Influence of the Stratospheric Potential Vorticity Distribution on the Brewer-Dobson Circulation

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Brewer-Dobson circulation is driven in part by breaking of planetary scale Rossby waves on the winter polar vortex.

Both wave propagation and wave breaking are controlled by PV distribution

(two separate ideas - linear, nonlinear)

e.g.

wave propagation:
. . . steep gradients act as a waveguide
. . . different dispersion relation for edge waves (polar vortex edge) and plane waves (uniform PV gradient)

wave breaking:
. . . steep PV gradients limit wave breaking

Know that winter stratospheric PV has step-like distribution (vortex edge, surf-zone, subtropical barrier)

. . . aircraft observations (Tuck, 1989; Waugh et al., 1994)

. . . dynamics of vortex stripping well-understood (Legras et al., 2001)

. . . also high resolution re-analysis; contour advection; etc

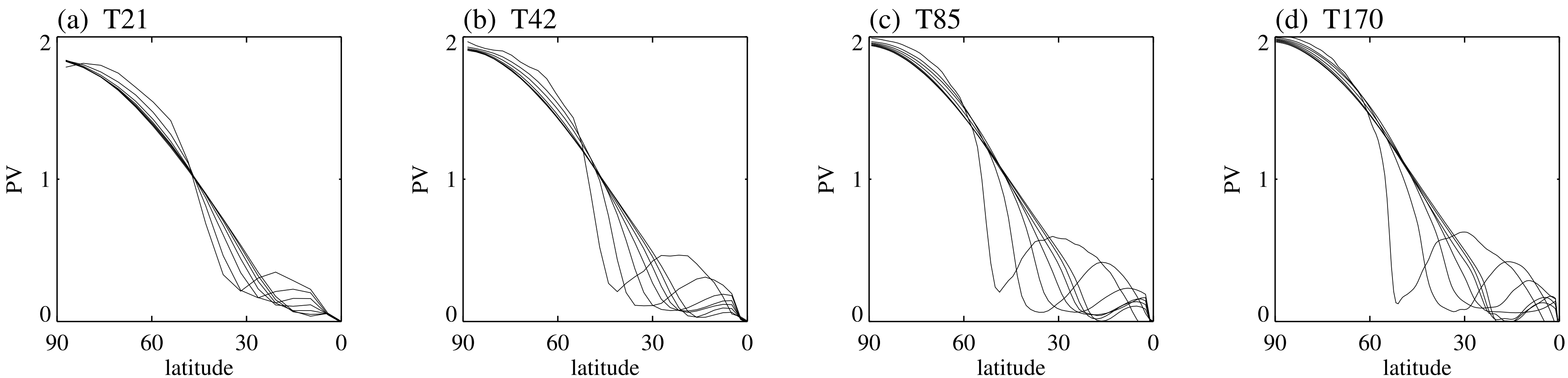
To resolve this PV distribution requires high model resolutions.

Low resolutions will smooth the step.
(e.g. T21: 16 grid points pole-equator; vortex edge width is 20 degrees)

. . . this will affect wave propagation/breaking
. . . diffusion + strain leads to anomalous vortex erosion and spurious transport.

How important is this?

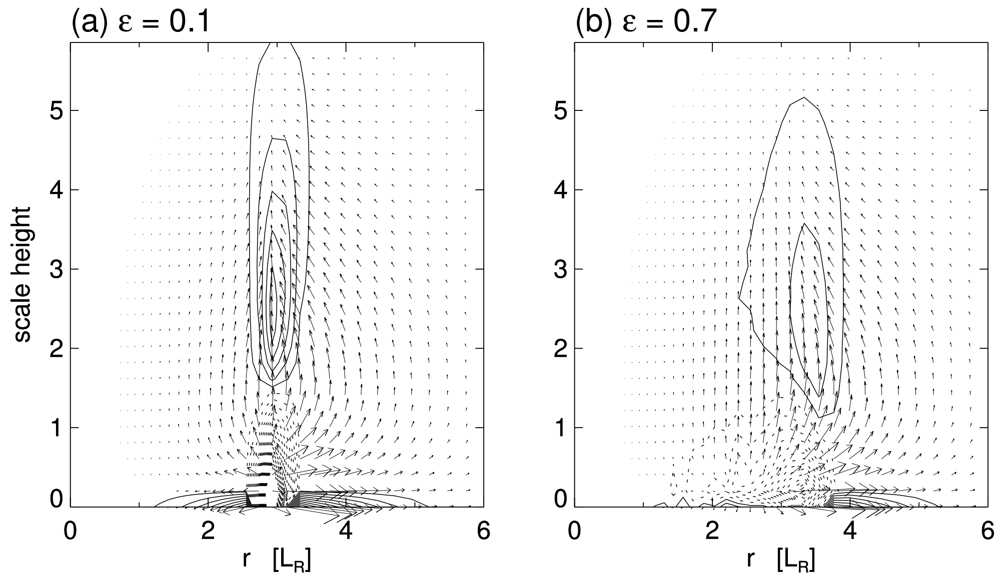
Example: cross section of PV on $\theta = 930\,$K for T21 – T170



. . . identical forcing and initial conditions (smooth vortex)
. . . lines are $t = 16, 18, 20, \ldots, 28$ days
. . . sudden warming around $t = 28$ days

Scott et al. (2004):
quasigeostrophic model; vortex edge width ε;
vortex parameters κ, J, r_0 independent of ε

modest increase in $\nabla \cdot \mathbf{F}$ with decreasing ε



But:

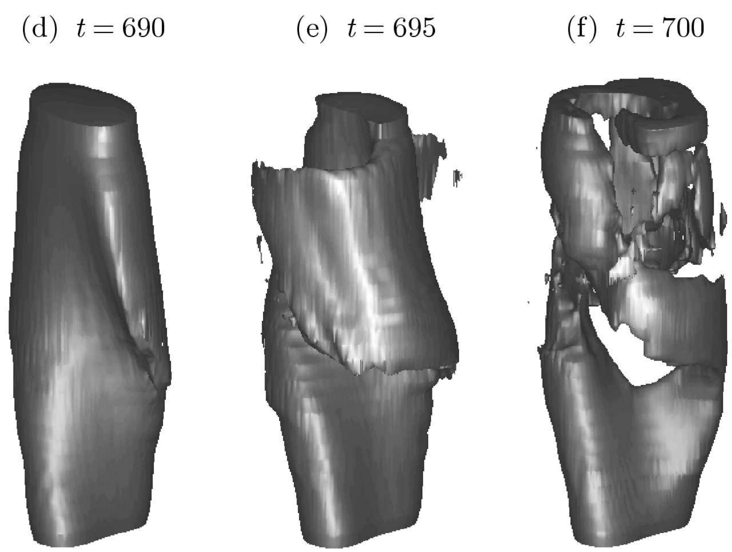
(i) difference in $\nabla \cdot \mathbf{F}$ partly due to change in $F^{(z)}$ at lower boundary (controlled by stratosphere)

(ii) did not consider barotropic mode

INTERNAL STRATOSPHERIC VARIABILITY

Steady forcing → *coherent, regular* stratospheric variability
Holton & Mass; Yoden; Scott & Haynes; Christiansen

. . . shown to persist at regular internal variability at higher resolutions
(Scott & Polvani, 2004, 2006)



natural variability on timescales of around 60 days

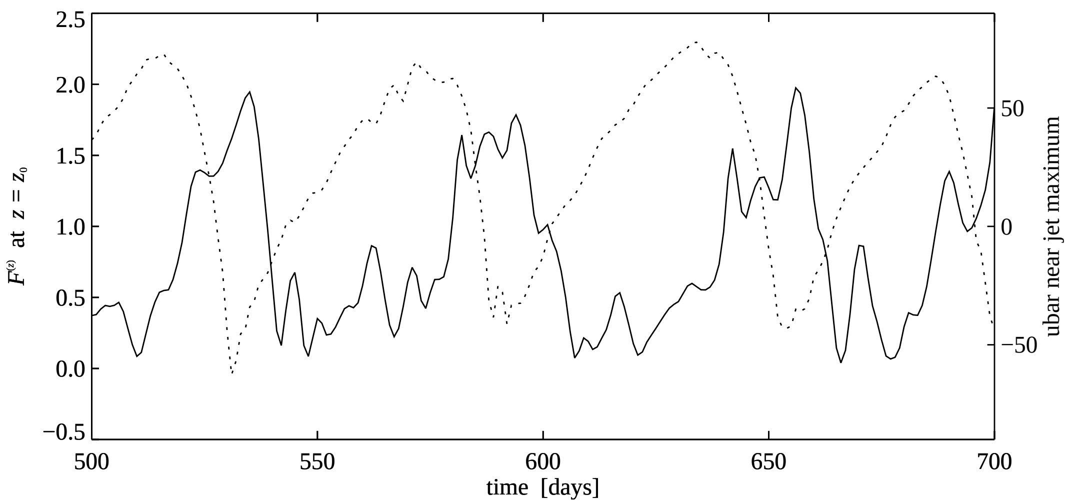
repeated sudden warmings

competition between dynamical forcing (wave breaking) and thermal relaxation

. . . pseudo-spectral, stratosphere-only primitive equation model
. . . 40 vertical levels
. . . thermal forcing to perpetual January
. . . lower boundary wave forcing – geopotential height perturbation

Here, wave forcing is time-independent (no tropospheric variability), yet *wave flux* through the lower boundary is strongly time-dependent: rapid increase as the polar vortex is decelerated

Sudden variations in $F^{(z)}$ are determined by the state of the stratosphere (Scott & Polvani, 2004, 2006)



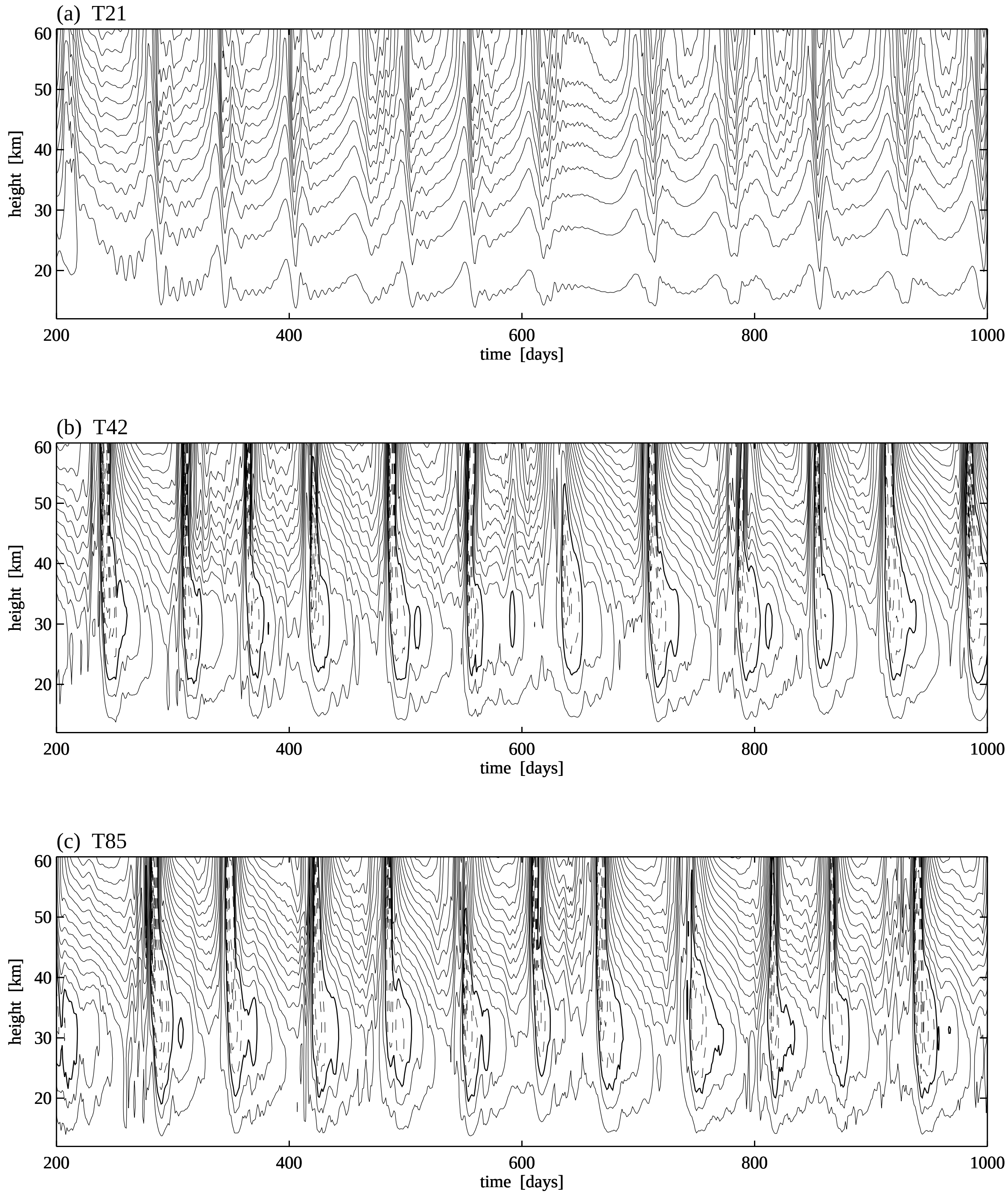
$F^{(z)}|_B$ (solid)
$\bar{u}$ at 60°, 40 km (dotted)

A sudden increase in wave flux at the tropopause is not necessarily caused by an increase in tropospheric wave forcing.

The stratosphere alone is able to modulate the wave flux.

sensitivity to horizontal resolution: T21, T42, T85

$\bar{u}(z,t)$ at 60° N

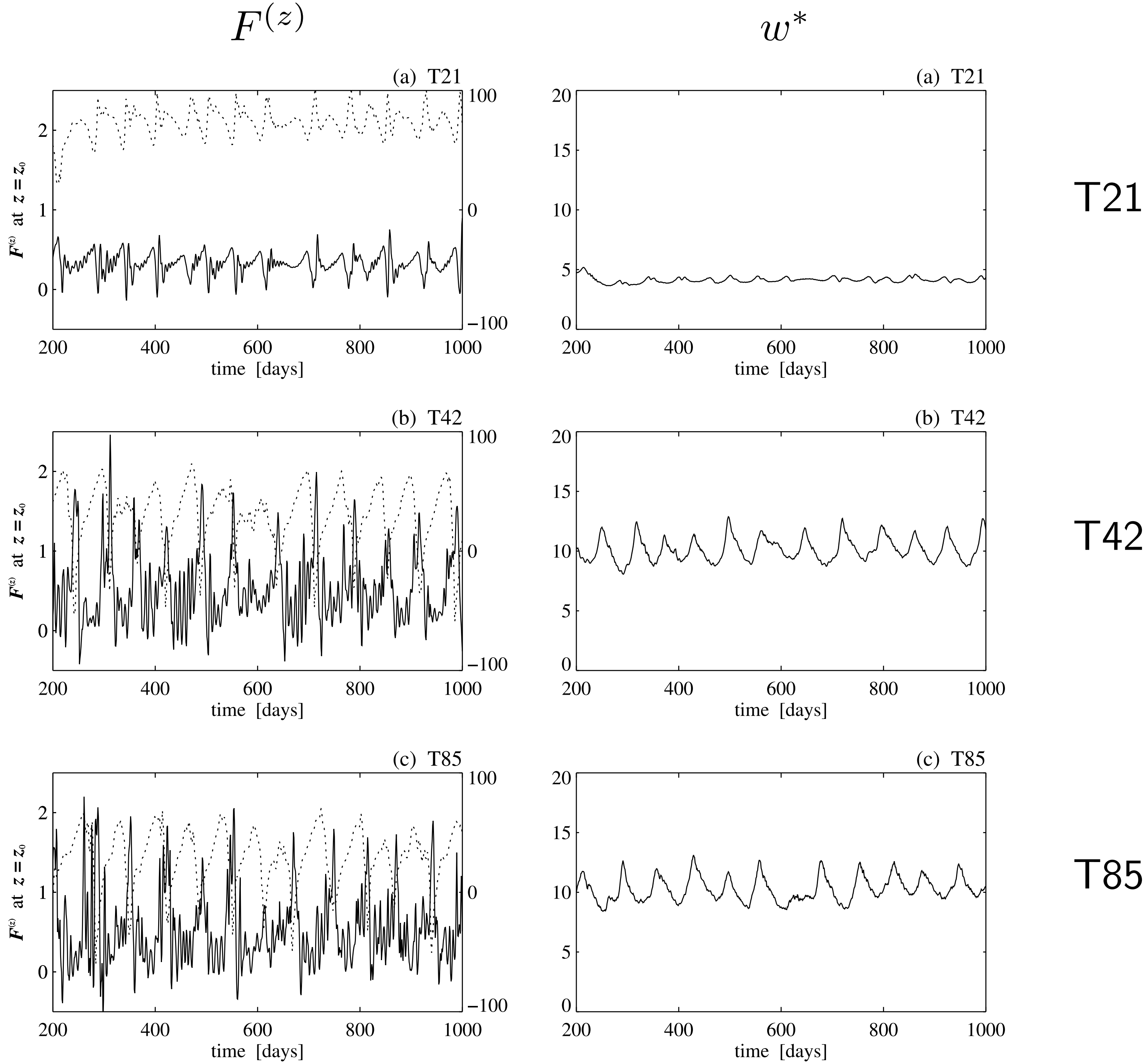


T21

T42

T85

sensitivity to horizontal resolution: T21, T42, T85



Stratospheric response depends on forcing amplitude, h_0

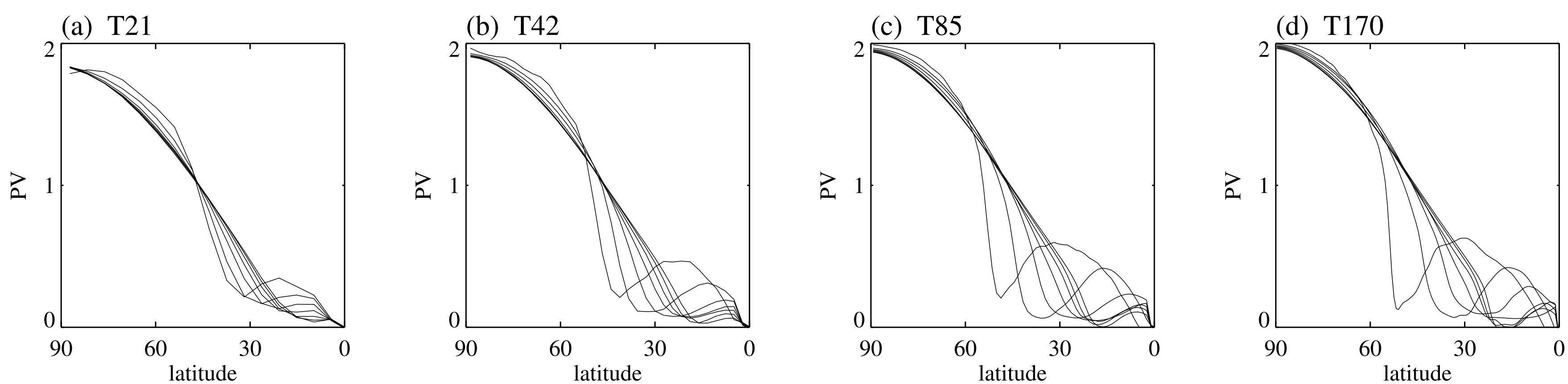
$h_0 \leq 200$, steady response
$h_0 \geq 400$, vacillations—repeated major warmings

But critical h_0 is higher at low resolution

T21: minor warmings only $400 \leq h_0 \leq 800$

Convergence at T42 for zonal-mean quantities and time-averages;
$\bar{u}$, (v^*, w^*), $\mathbf{F}$, etc.

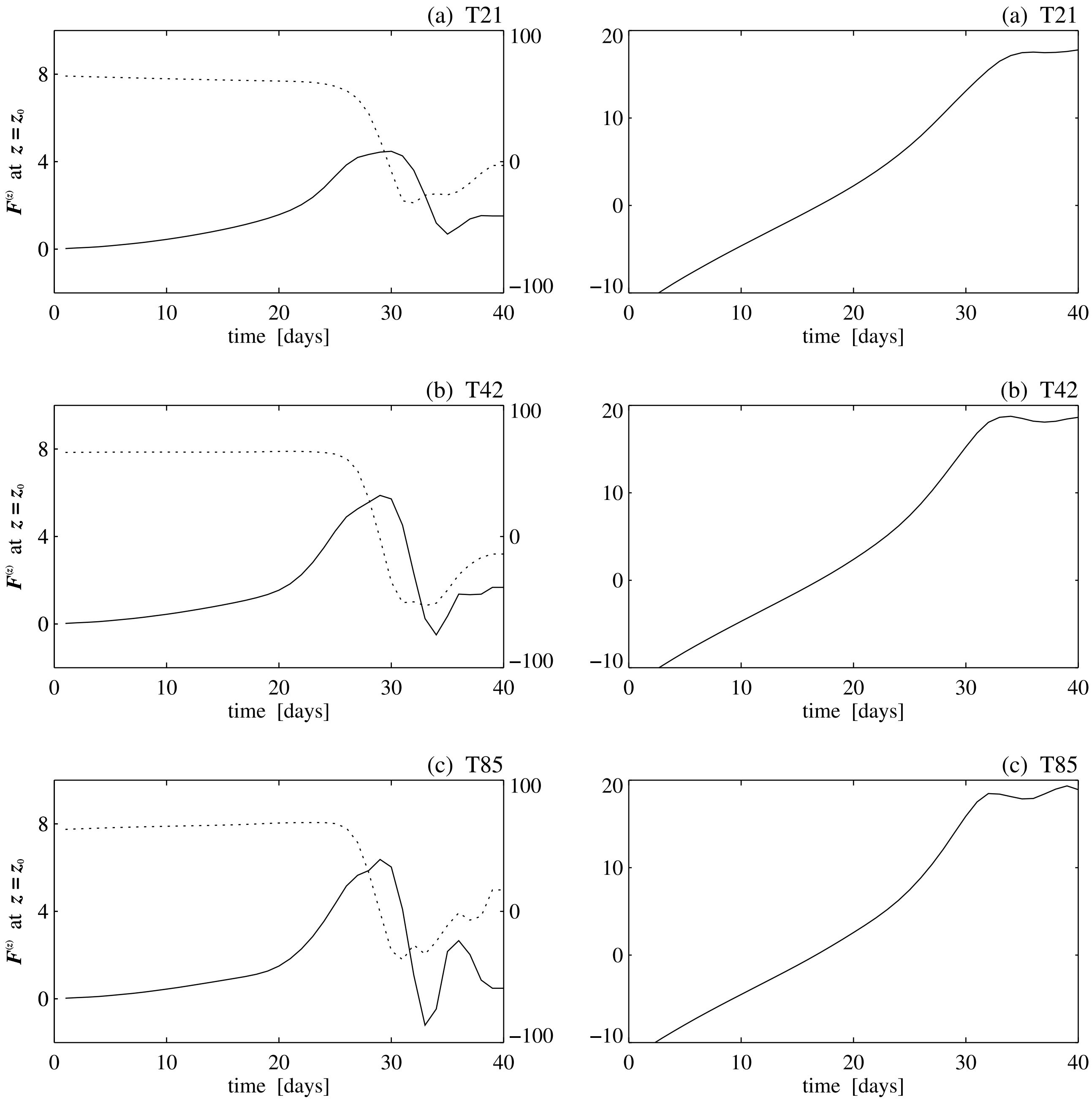
(but not instantaneous, extreme values etc.)



Different for initial value problem:

$F^{(z)}$ | w^*

T21 / T42 / T85



BAROTROPIC MODE (Esler & Scott, 2005)

Consider an idealized cylindrical polar vortex

$$Q(r,z) = \begin{cases} Q_0 & r < R \\ 0 & \text{otherwise,} \end{cases}$$

Assume disturbances to the vortex edge to position $r = R + \eta$:

$$\left(\frac{\partial}{\partial t} + \mathbf{u} \cdot \nabla\right)(\eta - r) = 0 \quad \text{on} \quad r = R + \eta$$

Get upward propagating waves (the Charney-Drazin spectrum):

$$\eta = \hat{\eta}(r)\rho_0^{-\frac{1}{2}} \exp i(k\theta + mz - \omega t) \qquad \text{for } \omega \in [\omega_-, \omega_+]$$

Also get barotropic mode with no vertical dependence

$$\eta = \hat{\eta}(r) \exp i(k\theta - \omega t) \qquad \text{for } \omega = \omega_0 < \omega_-$$

Conservation of wave activity:

$$\frac{\partial A}{\partial t} + \frac{\partial F^{(z)}}{\partial z} = 0$$

Integrate in the vertical:

$$\frac{d\mathcal{A}}{dt} = F_B^{(z)}$$

Total angular momentum:

$$\mathcal{M} + \mathcal{A} = \text{constant} \qquad \Longrightarrow \qquad \frac{d\mathcal{M}}{dt} = -F_B^{(z)}$$

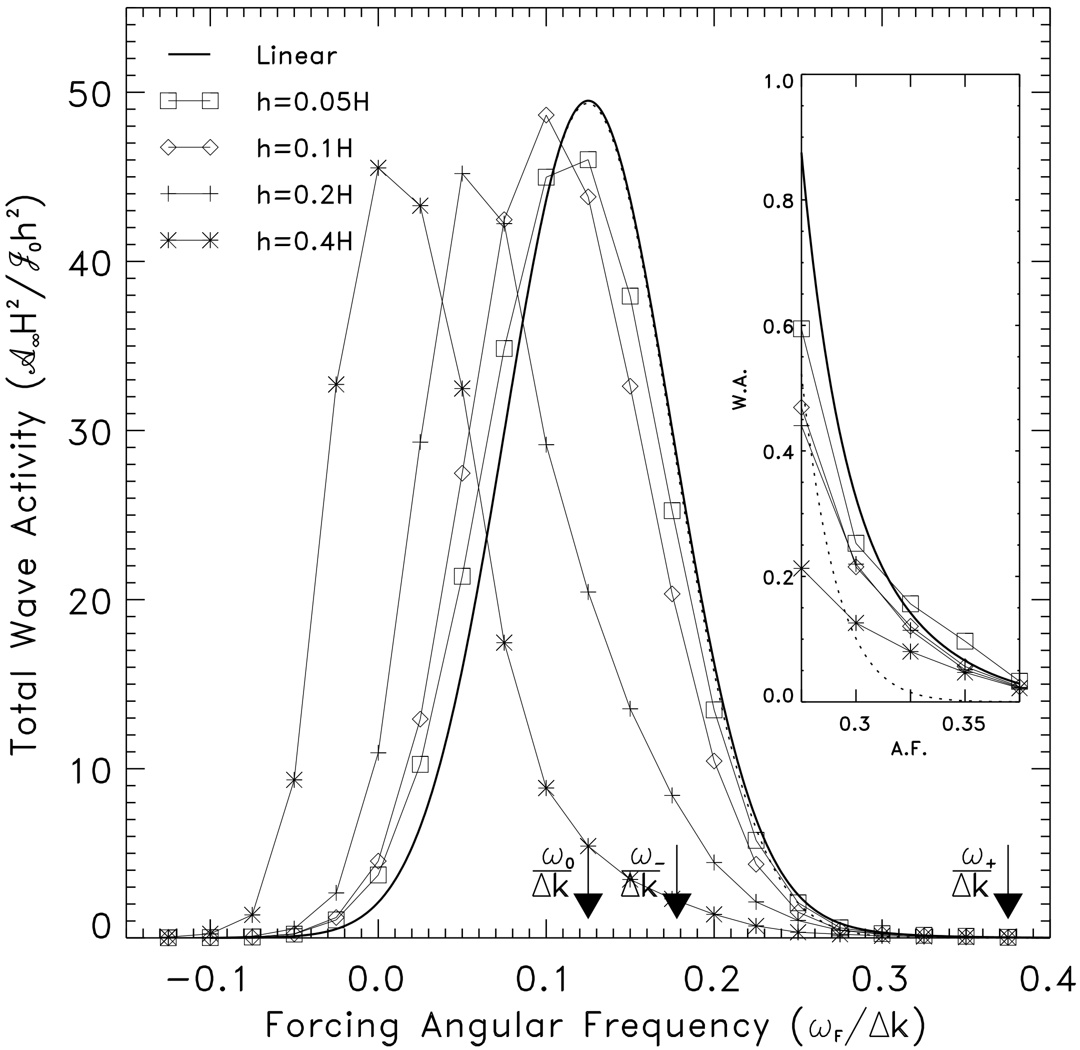
I.e.: change in vortex angular momentum = total upward wave flux

Define the relative response to the barotropic/Charney-Drazin modes:

$$\mathcal{R} = \frac{\mathcal{F}_0}{\mathcal{F}_{\text{CD}}}$$

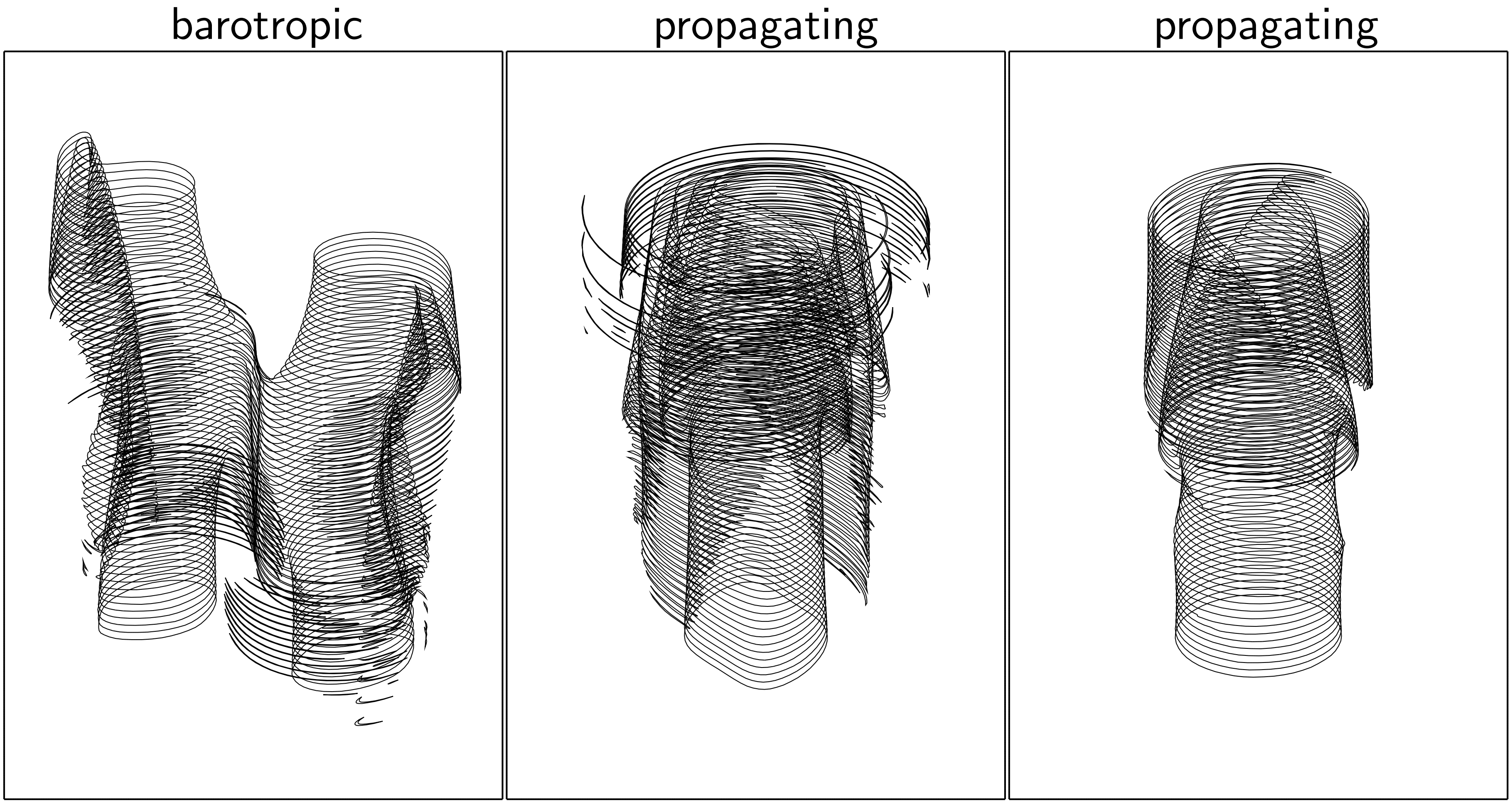
$\mathcal{R}$ is $\mathcal{O}(10)$–$\mathcal{O}(100)$ (. . . equal forcing at all frequencies)

[$F_B^{(z)}$ is given in terms of the forcing *history*]

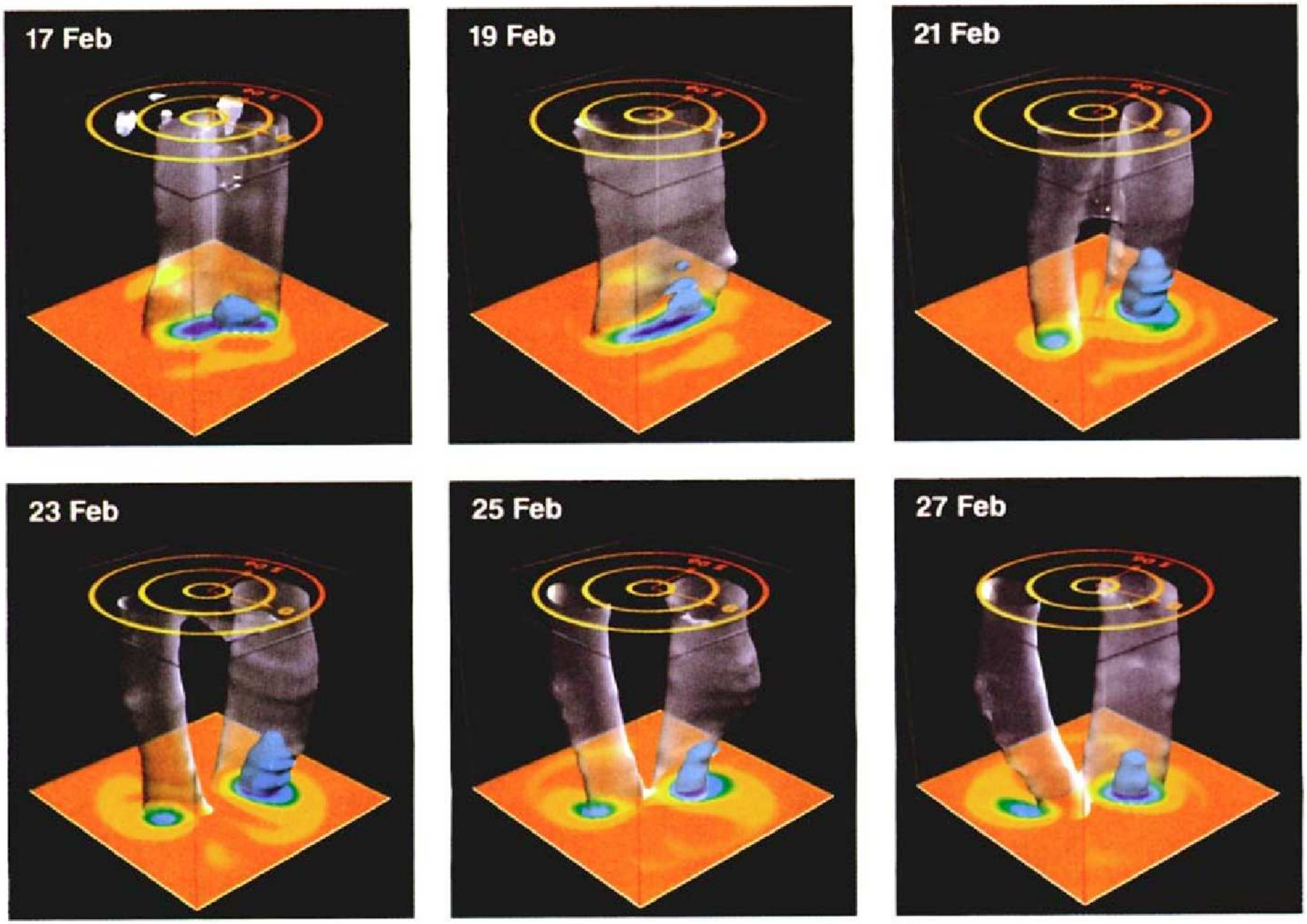


Resonant forcing at ω_0 gives rise to a much larger vortex response than forcing of upward propagating waves

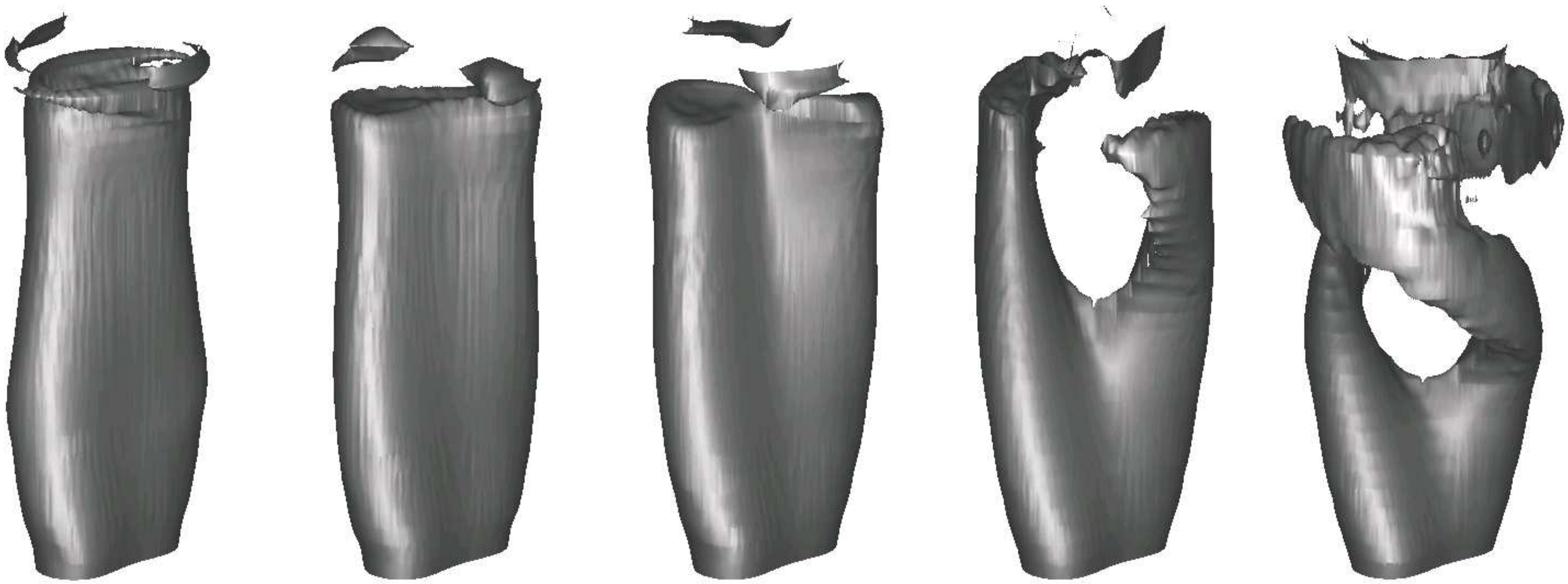
Identical calculations apart from forcing frequency:



February 1979 major warming (Manney et al., 1994)



Barotropic mode in internal variability



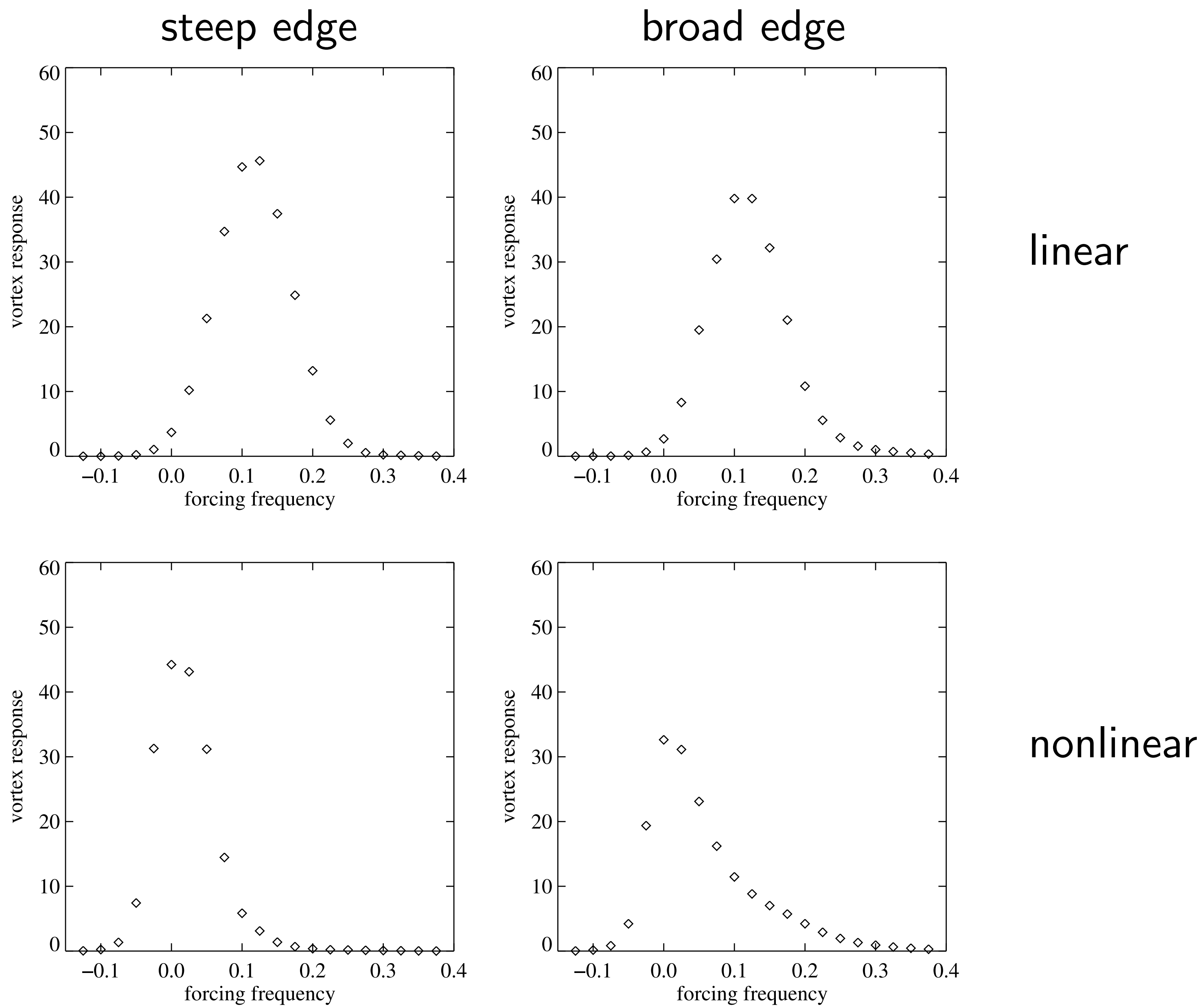
Modify traditional picture

. . . "upward propagation" of planetary waves → wave breaking, vortex deceleration, descent of critical level, etc (Matsuno, 1971)

to include

. . . near-resonant excitation of the barotropic mode, in particular for vortex splitting

Effect of resolution on excitation of the barotropic mode?



SUMMARY/CONCLUSIONS

For a given wave flux entering stratosphere, BD circulation is insensitive to horizontal resolution.

However, the stratosphere exerts control over upward wave fluxes.

Low resolution requires larger forcing amplitude for internal variability and repeated sudden warmings.

Or, equivalently, for a given forcing amplitude, low resolution model has fewer/weaker sudden warmings, hence weaker BD circulation:

. . . different solution branch of internal variability
. . . weaker response in the barotropic mode for smooth vortex edge

But T42 probably OK.