Convectively Coupled Gravity Waves in Shear

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Workshop on Multiscale Processes in the Tropics

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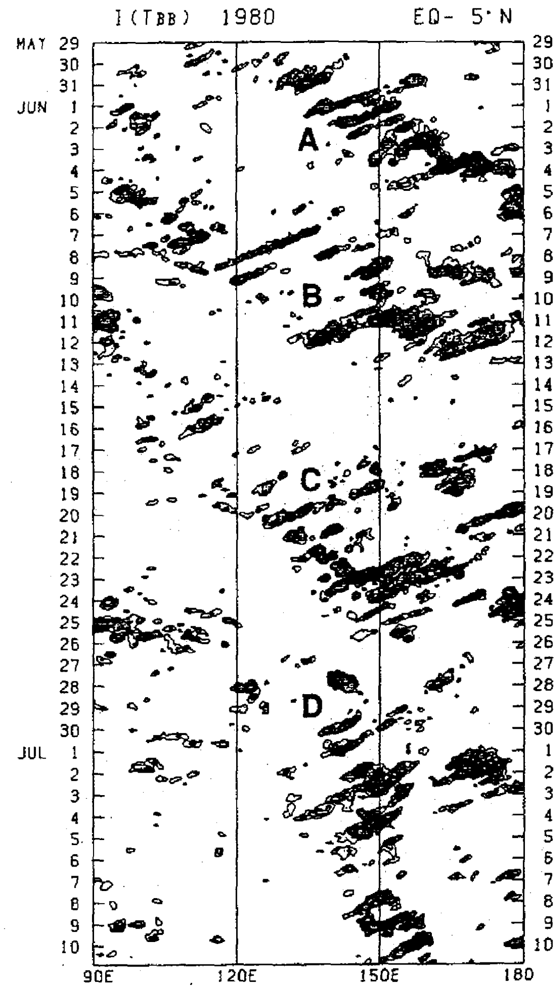
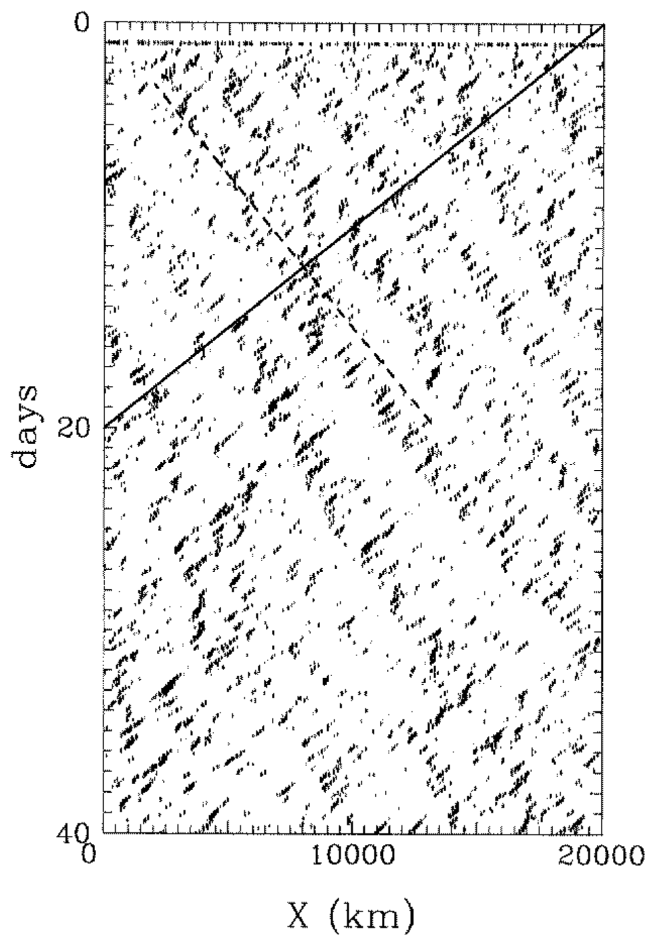
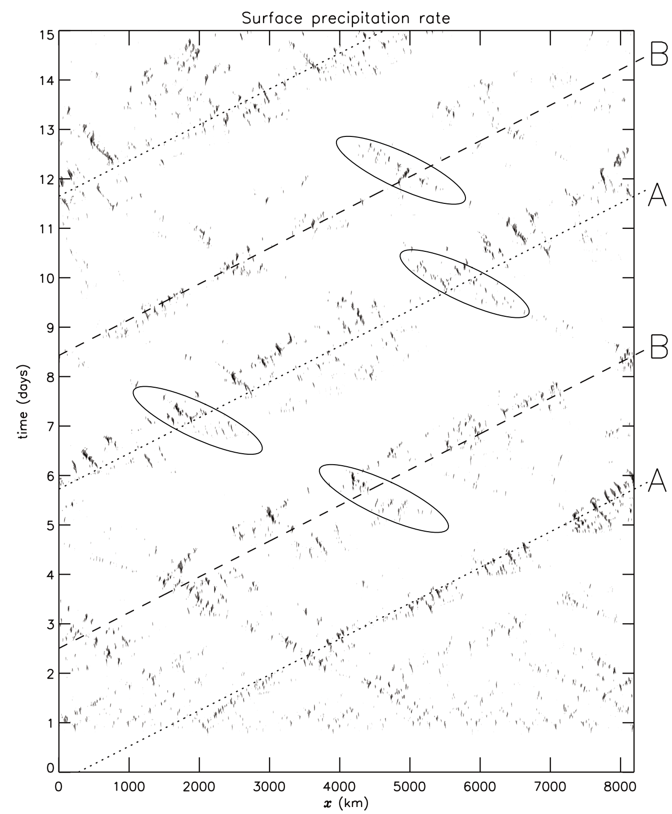
Convectively coupled gravity waves: Synoptic scale envelopes of mesoscale cloud systems



Nakazawa (1988)



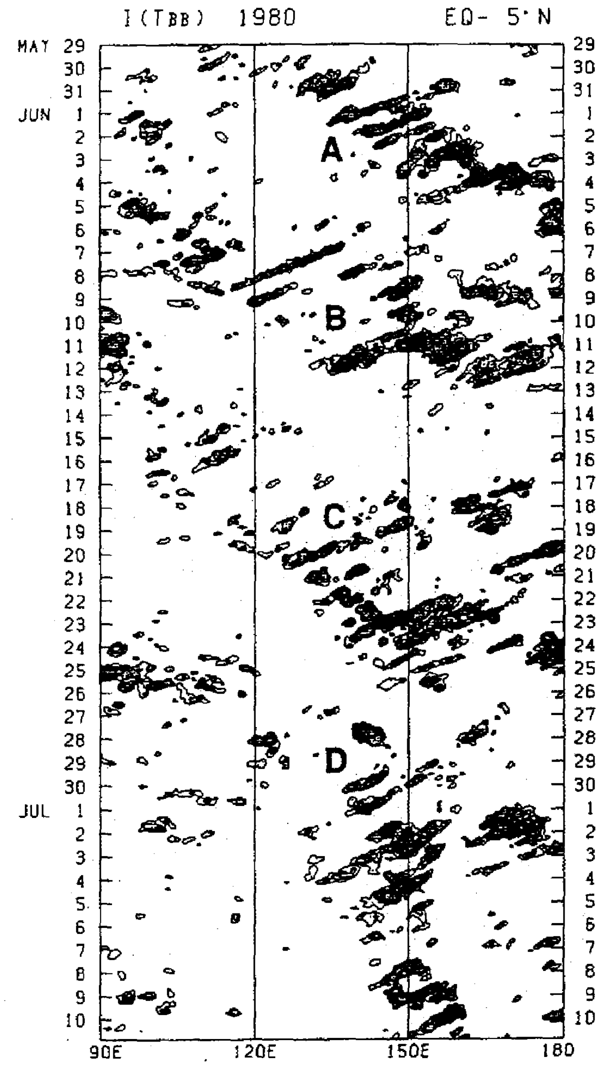
Grabowski and Moncrieff (2001)



Tulich, Randall, Mapes (2007)

Embedded cloud systems propagate in opposite direction of wave envelope

Convectively coupled gravity waves: Physical mechanisms on mesoscales and synoptic scales



<u>Mesoscales</u>

New cloud systems tend to form on a preferred side of preexisting cloud systems

<u>Synoptic scales</u>

Instability of wave disturbance

Mapes (2000), Khouider and Majda (2006)

Question: How do CCWs behave in the presence of wind shear?

Is there a preferred propagation direction?

Outline

1. What causes cloud systems to organize into wave trains?

    - Mesoscale gravity waves in shear
    - Linear and nonlinear models

    Stechmann and Majda (2009); Stechmann, Majda, Khouider (2008)

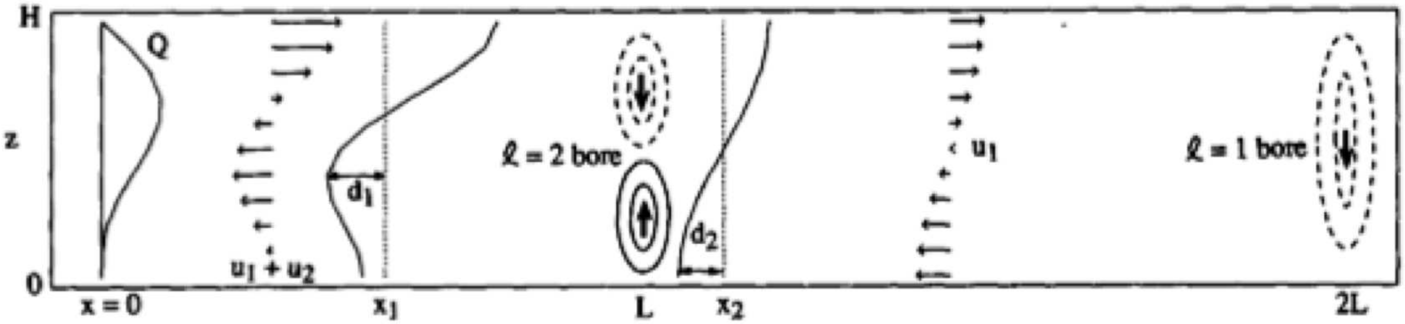
2. How does wind shear affect synoptic scale wave instabilities?

    - Convectively coupled wave–mean flow interaction
    - Implications for the Madden–Julian oscillation

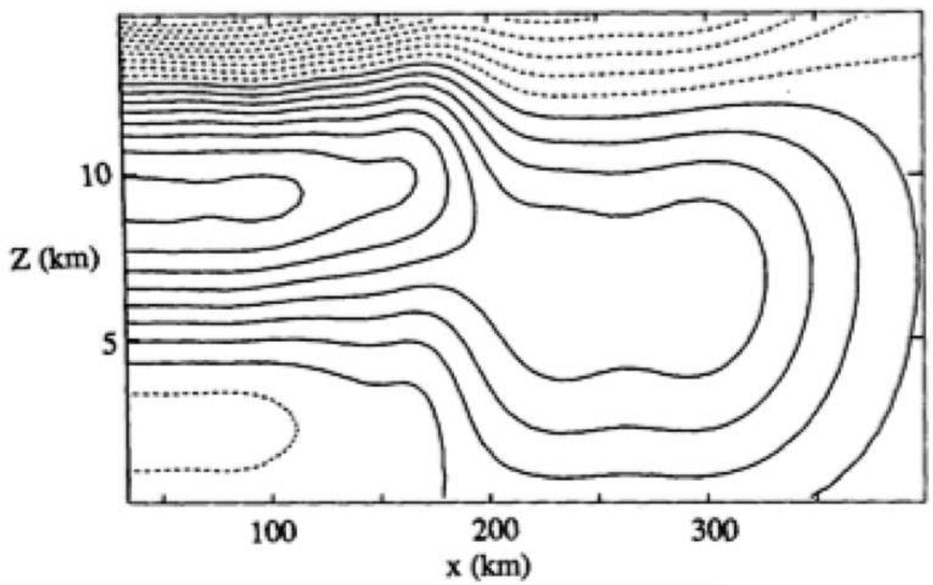
    Majda and Stechmann (2009)

Gravity waves and organized convection

Gravity waves excited by convection can favor/trigger new nearby convection



Buoyancy contours



from Mapes (1993)

Gravity waves and organized convection

Previous work:

Simplified models without wind shear

- Nicholls et al (1991), Pandya et al (1993), Mapes (1993), Liu and Moncrieff (2004)

Cloud resolving models with/without shear

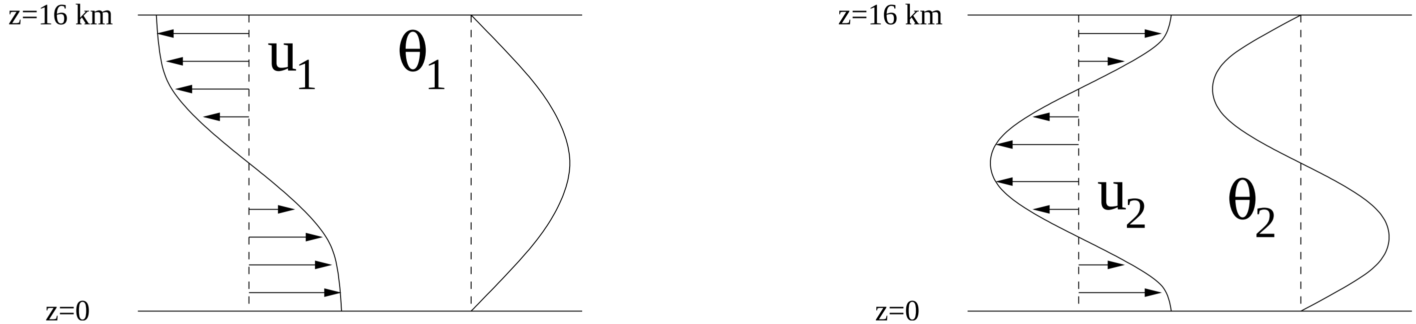
- Bretherton and Smolarkiewicz (1989), Oouchi (1999), Lane and Reeder (2001), Shige and Satomura (2001), Lac et al (2002), Tulich and Mapes (2008)

Present work:

Simplified nonlinear model with wind shear

- Stechmann and Majda (2009), Stechmann, Majda, Khouider (2008)

A simple model with waves in shear



Project nonlinear equations

$$\partial_t U + U\partial_x U + W\partial_z U + \partial_x P = 0$$

onto vertical modes

$$U(x,z,t) = u_1(x,t)\sqrt{2}\cos\frac{\pi z}{H} + u_2(x,t)\sqrt{2}\cos\frac{2\pi z}{H}$$

The result is ...

2-Mode Shallow Water Equations

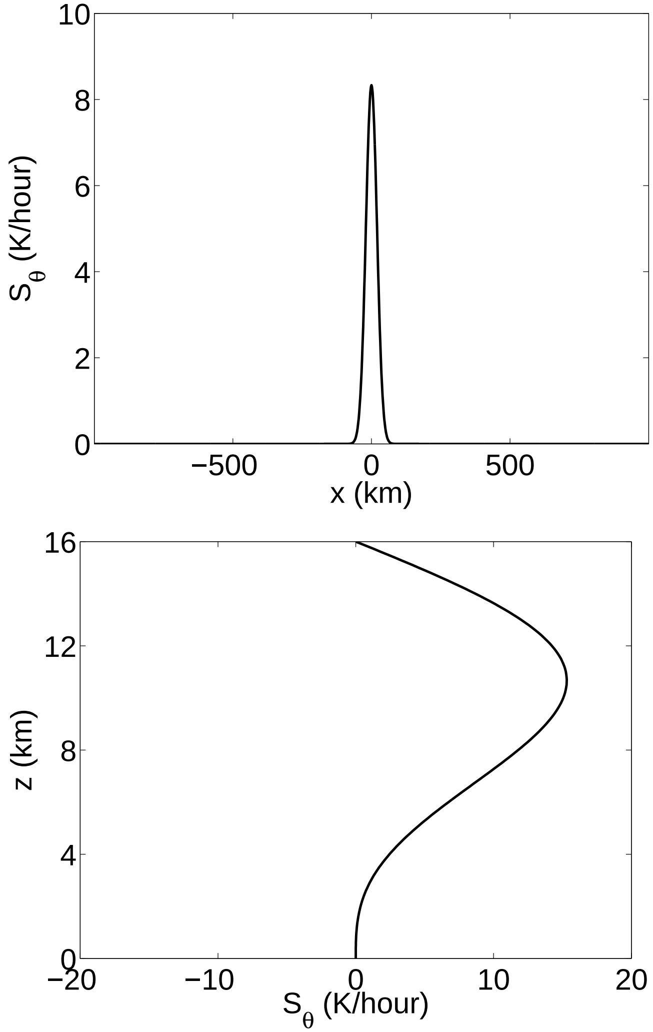
$$
\begin{cases}
\dfrac{\partial u_1}{\partial t} - \dfrac{\partial \theta_1}{\partial x} & = & -\dfrac{3}{\sqrt{2}}\left[u_2\dfrac{\partial u_1}{\partial x} + \dfrac{1}{2}u_1\dfrac{\partial u_2}{\partial x}\right] \\[2ex]
\dfrac{\partial \theta_1}{\partial t} - \dfrac{\partial u_1}{\partial x} & = & -\dfrac{1}{\sqrt{2}}\left[2u_1\dfrac{\partial \theta_2}{\partial x} + 4\theta_2\dfrac{\partial u_1}{\partial x} - u_2\dfrac{\partial \theta_1}{\partial x} - \dfrac{1}{2}\theta_1\dfrac{\partial u_2}{\partial x}\right]
\end{cases}
$$

$$
\begin{cases}
\dfrac{\partial u_2}{\partial t} - \dfrac{\partial \theta_2}{\partial x} & = & 0 \\[2ex]
\dfrac{\partial \theta_2}{\partial t} - \dfrac{1}{4}\dfrac{\partial u_2}{\partial x} & = & -\dfrac{1}{2\sqrt{2}}\left[u_1\dfrac{\partial \theta_1}{\partial x} - \theta_1\dfrac{\partial u_1}{\partial x}\right]
\end{cases}
$$

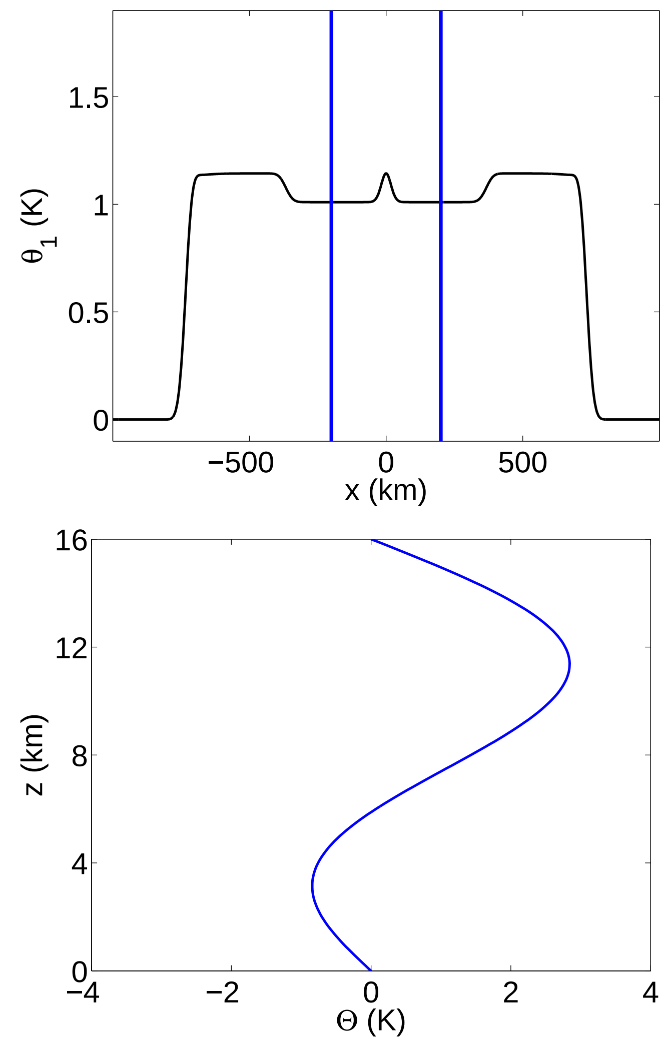
- Nonlinear, hydrostatic internal gravity waves with effect of background shear

Numerical experiment WITHOUT wind shear

Forcing

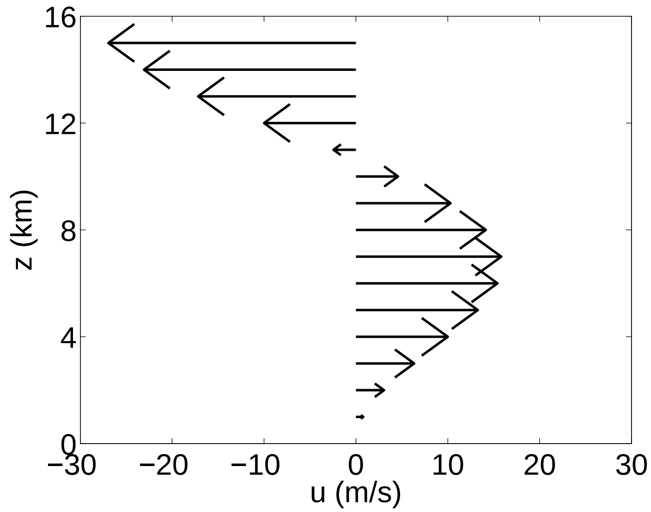


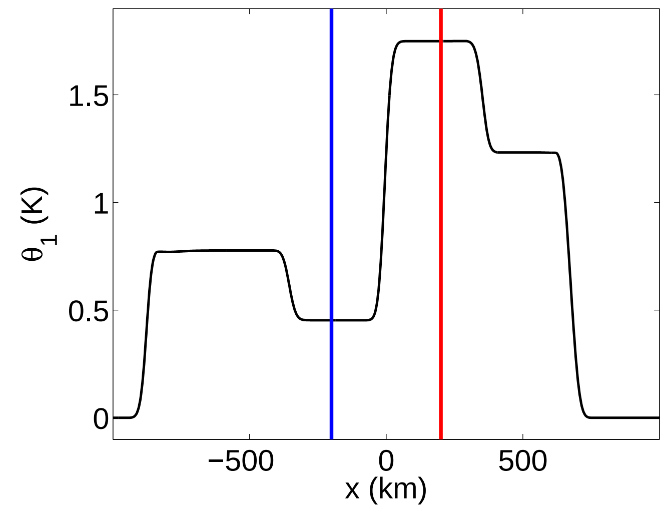
Potential temp. response

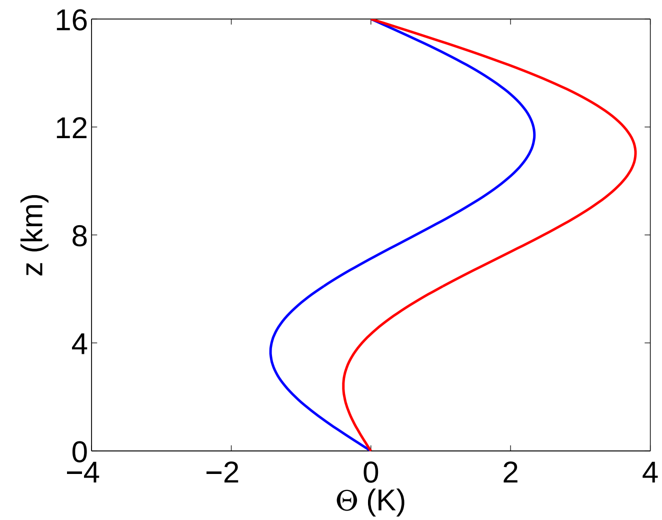


Results symmetric to east and west of forcing

Numerical experiment WITH wind shear







- West of forcing is more favorable for new convection than east
- In agreement with observations for this wind shear (Wu and LeMone, 1999)
- Consistent with features of CCW envelope and embedded cloud systems

Linear theory

A measure of the east–west asymmetry due to wind shear:

- the jump in θ across the source, $[\theta] = \theta^+ - \theta^-$

Linearized equations with singular source term:

$$\partial_t \mathbf{u} + A(\bar{\mathbf{u}})\partial_x \mathbf{u} = \mathbf{S}^* \delta(x)$$

Rankine–Hugoniot jump conditions at location of source:

$$A(\bar{\mathbf{u}})[\mathbf{u}] = \mathbf{S}^*$$

Results: linear theory agrees with nonlinear simulations to within 10 %

Optimal shears for east–west asymmetry

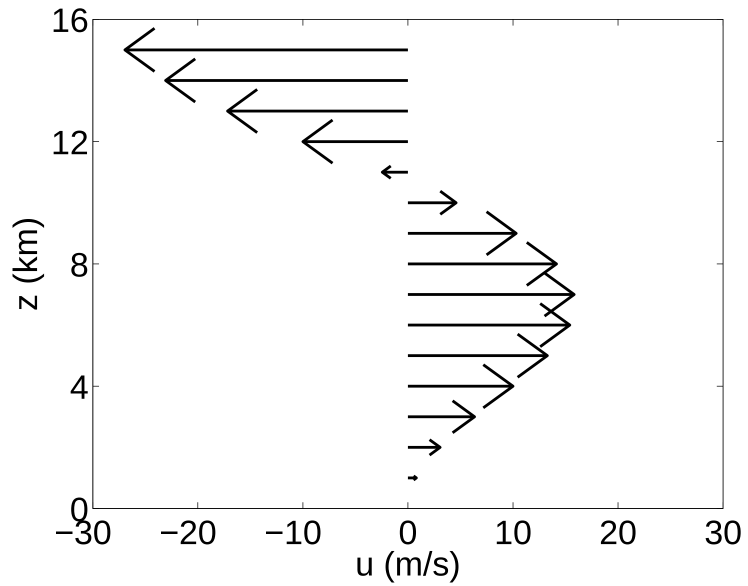
Which shear profiles $\bar{U}(z)$ maximize $[\theta_1]$?

Which shear profiles $\bar{U}(z)$ lead to $[\theta_1] = 0$

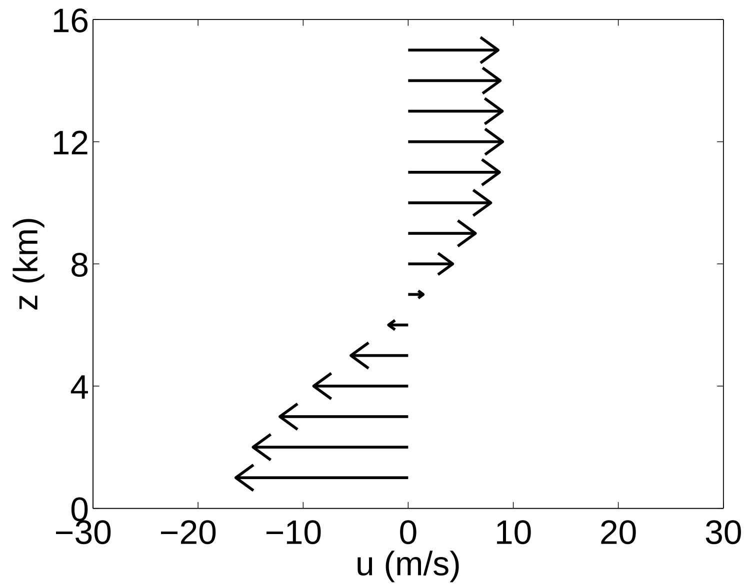
Use linear theory solutions: $A[\mathbf{u}] = \mathbf{S}^*$

Results:

Jet shears maximize θ_1



Profiles with zero shear at upper levels lead to $[\theta_1] = 0$



Summary of Part 1

- 2-mode shallow water equations:
  - simplified nonlinear model for waves interacting with wind shear

- Wind shear can lead to east–west asymmetry
  - *predictions of preferred propagation direction for convectively coupled gravity waves in a background wind shear*
  - jet shears lead to largest east–west asymmetry
  - linear theory is accurate to within 10 % (usually)

Outline

1. What causes cloud systems to organize into wave trains?

    - Mesoscale gravity waves in shear
    - Linear and nonlinear models

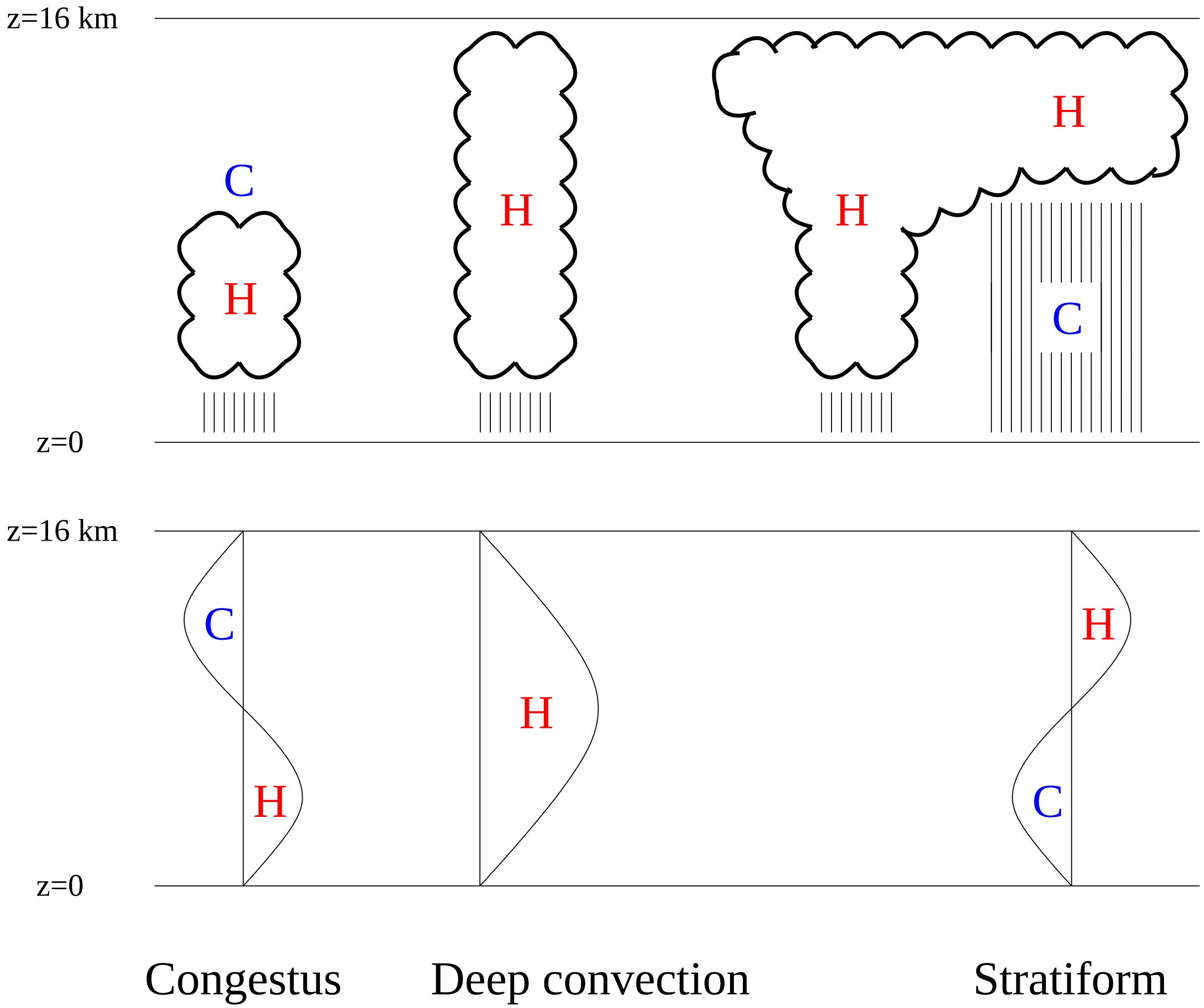
    Stechmann and Majda (2009); Stechmann, Majda, Khouider (2008)

2. How does wind shear affect synoptic scale wave instabilities?

    - Convectively coupled wave–mean flow interaction
    - Implications for the Madden–Julian oscillation

    Majda and Stechmann (2009)

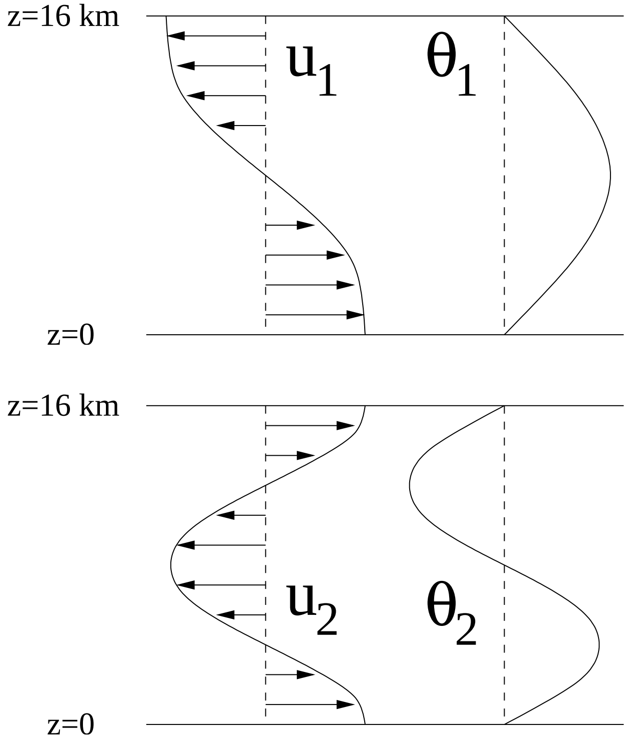
Synoptic scale instabilities and conv. coupled waves: The Multicloud Model (Khouider and Majda 2006)



- Three cloud types
- Two vertical modes

Equations of the multicloud model

Two linear shallow water systems, coupled through nonlinear source terms:



$$\begin{cases} \dfrac{\partial u_1}{\partial t} - \dfrac{\partial \theta_1}{\partial x} & = & -\dfrac{1}{\tau_u} u_1 \\ \dfrac{\partial \theta_1}{\partial t} - \dfrac{\partial u_1}{\partial x} & = & H_d - R_1 \end{cases}$$

$$\begin{cases} \dfrac{\partial u_2}{\partial t} - \dfrac{\partial \theta_2}{\partial x} & = & -\dfrac{1}{\tau_u} u_2 \\ \dfrac{\partial \theta_2}{\partial t} - \dfrac{1}{4}\dfrac{\partial u_2}{\partial x} & = & H_c - H_s - R_2 \end{cases}$$

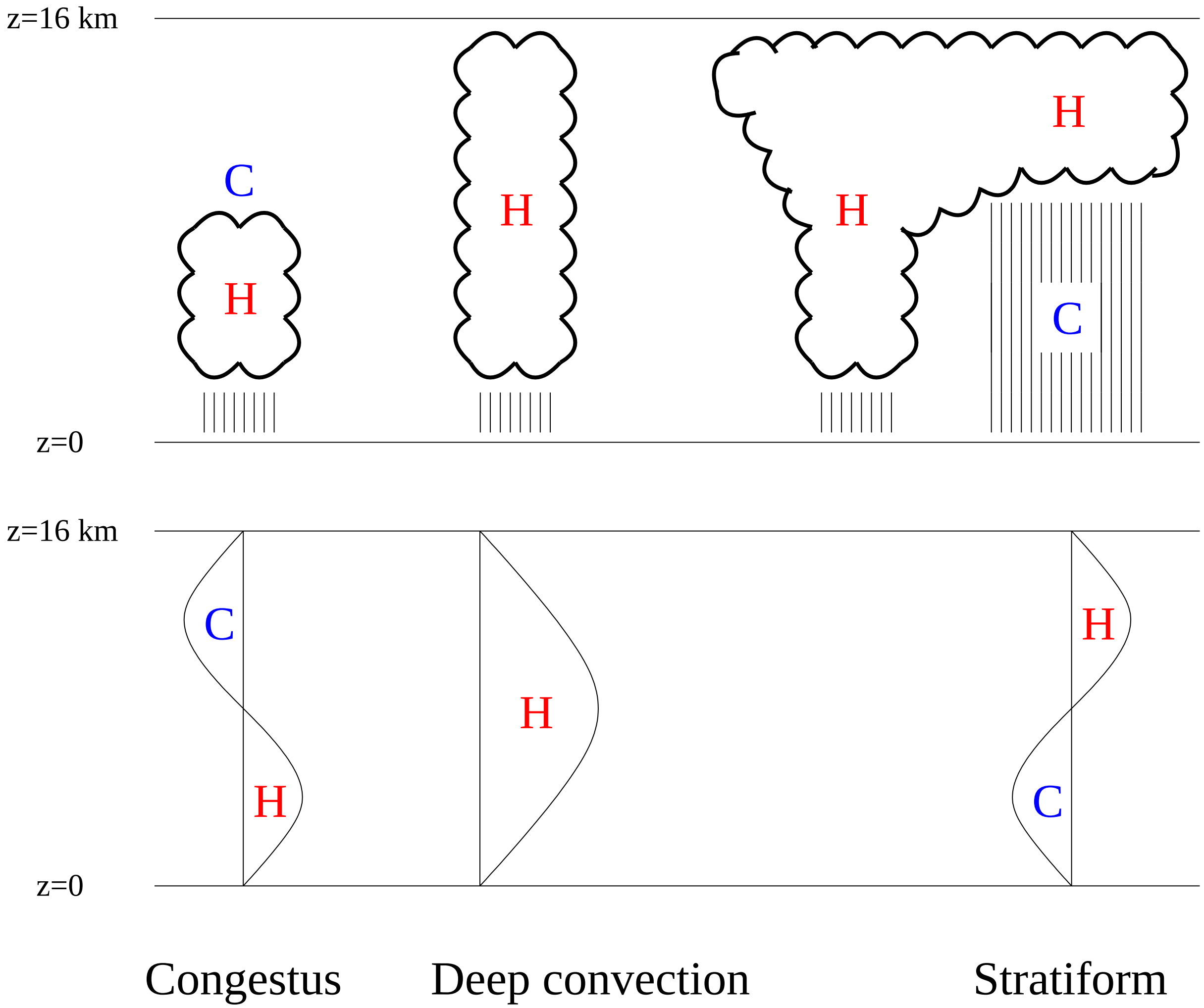
H_d = Deep convective heating $\qquad$ H_c = Congestus heating

R = Radiative cooling $\qquad$ H_s = Stratiform heating

+ 4 more prognostic equations for θ_{eb}, q, H_s, H_c

+ diagnostic equations for some source terms

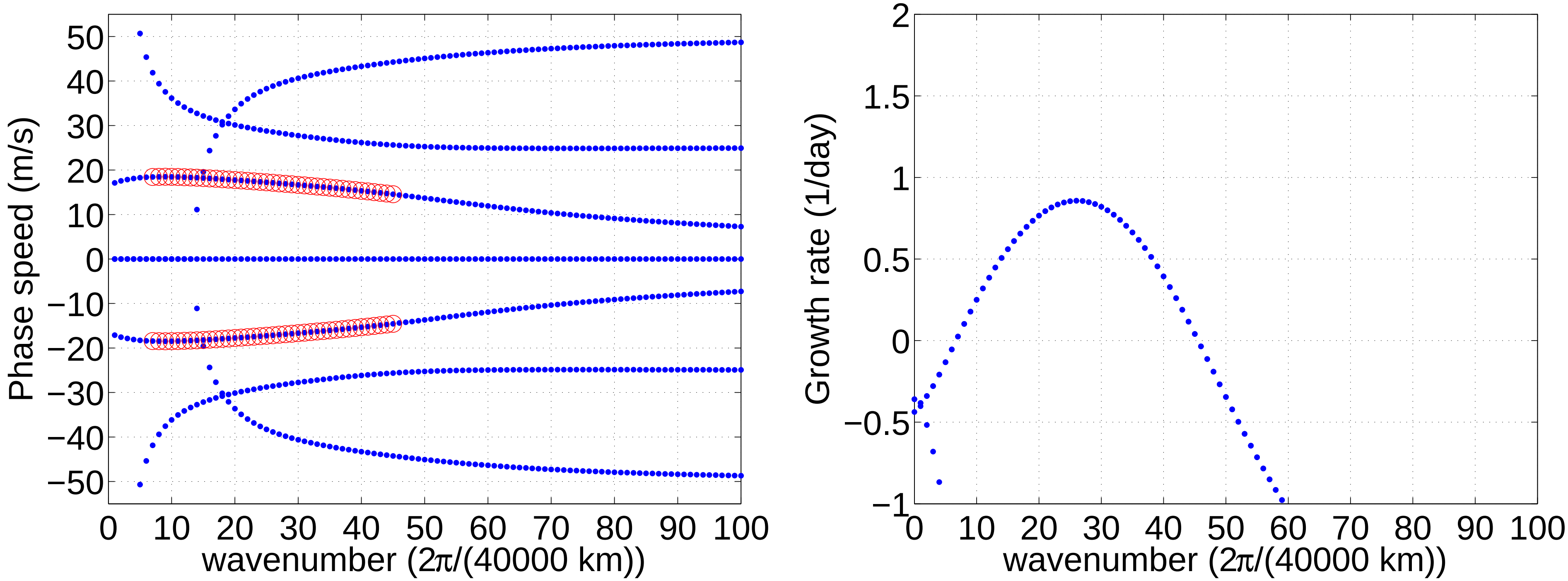
Synoptic scale instabilities and conv. coupled waves: The Multicloud Model (Khouider and Majda 2006)



- Three cloud types
- Two vertical modes

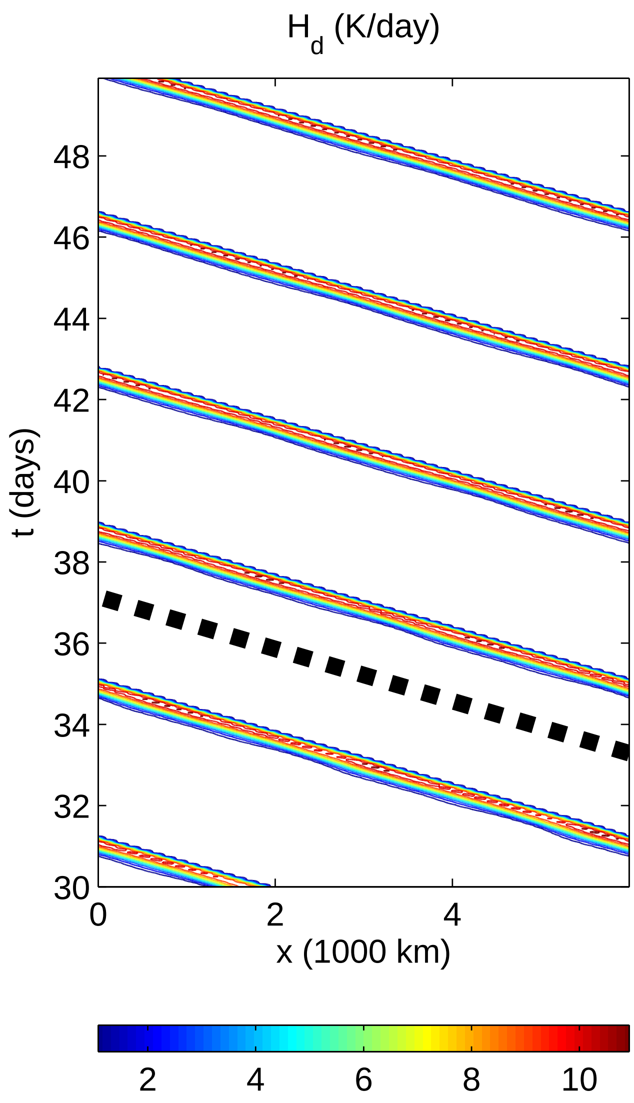
CCWs in the Multicloud Model

Linear theory

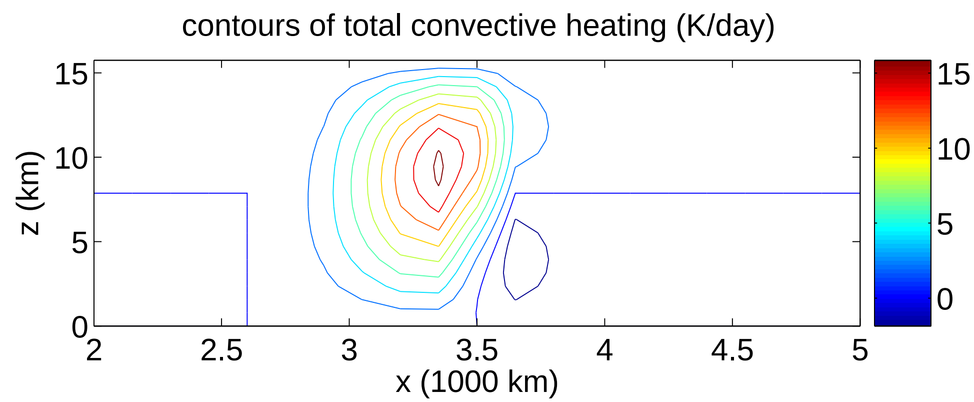


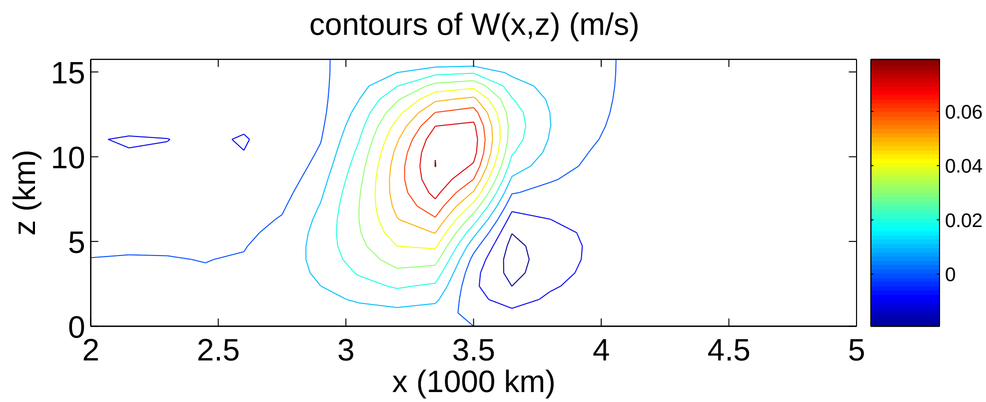
CCWs in the Multicloud Model

Nonlinear simulation



Westward propagation at 18 m/s



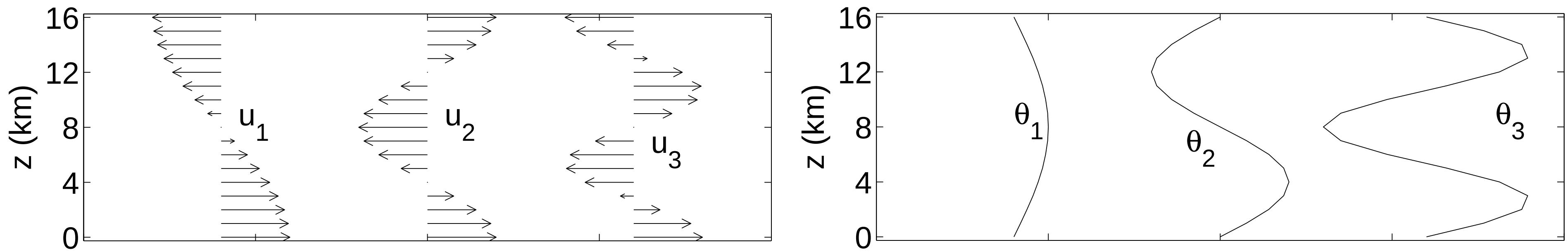


Vertical tilts in wave structures

Modifications to the multicloud model to include effects of wind shear

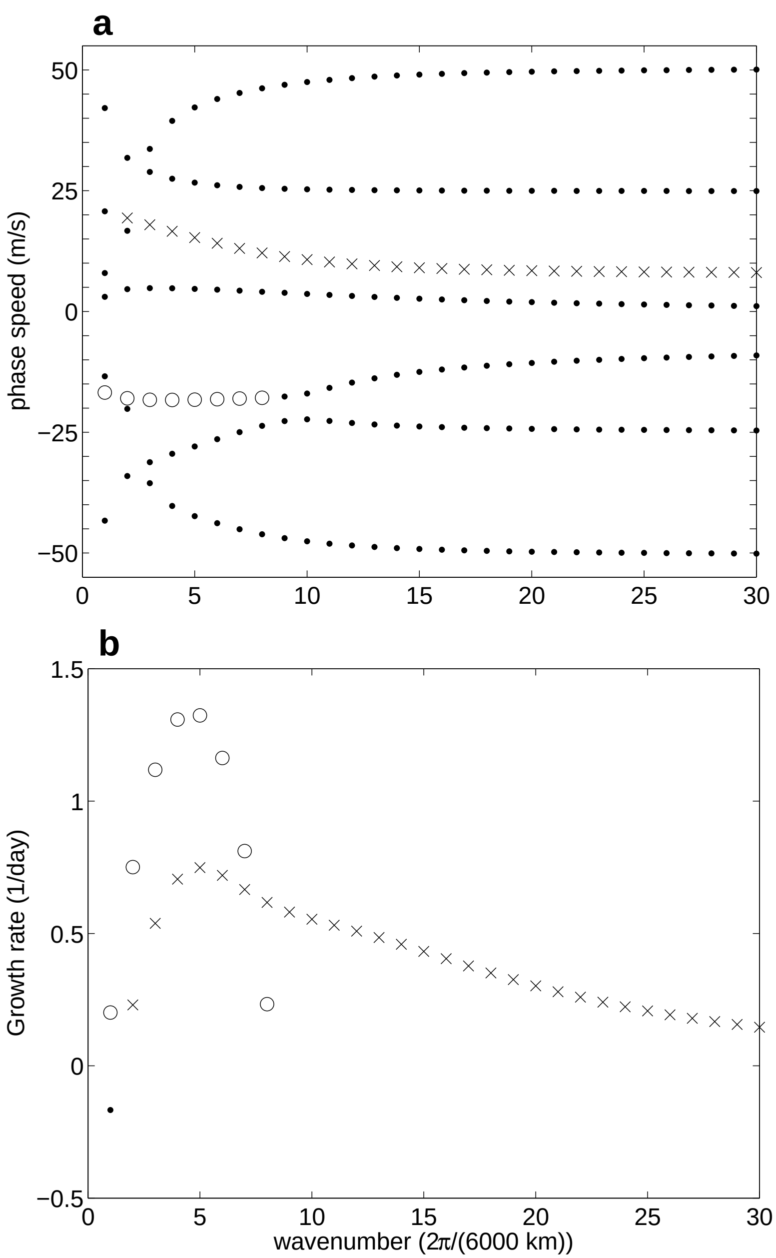
1. Add a *nonlinear* dynamical core by using 2-mode shallow water equations

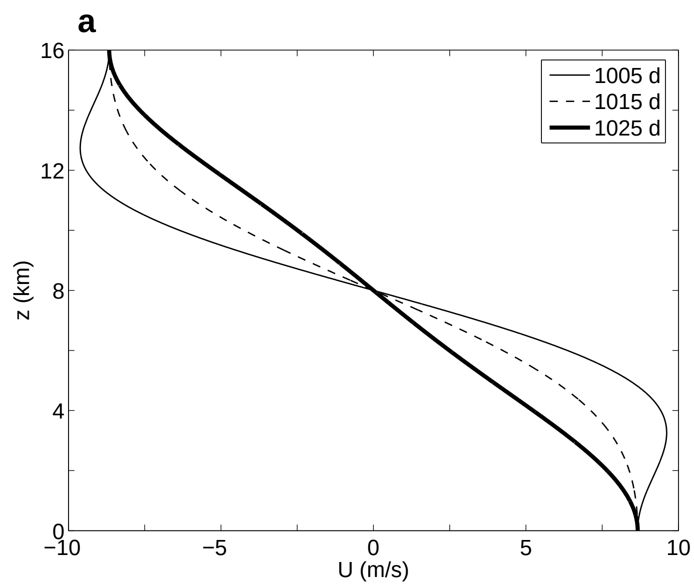
2. Add a 3rd baroclinic mode to capture low-level wind shear (and CMT)



Linear theory with background wind shear

$t = 1005$ days





- *Westward*-propagating CCWs favored at *larger* scales
- *Eastward*-propagating CCWs favored at *smaller* scales

- Wind shear chooses a preferred propagation direction for synoptic scale wave instabilities

- Wind shear chooses a preferred propagation direction for synoptic scale wave instabilities

- Another important effect: waves can drive changes in wind shear through convective momentum transports

Dynamic model for convective wave–mean interaction

$$\frac{\partial \bar{U}}{\partial T} + \frac{\partial}{\partial z}\langle \overline{w'u'} \rangle = 0$$

$$\frac{\partial u'}{\partial t} + \bar{U}\frac{\partial u'}{\partial x} + w'\frac{\partial \bar{U}}{\partial z} + \frac{\partial p'}{\partial x} = S'_{u,1}$$

(with similar equations for other variables)

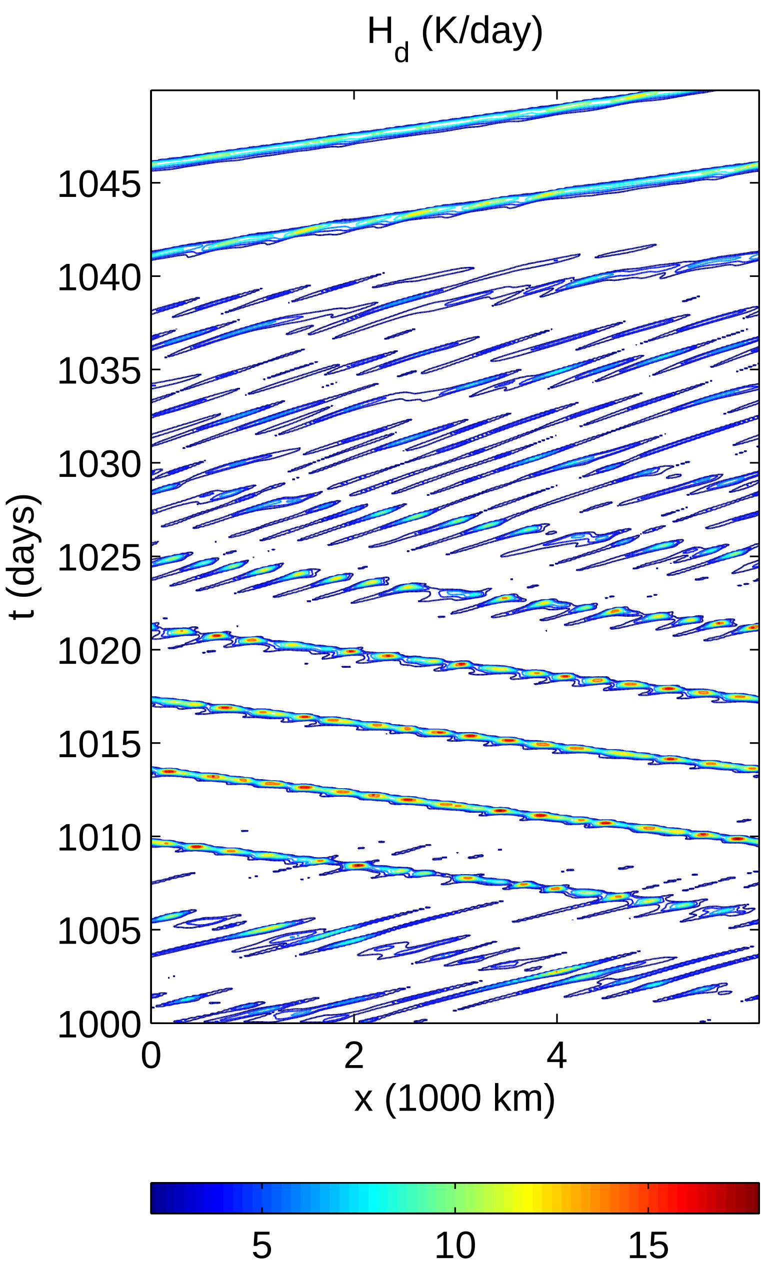
Key features of the model:

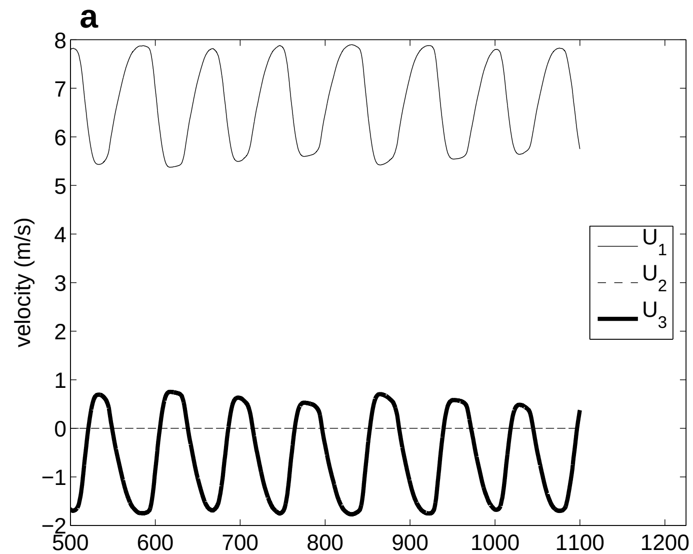
- Eddy flux convergence of wave momentum, $\partial_z \langle \overline{w'u'} \rangle$, feeds the mean flow $\bar{U}$
- Advection of the waves u' by the mean flow $\bar{U}$
- Mean flow time scale $T = \epsilon^2 t$ is longer than that for the waves

Multiscale asymptotic derivation of model

Use multicloud model of Khouider and Majda (2006) as model for convectively coupled waves u', θ', etc.

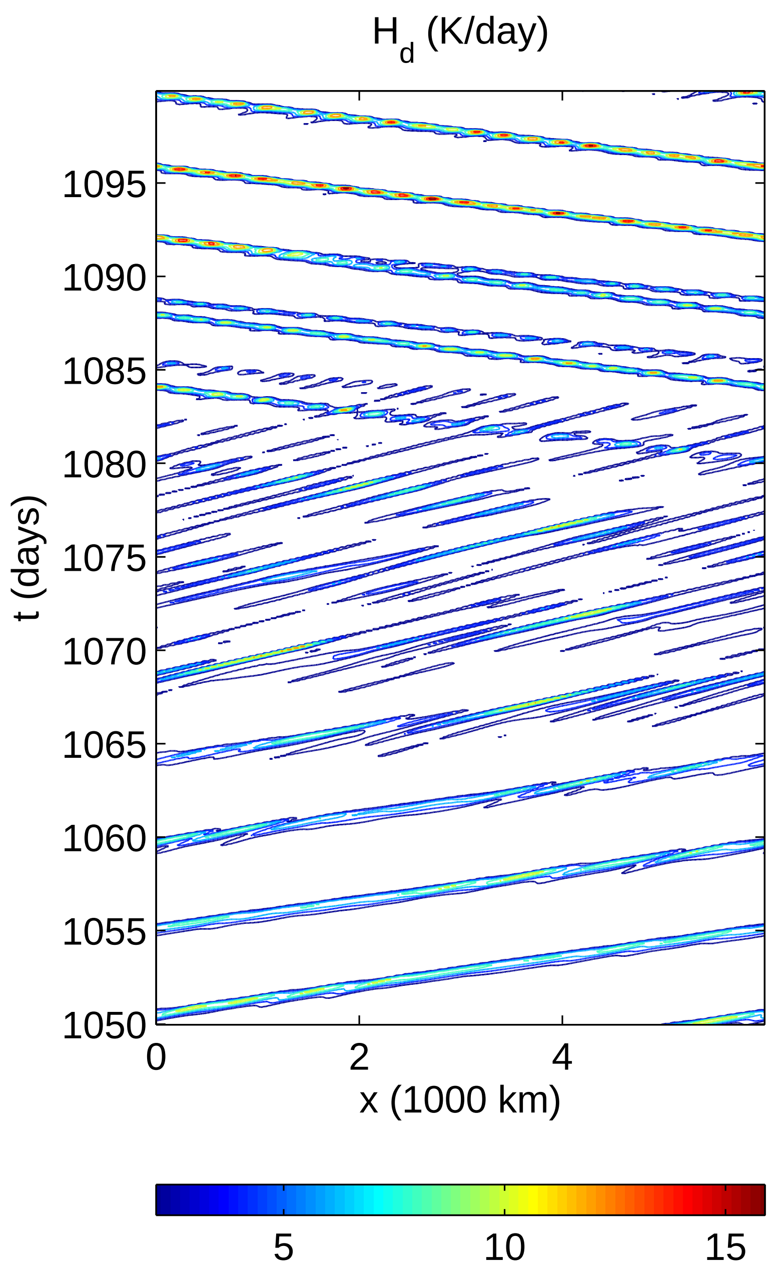
Intraseasonal oscillations and multiscale waves

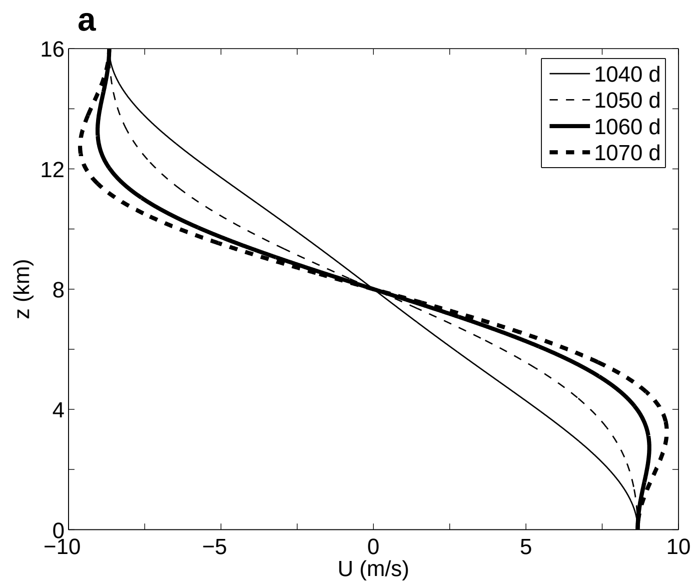




- Two-way interactions between CCWs and mean flow
- Either coherent or scattered waves depending on mean wind

Westerly wind burst intensification

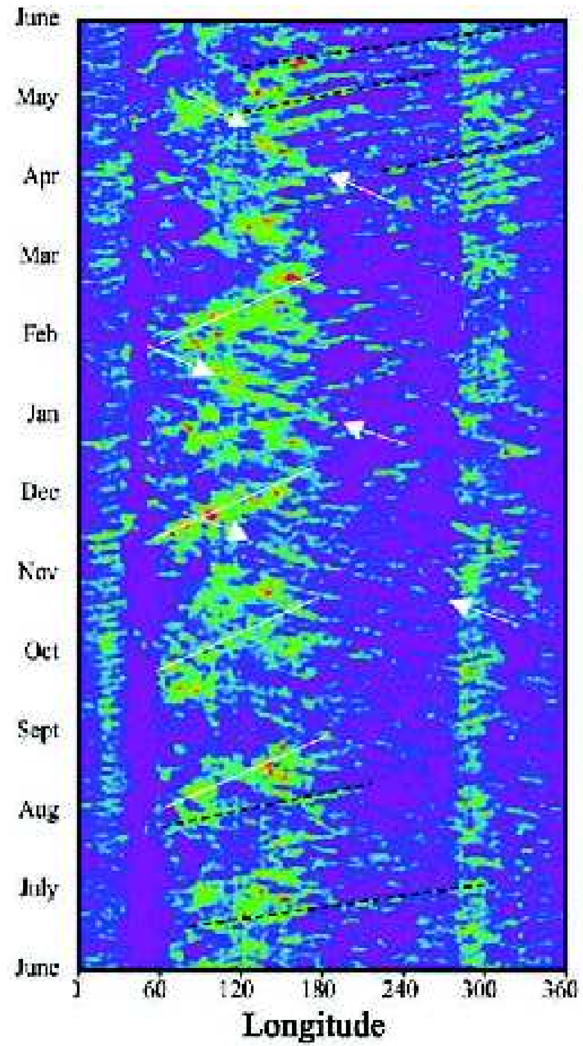




- Eastward-moving waves accelerate low-level jet as in westerly wind burst of Madden–Julian oscillation

Relevance to the Madden–Julian oscillation

Results suggest cooperative interaction between convectively coupled waves and the MJO



Zhang (2005)

To obtain a realistic MJO, global climate models will need

- proper representation of CCWs (including vertical tilts)
- proper representation of interactions between CCWs and larger-scale environment

Cloud-Resolving Model (CRM) simulations of CCWs:

What is the role of CMT from mesoscale convection?

Results vary depending on strength of momentum damping:

$$\frac{\partial u}{\partial t} = -\frac{1}{\tau}u + \cdots$$

- Held et al. (1993): No momentum damping: Long-time oscillation develops
  - Is this due to CMT interactions or stratospheric interactions?
- Grabowski & Moncrieff (2001): Weak momentum damping:
  CCWs develop with significant CMT
- Tulich et al. (2007): Stronger momentum damping:
  CCWs develop with little or no CMT
- Held et al. (1993): Intense momentum damping:
  Convection shut down except at a few grid points

Summary

1. What causes cloud systems to organize into wave trains?

   - Mesoscale gravity waves in shear
   - Wind shear can lead to east–west asymmetry

   Stechmann and Majda (2009)
   Stechmann, Majda, Khouider (2008)

2. How does wind shear affect synoptic scale wave instabilities?

   - Wind shear creates preferred propagation direction
   - Convectively coupled wave–mean flow interaction
   - Acceleration of low-level jet as in westerly wind burst of MJO

   Majda and Stechmann (2009)