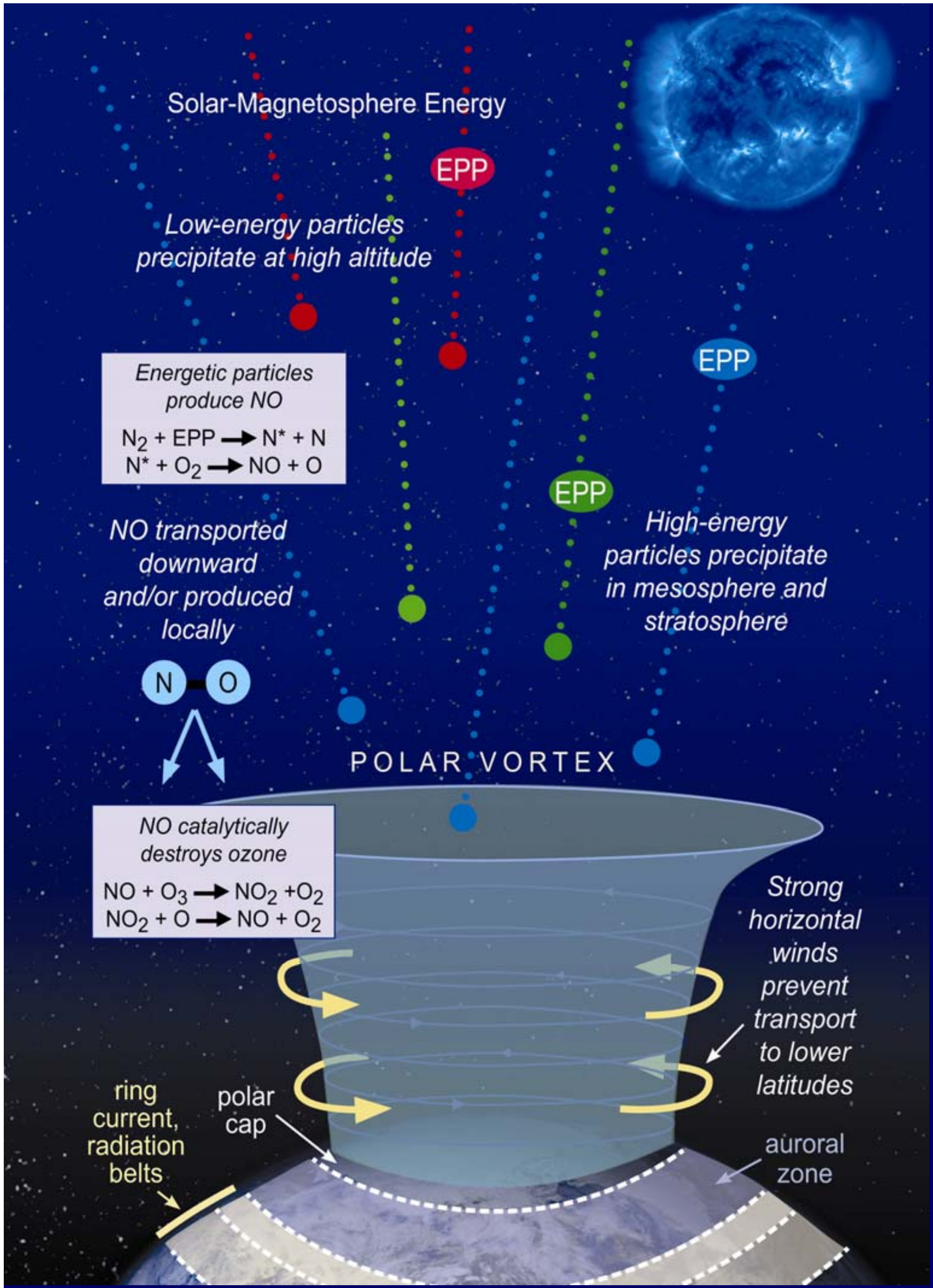



# Effects of Solar Variability on the Stratosphere

**Cora Randall** (University of Colorado, USA)

**Lon Hood:** (LPL, Tucson, AZ, USA)

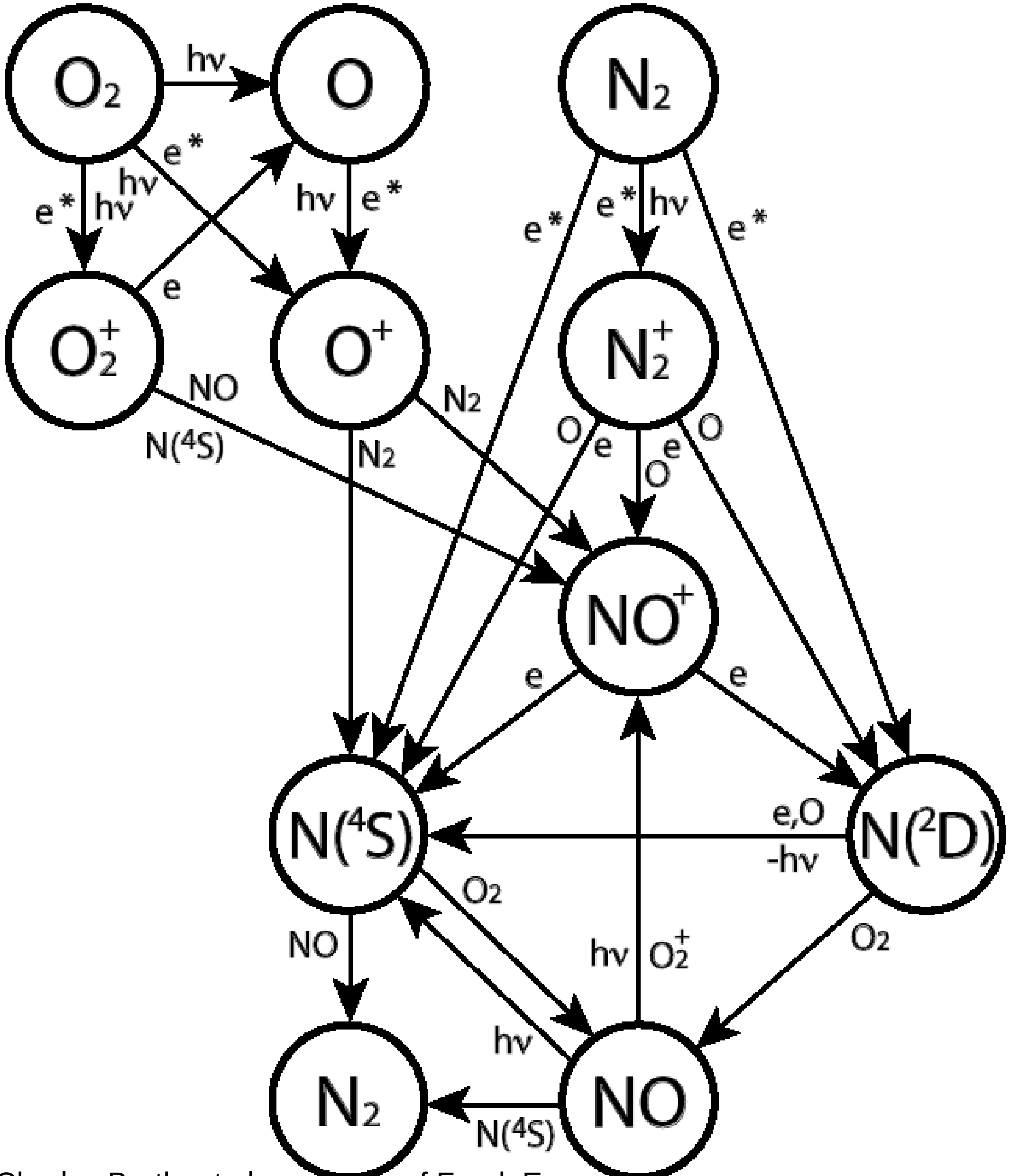
**Charles Jackman:** (GSFC, Greenbelt, MD, USA)

**Manuel Lopez-Puertas:** (IAA, Granada, Spain)

**Daniel Marsh:** (NCAR, Boulder, CO, USA)

**David Siskind:** (NRL, Washington, DC, USA)

Cora Randall et al., SPARC 2008




Charles Barth, et al., courtesy of Frank Eparvier

**Energetic Particle Precipitation (EPP)**

↓↓↓

**Ionization & Dissociation**

↓↓↓

**$NO_x$ and $HO_x$**

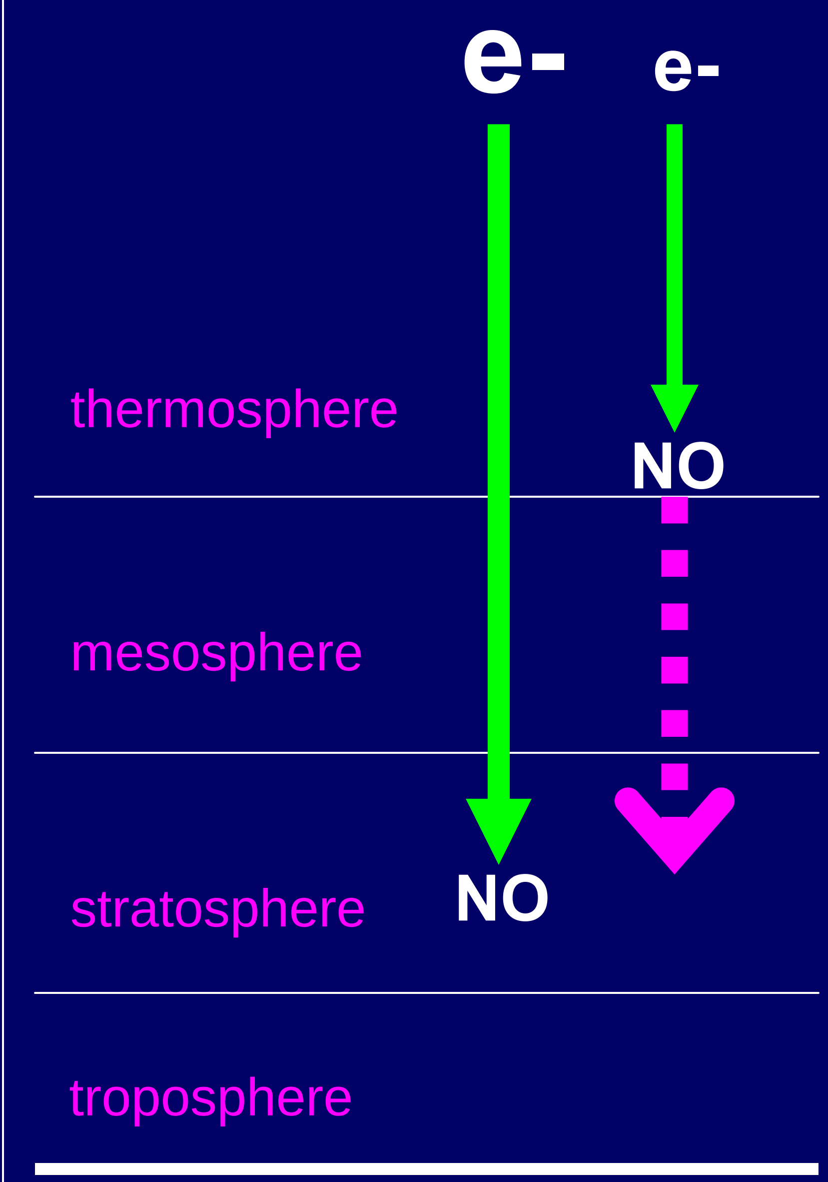
**$NO_x$ and $HO_x$ Destroy Ozone**

Cora Randall et al., SPARC 2008

# EPP effects on the stratosphere depend on energy of precipitating particles

**High Energy: $NO_x$ produced directly in stratosphere**
(>300 keV $e^-$, 30 MeV $p^+$)
**"Direct Effect"**

**Low Energy: $NO_x$ produced in thermosphere or upper mesosphere**
**But can be transported to stratosphere during polar night**
**"Indirect Effect"**




Cora Randall et al., SPARC 2008

# DIRECT Effect of EPP on the Stratosphere

## NO is produced locally

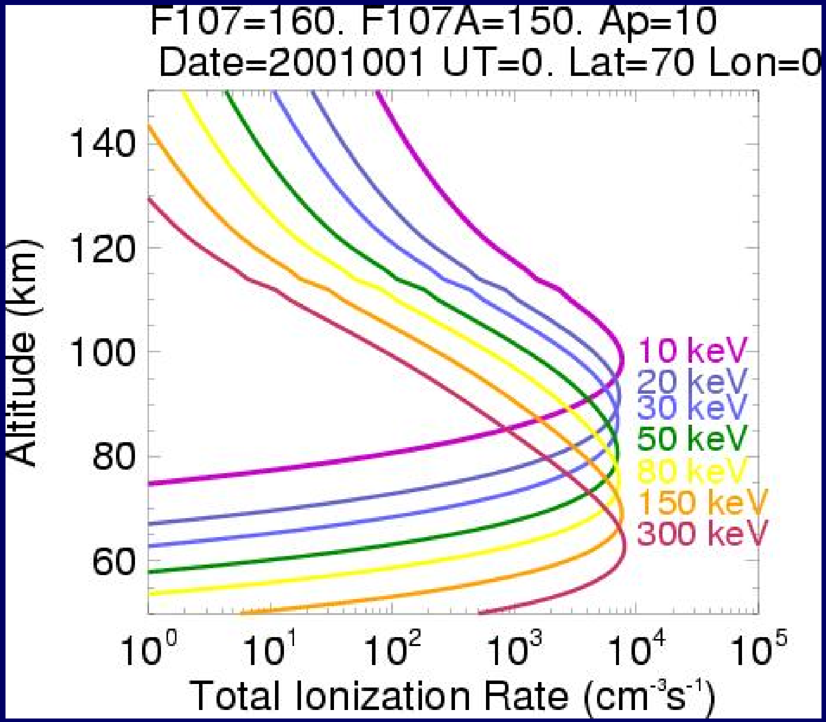
- **Requires highly energetic particles**

**Thermosphere:** < 30 keV electrons
< 1 MeV protons

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

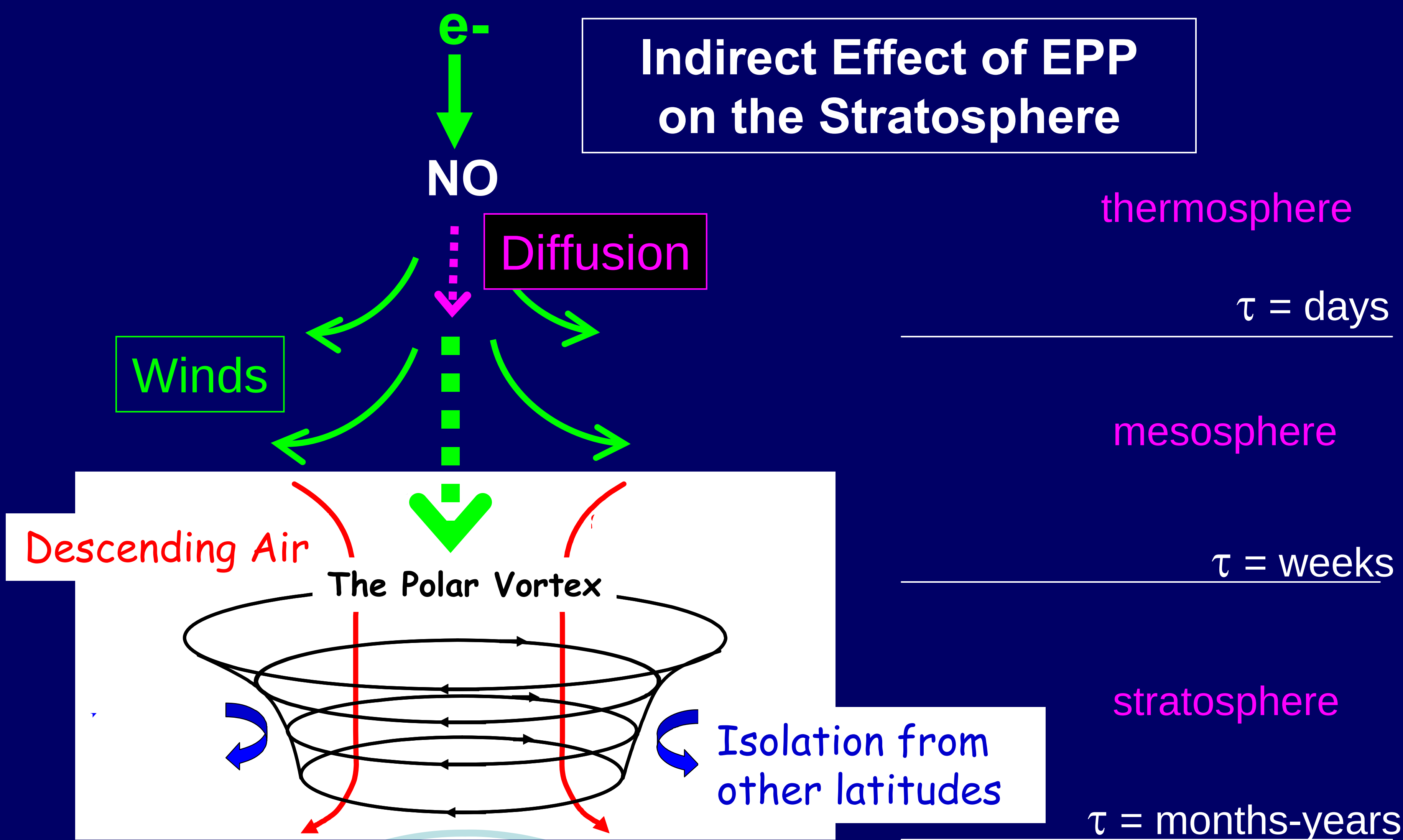
**Stratosphere:** > 300 keV electrons
> 30 MeV protons

- **Sporadic production**
e.g., several SPEs per solar cycle




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

# Indirect Effect of EPP on the Stratosphere

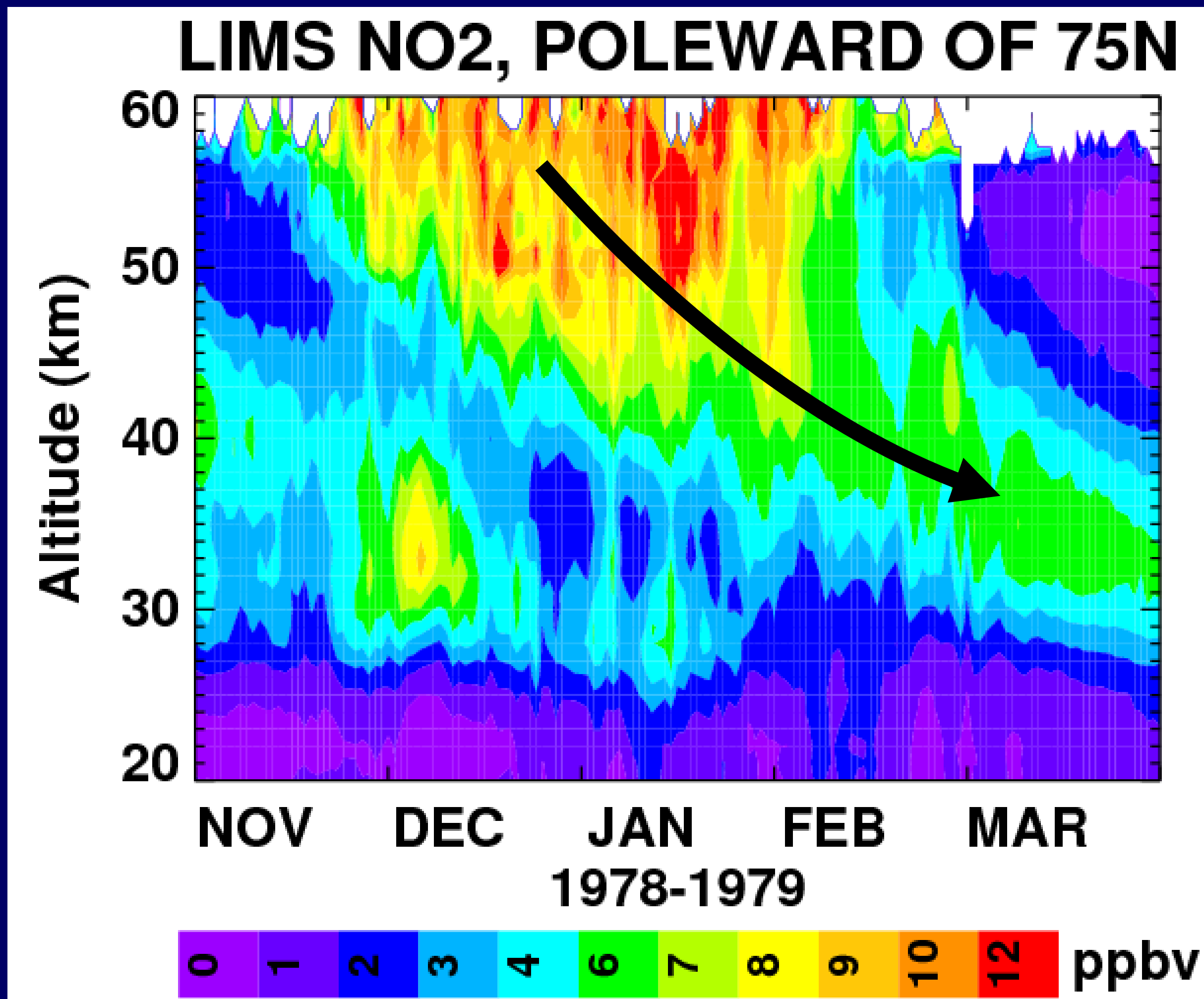



Must understand interannual variability in NO production and SMLT dynamics

Cora Randall et al., SPARC 2008

# What observational evidence suggests EPP effects on the stratosphere?

# First satellite observations of EPP Indirect effect from LIMS in NH, 1978-1979




Cora Randall et al., SPARC 2008

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

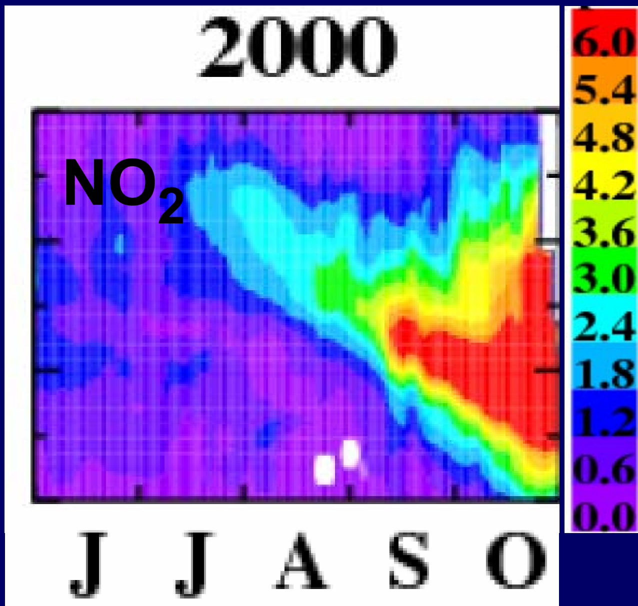
**EPP Investigations used solar occultation data from SAGE, HALOE, and POAM**

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

**In 2003 more data become available**

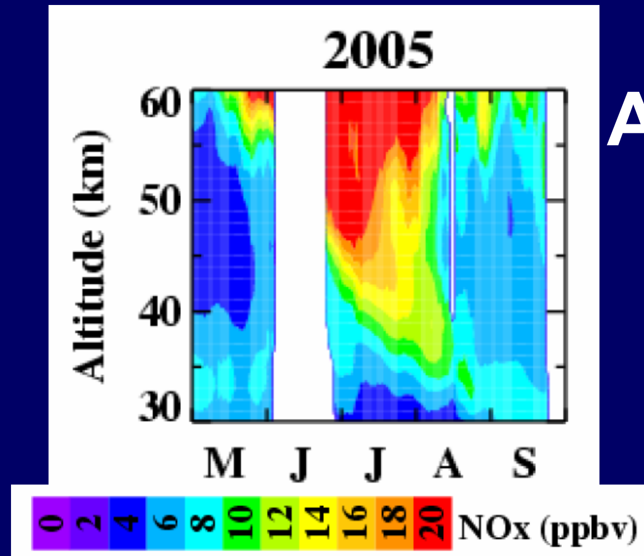
**e.g., GOMOS, MIPAS, SCIAMACHY, ACE-FTS**

## POAM: SH



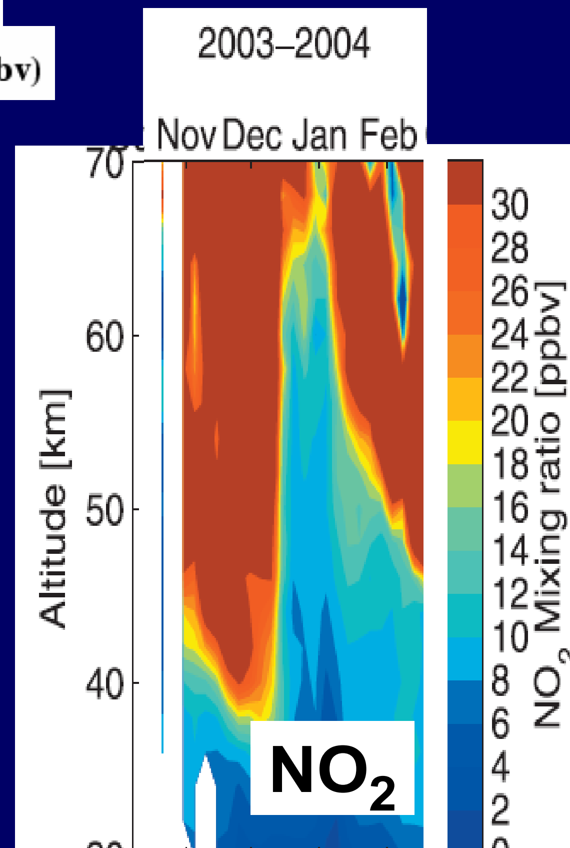

Randall et al., 2007

## ACE-FTS: SH




Randall et al., 2007

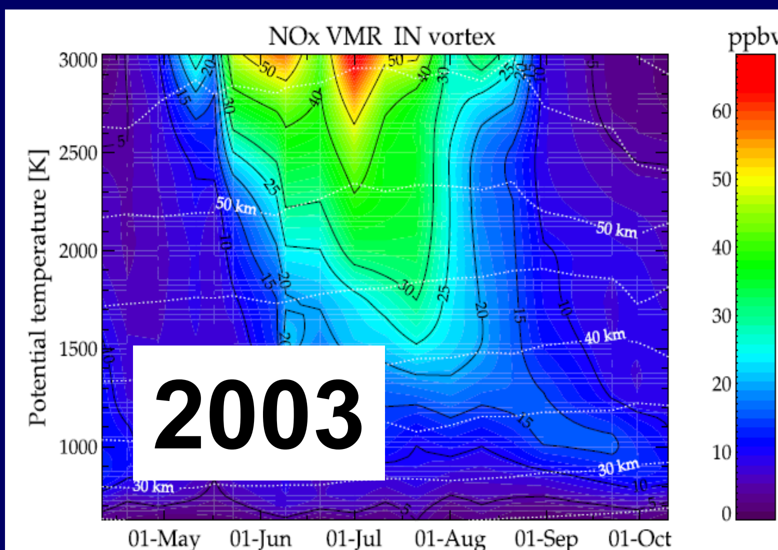
## GOMOS: NH




Seppala et al., GRL 2007

## MIPAS: SH

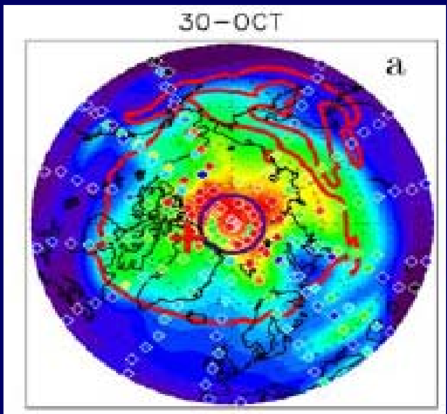
Funke et al., 2005



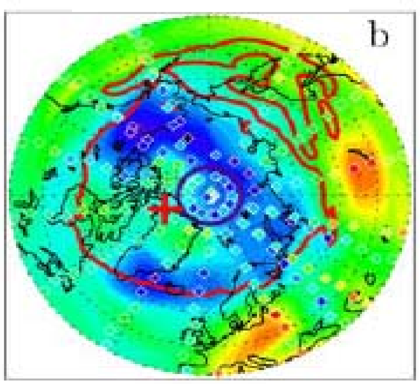

Cora Randall et al., SPARC 2008

# EPP-$NO_x$ enhancements accompanied by ozone reductions

MIPAS NOx

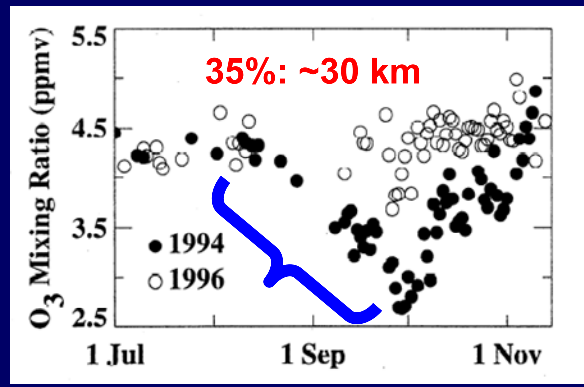



MIPAS O3



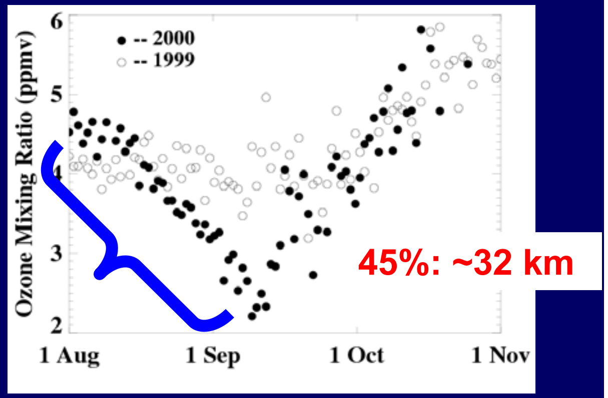

Lopez-Puertas et al., 2005

POAM ozone: 1994 vs. 1996

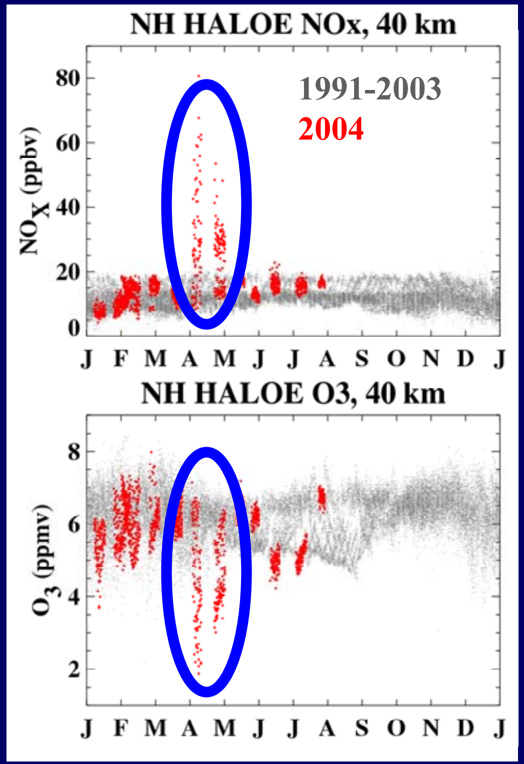



From Randall et al., 1998

POAM ozone: 1999 vs. 2000

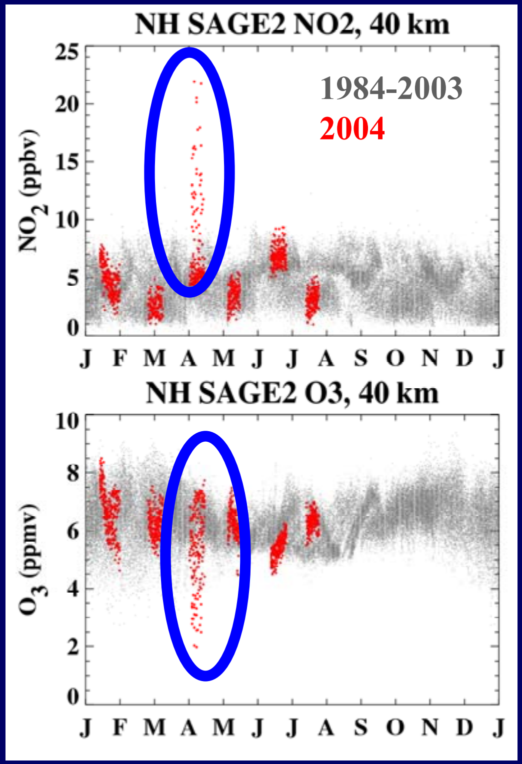



From Randall et al., 2001



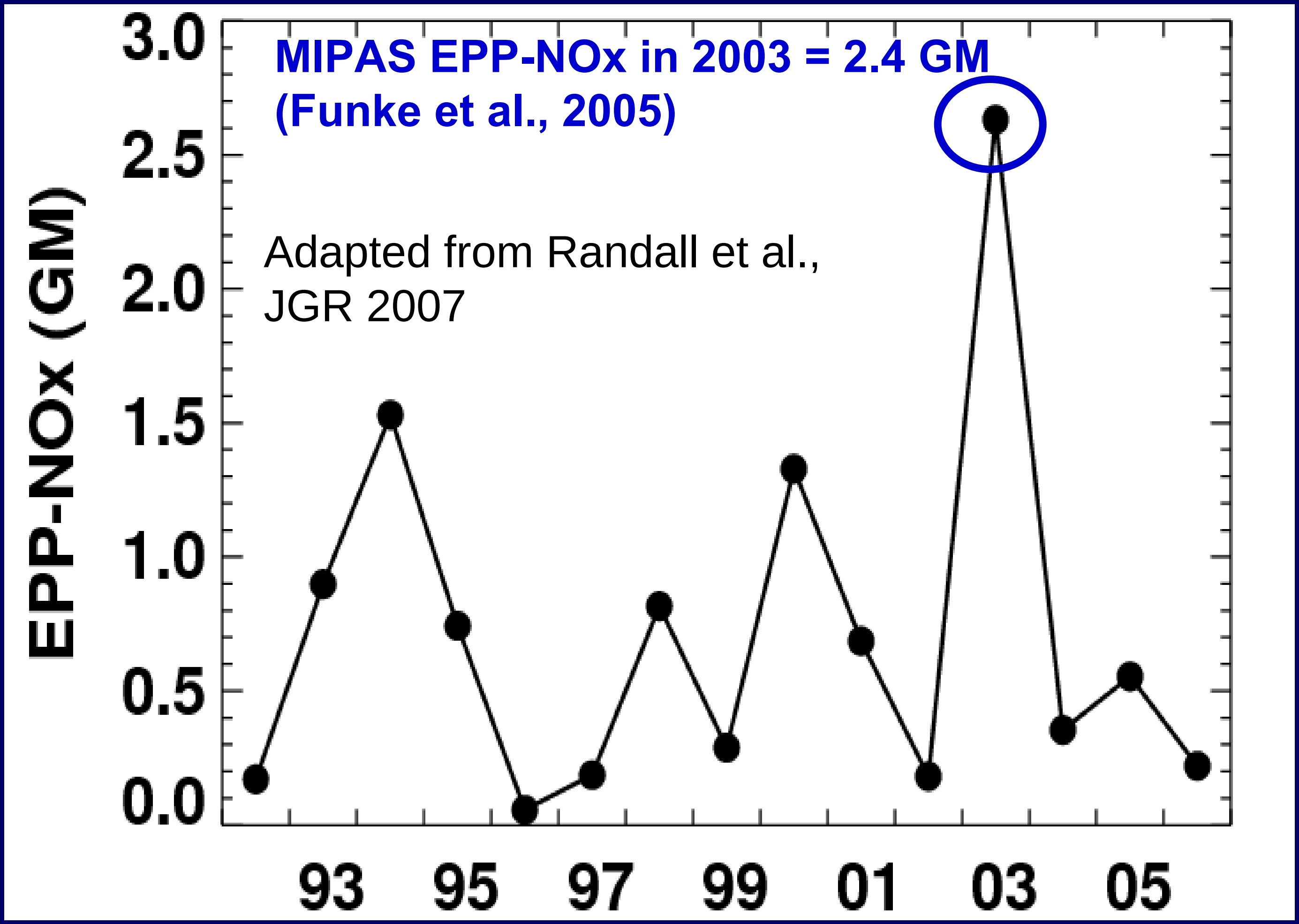

Randall et al., 2005

Cora Randall et al., SPARC 2008




Randall et al., 2005

# EPP-$NO_x$ entering the *Southern Hemisphere* Stratosphere



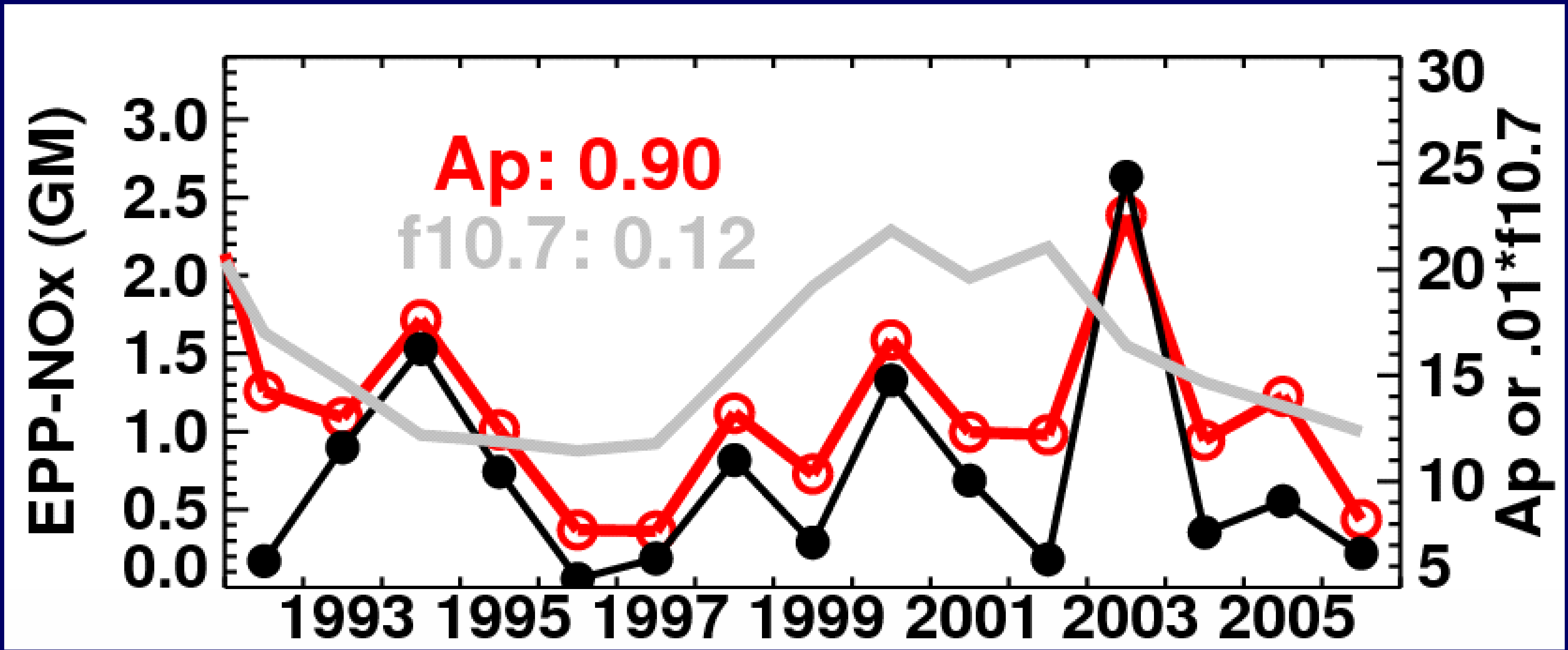

**How significant is this?**

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 Solar f10.7 (Apr-Aug)



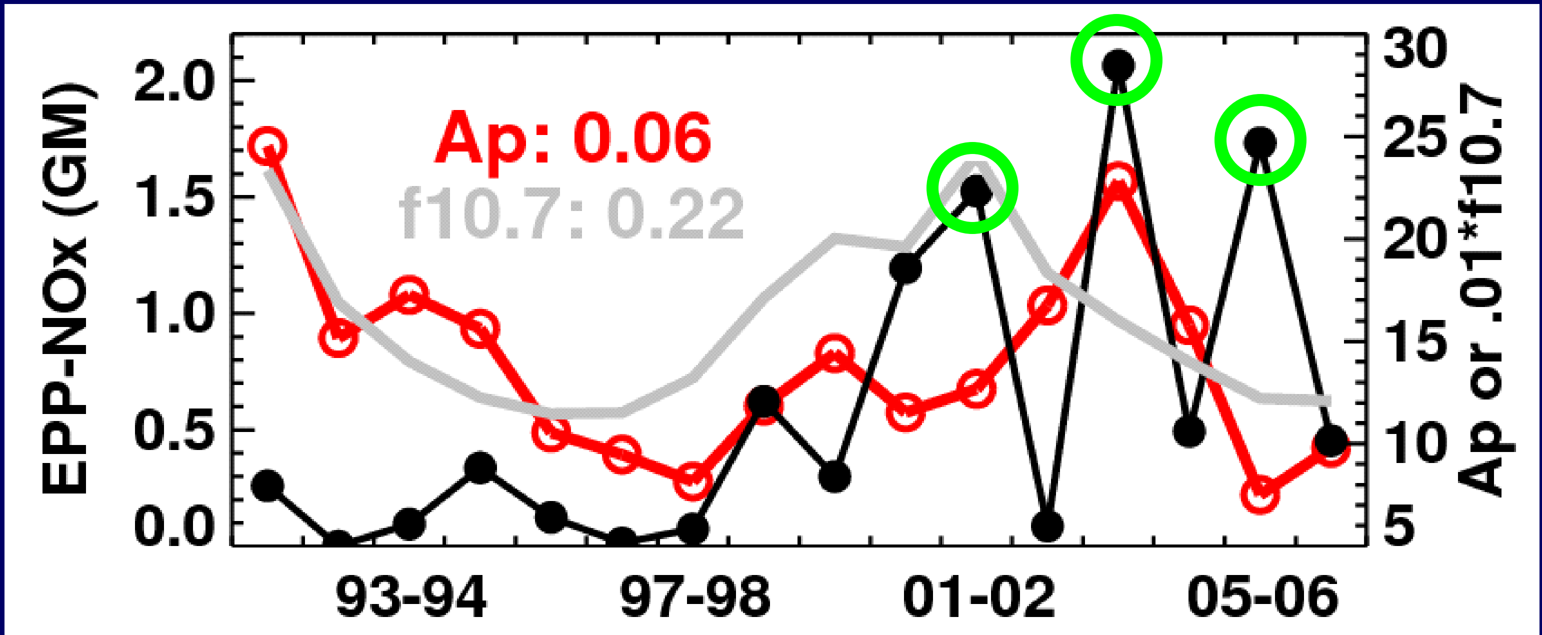

Adapted from Randall et al., JGR 2007

**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**

Cora Randall et al., SPARC 2008

# EPP-$NO_x$ entering the *Northern Hemisphere* Stratosphere vs. Ap & F10.7




**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

**2003-2004 and 2005-2006 were characterized by mid-winter warmings followed by increased mesospheric descent and an anomalously large upper stratospheric vortex.**

(Hauchecorne et al., 2007; Manney et al., 2005; Randall et al., 2006; Siskind et al., 2007)

**Enhanced vertical transport brings down more EPP-$NO_x$, which is confined in the strong vortex**

# The EPP Story 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.

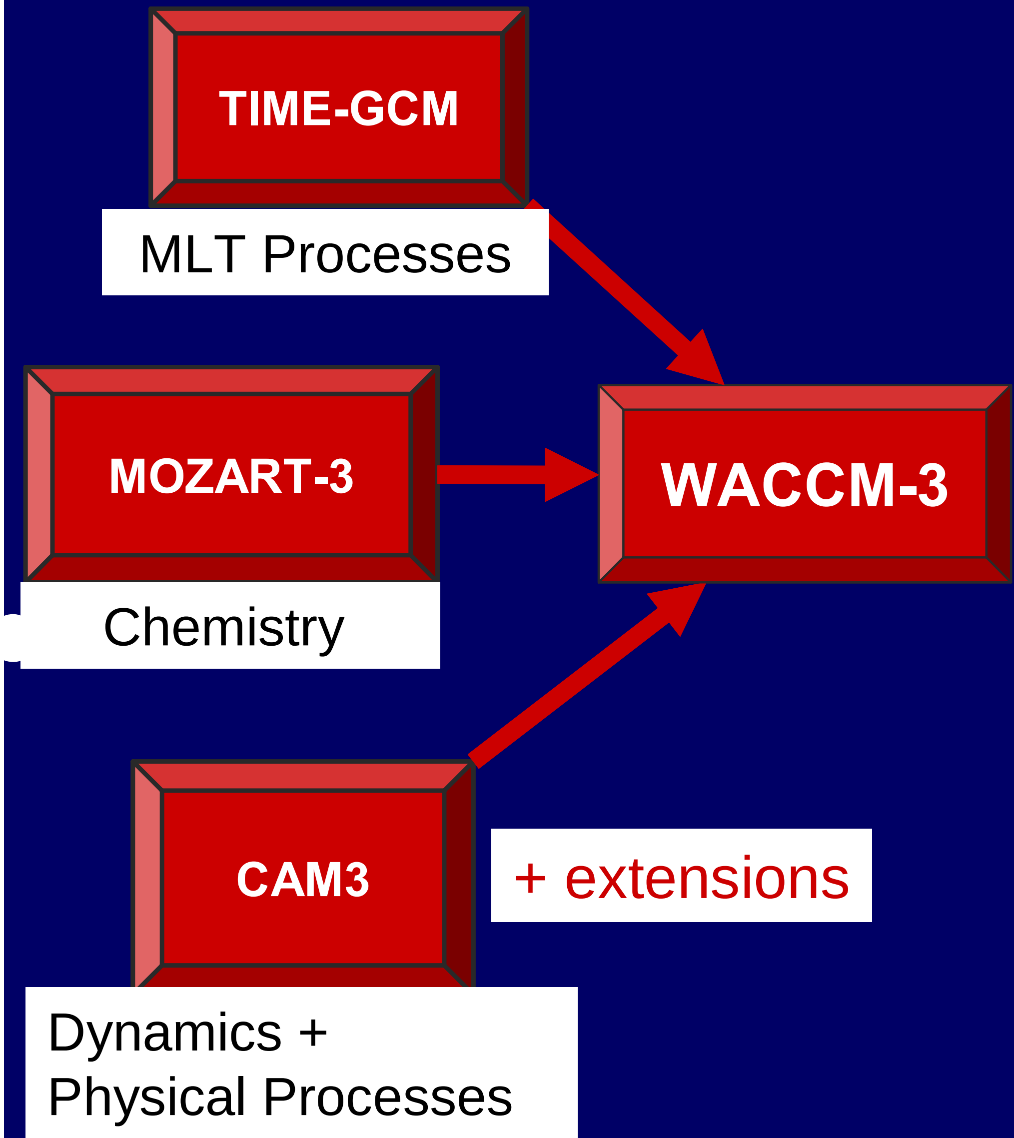
- Ozone is depleted by EPP-$NO_x$ by 35% or more.

- Contribution of EPP-NOx to the stratosphere does not correlate well with the solar cycle.

- Understanding wave mean flow interactions is required to elucidate mechanisms controlling solar cycle variability.

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

# What do the models say about EPP effects on the stratosphere?

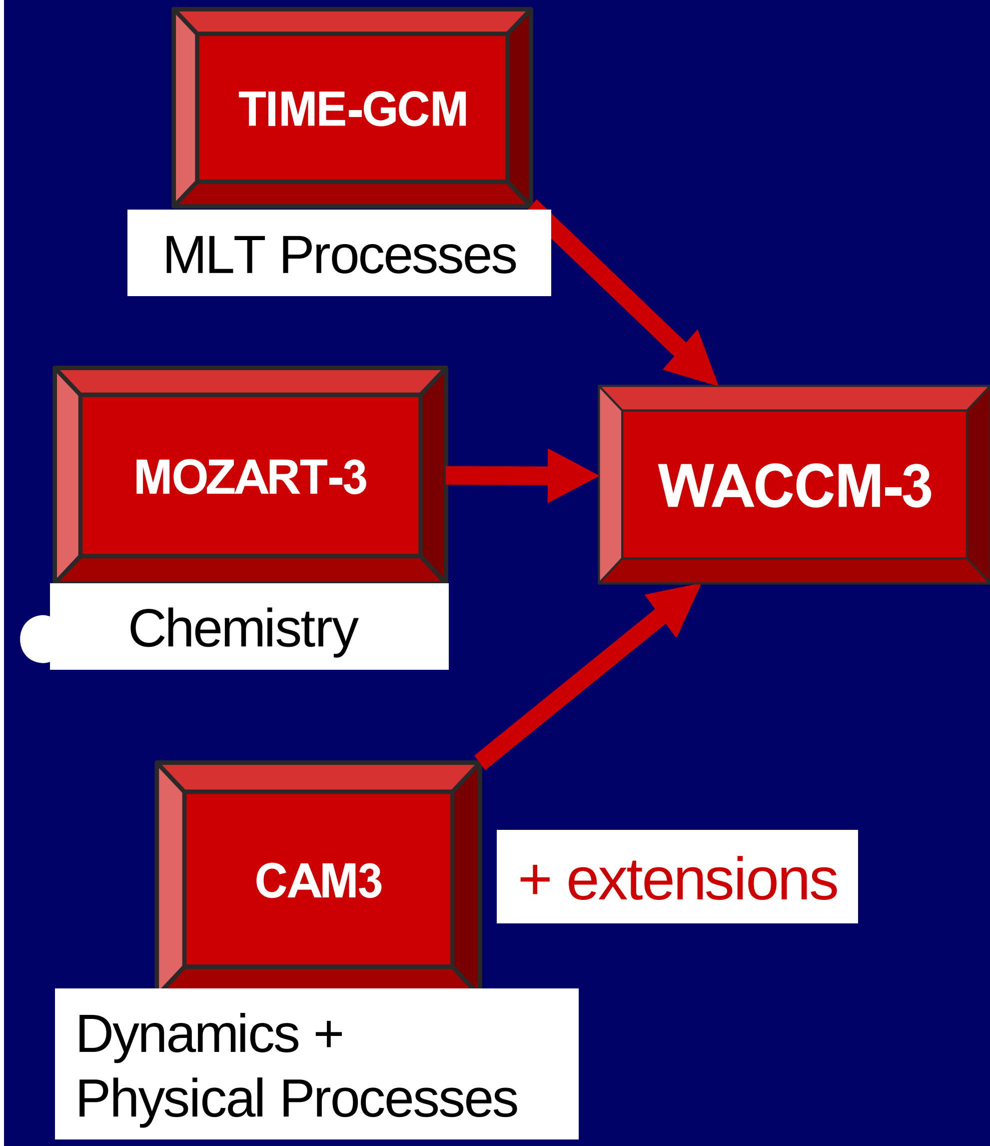



(Adapted from Rolando Garcia)

## Whole Atmosphere Community Climate Model

A 3D coupled chemistry climate model

- 0 to ~145 km
- Comprehensive chemistry incl. heterogeneous rx
- Interactive Chemistry or Specified Meteorology
- 1-1.5 km vertical resolution in stratosphere
- 1.9º x 2.5º or 4 x 5º horizontal resolution
- Ref: Garcia et al., 2007




(Adapted from Rolando Garcia)

## WACCM Parameterization of Precipitation Effects

### Aurora

- Input = Kp
- Distribution = Auroral Oval
- Roble and Ridley, 1987

### SPEs

- Input = GOES proton flux
- Distribution = polar cap
- Jackman et al., 2008

### Medium Energy Electrons

(30 keV – 1 MeV)

- Input = MEPED electron flux
- Distribution = Codrescu patterns (JGR, 1997)
- Fang et al., 2008

# WACCM Simulations of Solar Proton Events

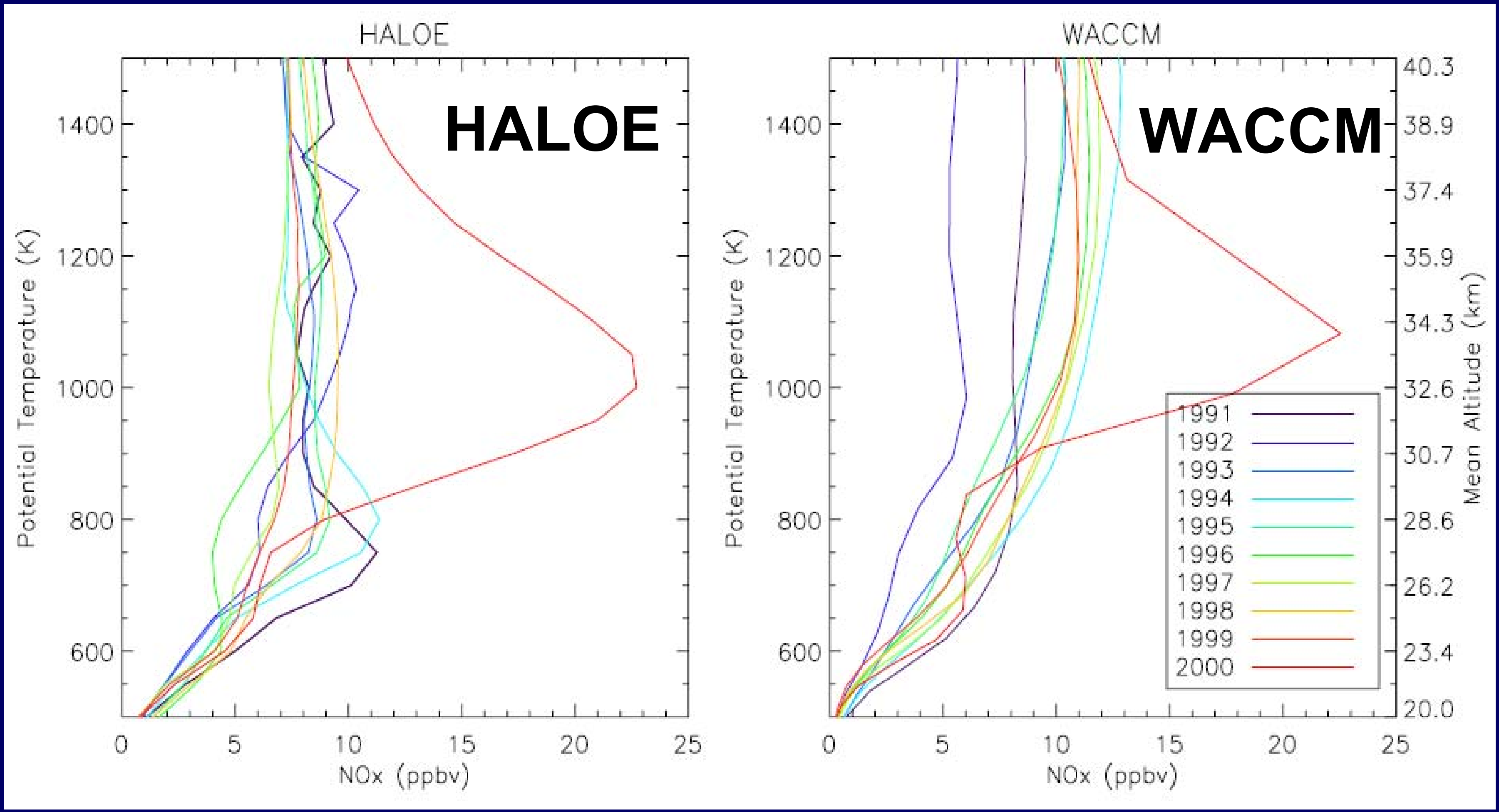
- Results show that SPEs can cause ~5% changes in polar stratospheric ozone that are evident in 5-year averages.

- Instantaneous ozone depletion exceeds 20%.

- $NO_y$ from the SPE interferes with lower stratospheric Cl and Br ozone loss cycles.

Cora Randall et al., SPARC 2008

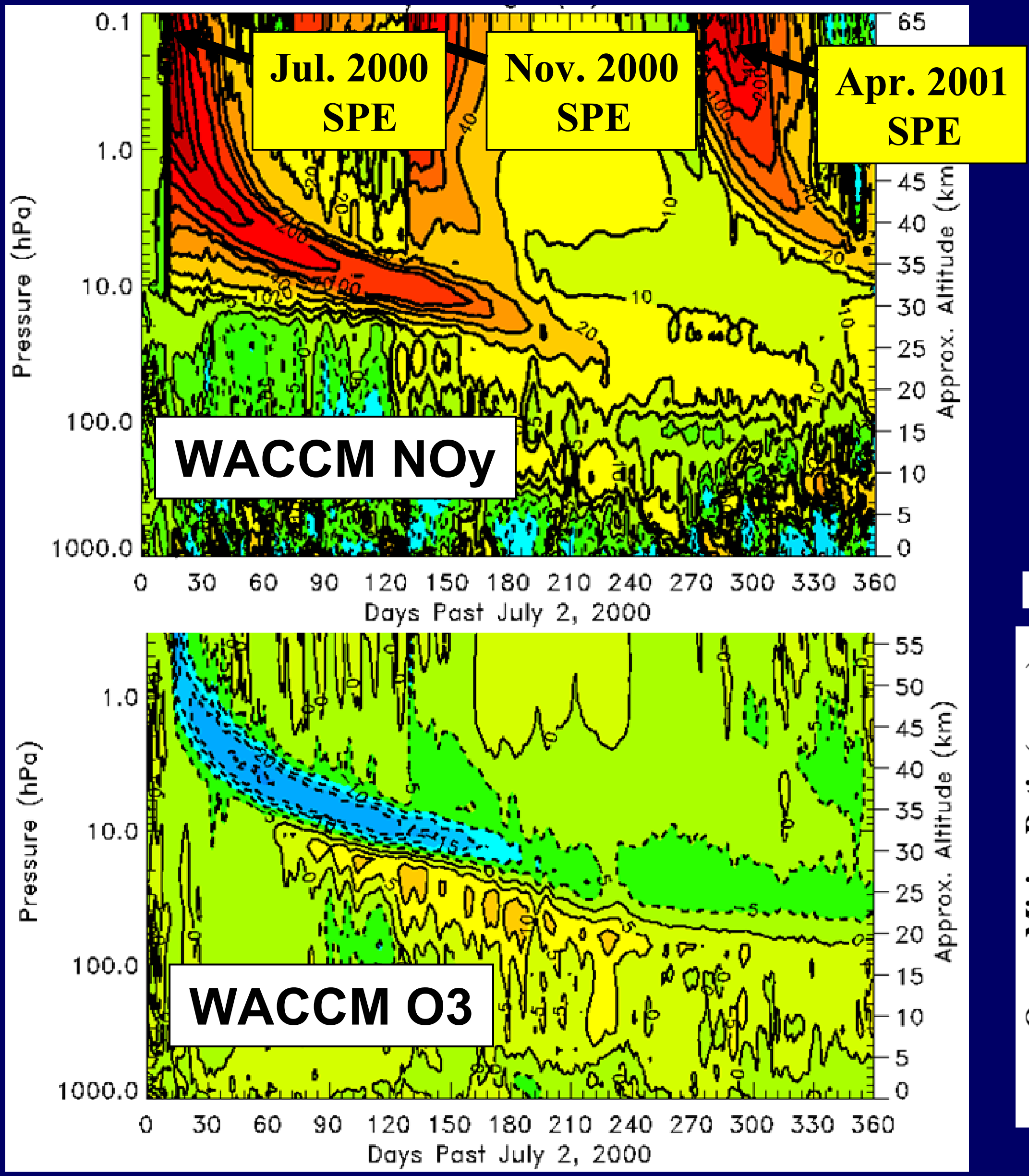
# WACCM simulation of NOx in the SH polar vortex after July 2000 SPE agrees with HALOE data




$NO_x$ in the SH polar vortex in Sept/Oct. Jackman et al., 2008.

Cora Randall et al., SPARC 2008

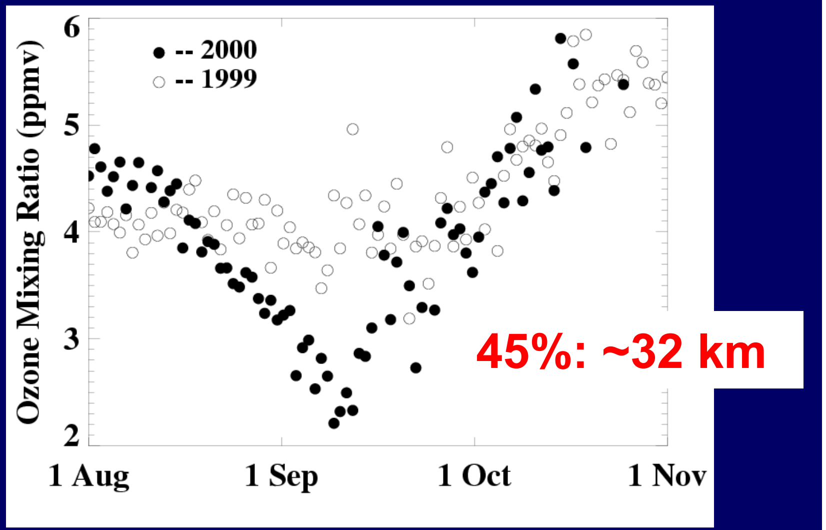
# WACCM simulates >20% ozone depletion after the July 2000 SPE.



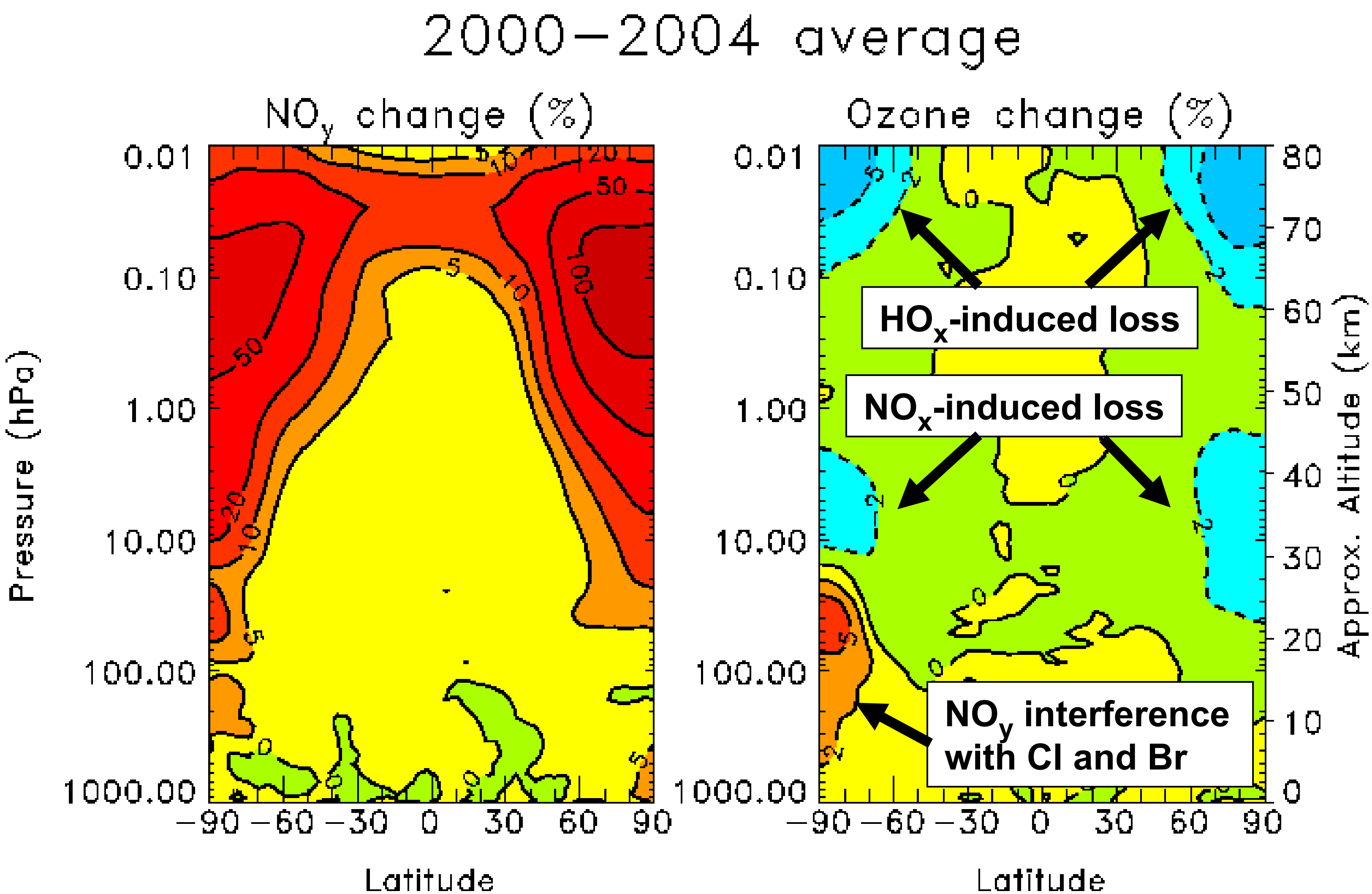

Jackman et al., 2008

**Agrees with POAM, which showed max depletion of 45%.**

POAM ozone: 1999 vs. 2000




From Randall et al., 2001




# Very Large SPEs in 2000, 2001, & 2003

Jackman, COSPAR 2008

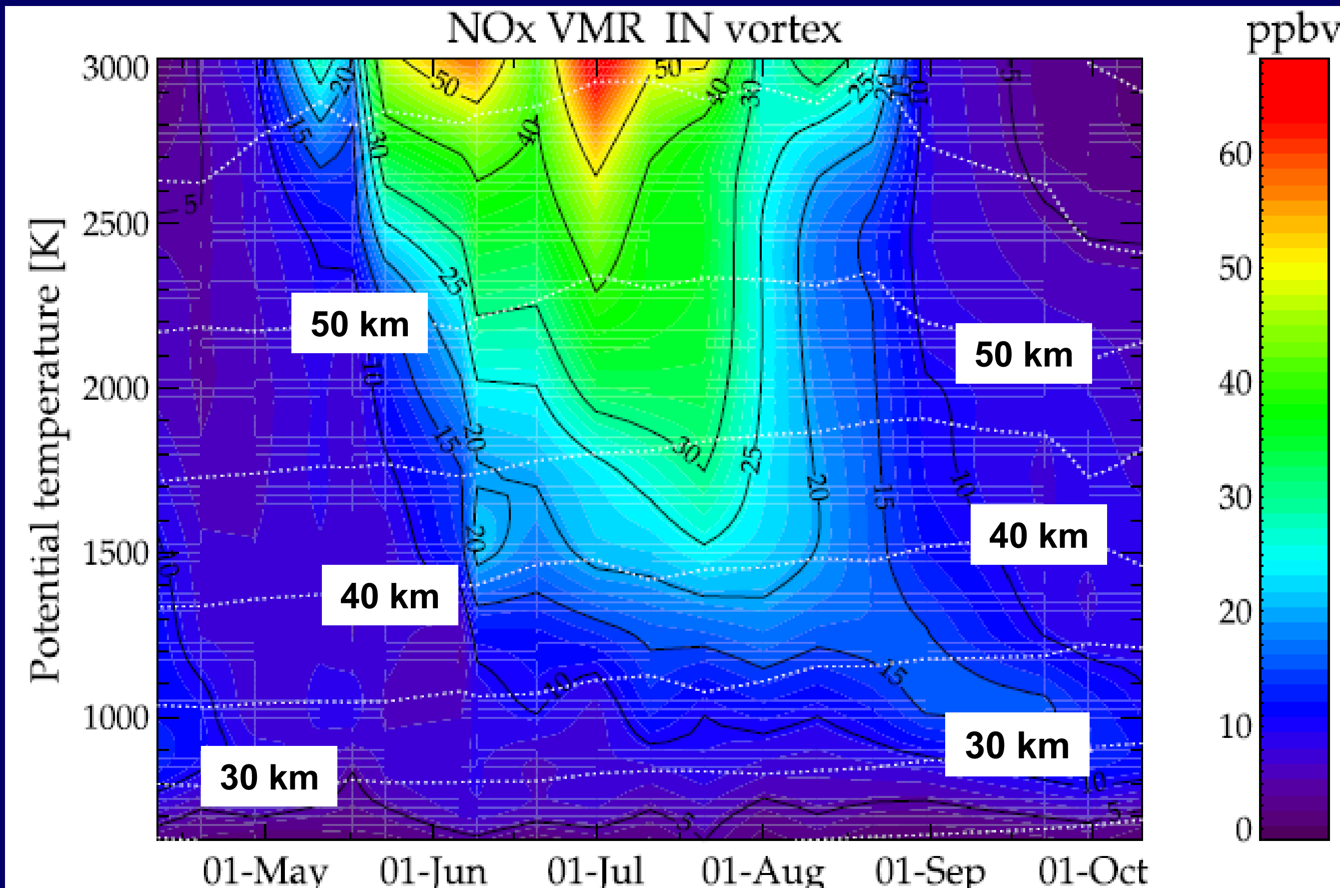
# WACCM Simulations of Auroral and MEE electron precipitation

- Results show that commonly observed levels of Auroral and MEE precipitation can cause ~5% changes in annual average polar stratospheric ozone and +/- 1 K changes in polar stratospheric temperature.

- Monthly average stratospheric ozone depletion exceeds 10%.

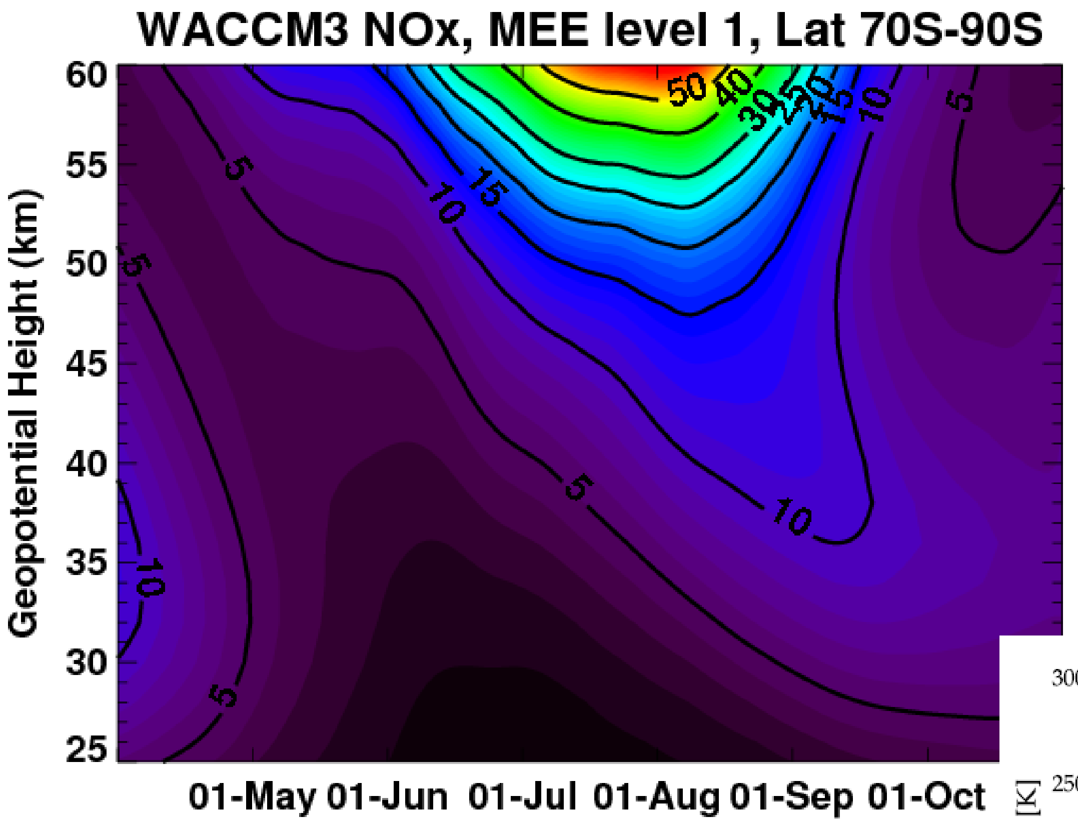
- Monthly average stratospheric temperature changes exceed 4 K.

## MIPAS $NO_x$ inside the Southern Hemisphere polar vortex in year 2003 (From Funke et al., 2005)




**EPP-$NO_x$ descends inside the SH stratospheric vortex from May through September**

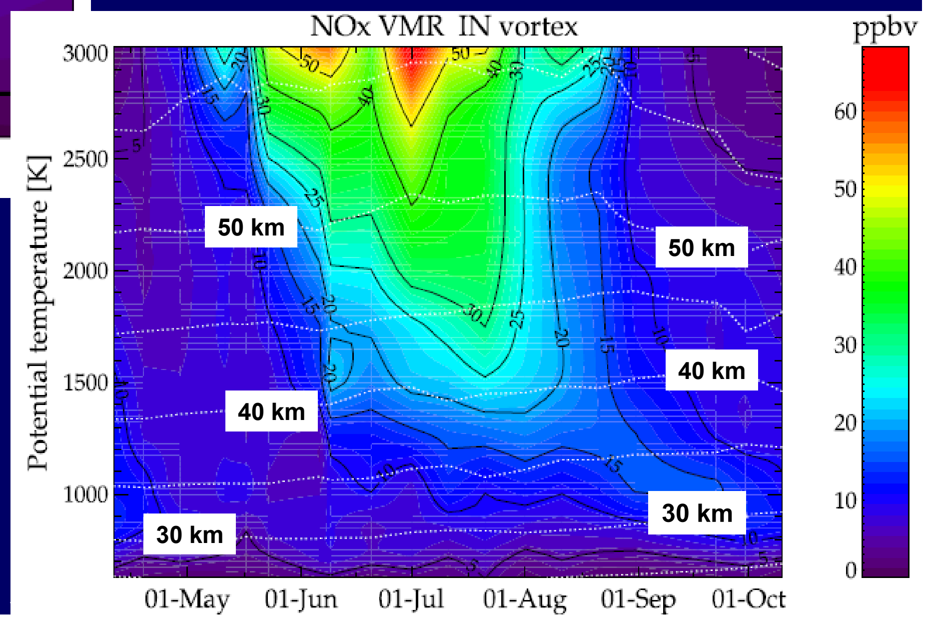
# WACCM simulation similar to MIPAS




- **70-90S**
- **Aurora + low-level MEE**

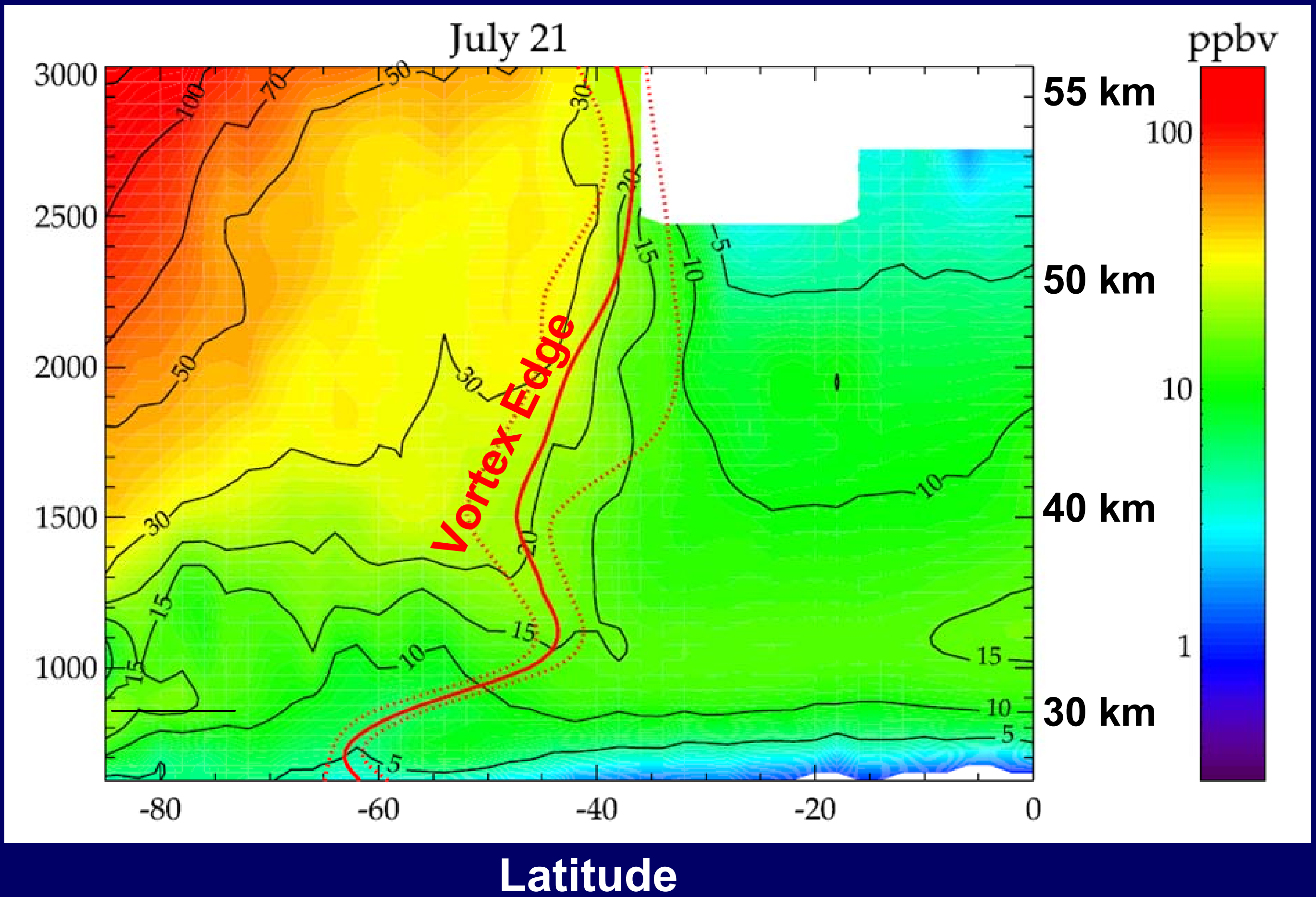
**(realistic simulation of 2003 geomagnetic activity)**

**MIPAS** →




Cora Randall et al.,

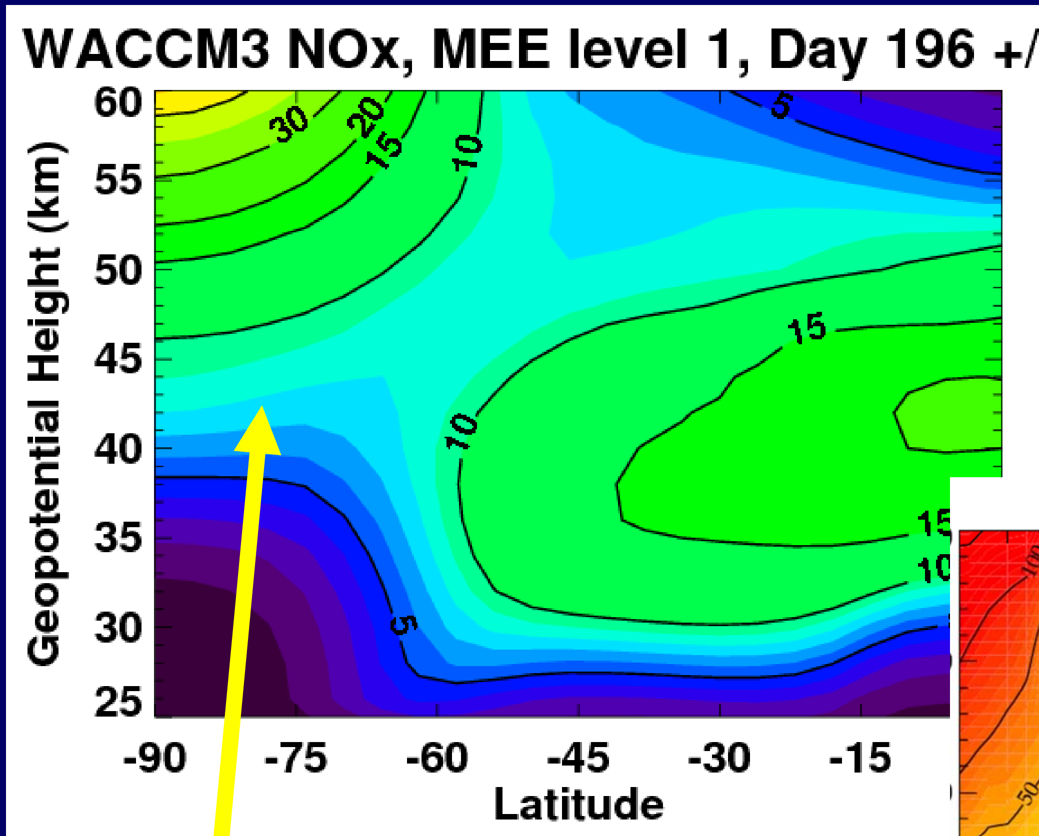
# Latitude dependence of MIPAS $NO_x$ on 21 July 2003 (from Funke et al., 2005).



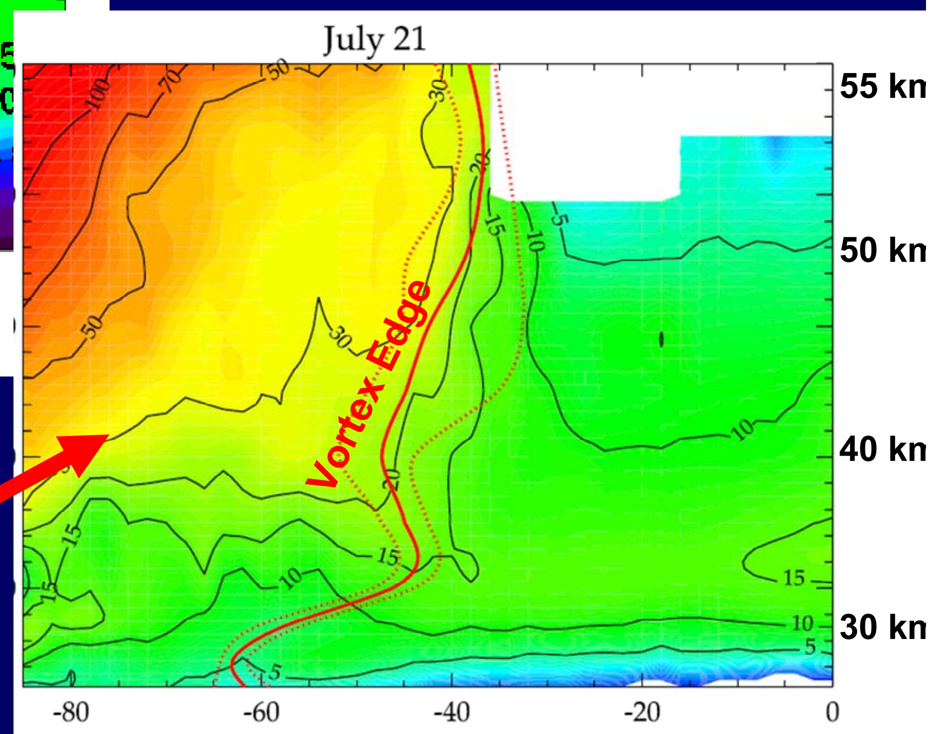

**EPP-$NO_x$ descending from the upper atmosphere fills in the SH polar region**

# WACCM NOx also fills in the polar region, but

WACCM $NO_x$ underestimate is evident.




MIPAS




Latitude

Descending $NO_x$ in south polar region

Cora Randall et al., SPARC 2008

# What is the quantitative effect of EPP-$NO_x$ ?

**Calculate $\Delta X = X(EPP) - X(A_p=3)$**

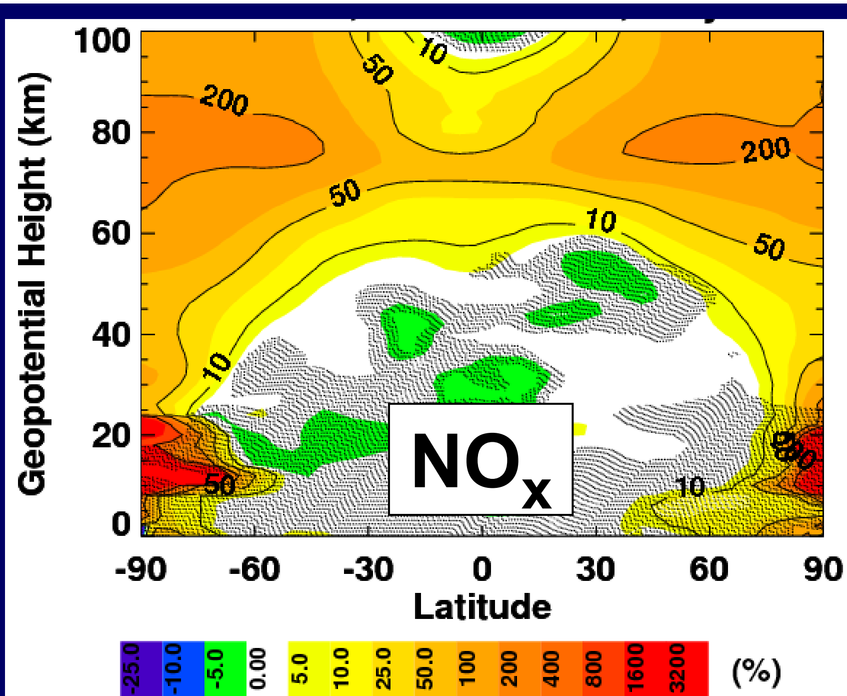
Aurora + MEE, but no SPE
Ap=27, MEE = level 1
Appropriate for SH 2003

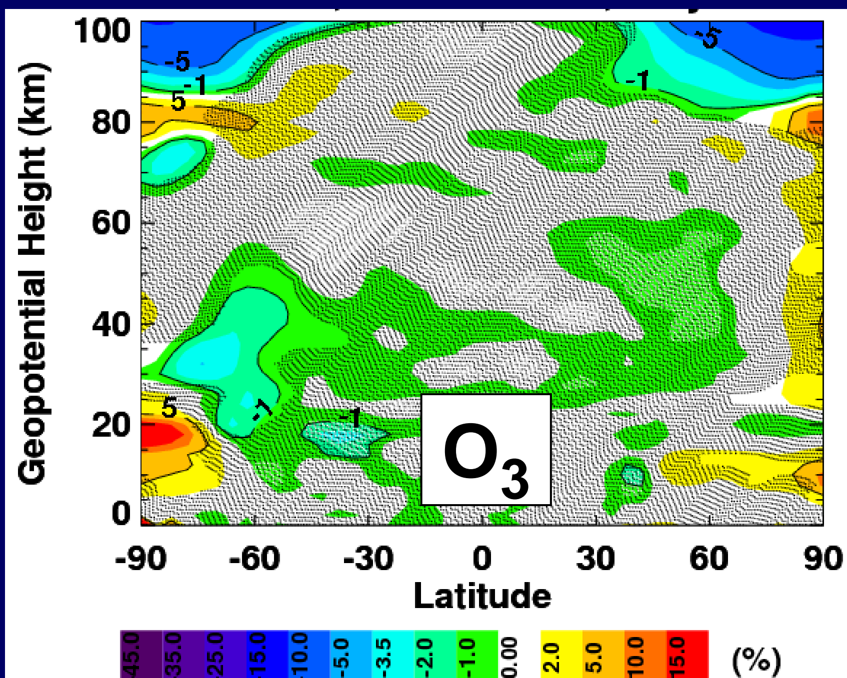
Essentially zero EPP

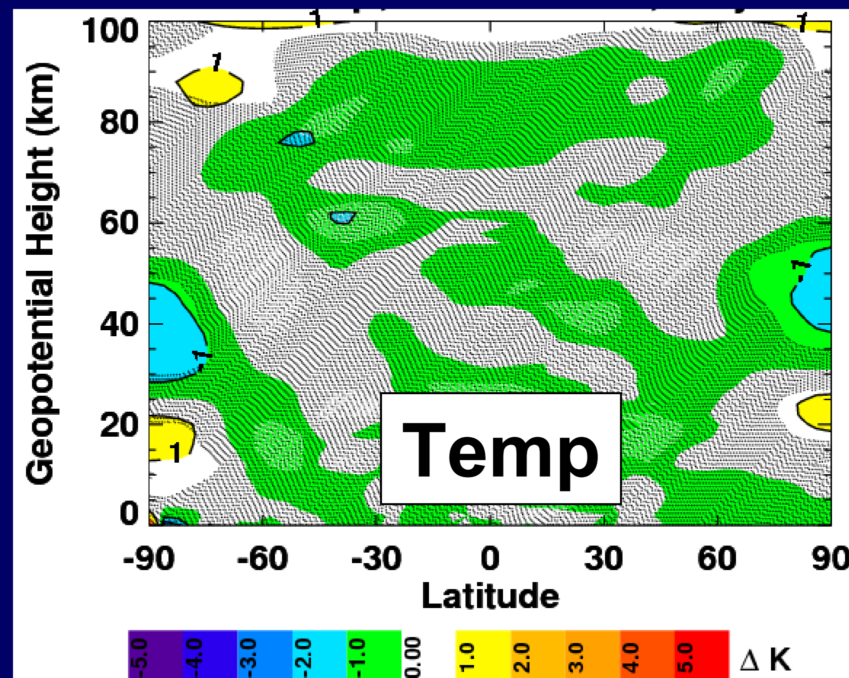
$X = NO_x$, $O_3$, Temperature

# Annual Average Differences:

## EPP minus NoEPP



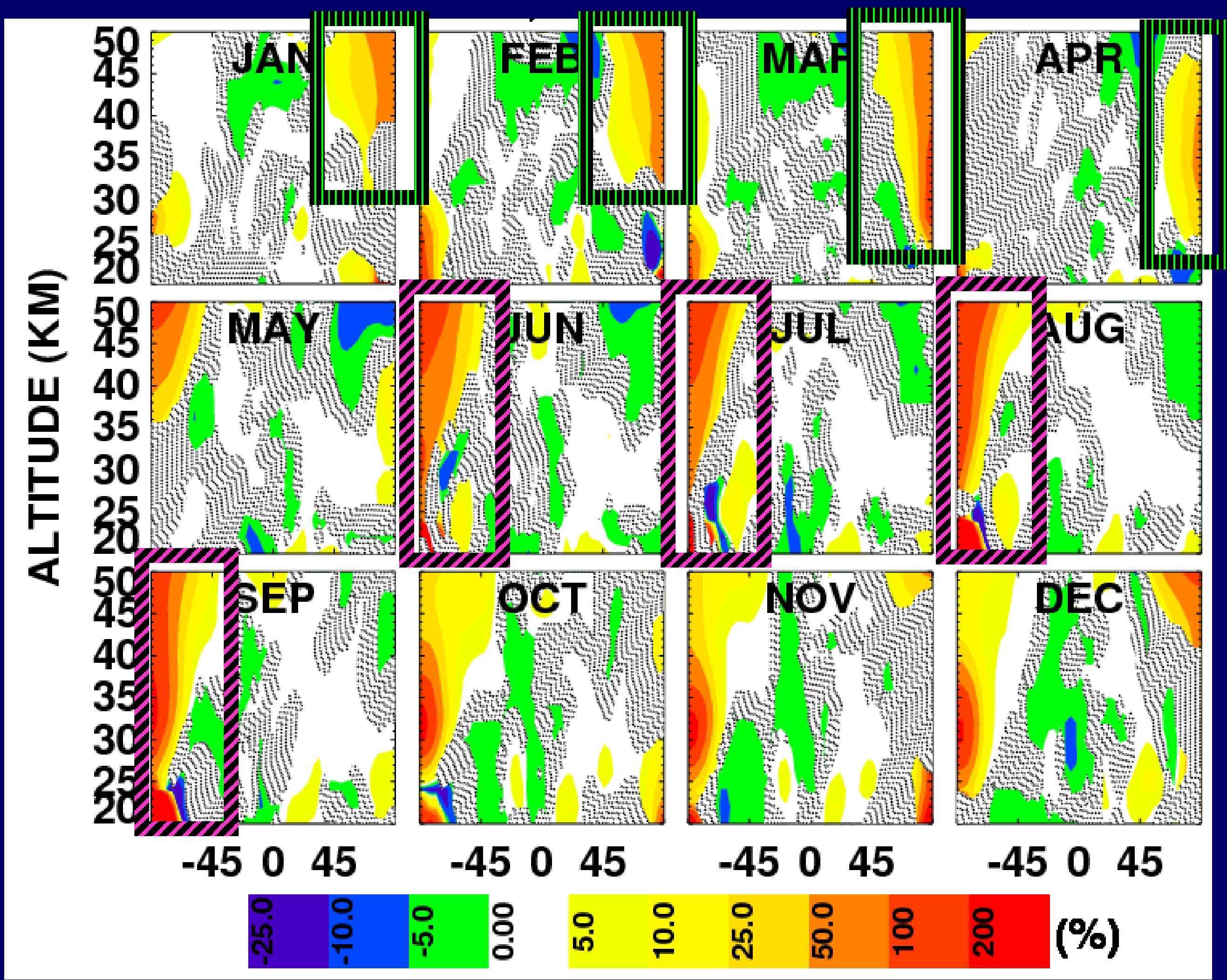




Cora Randall et al., SPARC 2008

# Where and when are the largest EPP effects in the stratosphere?

# WACCM monthly average differences show $NO_x$ descending in NH & SH



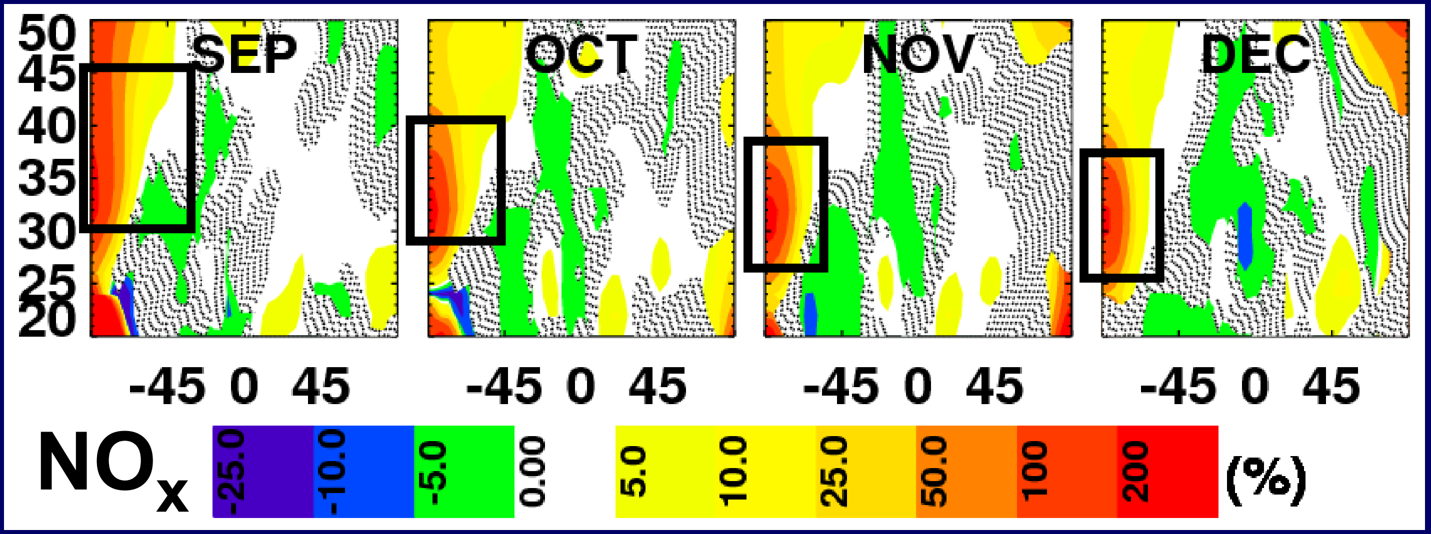

Increases in SH larger than in NH

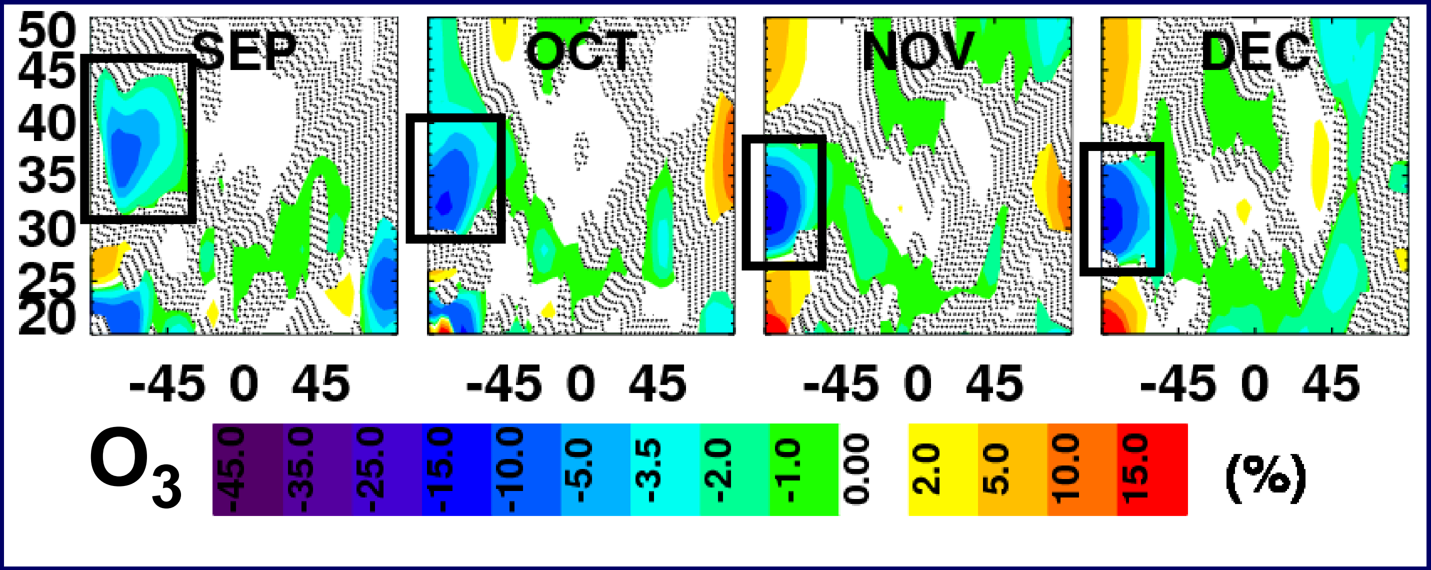
Largest NH increases in Jan-Apr

Largest SH increases in Jun-Sep

Cora Randall et al., SPARC 2008

# Ozone loss >10% caused by descending EPP-$NO_x$ in SH polar region




Cora Randall et al., SPARC 2008

# EPP-$NO_x$ induced ozone loss not prominent in WACCM in NH

**But:**

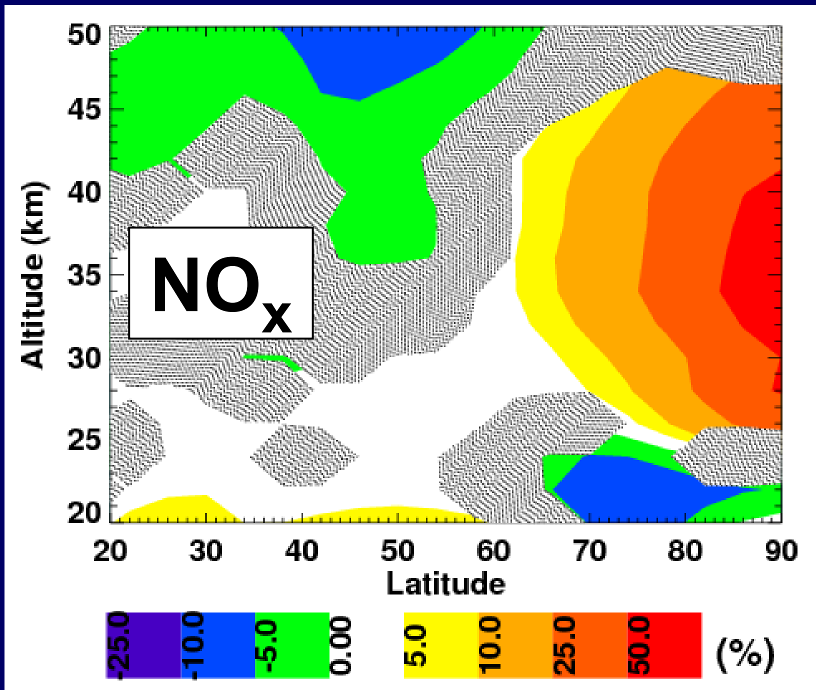
**WACCM shows significant temperature differences in both hemispheres (shown next)**

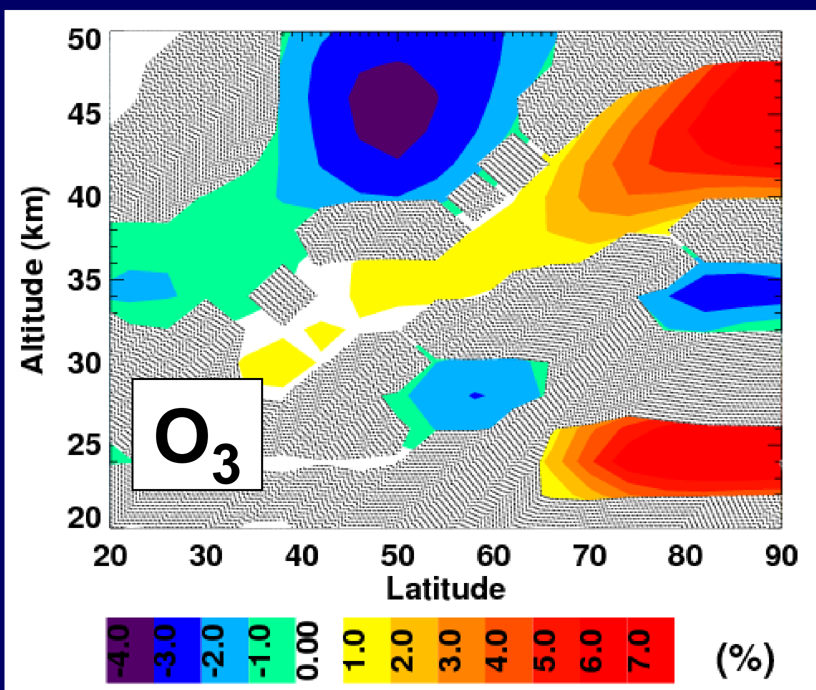
**Lack of correlation between EPP-$NO_x$, $O_3$, and temperature suggests EPP affects temperature through dynamical processes**

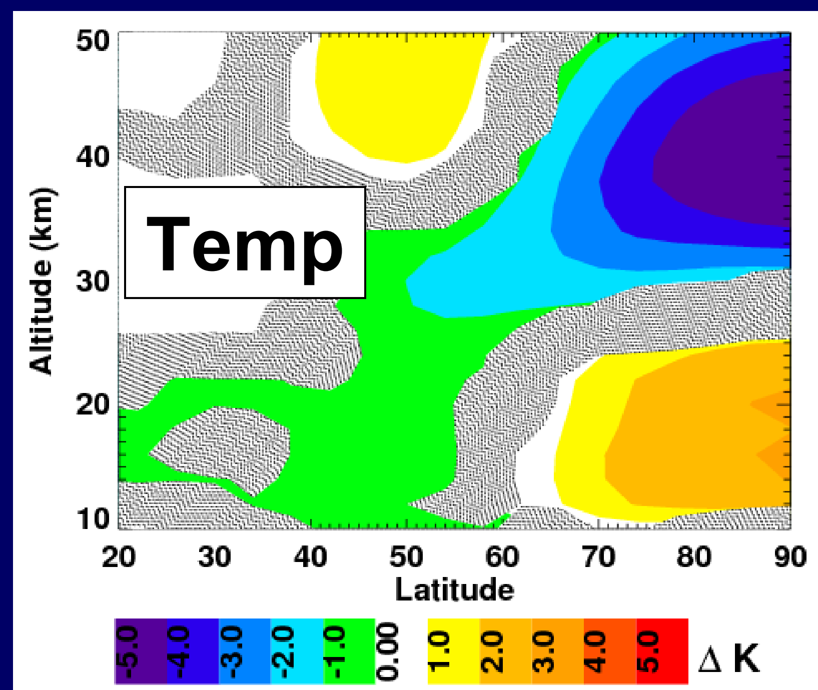
# WACCM Δ for April

**There is not an obvious correlation between EPP-$NO_x$, $O_3$, and Temperature**

## Dynamics?



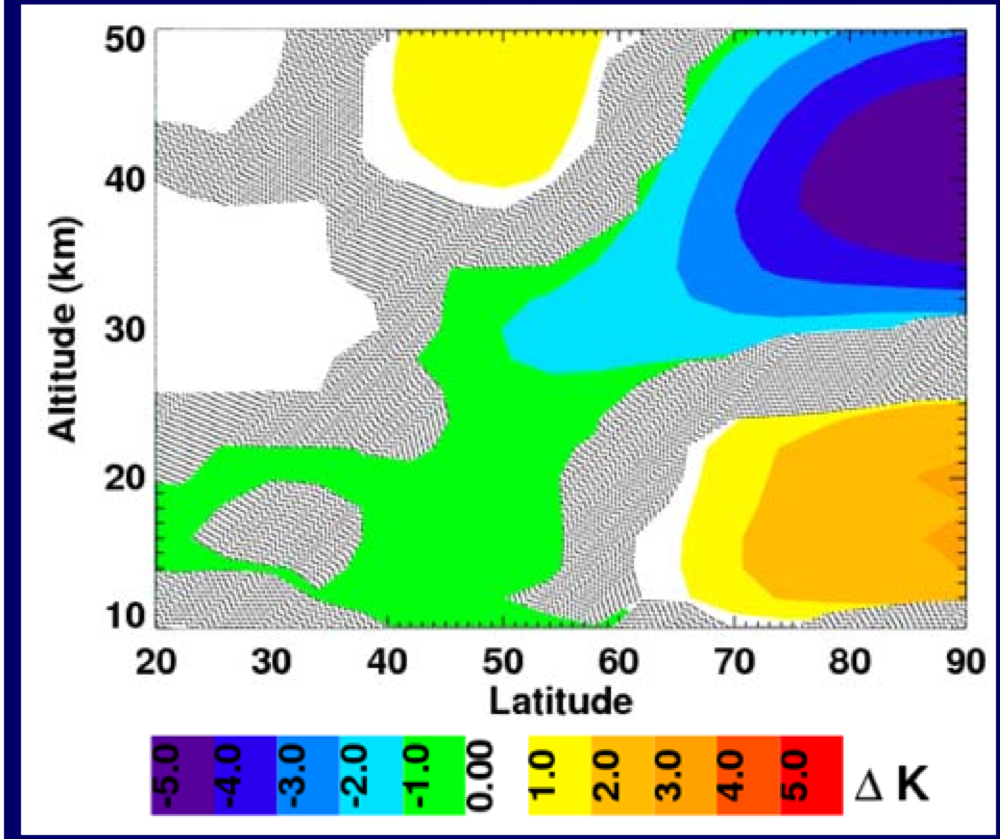



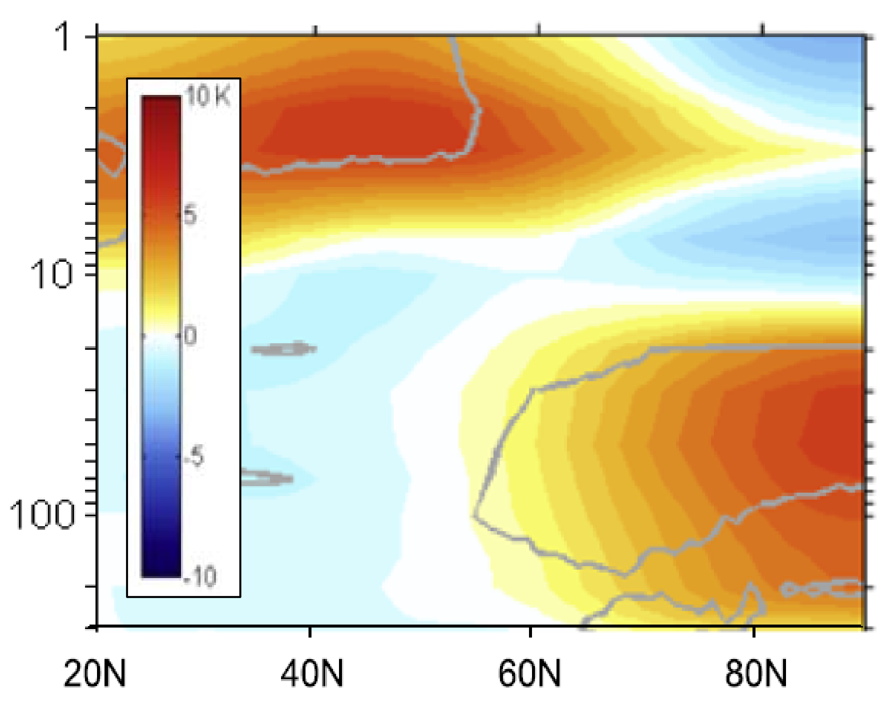

Cora Randall et al., SPARC 2008

**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

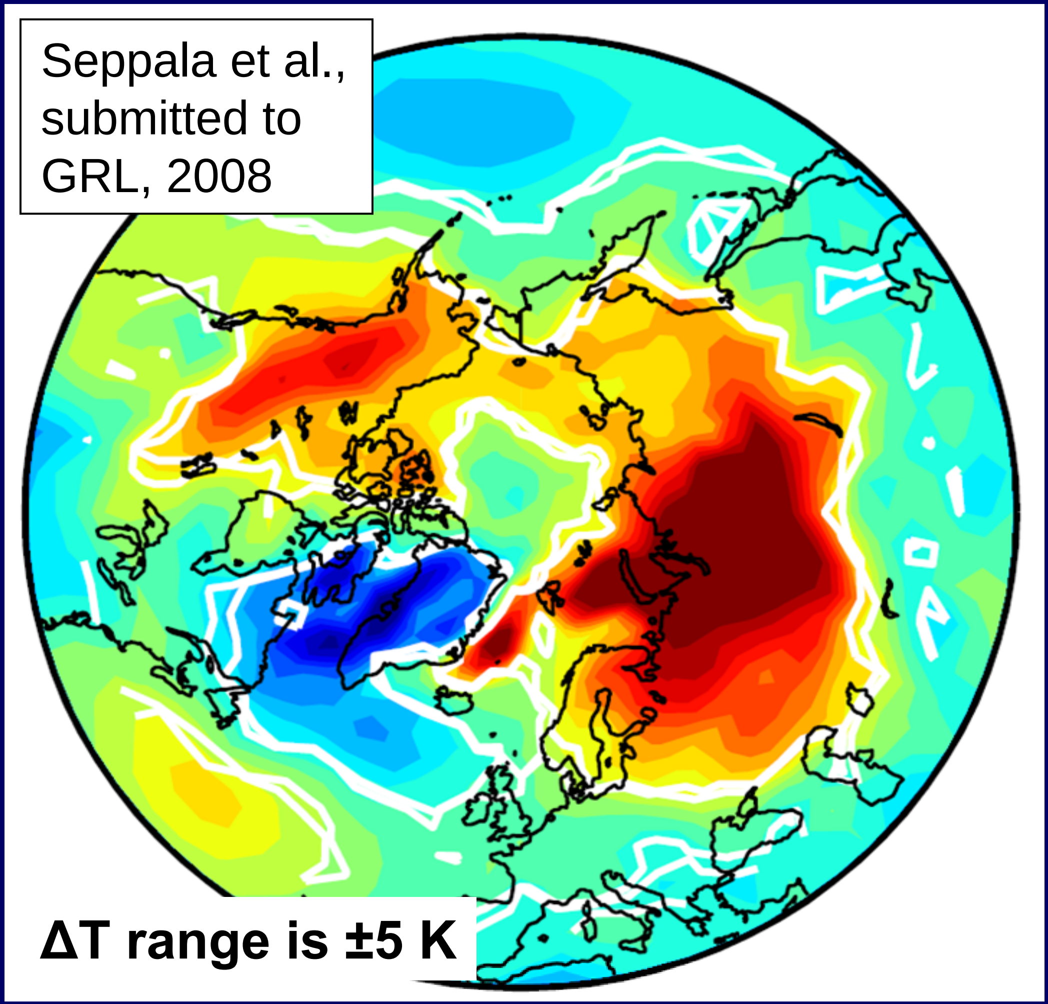



Lu et al., JGR 2008

# Does EPP have an effect on surface level air temperatures?

WACCM runs here use specified SSTs, so they are not appropriate for addressing this question.

Seppälä et al. (submitted to GRL) have looked at ERA-40 data....




**DJF surface air temperature differences between years with high and low Ap Index.**

**[1961, ’83, ’84, ’93]**
**minus**
**[1966, ’71, ’72, ’98]**

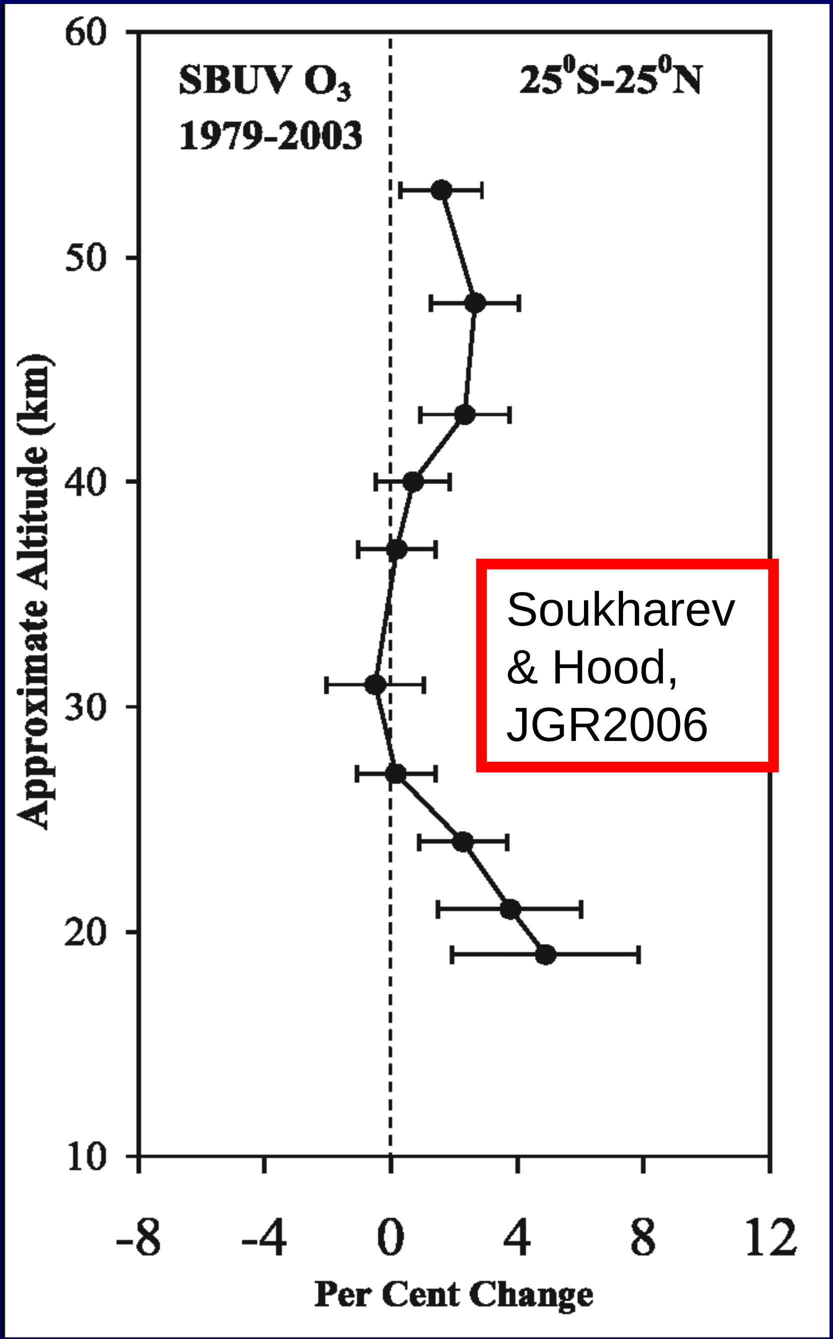
- **Similar F10.7 (100-125)**
- **Similar QBO & ENSO**

**But: NAM in High Ap years ~1 unit higher on average than in Low Ap years, so results are inconclusive.**

**Temperature pattern similar to NAM positive phase.**

# How do the EPP effects compare to solar irradiance effects?

## First look at ozone...

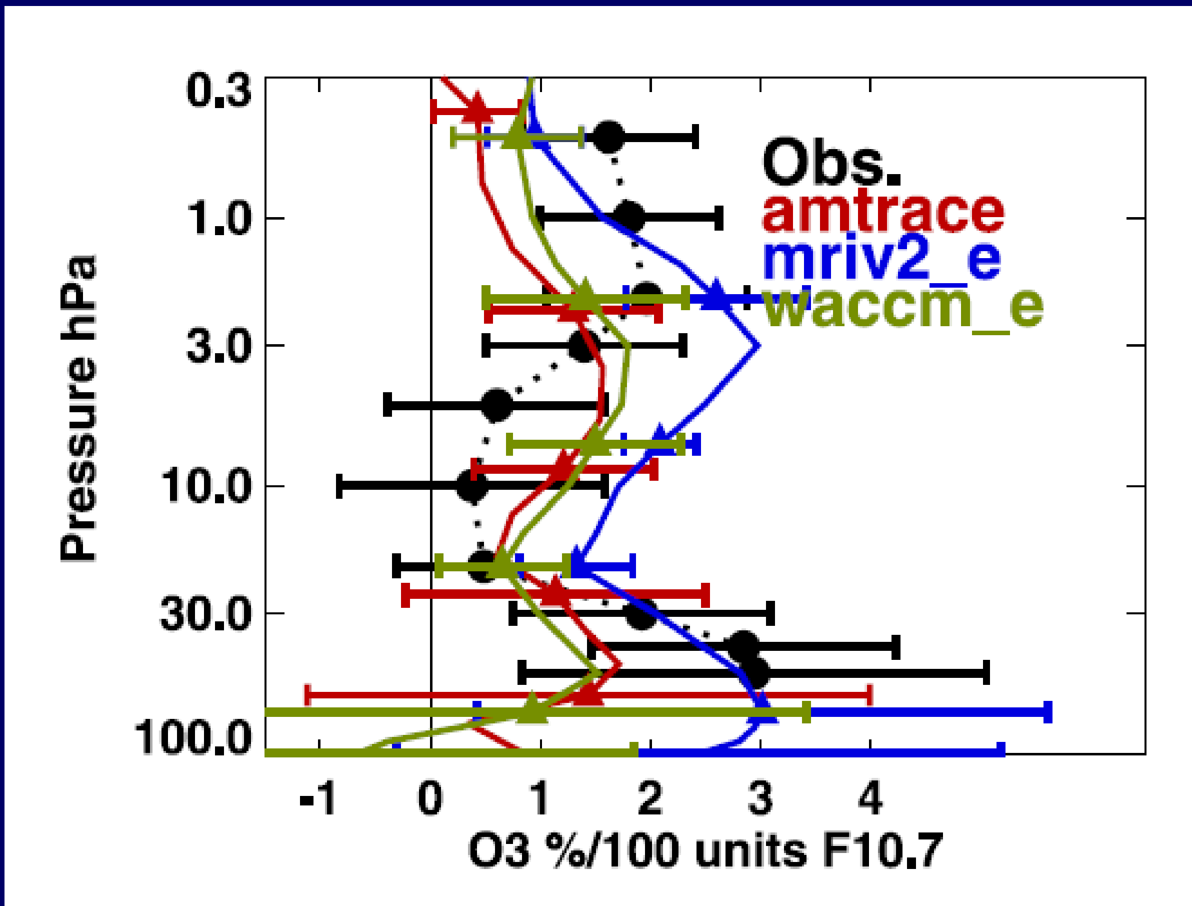



# Solar Cycle Effects in SBUV Ozone: 25S to 25N

**Change in upper stratosphere: ~1% – 3%**

**Change in lower stratosphere: ~2% – 4%**

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



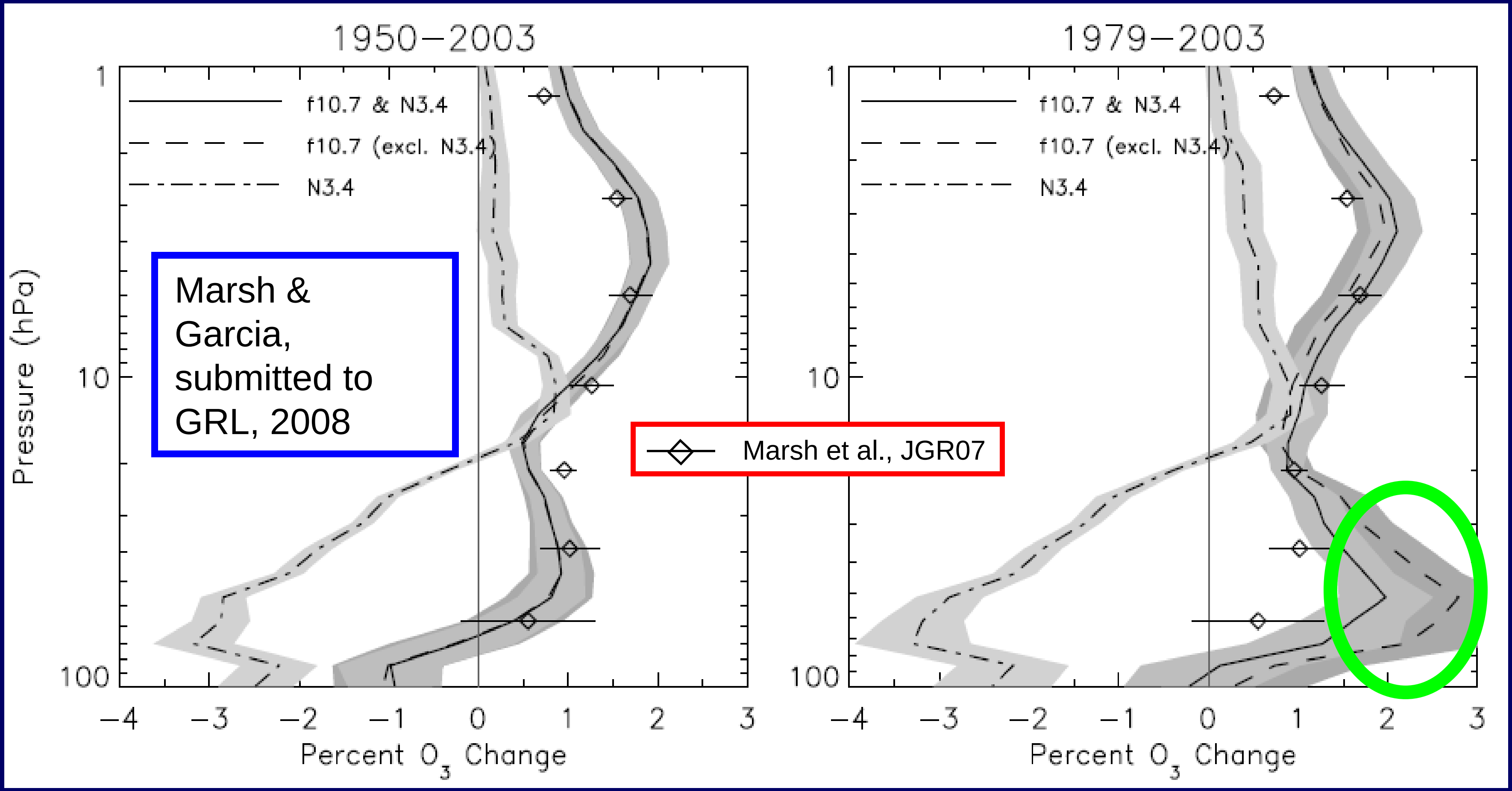

From Austin et al., JGR 2008

**Simulations agree with observations**

**Change in upper stratosphere: ~2% Max to Min**

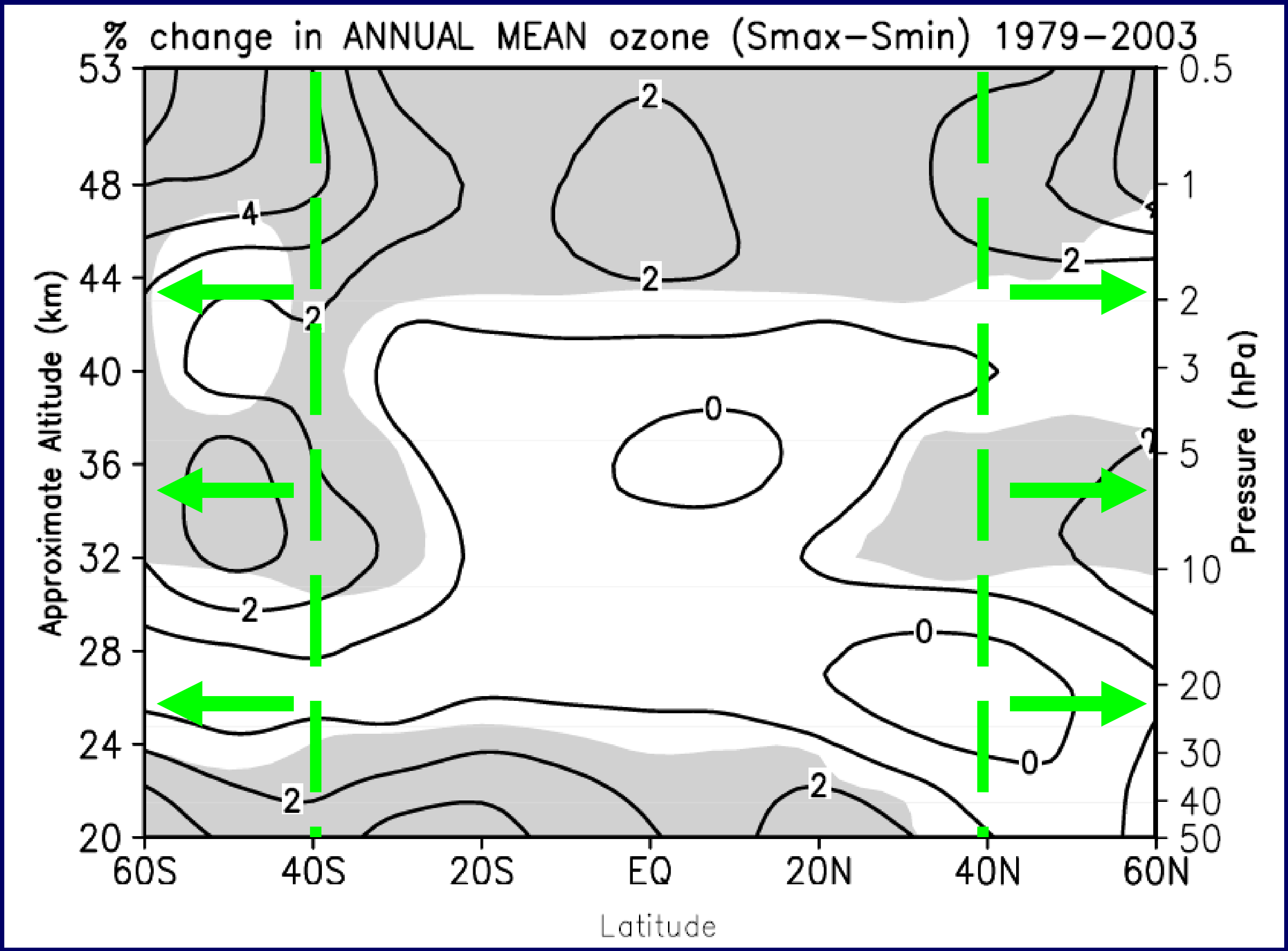
**Change in lower stratosphere: ~2% Max to Min**

# Solar Cycle Effects in WACCM Ozone: 24S to 24N




**"Some of the decadal variability in tropical ozone previously attributed to solar variability may instead be related to the occurrence of ENSO events."** [Marsh & Garcia]

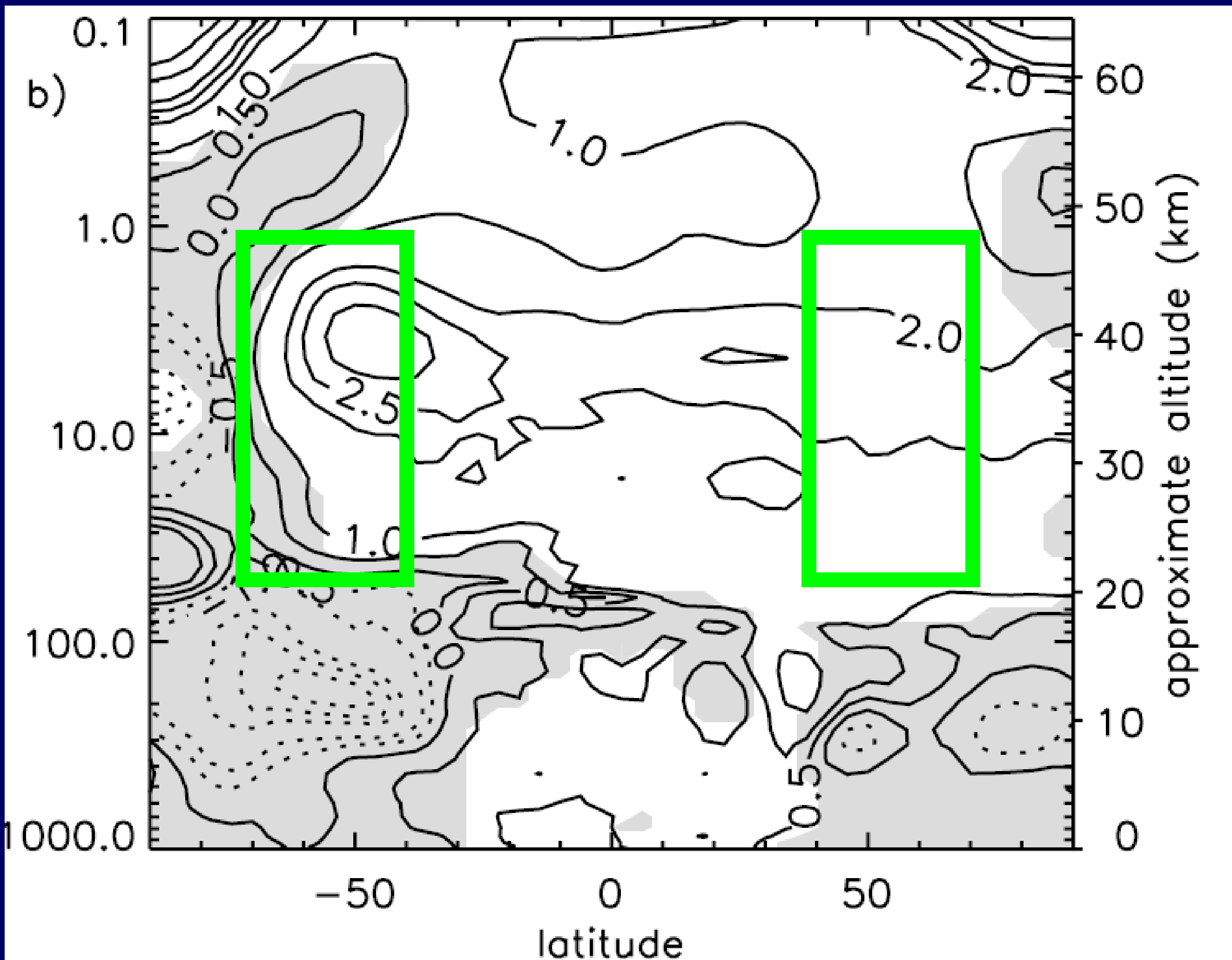
# Solar Cycle Effects in SBUV "Polar" Ozone (40-60 deg)




**Largest changes from solar max to solar min are ~1-4%.**

From Soukharev and Hood, JGR 2006

# Solar Cycle Effects in WACCM "Polar" Ozone




**Largest changes from solar max to solar min are ~1-3% near 40-70 deg N and S**

From Marsh et al., JGR07

# Summary of Solar Cycle Responses in Ozone

**Tropical *upper* stratospheric $O_3$**
**SBUV (SH06): ~3.0%**
**WACCM (MG08): ~2.5%**

**Tropical *lower* stratospheric $O_3$**
**SBUV (SH06): ~4.0%**
**WACCM (MG08): ~2.5%**

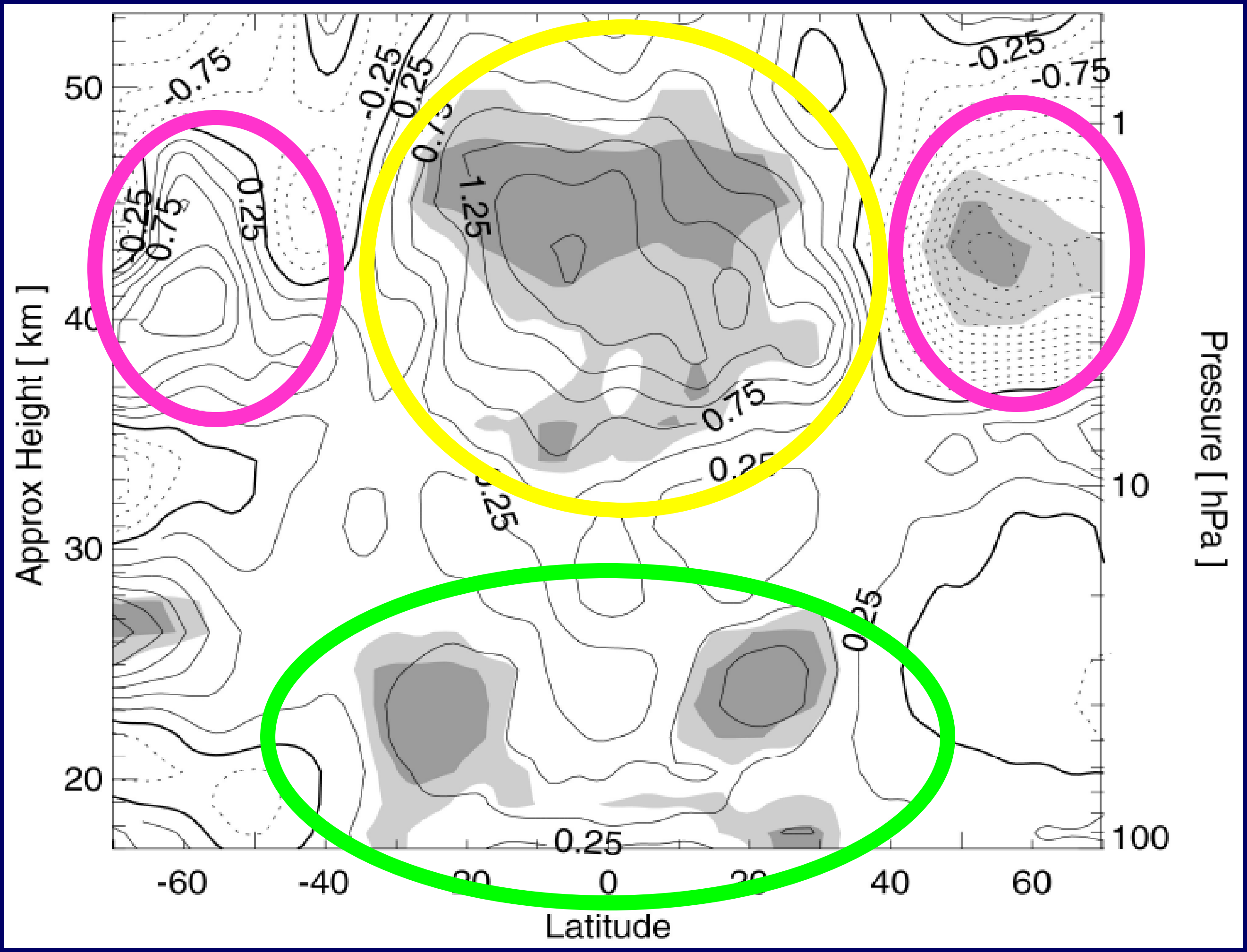
**Polar stratospheric $O_3$**
**SBUV (SH06): ~1.0-4.0%**
**WACCM (M07): ~1.0-3.0%**
[Largest changes above 30 km]

- Models in basic agreement with observations
- Solar cycle variation similar in magnitude to EPP effects in polar region

# How do the EPP effects compare to solar irradiance effects?

## Now look at temperature...

# ERA-40 Temperatures Solar Max vs. Solar Min



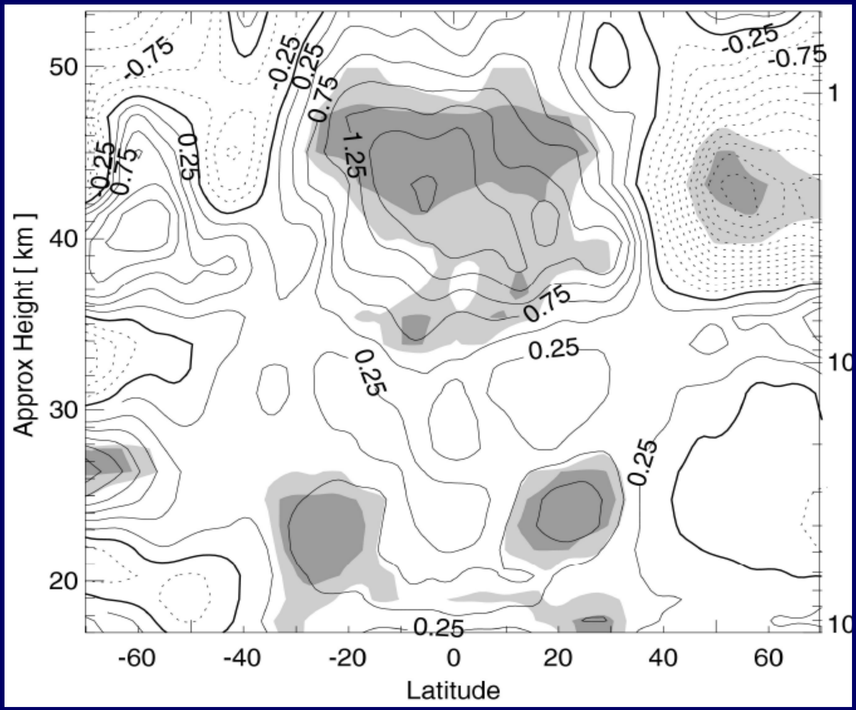

From Gray et al., submitted to JAS 2008.

**Tropical upper strat: ΔT ~0.75-1.5 K**

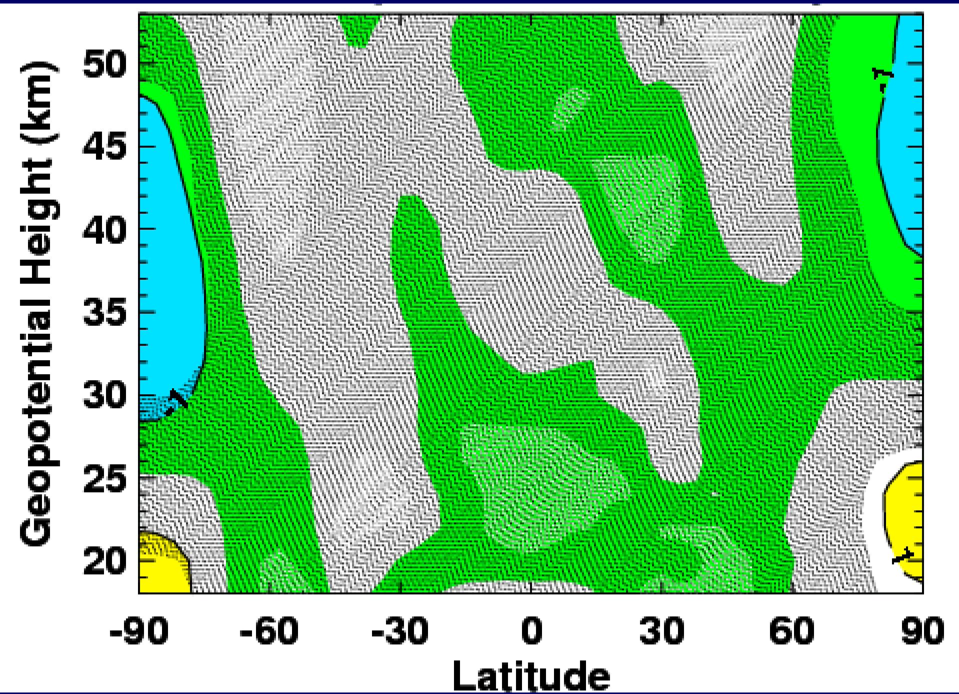
**Tropical lower strat: ΔT ~0.5 K**

**Polar (40-60) upper strat: ΔT>2K (+/-)**

## ERA-40 Temperatures Solar Max vs. Solar Min




## WACCM Annual Avg ΔT, EPP vs. NoEPP




**EPP effect on ΔT similar in magnitude to solar cycle (+/- 1 K), but poleward of ERA-40 analysis**

Cora Randall et al., SPARC 2008

# Conclusions

**Solar Irradiance and EPP variability are of similar relevance to the stratosphere.**

**Both lead to annually averaged ozone changes on the order of several % and temperature changes on the order of 1 K.**

**Largest EPP effects occur in polar regions.**

**Significant EPP effects do not require anomalous geomagnetic activity – meteorology matters.**

**Wave activity influences response of atmosphere to solar variability, so understanding coupling is imperative.**

**EPP must be included in simulations to accurately represent stratospheric variations over a solar cycle.**

# Some Questions

**What are the dynamical mechanisms that link geomagnetic activity to atmospheric change?**

**Does geomagnetic activity affect surface level temperatures?**

**Are coupling mechanisms from the surface to the MLT changing?**

**Is there feedback between EPP and the coupling?**