Case Studies of the middle atmosphere response to gravity wave drag using NOGAPS-ALPHA at varying resolutions

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With thanks to the NOGAPS-ALPHA team
(ALPHA: Advanced Level Physics High Altitude)

Overall theme: **Use high-altitude analysis** ***(3D-Var (NAVDAS), Eckermann et al., 2009; Hoppel et al., 2008)*** **to initialize and compare with a series of short/medium term NOGAPS-ALPHA forecasts**

Forecast model resolutions: **T79, T239, T479**

Acknowledgements: **Funding was provided by the Office of Naval Research and the NASA Heliophysics Theory Program**

Two Specific Topics

1. Case studies of the SSWs of 2008 (minor) and 2006 (major, extended) with combinations of parameterized GWD scheme

   orographic (OGWD): Palmer et al (1986)
   non-orographic ("multiwave") (MGWD): Garcia et al. 2007

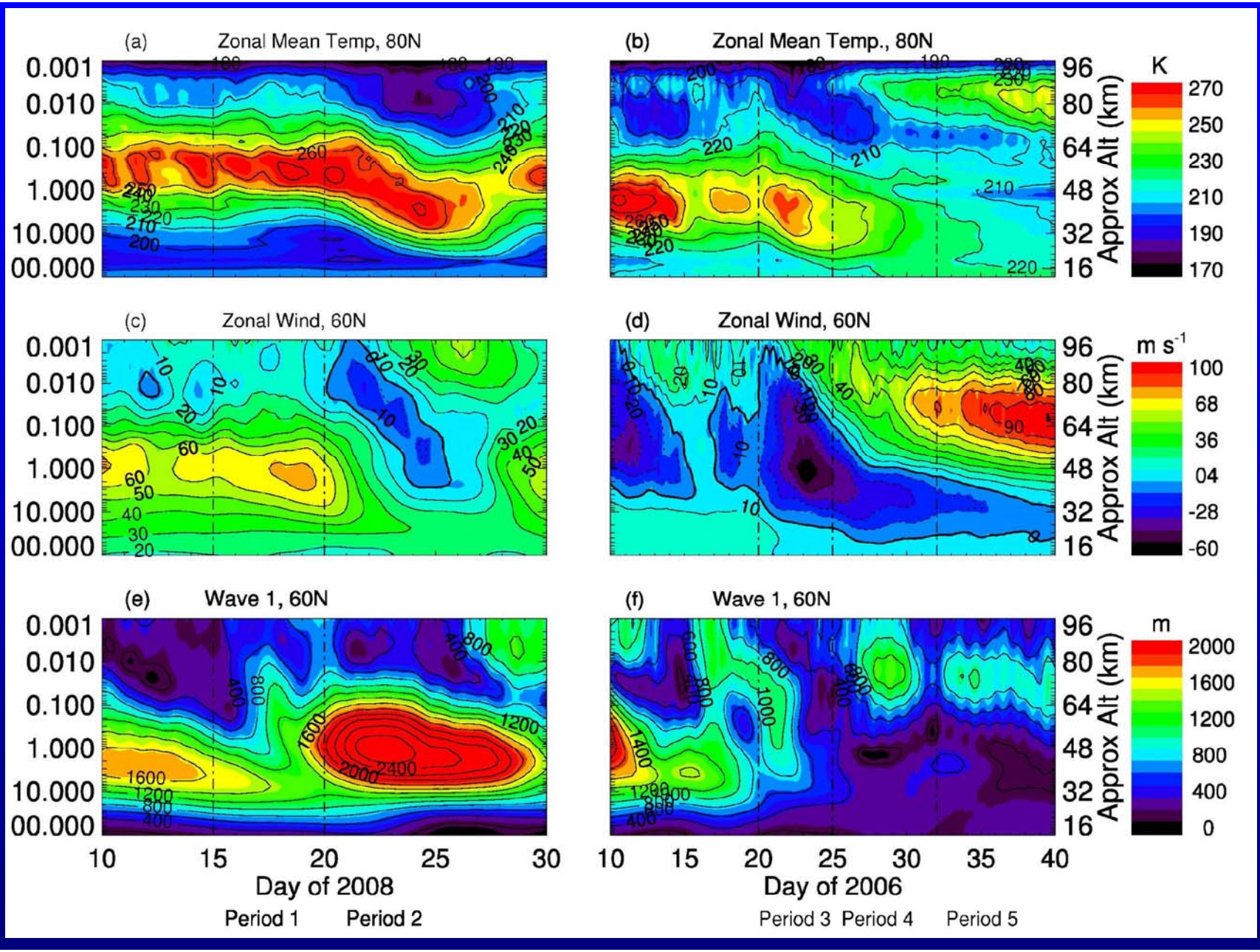
   What are the relative roles of OGWD and MGWD in the various phases of an SSW?

2. Solstice forecasts at a range of resolutions, including T479, without any parameterized GWD

   Look at GWD features: warm winter stratopause
   cold summer mesopause

   What spatial resolution is required to model GWD features without parameterizations?

NAVDAS and the NH winters of 2006 and 2008



Five Periods, 3 Forecasts Each

Label	*Dates*	*Description*
Period 1	15–20 Jan 2008	dynamically quiet
Period 2	20–25 Jan 2008	minor warming
Period 3	20–25 Jan 2006	major warming, initial phase
Period 4	25–30 Jan 2006	major warming, extended phase
Period 5	2–7 Feb 2006	major warming, extended phase

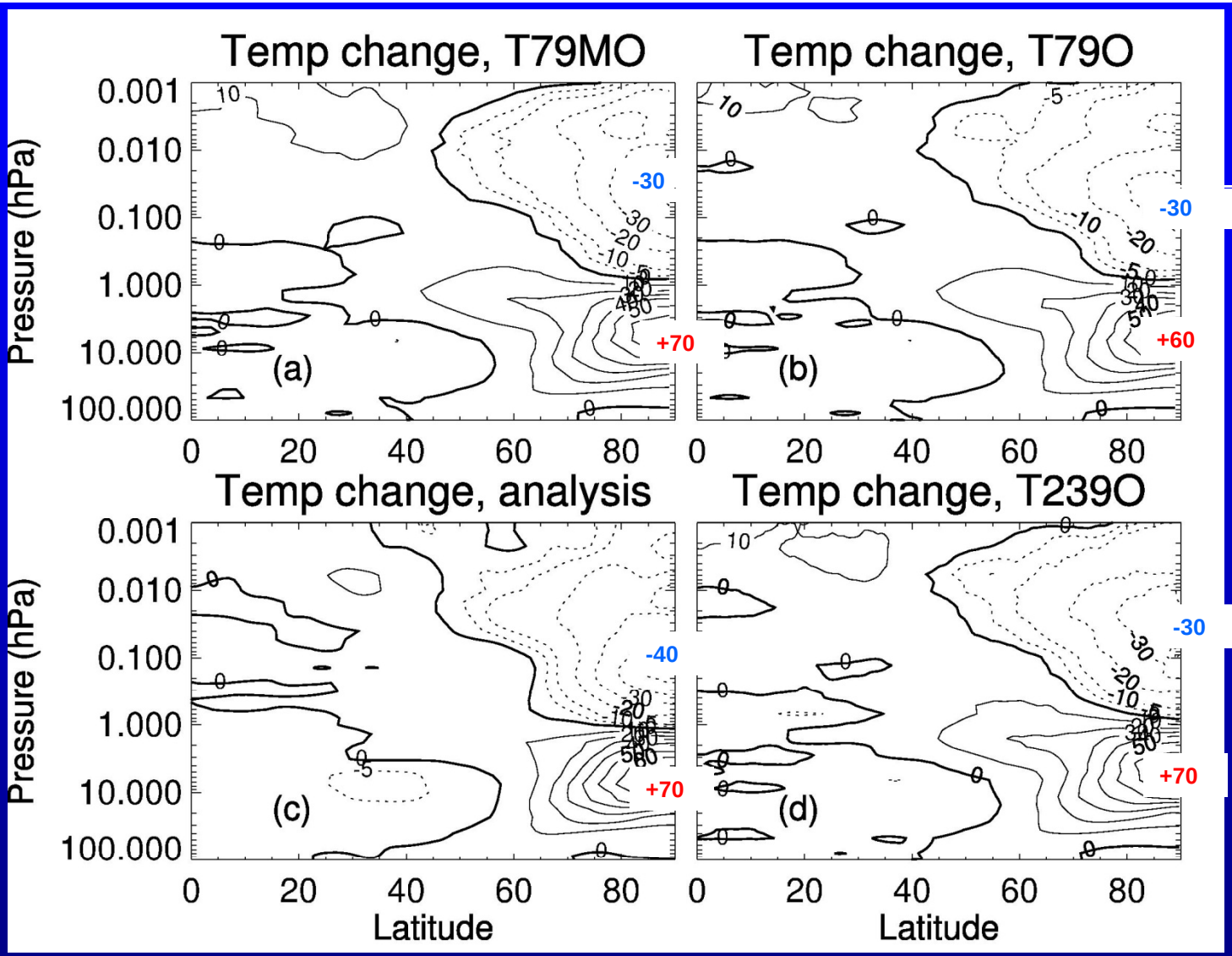
Three forecasts per period:

- **T79O:** OGWD only
- **T79MO:** Both OGWD and MGWD
- **T239O:** OGWD only, but higher spatial resolution

(note: NAVDAS is always T79)

Compare absolute forecasts and changes over each 5 day period with NAVDAS

3 Simulations of minor 2008 warming (Period 2): Jan 24-Jan 20th



In general, differences are not large, *but* cooling at 0.01 hPa is better simulated in MO

Diagnostics of zonal momentum: TEM formulation

$$\overline{u}_t + \overline{v}^* \left[(a\cos\phi)^{-1} (\overline{u}\cos\phi)_\phi - f \right] + \overline{w}^* \overline{u}_z = (\rho_o a\cos\phi)^{-1} \nabla \cdot \mathbf{F} + X,$$

Two components of F, Eliassen-Palm (EP) Flux

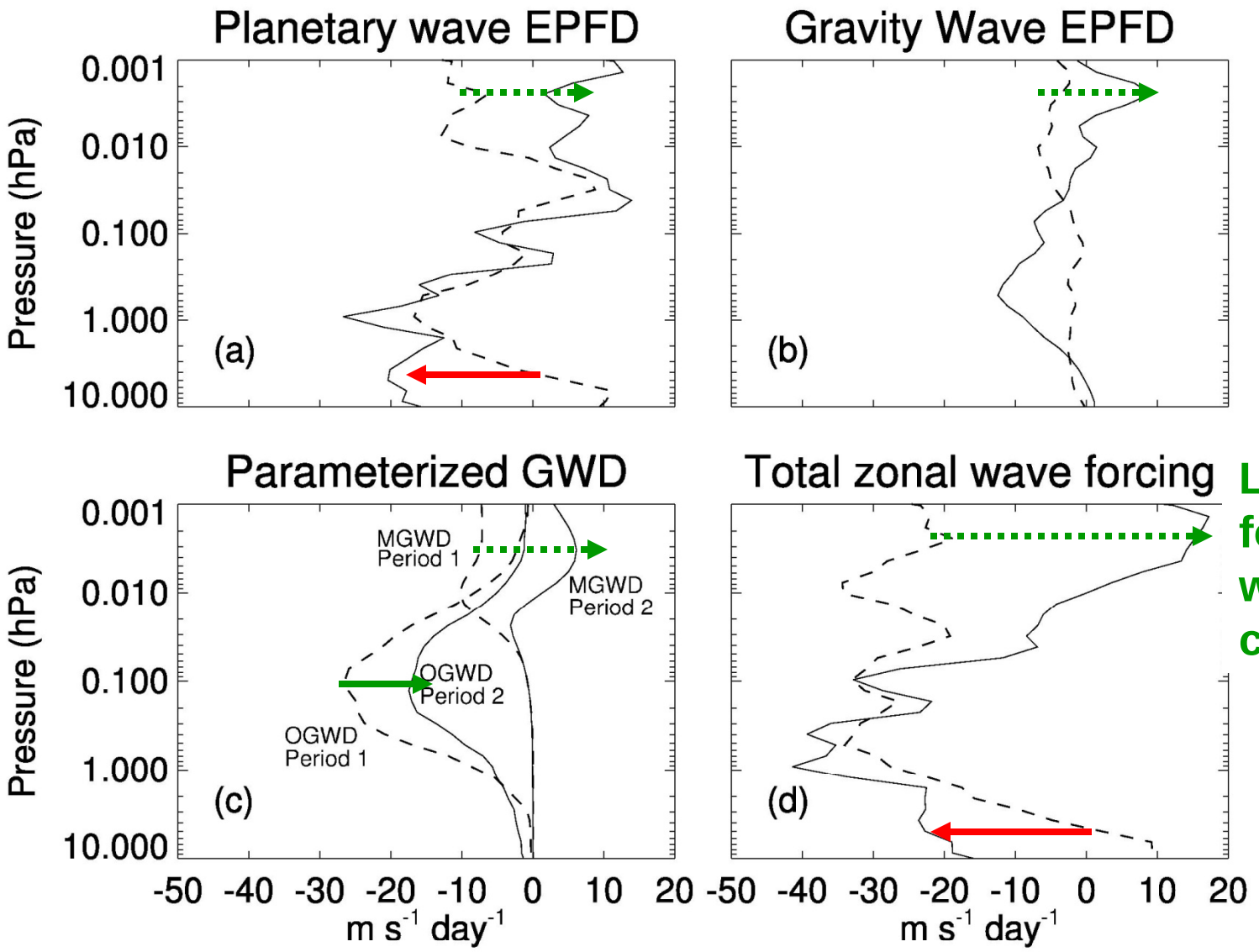
$$\mathbf{F_p}[\phi, z] = \rho_o a\cos\phi \left[(\overline{u}_z \overline{v'\theta'}/\overline{\theta}_z - \overline{u'v'}), \left(f - \frac{1}{a\cos\phi} [\overline{u}\cos\phi]_\phi \right) \overline{v'\theta'}/\theta_z \right],$$

$$\mathbf{F_g}[z] = \rho_o a\cos\phi \left[\overline{-[u'w']} \right].$$

3 gravity wave forcing terms

X is broken out according to X_O and X_M

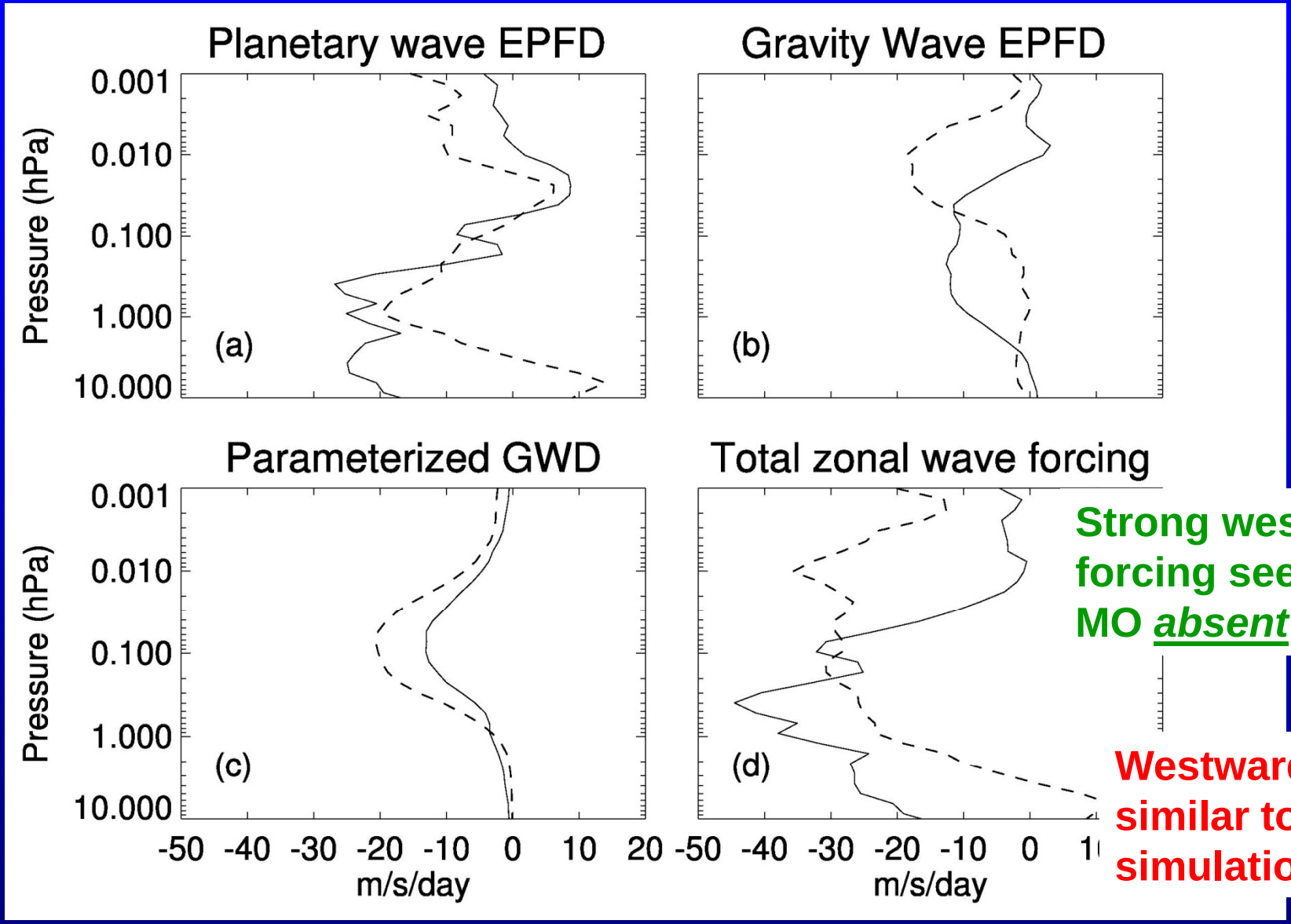
TEM Diagnostics T79, Periods 1 (dash) and 2 (solid)



Large net eastward forcing coincides with mesopheric cooling

Westward forcing coincides with stratospheric warming

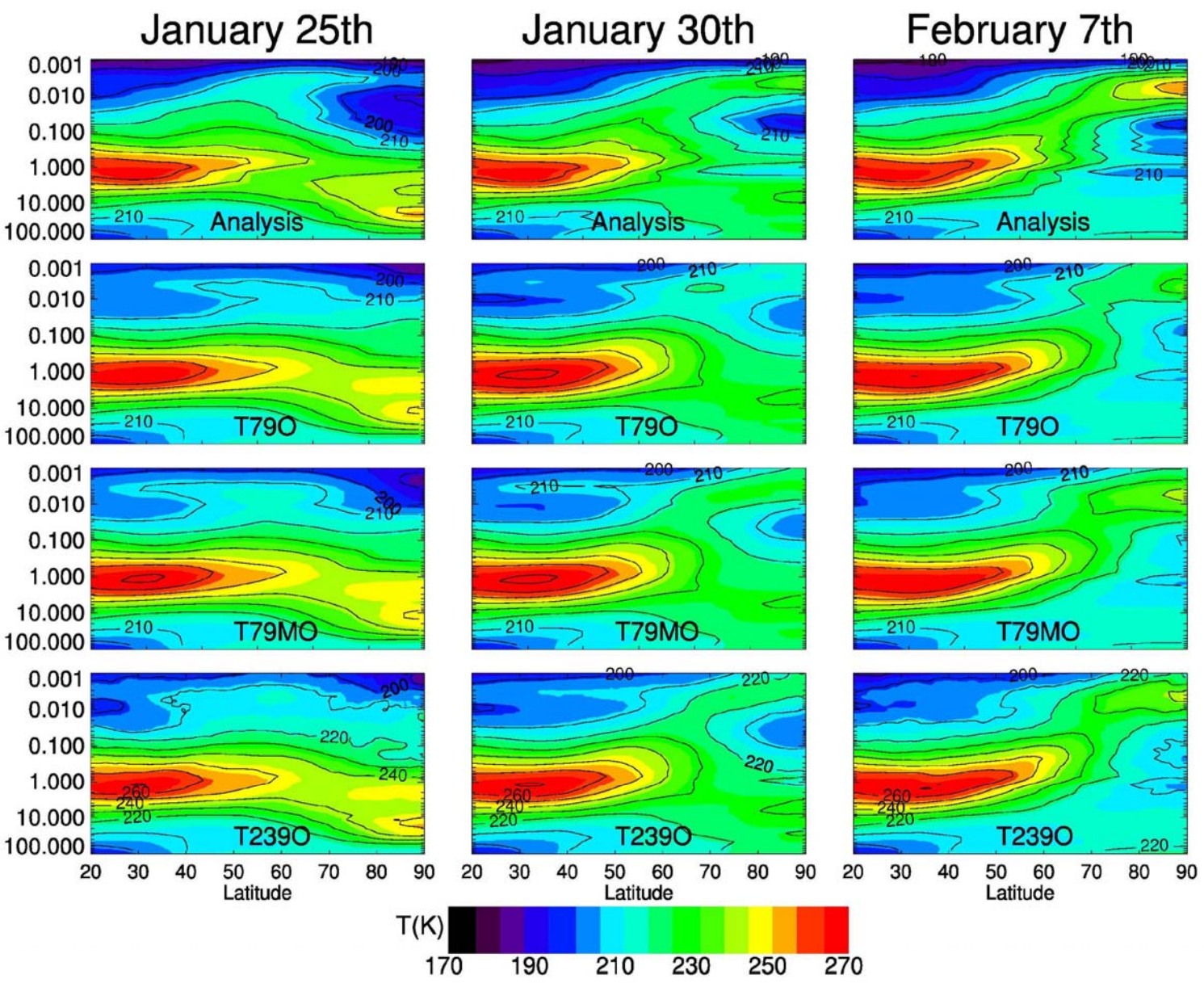
TEM Diagnostics, T239 for Periods 1 (dash) and 2 (solid)



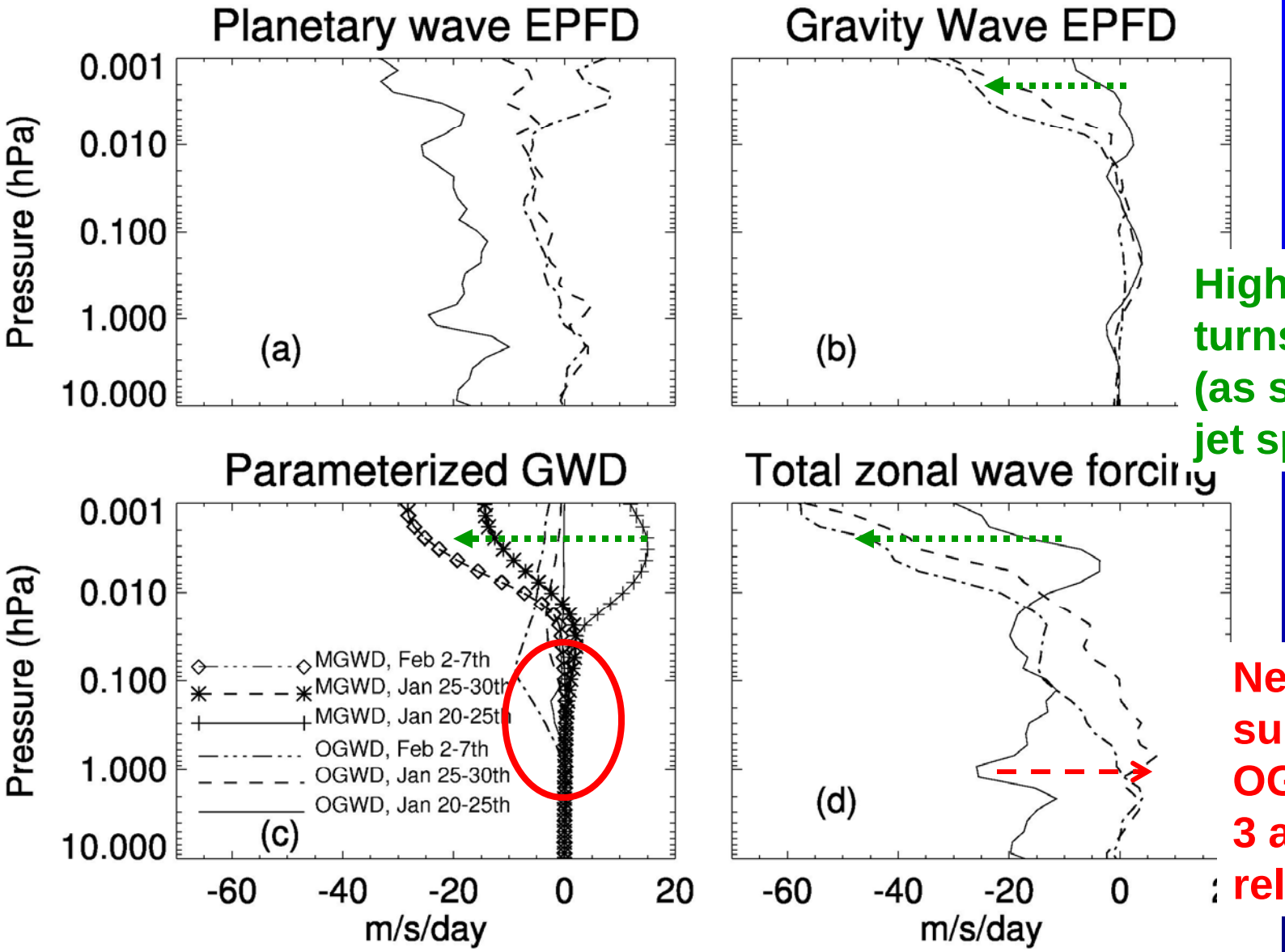
Strong westward forcing seen in T79 MO *absent* here

Westward forcing similar to T79 simulations

Three simulations of the 2006 event



TEM Diagnostics T79, Periods 3-5 (solid, stars,diamonds)

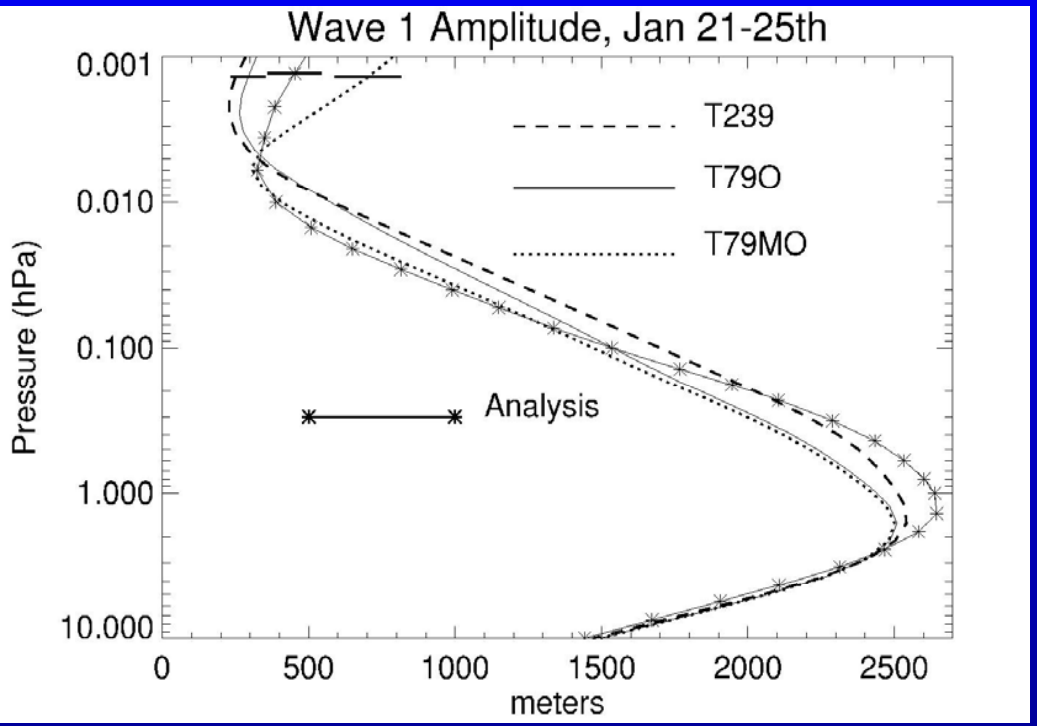


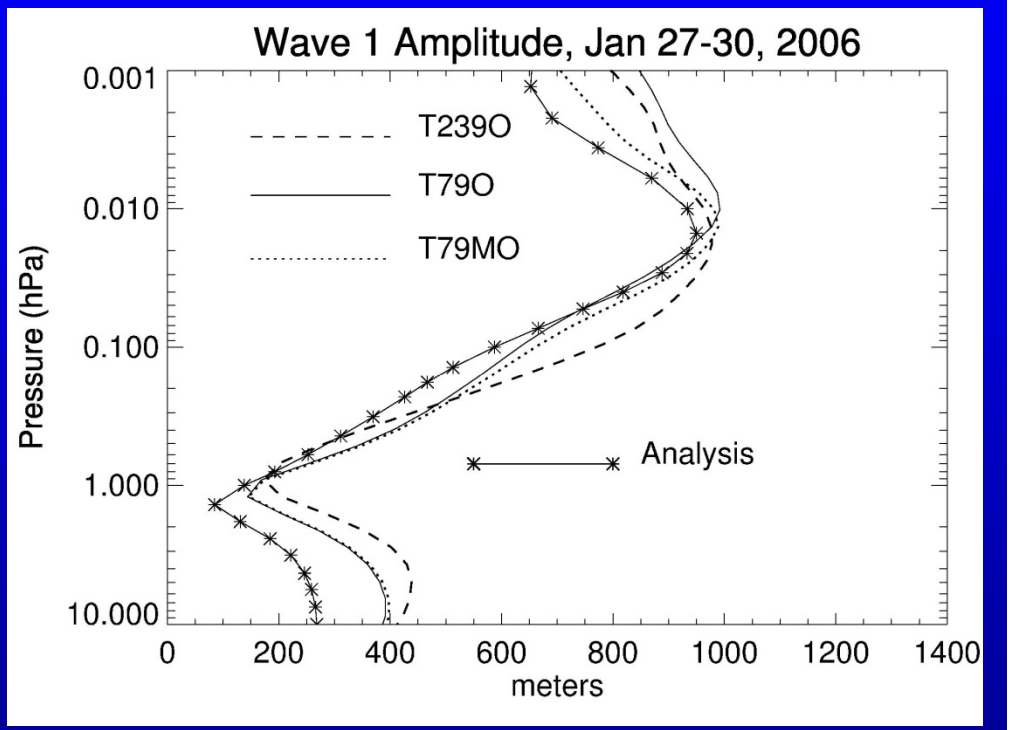
High alt forcing turns westward (as stratospheric jet spins up)

Near-complete suppression of OGWD in Periods 3 and 4 → radiative relaxation

Two sources of high altitude planetary wave

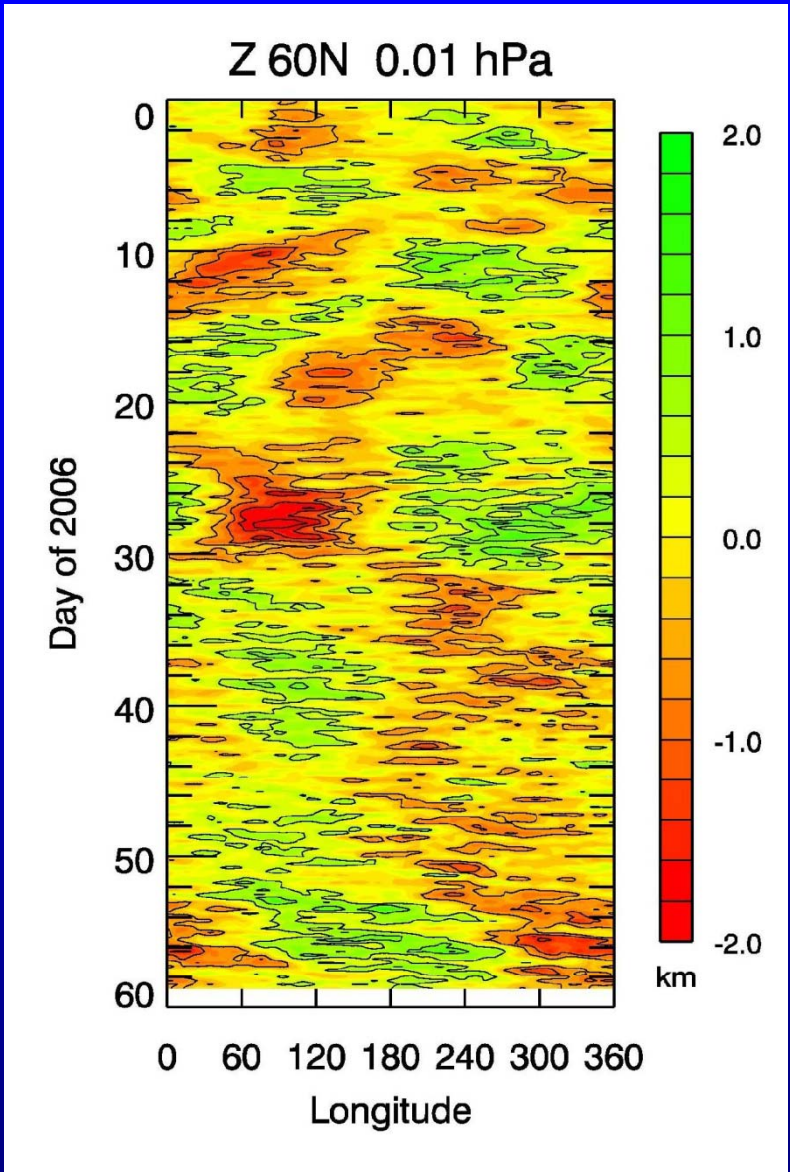
2008 **2006**





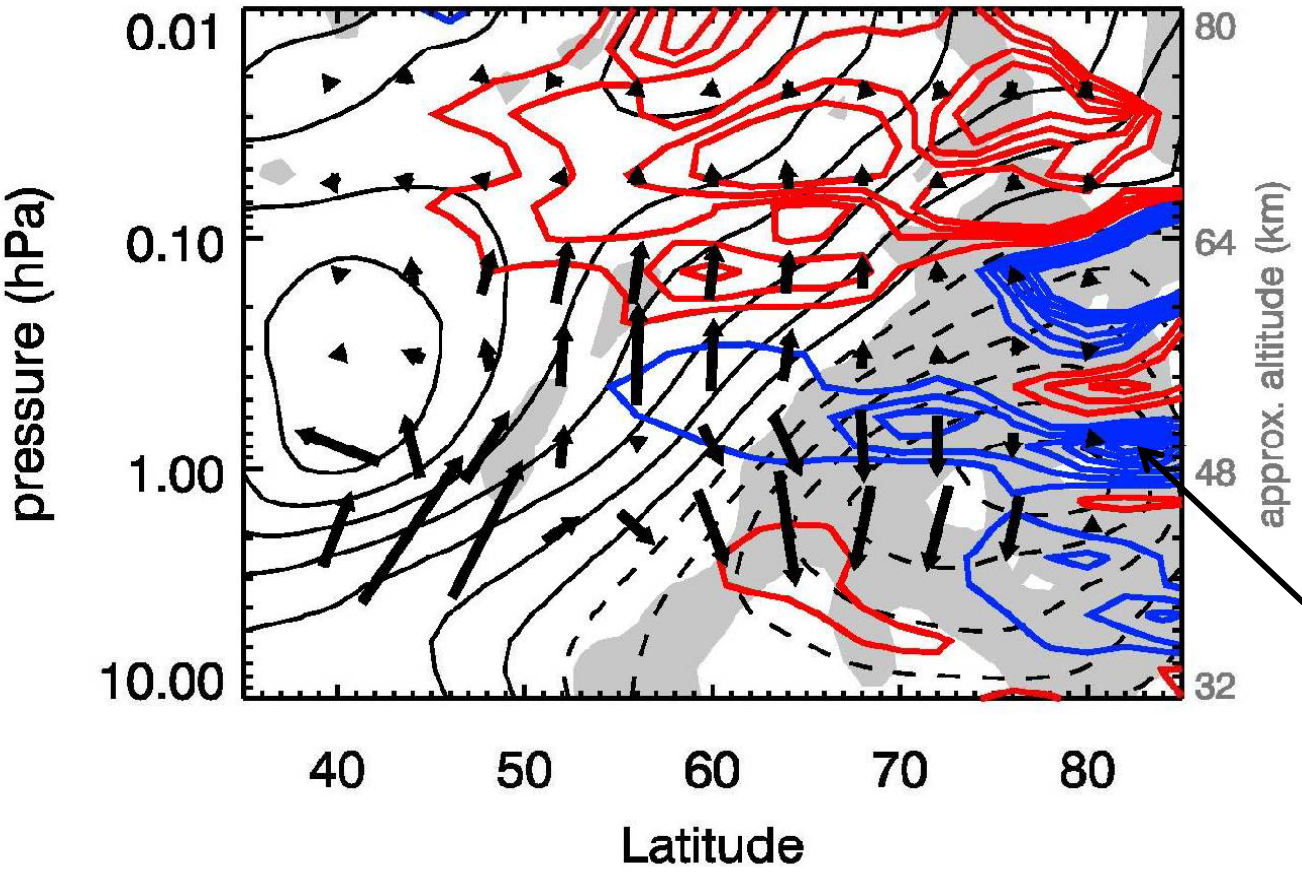
1. **Longitudinally asymmetric GWD (in 2008)**
2. **Instabilities near the stratopause (in 2006)** **(Thayer et al., 2010)**

Hovmoller of geopotential height anomaly



Quasi 8-10 day traveling wave changes to a quasi-stationary wave

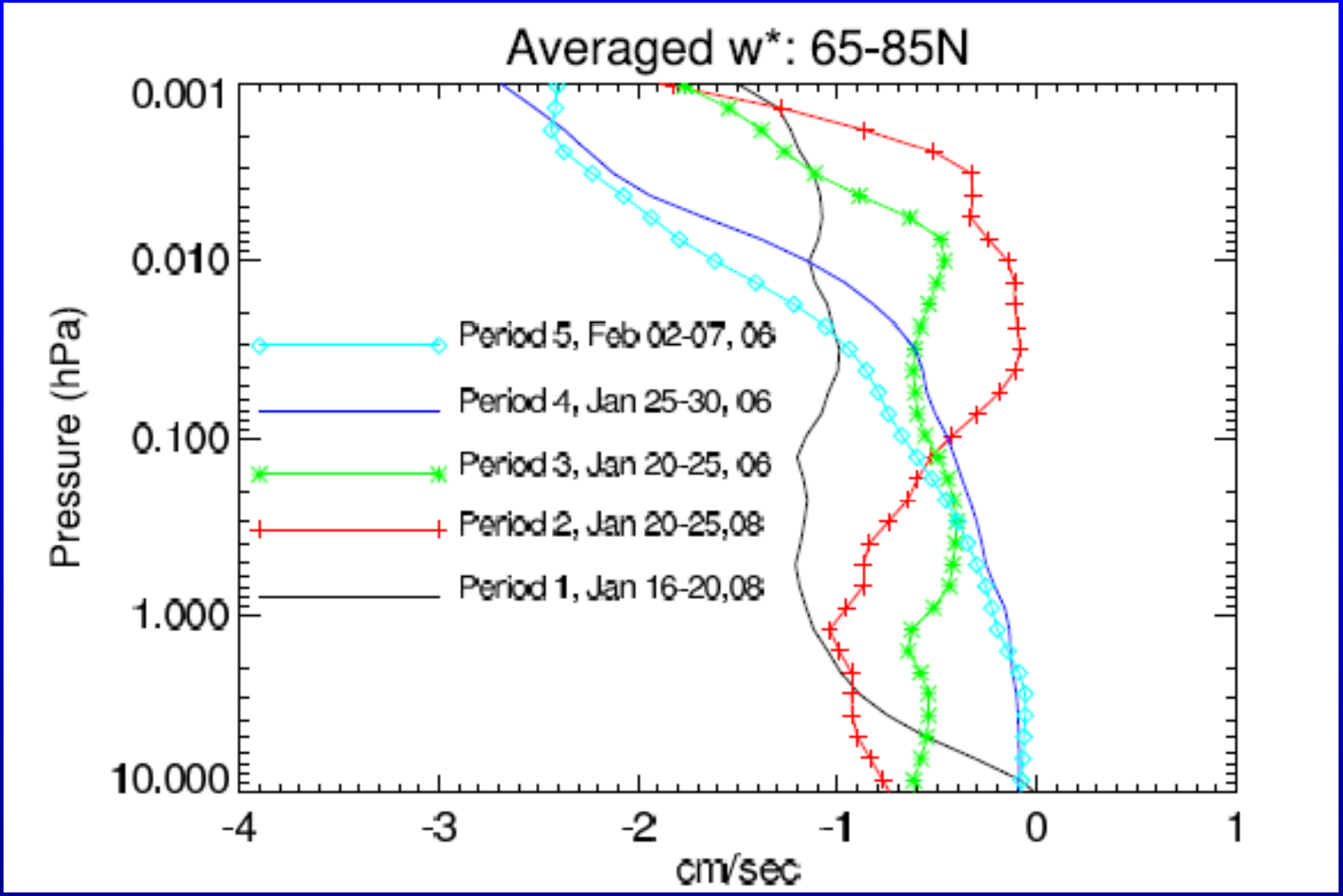
EP Flux Vectors for 27 January 2006



Wave source?

Blue: divergence, red: convergence

Enhanced Descent in Extended Phase



Topic 2: Forecasts with only resolved Gwaves

lat/lon	2 km	1 km
1.50°	T79, L74	T79, L115
0.50°	T239, L74	T239, L115
0.25°	T479, L74	xx

Background: Gravity Wave Resolving (GWR) middle atmosphere models

Hamilton, colleagues (1991, 2001,2006, 2008): Increased horizontal resolution

Watanabe et al (2008): Increased vertical resolution (L256, only T213)
Subsequent studies (Sato et al., 2009; Sato et al., 2012)

Here: 10 day forecasts for June 2007 and January 2008 w/o parameterized GWD.
Compare forecast minus analysis (F-A) as measure of model bias and guide to accuracy of the physics (i.e. the resolved gravity waves)

Specific Questions/Topics

What is the effect of changing horizontal and vertical resolution on gravity wave driven features?

→ cold summer mesopause

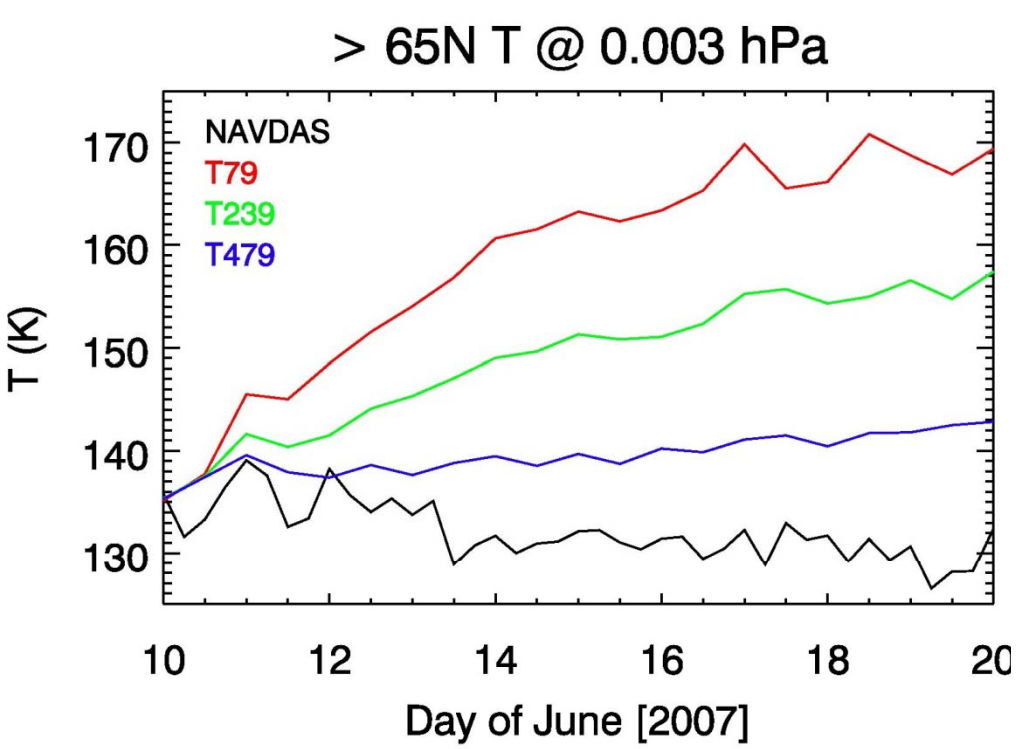
→ warm winter stratopause

Where are the gravity waves in NOGAPS-ALPHA and how do we compare with other published GWR models?

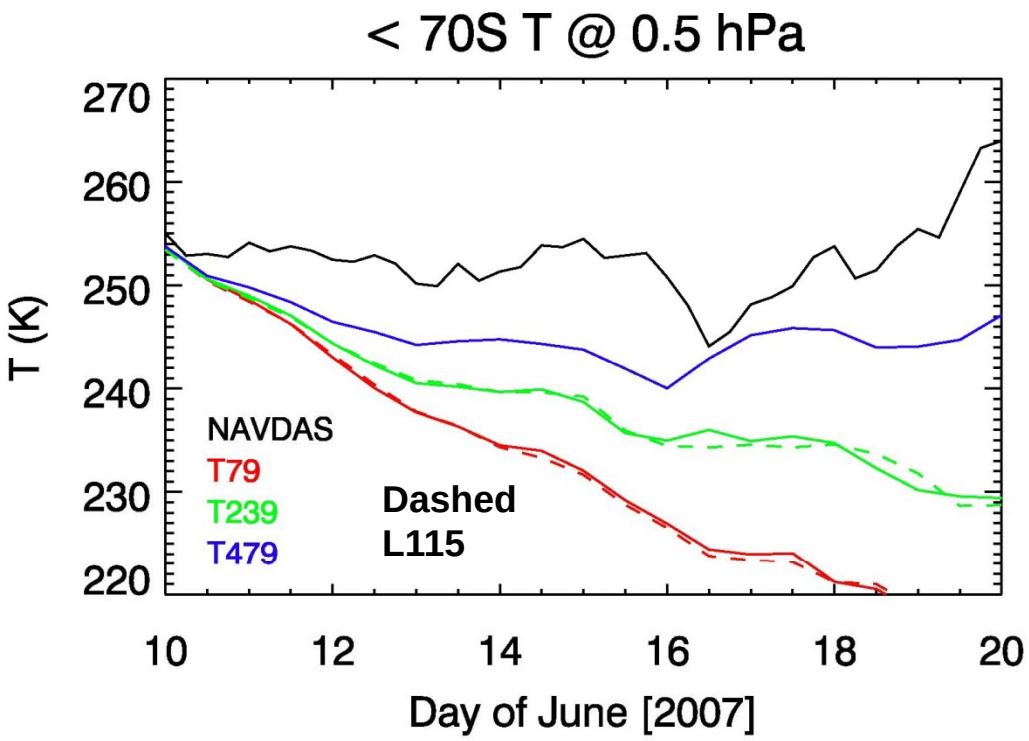
Highlight an important uncertainty in defining a critical resolution for resolving gravity waves

Time Evolution: GWD-sensitive regions

Summer Mesopause

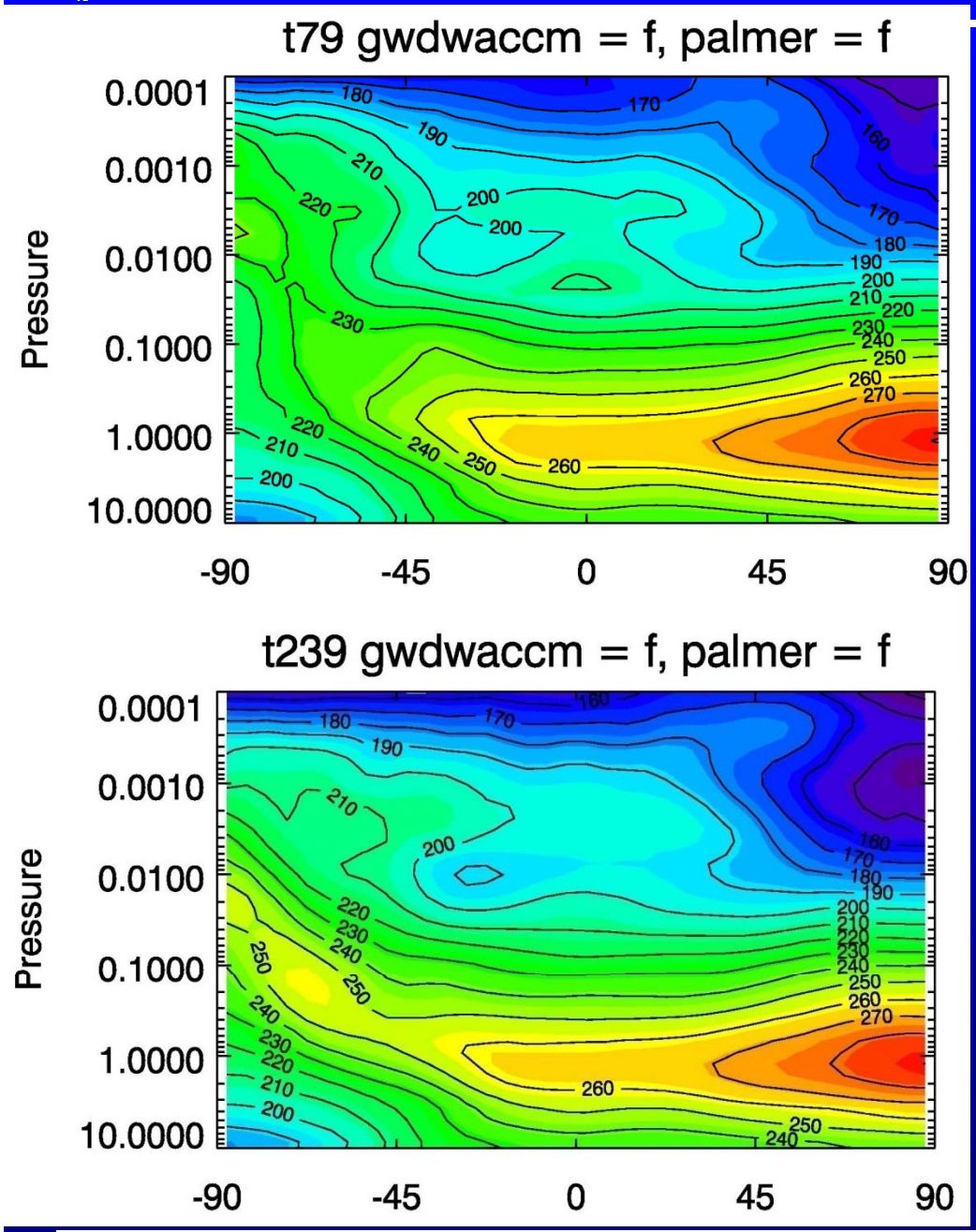


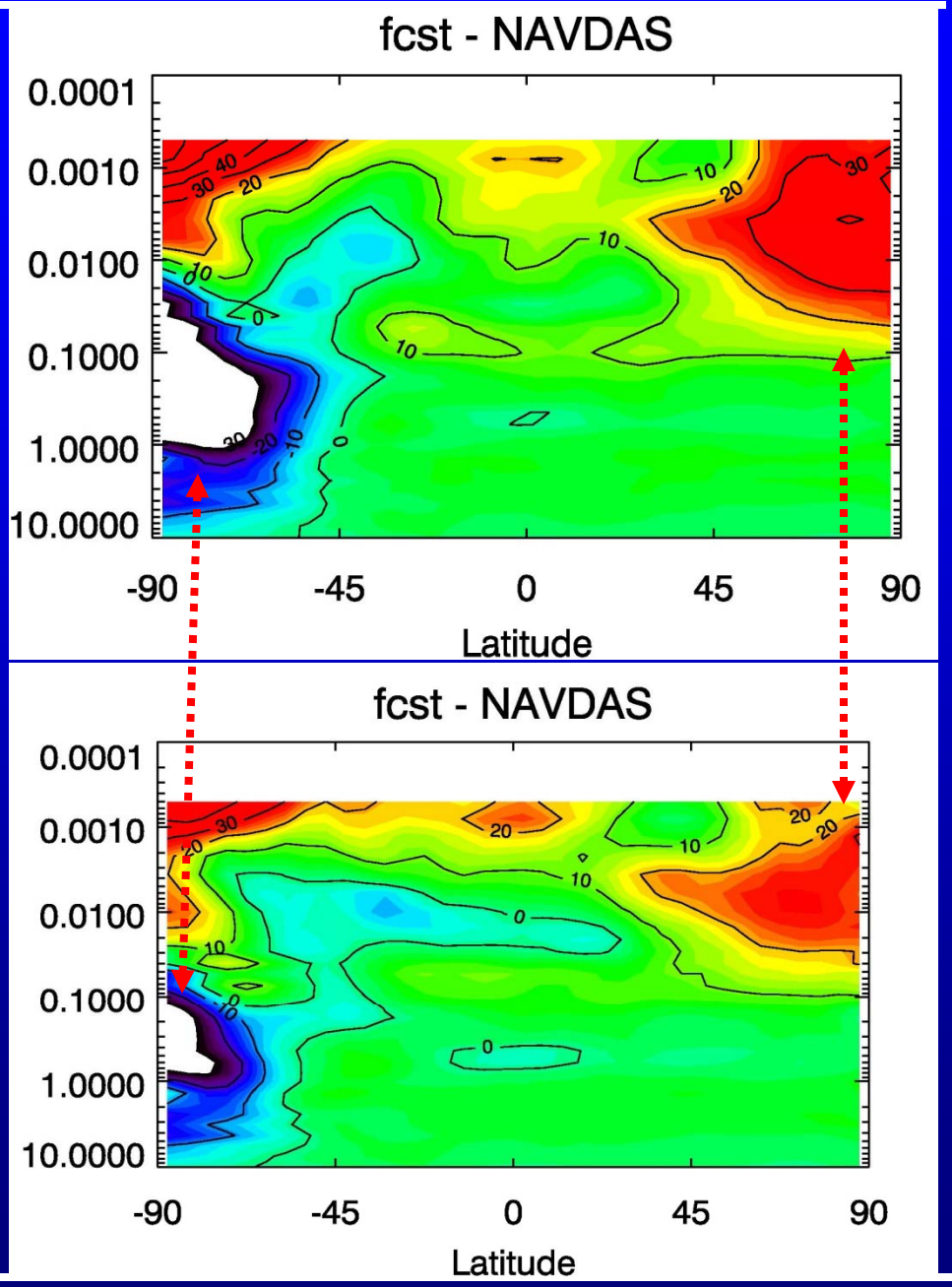
Winter Stratopause



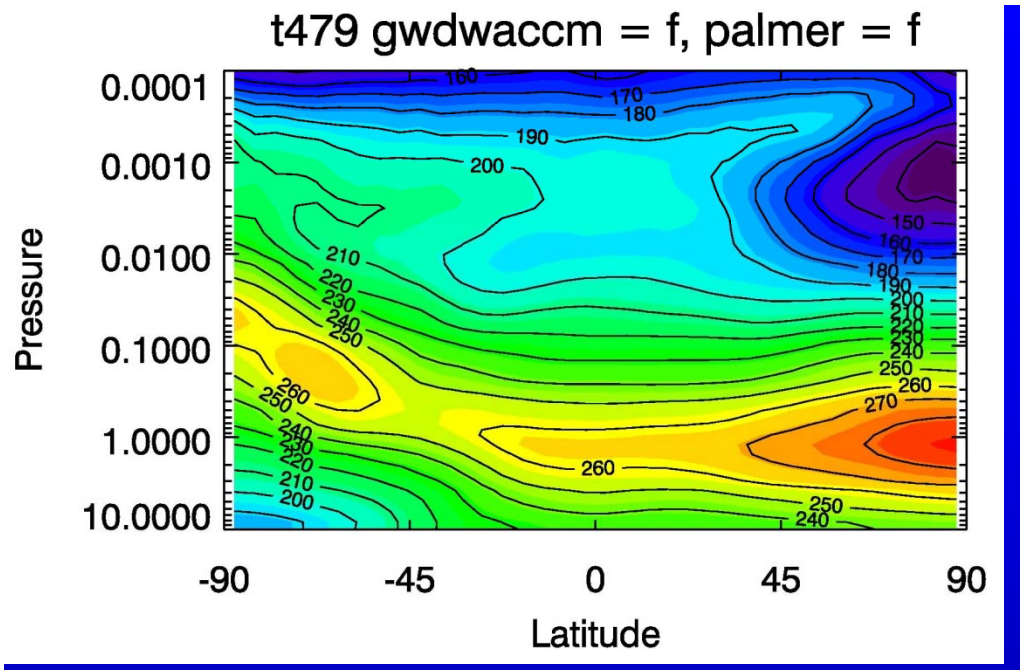
Divergences between forecast and analysis attributed to relative lack of resolution of GWD

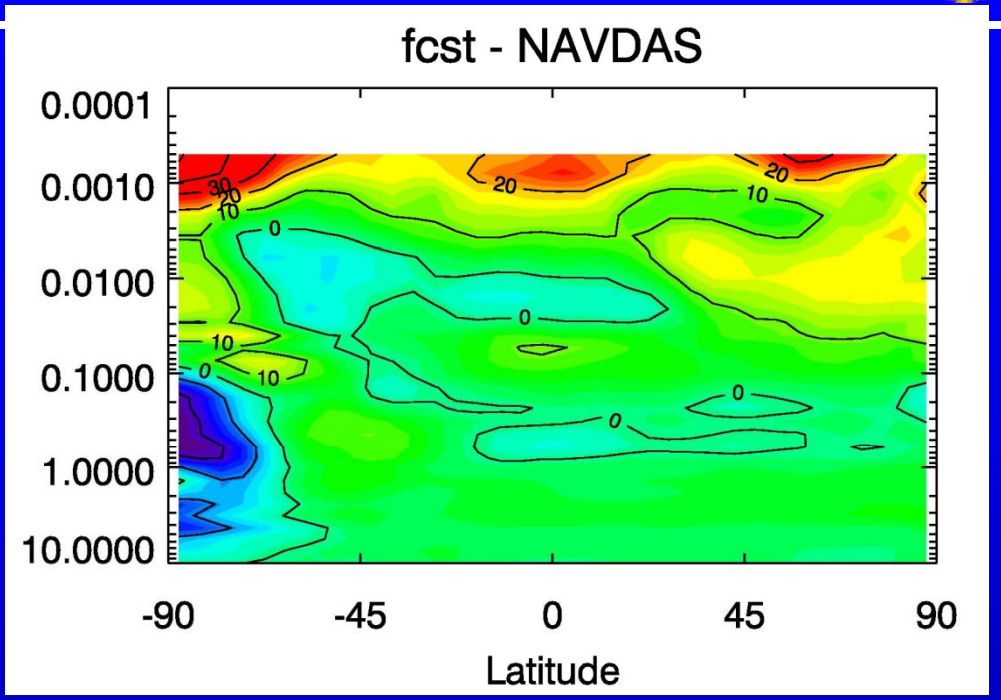
2D plot at 240 hours: T79 and T239 with Analysis



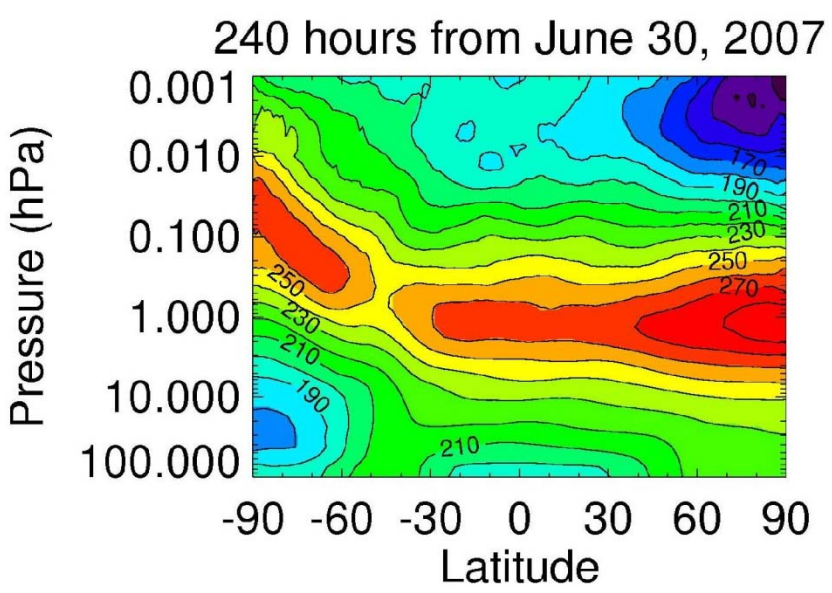


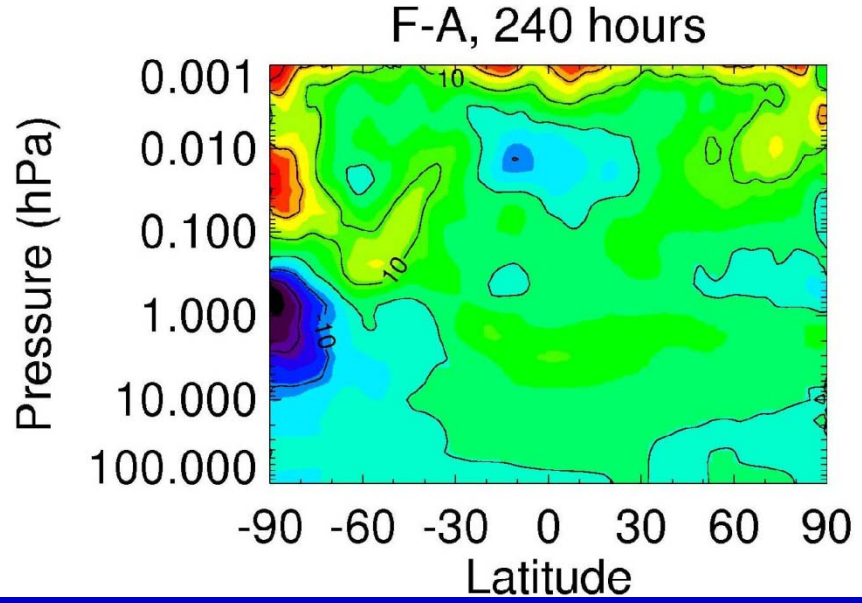
T479 at 240 hours

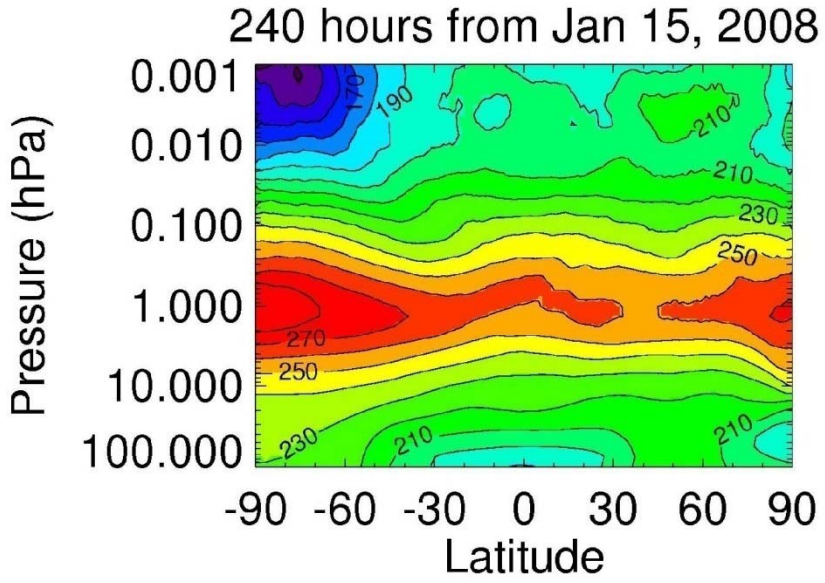


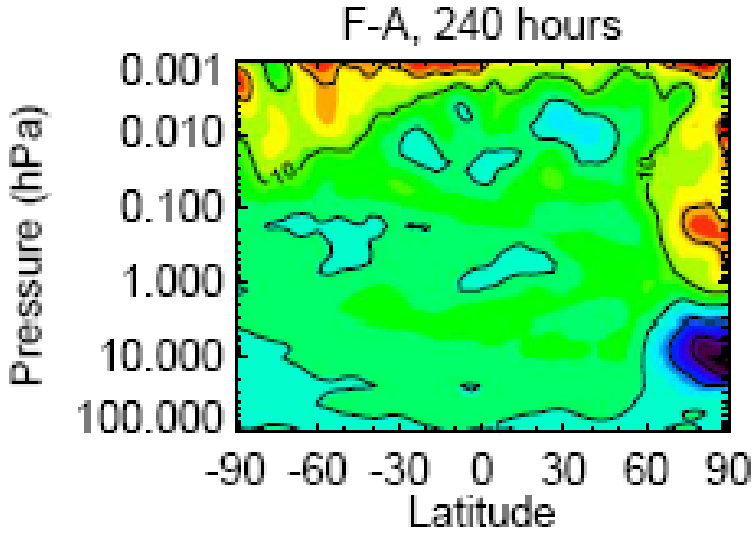


T479, Two other Cases



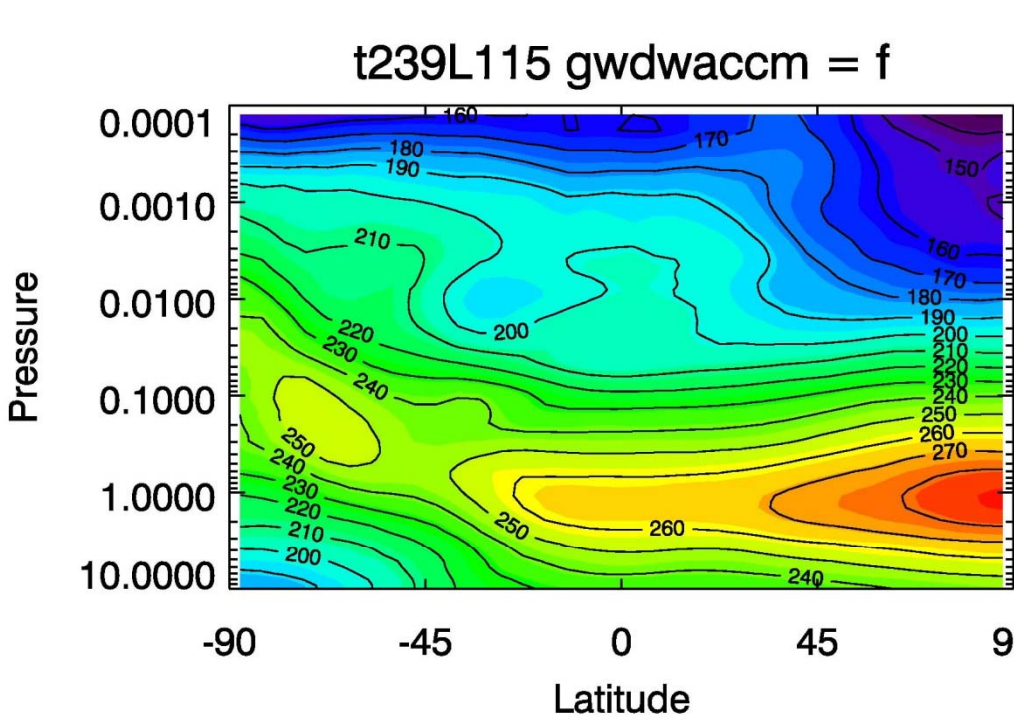


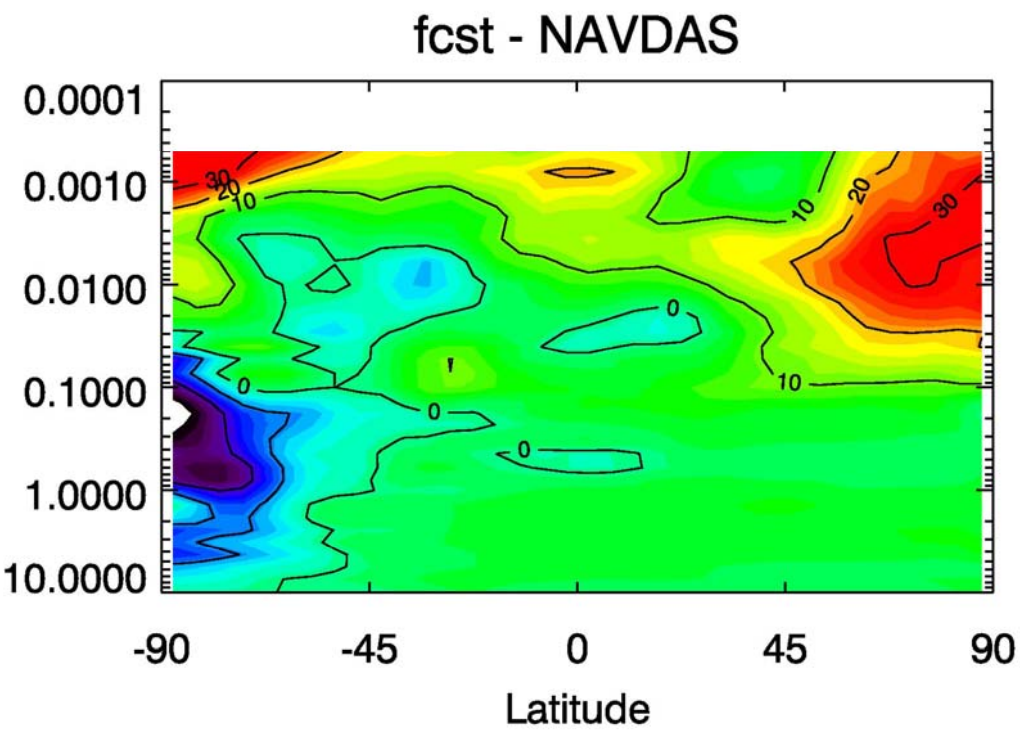




Effect of Higher vertical resolution: T239L115

L115: 25 levels troposphere, ~80 levels to ~0.001 mb, 10 levels to the top
vertical resolution increased from 2 km → 1 km in strat and mes.

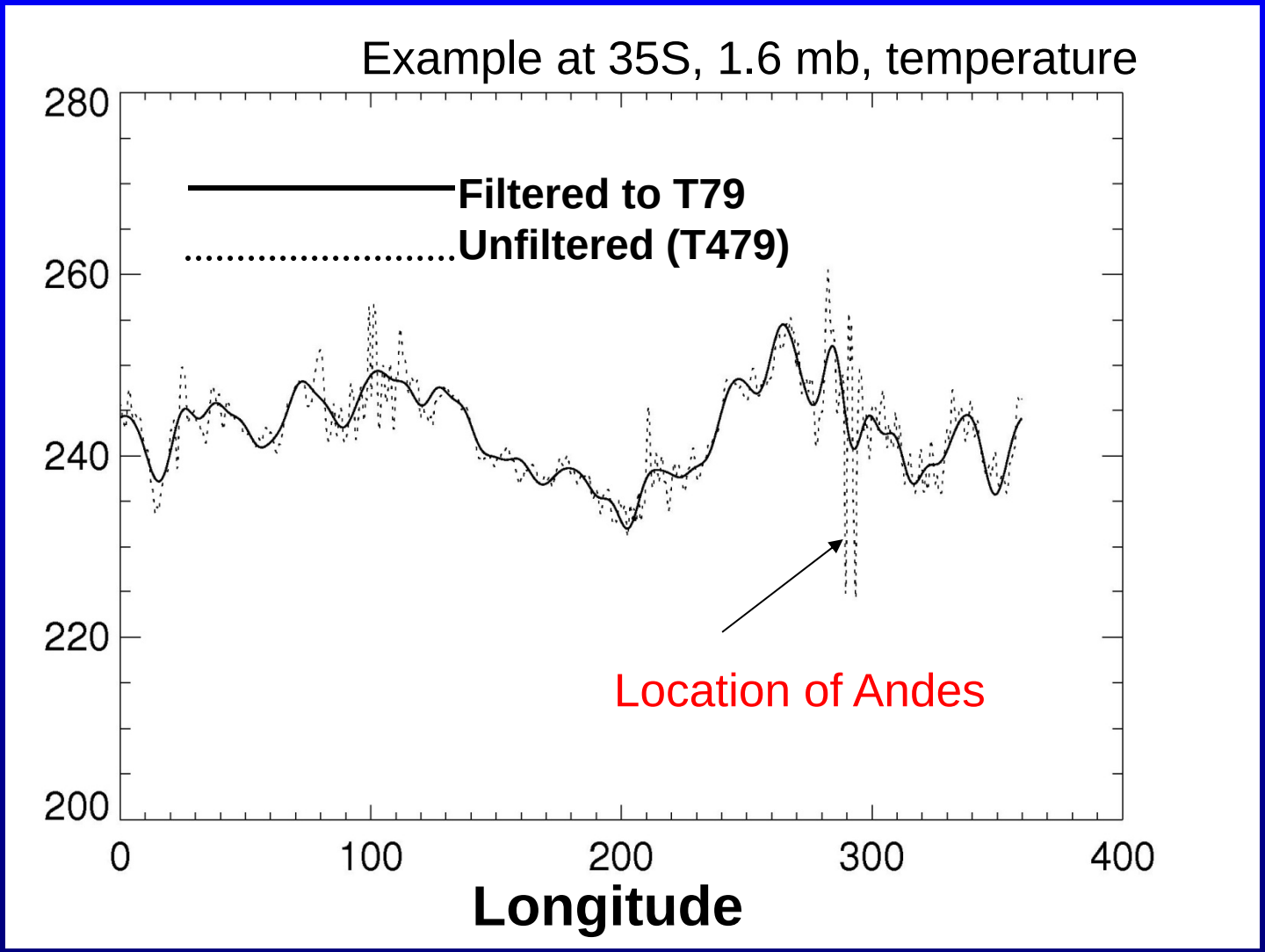




No better than T239 L74!

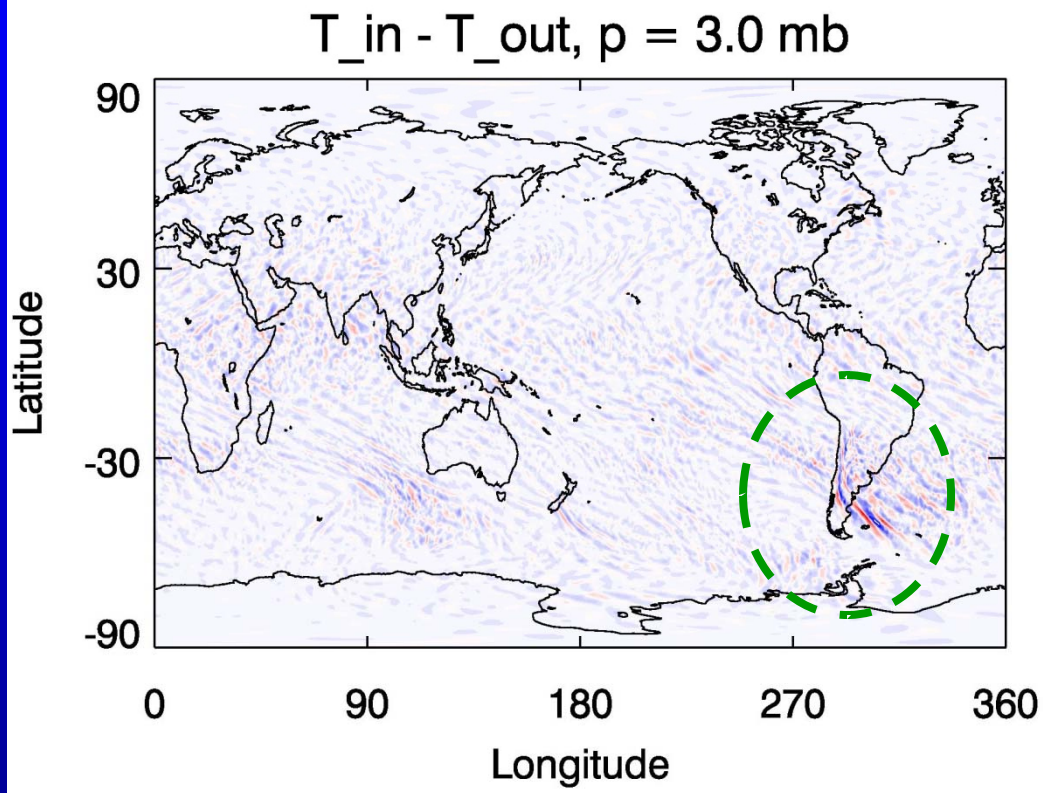
What do we resolve at high resolution?

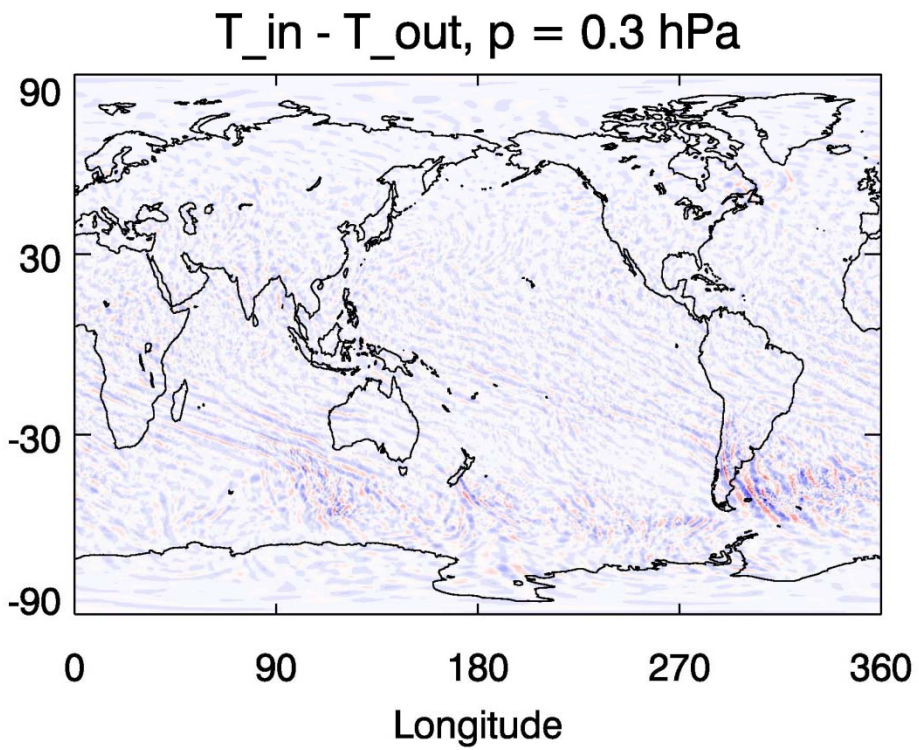
Filter the T479 runs



Difference between T479-T79 temperatures

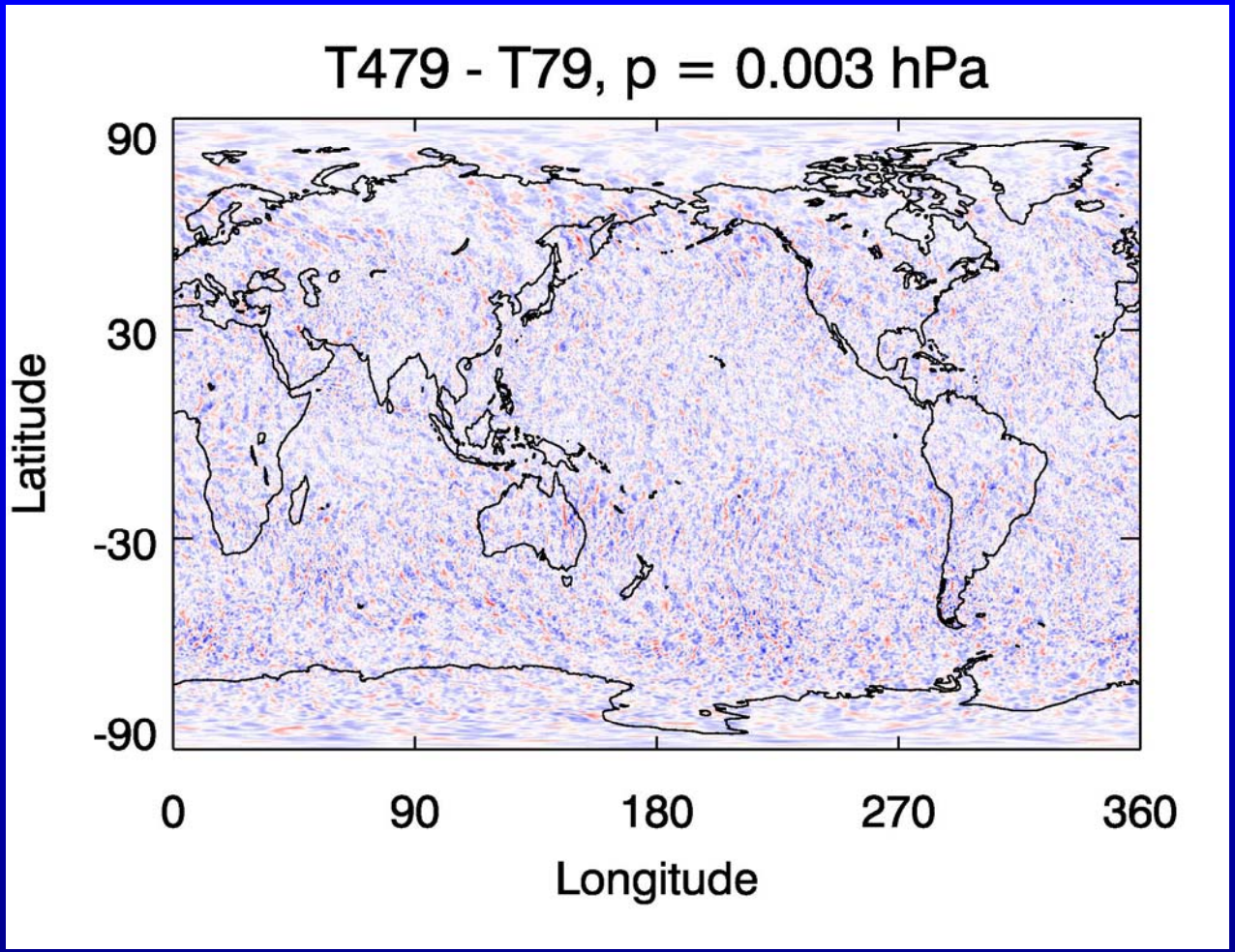
Global snapshot of small scale waves (120 hours after June 10)





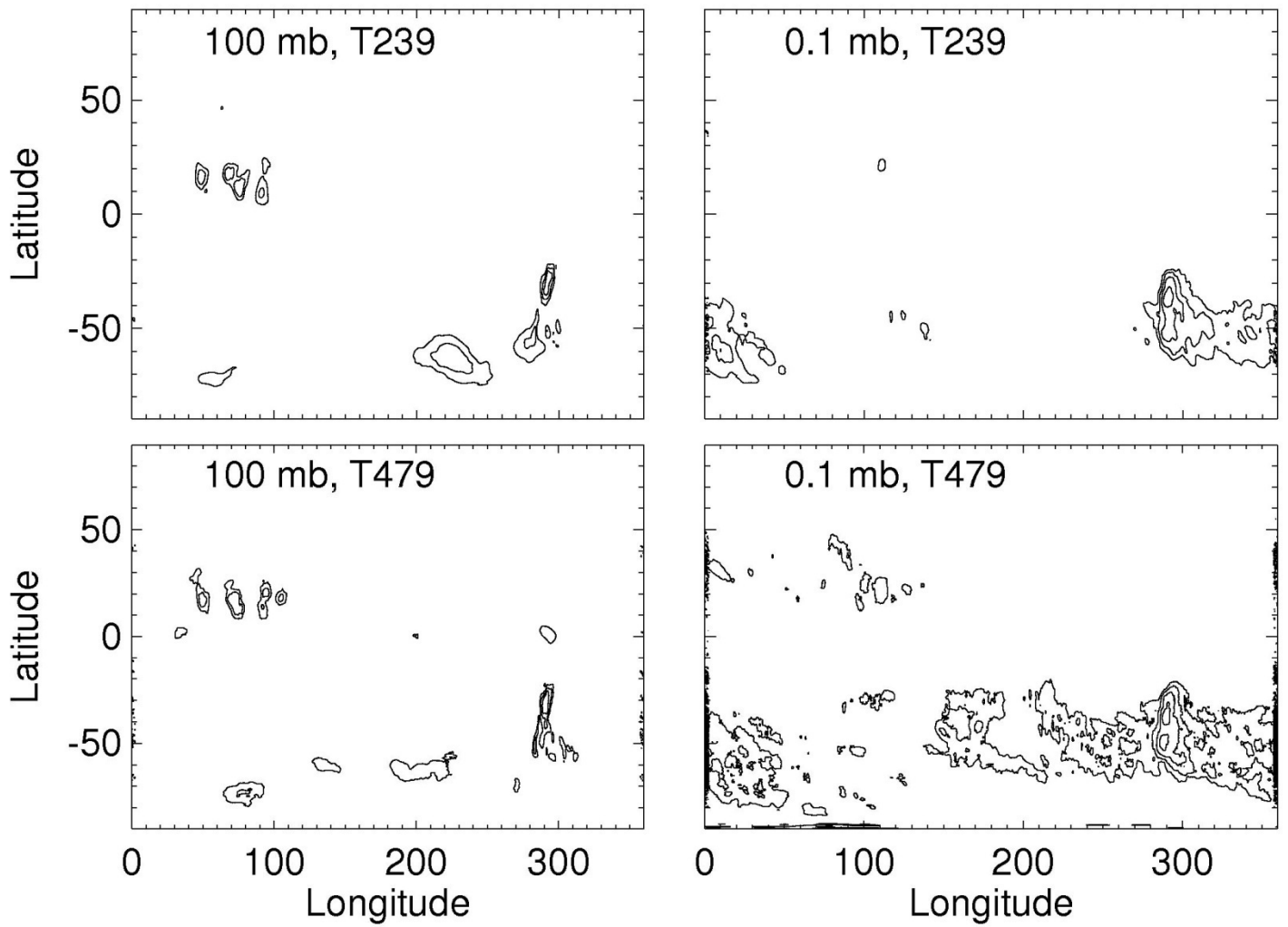
In USLM, most activity is in the winter hemisphere

T479-T79 at the mesopause

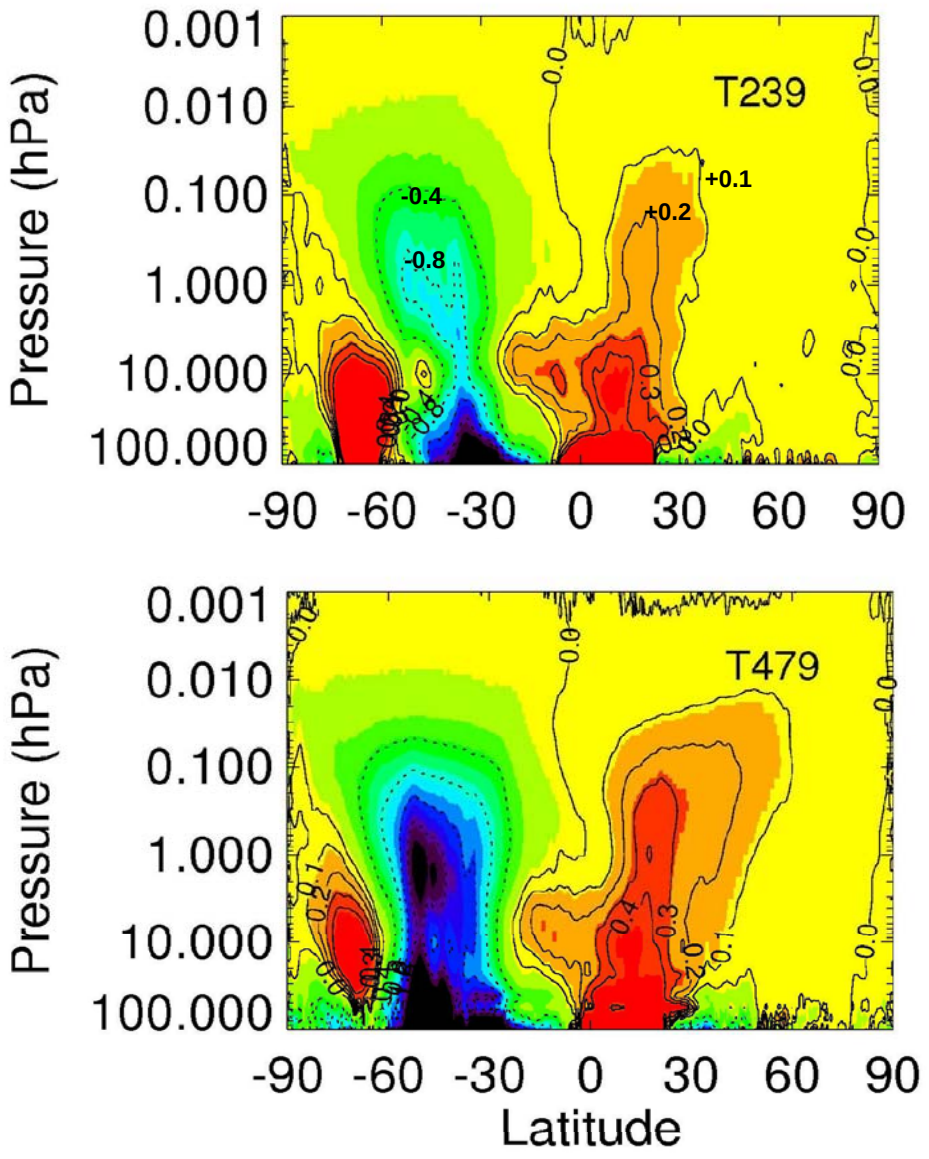


Small spatial scales evident in both summer and winter

Momentum flux for different model resolutions

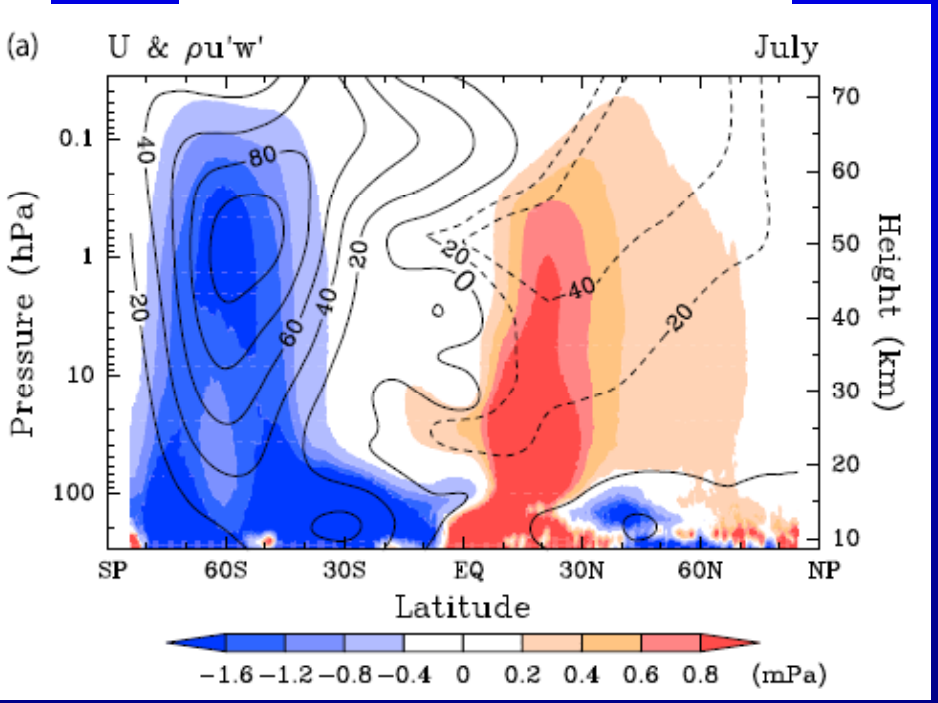


Momentum Flux, June 10-20th average



Moderate resolution

Sato et al. Figure 3



Dissipation and the horizontal spectrum of wind variance

Models have to dissipate energy at high wave numbers
(4^{th} order diffusion → hyperdiffusion)
How this is done can change the effective resolution (Skamarock, 2004)

Timescale for dissipation- vary K_h
(our baseline runs use 2.8 hours for T479)

$$\frac{a^4}{K_h(n_T(n_T+1))^2}.$$

Validate the dissipation by the kinetic energy spectrum/mass
Koshyk et al., 1999; Koshyk and Hamilton, 2001

$$E_{n,m} = \frac{a^2}{4n(n+1)}\left(|\xi_{n,m}|^2 + |\delta_{n,m}|^2\right),$$

Effective Horizontal Resolution of a GCM from "Rolloff" in Horizontal Wavenumber Spectra

Skamarock, [Mon. Wea. Rev., 2004]

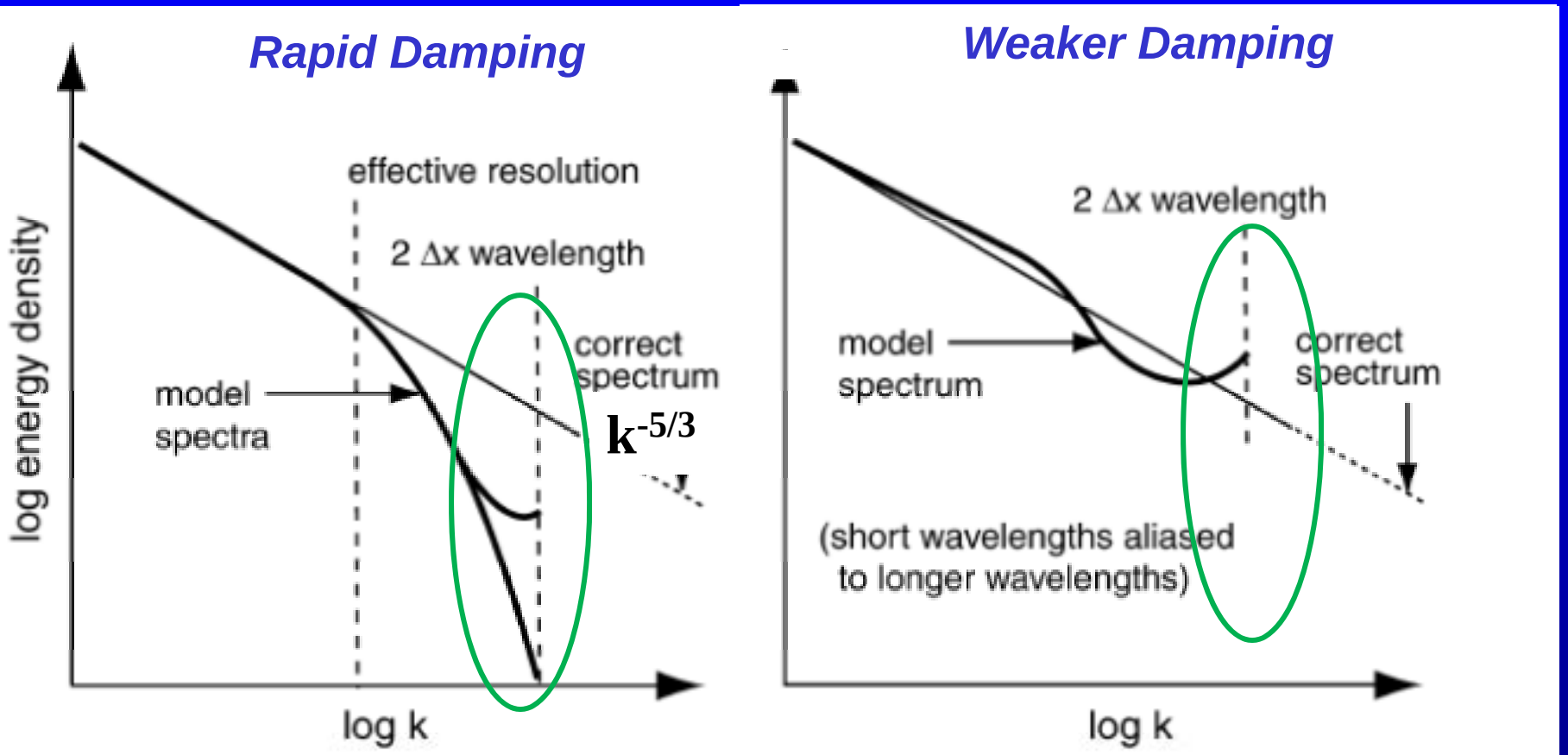
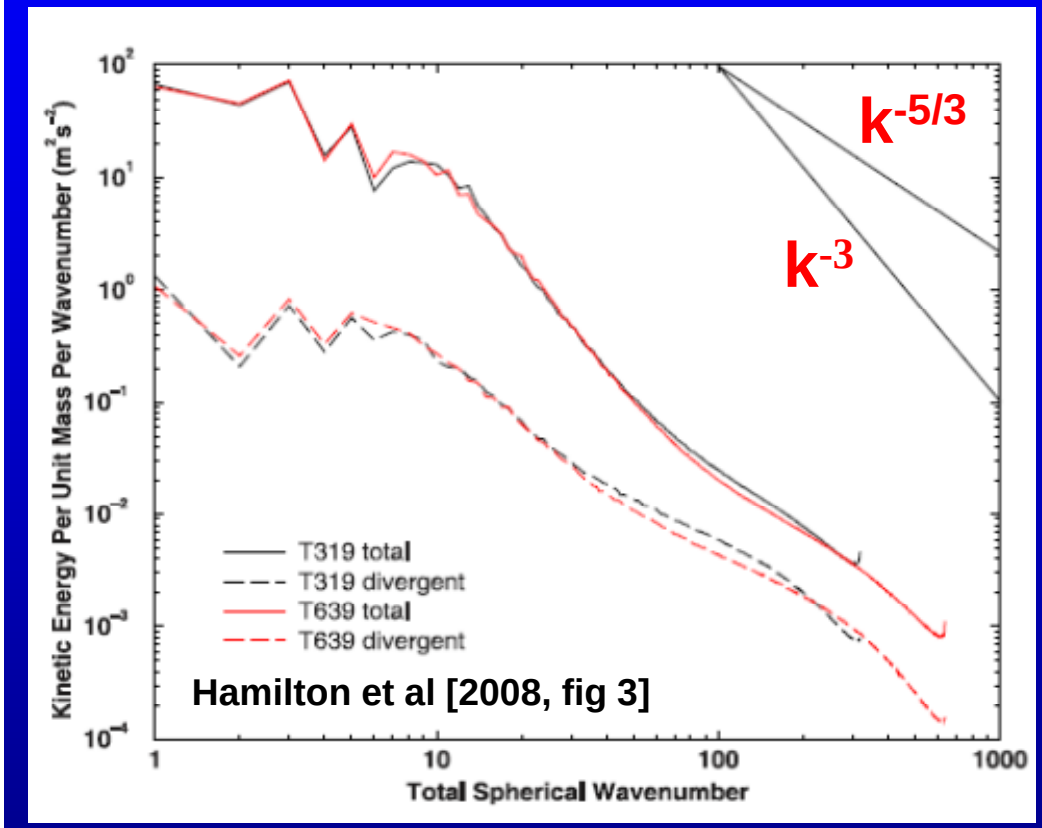
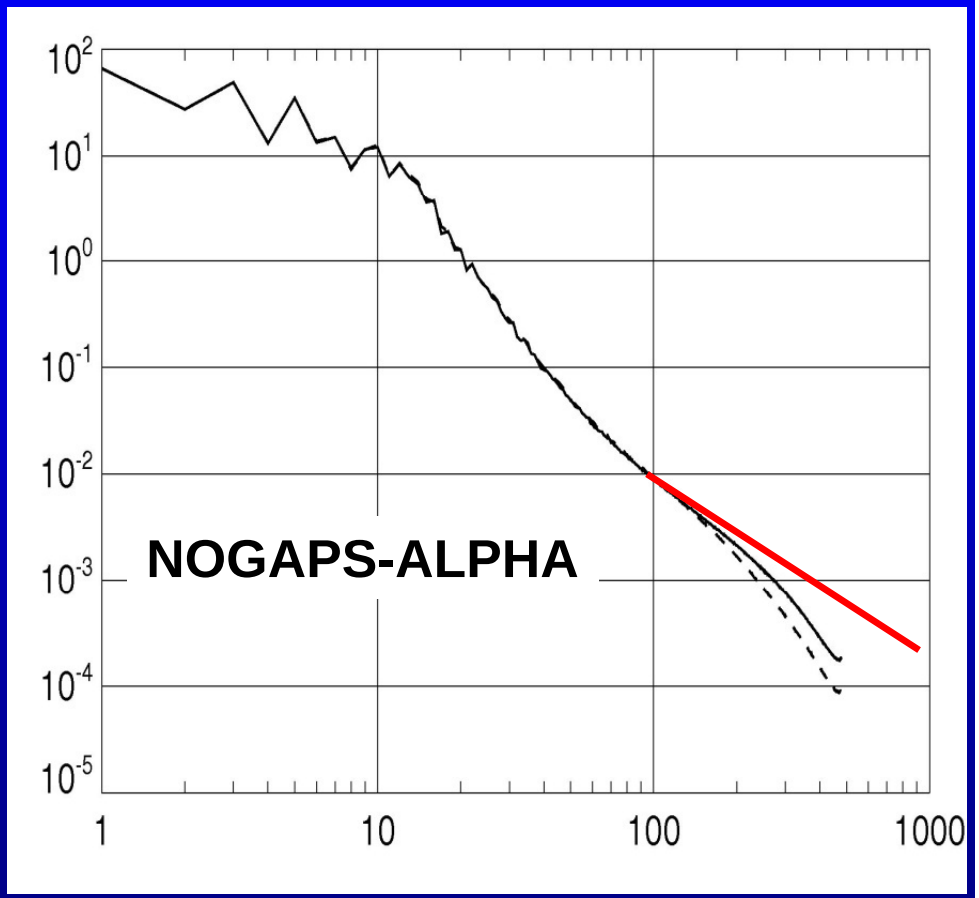


FIG. 10. Schematic depicting the possible behavior of spectral tails derived from model forecasts. Using the methodology outlined in the appendix to compute the spectra, limited-area models (including WRF) usually produce the slightly upturned tail shown at left.

Spectral Diffusion and Kinetic Energy Spectrum

200 mb

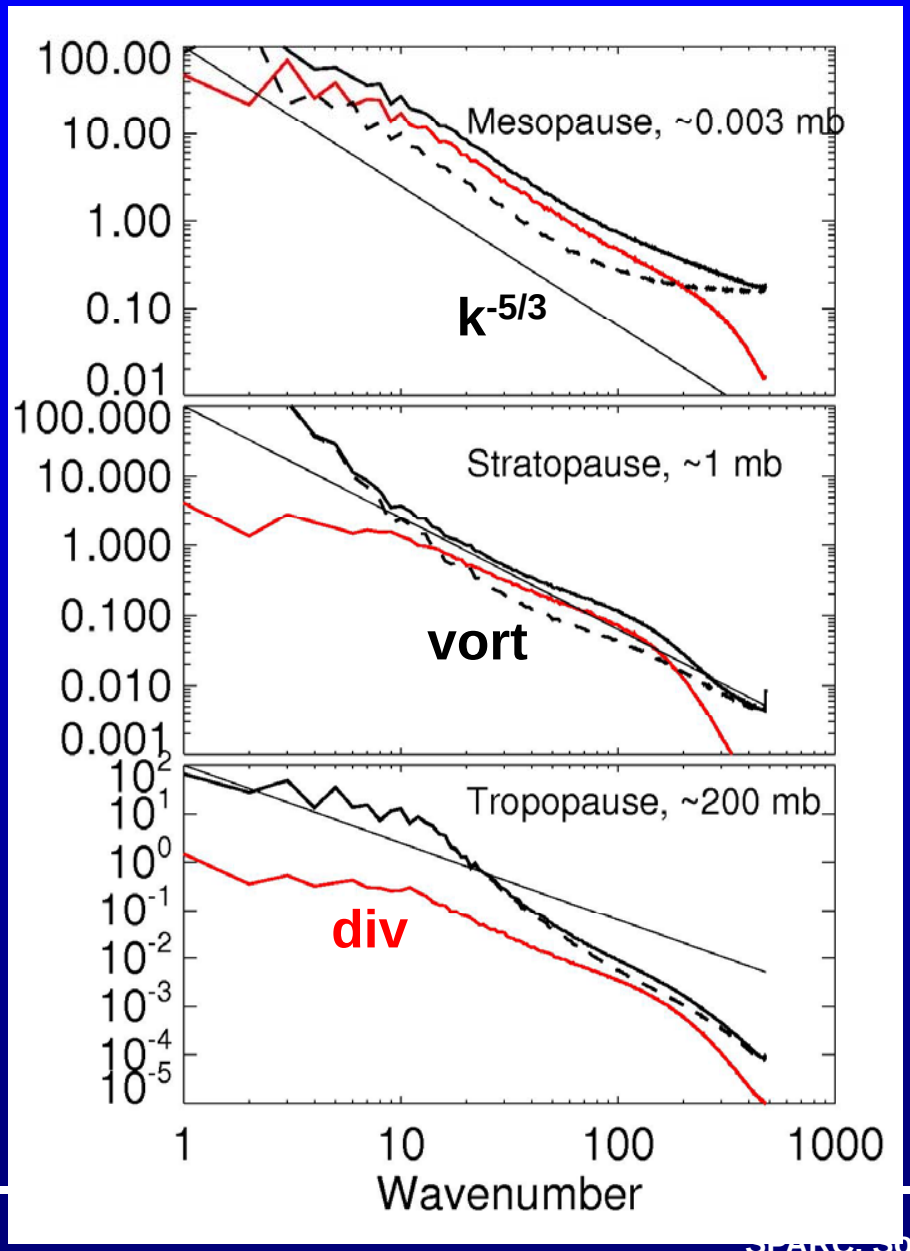




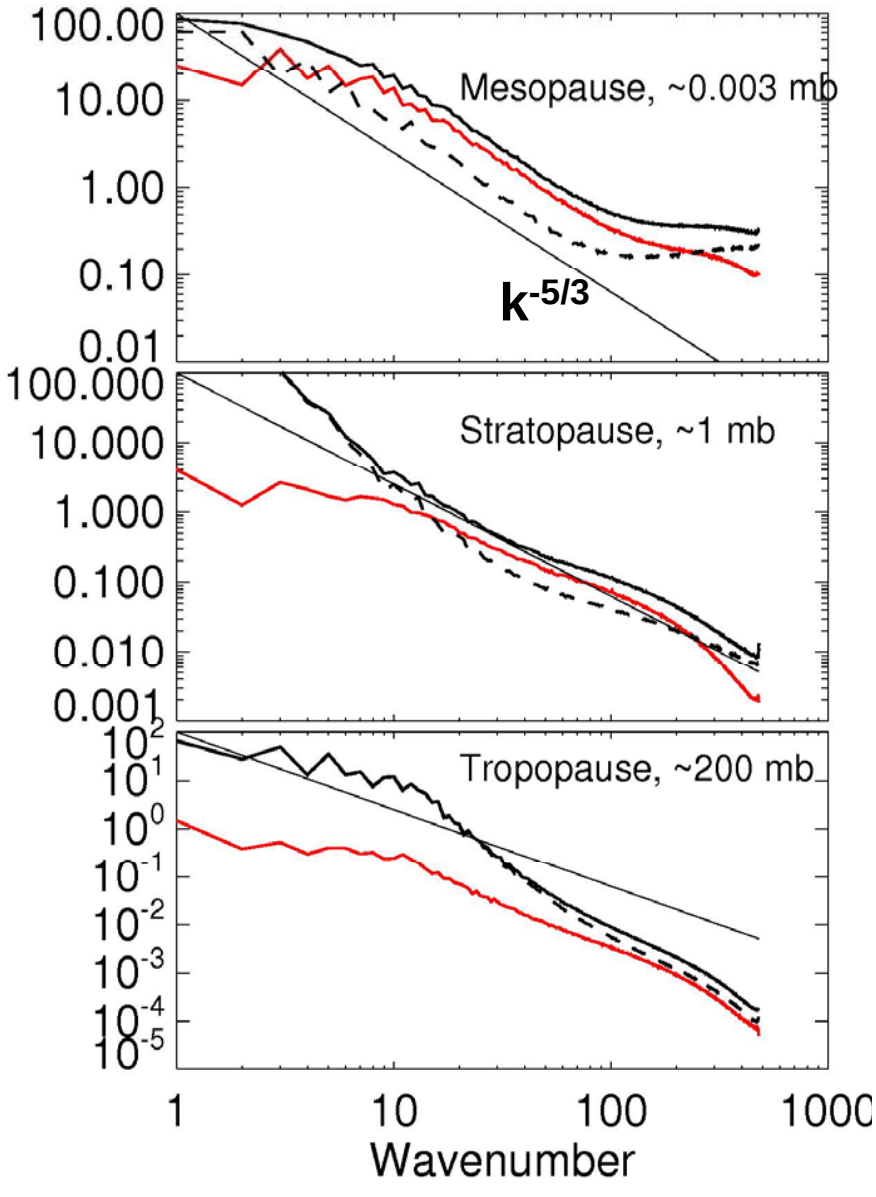
NOGAPS-ALPHA seems steeper at high wavenumber than $k^{-5/3}$

KE spectra for two diffusion time scales

Fast Diffusion (1.4 hours)

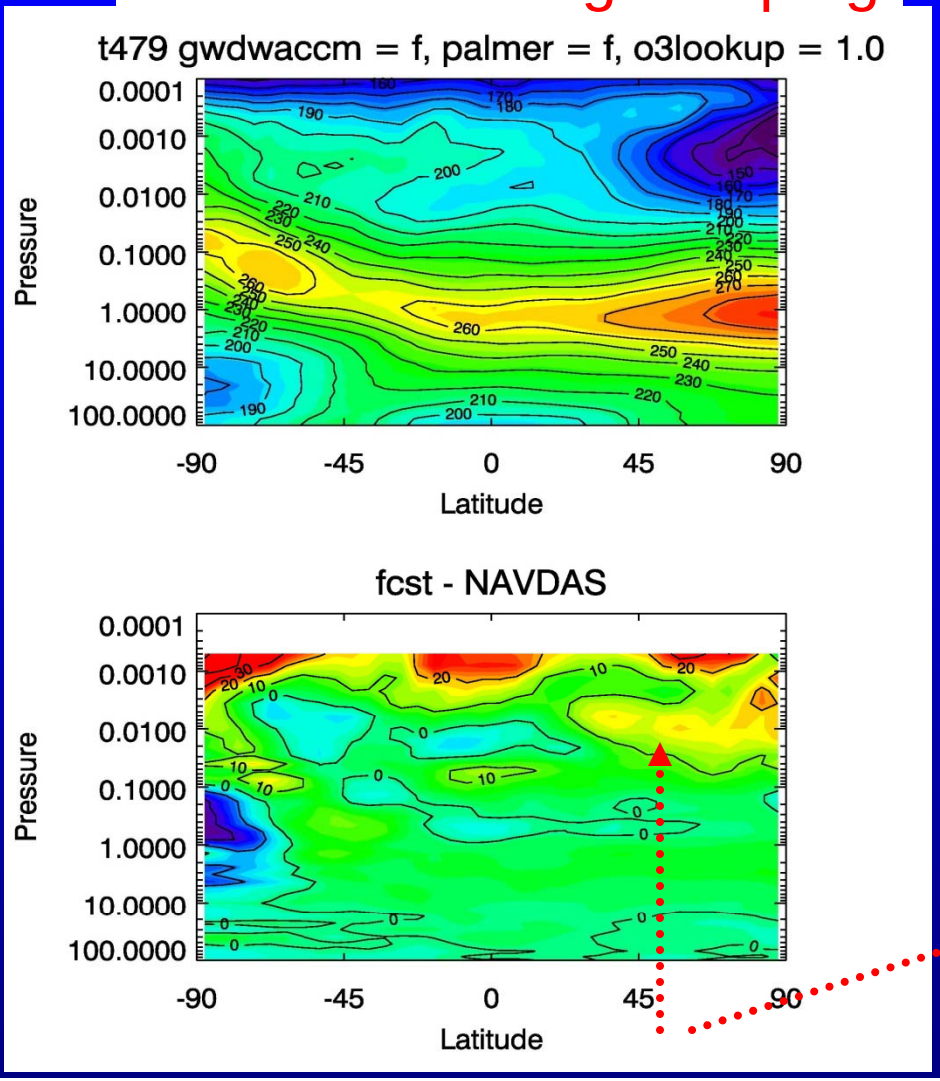


Slow Diffusion (5.6 hours)

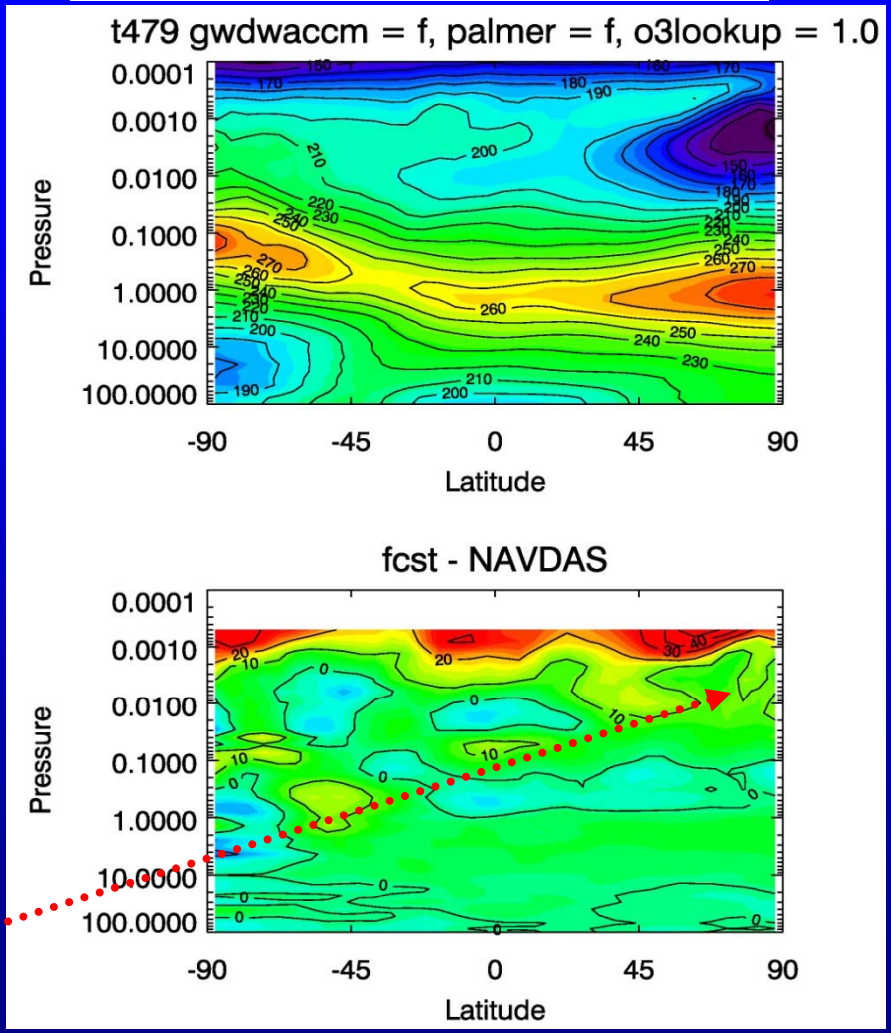


Changing spectral diffusion → Zonal mean effects

1.4 hours: strong damping



5.6 hours: weak damping



Weaker damping yields colder summer mesopause and warmer winter stratopause

Conclusions Part 1

2008 was a minor warming:

- Some attenuation of OGWD
- High altitude eastward forcing (mesospheric cooling), better resolved with "multiwave" GWD but effects are minor

2006 was a major → extended warming

- heavy attenuation of OGWD
- ***Defining characteristic:*** MGWD swings from eastward → westward

T239 with only OGWD is insufficient to resolve all GWs

Two sources of high altitude planetary waves

- in 2008: asymmetric GWD
- in 2006: instabilities at the stratopause

Conclusions, Part 2

Our approach using DA + 10 day forecasts is viable for exploring resolution effects.

Increased horizontal resolution is more effective than increased vertical resolution for extratropical zonal mean middle atmosphere simulations

T479 is insufficient (in our model) to capture winter stratopause or summer mesopause unless spectral diffusion is unrealistically weak. Gravity wave activity significant for $k > 239$.

What resolution is needed? No single answer.

Instead of GWD parameterization tuning, must consider spectral dissipation at high wave numbers also, convection scheme, numerical solver

T239-L74 for another start date (June 30th → Jul 10)