The role of the Brewer-Dobson circulation and solar variability in the ozone-climate interaction

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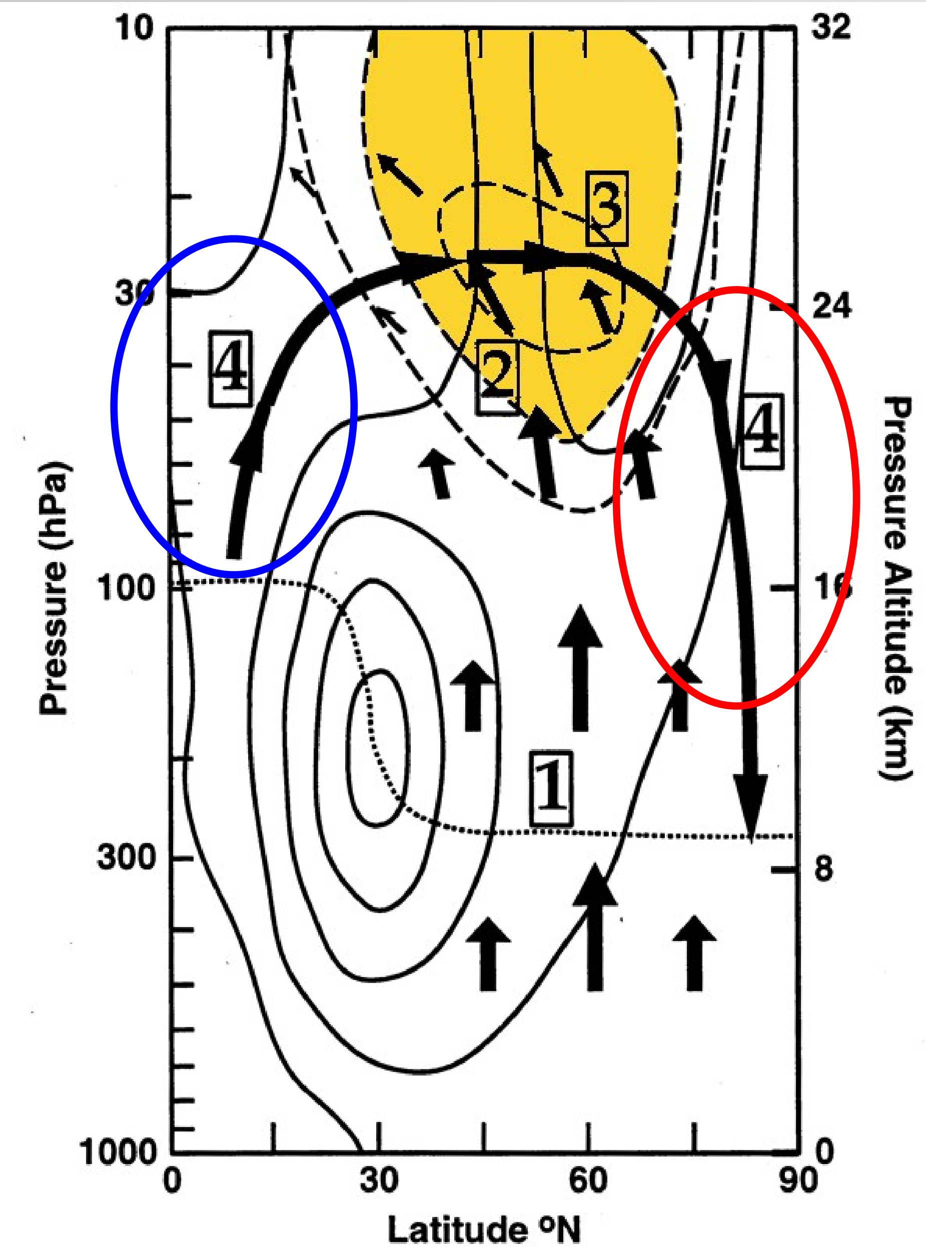
Overview

- The Brewer-Dobson (BD) circulation: Introduction
- Dynamical control of stratospheric temperatures and ozone chemistry
- ozone trends: role of BD circulation and solar variability
- Brewer-Dobson circulation and stratospheric water vapor
- Conclusion: „simple“ view of ozone-climate interaction

Planetary waves and residual (Brewer-Dobson) circulation



Newman et al. (2001)

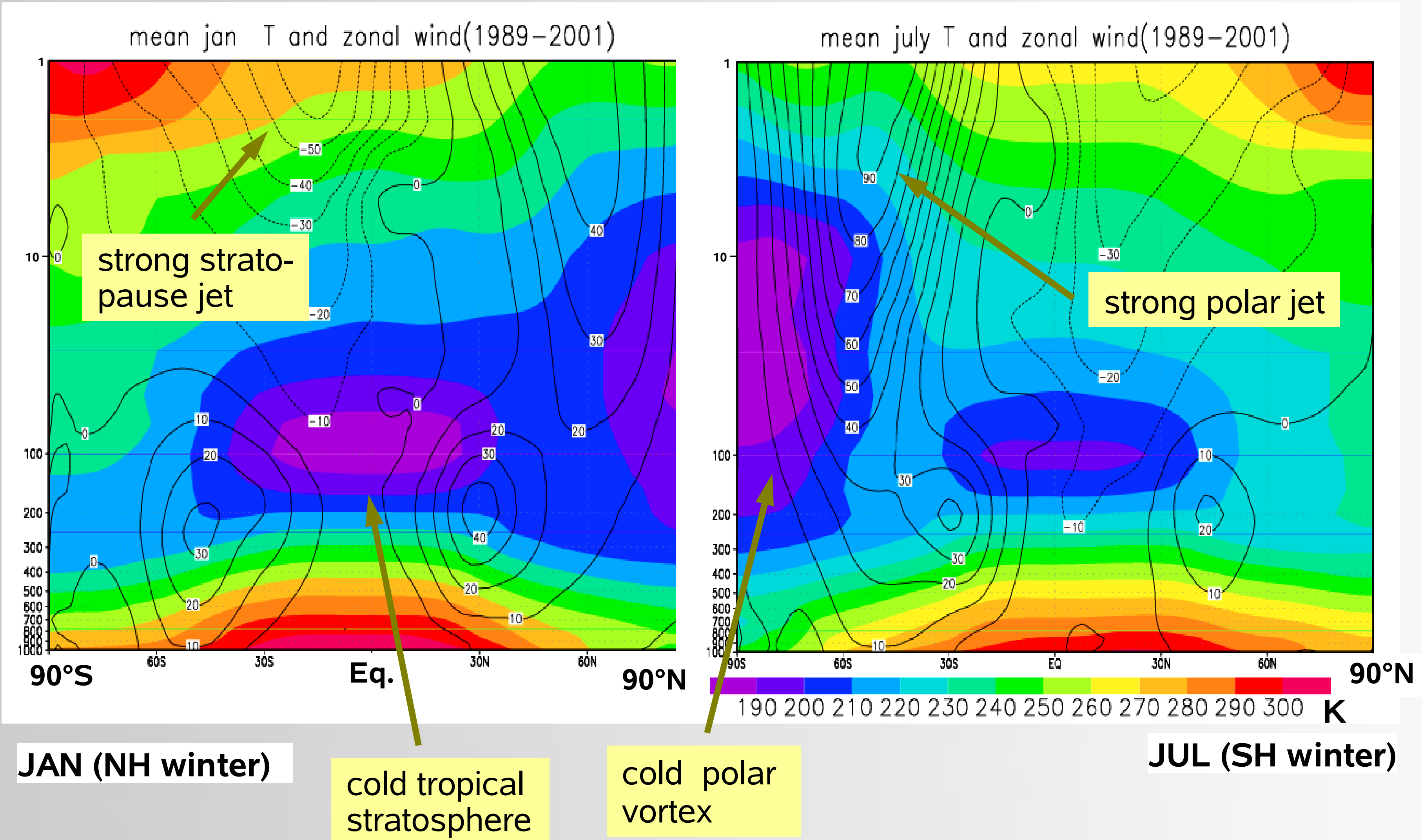
- Propagation of planetary waves into stratosphere **(1)**
  - Eddy heat flux $\overline{v\ T}$

- Deposition of easterly momentum **(2)**
  - EP flux convergence $-\nabla \cdot \vec{E}$

- deceleration of stratospheric westerlies/geostrophic balance requires then a small meridional (residual) wind component **(3)**

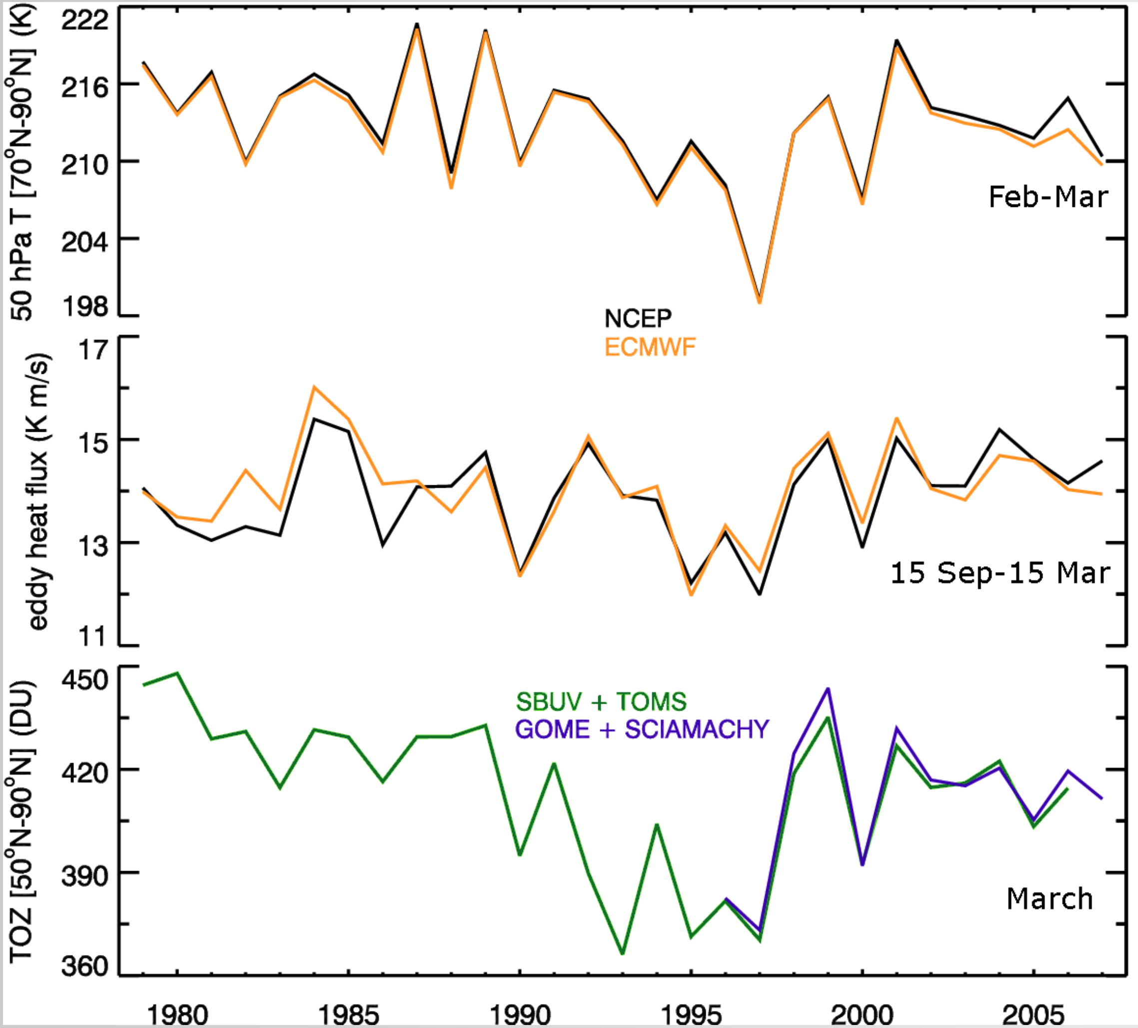
- residual circulation causes uplifiting in tropics (cooling) and descent in polar region (warming) **(4)**

seasonal variability in temprature



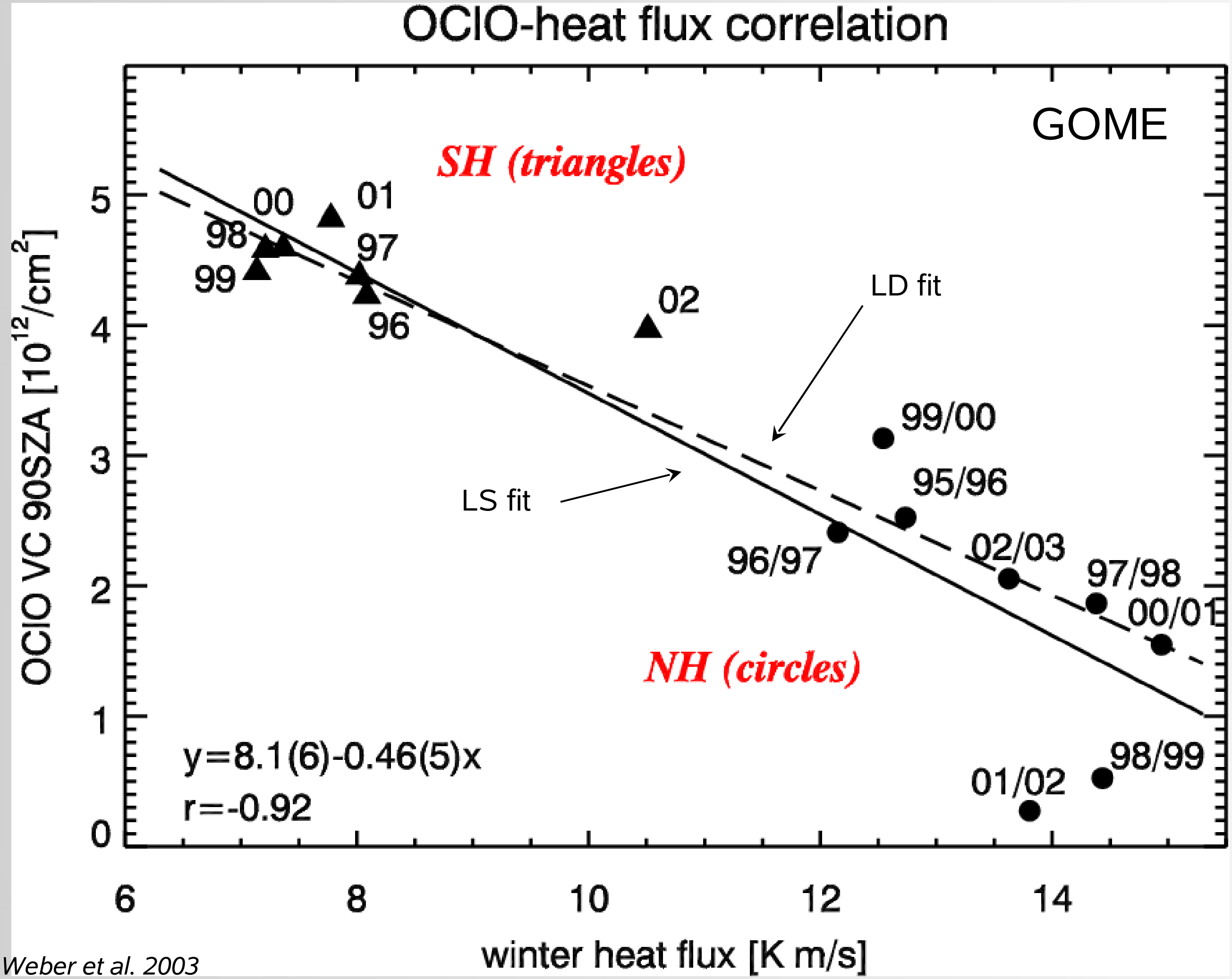
- Link of T variability in tropics (Yulaeva et al. 1994) and in polar region (Newmann et al. 2001) to planetary waves

polar temperatures, BD circulation, and O3



- Inter-annual variability in polar ozone, winter eddy heat flux/BD circulation strength, and spring ozone
- Ozone recovery related to 20y Montreal protocol?

Dynamical control of ozone chemistry: chlorine activation

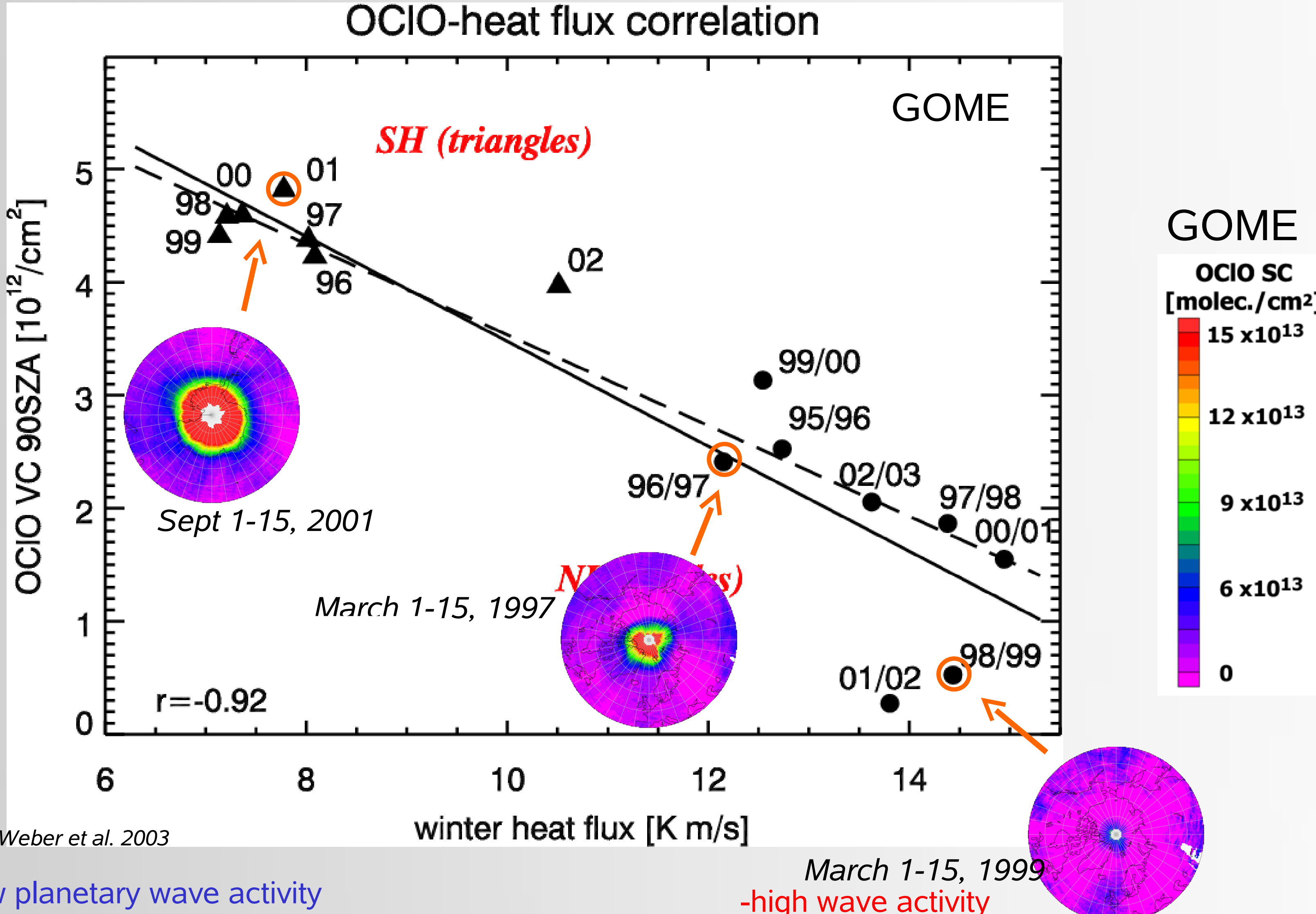


Update Weber et al. 2003

high PSC volume
Low T

low PSC volume
High T

Dynamical control of ozone chemistry: chlorine activation



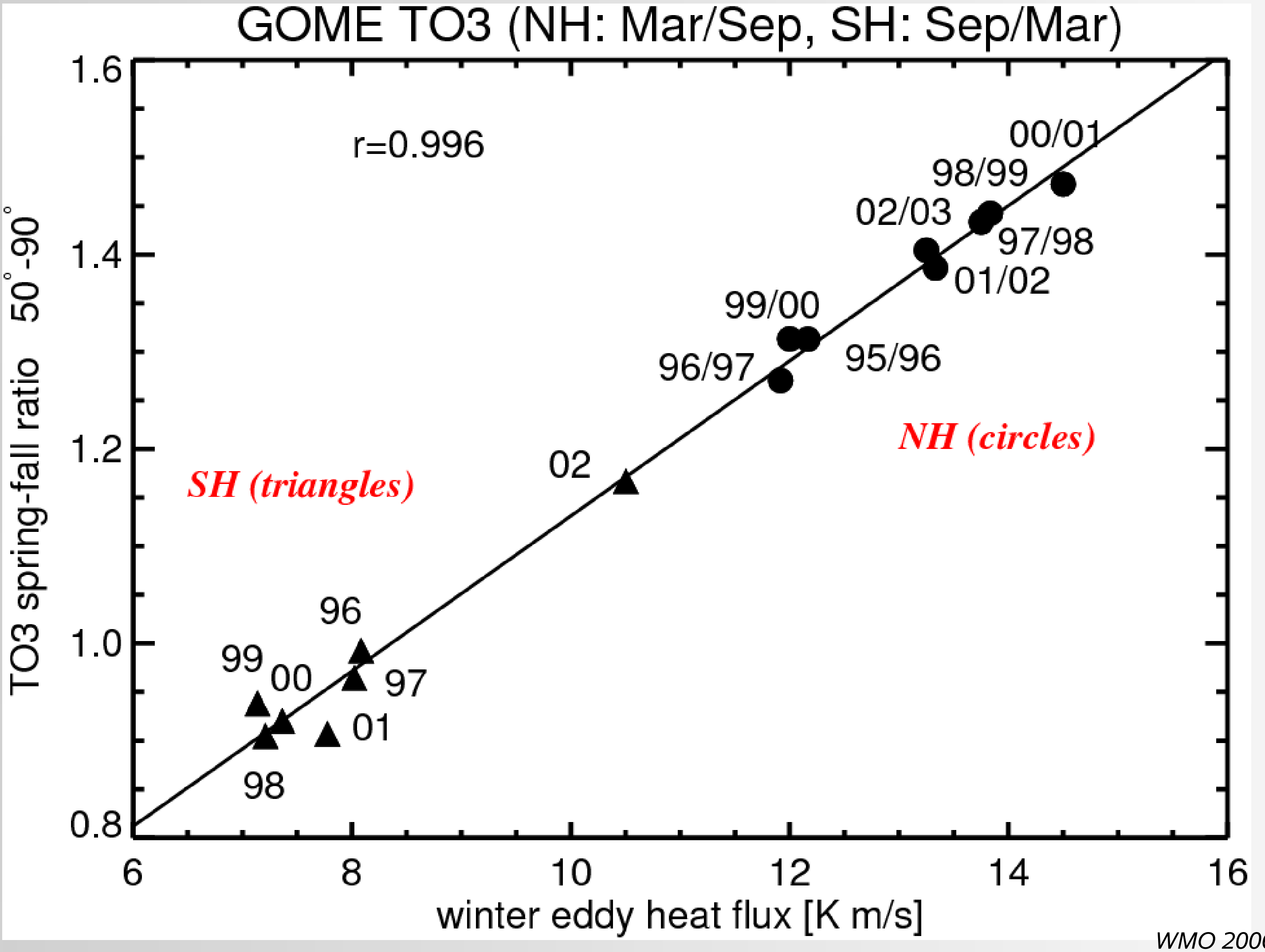
Update Weber et al. 2003

- -low planetary wave activity
- -low T
- -high PSC volume

⟷

- -high wave activity
- -high T
- -low PSC volume

Coupling of chemistry and transport in polar ozone

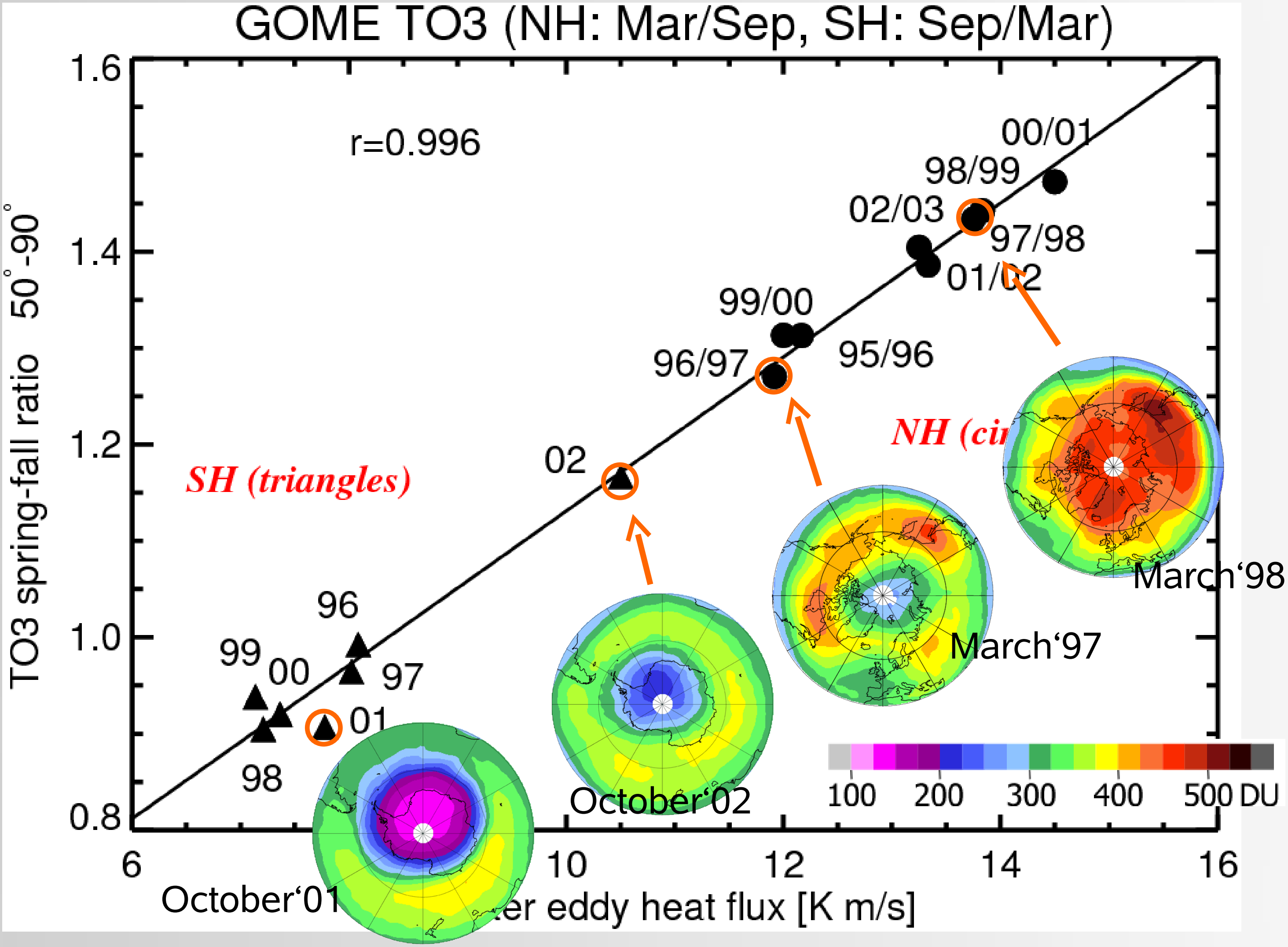


WMO 2006

-weak Brewer-Dobson circulation
-high polar ozone loss

-strong Brewer-Dobson circulation
-enhanced ozone transport

Coupling of chemistry and transport in polar ozone



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→

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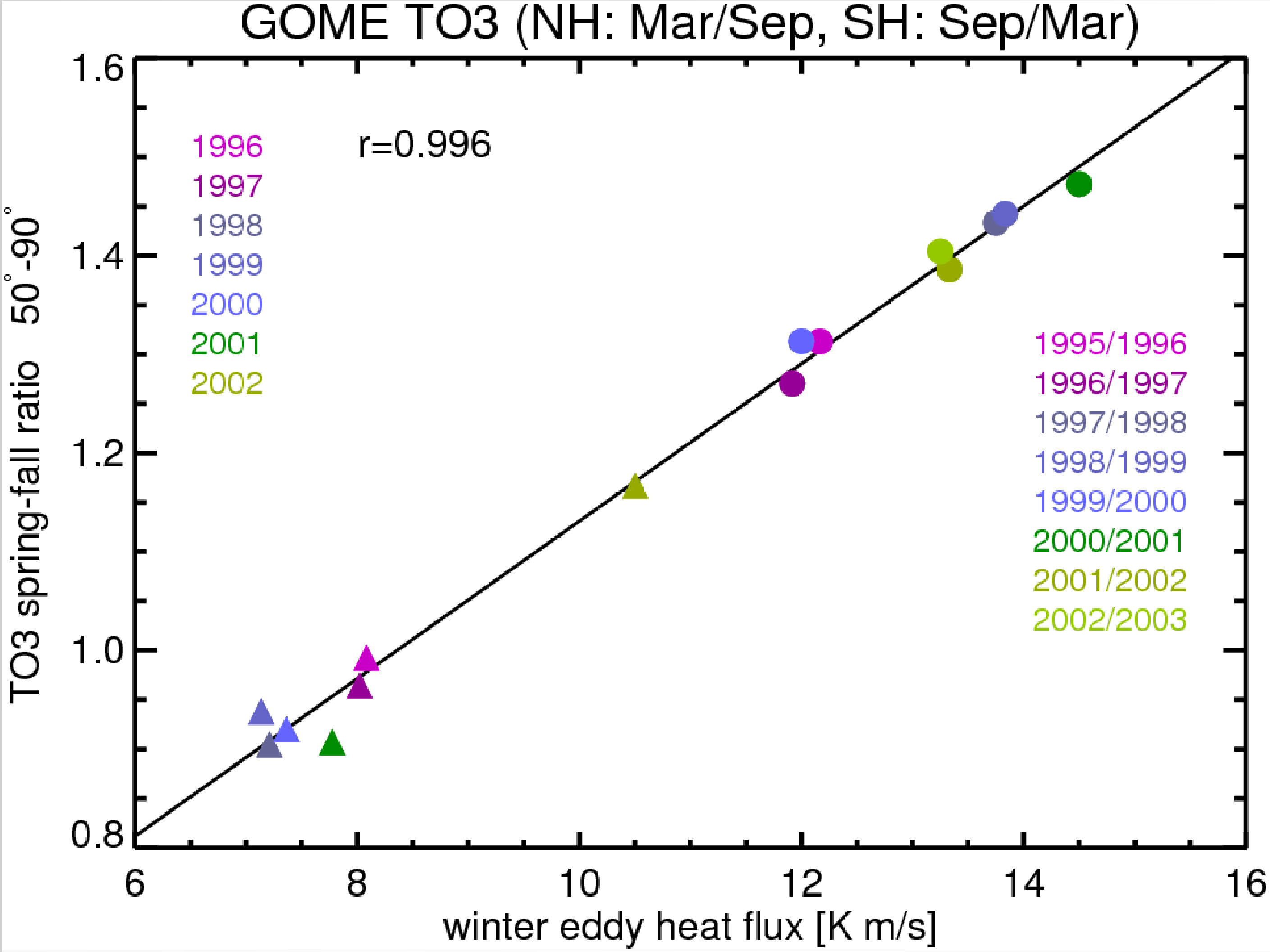
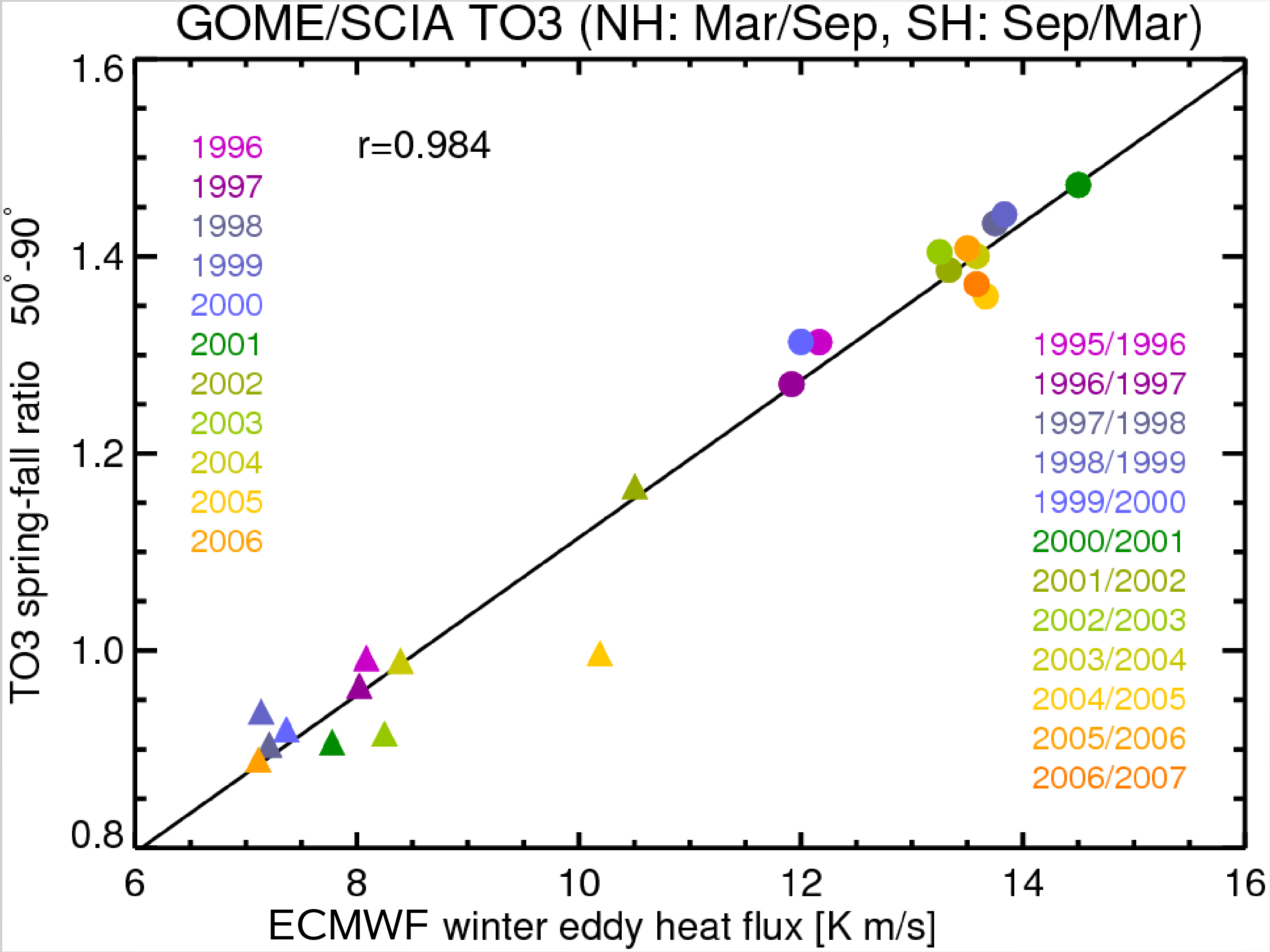
Coupling of chemistry and transport



...same as before, now in color

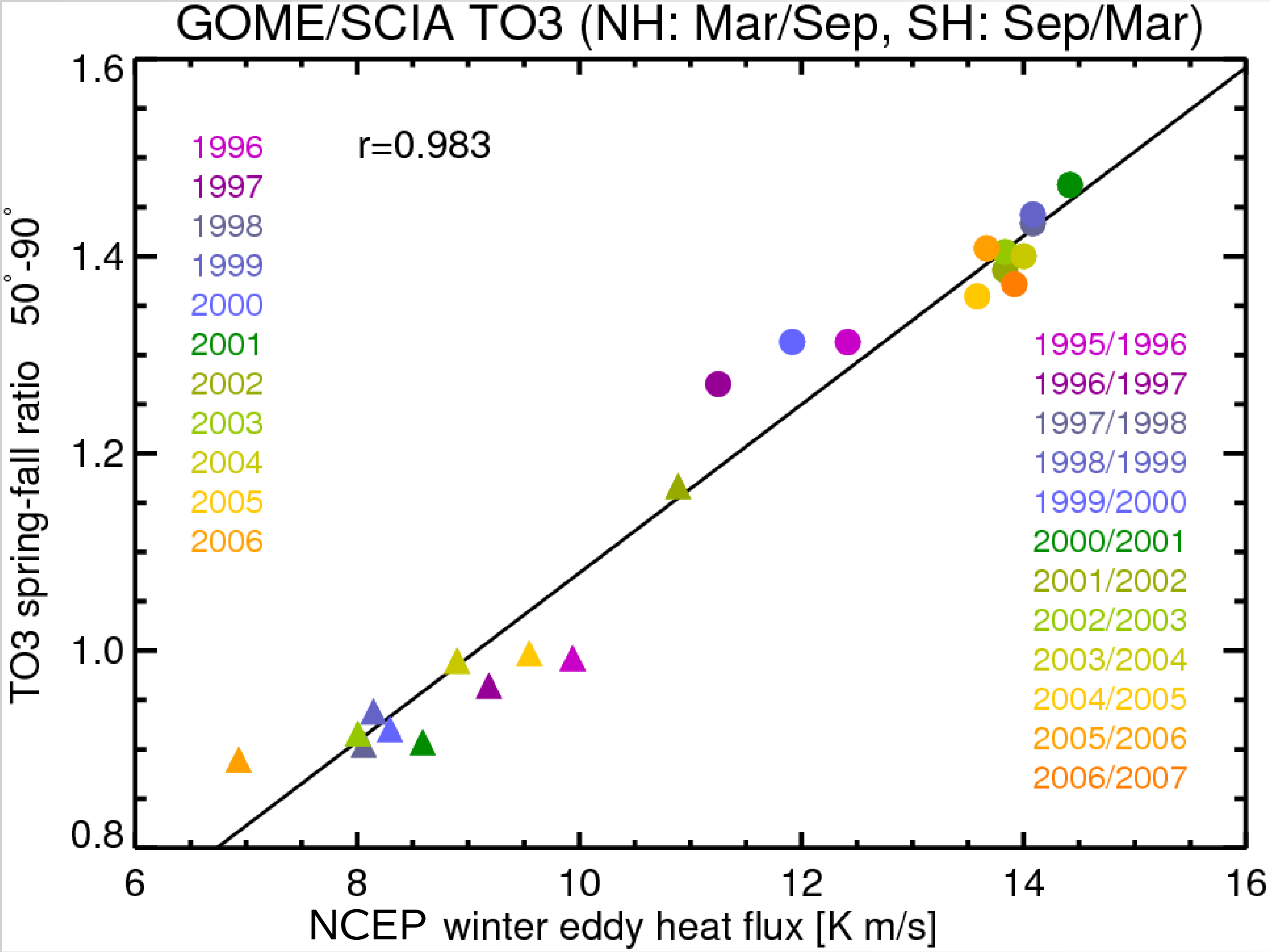
Coupling of chemistry and transport



... adding SCIAMACHY data: 2003-2007

- Large differences between ECMWF/ERA40 and NCEP eddy heat fluxes!

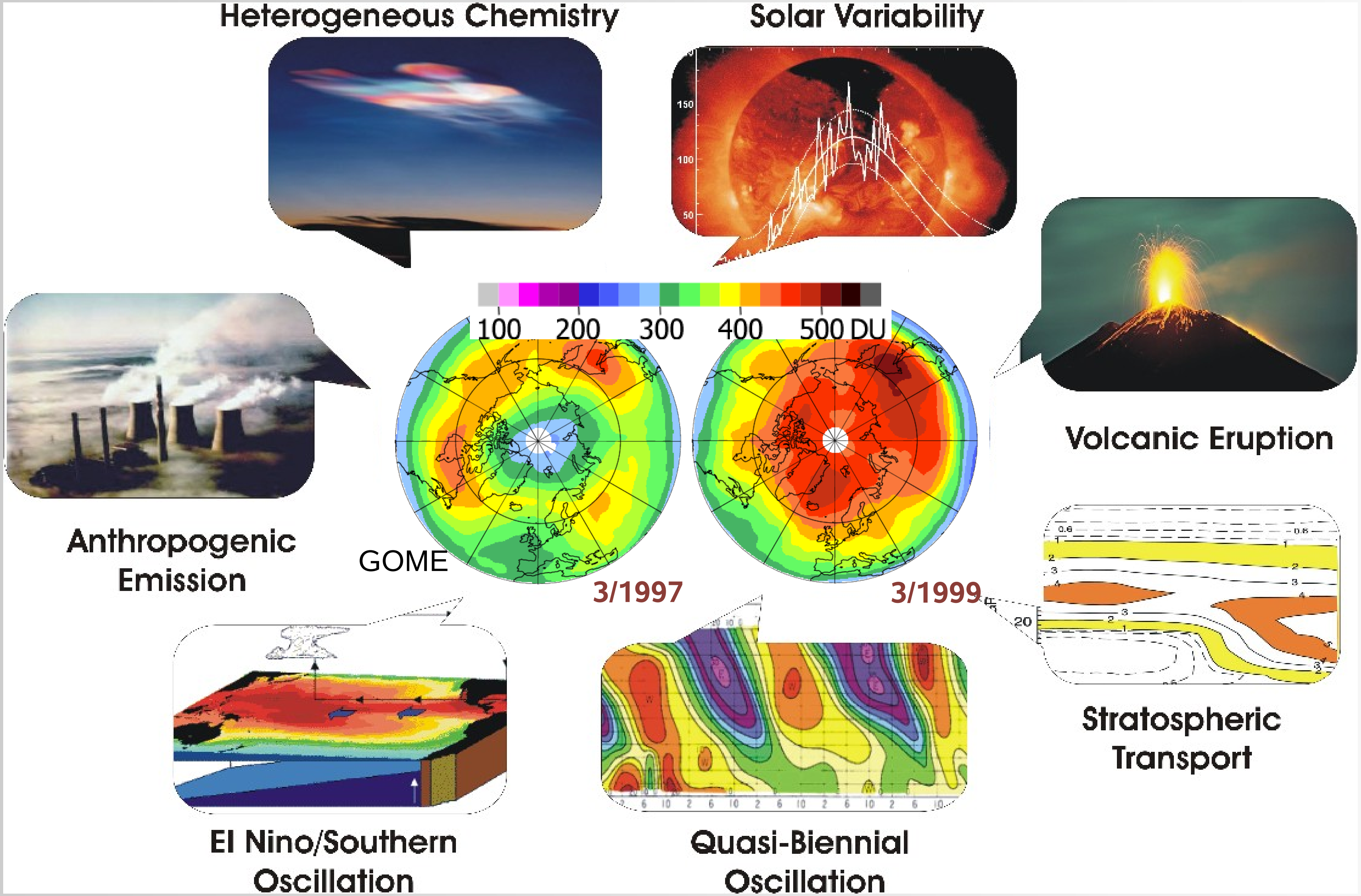
Coupling of chemistry and transport



... adding SCIAMACHY data: 2003-2007

- Large differences between ECMWF/ERA40 and NCEP eddy heat fluxes!
- How reliable is the eddy heat flux as a proxy for BD circulation strength?

Processes responsible for ozone variability



- processes intereract with each other
  - ➔ radiation – chemistry - dynamics coupling

Ozone trends and statistical analysis

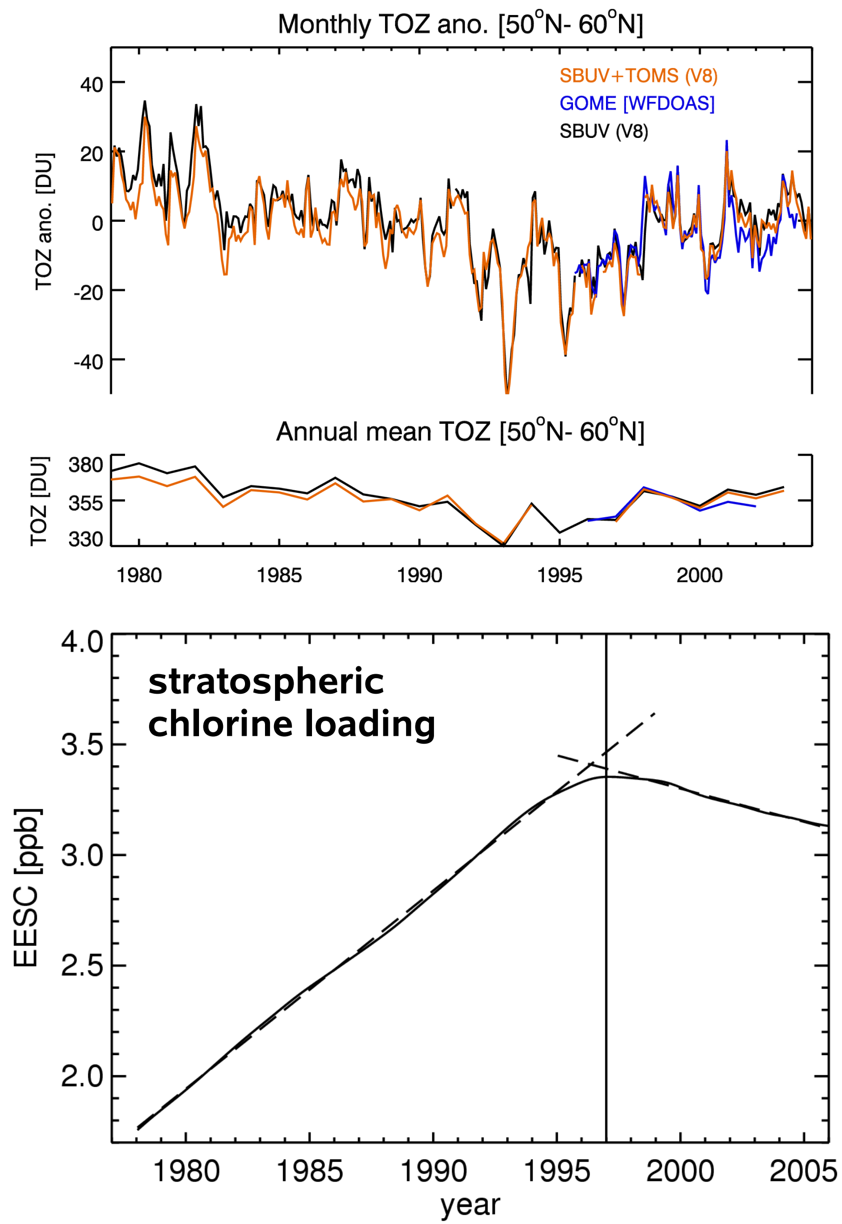
Data for statistical analysis:

- SBUV V8 total ozone
- ERA40 re-analysis

Terms included in multi-variate linear regression:

- EESC (equivalent effective stratospheric chlorine)
- Winter integrated eddy heat flux
- QBO at 50 hPa and 10 h Pa
- El Nino – Southern osciallation (SOI)
- Stratospheric aerosol (Pinatubo, El Chichon
- Solar term (Mg II index)

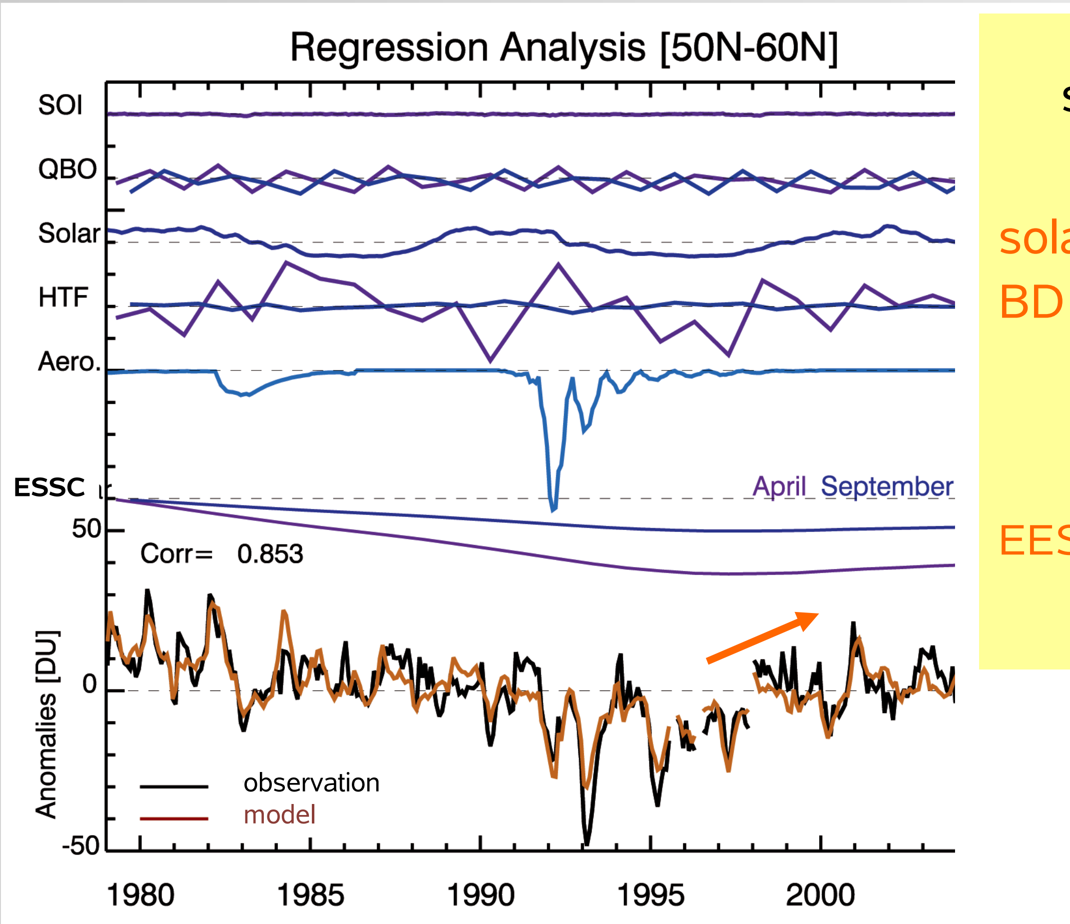
ozone recovery?



Dhomse et al. (2006)

Stratospheric ozone trends, solar cycle, and stratospheric chlorine

Total ozone anomalies 1978-2003



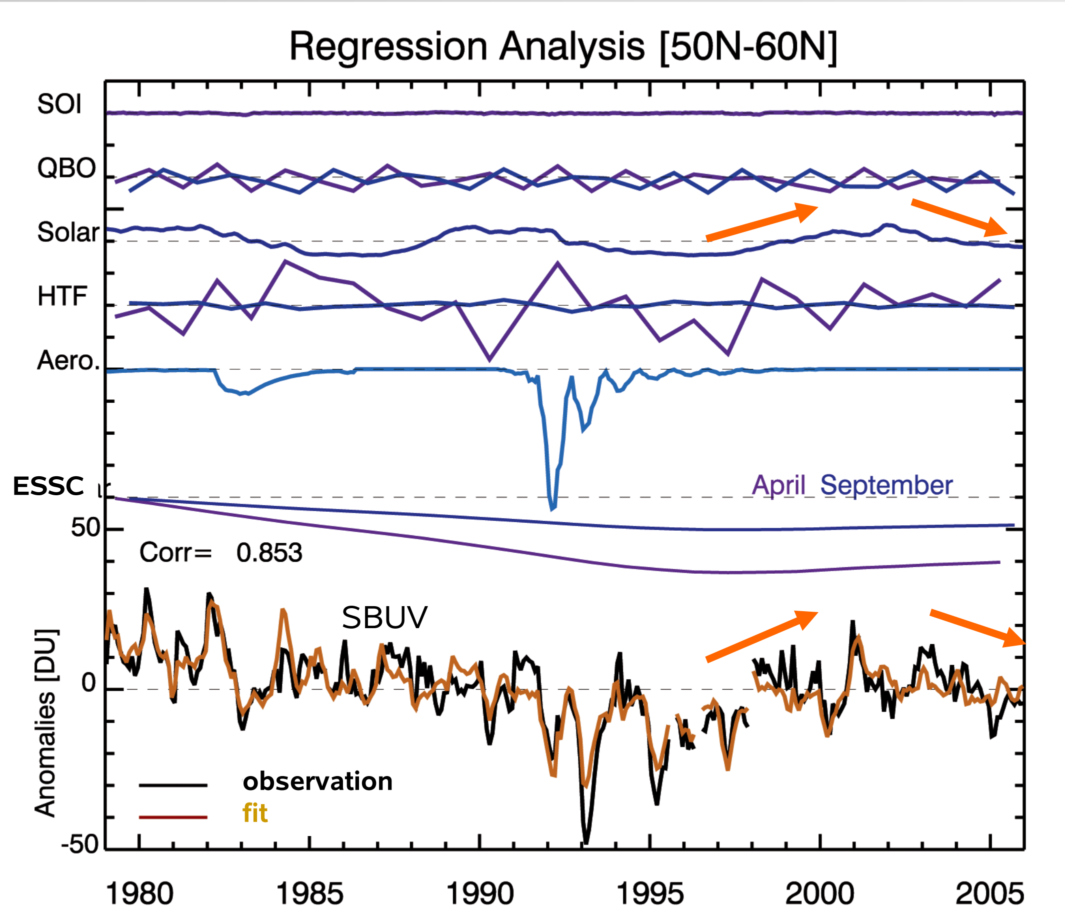
Dhomse et al. 2006

trends
since mid nineties

solar
BD circulation/HTF
EESC (halogens)

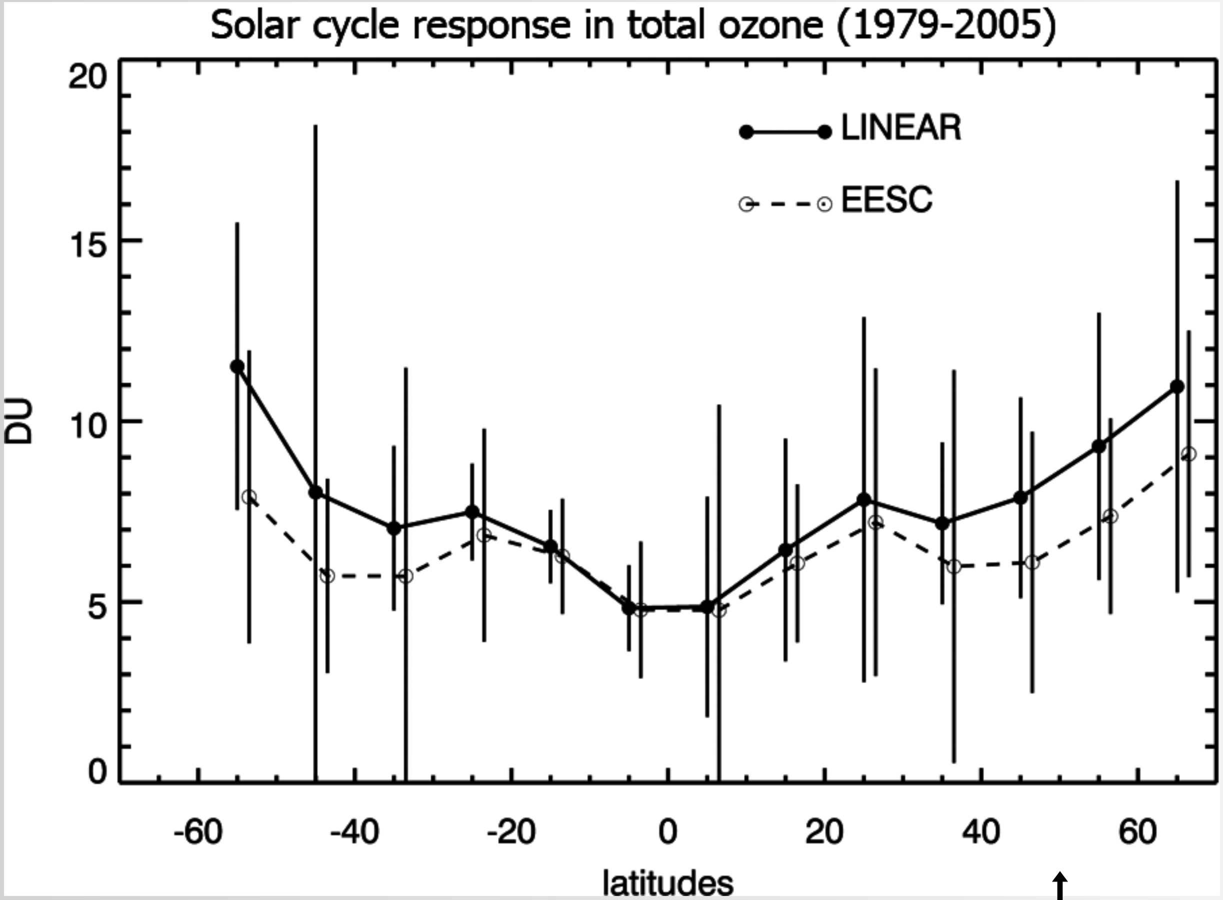
Stratospheric ozone trends, solar cycle, and stratospheric chlorine

Total ozone anomalies 1978-2005

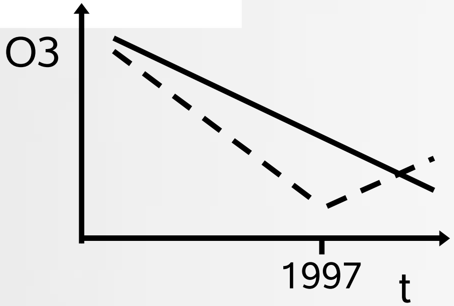


- Solar response evident at high latitudes (shown here for 50°-60°N)
- Is there a connection between circulation changes and solar activity?

solar cycle response on column ozone

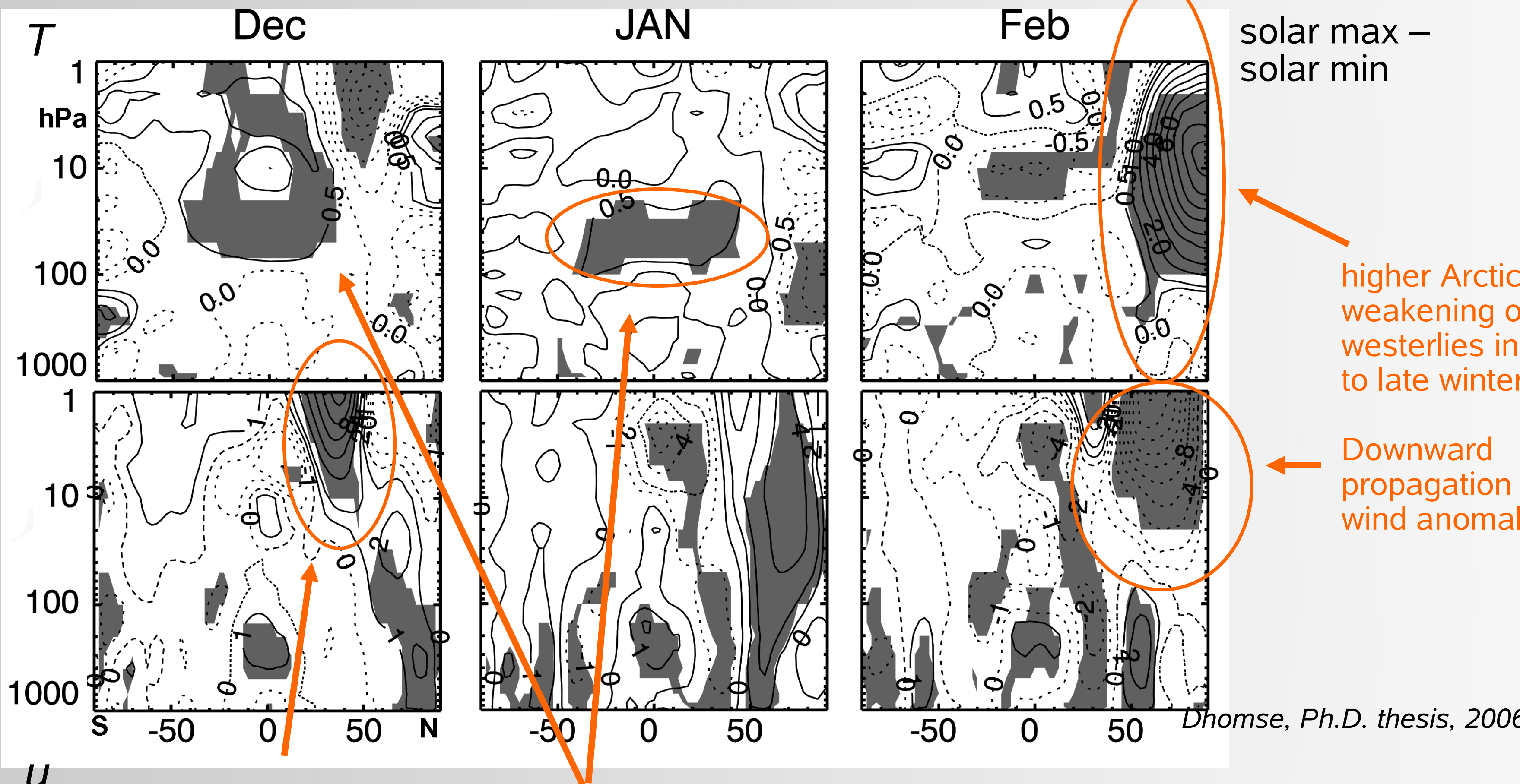


solar max – solar min



- Solar cycle response up to 12 DU when assuming a linear downward trend until 2005
- Accounting for EESC trend, solar cycle response varies from 5 DU (tropics) to 9 DU (high latitudes)
  - ➔ high latitude solar response via dynamical processes?

NH u and T response to solar cycle



solar max – solar min

higher Arctic T and weakening of westerlies in mid- to late winter

Downward propagation of wind anomalies

More westerly SJ

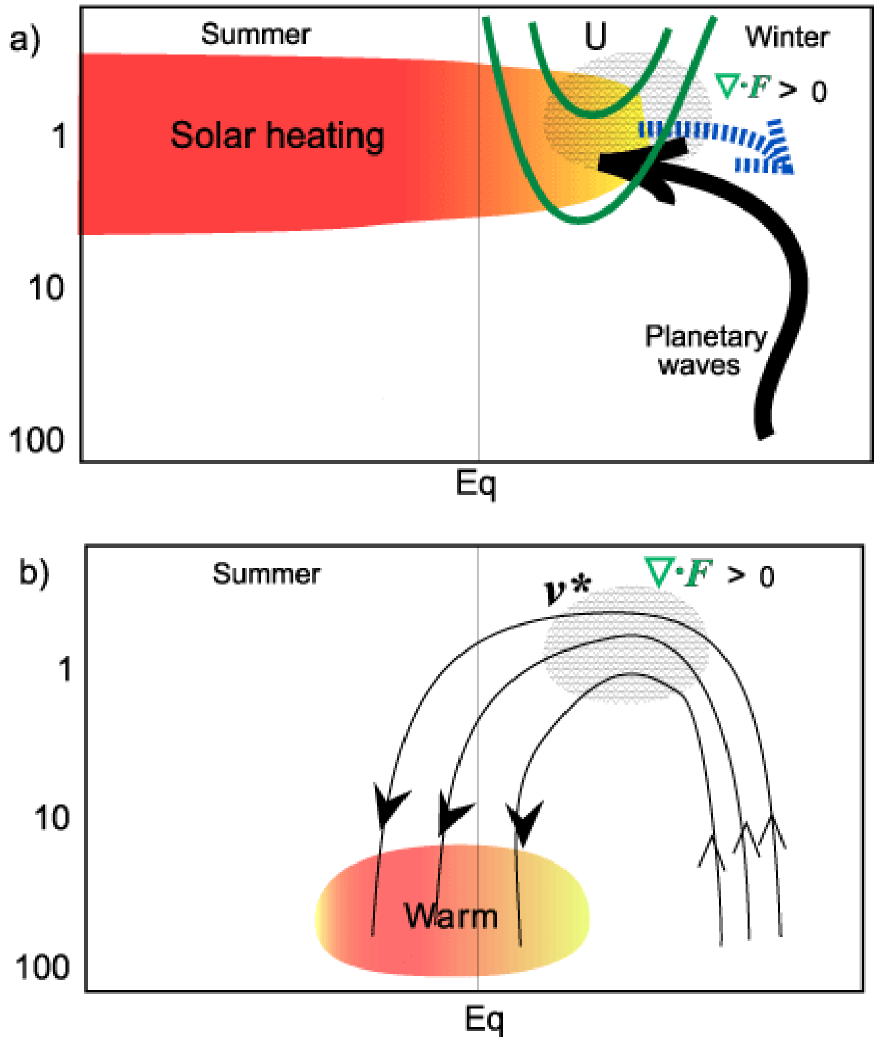
temperature response in tropics

- Change in zonal mean wind (u) in m/s and zonal mean temperature (T) in K for a change of 113 solar flux units (F10.8 units) from a multi-variate regression of ERA40/ECMWF (1979-2005)

- Solar max: major warmings in late winter/weak polar vortex in late winter
- Solar min: major warmings in early winter/strong polar vortex in late winter

see also Grey (2003)

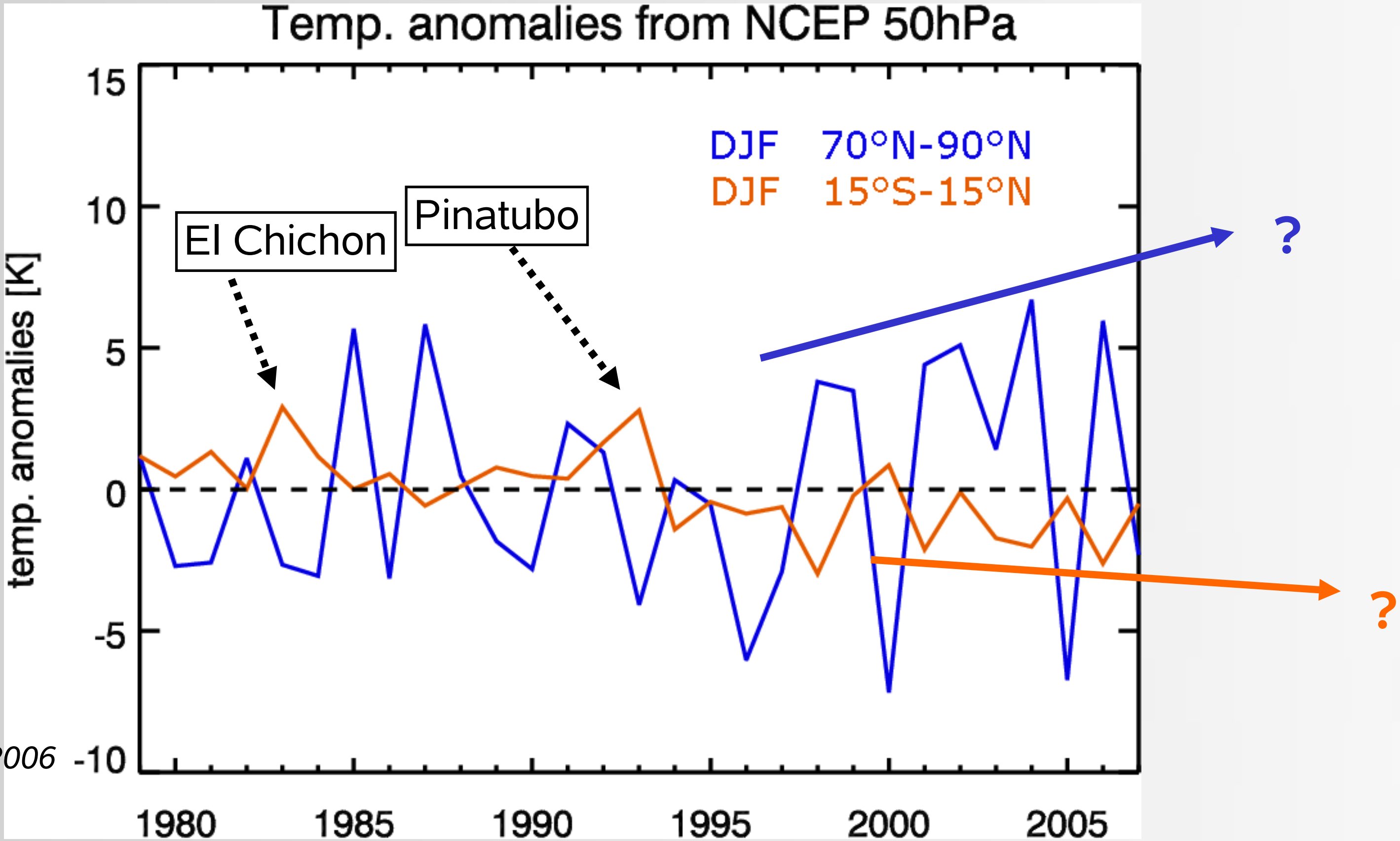
Solar variabilit, planetary waves, polar O3 loss



Kodera and Kuroda (2002)

- extra solar heating during solar max strengthens subtropical stratopause jet (SJ) in early winter
  - ➔ **radiative response**
- Strengthening of westerlies (SJ) means reduced wave progation and reduced BD circulation /warming of tropical tropopause region in early winter
  - ➔ **dynamical response**
  - ➔ **weak BD circulation in early winter**
- Deflection of planetary waves away from subtropics (towards pole) while SJ descends downwards and polewards, leading to weakening of polar night jet (polar vortex) in mid- to late winter
  - ➔ **strong BD circulation**
- warmer polar stratospheric temperatures with reduced polar ozone loss in late winter
  - ➔ **chemical response**

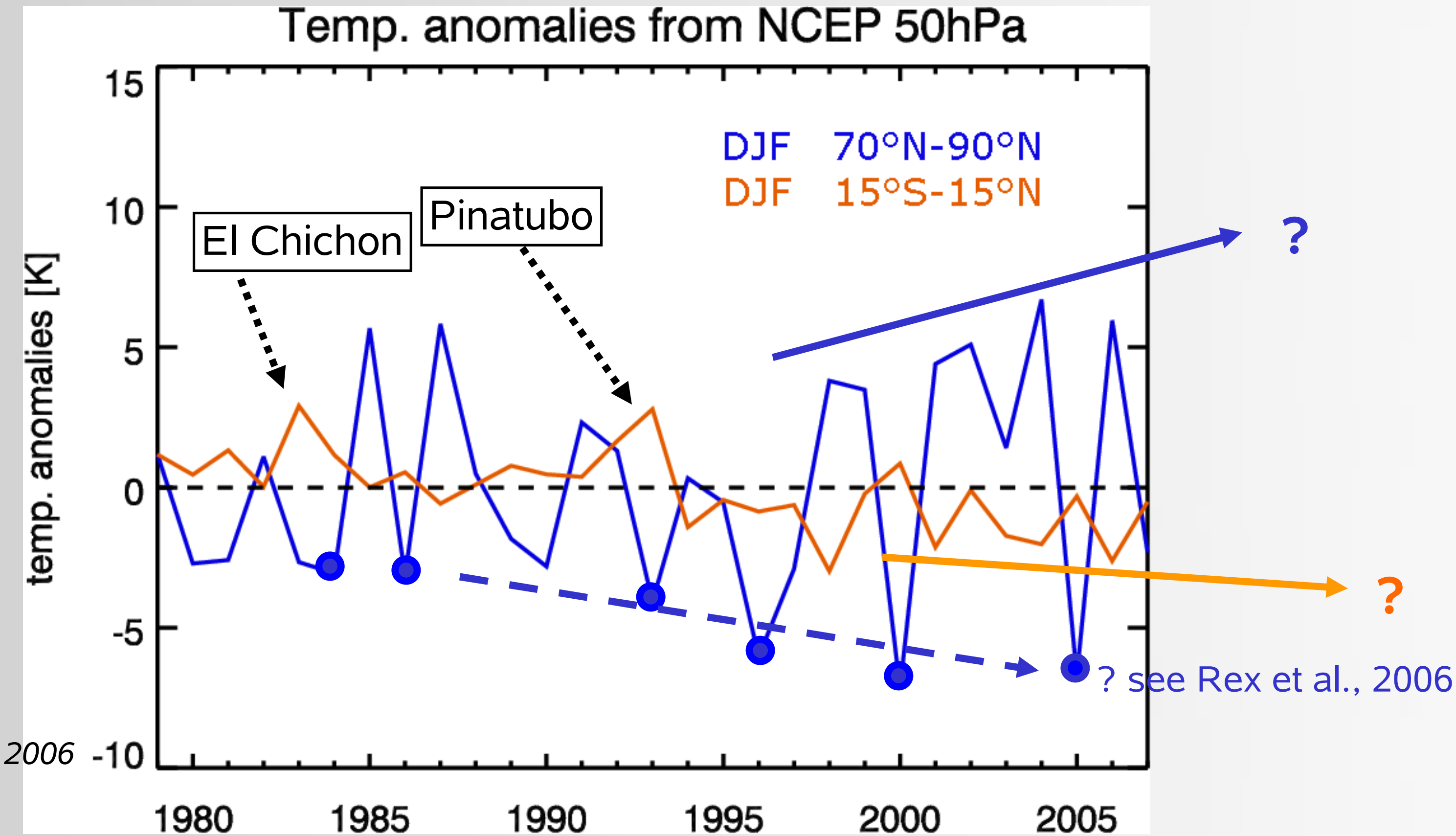
Stratospheric temperature, volcanic aerosols, and BD circulation



Update Dhomse et al., 2006

- Impact of El-Chichon and Pinatubo
  - ➔ increase in stratospheric temperatures in the tropics (increase of 2-3K @ 100hPa for about 1-2 years
- anti-correlation between Arctic and tropical LS temperature (r 0.5)
  - ➔ aerosol effect on Brewer-Dobson circulation (El Chichon, Mt. Pinatubo)?

Stratospheric temperature, volcanic aerosols, and BD circulation



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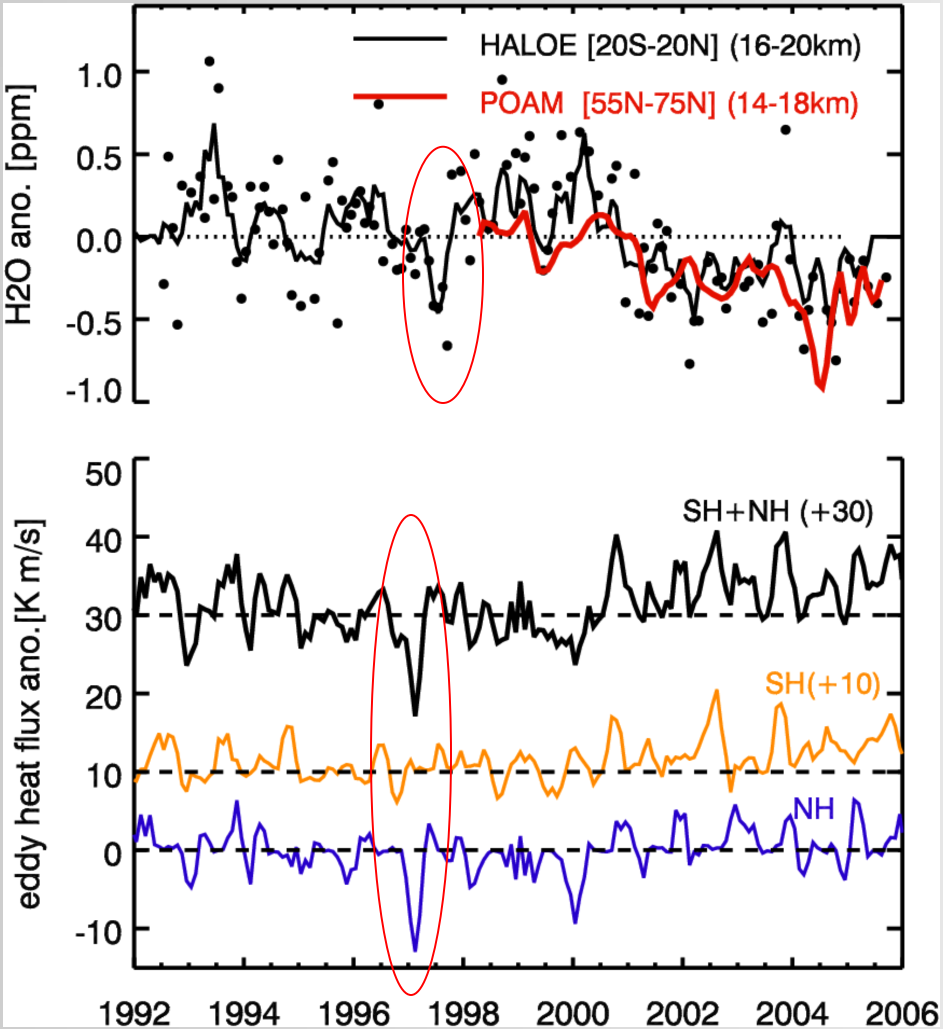
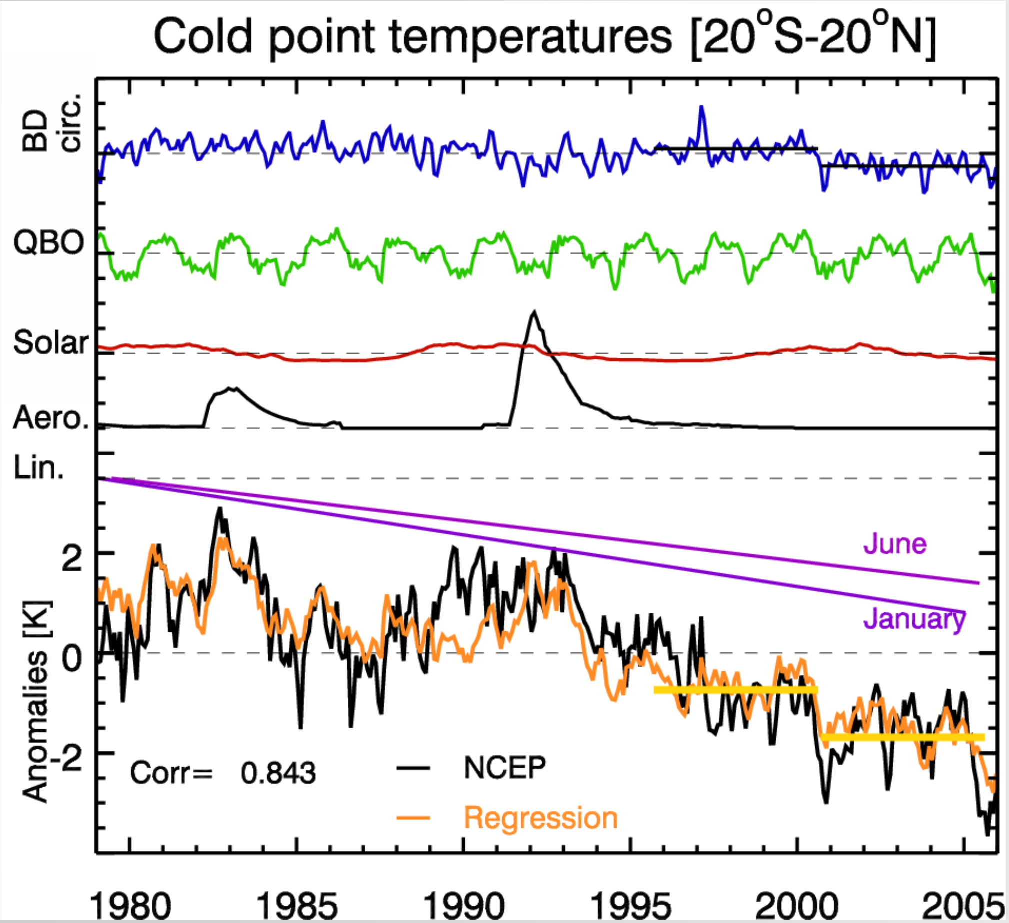
Stratospheric water vapor and BD circulation



Dhomse et al., ACPD, 2007, revised

- Water vapor anomaly above tropical tropopause
  - ➔ BD circulation strength increase in both hemispheres (Dhomse et al., 2007)
  - ➔ Persistent low H2O since 2001 to the present (see also Randel et al., 2006)
- Other processes may also be relevant for stratospheric water vapor changes (tropical convection, equatorial waves)

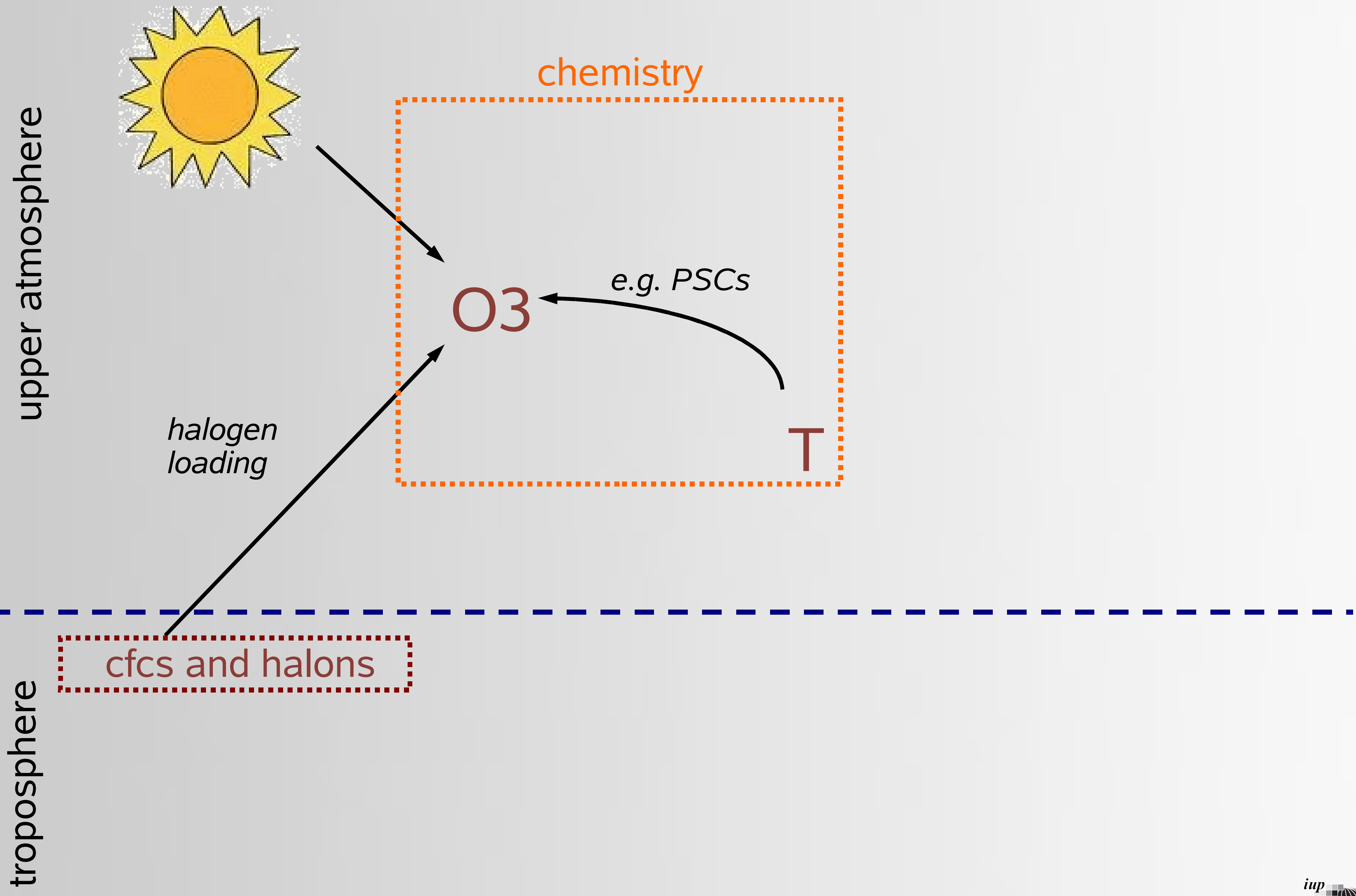
Stratospheric water vapor and BD circulation



Dhomse et al., ACPD, 2007, revised

- Water vapor anomaly above tropical tropopause
  - ➔ BD circulation strength increase in both hemispheres (Dhomse et al., 2007)
  - ➔ Persistent low H2O since 2001 to the present (see also Randel et al., 2006)
- BD circulation changes since 2001 contributed to a ~0.5 K cooling near tropical tropopause
- Longterm downward trend of about 1K/decade (stratospheric cooling due to O3 depletion and CO2, e.g. Langematz et al 2003, Thompson and Solomon, 2005, WMO 2006)

Ozone-climate interaction



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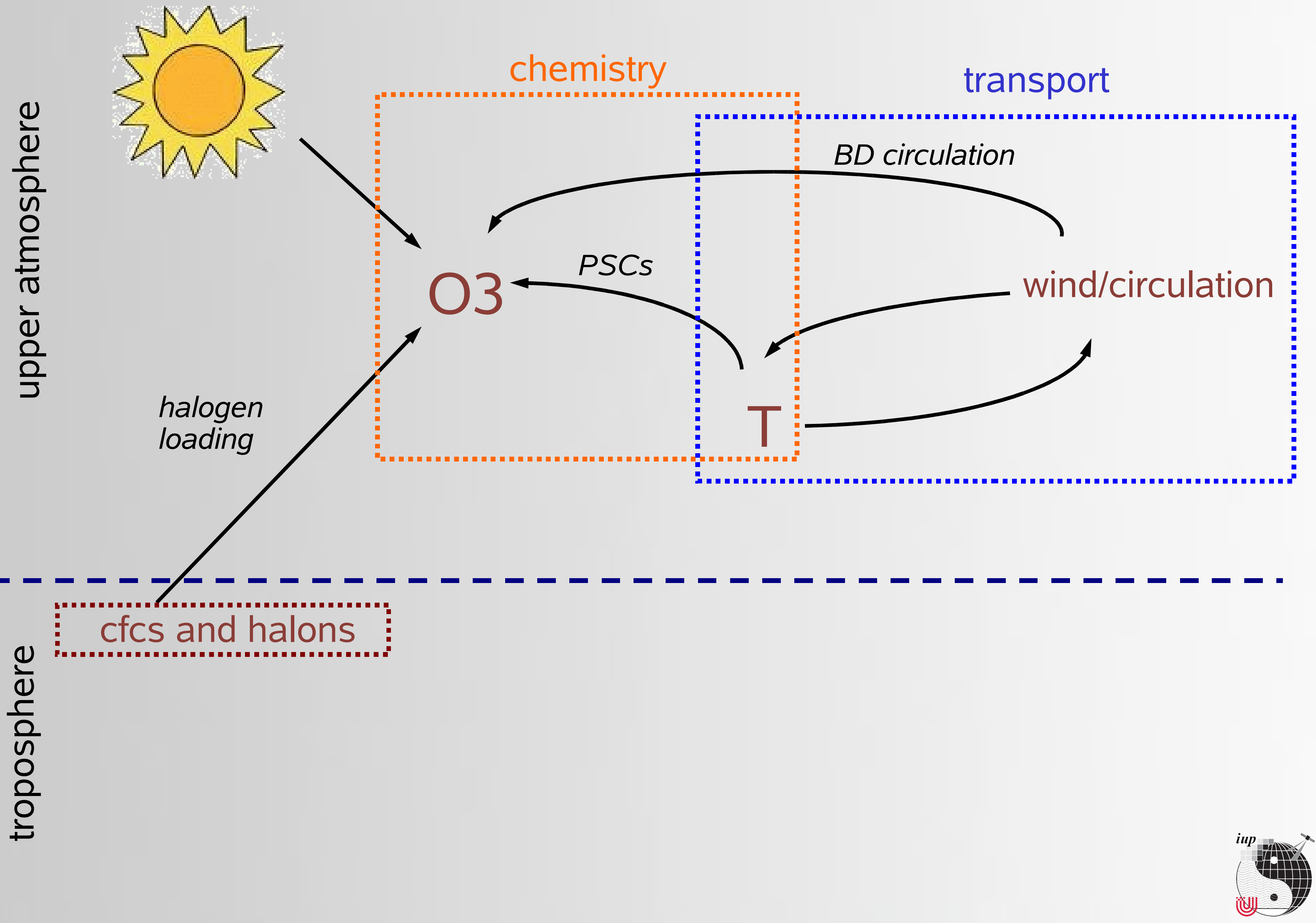

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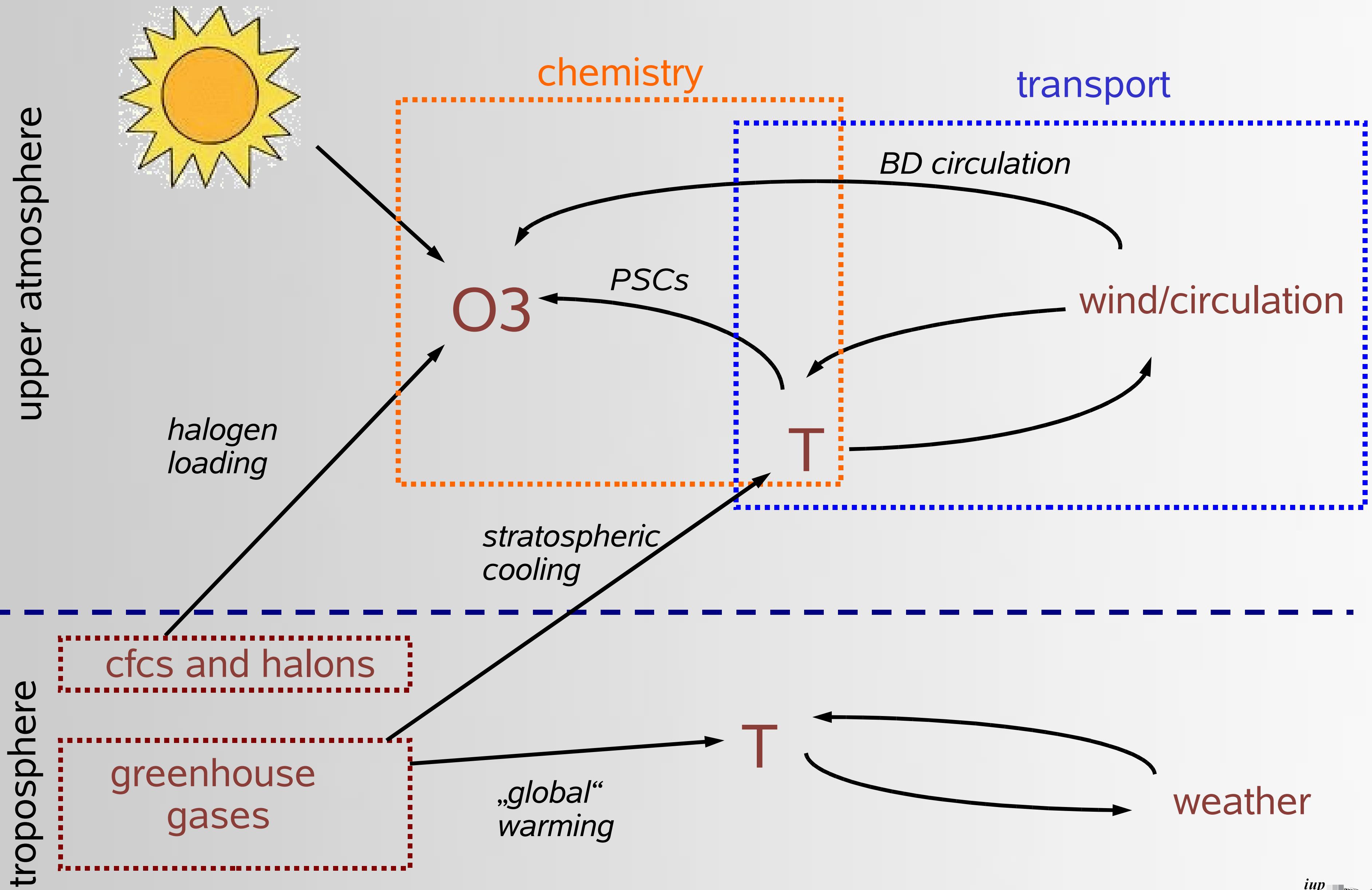

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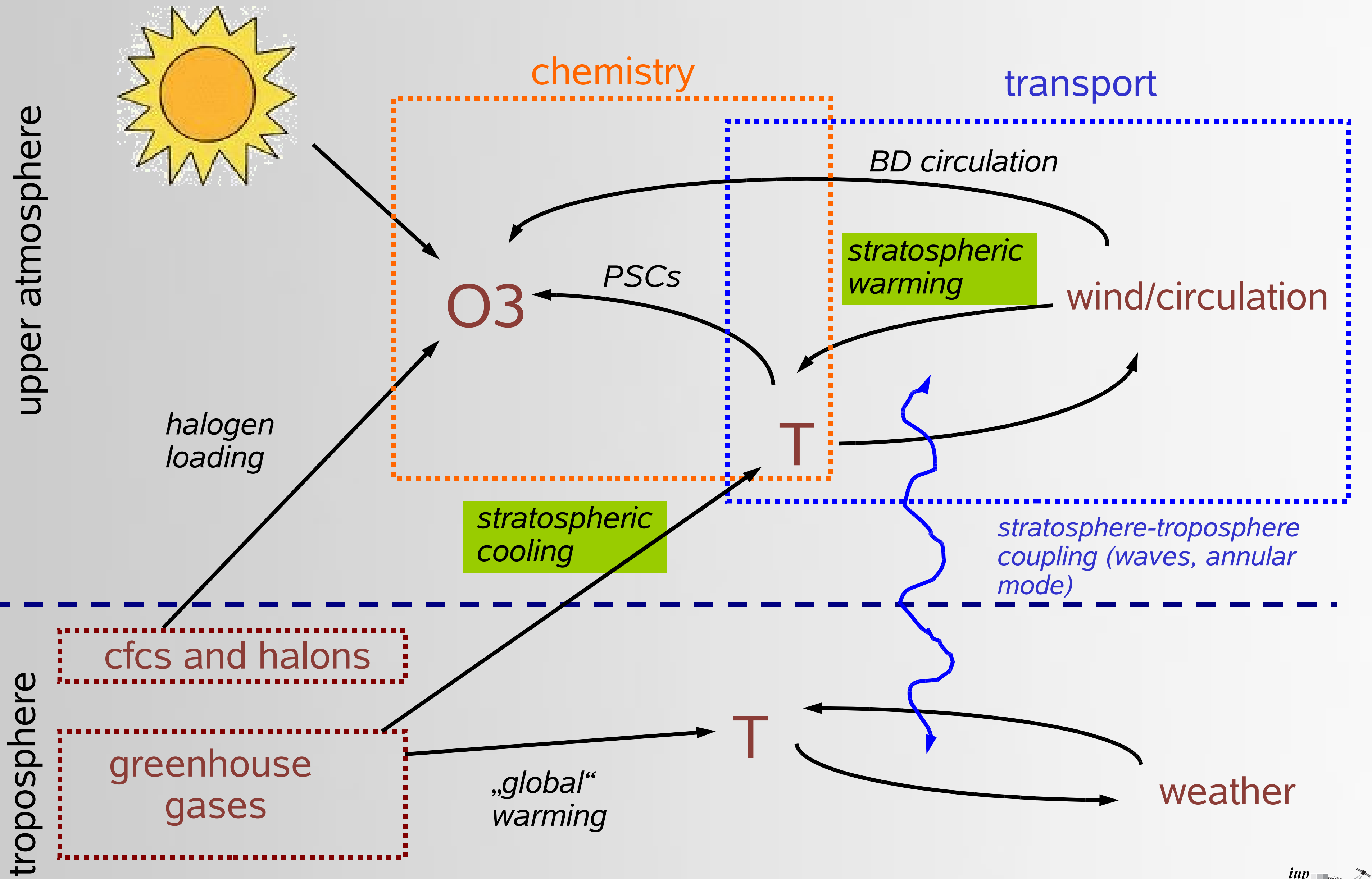
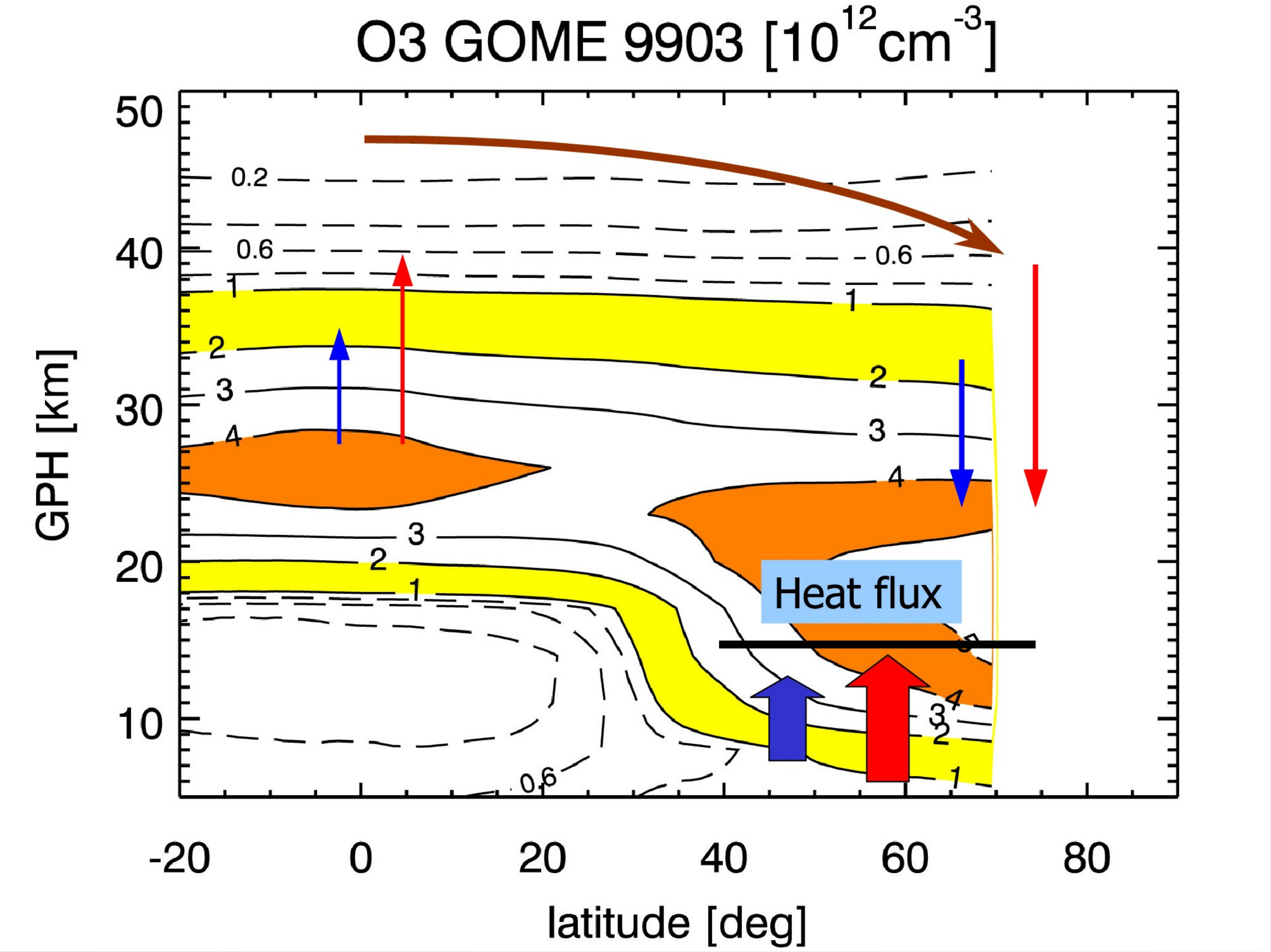
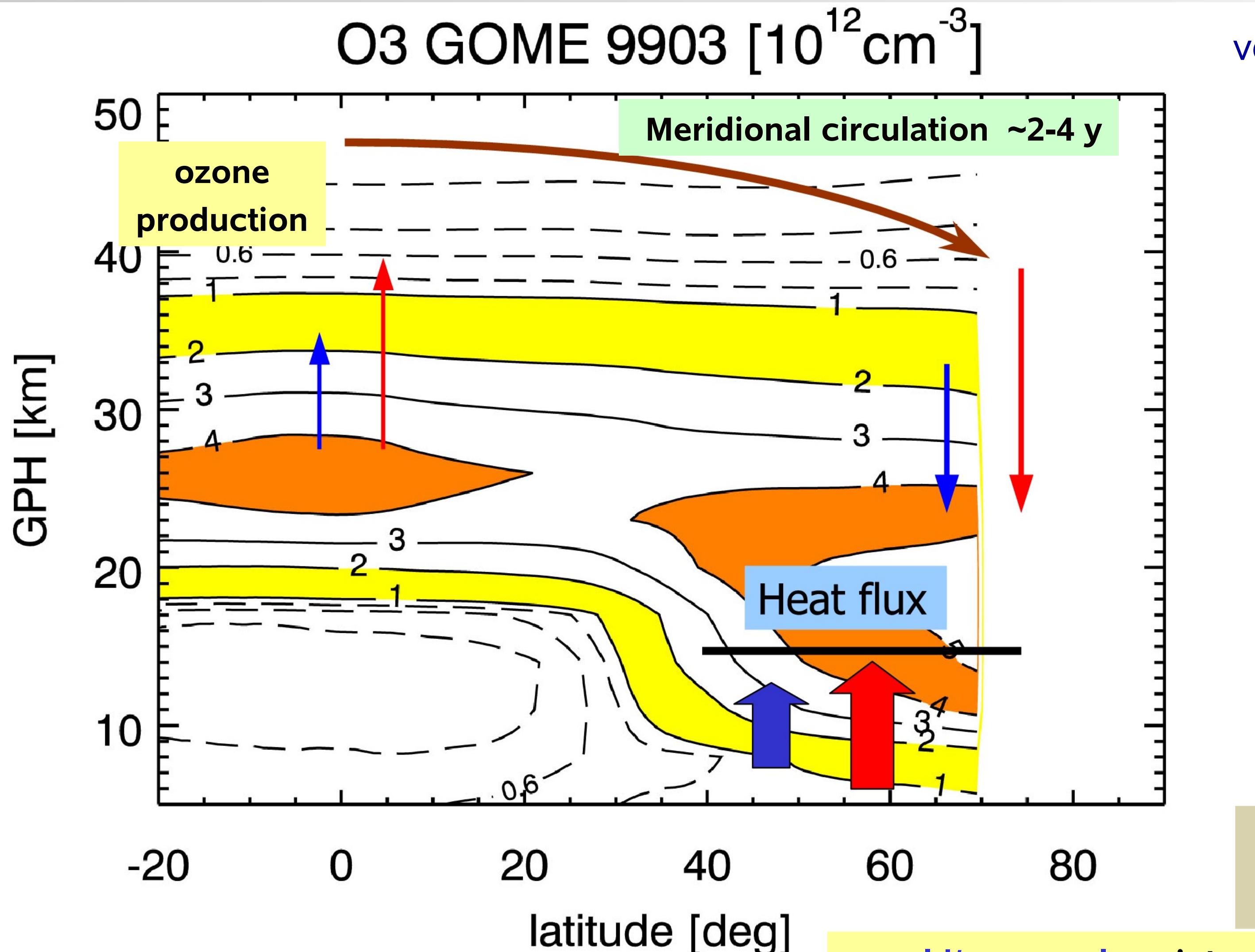


Residual Circulation and ozone



Residual Circulation and ozone



vertical EP (heat) flux/
Planetary scale
wave activity
Extratropical Pump

⇩

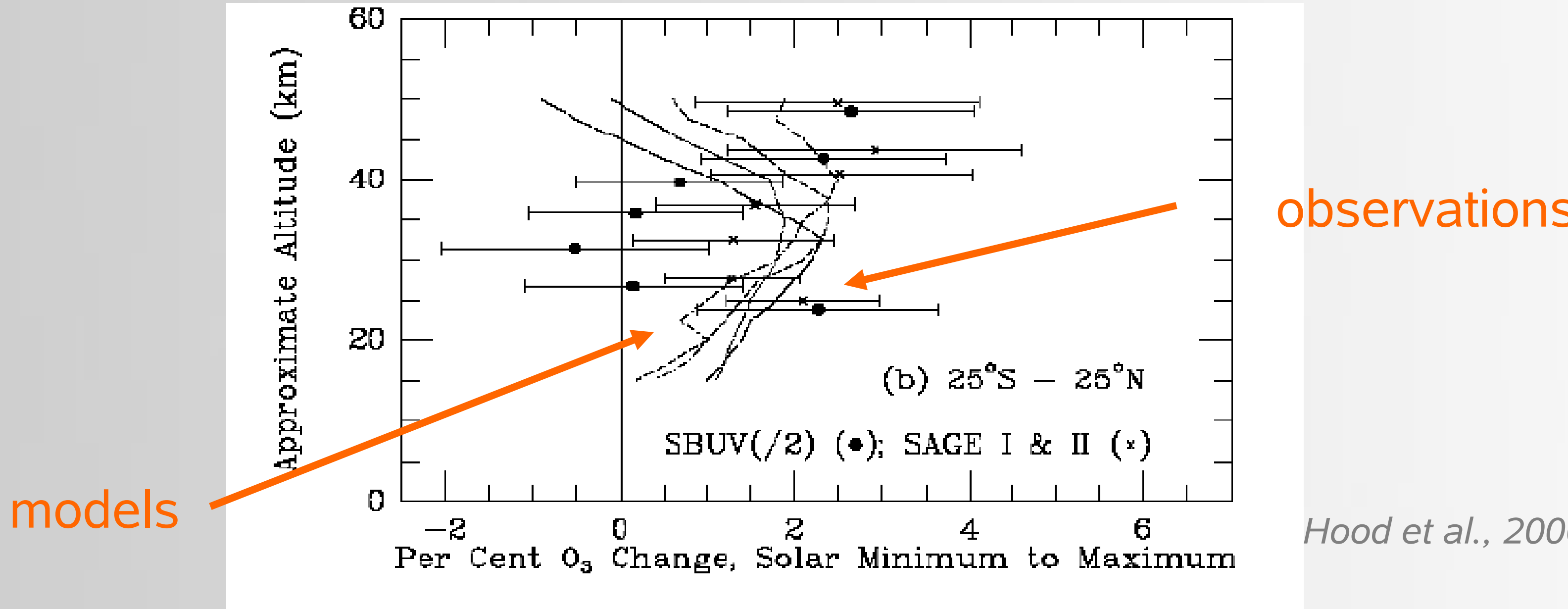
Brewer-Dobson
circulation
Residual circulation

⇩

Ozone & T variability
chemistry/transport

cold/warm polar winters
heterogenous/gasphase
chemistry

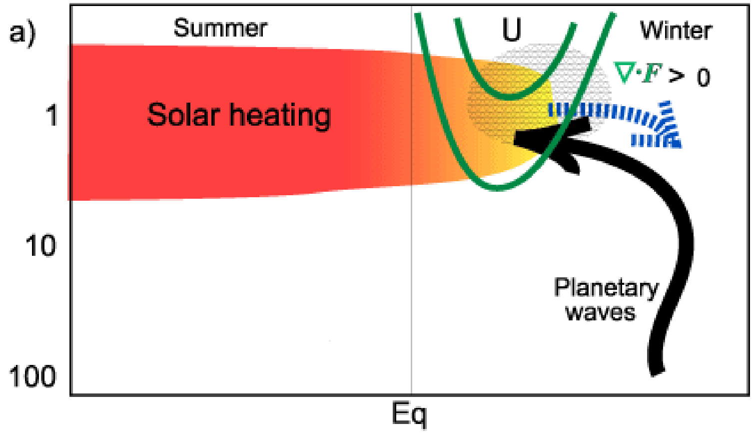
ozone and solar cycle variability



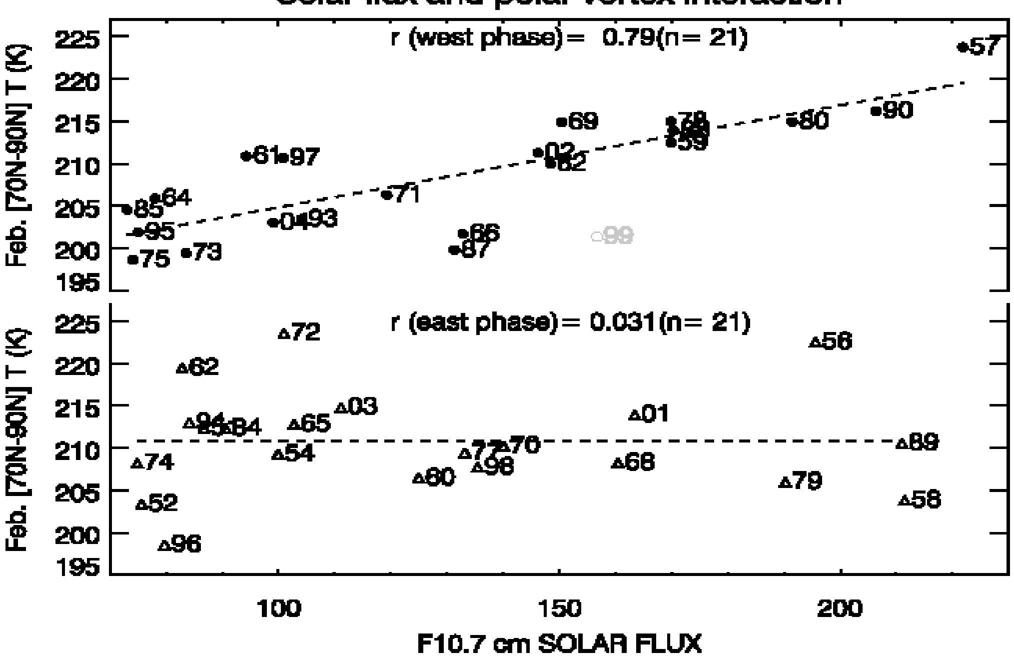
Hood et al., 2006

- Models do not show the double peak (25 and 50 km altitude) in sol
  - ➔Possible reasons
    - Data record too short (~2.5 solar cycles)
    - NOx from particle (electron precipitation) leads to ozone destruction during solar minimum in middle stratosphere -> BUT: equires „huge“ amounts of Nox
    - Reduced ozone production (less sunlight) in middle stratosphere from enhanced ozone in the upper stratosphere
    - Interference from QBO (not well represented in models) and associated dynamical effects
    - Lower stratospheric solar signature are probably from dynamical response to solar variability

Solar coupling, planetary waves, and QBO



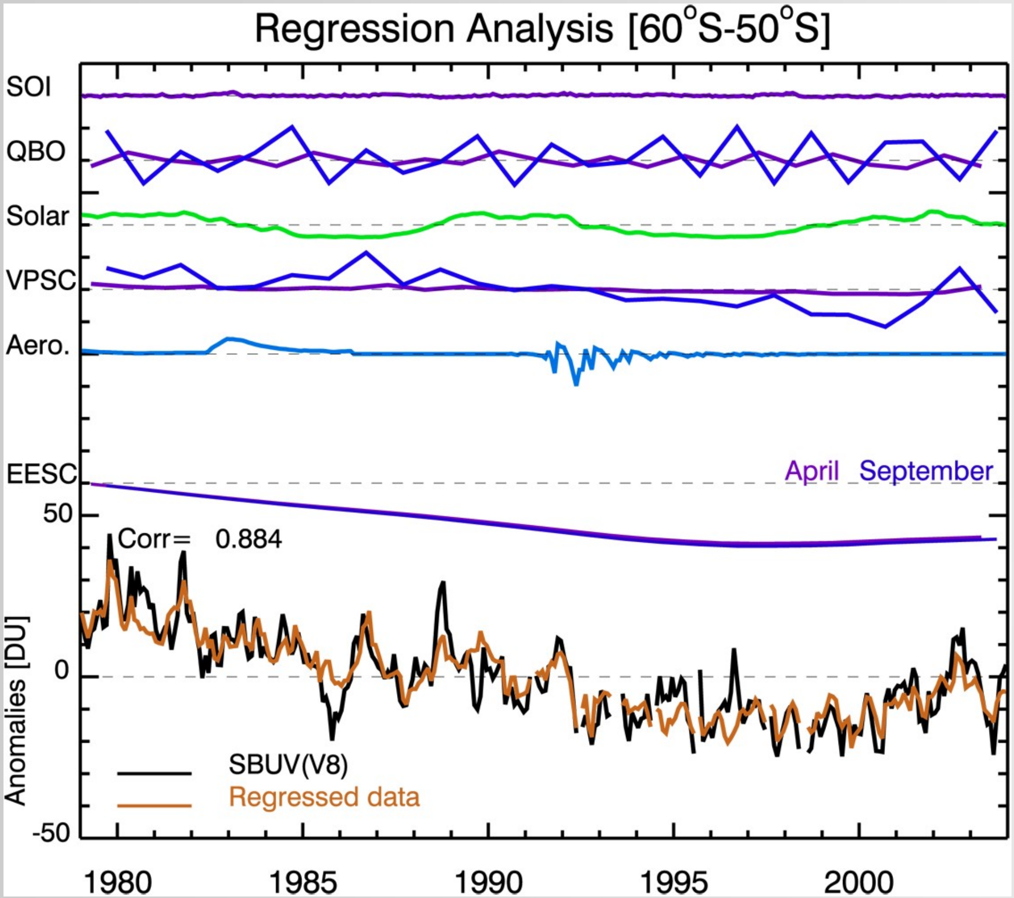
Kodera and Kuroda (2002)



- extra solar heating during solar max strengthens subtropical stratopause jet (SJ) in early winter
  - ➔ **radiative response**
- Deflection of planetary waves away from subtropics (towards pole) while SJ descends downwards and polewards
- Weakening of polar night jet (polar vortex) in mid- to late winter
- warmer polar stratospheric temperatures (mostly during QBO west phase)
  - ➔ **Dynamical-chemical response**

Update from Labitzke,1987, and Labitzke and van Loon, 1988

What about SH mid- to high latitudes?



- Eddy heat flux calculation less reliable in SH/ better use Vpsc as a proxy for temperature amd dynamical variability
- Differences to NH:
  - ➔ larger QBO contribution in spring
  - ➔ Little influence from major volcanic eruptions (not understood)
- EESC turnaround also modest like in NH, linear trend will fit as well
- Solar cycle influence evident up to polar latitudes

Charged particle influence on wave driving and March total ozone?

high electron flux during solar minimum

↓ ?

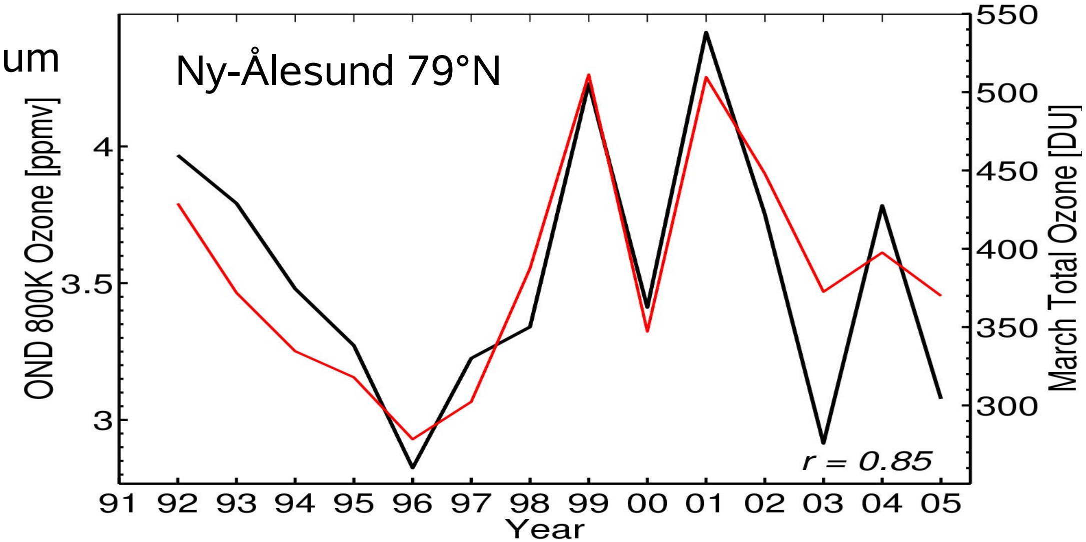
low upper stratospheric ozone in autumn

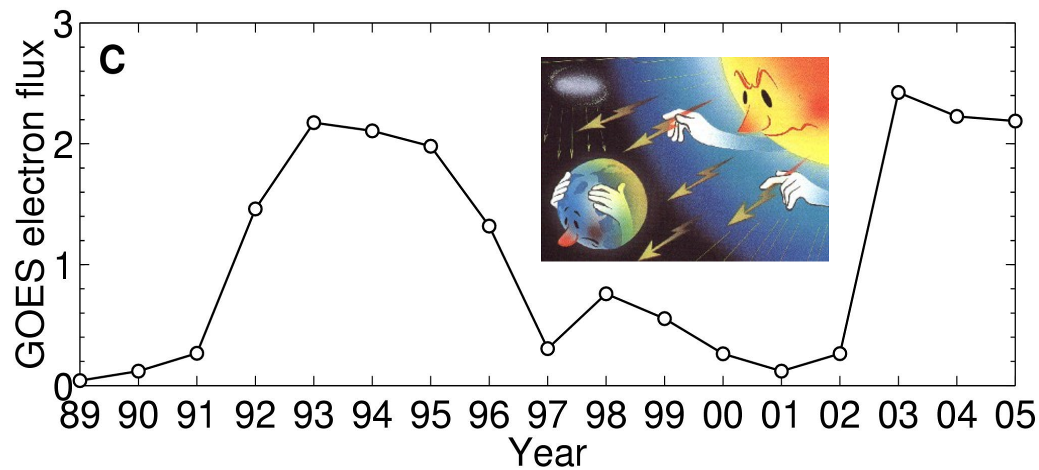
↓

Reduced winter wave driving

↓

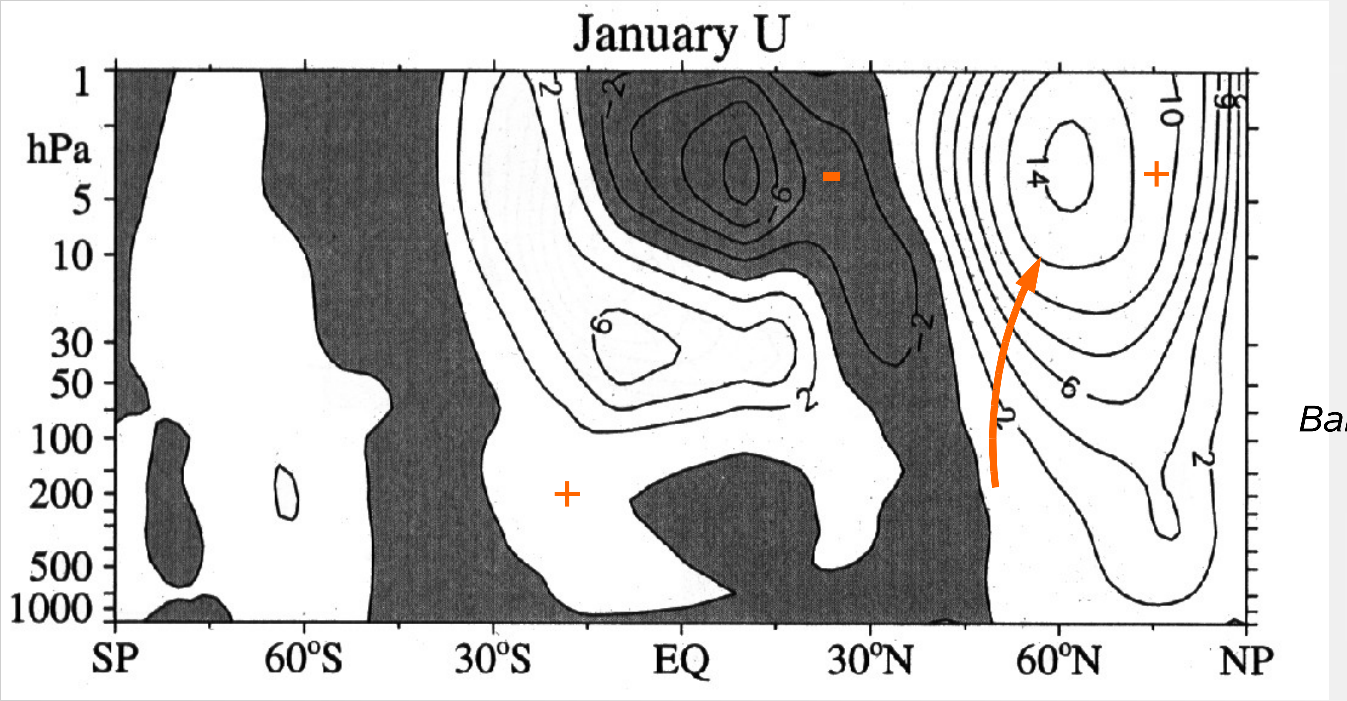
low total ozone in late winter





Kawa et al., (2005), Sinnhuber et al. (2005)

QBO and Brewer-Dobson circulation



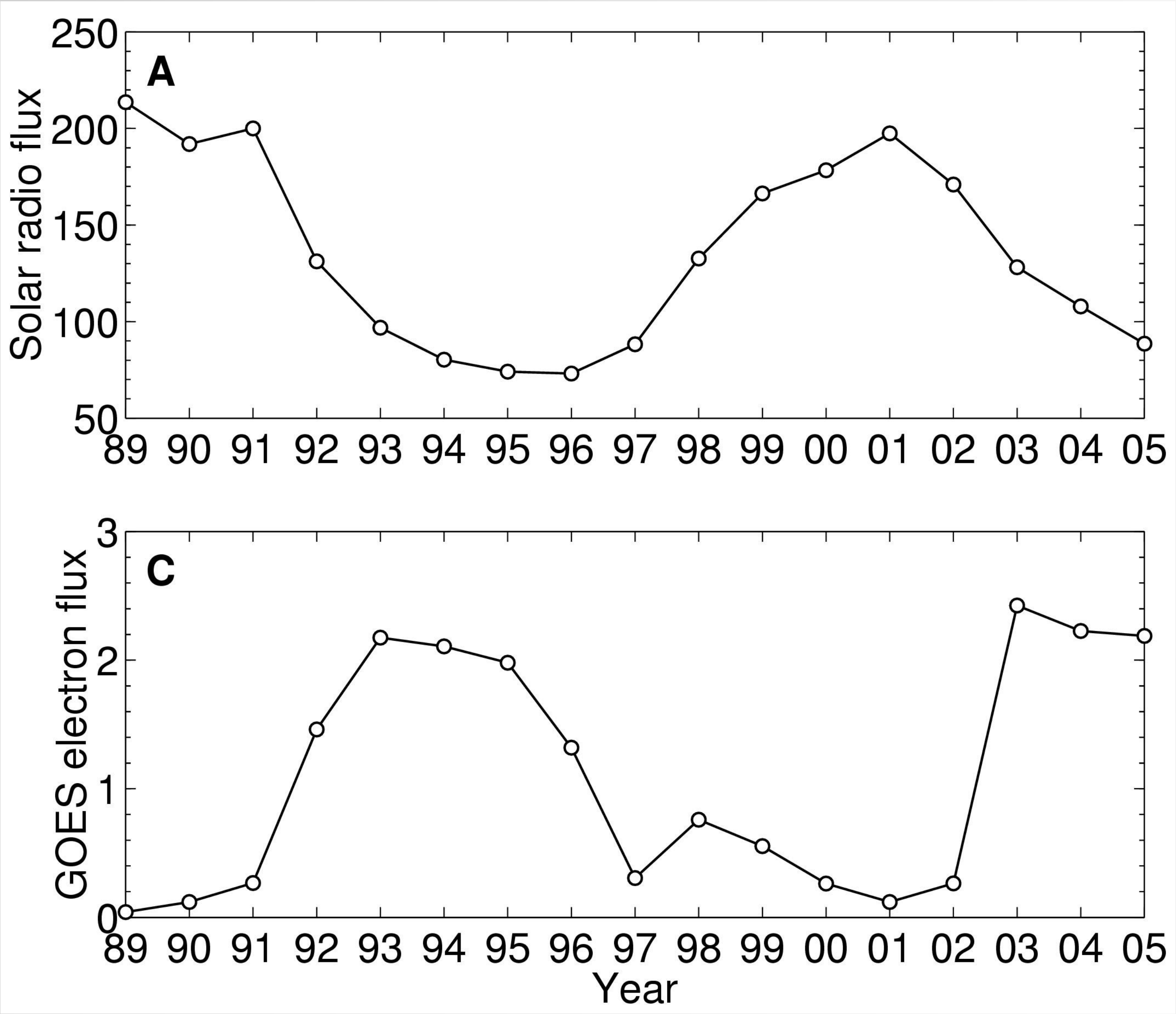
Baldwin et al. (2001)

January zonal mean u wind differences:
QBO west (40hPa, EQ) minus QBO east (40hPa, EQ)

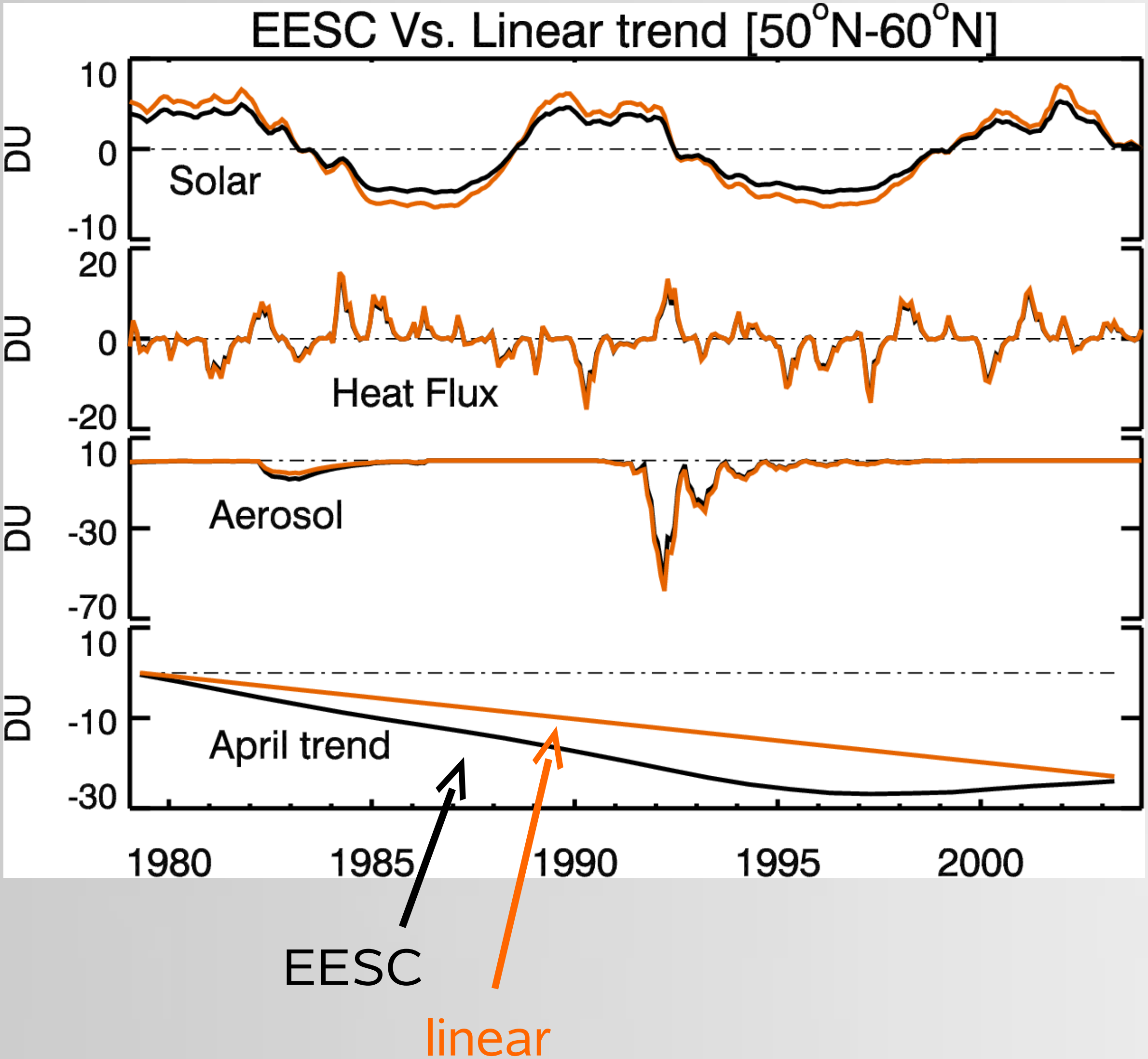
Holton-Tan mechanism (1980)

- During equatorial QBO west phase planetary waves are deflected polewards (wave propagation only into westerlies)
- Enhanced planetary wave driving at mid-to high latitudes
- depositing easterly momentum/weakening of polar vortex

What is the evidence for electron precipitation?



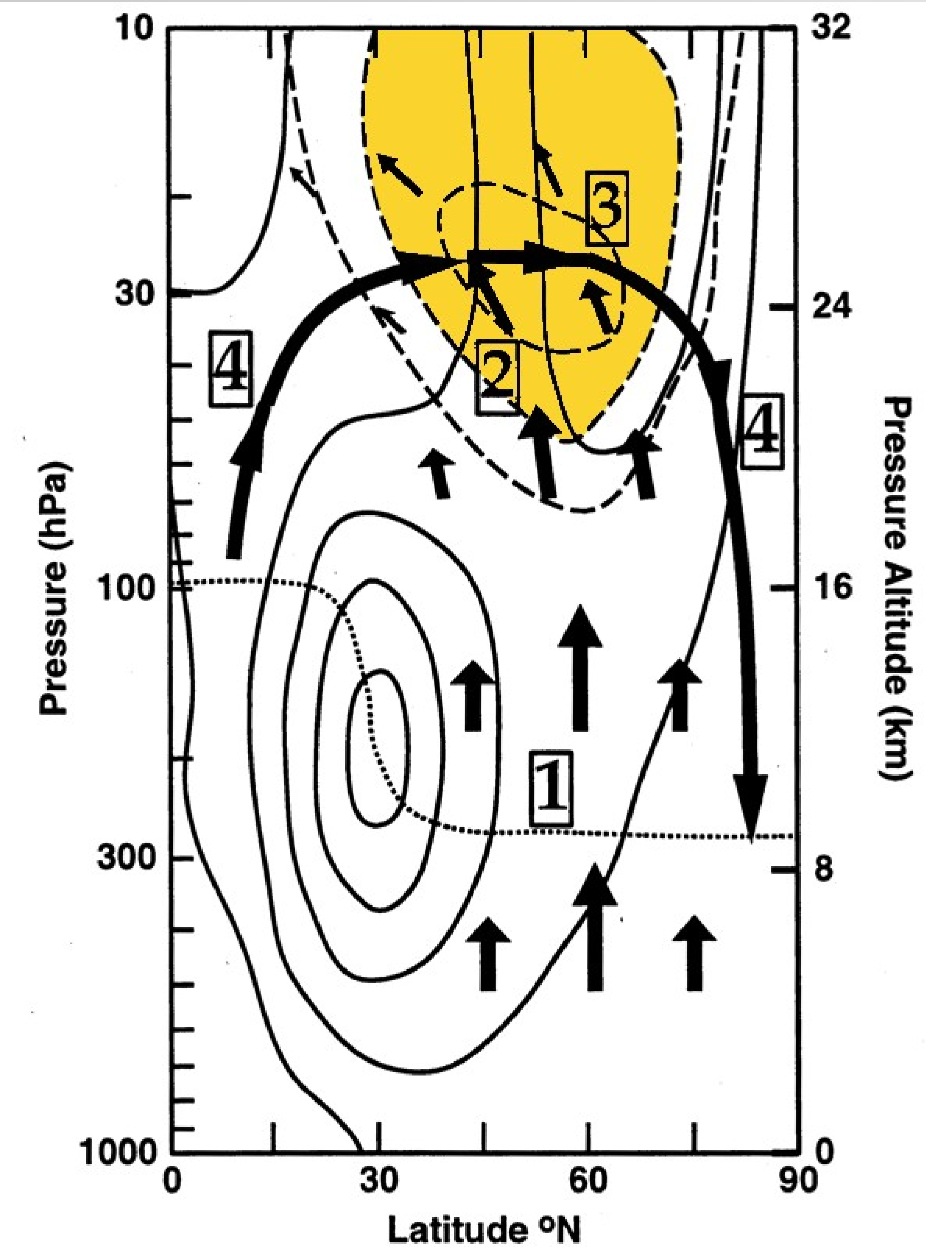
Linear trend until or EESC trend



- Assuming continous linear downward trend
  - ➔Larger ozone variability due to solar cycle (±8 DU)
  - ➔Aerosol and wave driving contribution remain unaltered

Dhomse et al. (2006)

Planetary waves and residual circulation

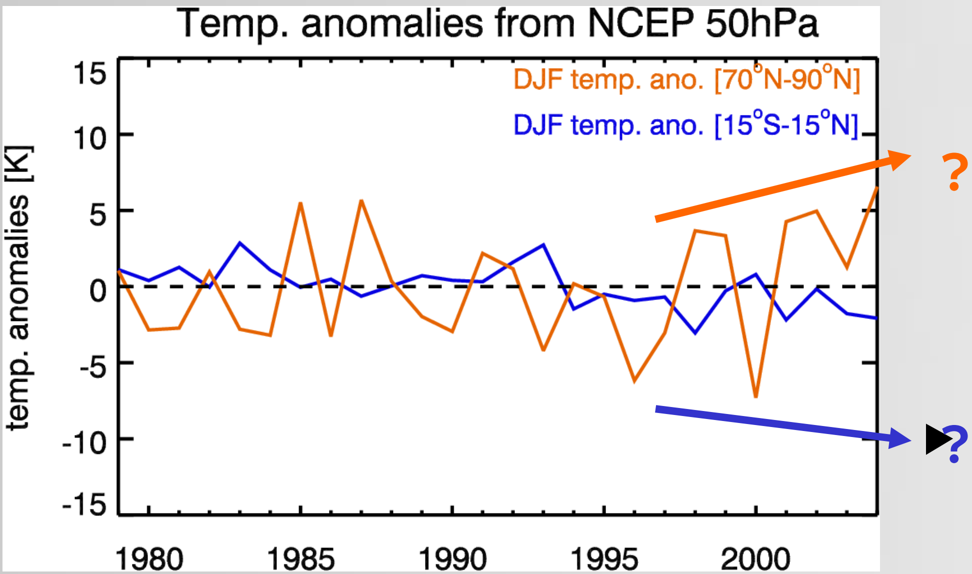


Newman et al. (2001)

Weak wave driving (mostly in SH):
→ waves refracted into subtropics
→ strong polar night jet
→ cold polar stratosphere
→ polar chemical ozone loss and reduced ozone transport (weak BD circulation)

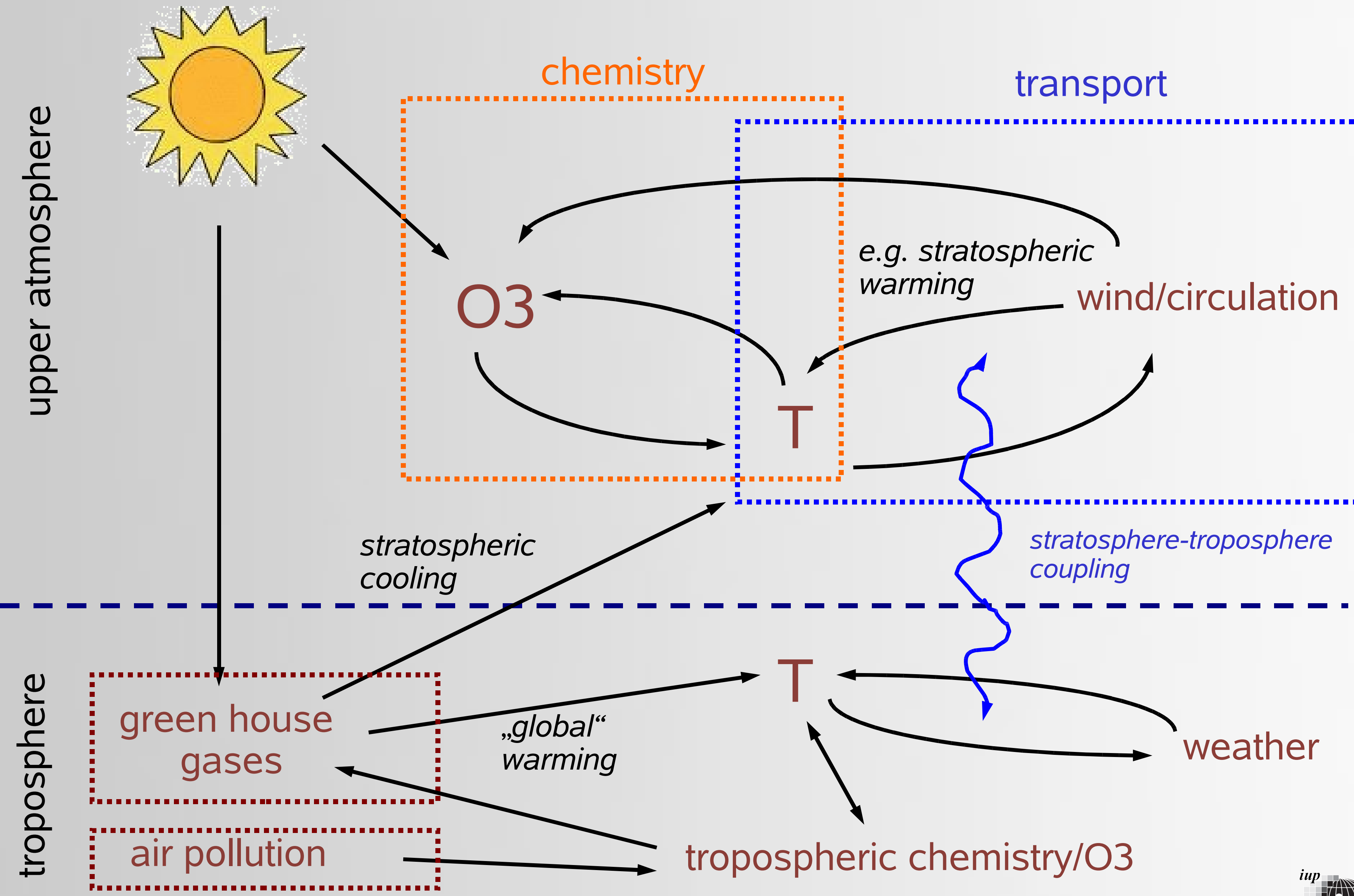
High wave driving (mostly in NH)
→ wave propagation towards pole
→ weak polar vortex
→ warm polar stratosphere
→ enhanced ozone transport & reduced polar chemical ozone loss (strong BD circulation

Conclusion

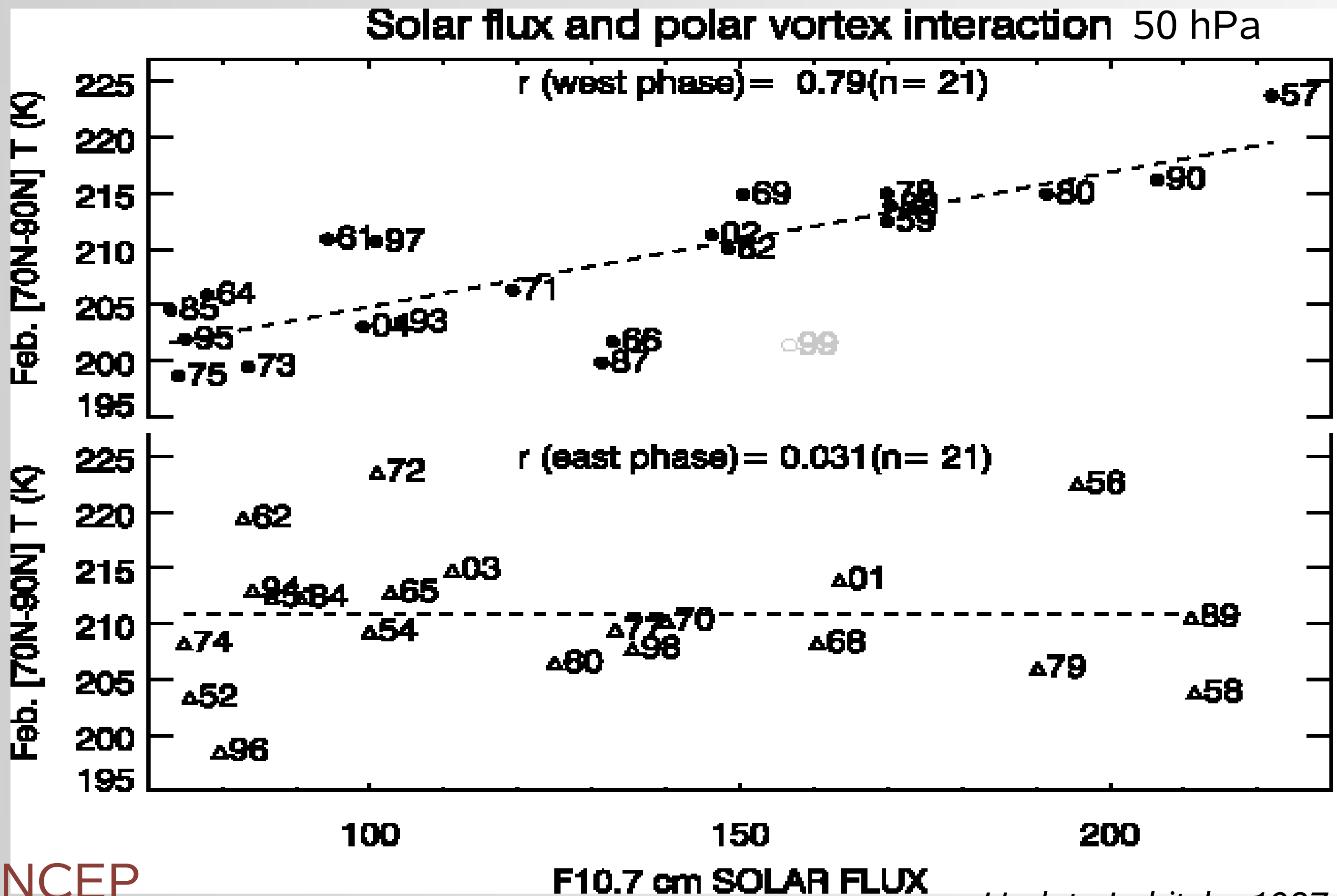


- Radiation-dynamics-chemistry coupling leads to high ozone variability in the lower stratosphere (ozone-climate interaction)
- Solar cycle influence on stratospherioc ozone from the tropics to the pole (mostly indirect effects via dynamics)
- Recent increase in total ozone since mid nineties
  - ➔ Reduced polar ozone loss (or enhanced wave activity)
  - ➔ Recent increase in NH polar temperature and tropical LS cooling in tropics
  - ➔ Not clear yet if that is a persistent trend (climate change?) or just part of decadal variability
  - ➔ modest contribution from EESC turnaround
- Still: longer time record is needed to better understand decadal variablity

Ozone-climate interaction



Coupling of tropics (QBO) and polar region (Arctic T)



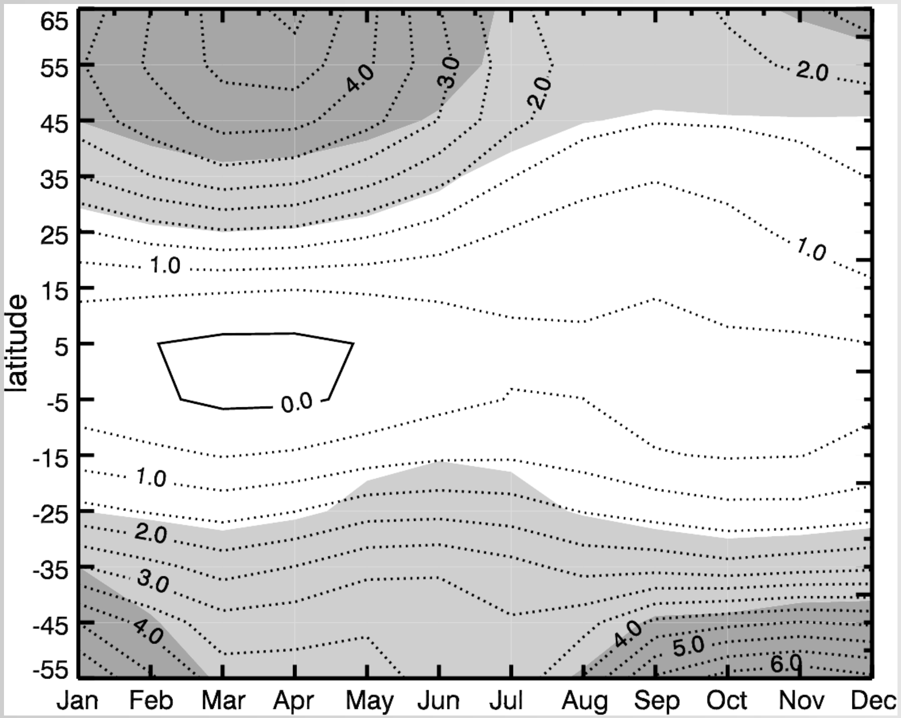
NCEP

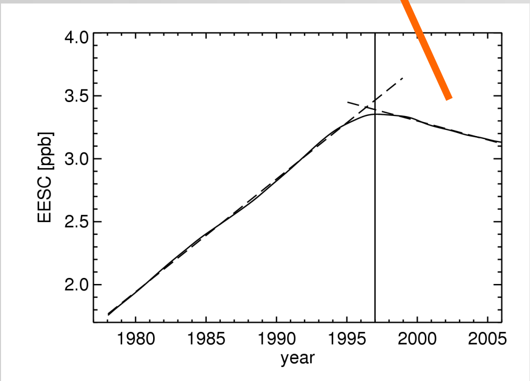
Update Labitzke,1987,
Labitzke and van Loon, 1988

- QBO: equatorial winds
- Holton-Tan mechanism: modification of planetary wave propagation (BD circulation) via QBO

Ozone recovery?

EESC trend since 1997 in DU/decade)





- Modest contribution from turnaround in stratospheric chlorine since late 1990s
- Larger contribution to recent TO3 changes from BD circulation changes and solar cycle
- Variability in TO3 (lower stratosphere) is high, more data is needed to separate ozone recovery from other decadal variation.