State of the Art of Mesospheric Modeling

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Overview: Focus on three dimensional global models → two types

1. Climate models, i.e. WACCM
(Whole Atmosphere Community Climate Model)

2. Weather models, i.e. the NRL NOGAPS-ALPHA model
(Navy Operational Global Atmospheric Prediction System)

- **a. Extension of the Navy's weather model to include middle atm.**
- **b. Case studies of specific events, Sept 2002** (for the stratosphere), **Jan/Feb 2005 vs. 2006** (for the mesosphere)
- **c. Comparison with observations**
- **d. What can this teach us about the atmosphere?**

Summary of 3D models
(which both include and care about the mesosphere)

NAME	DOMAIN	RECENT REFERENCE
CMAM	71 levels, 0 to .0006 hPa	Fomichev et al., JGR, 2004
HAMMONIA	67 levels, 0 to 250 km	Schmidt et al., J. Clim, 2006
LIMA	150 levels, 30-150 km	Berger and Lubken, GRL, 2006
NOGAPS-ALPHA	60-74 levels, 0 to .005-.0005 hPa	Siskind et al., GRL, 2007
ROSE	64 levels, 90 hPa to 188 km	Smith and Marsh, JGR, 2005
TIMEGCM	45 levels, 30 to ~500 km	Liu and Roble, JGR, 2002
WACCM	66 levels, 0 to 4.5e-6 hPa	Garcia et al., JGR, 2007
SMLTM	16 km – 200 km (1/2 scale ht res.)	Akmaev et al., JASTP, 2006
IDEA (NOAA/CU)	0-600 km	none yet?

See Eyring et al., JGR, 2006 for long list of models which may have tops at .01 hPa, but don't really consider the mesosphere

Comparing a climate with a weather model

Parameter\Model → ↓	WACCM	NOGAPS-ALPHA
Vertical Domain	***Slightly greater vertical domain*** 0-~145 km, vertical res: 1 – 3.5 km	0 - ~115 km vertical res: 0.5 – 2 km
Horizontal Domain	Either 1.9 x 2.5 or 4 x 5 degrees	***greater spatial resolution*** either 1.5 or 0.5 deg (T79 or T239 spectral)
Physics/chemistry	MOZART (complete ozone chemistry) Molecular diffusion Complete SW heating (EUV, FUV and UV) NLTE LW cooling above 65 km (CO2,NO) Auroral processes (ion drag, joule heating) Parameterized gravity waves	Parameterized (and operational $O_{3)}$ NLTE cooling above 75 km New: WACCM GW param Future: SW and chemical heating
Forcing	Tropospheric values of chemical tracers Monthly SSTs F107-based solar flux All going back to 1950	Temps every 6 hours from NAVDAS assimilation (only up to 10 mb, merge to CIRA above that level) Daily SST, ice, snow fields O_3 from Goddard assim.

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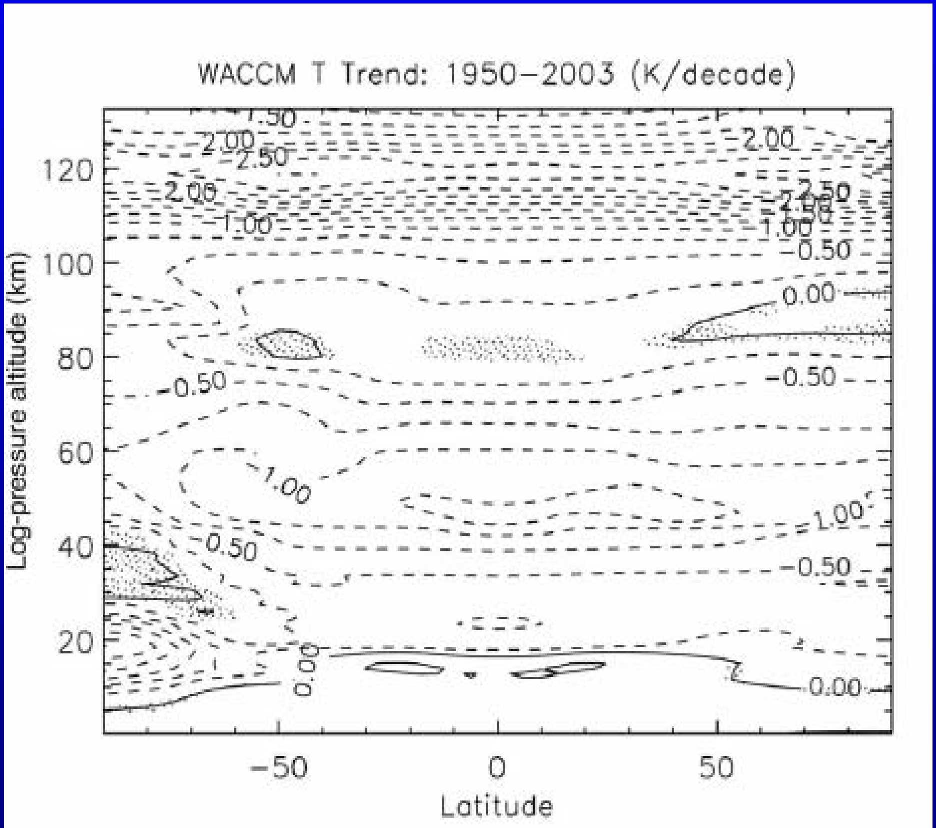
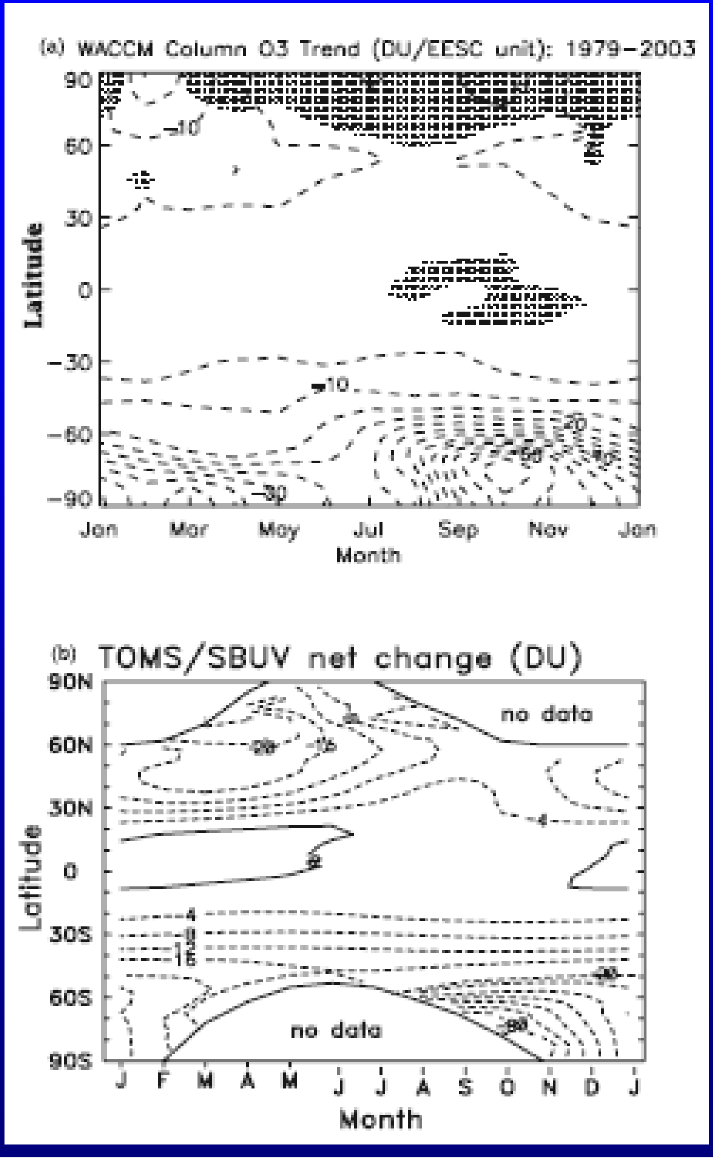
Summary of WACCM applications- trend studies
(temperature, ozone, water vapor)

WACCM: Simulation of secular trends in the middle atmosphere, 1950-2003 (Garcia et al)

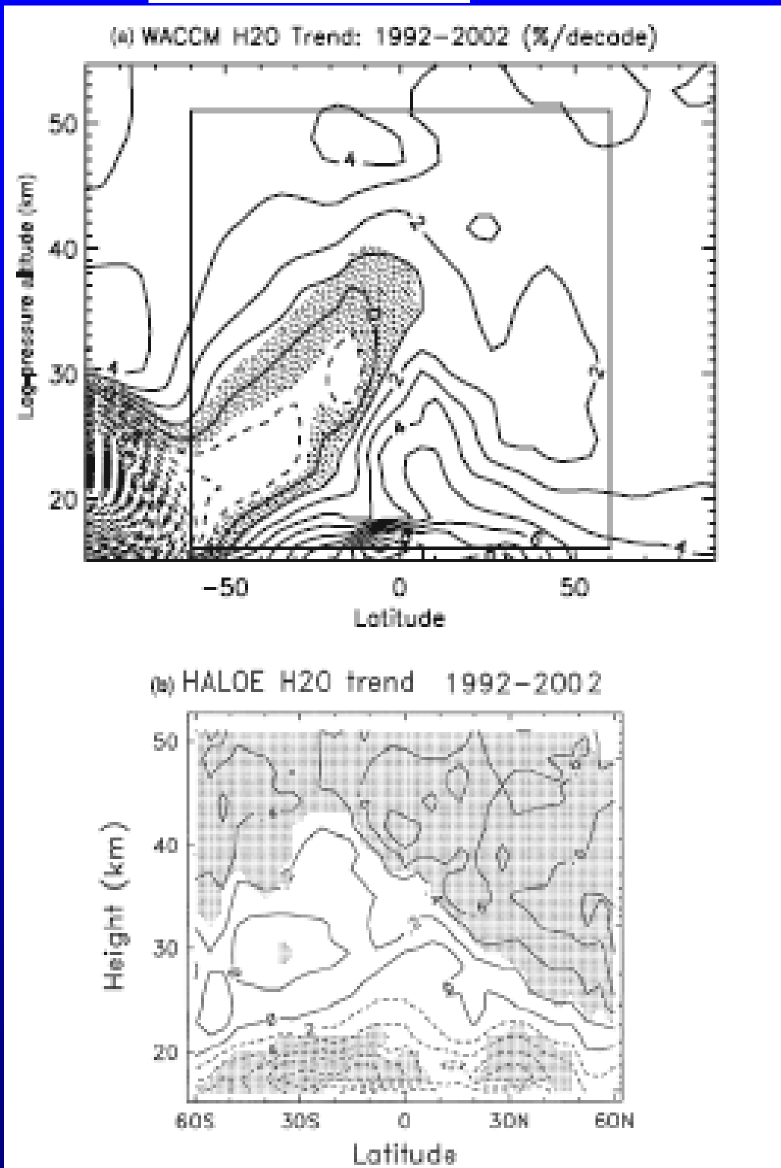
Temperature



Ozone



Water Vapor



Summary

Temp, ozone trends generally are consistent with observations.

Water vapor trends are not → possibly due to missing low frequency variations from the QBO, volcanoes, and El Nino which confound trend studies unless 50 years of data are used (which we don't have)

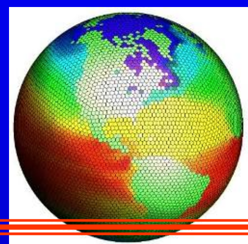
Combination of T and H_2O trends will be able to drive a PMC parameterization to look at PMC trends over the last 50 years (although the implication is that interpreting decadel trends is much more complicated)

Nomenclature: NOGAPS and NOGAPS-ALPHA

ANALYSIS

"Best" Estimate of the Current Global Atmospheric State

Global Forecast Model



Short Term (0-6 hour) Forecasts

+1 day *+2 days* *+3 days….*

Longer Term Forecasts

must complete in <6 hours of real ("wallclock") time

FNMOC: <20 min per forecast day

NOGAPS-ALPHA development

Short Term Forecast Error Estimates

Statistical Global "Data Assimilation" System (NAVDAS)

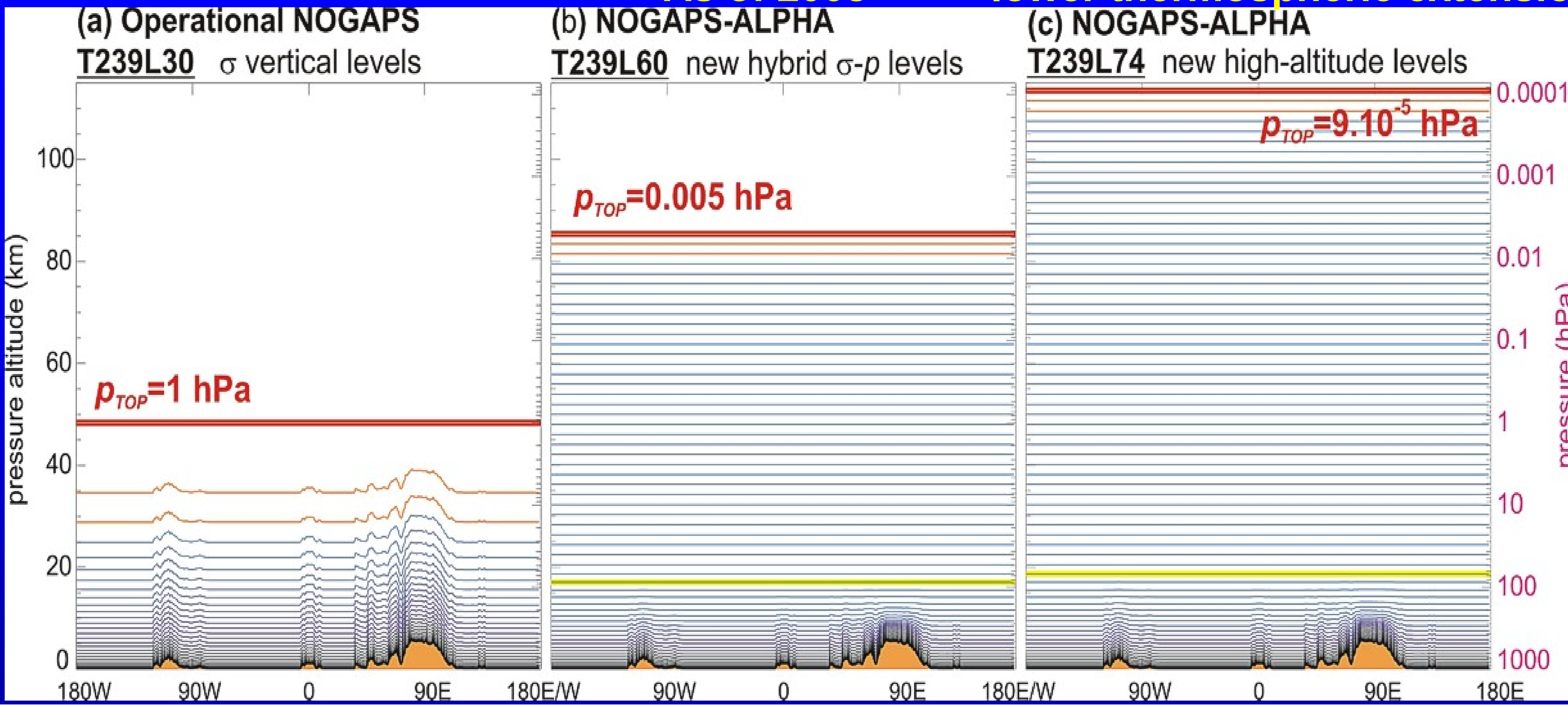
Data Quality Control & Errors/Biases

Global Observations come in the next 0-6 hours

NOGAPS-ALPHA (Advanced Level Physics High Altitude),

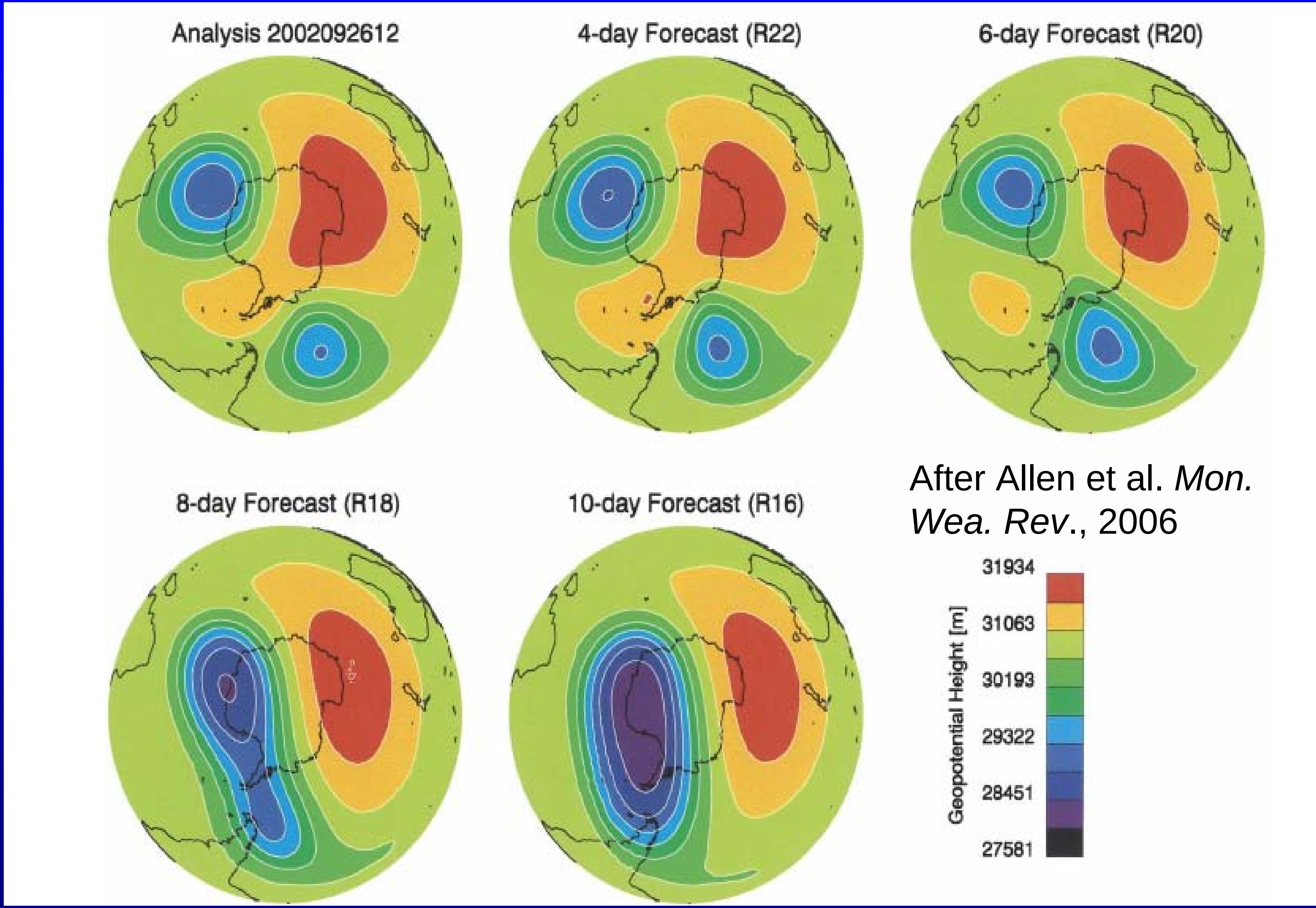
Steve Eckermann, J. McCormack, L.Coy

As of 2005 lower thermospheric extension



- new hybrid *σ-p* vertical coordinate specified to maintain smooth vertical layer thickness profiles over all topography; increased vertical domain
- better vertical resolution in middle atmosphere
- new physics packages (short wave (MUV) heating, prognostic ozone)
- non-LTE cooling (Fomichev) extends model to 110-115 km (74 levels)
- non-zero phase speed gravity waves (shown for the 1st time here)

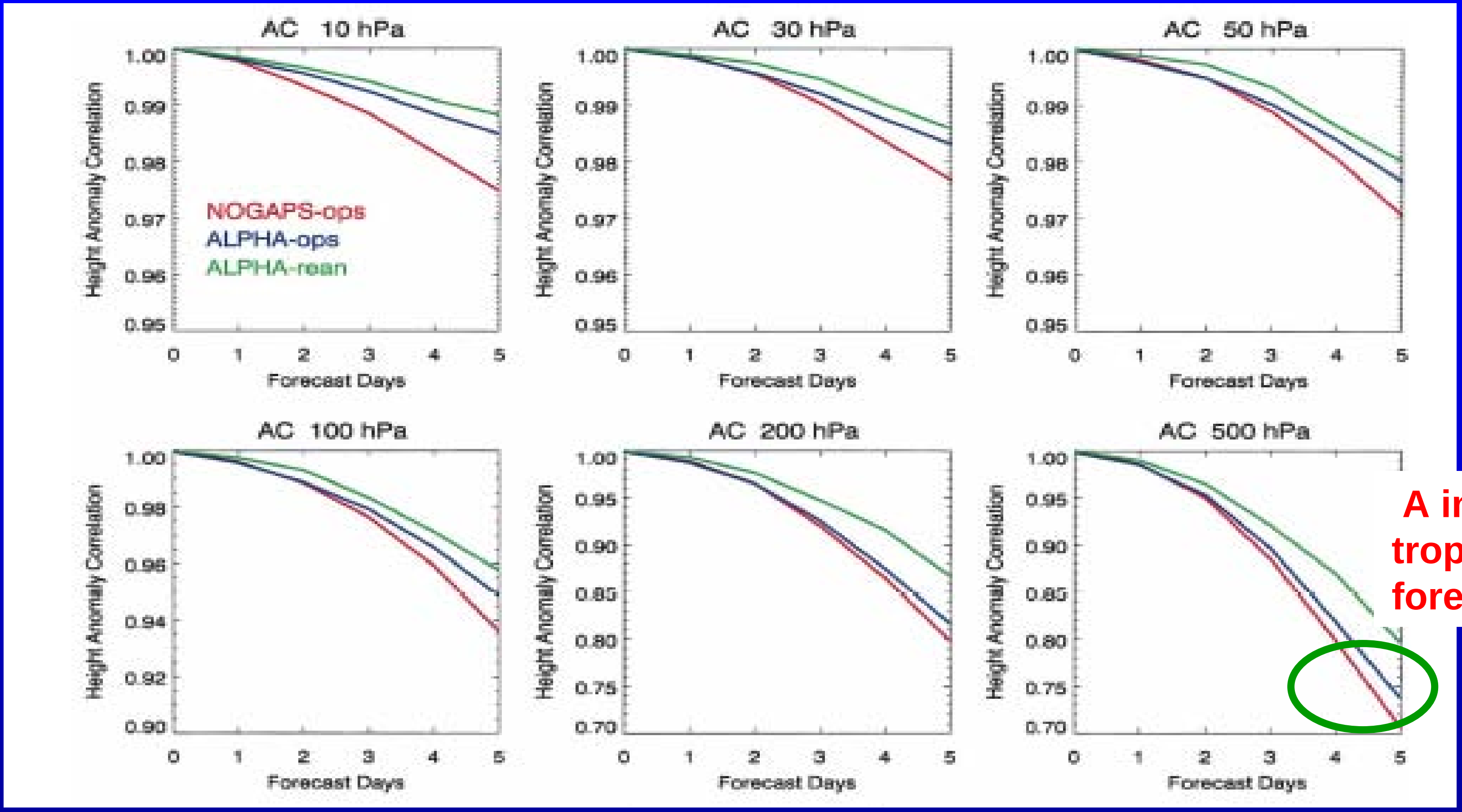
Stratospheric Weather Forecasting: Analysis of 10 mb Temperature on 26 September 2002



After Allen et al. *Mon. Wea. Rev*., 2006

Impact on Weather Forecasting

Skill Scores: Geopotential Height Anomaly Correlation



A improved tropospheric forecast!

NOGAPS-ops	→	ALPHA-ops	→	ALPHA-rean
NOGAPS T239L30 initialized with MVOI analysis		NOGAPS-ALPHA T239L54 initialized with MVOI analysis		NOGAPS-ALPHA T239L54 initialized with NAVDAS reanalysis

Allen et al., Monthly Weather Review, 134, 498-518, 2006.

CHEM2D-OPP: A fast Linear O3 parameterization
(from 2D model with complete chemistry)

The *current operational ozone* scheme in NCEP/GFS (as of 8/22/06)
(also transitioned to FNMOC for creating fully prognostic ozone in NOGAPS)

Tested in several different global ozone assimilation systems:

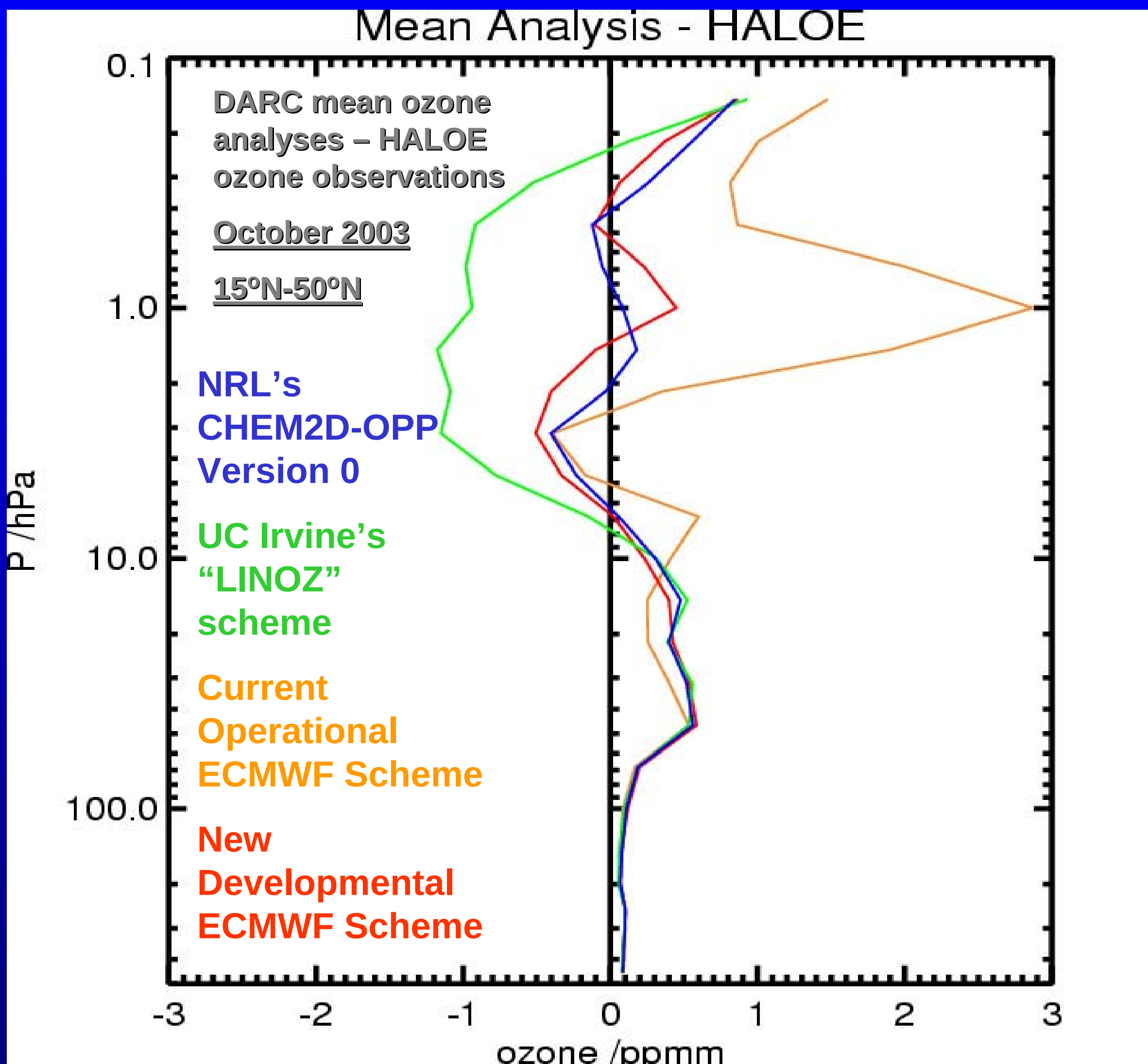
1. NRL's new Global Ozone Assimilation & Testing System (GOATS) . *Coy et al., ACPD,2006*

2. Univ. of Reading Data Assimilation Research Centre (DARC) system, *Geer et al., ACPD, 2006.*

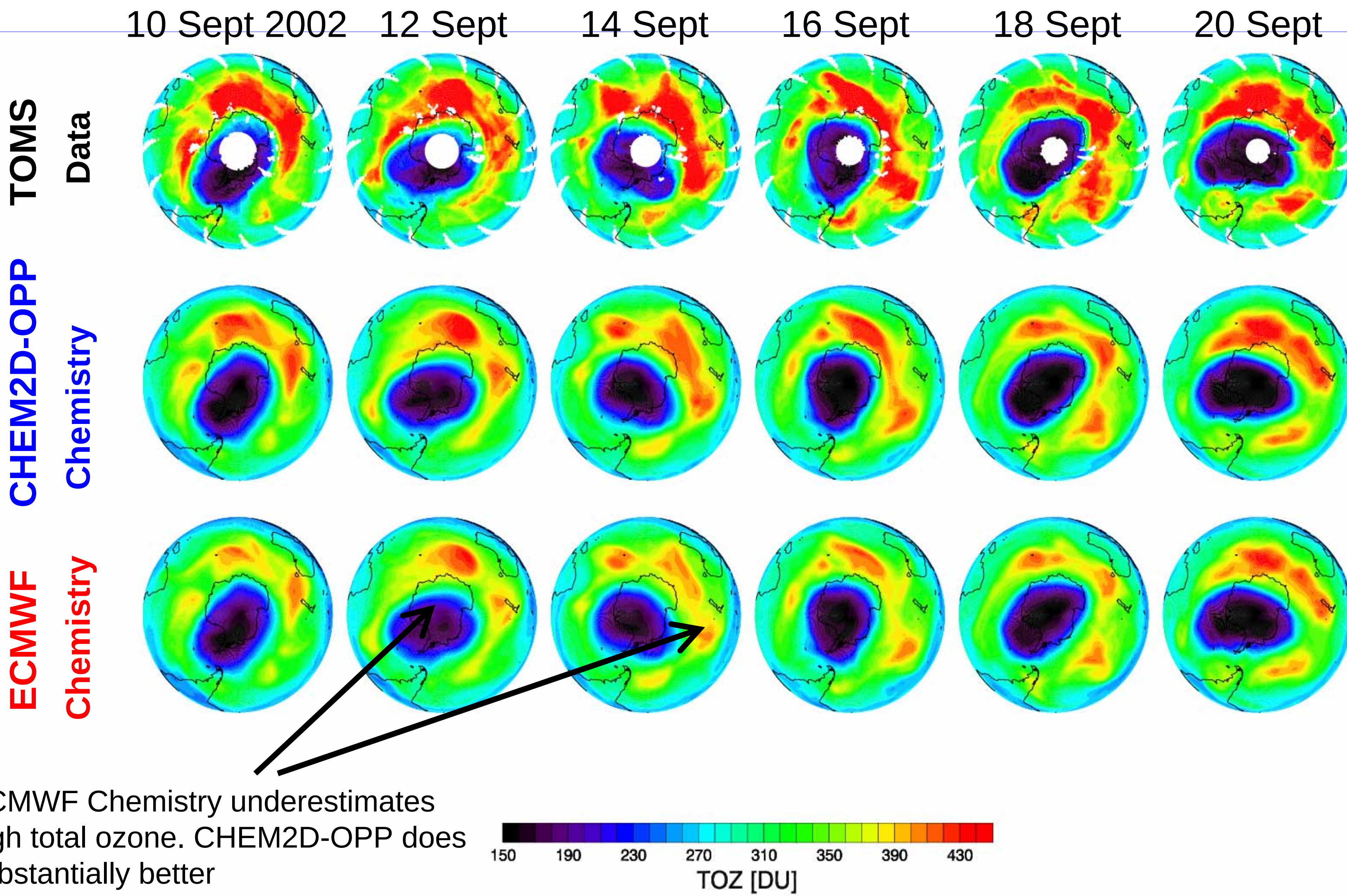
3. NCEP/GFS, JCSDA newsletter June 2006

4. Developmental CHEM2D-OPP versions consistently outperform existing "fast ozone" schemes of the ECMWF, NASA Goddard, & UC Irvine, *McCormack et al, ACP, 2006*

Recommended as the preferred ozone scheme in the UKMO/DARC model [*Geer et al., QJRMS, 2006*]



Ozone Data Assimilation Tests Using NOGAPS-ALPHA with CHEM2D-OPP and ECMWF Chemistry



ECMWF Chemistry underestimates high total ozone. CHEM2D-OPP does substantially better

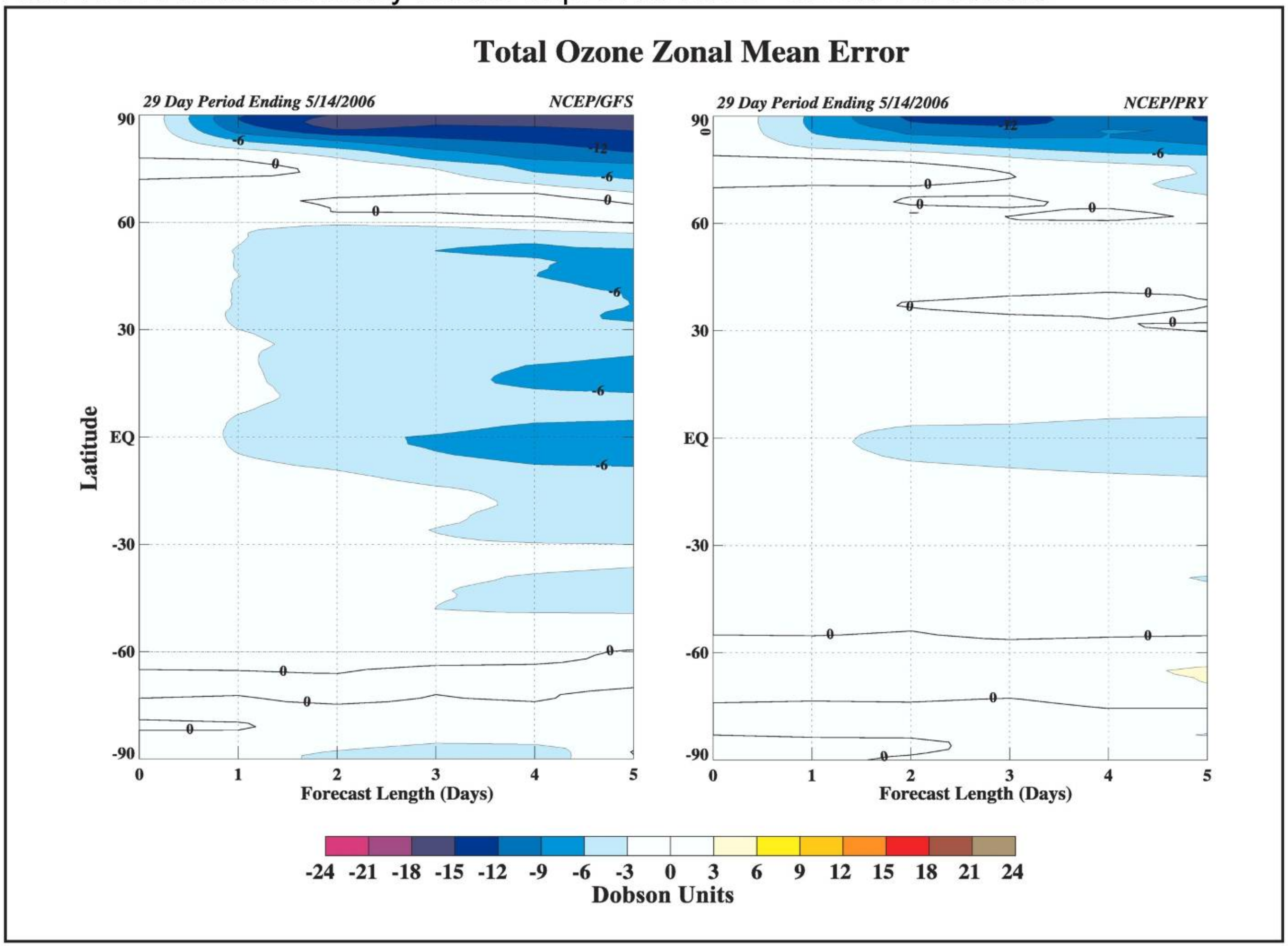
Report from the JCSDA

June, 2006 quarterly newsletter

JCSDA Quarterly No. 15, June 2006

Operational in the National Weather Service GFS, 8/22/06

New NRL Photochemistry Model Improves NCEP Ozone Forecasts



CEDAR Tutorial #2, June 07
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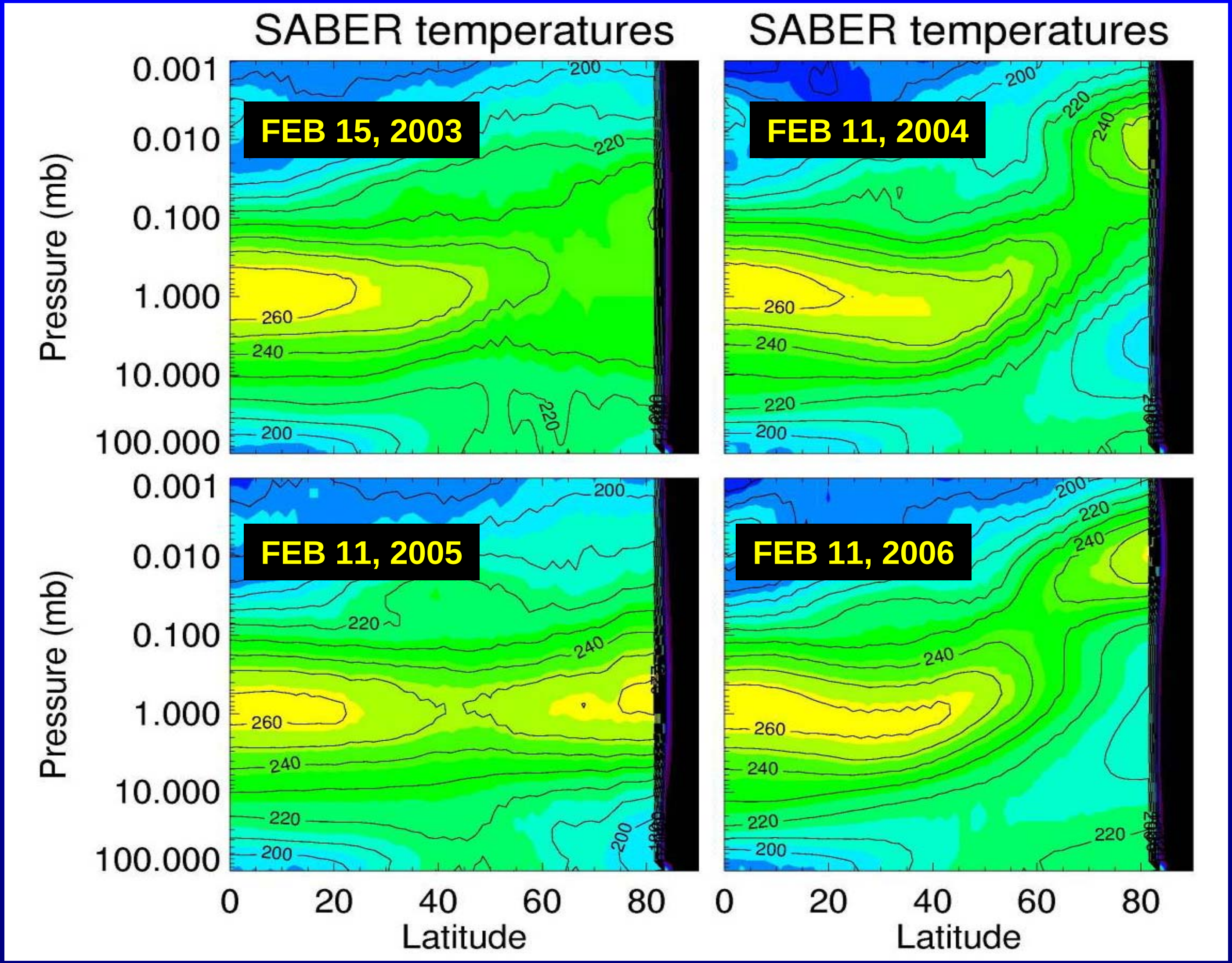
Mesospheric Interannual Variability
from SABER IR instrument on NASA/TIMED satellite

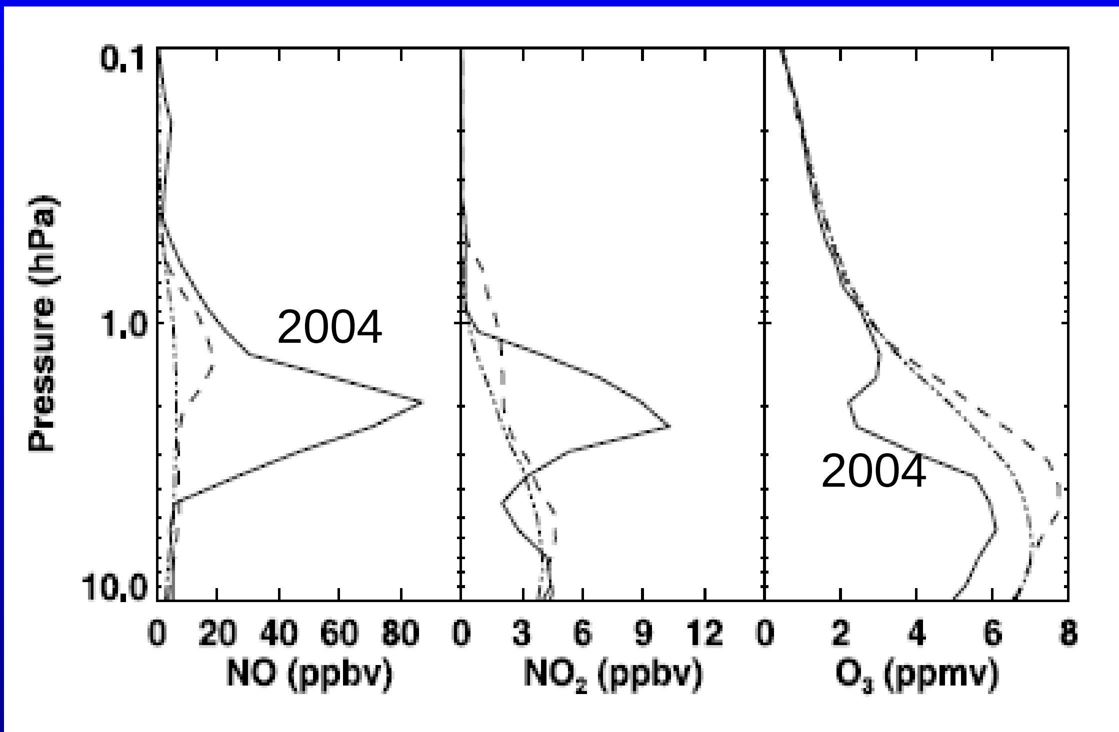
Normal years (215-220K at 75 km)

Anomalous years (240-250K at 75 km)

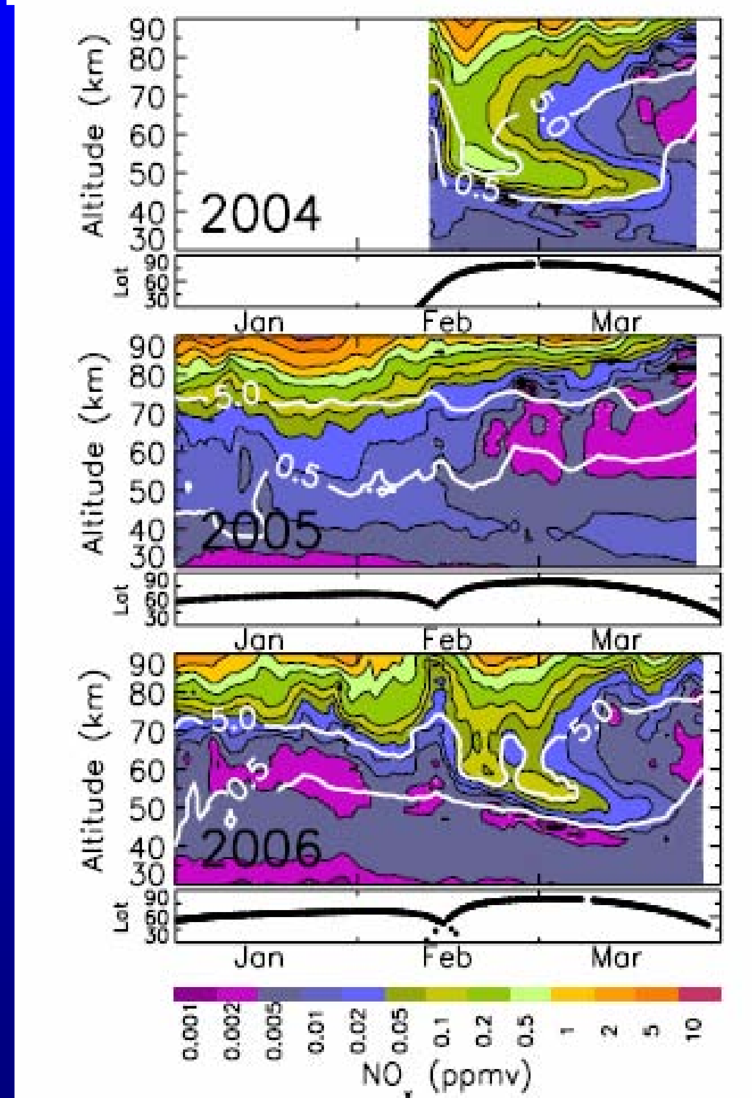


Unusual NOx enhancements- descent from above

HALOE profiles
(Natarajan et al., GRL, 2004)



3 Years of NO and CO from ACE
(Randall et al.. GRL 2006)



NOGAPS ALPHA simulations

Can NOGAPS explain this unusual temperature structure?
Can the model provide a link between this structure and the descent of thermospheric NO into the stratosphere?

Cold start initialization: Jan 31, 2005 and 2006.
Free running GCM for 2 weeks, T79 resolution 1.5^o resolution, L74
Also some T239 calculations (0.5^o resolution)

Three GW drag approaches

1) Test three orographic (mountain wave) parameterizations

- **a) Nothing: Usually least realistic. Zonal winds generally become unacceptably large**
- **b) Rayleigh friction: forces drag on zonal wind to mimic gravity waves- usually better than nothing, (except here)**
- **c) A realistic orographic scheme (Palmer et al): Accounts for location of mountain wave sources and filtering by zonal winds, state of the art for tropospheric systems 10-15 years ago**

The above results were recently published in GRL (Siskind et al., May 07)

2) High resolution without parameterization

3) WACCM scheme for non-orographic waves

effects of spectral width, efficiency, flux

Some background on mountain waves
(Eckermann and Preusse, Science, 1999)

- the Cryogenic Infrared Spectrometers and Telescopes for the Atmosphere (CRISTA) and NRL's MAHRSI instrument were deployed into orbit on the Shuttle Pallet Satellite (SPAS) by Atlantis during STS-66 (November, 1994).
- this is shown in photo in panel A, taken over southern South America (see panel C) on Nov 4, 1994. Banded wave clouds can see seen downstream of the Andean Ridge
- Two days later (Nov 6, 1994) CRISTA acquired sequence of stratospheric temperature profiles over this region (labeled 1,2,3 in panels B and C)
- various tests prove the oscillations in measured temperatures panel B are mountain waves: e.g.,

theoretical vertical wavelength

$$(\lambda_z)_{theory} = \frac{2\pi\bar{U}}{N}$$

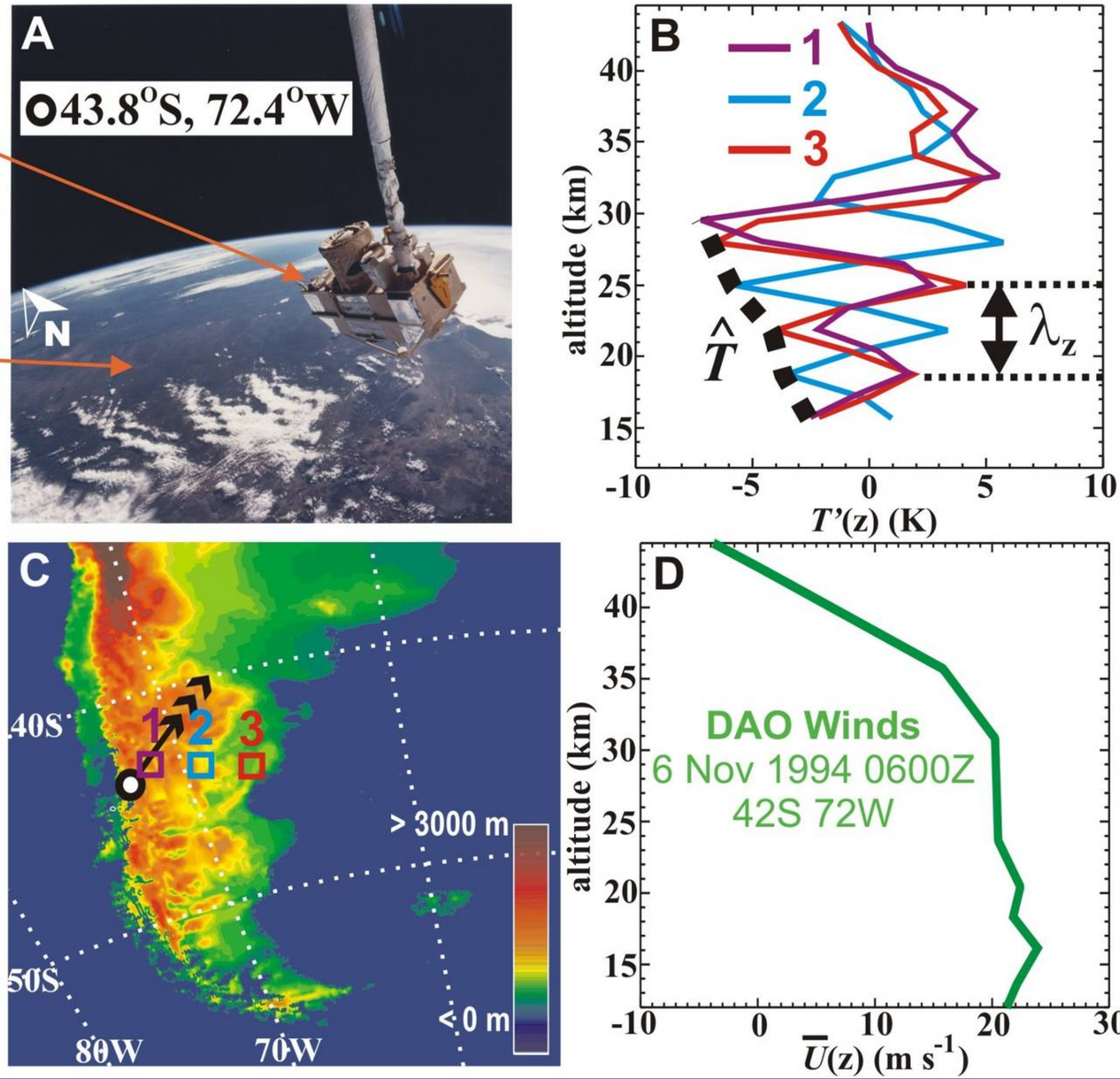
Background wind speed perp. to ridge ($\bar{U}$); Background Brunt-Vaisala frequency (N)

At 42°S, $\bar{U} \sim 20\text{-}23$ m s^{-1}, $N \sim 0.02$ rad s^{-1} (see panel D)

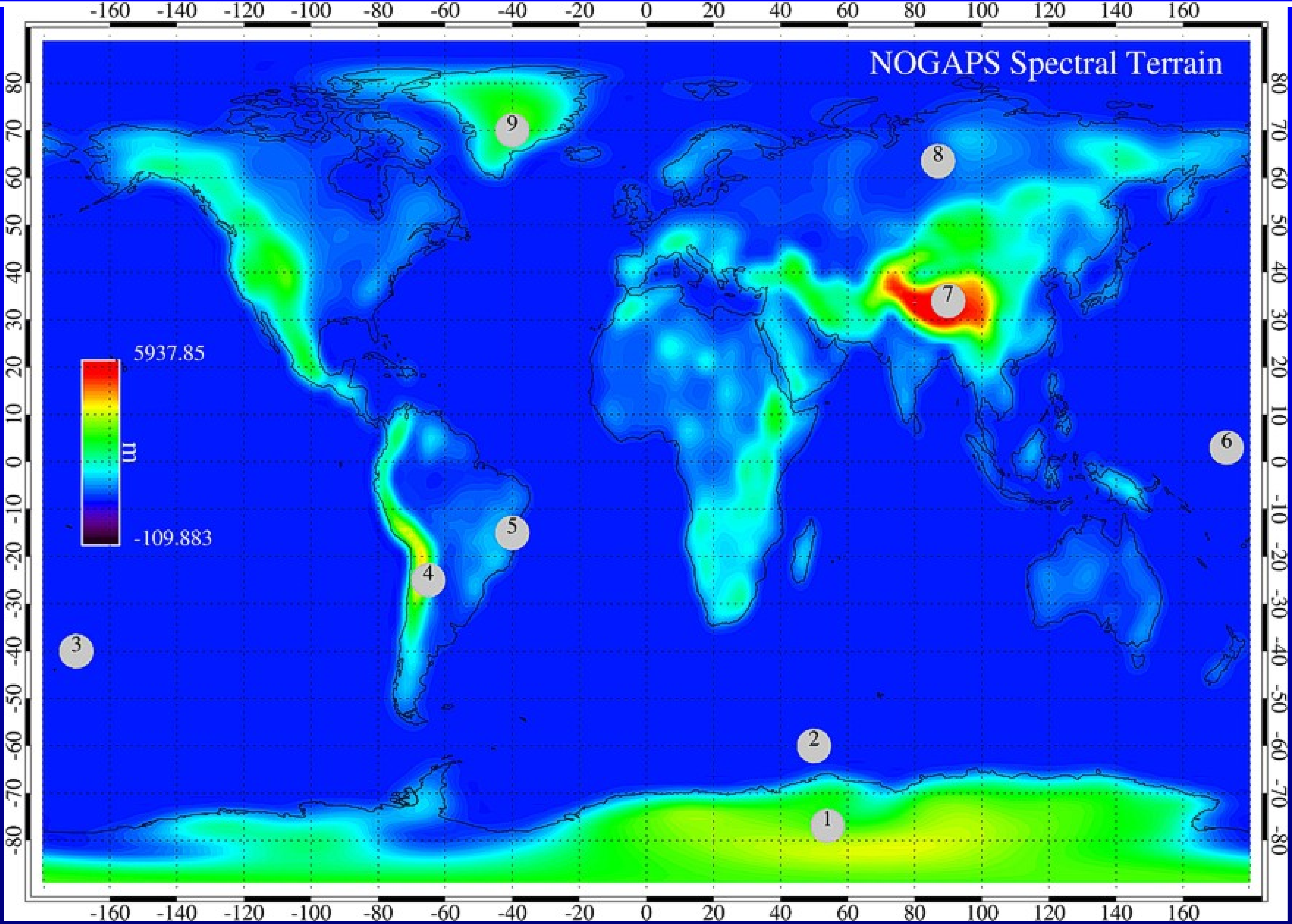
$$(\lambda_z)_{theory} \sim 6\text{-}7 \text{ km}$$

Measured CRISTA T'(z) Perturbations from inspection of panel B

$$\lambda_z \sim 6.5 \text{ km}$$

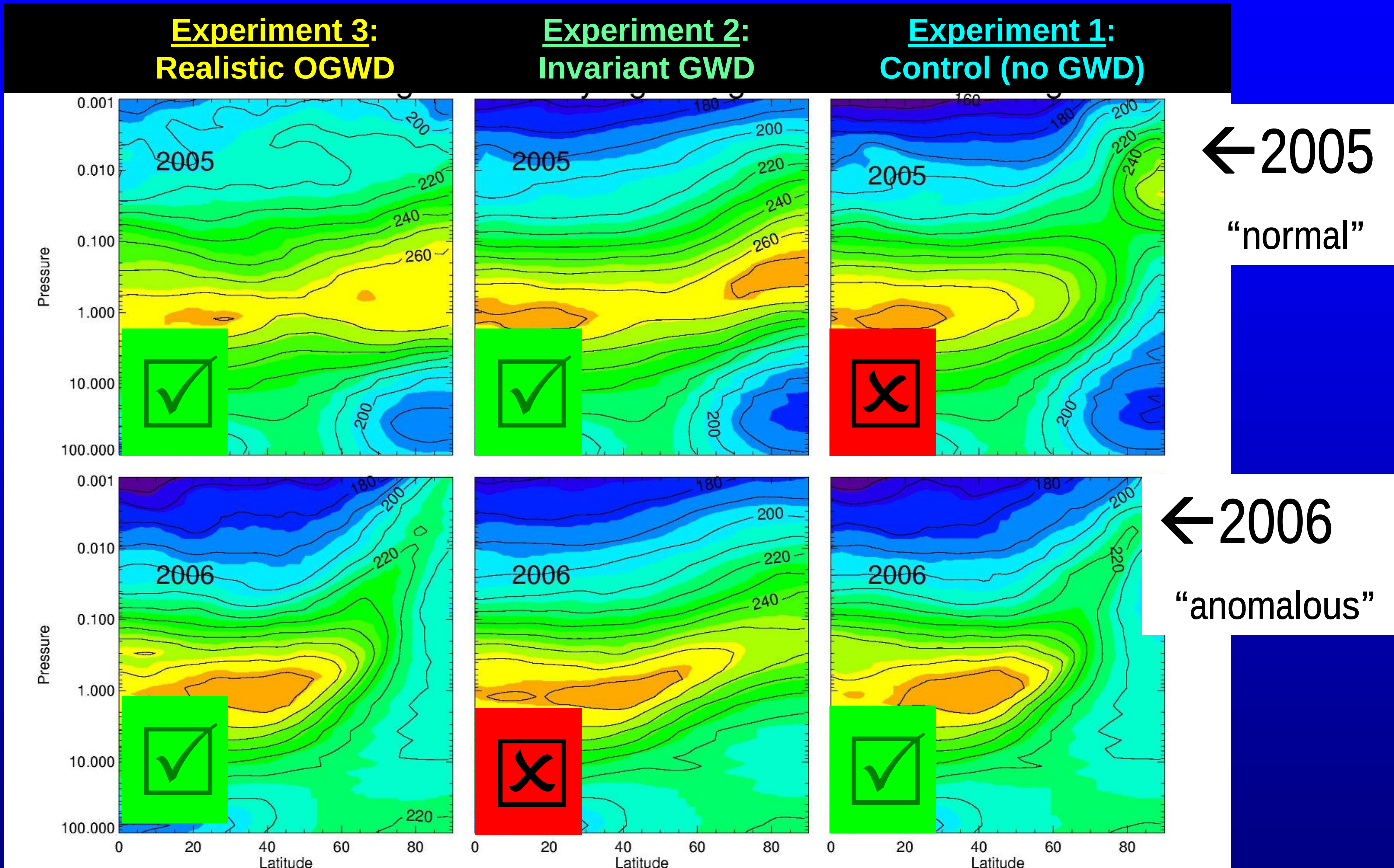


Spectral Terrain for Orographic Parameterization



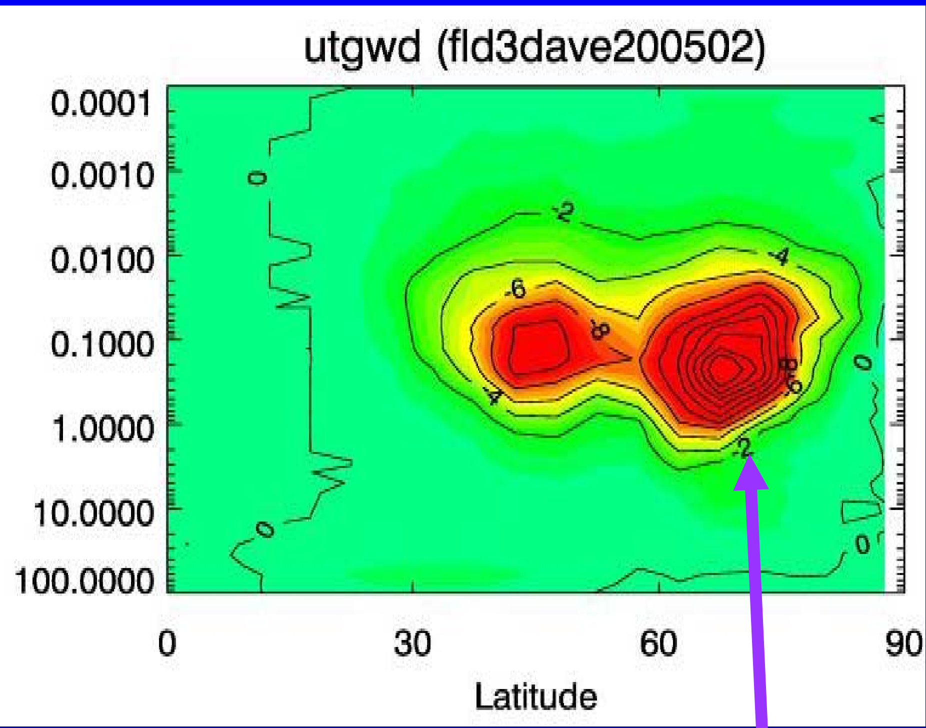
#1. Results of 6 simulations:

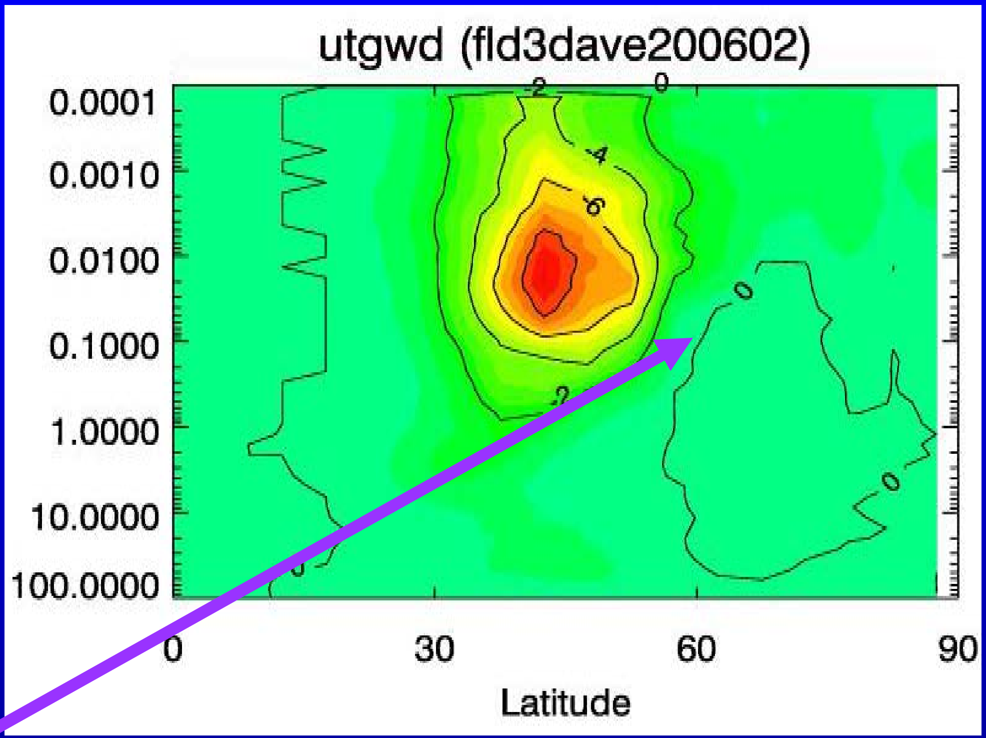
3 parameterizations x 2 years



Suggests "anomalous" 2006 due to heavily suppressed mesospheric OGWD

Test Hypothesis: Zonal Mean GWD





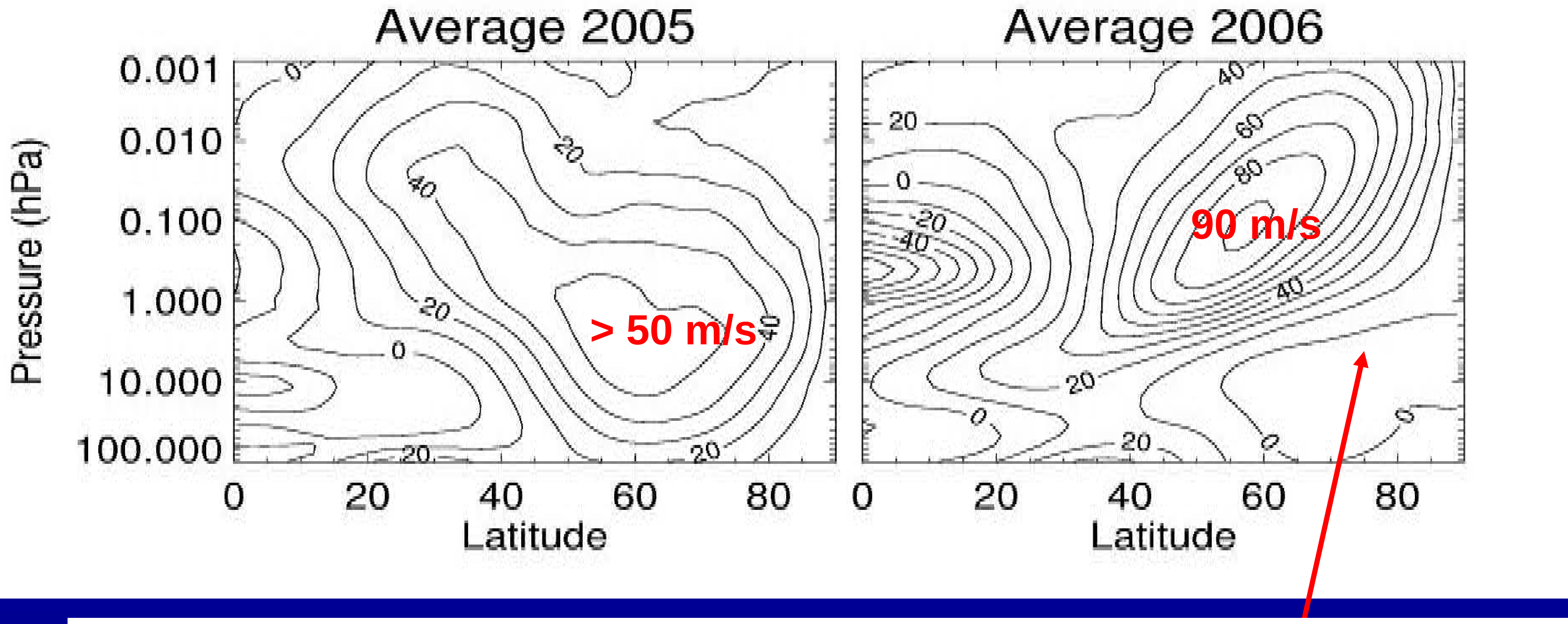
Much weaker GWD in 2006 occurs (and ~15 km higher than in 2005)
→no lower mesospheric drag poleward of 60N

Why?

Zonal mean winds

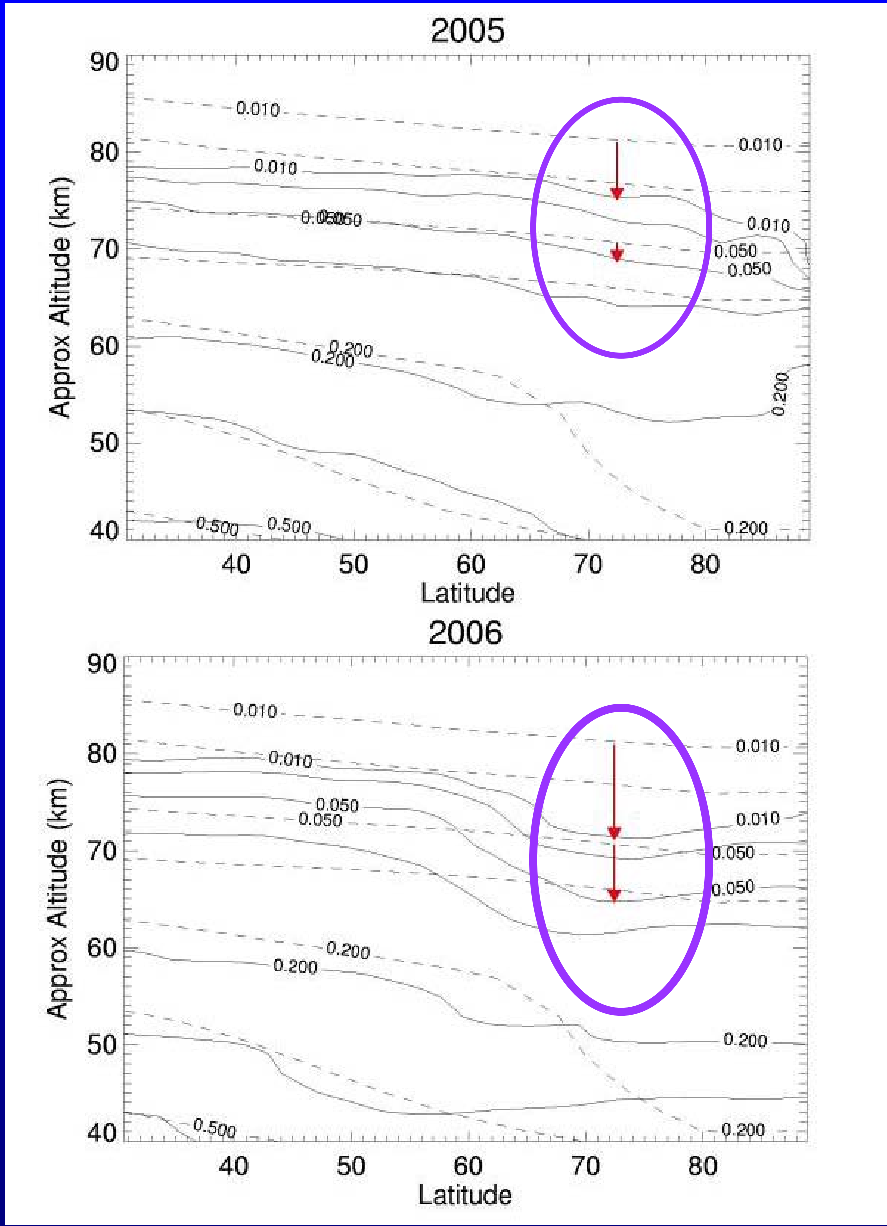
In 2005, Rayleigh friction is better than doing nothing, (Palmer et al drag is best)
In 2006, doing nothing is better than Rayleigh friction- unusual!
This suggests an absence of mountain waves in 2006

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)

Calculated *net* tracer Descent:
Greater in 2006 than in 2005



NOGAPS CH_4 is Initialized with the dashed lines.
("pseudo-CH_4": like CH_4 in distribution and chemistry, but initialized only with 2D climatology)

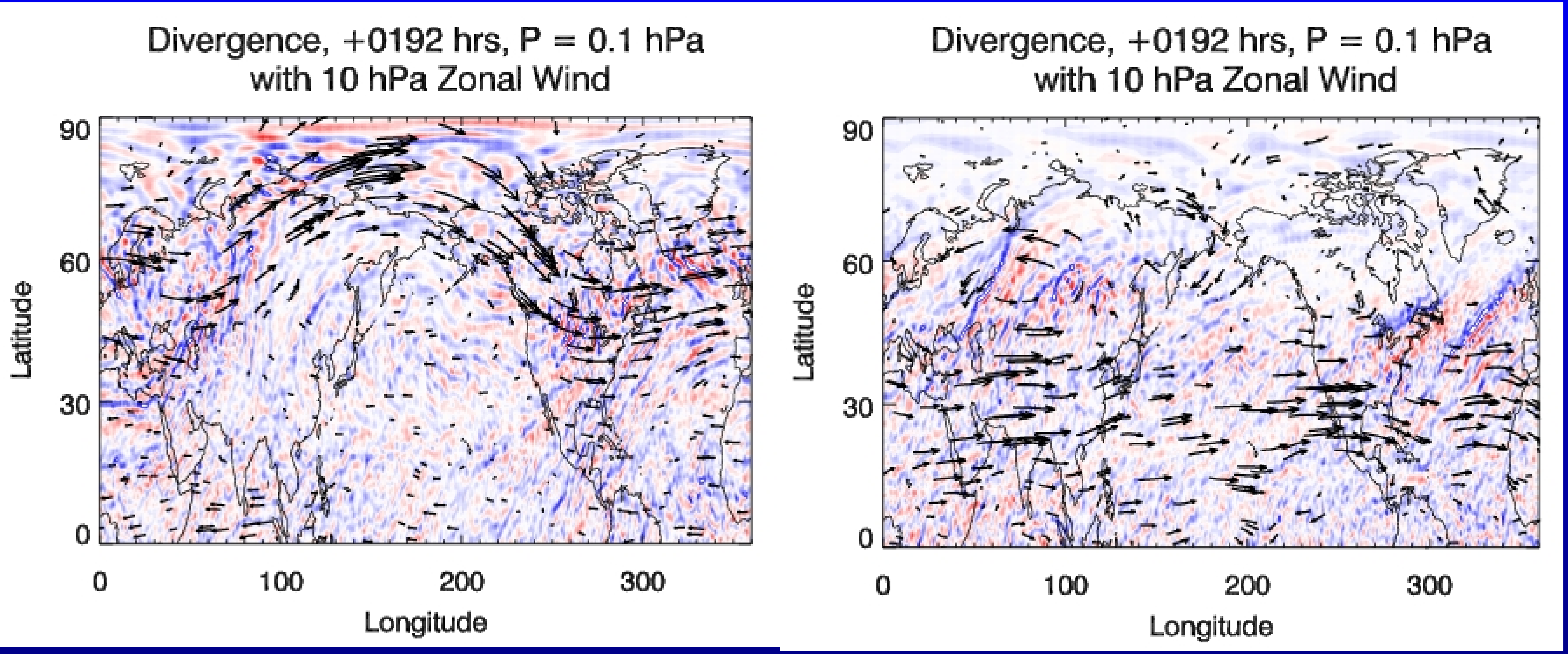
.01 ppmv contour:
descends 10 km in 2006
only 4 km in 2005

.05 ppmv contour
descends 6 km in 2006
only 2 km in 2005

#2. A high resolution view of gravity waves (65 km)

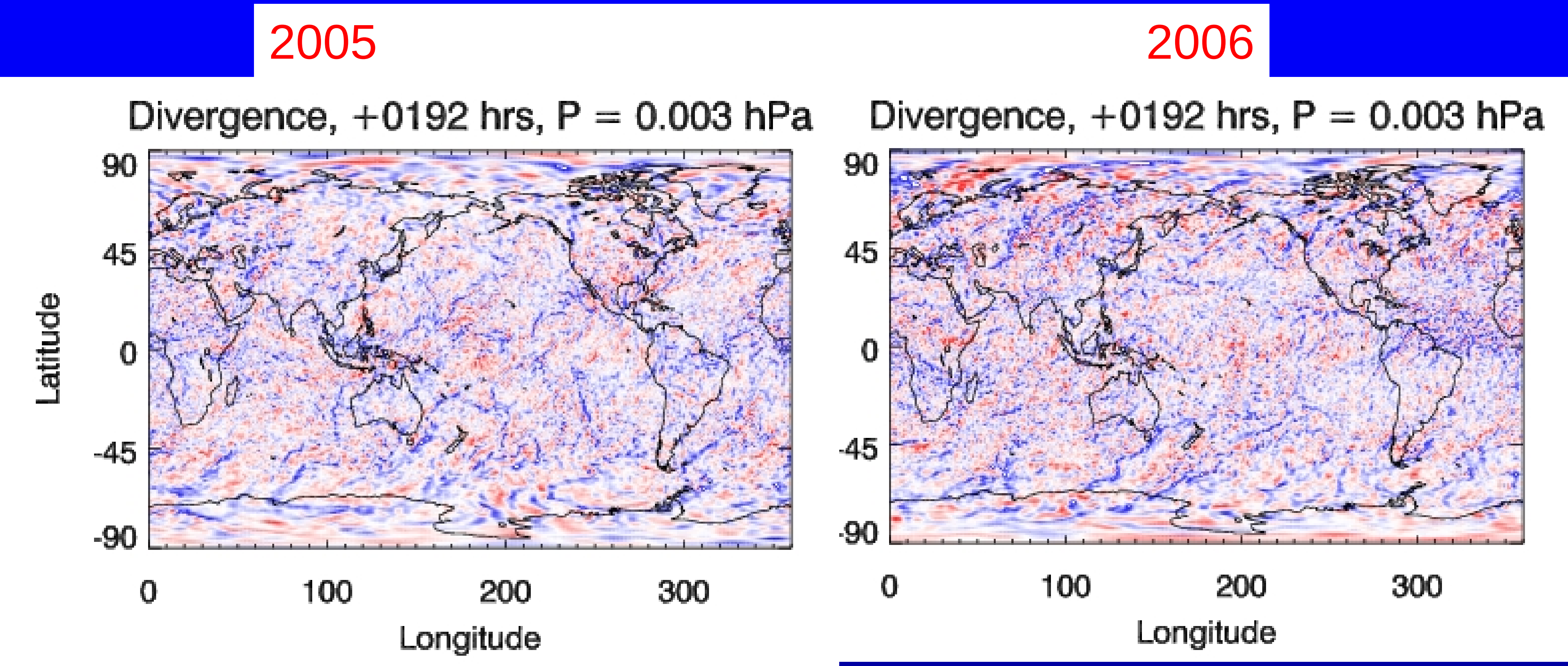
Resolved waves in T239 simulation to compare with T79 parameterization

2005 2006



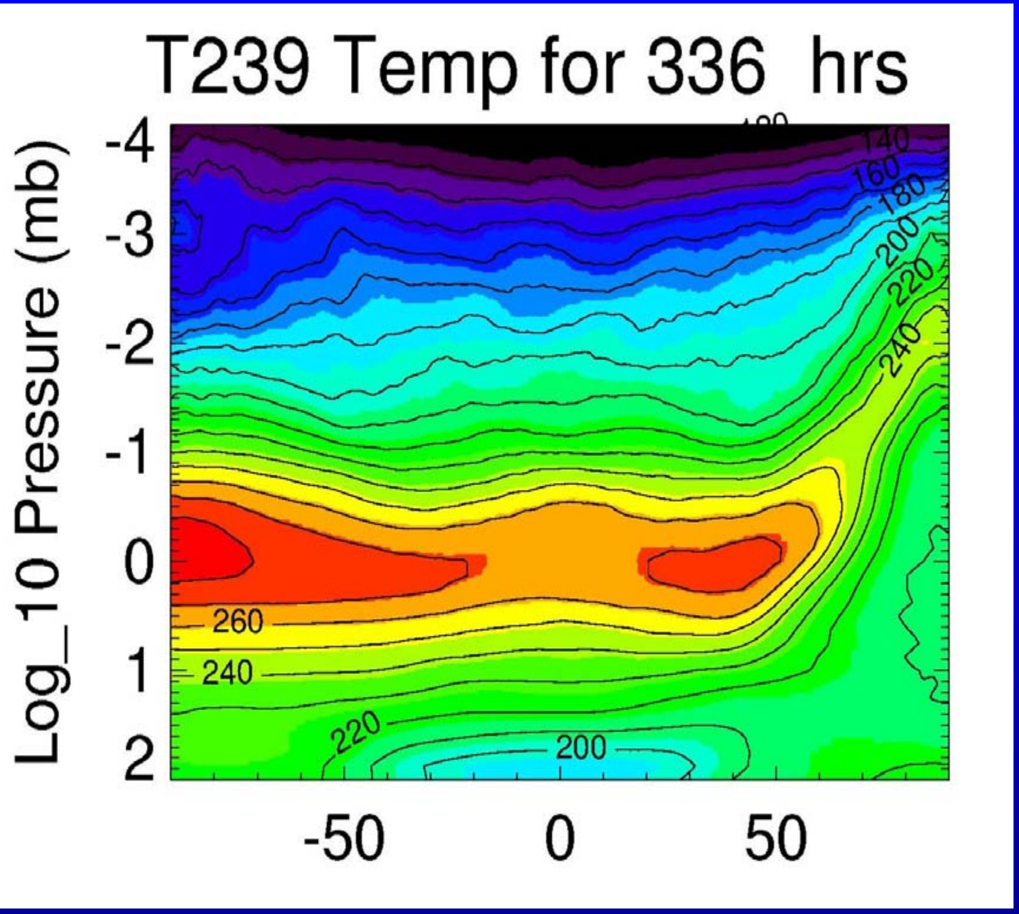
Gravity waves suppressed poleward of 60N in 2006, by weak stratospheric winds

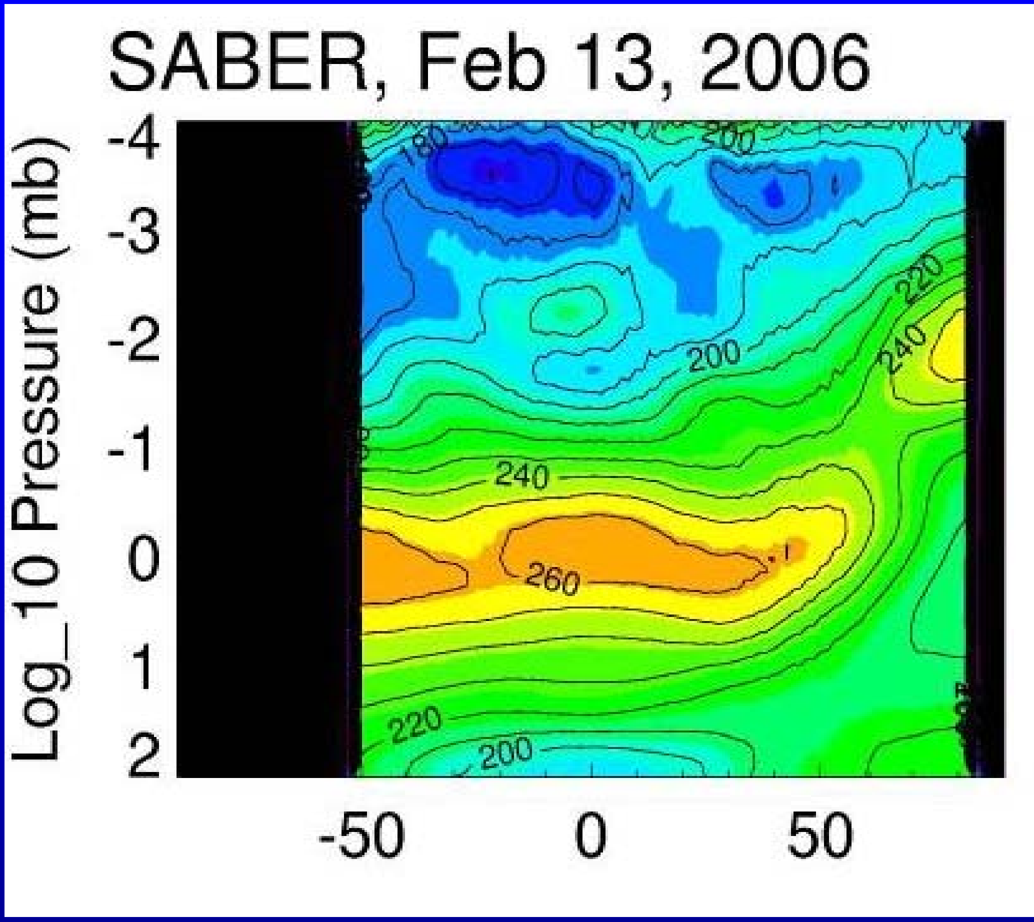
#2. High resolution gravity waves (85 km)



At the higher altitudes, it appears that there are more waves in 2006. Why? non-orographic waves?

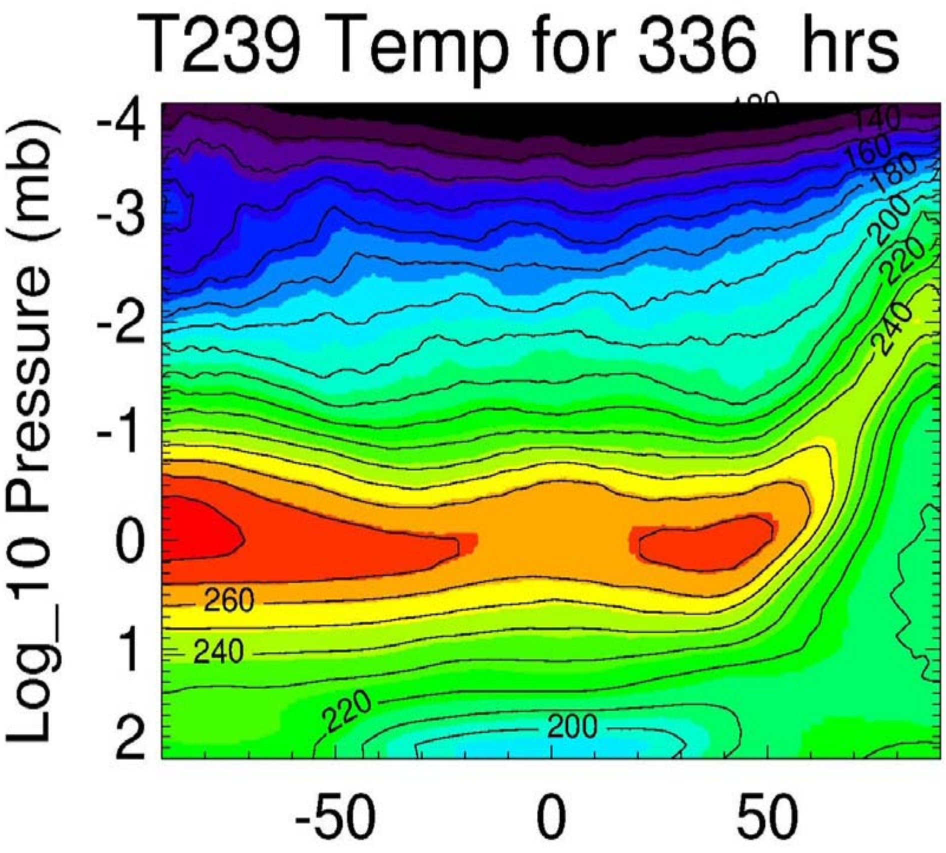
#2. Zonal mean temps: T239 simulation vs. SABER (no GWD parameterization- only whatever the model resolves)

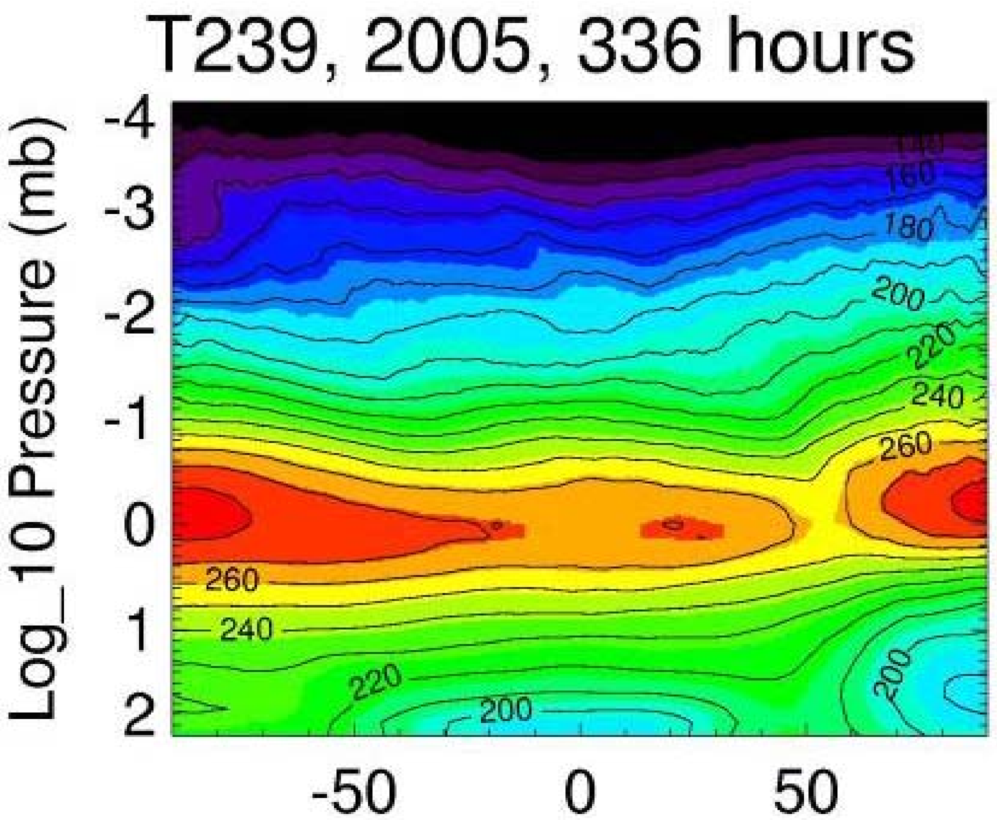




1. Displaced Stratopause is reproduced at correct altitude (still ~ 15K too cold)
2. Hints of a cold summer mesopause, but not well defined.
3. Summer/low-lat stratopause discrepancy → initial conditions?

Differences with 2005





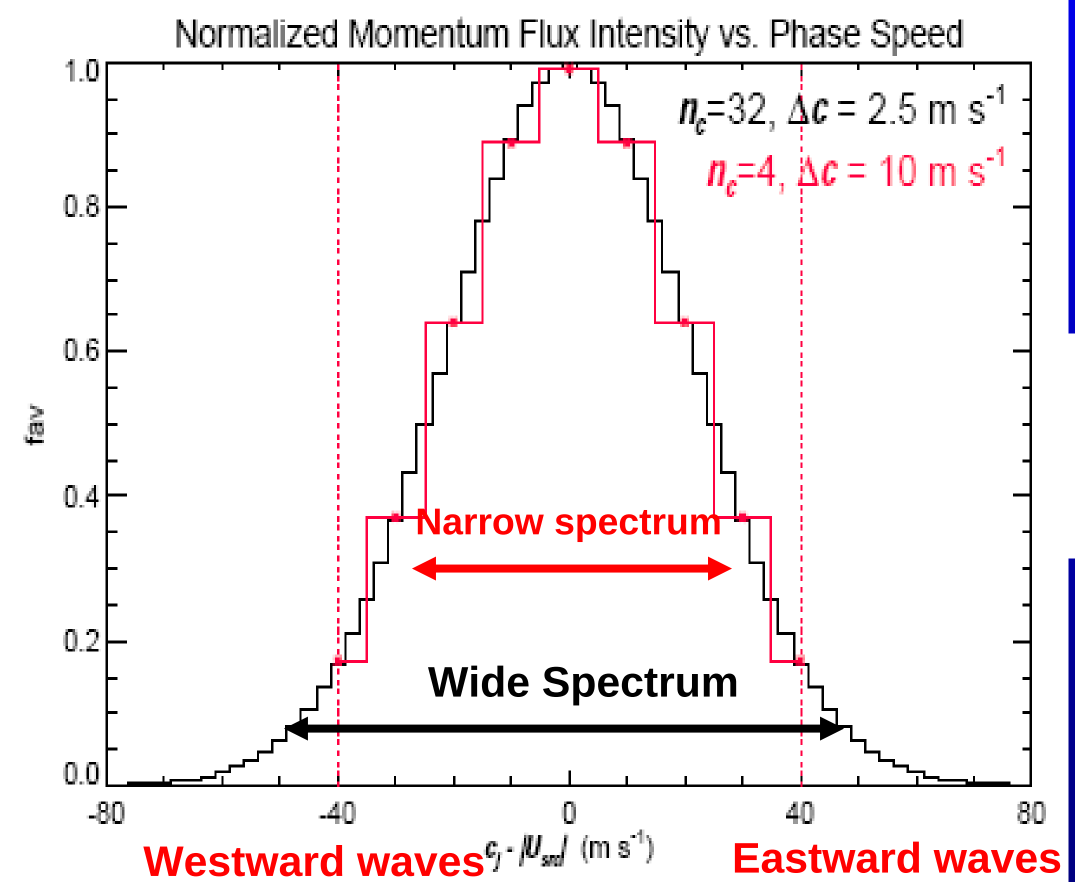
Resolved waves capture the interannual variability. The 2005 simulation remains too cold
In the lowermost stratosphere and too warm at the stratopause.
Also neither simulation shows a well defined cold summer mesopause.

#3. Testing WACCM Gravity Wave Drag Scheme for NOGAPS-ALPHA

A gravity wave spectrum can be included by setting the number of waves to be greater than zero. In that case,

$$\tau_s(c_\ell) = \tau_b \exp\left[-\left(\frac{c_\ell}{30}\right)^2\right]$$

$$c_\ell \in [0, \pm 10, \pm 20, ...] . \qquad (4.e.19)$$



As we'll see, the wide spectrum is needed to generate a cold summer mesopause

(bkgnd) Propagation of different phase speed waves

(Siskind et al., JGR, 2003)

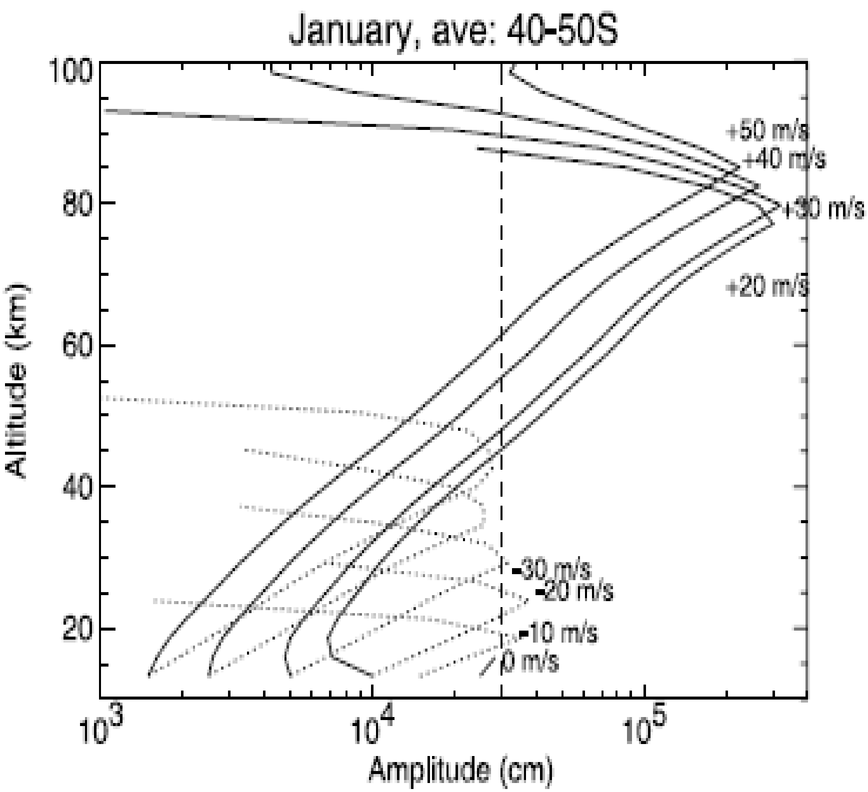
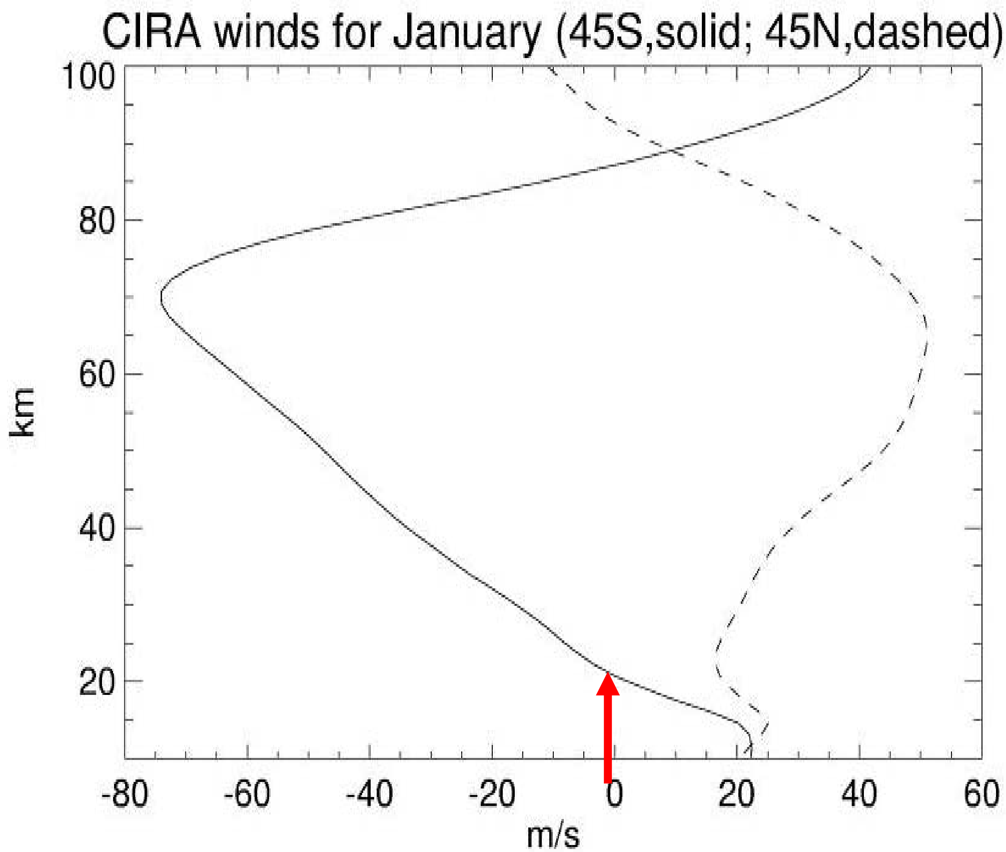


Figure 4. Vertical displacement amplitudes of 11 gravity waves in the BL model. The vertical long dashed line is a simple fiducial to aid a better comparison of the lower stratospheric amplitudes.



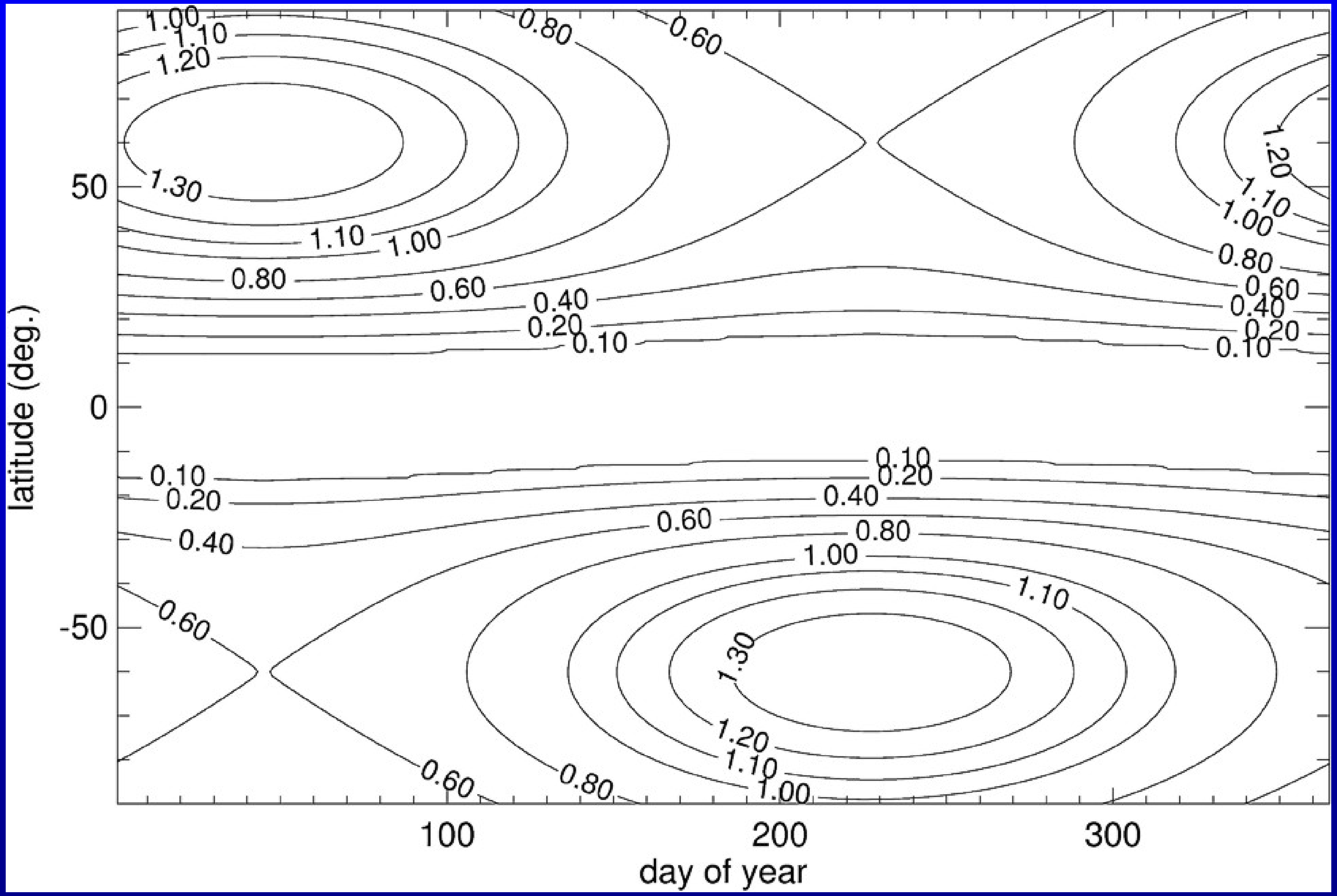
Mountain waves hit critical line in summer, pass through in winter.

Eastward waves pass through in summer to upper mesosphere.

Saturation amplitude depends upon (c-u) which is different for each wave

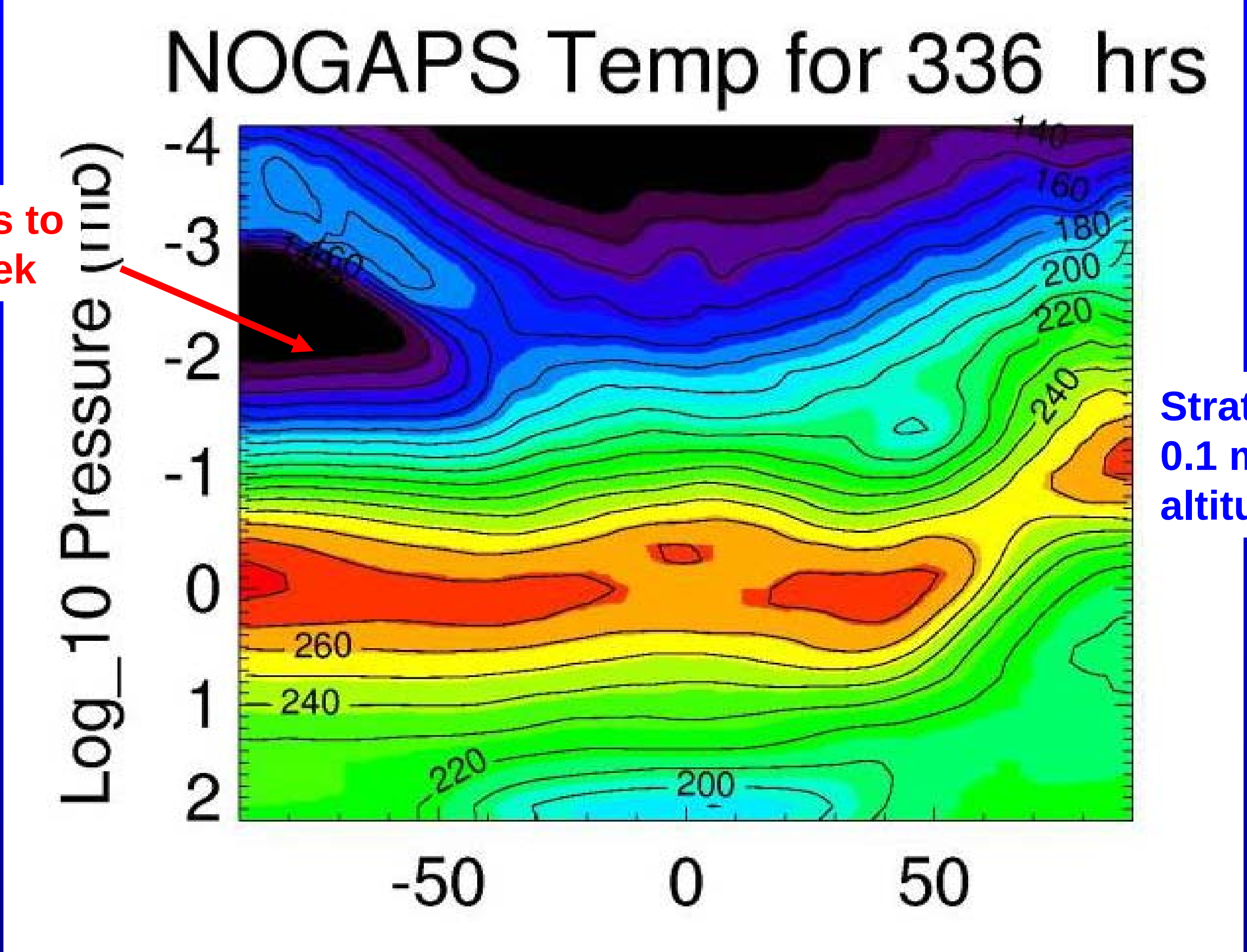
#3. WACCM Source Spectrum (Garcia)

Seasonally dependent, max in winter, equatorial minimum (other resolved waves Important there); **(based upon diagnosis by Charron and Manzini (2002))**



This forcing can be scaled a couple of different ways. Here we use an efficiency (or intermittancy) factor. Also Garcia suggests scaling a source magnitude scaling (τ)

#3. Two week calculation with WACCM MGWD param. (T79)



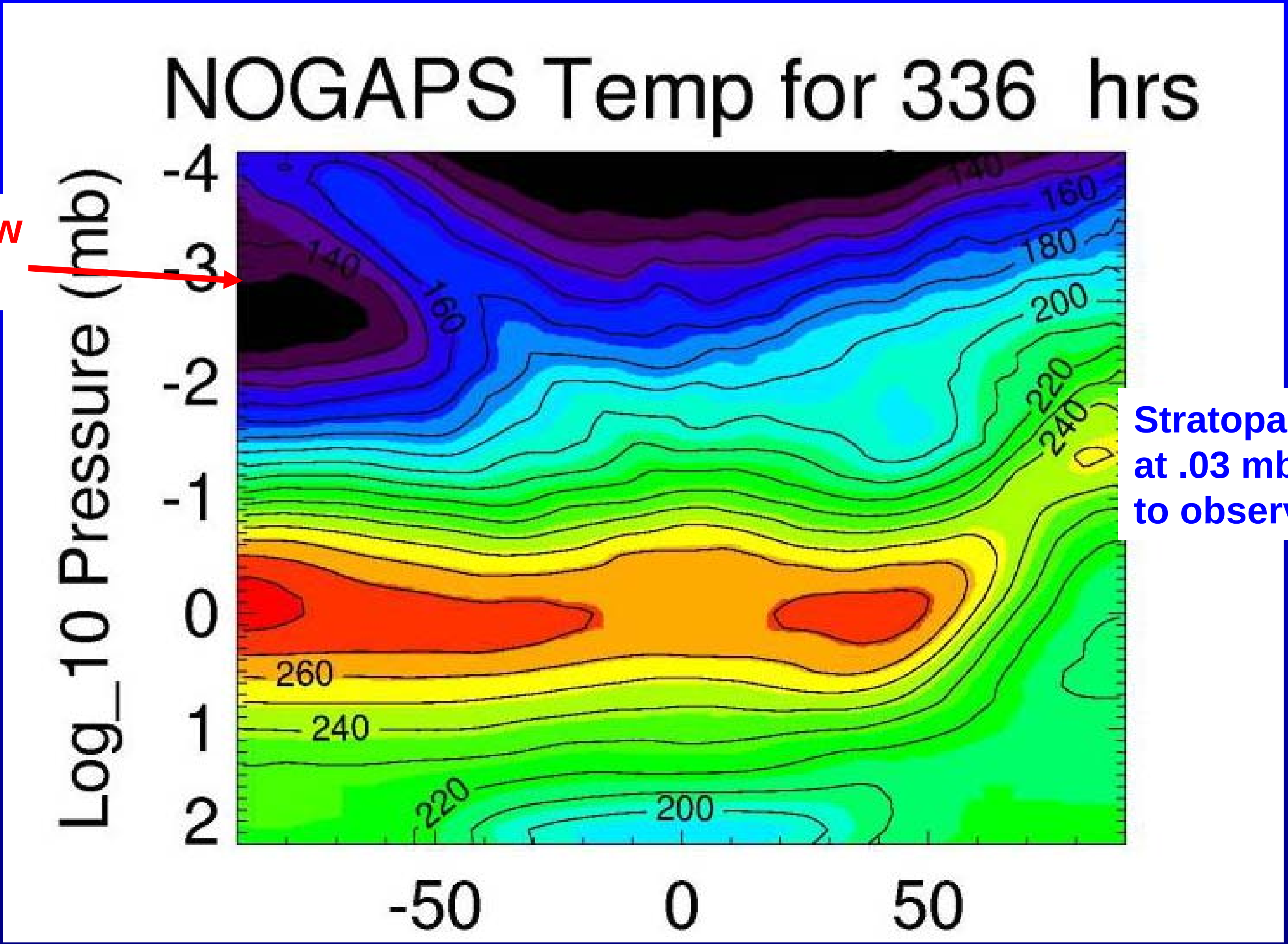
T_min drops to 95K in 1 week

Stratopause at 0.1 mb (too low in altitude)

Both summer and winter suggest *too much gravity wave drag*

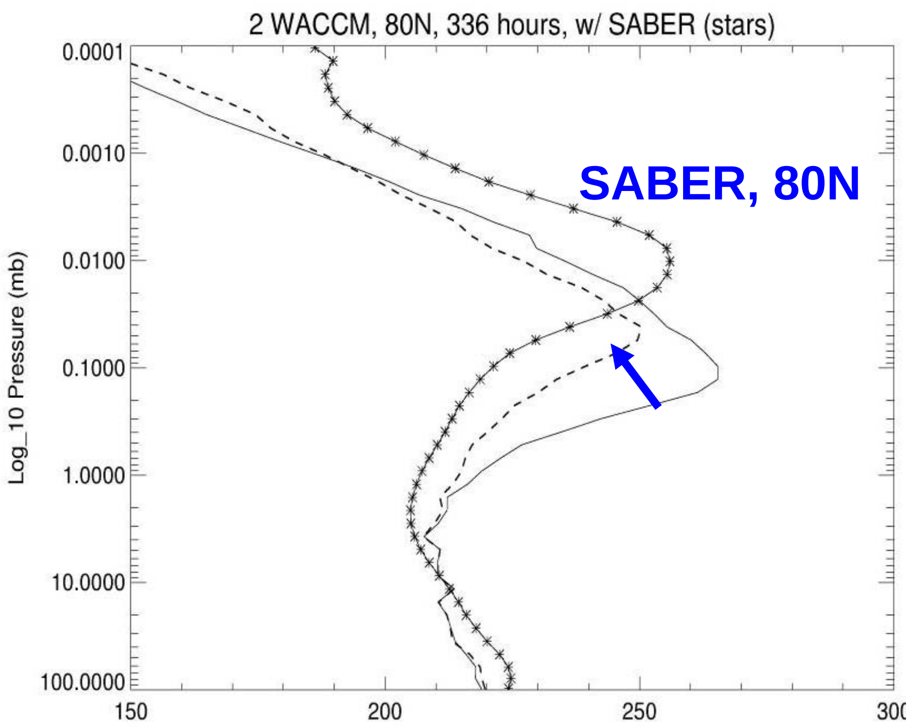
#3. With GWD efficiency cut by factor of 2.5

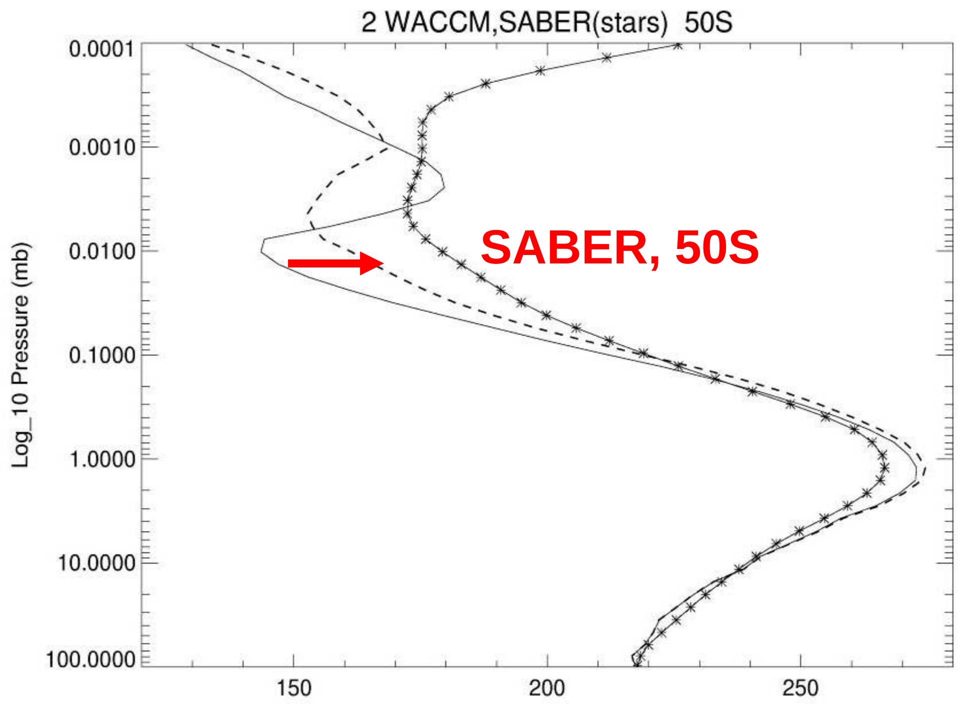
Tmin now 117 K



Stratopause now at .03 mb, closer to observed alt

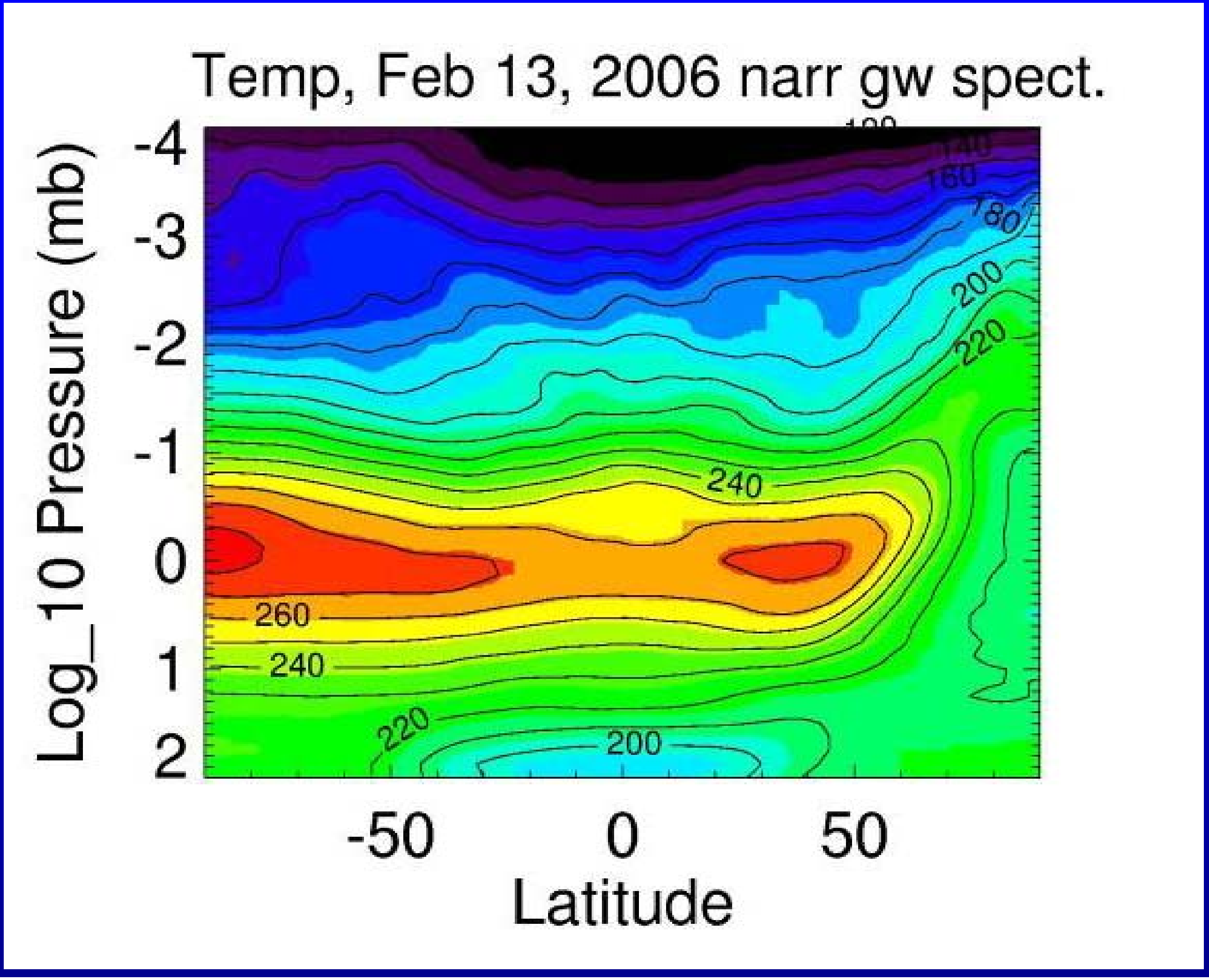
Comparison of the two calculations with SABER





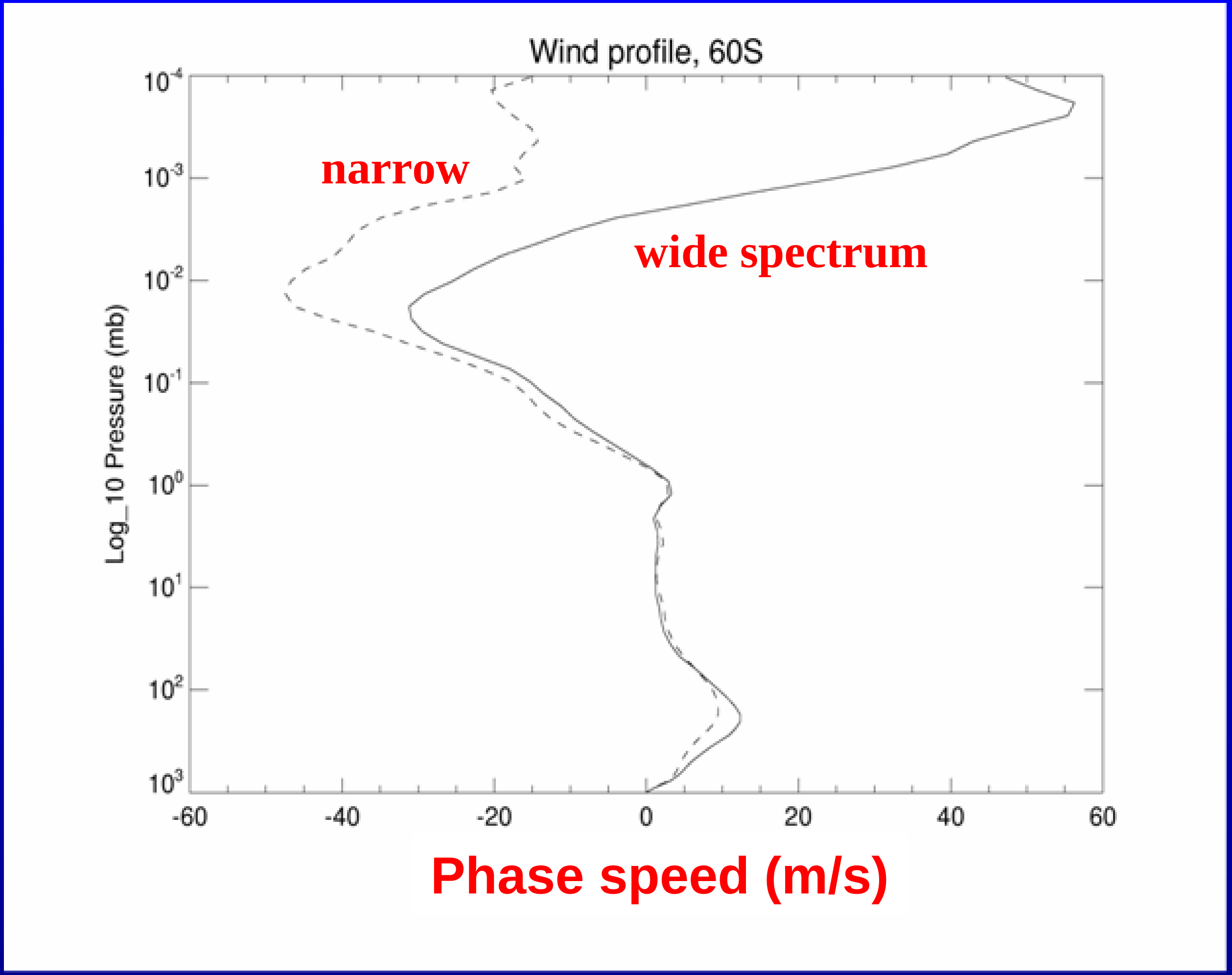
Conclusion: Reducing the efficiency improves the agreement with SABER in *both* hemispheres. There is still some slack to further reduce the efficiency or possibly the source flux.

#3. Finally with a narrow spectrum
(no waves > 40 m/sec)



Summer mesopause largely disappears, displaced stratopause in winter becomes much weaker → conclusion: need fast waves for the cold summer mesopause and for the wintertime displaced stratopause

#3. Effects of spectrum width on zonal winds



Fast eastward waves responsible for wind reversal above the mesopause

Conclusions (specific)

Unusual temperature structure in the mesosphere in 2006 result from changes in gravity wave filtering in the stratosphere.

Normally, the warm winter stratopause is sensitive to orographic waves; in 2006, non-zero phase speed waves were more important as orographic waves were absent.

The high resolution NOGAPS captures a lot of the winter structure, but does not get much of the cold summer mesopause. To simulate the summer mesopause, fast eastward waves must be postulated.

The WACCM GWD parameterization works well in NOGAPS-ALPHA with some evidence for different tuning required.

Conclusions (philosophical)

Both climate (WACCM) and weather (NOGAPS ALPHA) models can yield information about the physics of the middle atmosphere. In the case of NOGAPS-ALPHA, we do this by performing case studies up to 80-85 km. These case studies have shed light on GW effects and how they vary in response to meteorological changes.

Coupling between the stratosphere and thermosphere:

Can suggest why some years are favored. In 2004 and 2006, it's the filtering of gravity waves by a disturbed stratosphere (we think)

Solar-terrestrial science needs to consider meteorological forcing by waves from the troposphere as much as solar/geomagnetic cycles

Future research

Improve physics of MLT region (above 80 km) → chemical heating, FUV heating

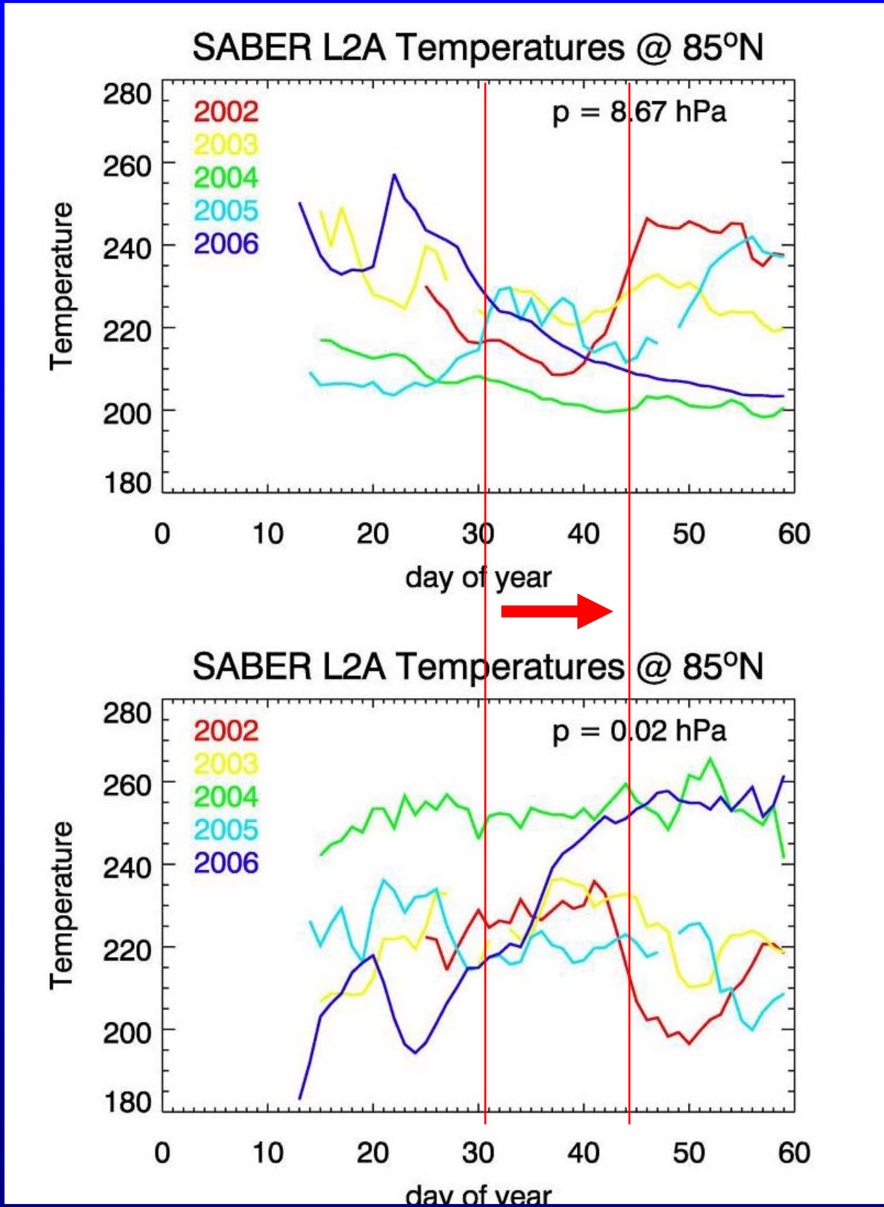
Support AIM and SHIMMER measurements of PMC/summer mesopause

ONR/DTRA initiative

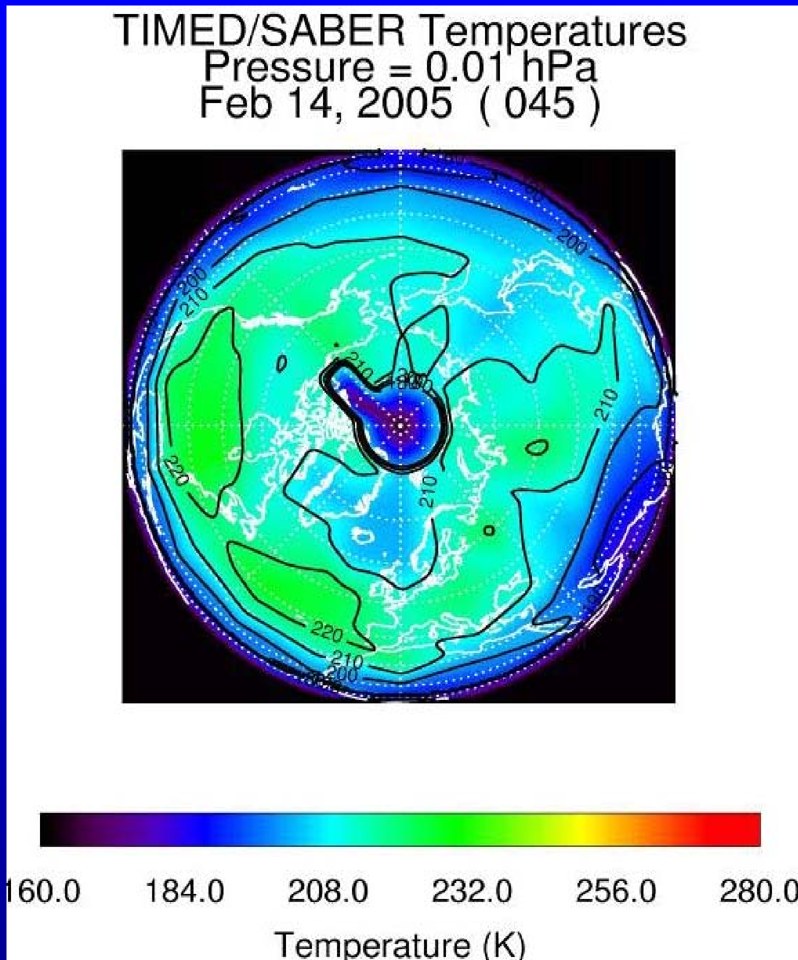
pass these waves up into USU T-I system →
link ionospheric forecasts to tropospheric/middle atmosphere forecasts

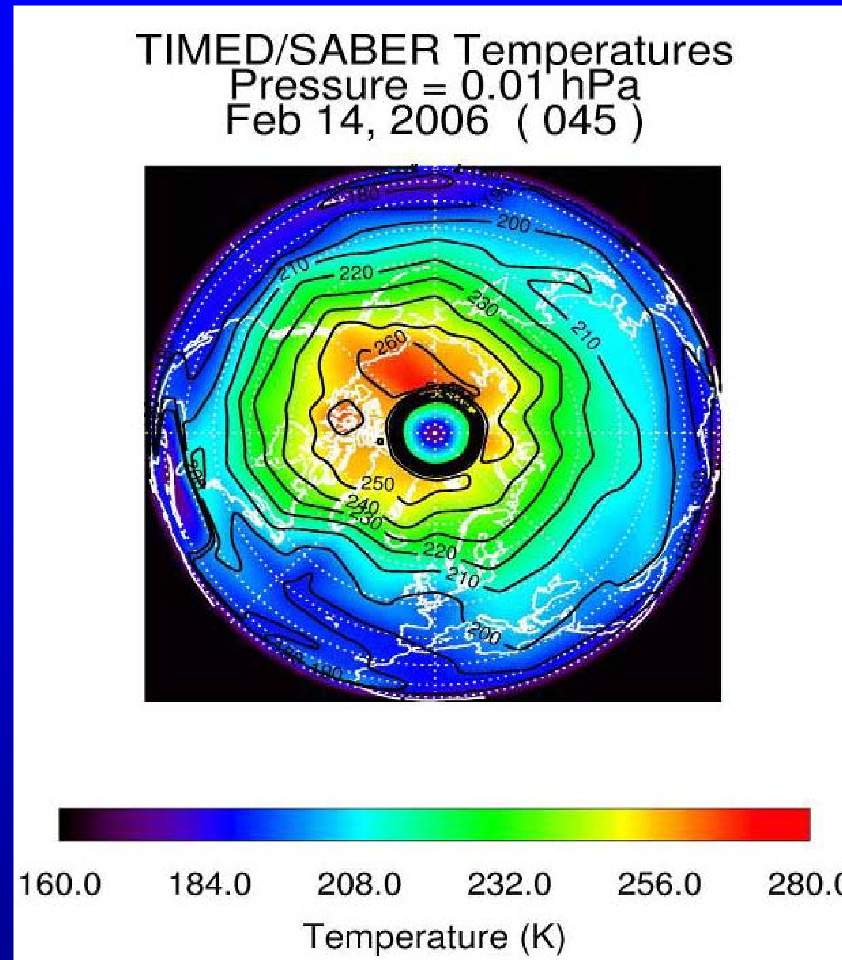
Back to NOGAPS-ALPHA: Period of simulation
(rising temp at .02 mb in 2006, falling at 9 mb)

The period covered by the simulation is between the vertical red lines.



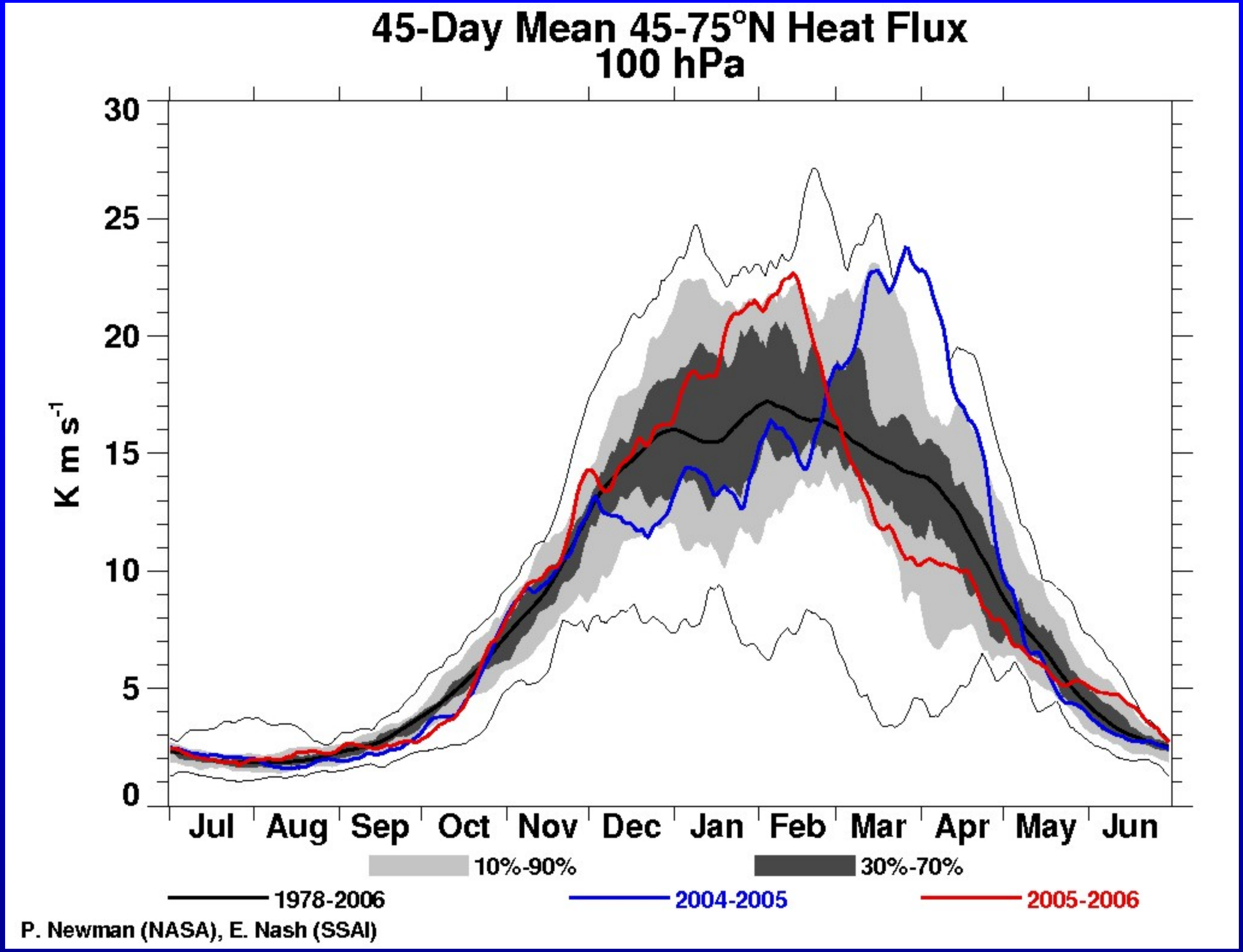
SABER data





Note: SABER data is not synoptic, so we can't directly compare model geopotential with observations.

Forcing from the troposphere
(proportional to upward component of Pwave activity)



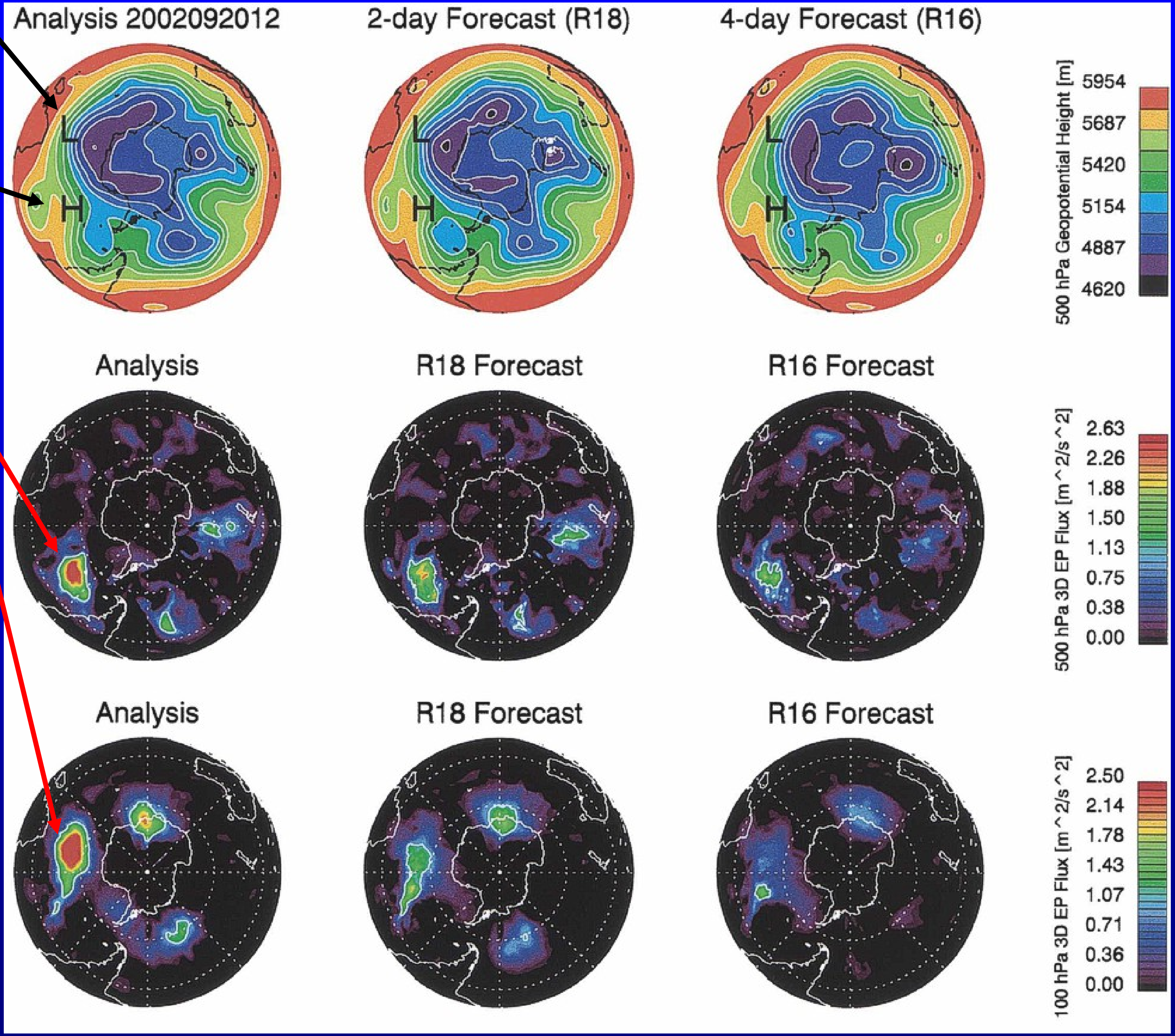
Polvani and Waugh (J. Clim, 2004) identify this quantity as best indicator of AO index at 10 mb. Thus weather forced from troposphere is as important (more so?) than the solar cycle in coupling thermospheric NO to stratospheric NOx!

Why Less Vortex Disturbance in the Longer Range Forecasts?

Strong blocking feature in South Atlantic

Blocking ridge (anticyclone) radiates strong Rossby wave fluxes into the stratosphere

Less 500 hPa ridging in +4 day forecast → less Rossby wave EP flux → less disturbed vortex

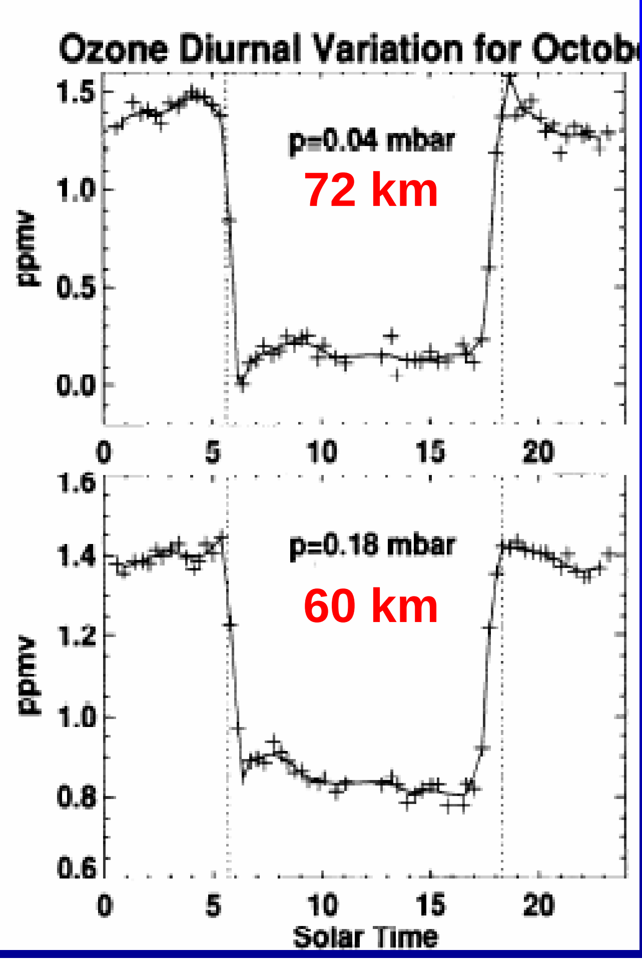


500 hPa geo-potential heights

500 hPa values of vertical component of 3D EP-Flux (*Plumb*, 1986)

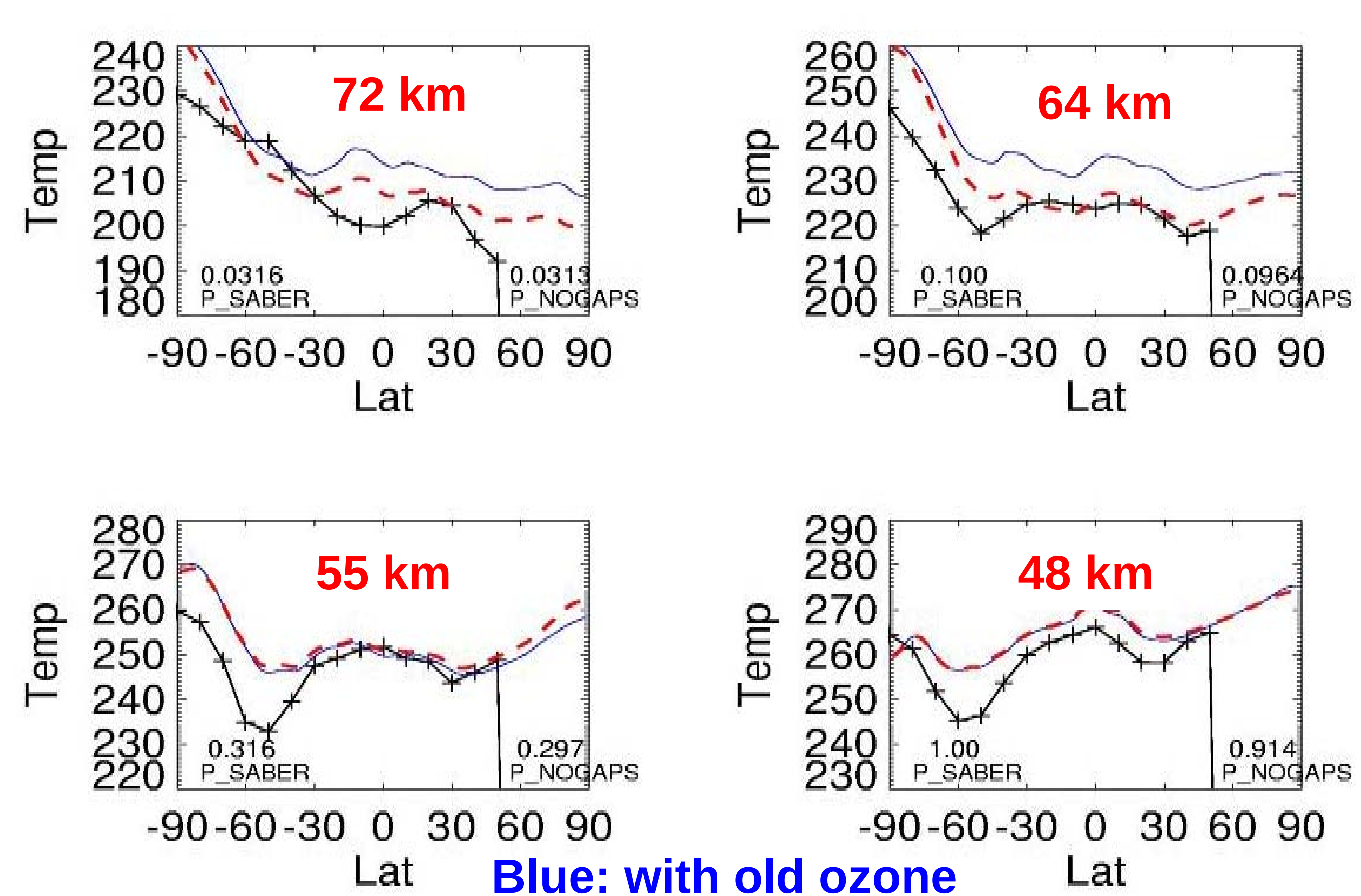
100 hPa values of vertical component of 3D EP-Flux

Effect of refining mesospheric ozone inputs



Ozone is lower in the day in mesosphere. Diurnal average climatologies will overestimate the heating!

Model-data comparison of temps with new ozone heating



Blue: with old ozone
Red: with new ozone