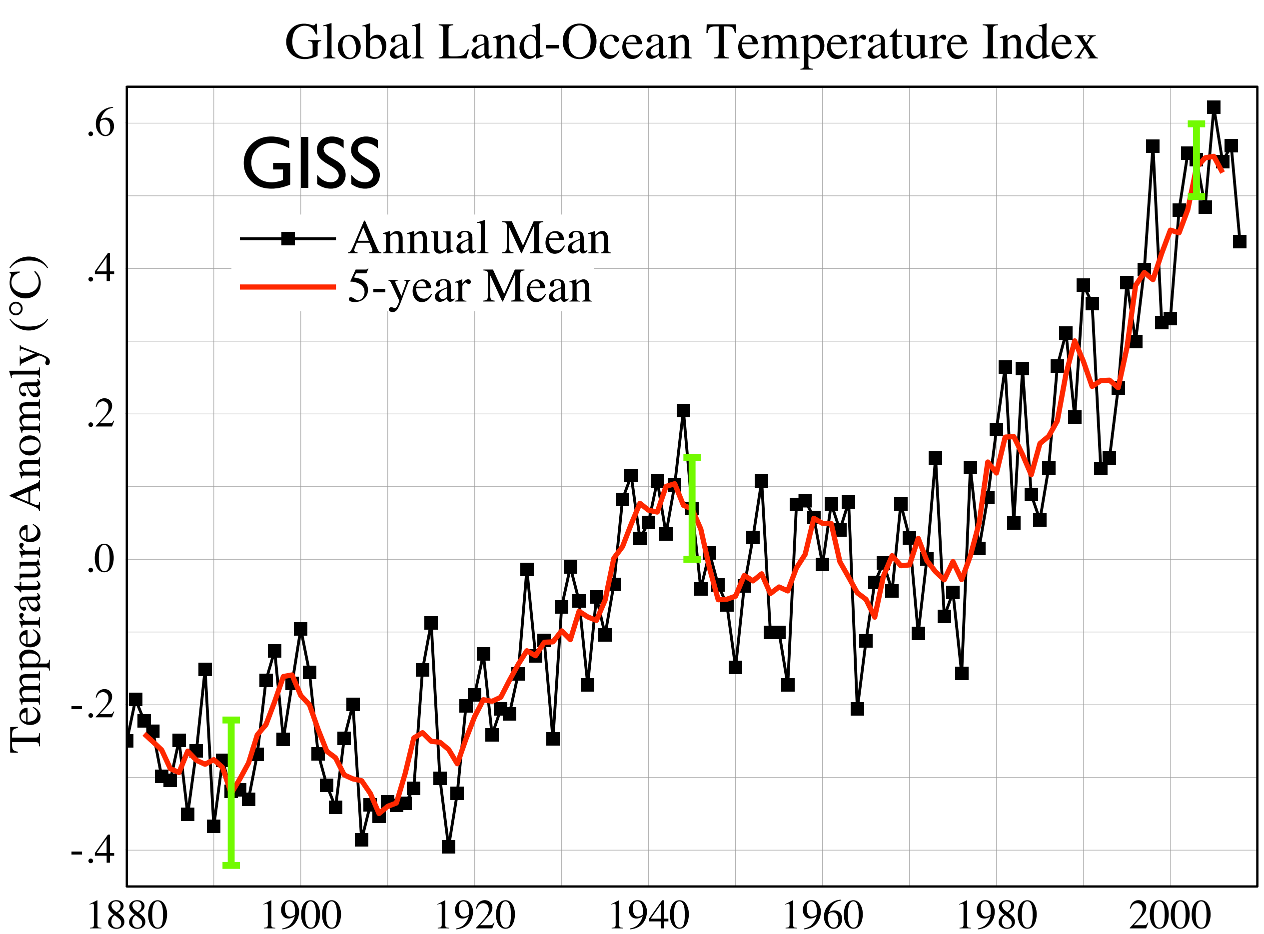
Cosmic rays and climate

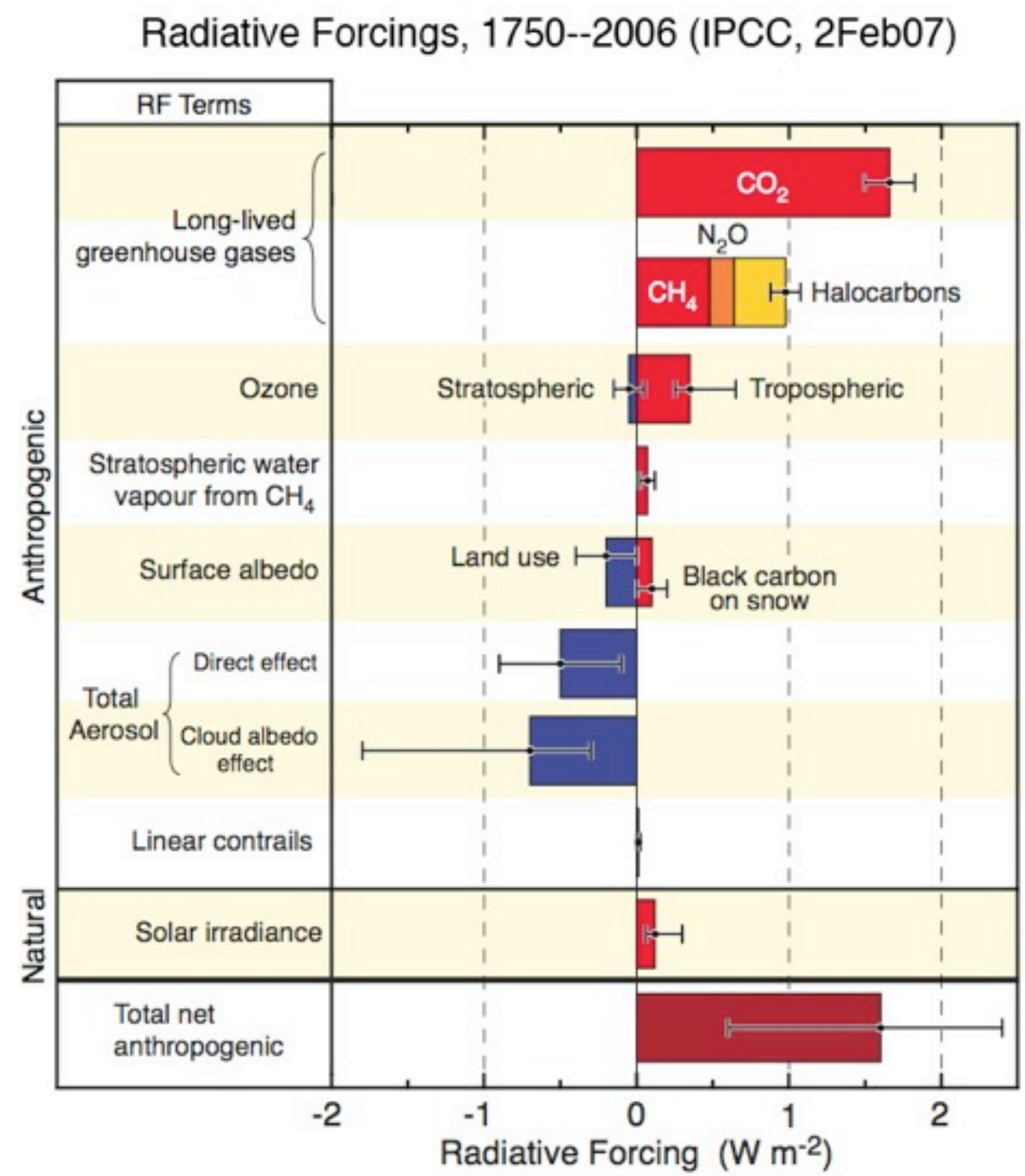
Jasper Kirkby /CERN

CERN Colloquium, 4 June 2009

1. Present climate change

Climate forcings (IPCC 2007)





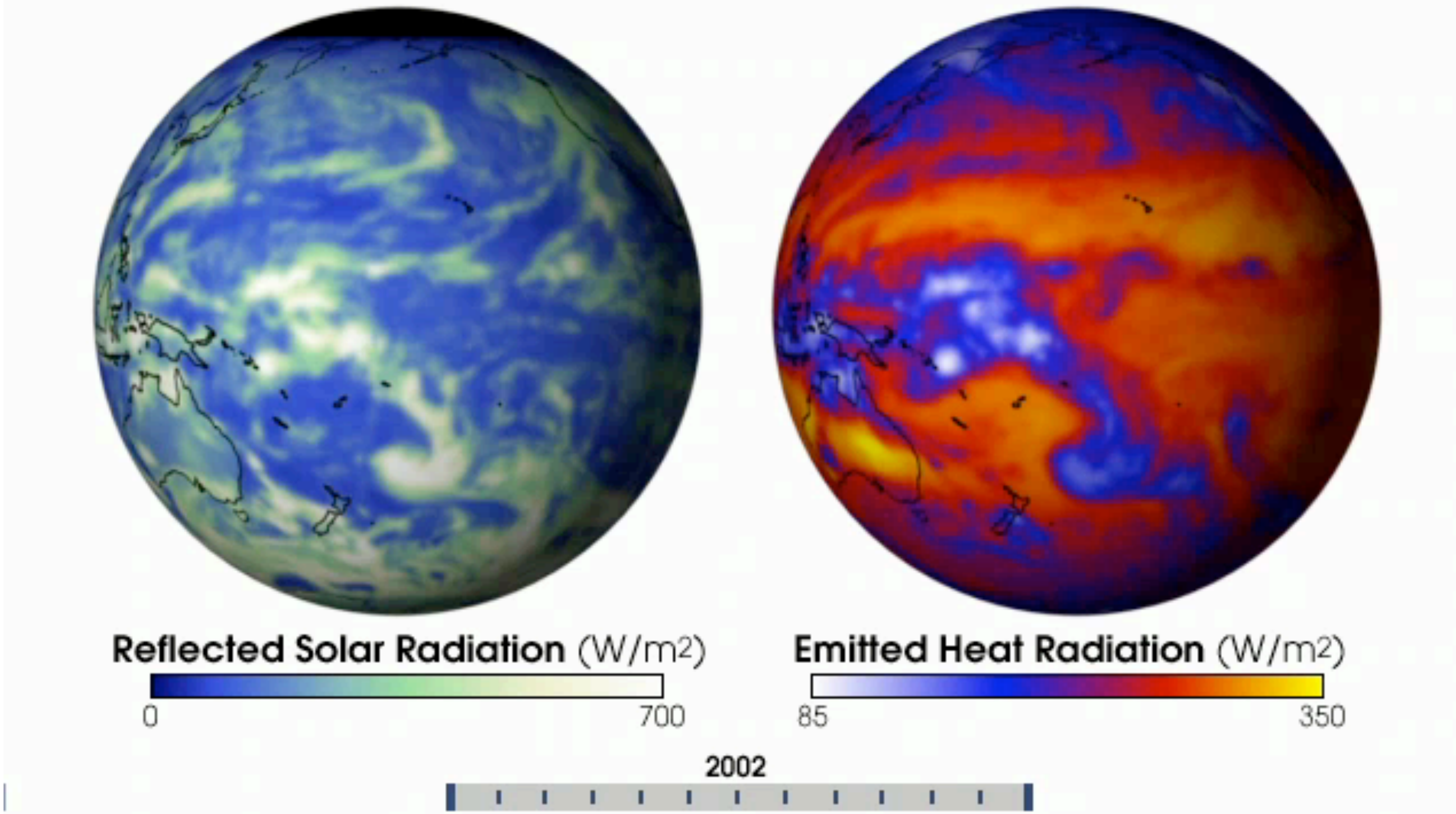
- 0.7°C rise since 1900 (not uniform)
- IPCC findings:
  - Total anthropogenic 1.6 W/m^2 (≅ 1 candle per 25 m^2)
  - Negligible natural (solar) contribution: 0.12 W/m^2
  - Clouds poorly understood

Why clouds are important for climate change

John Constable, Cloud study, 1821

- Clouds cover ~65% of globe, annual average
- Net cooling of 30 W/m^2
- c.f. 1.6 W/m^2 total anthropogenic

NASA CERES satellite

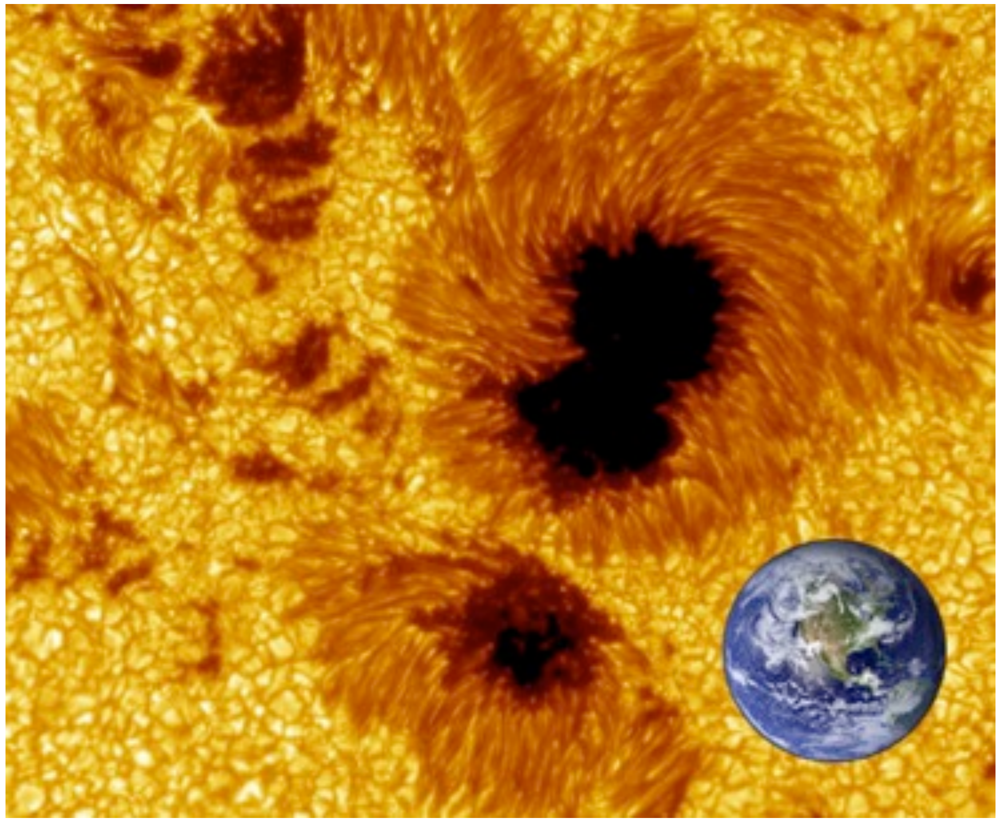


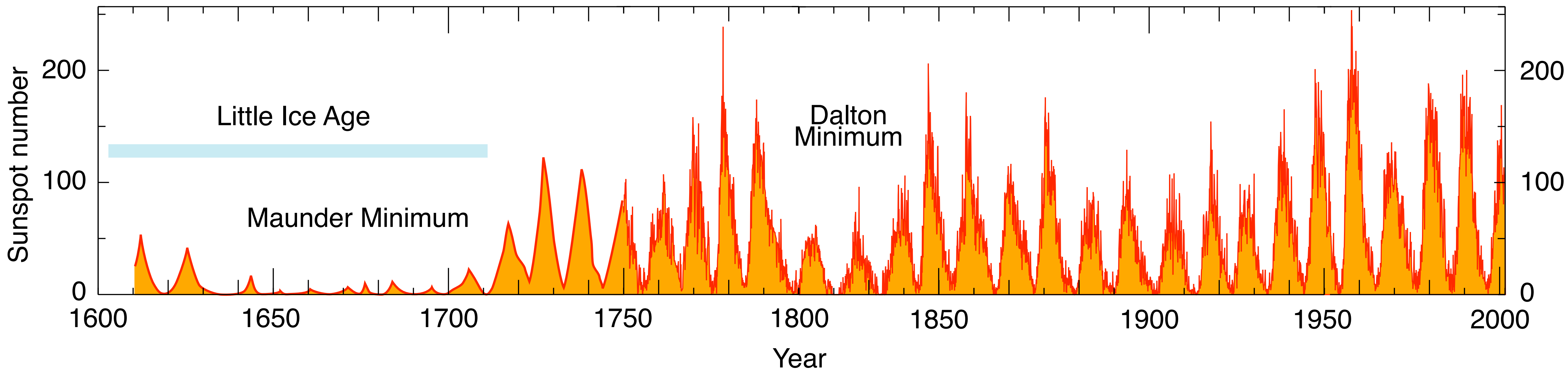
- Data from CERES satellite (Clouds and Earth's Radiant Energy System)
- Clouds (and oceans) are poorly simulated in climate models (finest grid sizes ~100 km x 100 km)

II. Evidence for pre-industrial solar-climate variability

- Numerous palaeoclimatic reconstructions suggest that solar/GCR variability has an important influence on climate
- However, there is no established physical mechanism, and so solar-climate variability is:
  - Controversial subject
  - Not included in current climate models

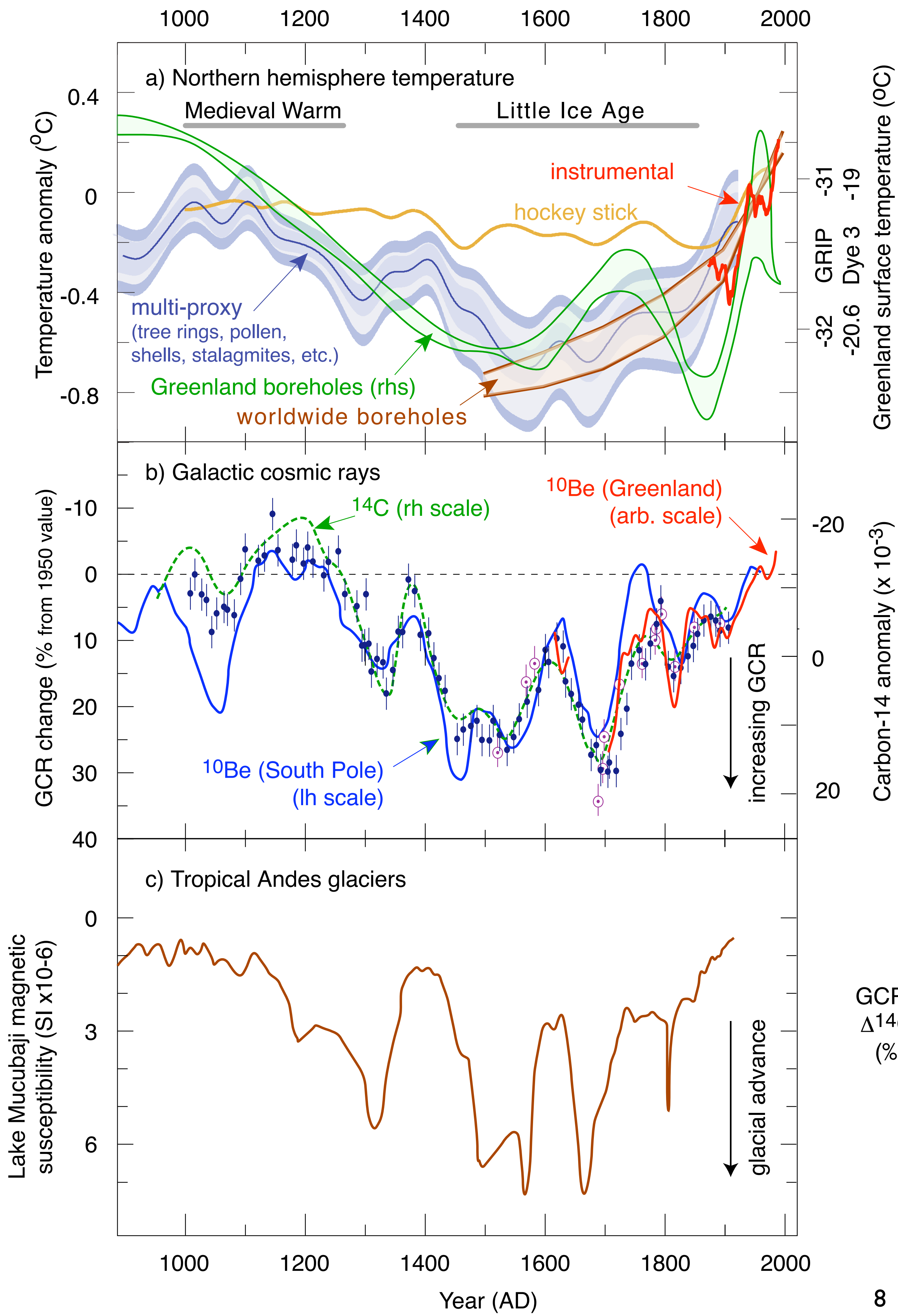
Little Ice Age and the sunspot record





- Inactive sun (low sunspot peak, long cycle length) ⇒ cold climate
- Active sun (high sunspot peak, short cycle length) ⇒ warm climate

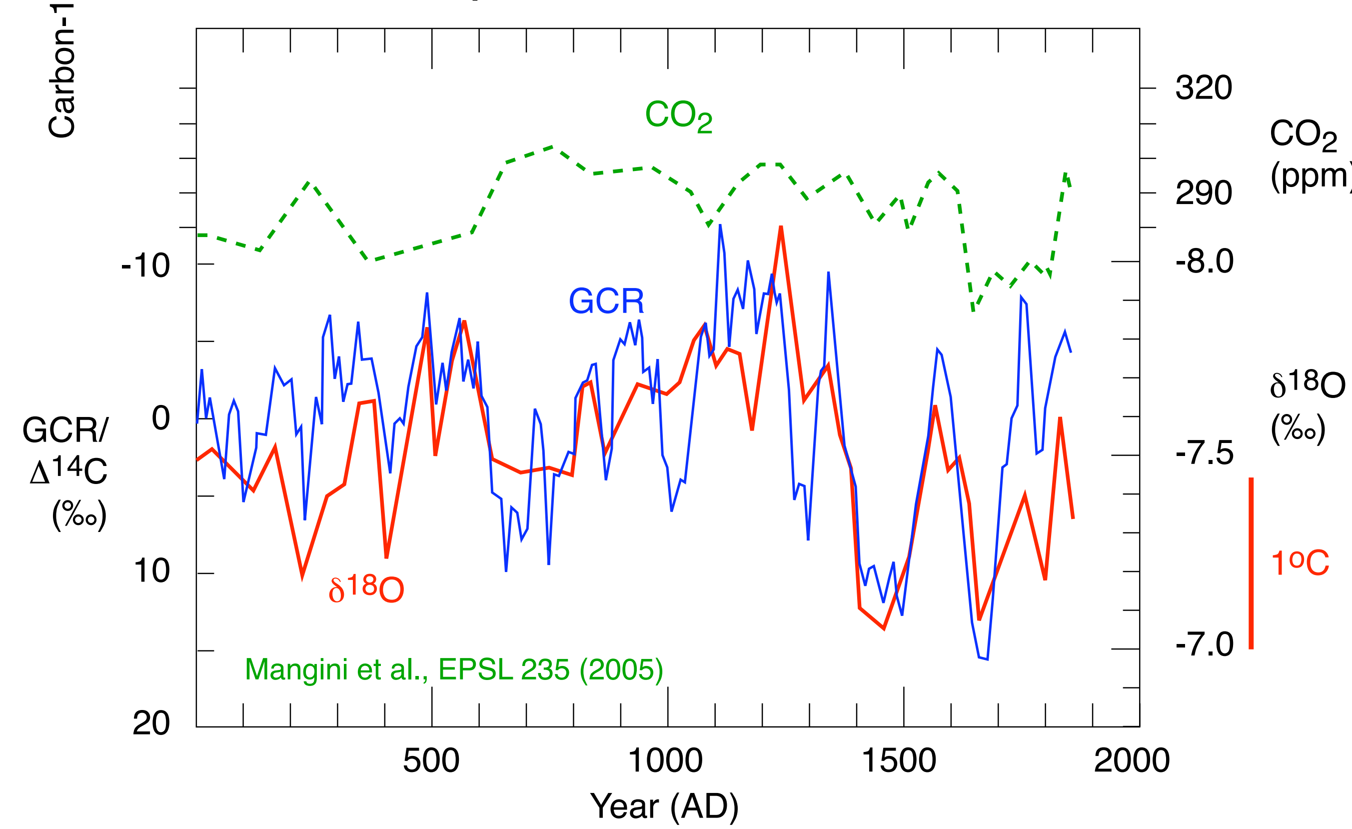
Global climate - last 2000yr



- Little Ice Age and Medieval Warm Period
- Global observations

high GCR flux	cool climate
low GCR flux	warm climate

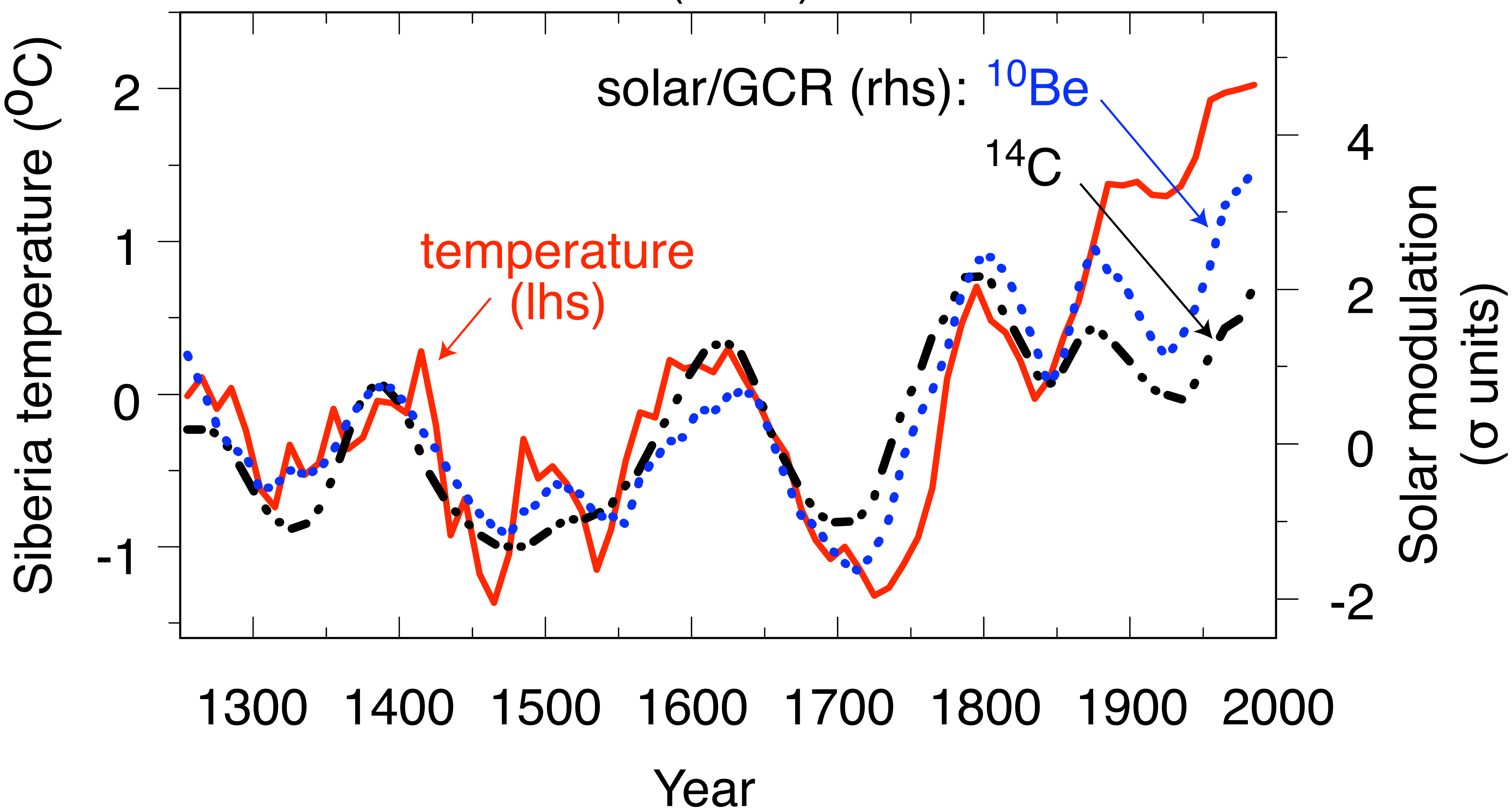
Austrian speleothem:



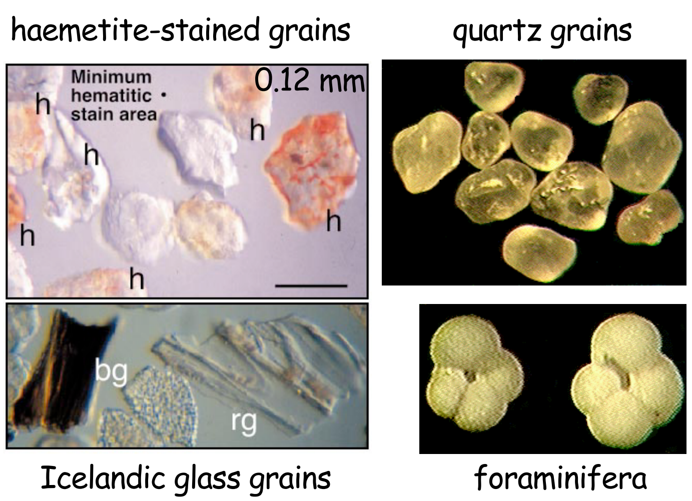
Siberian climate - last 700 yr

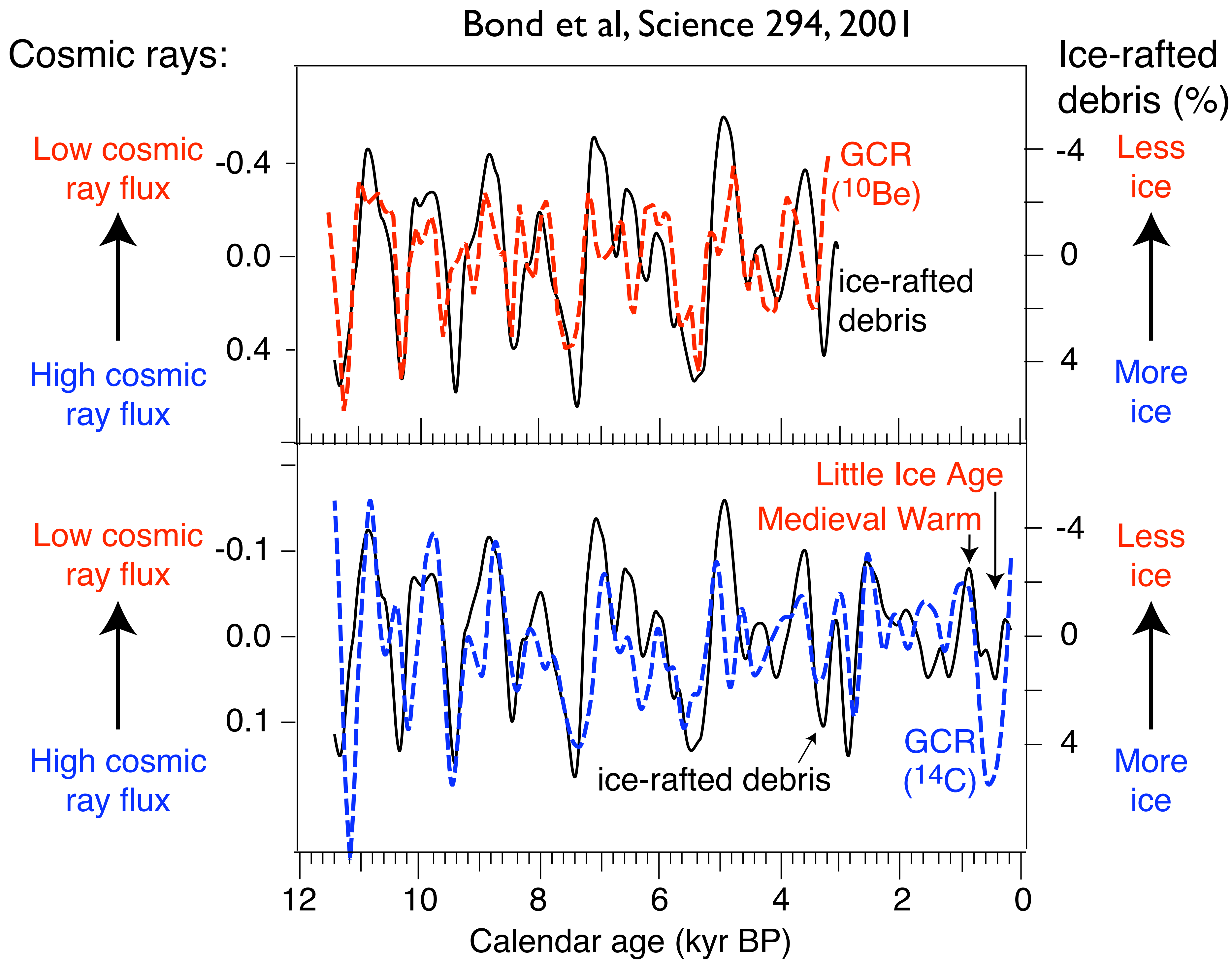
- Correlation recently reported between solar/GCR variability and temperature in Siberia from glacial ice core
- 30 yr lag (ie. ocean currents may be part of response)

Eichler et al. GRL 36 (2009)



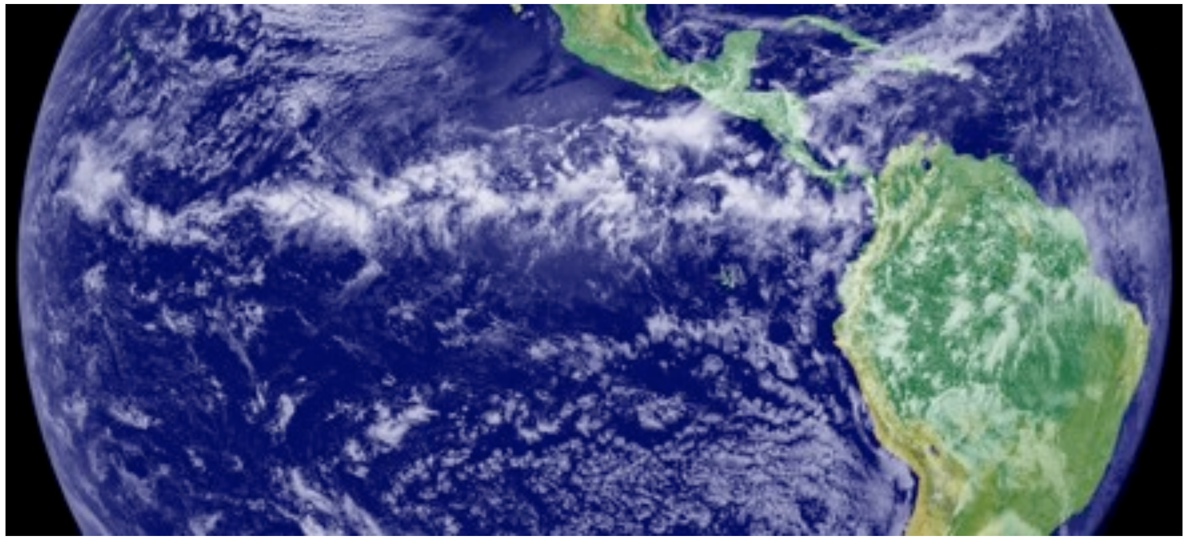
N. Atlantic ice rafted debris - last 10 kyr (Holocene)



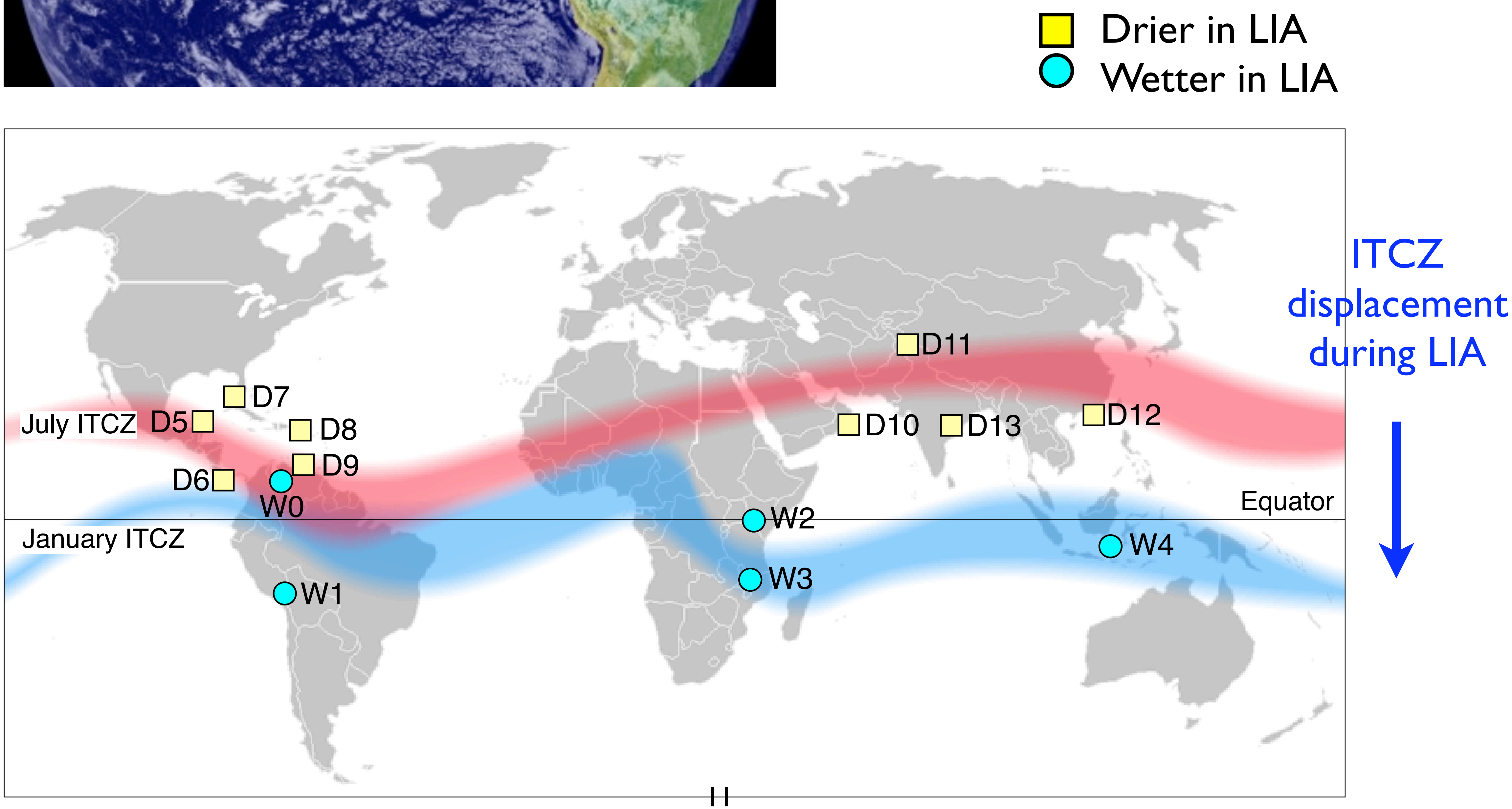


- LIA is merely the most recent of around 10 such events in Holocene

GCR influence on ITCZ/monsoon in Little Ice Age?

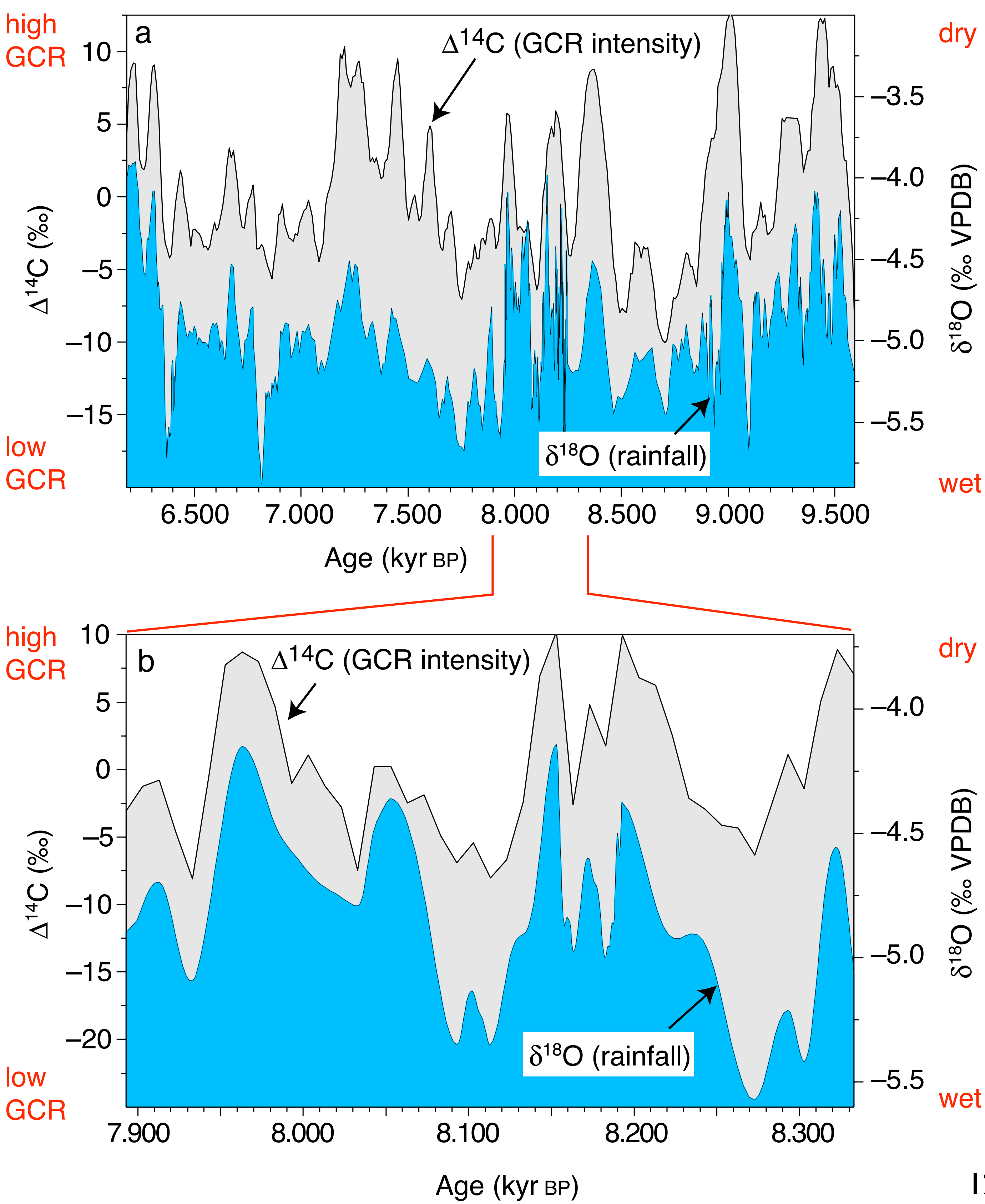


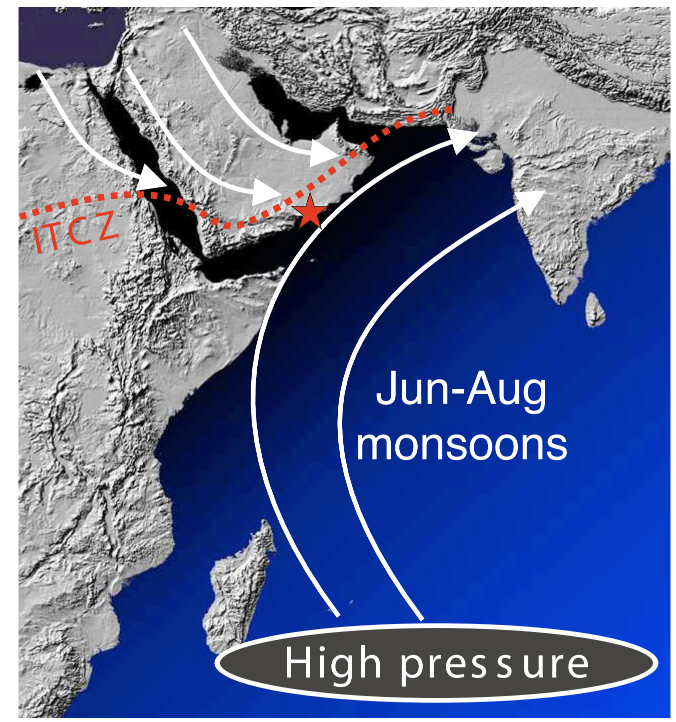
high GCR flux	southerly ITCZ shift
low GCR flux	northerly ITCZ shift



Indian Ocean monsoon - 6.5-9.5 kyr ago

U. Neff et al. (Nature 411, 2001)

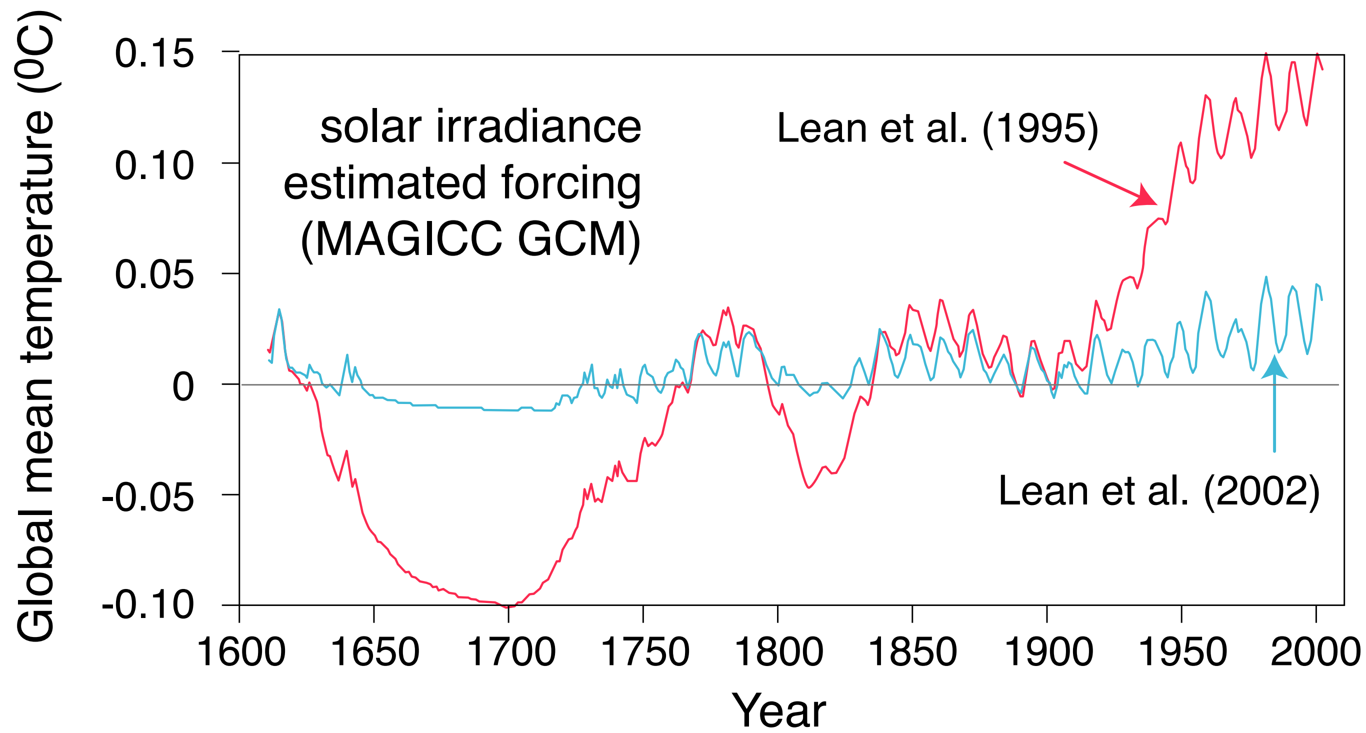




- Solar/GCR forcing of Indian Ocean monsoons (ITCZ migration) on centennial—even decadel—timescales

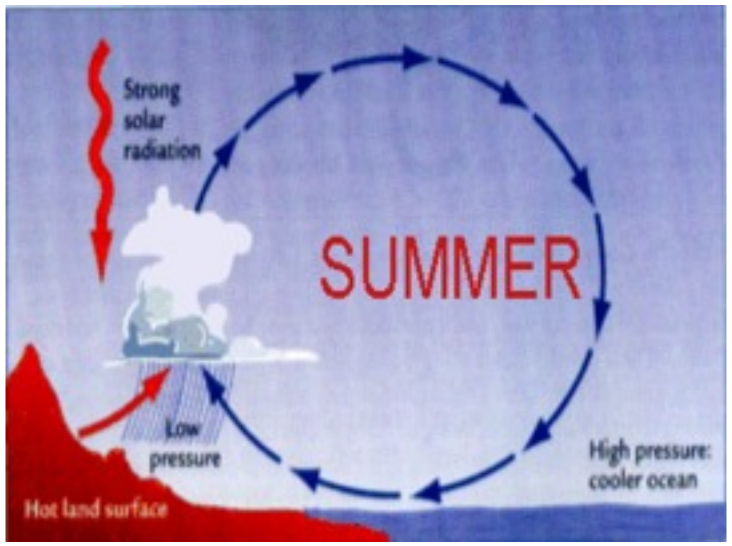
Solar-climate mechanisms

- Candidates for solar-climate variability:
  - direct effect:
    - ✦ total solar irradiance
    - ✦ solar UV
  - indirect effect:
    - ✦ galactic cosmic rays (GCRs) /ionising particles

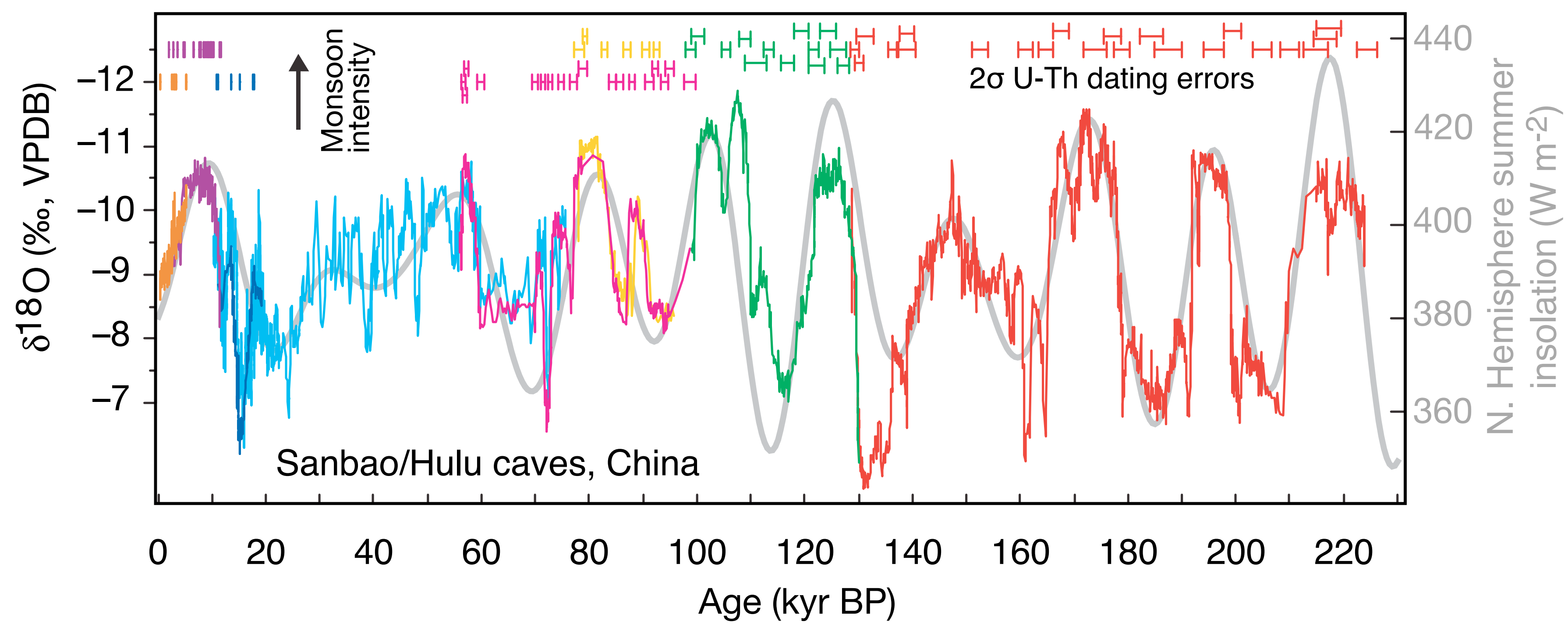


- Can be resolved in principle since GCRs are, in addition to 11-year solar cycle, modulated by:
  - solar magnetic disturbances (esp. high latitude effects)
  - geomagnetic field (low latitude effects)
  - galactic environment

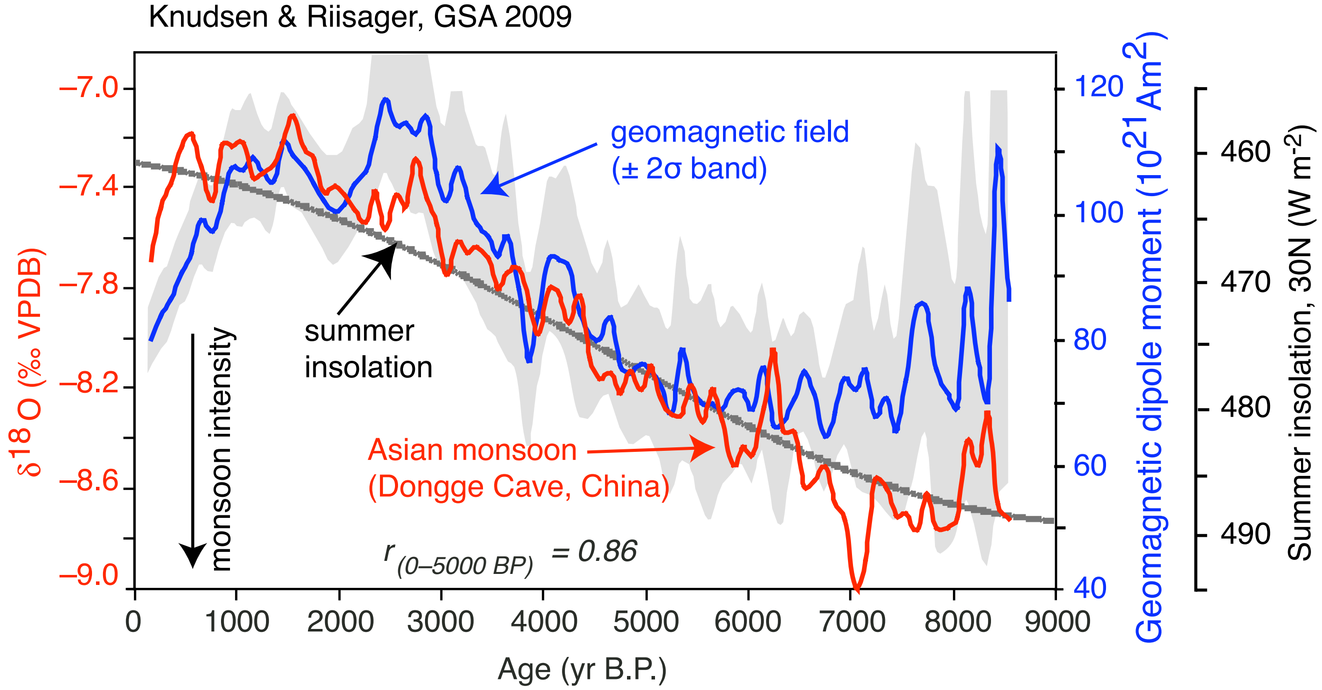
Asian monsoon and geomagnetic field

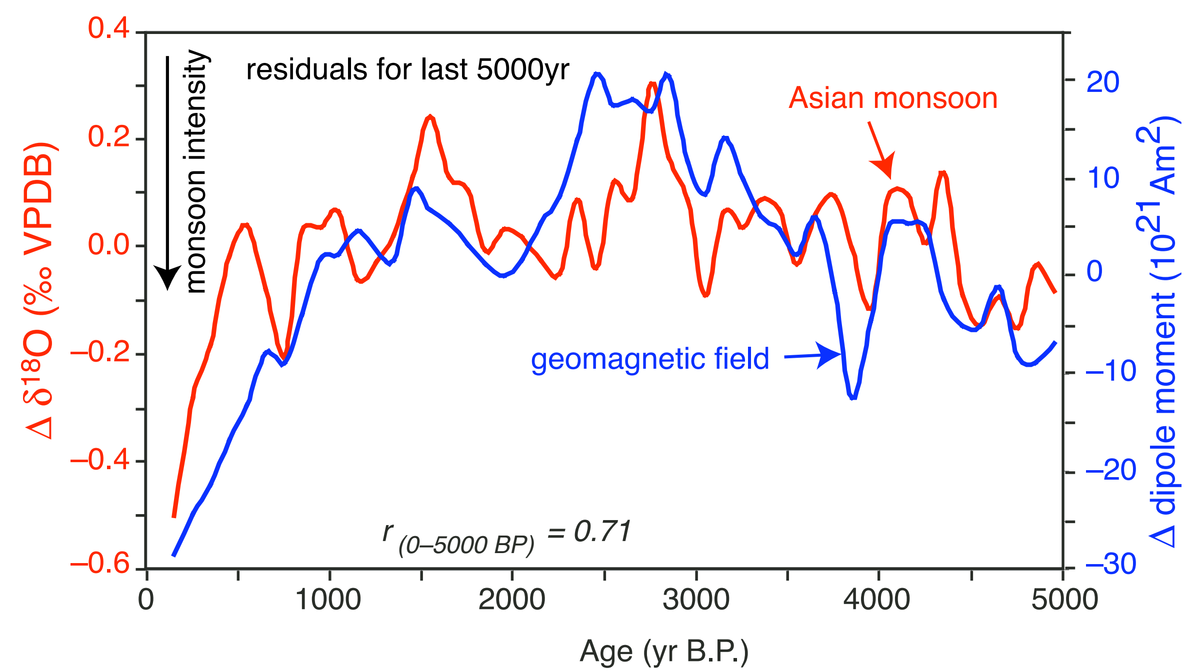


East Asian monsoon instensity; Wang et al., Nature 451, 2008



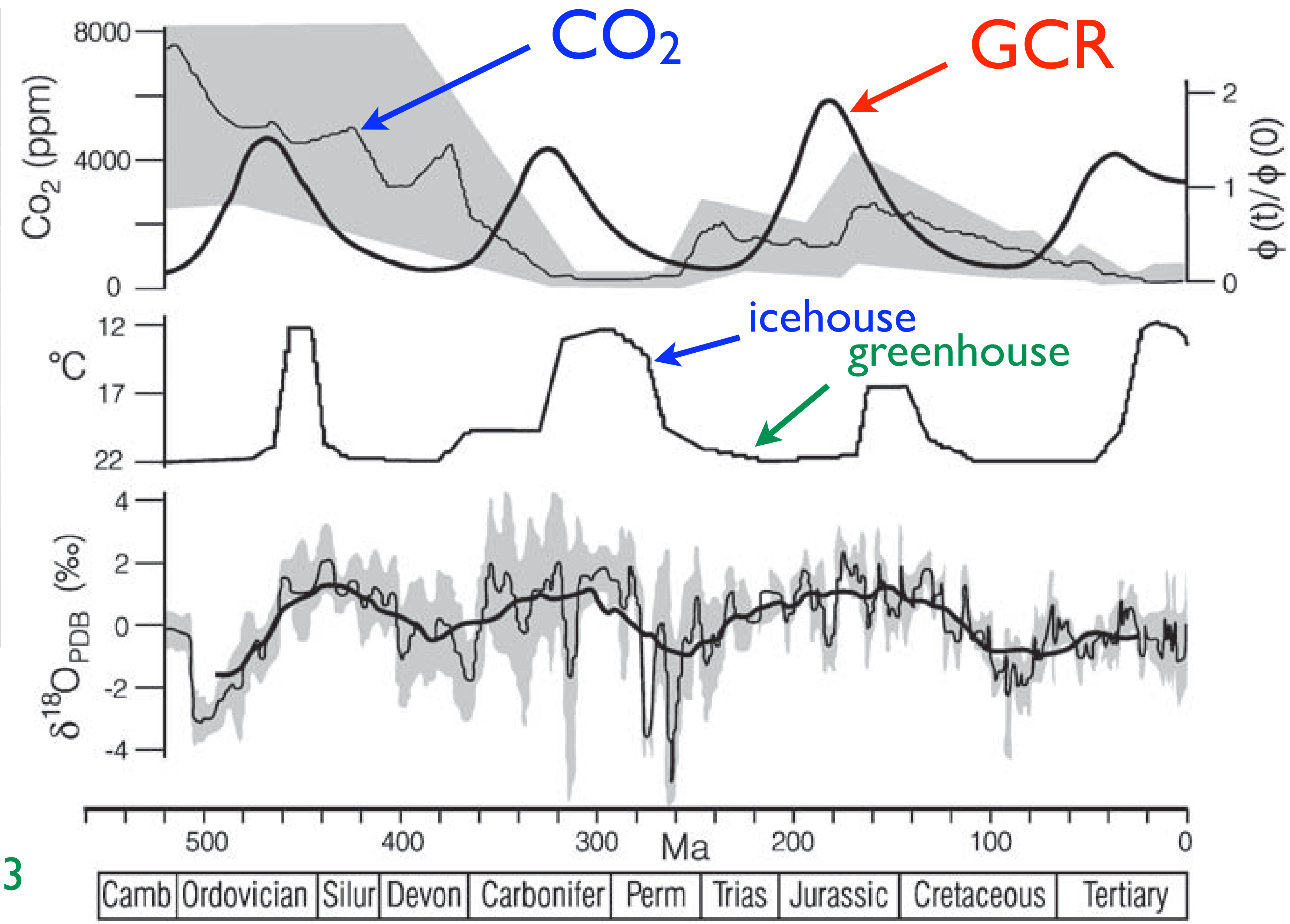
Knudsen & Riisager, GSA 2009





- Asian monsoon controlled by orbital insolation - with strong millennial-scale variability
- Possible influence of geomagnetic field on Asian monsoon?
- Opposite sign of effect: lower B field → increased GCR → increased monsoon intensity, which could result from latitudinal differences of solar- and geomagnetic modulations

Galactic modulation of climate? - 500 Myr

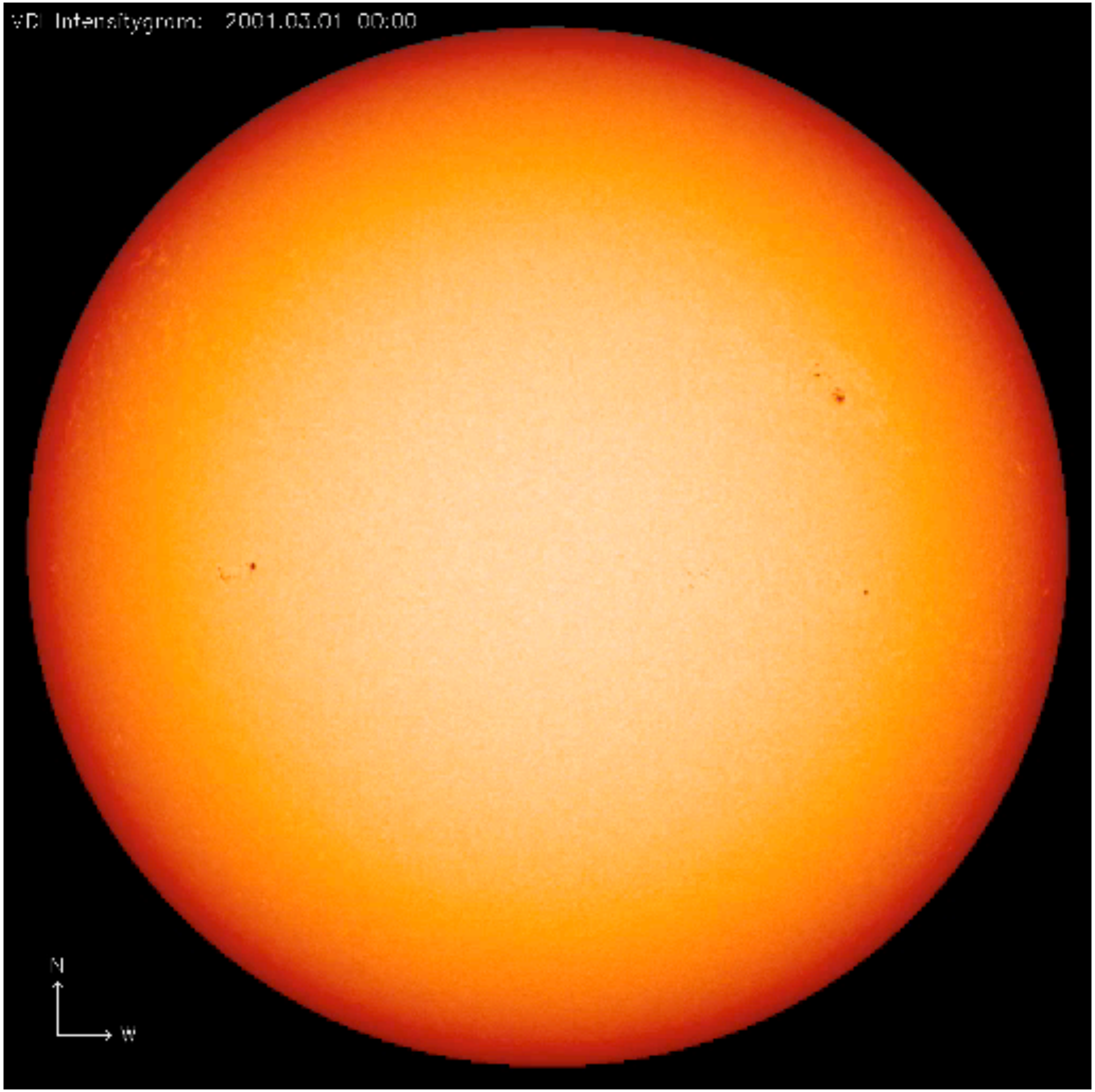


Shaviv & Veizer, GSA Today, 2003

- Orbital period of Sun/Earth around Milky Way ~550Myr
- High GCR flux in spiral arms => 140 Myr period
- Same period and phase found in benthic sea temperature (4°C amplitude) and ice age epochs (icehouse/greenhouse)

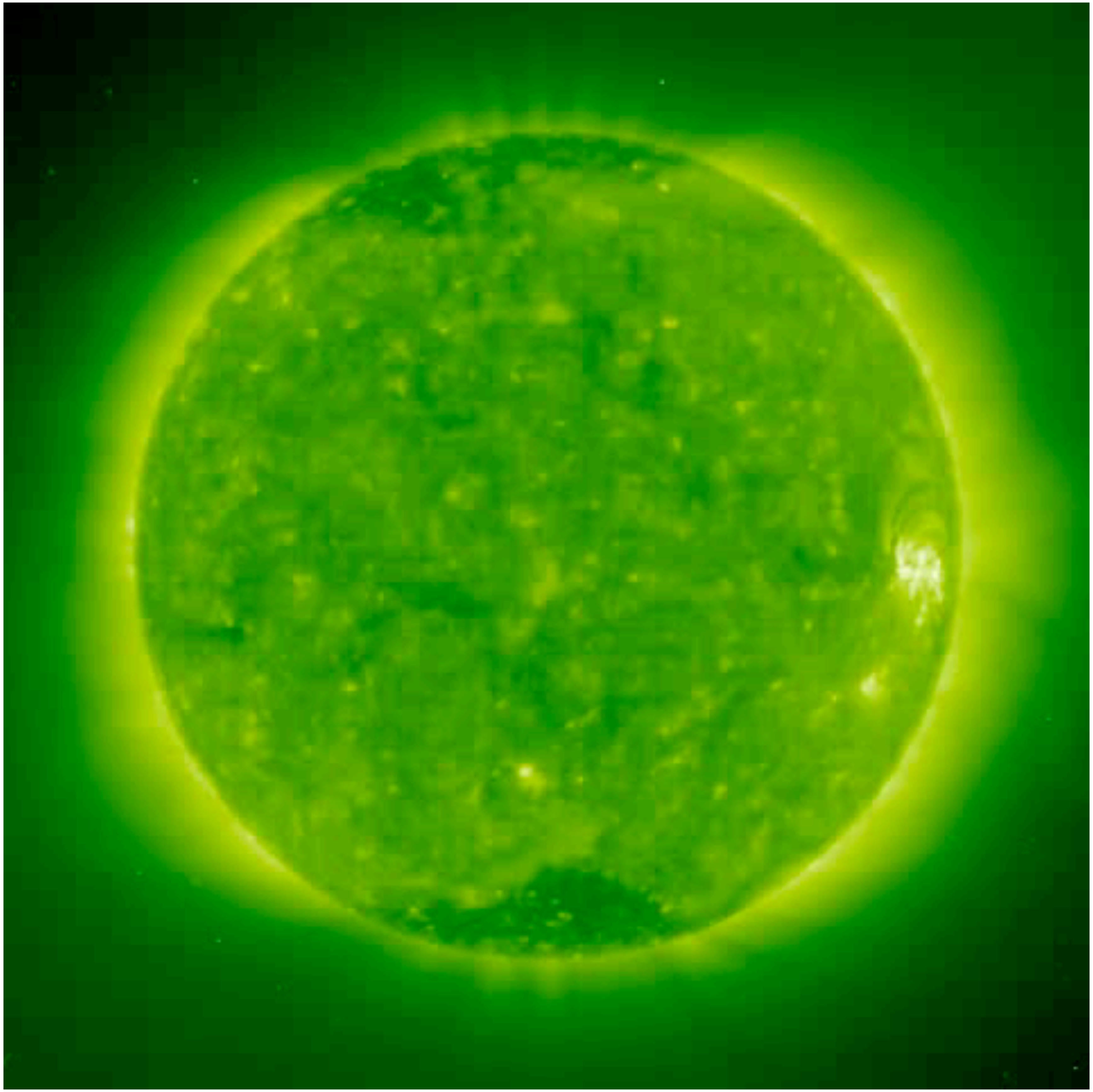
III. Solar variability in the 20th century

Sun (photosphere) seen in visible (677nm) at solar max (2001)



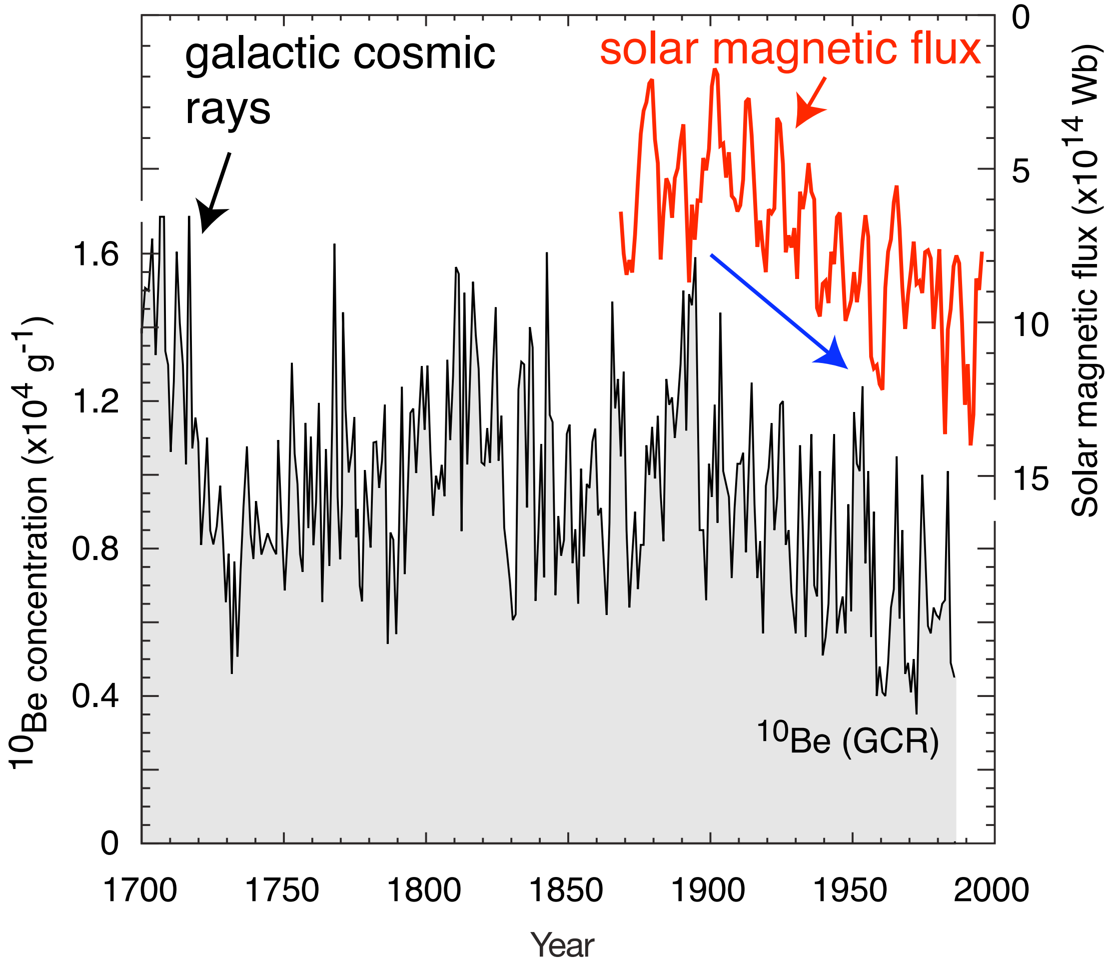
NASA/ESA
SOHO

Sun (corona) seen with extreme UV eyes (20nm)

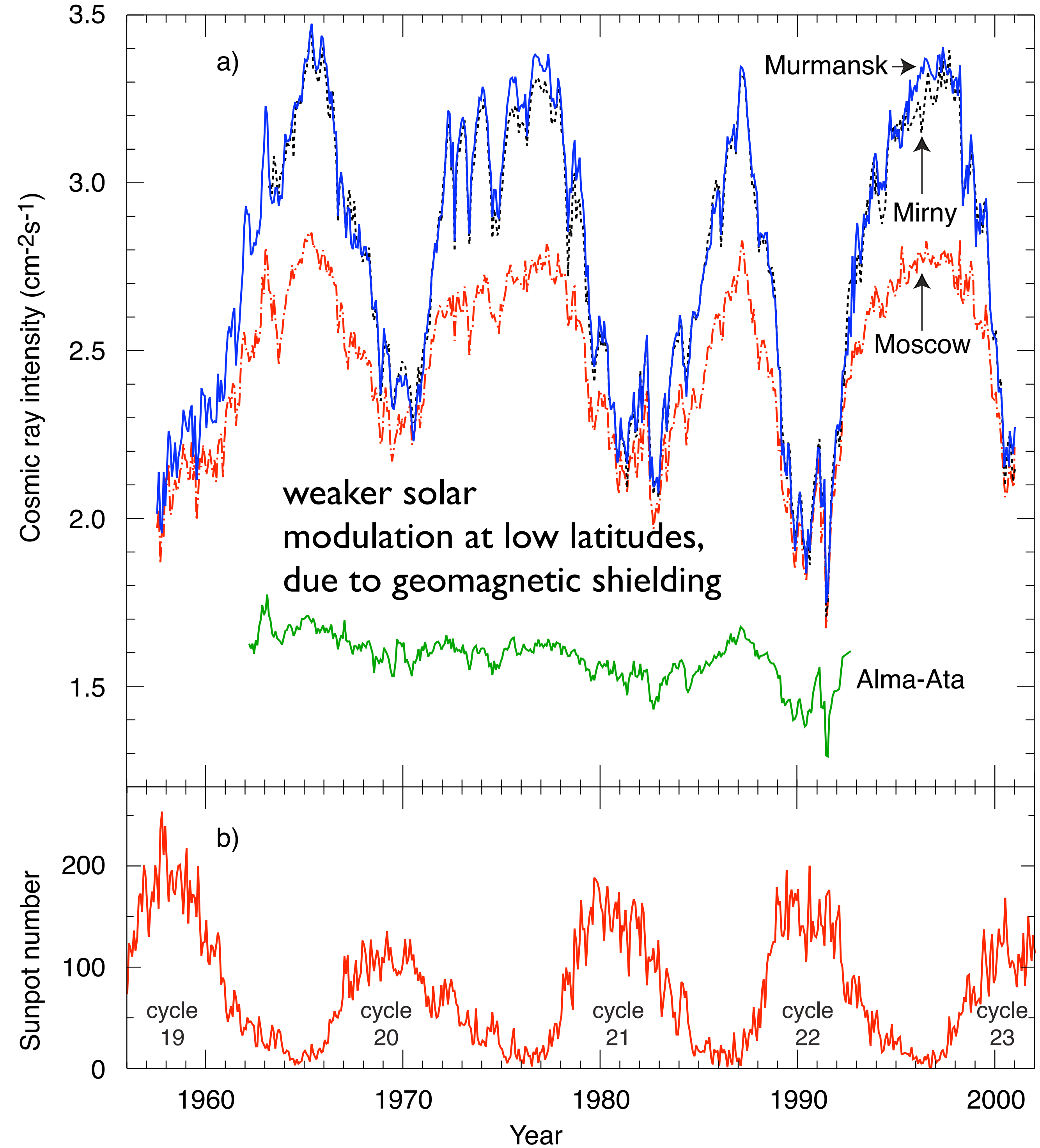


NASA/ESA
SOHO

Cosmic ray changes during 20th century

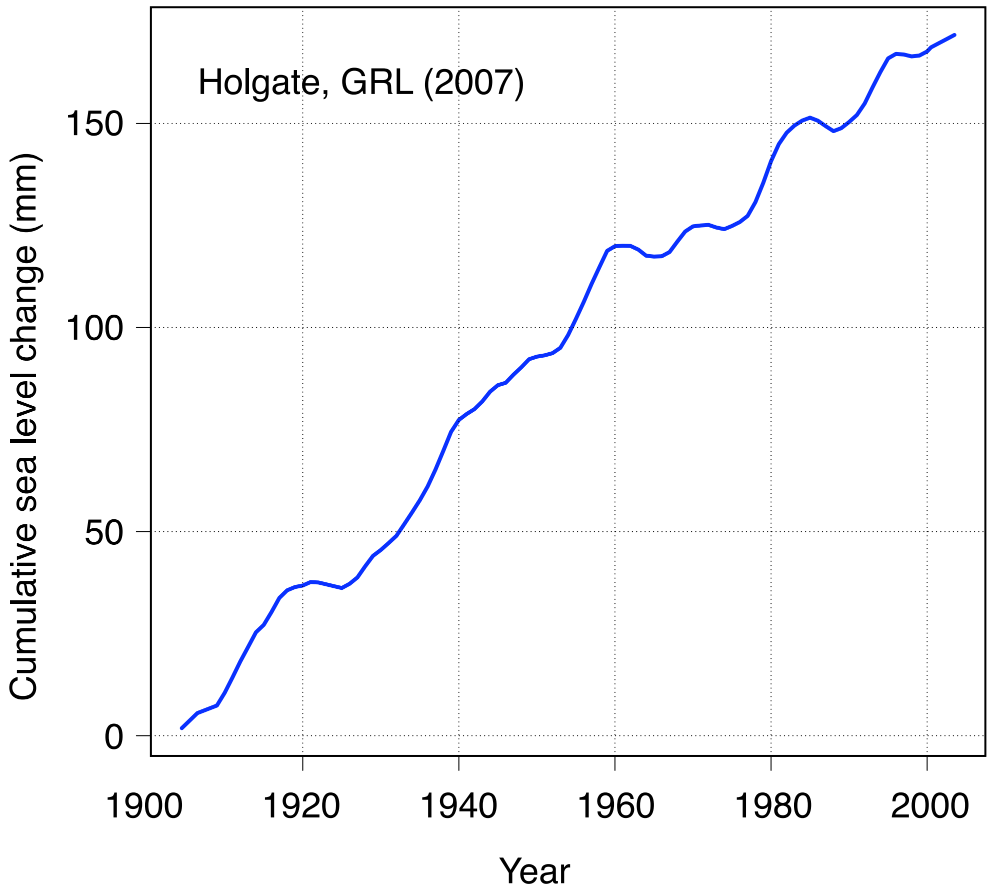


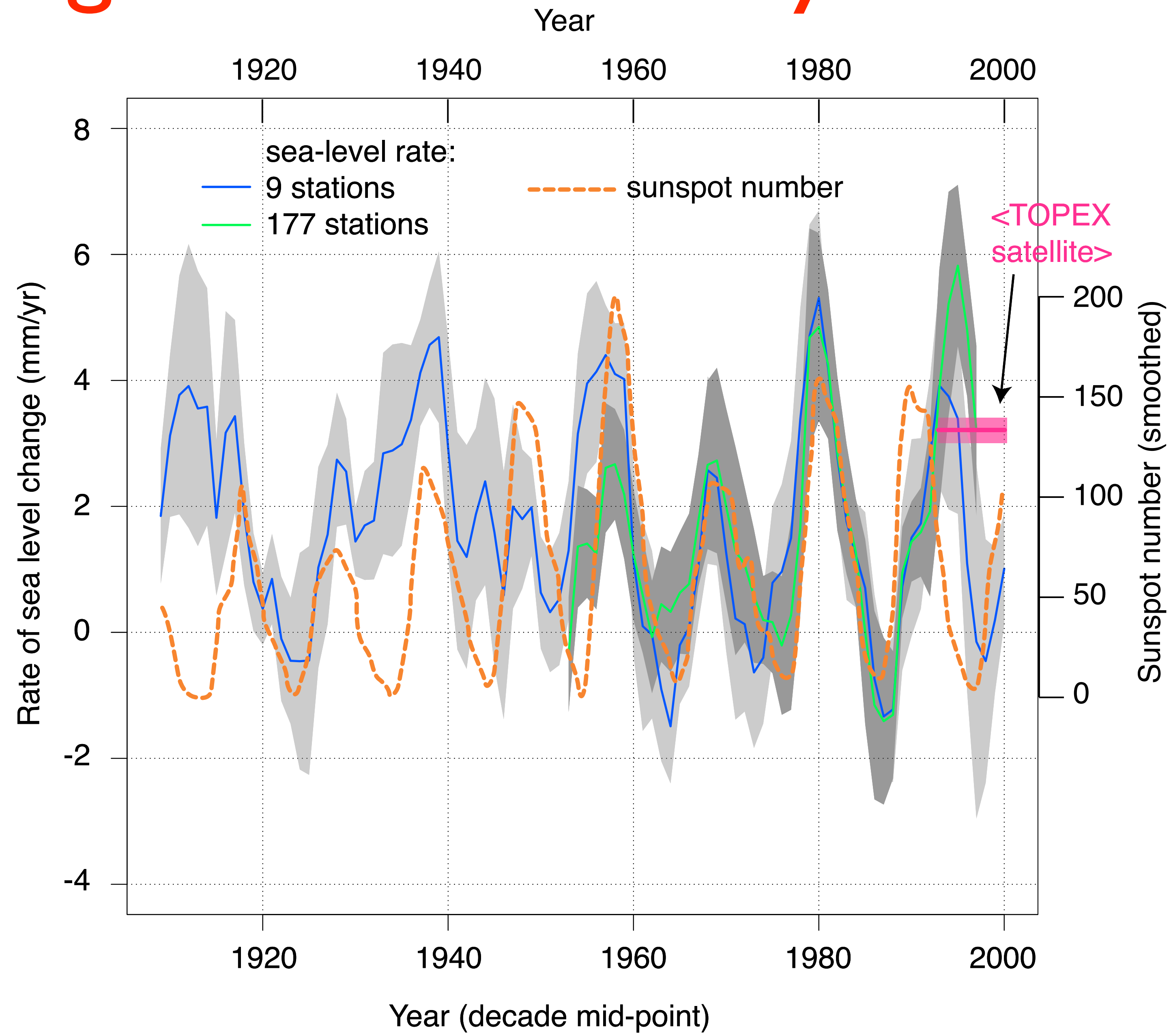
Lebedev balloon GCR data:



- Solar open magnetic flux increased by x2.3 in 20th century
- GCR net decrease by ~20% (mostly in 1st half of century)
- Largely only solar cycle variations of GCR flux in 2nd half

Sea-level change in 20th century



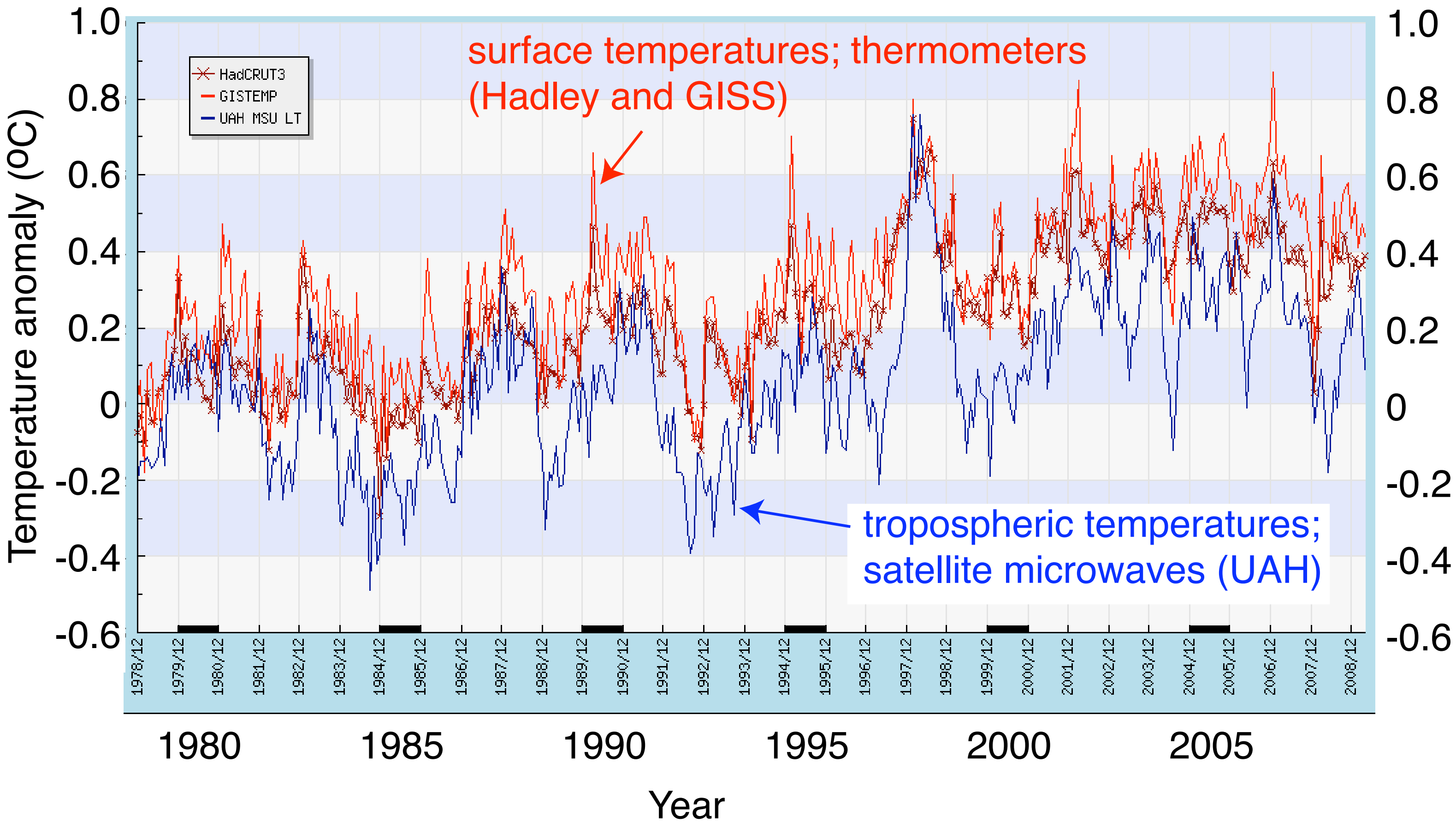


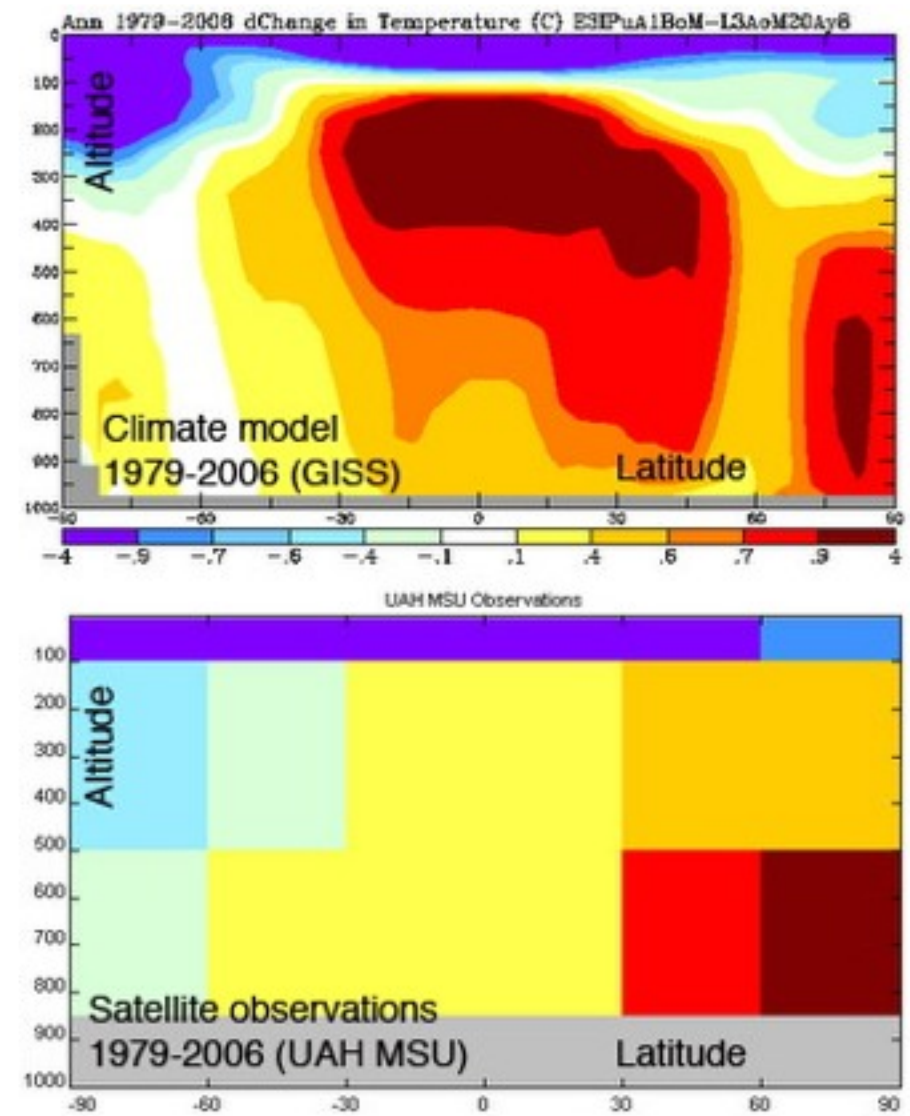
- Steady rise of sea-level; mean rate = 1.7 mm/yr
- No increase in rate during recent decades
- Thermal expansion of oceans (mainly) + land ice melting
- Rate of sea-level rise is strongly modulated

⇒ solar modulation? (but solar irradiance variation is too small)

Sea-level positive feedback

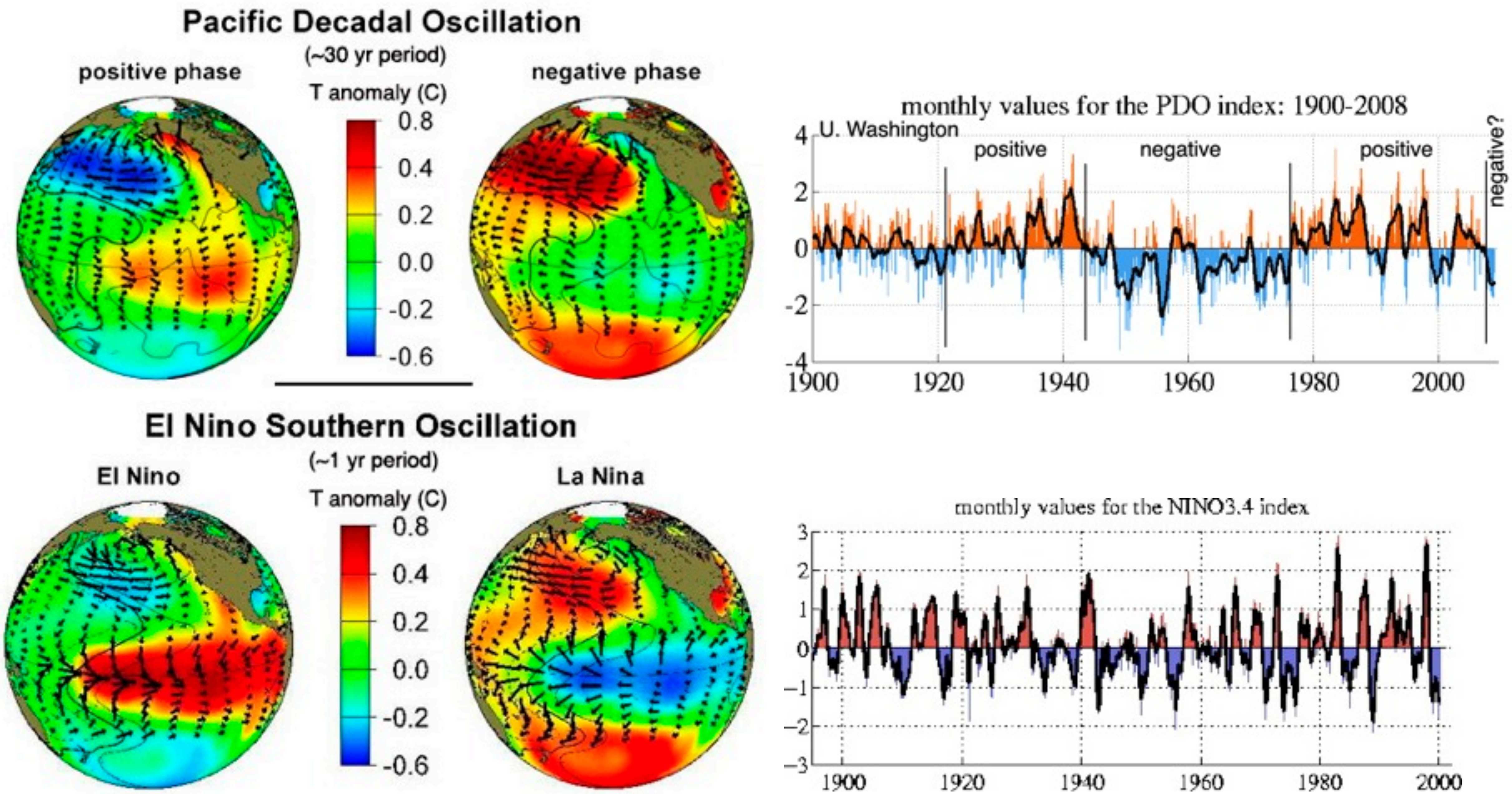
Recent global temperatures - last 30 yr





- Most of ~2 yr fluctuations due to El Niño-Southern Oscillation (eg 1997-98) + volcanoes (El Chichon 1982, Pinatubo 1991)
- Satellite and radiosonde (tropospheric) data show
  - less warming than thermometer measurements of surface
  - no enhanced upper tropospheric warming, expected from GHG
- Mean global temperatures flat over last 8 years. Cause not known but CO_2 increasing, so must be natural forcing

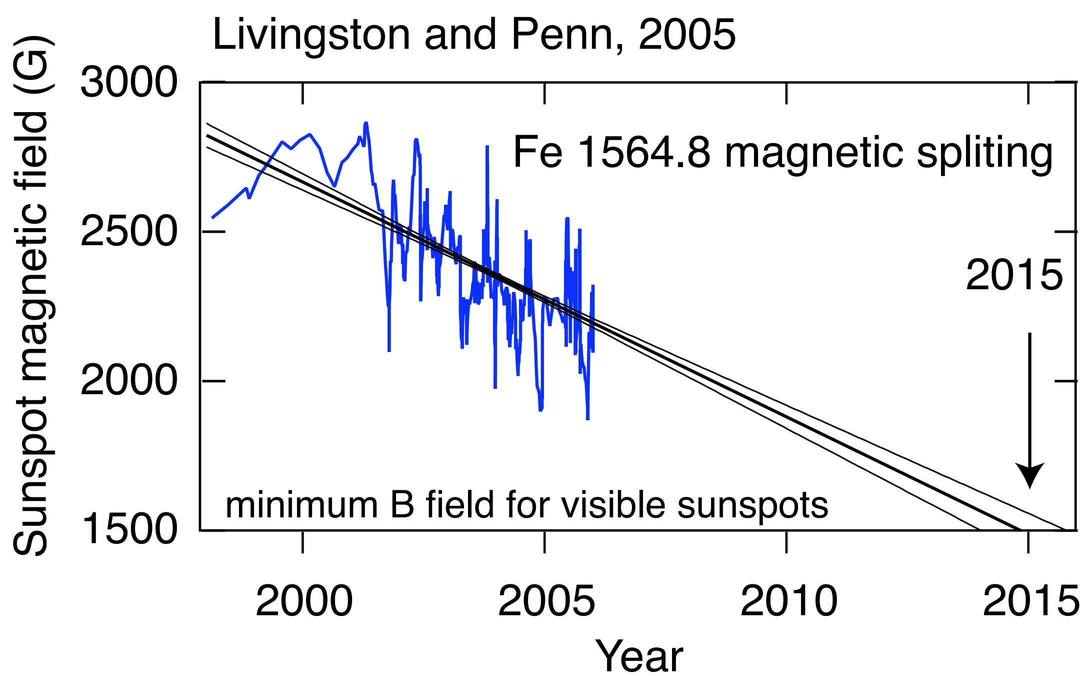
Pacific Decadel Oscillation

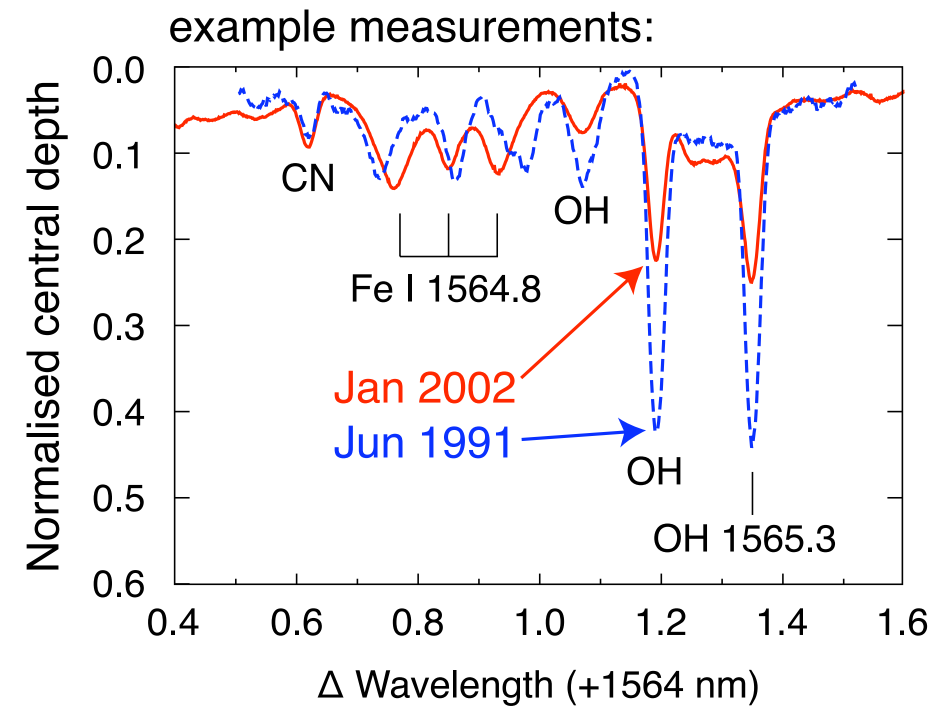


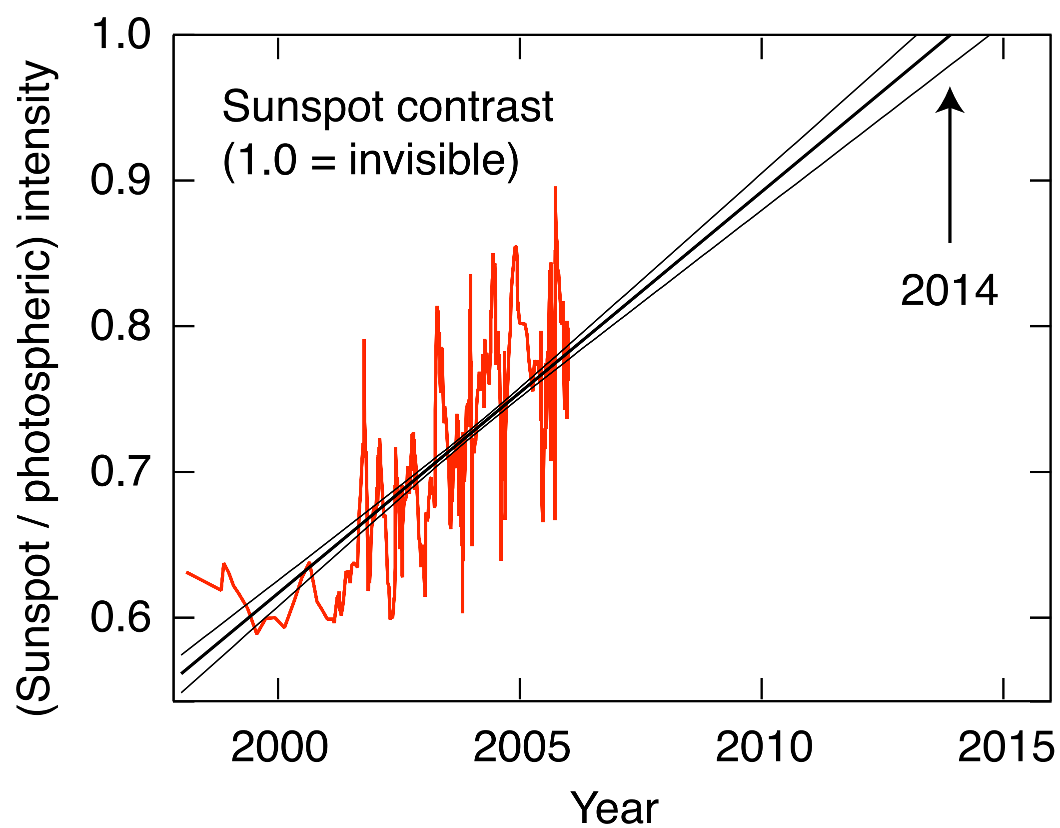
- PDO (Hare 1996) is similar to ENSO (temperature anomalies and surface winds), except for long (30 yr) periodicity and primary effect on Pacific NW
- PDO transitions coincide with gradient changes of global temperatures
- PDO may be shifting to negative phase

Sunspot weakening

Livingston and Penn, National Solar Observatory, Tucson, AZ
"Sunspots may vanish by 2015", submitted 2005 (rejected for publication)



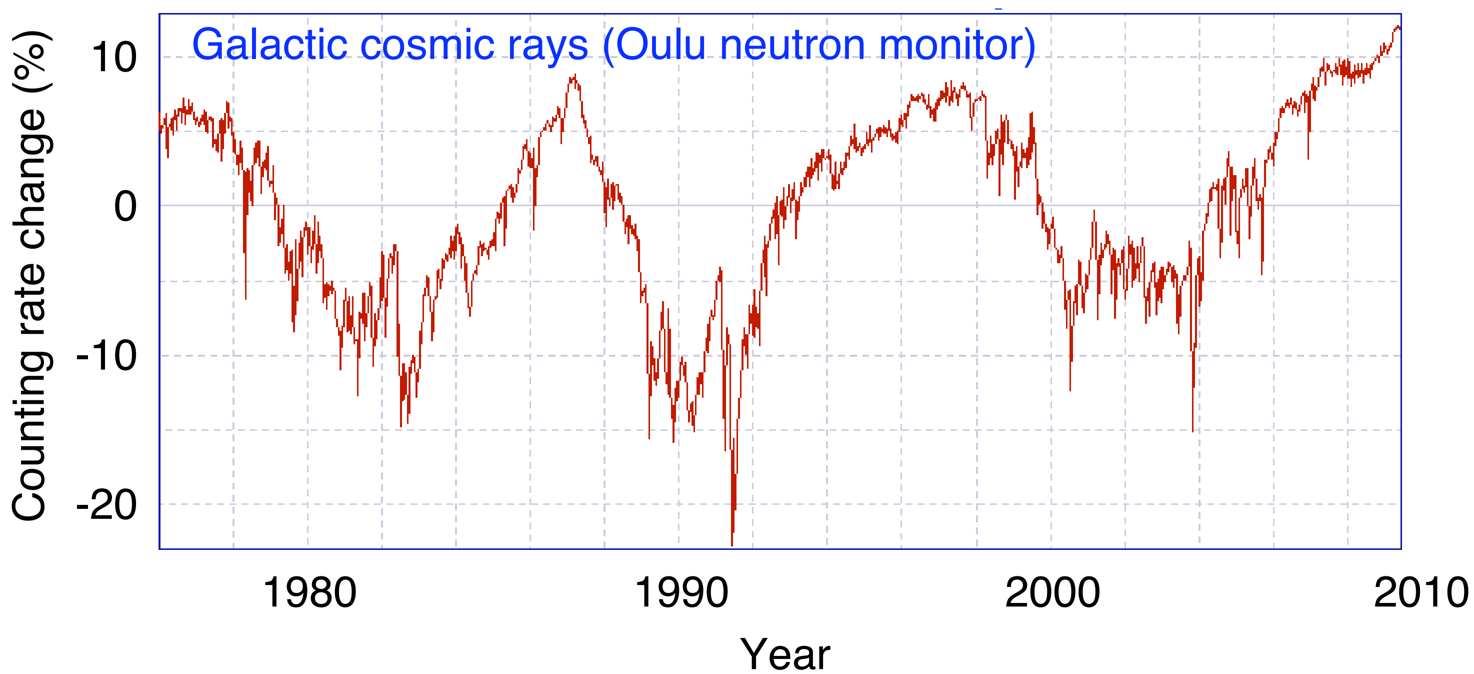


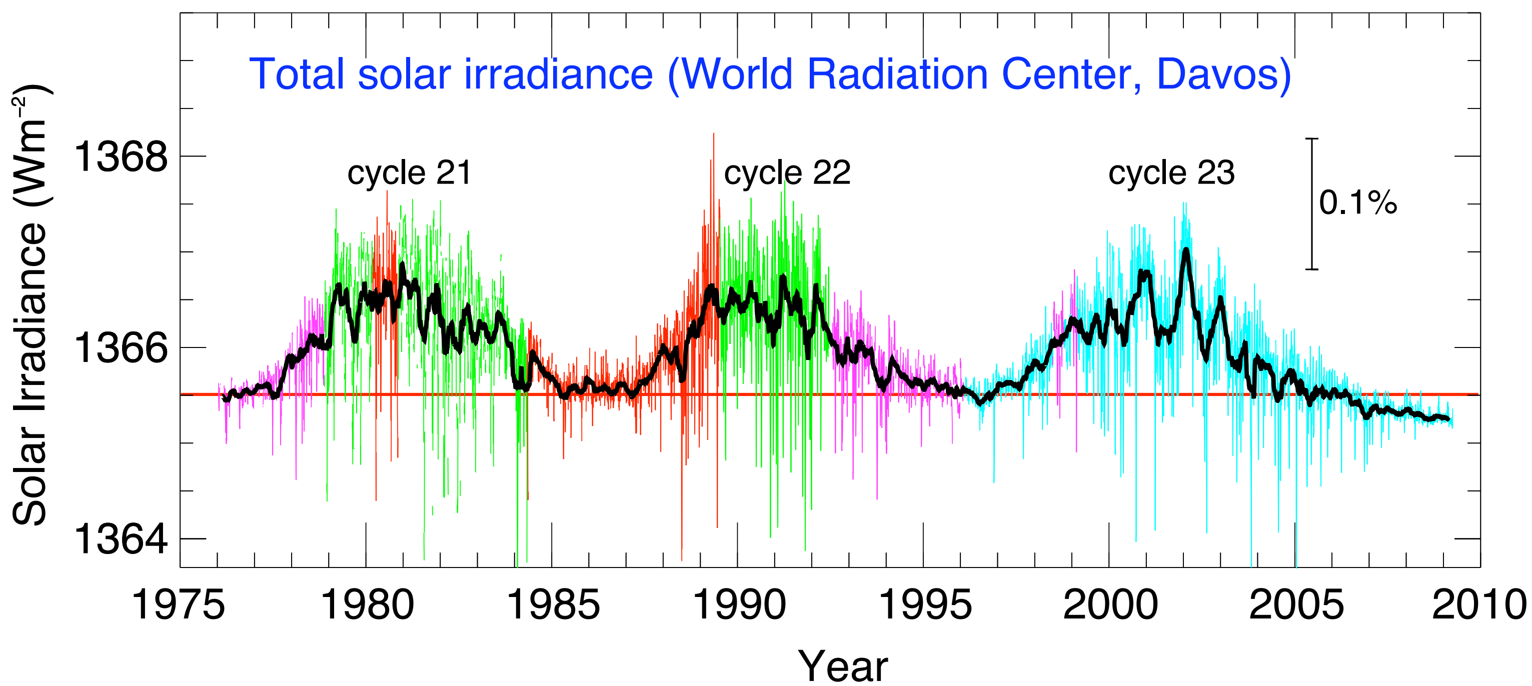


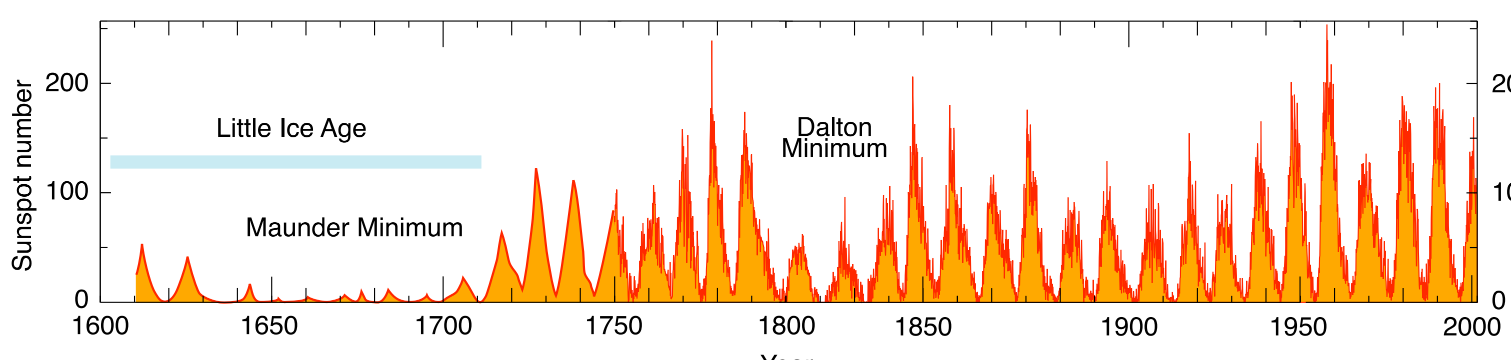
- Temperature-sensitive molecular lines
- Zeeman splitting of Fe I line
- Continuum brightness of sunspot umbrae

- Sunspot umbrae warming at 45K /yr
- Sunspot magnetic fields decreasing at 77 G/yr
- Independent of sunspot cycle
- Linear extrapolation ⇒ sunspots vanish after 2015 (like Maunder Minimum)

Current very low solar activity





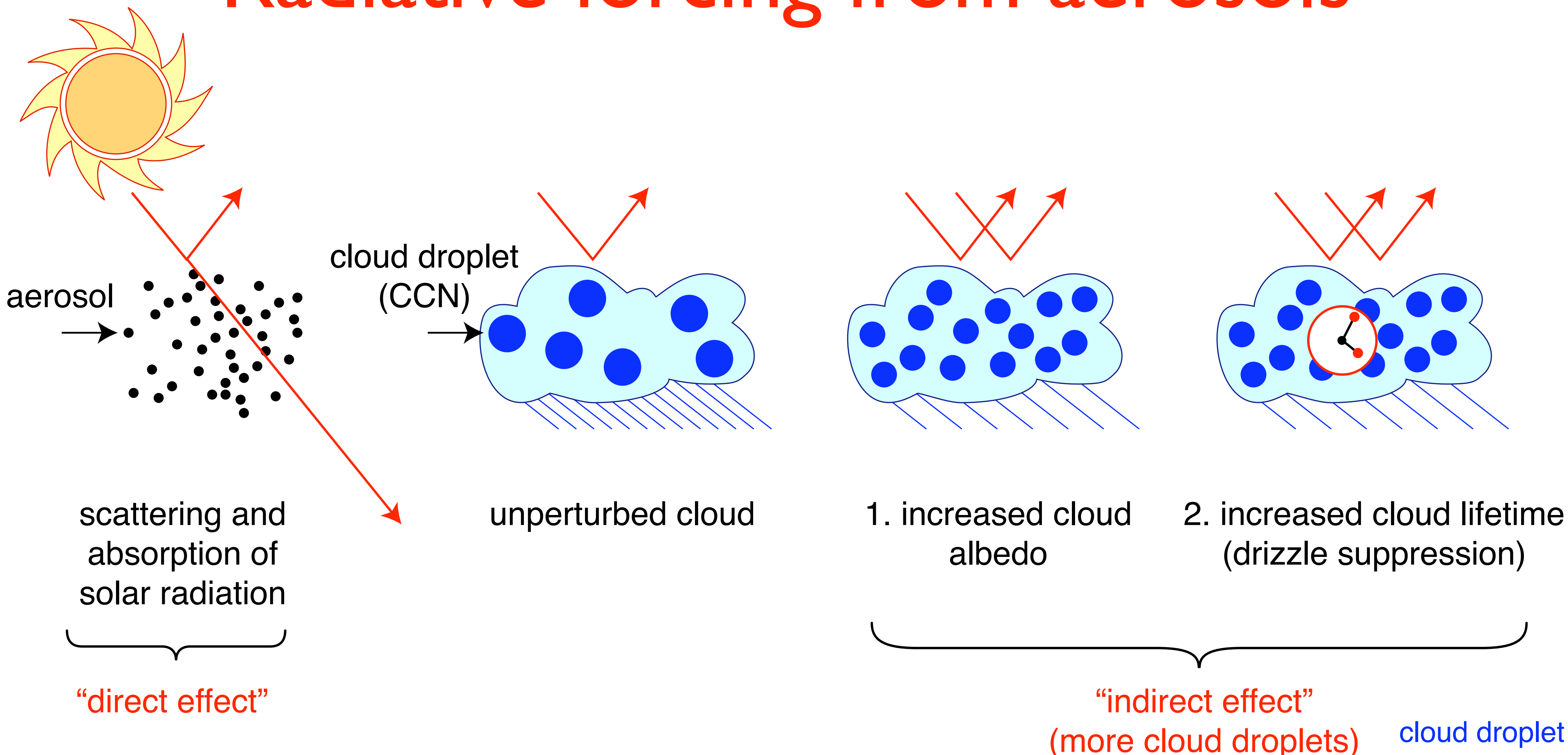


- Currently one sunspot on Sun, and GCRs high
- Next sunspot cycle 24 is very late
- Mean sunspot cycle length is 11.1 yr
- Length of cycle 23 is now >13.1 yr
- Last time such a long cycle occurred was cycle 4 (1784-1798) just before the Dalton minimum - coincided with notable cold period of few decades
- We live in interesting times for the Sun... (hopefully a blessing not a curse)

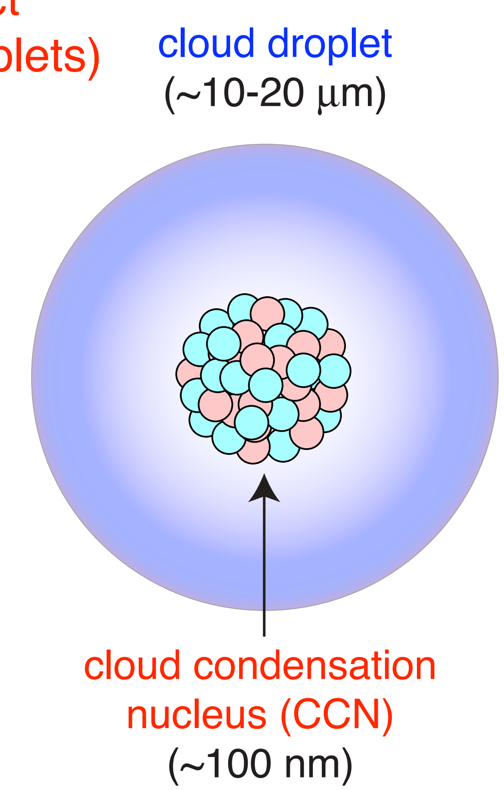
IV. Physical mechanism

- GCRs/ionising radiation may affect cloud amount via:
  - CCN number concentration, and/or
  - ice particle formation in clouds

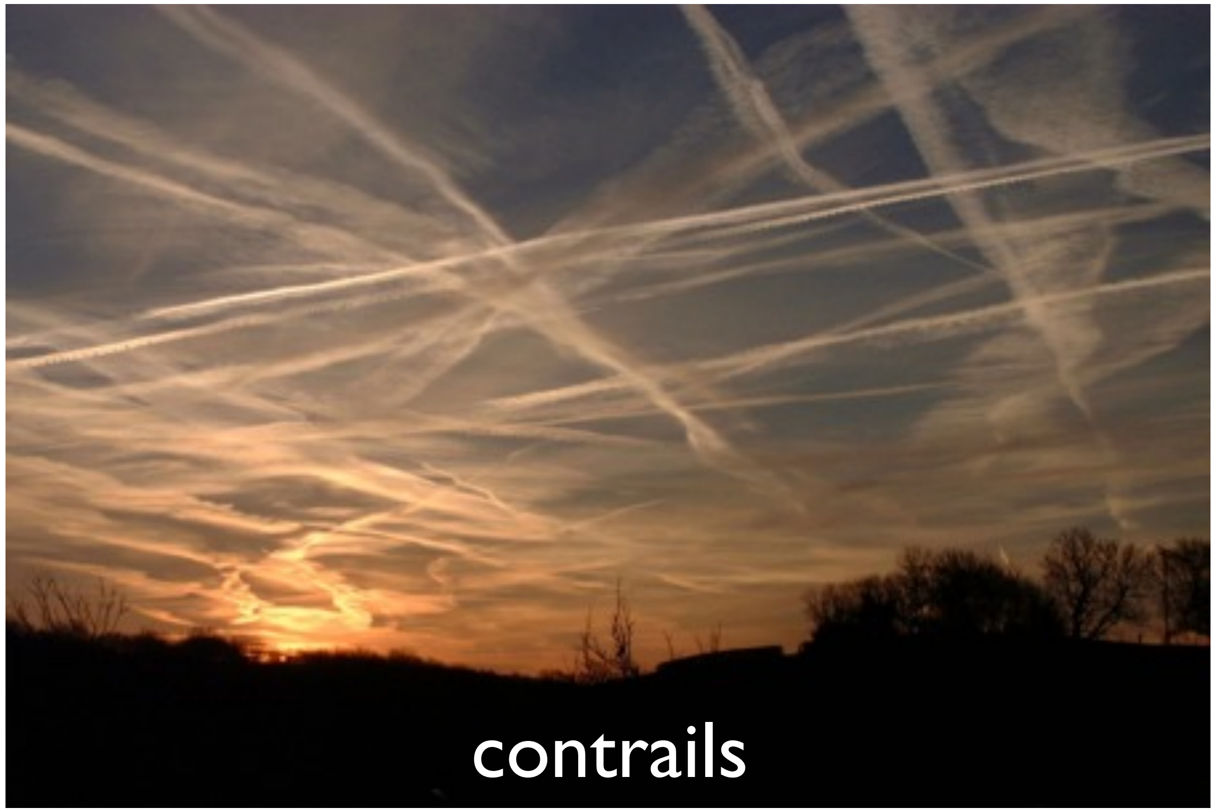
Radiative forcing from aerosols

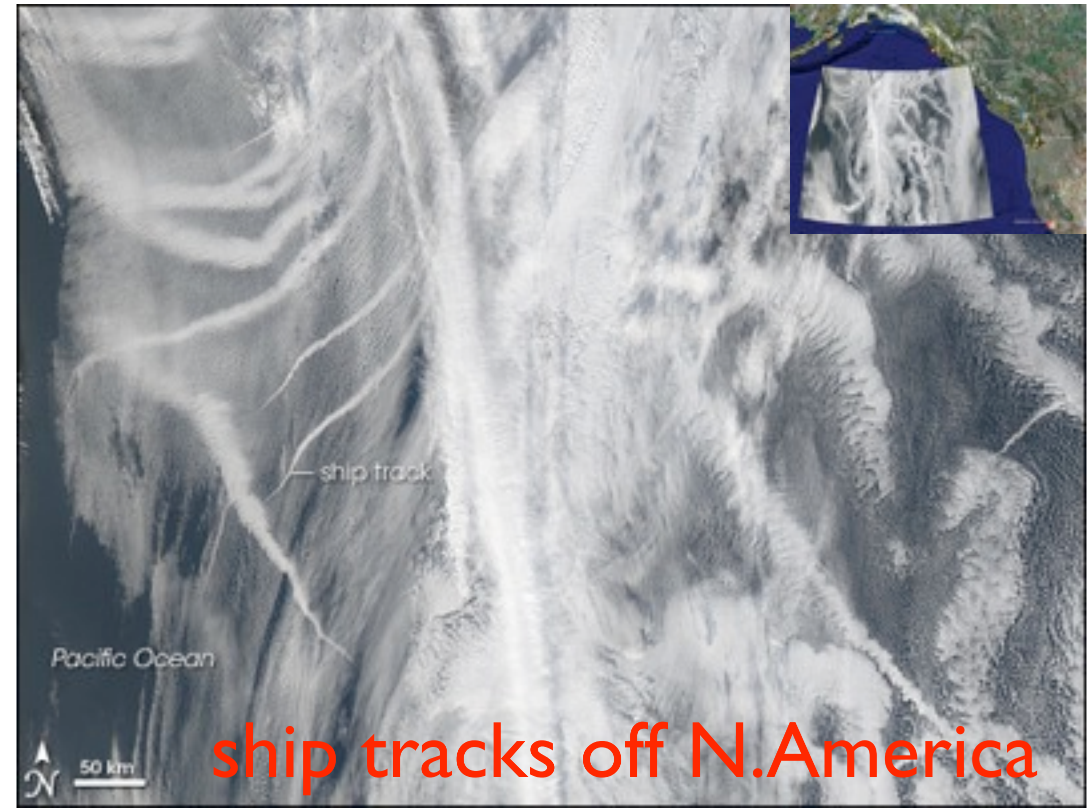


- All cloud droplets form on aerosol "seeds" known as cloud condensation nuclei - CCN
- Cloud properties are sensitive to number of droplets
- More aerosols/CCN
  => brighter clouds, with longer lifetimes



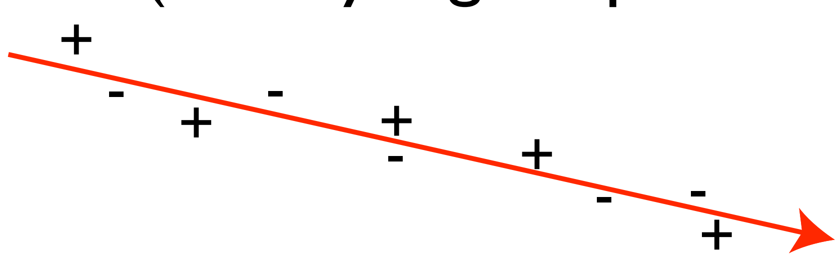
Seeds for cloud formation


contrails

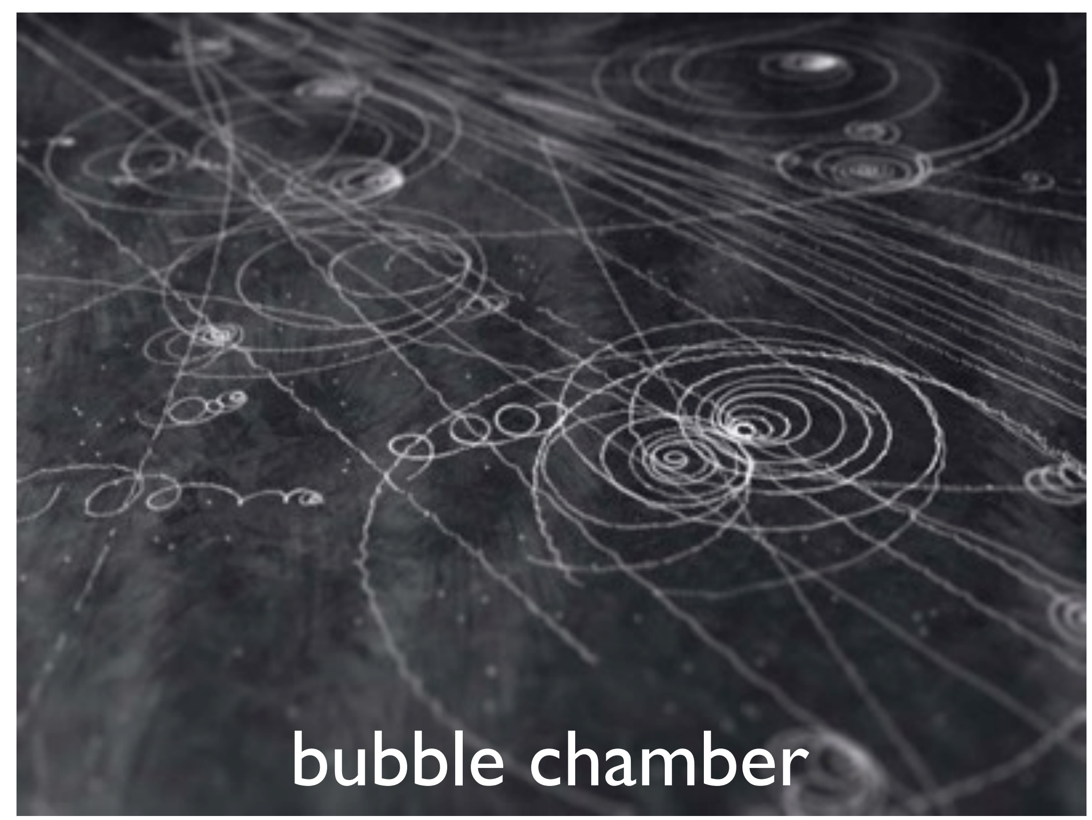


ship tracks off N.America

- Aerosol particles = condensation seeds
- Charged particles = condensation seeds
  (at very high supersaturations)

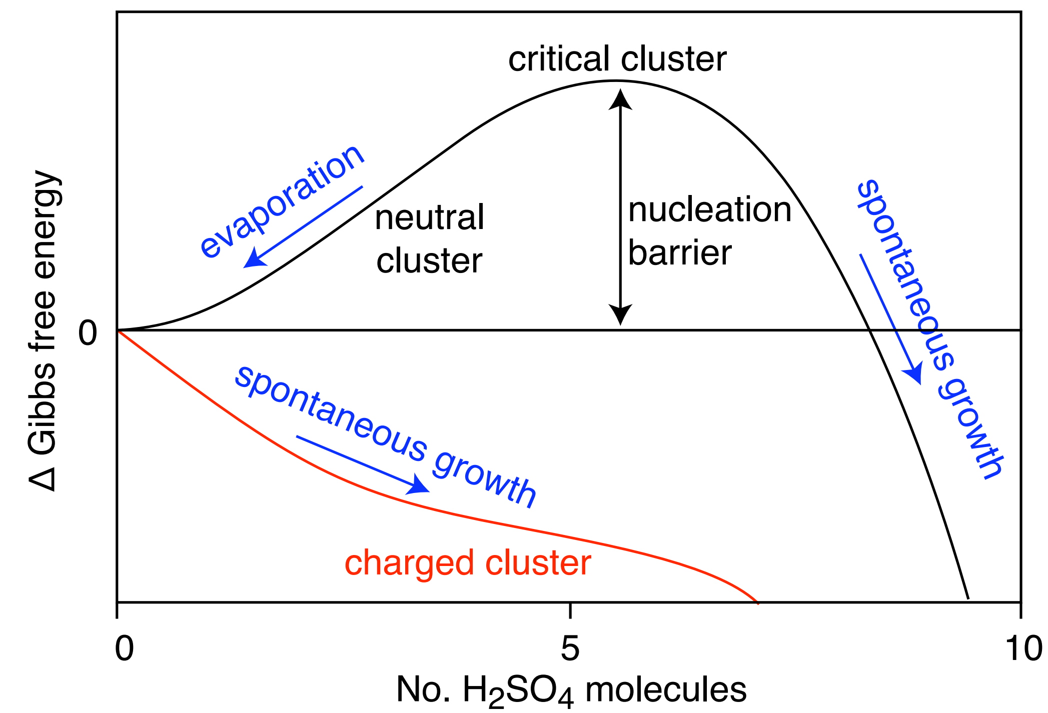


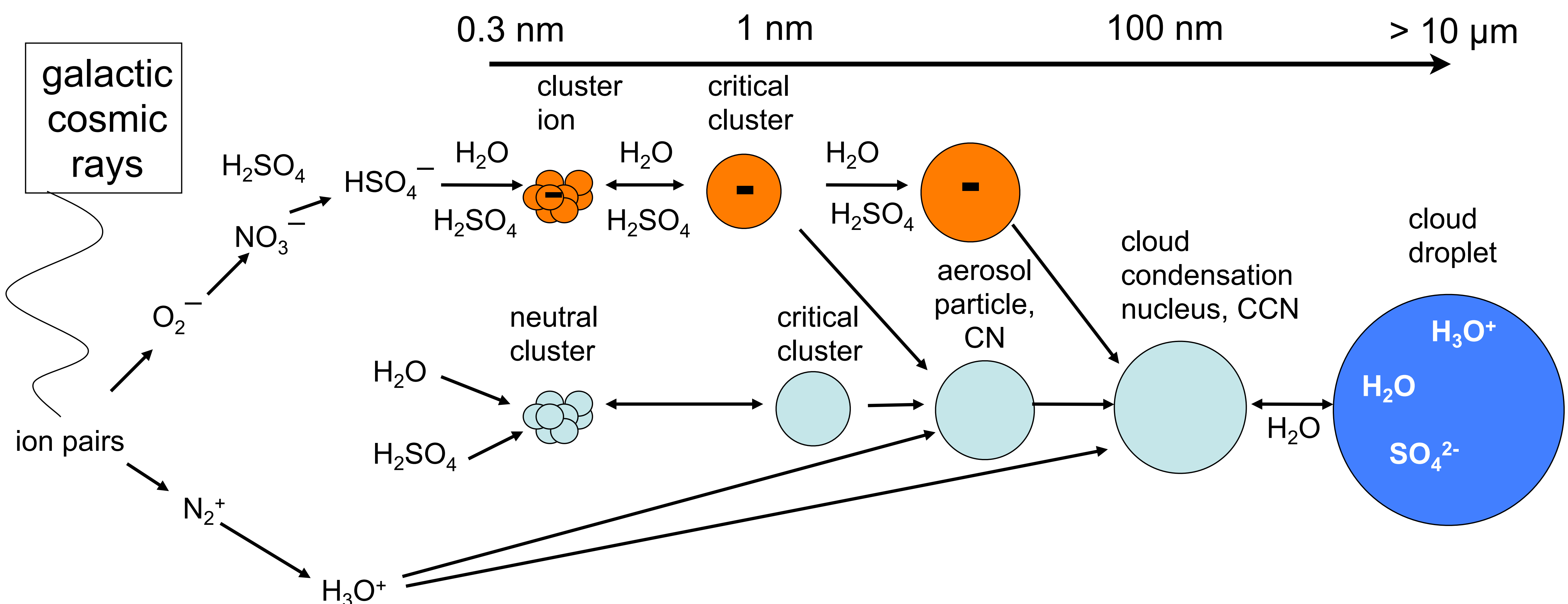
- Can cosmic rays, under natural conditions, influence aerosols, clouds and climate?


bubble chamber

Possible mechanism

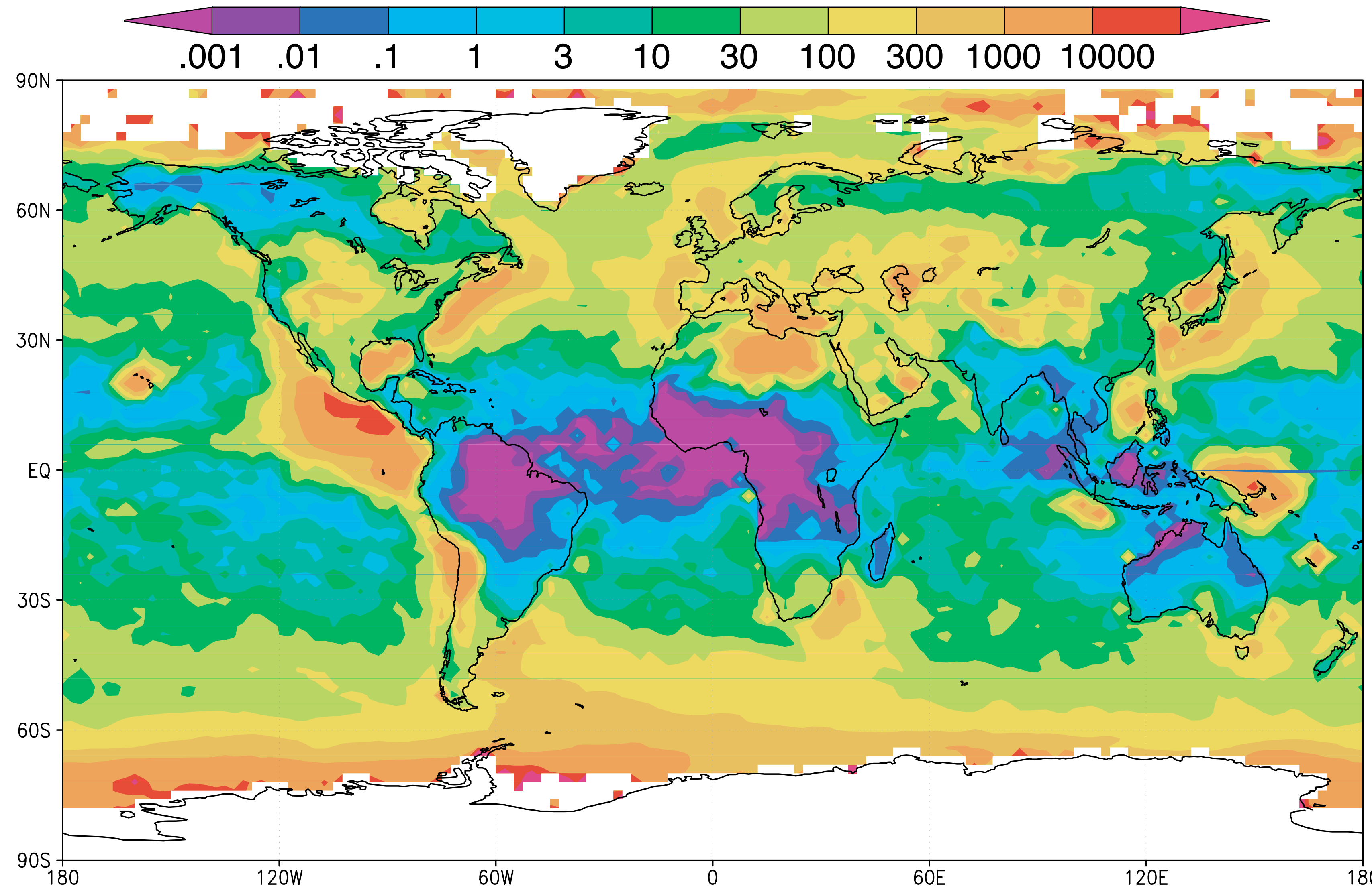
- Important source of cloud condensation nuclei is gas-to-particle conversion:
  trace gas → CN → CCN
- Ion-induced nucleation pathway is energetically favoured but limited by the ion production rate and ion lifetime





Is ion-induced nucleation globally important?

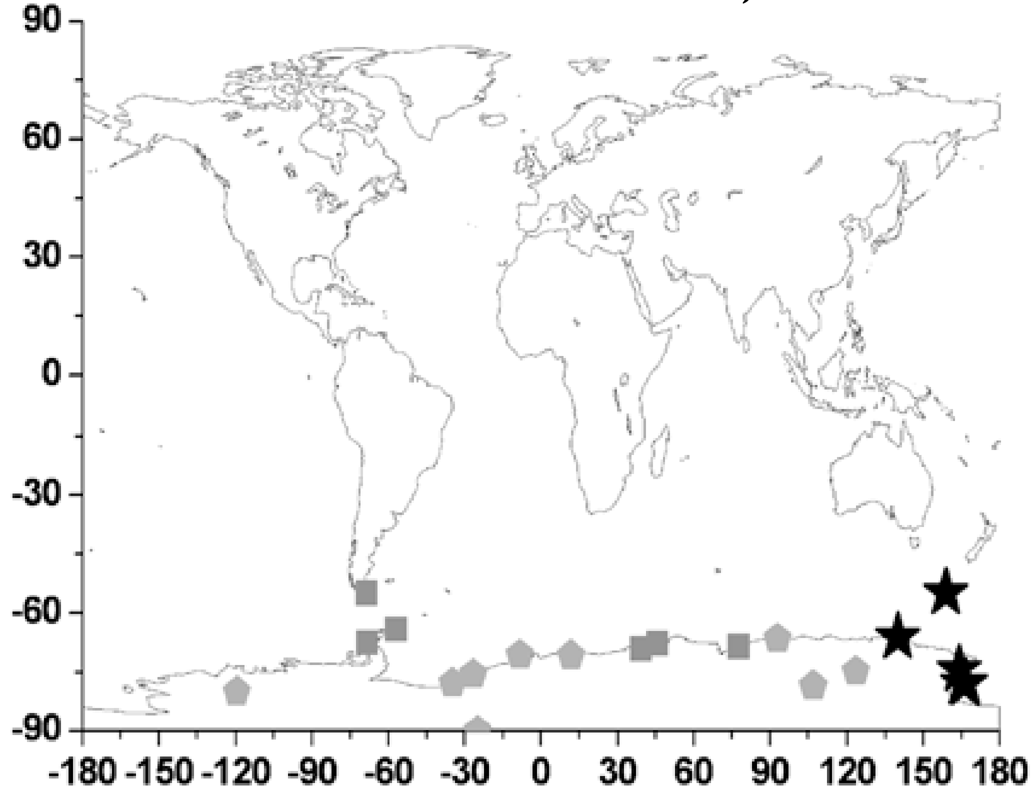
F. Yu et al., ACP 2008
Ratio of ion-induced nucleation rates to all primay aerosol sources (dust, sea salt, black carbon, organic carbon) - for lowest 3km altitude

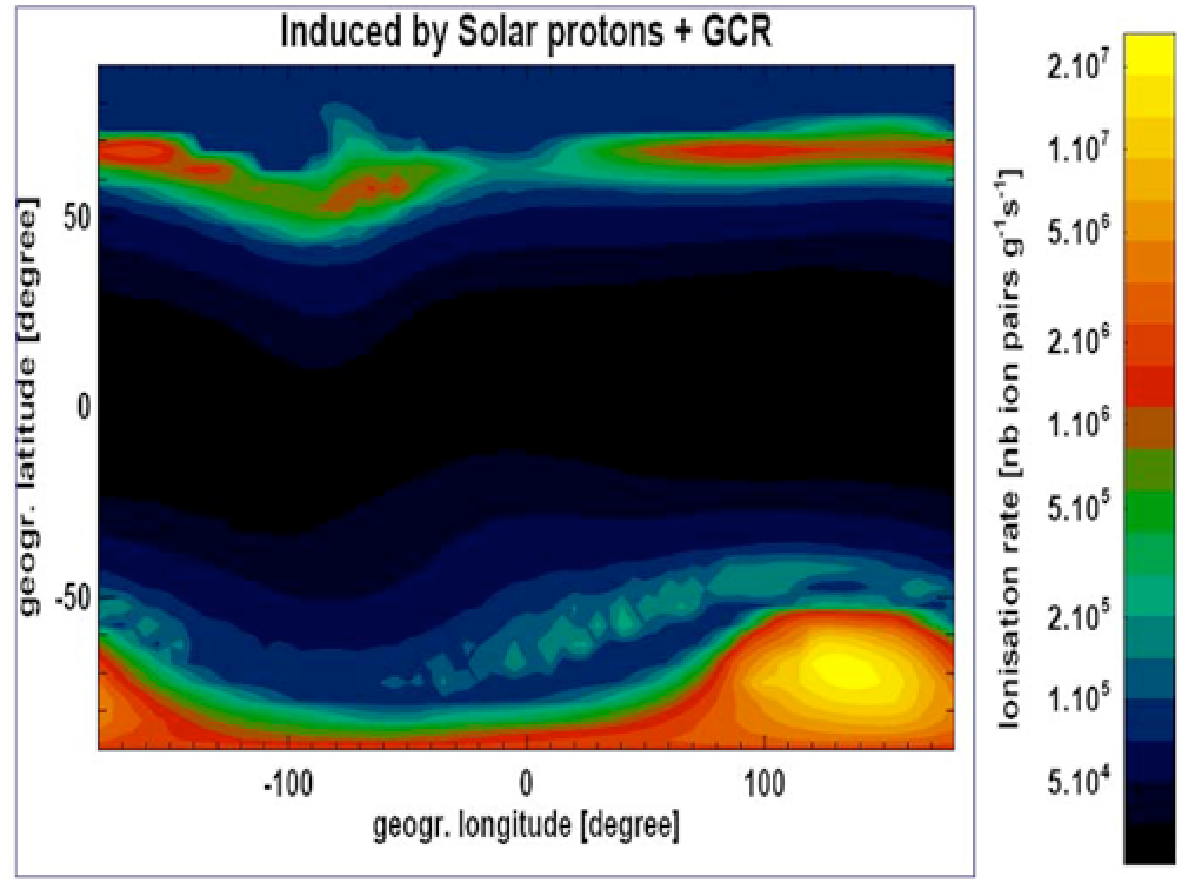


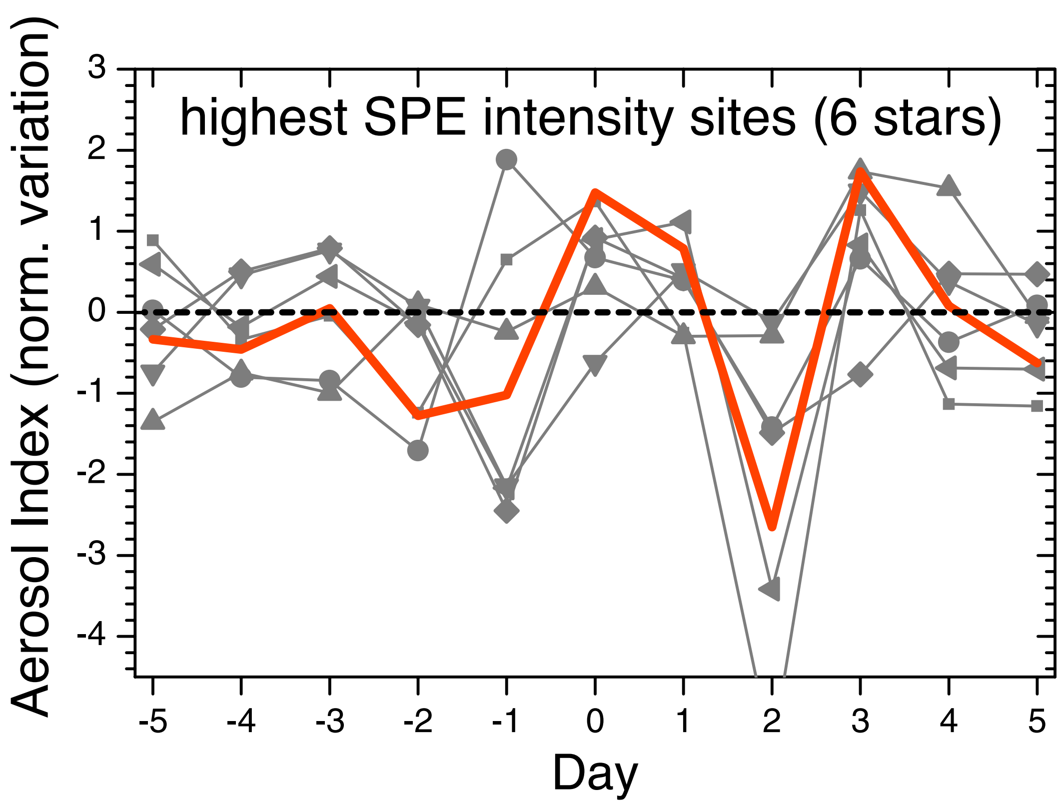
- Modeling studies:
  - Kazil et al. ACP 2006: “No”
  - Pierce & Adams GRL 2009: “No”
  - Yu et al., ACP 2008: “Yes”
- All modeling studies depend on uncertain experimental parameters
- Atmospheric observations over land (boreal forest) suggest ~10-20% of new particles are ion-induced (Laakso et al, 2007), but alternative model interpretation of same dataset (Yu and Turco, 2008) find much higher fraction, ~80%
- Ion-induced nucleation likely to be more important over oceans and at high altitudes (lower background aerosols, trace gas concentrations and temperatures) - but few measurements exist

Aerosol production by solar cosmic rays

Mironova et al, GRL 2008



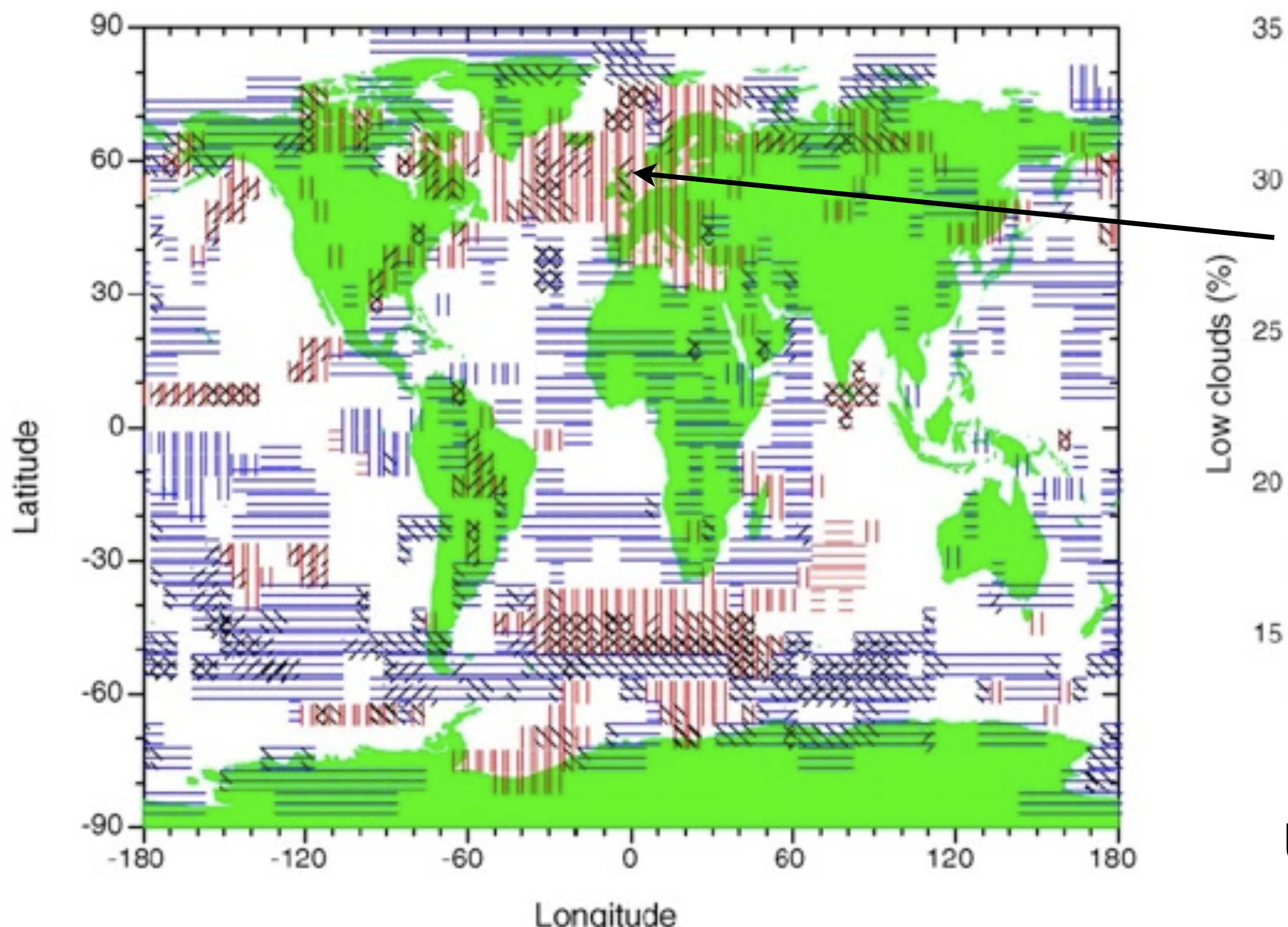


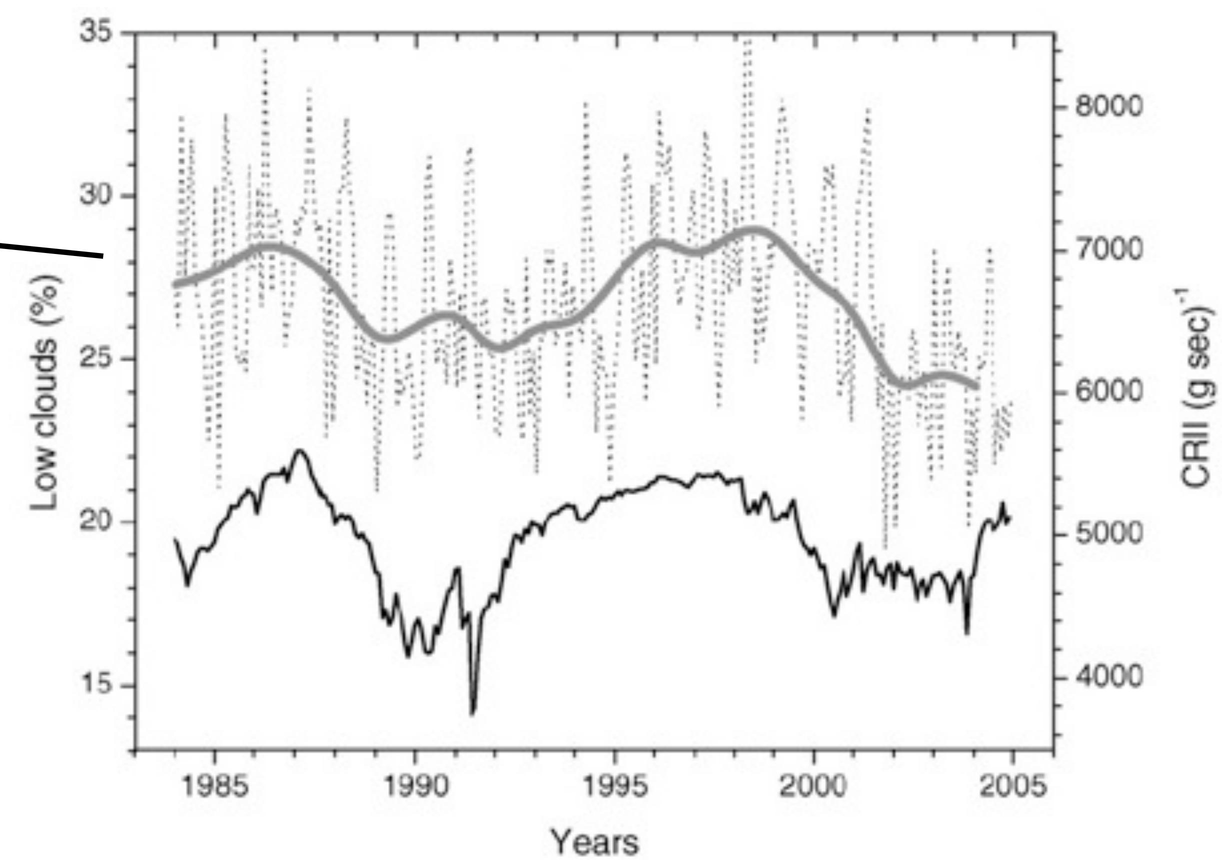


- Solar proton event 20 Jan 2005 (GLE)
- TOMS satellite measurement of optical depth/Aerosol Index (AI)
- Increase of sulphate/nitrate aerosol
- Further satellite/LIDAR observations have been made of increased aerosol production in atmosphere due to ionising particles

Cloud observations

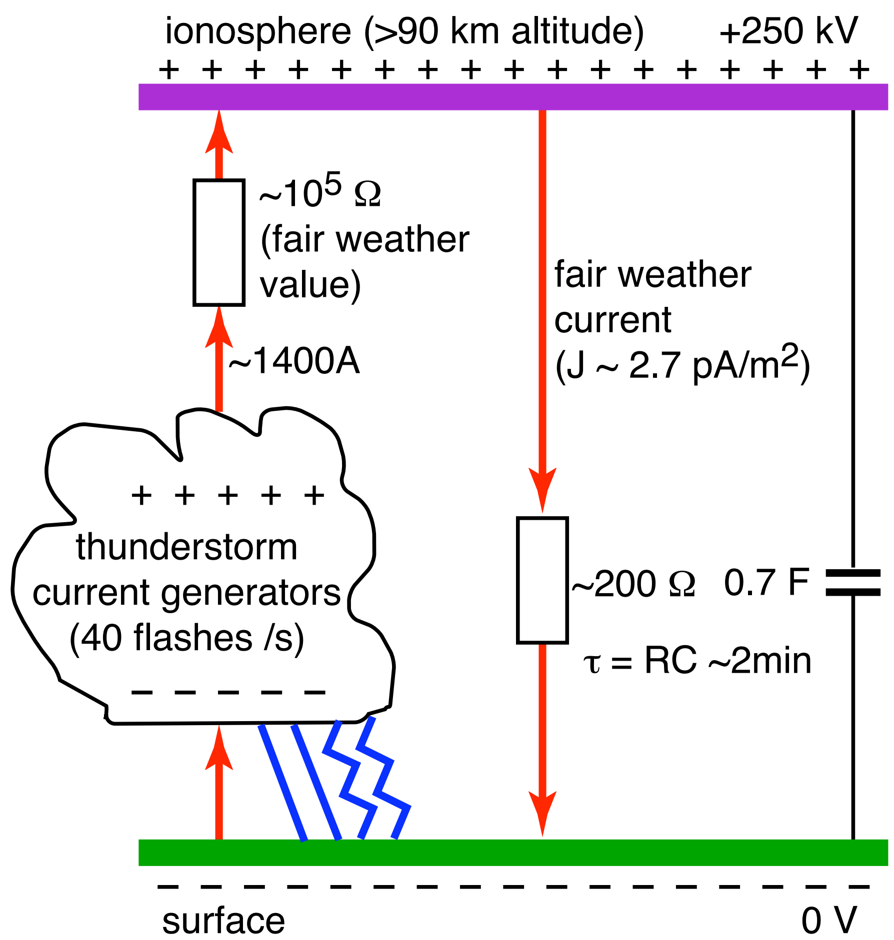
- Original GCR-cloud correlation made by Svensmark & Friis-Christensen, 1997
- Many studies since then supporting or disputing solar/GCR - cloud correlation
- Not independent - most use the same ISCCP satellite cloud dataset
- No firm conclusion yet - requires more data - but, if there is an effect, it is likely to be restricted to certain regions of globe and at certain altitudes & conditions
- Eg. correlation (>90% sig.) of low cloud amount and solar UV/GCR, 1984-2004:

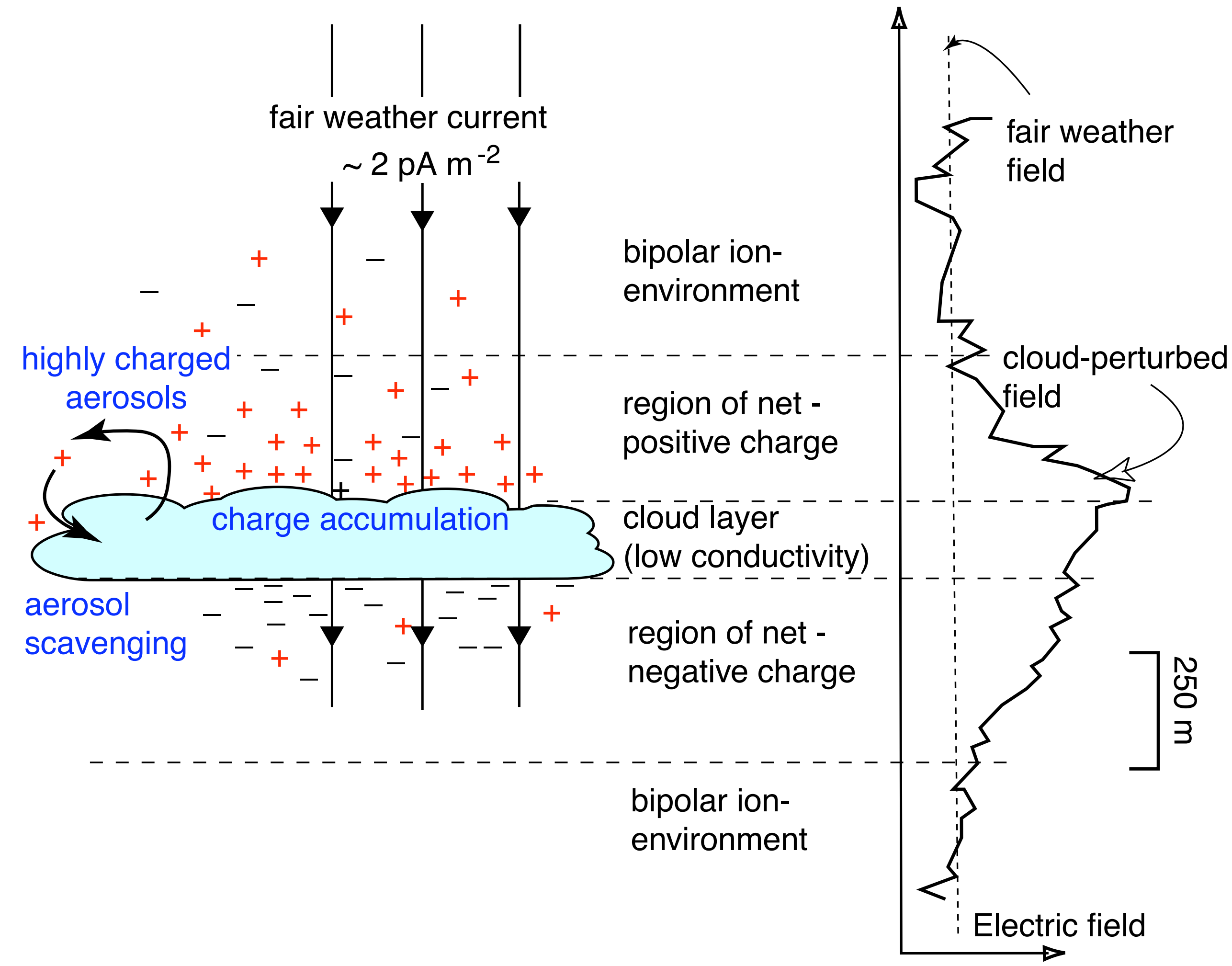




Usoskin et al, GRL 2006

Global electrical circuit





- Cosmic rays ionise atmosphere and control Earth-ionosphere conductivity
- Large aerosol charges at cloud boundaries => unipolar space charge region
- Can be entrained inside clouds and may affect:
  - Rate of aerosol accretion by cloud droplets
  - Ice particle formation
  - Atmospheric dynamics
- Largest ionisation in polar regions; many observations of cloud and T/P changes caused by Forbush decreases, solar disturbances, magnetic sector crossings...

V. CLOUD experiment at CERN

CLOUD collaboration

- 19 institutes from Europe, Russia and USA
- 14 atmospheric institutes + 5 space/CR/particle physics
- CLOUD-ITN network of 10 Marie Curie fellows: 8 PhD students + 2 postdocs

Austria:
University of Innsbruck, Institute of Ion Physics and Applied Physics
University of Vienna, Institute for Experimental Physics

Bulgaria:
Institute for Nuclear Research and Nuclear Energy, Sofia

Estonia:
University of Tartu, Department of Environmental Physics

Finland:
Helsinki Institute of Physics and University of Helsinki, Department of Physics
Finnish Meteorological Institute, Helsinki
University of Kuopio, Department of Physics
Tampere University of Technology, Department of Physics

Germany:
Goethe-University of Frankfurt, Institute for Atmospheric and Environmental Sciences
Leibniz Institute for Tropospheric Research, Leipzig

Portugal:
University of Lisbon, Department of Physics

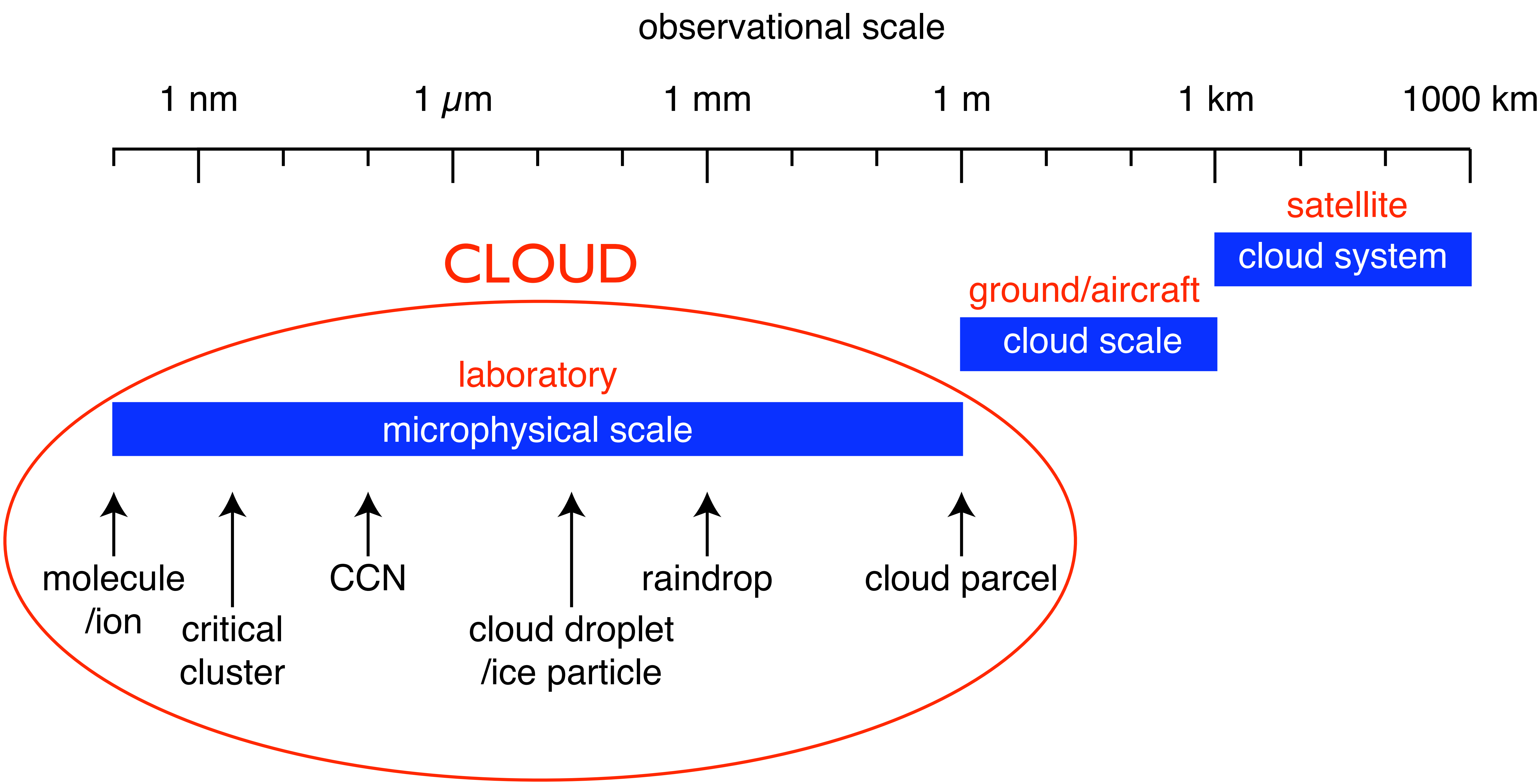
Russia:
Lebedev Physical Institute, Solar and Cosmic Ray Research Laboratory, Moscow

Switzerland:
CERN, Physics Department
Fachhochschule Nordwestschweiz (FHNW), Institute of Aerosol and Sensor Technology, Brugg
Paul Scherrer Institute, Laboratory of Atmospheric Chemistry

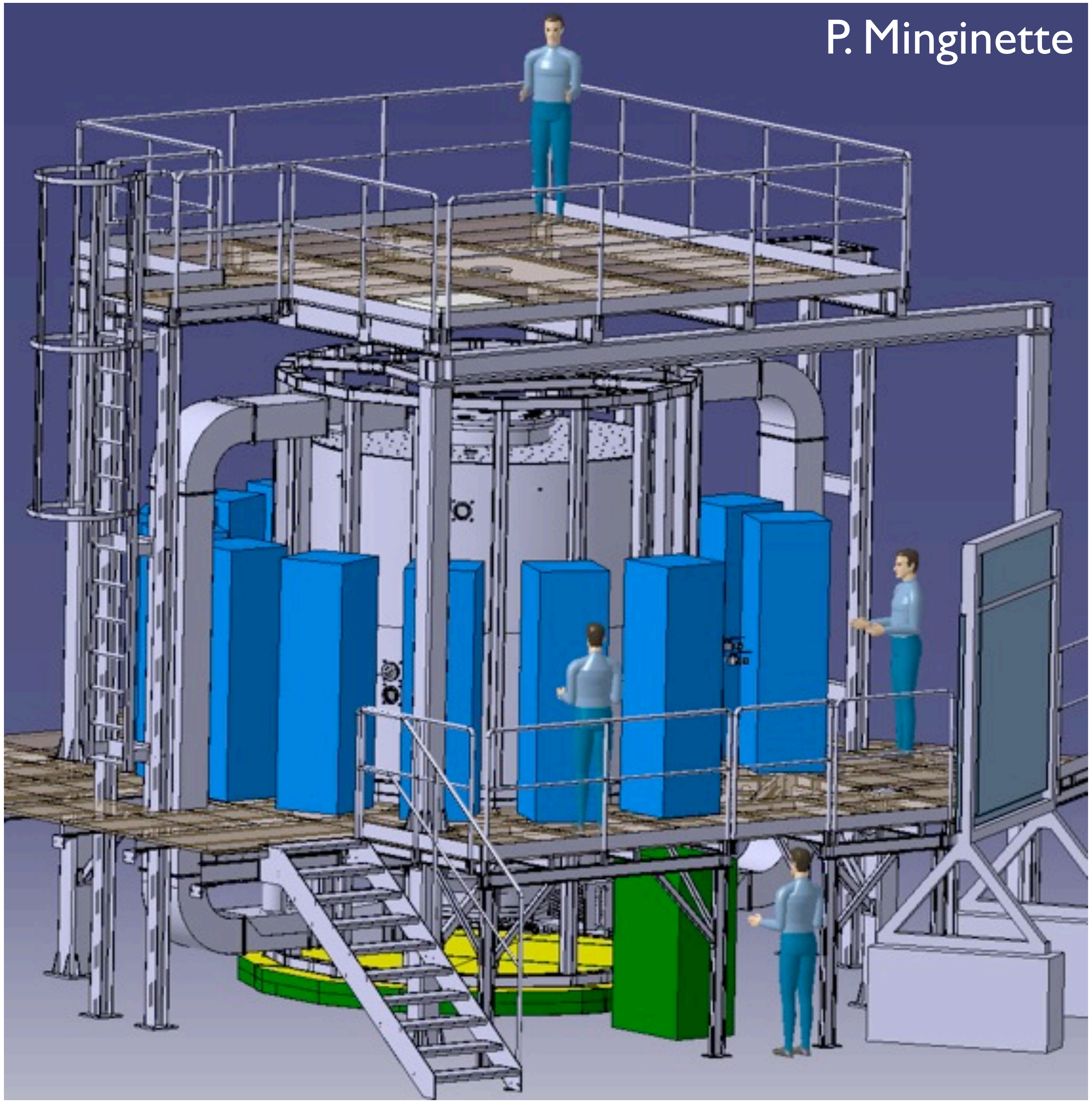
United Kingdom:
University of Leeds, School of Earth and Environment
University of Reading, Department of Meteorology
Rutherford Appleton Laboratory, Space Science Department

United States:
California Institute of Technology, Division of Chemistry and Chemical Engineering

Cloud observational scales

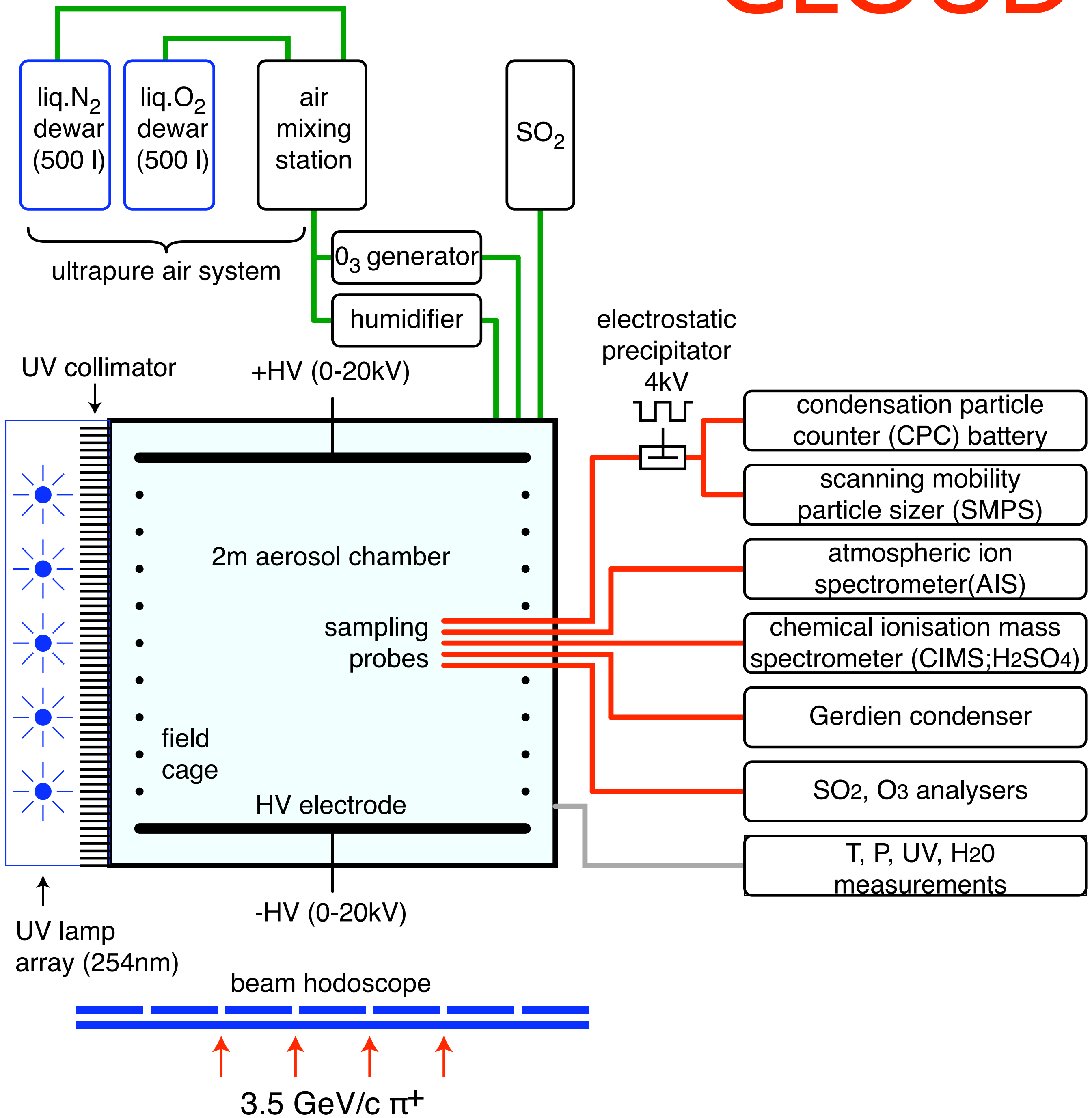


CLOUD method



- aerosol chamber + state-of-the-art analysing instruments in CERN PS beamline
- laboratory expts. under precisely controlled conditions (T, trace gases, aerosols, ions)
- study aerosol nucleation & growth; and cloud droplet & ice particle microphysics - with and without beam

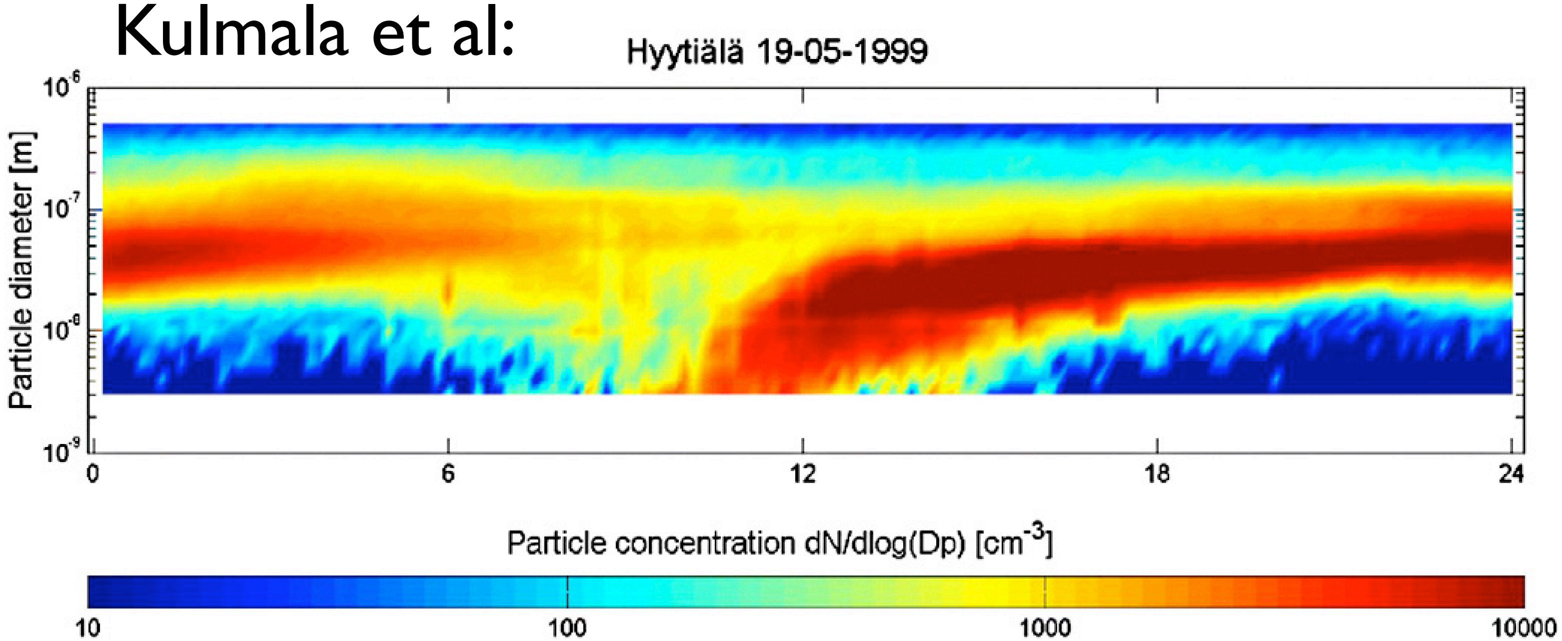
CLOUD-06

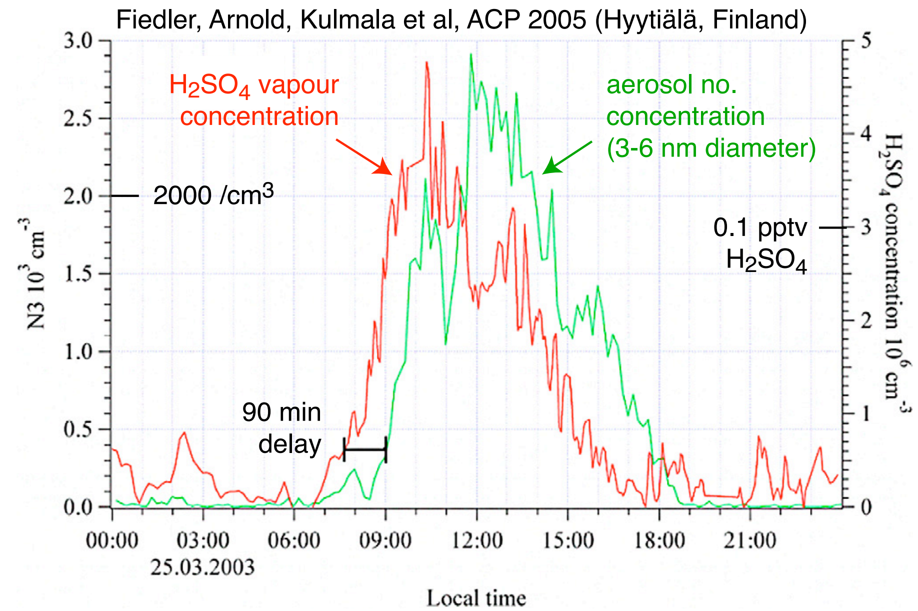


- Beam tests of pilot CLOUD experiment at CERN PS in Oct/Nov 2006
- Aims:
  - Technical input for CLOUD design
  - First physics measurements (H_2SO_4 ion-induced nucleation)

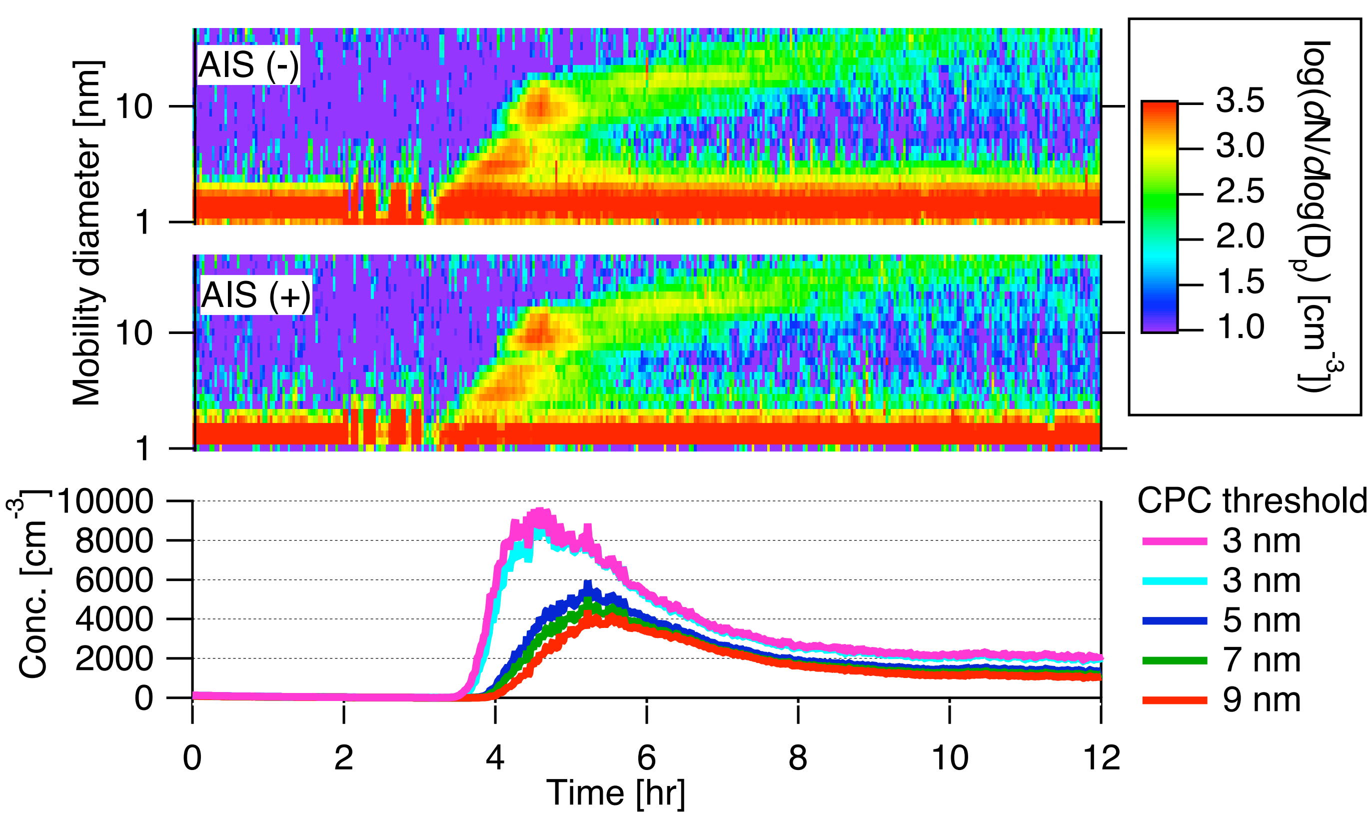
Aerosol bursts

Kulmala et al:



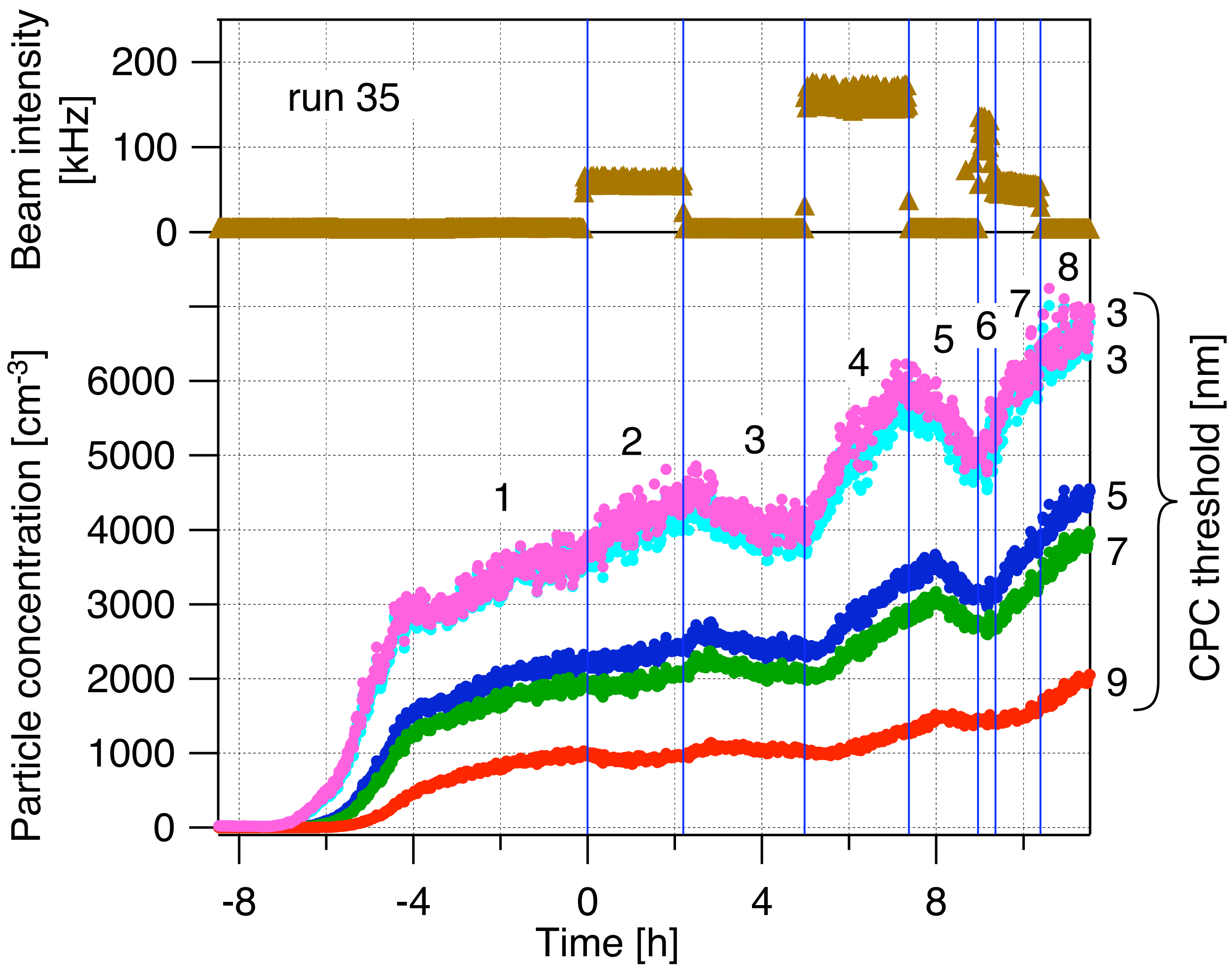


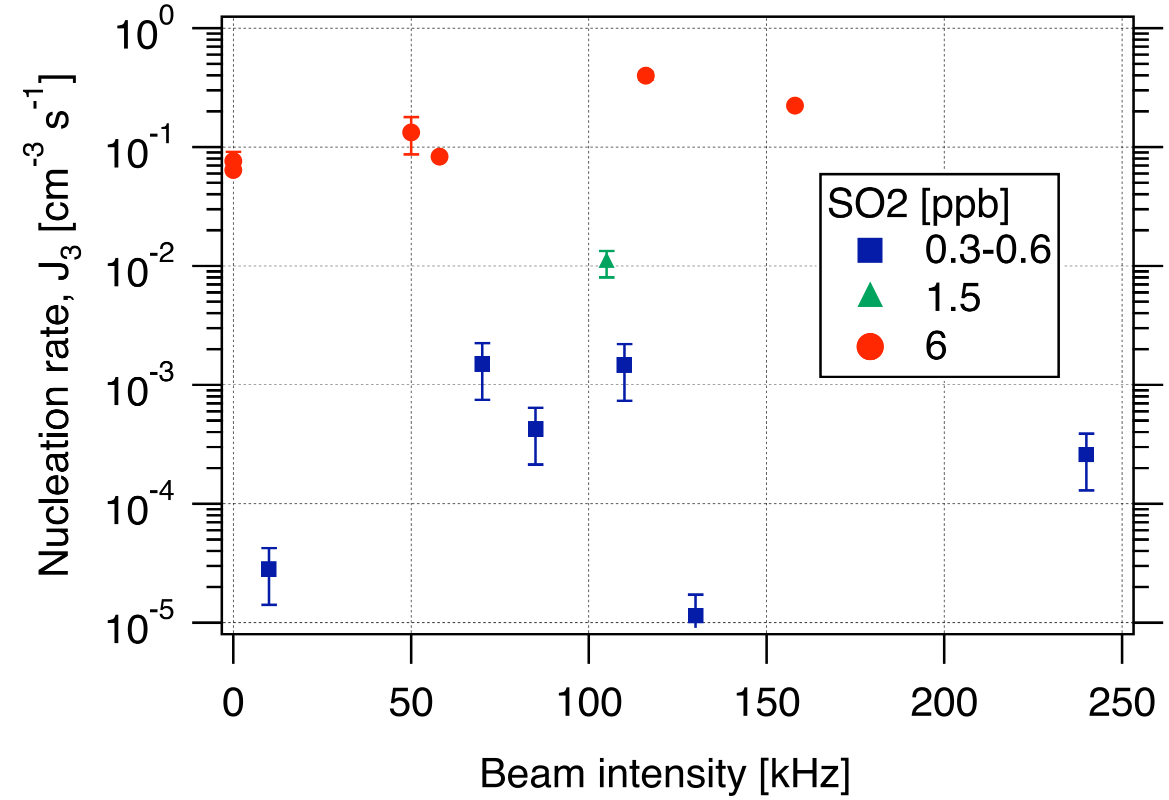
CLOUD-06 measurements:



- Bursts of aerosol particle production growing to CCN size in few hours observed throughout troposphere
- Associated with H_2SO_4 production, but at very low concentrations
- Not yet understood:
  - Extra vapours (NH_3, VOC)?
  - Ion-induced nucleation?

CLOUD-06 results



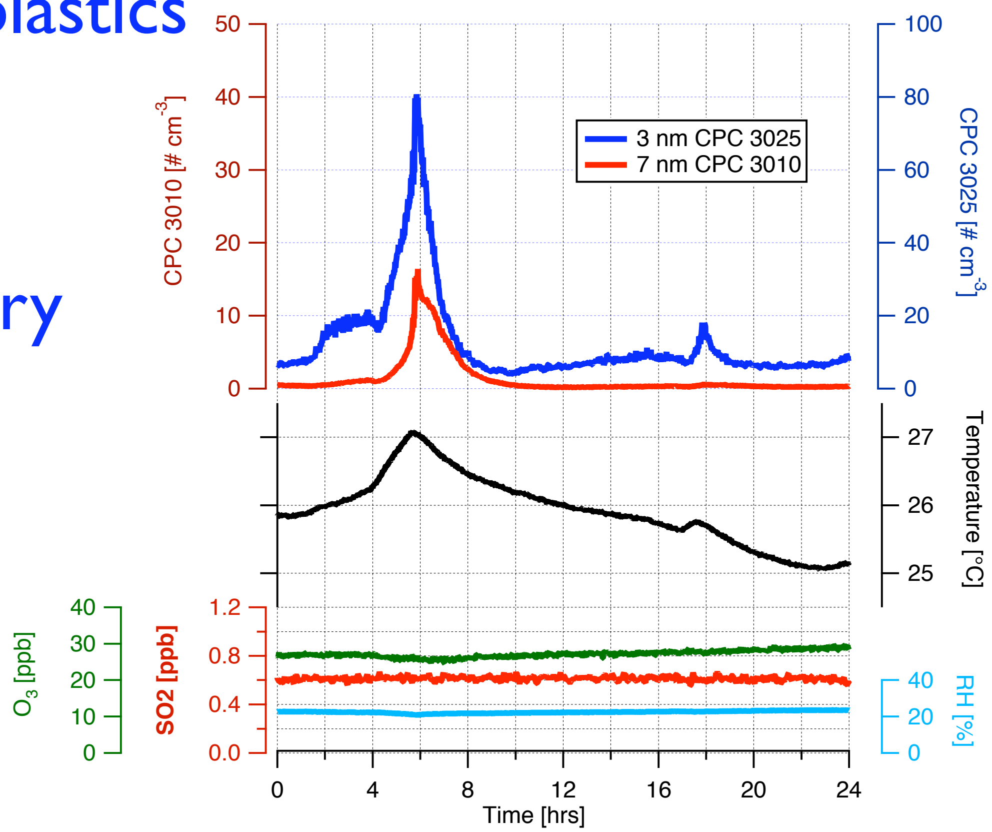


- Results of pilot CLOUD run:
  - validated the basic experimental concept of CLOUD
  - suggestive evidence for ion-induced nucleation of H_2SO_4-H_2O under atmospheric conditions
  - provided important technical input for CLOUD design

CLOUD-09 design requirements

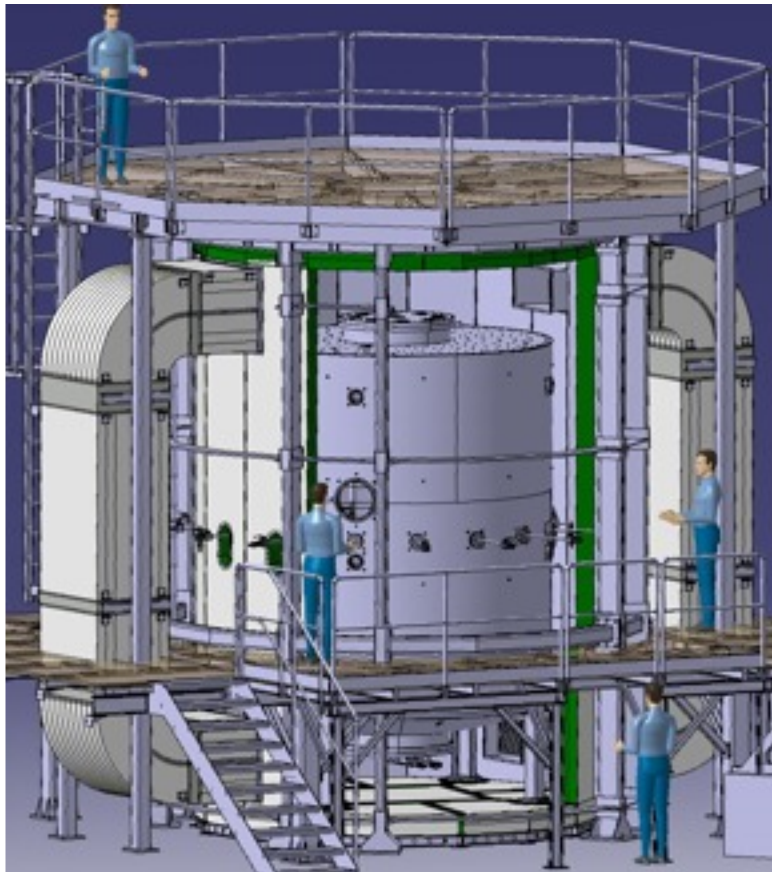
- Large chamber:
  - Diffusion lifetime of aerosols/trace gases to walls ~L^2
  - Dilution lifetime of makeup gases ~L^3

  => 3m chamber has typically 5-10 hr lifetimes
- Ultra-clean conditions:
  - Condensable vapours, eg. [H_2SO_4] ~0.1 pptv
  - Ultrapure air supply from cryogenic liquids
  - UHV procedures for inner surfaces, no plastics
- Temperature stability and wide T range
  - 0.1°C stability
  - Fibre-optic UV system for photochemistry
  - -90C → +100C range
- Field cage up to 30 kV/m:
  - Zero residual field
- Particle beam
  - Wide beam for ~uniform exposure



- Comprehensive analysers (measure "everything", as for collider detectors...)
  - Mass spectrometers for H_2SO_4, organics, aerosol composition

CLOUD-09 chamber at CERN



CLOUD plans

- 2009:
  - commission CLOUD-09
  - study H_2SO_4-H_2O nucleation with and without beam
  - reproducibility of nucleation events
  - PTR-Mass Spect. to measure organics at 10 pptv level
  - new ion-TOF Mass Spect. for ion characterisation
- 2010:
  - commission thermal system (-90C → +100C)
  - study H_2SO_4/water + volatile organic compounds with and without beam
  - temperature dependence (effect of altitude)
- 2011-2013:
  - extend studies to other trace vapours, and to cloud droplets & ice particles (adiabatic expansions in chamber)

Conclusions

- Climate has continually varied in the past, and the causes are not well understood - especially on the 100 year timescale relevant for today's climate change
- Strong evidence for solar-climate variability, but no established mechanism. A cosmic ray influence on clouds is a leading candidate
- CLOUD at CERN aims to study and quantify the cosmic ray-cloud mechanism in a controlled laboratory experiment
- The question of whether - and to what extent - the climate is influenced by solar/cosmic ray variability remains central to our understanding of anthropogenic climate change