# Atmospheric Coupling via Energetic Particle Precipitation (EPP)


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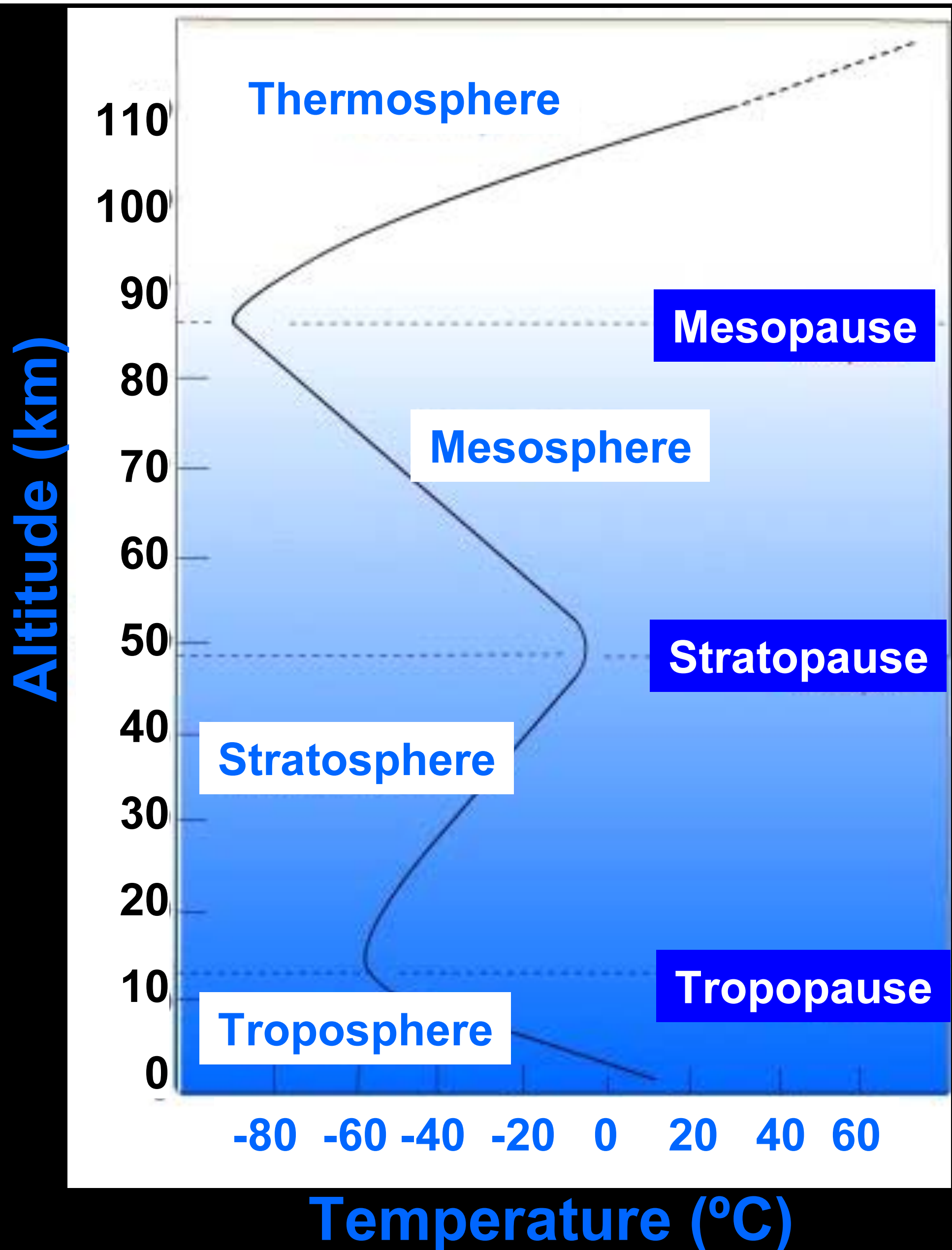



# Vertical Coupling

- Troposphere to thermosphere
- In the polar region
- Mainly in winter

## Outline

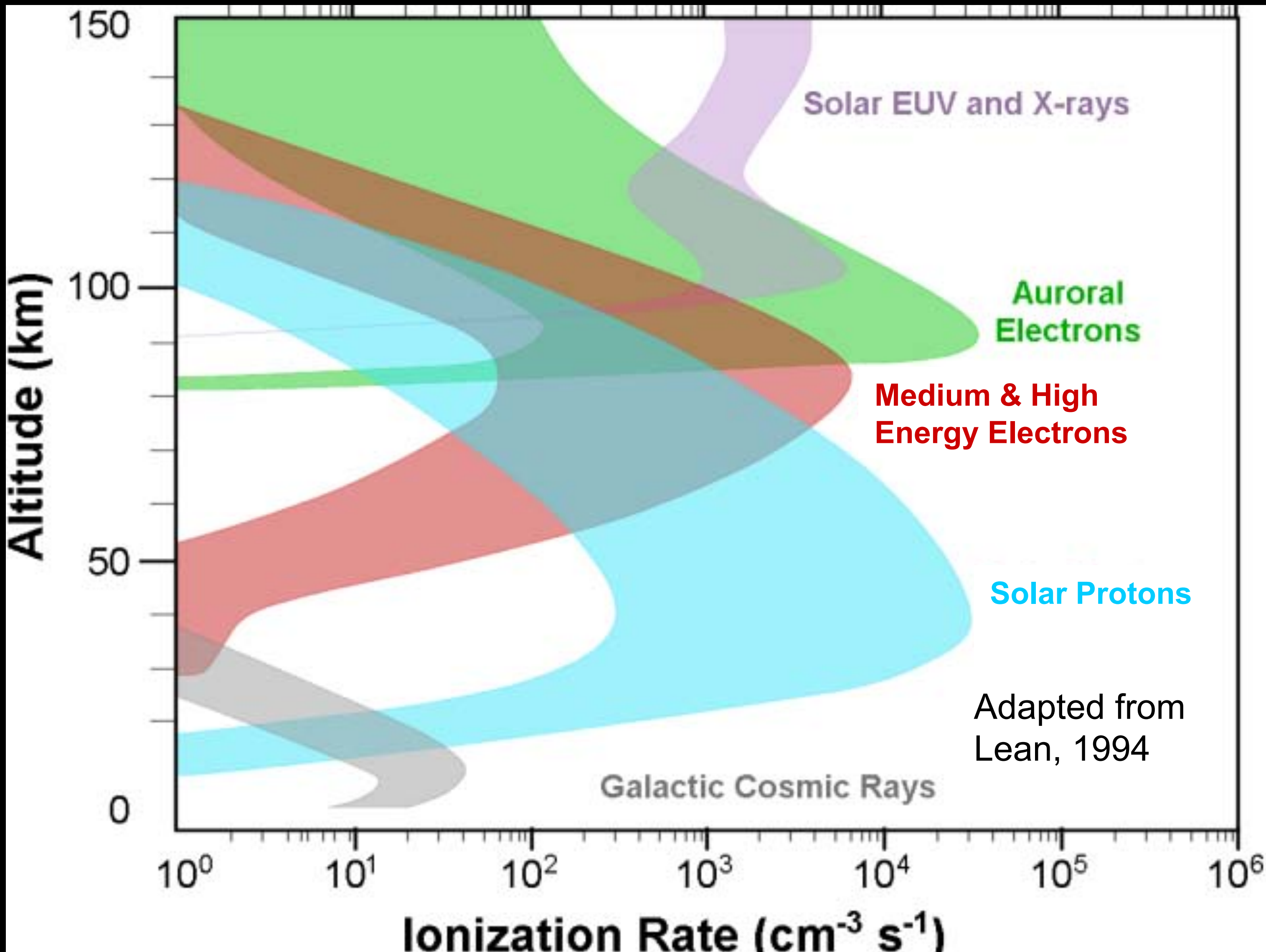
Intro to Mechanism

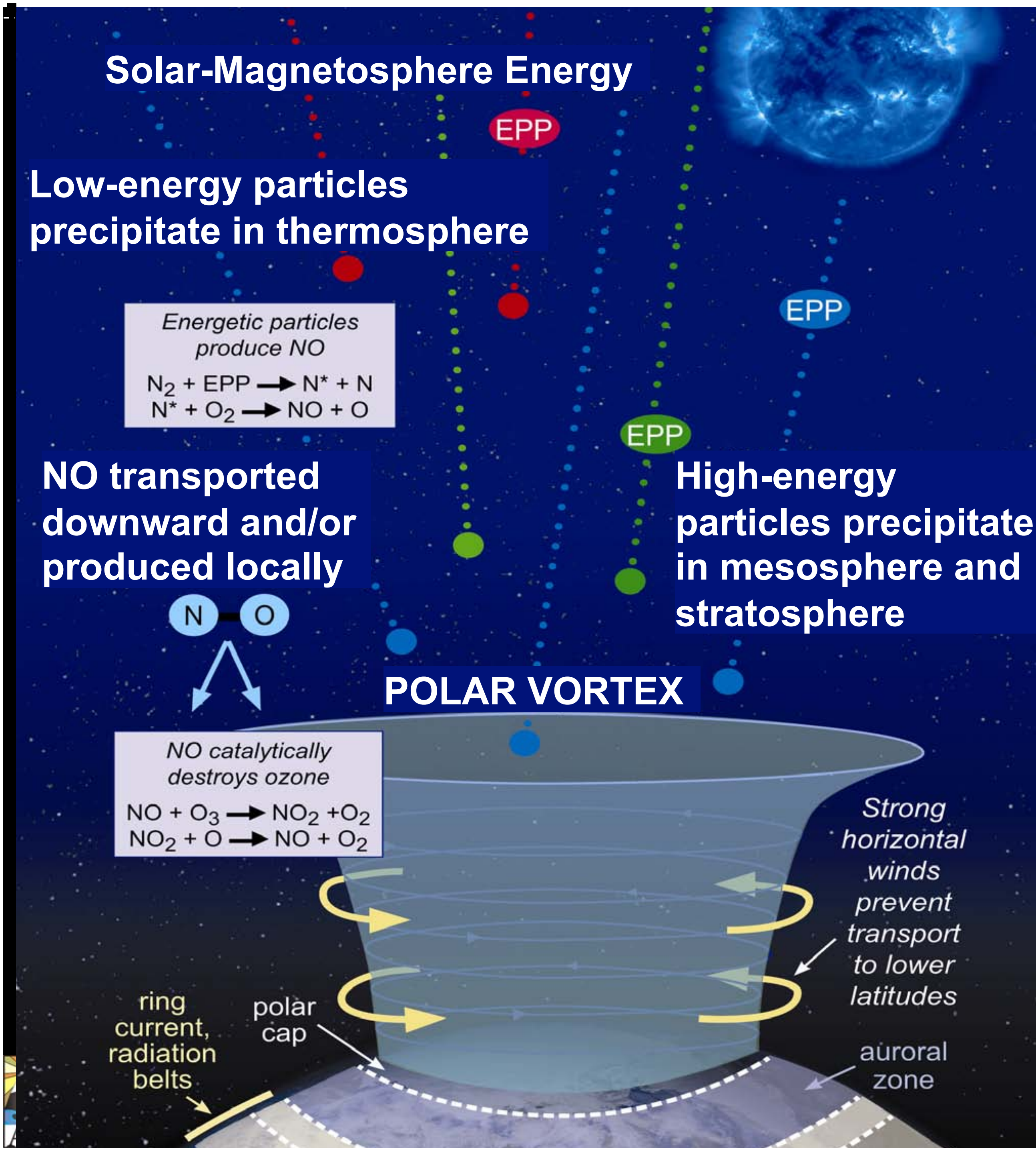
Historical Evidence

Recent Anomalies

Model Results

# Energetic Particle Precipitation






# Energetic Particle Precipitation (EPP)

↓↓↓

**Ionization & Dissociation**

↓↓↓

**$NO_x$ and $HO_x$**

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

2010

# EPP Effects on the Stratosphere

**DIRECT EFFECT (DE):** **$NO_x$ *produced in* stratosphere.**

- **Requires highly energetic particles**

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

- **Sporadic production**

**INDIRECT EFFECT (IE):** **$NO_x$ produced in mesosphere or thermosphere and *descends to* stratosphere**

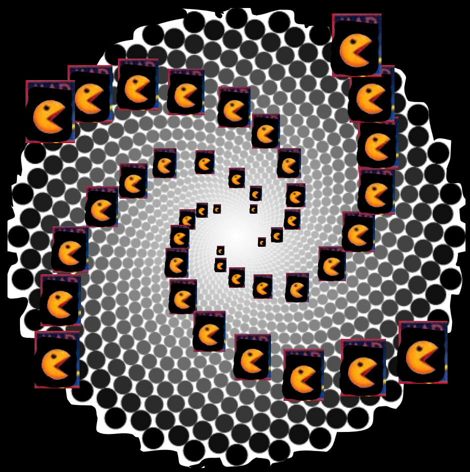
- **Requires only medium or low energy particles**
- **Routine production**

# EPP Indirect Effect

NO produced in mesosphere or thermosphere and *descends to* stratosphere

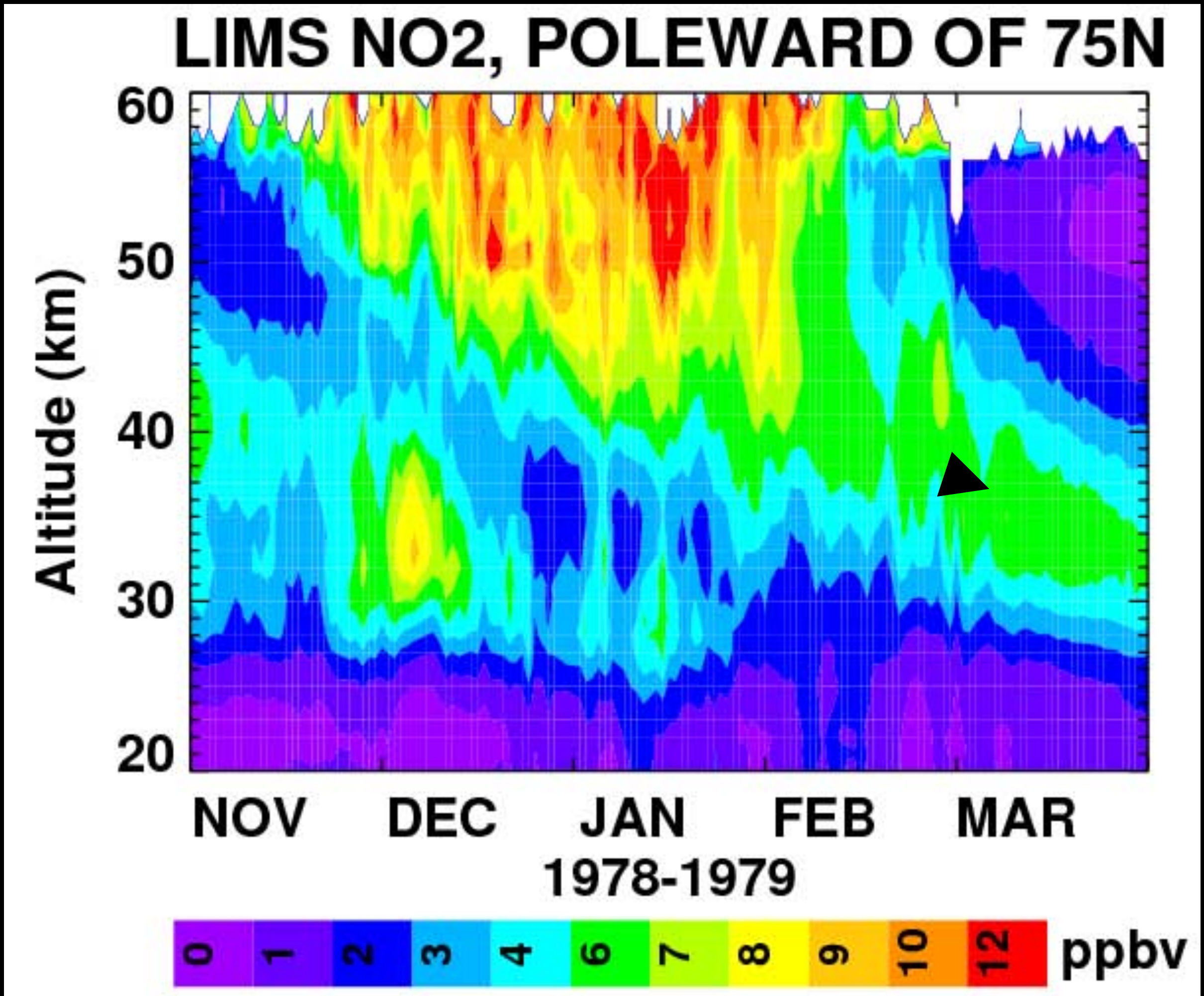
Routine production, but MLT $NO_x$ has lifetime of days, so stratospheric effects require efficient downward transport

- Polar night
- Strong descent in MLT
- Confinement in Polar Vortex



$NO_x$ in stratosphere destroys ozone

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




**EPP is the ONLY source of mesospheric $NO_x$ in the polar winter!**

Based on Russell et al., 1984

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

**EPP Investigations mainly 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 became available**

**e.g., GOMOS, MIPAS, SCIAMACHY, ACE-FTS**
**(Still cannot measure polar night NO in MLT)**

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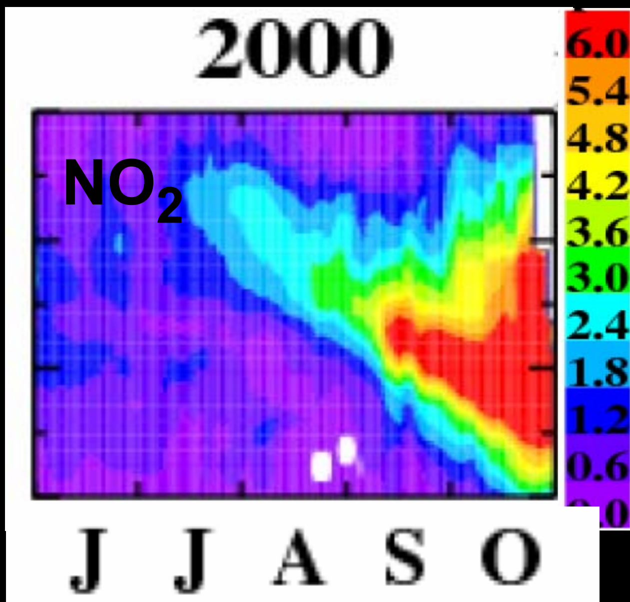
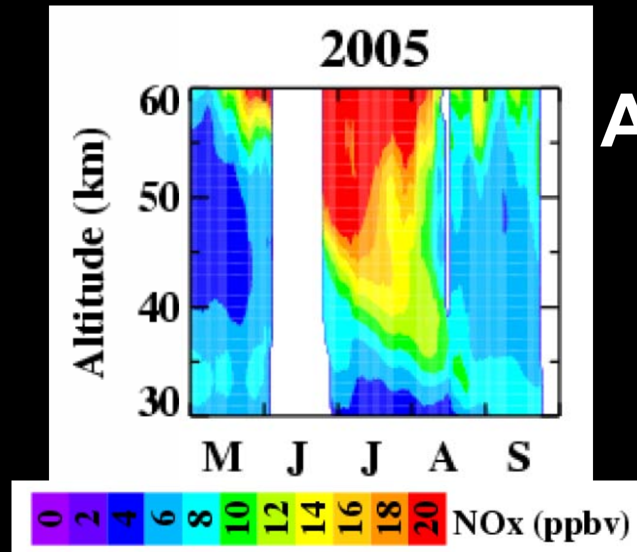
## POAM: SH




Randall et al., 2007

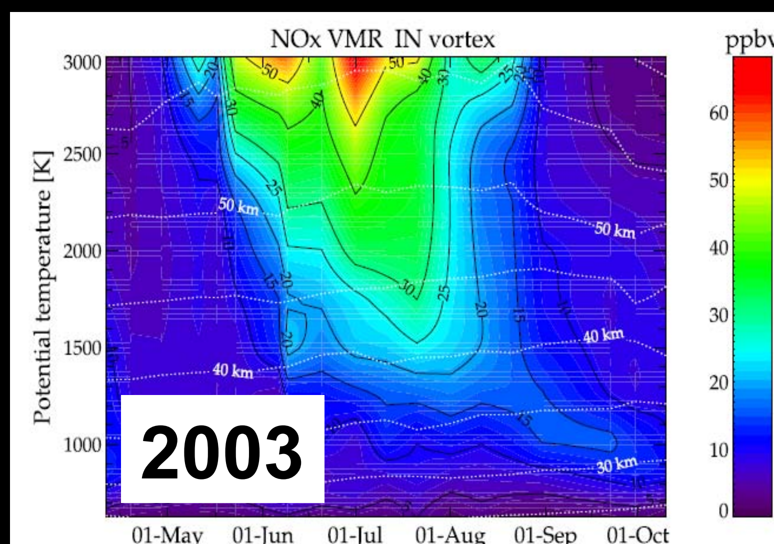
## ACE-FTS: SH



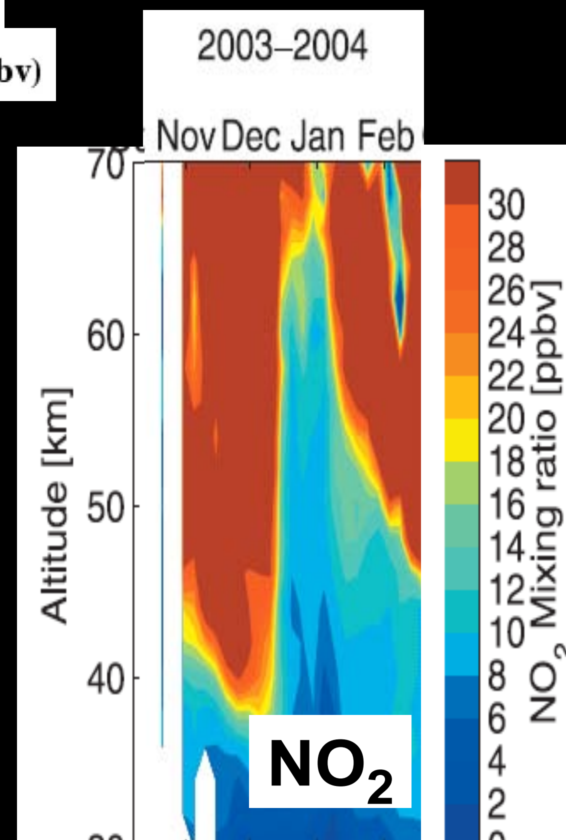

Randall et al., 2007

## MIPAS: SH

Funke et al., 2005



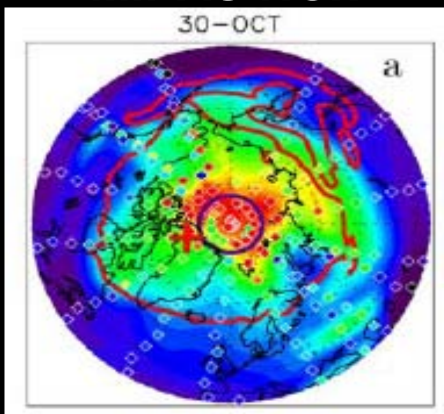

## GOMOS: NH



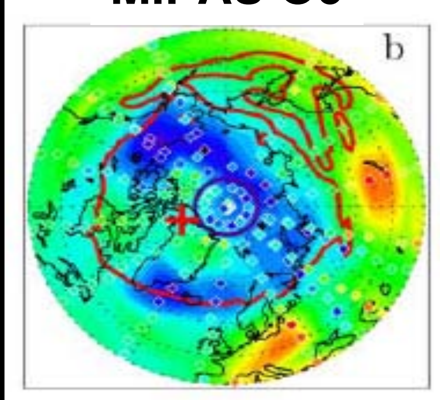

Seppala et al., GRL 2007

# EPP-$NO_x$ enhancements accompanied by ozone reductions

MIPAS NOx

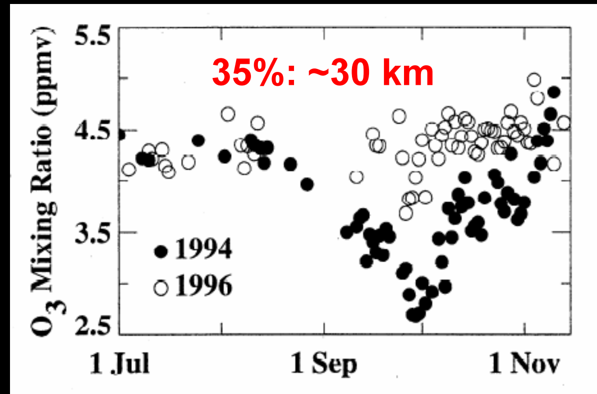



MIPAS O3



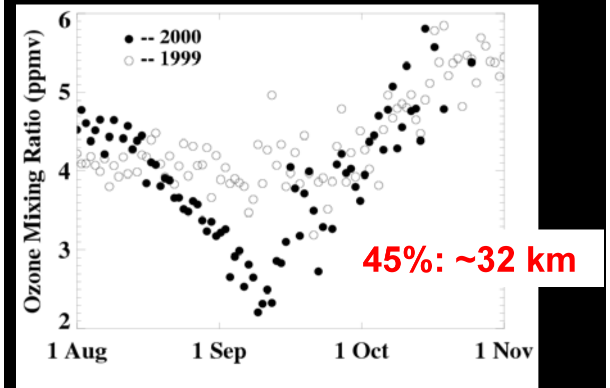

Lopez-Puertas et al., 2005

POAM ozone: 1994 vs. 1996

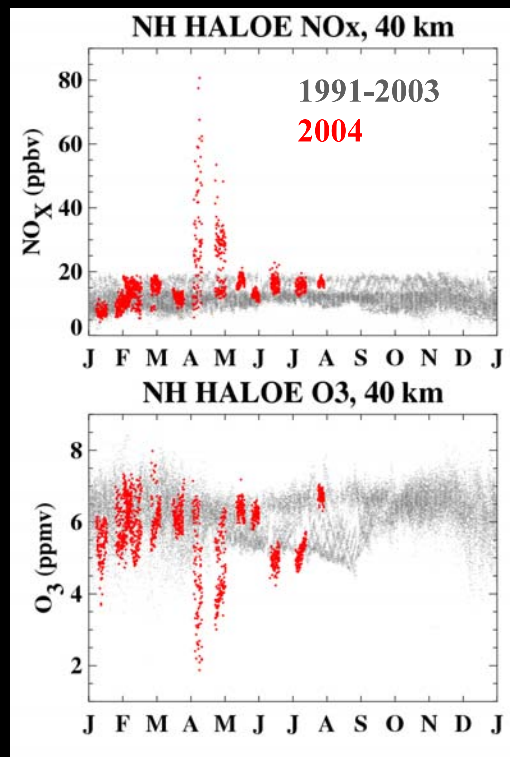



From Randall et al., 1998

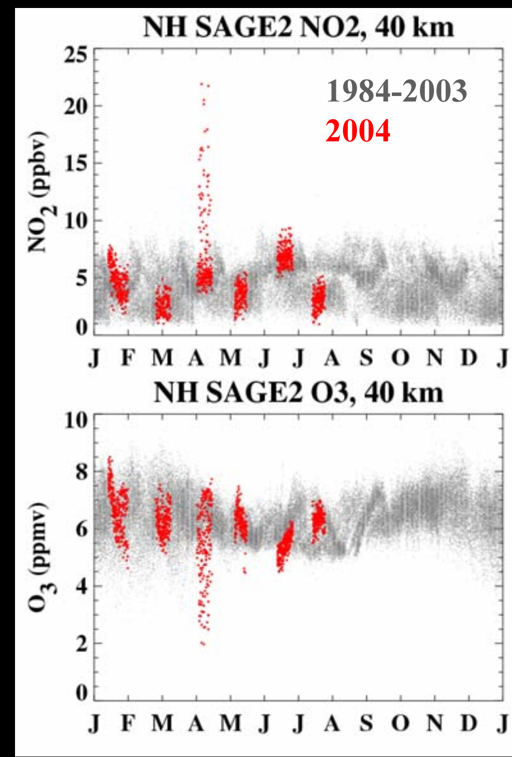
POAM ozone: 1999 vs. 2000




From Randall et al., 2001

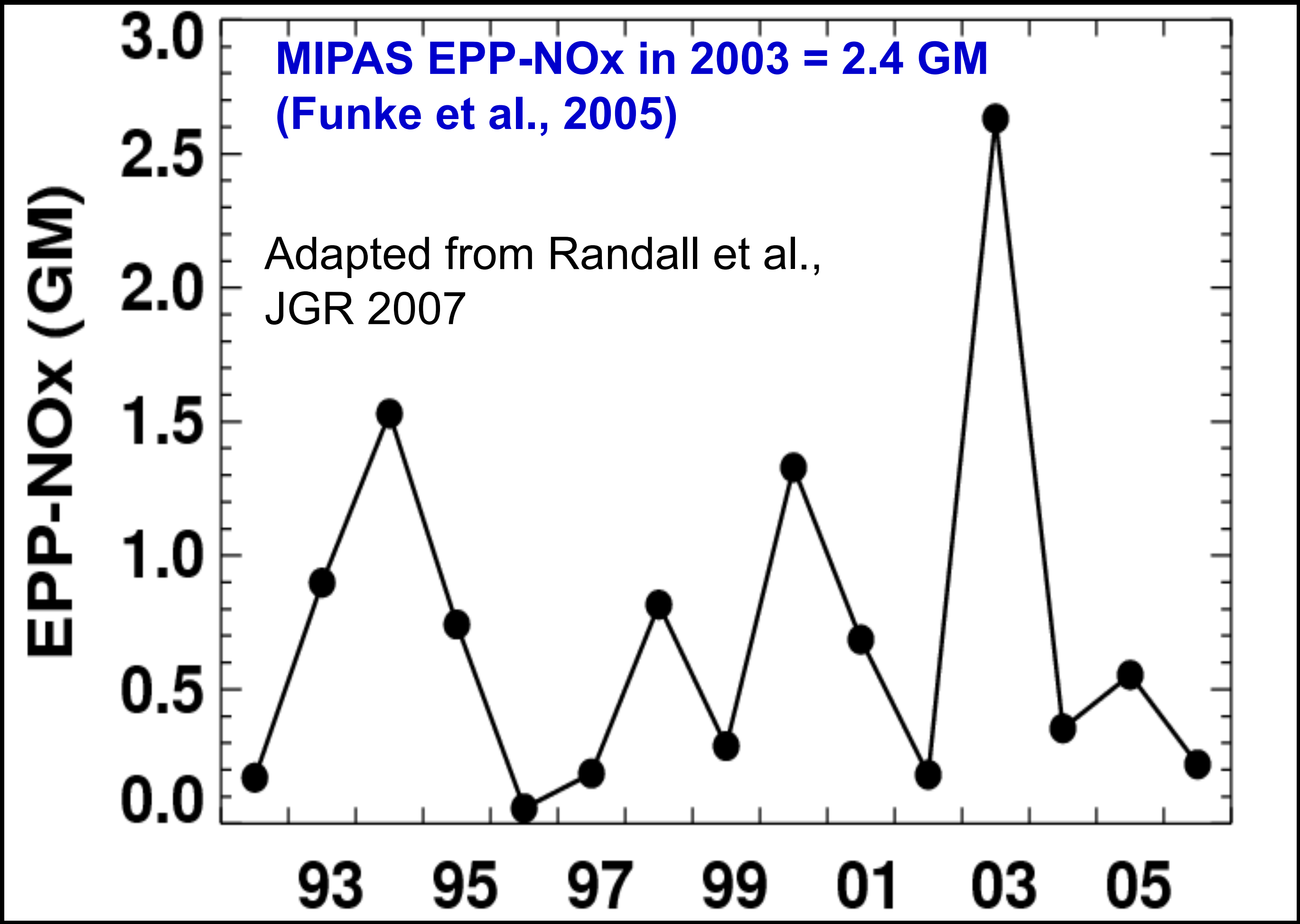



Randall et al., 2005




Randall et al., 2005

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



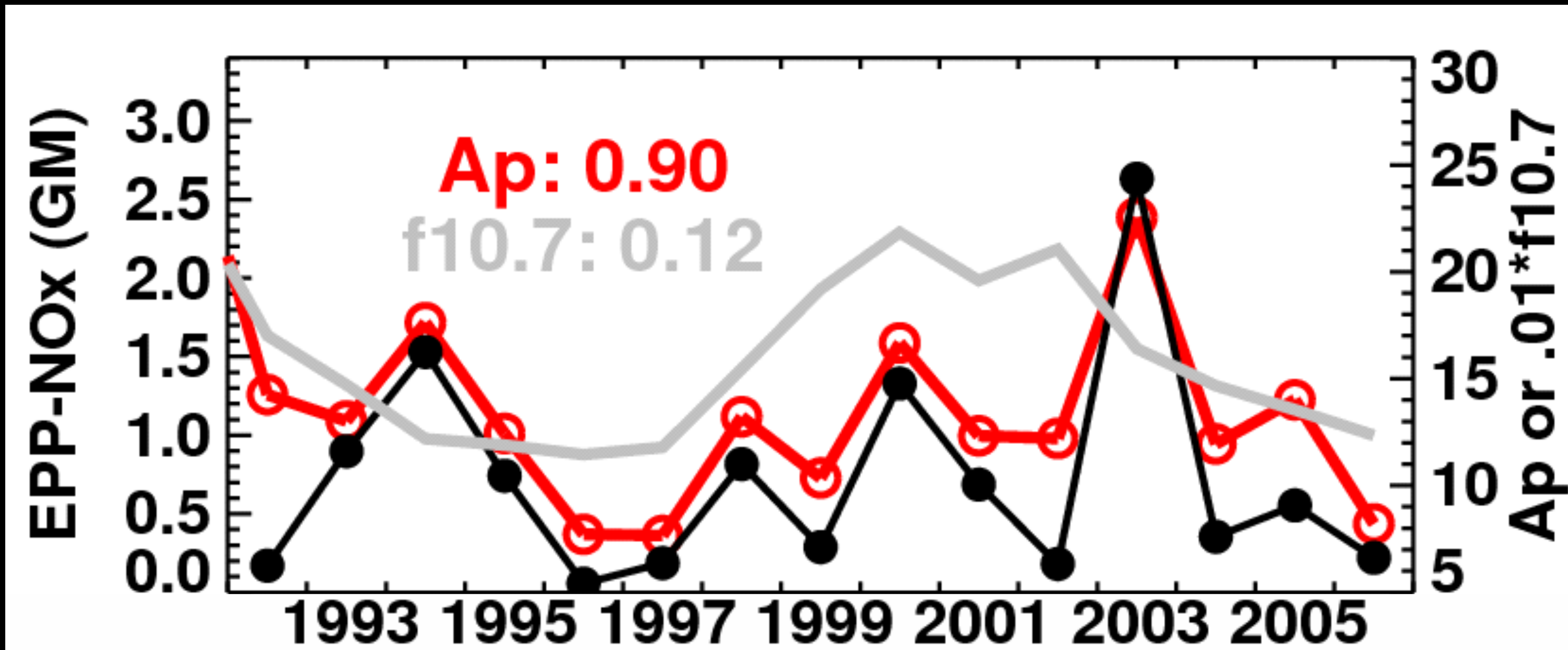

**How significant is this?**

Up to 10% of total SH $NO_y$ (rest from $N_2O$ oxidation)

**Up to 40% of polar $NO_y$**

**What determines the interannual variability?**

# Correlation of EPP $NO_x$ entering the SH stratosphere with Ap and Solar f10.7 (Apr-Aug)

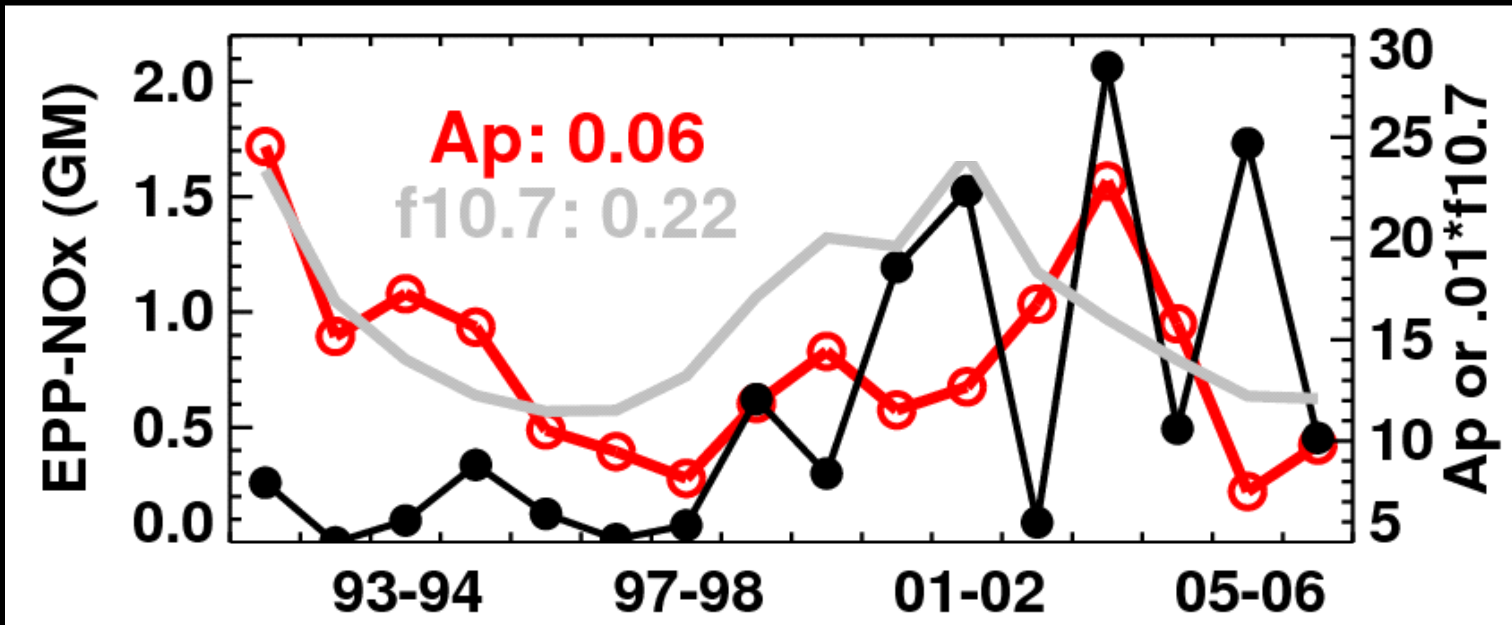



Adapted from Randall et al., JGR 2007

**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: Stable Dynamics!**

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

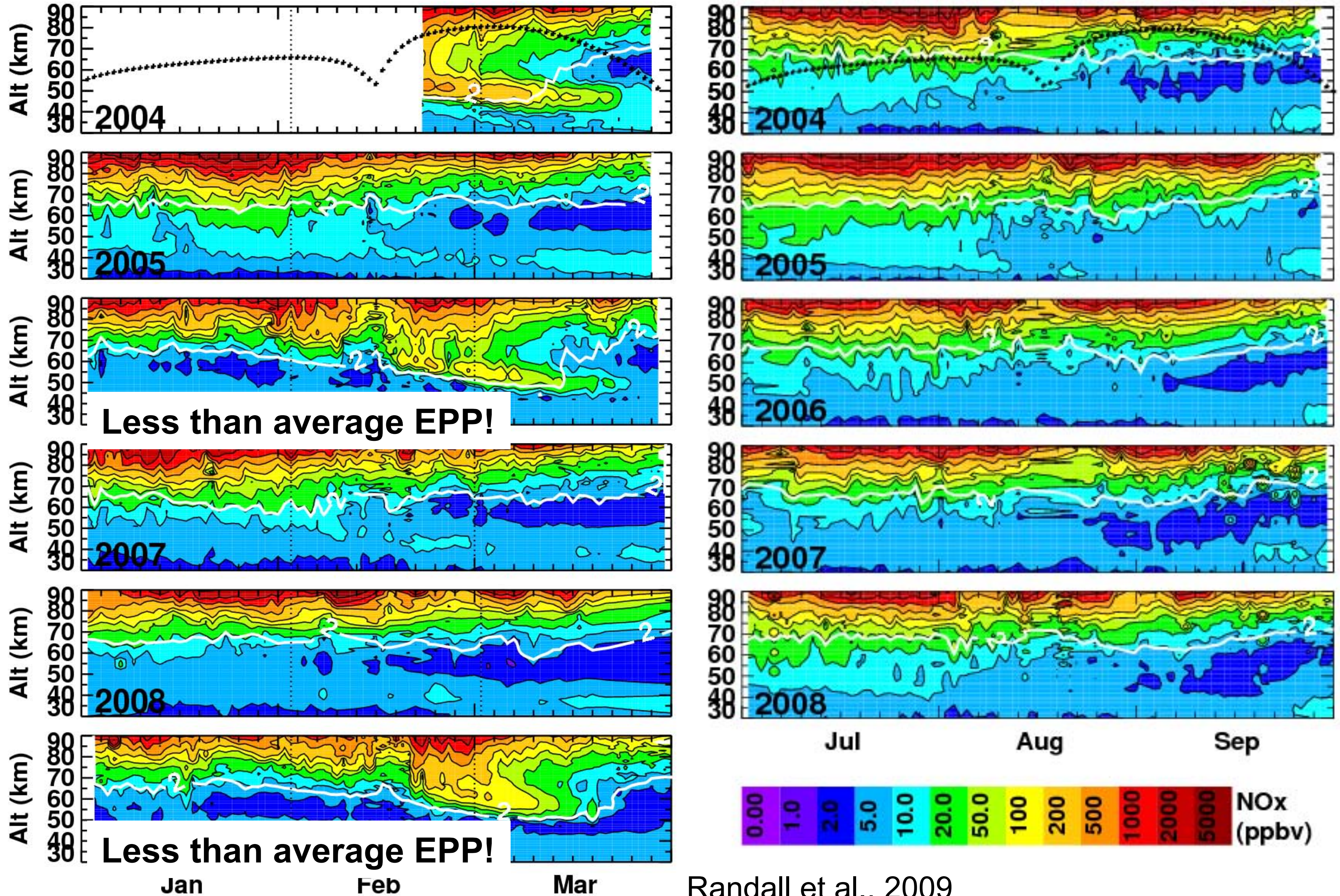



**In NH, correlations with Ap index & F10.7 are poor.**

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

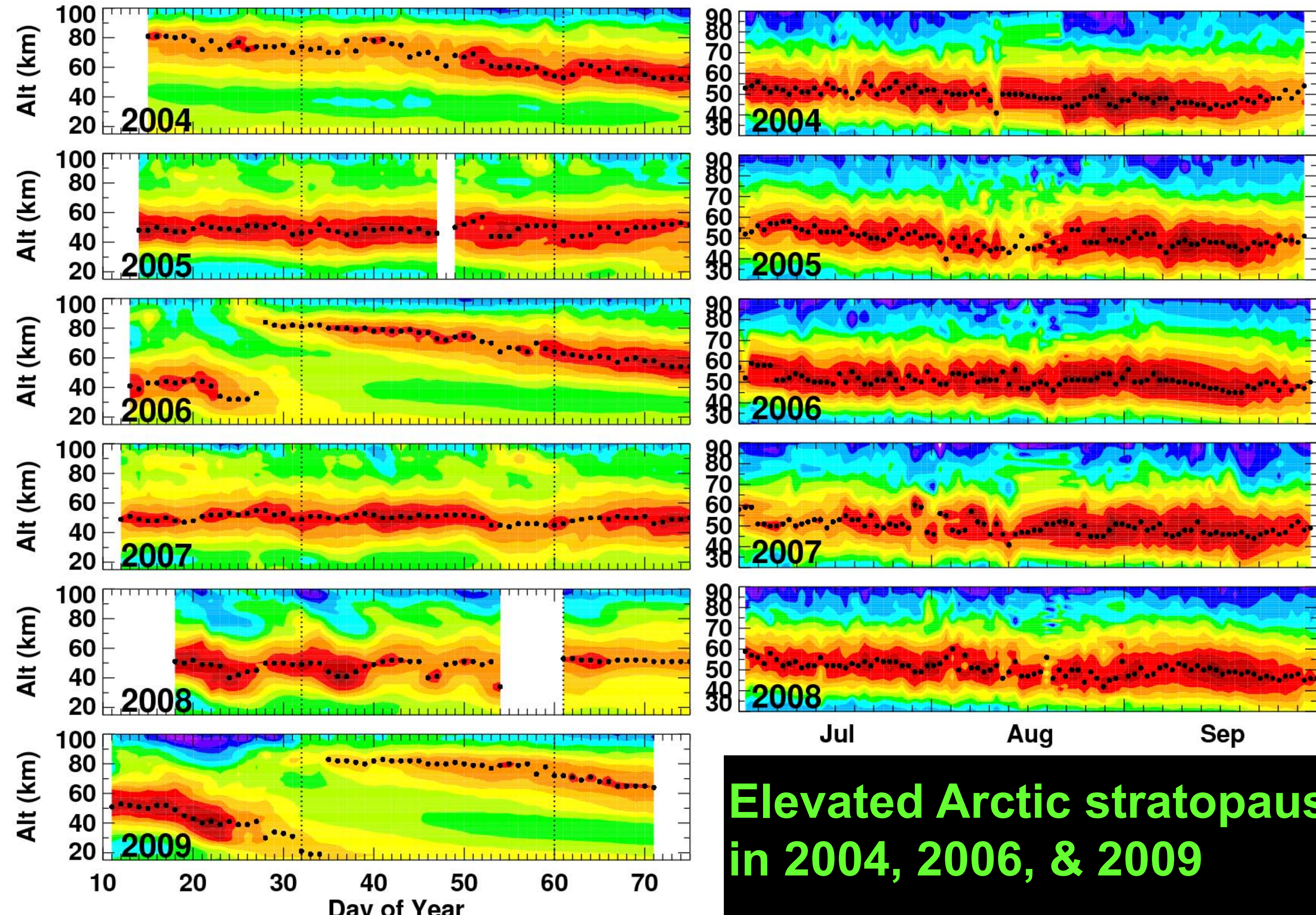
**2001-2002:** SPE **2003-2004:** SPE+Met **2005-2006:** Met

# NORTH ACE $NO_x$ 2004 – 2009 SOUTH




Randall et al., 2009

# NORTH SABER & ACE Polar Temp SOUTH




**Elevated Arctic stratopause in 2004, 2006, & 2009**

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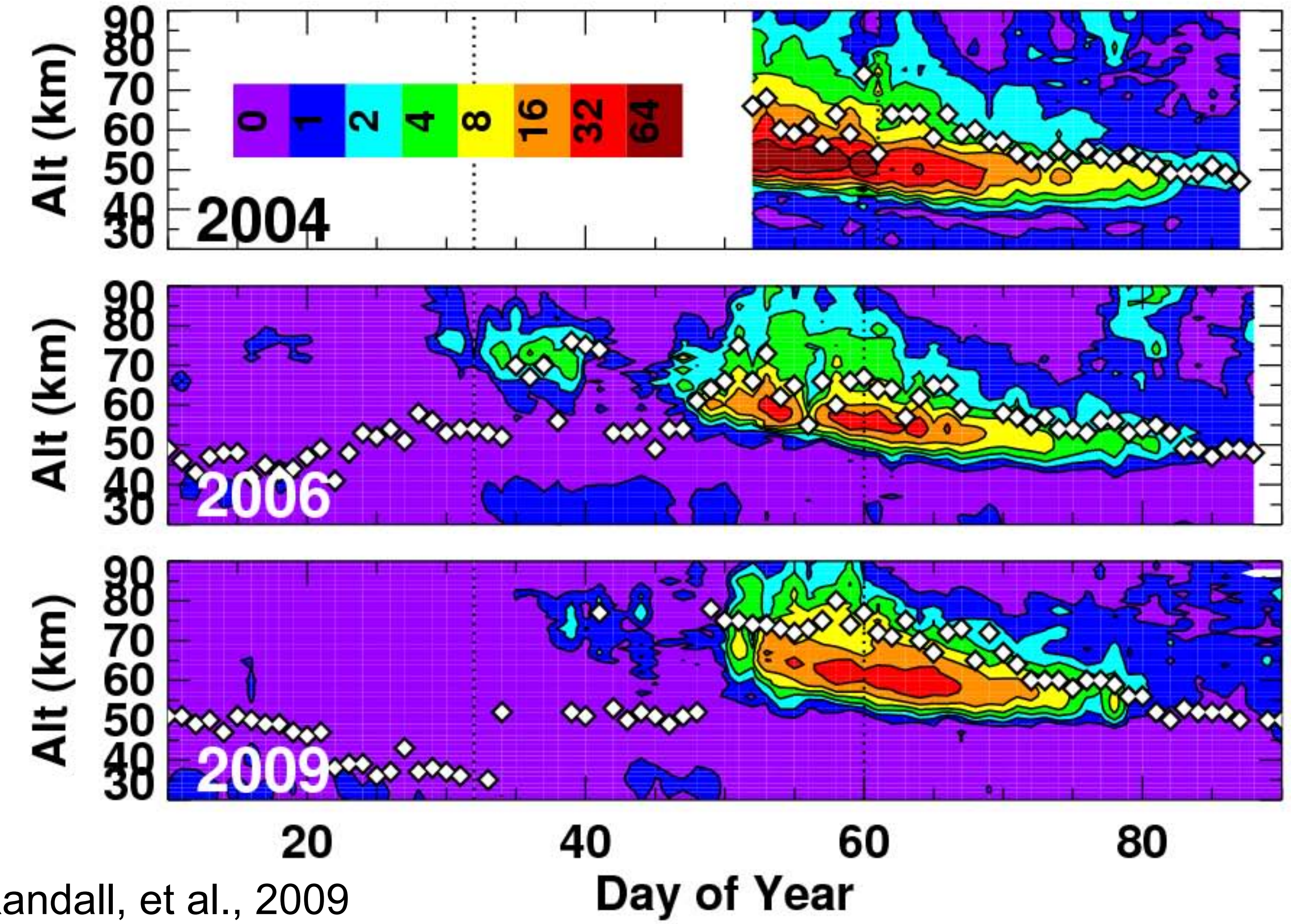
Slightly different temperature color scales; range from ~170K-270K (blue-red).

# Ratio of observed $NO_x$ in 2004, 2006, & 2009 to average $NO_x$ in 2005, 2007, & 2008




Randall, et al., 2009

**$NO_x$ enhancements coincide with elevated stratopause**

Elevated stratopause indicative of enhanced descent in (normal) mesosphere region (adiabatic compression).

Enhanced descent brings down more EPP-$NO_x$.

More efficient transport leads to large stratospheric EPP IE even when EPP itself is well below average.

What is the mechanism?

Begins with extraordinary sudden stratospheric warming (strong and persistent; Manney et al., 2005; 2008; 2009)

**1.** **Stratospheric Warming: Equator-to-pole T gradient reverses → Zonal wind reverses direction**

**2.** **Planetary waves cannot propagate upward so upper stratosphere & lower mesosphere cool**

**3.** **Causes reformation of very strong upper vortex and westerly winds**

**4.** **Gravity waves with westward phase speed preferentially propagate to the mesosphere**

**5.** **Mesospheric westerly zonal wind slows → induces poleward meridional wind to balance pressure gradient & Coriolis**

**6.** **Leads to enhanced descent in the polar mesosphere**

- **Brings down more $NO_x$**
- **Adiabatic compression results in elevated stratopause**

[Hauchecorne et al., 2007; Siskind et al., 2007; Sahishkumar & Sridharan, 2009; Winick et al., 2009]

**Why did we get such impressive stratospheric warmings and recovery in 2004, 2006, & 2009 ?**
**We don’t know.**

**Maybe climate change, but still speculative**

- Although 2004, 2006, and 2009 were highly unusual, the frequency of SSW seems to be increasing (~1 per year since 1999, twice as frequent as in previous half-century)

- Models predict more variability with climate change, so extremes might occur more often

- Models inconclusive with regard to frequency & strength of SSWs

# The EPP IE 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-$NO_x$ to the stratosphere does not correlate well with the solar (F10.7) cycle.

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

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

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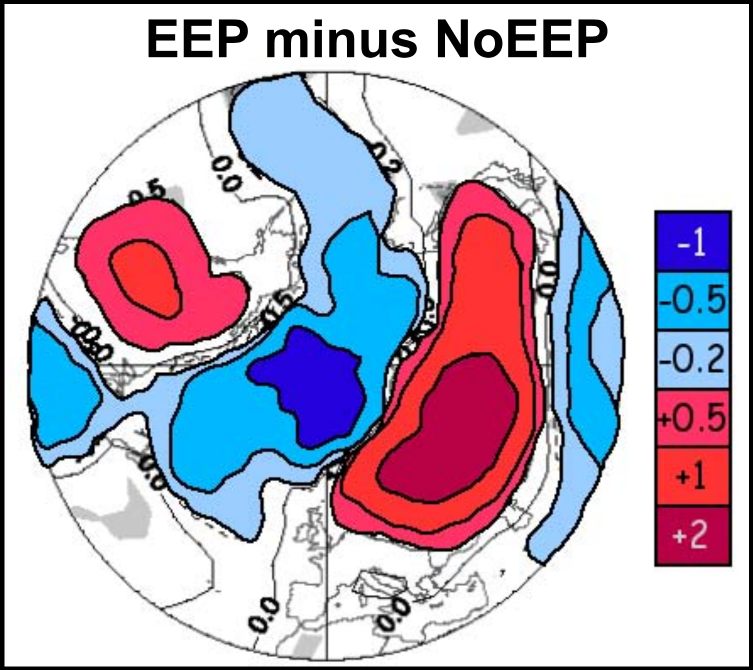
# Aside #1

## Does EPP affect surface air temperature?

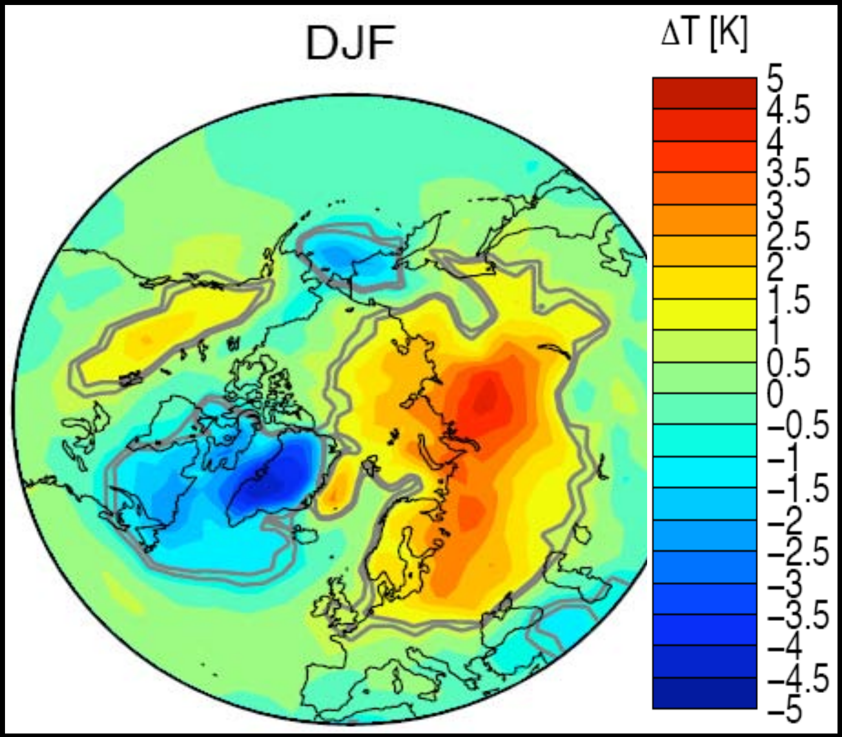
**CCM MODEL**

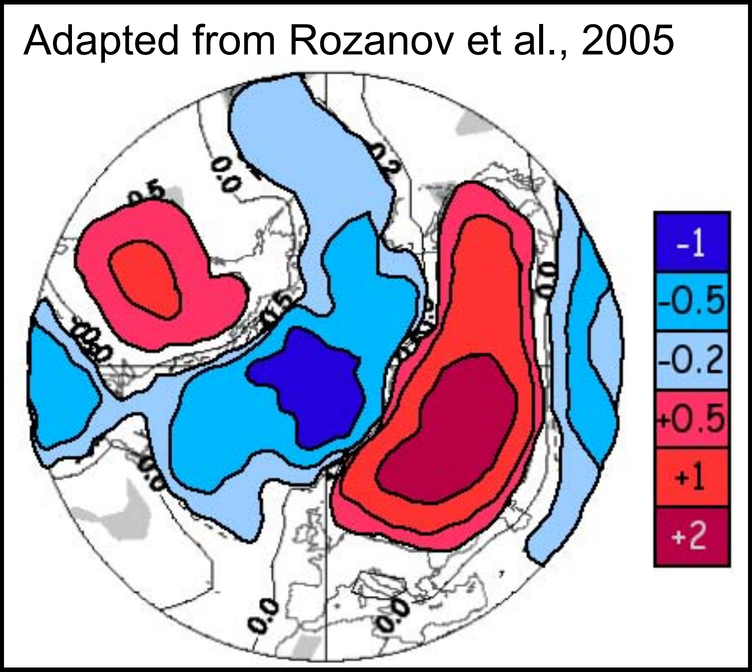



From Annika Seppälä, FMI

**Rozanov et al., 2005. Model results for DJF surface air temperature differences (NH).**

# Is there empirical evidence that EPP-$NO_x$ affects climate?



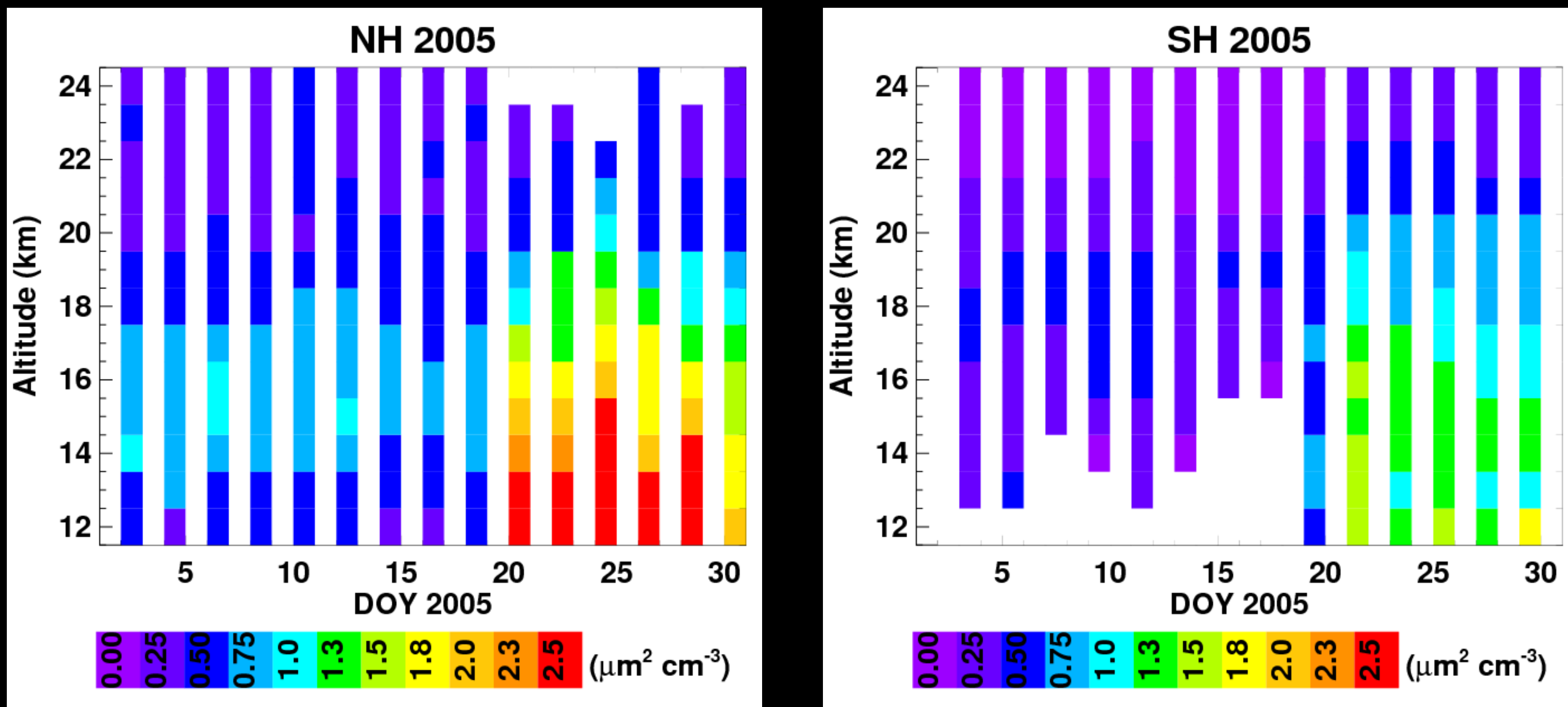




**Seppälä et al., JGR 2009:**

- **Analysis of ERA-40 temperatures yields statistically significant surface air temperature differences between years with high and low EPP.**
- **Can rule out correlation with solar flux, QBO, ENSO, SAM**
- **Possible correlation with NAM or random variations in SST**

# Aside #2

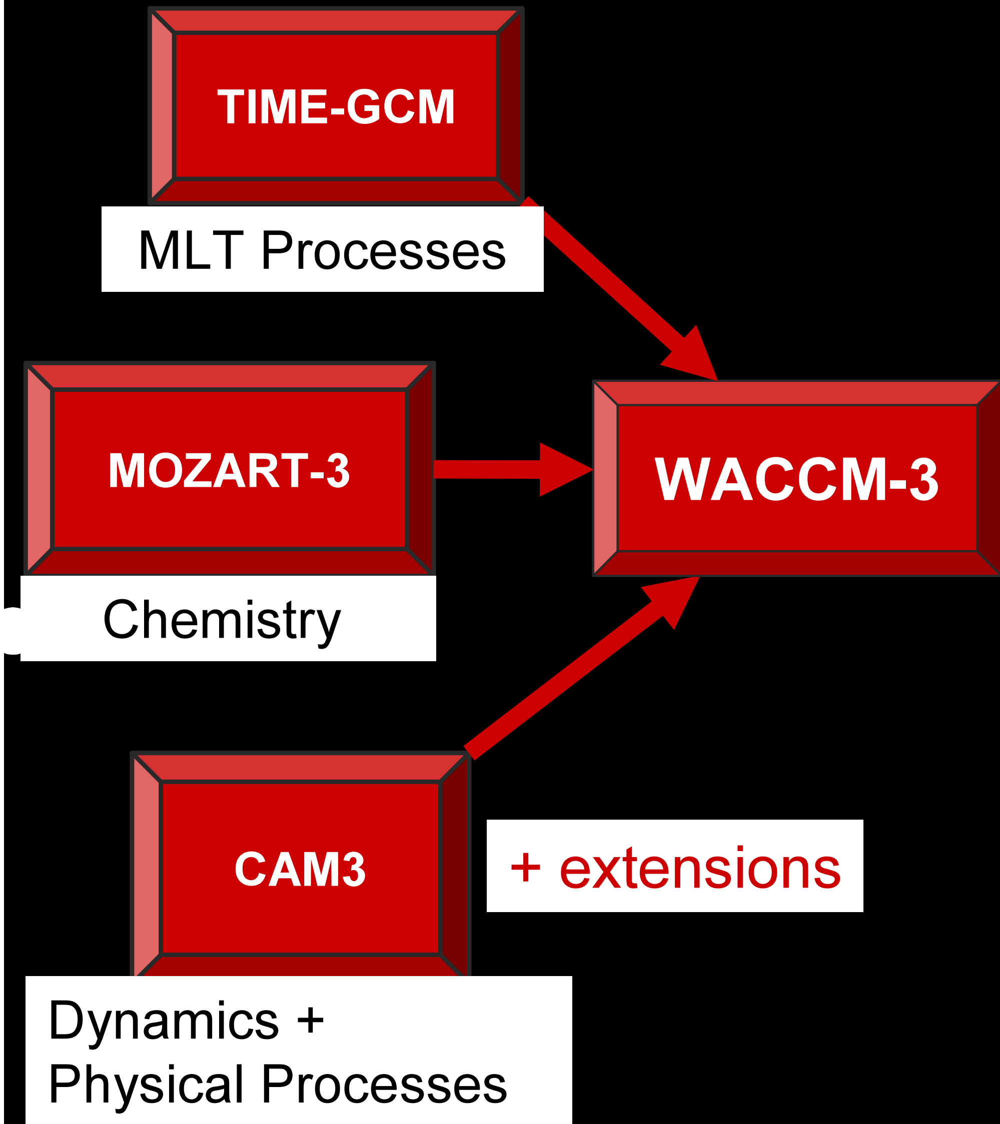
## What about EPP effects on clouds/aerosols?




**POAM III aerosol surface area increased significantly (>2σ) after January 2005 SEPs.**

- **Dynamical cause ruled out.**
- **No other such increase in 8-year record.**
- **No information from POAM at lower altitudes**

Mirinova et al., in preparation

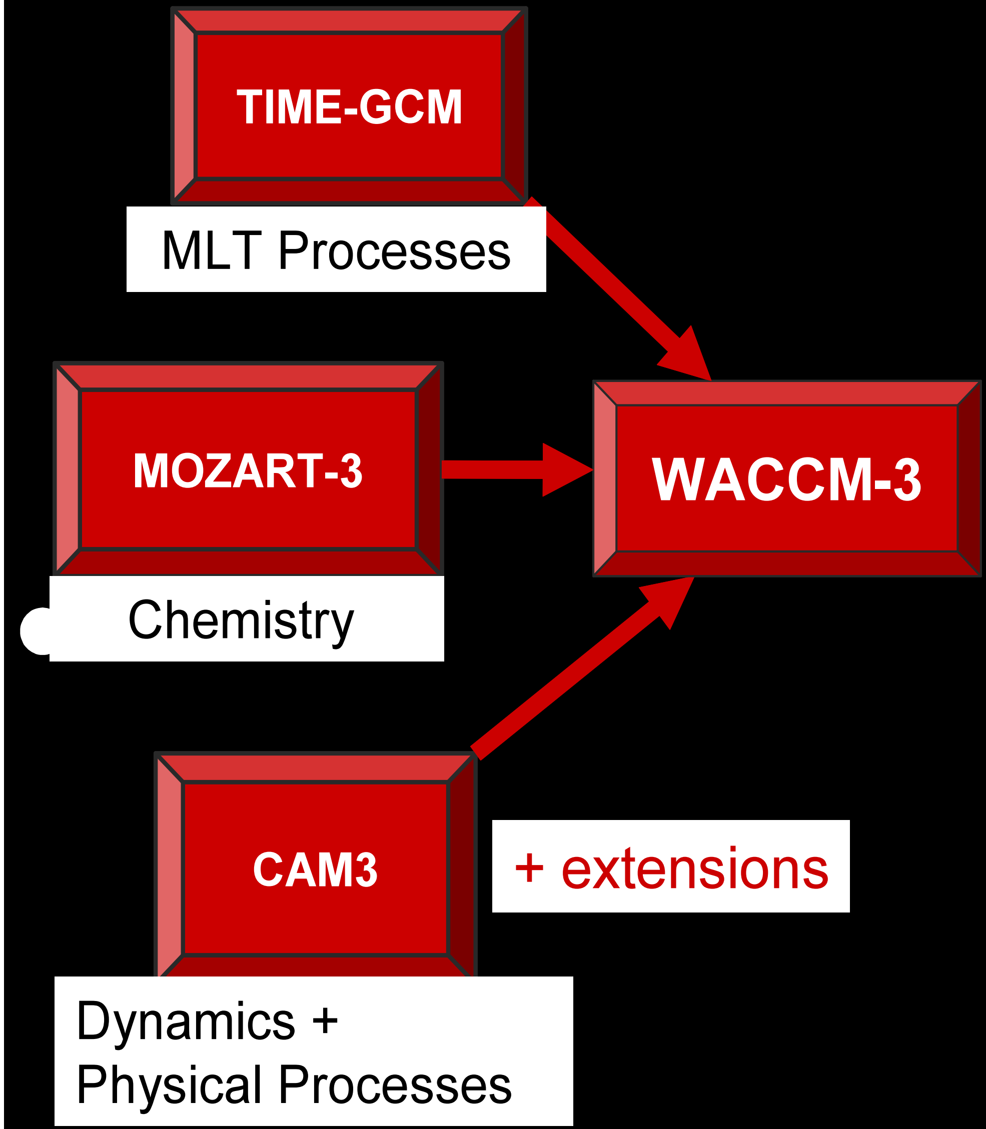



## Whole Atmosphere Community Climate Model

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)




(Adapted from Rolando Garcia)

# WACCM Parameterization of Precipitation Effects

## Aurora

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

## Medium Energy Electrons

(30 keV – 2.5 MeV)

- Input = MEPED activity level (or hemispheric power)
- Distribution = Statistical patterns [Codrescu et al., JGR, 1997)
- Fang et al., 2008

## WACCM Runs (free-running coupled climate-chemistry model):

- Seasonally varying (but annually invariant) SSTs
- Constant F10.7 = 210
- 1995 greenhouse gas and halogen concentrations

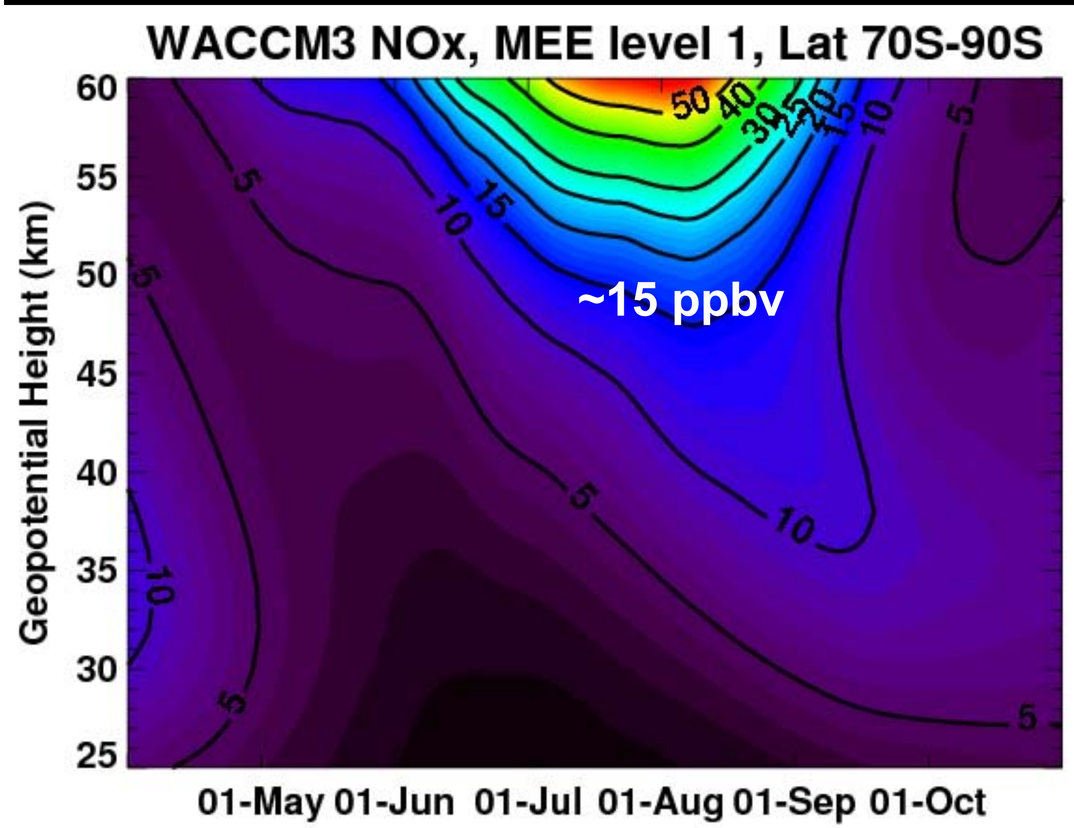
**Daily (repetitive) forcing with 3 cases of EPP:**

**Case 1:** ~Zero particle precipitation, Kp=2/3 (Ap=3)
80 years (after spin-up) = 80-member ensemble

**Case 2:** Moderate auroral electrons, Kp=4 (Ap=27)
50 years (after spin-up) = 50-member ensemble

**Case 3:** Moderate auroral electrons plus >30 keV electrons (level 1; occurs 40% of the time)
50 years (after spin-up) = 50-member ensemble

# WACCM simulation similar to MIPAS




- 70-90º S Latitude
- Case 3

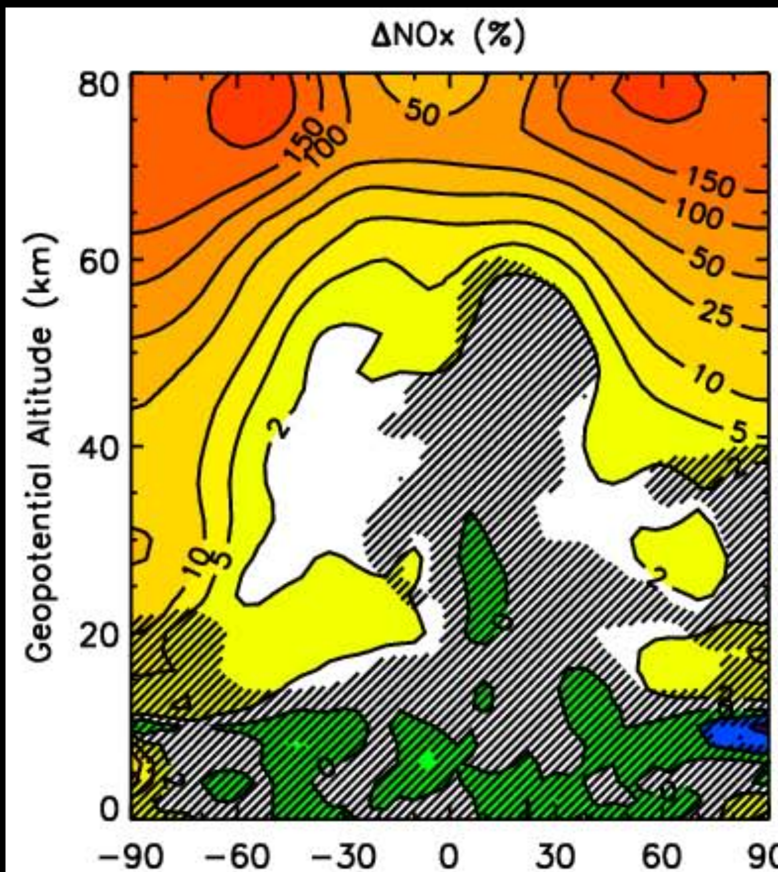
(realistic simulation of 2003 geomagnetic activity)

50 km
50 km
40 km
40 km
30 km
30 km

But WACCM underestimates EPP-$NO_x$ by about a factor of 2.

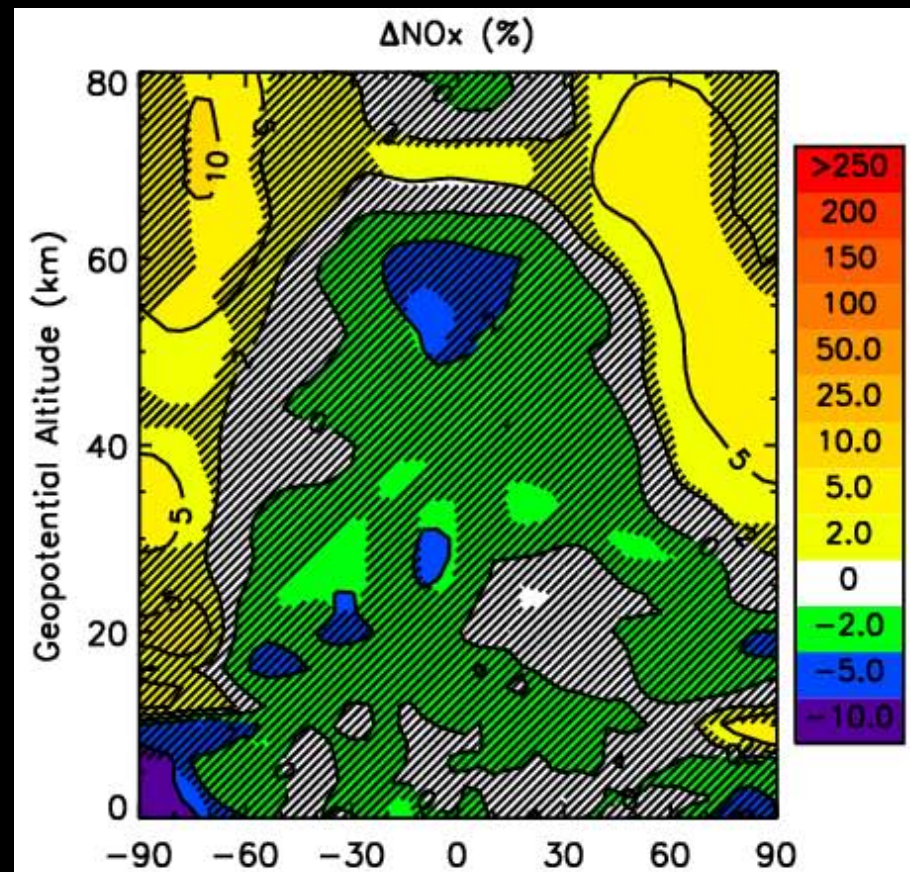
# Change in $NO_x$ due to EPP: Annual Averages

## Aurora Effect
## Case 2 minus Case 1




Latitude

## MEE Effect
## Case 3 minus Case 2



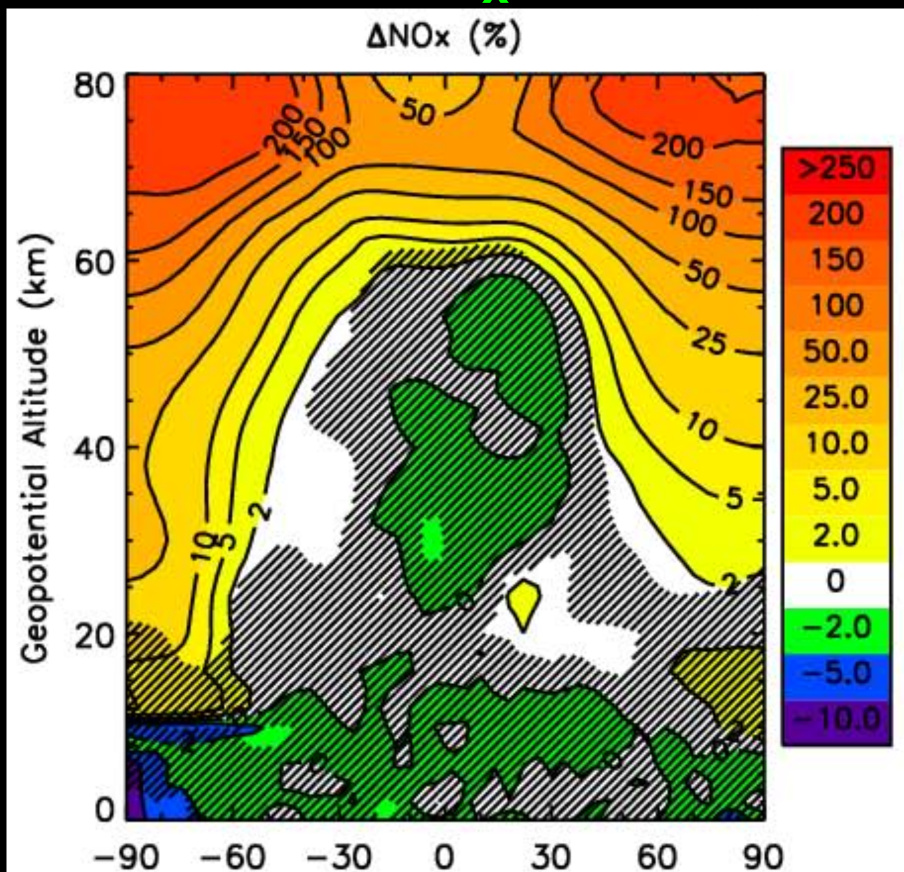

Latitude

Regions without cross-hatching significant at 95% level

# Change in $NO_x$ and $O_3$ due to EPP

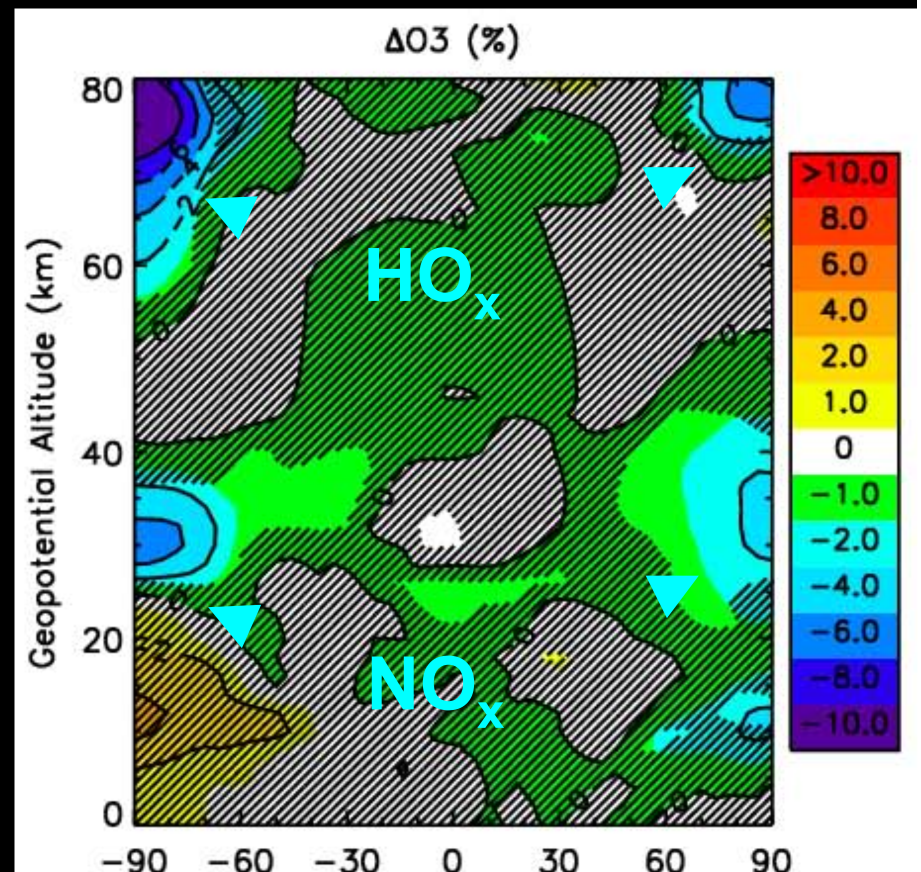
## Annual Averages: Aurora + MEE (Case 3 minus Case 1)

### $NO_x$




Latitude

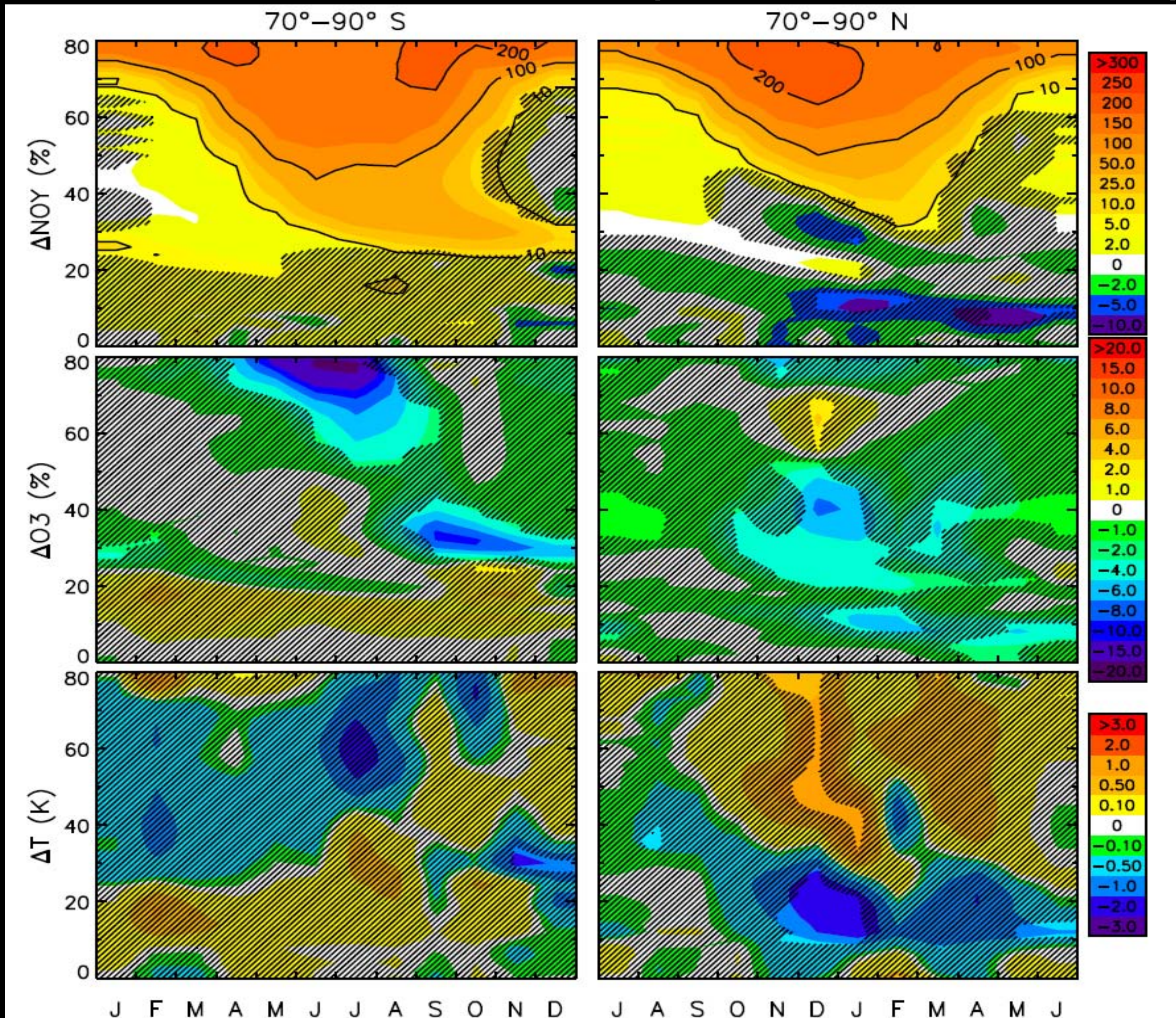
### Ozone



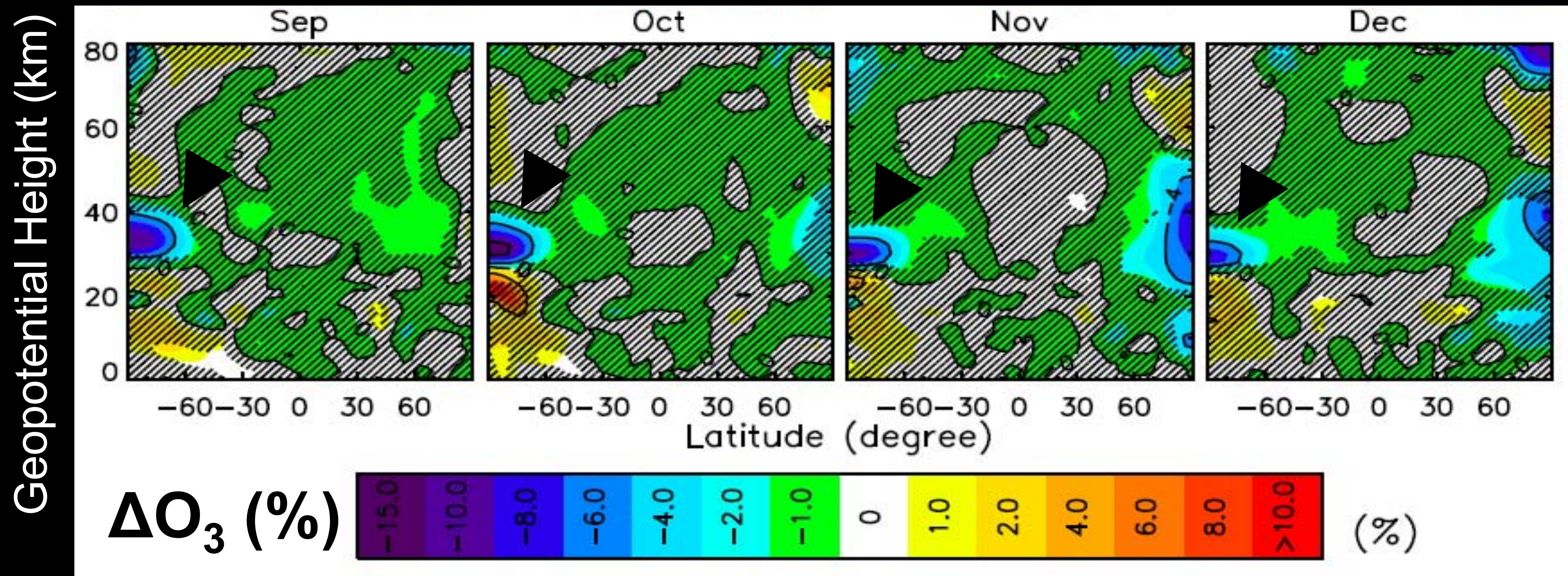

Latitude

Regions without cross-hatching significant at 95% level

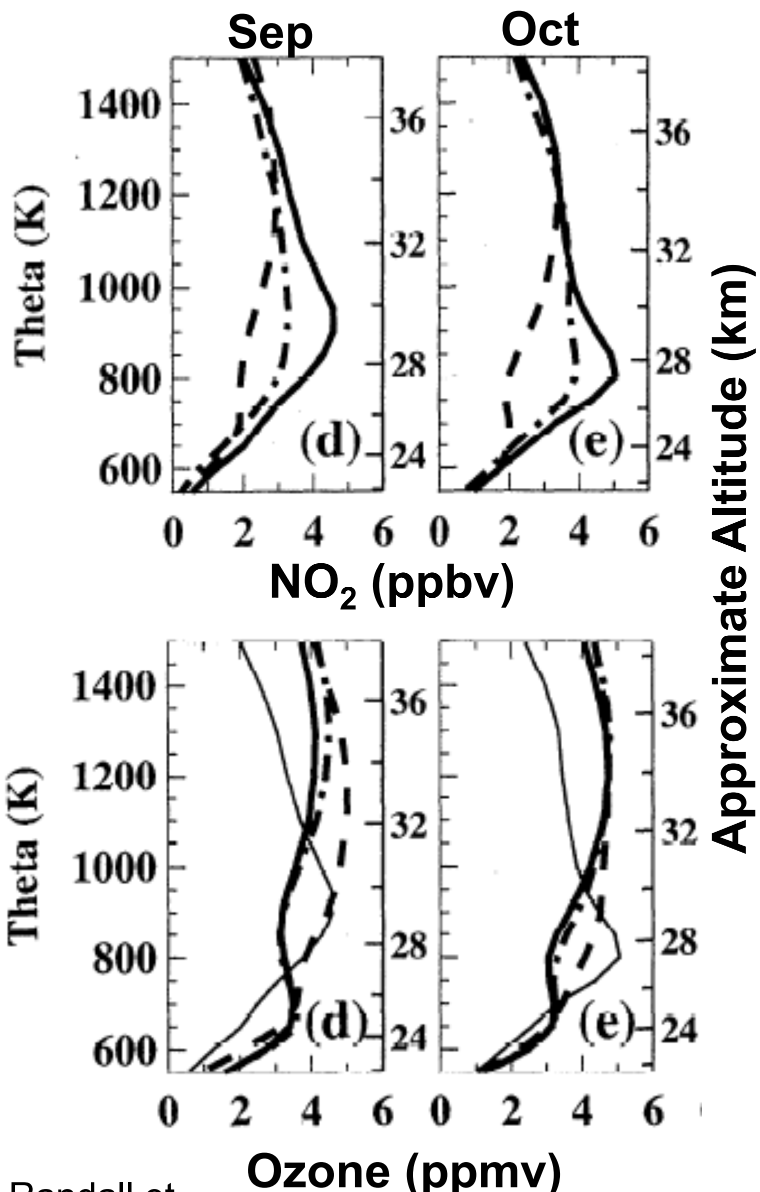
# Auroral Effect Time Series (Case 2 minus Case 1)



# Monthly average ozone depletion of up to 15% at high southern latitudes, 30-40 km

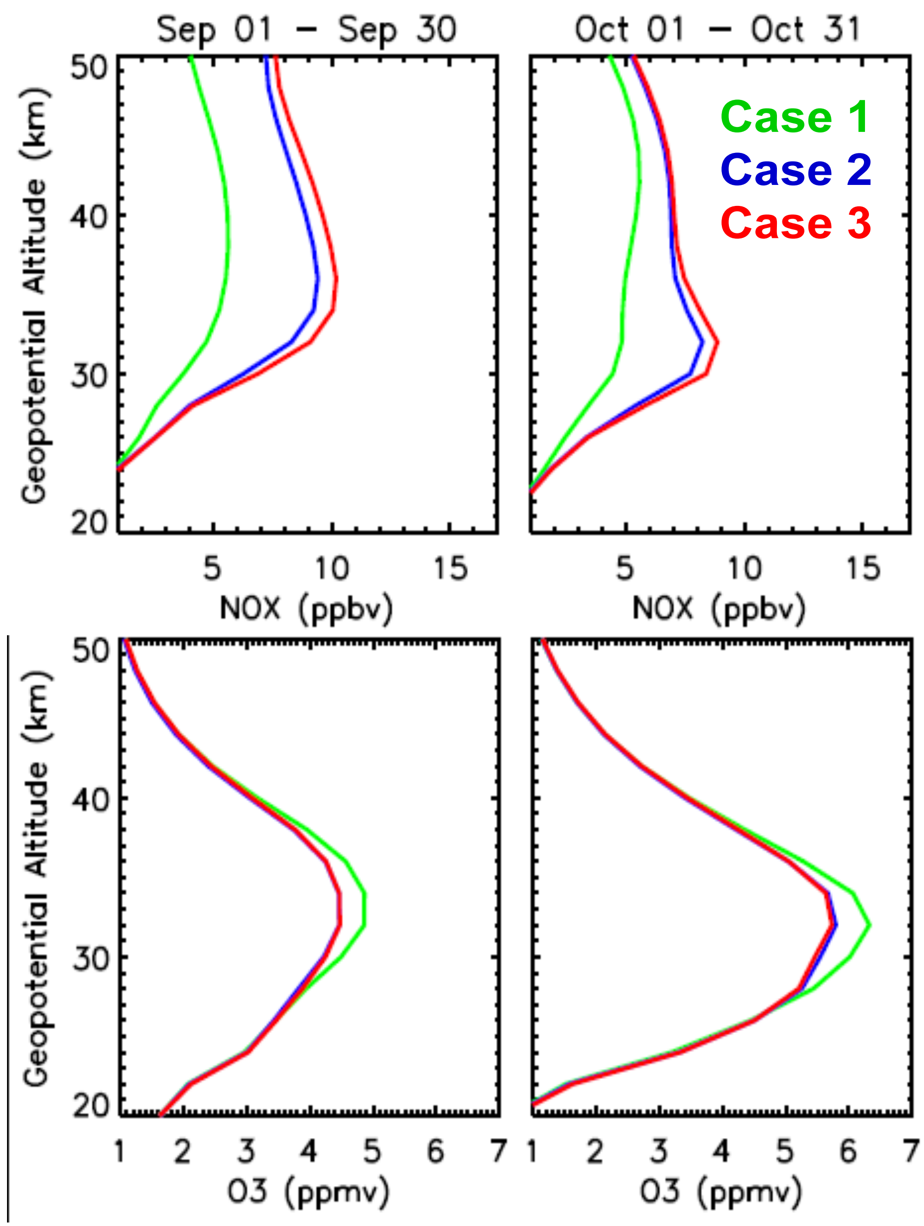



## Corresponds to catalytic $NO_x$ destruction




Randall et al., 1998

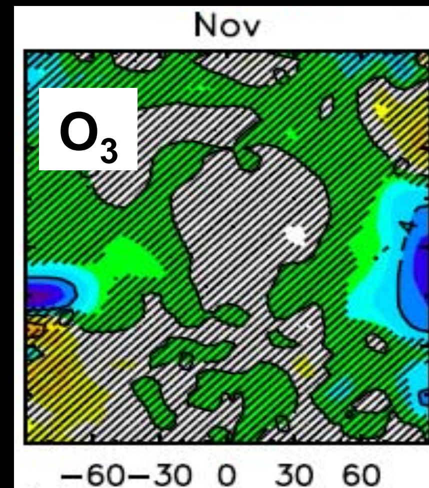
**POAM Data** 1994 1996



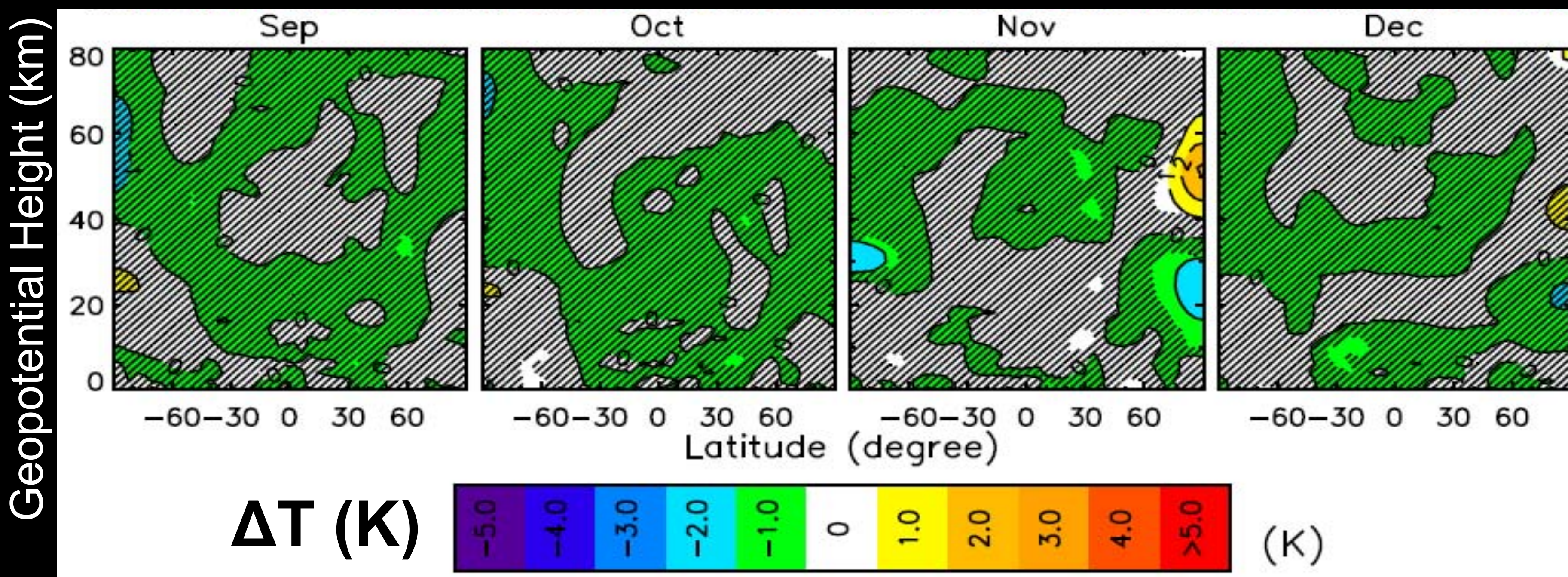

**WACCM**

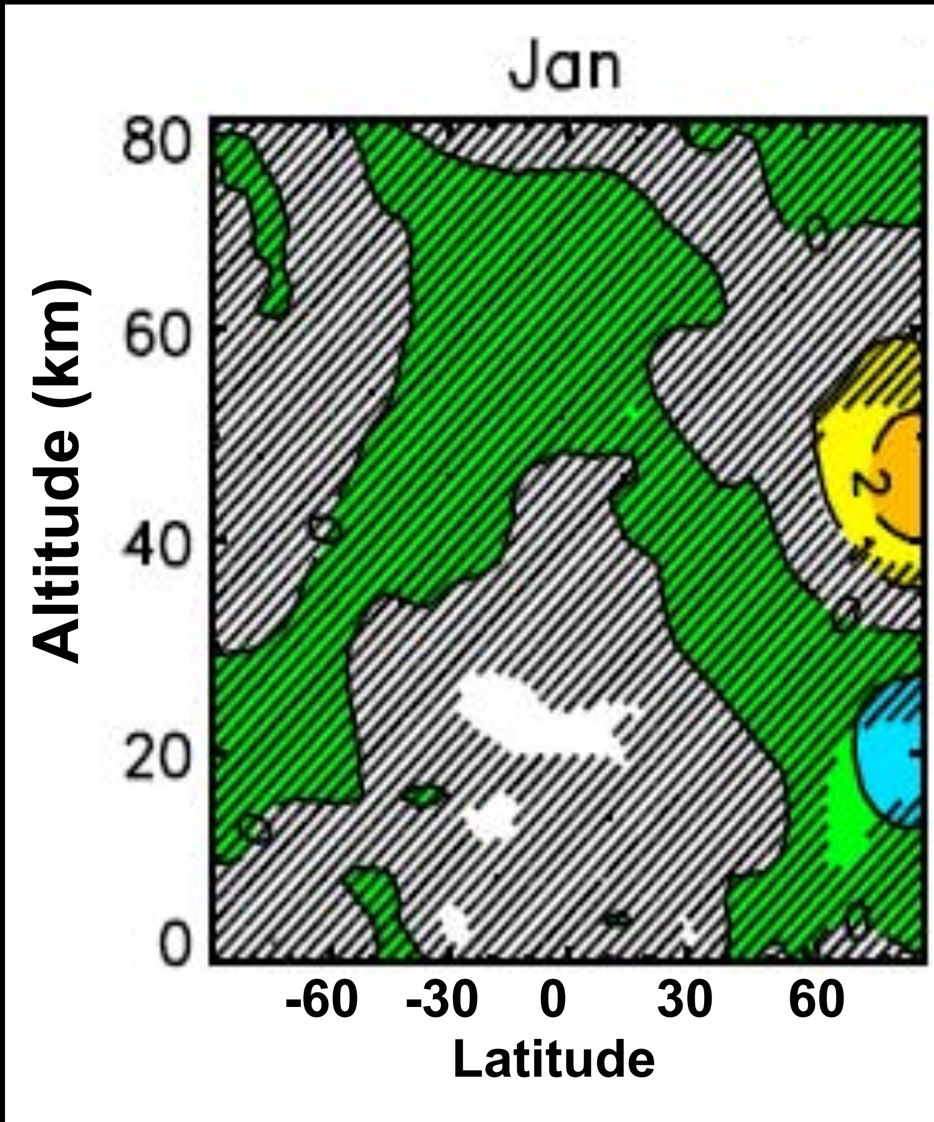
**Up to 2 K monthly average temperature changes due to Aurora + MEE.**

**Are these changes consistent with ozone?**




Is heating due to less radiative cooling by O3 in polar night upper stratosphere?






# Are temperature effects valid?

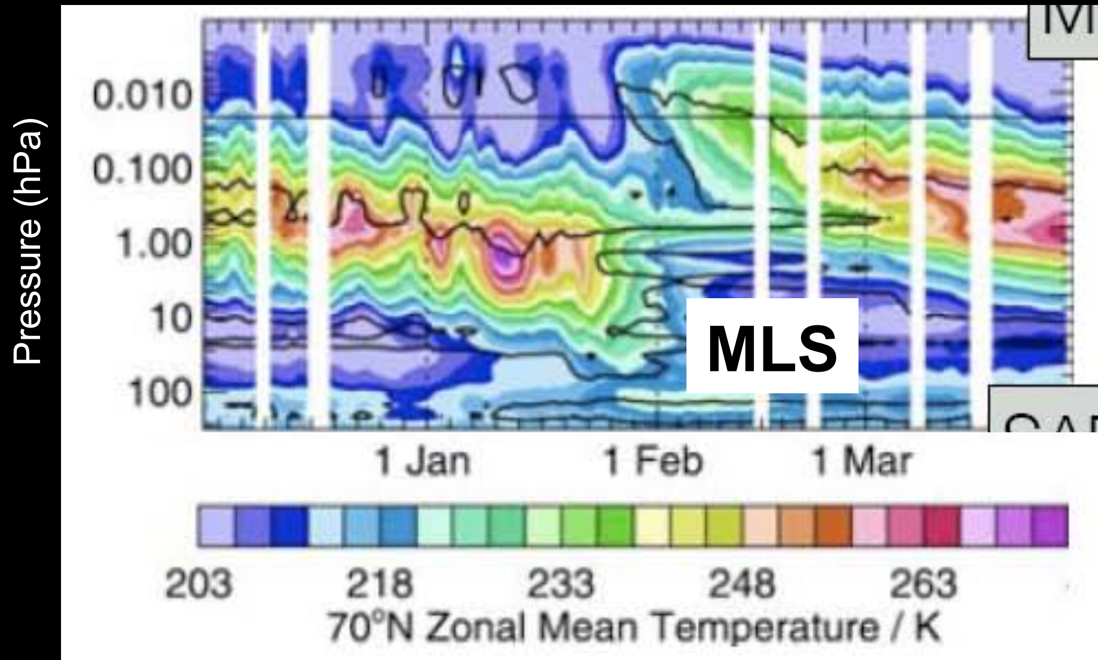
Still trying to understand statistical significance:

Statistically significant differences found between two sets of 80-member ensembles, both with same forcing.

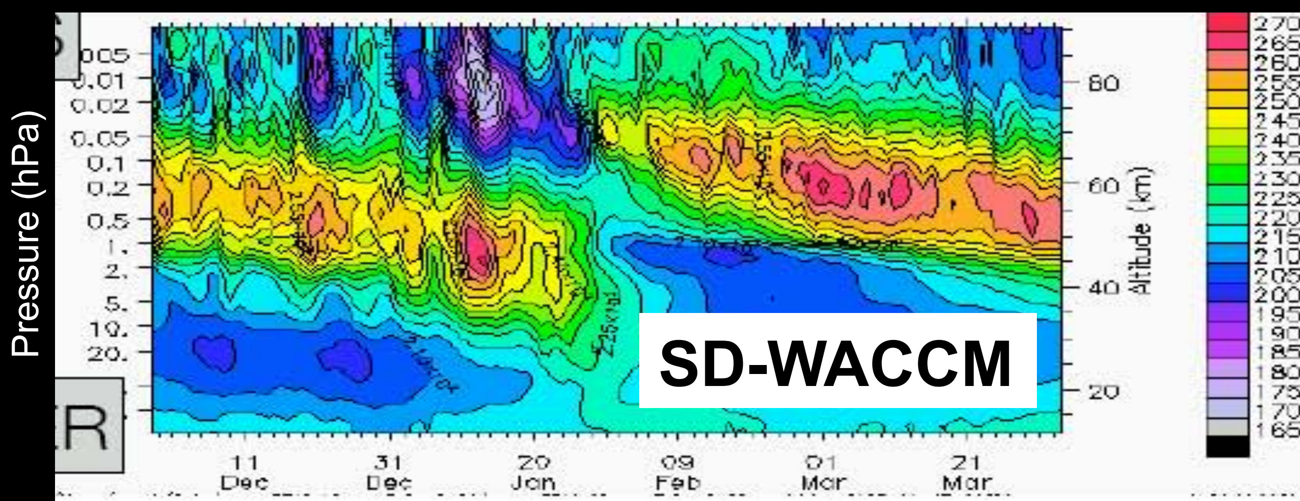
## Summary of WACCM Model Results

- Free-running WACCM-EEP compares well qualitatively to observations for typical (i.e., low) EEP conditions
  - Clear descent of EPP-$NO_x$
  - Corresponding ozone depletion
- Descending $NO_x$ underestimated by factor of ~2 even for standard meteorological conditions
- Concerns about T statistics in polar stratosphere
- Specified SSTs, so cannot probe tropospheric effects
- Never see elevated stratopause as in 2004, 2006, 2009

# SD-WACCM vs. MLS Temperatures, 2006




**If WACCM is nudged to Met assimilation (e.g., GEOS-5) temperature & winds in stratosphere, elevated stratopause is captured.**




**Still must modify SD-WACCM for MEE.**

Figures courtesy of Dan Marsh, NCAR

# Conclusions & Outstanding Questions

EPP DE (Jackman talk) and IE significantly affect polar stratospheric $NO_y$ and Ozone.

Temperature effects not yet quantified.

WACCM underestimates EEP effects for baseline conditions.

Free-running model does not simulate unusual meteorology of 2004, 2006, 2009.

# Some Questions

**What is $NO_x$ *really* doing in the polar night?**

**What are the detailed dynamical mechanisms that link EPP to atmospheric change?**

**Does EPP affect surface level temperatures?**

**Are coupling mechanisms from the surface to the MLT changing (more favorable for enhanced EPP-$NO_x$ descent)?**

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

# Thanks very much!