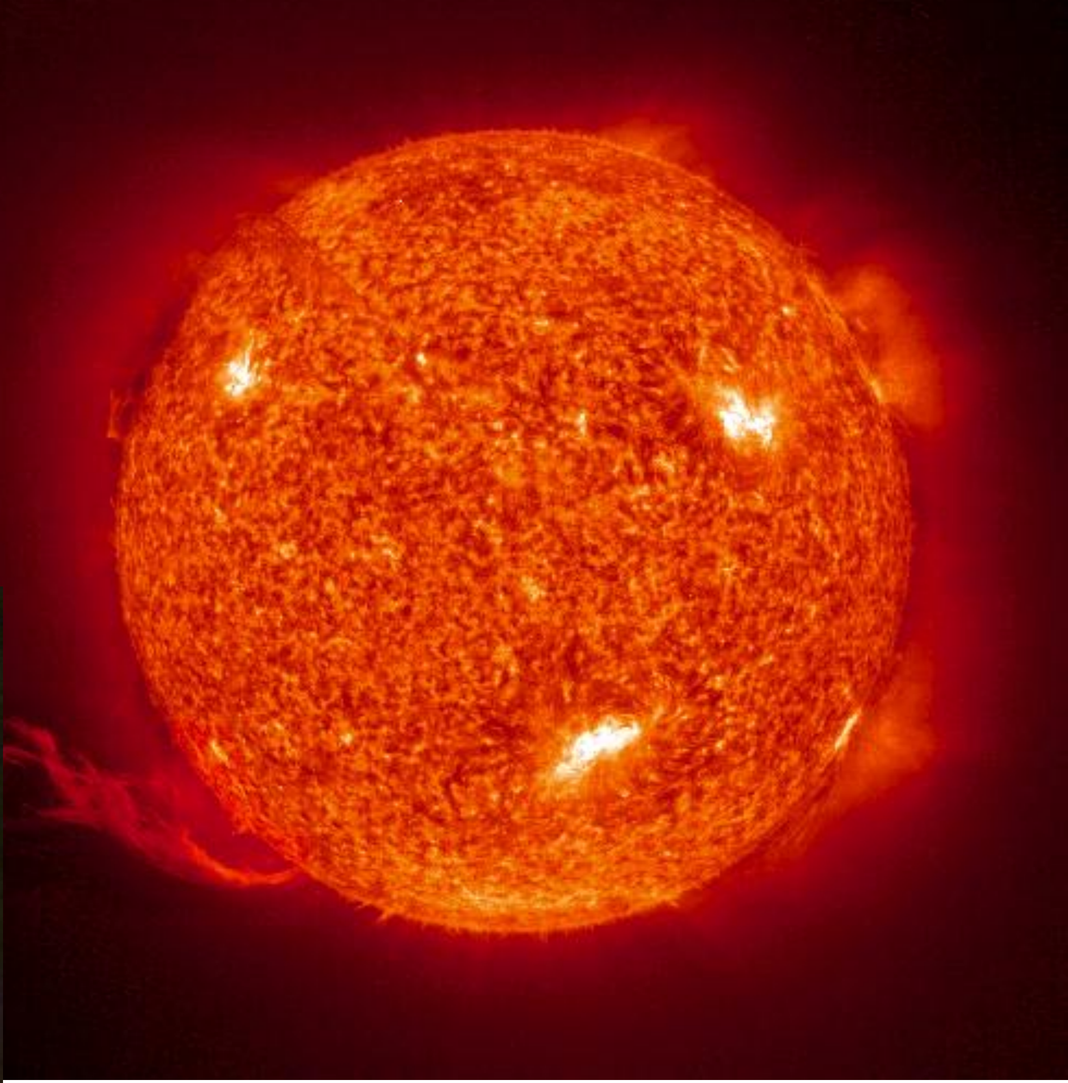
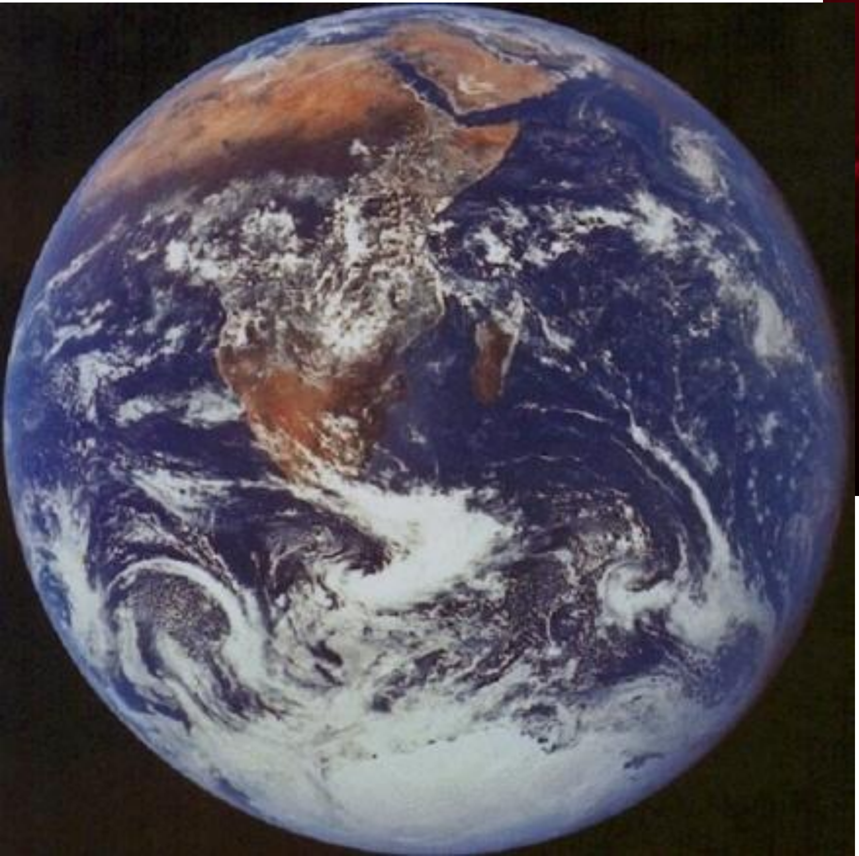
Solar variability and climate

Joanna D. Haigh





Imperial College London

h 2008

Solar influence on climate – the media view

March 2007 *All global warming is due to enhanced solar activity.*

Daily Mail

13 September 2007

Global warming? It's natural, say experts

by BARRY WIGMORE

Climate change is much more likely to be part of a cycle of warming and cooling that has happened regularly every 1,500 years for the last million years, they say.

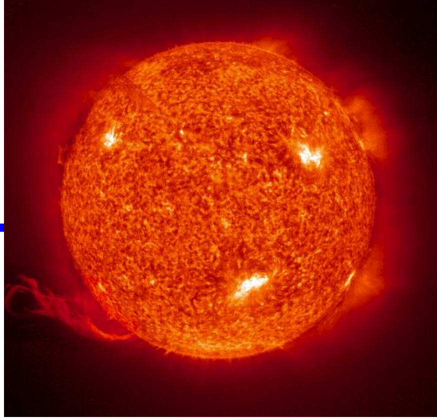
Mr Singer said: "This can all be explained by the Sun's activity."

Solar influence on climate – the media view

September 2006

Reduced solar activity will buy us time to reduce greenhouse gas emissions.

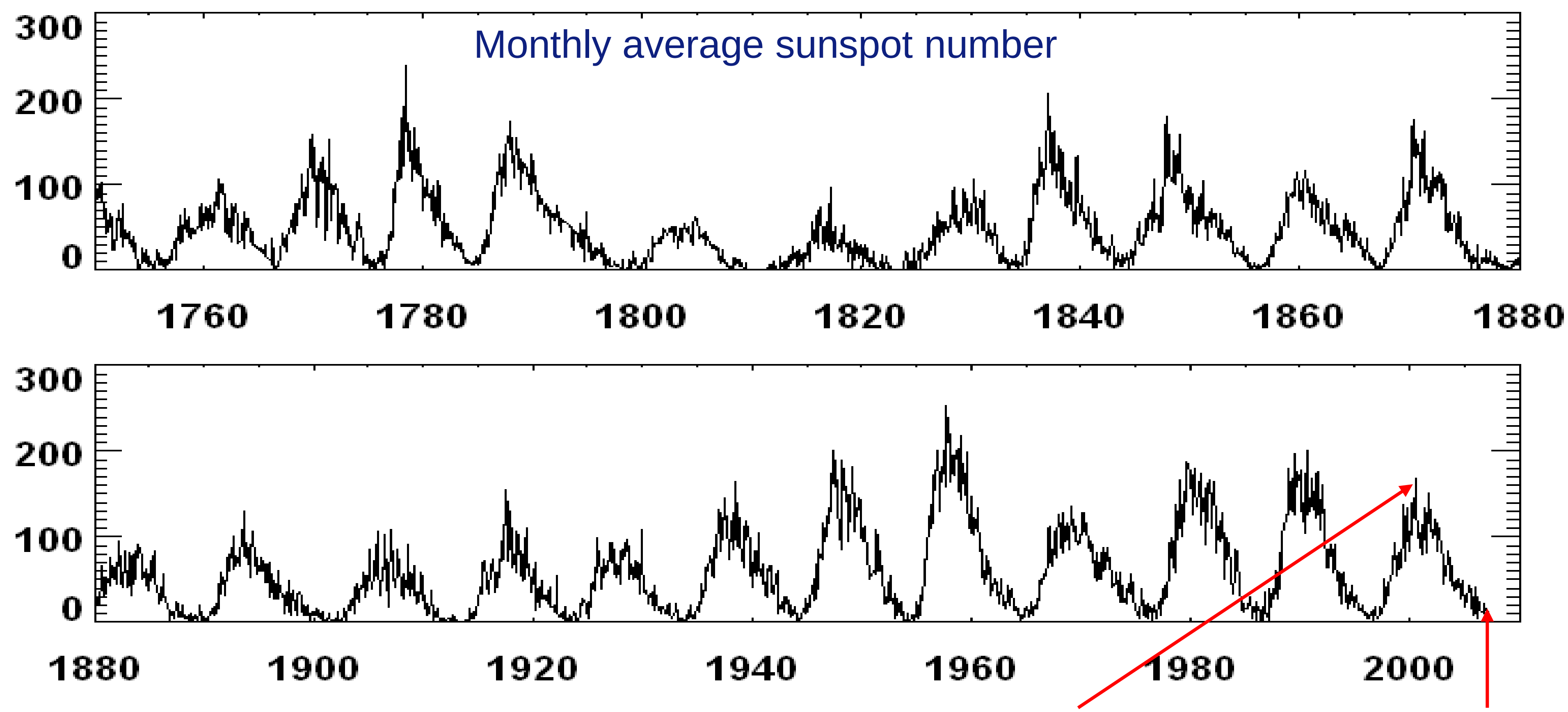
Solar variability and climate



Variations in solar activity / energetic output.

Solar signals in climate records.

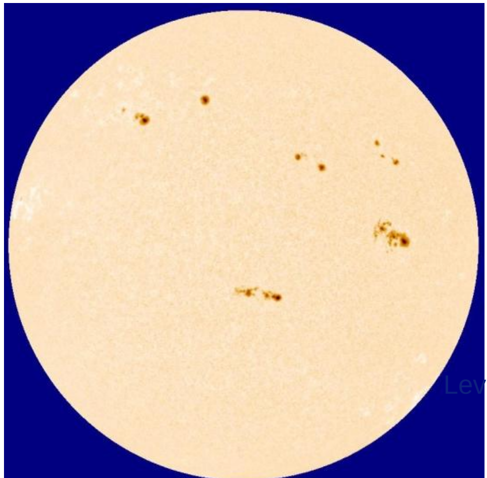
Mechanisms for solar influence on climate.

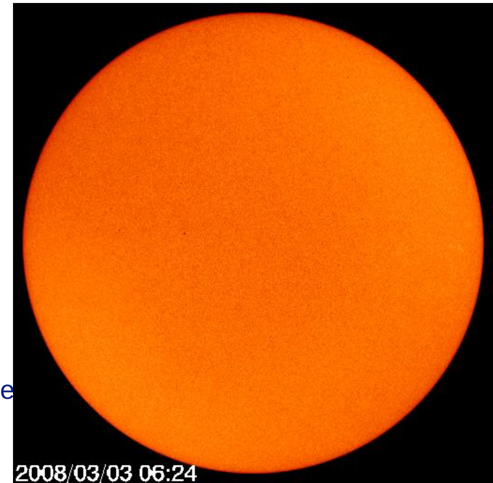

Monthly average sunspot number

20 March 2000

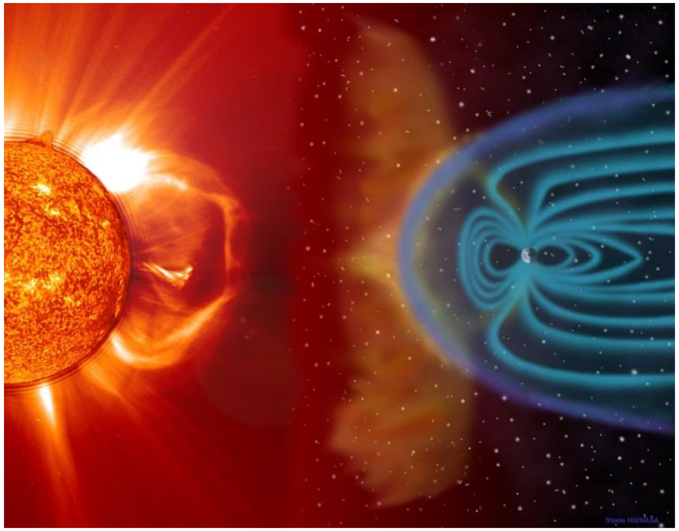
3 March 2008

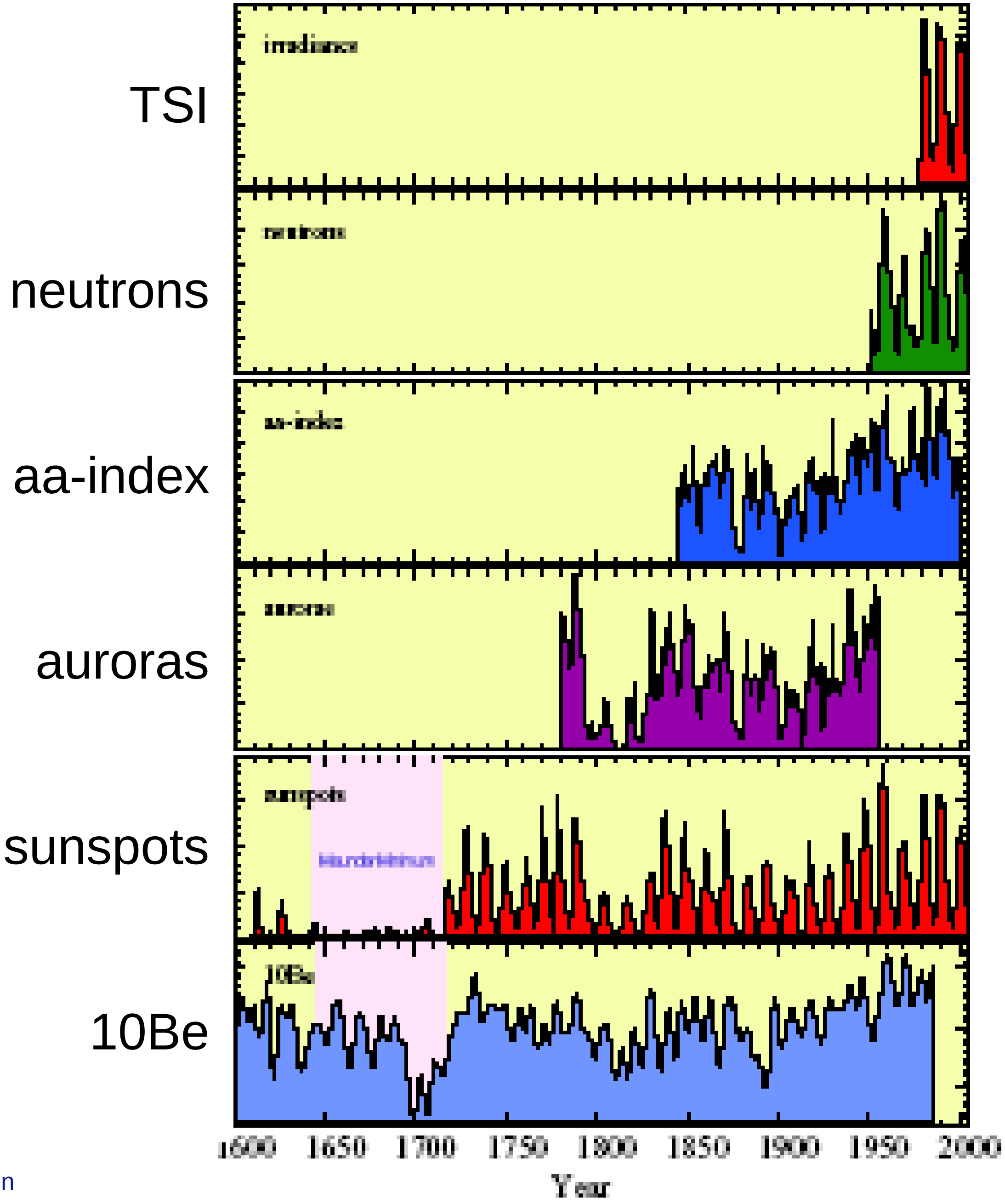
Sunspot cycle





Solar activity indicators

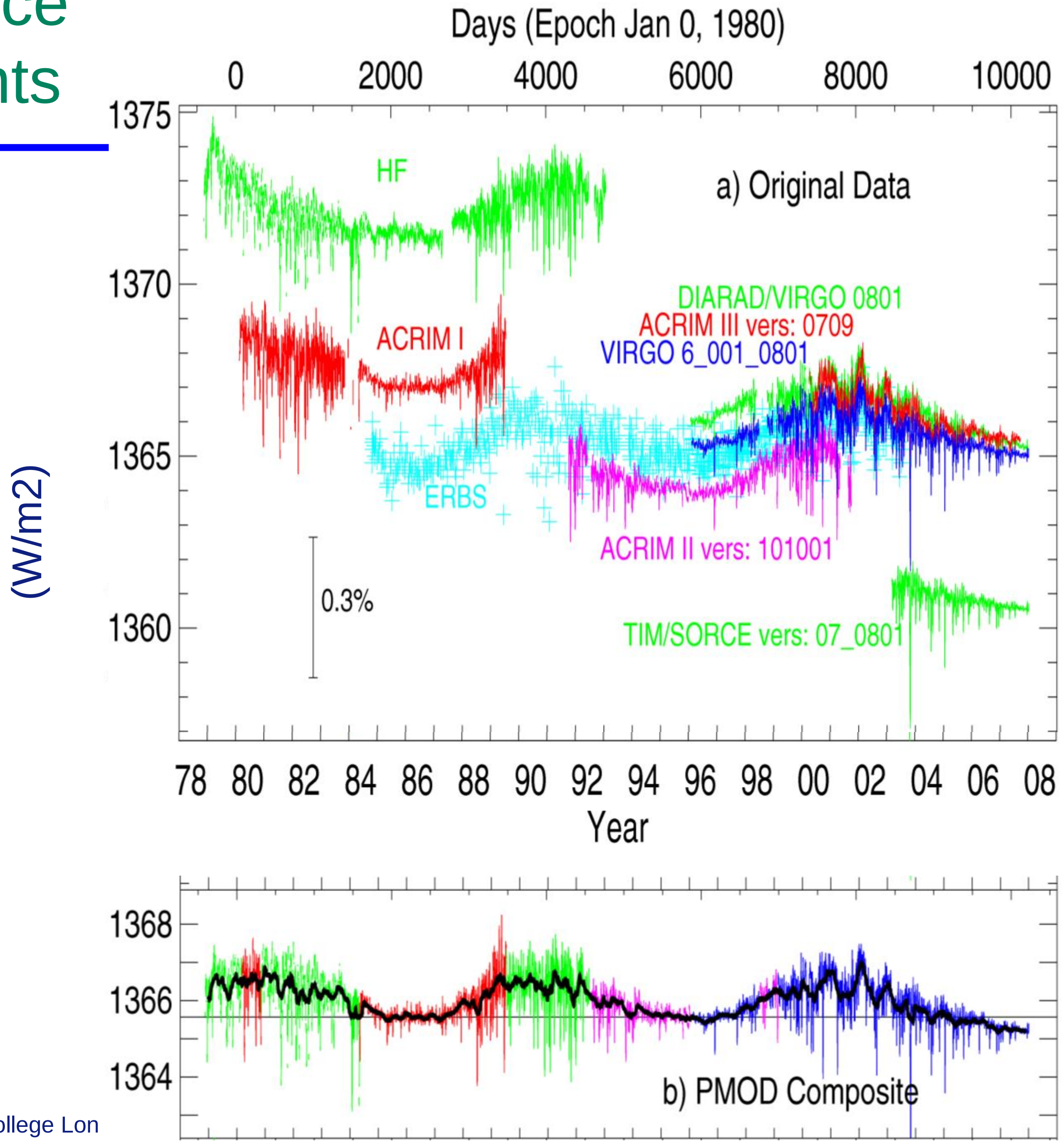




Beer et al 2006

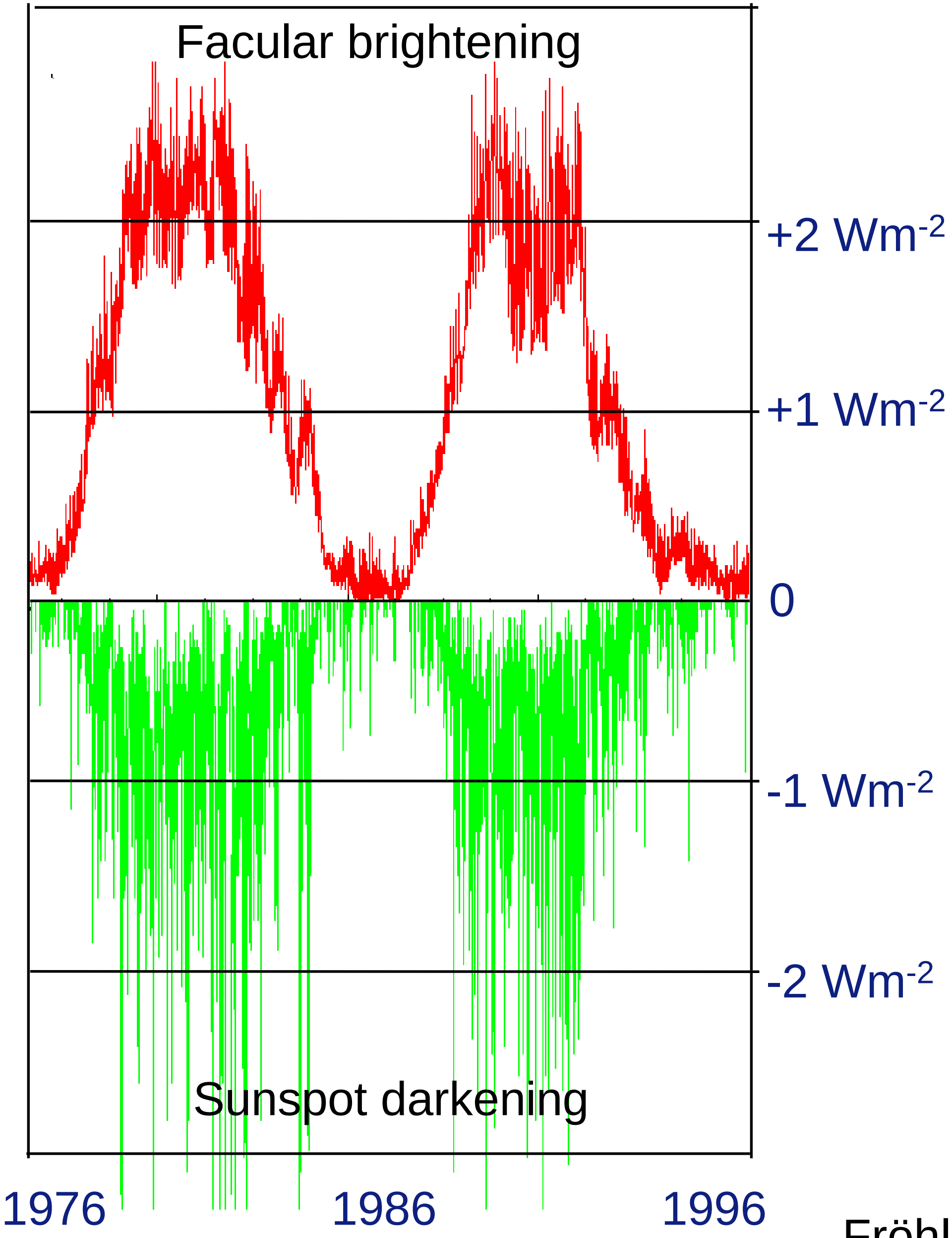
Total solar irradiance (TSI) measurements

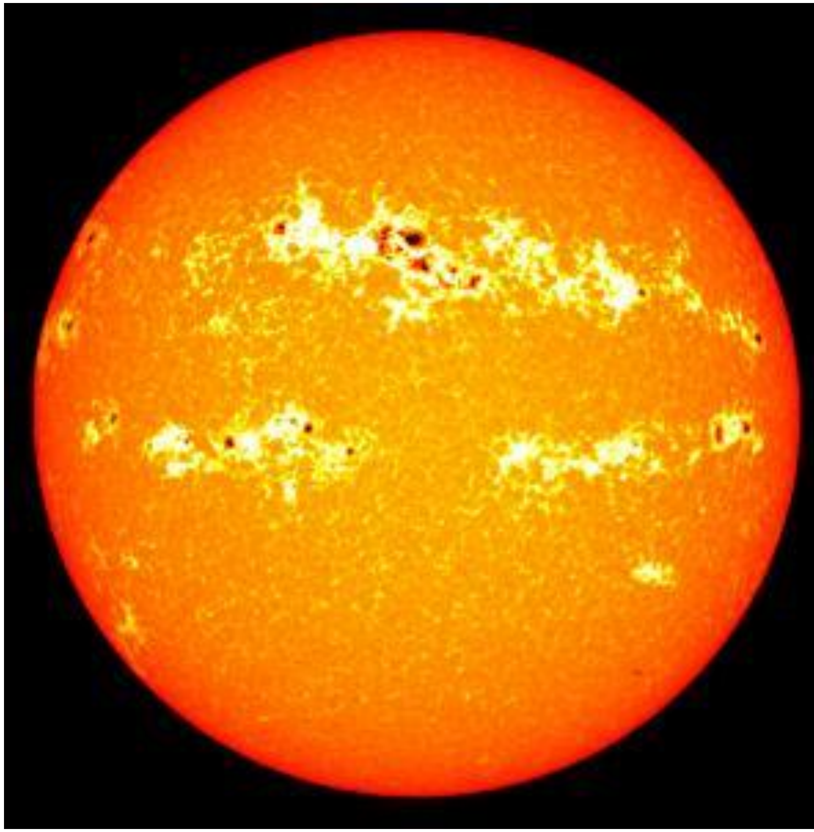
from satellites



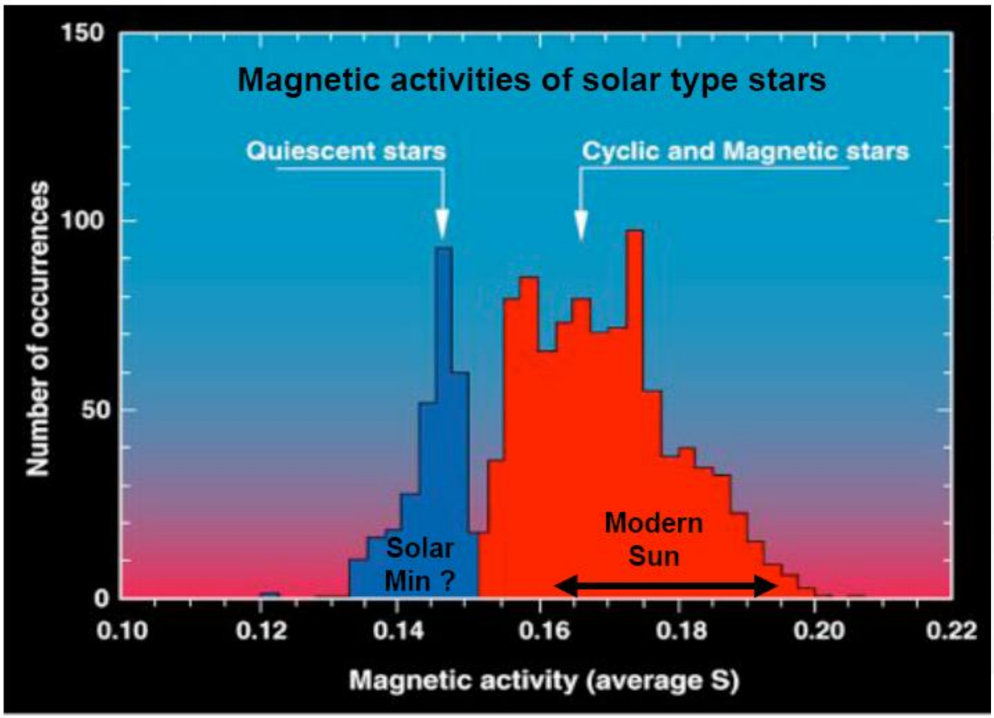
(Claus Fröhlich, PMOD)

Sunspots, faculae and TSI



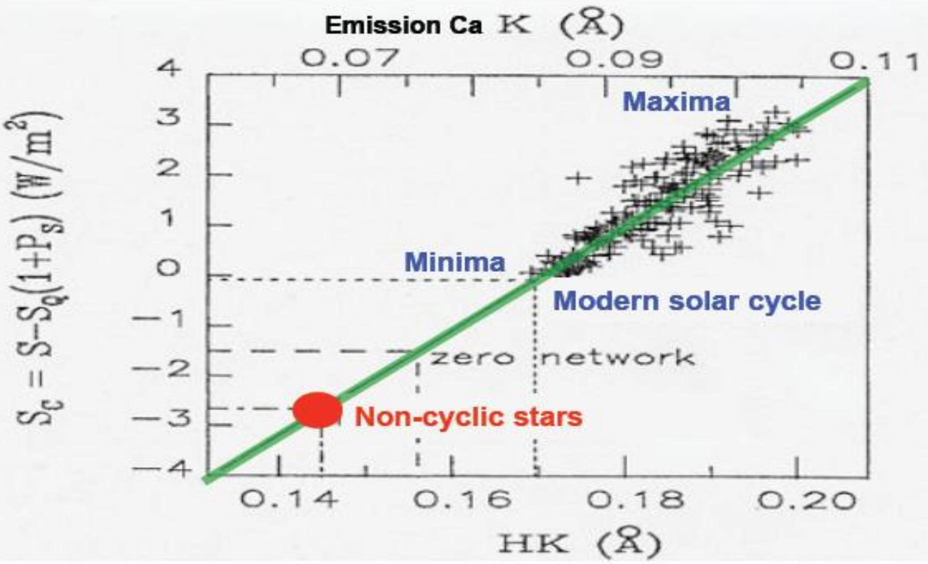


Fröhlich, 2000

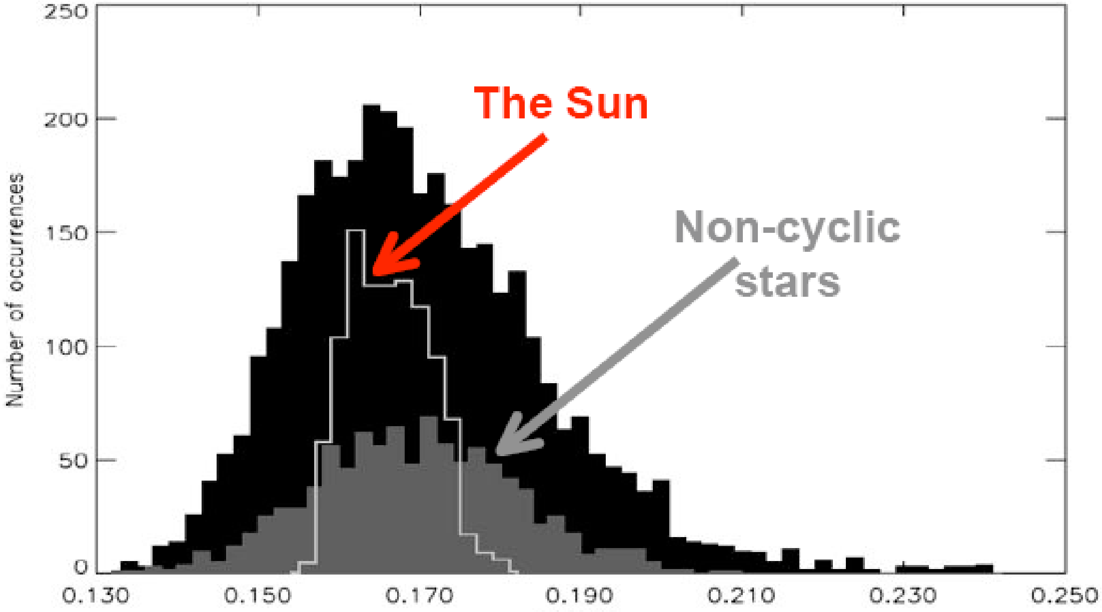


After Baliunas & Jastrow, 1990

The magnetic activity of the Sun is correlated with its irradiance in W/m²



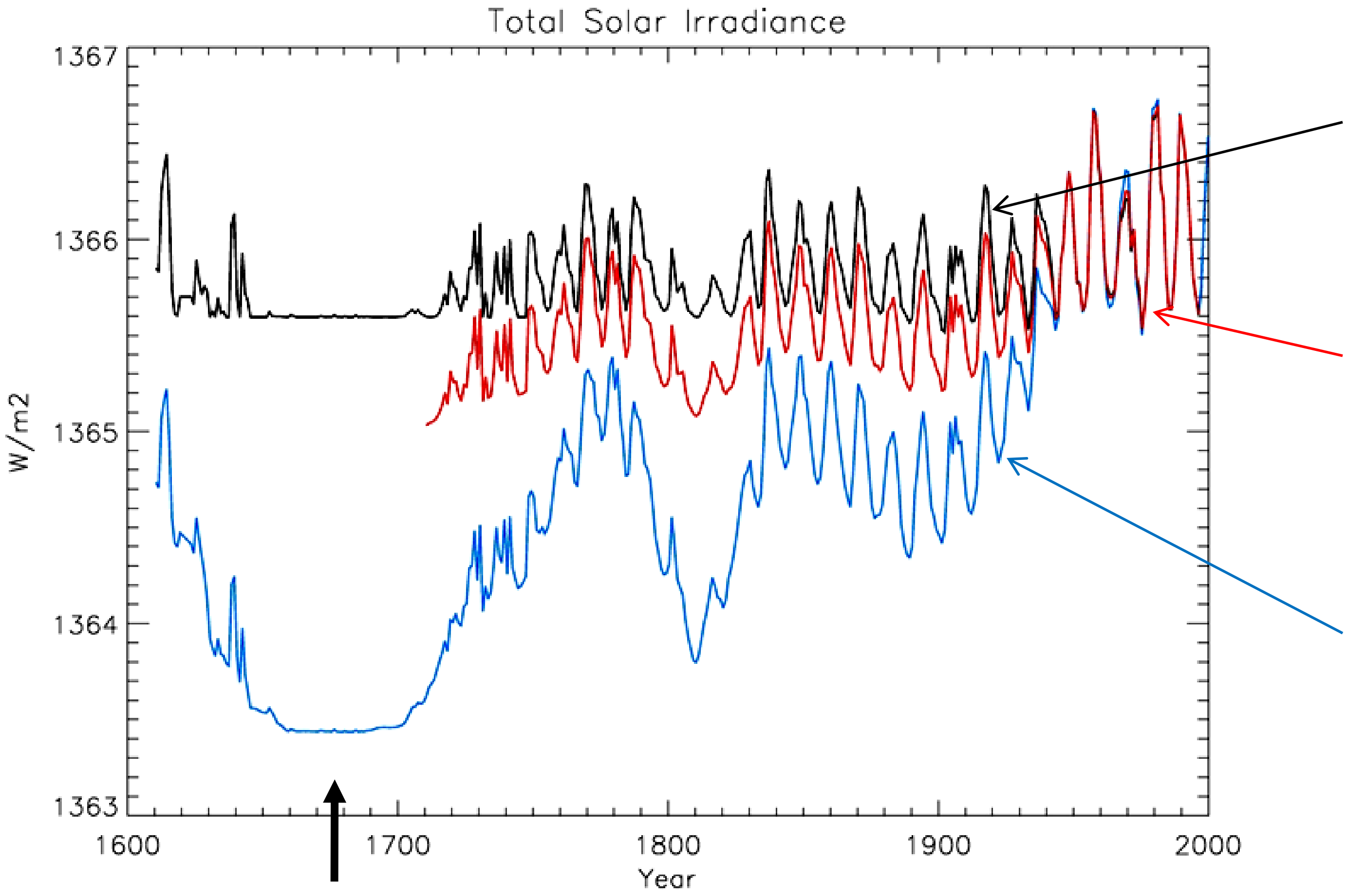
Lean et al. 1992



Hall & Lockwood 2004

Solar activity from analogy with Sun-like stars

Historical reconstructions of TSI



sunspots only, i.e. no long-term trend

long-term trend from model of solar surface magnetic field

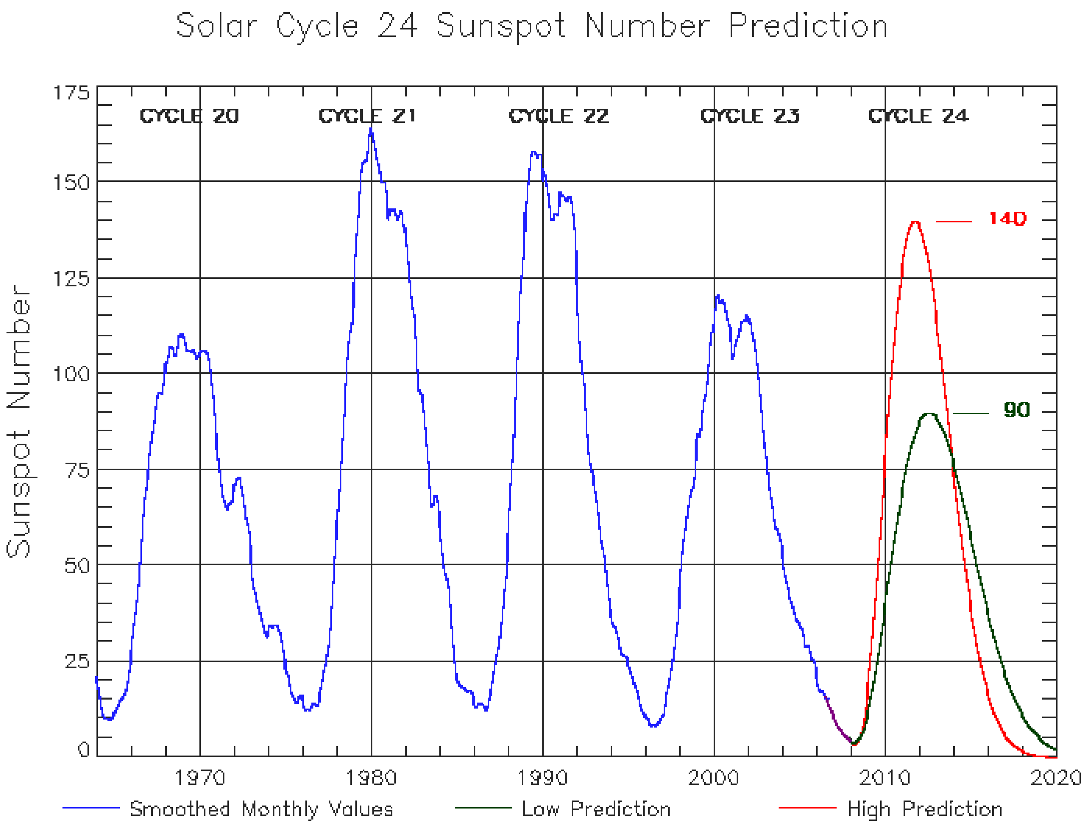
long-term trend based on “Sun-like” stars

Maunder Minimum

(based on Wang et al, 2005)

Prediction for Solar Cycle #24

press release by NASA/NOAA prediction panel 27 Apr 2007

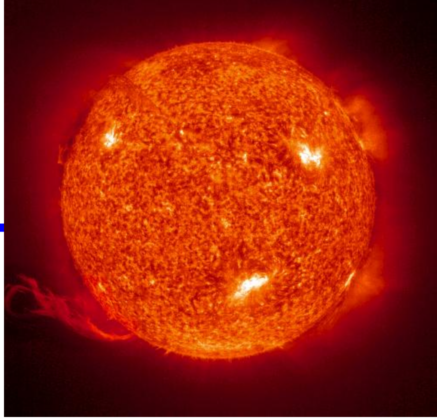


Half the panel predicts 140 ± 20 peaking Oct 2011

Half the panel predicts 90 ± 10 peaking Aug 2012

!!

Solar variability and climate



Variations in solar activity / energetic output.

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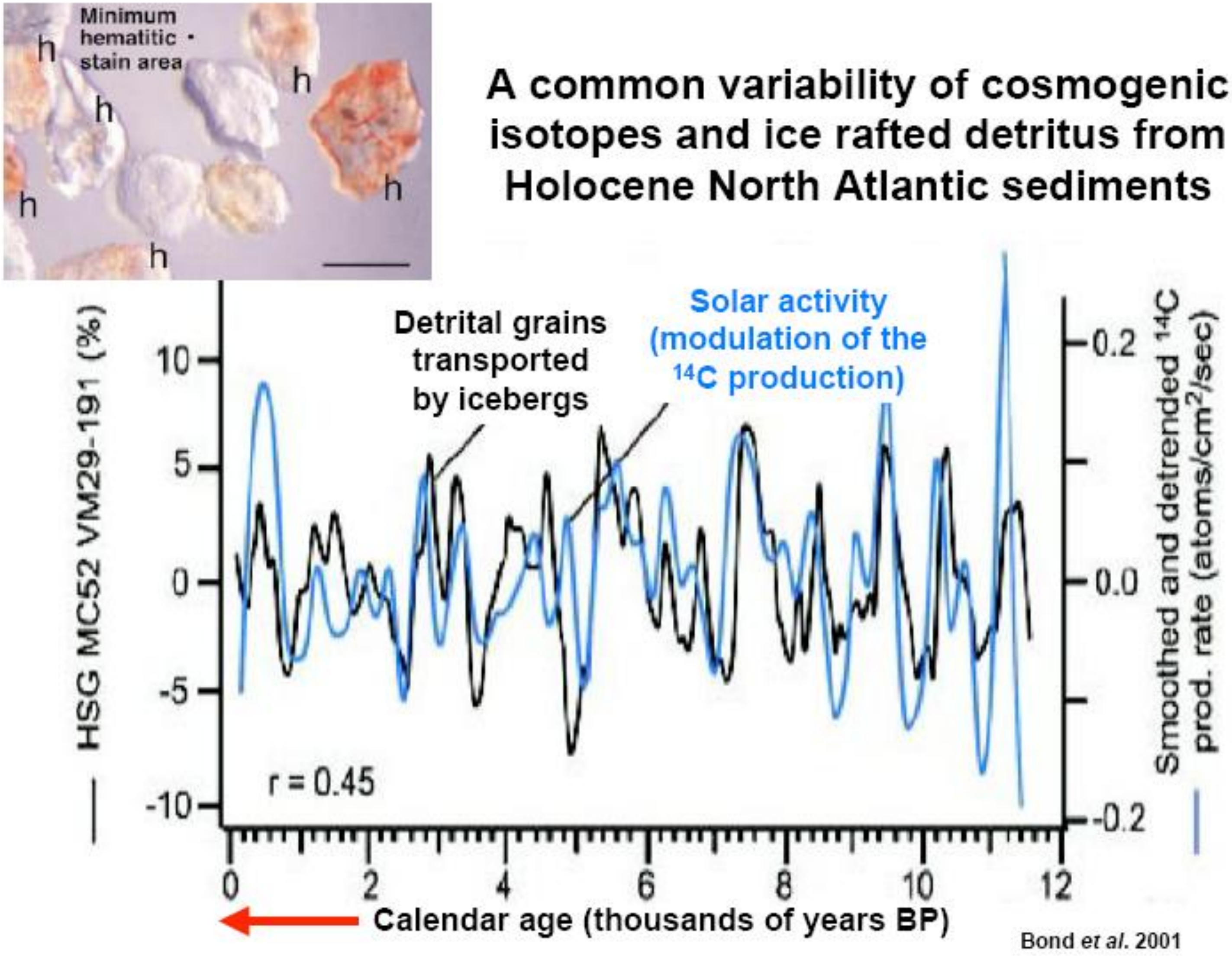
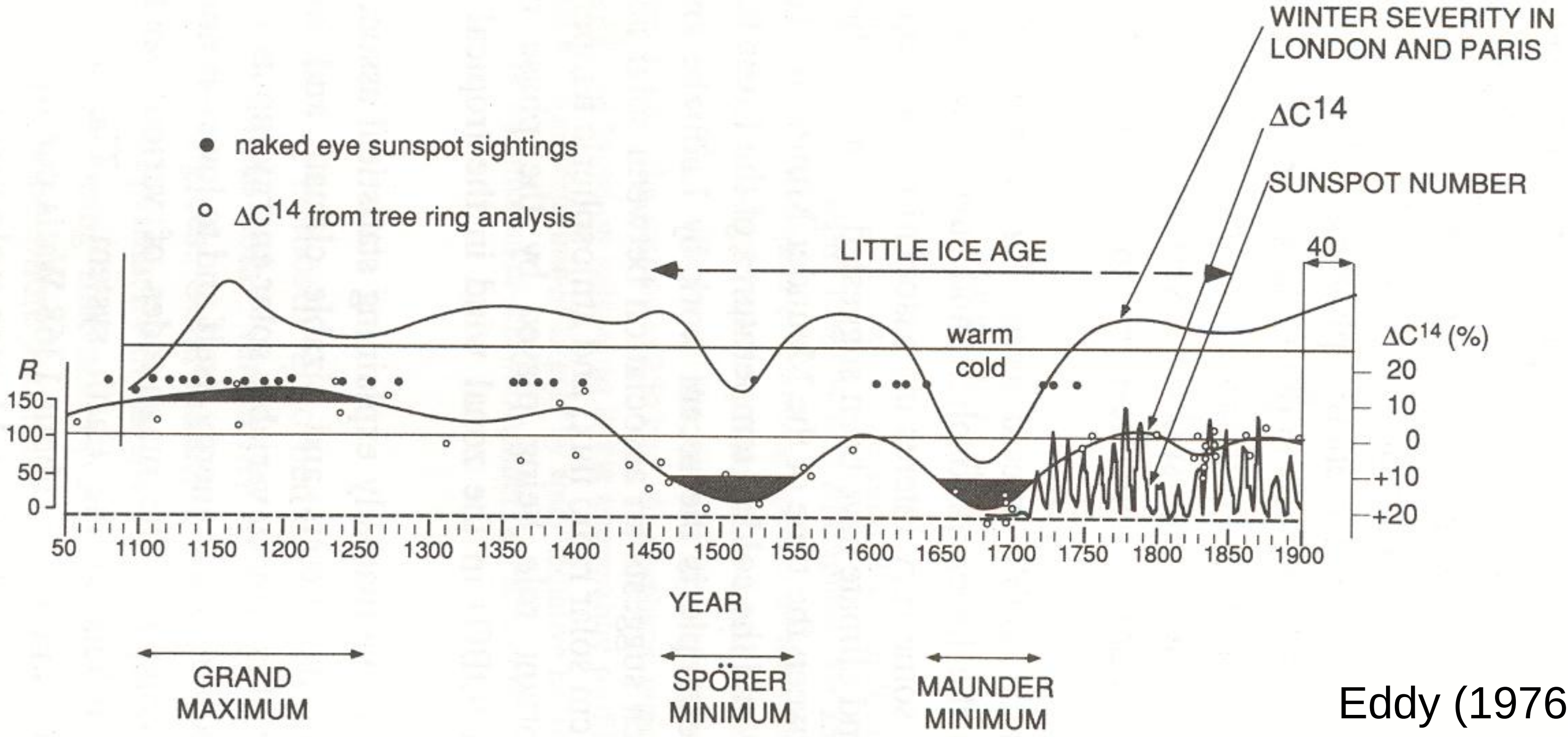
N. Atlantic ice-rafted debris



A common variability of cosmogenic isotopes and ice rafted detritus from Holocene North Atlantic sediments

Bond *et al.* 2001

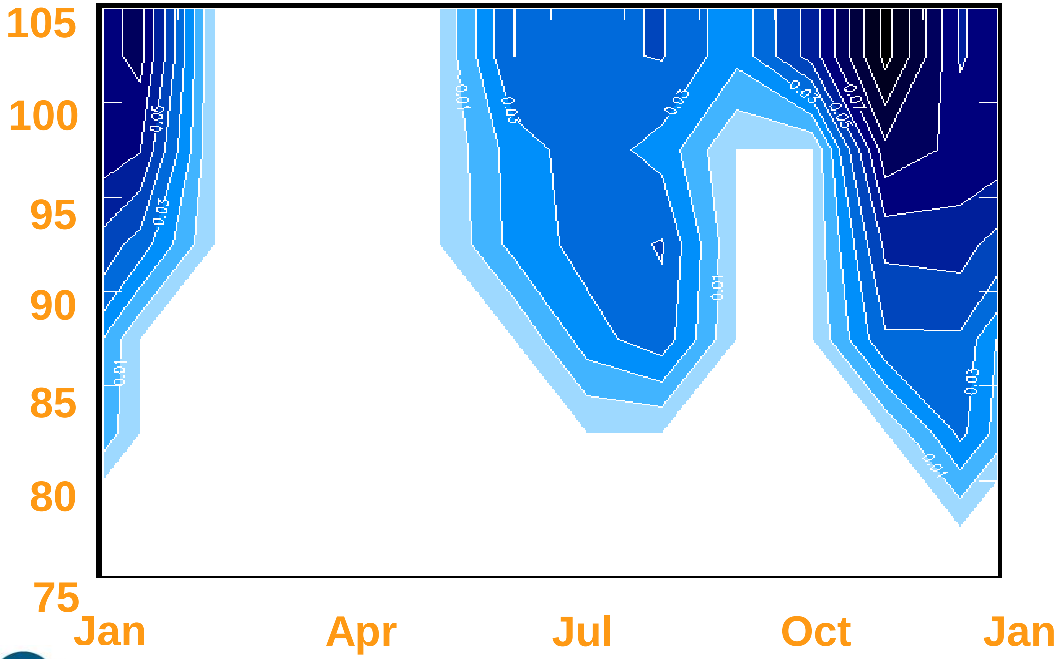
Temperature in NW Europe



Eddy (1976)

Solar cycle change in upper atmosphere

Meridional winds over Halley (76°S)



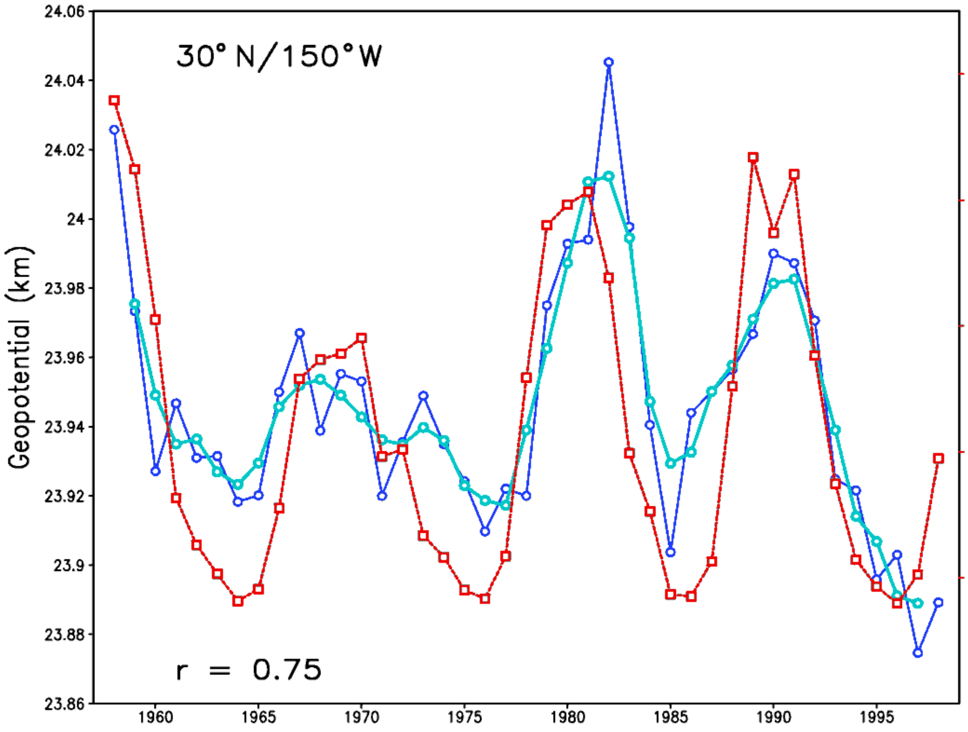
These changes are approximately 50% of the mean wind value

Martin Jarvis

British Antarctic Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

Solar cycle in atmospheric temperatures

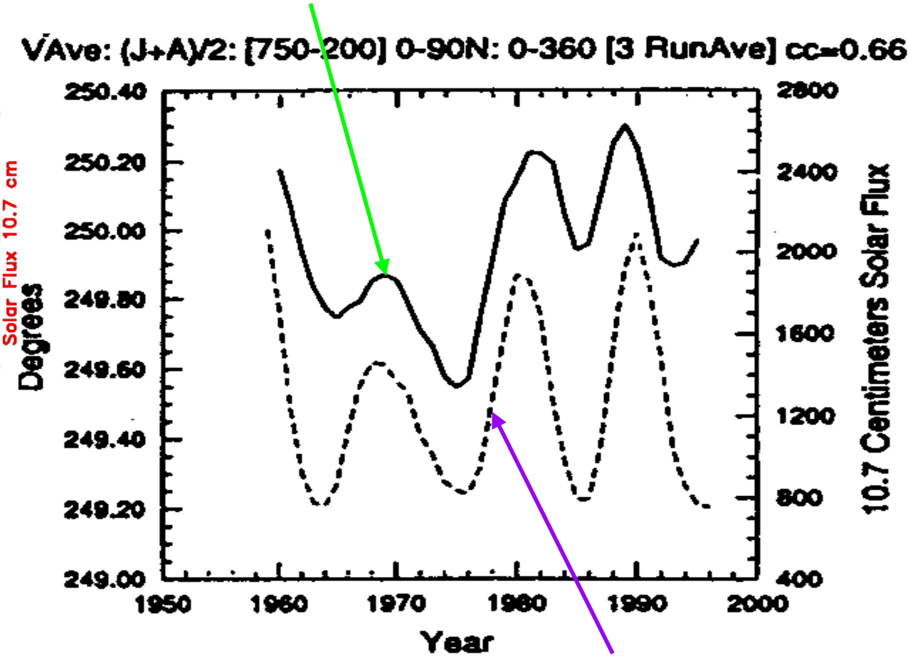
30 hPa geopotential height (annual mean, Hawaii)



Labitzke and van Loon (2000)

Upper tropospheric temperatures (July&August)

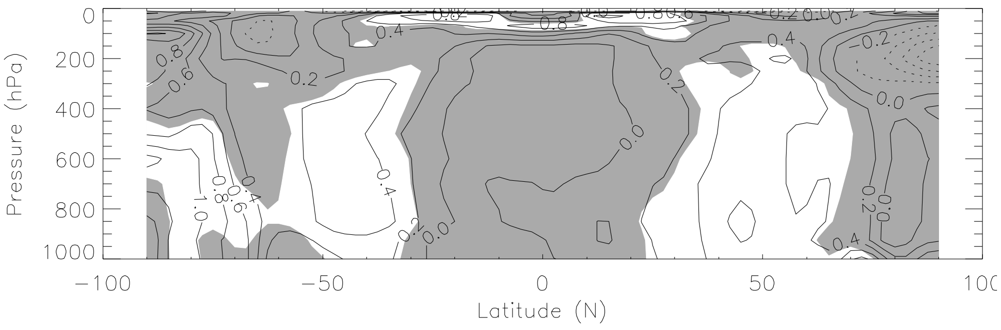
750-200hPa thickness,
3-year running average



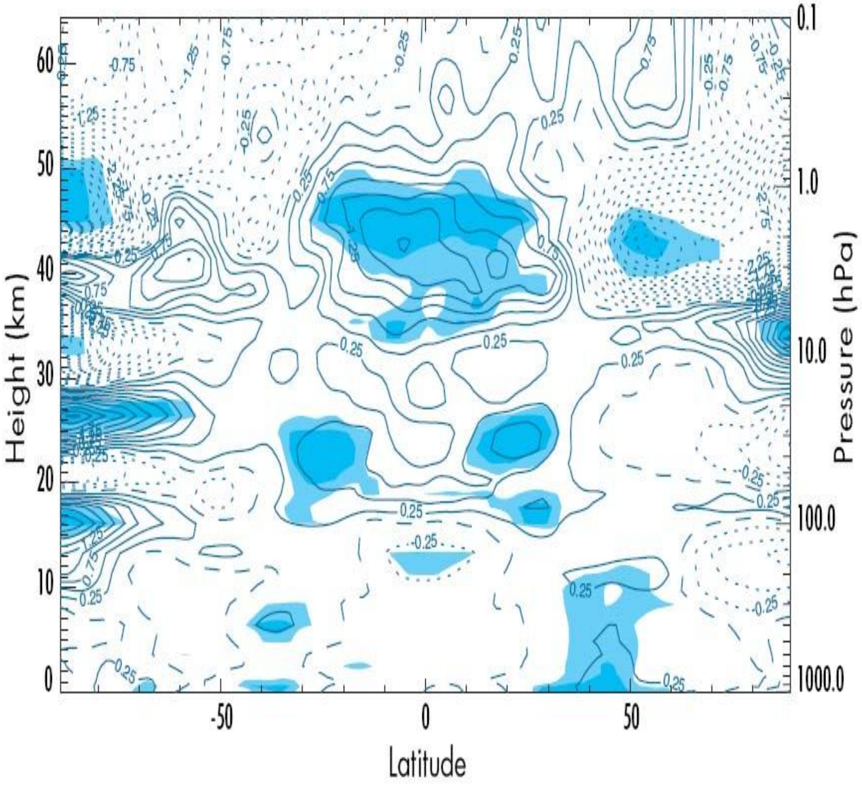
solar 10.7cm flux

van Loon and Shea (2000)

Solar cycle change in zonal mean temperature

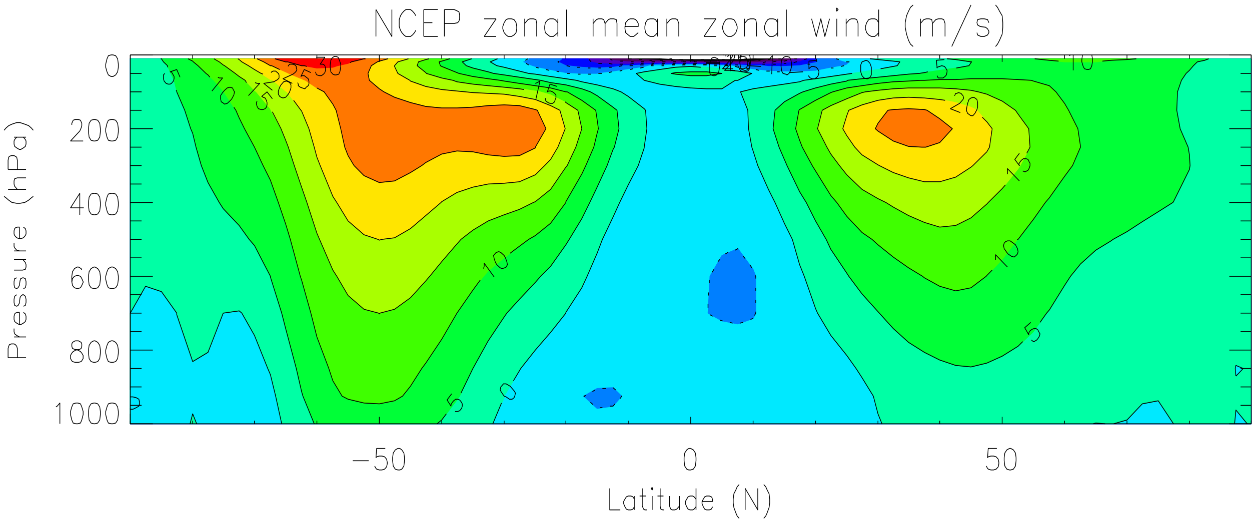


NCEP data, Haigh (2003)

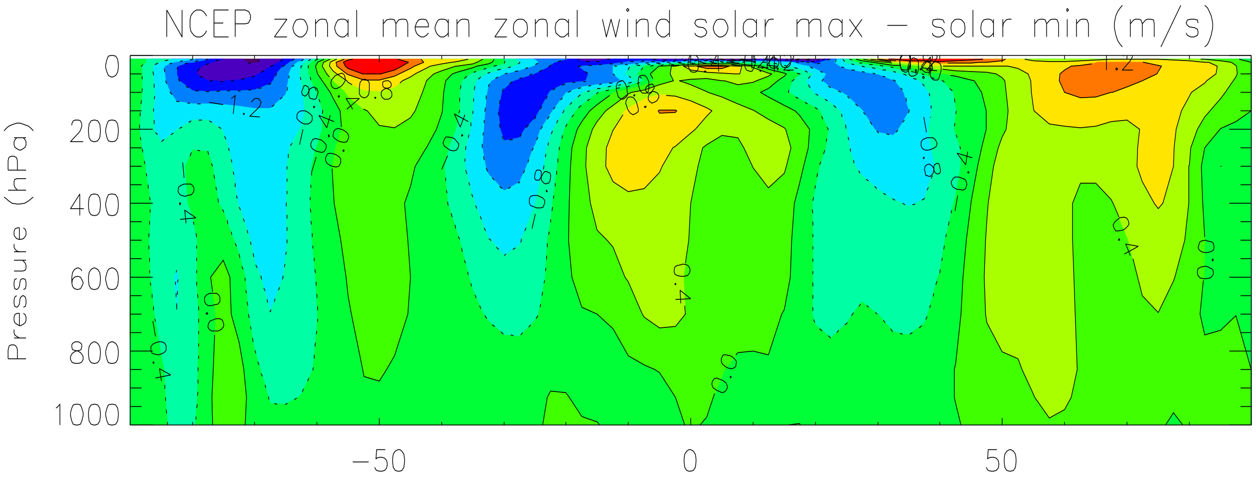


ERA-40 data, Crooks & Gray (2005)

Solar cycle signal in westerly wind



mean

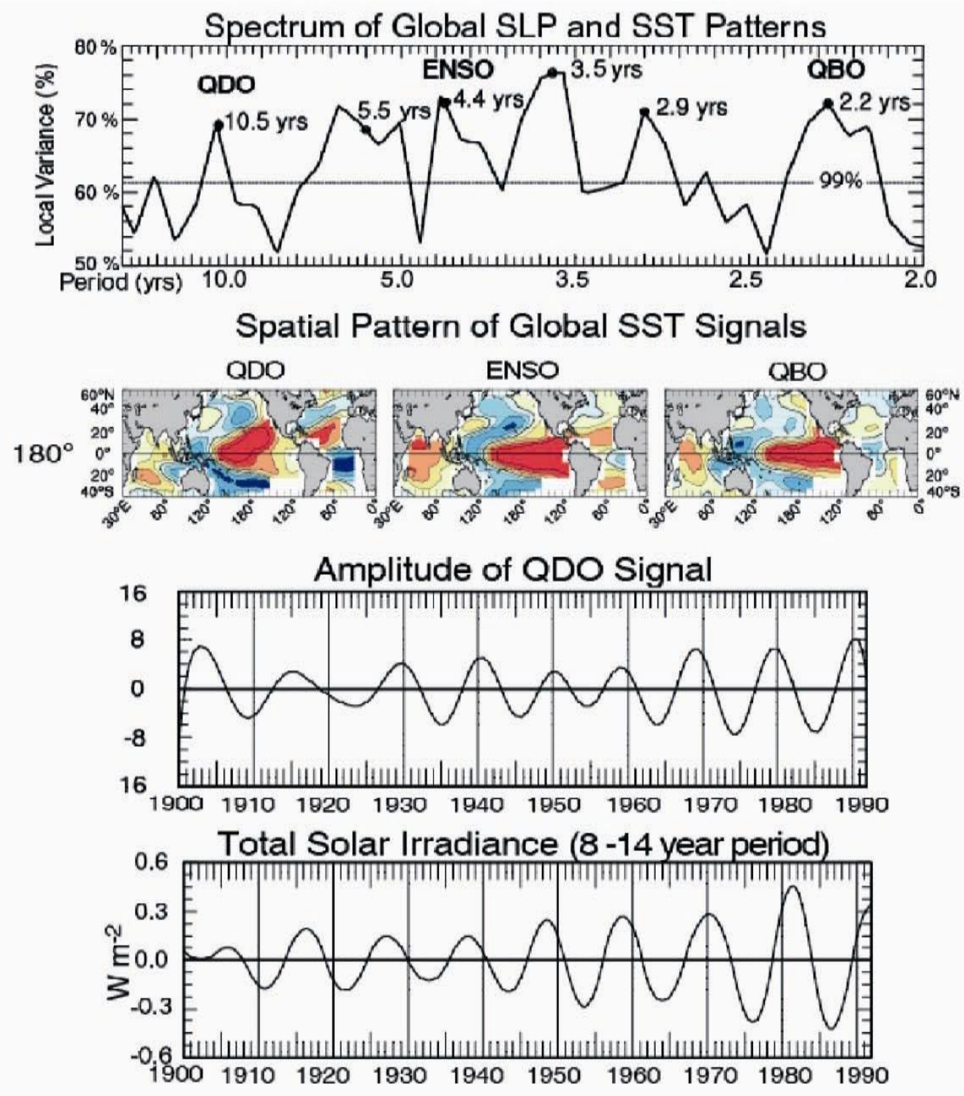


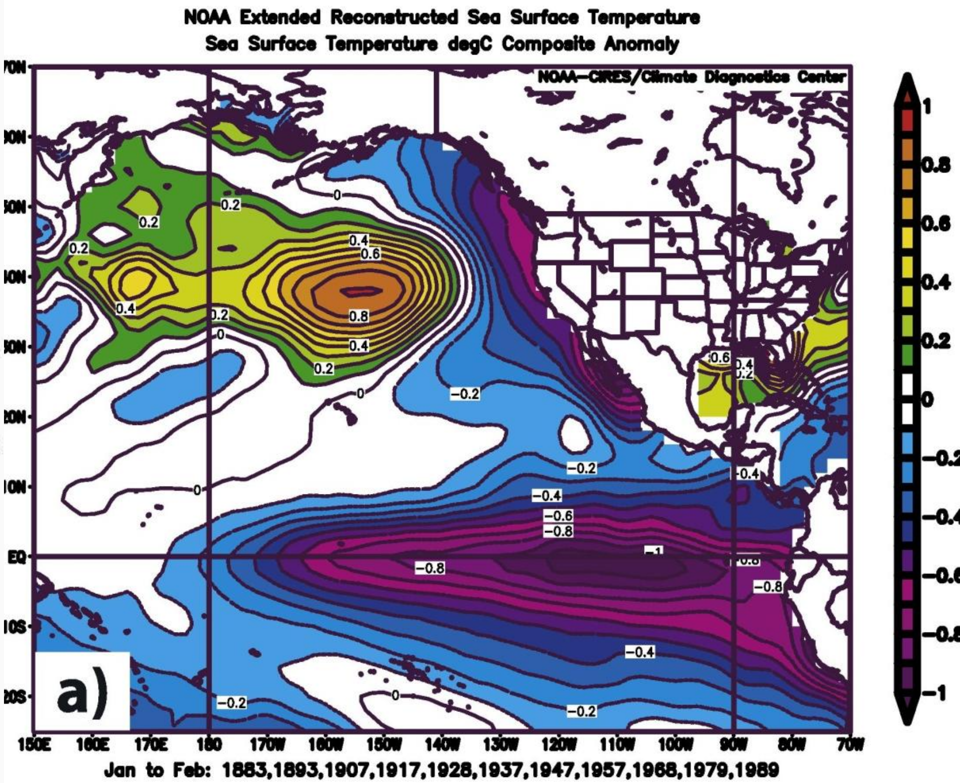
max-min

Weakening and poleward shift of the mid-latitude jets

Haigh, Blackburn & Day (J.Clim., 2005)

Pacific Sea Surface Temperatures



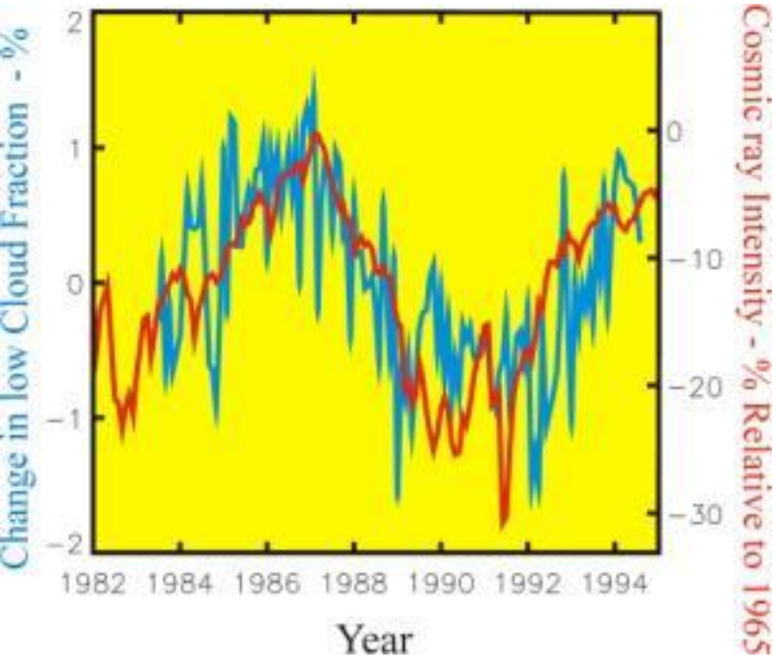


solar max anomaly
(van Loon et al 2007)

White and Touree (2003)

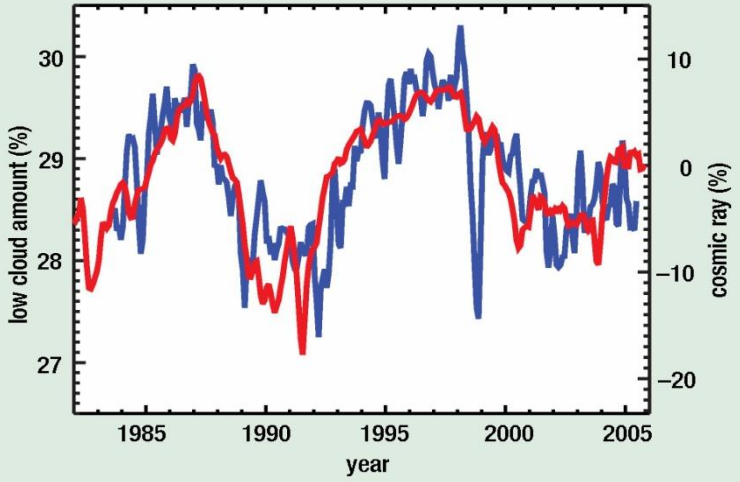
Low cloud and galactic cosmic rays

Marsh & Svensmark 2000



Svensmark, A&G 2007

3: As in figure 2, the low-cloud comparison extends over a longer period.



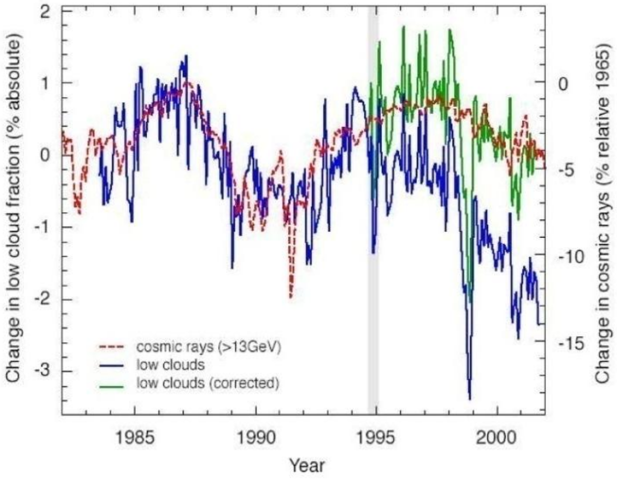
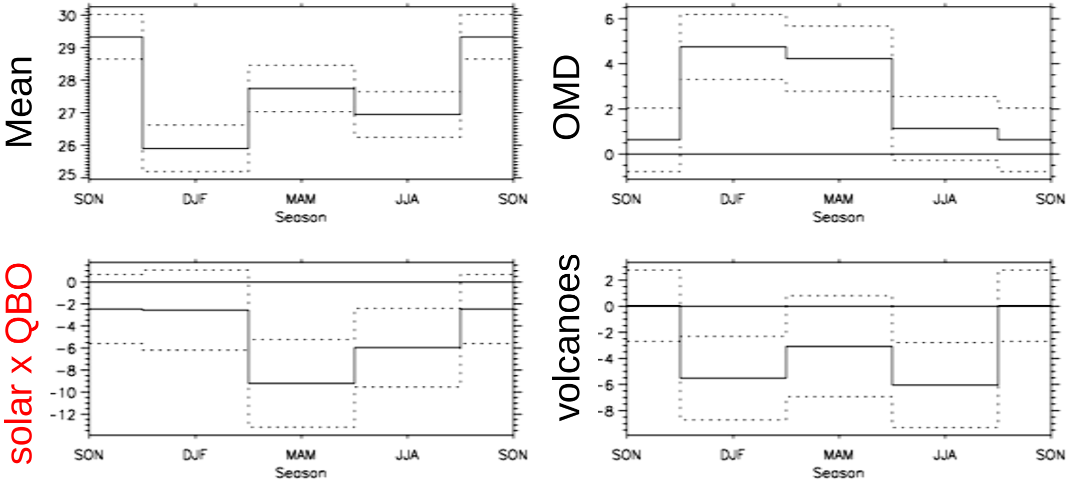
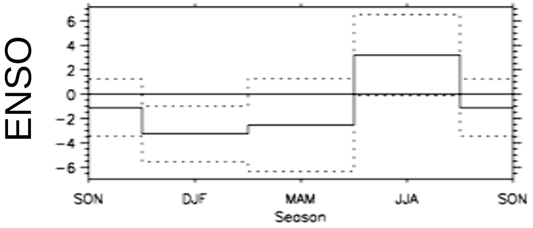


Figure 5.4. Variation of low cloud cover (ISCCP-D2 data) and cosmic rays between 1984 and 2002. The green curve shows data obtained by applying satellite calibrations. (Redrawn from Marsh and Svensmark, 2003).

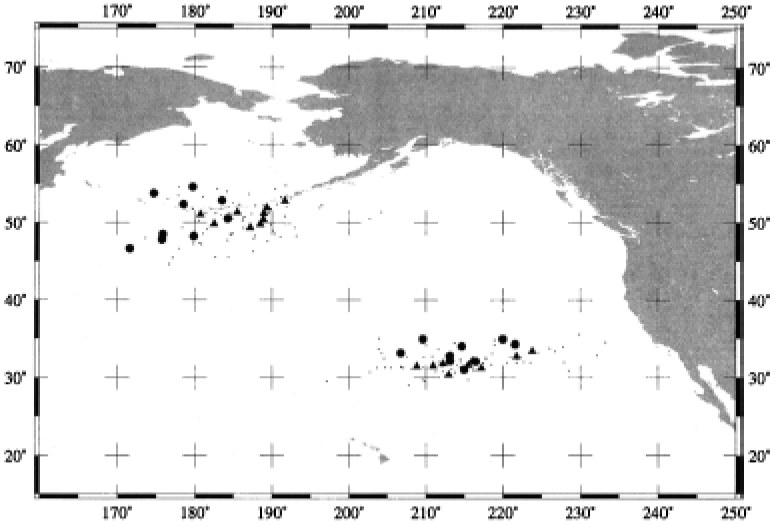
Gray, Haigh & Harrison, 2005

Climate modes



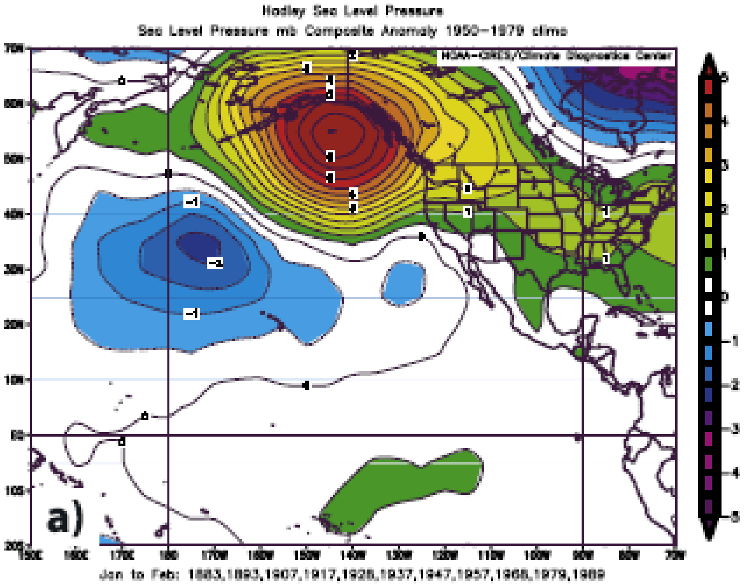


Seasonal signals in the Southern Annular Mode (Roscoe and Haigh 2007)

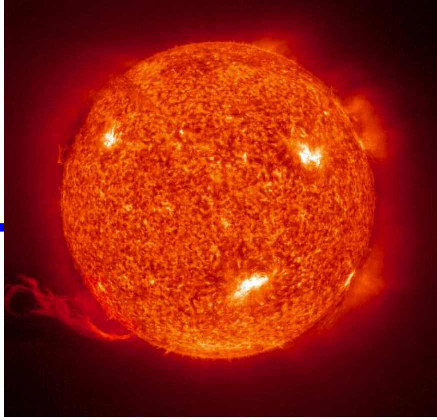


Centres of Aleutian Low & Hawaiian High
solar max ● solar min ▵
(Christoforou and Hameed 1997)

Mean sea level pressure
solar maximum anomaly
(van Loon, Meehl and Shea 2007)



Solar variability and climate



Variations in solar activity / energetic output.

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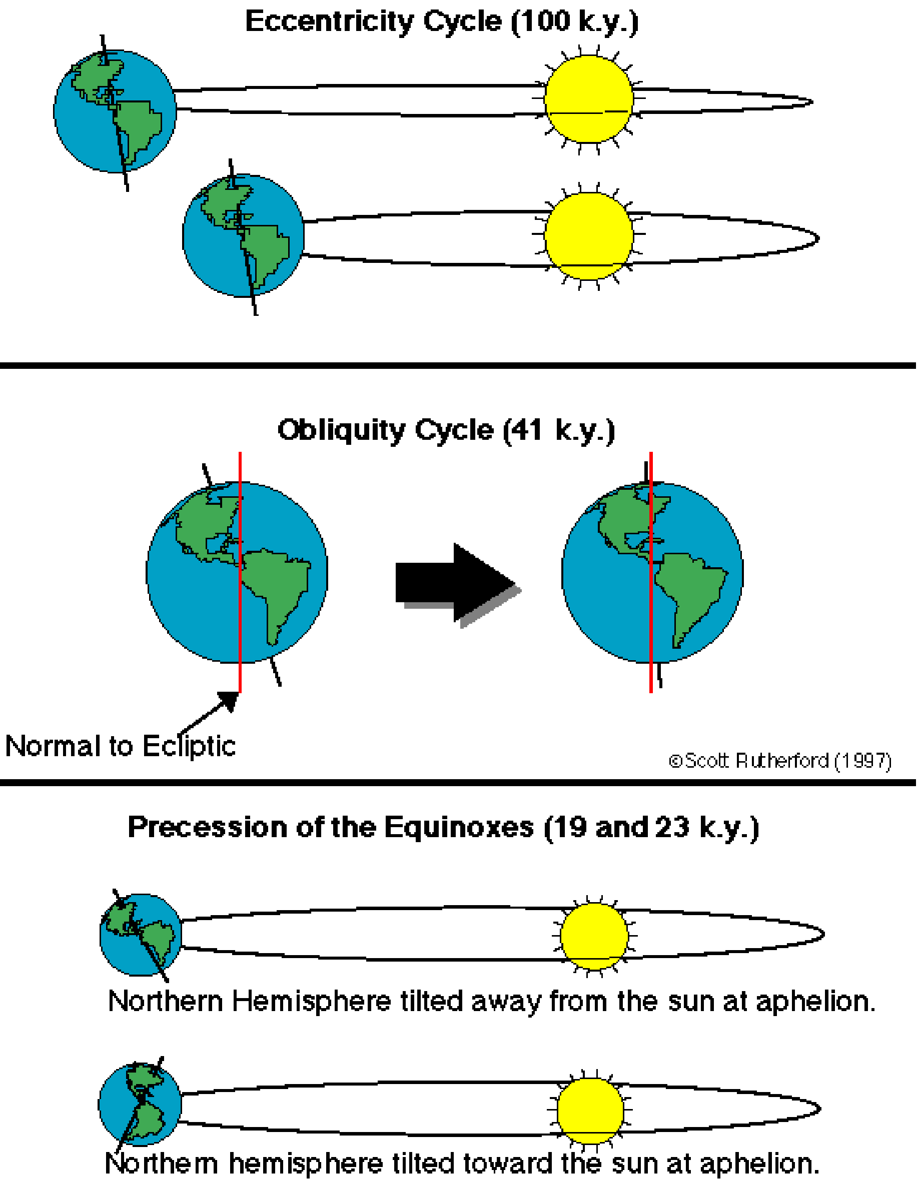
Mechanisms for solar influence on climate.

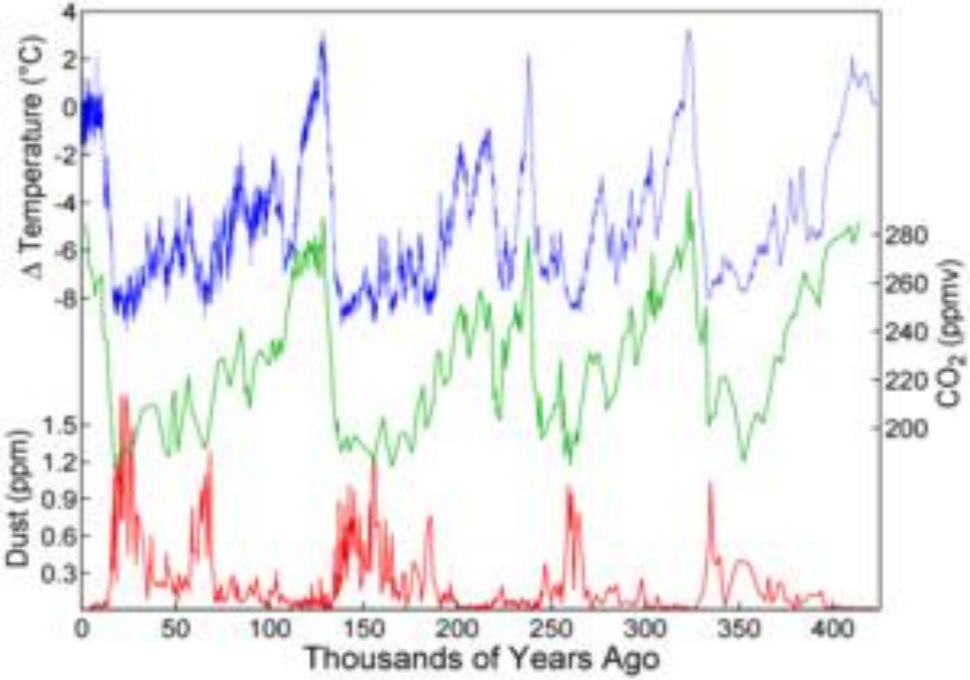
How might solar activity influence tropospheric climate?

Total solar irradiance (orbital variations or variable emission)	Radiative forcing: sea surface temperatures
Solar UV irradiance	Heating the upper & middle atmosphere, dynamical coupling down to troposphere Middle & lower atmosphere chemistry
Solar energetic particles	Ionisation of upper & middle atmosphere: magnetosphere – ionosphere – thermosphere coupling Middle atmosphere chemistry
Galactic cosmic rays	Ionisation of lower atmosphere: effect on electric field cloud condensation nuclei

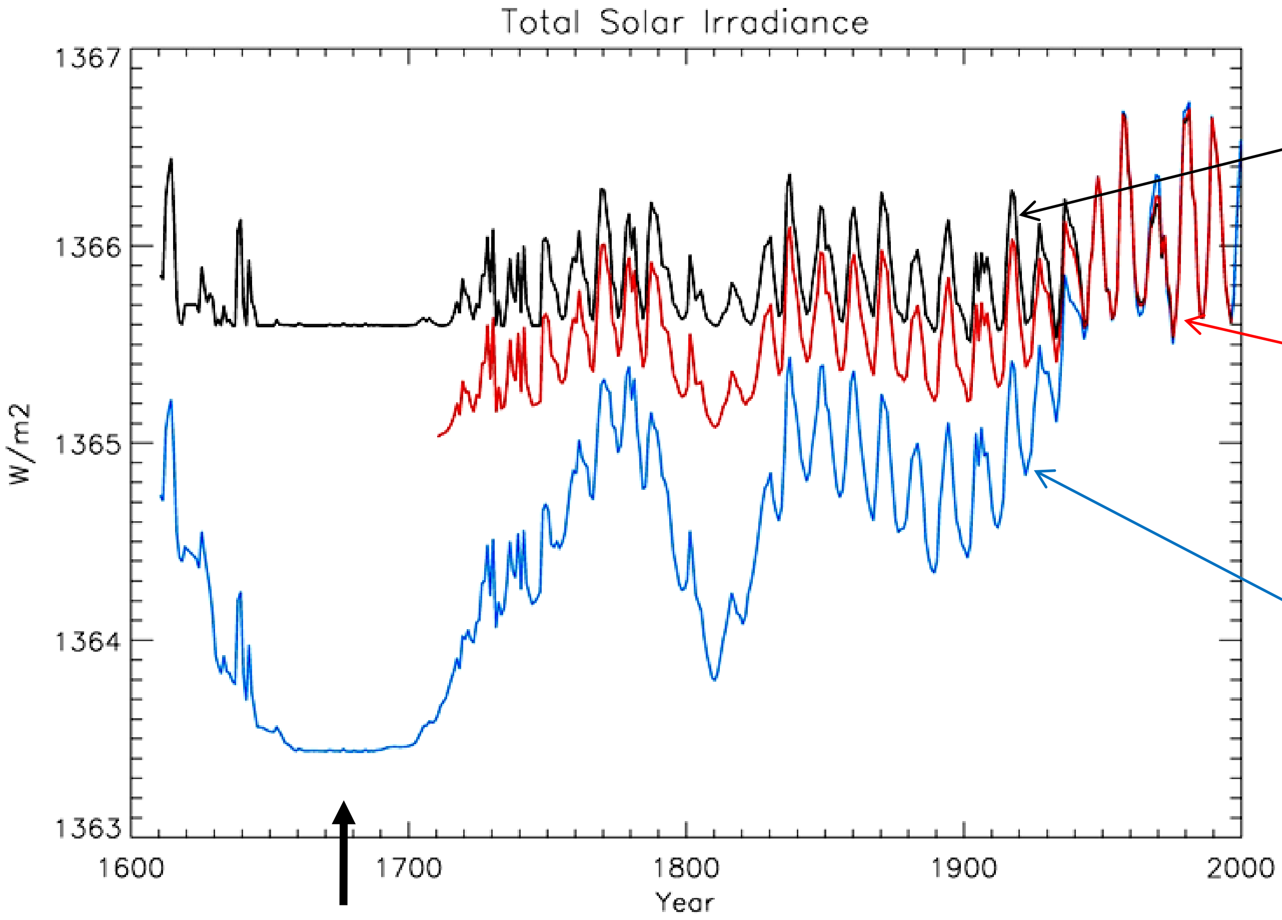
Earth’s orbital parameters



Milankovitch climate cycles



Historical reconstructions of TSI



sunspots only, i.e. no long-term trend

long-term trend from model of solar surface magnetic field

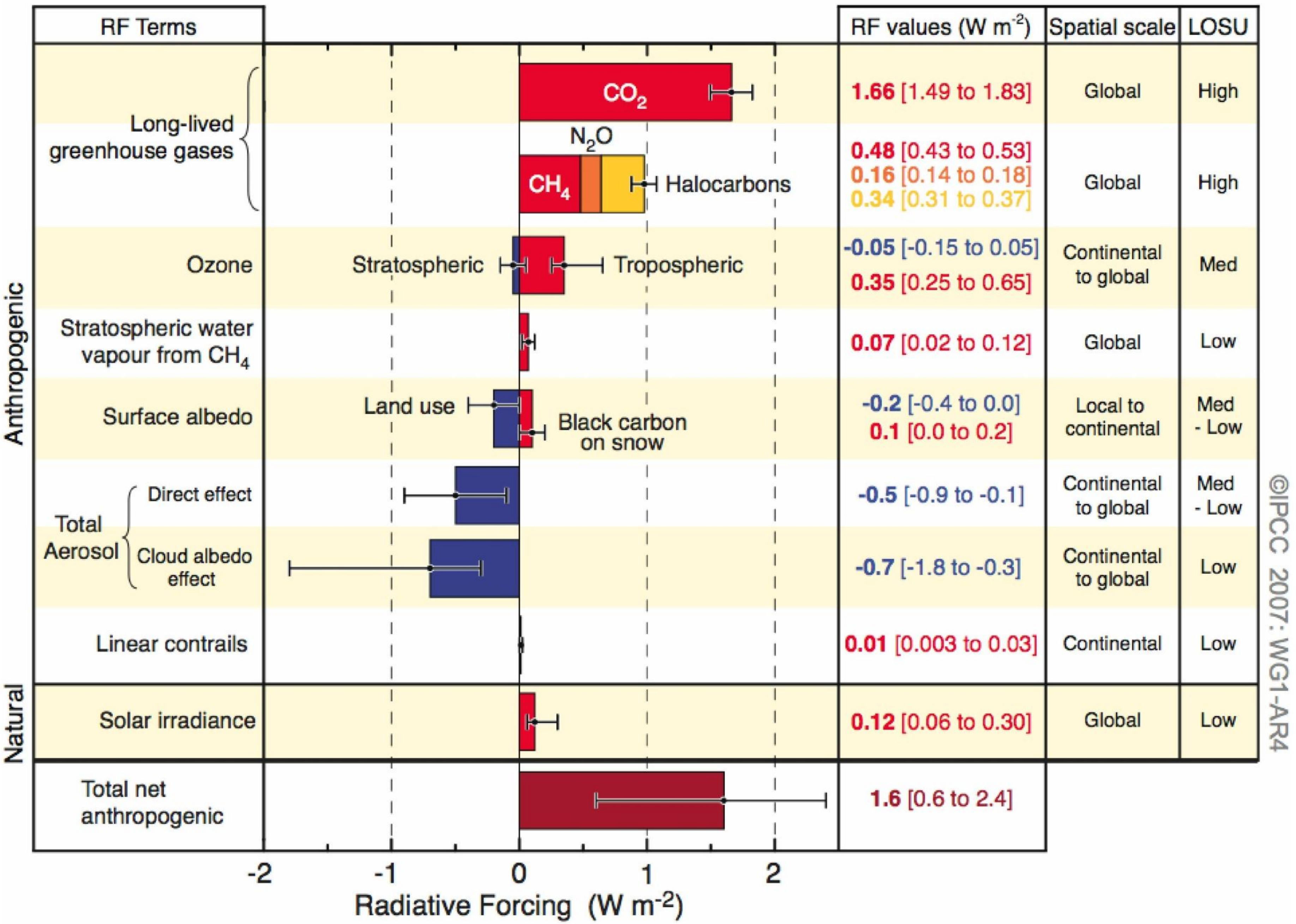
long-term trend based on “Sun-like” stars

Maunder Minimum

(based on Wang et al, 2005)

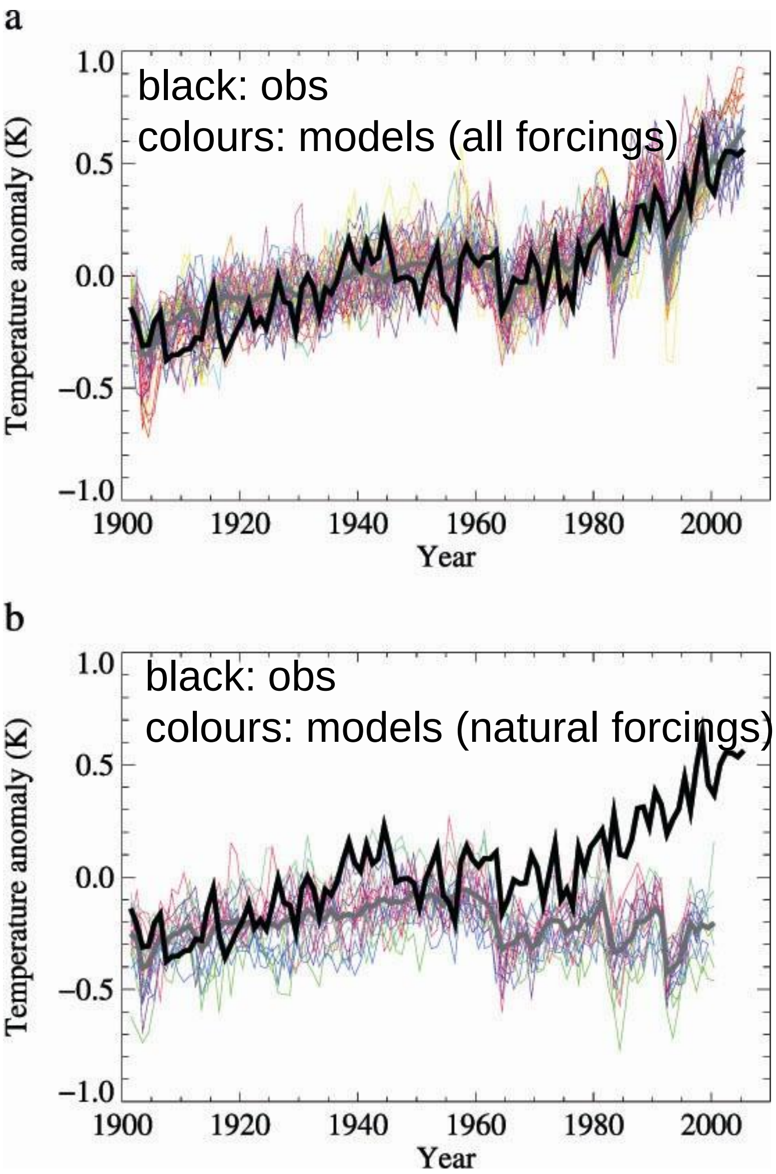
$$RF = \frac{1}{4}(1-\alpha)\Delta TSI \approx \frac{\Delta TSI}{6}$$

Radiative Forcing Components



RF Terms	RF values (W m^{-2})	Spatial scale	LOSU
Long-lived greenhouse gases: CO_2	**1.66** [1.49 to 1.83]	Global	High
CH_4 N_2O Halocarbons	**0.48** [0.43 to 0.53] **0.16** [0.14 to 0.18] **0.34** [0.31 to 0.37]	Global	High
Ozone: Stratospheric Tropospheric	**-0.05** [-0.15 to 0.05] **0.35** [0.25 to 0.65]	Continental to global	Med
Stratospheric water vapour from CH_4	**0.07** [0.02 to 0.12]	Global	Low
Surface albedo: Land use Black carbon on snow	**-0.2** [-0.4 to 0.0] **0.1** [0.0 to 0.2]	Local to continental	Med - Low
Total Aerosol: Direct effect	**-0.5** [-0.9 to -0.1]	Continental to global	Med - Low
Cloud albedo effect	**-0.7** [-1.8 to -0.3]	Continental to global	Low
Linear contrails	**0.01** [0.003 to 0.03]	Continental	Low
Solar irradiance	**0.12** [0.06 to 0.30]	Global	Low
Total net anthropogenic	**1.6** [0.6 to 2.4]		

Solar variability and global mean surface temperatures



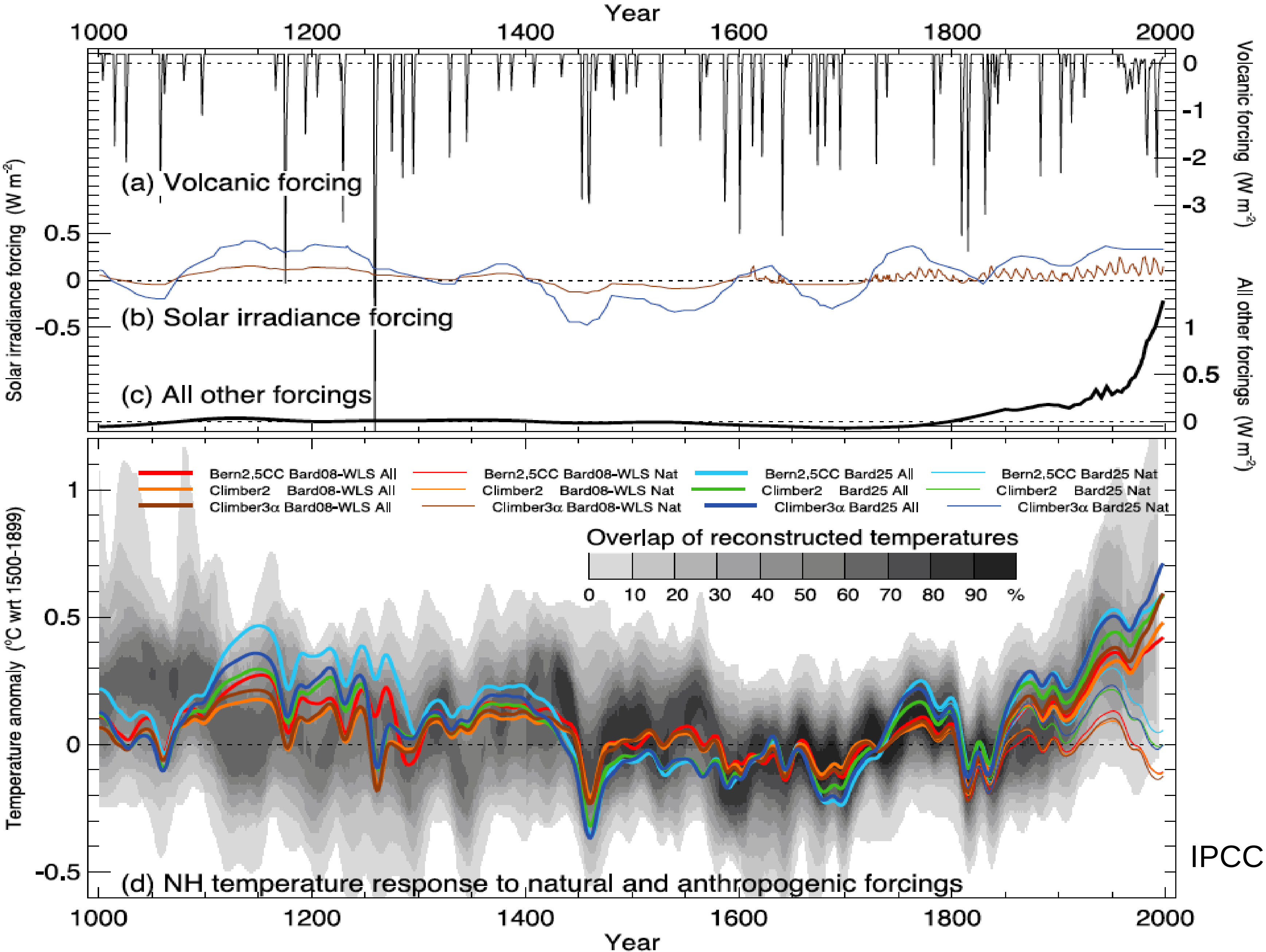
black: obs
colours: models (all forcings)

black: obs
colours: models (natural forcings)

NB: In IPCC 4AR
the solar forcing used in
the GCM simulations is
inconsistent with
(larger than) that
used for the RF Table

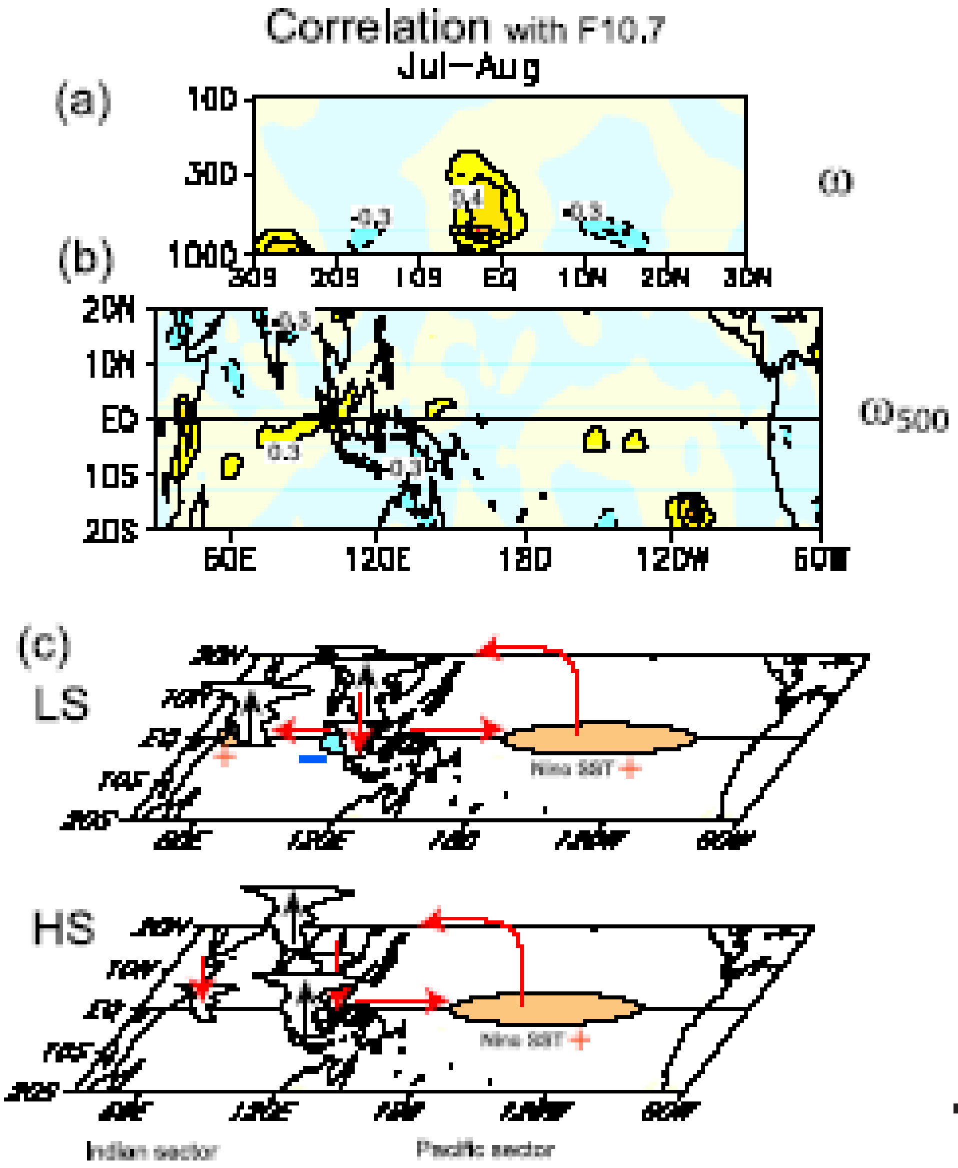
IPCC 2007

Model (EMICs) sensitivity to forcings



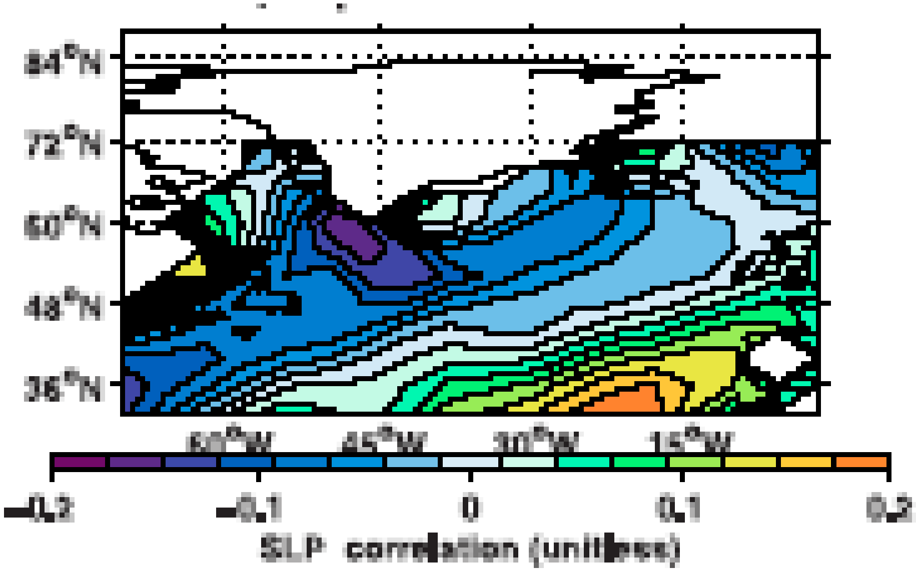
IPCC 2007

Coupling of ENSO and Indian monsoon: modulated by solar cycle

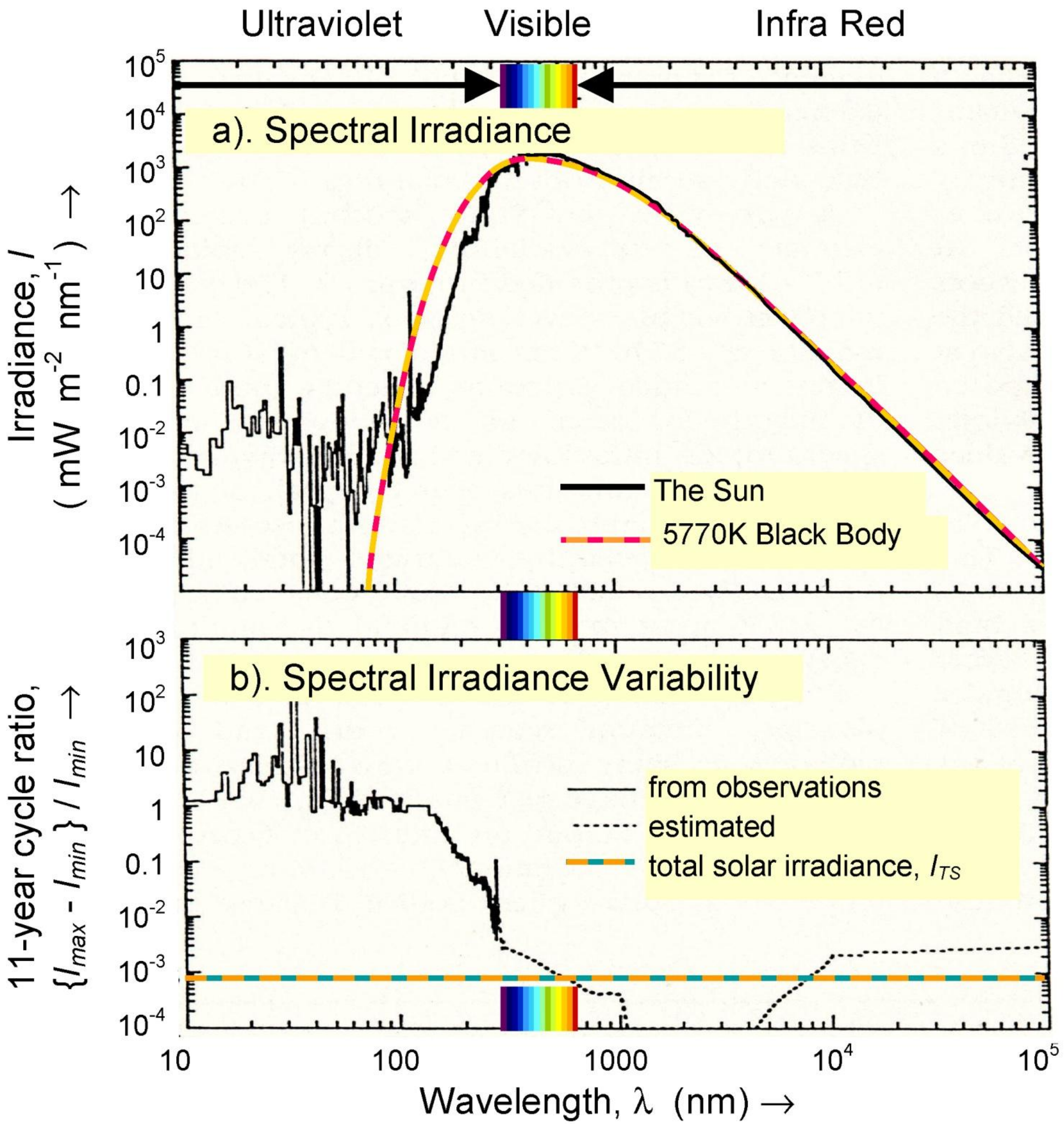


Kodera et al, 2007

Correlation of observed surface meridional wind in N. Atlantic with ENSO index (Emile-Geay et al 2007)



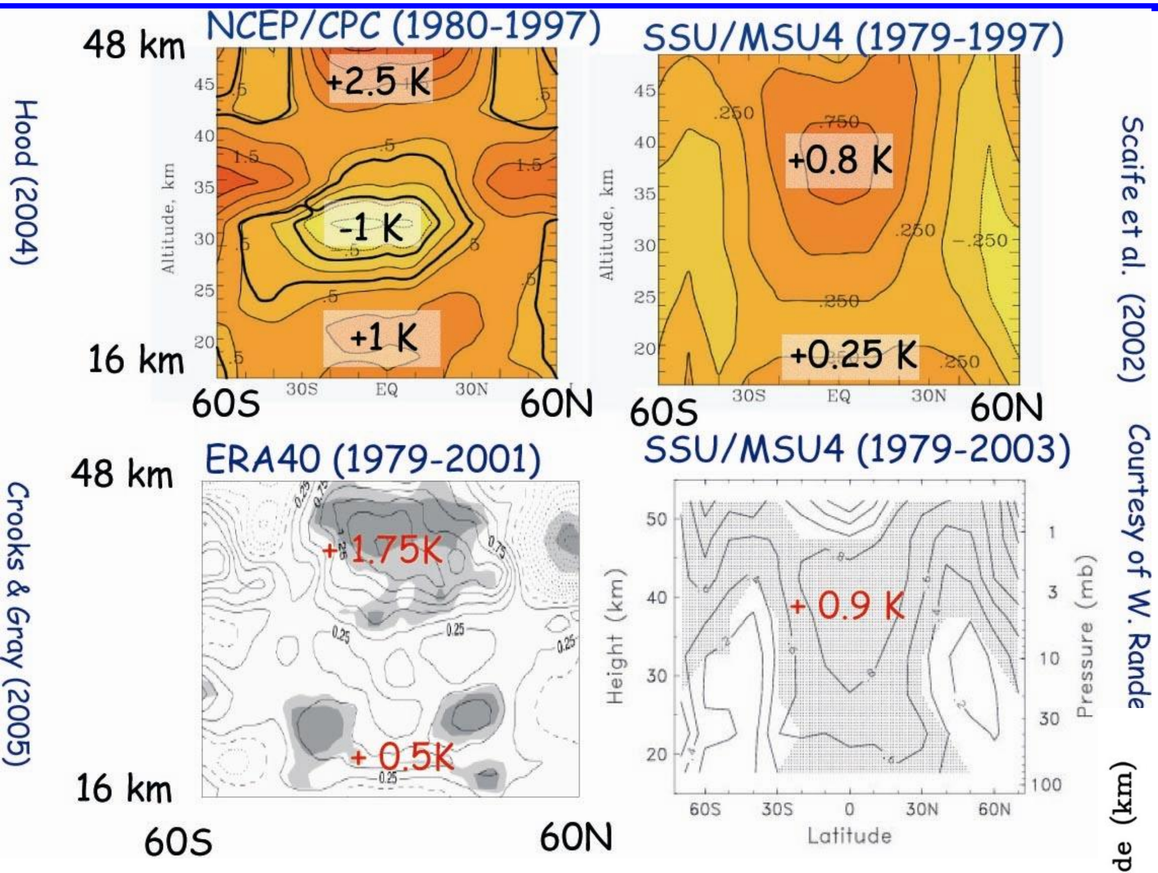
Solar spectrum



Lean (1991)

[adapted by Lockwood]

Solar cycle in the stratosphere



Hood (2004)

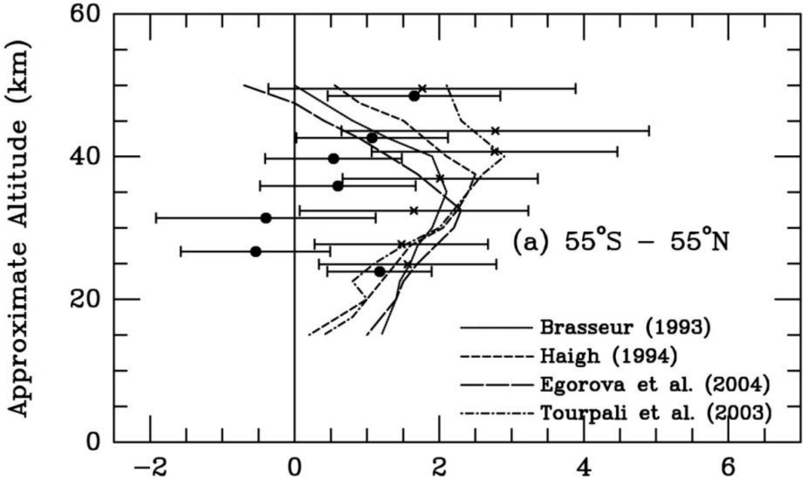
Scaife et al. (2002)

Crooks & Gray (2005)

Courtesy of W. Randel

Temperature

Ozone

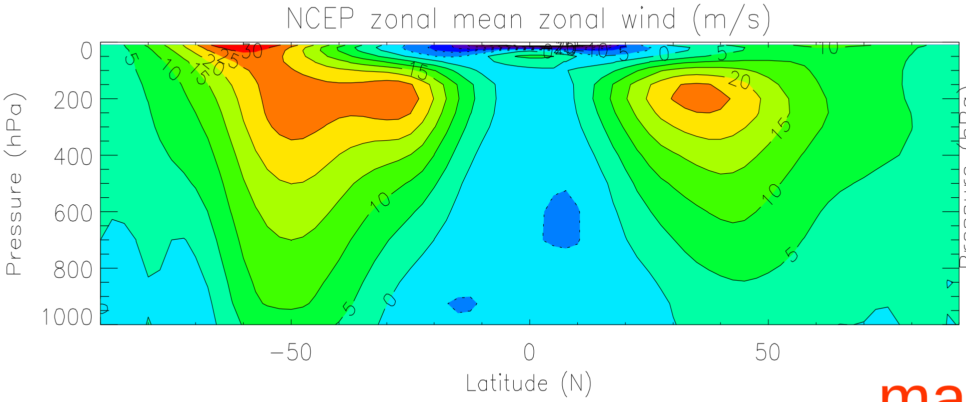


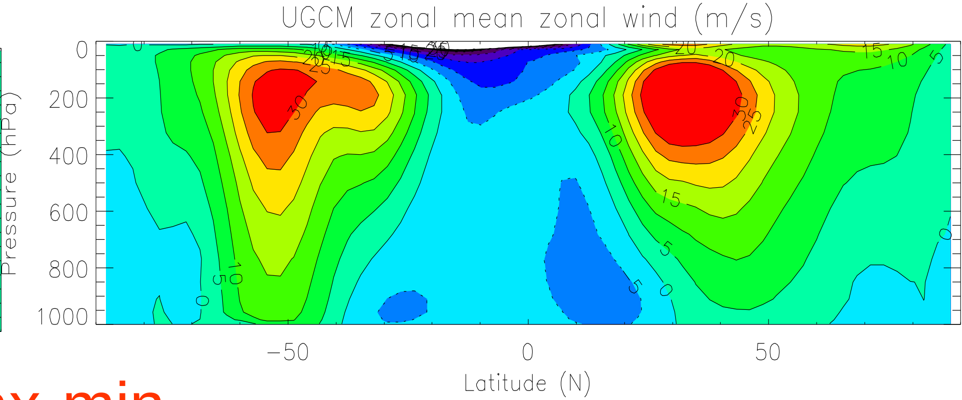
Solar cycle in zonal mean zonal wind

Observations

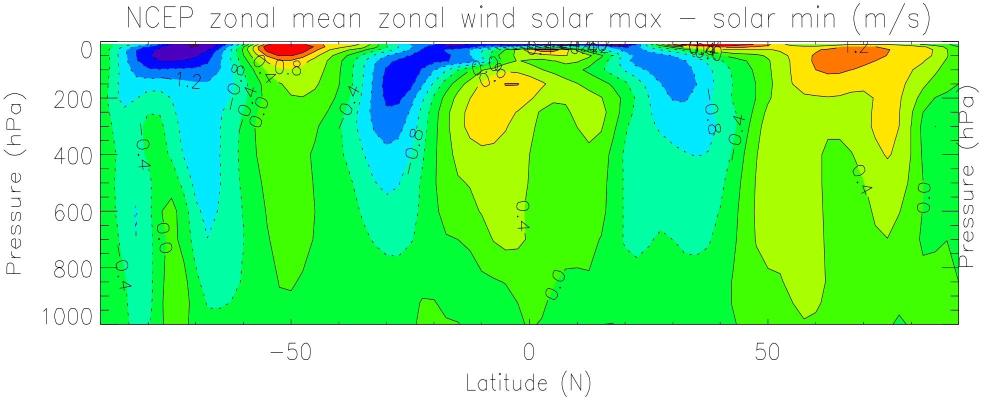
GCM UV experiment

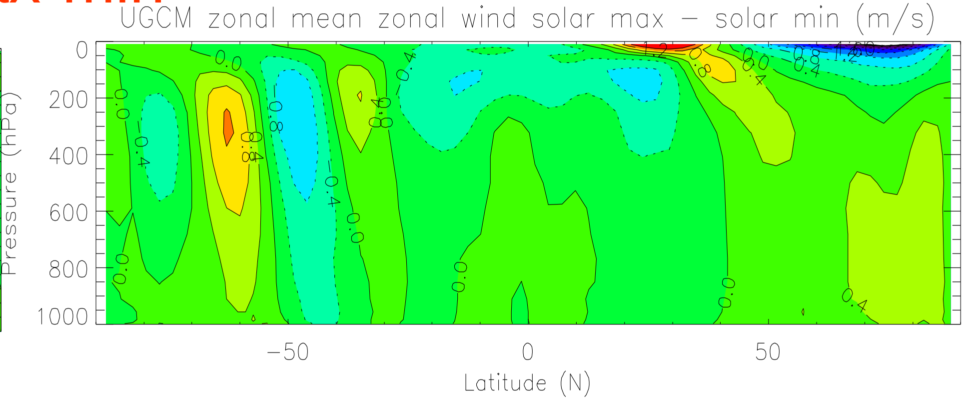
mean


NCEP zonal mean zonal wind (m/s)


UGCM zonal mean zonal wind (m/s)

max-min


NCEP zonal mean zonal wind solar max − solar min (m/s)


UGCM zonal mean zonal wind solar max − solar min (m/s)

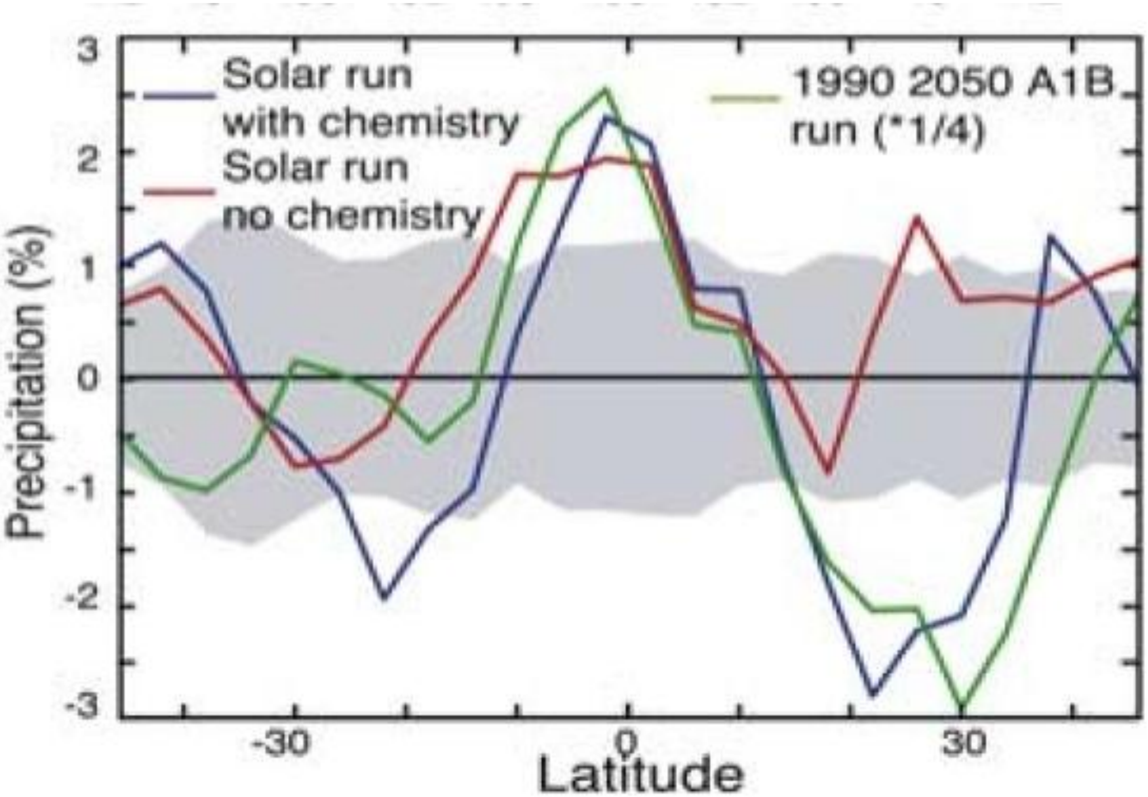
Haigh et al (J.Clim. 2005)

Haigh (*Science* 1996, *QJRMS* 1999)

SSTs and tropical hydrology (GCM)

Stratospheric chemistry important (Shindell et al 2006)

Zonal mean precipitation



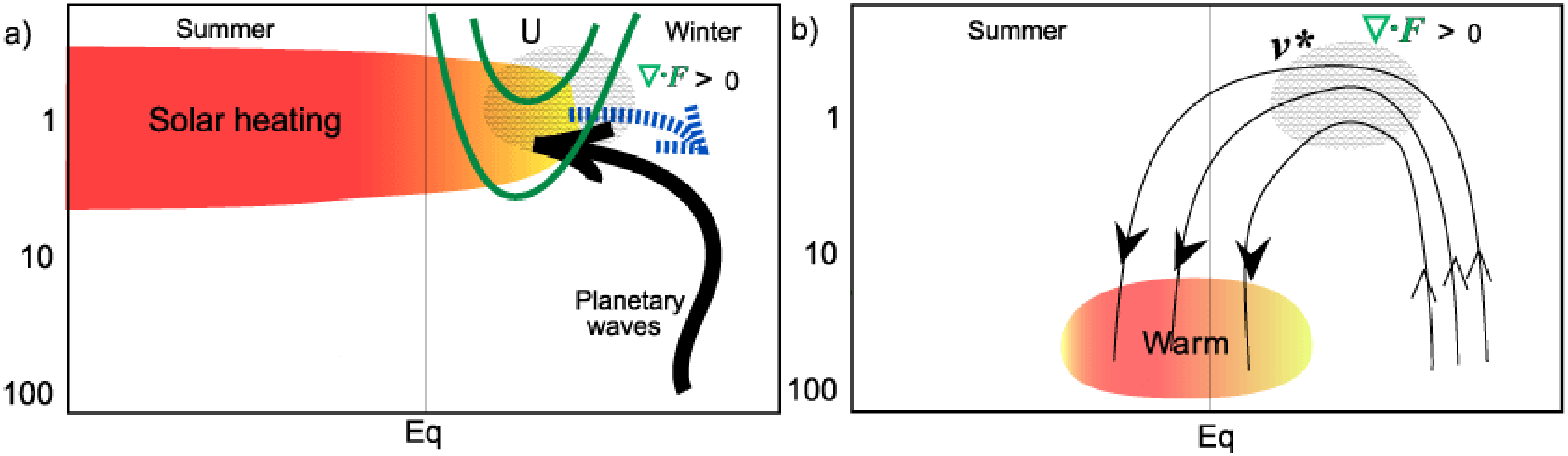
Mechanisms for stratosphere-troposphere coupling

(in the context of solar variability)

Changes in lower stratosphere static stability:

- Direct impact on convection, Hadley and Walker cells (tropical). [*Admiral Fitzroy*, Rind, Kodera, Salby]
- Impact on refraction/reflection of planetary scale waves (polar). [Bates, Geller, Kodera, Rind]
- Impact on momentum deposition of synoptic scale waves.

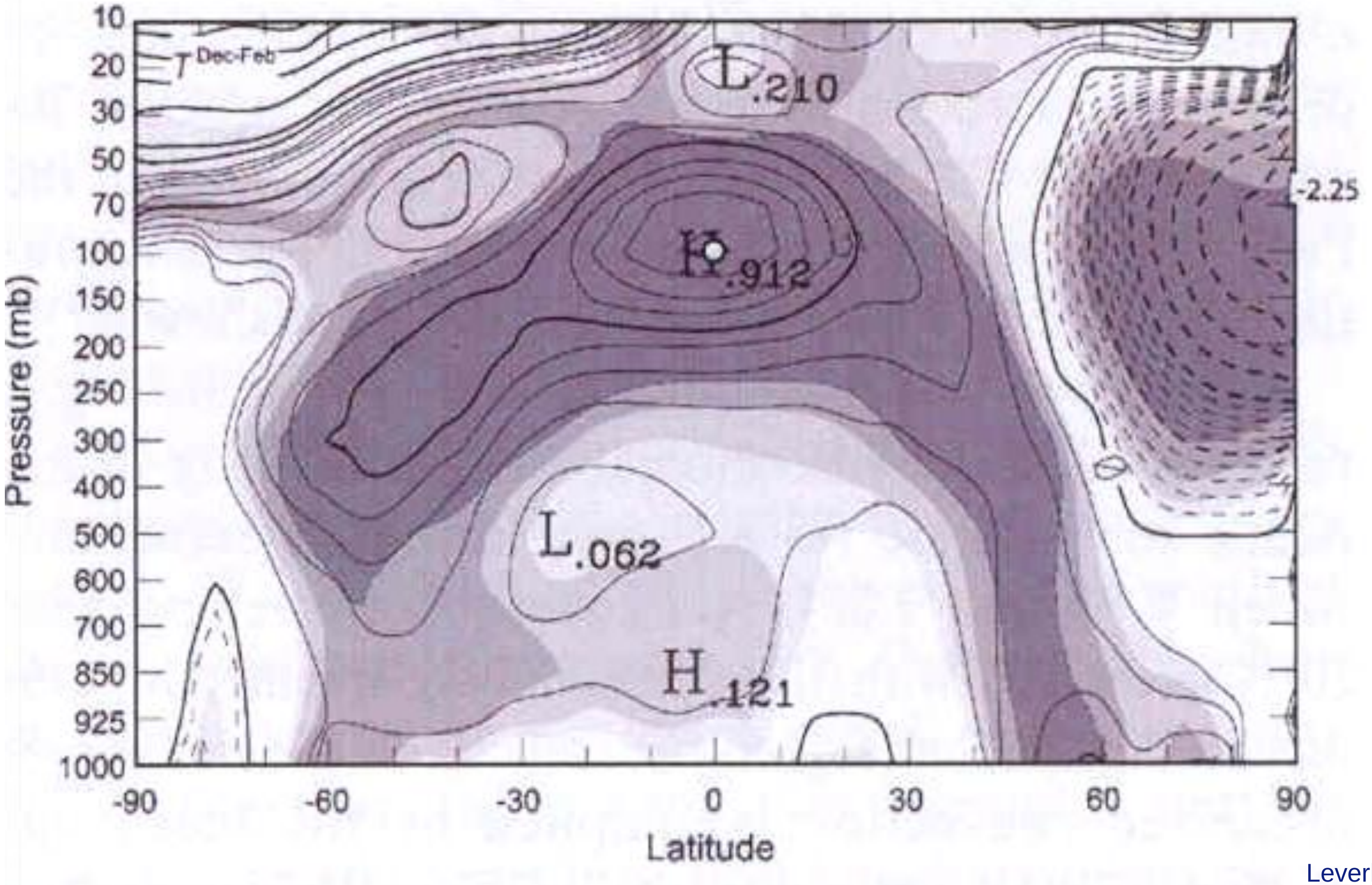
Polar Night Jet and the Brewer-Dobson Circulation



Kodera and Kuroda (2002)

Observed interaction between the Brewer-Dobson circulation and the Hadley circulation

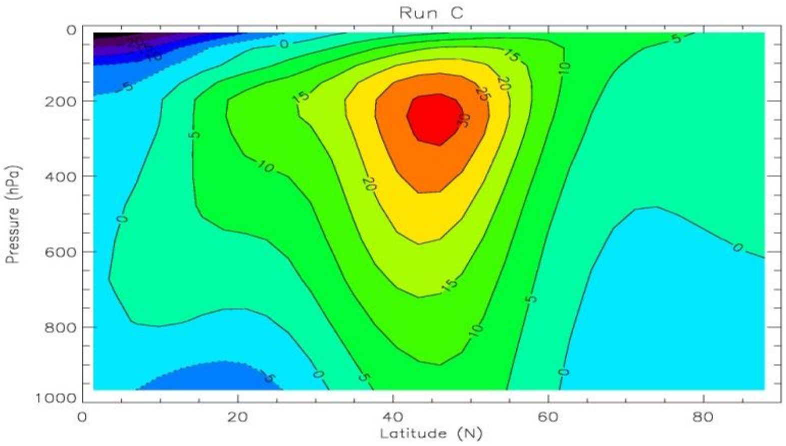
Correlation of equatorial temperature at 100hPa with temperatures elsewhere



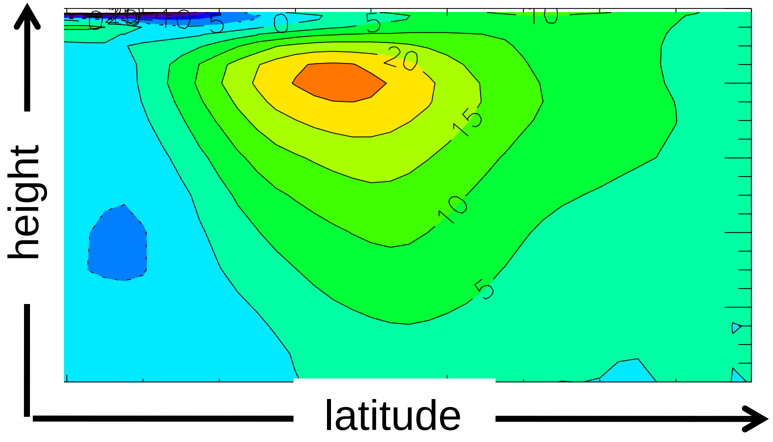
Salby and Callaghan, 2005

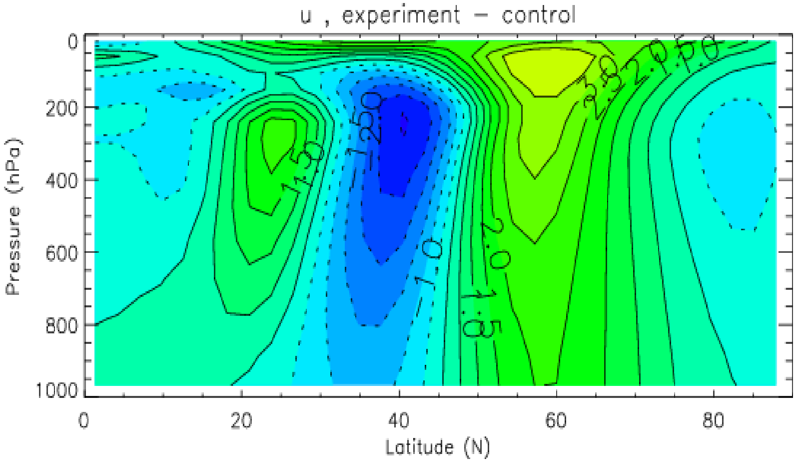
Simple GCM:
heating applied ONLY in the tropical stratosphere:

Model zonal wind Observations of solar impact

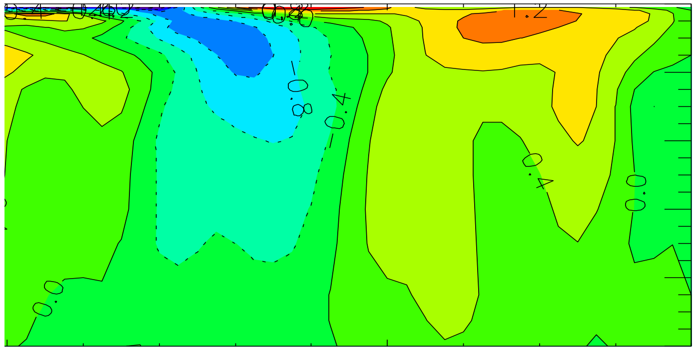


mean



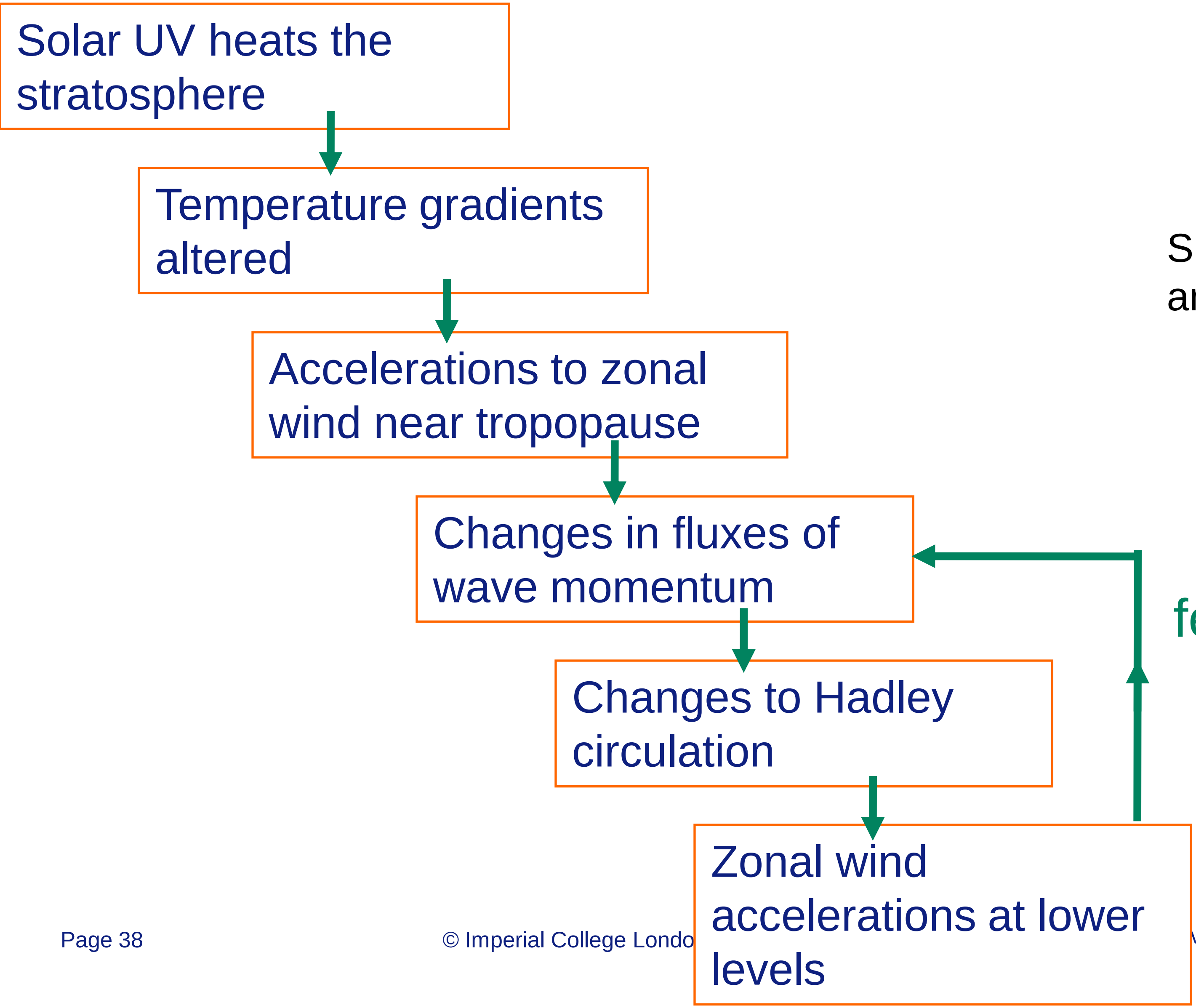


solar
max - min



the jet weakens and moves polewards

Outline of synoptic eddy mechanism:



Solar UV heats the stratosphere

Temperature gradients altered

Accelerations to zonal wind near tropopause

Changes in fluxes of wave momentum

Changes to Hadley circulation

Zonal wind accelerations at lower levels

feedback loop

Simpson, Blackburn and Haigh, 2008

How might solar activity influence climate?

Changes in total solar irradiance
  Net heating/cooling of climate system.

Changes in solar UV irradiance
  Heating the upper & middle atmosphere (+ozone chemistry).
  - dynamical coupling down to the lower atmosphere.

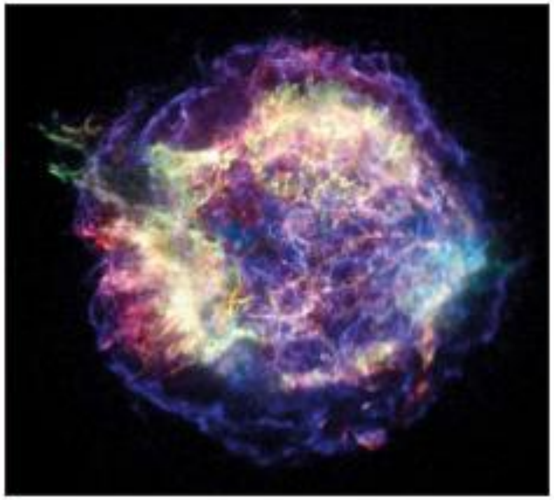
Solar modulation of galactic cosmic rays
  Ionisation of lower atmosphere by GCRs
  - effect on cloud condensation nuclei.

Cosmoclimatology: a new theory emerges

Henrik Svensmark draws attention to an overlooked mechanism of climate change: clouds seeded by cosmic rays.

ABSTRACT

Changes in the intensity of galactic cosmic rays alter the Earth's cloudiness. A recent experiment has shown how electrons liberated by cosmic rays assist in making aerosols, the building blocks of cloud condensation nuclei, while anomalous climatic trends in Antarctica confirm the role of clouds in helping to drive climate change. Variations in the cosmic-ray influx due to solar magnetic activity account well for climatic fluctuations on decadal, centennial and millennial timescales. Over longer intervals, the changing galactic environment of the solar system has had dramatic consequences, including Snowball Earth episodes. A new contribution to the faint young Sun paradox is also on offer.



1. Cosmic rays (relativistic electrons) stirring in the Cassiopeia A supernova remnant make these wispy blue lines of energetic X-ray emissions seen by NASA's Chandra X-ray Observatory. (NASA/CXC/UMass Amherst/M D Stage *et al.*)

Data on cloud cover from satellites, compared with counts of galactic cosmic rays from a ground station, suggested that an increase in cosmic rays makes the world cloudier. This empirical finding introduced a novel connection between astronomical and terrestrial events, making weather on Earth subject to the cosmic-ray accelerators of supernova remnants in the Milky Way. The result was announced in 1996 at the COSPAR space science meeting in Birmingham and published as "Variation of cosmic-ray flux and global cloud coverage – a missing link in solar-climate relationships" (Svensmark and Friis-Christensen 1997).

The title reflected a topical puzzle, that of how to reconcile abundant indications of the Sun's influence on climate (e.g. Herschel 1801, Eddy 1976, Friis-Christensen and Lassen 1991), with the small 0.1% variations in the solar irradiance over a solar cycle measured by satellites. Clouds exert (on average) a strong cooling effect, and cosmic-ray counts vary with the strength of the solar magnetic field, which repels much of the influx of relativistic particles from the galaxy. The connection offers a mechanism for solar-driven climate change much more powerful than changes in solar irradiance.

During the past 10 years, considerations of the galactic and solar influences on climate have progressed so far, and have found such widespread applications, that one can begin to speak of a new paradigm of climate change. I call it cosmoclimatology and in this article I suggest that it is already at least as secure, scientifically speaking, as the prevailing paradigm of forcing by variable greenhouse gases. It has withstood many attempts to refute it and now has a grounding in experimental evidence for a mechanism by which cosmic rays can affect cloud cover. Cosmoclimatology already interacts creatively with current issues in solar–terrestrial physics and astrophysics and even with astrobiology, in questions about the origin and survival of life in a high-energy universe. All these themes are pursued in a forthcoming book (Svensmark and Calder 2007).

How do cosmic rays help make clouds?

The comparisons of data on clouds and cosmic rays, with which the story began, continued to pay off. They confirmed that cloudiness is more clearly linked with solar-modulated galactic cosmic rays than with other solar phenomena such as sunspots or the emissions of visible light, ultraviolet and X-rays (Svensmark 1998). A big step forward came with the realization that the lowest clouds, below about 3km in altitude, respond most closely to variations in the cosmic rays (Marsh and Svensmark 2000), a counter-intuitive finding for some critics (e.g. Kristjánsson and Kristiansen 2000). Figure 2 compares data from the International Satellite Cloud Climatology Project and the Huancayo cosmic-ray station. There is no correlation at high and middle altitudes, but an excellent match at low altitudes.

In figure 3, the correspondence between low clouds and cosmic rays is seen to persist over a longer timescale. A simple interpretation is that there are always plenty of cosmic rays high in the air, but they and the ions that they liberate are in short supply at low altitudes, so that increases or decreases due to changes in solar magnetism have more noticeable consequences lower down.

The involvement of low-level clouds provided an experimental opportunity. The chief objection to the idea that cosmic rays influence cloudiness came from meteorologists who insisted that there was no mechanism by which they could do so. On the other hand, some atmospheric physicists conceded that observation and theory had failed to account satisfactorily for the origin of the aerosol particles without which water vapour is unable to condense to make clouds. A working hypothesis, that the formation of these cloud condensation nuclei might be assisted by ionization of the air by cosmic rays, was open to microphysical investigation by experiment.

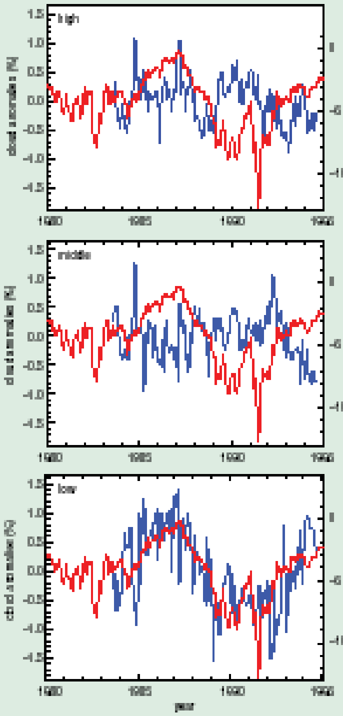
Experimental tests

In 1998 Jasper Kirkby at the CERN particle physics lab in Geneva proposed an experiment called CLOUD to investigate the possible role of cosmic rays in atmospheric chemistry. The idea was to use a beam of accelerated particles to simulate the cosmic rays, and to look for aerosols produced in a reaction chamber containing air and trace gases. The temperature and pressure would be adjustable to simulate conditions at different levels in the atmosphere. Kirkby assembled a consortium of 50 atmospheric, solar–terrestrial and particle physicists from 17 institutes to implement it (CLOUD proposal 2000), but regrettably there were long delays in getting the project approved and funded. The go-ahead eventually came in 2006 and the full experiment at CERN should begin taking data in 2010.

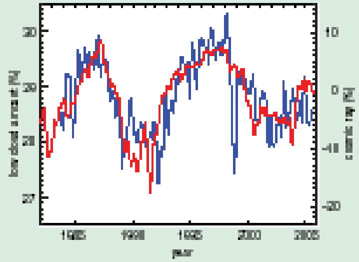
Meanwhile, in Copenhagen, the discovery that low-level clouds are particularly affected by cosmic-ray variations suggested that a simpler experiment, operating only at sea-level temperature and pressure, might capture some of the essential microphysics. Instead of a particle beam, we used natural cosmic rays, supplemented by gamma rays when we wanted to check the effect of increased ionization of the air. Our team set up the experiment in the basement of the Danish National Space Center, with a large plastic box containing purified air and the trace gases that occur naturally in unpolluted air over the ocean. Ultraviolet lamps mimicked the Sun's rays. During experiments, instruments traced the chemical action of the penetrating cosmic rays in the reaction chamber. We called the experiment SKY, which means "cloud" in Danish.

By 2005 we had found a causal mechanism by which cosmic rays can facilitate the production of clouds (Svensmark *et al.* 2007). The data revealed that electrons released in the air by cosmic rays act as catalysts. They significantly accelerate the formation of stable, ultra-small clusters of sulphuric acid and water molecules which are building blocks for the cloud condensation nuclei. Figure 4 shows a typical run. Vast

2. At different levels in the atmosphere (high >6.5km, middle 6.5–3.2km and low <3.2km) the blue line shows variations in global cloud cover collated by the International Satellite Cloud Climatology Project. The red line is the record of monthly variations in cosmic-ray counts at the Huancayo station. While there is no match at the higher altitudes, a close correspondence between cosmic rays and clouds low in the atmosphere is plain to see. (Marsh and Svensmark 2000)



3. As in figure 2, the low-cloud comparison extends over a longer period.

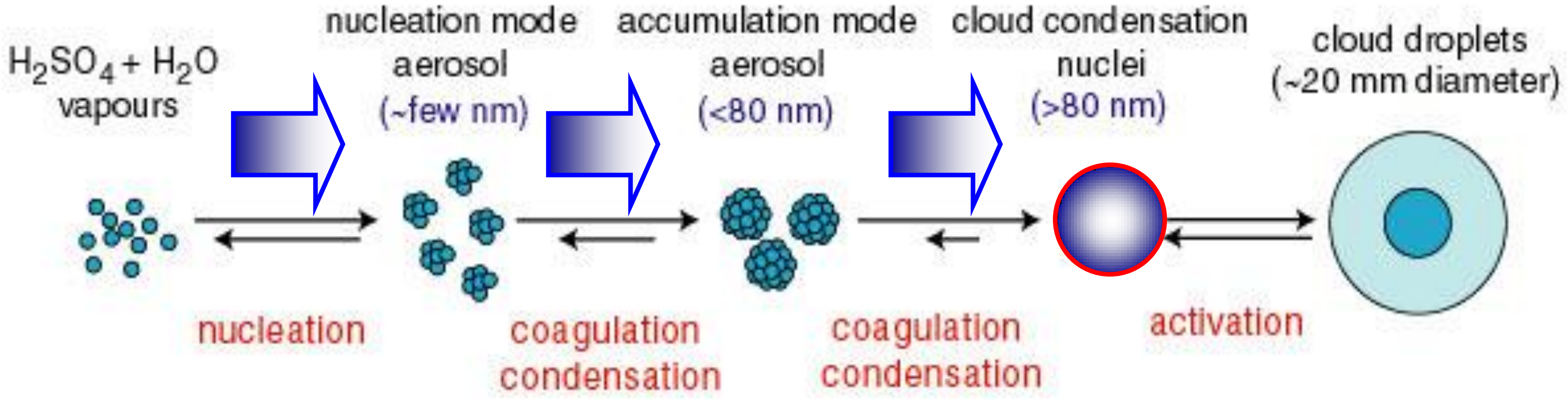


Ion-induced nucleation of cloud droplets

Charge-mediated nucleation

Charge-enhanced coagulation

Increased CCN concentration



Carslaw et al (2002)

Questions to be addressed:

- What is known about solar activity, and solar spectral irradiance incident at Earth, on paleo timescales, over recent millennia and on timescales down to the 11-year activity cycle?
- To what extent can recent measurements of solar irradiance inform reconstructions of past values?
- How good are the proxies of solar activity?
- What signals of solar influence have been robustly detected in climate in paleo records and on timescales down to the 11-year activity cycle?
- Do geographically similar signals appear at different timescales?
- What mechanisms, in addition to direct radiative forcing, may be involved in the solar modulation of climate?