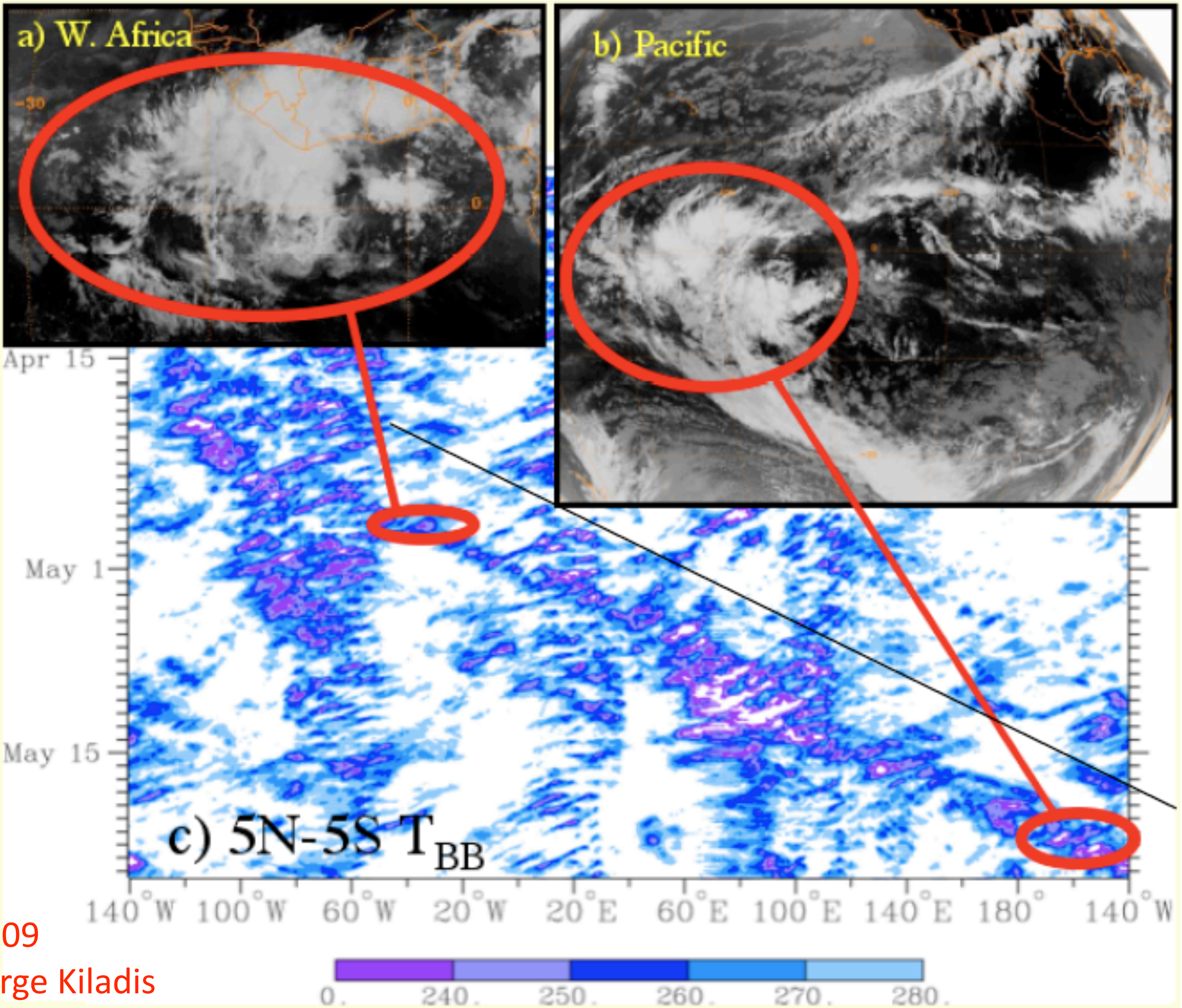
Large-scale convectively coupled tropical transients

Zhiming Kuang



From Mapes, 2009

Courtesy of George Kiladis

Figure 1: A moist Kelvin wave in April-May 1998 (studied by Straub et al. 2006). Panels a and b show infrared images roughly at the places and times indicated on the time-longitude brightness temperature section c. (panel c courtesy of G. Kiladis). The black slanted reference line has a slope of 10 degrees per day, or 13 m/s.

Space-time spectra

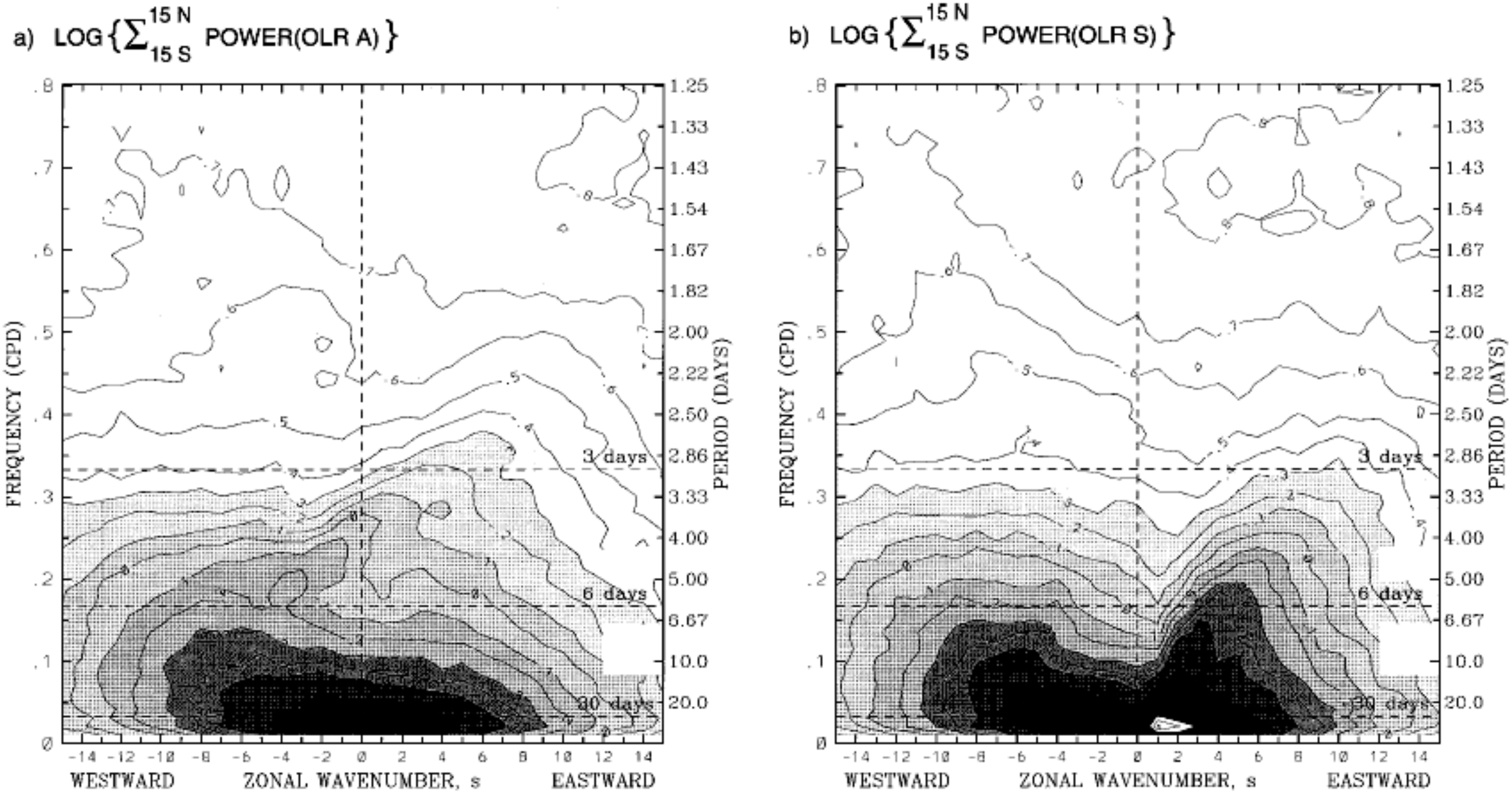
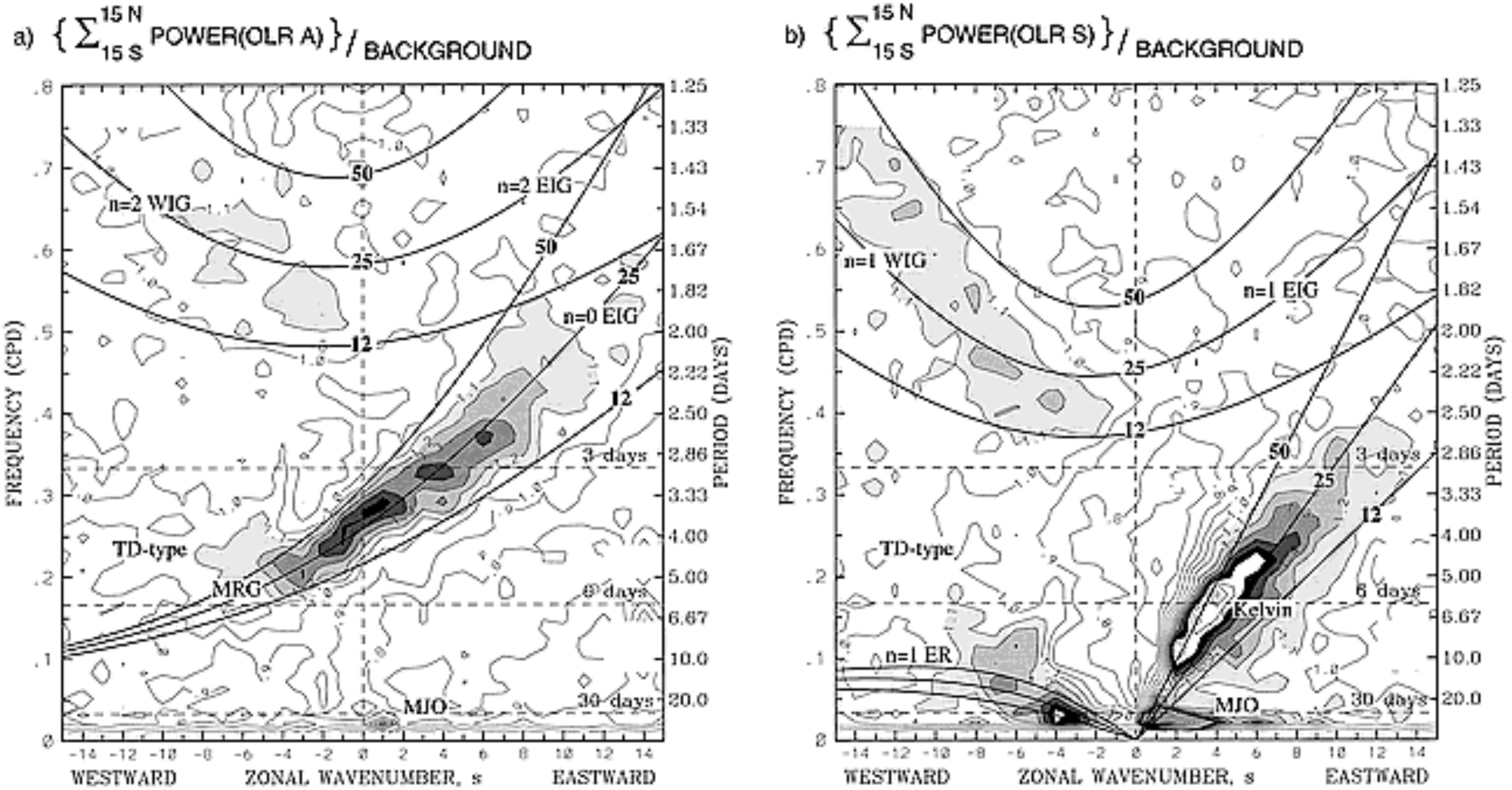


FIG. 1. Zonal wavenumber-frequency power spectra of the (a) antisymmetric component and (b) symmetric component of OLR, calculated for the entire period of record from 1979 1996. For both components, the power has been summed over 15°S–15°N lat, and the base-10 logarithm taken for plotting. Contour interval is 0.1 arbitrary units (see text). Shading incremented in steps of 0.2. Certain erroneous spectral peaks from artifacts of the satellite sampling (see text) are not plotted.

Wheeler and Kiladis, J. Atmos. Sci., 1999

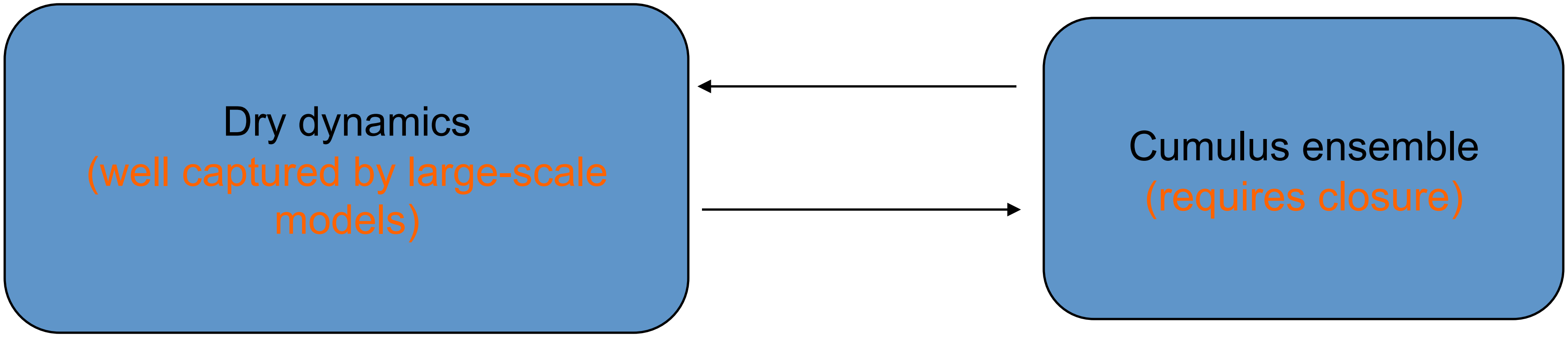
Space-time spectra

(with background red noise removed)



Wheeler and Kiladis, J. Atmos. Sci., 1999

A general and useful framework for large-scale organization of moist convection



Dry dynamics
(well captured by large-scale models)

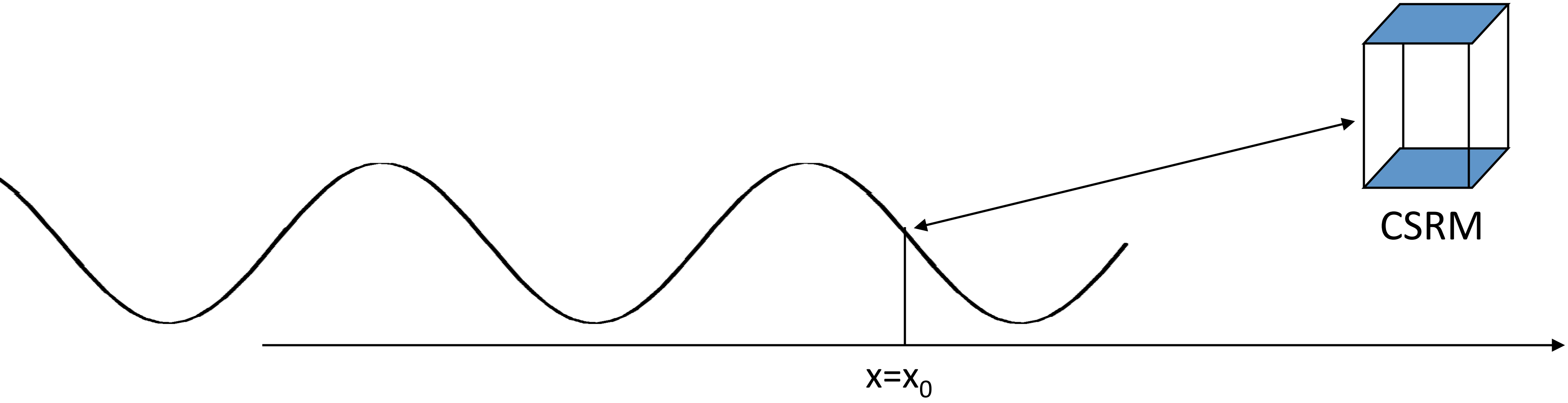
Cumulus ensemble
(requires closure)

Cloud-system-resolving models (CSRMs) do quite well but are more expensive

Simplify the problem

(both conceptually and computationally)

- Interaction between convection and 2D linear gravity waves
- One horizontal wavenumber at a time
- Use a cloud-system-resolving model (CSRM) to represent a vertical line in the wave



$$\overline{\rho} u'_t = -p'_x - \varepsilon \overline{\rho} u', \tag{1}$$

$$(\overline{\rho} u')_x + (\overline{\rho} w')_z = 0, \tag{2}$$

$$p'_z = \overline{\rho} g \frac{T'}{\overline{T}}, \tag{3}$$

We treat a single horizontal wavenumber k at a time

$$\left\{\left(\frac{\partial}{\partial t} + \varepsilon\right)[\overline{\rho} w'(x_0, z, t)]_z\right\}_z = -k^2 \frac{\overline{\rho} g}{\overline{T}} T'(x_0, z, t).$$

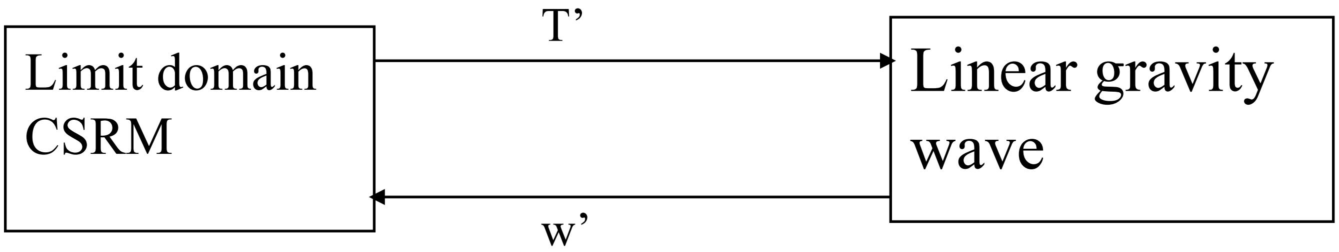
and use a small-domain CSRM to represent a vertical line at x_0

Kuang, JAS,
2008

$$T'_t + \boxed{w'\left(\frac{d\bar{T}}{dz} + \frac{g}{c_p}\right)} = S'_T$$

$$q'_t + \boxed{w'\frac{d\bar{q}}{dz}} = S'_q$$

Wave influence on convection



Limit domain CSRM

T’

Linear gravity wave

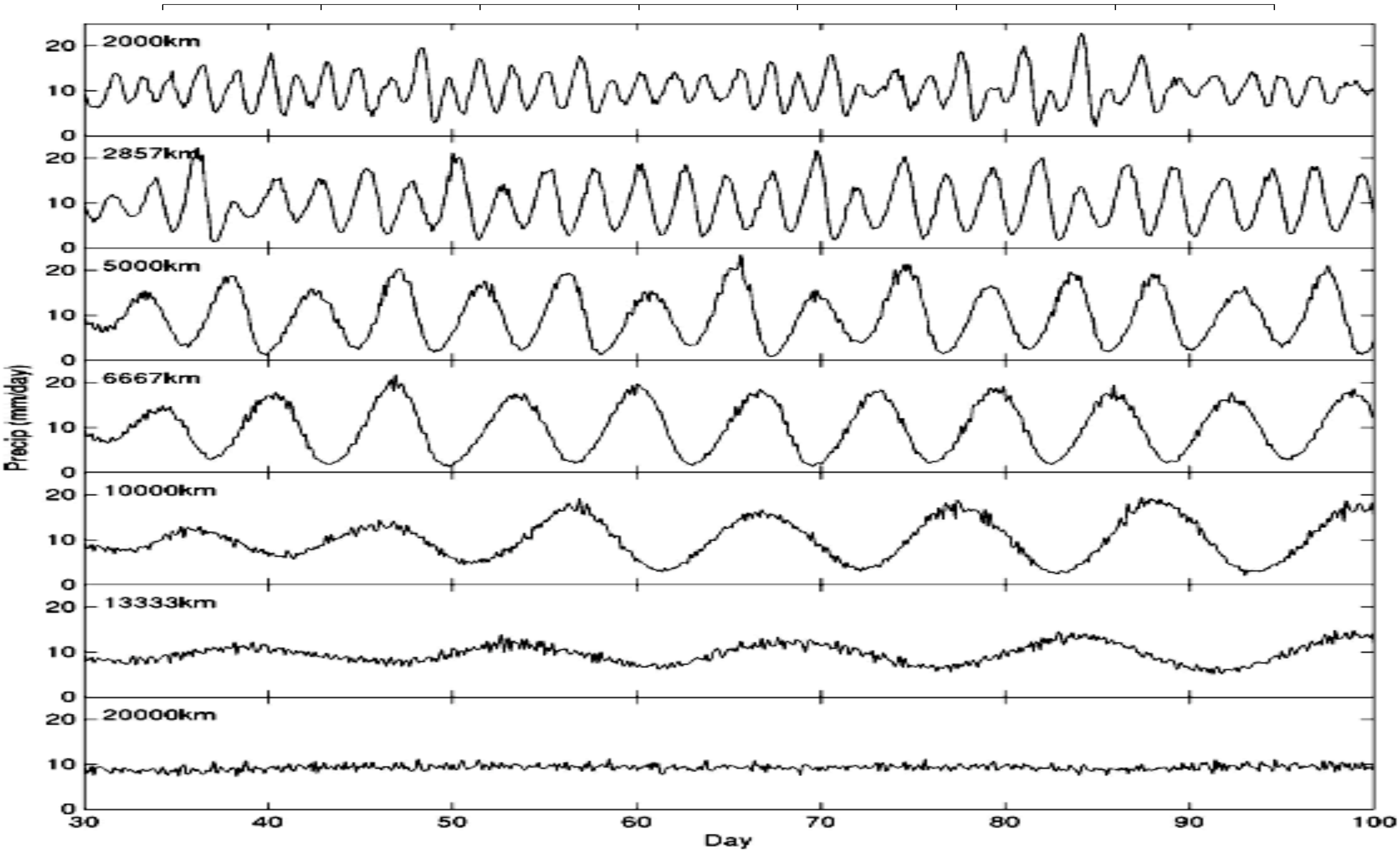
w’

Kuang, JAS, 2008

Model and setup

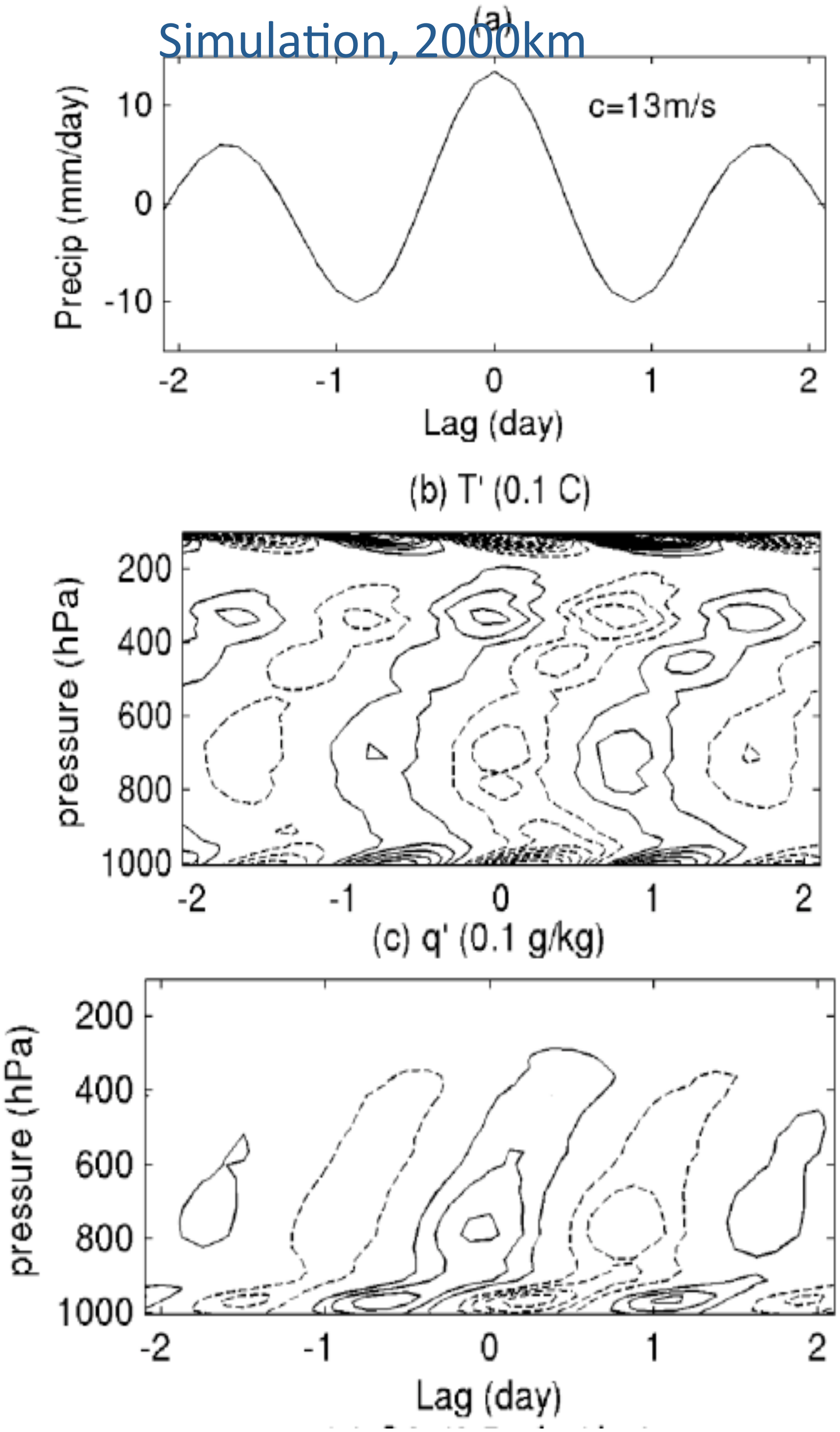
- SAM by Marat Khairoutdinov
- dx=dy=2km, nx=ny=192, nz=64
- Mean vertical advection of TOGA-COARE
- Fixed radiative cooling and bulk formula for surface heat fluxes
- Mechanical damping time is uniform in height

Development of convectively coupled waves (ε=1/(10days))

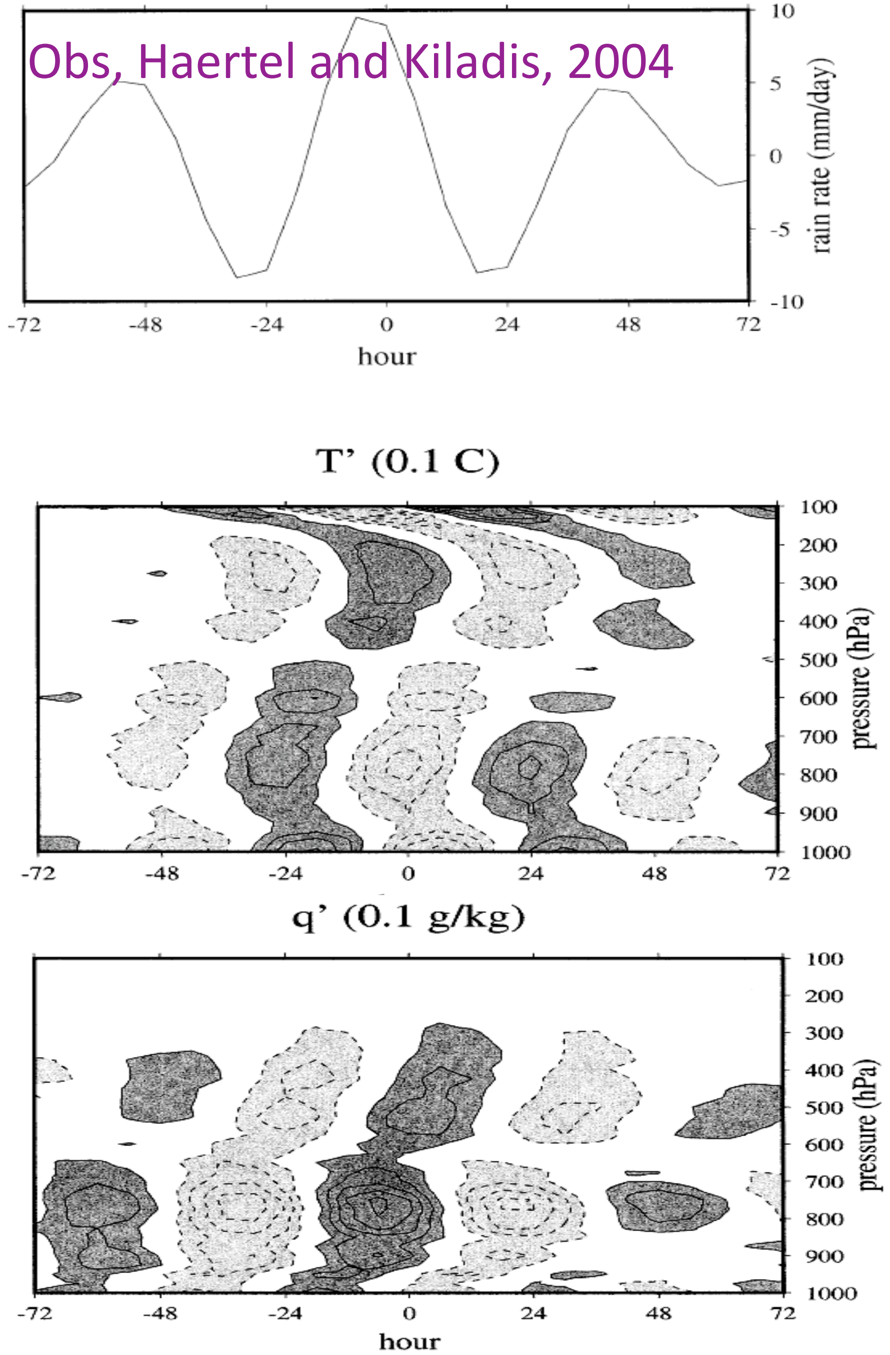


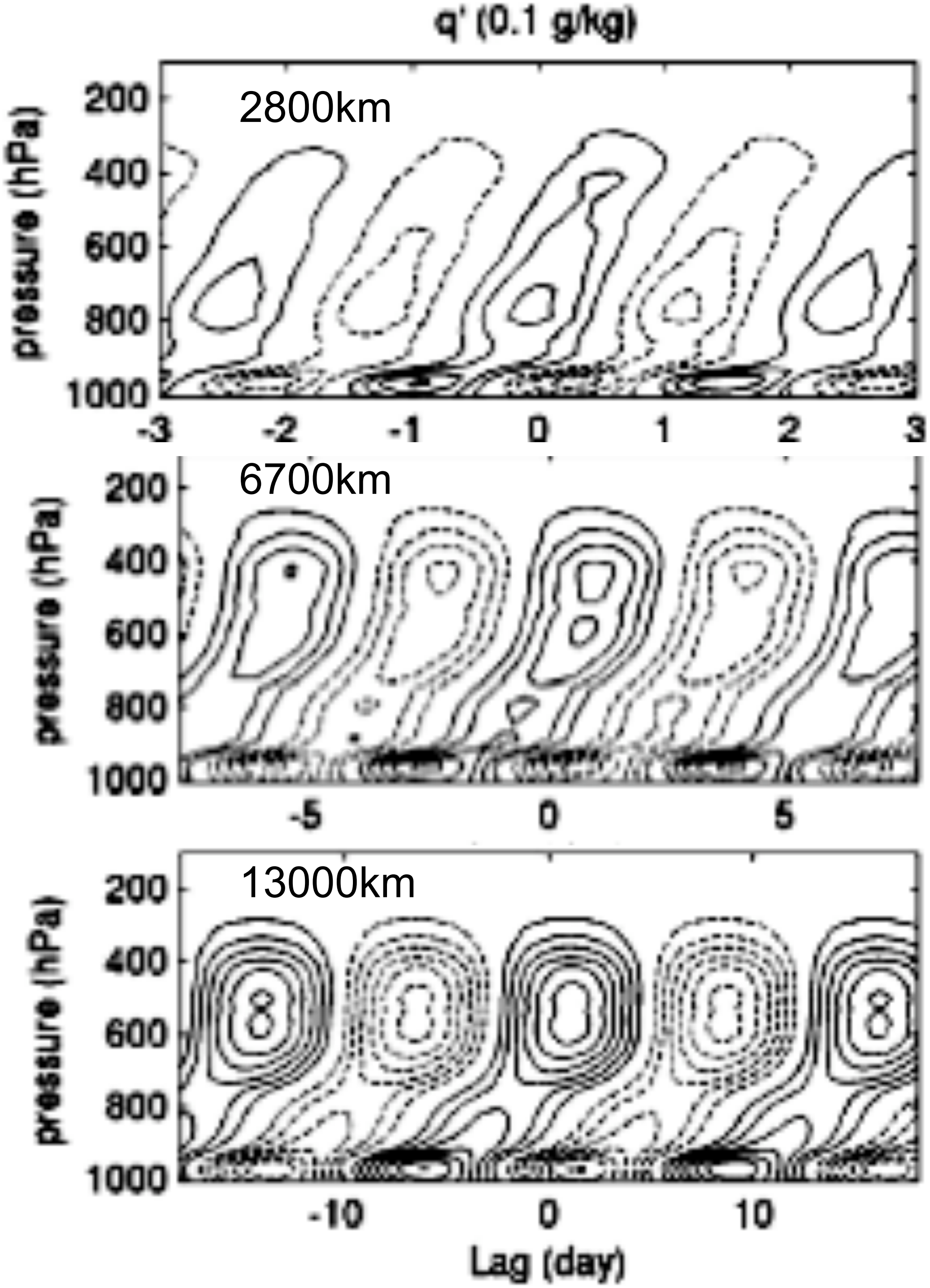
Without coupling to gravity waves, the std of precip is 0.6mm/day

Simulation, 2000km



Obs, Haertel and Kiladis, 2004



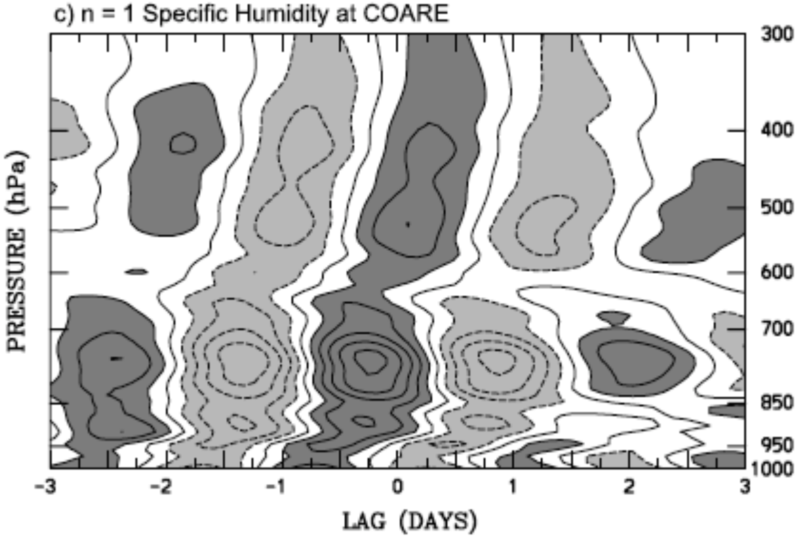


Dependence of wave structure on the horizontal wavelength

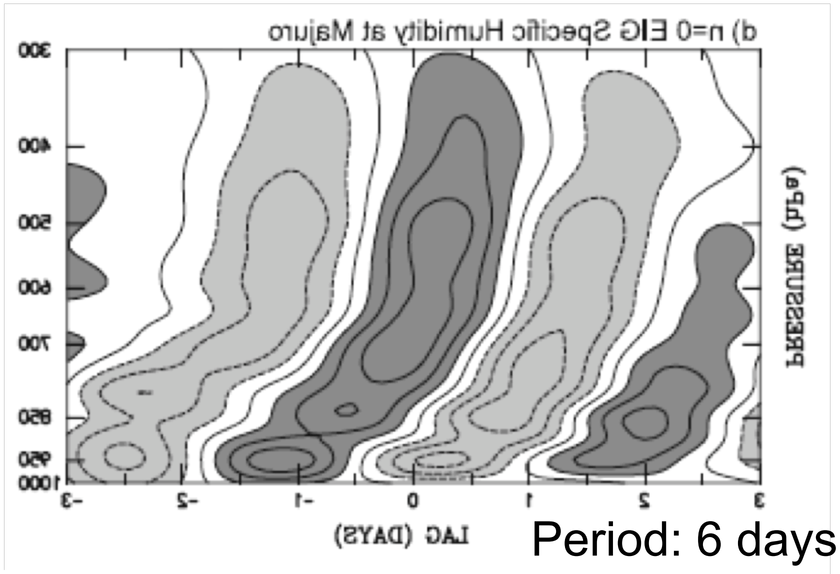
Kuang 2008, JAS

Observations

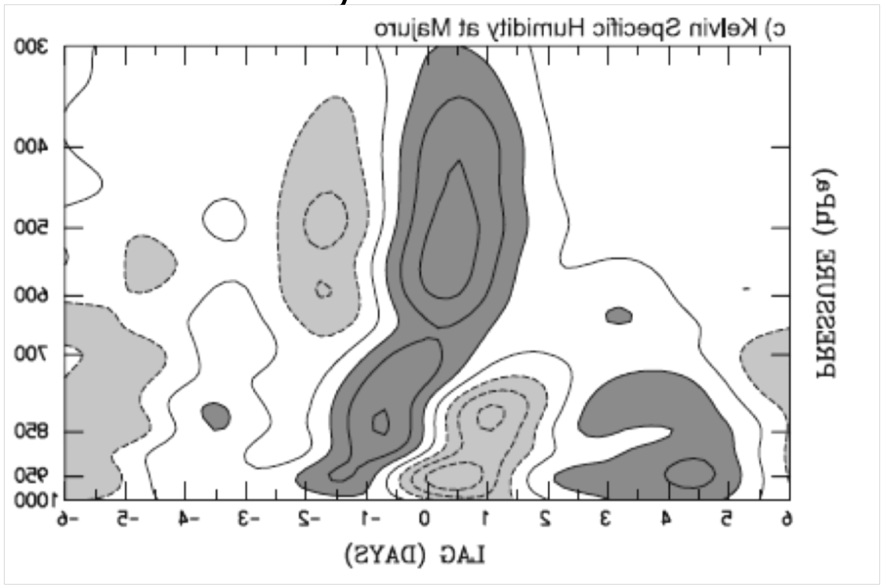
Period: 2 days



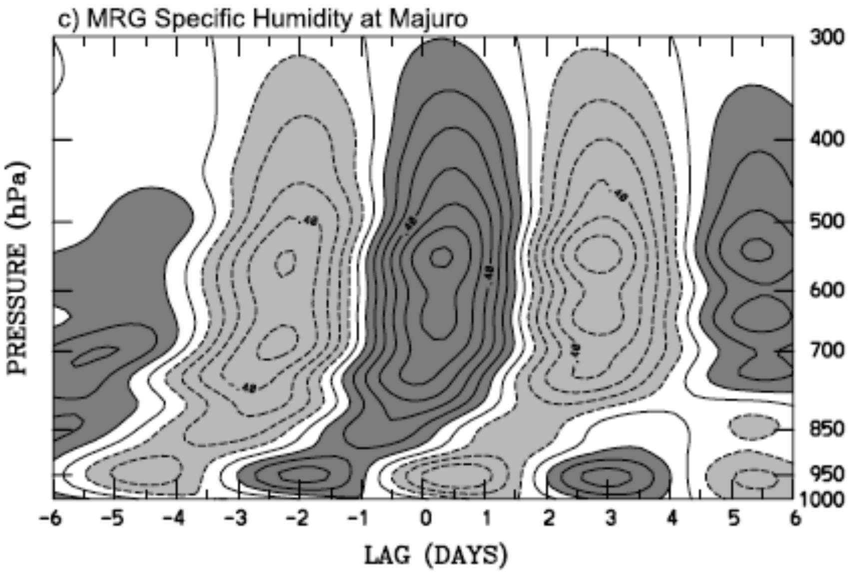
Period: 3 days



Period: ~4 days



Period: 6 days



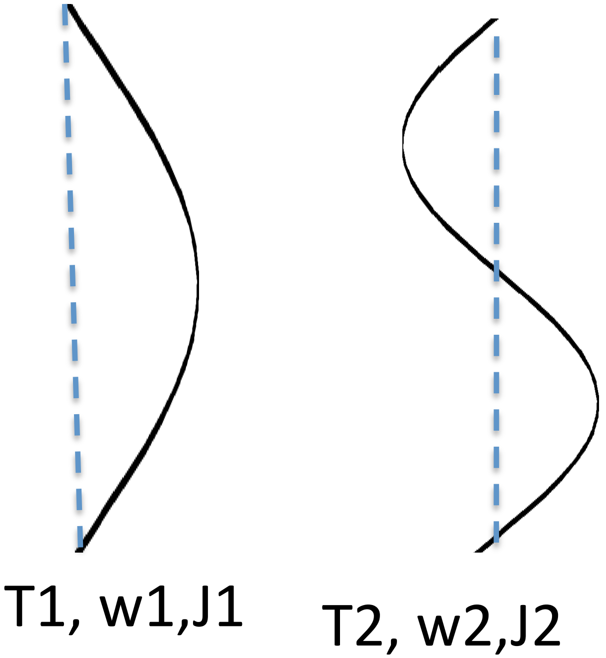
Kiladis et al., 2009, Review of Geophysics

- Perform experiments with modified physics → radiative and surface flux feedbacks unimportant…
- Derive linear response functions (see Mike Herman's talk)

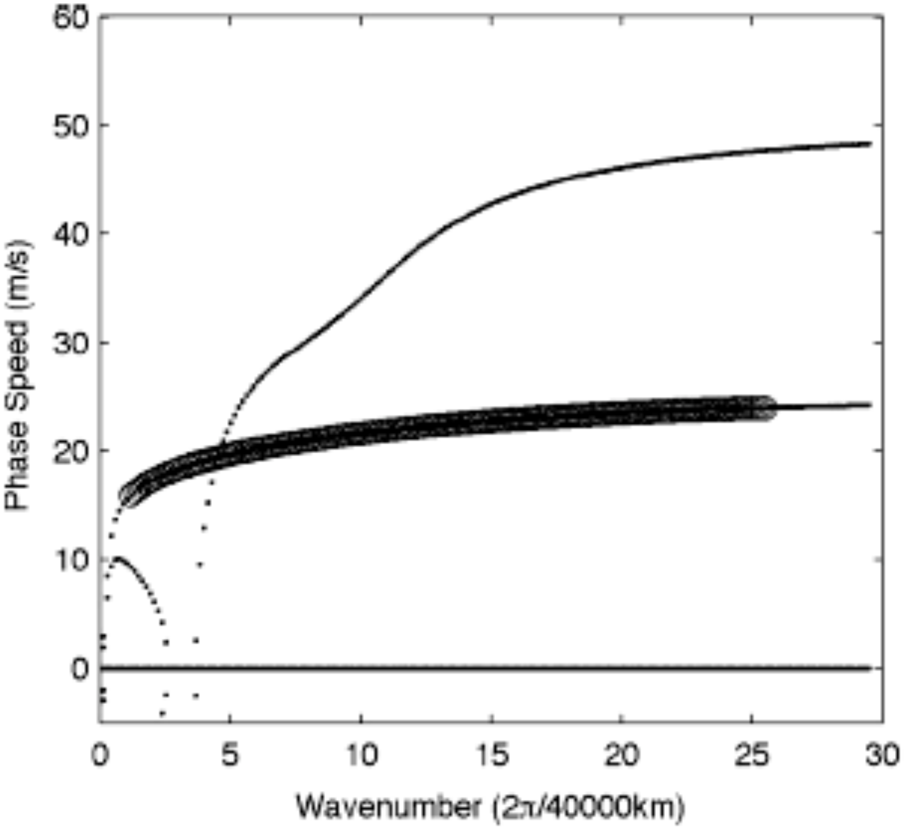
A toy model

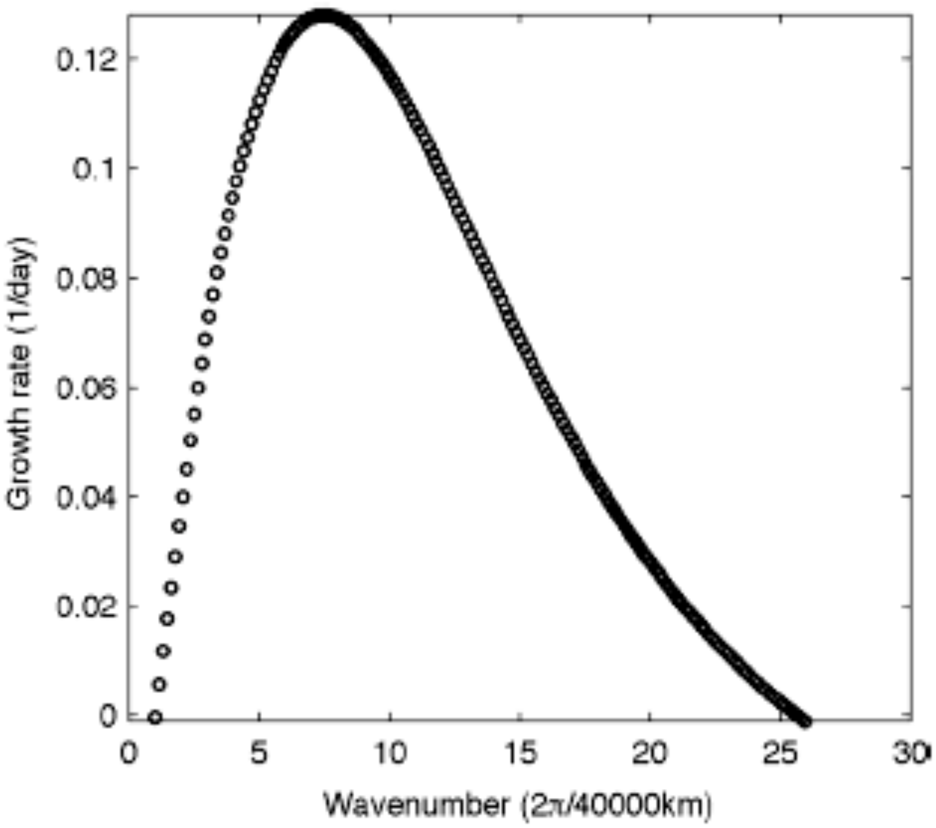
- Two vertical modes plus a subcloud layer (Mapes 2000 and others) and a prognostic moisture equation (Khouider and Majda, 2006)
- Treatment of convection (Kuang, 2008)
  - Shallow quasi-equilibrium
  - Mid-tropospheric moisture modulates

  the shape of convective heating

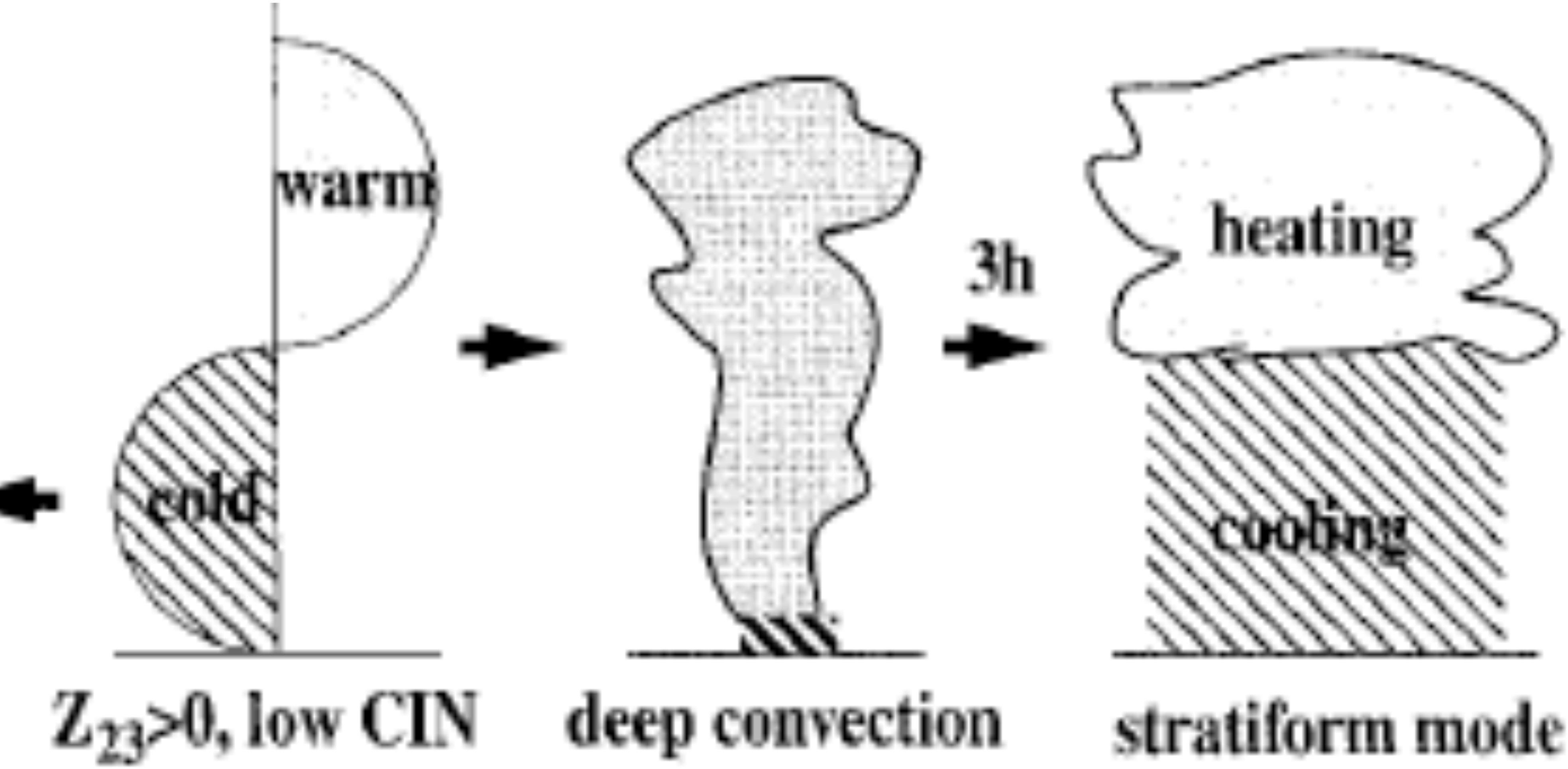


Phase speeds and growth rates

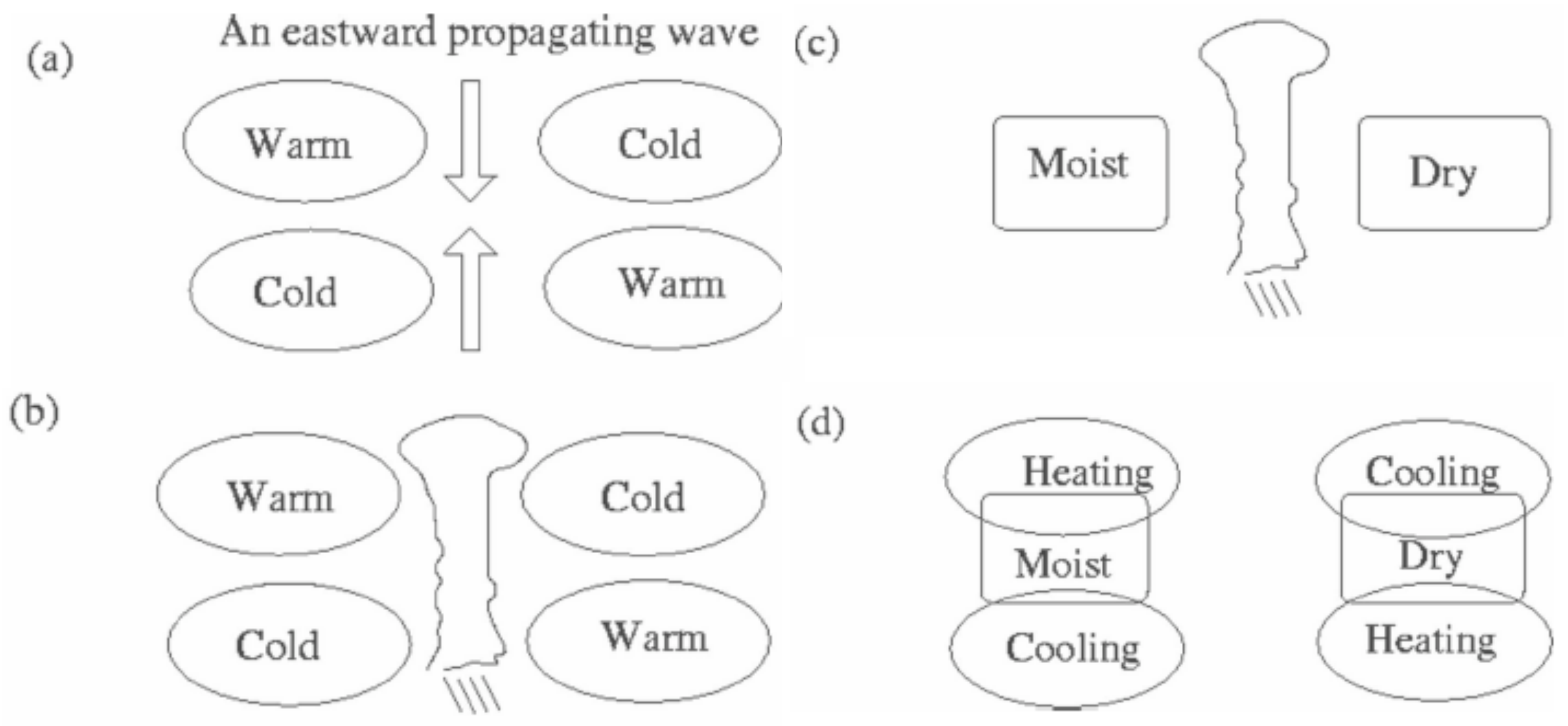




Direct stratiform instability (Mapes 2000)

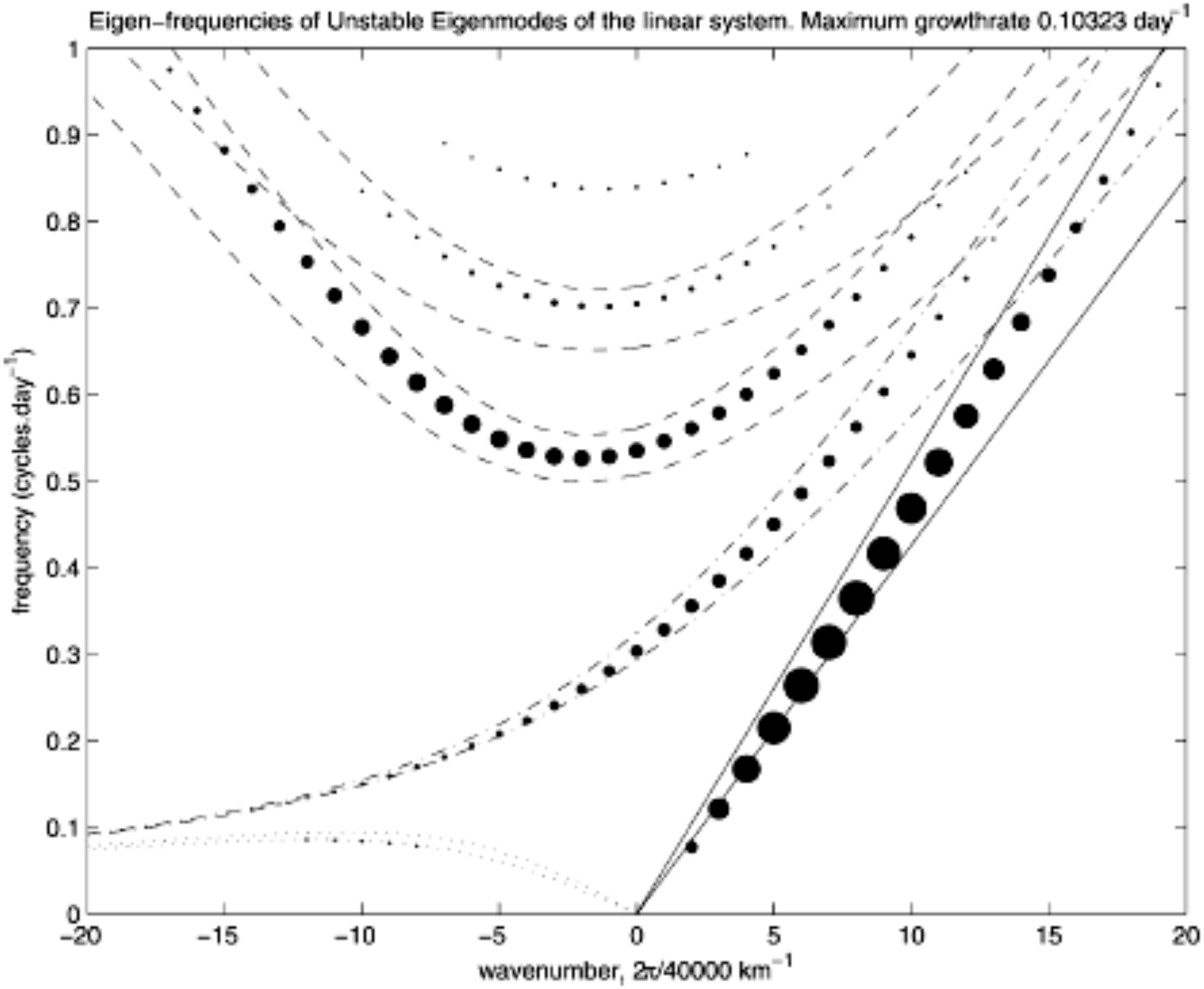


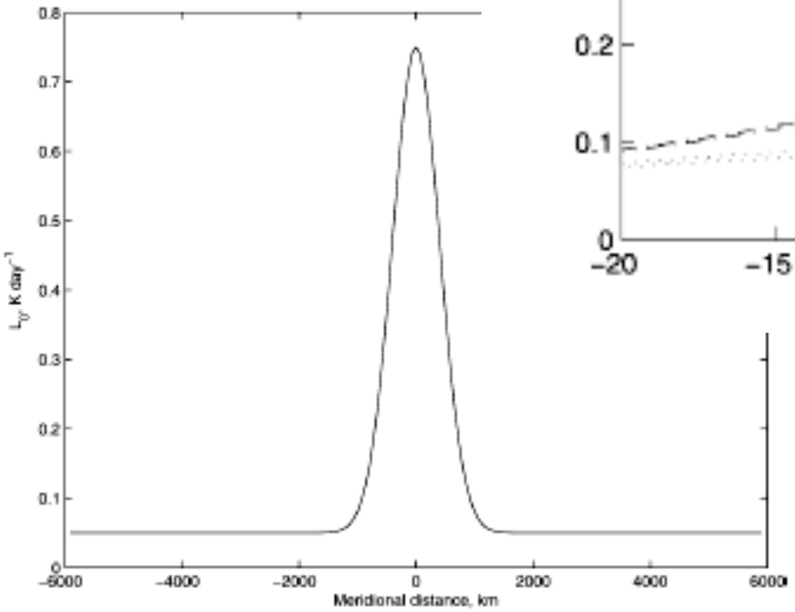
Moisture-stratiform instability



Kuang, A moisture-stratiform instability for convectively coupled waves, JAS, 65, 834-854, (2008)

Extending the toy-model to the equatorial beta-plane: Single-ITCZ



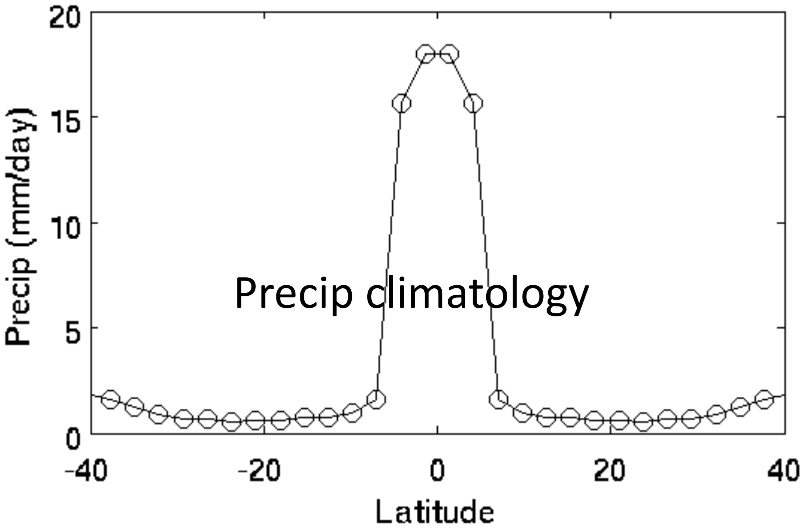


Andersen and Kuang, JAS, 2008

Equatorial waves

Superparameterized CAM simulation with

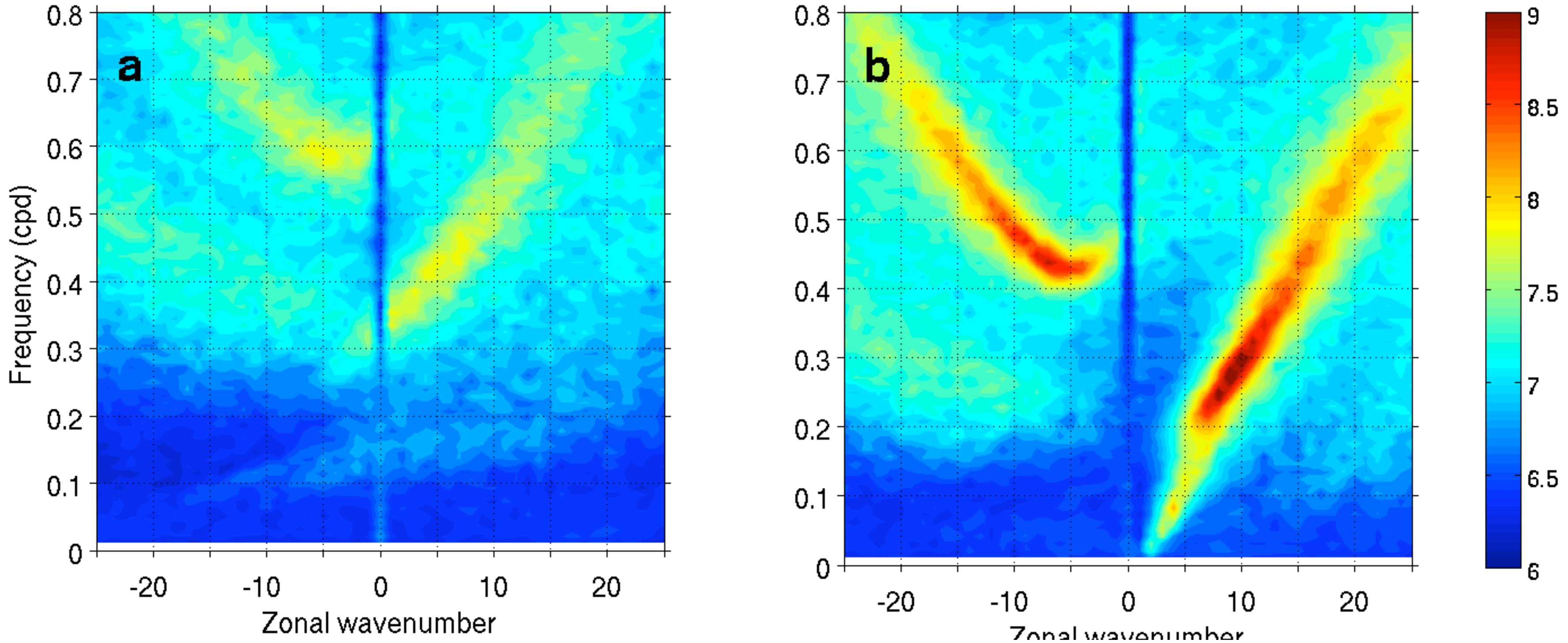
- zonally homogenized radiation, surface heat flux, and surface drag
- linearized equations of motion
- no horizontal advection of moisture
- Mean state maintained by nudging
- 1-day Newtonian damping is used to control wave growth



Raw rainfall spectra

Antisymmetric (log10(Power))

Symmetric (log10(Power))



- No MJO
- The spectra are no longer red

With feedbacks in diabatic sources to the column-integrated moist static energy

“Moisture modes”: instability in the column integrated moist static energy

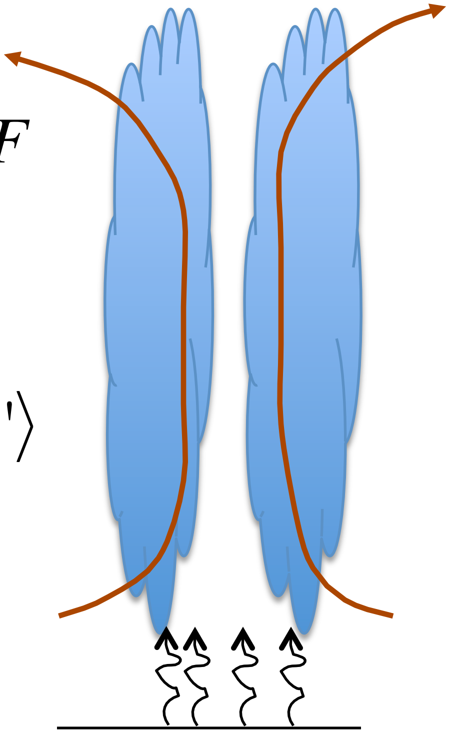
The simplest form

$$\frac{d\langle h\rangle}{dt} = \left\langle -w\frac{\partial h}{\partial z}\right\rangle + F$$

$$\approx -MLP' + \alpha LP'$$

$$= (\alpha - M)L\frac{dP}{d\langle h\rangle}\langle h'\rangle$$

$$M \equiv \frac{\left\langle w\frac{\partial h}{\partial z}\right\rangle}{\left\langle w\frac{\partial s}{\partial z}\right\rangle}$$



<>: mass weighted column integral
h: Moist static energy
s: dry static energy
w: vertical velocity
P’: precipitation anomaly
L: Latent heat of vaporization
M: Gross moist stability
α: Feedback in MSE sources

- Gross moist stability (GMS) has been widely used in simple models of Madden-Julian Oscillation (Neelin and Yu, 1994; Sobel et al., 2001; Fuchs and Raymond, 2002,2005, 2007; Raymond and Fuchs, 2007,2009; Maloney, 2009; Sugiyama, 2009ab;)
- These models all assume a constant GMS and the MJO models do not provide the planetary scale selection
- We will examine variations in the GMS using a cloud-system resolving model (CSRM). The CSRM used is System for Atmospheric Modeling (SAM) by Marat Khairoutdinov at Stony Brook.

Modeling the feedback from the large-scale flow

$$\left\{\left(\cancel{\frac{\partial}{\partial t}} + \varepsilon\right)[\bar{\rho} w'(x_0, z, t)]_z\right\}_z = -k^2 \frac{\bar{\rho} g}{\bar{T}} T'(x_0, z, t).$$

Estimate the Gross Moist Stability

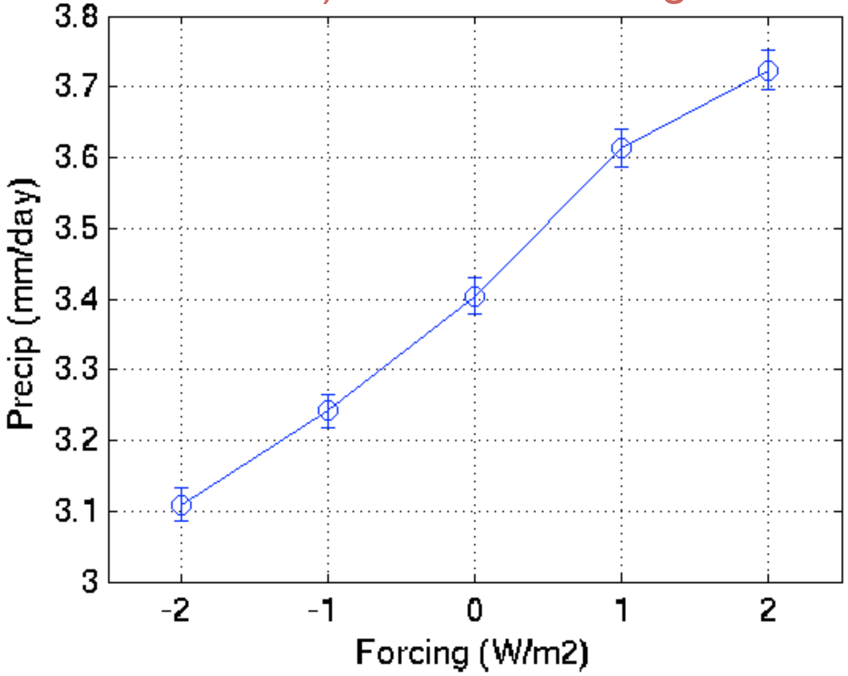
Apply a fixed forcing in column MSE, run the model to steady state (with feedback from the large-scale flow), and record the precipitation anomaly

$$0 = \frac{d\langle h\rangle}{dt} = \left\langle -w\frac{\partial h}{\partial z}\right\rangle + F$$

$$\rightarrow M \equiv \frac{\left\langle w\frac{\partial h}{\partial z}\right\rangle}{\left\langle w\frac{\partial s}{\partial z}\right\rangle} = \frac{\left\langle w\frac{\partial h}{\partial z}\right\rangle}{LP'} = \frac{F}{LP'}$$

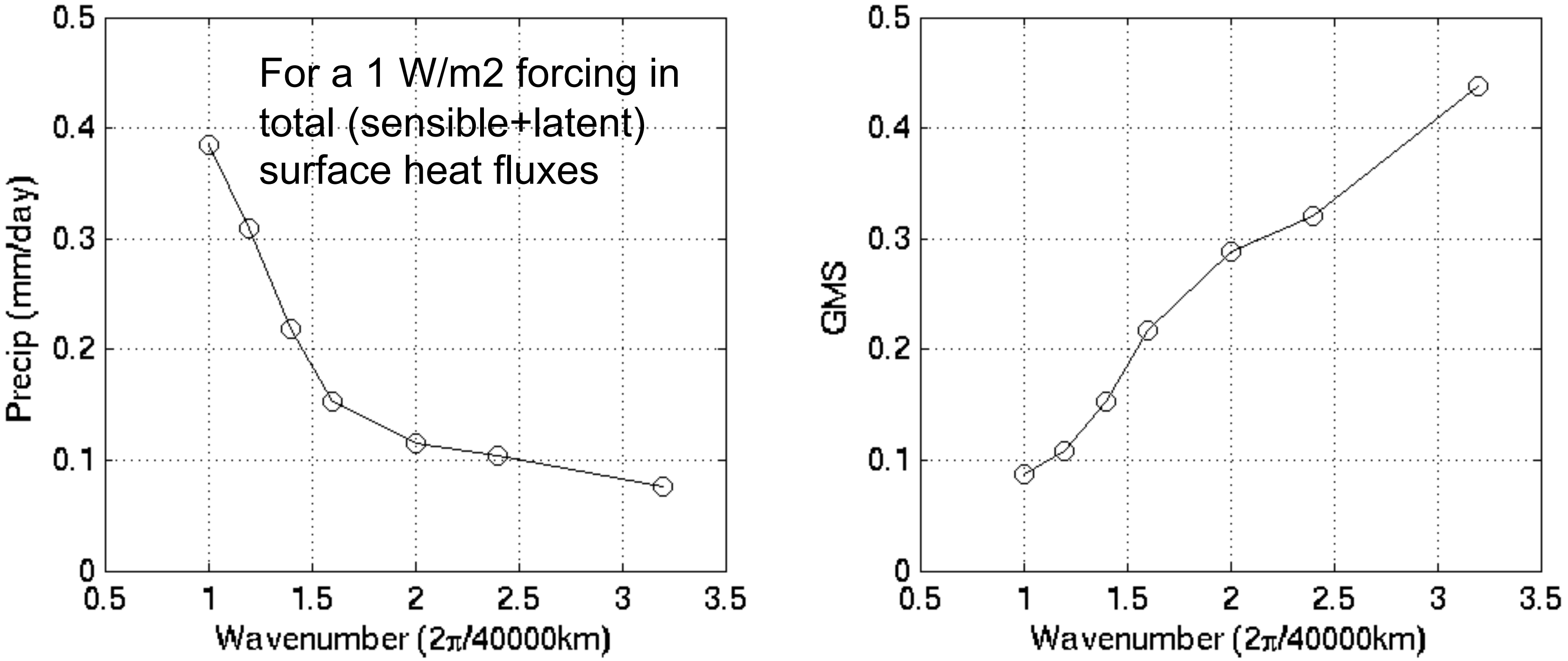
<>: mass weighted column integral
h: moist static energy (MSE)
s: dry static energy
P’: precipitation anomaly
L: latent heat of vaporization
M: Gross moist stability
F: forcing of column MSE

Response to surface (latent +sensible) heat flux forcing



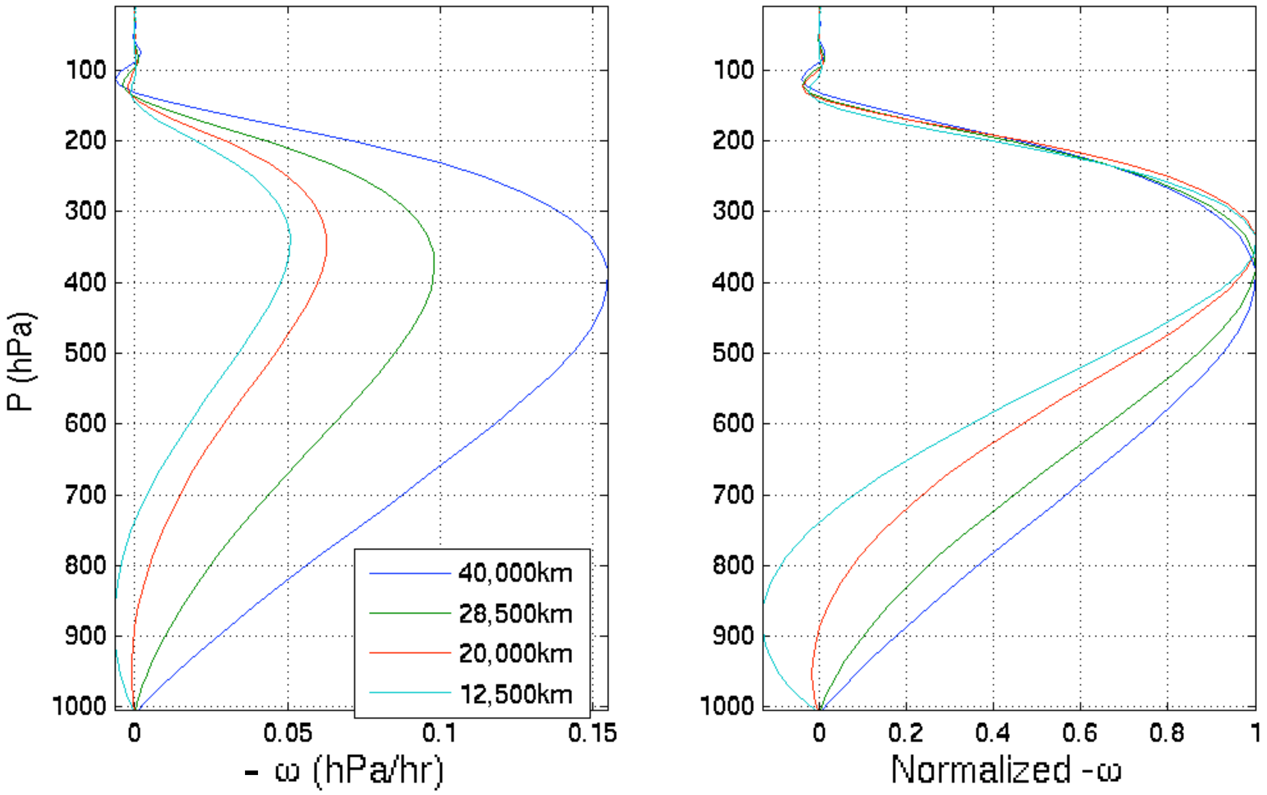
For a horizontal wavelength of 25000km
A 2.5-day Rayleigh damping time is used

Wavelength dependence of the GMS


For a 1 W/m2 forcing in total (sensible+latent) surface heat fluxes

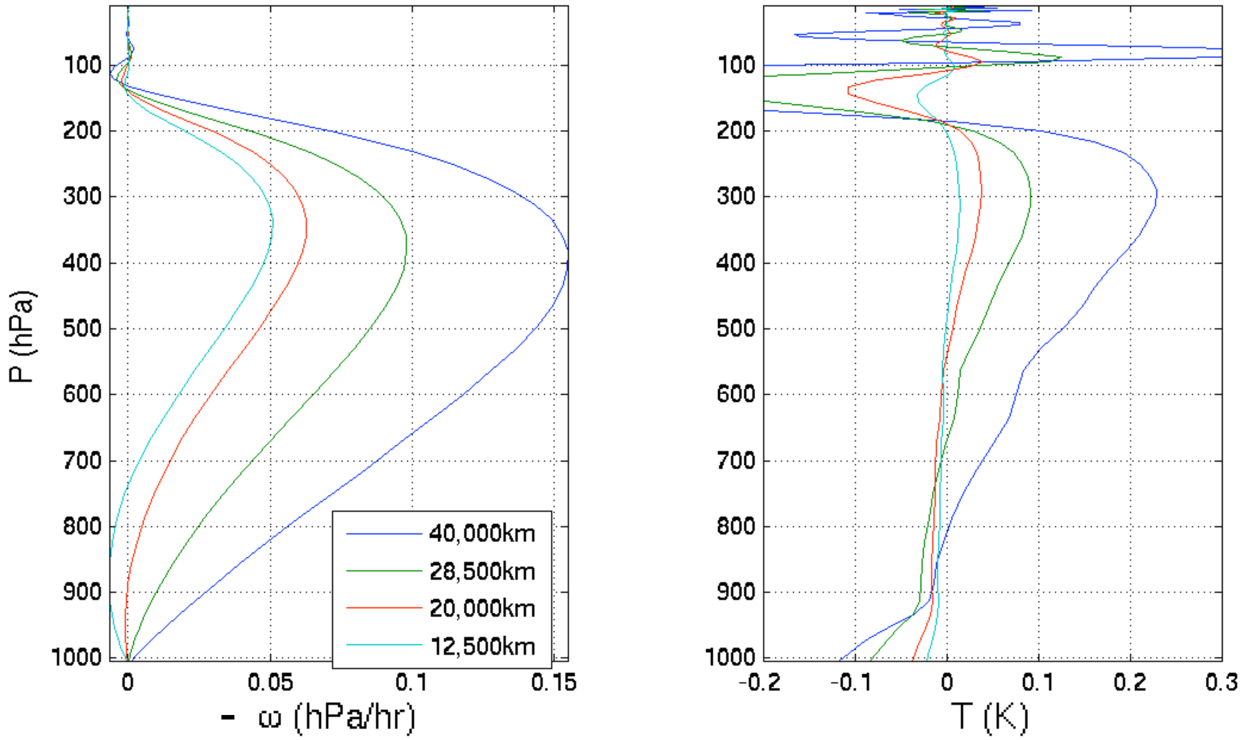
A 2.5-day Rayleigh damping time is used

Variable vertical velocity profiles



Top-heavy vertical velocity profiles yield greater gross moist stability. The question is: why do shorter wavelengths have more top-heavy vertical velocity profiles?

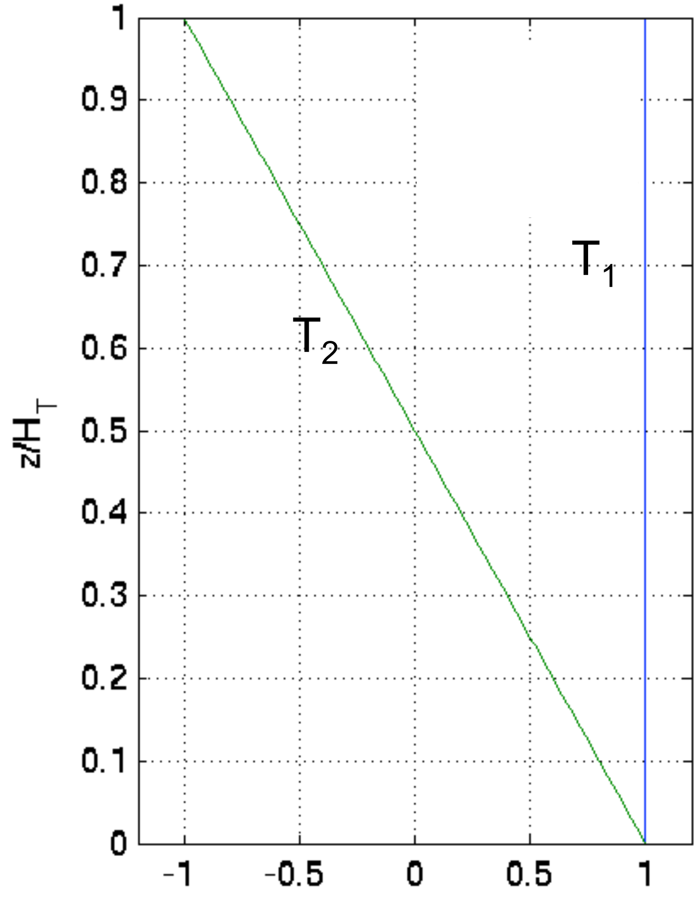
Significant temperature anomalies at longer wavelengths



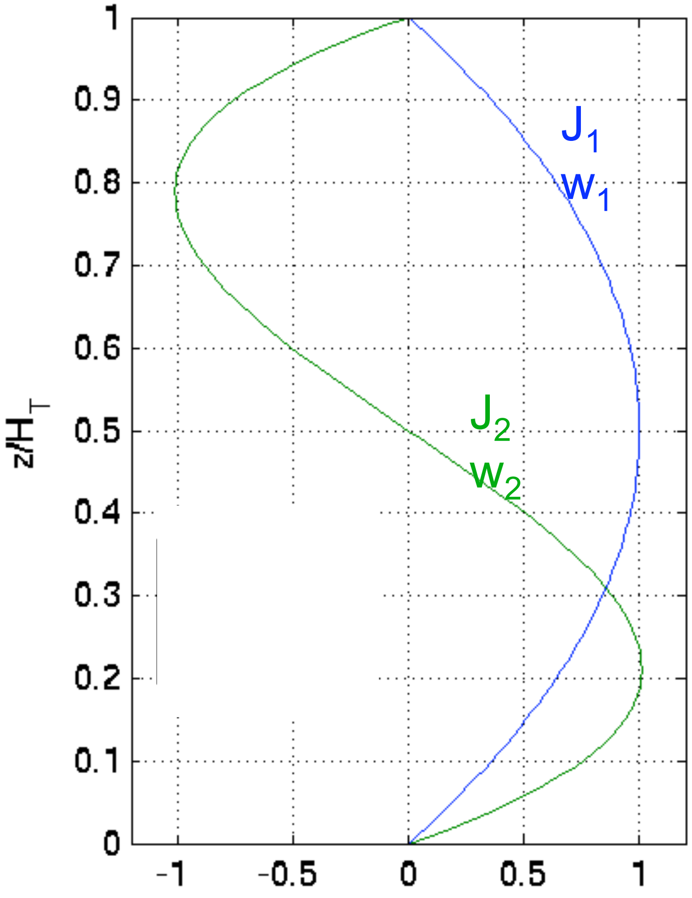
$$\left[\varepsilon\left(\bar{\rho}w'(x_0,z,t)\right)_z\right]_z = -\boxed{k^2}\,\frac{\bar{\rho}g}{\bar{T}}T'(x_0,z,t)$$

A toy model with two vertical structures

Temperature modes (T_1, T_2)



Vertical velocity (w_1 and w_2) and convective heating (J_1 and J_2) modes



- Heat balance

$$w_j = J_j$$

- Momentum balance + continuity + hydrostatic balance

$$w_j = \frac{\boxed{k^2}}{\varepsilon} c_j^2 T_j \qquad \left(i.e. \left[\varepsilon \left(\bar{\rho} w'(x_0, z, t) \right)_z \right]_z = -k^2 \frac{\bar{\rho} g}{\bar{T}} T'(x_0, z, t) \right)$$

- Free troposphere moisture balance (modified from Khoudier and Majda, 2006; Kuang 2008)

$$0 = \frac{\partial q}{\partial t} = m_1 w_1 + m_2 w_2 - m_q q$$

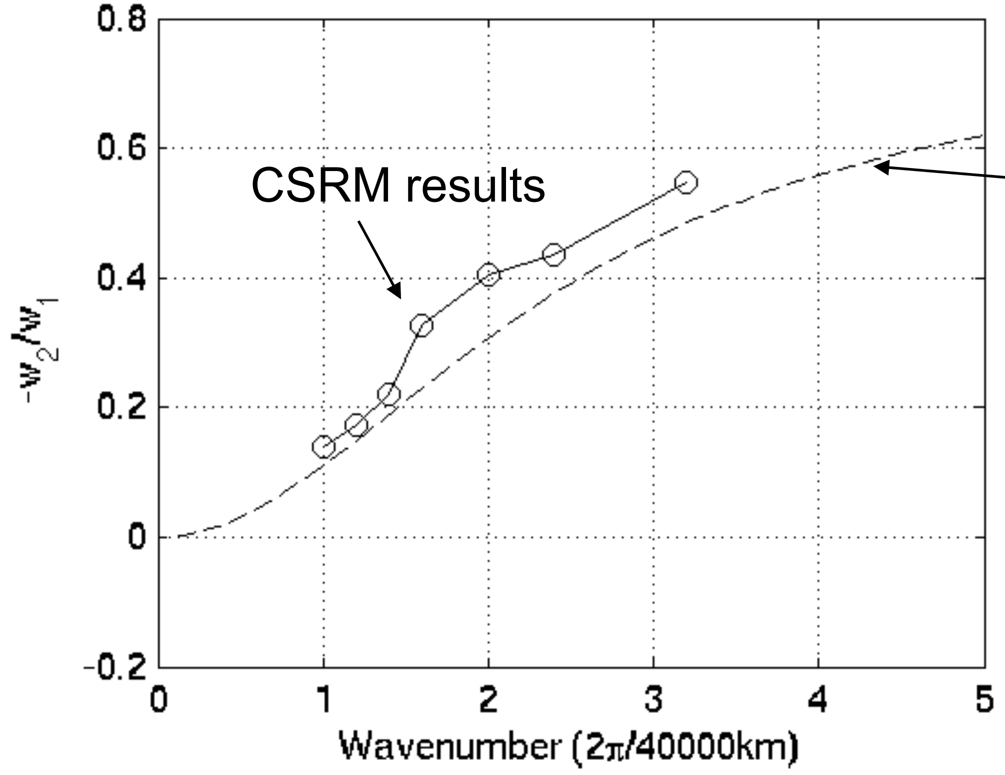
- Control on the height of convection (modified from Kuang, 2008)

$$J_2 = -\gamma_q q \boxed{- \gamma_T T_2}$$

Toy model results

$$A \equiv -\frac{w_2}{w_1}$$

a measure of the top-heaviness of the vertical velocity profile

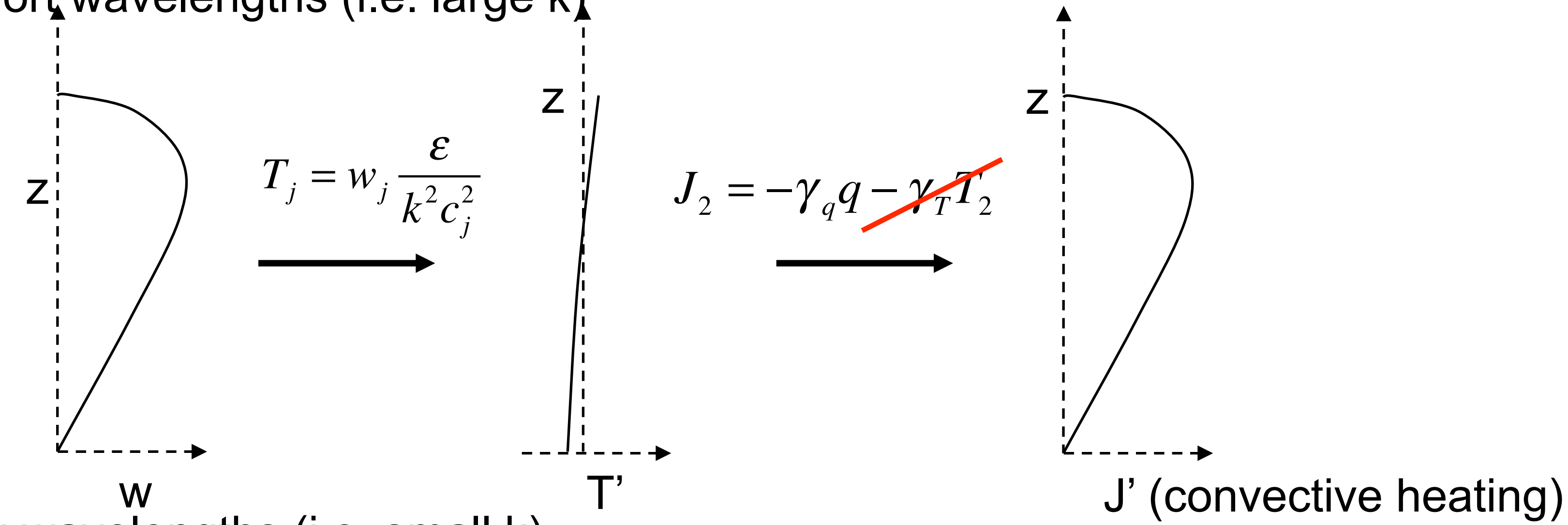


CSRM results

Toy model result

A schematic view

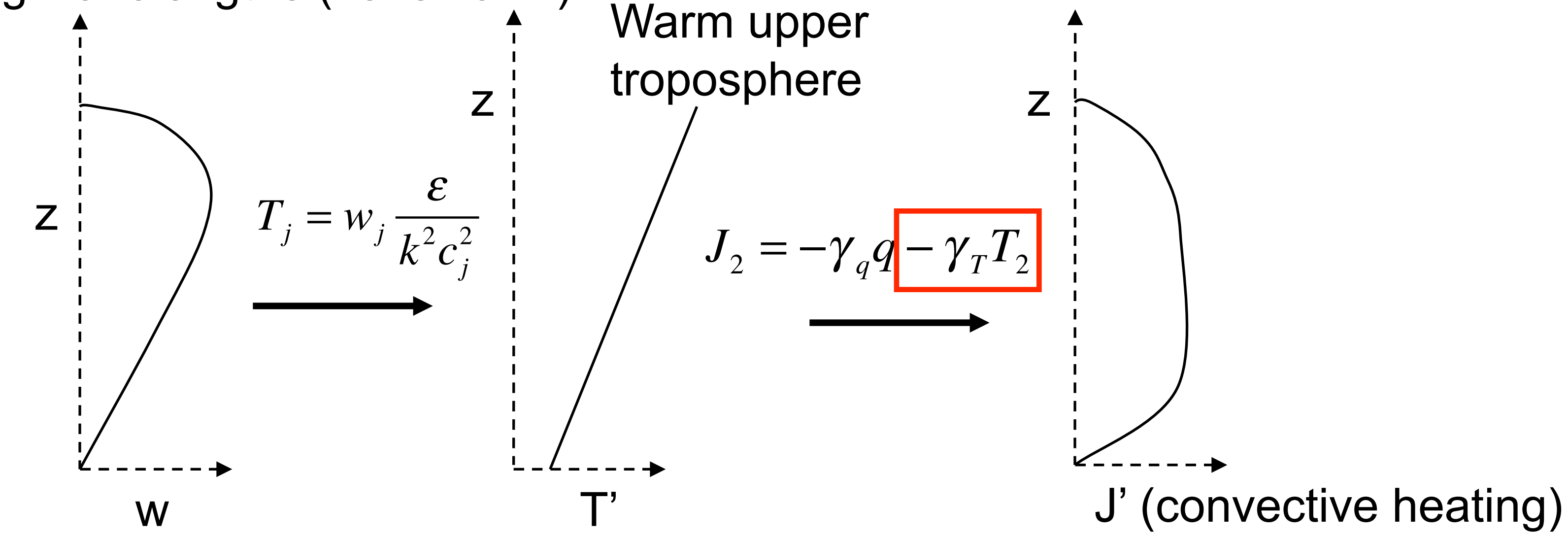
For short wavelengths (i.e. large k)



$$T_j = w_j \frac{\varepsilon}{k^2 c_j^2} \longrightarrow$$

$$J_2 = -\gamma_q q - \cancel{\gamma_T T_2} \longrightarrow$$

For long wavelengths (i.e. small k)



Warm upper troposphere

$$T_j = w_j \frac{\varepsilon}{k^2 c_j^2} \longrightarrow$$

$$J_2 = -\gamma_q q \boxed{-\gamma_T T_2} \longrightarrow$$

Instability in the column-MSE or “moisture modes” favors planetary scale

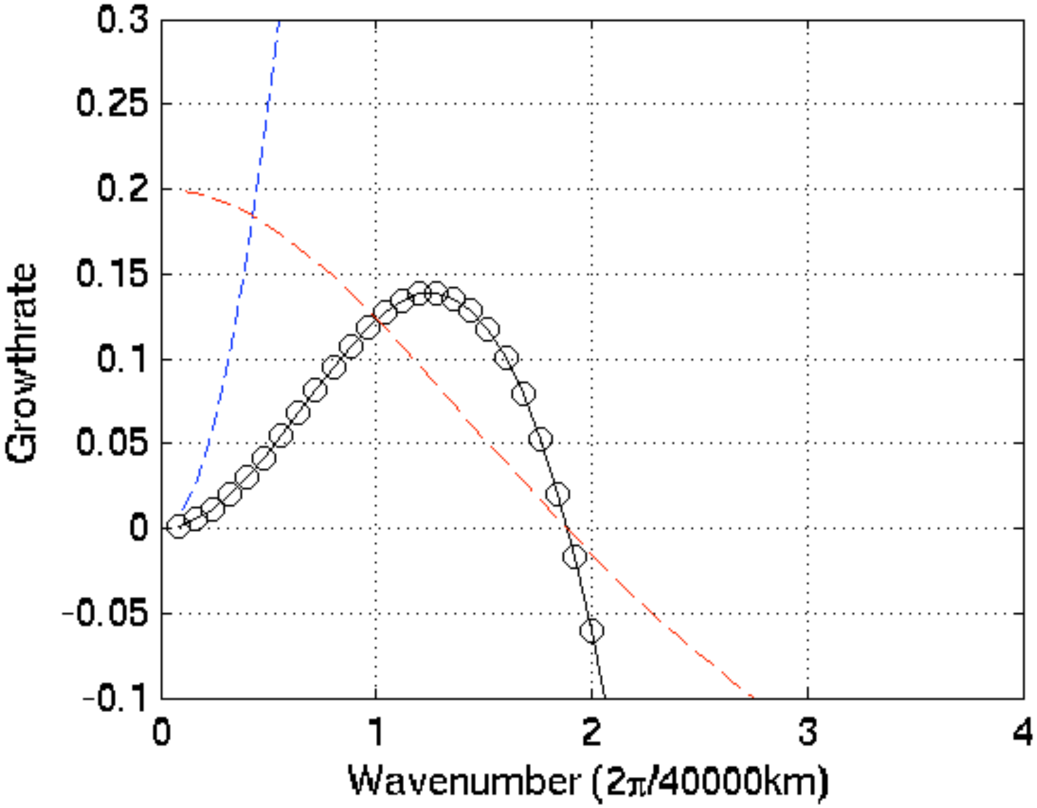
$$\frac{d\langle h'\rangle}{dt} = \left\langle -w\frac{\partial h}{\partial z}\right\rangle + \alpha LP'$$

$$= -MLP' + \alpha LP'$$

$$= \boxed{(\alpha - M)L\frac{dP}{d\langle h\rangle}}\langle h'\rangle$$

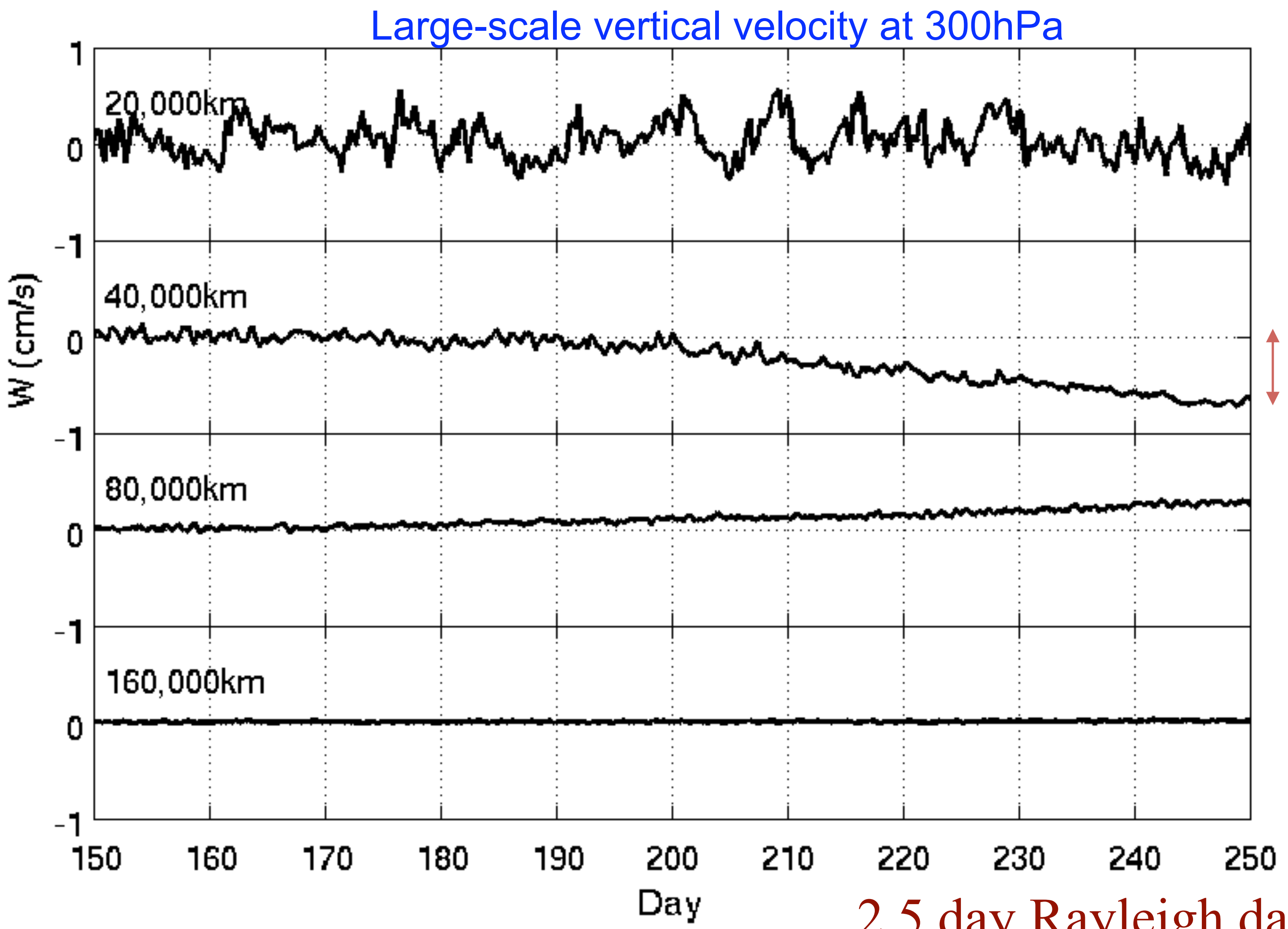
$$\frac{dP}{d\langle h\rangle} \propto k^2$$

$$growthrate \propto k^2(\alpha - M)$$



- At very long wavelengths, the feedback from the large-scale flow is very weak

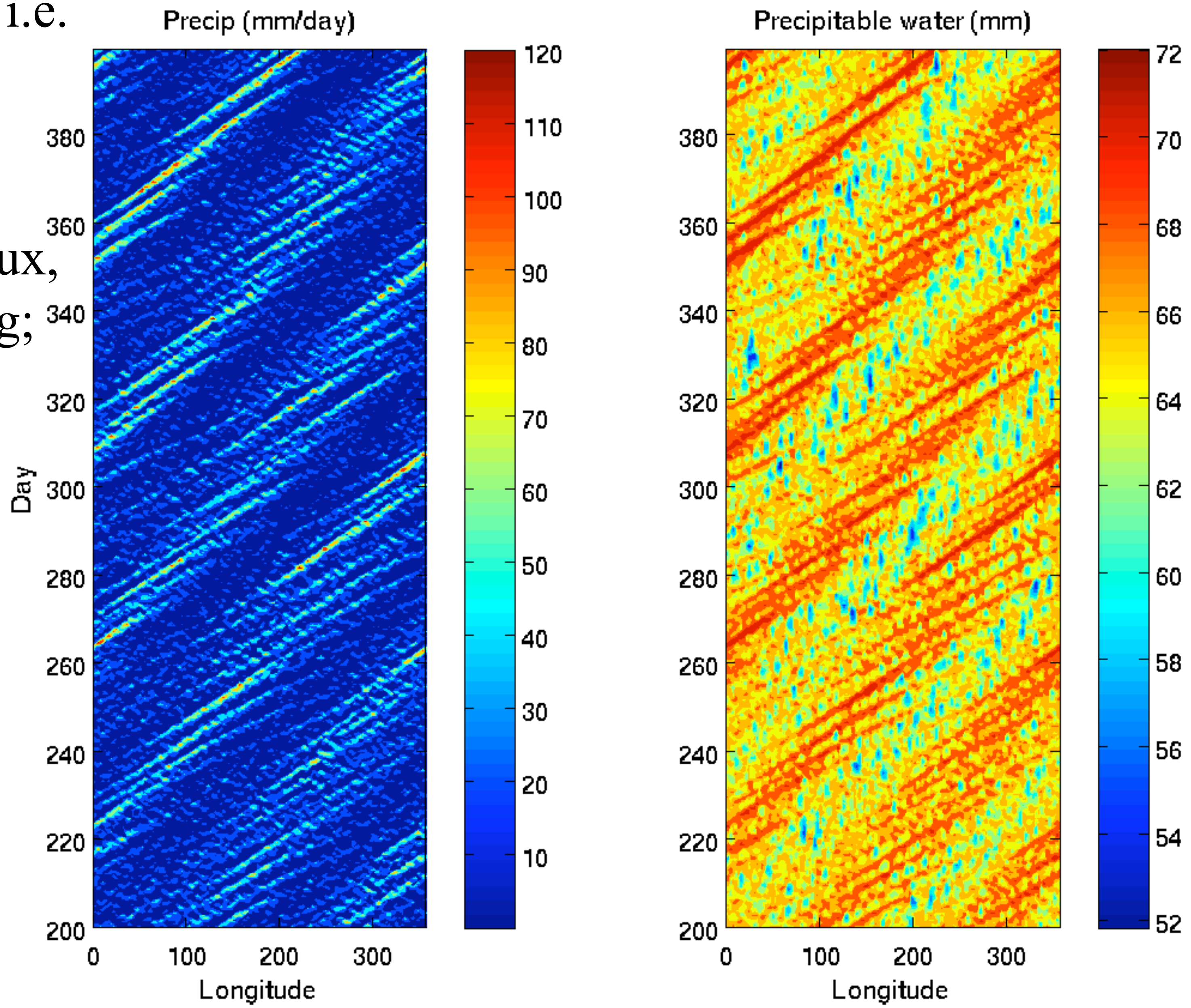
CSRM simulations with surface MSE flux anomaly = 0.2LP’



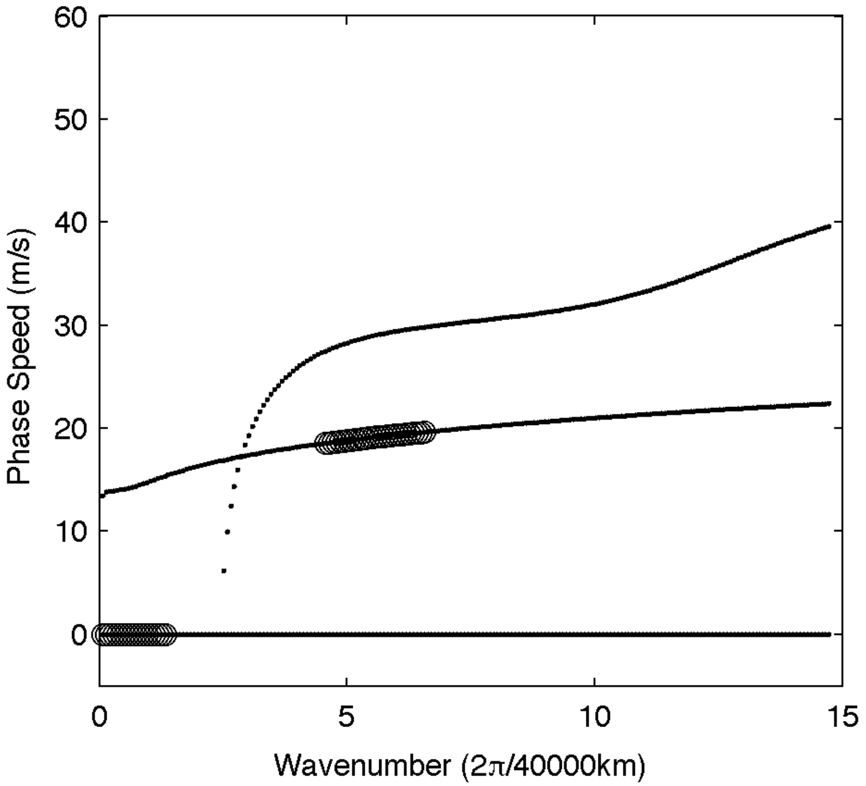
~2.5mm/day

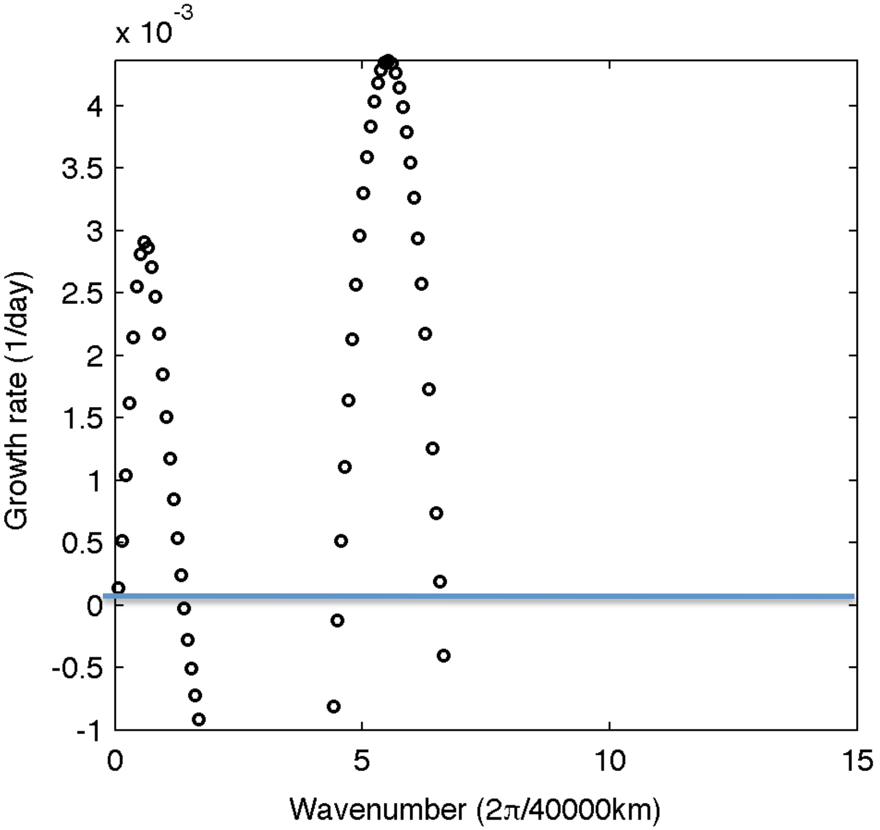
2.5 day Rayleigh damping

SPCAM simulation with $\alpha=0.05$. It is otherwise the same as the case shown earlier, i.e. with zonally homogenized radiation, surface heat flux, no surface drag; linearized equations of motion etc…



Put waves and moisture modes together (2D gravity waves)





Summary

- We examined the basic instability behind convectively coupled waves using CSRM in a linear wave framework, starting with 2D gravity waves and then to the equatorial beta plane
- A simple form of column-MSE instability or “moisture modes” due to feedbacks from column MSE sources favors planetary scales because of variations in the gross moist stability.