Processes which govern the coupling between middle and upper atmospheric odd nitrogen

D.E. Siskind

Prepared for the High Energy Particle Precipitation in the Atmosphere (HEPPA) Workshop, Oct 6, 2009

Outline

1. **Overview of atmospheric odd nitrogen**
2. **Atmospheric structure in the zonal mean**
3. **Overview of waves and transport**
4. **HALOE Data (mesosphere, stratopause, mid-stratosphere)**
5. **NH NOx and stratospheric weather**
6. **3D Modeling of vertical coupling (weather, climate)**
7. **Conclusion/The future**

Theme:

How much of the odd nitrogen in the lower/middle atmosphere owes its origin to high altitude processes?

1. What is odd nitrogen?

$NOx = N(^4S, ^2D) + NO + NO_2 + HNO_3 + 2 \times N_2O_5$

Two sources:

1) $N_2O + O(^1D) \rightarrow 2\ NO$ — stratosphere
2) N_2 + energetic electrons $\rightarrow$ 2 N — thermosphere

Source 1) operates below 40 km since N_2O comes from the troposphere

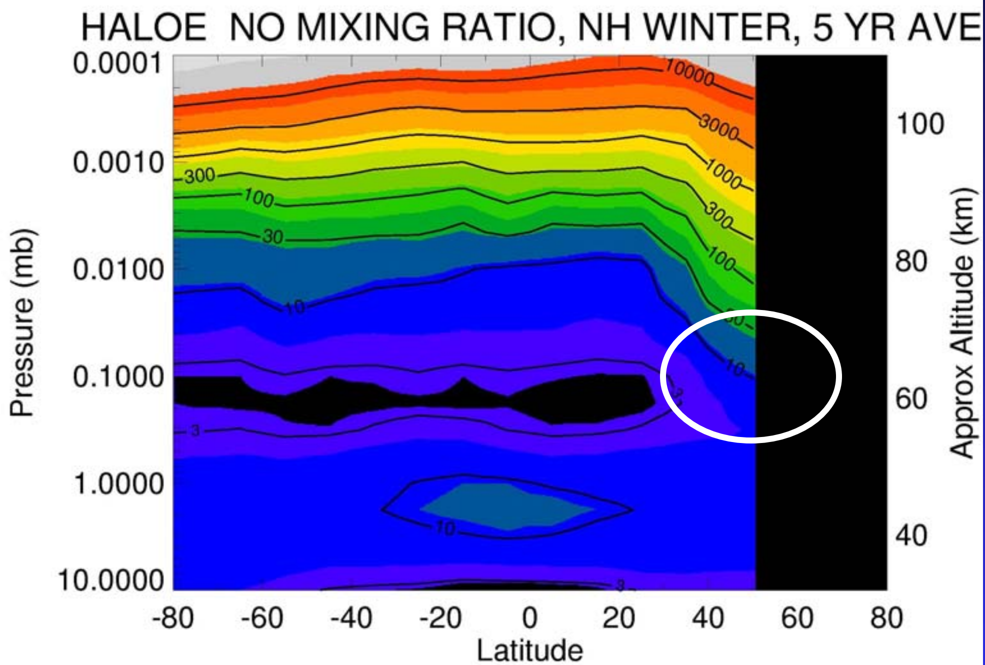
Source 2) operates over many altitudes, but mainly above 90 km
NO production reflects soft X ray or energetic particle precipitation

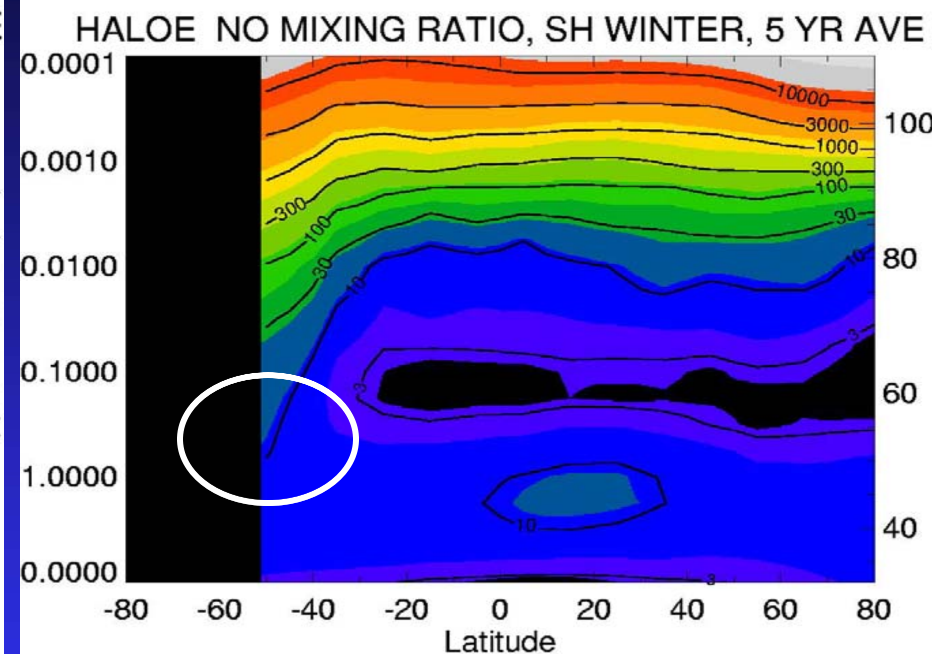
One Sink:

$NO + h\nu$ (FUV) $\rightarrow N + O$ followed by
$N + NO \rightarrow N_2$

Time scales: days in upper mesosphere; weeks in stratosphere

1. Two odd nitrogen layers in the atmosphere

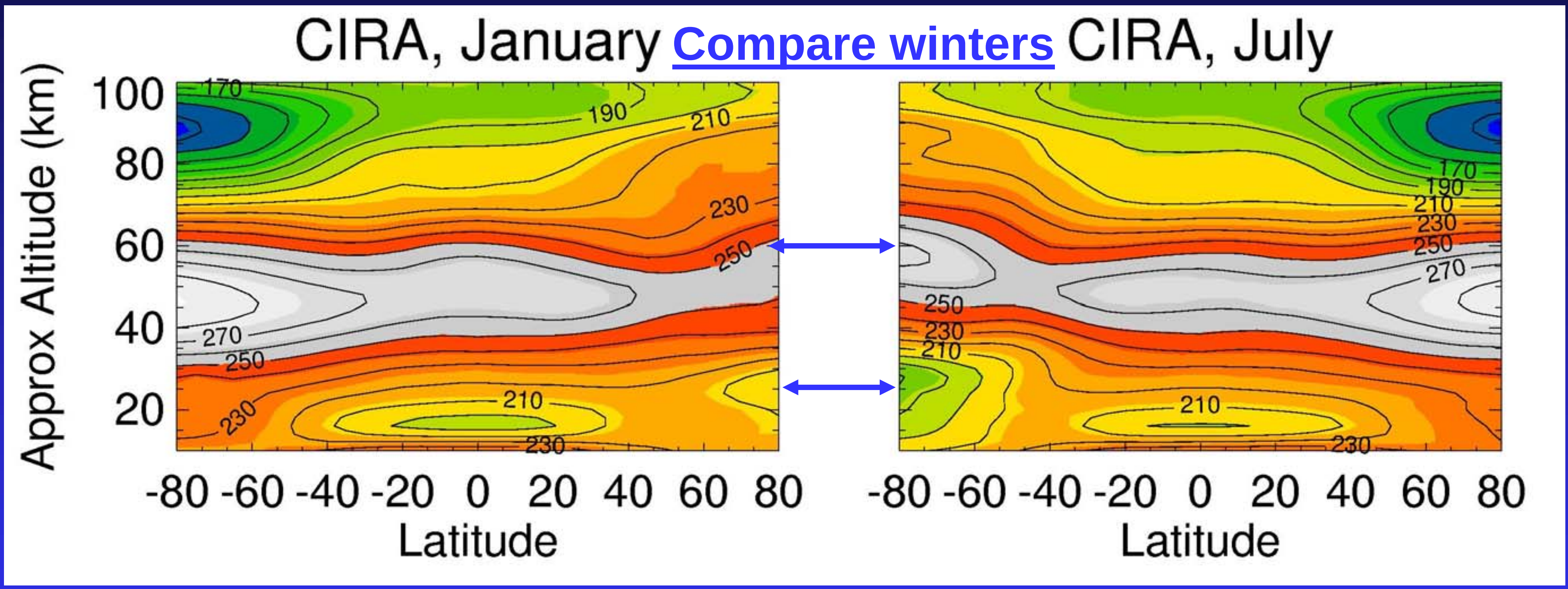




In mixing ratio units, most of the odd nitrogen is in the thermosphere. Winter descent brings down to mesosphere and below. ***EPP-Indirect Effect (IE)*** (Randall et al., 2007)

Note that descent to lower altitudes is more apparent in SH

2. Zonal mean atmospheric structure



Summer stratopause is warm: **radiation (easy)**
Winter polar stratosphere is cold **radiation (easy)**
Winter stratopause is also warm!: **dynamics**
Mesopause temp is out of phase with solar heating: **dynamics**

SH winter: warmer at 50 km, colder at 20 km **dynamics**

2. Linking temperature→ winds

Geostrophic balance: Coriolis force against pressure gradient

$$u = \frac{-1}{f}\frac{\partial \Phi}{\partial y}$$

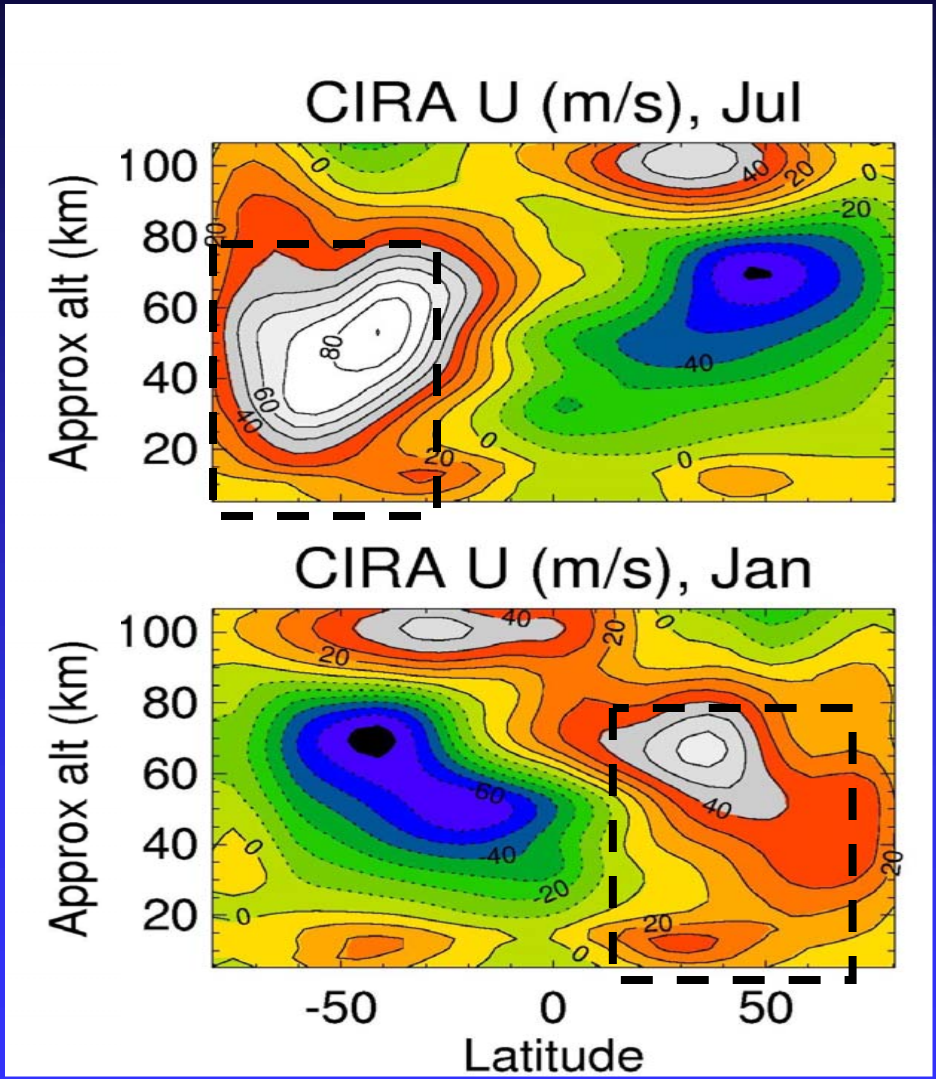
Where Φ is the geopotential (work required to lift an air parcel to a given height- proportional to temperature and pressure). Implication is that wind flow is proportional and perpendicular to pressure gradients.

Thermal wind: The vertical shear of the zonal wind (differentiate geostrophic wind, subst. Geopotential defn)

$$f\frac{\partial u}{\partial \ln p} = R\left(\frac{\partial T}{\partial y}\right)$$

Latitudinal temperature gradient is linked to strength of zonal winds

2. The zonal wind: Focus on Wintertime jets



Equatorward tilt of the westerly jets.
→ Polar vortex expands with altitude.

Stronger jet in SH
→ consistent with underlying colder lower stratosphere
→ correlates with greater stability of the SH polar vortex

Jets decay above 70 km
→ Wave breaking (either planetary waves or orographic GWD)
→ Wave breaking can drive descent
→ Also possible mixing out of polar night.

3. Overview of Waves and Transport (Height-latitude) : Some History

Brewer (1949): Tropical temperatures cold enough to explain middle atm. dryness, but mid-high latitudes were not
→Tropical upwelling, extratropical descent

Dobson (1956): Ozone production largest in the tropics, But ozone column densities largest at high latitudes
→ Downward-poleward transport

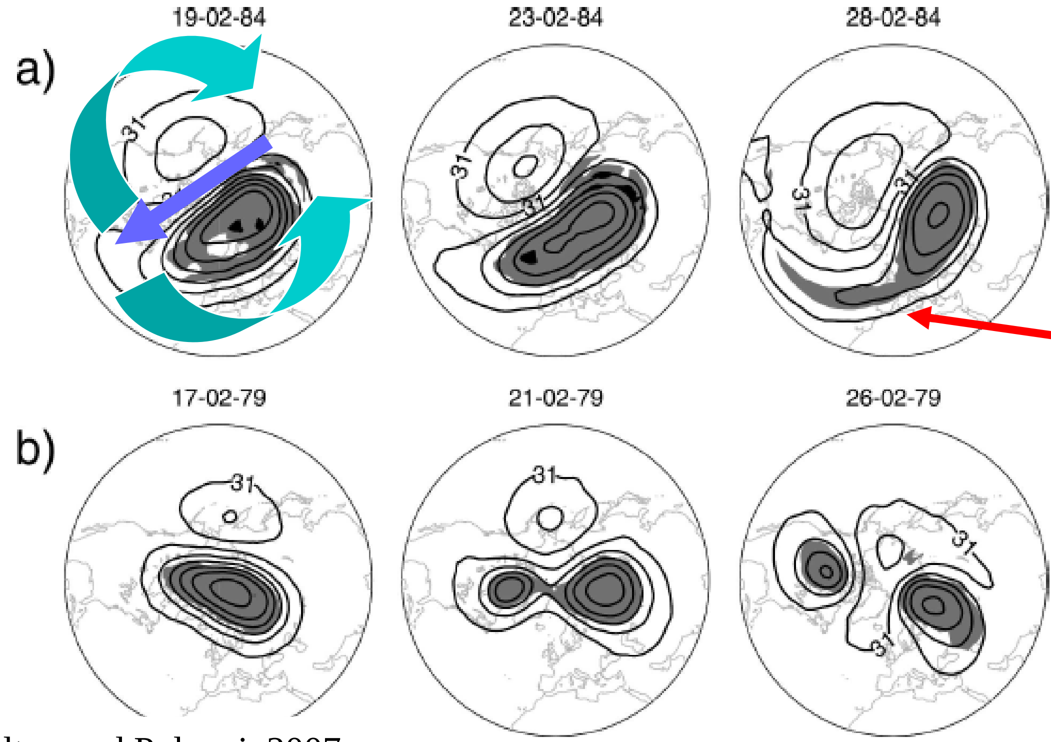
This is driven by specific waves that act against the zonal winds

3. First wave type: planetary waves

Restoring force is the latitudinal variation of Coriolis effect (conserves parcel vorticity).

See Figure 7.11 of Holton's Dynamical Meteorology text

Waves and the vortex



Charlton and Polvani, 2007

Breaking of Wave #1 can yield momentum transfer and mixing of air masses

Splitting of the vortex is wave #2. No breaking seen here, although polar air has greater exposure to sunlight

3. Second wave type: gravity waves
(review by Fritts and Alexander, Rev. Geophys, 2003)

Vertically propagating waves associated with buoyancy restoring force = $-N^2\delta z$,

where N is the buoyancy frequency (Brunt-Vaisalla)

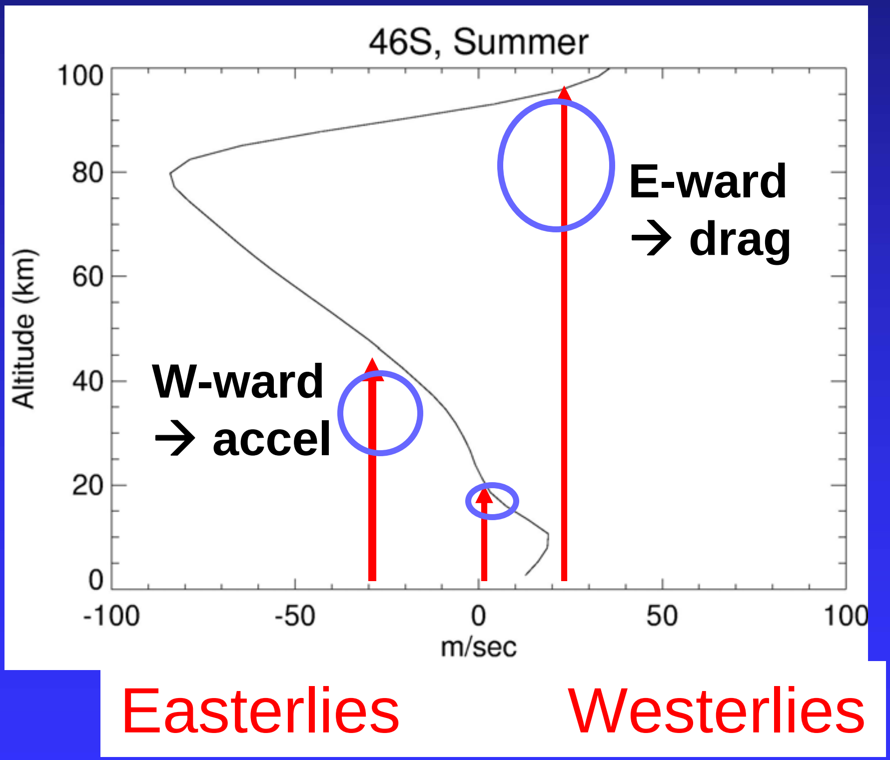
3 main Sources: Convection (tropics), flow over topography (m Waves), jet stream shears

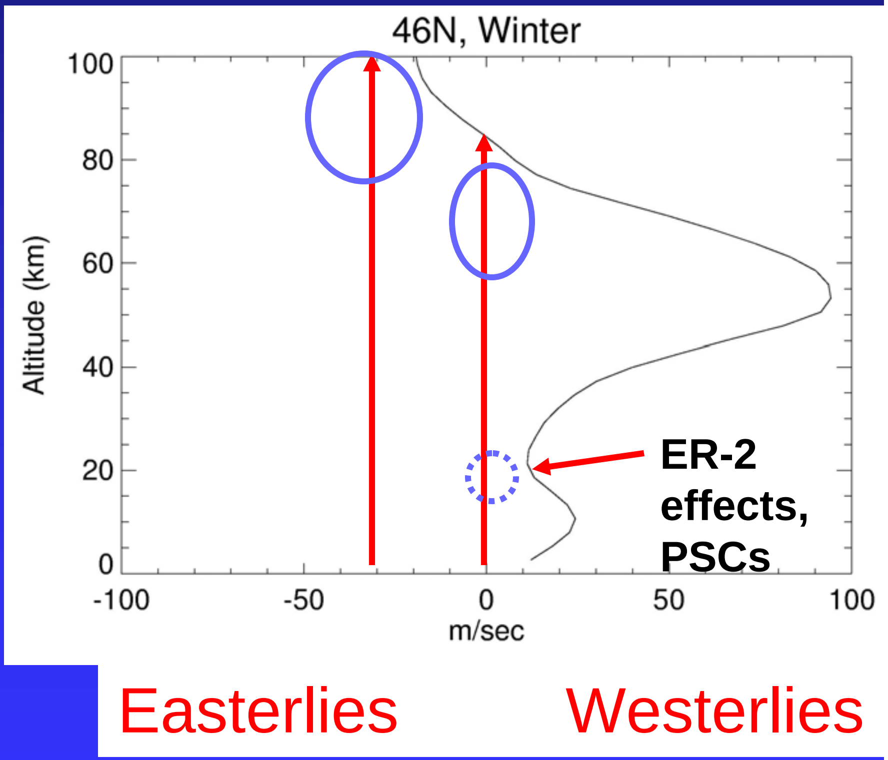
Gwaves grow with height and then overturn and break

Gravity waves are too small (or rapid) to easily resolve explicity, so they are typically parameterized by most 3D models (a hard problem!)

3. Winds and gravity wave breaking/filtering

1. <u>Critical level dissipation-</u> wave momentum completely deposited
2. <u>Non-linear dissipation</u>: waves become large amplitude
Convective unstability ($\delta\theta/\delta z = 0$)- the Lindzen criteria. This is generally at and just below critical layers. Waves "drag" the flow toward the phase speed of the wave.



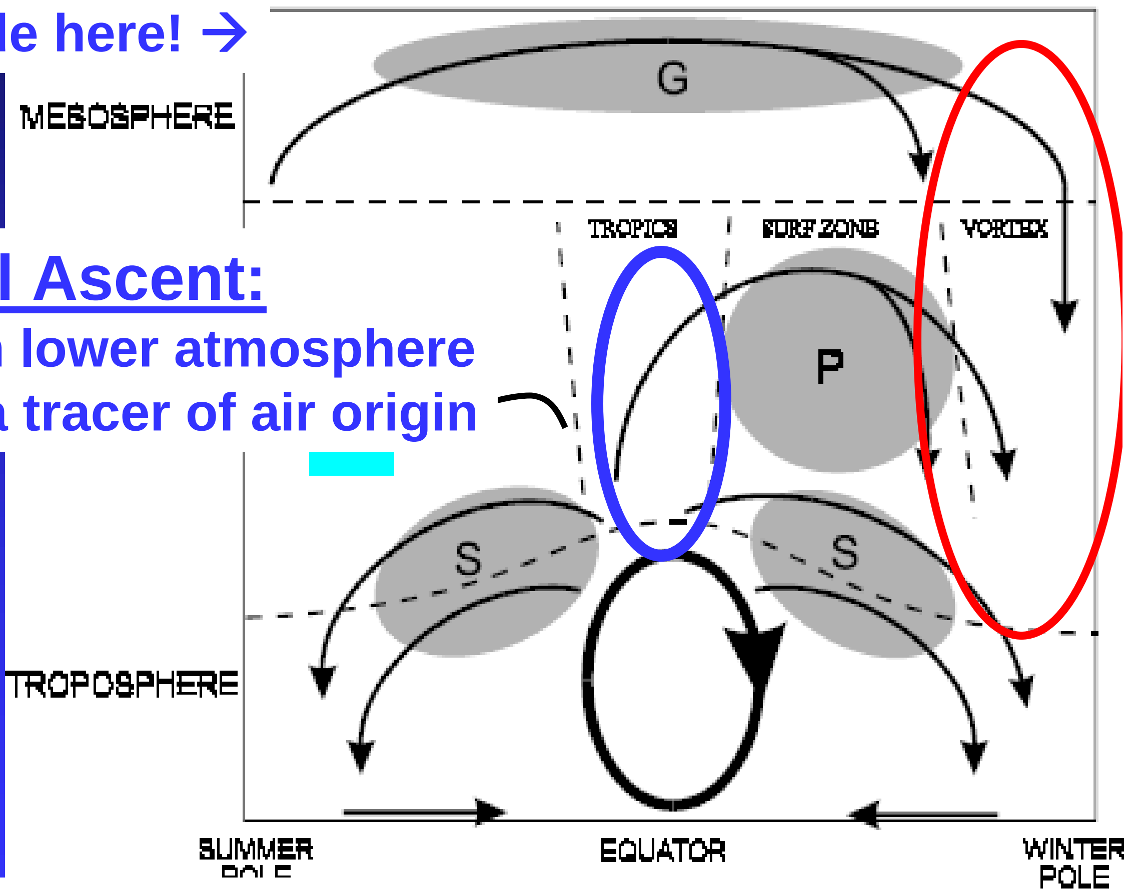


3. Middle atmospheric transport circulation

2 regimes Equator-to-pole: Stratosphere, planetary wave driven
Pole-to-pole: Mesosphere, gravity wave driven

PMCs made here! →

Tropical Ascent:
CH4 from lower atmosphere used as a tracer of air origin



Descending air
Coupling between mesosphere and Stratosphere.
Warm stratopause

(from review by Plumb, 2002)

3. Strength of meridional motion

From steady state zonal momentum equation (See Garcia, JAS, 1987)

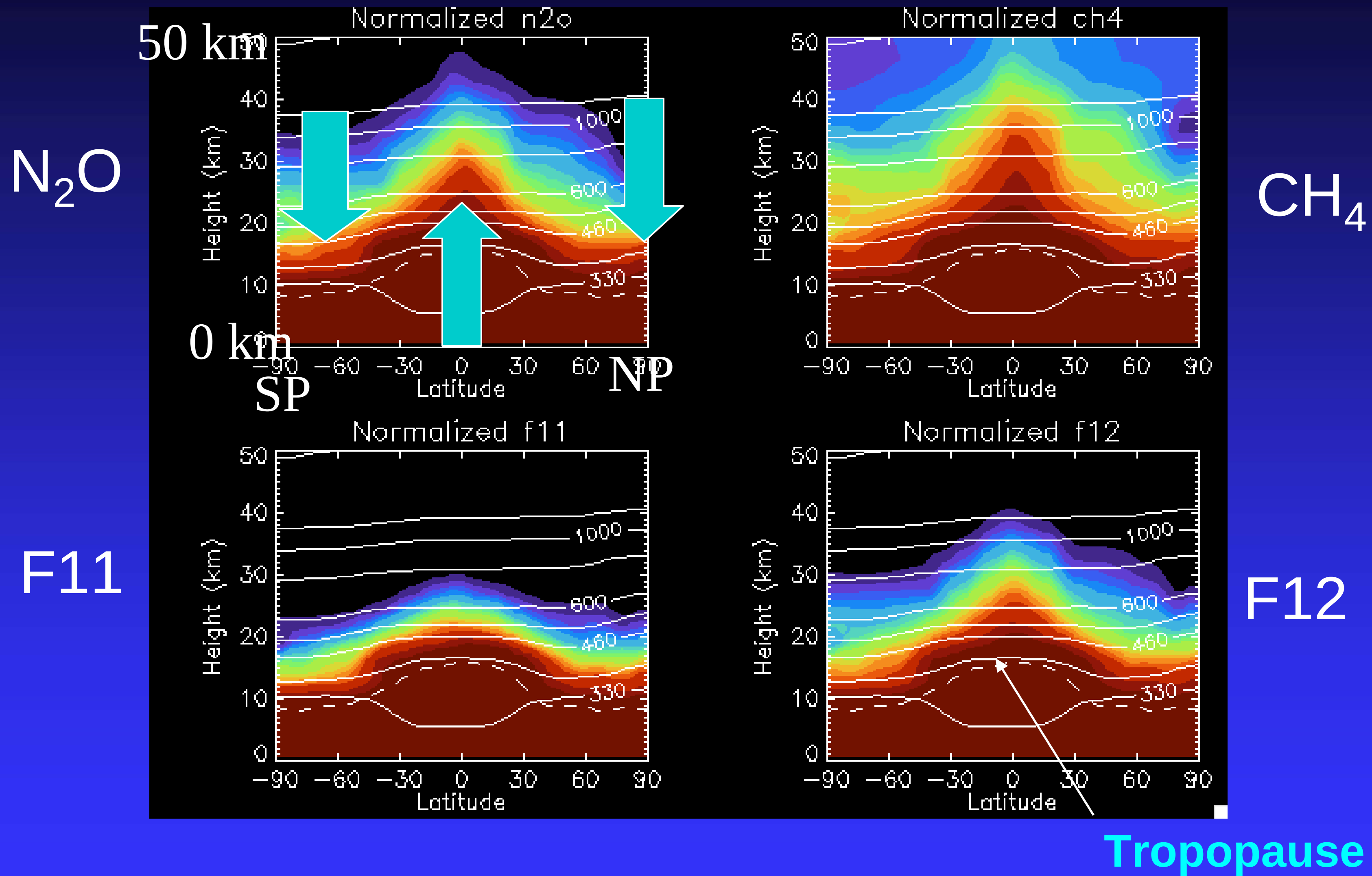
$$-f\, v^* = \nabla \cdot F, \text{ where } F \text{ is momentum}$$

Where f ~ 10^{-4} s^{-1} at 45N and $\nabla \cdot F$ is of order 50-100 m/sec/day

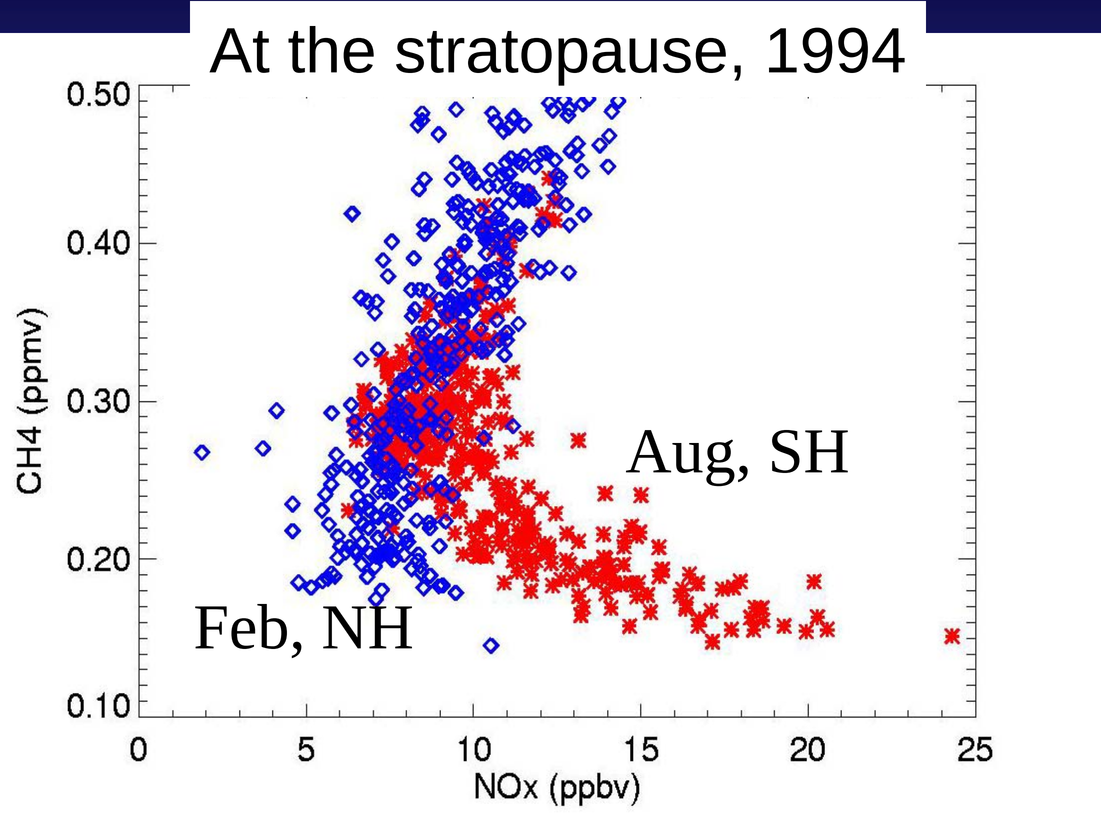
→ v* ~ 5-10 m/sec (10 deg of lat/day)
→ From continuity, w* is 1-4 cm/sec (1-4 km/day)

Material injected at the equator goes to the pole in ~ 1 week
Winter descent to stratopause in ~ 1 month → warming
Ascent in polar summer → cooling (PMC formation)

3. Tropical Upwelling of source gases



4. HALOE Data: Stratospheric CH_4 vs. NO_x



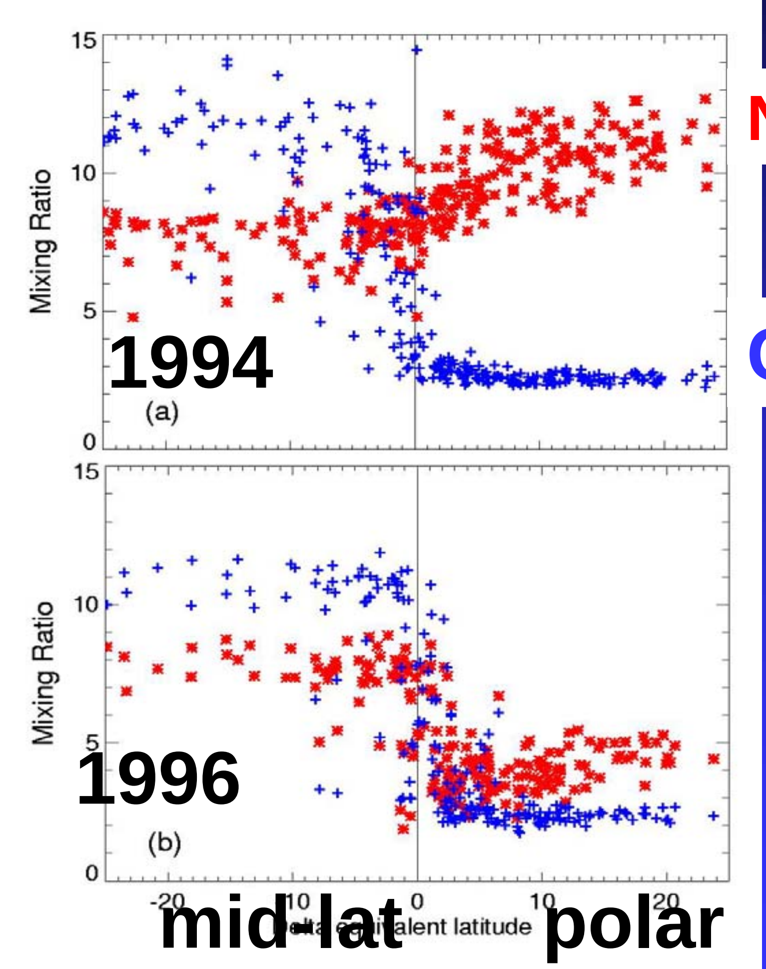
NOx enhancement at the lowest CH4 values indicates very high altitude air and probably an auroral source of NOx to the middle atm. NH response is generally weaker.
(until recent years)

For a long time, SH was thought to be the place to see NOx enhancements. *Why?* *Answer: Stability of polar vortex*

4. HALOE data in SH springtime polar vortex

At ~28 km, October, SH

1994 was a year of high geomagnetic activity

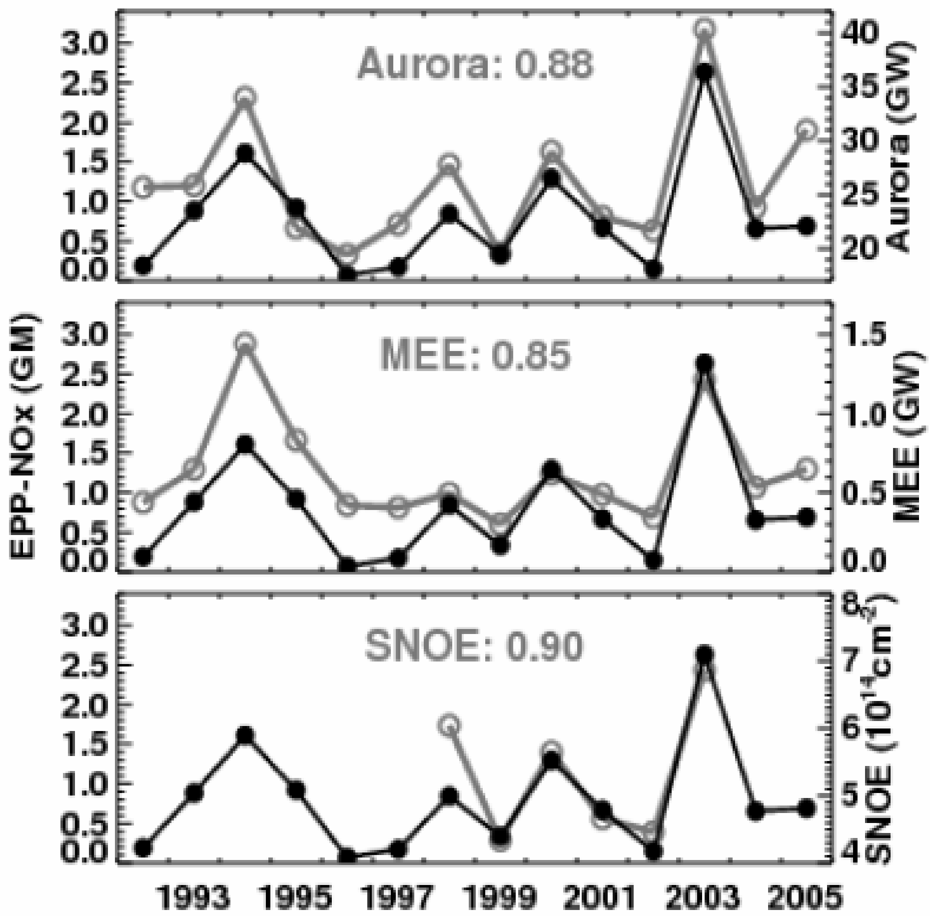


$NO_X = NO+NO_2$

CH_4 X 10

Low NOx→ low geomagnetic activity!

4. Summary of HALOE: correlation with geomagnetic activity



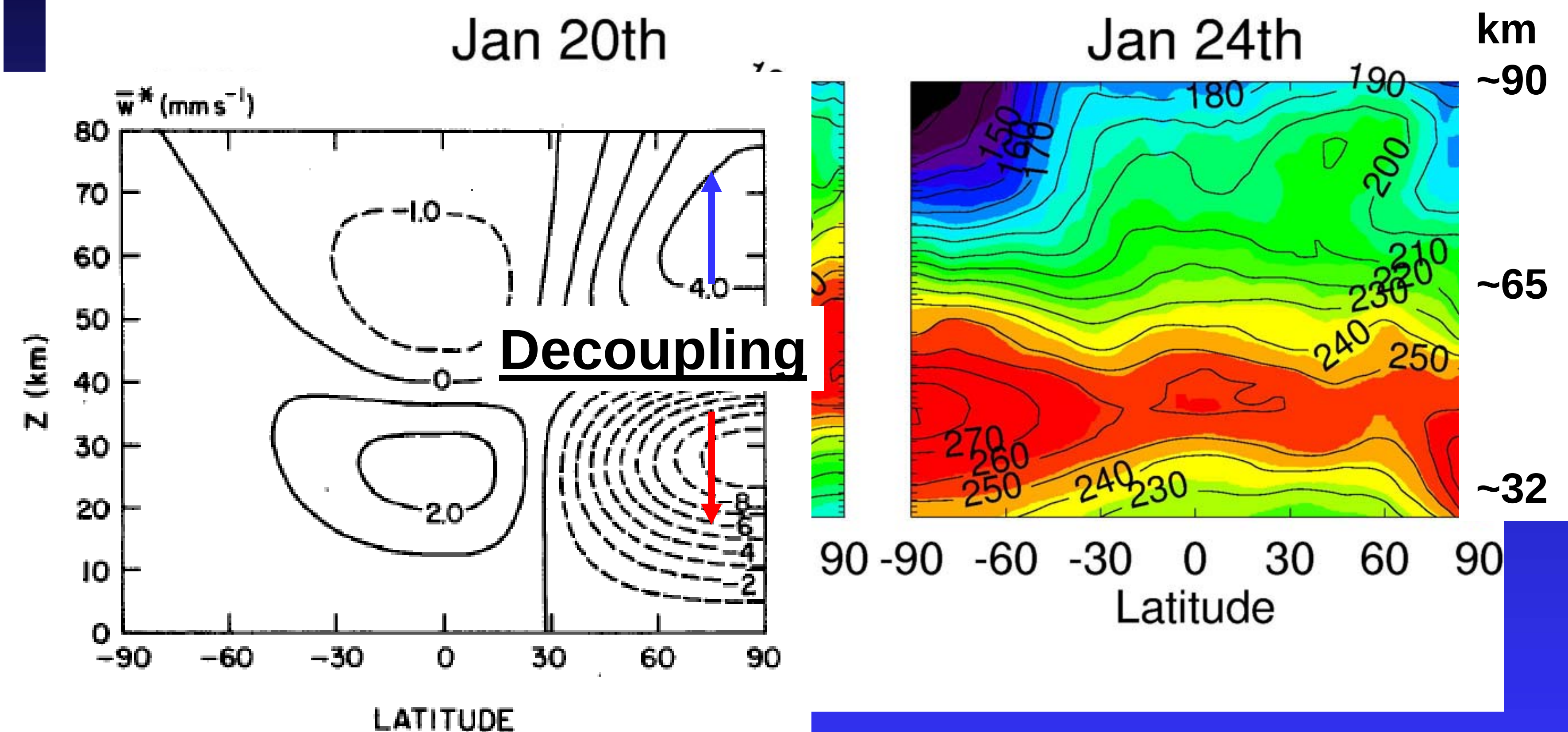
Use 45 km to capture all the NOx entrained in the stratosphere. (Funke, Randall)

Correlation with energies < 30 keV and SNOE suggest source is above 80 km (not REPs)

Stratospheric budget is ~30 GM Thus max of 10% contribution

5. Stratospheric warmings and decoupling

Stratospheric warmings associated with mesospheric coolings



From Garcia, JAS, 1987
theoretical response of transport
to a simulated stratospheric warming

5. Current Events

3 years of NO and CO descent observed by ACE (Randall et al., 2007)

2004 and 2006 show tongues of NO descending into the stratosphere

HALOE data by Natarajan et al.,2005

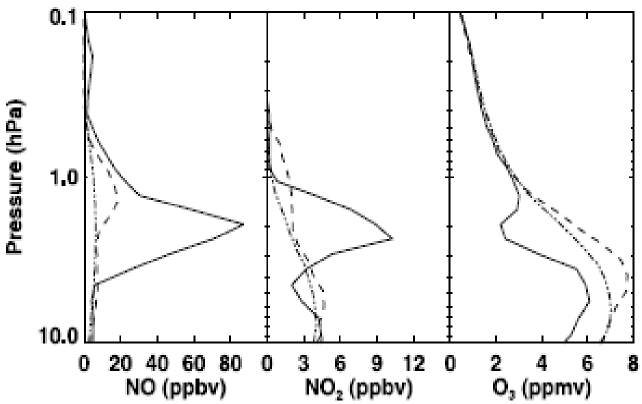
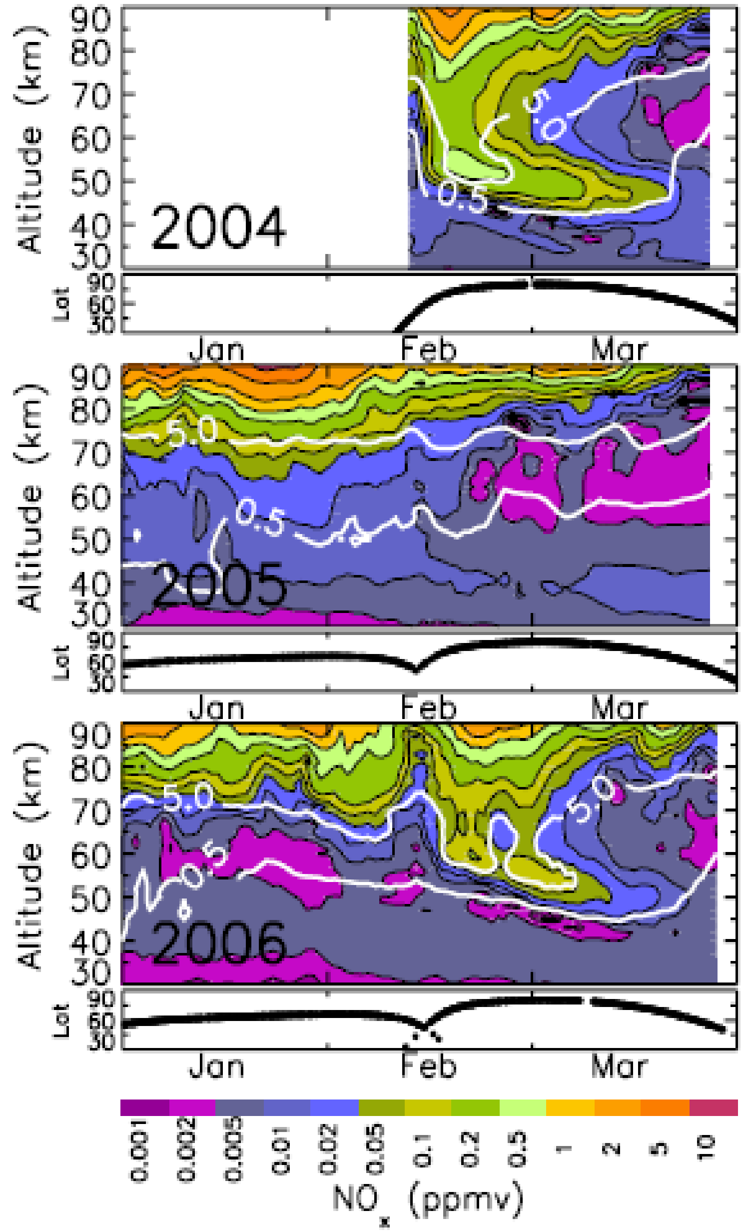


Figure 3. Sunrise NO, NO_2, and O_3 mixing ratio profiles for 2 different HALOE scans on April 5, 2004 (≈68N). Solid lines represent the scan with elevated levels of NO_x, and dashed lines represent the scan with normal levels of NO_x. Dash-dotted lines represent sunrise zonal mean profiles for April 12, 2003.



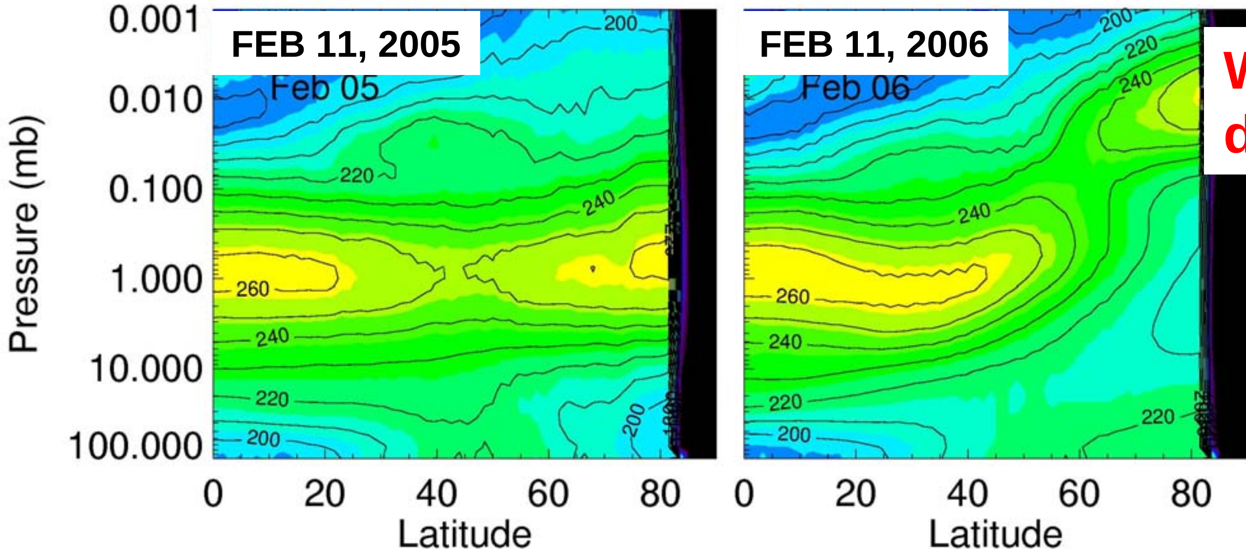
5. Unusual Strat. Warmings → NOx descent

Old view: SSWs will interrupt the NOx descent

1) causing upwelling
2) Mixing air out of the polar night

So…. SH is the place to look for NOx coupling

New view: *Extended* SSWs linked to enhanced descent in NH



Warm air here implies descent

6. 3D models: Two Approaches

1. **<u>Weather models</u>: case studies, short term forecasts**
   example: NOGAPS-ALPHA
   (Navy Operational Global Atmospheric Prediction System: Advanced Level Physics High Altitude)

2. **<u>Climate models</u>: Typically coupled with chemistry**
   Long term simulations. Budget of atmospheric odd nitrogen

I will discuss #1 to understand the 2006 event (it also occurred in 2004 and 2009)

Literature review for #2

6. Defining and explaining NOGAPS

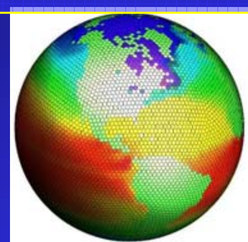
The Naval Operational Global Atmospheric Prediction System

ANALYSIS

For a specific date

"Best" Estimate of the Current Global Atmospheric State

Global Forecast Model



Forecasts of various lengths

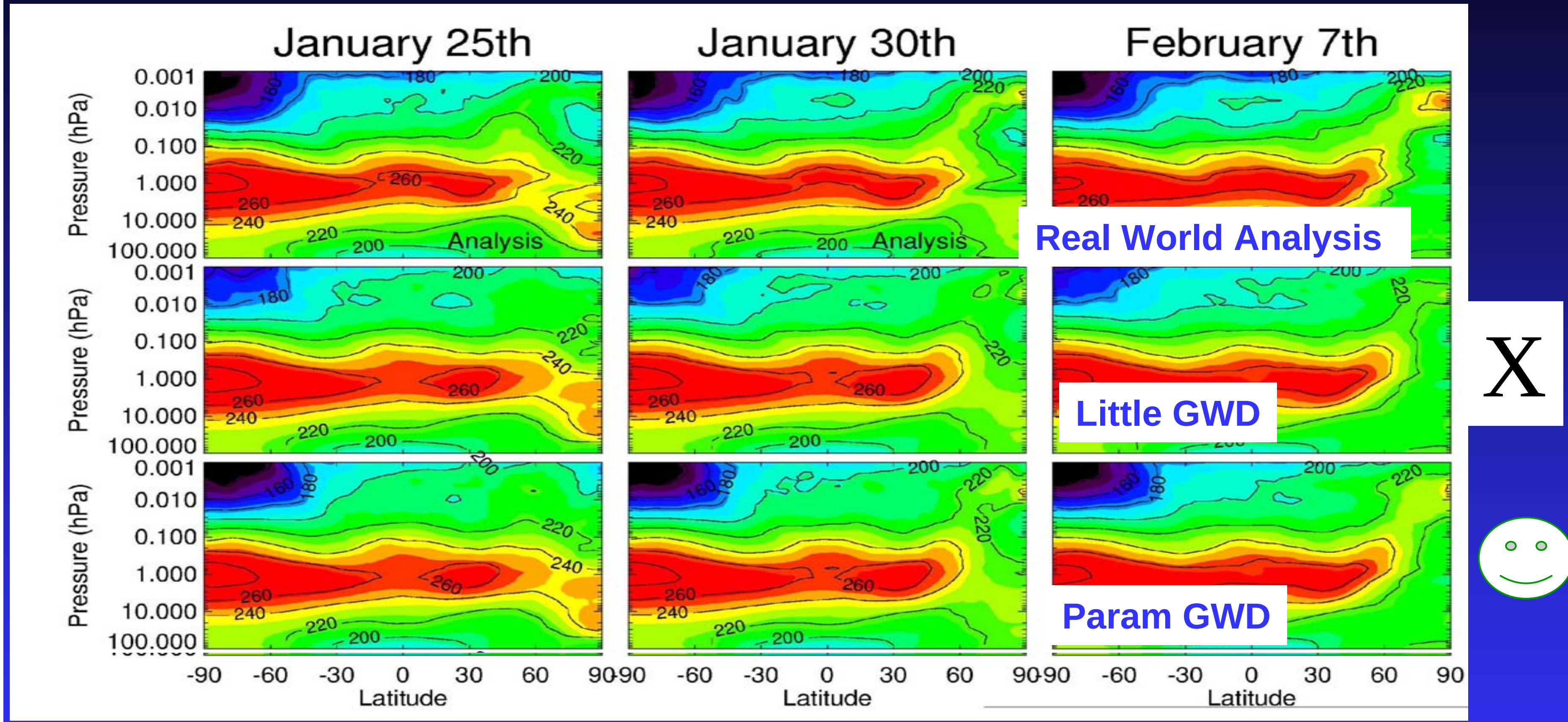
Greater than 6 hrs

New observations
(incl. MLS and TIMED/SABER)

Data Assimilation (NAVDAS)

Effective domain of system: **sfc to ~90 km (.001 mb), 2 km vert. res.**
Middle atm physics: **GW-drag, ozone heating, non-LTE cooling, H_2O**

6. Models of high alt. stratopause evolution

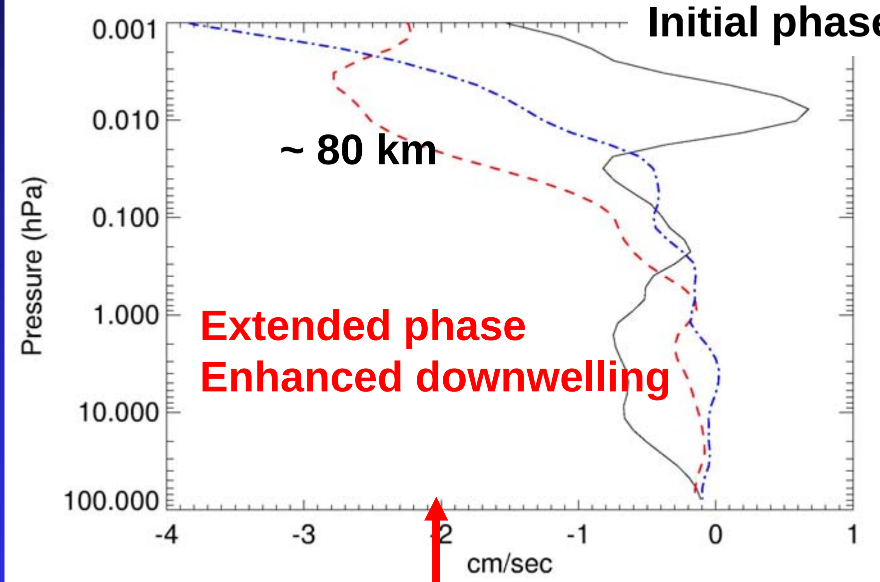


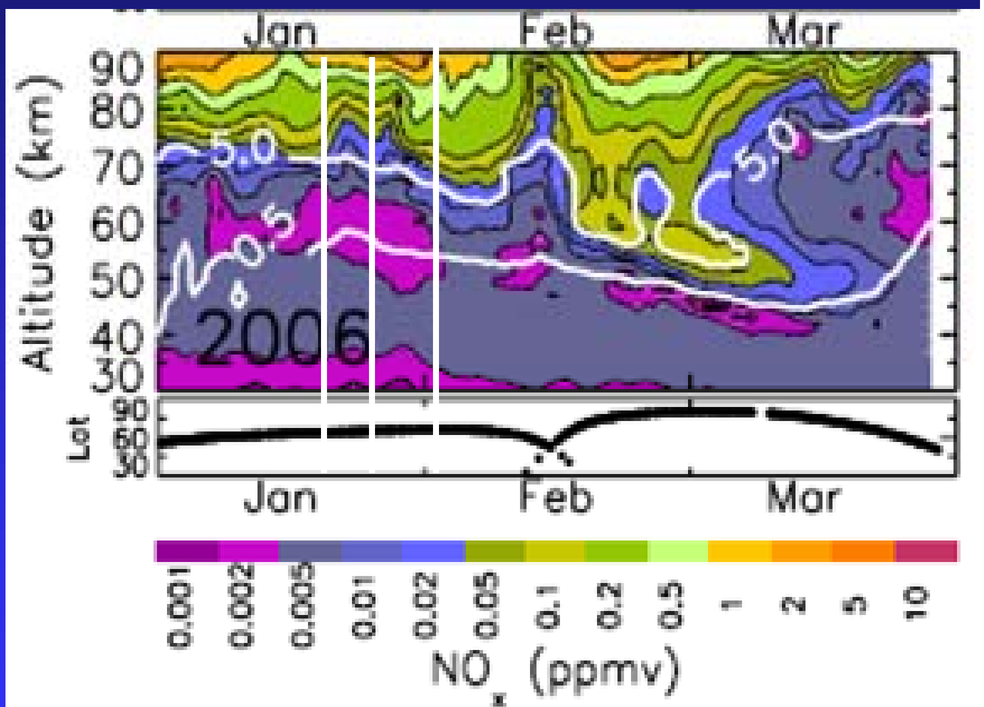
Initial phase (Jan 25th): a conventional SSW
Extended phase: High altitude stratopause linked to unusual middle atm. zonal winds and enhanced GWD at 90 km

6. Calculated vertical motion during SSW → changes sign from up to down

Average descent, 60-85N

Initial phase: upwelling





2 km/day

6. Second approach to 3D modeling: Climate

NOGAPS can tell us what is happening in these unusual events
But does not do chemistry, or seasonal integrations. Can not
tell us the budget (net entrainment) of NOx into the stratosphere.

Coupled-chemistry climate models:

- UIUC (Rozanov et al., GRL, 2005)
- Berlin (Langematz et al., GRL, 2005)
- WACCM (Marsh et al., JGR, 2007; Richter et al., 2009 in press)

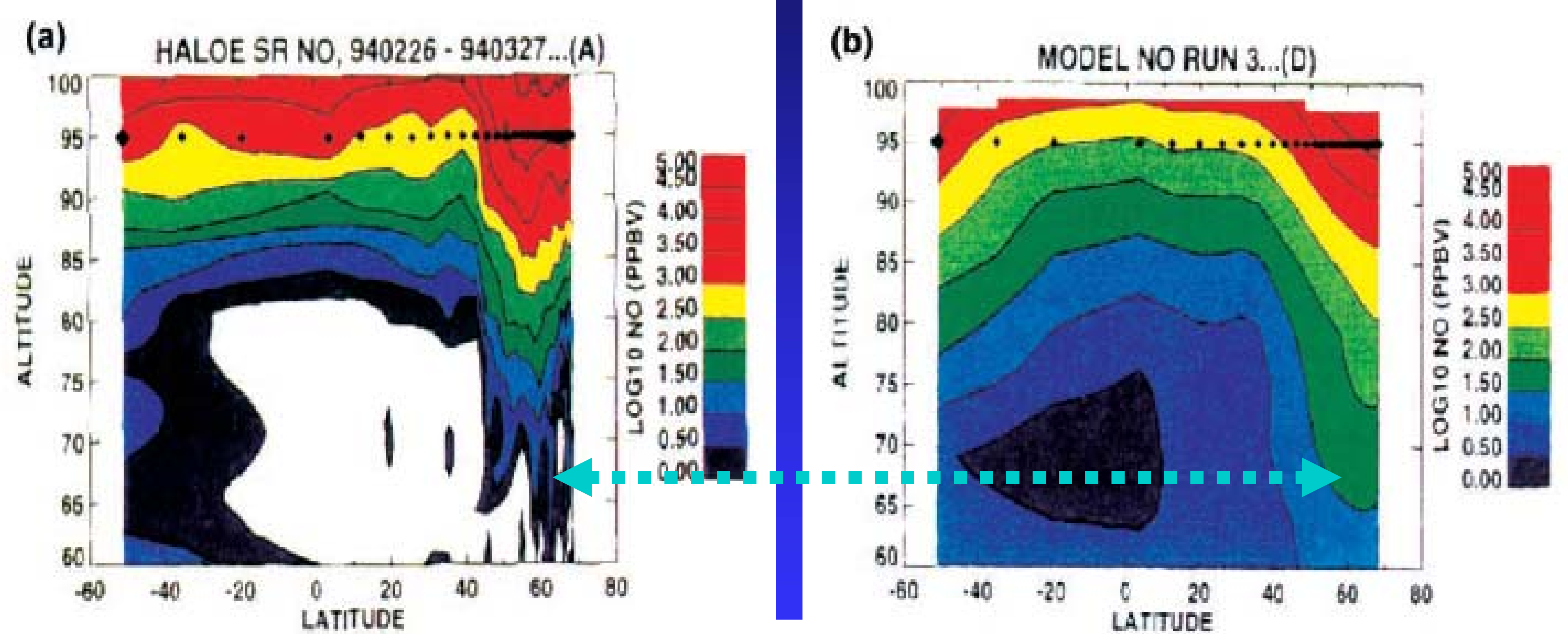
Issues: UIUC and Berlin overestimate the sources or use the wrong indicator.

WACCM has problems with dynamics in the SH winter and does not simulate the extended SSWs recently seen.

6. UIUC/Rozanov model

Likely source overestimate based upon comparison of Callis 2D model would take their 36 GM → 3.6 GM, in better agreement with est. from data)

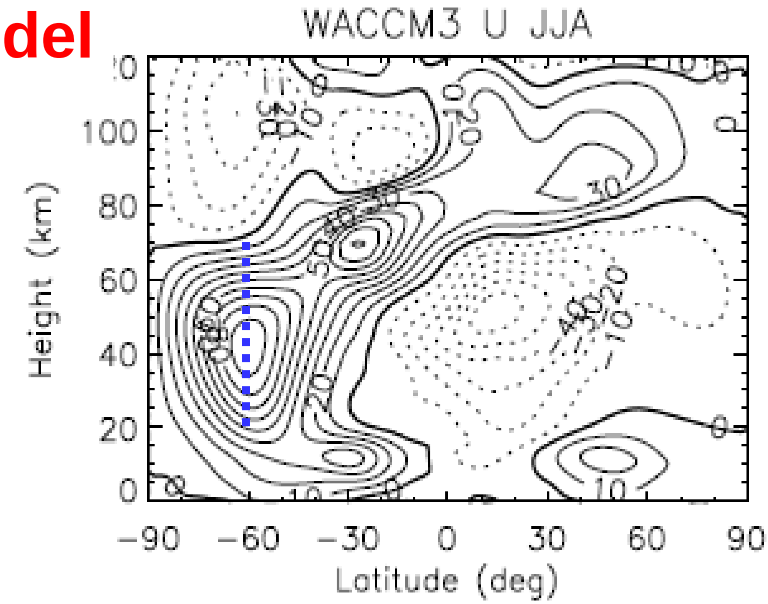
Model shows 30 ppbv at 65 km; HALOE shows 3 ppbv

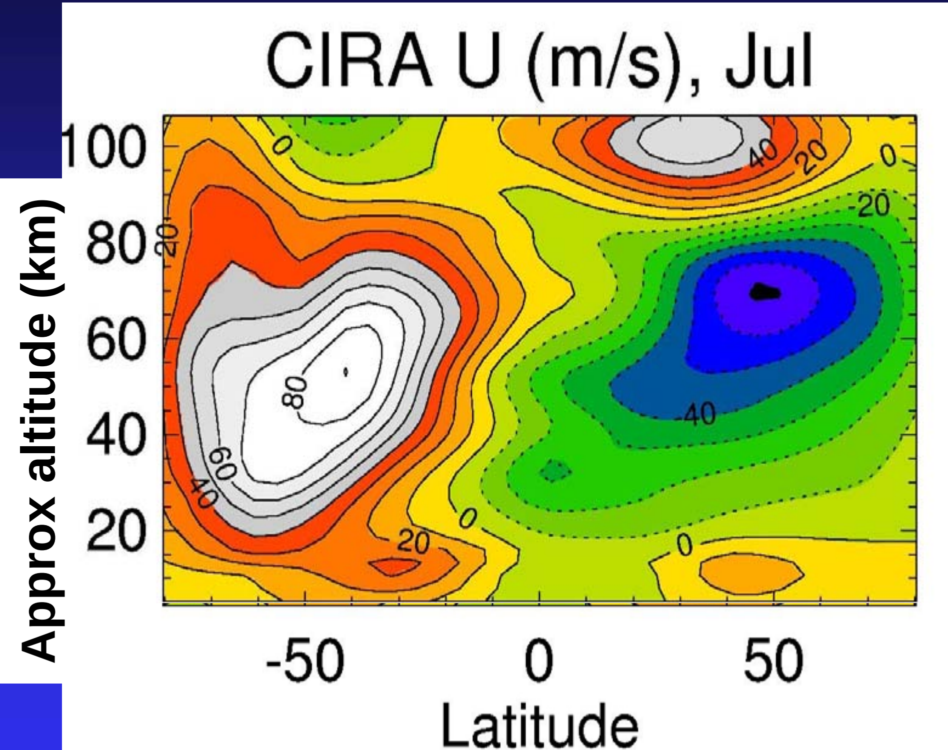


Siskind, 2002

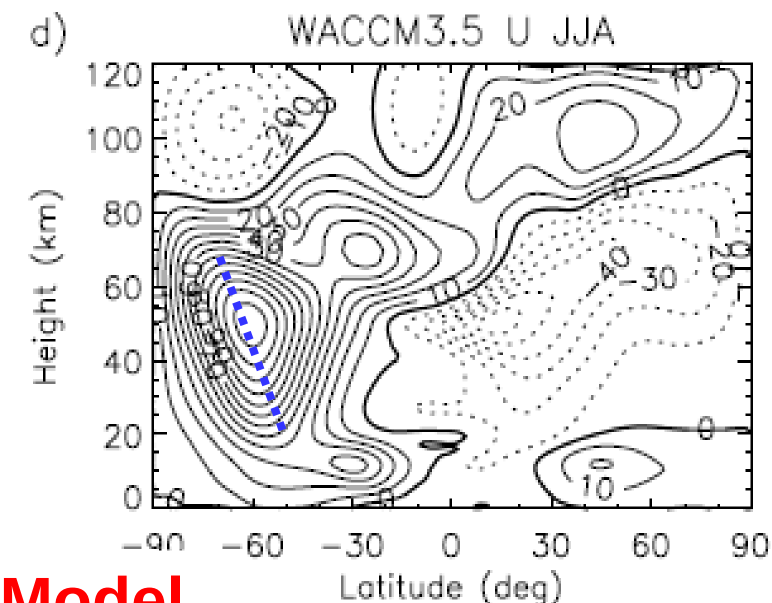
6. WACCM Winds

Old Model





Peak winter jet = 80-90 m/s

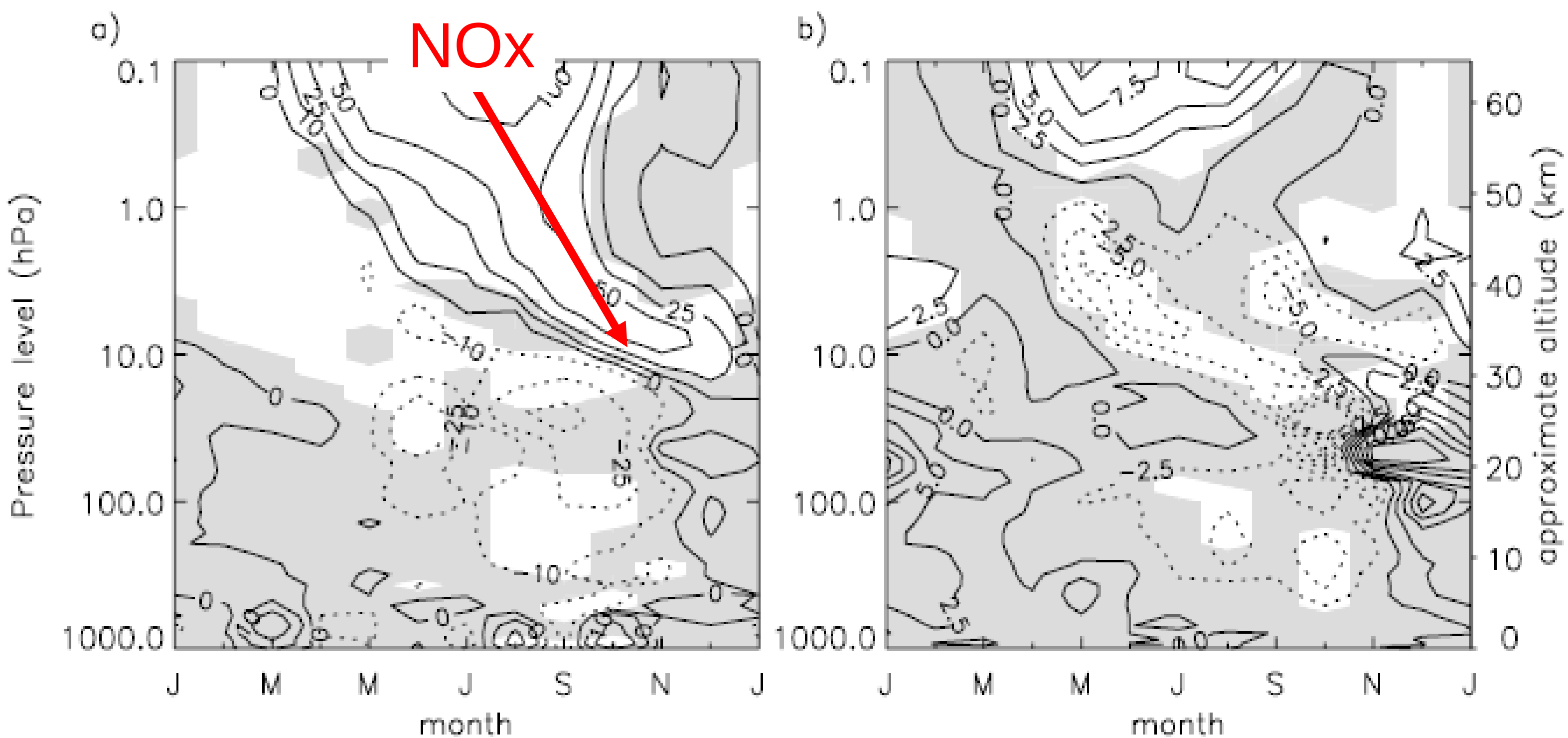


WACCM jet is too fast and got faster with new model

New Model

6. WACCM NOx descent

Ozone effect is small, maybe too small?



From Marsh et al., 2007

Figure 9. a) Percent change in monthly mean NOy for solar maximum relative to solar minimum at 90°S. b) As in a) but for ozone. Unshaded regions are significant at the 95% level.

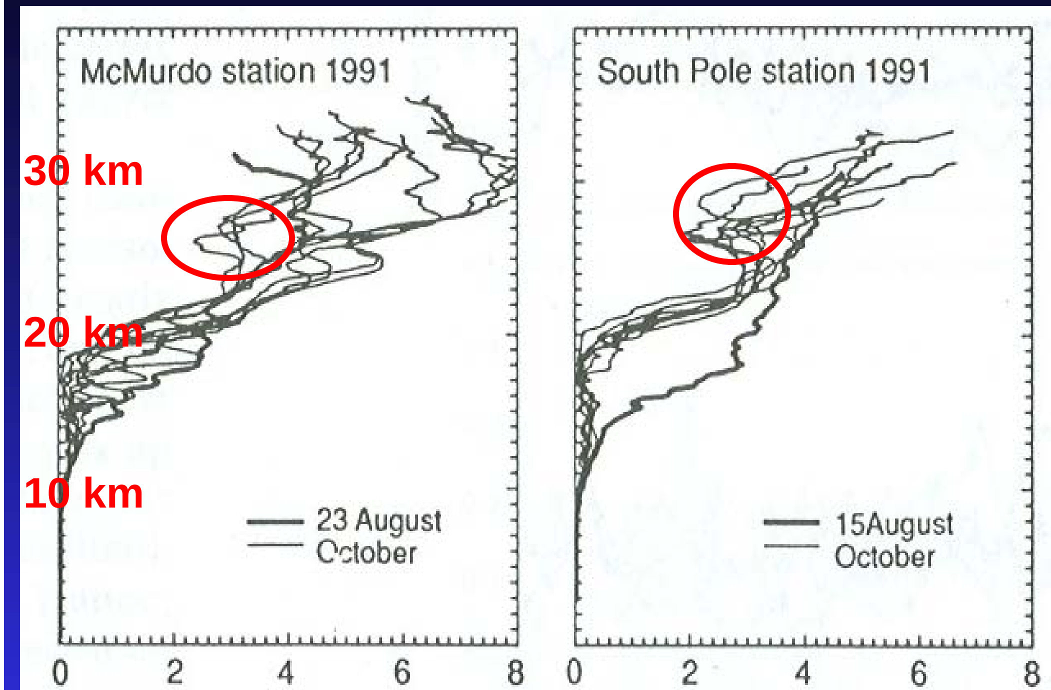
7. Conclusion/Future

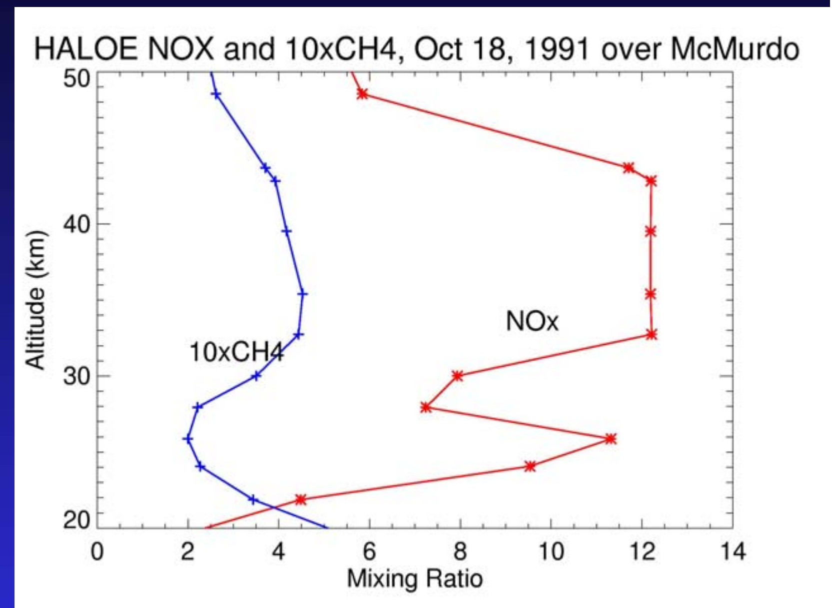
1. Morphology of EPP-IE
   Every year in SH → strong correlation with geomagnetic activity
   Episodically in NH → strong dynamical control
   Source: electrons < 30 keV

2. Impact on stratospheric NOx budget?
   SH: Up to 10% of SH NOx. (more locally?)
   In NH: more dilution. Maybe ½ of SH value?
   Models not ready to answer this (op-ed), some are too high others might be too low

3. The future with more CO_2?
   Randel and Garcia (2007): Transport circulation will speed up
   (Controversial since a test w/ SF6 observations was marginal)
   Sue Solomon (priv. comm, 2009): implies that NOx coupling will increase → more O_3 decr → more feedback on stratosphere
   Why are all these extended SSWs suddenly happening?

Reinterpreting old data



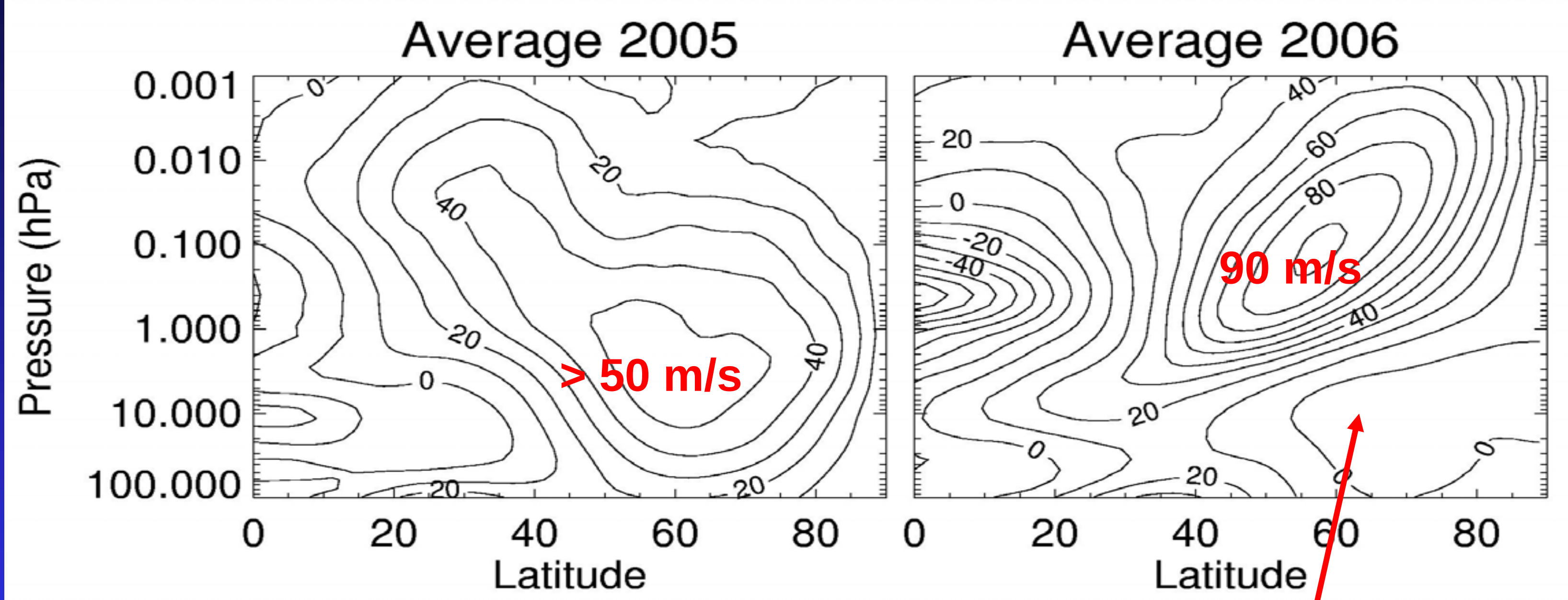


Balloon measurements by Hofmann et al., Nature, 1992. An upward extension of the ozone hole?

No! Enhanced NOx from the upper mesosphere.

Zonal Mean Winds differ from 2005 to 2006

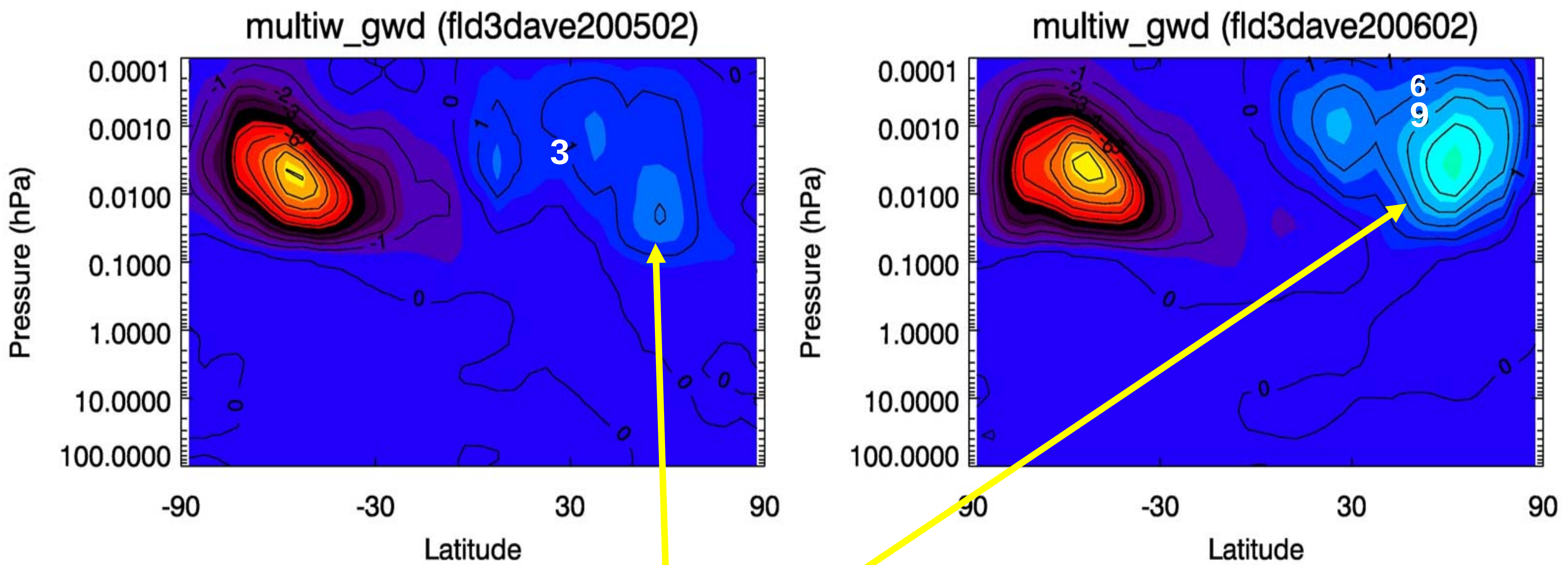
Mean zonal winds from model



Weak winds, gravity waves **(actually mountain waves with zero phase speed)** **will encounter lots of critical lines. Absence of drag allows strong upper level vortex to develop at 0.1 mb (65 km)**

The different character of the background will means the nature of the gravity waves will change dramatically as the SSW progresses

Comparison of GWD for a quiet year and the disturbed year (2005 and 2006)



High altitude drag from fast waves appears in 2006, but were absent in 2005. This is the opposite behavior from the mountain waves.

3. Differences between mesospheric and stratospheric transport- summary

Stratosphere: **planetary wave breaking**

one-sided forcing (always westward). Mostly in winter.

Transport is equator→ pole

Mesosphere: **Gravity wave breaking**

Two-sided (E-ward and W-ward traveling waves)

Filtering by the stratosphere means:

W-ward in winter → to the winter pole

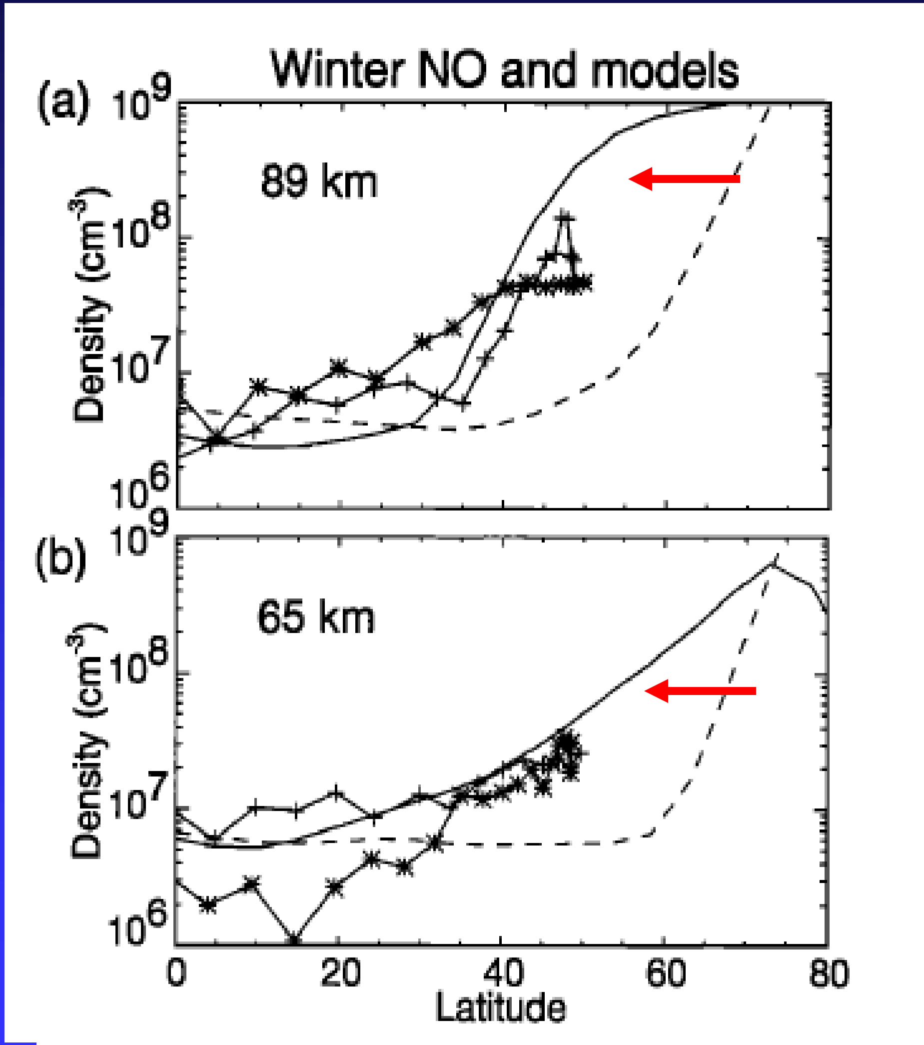
E-ward in summer → to the equator

This makes mesospheric transport “single celled”.

Transport is pole →pole.

Mixing: **breaking planetary waves can pull air out of dark polar regions → NO photolysis and loss**

4. HALOE Data: First the mesosphere,2D model and mixing (parameterized planetary waves), Siskind et al., JGR, 1997)



Horizontal mixing (solid lines) Will bring NOx out of polar night.

→Net effect is more dissociation And less entrainment in the stratosphere

Changing approach to horizontal mixing in 2D model yielded factor of 3 change in NOx entrainment (Siskind et al., AGU monograph, 2000)