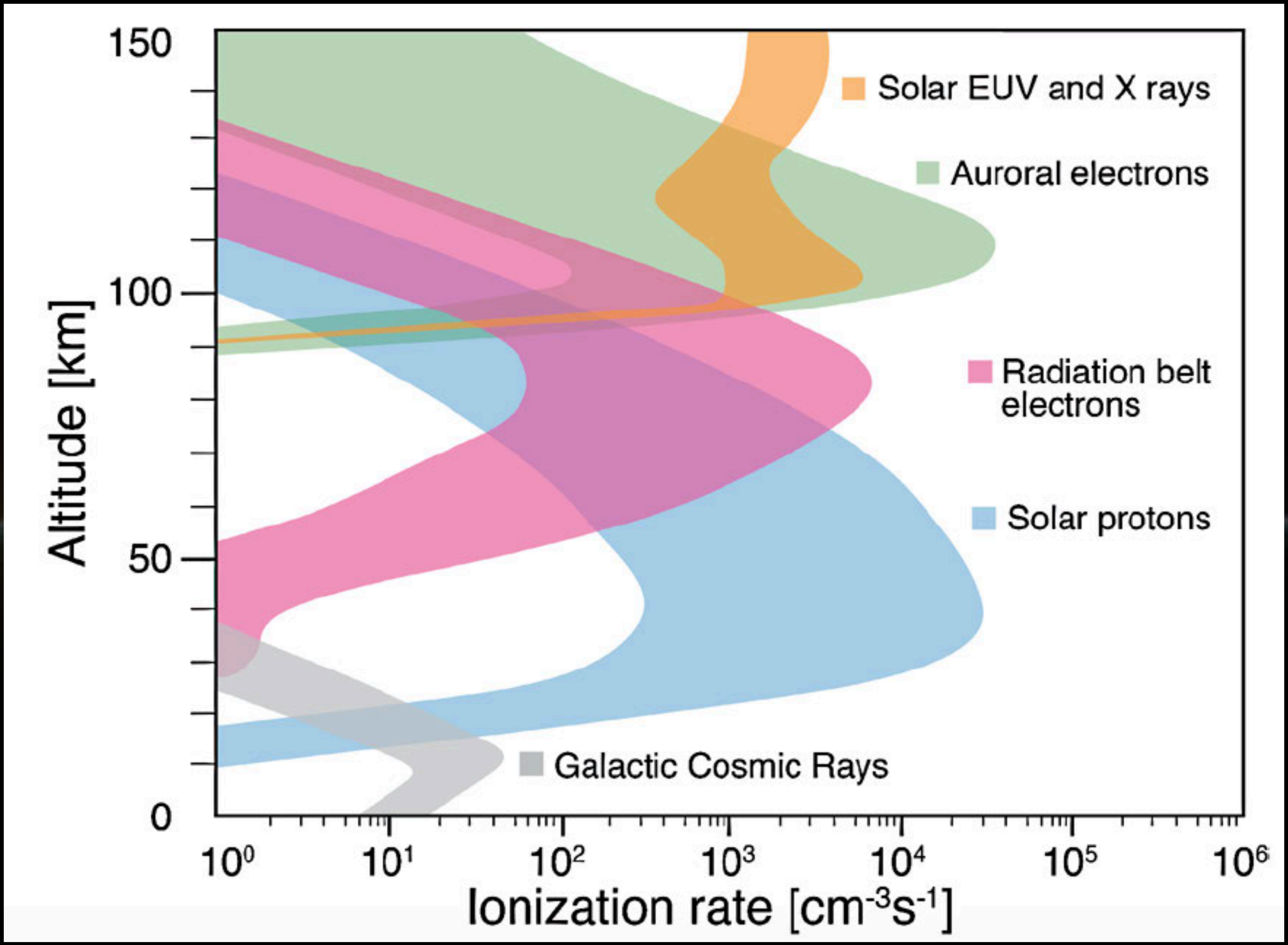
- Energetic electrons originate from the solar wind – trapped in the magnetosphere or Van Allen radiation belt – accelerated during magnetic substorms until they precipitate into the atmosphere (polar regions), effect largest during declining phase of SC
- Production of NO_x, HO_x restricted to upper atmosphere (thermosphere, mesosphere, upper stratosphere at high geomagnetic latitudes)
- NO_x can be transported by polar downwelling into winter polar stratosphere
- Ozone changes during high geomagnetic activity can strengthen northern hemisphere polar vortex (Seppälä et al., 2013) → force a positive phase of NAO/ SAO



Arsenovic et al., 2016

Model simulation diff. MEE-NOMEE

Ionization rates of energetic particles and solar radiation in the Earth's atmosphere



Mironova et al. 2015

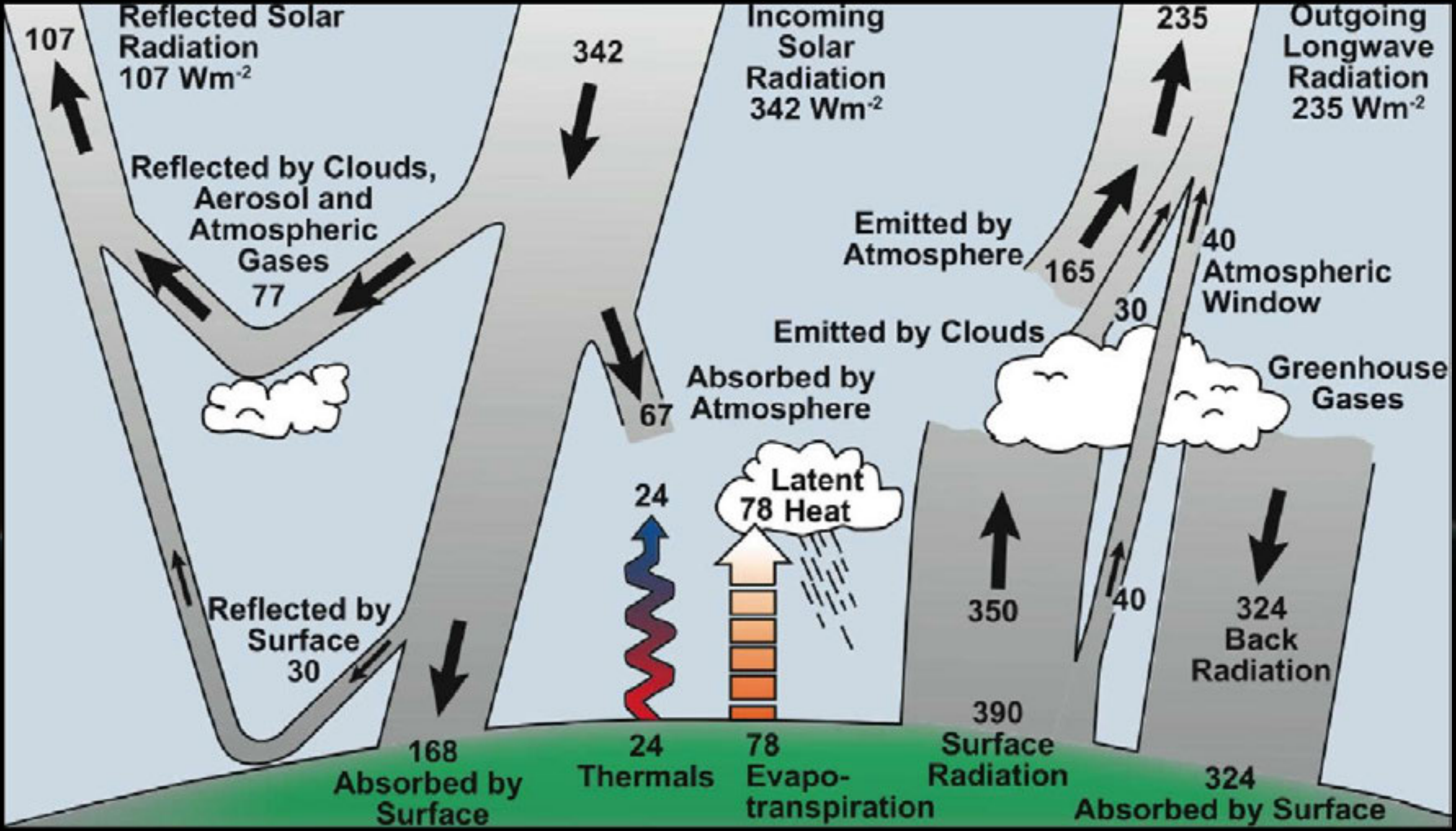
Amplification mechanisms!?

Cosmic ray shower (cascade)

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

How such small energy can influence our climate system?

Earth's radiative balance and clouds



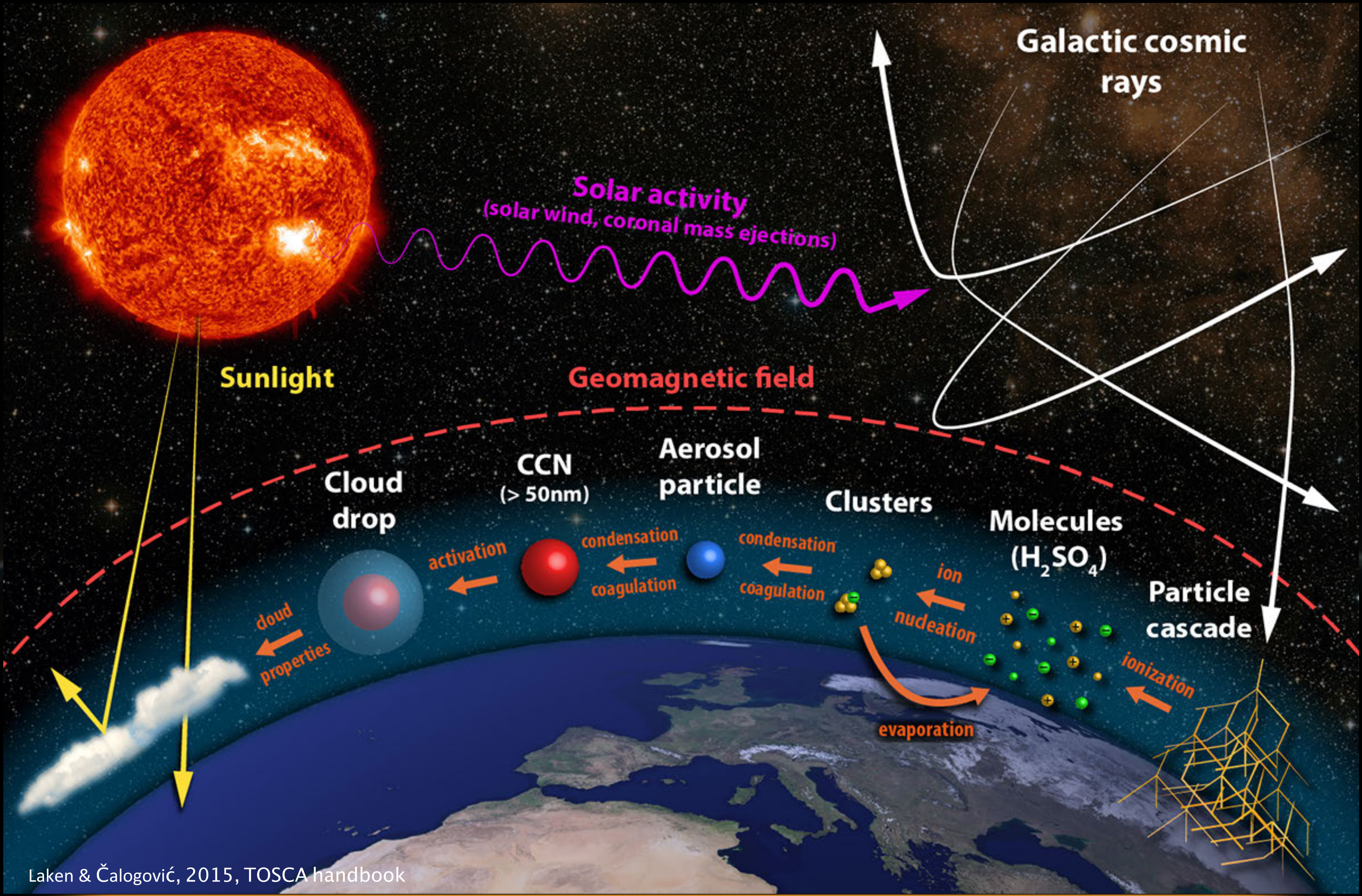
Houghton et al., 1996

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.

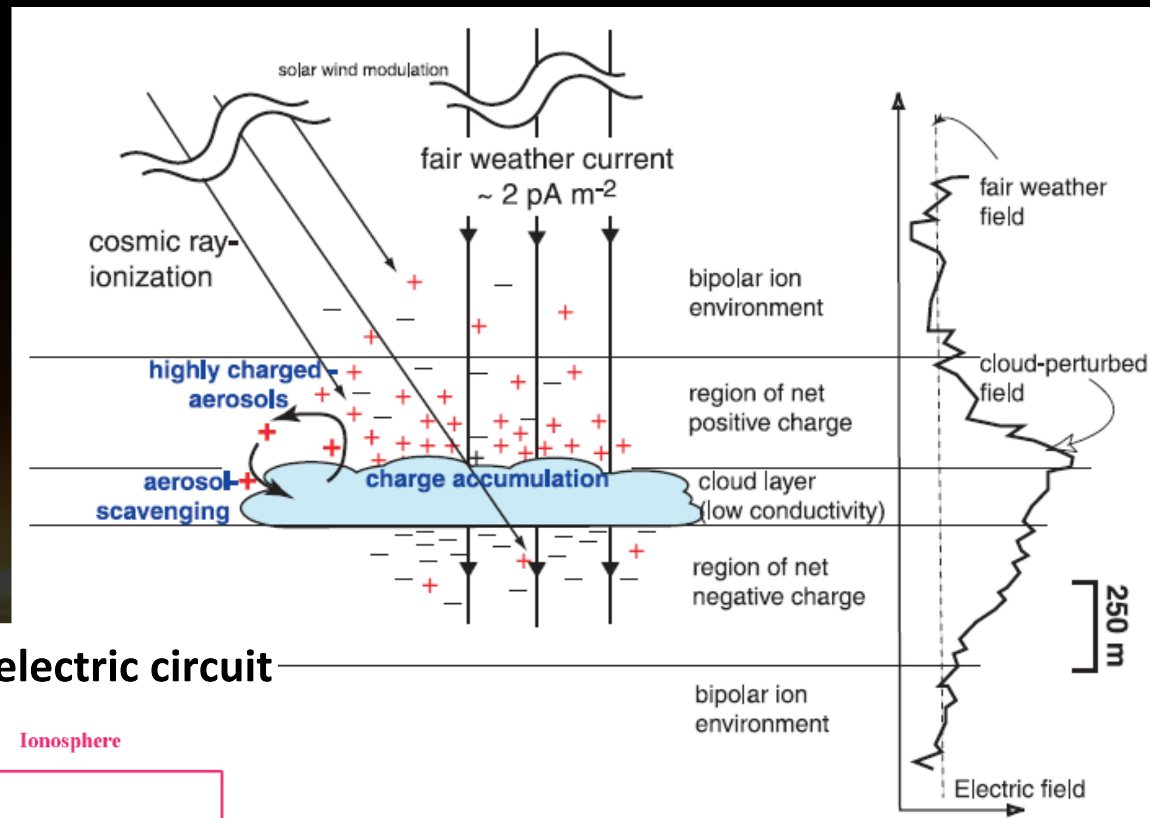
(b) ”Near cloud” mechanism: operates via global atmospheric electric circuit modulated by cosmic ray flux → changes in the cloud microphysics (current density-cloud hypothesis) - Tinsley, 1996; 2000.

“Clear-air” mechanism



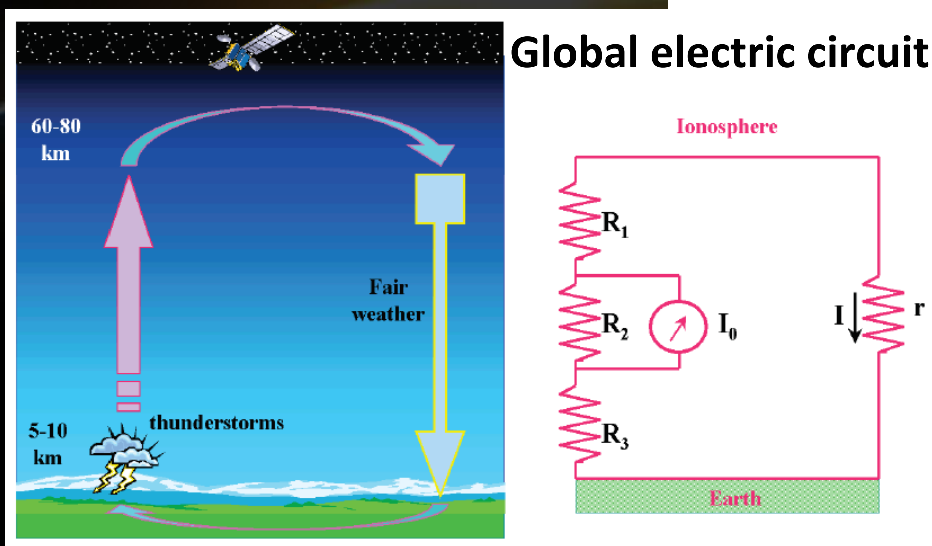
"Near-cloud" mechanism

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

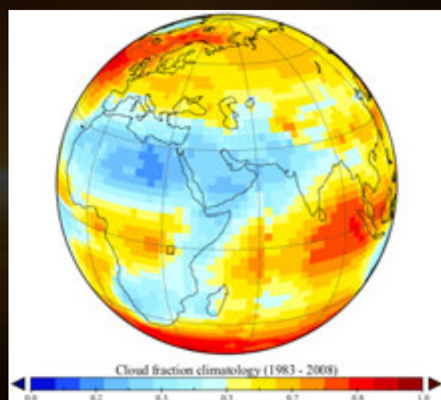


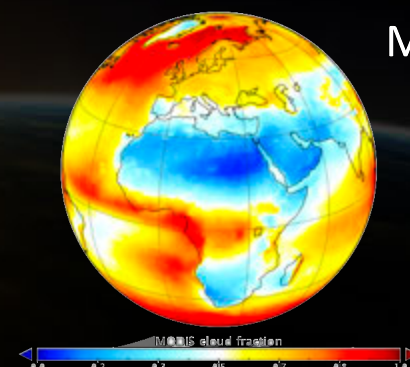
Makino and Ogawa, 1984

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°

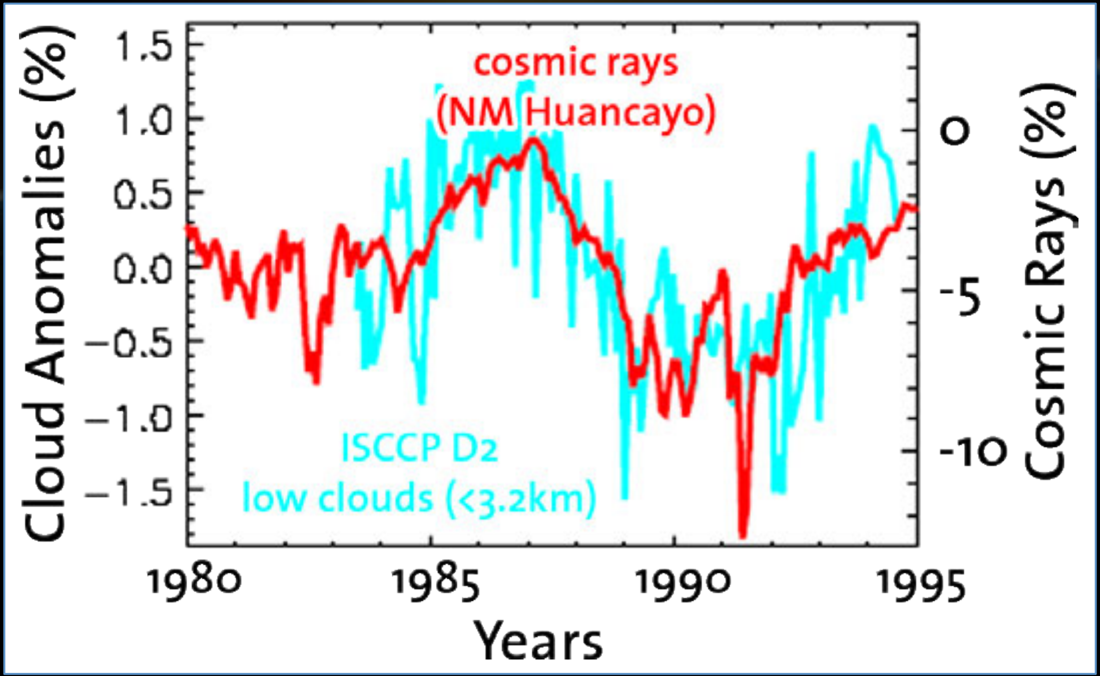
The hypothesized link between cosmic ray flux and cloud cover
Long-term studies

Svensmark and Friis-Chistensen (1997)

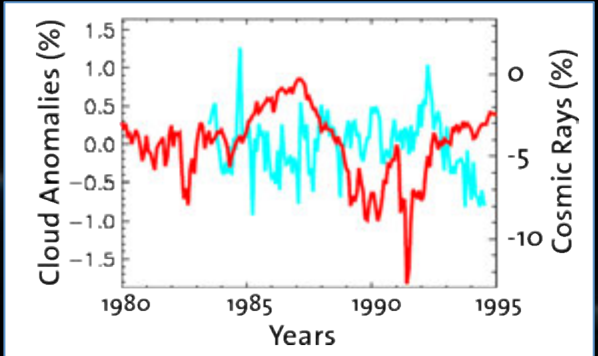
- analyzed one solar cycle and reported that global cloud cover changed in phase with the GCR flux by 2-3% → radiative forcing (0.8 – 1.7 W/m^2) comparable with greenhouse gases forcing

Marsh and Svensmark, 2000

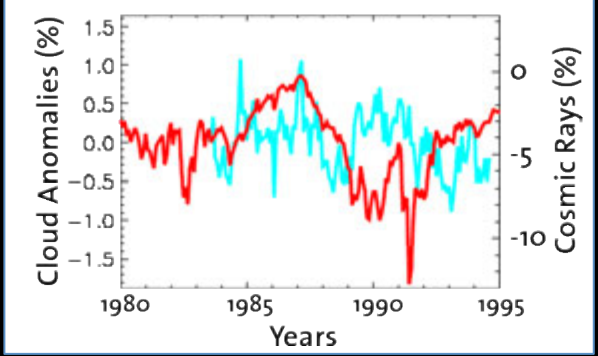
low clouds (0-3.2km)



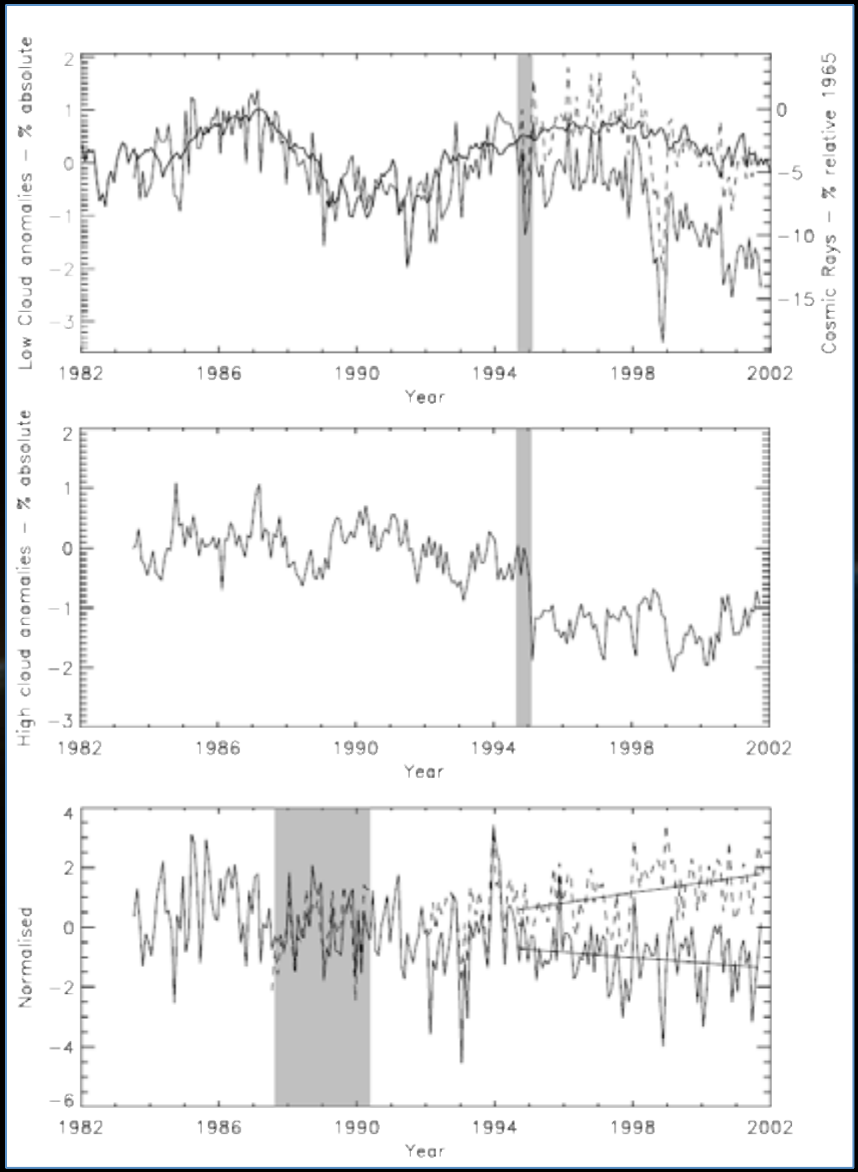
middle clouds (3.2 - 6.5 km)



high clouds (> 6.5 km)



Marsh and Svensmark, 2003



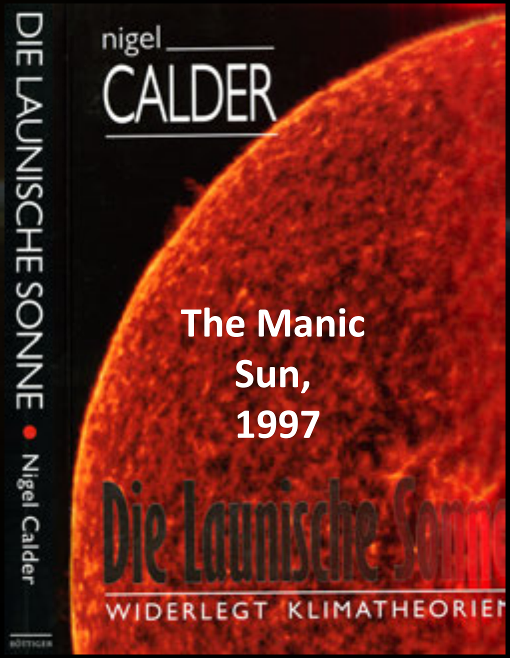
- After year **1995** there is **no correlation** anymore between cosmic rays and clouds
- Marsh and Svensmark, 2003 tried to correct ISCCP cloud dataset **on their own**

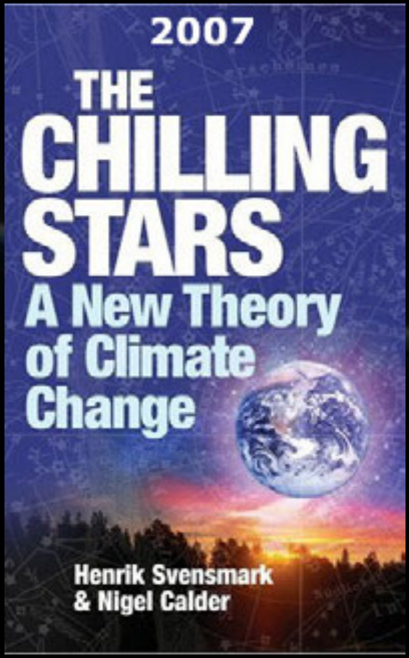
Many critics for a found correlation…

…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…

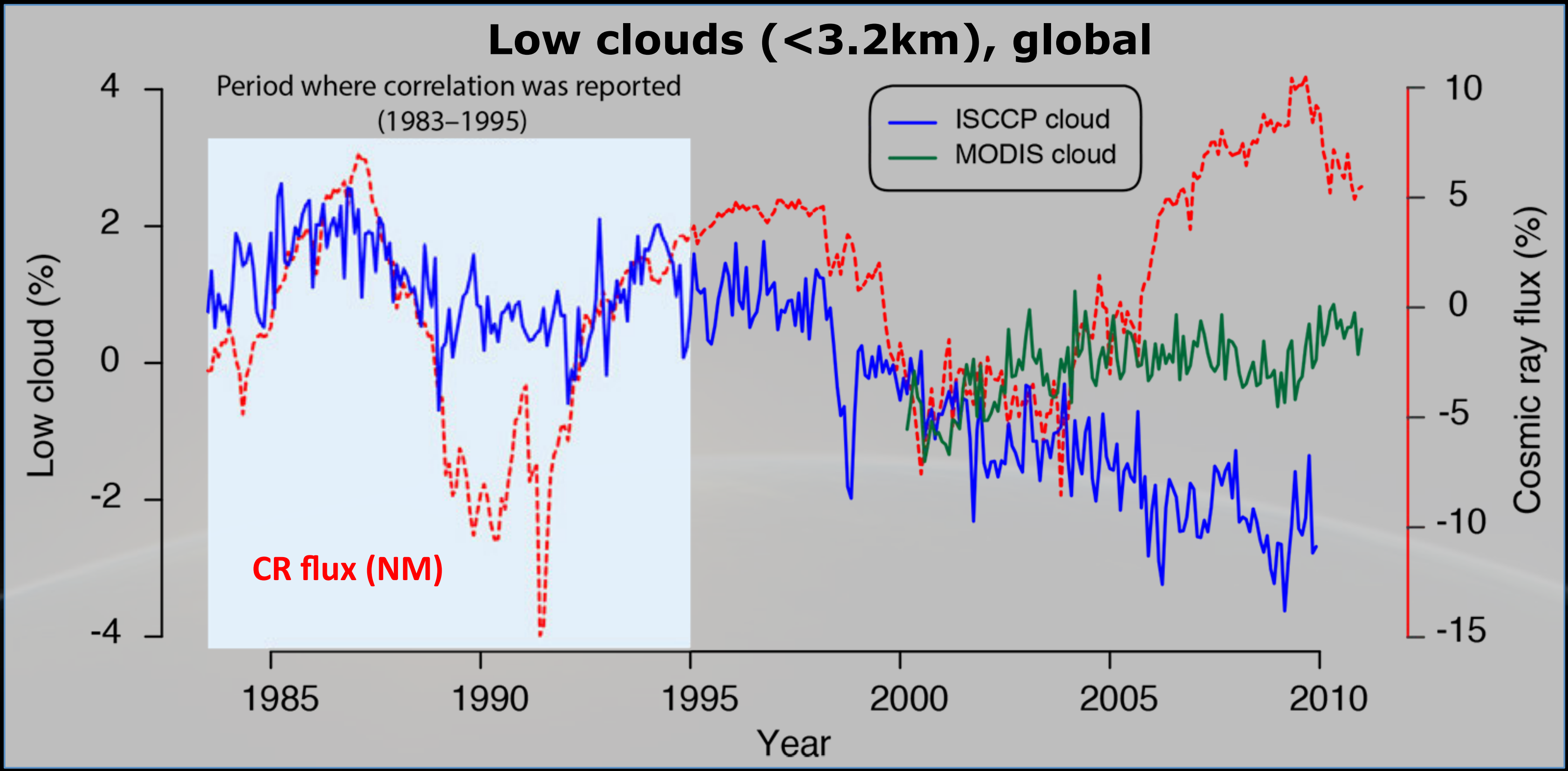
- …danish group ignored majority of this critics and gave basis for **"Cosmoclimatology"** hypothesis (Svensmark, 2007) - Earth's climate is solar-driven with minor human contribution to recent climate change.
- Various groups and climate sceptics used these arguments – eg. Nongovermental Panel on Climate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





These (incorrect) arguments are still used today!

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



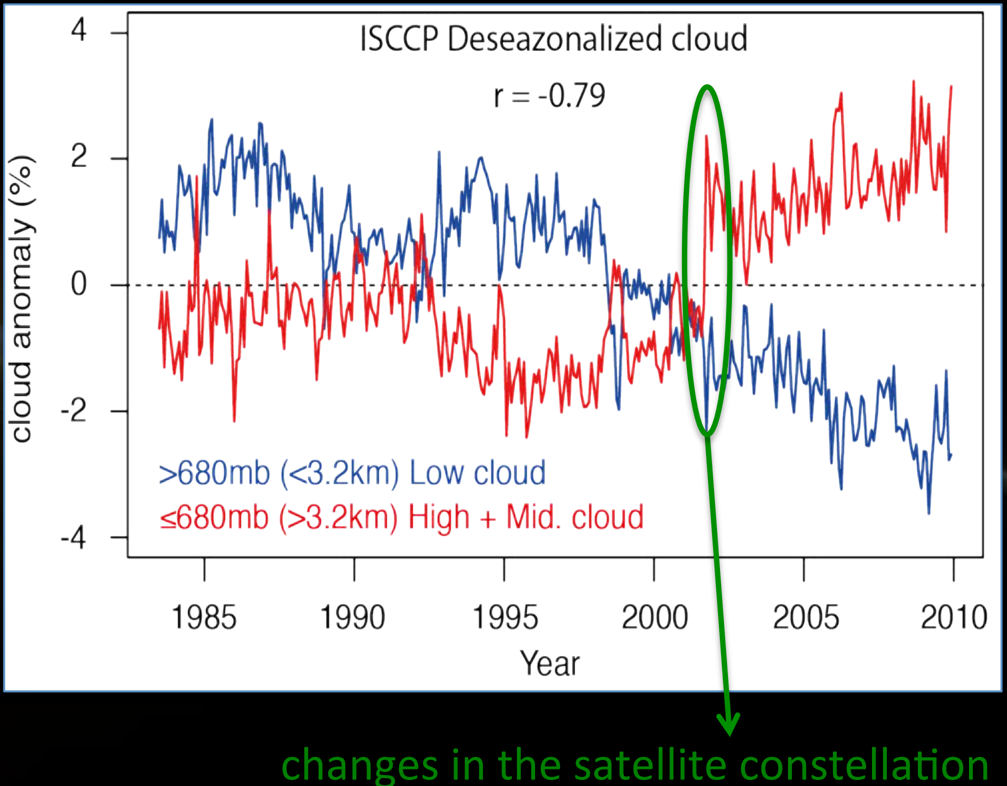
- Correlation only in low (<3.2km) ISCCP cloud (1983–1995)
- High correlation from 12-month smoothed data (df=4)
- Low (non-significant) correlation from unsmoothed data

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

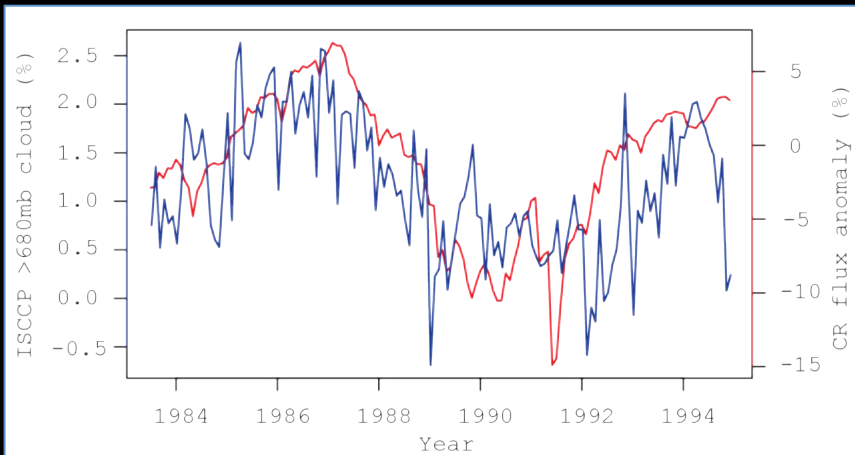
Evidence for CR – cloud link is based on low level clouds:
these data are not reliable!

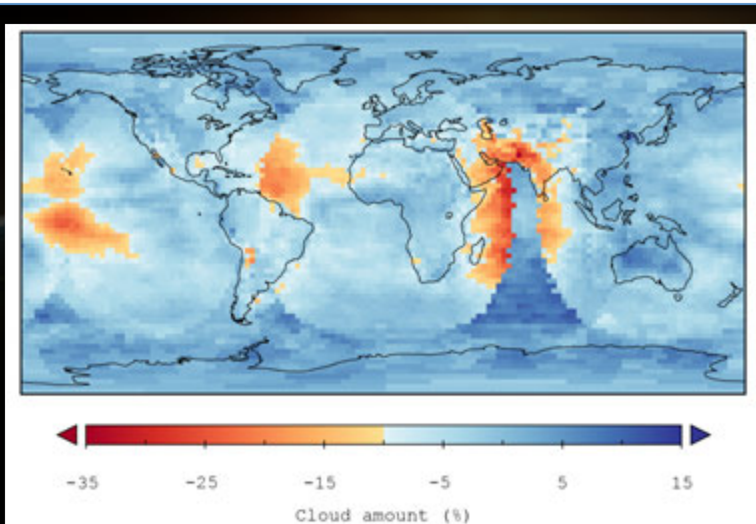


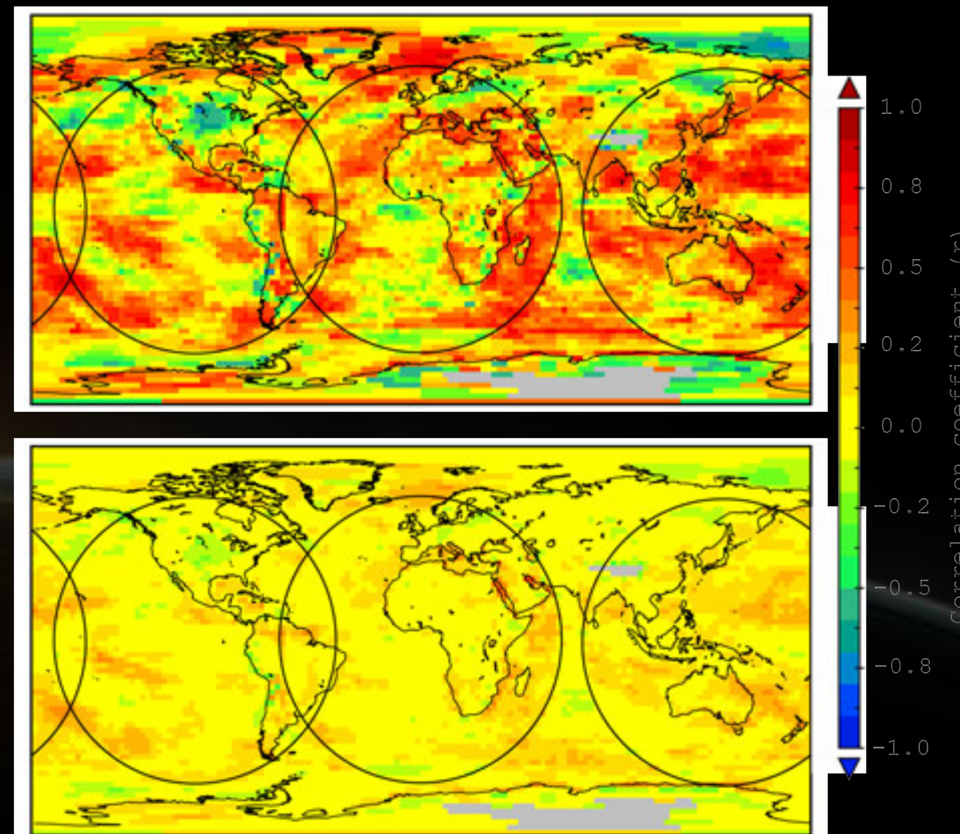
Laken, Pallé, Čalogović & Dunne, 2012, SWSC

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

Correlations between CR flux and clouds are artificial



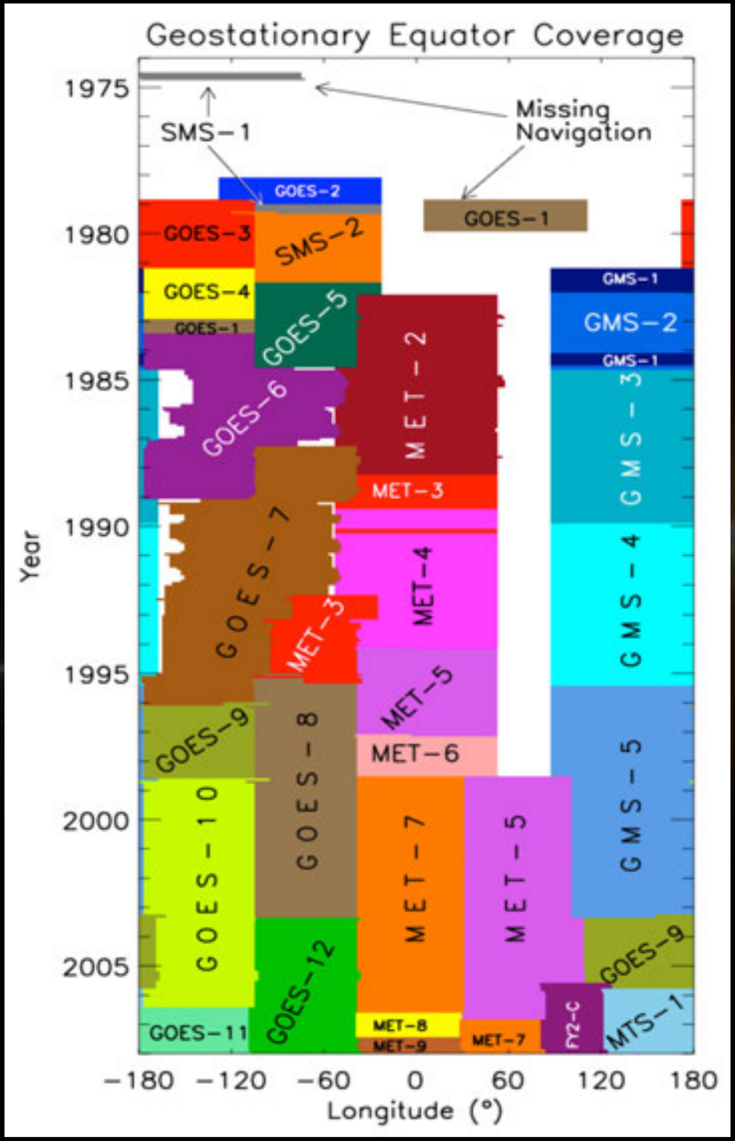


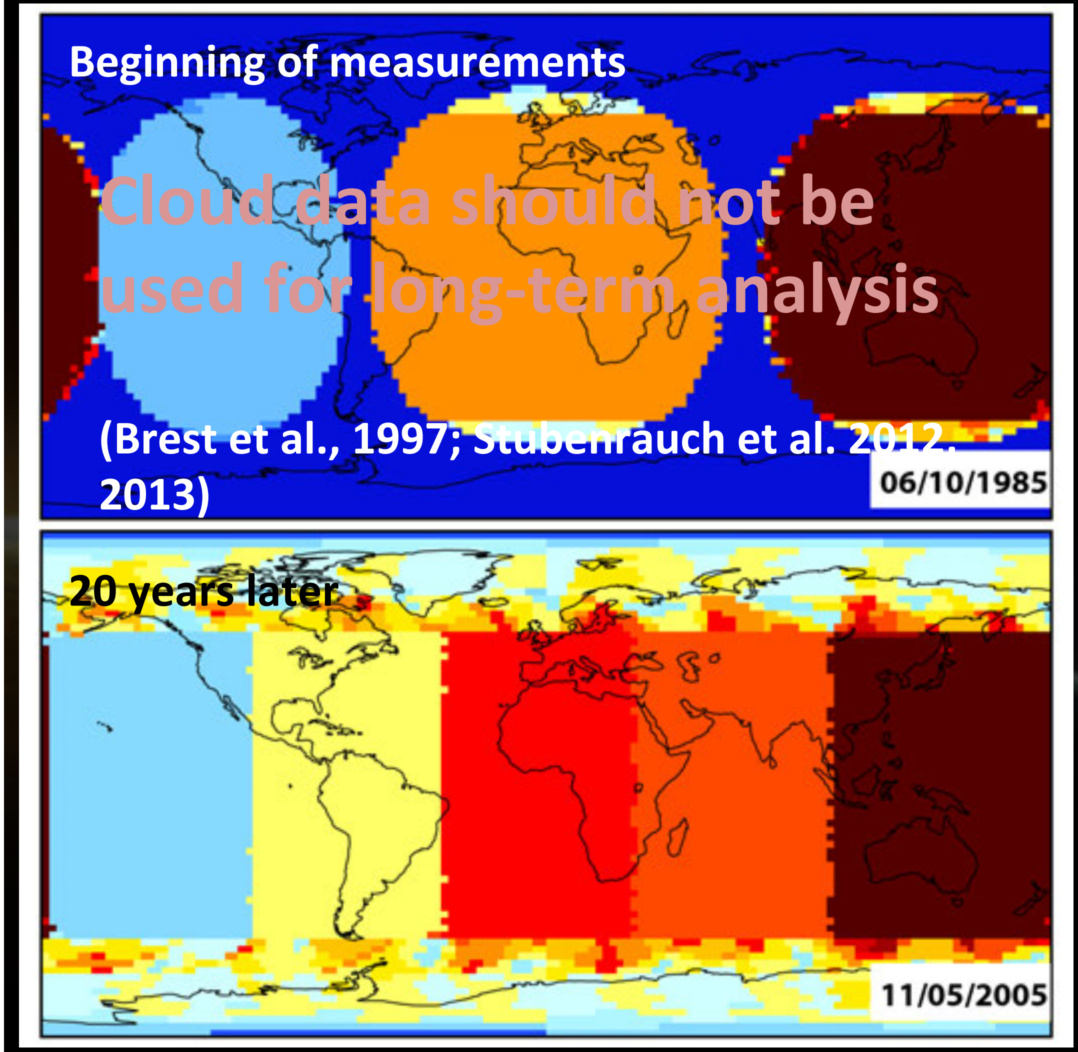


Laken, Pallé, Čalogović i Dunne, 2012, SWSC

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.

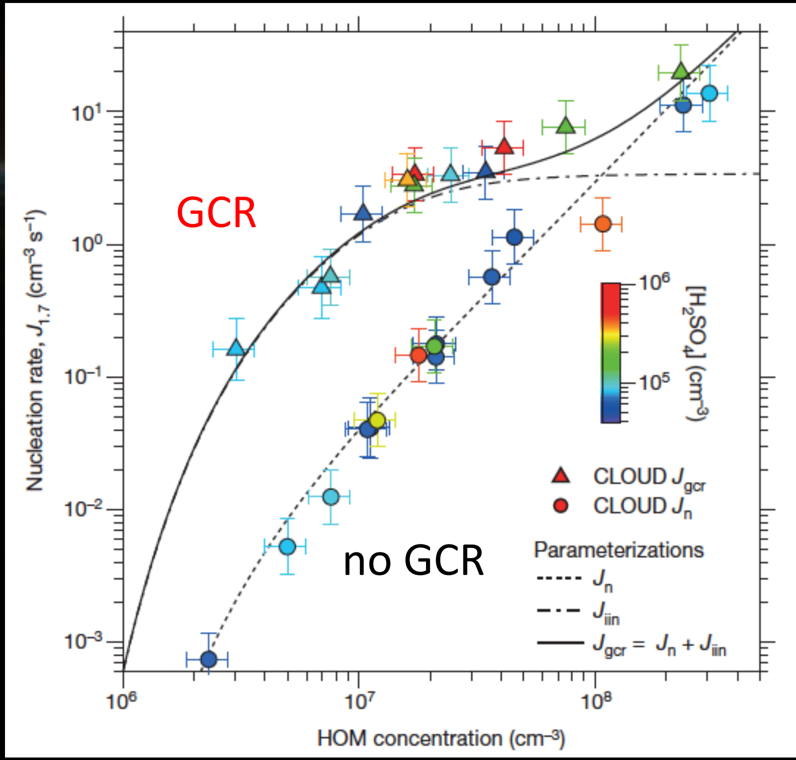
- Sulfuric acid – important species for CCN nucleation
- **Ion-induced aerosol nucleation 10x faster than binary homogeneous nucleation**
- Nucleation in presence of ammonia (stabilizing agent) → **100 do 1000x** faster than ion-induced nucleation
- Nucleation with acid-amines → **1000x** faster than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

Almeida et al., 2013, Nature

Organic particles also play a major role in particle nucleation

- About 50% of Cloud Condensation Nuclei (CCN) originate from atmospheric nucleation (Merikanto et al, 2009)
- CLOUD experiments show that pure organic vapours (Highly Oxygenated Molecules, HOM) can alone drive nucleation (Kirkby et al., 2016, Nature)

- Nucleation of organic particles important in environments with low sulfuric acid concentration (<u>unpolluted regions</u>)
- GCR increase the ion-induced nucleation rate by **10-100 times** compared to neutral nucleation
- Ions account for only 10% of nucleation in planetary boundary layer (Hirsikko et al., 2011)

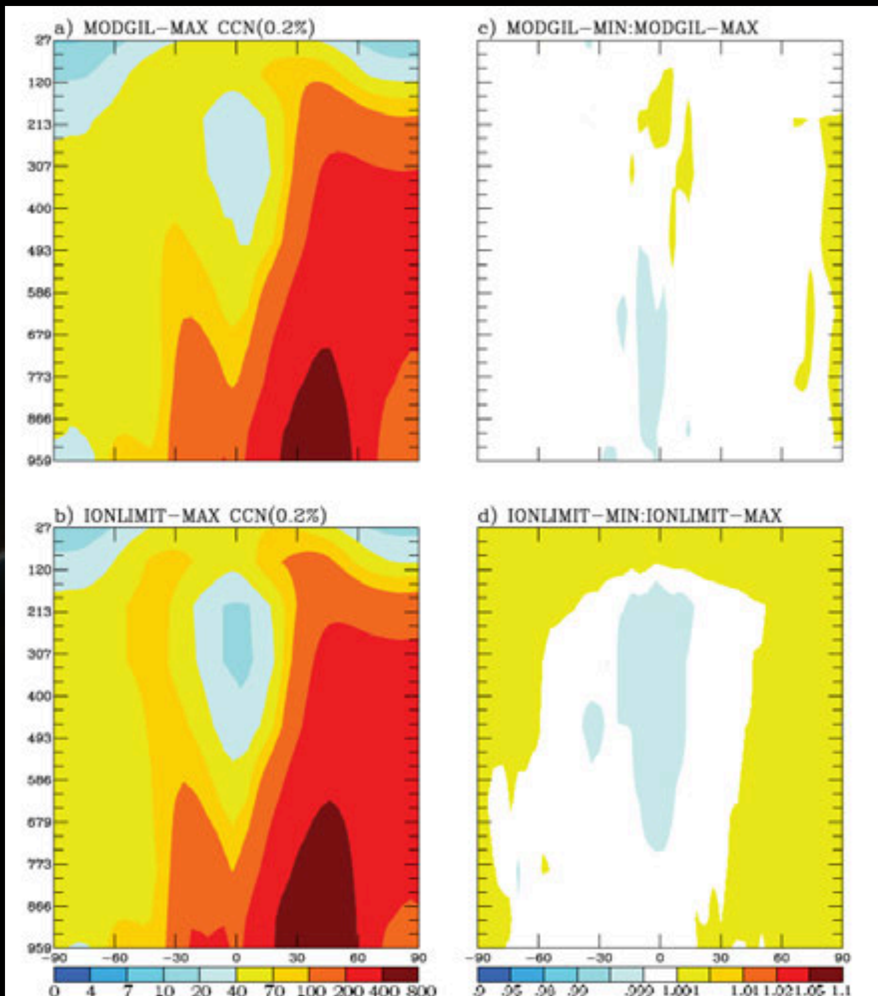


Kirkby et al, 2016, Nature

Model studies show minor impact to alter CCN populations

CCN concentrations during solar max

Difference (solar max – solar min)



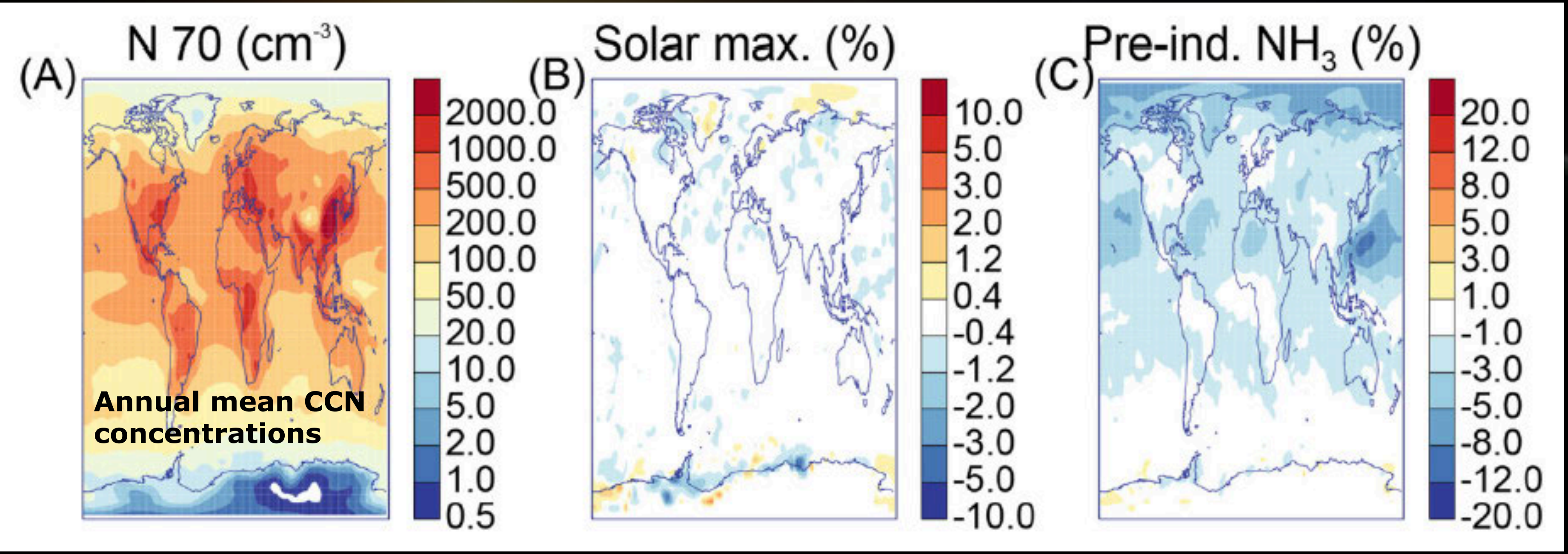
Pierce and Adams, 2009

- 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

Simulations using particle nucelation from CLOUD measurements

Dunne et al., 2016, Science

- Global model of aerosol formation using CLOUD results involving sulfuric acid, ammonia, ions and organic compounds
- Global mean change in CCN during solar cycle (about 850m altitude) is only **0.1%** and locally up to **1%**
- Global mean change in CCN is **1.7%** lower during pre-industrial period than today and locally up to **10-20%** (80% increase in ammonia emissions during industrial period)



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

- Satellite cloud estimates have limitations and calibration errors - long-term analysis is problematic at best
- 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**)

Can short-term studies solve these issues?

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** in long-term studies 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
- 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)
- Top-down (TSI) and bottom-up (UV) mechanisms as well as impact of energetic particles (EPP) on the atmospheric chemistry can change the regional scale circulations, affect the internal climate oscillations and in turn explain the large amount of observed climate varibility induced by the solar activity

Thank you for your attention!

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