Effects of the 11-Year Solar Cycle on the Atmosphere from the surface to the lower thermosphere

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Outline

- The atmospheric response to irradiance variations during the 11-year solar cycle
  - Motivation
  - Model description and Experimental Setup
  - Ozone
  - Temperature
  - Dynamics
  - Summary

The sun - our energy source

- Solar energy is the most important energy source for Earth
  - **Sun: 342 W/m^2 averaged over the Earth surface and a year**
  - internal energy produced by Earth about 0.087 W/m2 (Pollack *et al*., 1993)
- Use of solar energy intercepted by Earth
  - 100% = solar constant, intercepting area = $\pi \cdot a^2$ = ¼ Earth surface
  - **31% reflected back to space**
  - **20% absorbed in the atmosphere**
  - **49% absorbed at the surface**
    - 23% evaporate water → latent heat flux to the atmosphere
    - 7% sensible heat flux to the atmosphere
    - 19% net emission by infrared radiation
      - 114% upward flux
      - 95% downward flux
  - **Greenhouse effect of atmosphere:** H2O, CO2, O3, clouds, aerosols **raises average surface temperature by about 30°C** compared to the black body temperature that equilibrates the average solar irradiation.

Variability of solar irradiation

Irradiation at the top of the atmosphere varies for different reasons:

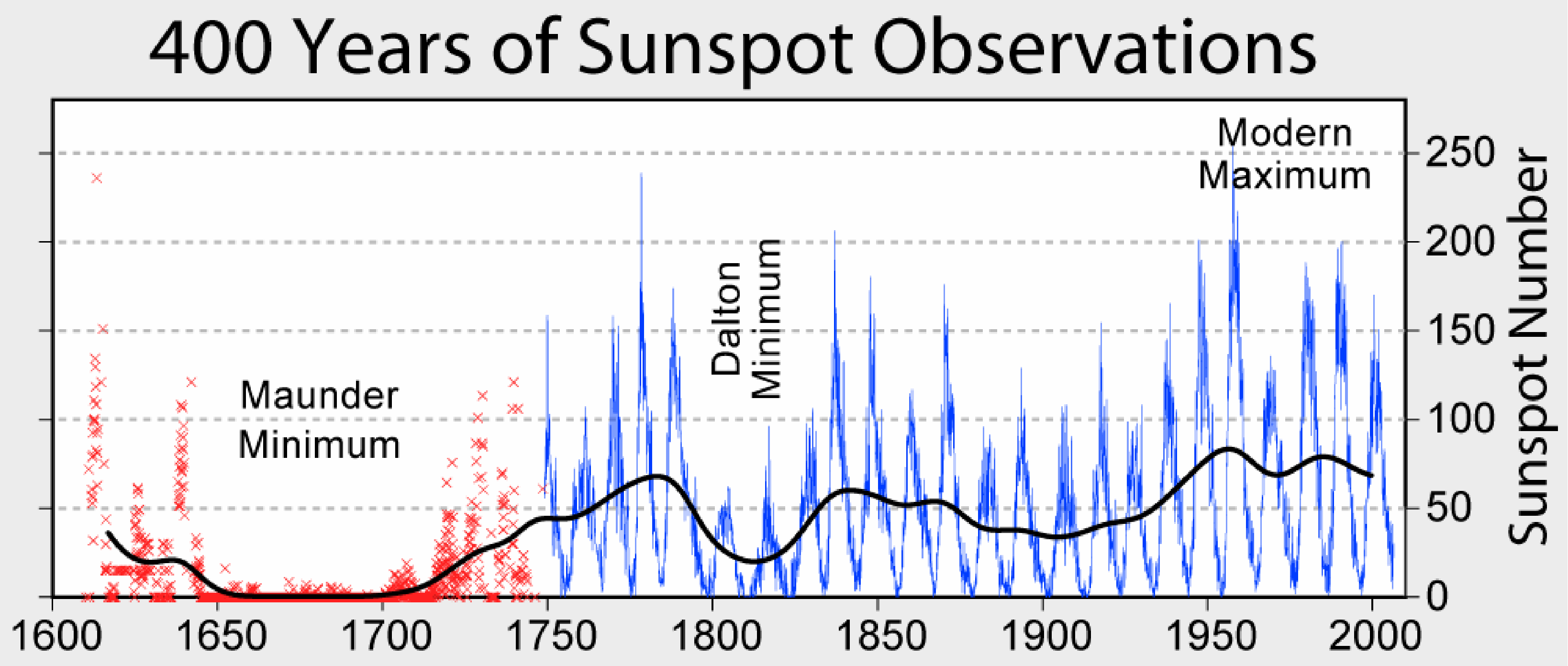
- Rotation of Earth → day night, diurnal cycle
- Tilt of Earth axis vs. ecliptic → annual cycle, summer/winter
- Eccentricity of orbit → more solar irrad. during NH winter
- All these factors change with time
  →Milankovich theory for ice ages

- Variability of solar emission → variability of solar “constant”
  “solar constant” = energy flux at average sun Earth distance
  = Total Solar Irradiation TSI

- **Only the last point is the subject of this presentation**

Discovery of solar variability - Sunspots

European record back to the early 17th century, telescope observations

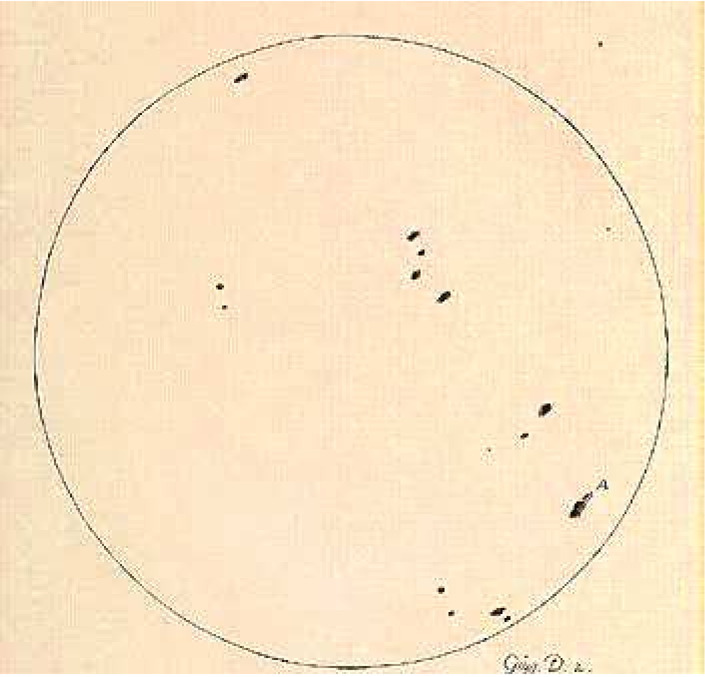


(source: Wikipedia)

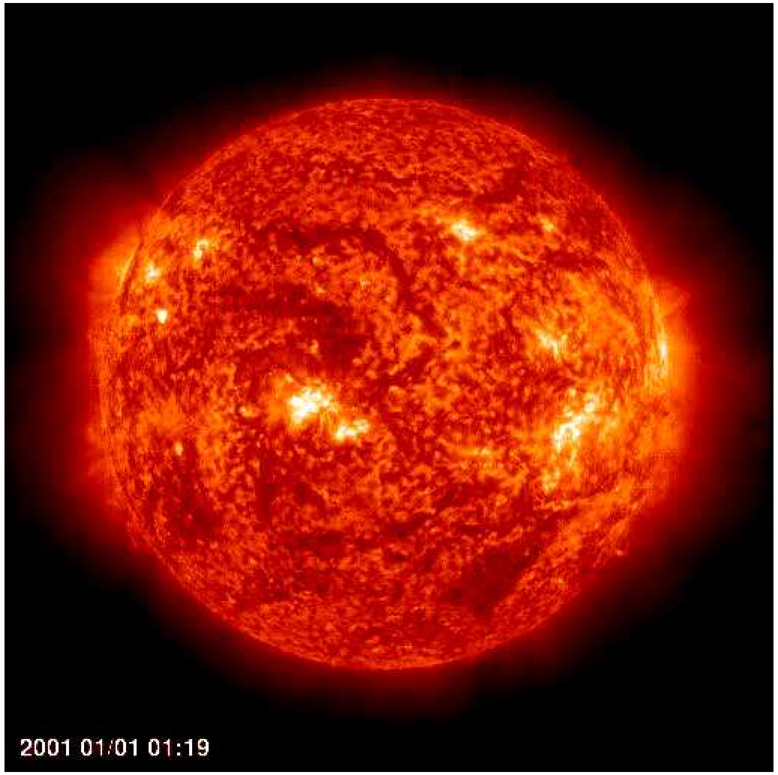
The Maunder Minimum happened to coincide with a cold period in Europe
→ Dutch winter paintings

The variability of the sun

Sunspots



Faculae

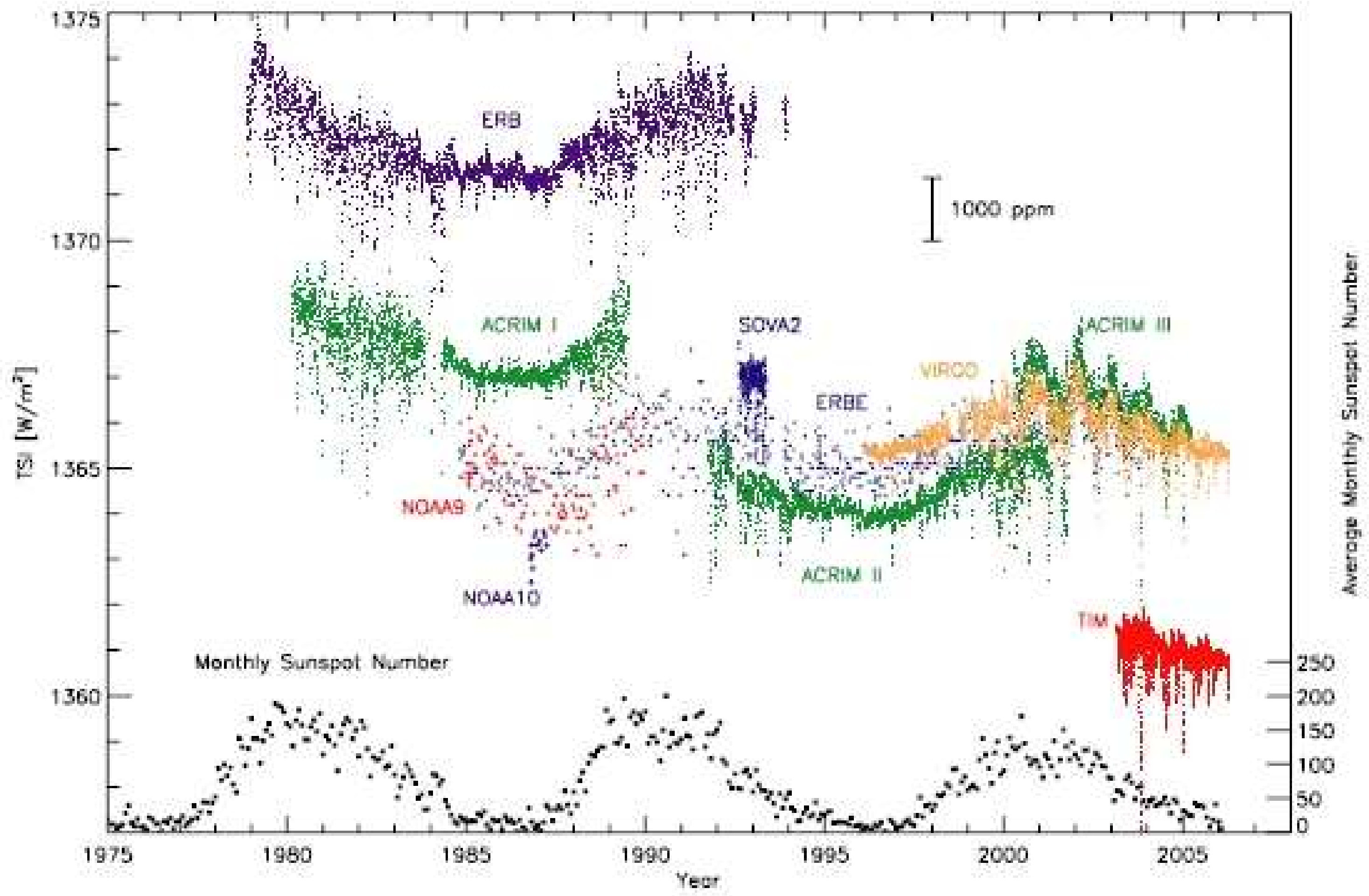


(source: Galileo Galilei, 1612)

(source: SOHO webpage)

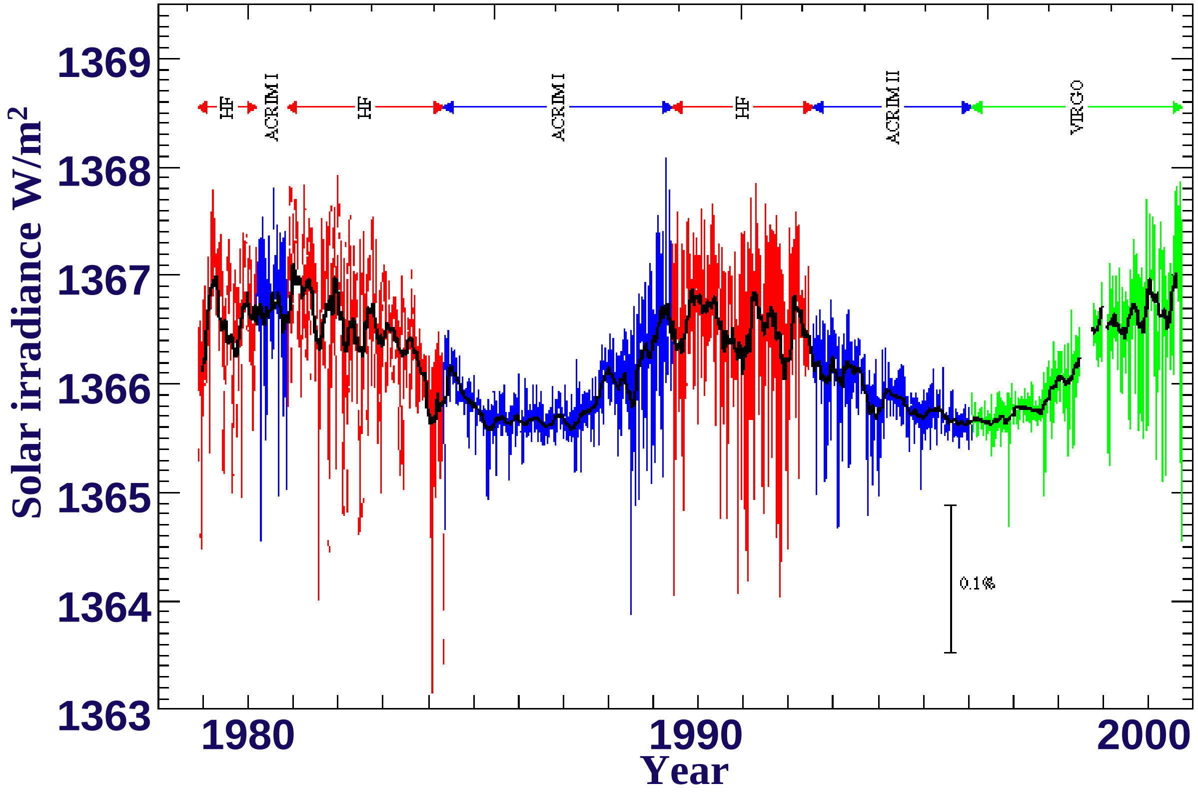
Satellite observations of the TSI

- From the ground: Difficult because of atm. Scattering and abs.
- From space since 1978 by several instruments
  Rottman, Space Science Reviews, 2006:



TSI time series

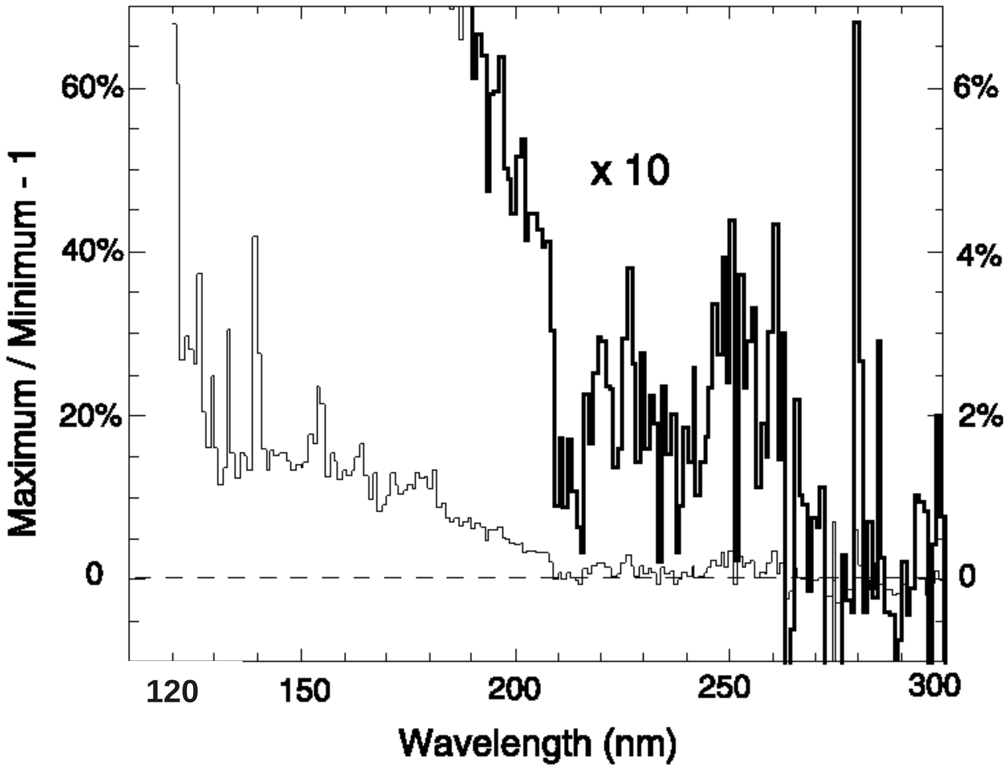
- TSI = ~1366 W/m2
  11-year solar cycle signal in TSI = ~0.1%
- Area averaged signal = 1366 W/m^2 · 0.001 · ¼ = 0.34 W/m^2



Fröhlich, Adv. Space Res. (2002)

Spectral maximum to minimum ratio in the UV

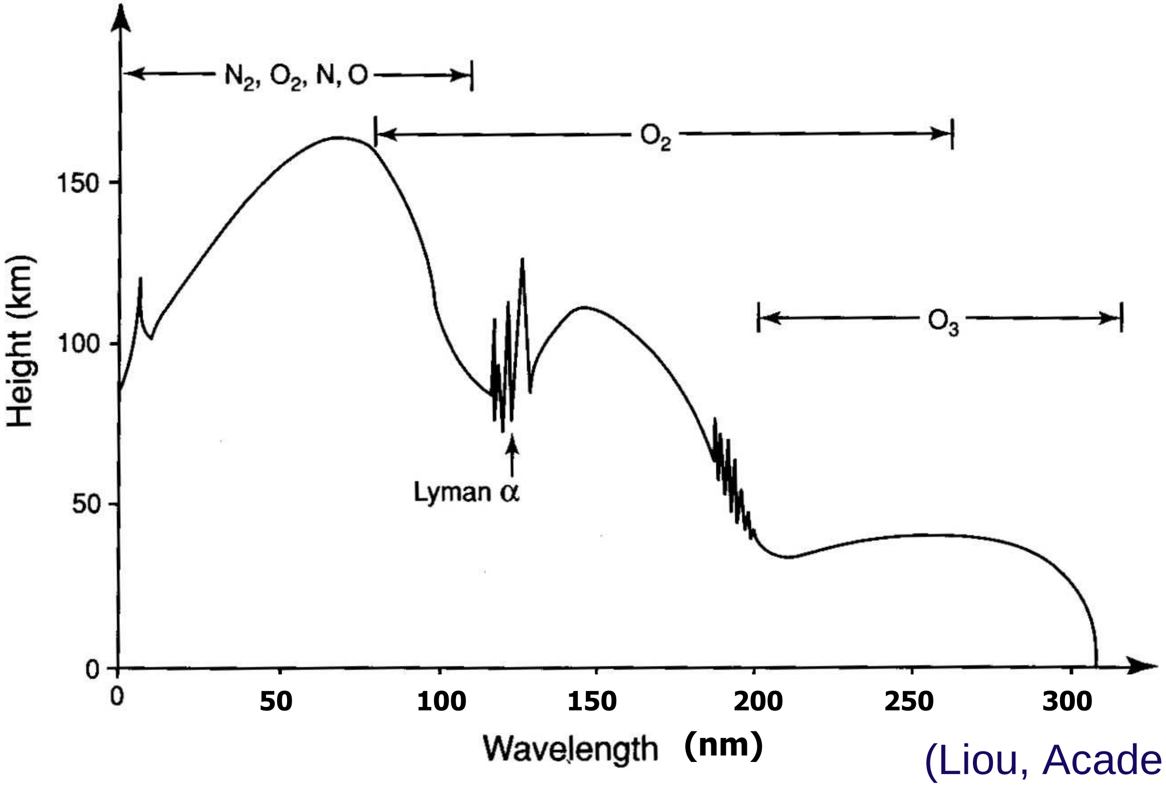
Variability of solar UV irradiance as given by UARS / SOLSTICE
(Maximum: 1992, Minimum: 1996)



(Rottmann, Space Sc. Rev., 2000)

Penetration depth of solar radiation in the atmosphere

- Significant solar cycle effects in chemical composition and temperature must be expected in upper and middle



(Liou, Academic Press, 2002)

How does solar variability modify the climate?

1. From the surface
    - Because 49% of the average solar irradiation si absorbed at the surface
    - Although TSI changes by only 0.1%?
    - Although thermal inertia of oceans is huge?

    → Involves coupling of atmosphere ocean

2. From the upper and middle atmosphere
    - Because spectral solar variability changes much stronger
    - Can change chemical composition and temperature
    - Although little energy is available in the UV spectrum?

    → Involves coupling of dynamical, chemical and physical processes

This study deals only with point 2.

Solar cycle effects in observations

- Is a **detection and attribution** problem as long as the processes are not fully understood

- **Detection:**
  - Other forcings may also occur at intervals similar to 11 y: Volcanoes: El Chichon 1982 and Mt. Pinatubo 1991
    → Difficulty to detect solar cycle signal in short time series
  - Must be guided by a working hypothesis

- **Attribution:**
  Atmospheric dynamical modes that can be excited by different forcings.
  → Difficulty to attribute observed variations in the lower atmosphere to solar cycle, or in the high latitude stratosphere

Attribution

Symposium sur les relations entre phénomènes solaires et terrestres

RELATIONS ENTRE PHENOMENES SOLAIRES ET TERRESTRES EN BIOLOGIE

par Hellmut BERG † *

Il existe une abondante littérature sur les relations entre phénomènes solaires et terrestres en biologie, mais en la parcourant, on ne peut s'abstenir parfois de sourire. En particulier, la périodicité de onze ans

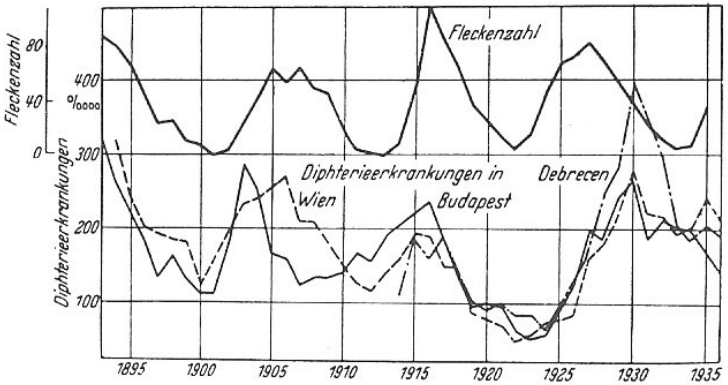


Fig. 1.

Courbe supérieure : activité solaire représentée par le nombre relatif de tac
(moyennes annuelles).

Courbes inférieures : nombre de cas de diphtérie dans trois villes de l
Centrale (moyennes annuelles).

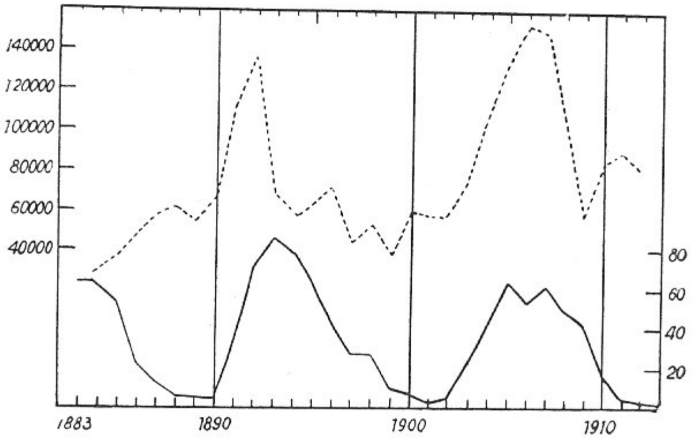
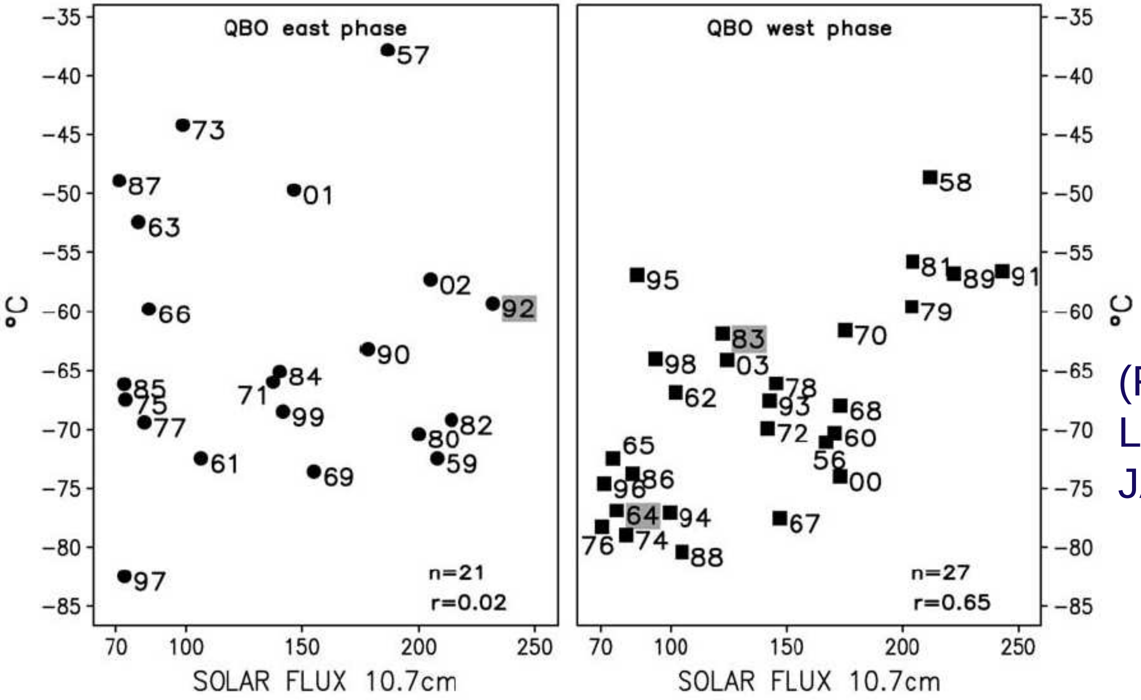


Fig. 2.

Courbe inférieure : activité solaire de 1883 à 1913.
Courbe supérieure : immigration juive aux Etats-Unis d'Amérique.

Solar cycle signal in North pole temperature at 30 hPa in February, depends on the phase of the QBO

North Pole temperatures, February, 30 hPa



(FU-Berlin data, Labitzke, JASTP, 2005)

Fig. 1. Scatter diagrams of the monthly mean 30-hPa temperatures (°C) in February at the North Pole against the 10.7 cm solar flux. Left: years in the EAST PHASE of the QBO ($n = 21$); right: years in the WEST PHASE ($n = 27$). The numbers indicate the respective years, shaded are 3 Februaries after large volcanic eruptions; r = correlation coefficient. Data: FU-Berlin 1956–2001; later ECMWF (Labitzke and Collaborators, 2002).

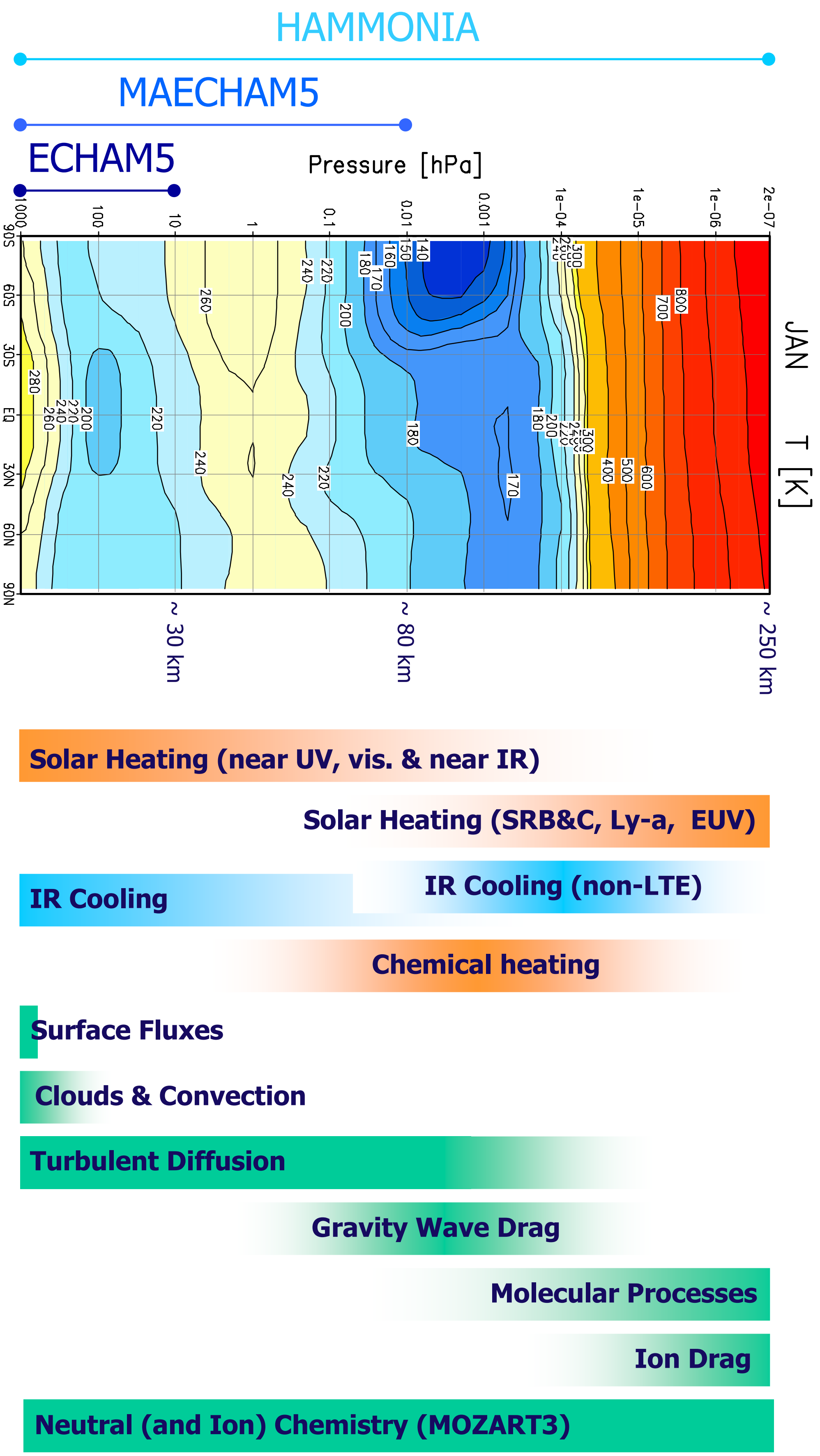
Numerical models

- Numerical models are the laboratory to test the role of processes in the climate, or to explore the dynamic variability of the climate system.

- Numerical models are:
  - Simplified numerical analogues of the real world
  - Can be employed for systematic experiments, unlike nature

- The numerical model used here: The HAMburg Model of the Neutral and Ionized Atmosphere **HAMMONIA**

HAMMONIA – a member of the ECHAM family



Solar Heating (near UV, vis. & near IR)

Solar Heating (SRB&C, Ly-a, EUV)

IR Cooling

IR Cooling (non-LTE)

Chemical heating

Surface Fluxes

Clouds & Convection

Turbulent Diffusion

Gravity Wave Drag

Molecular Processes

Ion Drag

Neutral (and Ion) Chemistry (MOZART3)

Max Planck
Institute for
Meteorology

Model configuration and experiments

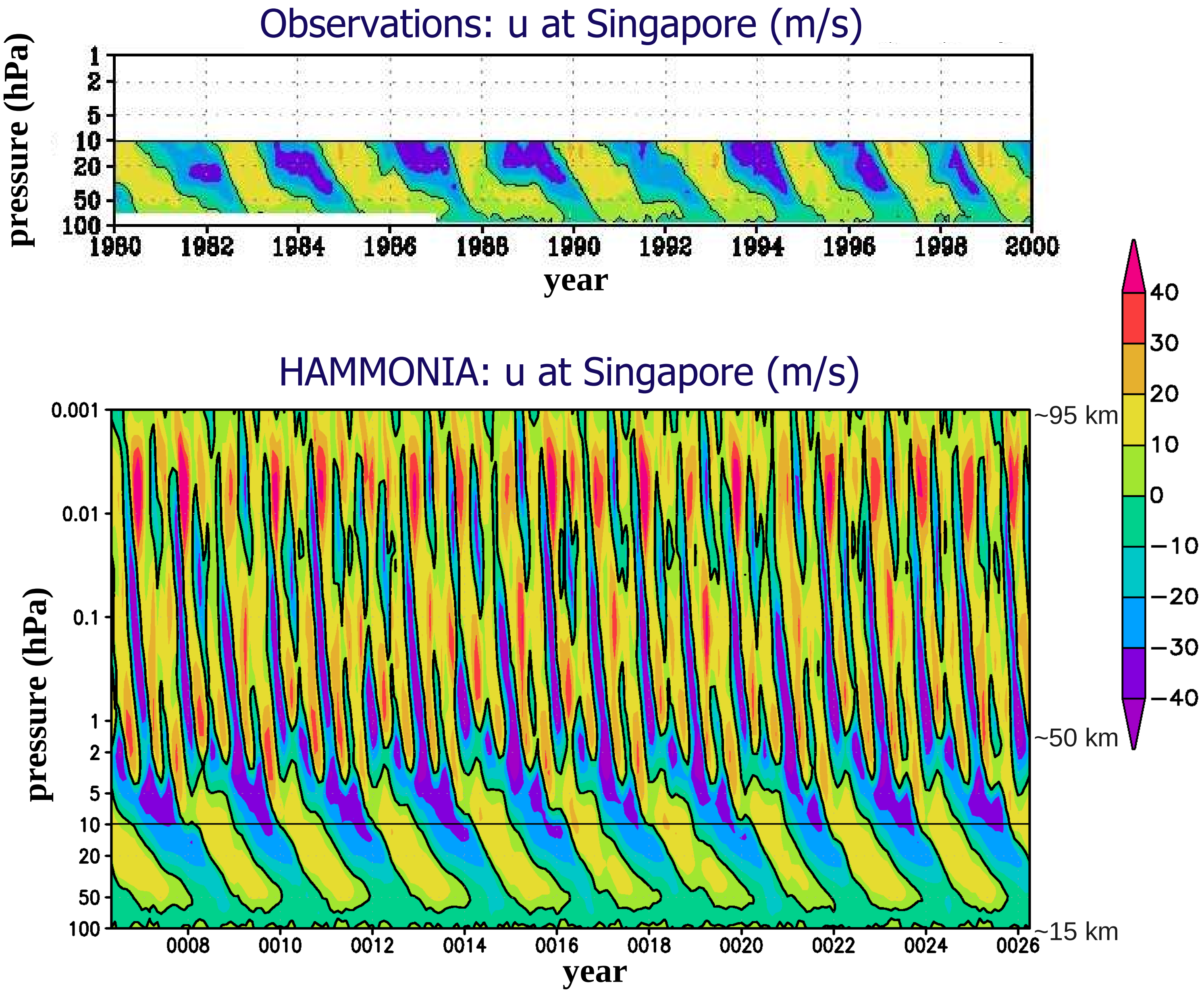
Configuration:

- Horizontal resolution in spectral space: max. wavenumber = 31
- Horizontal resolution of the associated grid: 3.75°x3.75°
- Vertical resolution: 119 layers up to 2.e-7 hPa or ~250 km

Experiments:

- Two experiments with permanent solar maximum and solar minimum irradiation, respectively
  - **Exp 1: 35 yr solar minimum (September 1986, F10.7=69)**
  - **Exp 2: 35 yr solar maximum (November 1989, F10.7=235)**
- Irradiance resolved at 1nm for λ>120nm (Lean et al.,JGR, 1997)
- Extreme UV modulated following (Richards et al., JGR, 1994)
- Thermospheric NO production is increased by 33% for solar maximum
- Sea surface temperature specified from observed climatology

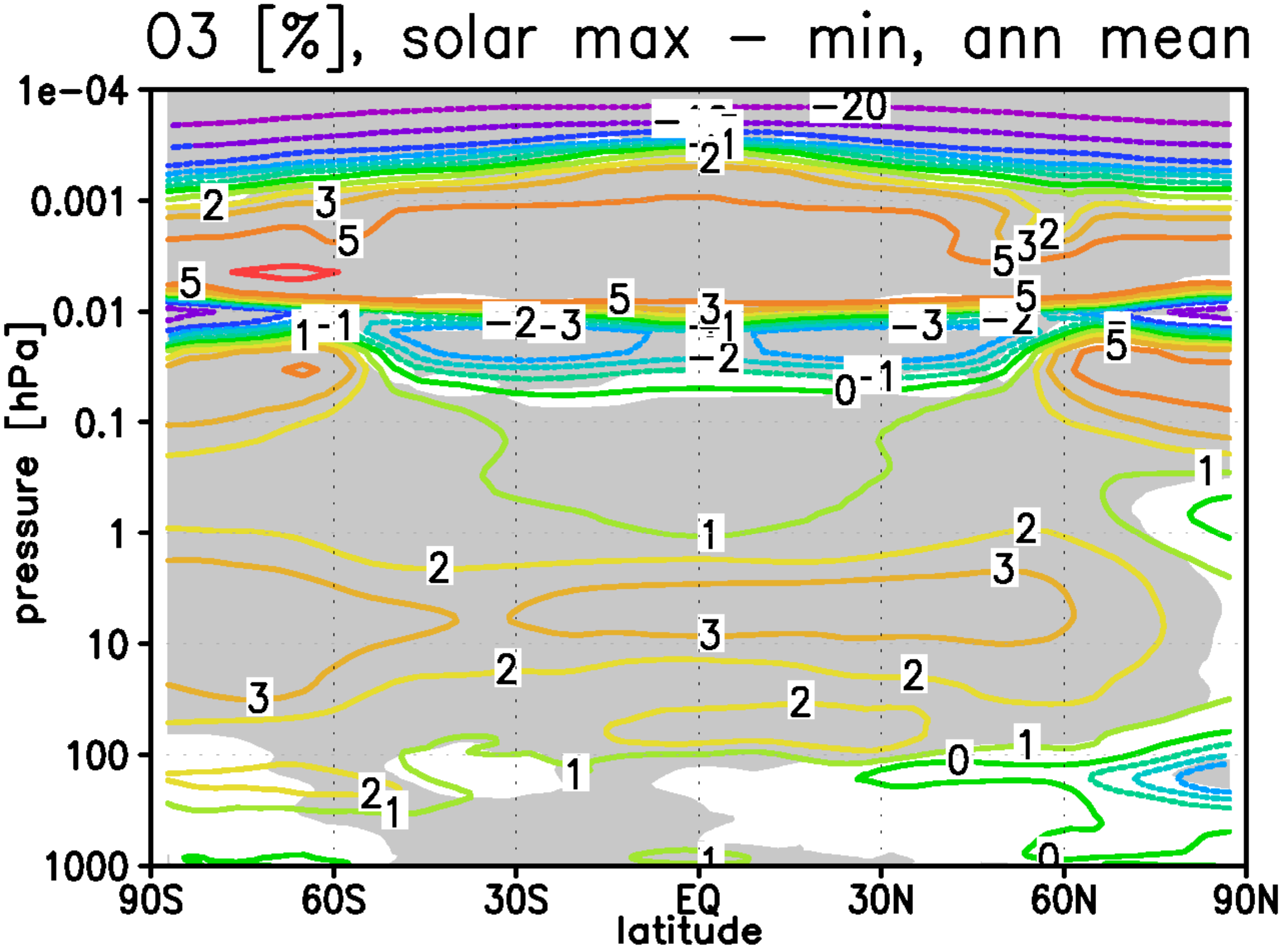
The quasi-biennial oscillation (QBO) observed and simulated



Observations: u at Singapore (m/s)

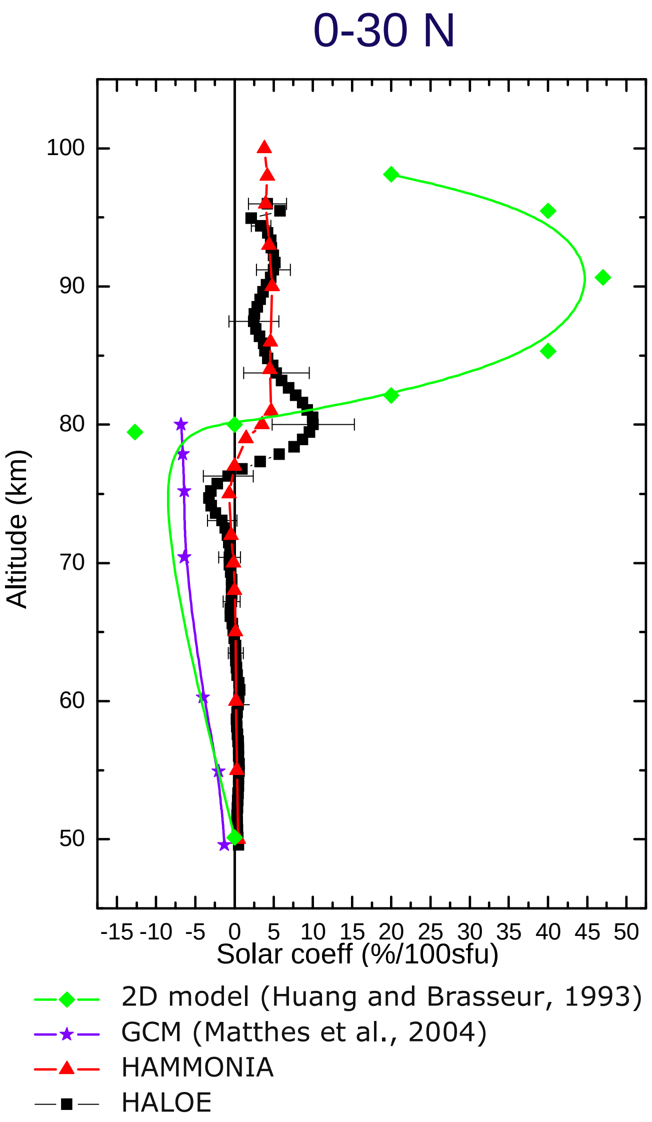
HAMMONIA: u at Singapore (m/s)

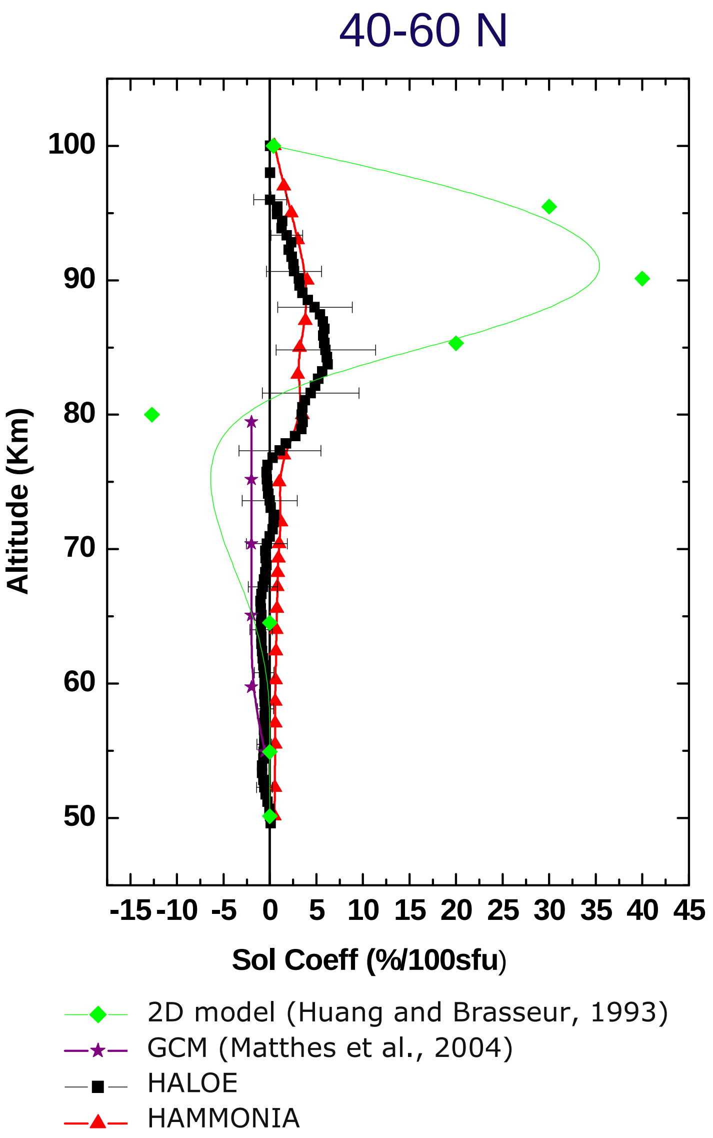
The solar cycle effect on annual mean ozone - simulated



gray: significance > 95%

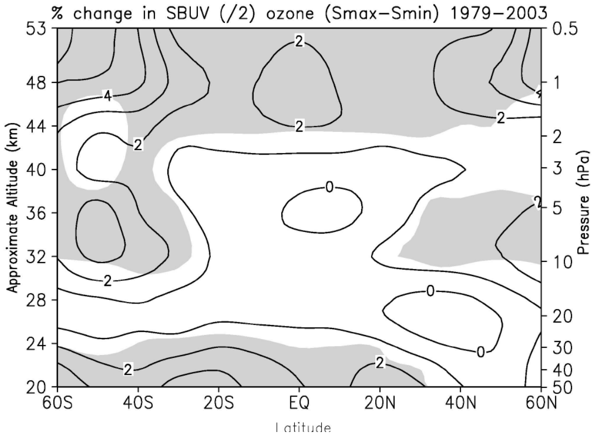
Solar cycle response of mesospheric ozone – observed and simulated

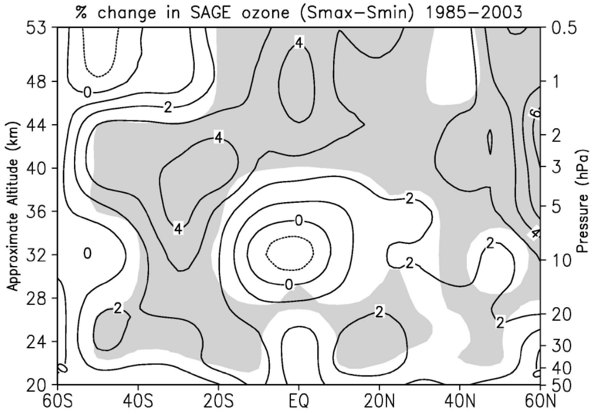


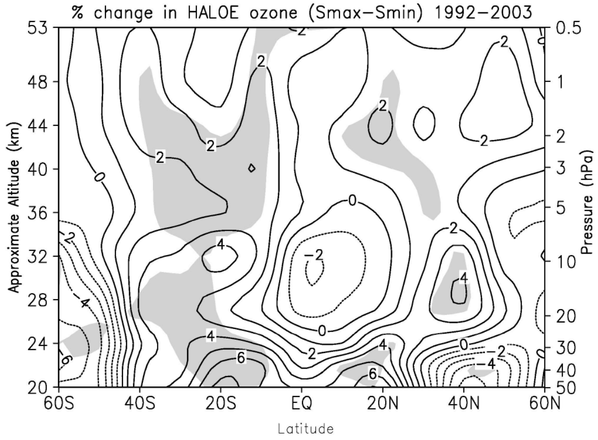


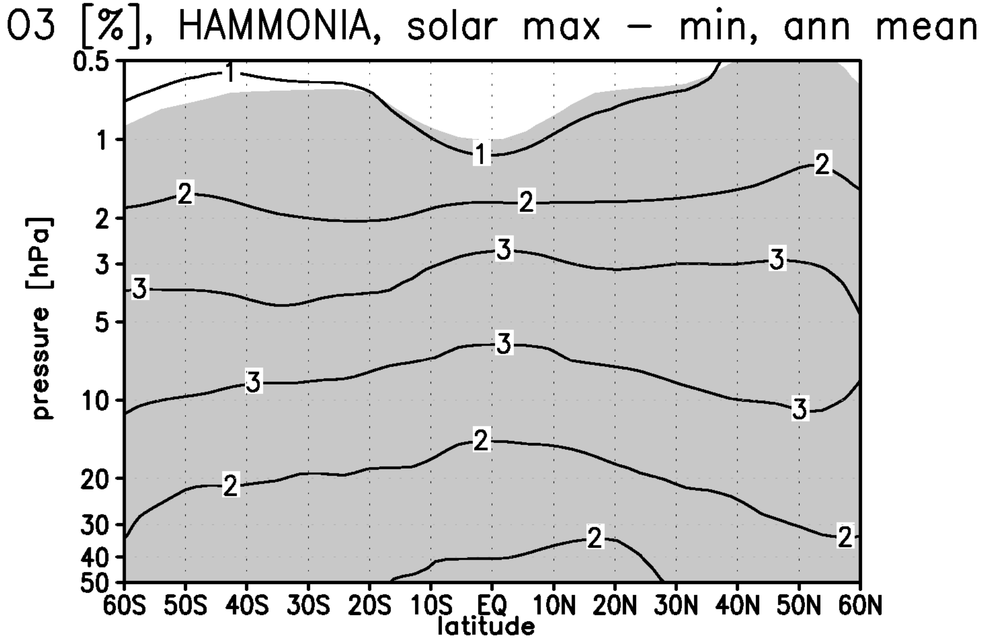
(courtesy by G. Beig, Pune, India)

Solar cycle response of stratospheric ozone observed and simulated





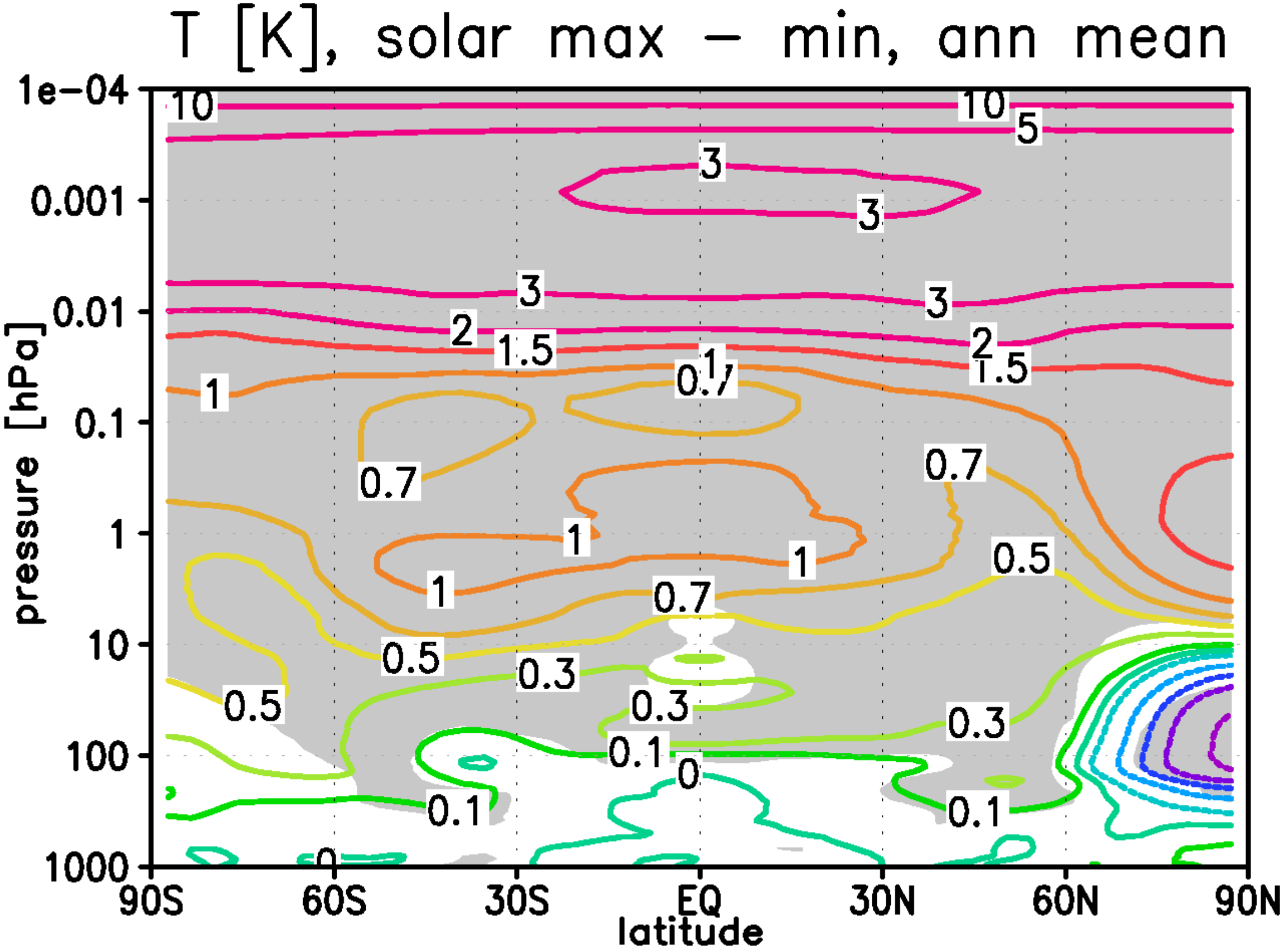




gray: significance > 95%

Observational analyses:
Soukharev and Hood (JGR, 2006)

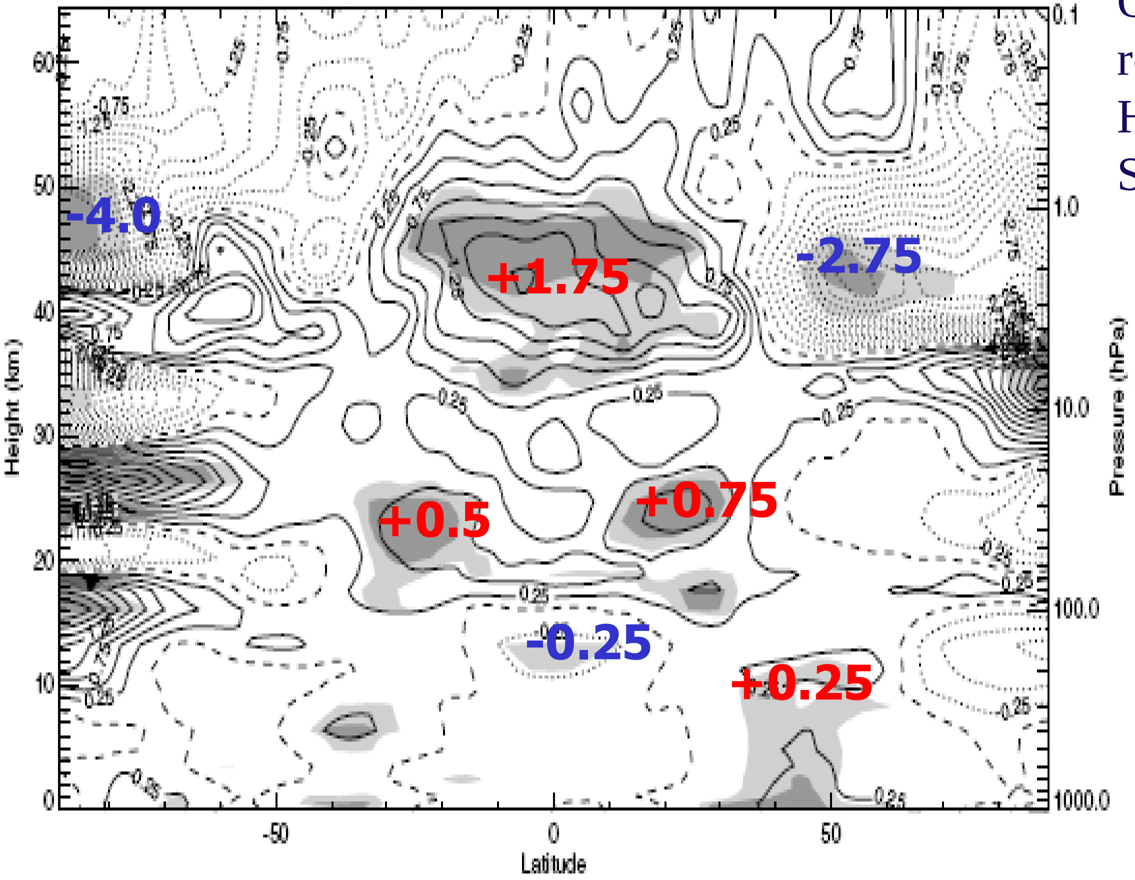
The solar cycle effect on annual mean temperature HAMMONIA



gray: significance > 95%

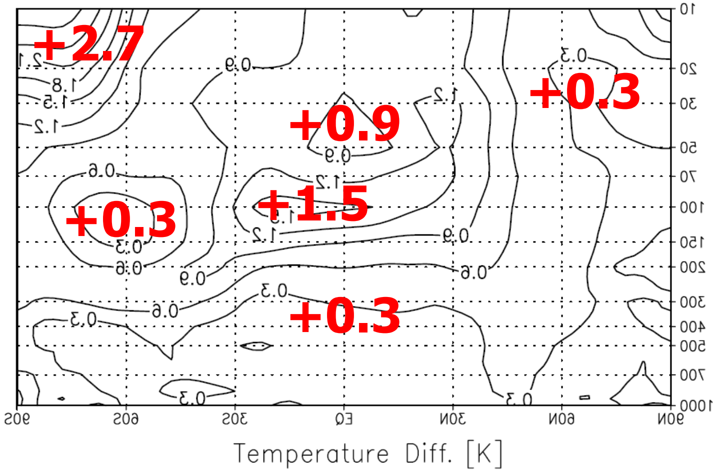
The solar cycle effect on annual mean temperature „observed“

ERA40, Crooks & Gray,
J.Climate, 2005



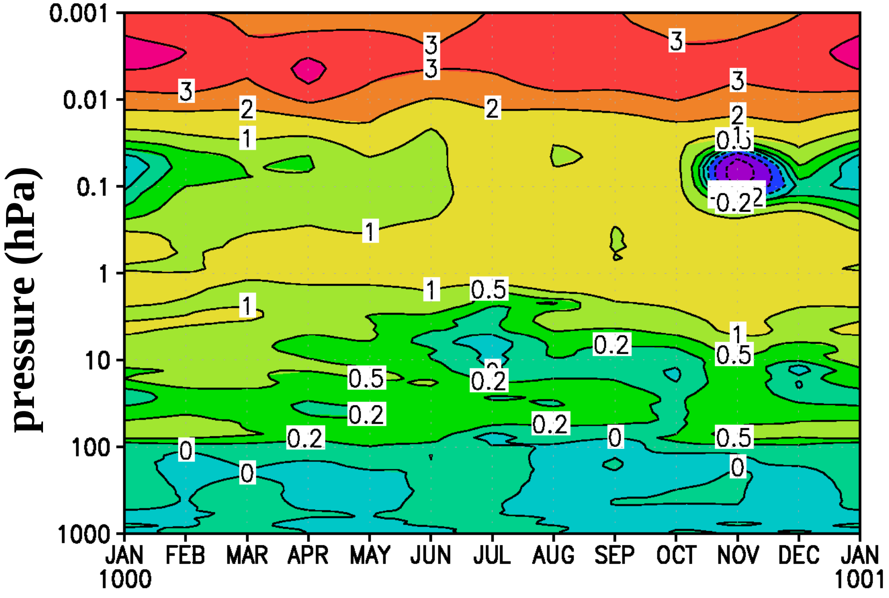
Other analyses of upper stratospheric reponse maximum:
Hood et al. (2004), SBUV: 0.75 K
Scaife et al. (2000), SSU/MSU: > 2K

NCEP/NCAR, Labitzke
et al., JASTP, 2002

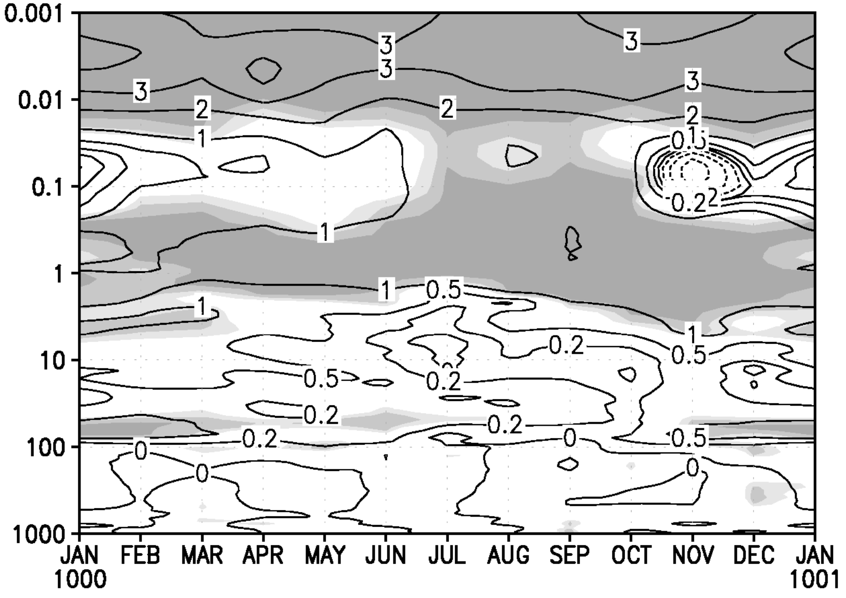


The annual cycle of the temperature response to the solar cycle

T (K), solar max – min, equator



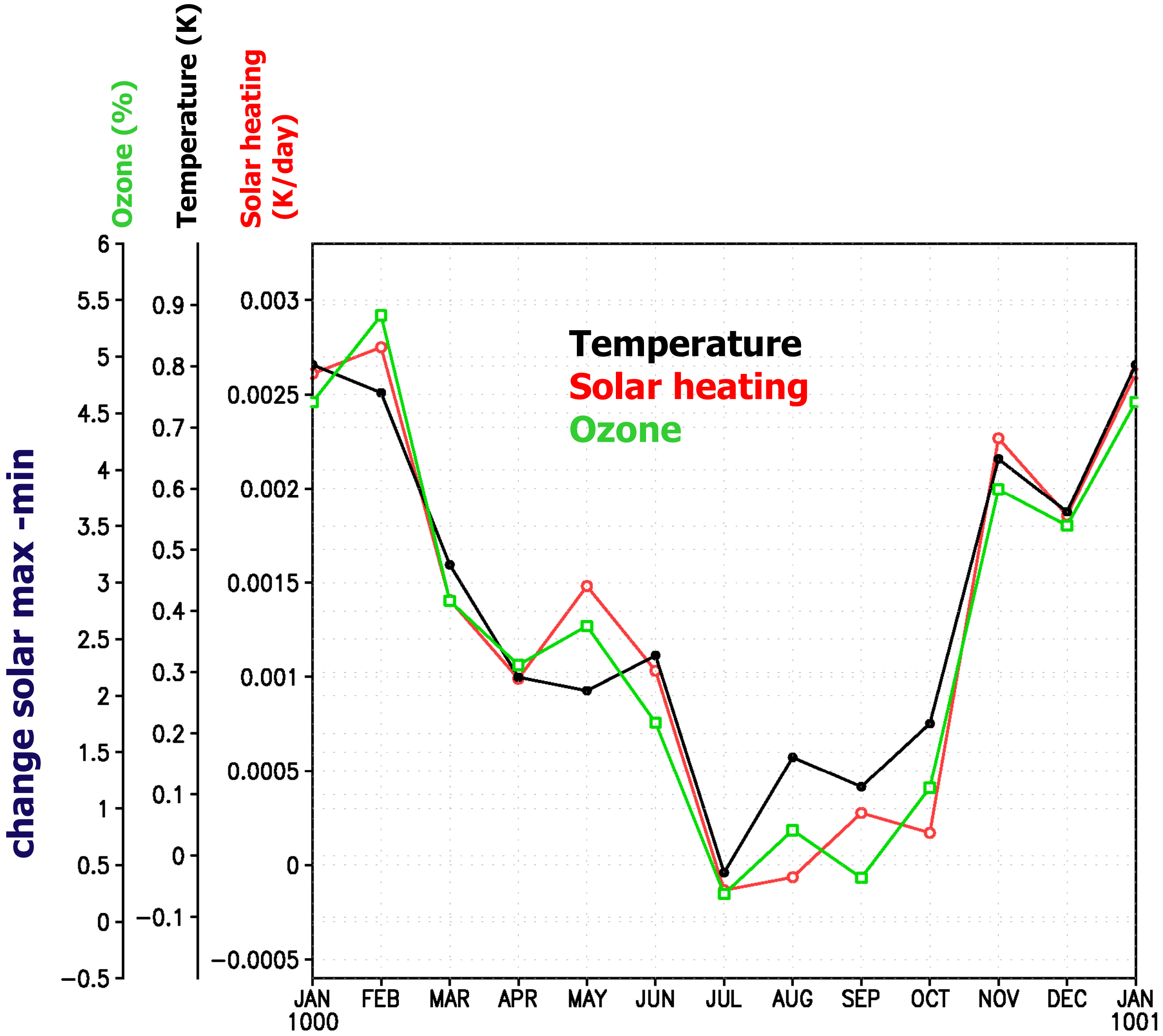
significance (%)



significance level : 90, 95, 99%

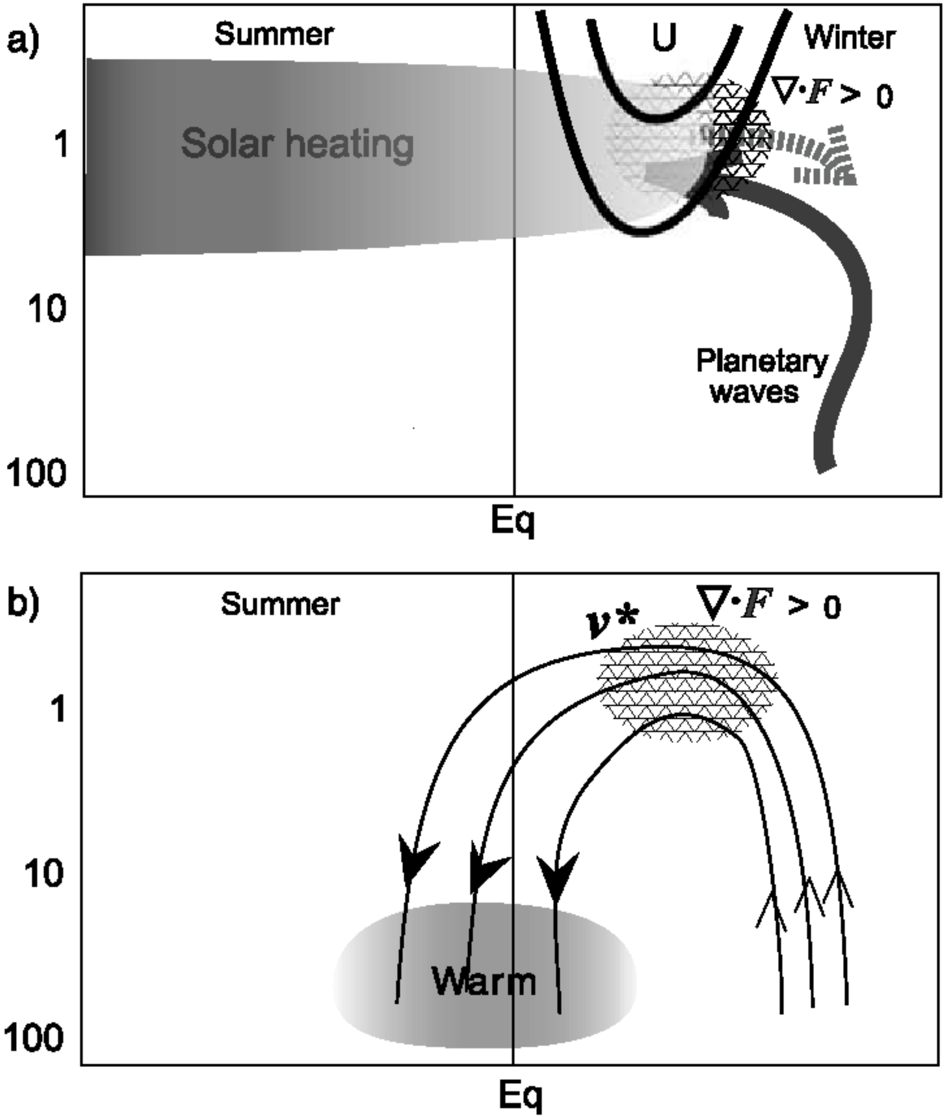
Wintertime temperature increase in the equatorial lower stratosphere (70 hPa)

Max Planck
Institute for
Meteorology



ZMAW

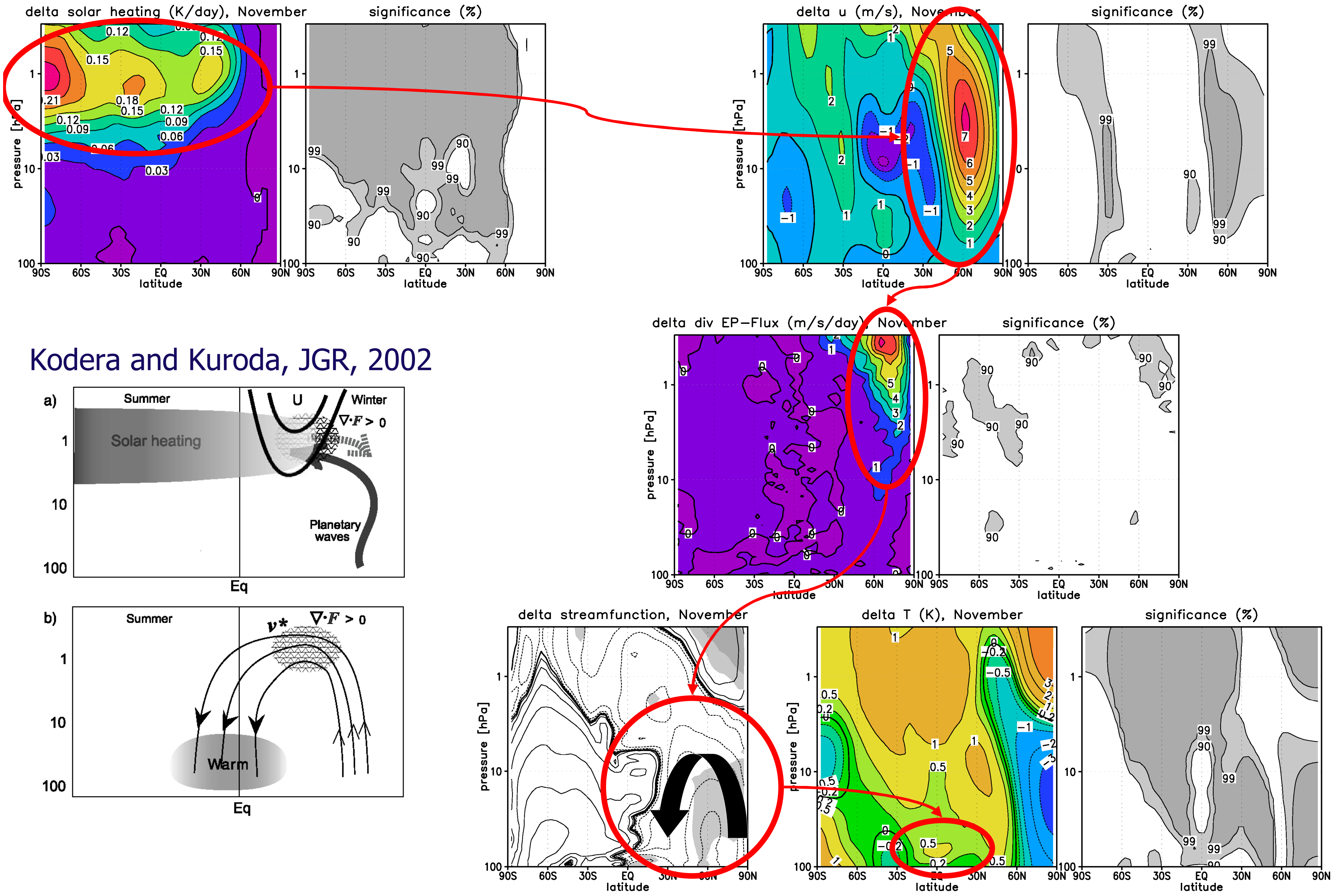
Solar cycle effect on the Brewer-Dobson Circulation



(Kodera and Kuroda, JGR, 2002)

1) Increased solar heating at the stratopause
2) Increase of the subtropical jet
3) Deflection of planetary waves from the subtropics
4) Positive anomaly of div Eliassen-Palm flux divergence
   → Reduced wave forcing
5) → Reduced Brewer Dobosn circulation
6) Warming in the lower equatorial stratosphere

Solar cycle effect on the Brewer-Dobson Circulation (November)

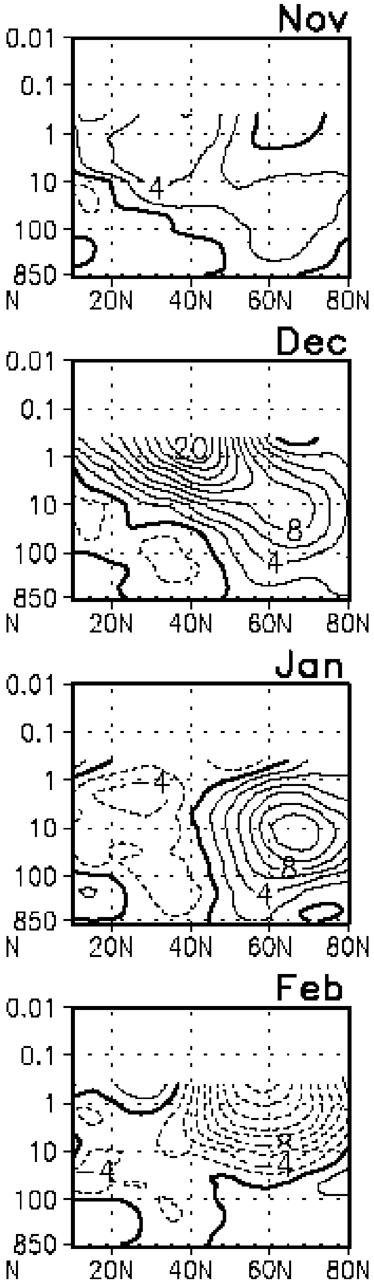


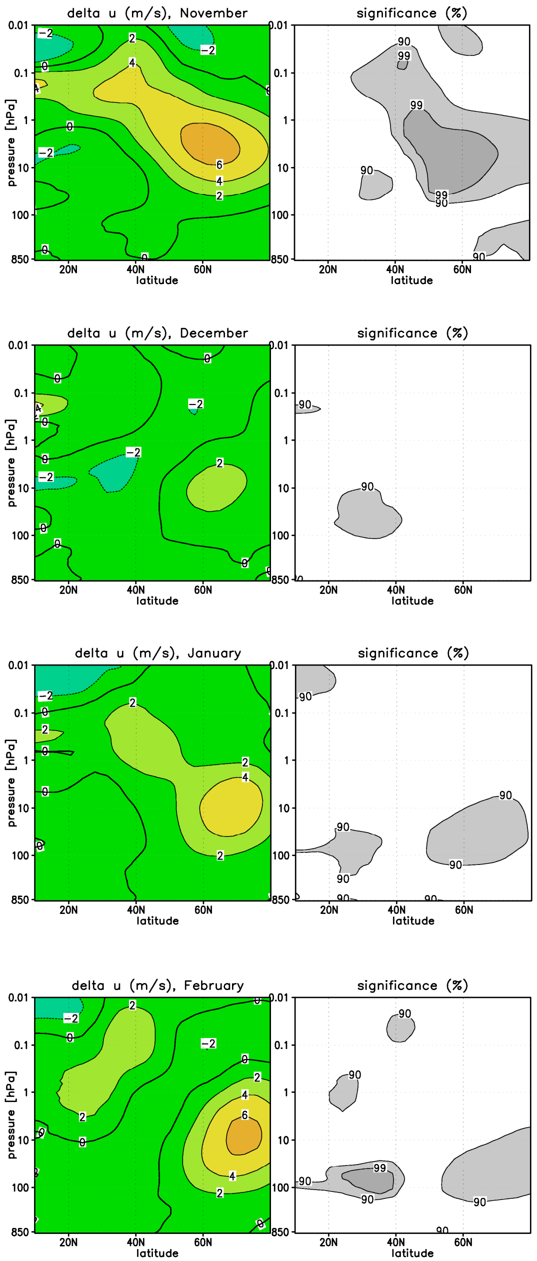
Kodera and Kuroda, JGR, 2002

Solar cycle effect on wintertime zonal mean zonal wind (solar max-solar min) – Northern hemisphere

NCEP analyses

(Matthes et al., JGR, 2004; Kodera & Kuroda, JGR, 2002)

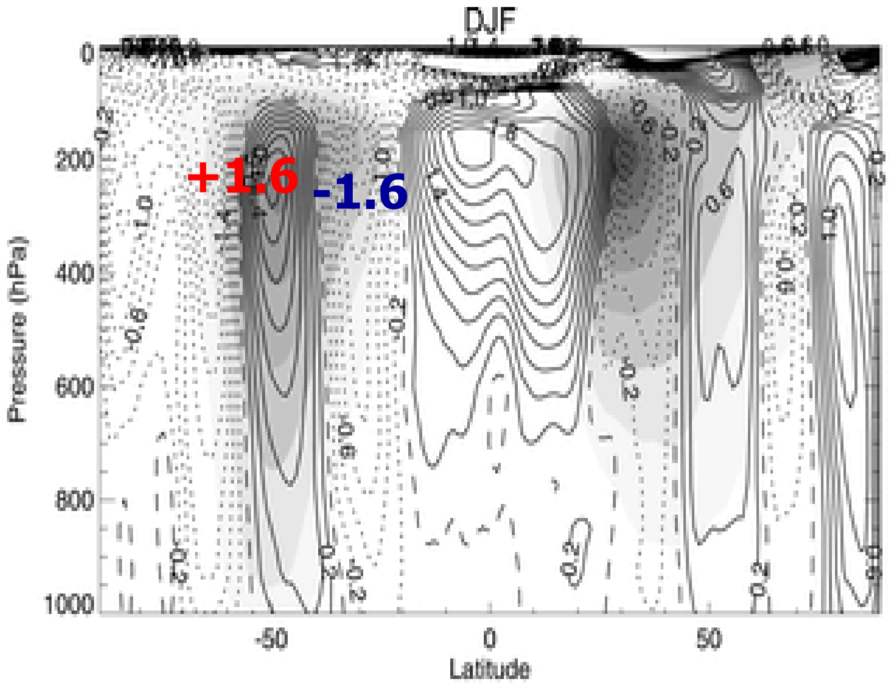




HAMMONIA

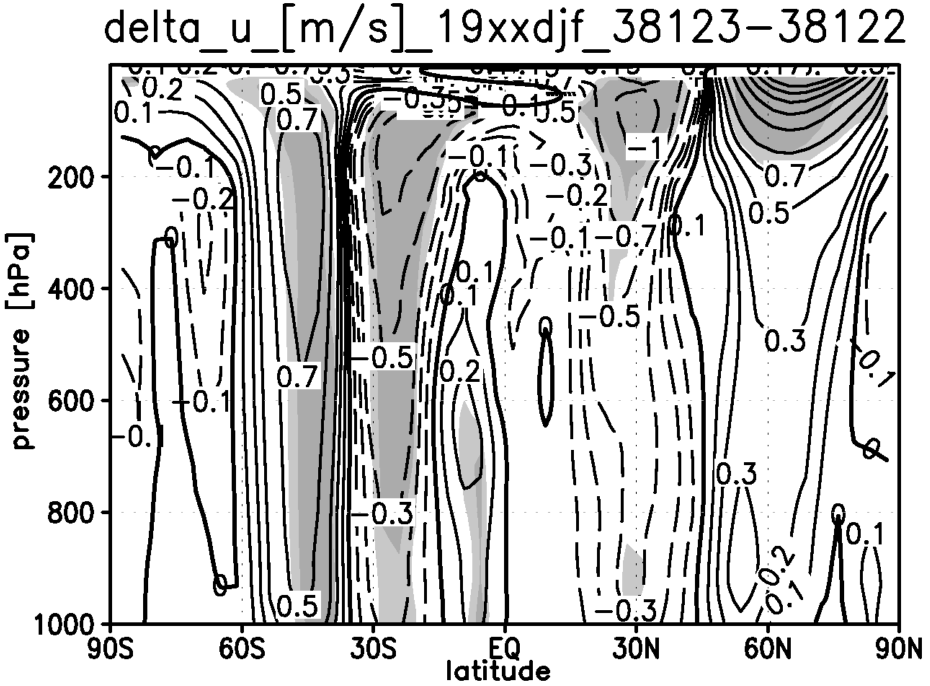
The solar cycle effect on tropospheric zonal wind – „observed“ and simulated

ERA40, Crooks&Gray, 2005



gray scale: absolute zonal wind

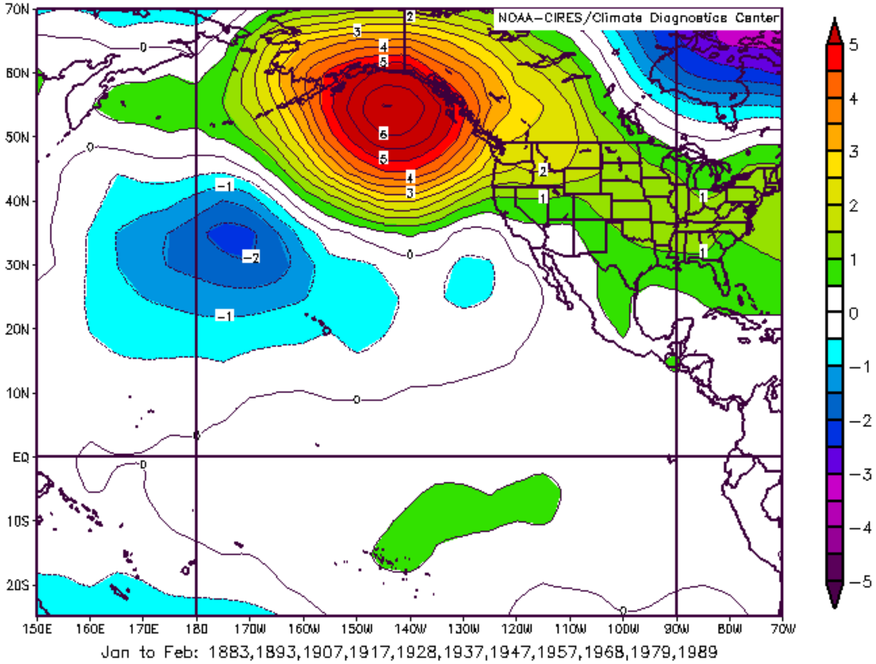
HAMMONIA



gray scale: significance (90,95%)

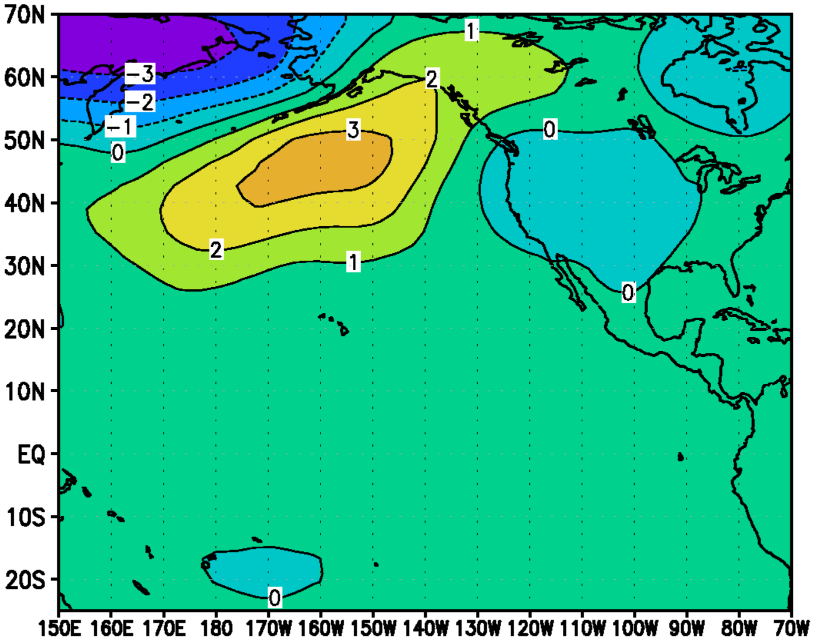
The solar cycle effect on sea-level pressure in the North Pacific

Hadley Centre data set, mean anomaly from 11 solar max years, slp (hPa), Jan/Feb



(van Loon et al., JGR, 2006)

HAMMONIA, solar max-min, slp (hPa), Jan/Feb



Conclusions (solar cycle experiments)

- The magnitude of the middle atmospheric ozone and temperature response is in agreement with observations. – But there is uncertainty in the structure?
- Some observed features of the dynamical stratospheric response are reproduced by the model:
  - Slowing of Brewer-Dobson-Circulation (November and January)
  - Low latitude lower stratospheric heating
  - Poleward downward movement of wintertime stratospheric jet increase
- The annual and zonal mean tropospheric zonal wind response is well reproduced.

References

- Publications based on this work:
  - Schmidt et al., J. Climate, 2006
  - Schmidt and Brasseur, Sp. Sc. Rev., 2006

- Review articles on many topics related to solar cycle effects on the climate
  - *Space Science Reviews,* **125,** 2006.

The End