Effects of Solar Variability on the Stratosphere

Cora Randall, LASP, University of Colorado, Boulder, USA

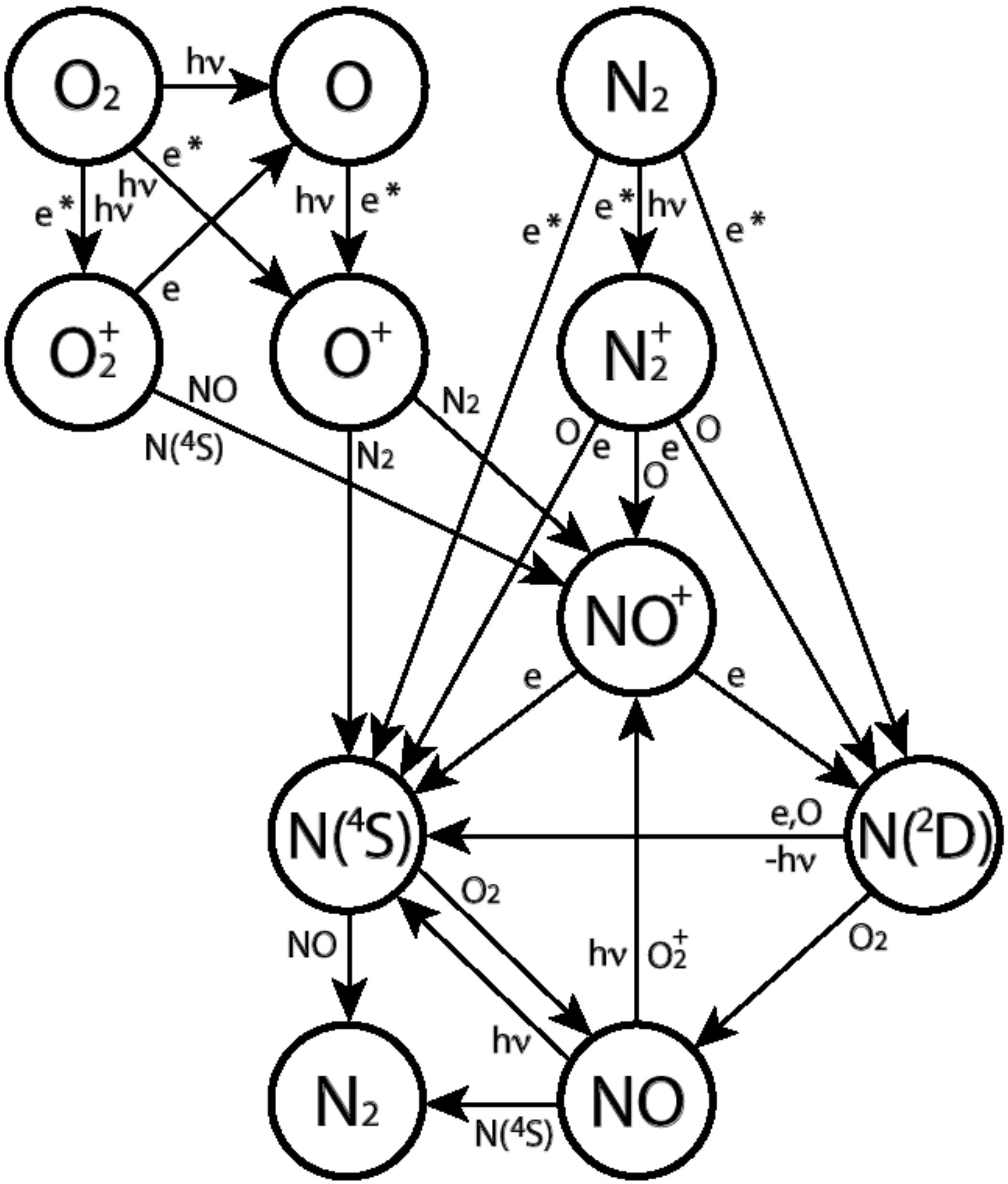
Lon Hood, LPL, University of Arizona, Tucson, USA

- Variations in solar and magnetospheric particle precipitation rates into the polar upper atmosphere with consequences at lower altitudes.

- 11-year solar UV effects on upper stratospheric ozone, radiative heating, and zonal winds with indirect consequences elsewhere in the stratosphere.

SPARC 4th General Assembly
Bologna, Italy
September 3, 2008

DEPARTMENT OF PLANETARY SCIENCES
LUNAR AND PLANETARY LABORATORY
The University of Arizona, Tucson AZ 85721



Charles Barth, et al., courtesy of Frank Eparvier

Energetic Particle Precipitation (EPP)

↓↓↓

Ionization & Dissociation

↓↓↓

NO_x and HO_x

NO_x and HO_x Destroy Ozone

(Mainly at high latitudes!)

EPP effects on the stratosphere depend on energy of precipitating particles

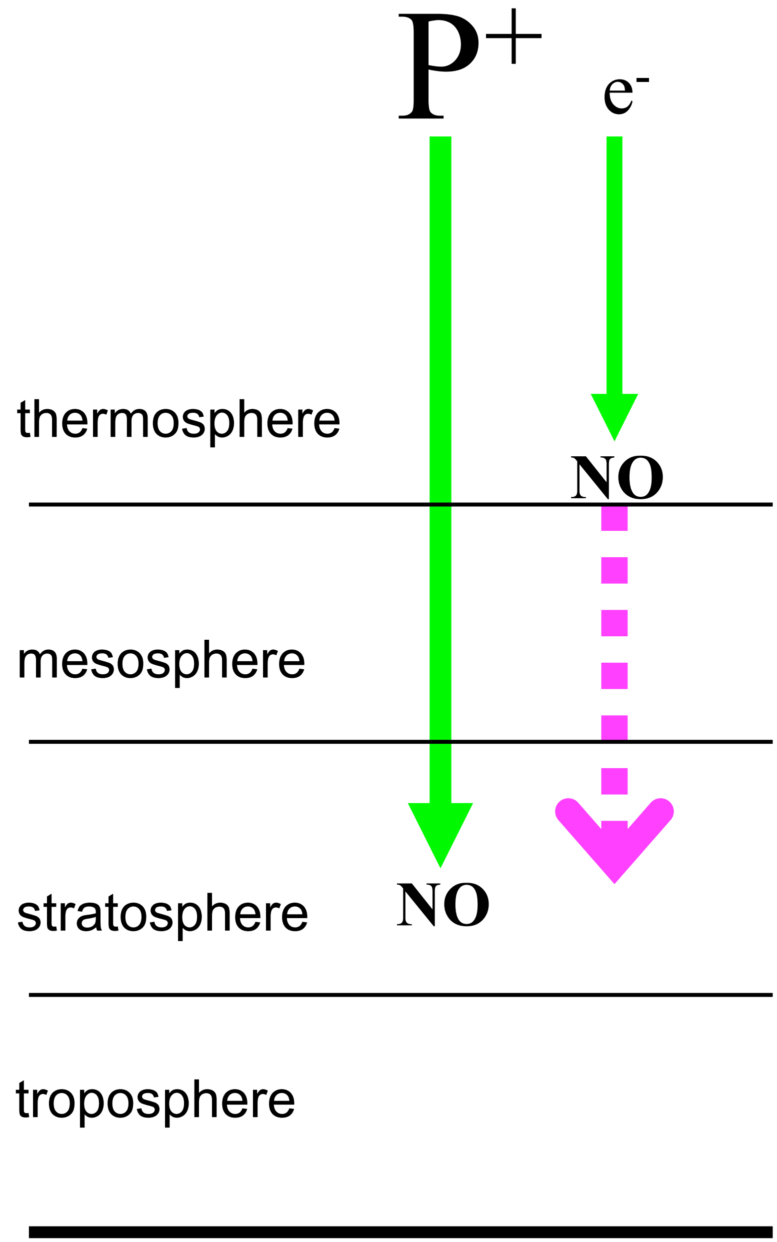
<u>High Energy</u>: NO_x produced directly in stratosphere (> 300 MeV e^-; 30 MeV p^+)

"Direct Effect"

<u>Low Energy</u>: NO_x produced in thermosphere or upper mesosphere

But can be transported to stratosphere during polar night (Solomon et al., 1982)

"Indirect Effect"



DIRECT Effect of EPP on the Stratosphere

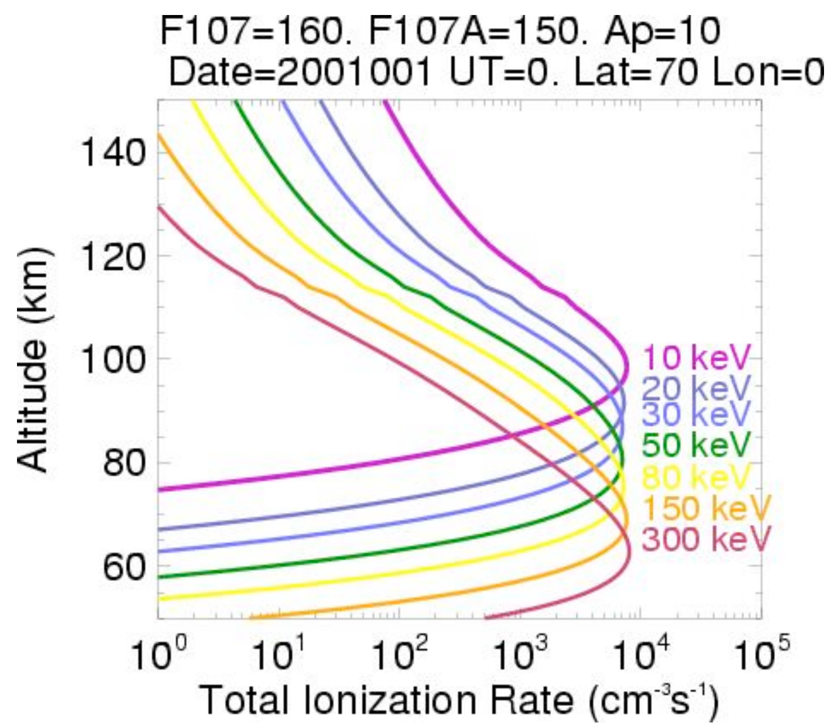
NO is produced locally

- **Requires highly energetic particles**

Thermosphere: < 30 keV electrons
< 1 MeV protons

Mesosphere: 30 - 300 keV electrons
1 - 30 MeV protons

Stratosphere: > 300 keV electrons
> 30 MeV protons

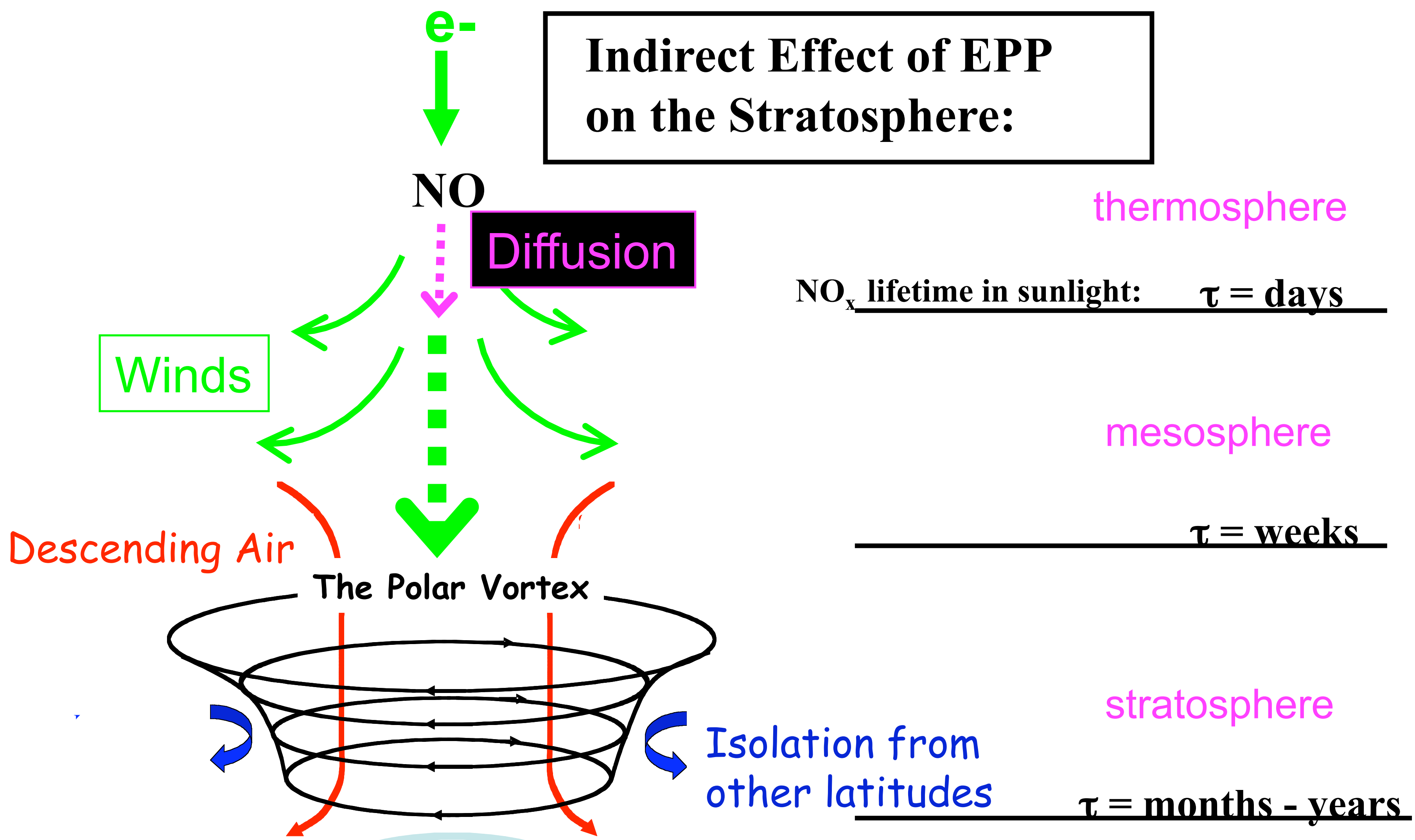


From Lynn Harvey; adapted from Eparvier et al., old submission

- **Sporadic production**

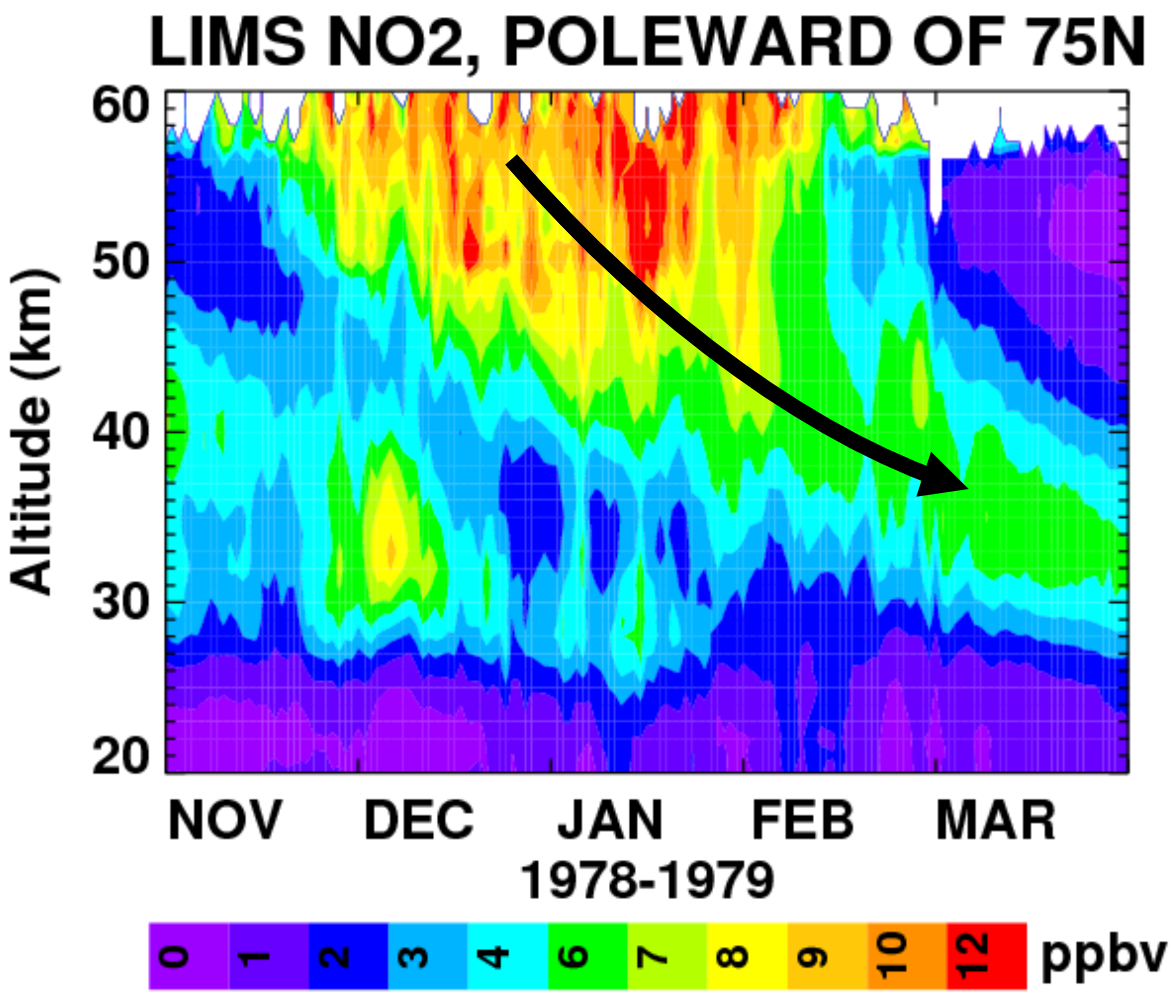
e.g., several SPE's per solar cycle

Indirect Effect of EPP on the Stratosphere:



Must understand interannual variability in NO production and SMLT dynamics

First Satellite Observations of EPP Indirect Effect from Nimbus 7 LIMS, 1978-79



Satellite observations of EPP-NO_x were sparse from 1979 to 2003.

EPP Investigations used solar occultation data from SAGE, HALOE, and POAM

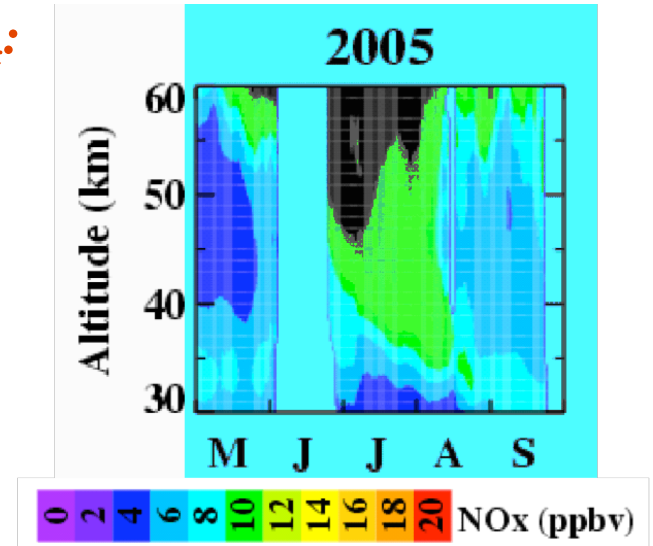
- **Sparse geographic coverage**
- **SAGE & POAM only measure NO_2 , not NO**
- **No polar night measurements**

In 2003, more data became available

e.g., GOMOS, MIPAS, SCIAMACHY, ACE-FTS

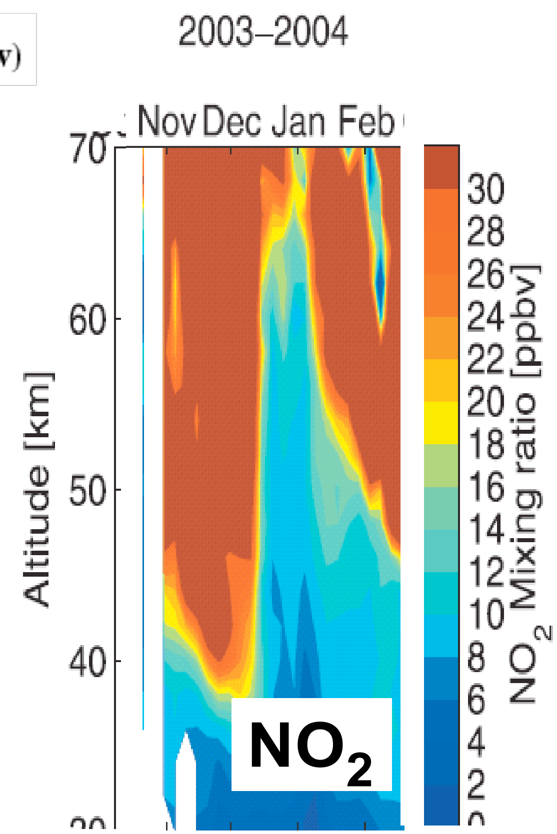
Examples of descending NO_x:

ACE-FTS (SH):



Randall et al., 2007

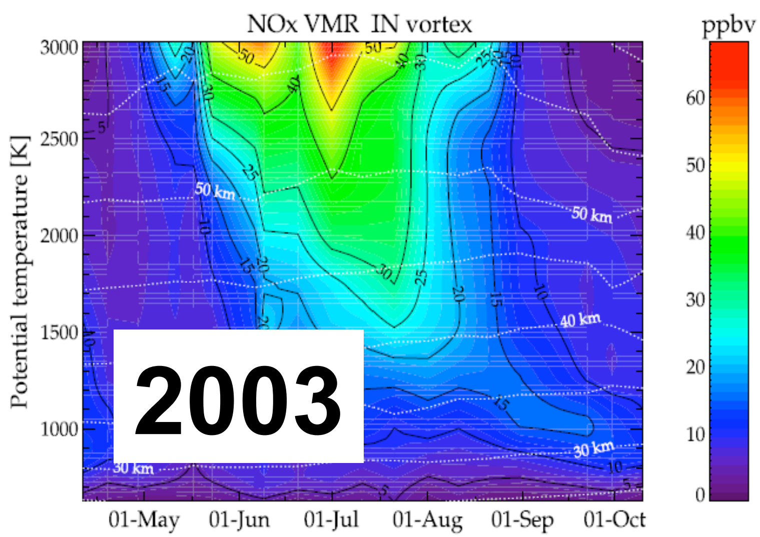
GOMOS (NH):



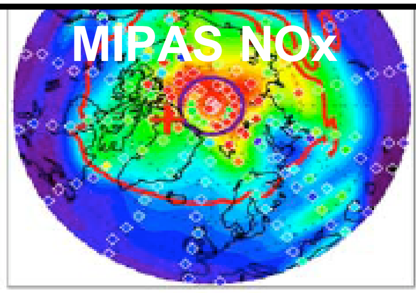
Seppala et al., GRL, 2007

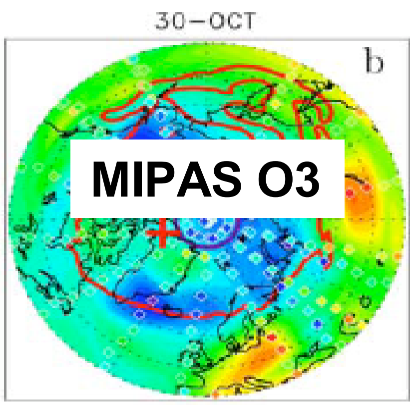
MIPAS (SH)

Funke et al., 2005



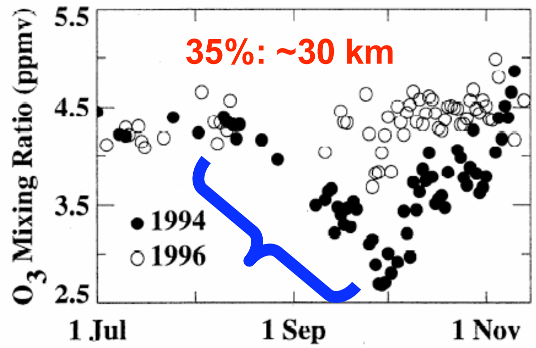
EPP-NO_x enhancements accompanied by O_3 reductions:



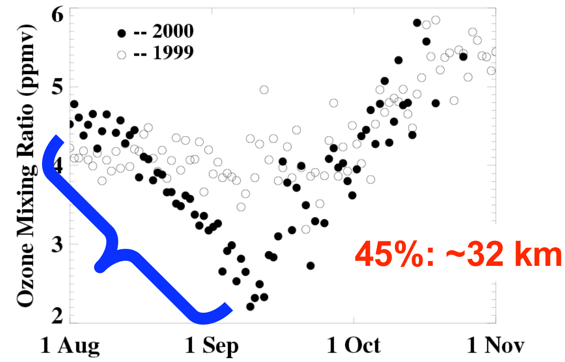


Lopez-Puertas et al., 2005

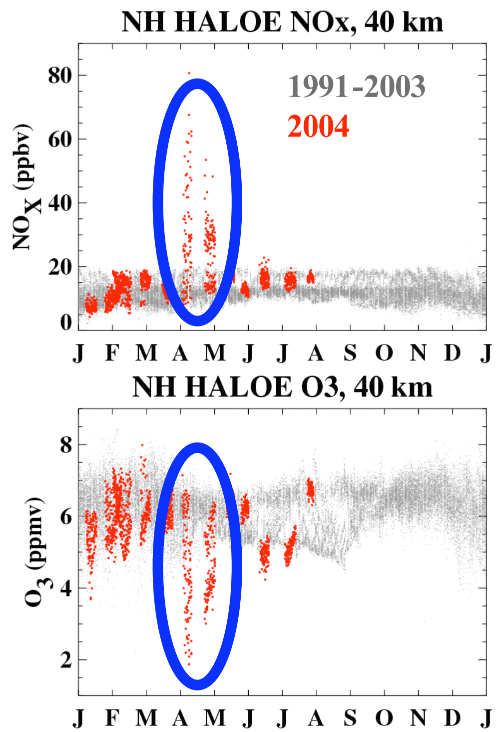
See also poster P32



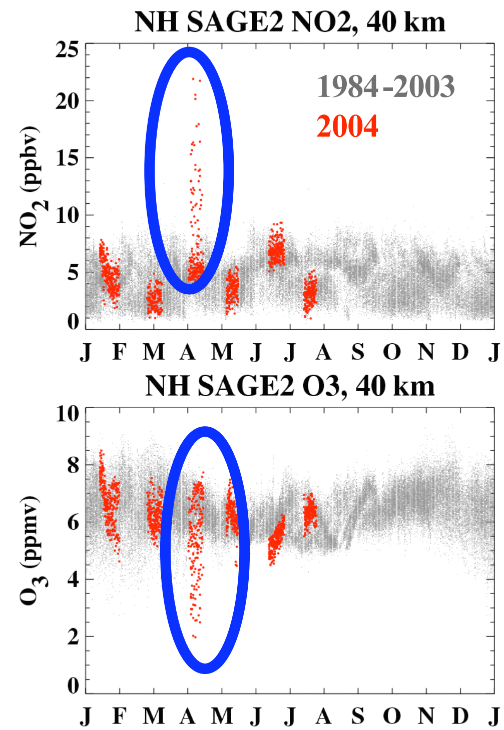
Randall et al., 1998



Randall et al., 2001

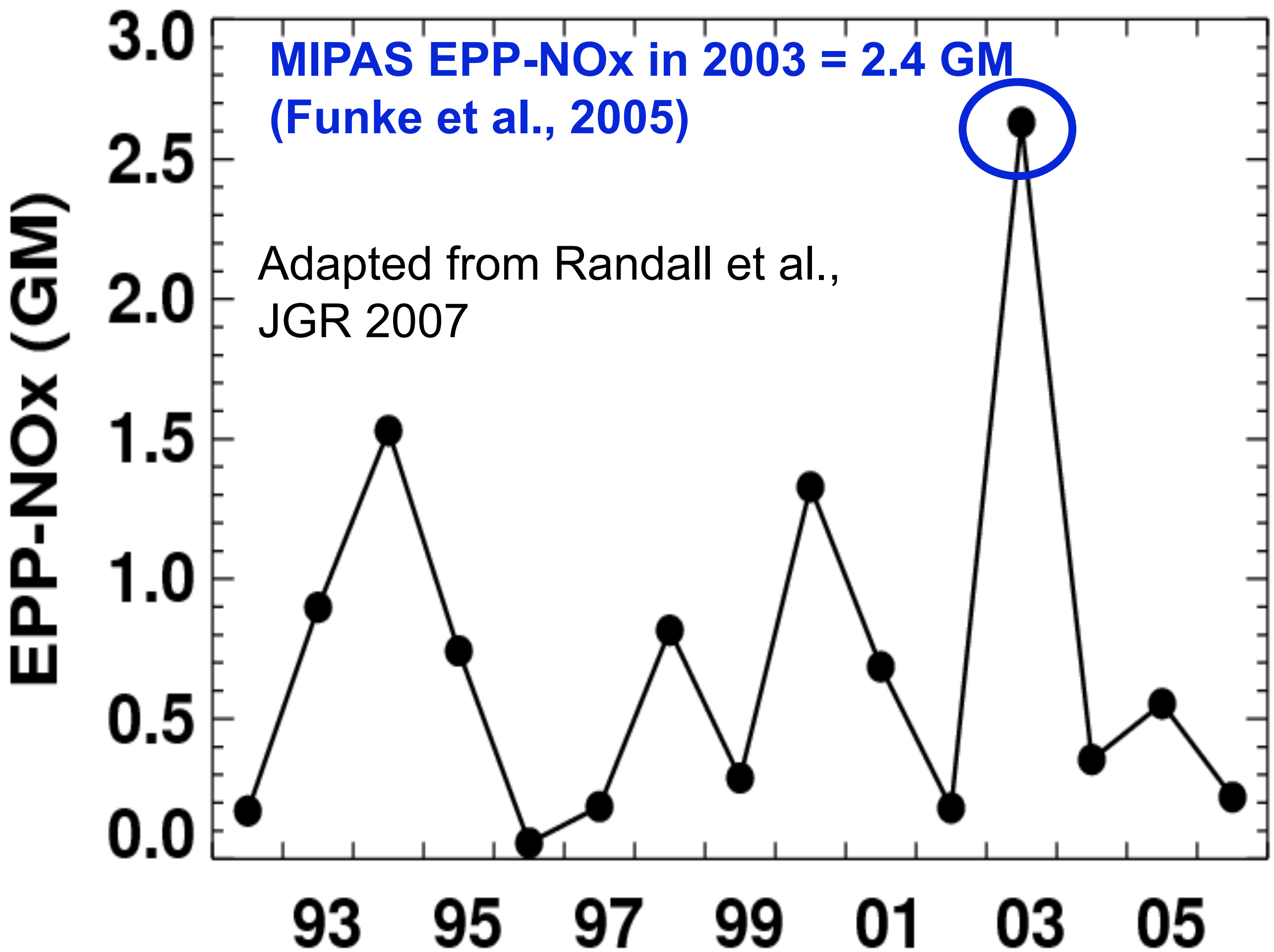


Randall et al., 2005



Randall et al., 2005

EPP-NO_x entering the SH polar stratosphere:



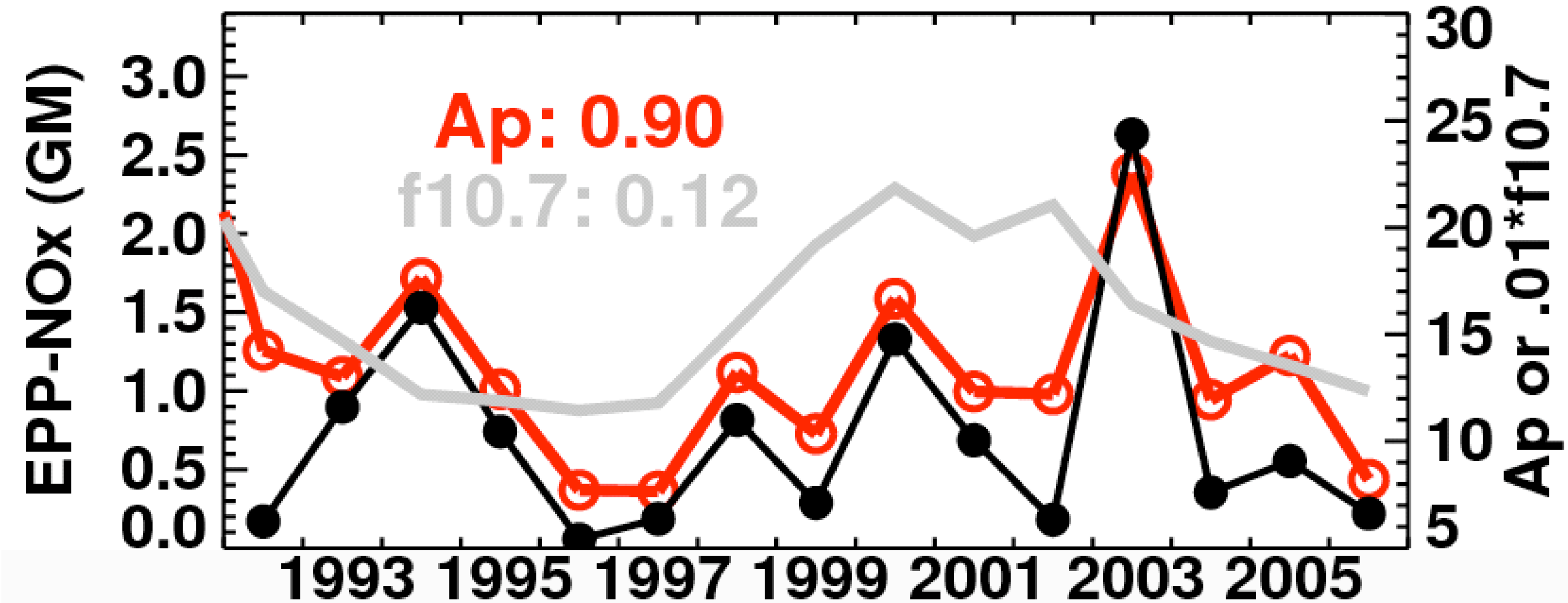
How significant is this?

Up to 10% of total SH NO_y from N_2O oxidation

Up to 40% of polar NO_y

Is it correlated with the solar cycle?

Correlation of EPP-NO_x entering the SH stratosphere with Ap and F10.7 (Apr - Aug)

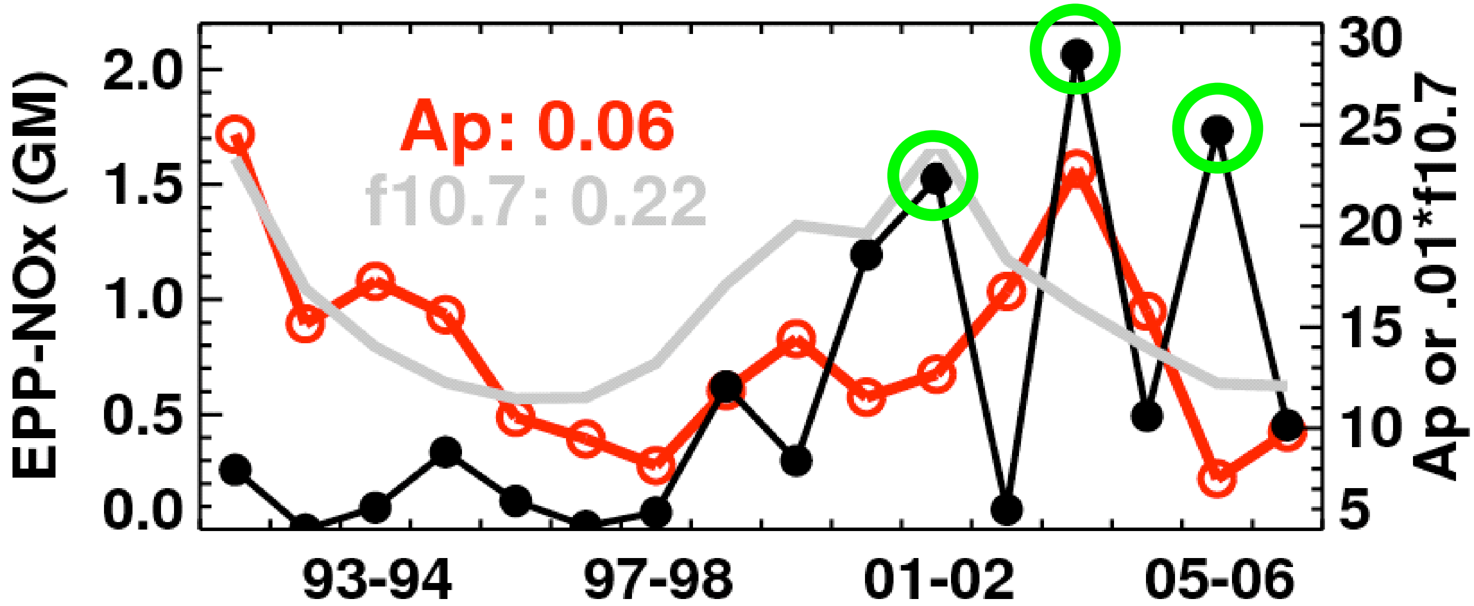


Adapted from Randall et al., JGR, 2007

Strong correlation with Ap (and auroral & MEE power, and thermospheric NO) but not F10.7

Variability in SH stratospheric NO_x from EPP controlled by variation in EPP-NO_x production

Correlation of EPP-NO_x entering the NH stratosphere with Ap and F10.7 (Apr - Aug)



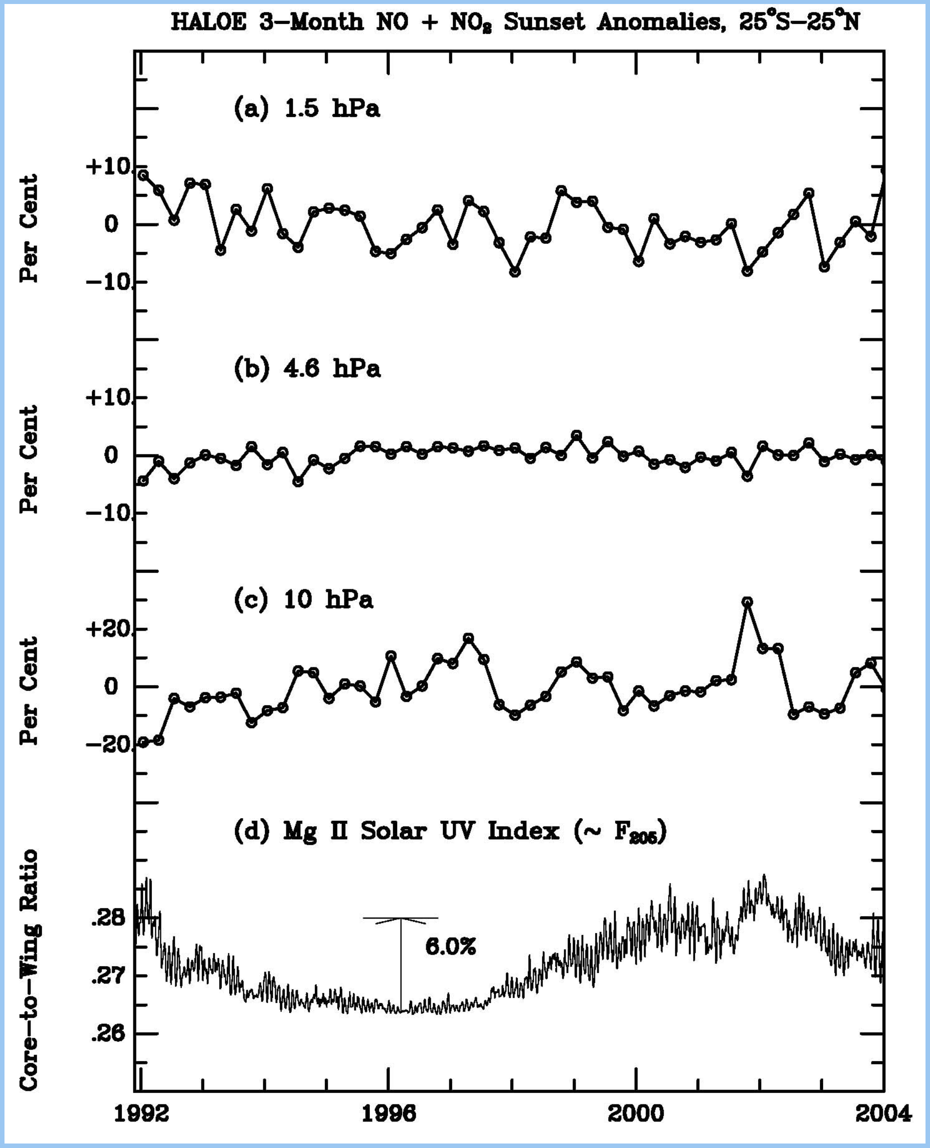
Adapted from Randall et al., JGR, 2007

In NH, correlations with Ap index & F10.7 are poor.

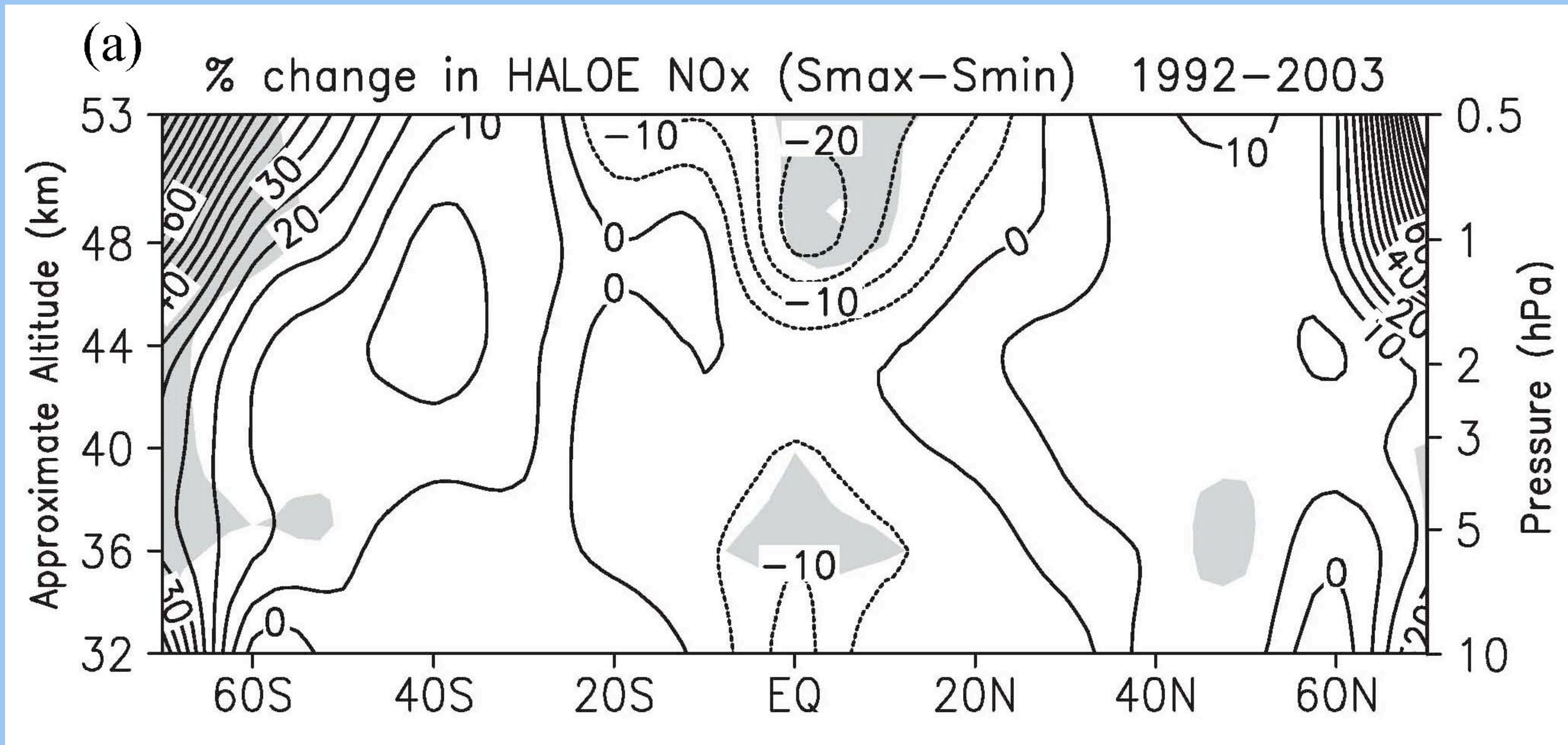
Both dynamical variability and EPP play critical roles in controlling the NH variability

2001-2002: SPE 2003-2004: SPE+Met 2005-2006: Met

Example 3-monthly time series of Version 19 HALOE NO + NO_2 (~ NO_x) sunset data averaged over low latitudes (25°S-25°N). At these levels in the tropics, there is little or no decadal variability. There is therefore no evidence in the HALOE data for large decadal variations that could directly cause major solar cycle variations of ozone at low latitudes.

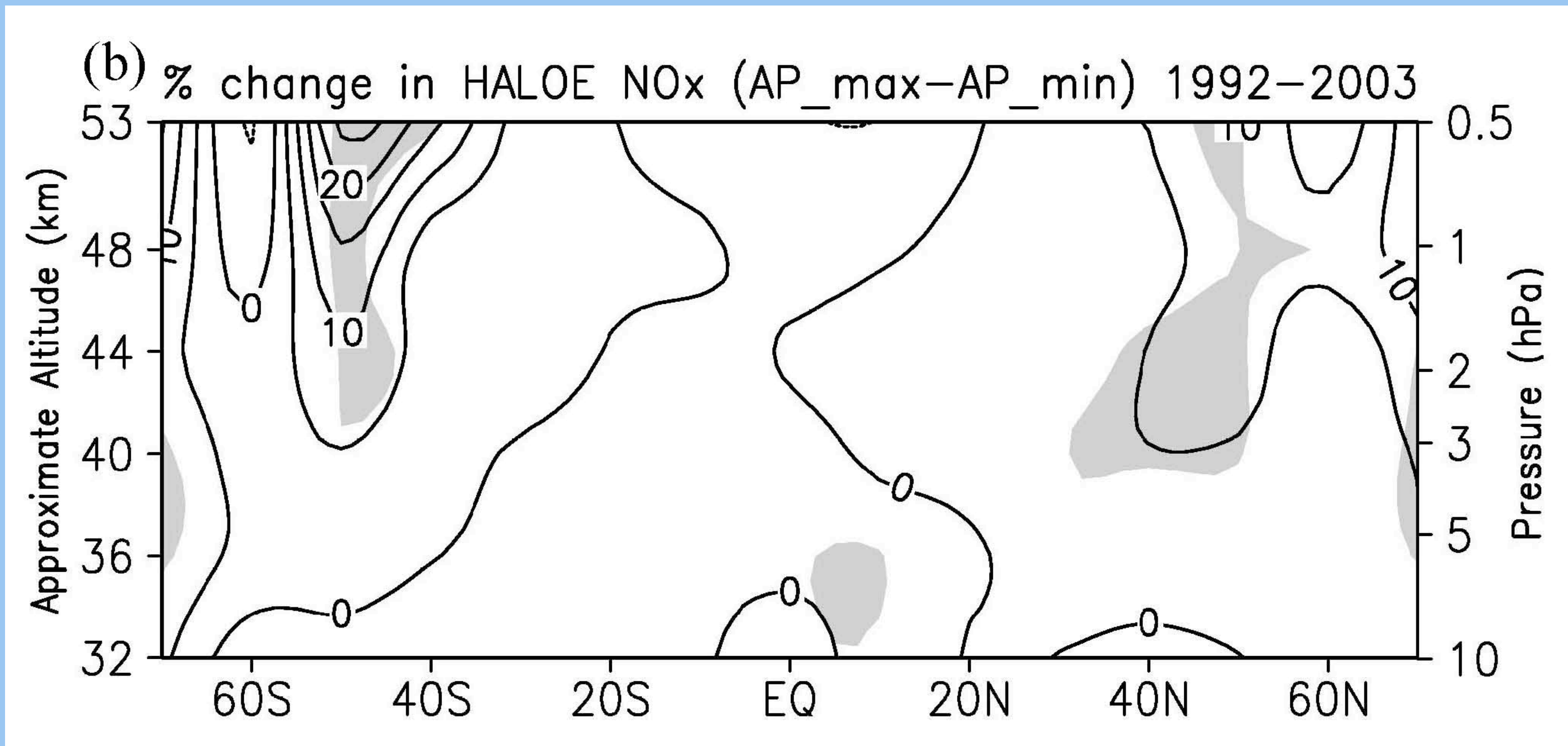


From Hood & Soukharev (2006)



From Hood & Soukharev (2006)

HALOE NO_x solar regression coefficient using S(t) = MgII UV index. Shaded areas are significant at the 95% confidence level. The negative response in the tropical stratopause region may be caused mainly by increased photolysis of NO under solar maximum conditions (Minschwaner and Siskind, 1993).



From Hood & Soukharev (2006)

HALOE NO_x solar regression coefficient using S(t) = Ap index. Shaded areas are significant at the 95% confidence level.

The EPP Story (so far!) from Observations

- EPP-NO_x is produced continually and can contribute up to 40% of polar stratospheric NO_x budget even in years with low geomagnetic activity. However, there is little evidence in HALOE data for decadal NO_x variations outside of the vortex.

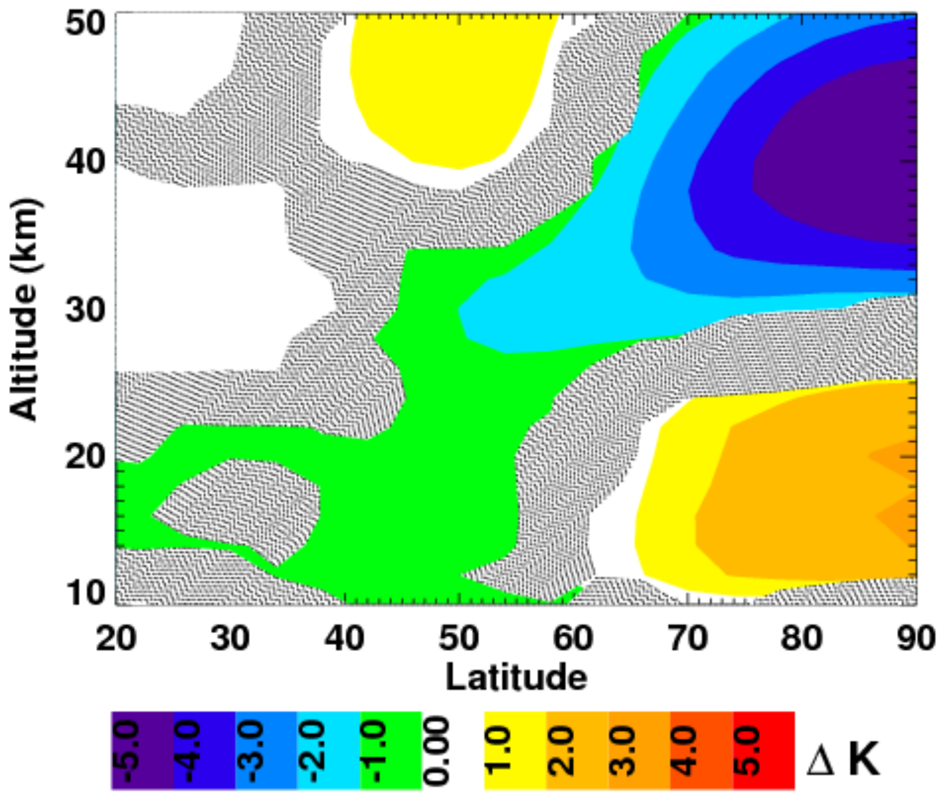
- Ozone is depleted by EPP-NO_x in the SH vortex by ≥ 35%.

- Contribution of EPP-NO_x to the polar stratosphere does not correlate well with the solar cycle; it correlates best with Ap.

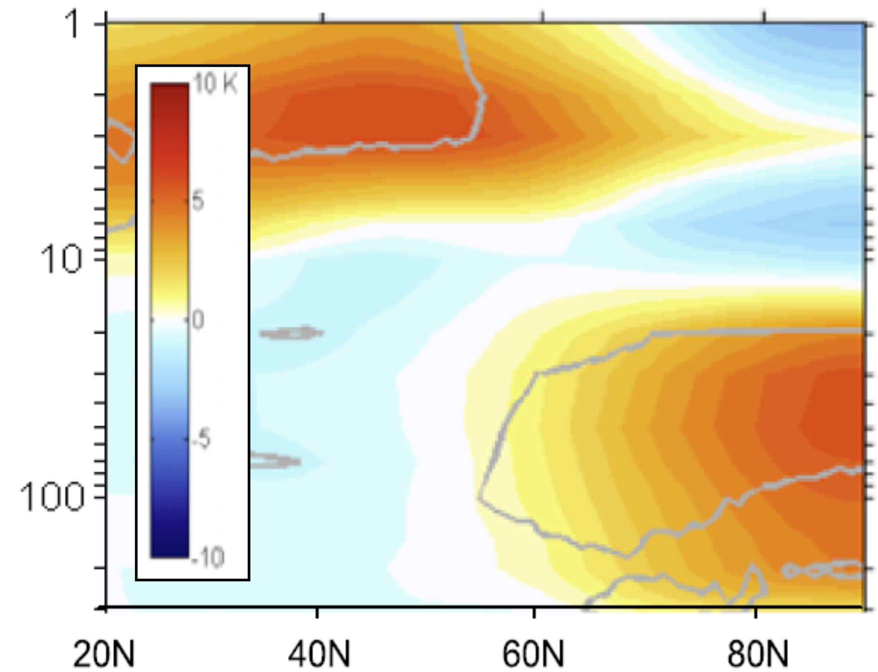
- Improved picture of EPP effects requires continuous nighttime observations of NO_x throughout the MLT.

Analysis of ERA-40 + Operational ECMWF Temperatures by Lu et al., (JGR 2008): ΔT for years with high Ap minus years with low Ap similar to WACCM.

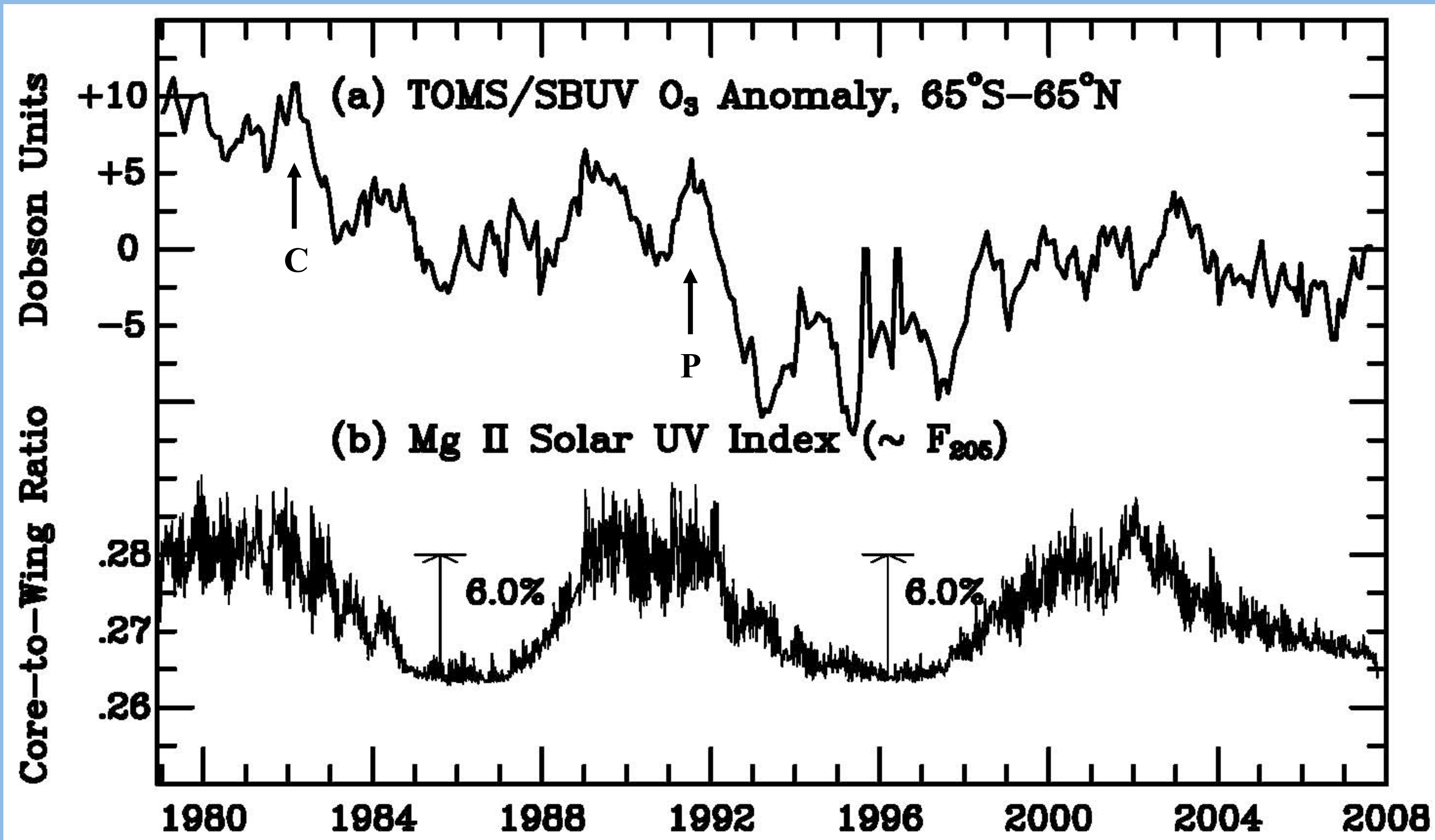
WACCM ΔT, April



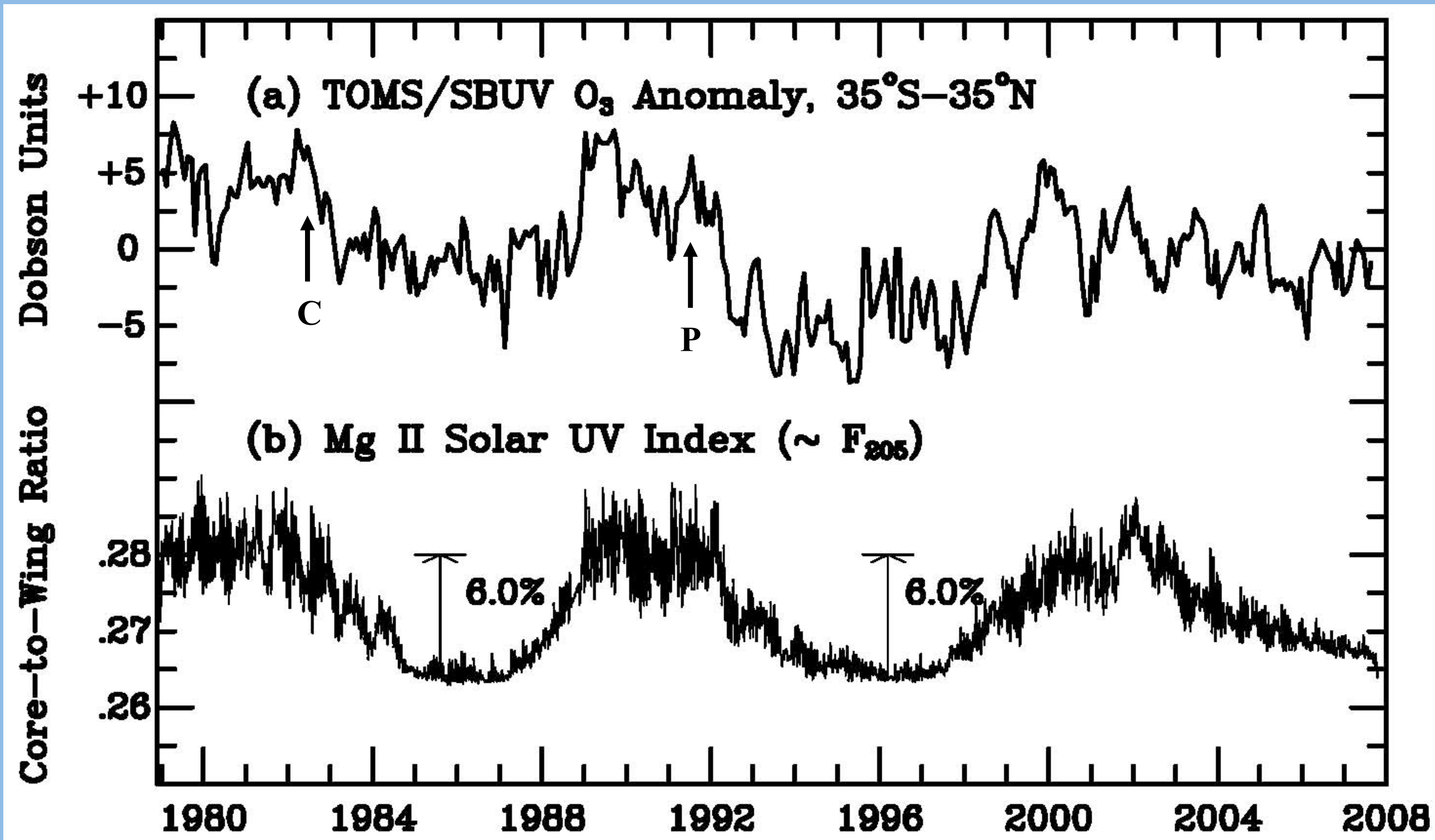
ECMWF ΔT, April



Lu et al., JGR 2008



Three sources of decadal-scale variability of total ozone in the Version 8 TOMS/ SBUV data record calibrated by Frith et al. (2004): A non-linear long-term trend, volcanic aerosol forcing, and the 11-year solar cycle.



At low latitudes, the solar cycle appears to be the dominant source of interannual variability; however, volcanic and long-term trend sources are still present to a lesser extent .

MULTIPLE REGRESSION STATISTICAL MODEL:

$$O_3'(t) = c_{trend}t + c_{QBO}u_{30mb}(t\text{-}lag_{QBO}) + c_{volcanic}Aerosol(t) +$$

$$c_{solar}MgII(t) + d_{ENSO}N3.4(t\text{-}lag_{ENSO}) + \varepsilon(t)$$

<u>where</u>:

$O_3'(t)$ = deviation of ozone from the seasonal mean

t = time measured in 3-month seasonal increments

$u_{30mb}(t\text{-} lag_{QBO})$ = NCEP 30 hPa equatorial zonal wind speed (lagged)

Aerosol(t) = Volcanic aerosol index (10 hPa and below only)

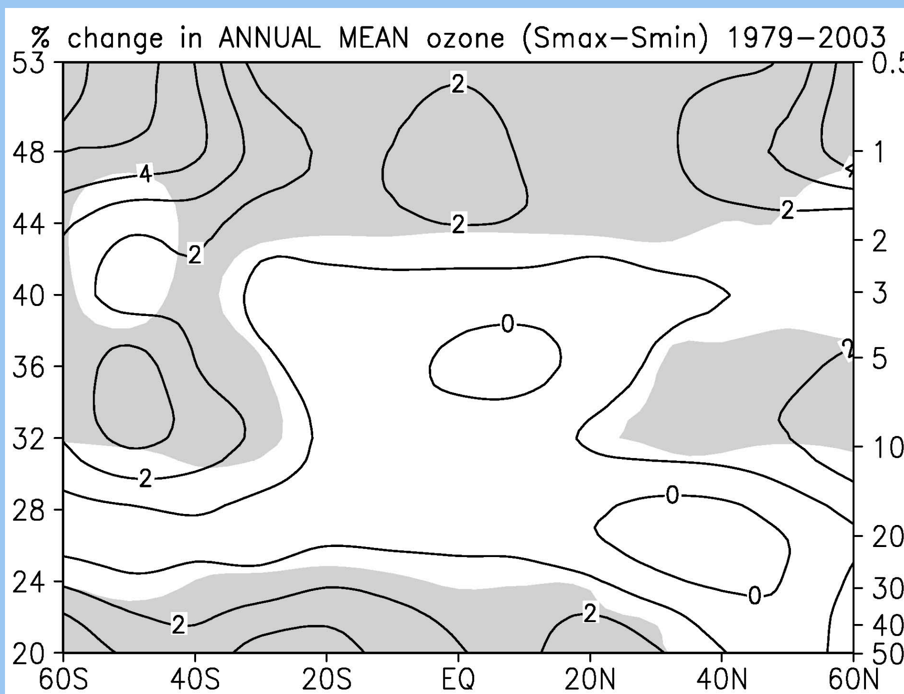
MgII(t) = Solar MgII UV index

$N3.4(t\text{-}lag_{ENSO})$ = Mean SST, 5^oS - 5^oN, 120^oW - 170^oW (lagged)

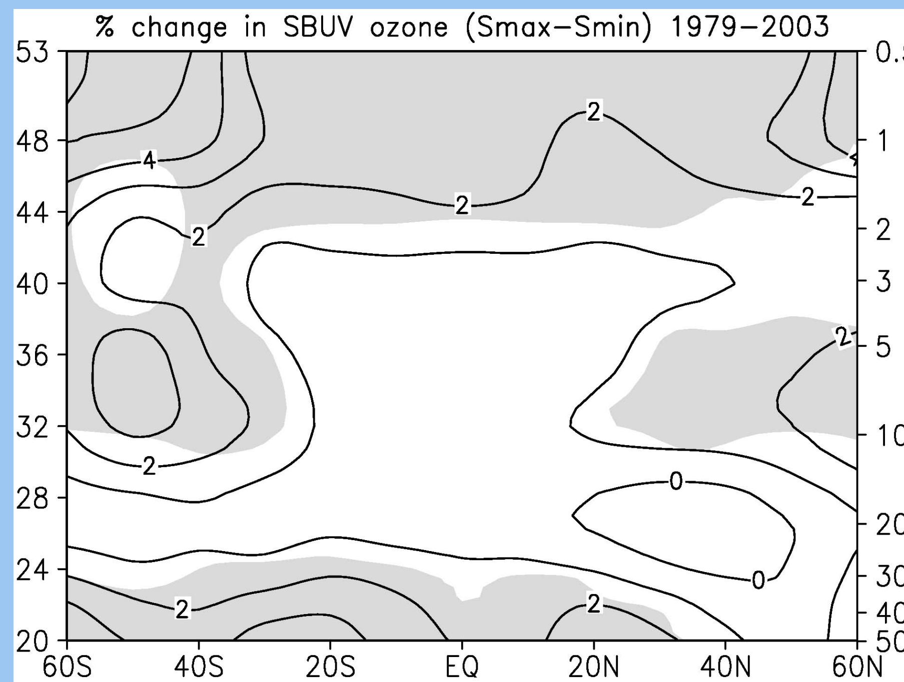
$\varepsilon(t)$ = residual error term

Annual mean ozone solar cycle regression coefficient derived from SBUV-SBUV(/2) data using two different multiple regression statistical models:

(a) Without ENSO term:

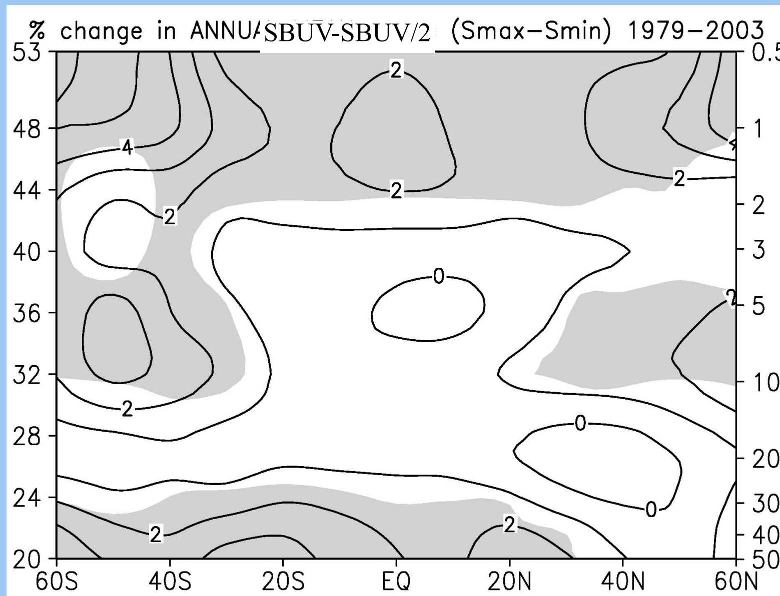


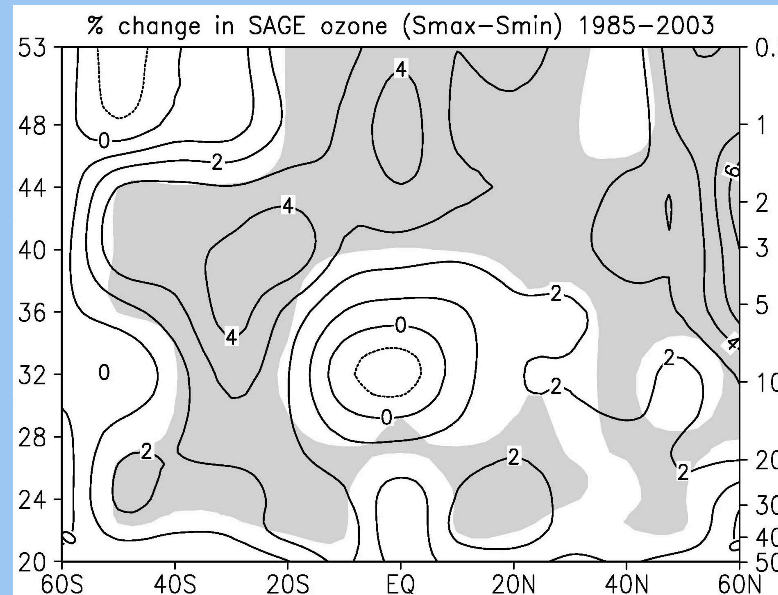
(b) With ENSO term (lag = + 3 mo.):

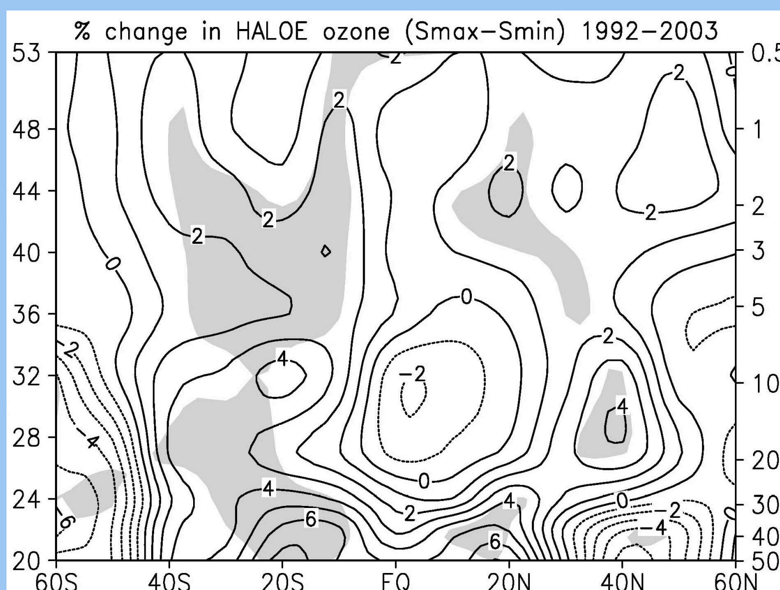


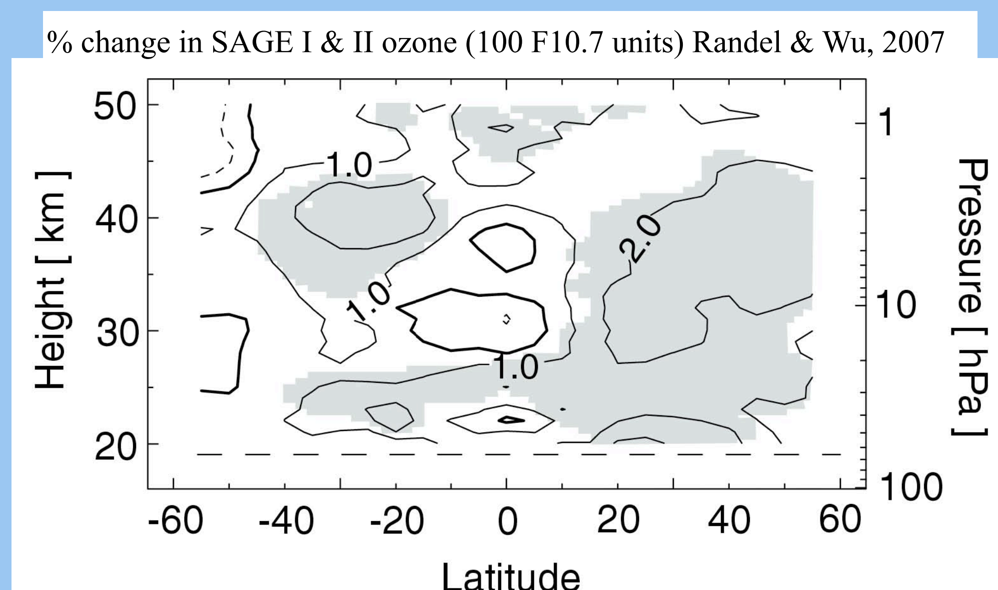
Conclusion: The ozone solar cycle response coefficients calculated using a standard multiple regression statistical model do not change significantly when an ENSO term is added to the model.

Annual mean O_3 profile solar cycle regression coefficient derived from three independent satellite data sets (Soukharev & Hood, 2006; Randel & Wu, 2007):





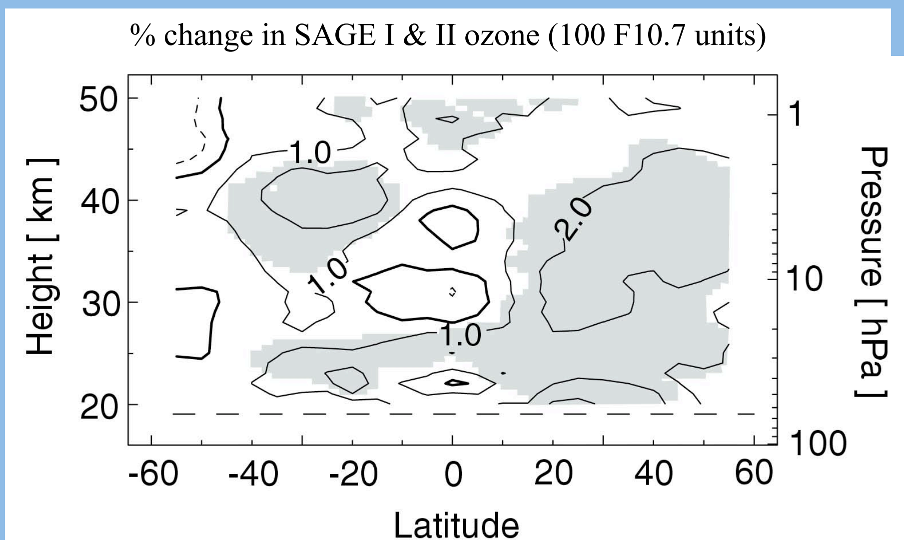




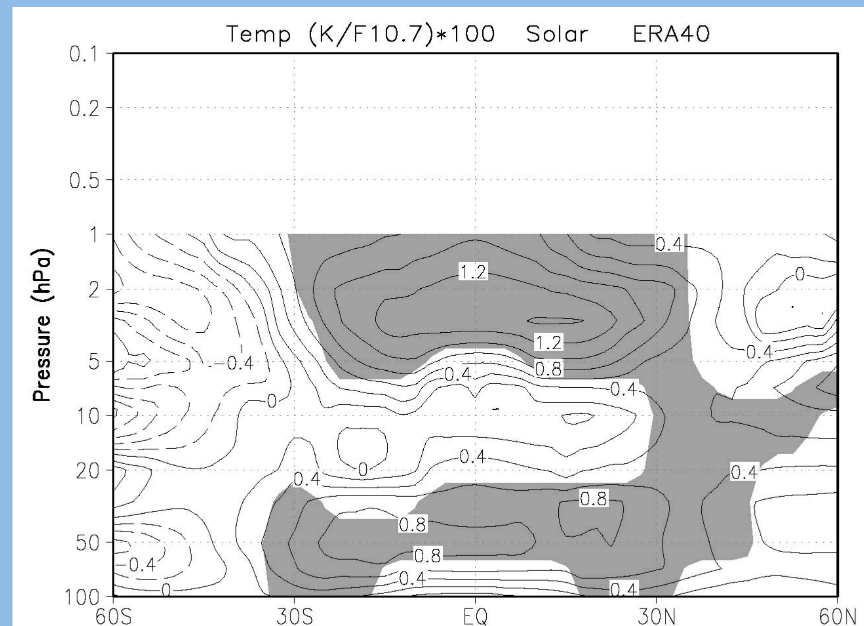
Shaded areas are statistically significant at 95% confidence.

Vertical structure of the stratospheric ozone and temperature response to the solar cycle as estimated by multiple regression analysis of available data sets:

(a) Ozone; e.g. Randel & Wu, 2007:



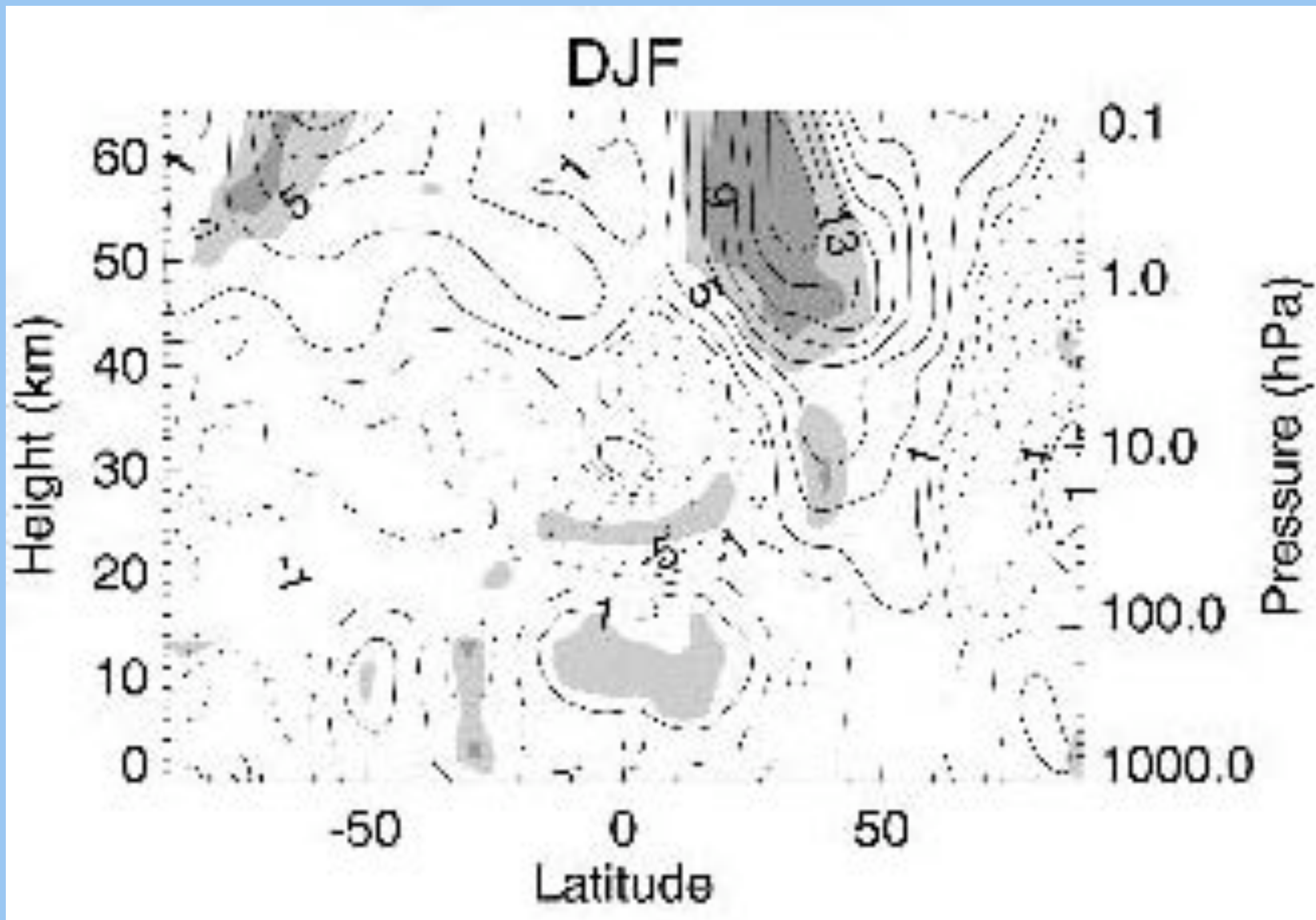
(b) Temperature; e.g. Shibata & Deushi, 2008:



Note: Gray et al., submitted manuscript, have recently calculated the expected temperature response using the observed ozone response in a fixed dynamical heating model. They find that the expected temperature response has a vertical structure similar to that derived by statistical analysis of ERA-40 reanalysis data.

ERA-40 Seasonal Zonal Wind Solar Regression Coefficient

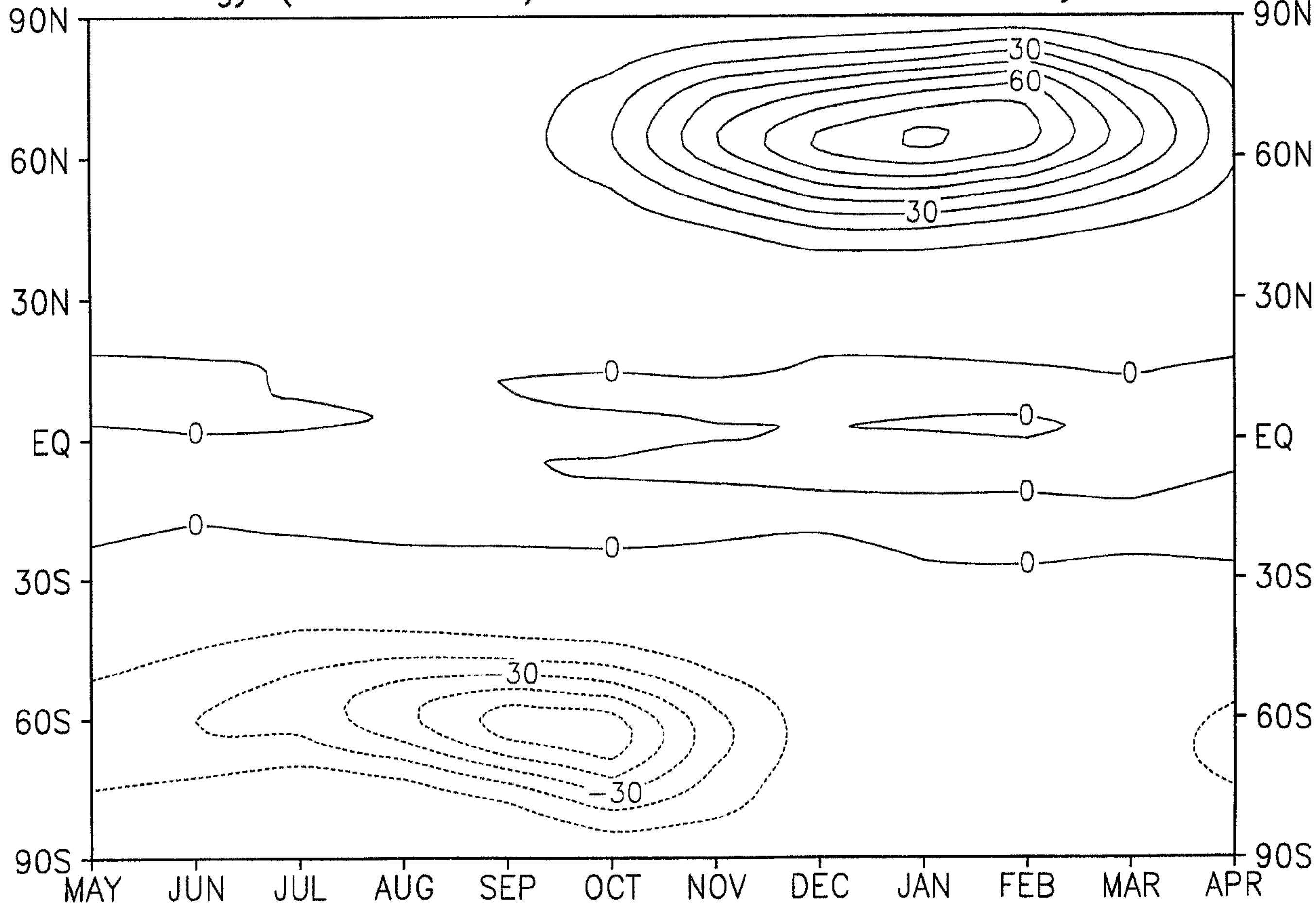
1979 - 2001 **Crooks and Gray [2005]**



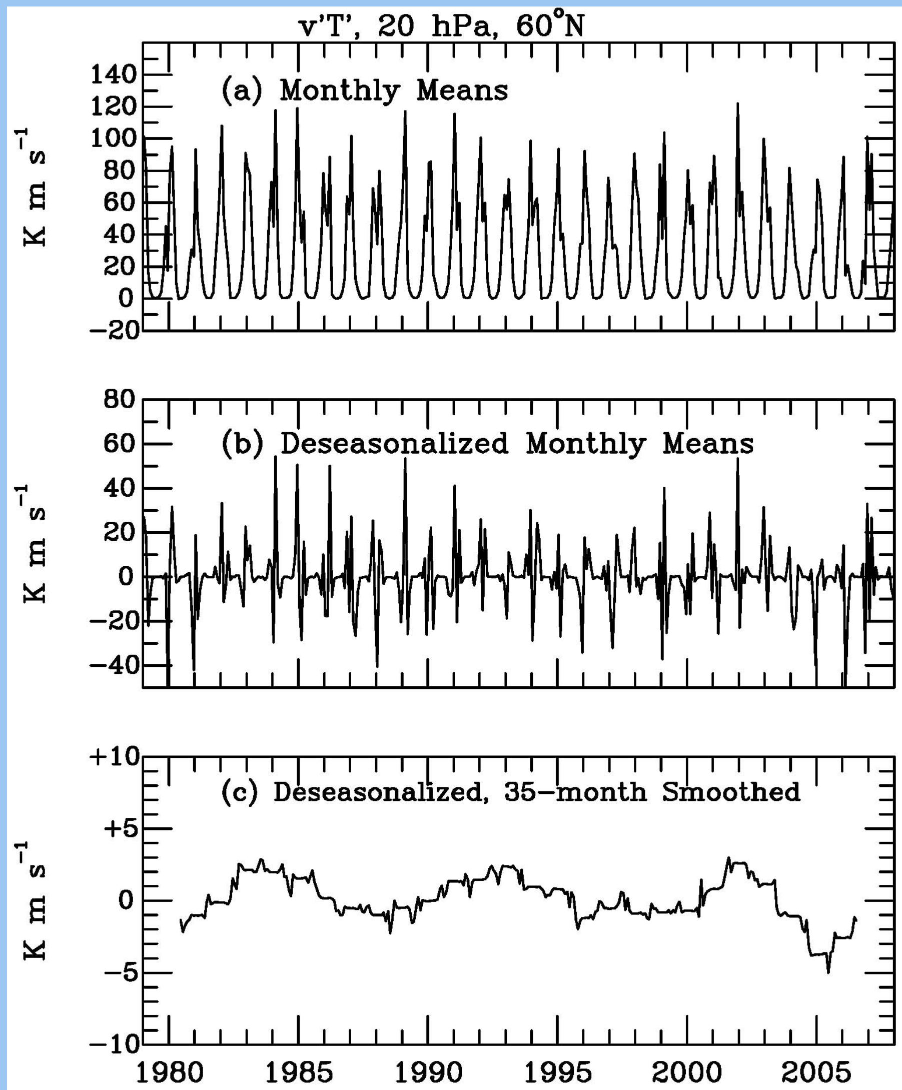
•Light shaded areas are significant at the 2σ (95% confidence) level; dark shaded areas are significant at 99% confidence

Extratropical wave forcing is largest in the N.H. and reaches a maximum near 60°N in the winter (DJF) season:

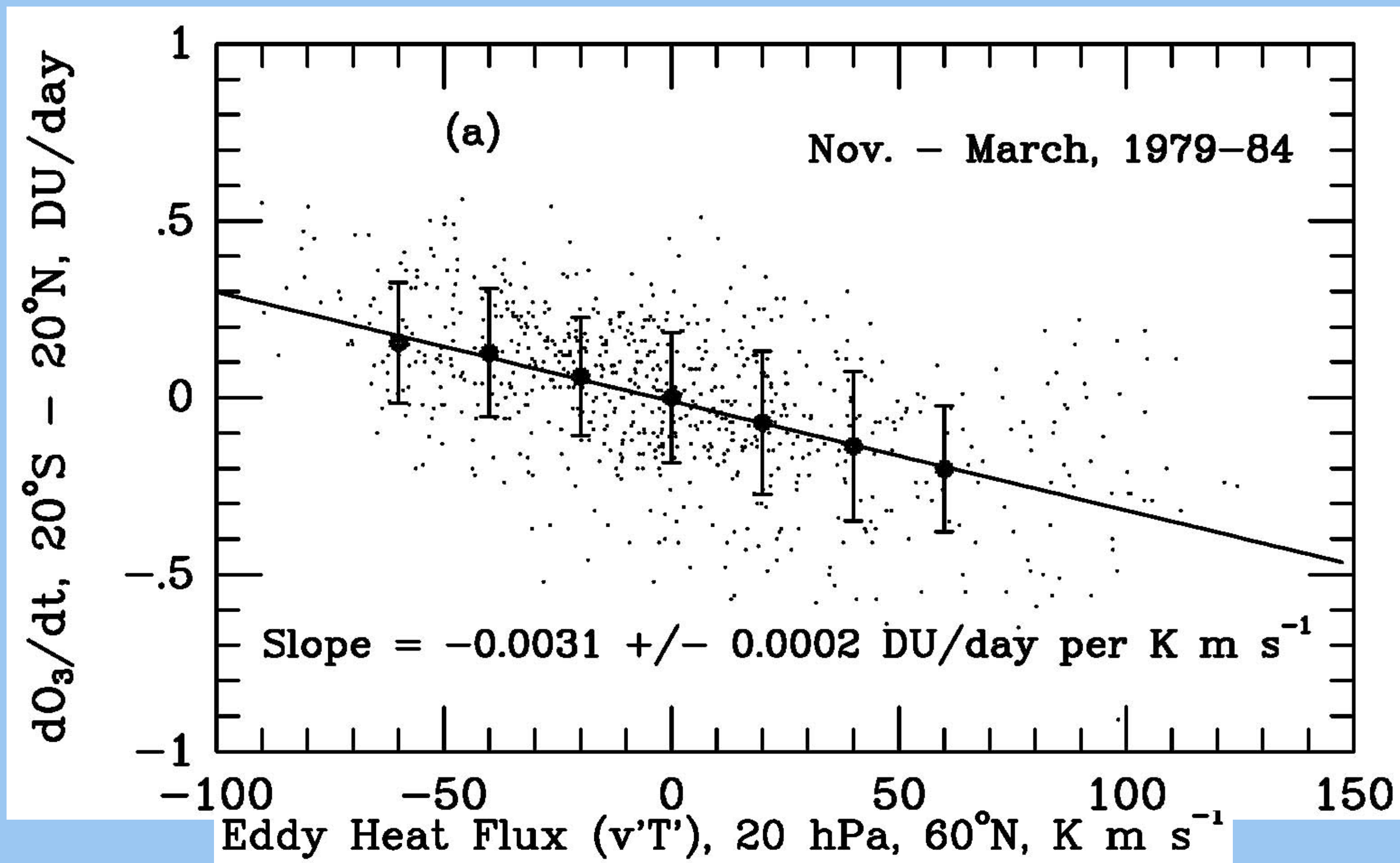
Climatology (1979–2001) of the 20-hPa Total Eddy Heat Flux $\overline{v'T'} \propto F_z$



Evidence for a decadal variation of averaged planetary wave flux at northern midlatitudes:



Updated from Hood and Soukharev, JAS, 2003.



Regression analysis of tropical column ozone tendencies versus eddy heat flux in the extratropical northern winter lower stratosphere.

What is the expected contribution of decadal variations in extratropical wave forcing to the observed decadal variation of tropical column ozone?

TEM Ozone Continuity:

$$\frac{\partial \overline{\chi}}{\partial t} \approx -w^* \overline{\chi}_z - (\overline{\chi} - \overline{\chi}_{eq}) / \tau_c$$

Where: $\overline{\chi}$ is zonal mean O_3 mixing ratio at a given level

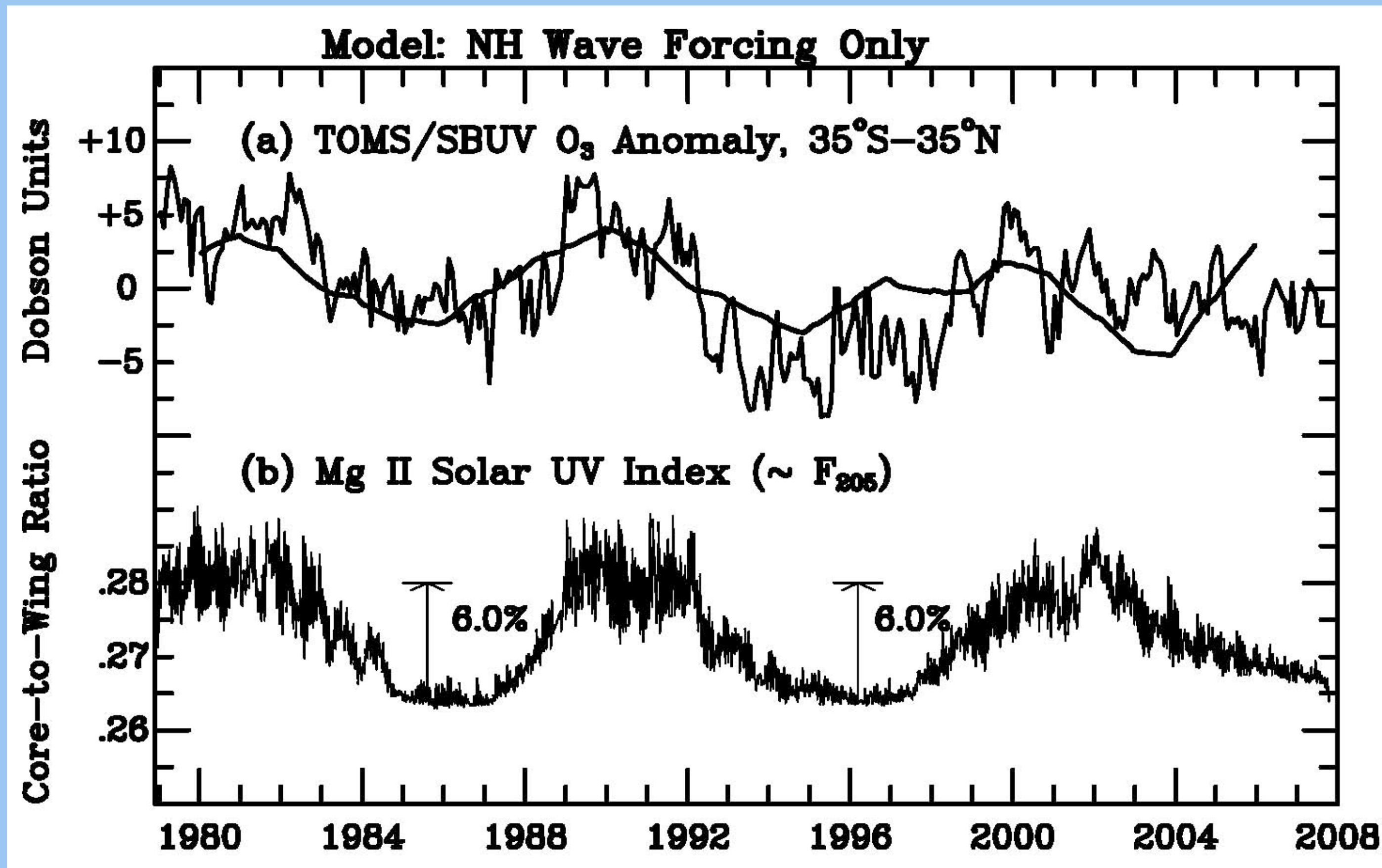
w^* is TEM vertical velocity

τ_c is the effective O_3 chemical lifetime

Or, if w^* in the tropical lower stratosphere is dominantly determined by extratropical wave forcing, and if A_N is a regression coefficient derived from observations of short-term deviations, then, to first order:

$$\boxed{\frac{dOz}{dt} \approx A_N \overline{v'T'}_{60N} - Oz/\tau_c}$$

where Oz is column ozone. (Hood & Soukharev, JAS, 2003)

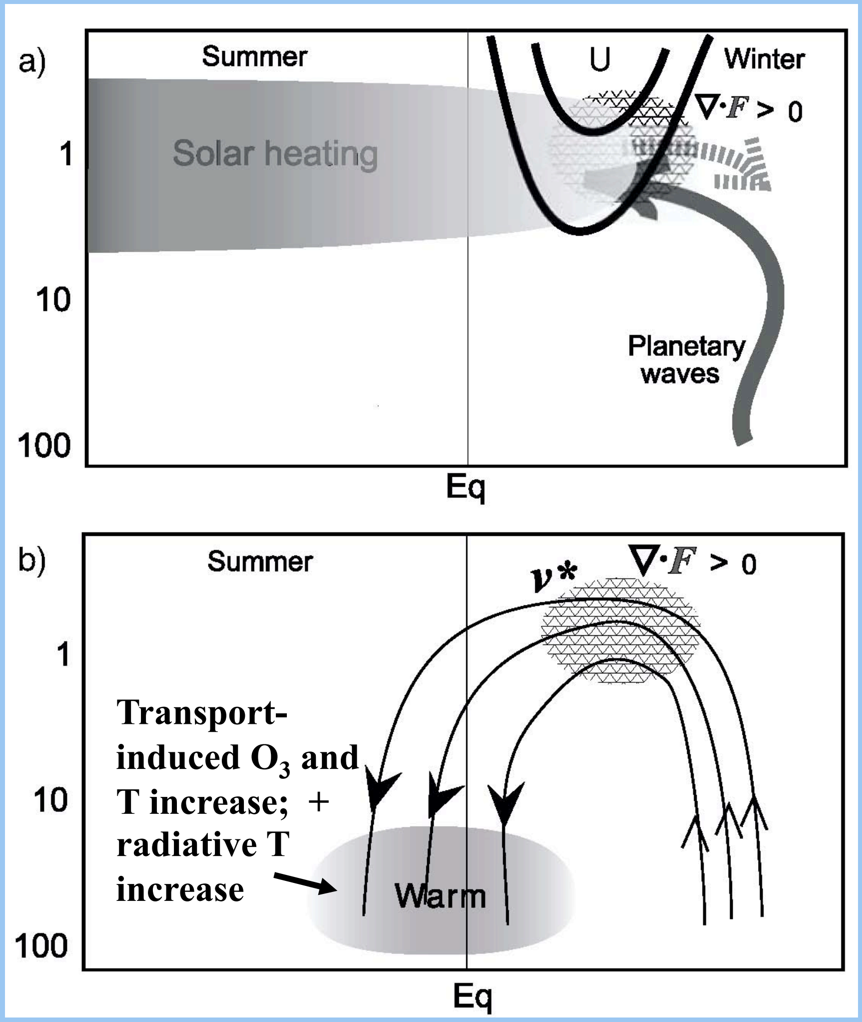


Updated from Hood & Soukharev (2003)

Total ozone variation in the tropics calculated from the simplified mechanistic model (solid continuous line) for $\tau_c \sim 800$ days and using only N.H. wave forcing.

A Possible Mechanism for Explaining the Solar Cycle Variation of Ozone and Temperature in the Tropical Lower Stratosphere:

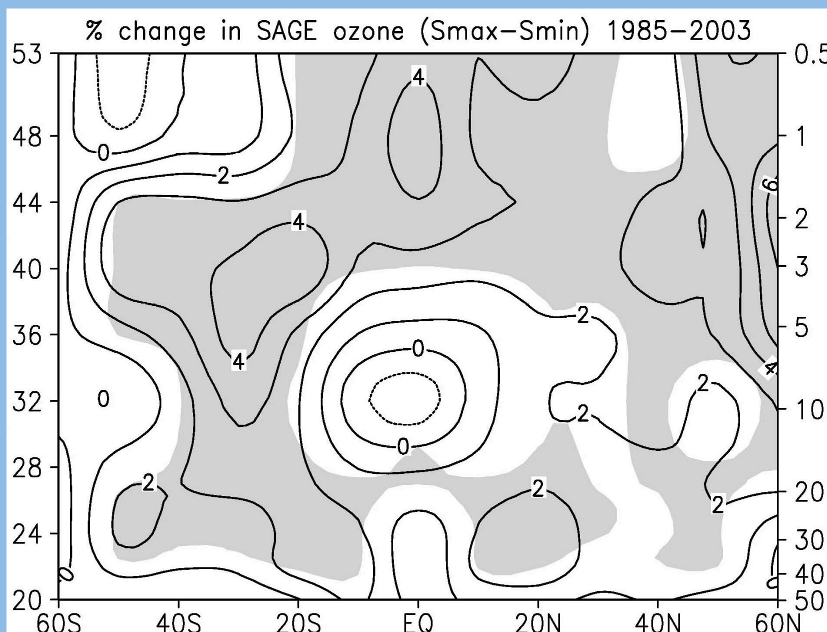
Solar ultraviolet forcing effectively reduces the tropical upwelling rate near and approaching solar maxima (Kodera and Kuroda, 2002). This produces a transport-induced O_3 and T increase in the tropical lower stratosphere. There is also a radiative T increase associated with the O_3 increase.



From Kodera and Kuroda (2002)

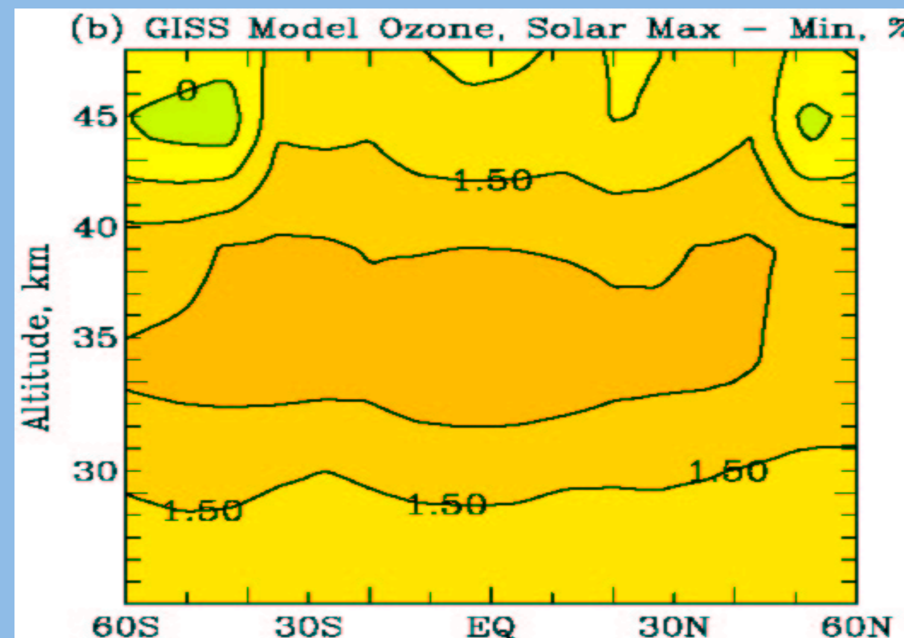
Why do we have this difference?

Observations:



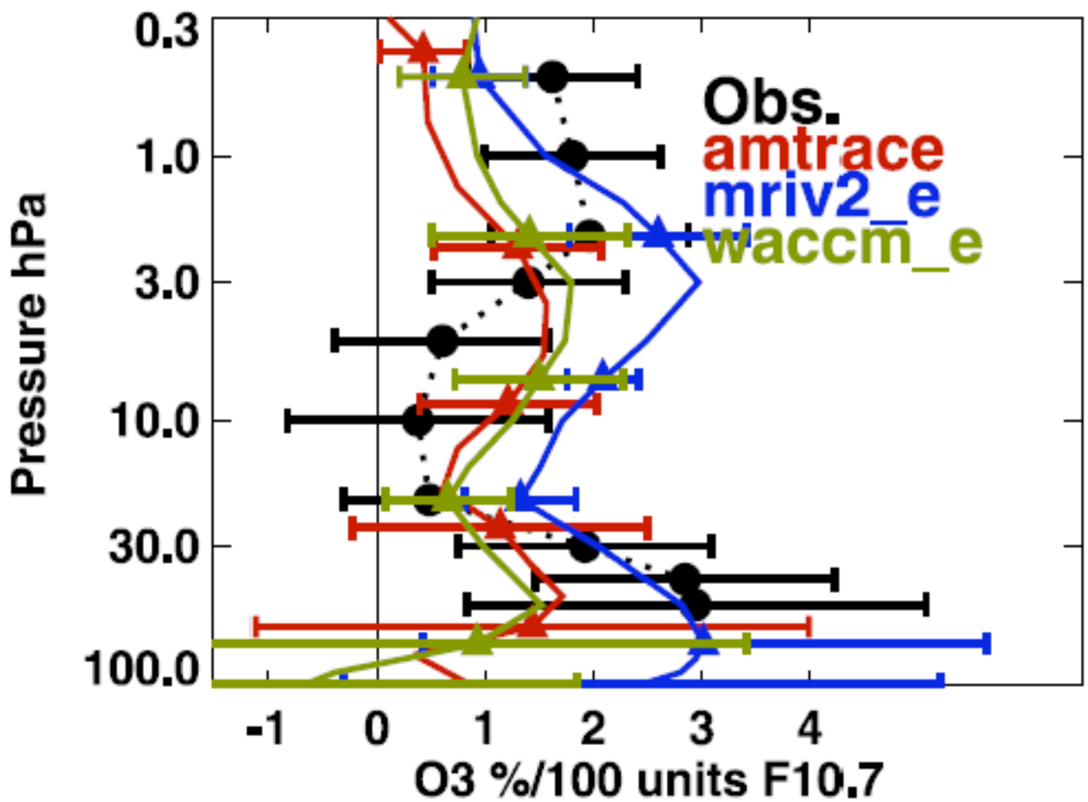
From Soukharev & Hood, 2006

Most Models:



Model Data courtesy of Drew Shindell

Simulations of Solar Cycle Effects in Ozone: 25S to 25N



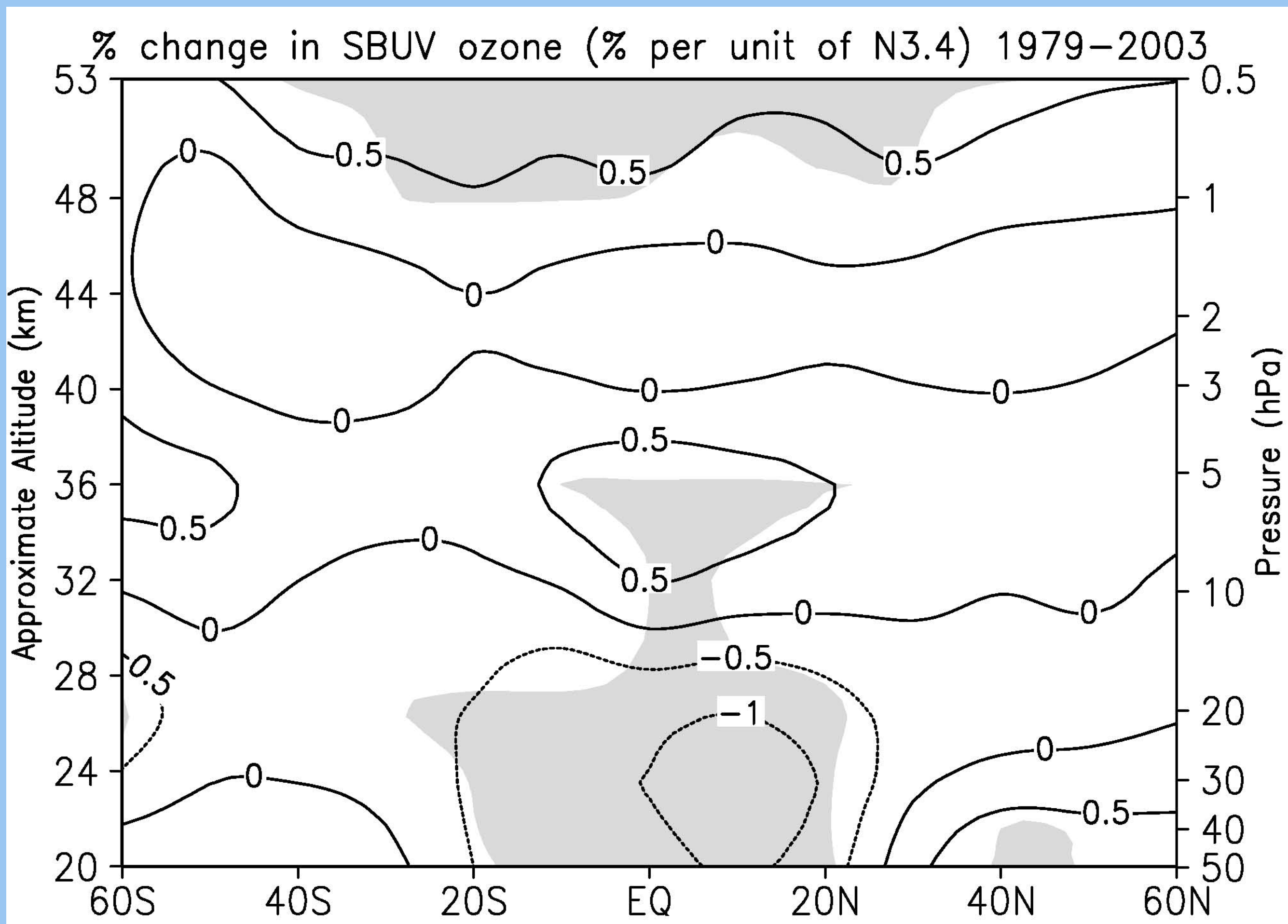
Several recent simulations appear to agree with observations

Change in upper stratosphere: ~2% Max to Min

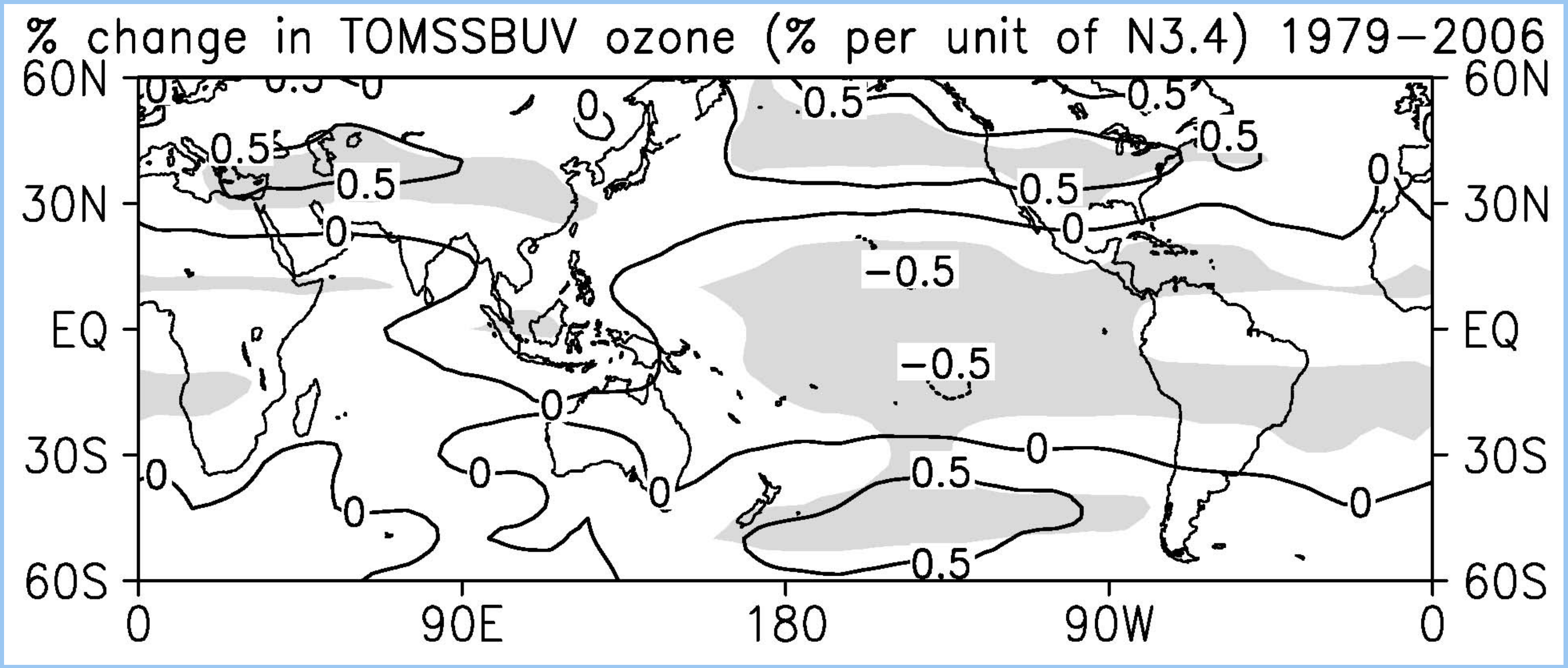
Change in lower stratosphere: ~2% Max to Min

From Austin et al., JGR 2008

Ozone ENSO Regression Coefficient (% per unit N3.4) derived from SBUV-SBUV(/2) data:

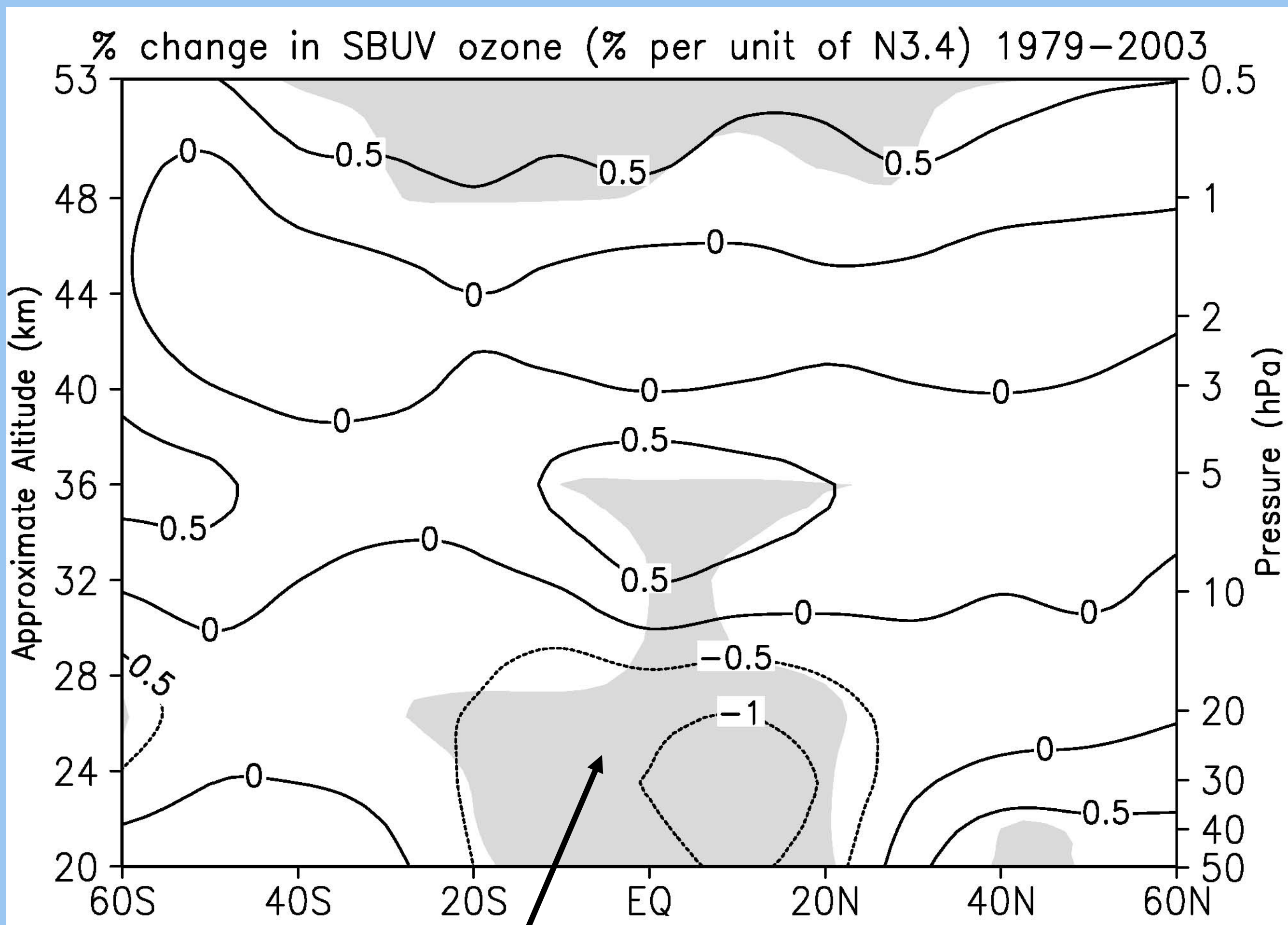


Ozone ENSO Regression Coefficient (% per unit N3.4) derived from TOMS-SBUV total ozone data (lag = + 3 mo.):



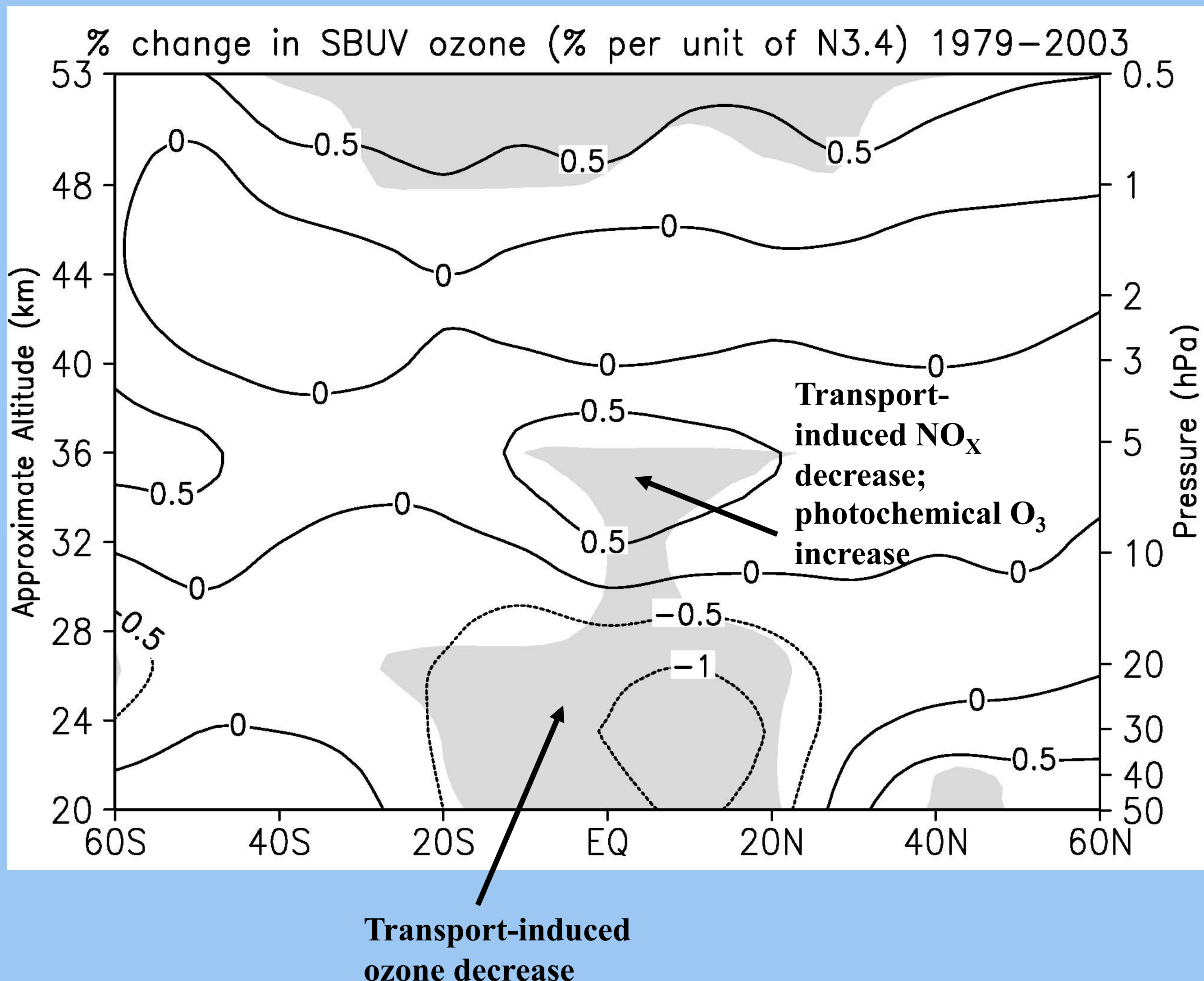
Note: Strongest signal is in equatorial eastern Pacific and subtropics. ⇒ Consistent with ENSO.

Ozone ENSO Regression Coefficient (% per unit N3.4) derived from SBUV-SBUV(/2) data:



Transport-induced ozone decrease

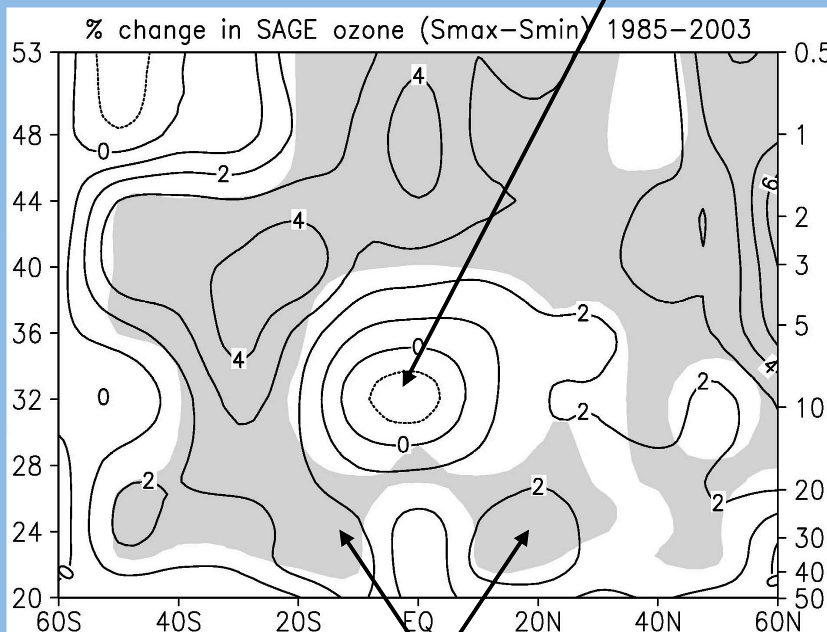
Ozone ENSO Regression Coefficient (% per unit N3.4) derived from SBUV-SBUV(/2) data:



Why do we have this difference?

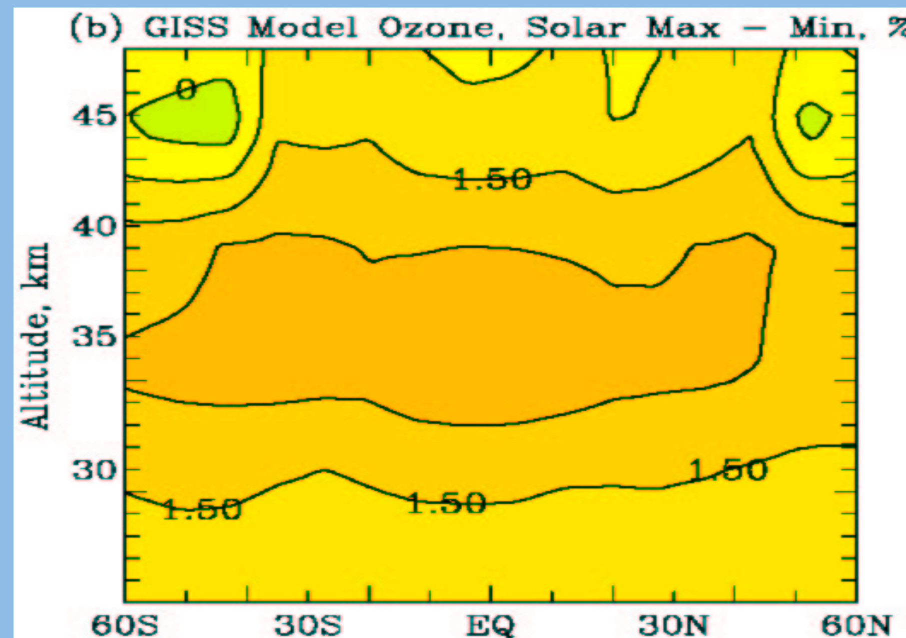
Solar cycle modulation of QBO; transport-induced NO_X increase; photochemical O_3 decrease

Observations:



Transport-induced O_3 increases

Many Models:



Model Data courtesy of Drew Shindell

<u>A Possible Explanation</u>: The upwelling rate in the tropics is decreased approaching solar maximum conditions. This relative downwelling directly increases ozone anomalies in the lower stratosphere where the ozone lifetime is long. In the tropical middle stratosphere, no direct transport-induced ozone increases occur. However, the solar cycle modulates the QBO period. Transport-induced increases in odd nitrogen then occur, which increases the ozone loss rate.

CONCLUSIONS RELATING TO UV FORCING

- **There is some concensus now that total column ozone varies significantly with the solar cycle, especially in the tropics.**

CONCLUSIONS RELATING TO UV FORCING

- **There is some concensus now that total column ozone varies significantly with the solar cycle, especially in the tropics.**
- **A recognition is emerging that the vertical structure of the ozone response at low latitudes is characterized by two peaks, one in the upper stratosphere and one in the lower stratosphere. The lower stratospheric response is the main cause of the total ozone variation.**

CONCLUSIONS RELATING TO UV FORCING

- There is some concensus now that total column ozone varies significantly with the solar cycle, especially in the tropics.

- A recognition is emerging that the vertical structure of the ozone response at low latitudes is characterized by two peaks, one in the upper stratosphere and one in the lower stratosphere. The lower stratospheric response is the main cause of the total ozone variation.

- A recent study by Gray et al. suggests that the vertical structure of the solar cycle temperature response should also have a double-peaked structure. This agrees with statistical analyses of the ERA-40 data set.

CONCLUSIONS RELATING TO UV FORCING

- **There is some concensus now that total column ozone varies significantly with the solar cycle, especially in the tropics.**

- **A recognition is emerging that the vertical structure of the ozone response at low latitudes is characterized by two peaks, one in the upper stratosphere and one in the lower stratosphere. The lower stratospheric response is the main cause of the total ozone variation.**

- **A recent study by Gray et al. suggests that the vertical structure of the solar cycle temperature response should also have a double-peaked structure. This agrees with statistical analyses of the ERA-40 data set.**

- **The causes of the double-peaked vertical structure in the ozone response remain incompletely understood. However, several recent model simulations appear to produce this structure.**