A Multicloud Model for Mesoscale Convective Systems

Boualem Khouider
University of Victoria

Mitch Moncrieff
National Center for Atmospheric Research

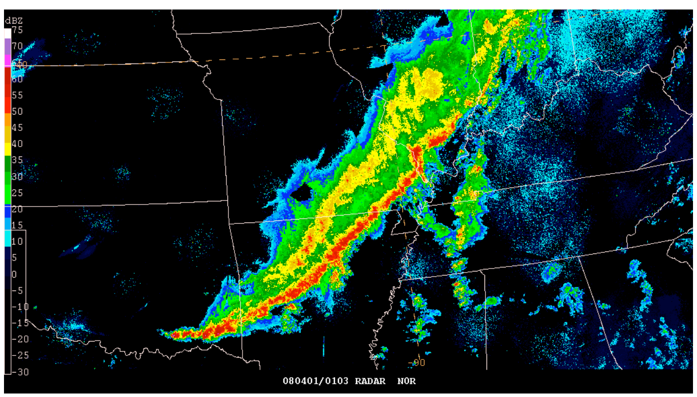
31 conference on Hurricanes and Tropical Meteorology,
31 March -- 4 April, 2014

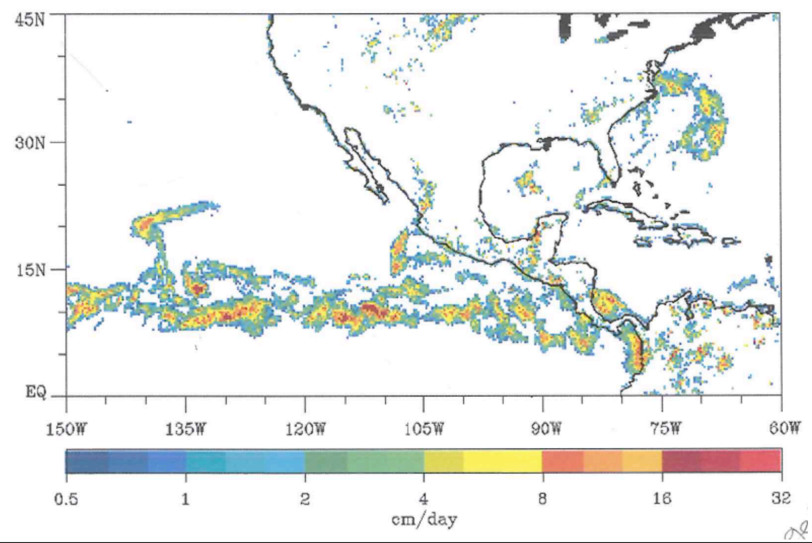
Outline

- Motivation
- Background
- The multicloud model with two moisture layers
- Linear theory results
- Discussion and conclusions

Motivation

- Mesoscale convective systems are ubiquitous in the tropics and extra-tropics
- They often develop in high CAPE and favourable vertical shear environments (Moncrieff, 1980)
- Comprise both shear parallel and shear perpendicular lines of convection (Dudhia and Moncrieff 1987)

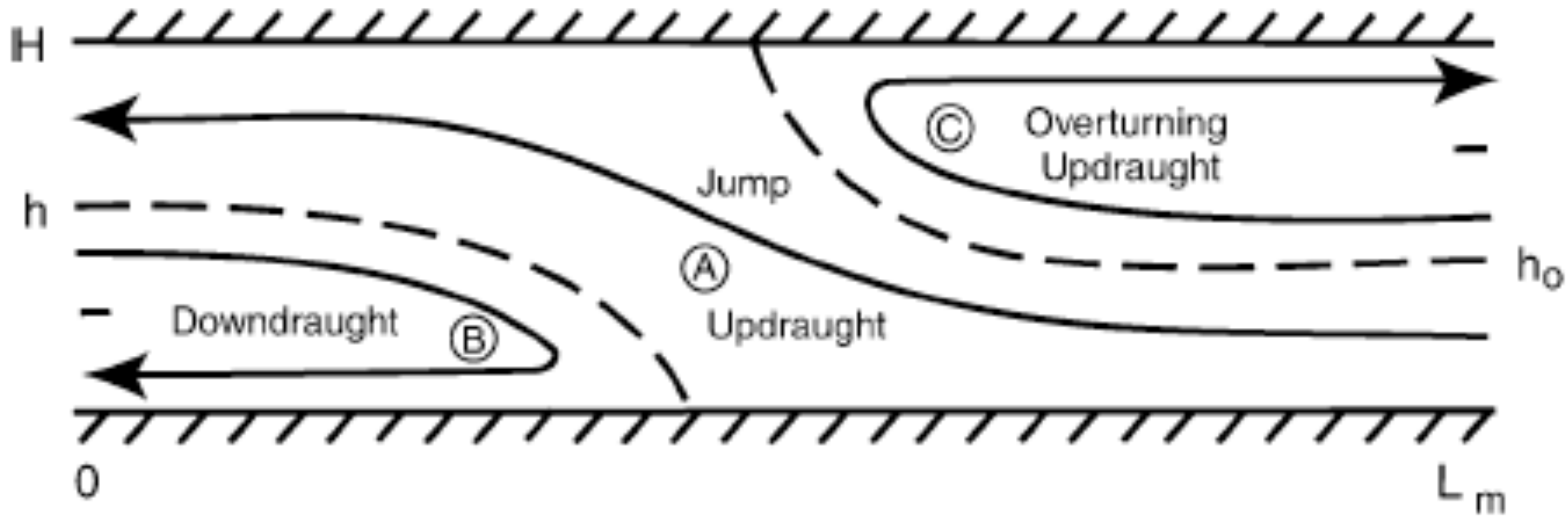




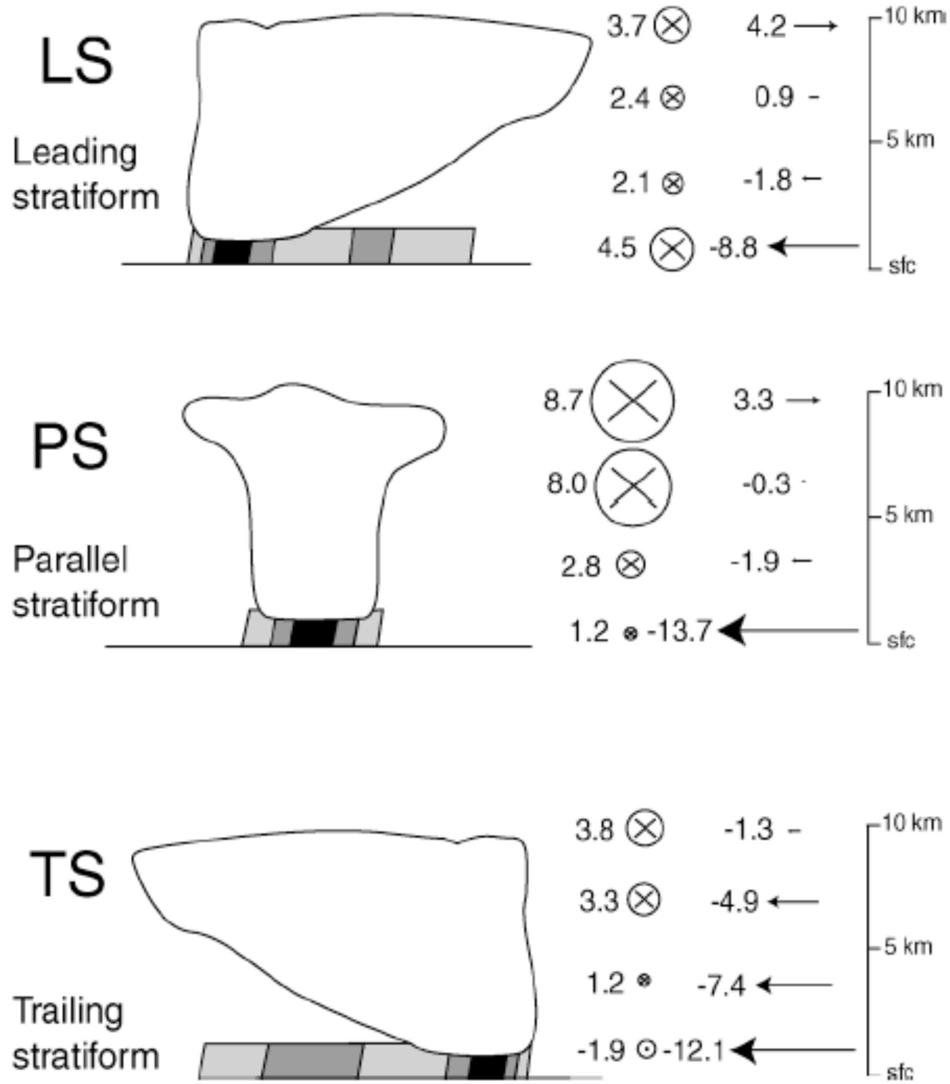
Motivation (continued)

- Coarse resolution GCMs do not resolve MCS's
- Their effect on large scale circulation is not understood
- Observation (Le Mone et al., Tung and Yanai, ...) and numerical modelling work (Moncrieff et al., Majda and Stechmann, Khouider et al., Khouider and Han, ...) suggest, in terms of momentum transport, both upscale and downscale effects are possible
- Here we propose to design a comprehensive yet simple model that captures various types of MCSs.
- Goal to parameterize MCSs in GCMs.

MCS archetypes

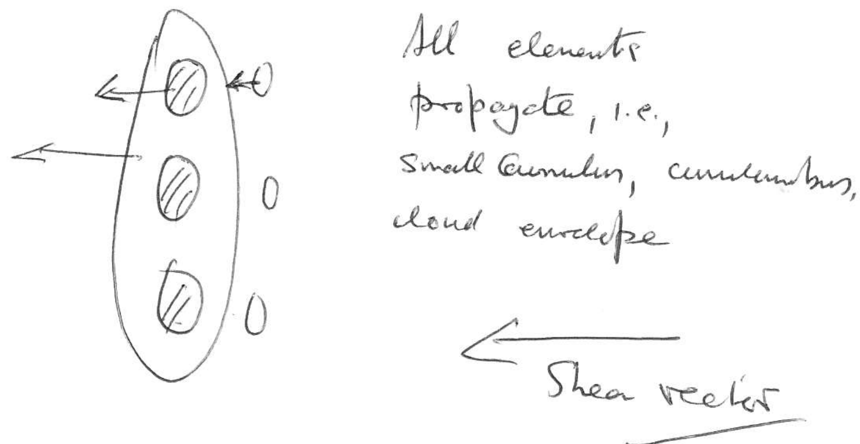


- Moncrieff (1992)

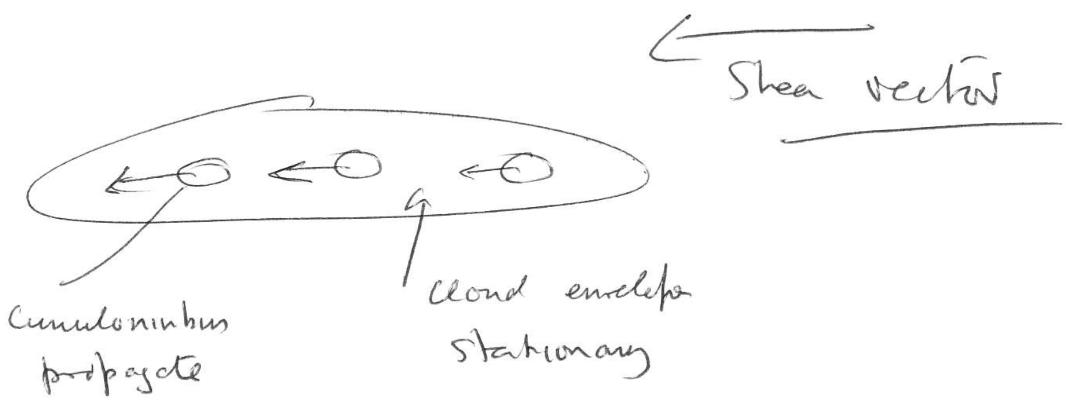


- Parker and Johnson (2004)

A) Shear-Perpendicular System



B) Shear-Parallel System



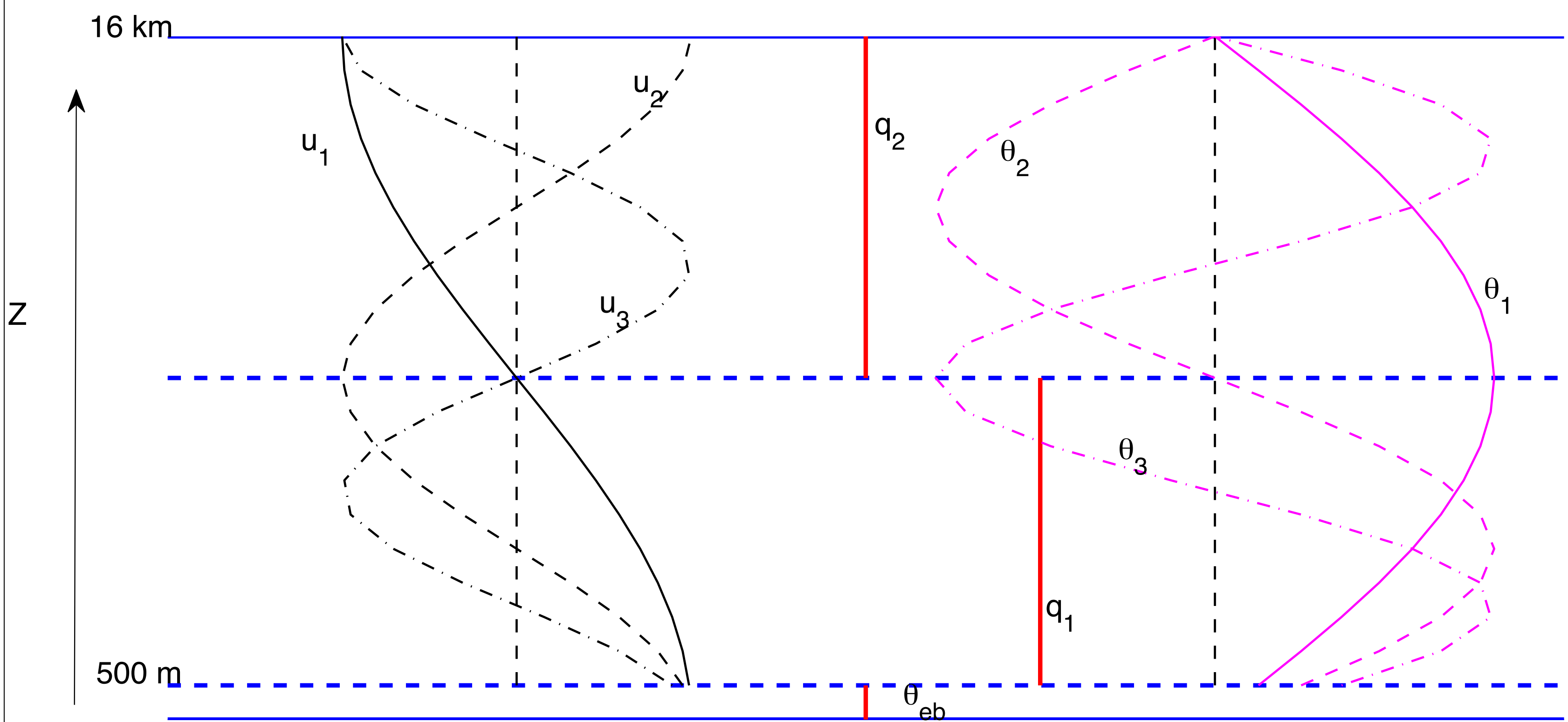
Dudhia et al. 1987, Dudhia and Moncrieff 1987

MCS’s in multicloud model

- Khouider and Majda (2006, 2008) proposed a multicloud model for synoptic scale convectively coupled waves (scale selective instability). Now used as a parameterization for MJO simulations.
- It is based on three cloud types: congestus, deep, and stratiform which force the first two baroclinic modes of wind and temperature. It uses midtropospheric moisture, and boundary layer theta_e
- Based on self-similarity of tropical convective systems, Stechmann (PhD thesis) “tuned” some model parameters (time scales) to “push” the instability to mesoscales
- Concurrent meso- and synoptic scale instabilities are also possible but there are some caveats. No extended stratiform regions!!

MCM with extended stratiform anvil

- Two moisture layers in the free troposphere
- Add a (new) stratiform heating component directly tied to upper level moisture anomaly (large scale condensation)
- Extend dynamics to three baroclinic modes



New moisture and stratiform equations

q1, q2 are perturbations from a background moisture profile

$$\frac{\partial q_1}{\partial t} + \sum_{j=1}^{3} \tilde{\alpha}_j \nabla \cdot (q_1 \mathbf{u_j}) + \sum_{j=1}^{3} \tilde{Q}_j^{(1)} \nabla \cdot \mathbf{u}_j = \frac{D}{H_m} - \frac{1}{H_m} w_m q_m + \frac{1}{\tau_{mt}}(q_2 - q_1) - P_1 \quad (37)$$

$$\frac{\partial q_2}{\partial t} - \sum_{j=1}^{3} \tilde{\beta}_j \nabla \cdot (q_2 \mathbf{u_j}) + \sum_{j=1}^{3} \tilde{Q}_j^{(2)} \nabla \cdot \mathbf{u}_j = \frac{1}{H - H_m} w_m q_m + \frac{k_m}{1 - k_m} \frac{1}{\tau_{mt}}(q_1 - q_2) - P_2. \quad (38)$$

$$P_1 = \frac{2\sqrt{2}}{\pi} \left[H_d - 2(H_s - H_c) \right] \quad \text{and} \quad P_2 = \frac{2\sqrt{2}}{\pi} \left[H_d + 2(H_s - H_c) \right].$$

Stratiform heating

$$H_s = s_1 H_{s,1} + s_2 H_{s,2}$$

s=0.75

$$H_{s,1} = \frac{1}{\tau_{cs}} \left[q_2 - \hat{q}_0 - \gamma_s (\beta_1 \theta_1 + \beta_2 \theta_2 + \beta_3 \theta_3) \right]^+ \text{ and } \frac{\partial H_{s,2}}{\partial t} = \frac{1}{\tau_{as}} (\alpha_s H_d - H_{s,2}),$$

Deep and congestus heating

CAPE

$$Q_d = \left\{ \bar{Q} + \frac{1}{\tau_c}\left[\quad \theta_{eb} \qquad\qquad - a_0 \left(\theta_1 + \gamma_2\theta_2 + \gamma_3\theta_3\right)\right] \right\}^+$$

Low-level CAPE

$$Q_c = \left\{ \bar{Q} + \frac{\alpha_c}{\tau_c}\left[\theta_{eb} - a_0' \left(\theta_1 + \gamma_2'\theta_2 + \gamma_3'\theta_3'\right)\right] \right\}^+$$

$$H_d = (1 - \Lambda)Q_d, \quad H_c = \Lambda Q_c$$

(Lambda is moisture switch function)

New MCM equations

$$\frac{\partial u_j}{\partial t} - \frac{\partial \theta_j}{\partial x} + \sum_{l=1}^{4}\left(\sum_{k=1}^{4} A^u_{jkl} u_k\right)\frac{\partial u_l}{\partial x} + B_{jj} u_j = 0, \quad j = 1,2,3,4$$

$$\frac{\partial \theta_j}{\partial t} - \frac{1}{j^2}\frac{\partial u_j}{\partial x} + \sum_{l=1}^{4}\left(\sum_{k=1}^{4} A^\theta_{jkl} u_k\right)\frac{\partial \theta_l}{\partial x} + \sum_{l=1}^{3}\left(\sum_{k=1}^{3} B^\theta_{jkl}\frac{\partial u_k}{\partial x}\right)\theta_l = C_j - \frac{1}{\tau_D}\theta_j, \quad j = 1,2,3,4$$

$$\frac{\partial q_j}{\partial t} + \left(\sum_{k=1}^{4} A^q_{jkl} u_k\right)\frac{\partial q_j}{\partial x} + \sum_{l=1}^{2}\left(\sum_{k=1}^{3} B^q_{jkl}\frac{\partial u_k}{\partial x} + B^q_{j0l}\right) q_l + \sum_{j=1}^{3}\tilde{Q}^{(i)}_j \frac{\partial u_j}{\partial x} = (2-j)\frac{D}{H_m} - P_j, \quad j = 1,2$$

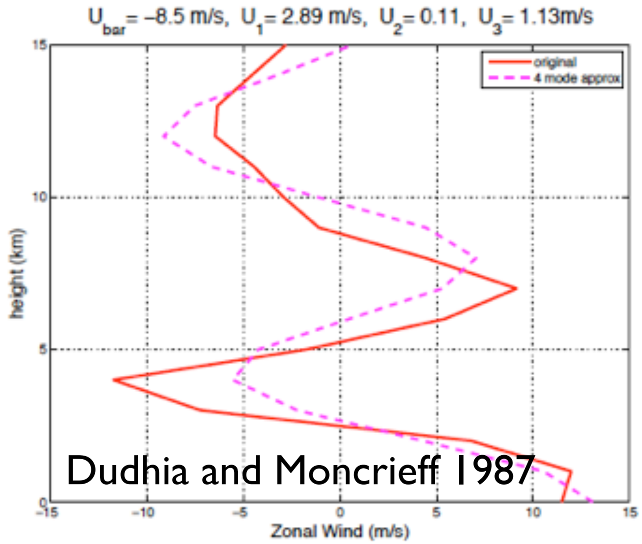
$$\frac{\partial \theta_{eb}}{\partial t} + \sqrt{2}\left(\sum_{j=1}^{4} u_j\right)\frac{\partial \theta_{eb}}{\partial x} = \frac{1}{\tau_e}(\theta^*_{eb} - \theta_{eb}) - \frac{1}{h}D \tag{47}$$

$$C_1 = H_d - Q_{R,1}$$

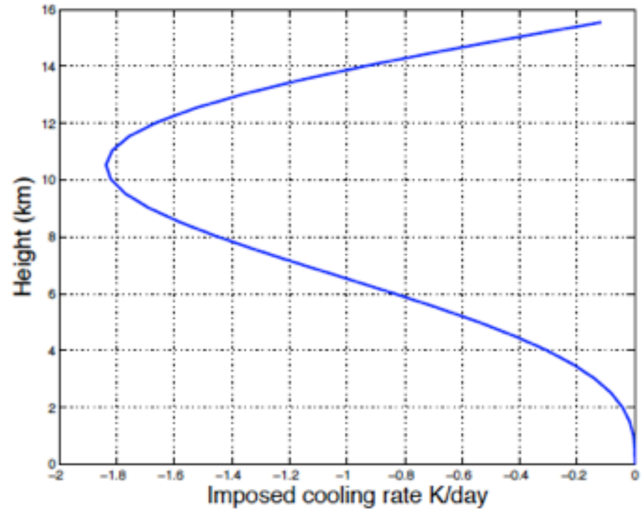
$$C_2 = H_c - H_s - Q_{R,1}$$

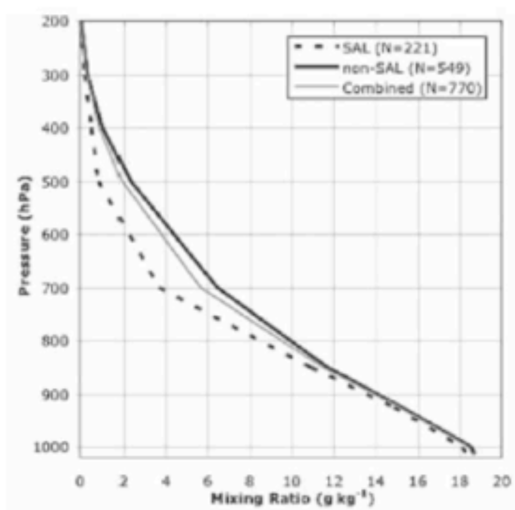
$$D = \frac{m_0}{\bar{Q}}\left[\bar{Q} + \mu(H_s - H_c)\right]^+ (\theta_{eb} - \theta_{em})$$

Set up and background

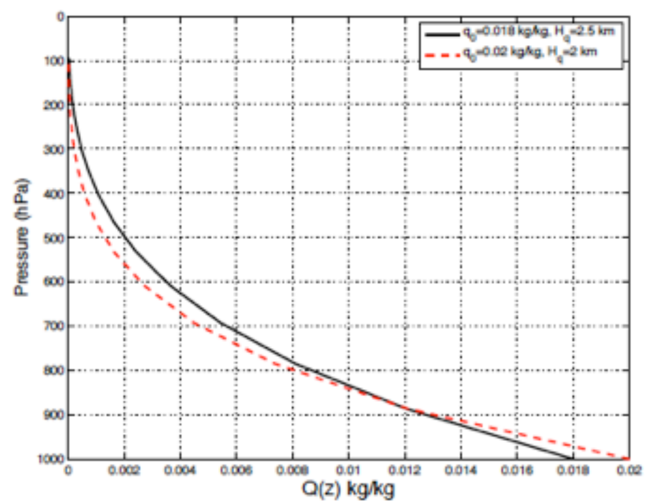


Dudhia and Moncrieff 1987



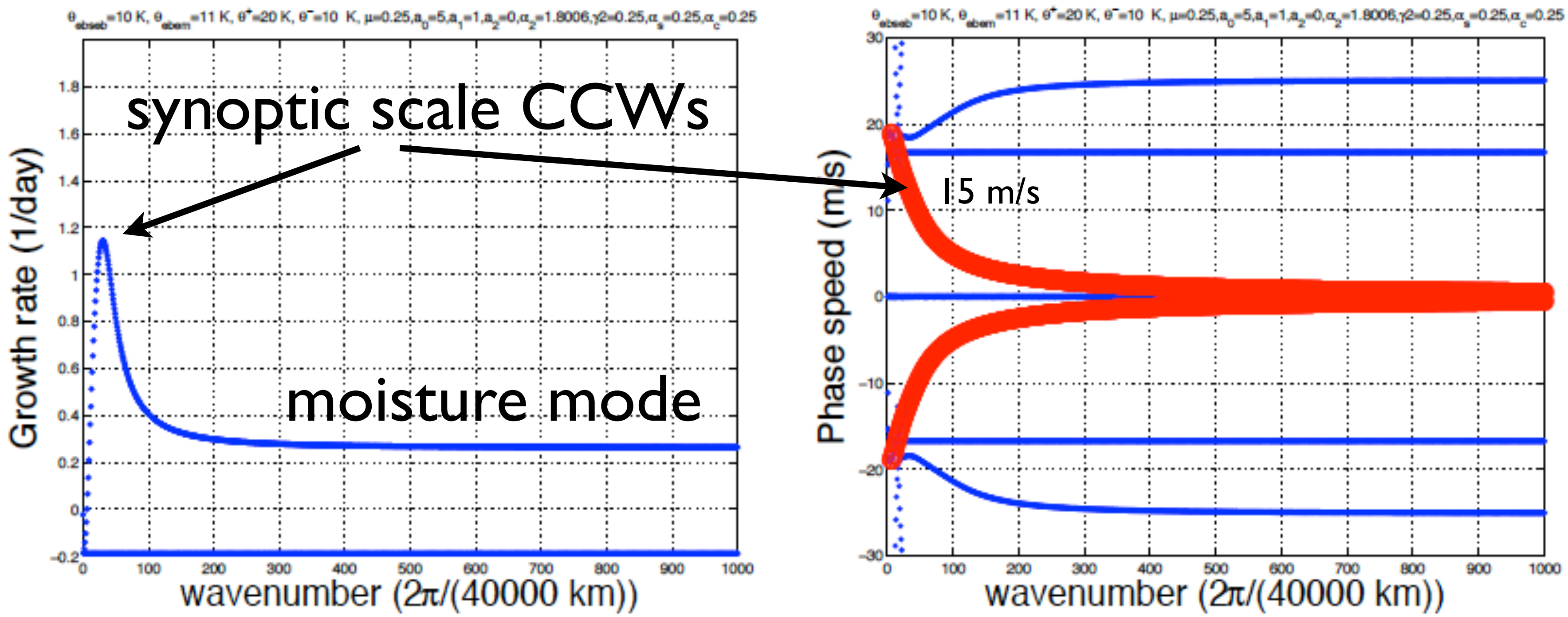


Dunion and Maron, 2008



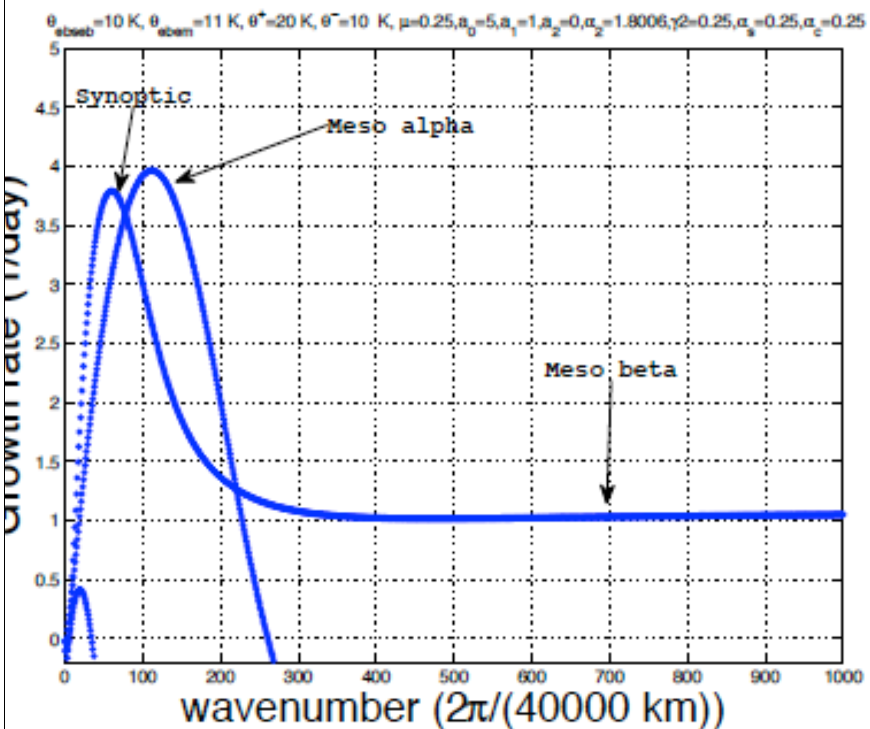
Linear Theory Results

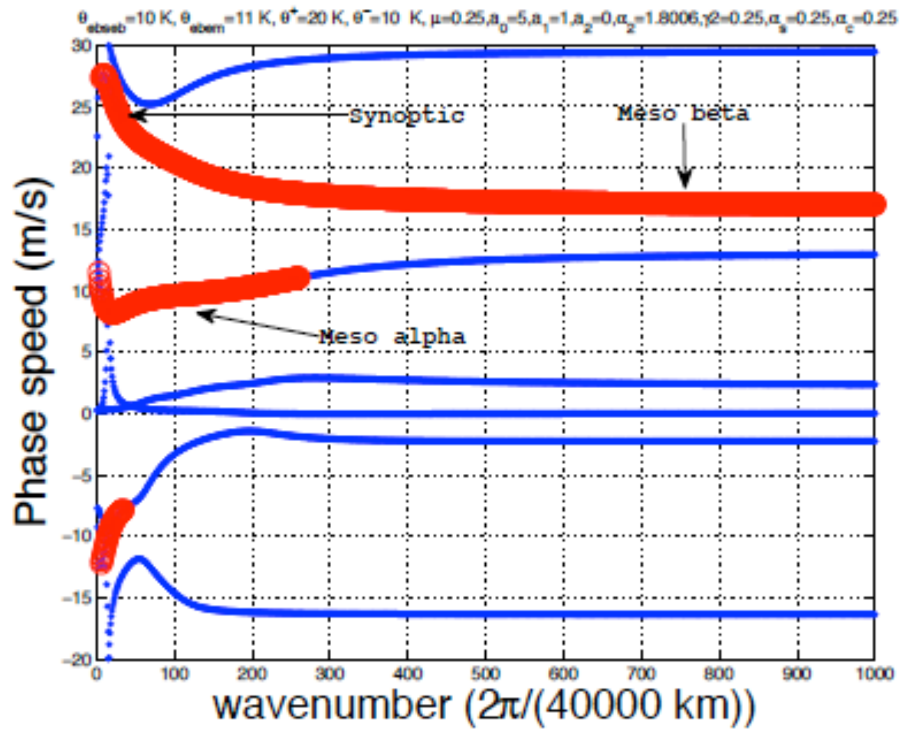
No Shear Case



(no beta effect-- fully symmetric)

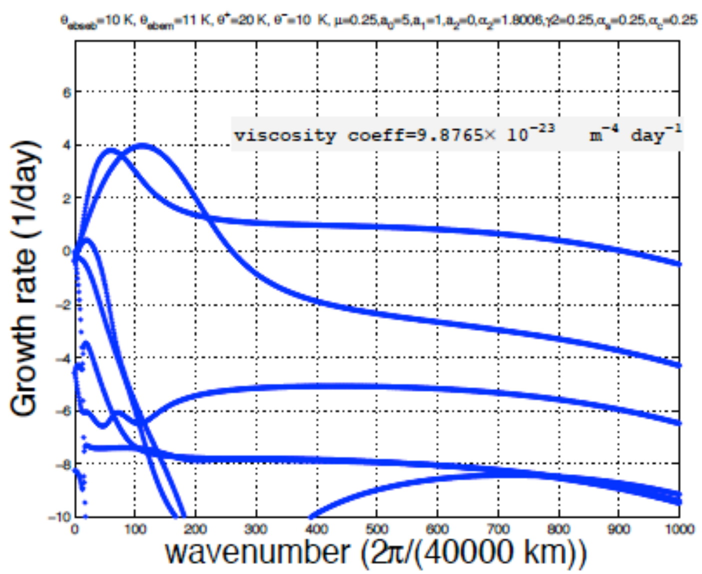
Shear case

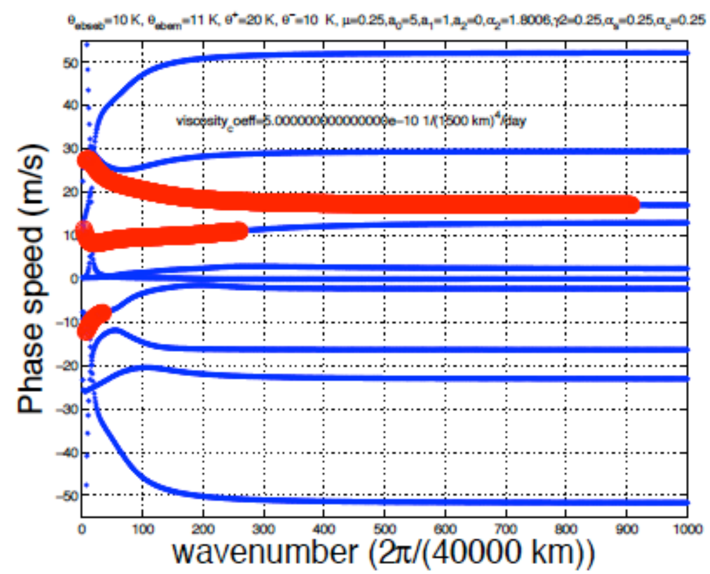

θebseb=10 K, θebem=11 K, θ+=20 K, θ−=10 K, μ=0.25,a0=5,a1=1,a2=0,α2=1.8006,γ2=0.25,αs=0.25,αc=0.25
Synoptic
Meso alpha
Meso beta
wavenumber (2π/(40000 km))


θebseb=10 K, θebem=11 K, θ+=20 K, θ−=10 K, μ=0.25,a0=5,a1=1,a2=0,α2=1.8006,γ2=0.25,αs=0.25,αc=0.25
Phase speed (m/s)
Synoptic
Meso beta
Meso alpha
wavenumber (2π/(40000 km))

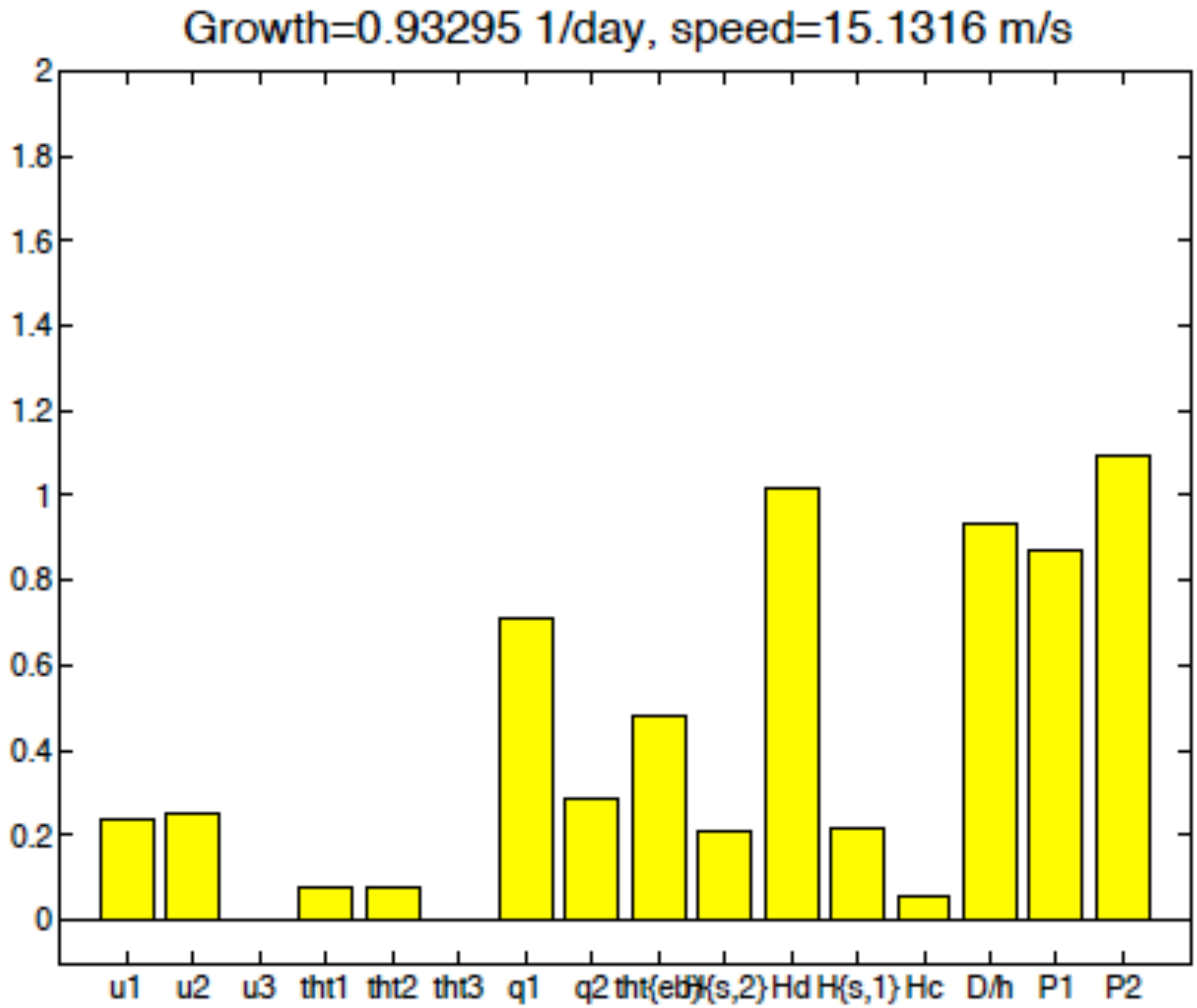
Adding hyper-viscosity

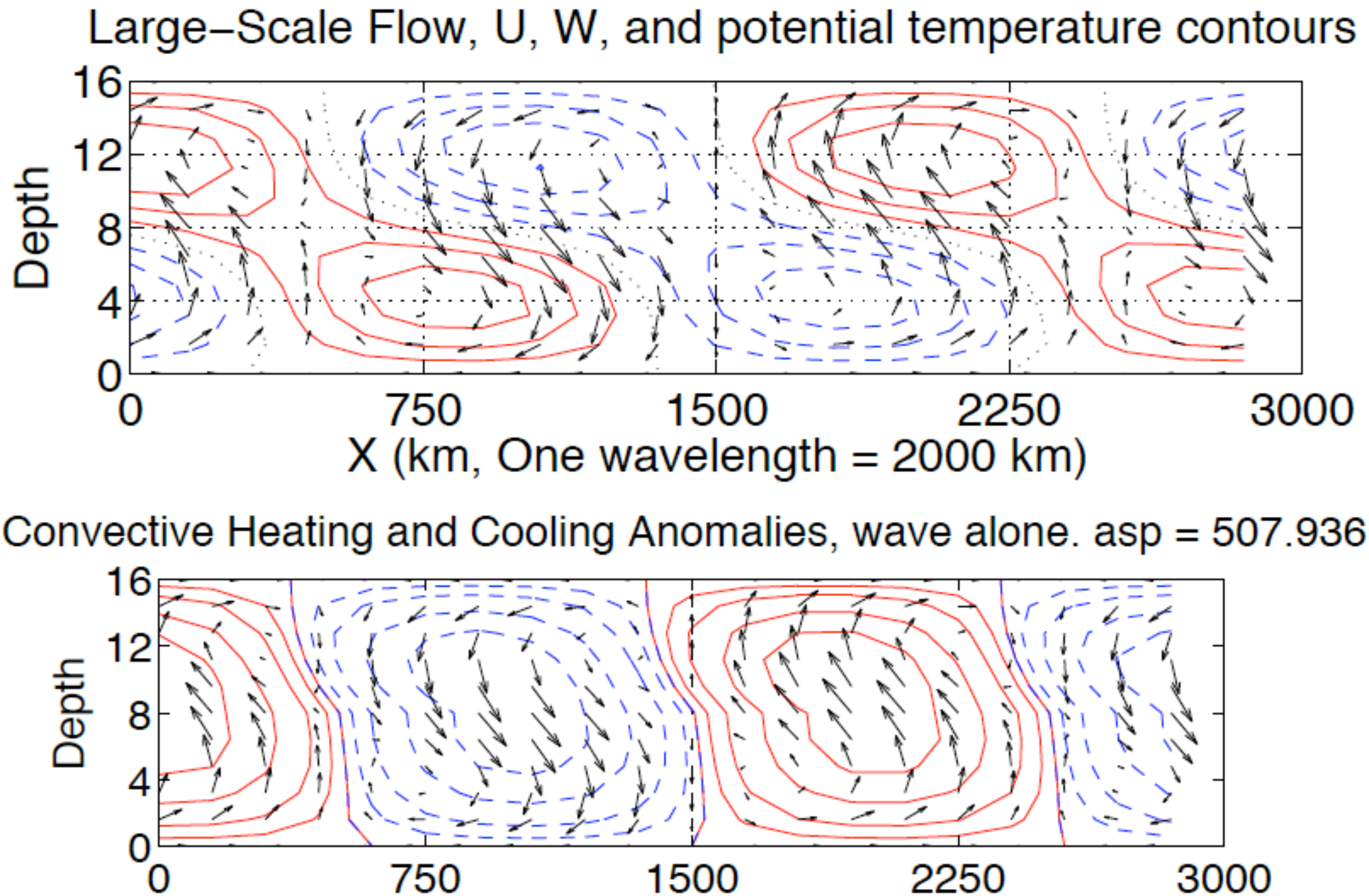
$$\frac{\partial U}{\partial t} + A\frac{\partial U}{\partial x} = BU + (-1)^{2p}\nu\nabla^{2p}U$$



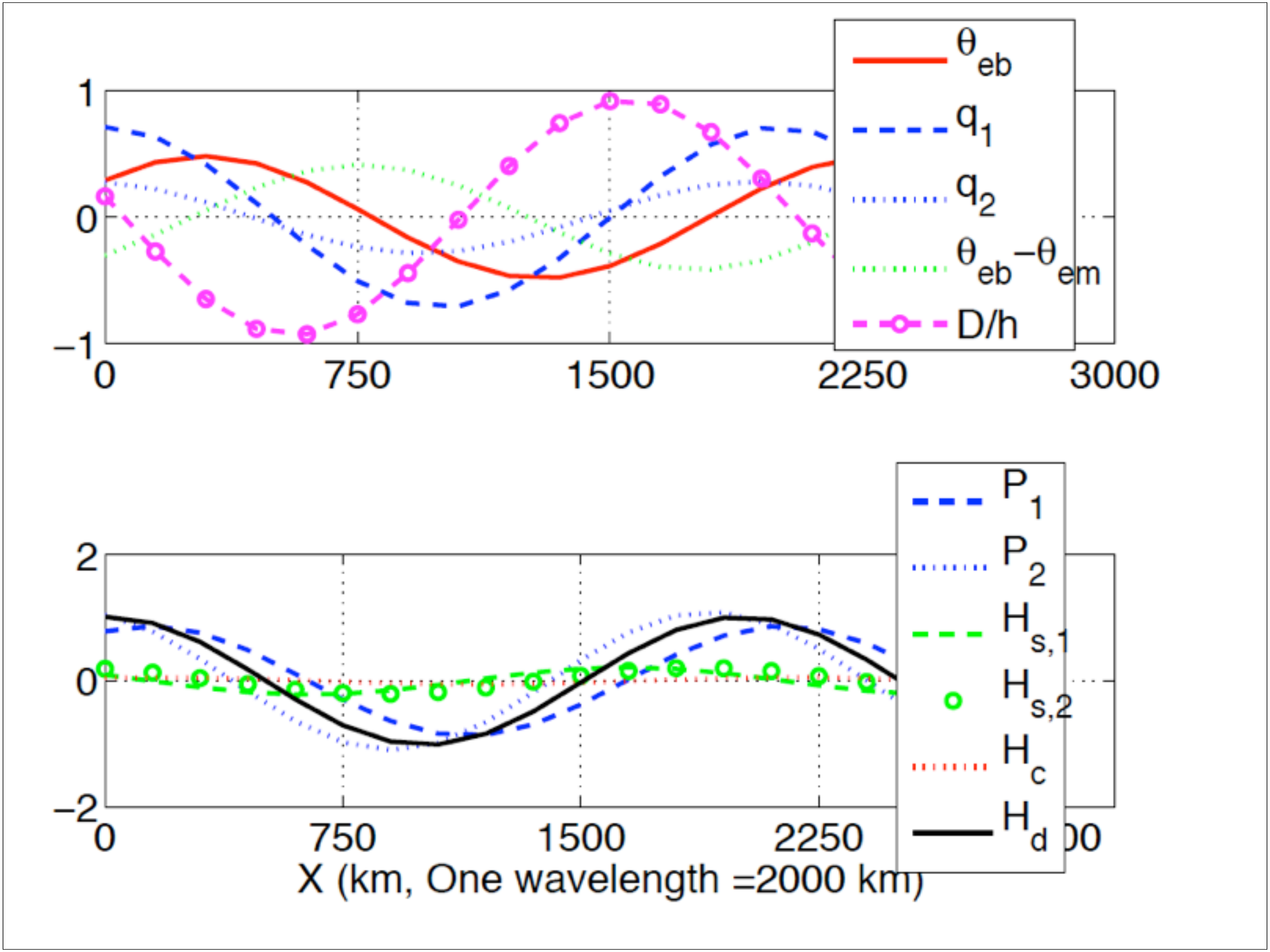


Synoptic scale wave in no-shear case



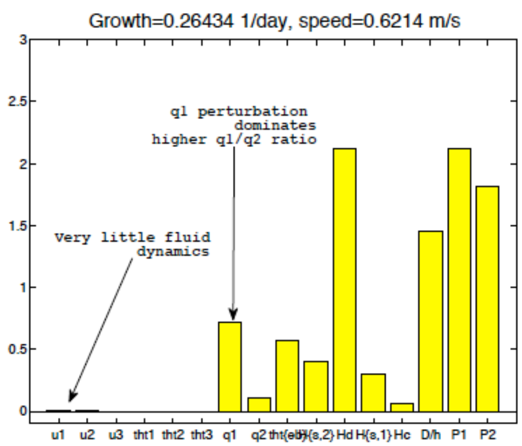


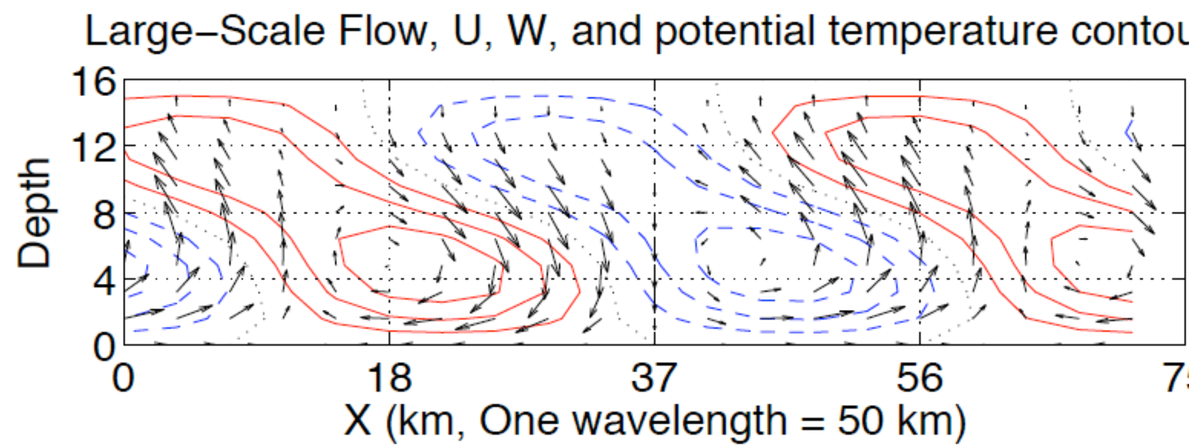
Large–Scale Flow, U, W, and potential temperature contours
Depth
X (km, One wavelength = 2000 km)
Convective Heating and Cooling Anomalies, wave alone. asp = 507.936
Depth

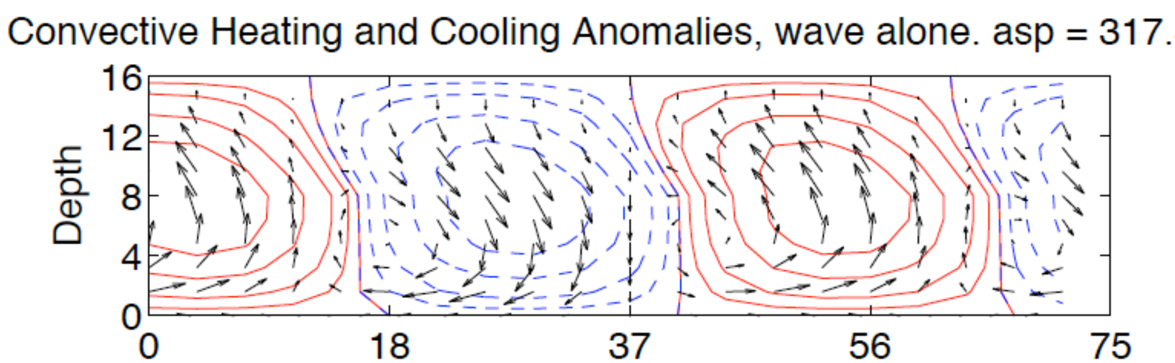


1
0
−1
0
750
1500
2250
3000
θeb
q1
q2
θeb−θem
D/h
2
0
−2
0
750
1500
2250
P1
P2
Hs,1
Hs,2
Hc
Hd
X (km, One wavelength =2000 km)

Structure of moisture mode





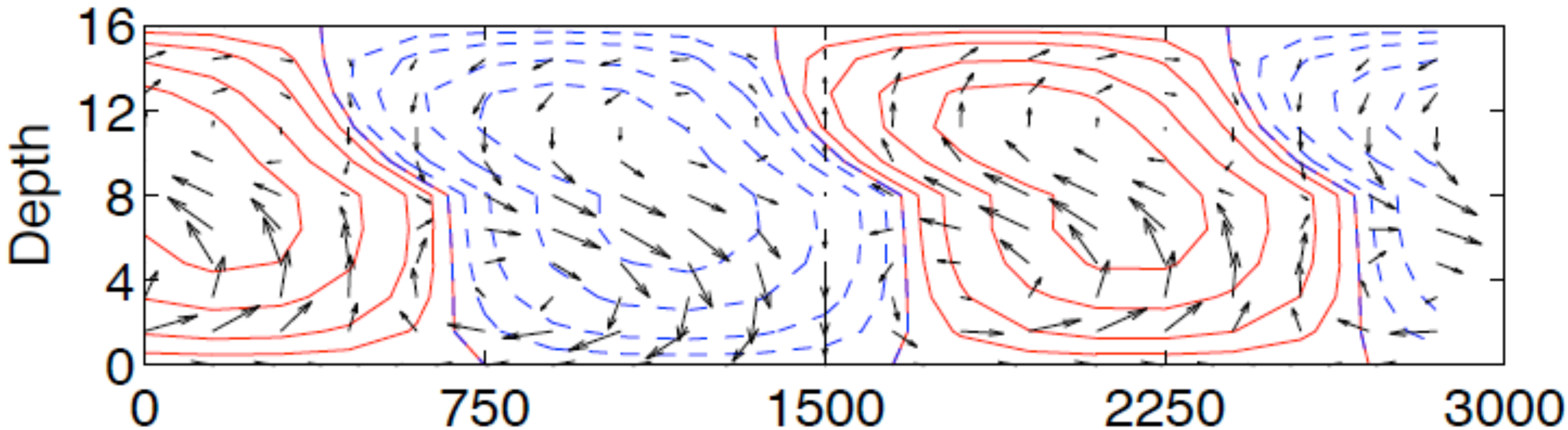


Weak fluid mechanics, Bottom heavy: q1>>q2:

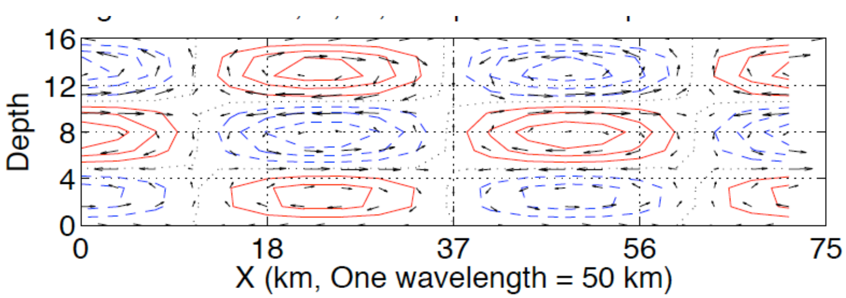
Cumulonimbus mode!

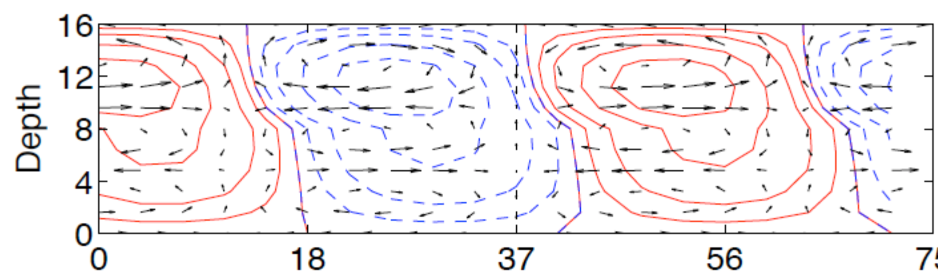
Shear case

- Structure of synoptic scale waves remains essentially the same--except for extended stratiform region (Lin and Mapes 2000)

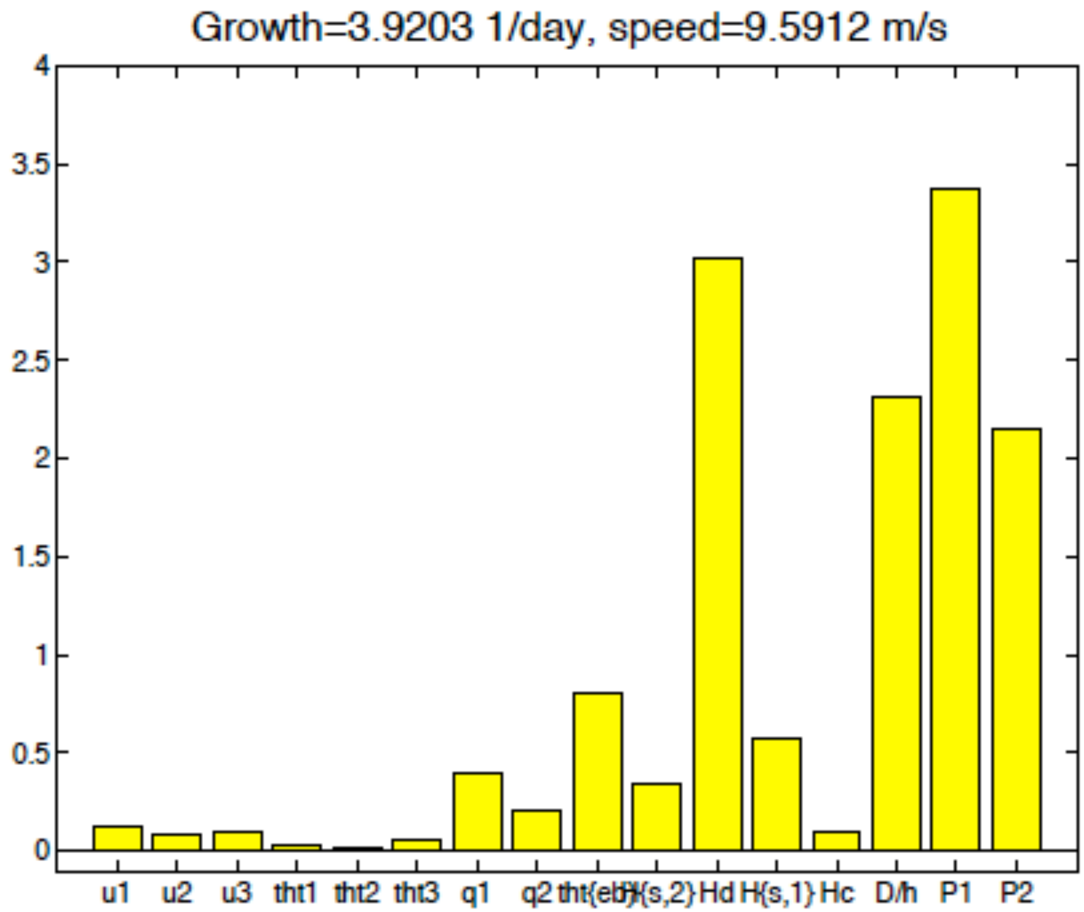


- Cumulonimbus mode has 3rd baroclinic structure and extended stratifrom regions due to shear advection

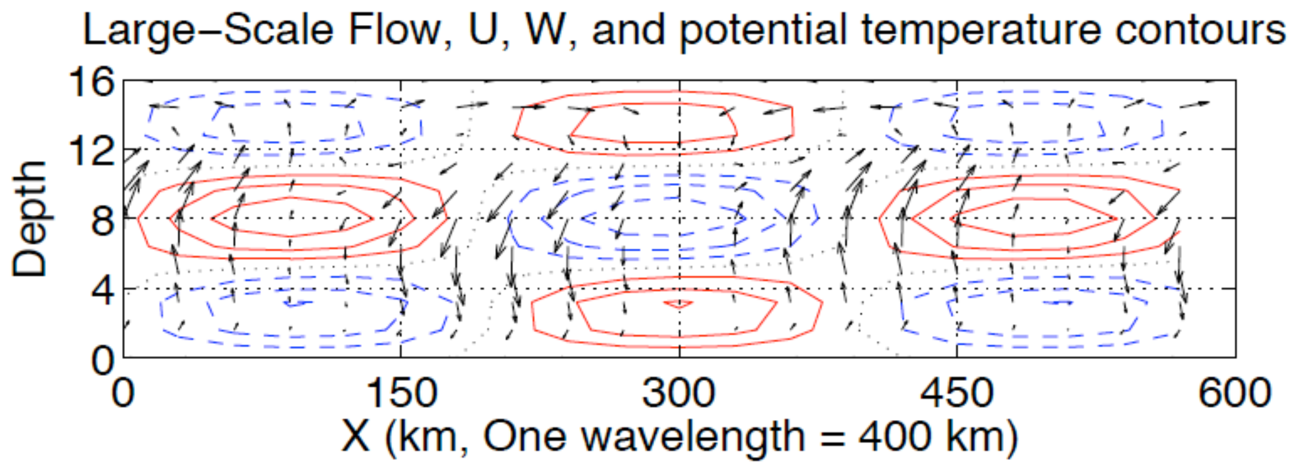




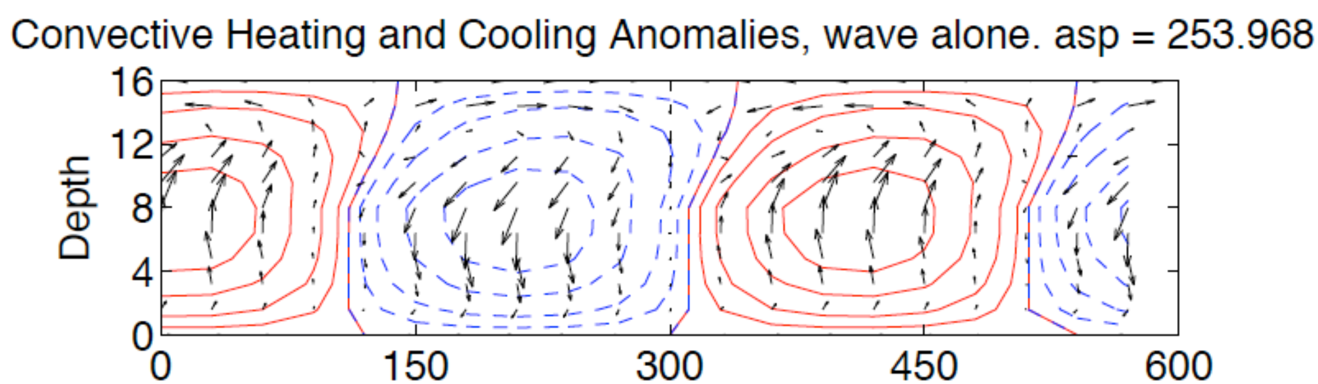
Meso-scale system mode



1) 3rd baroclinic, 3) Hs1>Hs2



Temperature has third baroclinic structure.
Not tiltted.



Wave moves in direction of near surface wind but tilted eastward according to easterly midlevel jet

Front Fed leading stratiform shear parallel system?

Discussion and conclusion

- A new moisture layer is added to the multicloud model to allow a separate closure for stratiform heating to mimic large-scale condensation
- Synoptic scale (linear) instability maintained and new stratiform extends nicely stratiform regions in the wake of deep convection + (cumulonimbus) mode instability appear at small scales
- Shear induces mesoscale waves with structure resembling "front fed leading stratiform MCS" (Parker and Johnson 2004)
- Presence of instability at both meso-alpha and meso-beta scale consistent with shear parallel MCS in Dudhia and Moncrieff (1987): Standing mesoscale system with embedded cumulonimbus elements!
- Preliminary results, parameter sensitivity needed in order to fully understand model physics. Nonlinear simulations underway.
- Goal is parameterization of MCS's in GCM, namely, CMT