Momentum Transport and Multiscale Interactions of Tropical Waves

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Outline

- Motivation
- The multicloud model
- Parametrization of mesoscale CMT
- Multiscale waves in MJO background

Satellite Observations: OLR

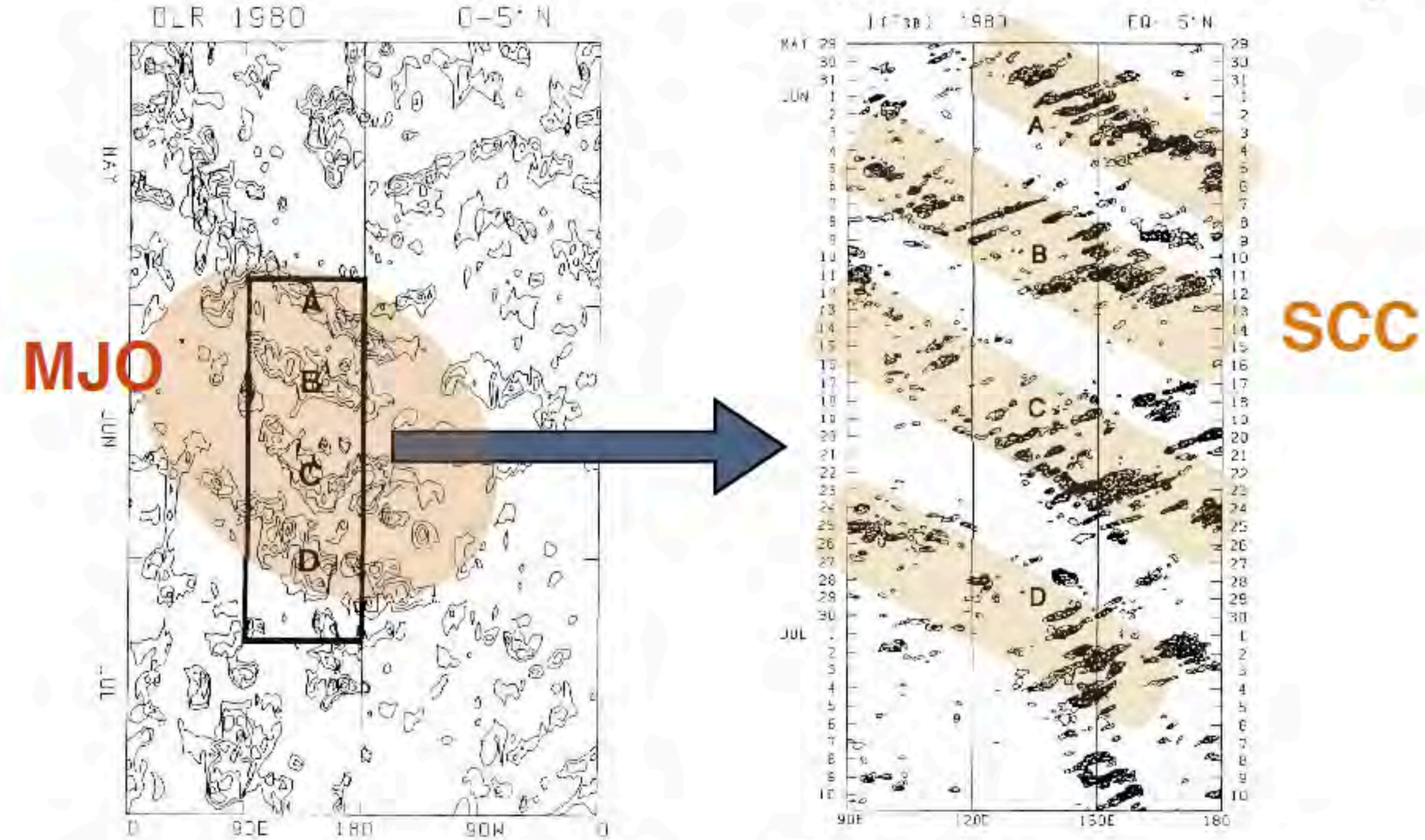
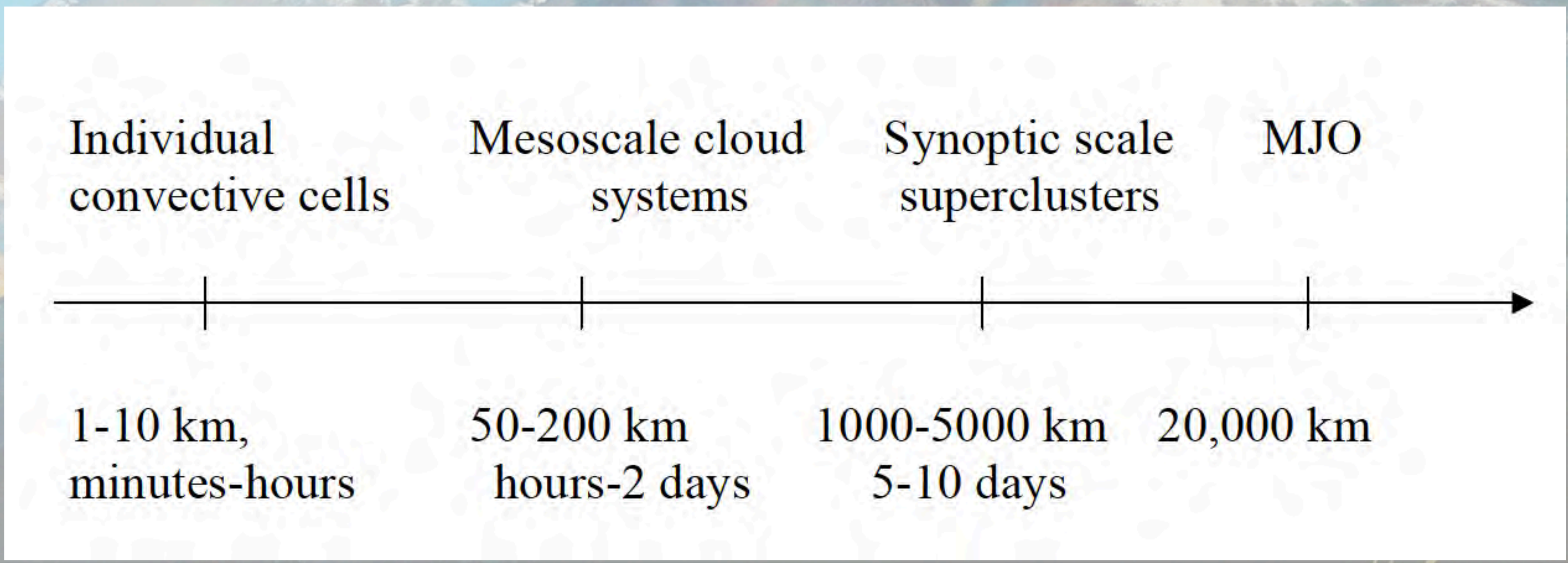


Fig. 1: MJO consists of Super Cloud Clusters (Nakazawa, 1988)

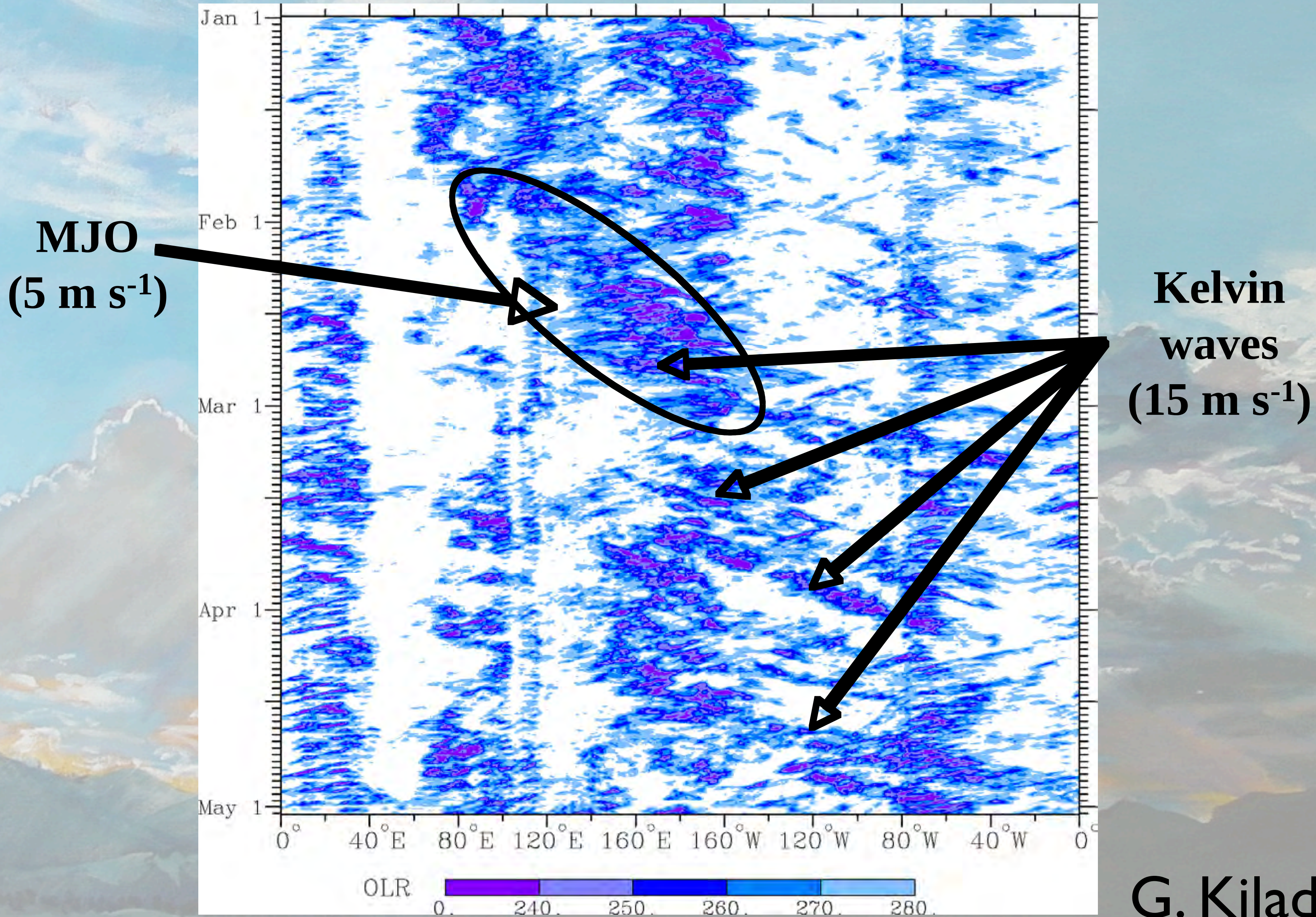
Multiscale convective systems

- Dominant tropical variability is associated with multiscale convective cloud systems
- Which involves propagating waves that are embedded in each other
- Influence on tropical rainfall and climate and weather patterns in both the tropics and extra-tropics



OBSERVATIONS OF KELVIN WAVES AND THE MJO

Time–longitude diagram of CLAUS Tb (2.5S–7.5N), January–April 1987



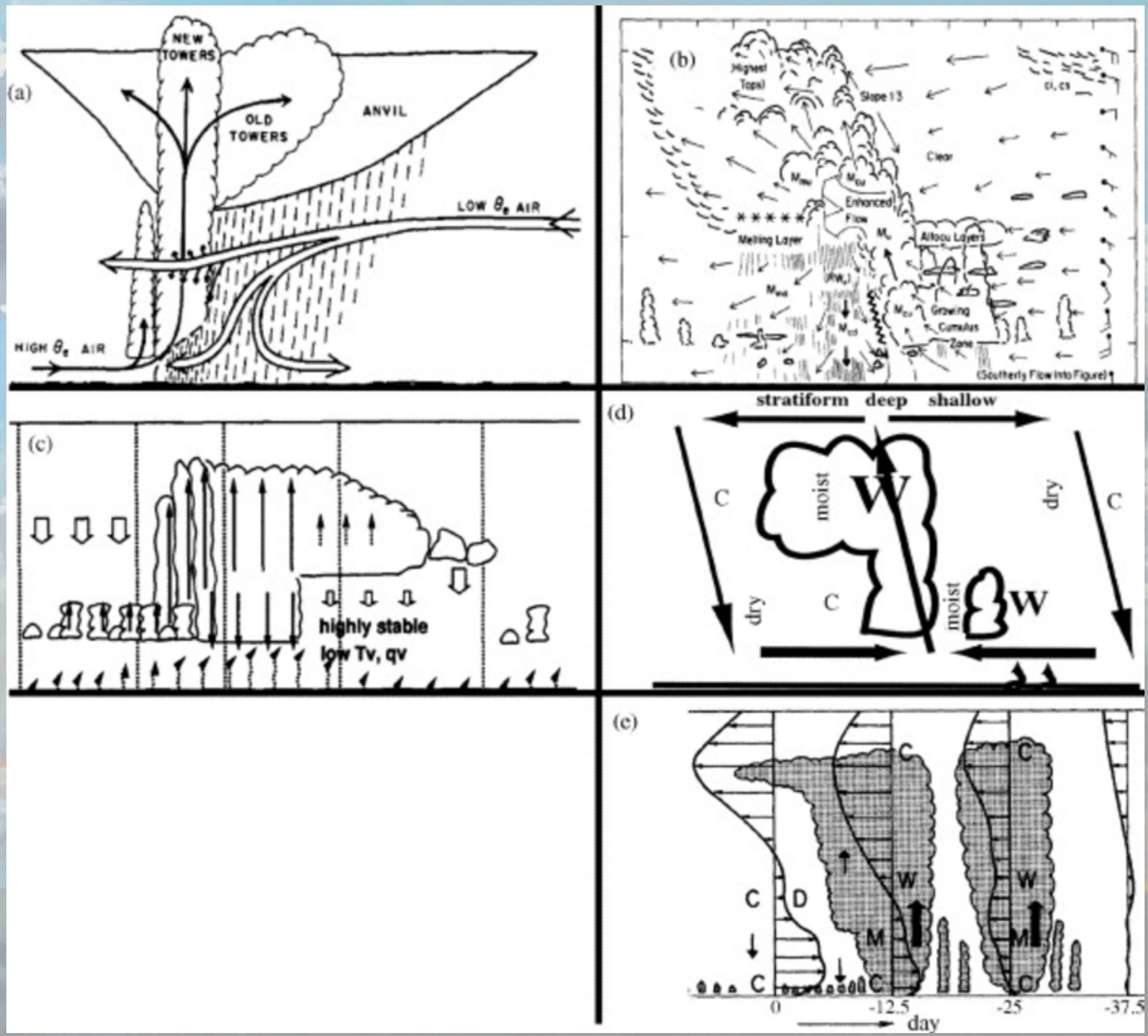
G. Kiladis

Self-similar structure of organized convection based on three cloud types: congestus, deep, and stratiform

Squall lines

C.C.W.

M.J.O.



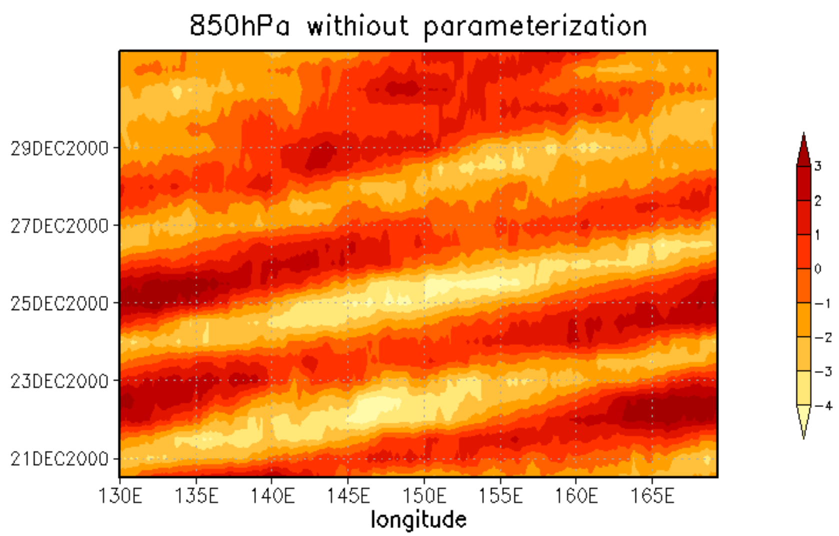
Compiled by Mapes et al. DAO. 2006

Evidence of upscale transport in a WRF simulation of a CCW

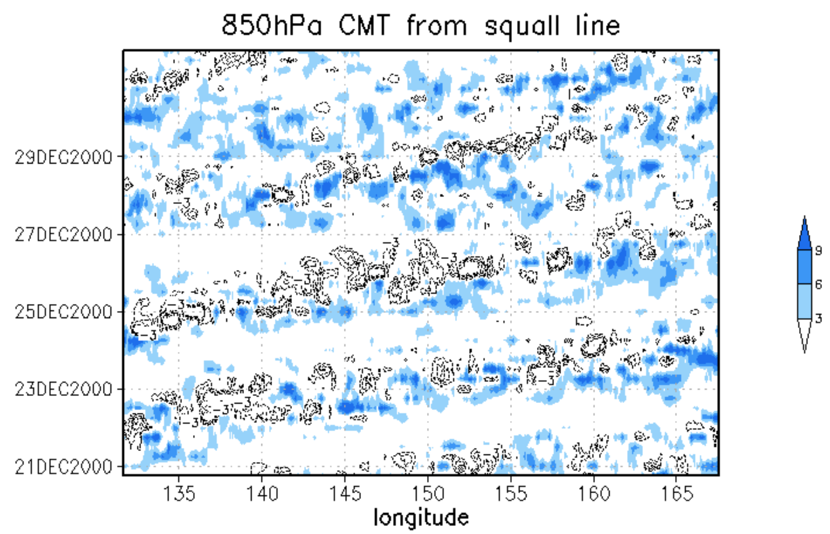
$L = 50$ km

$$u = \bar{u} + u'$$

$$\overline{f(x,y)} = \frac{1}{4L^2} \int_{x-L}^{x+L} \int_{y-L}^{y+L} f(x', y') dx'\, dy'$$



4500 km



$$\overline{\langle u'w' \rangle_z}$$

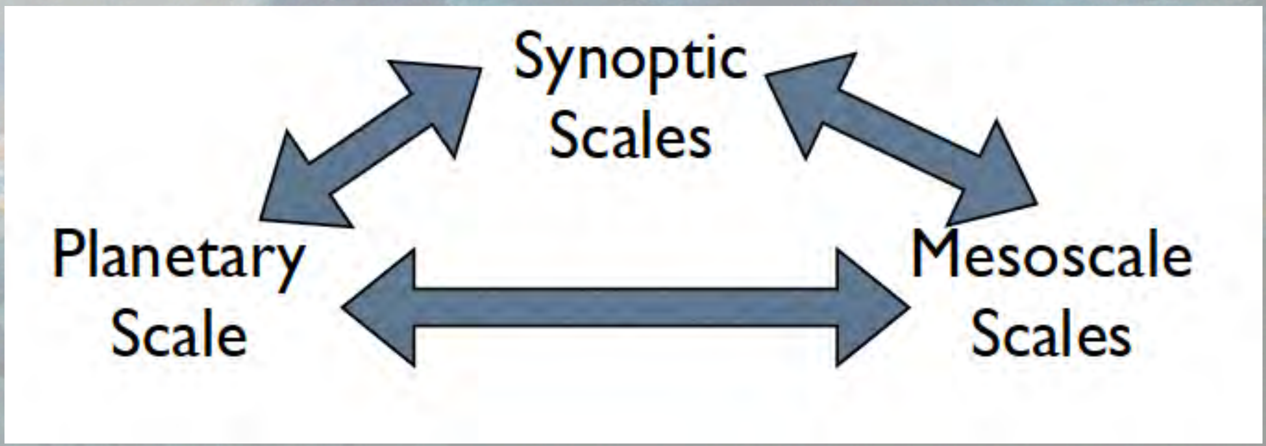
Interactions across scales

Zonal Momentum Equation: $u_t + \vec{V} \cdot \nabla u - fv = -p_x$

$u = \bar{u} + u'$; Wave envelope + embedded waves

$$\bar{u}_t + \bar{\vec{V}} \cdot \nabla \bar{u} - f\bar{v} = -\bar{p}_x - \overline{(u'w')_z} + \bar{S}$$

$$u'_t + \bar{\vec{V}} \cdot \nabla \bar{u}' + \vec{V}' \cdot \nabla \bar{u} + \vec{V}' \cdot \nabla u' - f\bar{v}' = -\bar{p}'_x$$



Cumulus parametrization

- On a GCM grid cell of 100-200 km, convection is a subgrid process--represented by cumulus parametrizations
- Superclusters are moist analogues of the equatorially trapped waves (Takayabu 1994, Wheeler & Kiladis 1999)--convectively coupled equatorial waves.
- GCMs perform poorly with regards to the MJO and superclusters due to inadequate treatment of organized convection (and mesoscale systems).
- Multicloud model (K. and Majda) has realistic convectively coupled waves and simulated MJO; next generation NCAR GCM at 170 km resolution.

Parametrization of CMT in GCMs

✦Convective clouds not only release latent heat from condensation and vertically redistribute heat and moisture but also transport momentum.

✦ Observational and numerical studies show that kinetic energy may be transferred from convection, via CMT, to large scales (LeMone 1983; Wu and Moncrieff 1996; Tung and Yanai 2002a,b, etc.).

✦The parameterization of upscale effect of CMT has been a challenging problem for a long time

✦ Convective momentum transport is not included in many GCMs. The inclusion of CMT improves mean climate (Zhang and Cho 1991, Lin et al. 2006, 2008).

✦ Majda and Stechmann (2008) proposed a stochastic model for mesoscale CMT with low computational overhead, focusing on squall lines--based on observations.

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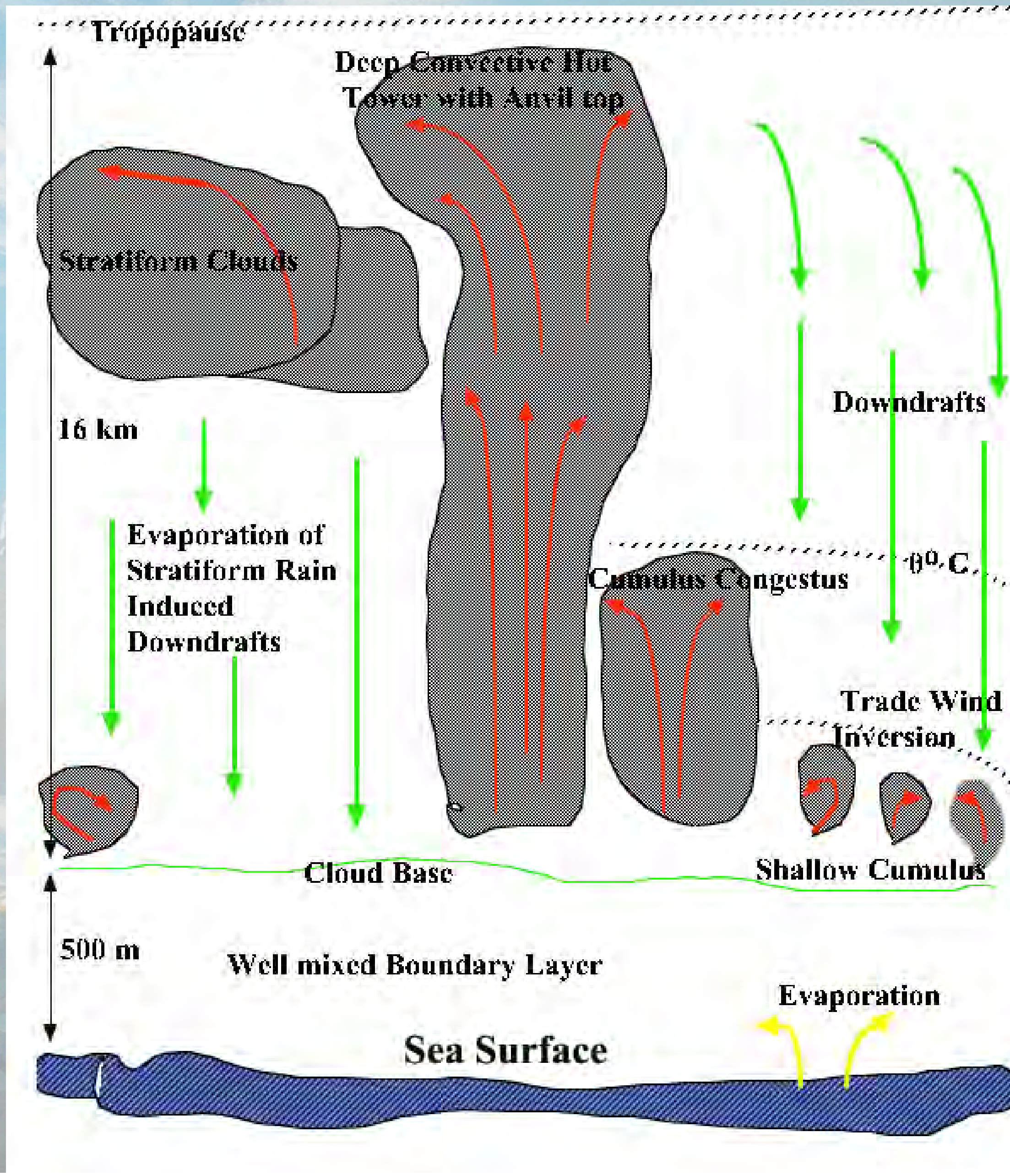
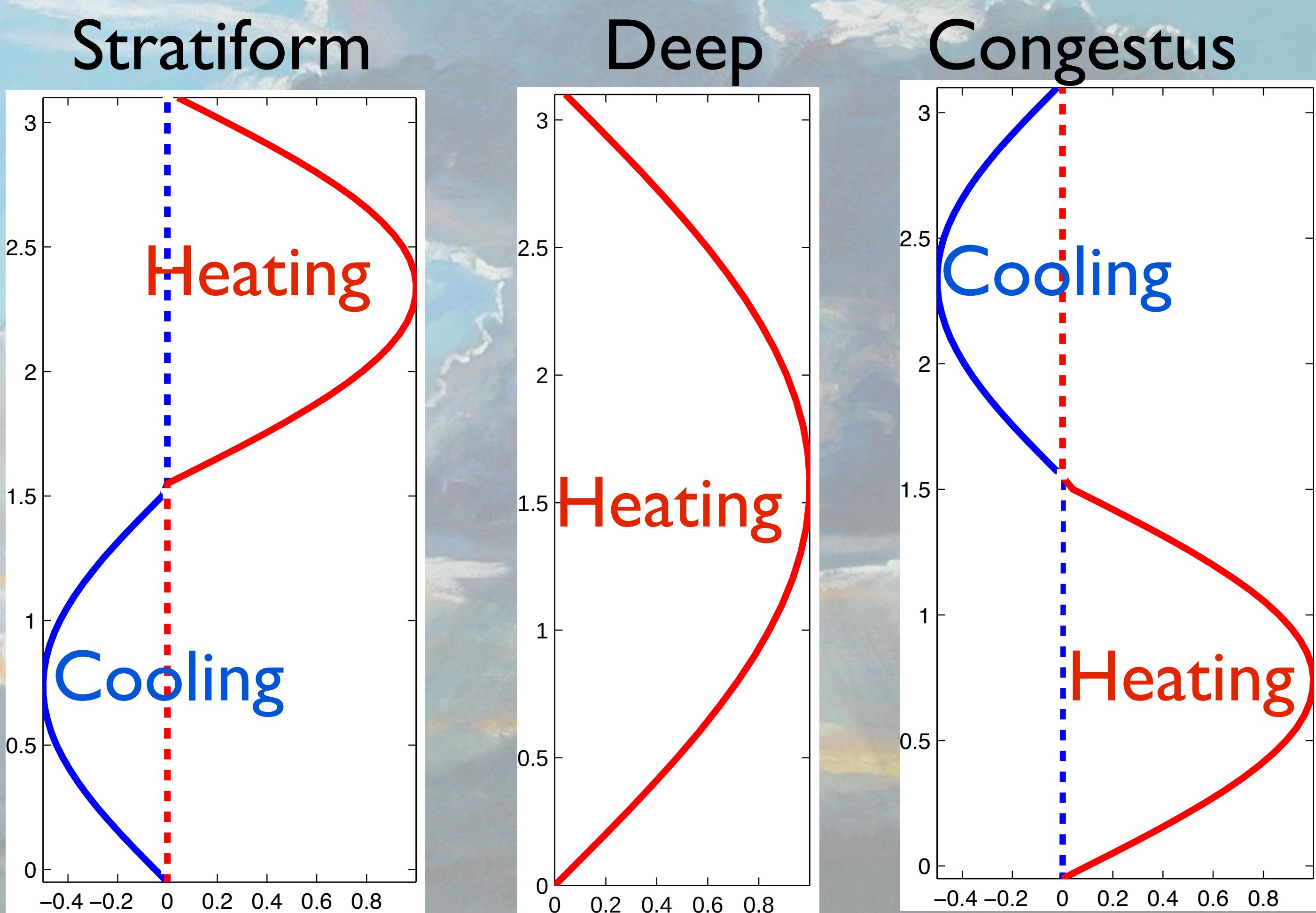
Cartoon View of The Multicloud Model



The multicloud model



The multicloud model dynamics

- Based on three cloud types, congestus, deep, and stratiform
- Dry lower troposphere favors congestus clouds while moist lower troposphere favors deep convection
- Stratiform clouds lag deep convection
- Associated heating profiles force the first two baroclinic modes of vertical structure
- MC Model is coupled to the boundary layer and to a vertically averaged moisture equation
- Momentum transport due to unresolved organized convection is not included

- Horizontal Velocity:

$$\mathbf{V} = \bar{\mathbf{U}} + \sqrt{2}\cos\left(\frac{\pi z}{H_T}\right)\mathbf{v}_1 + \sqrt{2}\cos\left(\frac{2\pi z}{H_T}\right)\mathbf{v}_2$$

- Vertical velocity:

$$w = -\frac{H_T}{\pi}\sqrt{2}\left[\sin(\frac{z\pi}{H_T})\ \mathrm{div}\ \mathbf{v}_1 + \frac{1}{2}\sin(\frac{2\pi z}{H_T})\ \mathrm{div}\ \mathbf{v}_2\right]$$

- Potential temperature:

$$\Theta = z + \sqrt{2}\sin(\frac{\pi z}{H_T})\ \theta_1 + 2\sqrt{2}\sin(\frac{2\pi z}{H_T})\theta_2.$$

- Tropospheric dynamics

1st Mode
$$\begin{cases} \dfrac{\bar{d}\mathbf{v}_1}{dt} + \beta y \mathbf{v}_1^\perp - \nabla\theta_1 = -C_d(u_0)\mathbf{v}_1 - \dfrac{1}{\tau_R}\mathbf{v}_1 \\ \dfrac{\bar{d}\theta_1}{dt} - \operatorname{div}\mathbf{v}_1 = H_d + \xi_s H_s + \xi_c H_c + S_1 \end{cases}$$

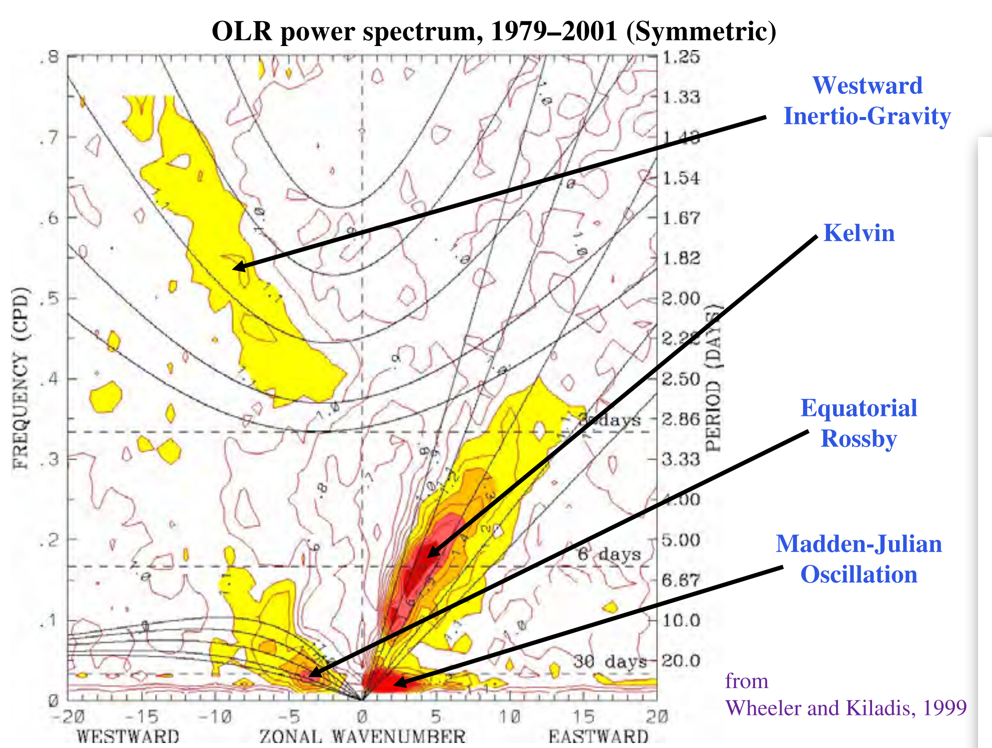
2nd Mode
$$\begin{cases} \dfrac{\bar{d}\mathbf{v}_2}{dt} + \beta y \mathbf{v}_2^\perp - \nabla\theta_2 = -C_d(u_0)\mathbf{v}_2 - \dfrac{1}{\tau_R}\mathbf{v}_2 \\ \dfrac{\bar{d}\theta_2}{dt} - \dfrac{1}{4}\operatorname{div}\mathbf{v}_2 = (-H_s + H_c) + S_2 \end{cases}$$

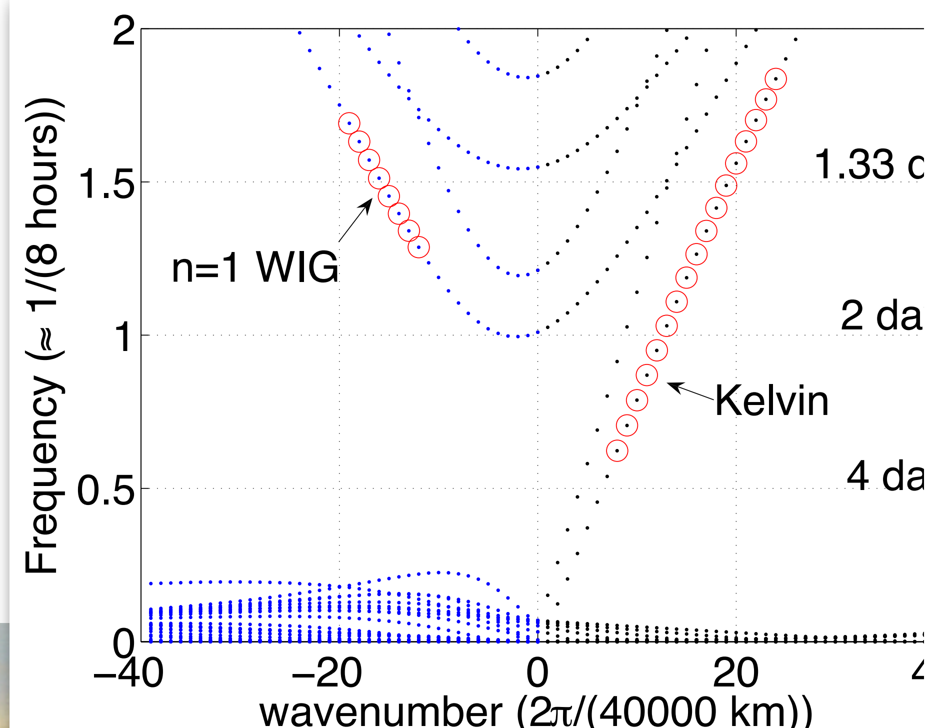
- Moisture Eqn: $P = \dfrac{2\sqrt{2}}{\pi}(H_d + \xi_s H_s + \xi_c H_c)$

$$\frac{\bar{d}q}{dt} + \operatorname{div}\left[(\mathbf{v}_1 + \tilde{\alpha}\mathbf{v}_2)q + \tilde{Q}(\mathbf{v}_1 + \tilde{\lambda}\mathbf{v}_2)\right] = -P + \frac{D}{H_T}$$

- Boundary layer: $\dfrac{\partial\theta_{eb}}{\partial t} = \dfrac{1}{h_b}(E - D)$

Multicloud Model qualitatively the observed wave spectrum of convectively coupled equatorial waves including the MJO





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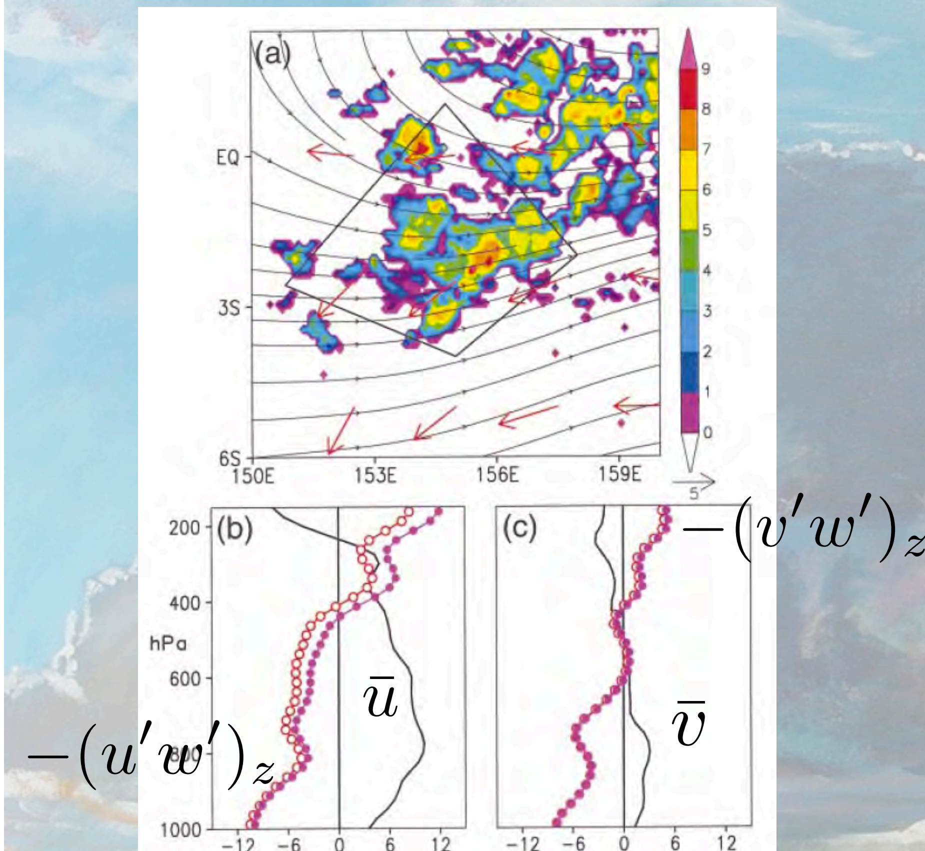
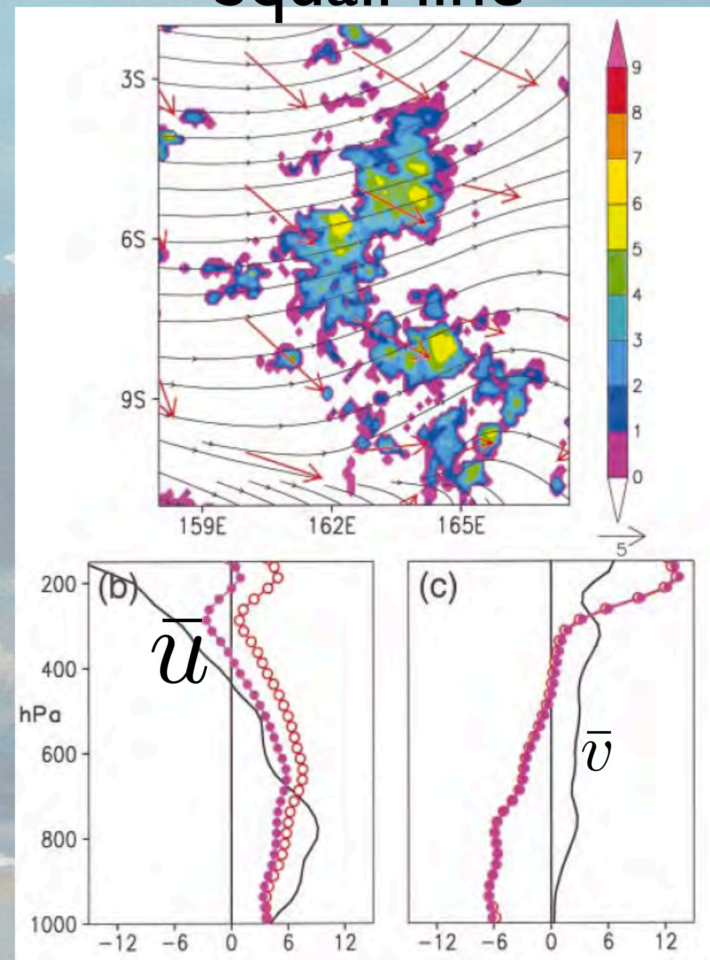
Observation of Tung and Yanai (2002)

Non-squall MCS



Squall line



Deceleration--cumulus friction

Acceleration of u

Note baroclinic Structure

Parametrization of mesoscale CMT

- Grid scale (zonal) momentum equation

$$\bar{u}_t + \bar{u}\bar{u}_x + \bar{v}\bar{u}_y + \bar{w}\bar{u}_z - f\bar{v} = -\bar{p}_x - \overline{(u'w')_z} + S_u$$

- Majda and Stechmann used a stochastic Markov jump process that transits between upright convection and squall line regimes according to background shear.
- CMT is upscale during the squall line regime and downscale during upright convection regime
- Here we use the mean-field approach with exponential-form distribution between regimes instead of the stochastic model

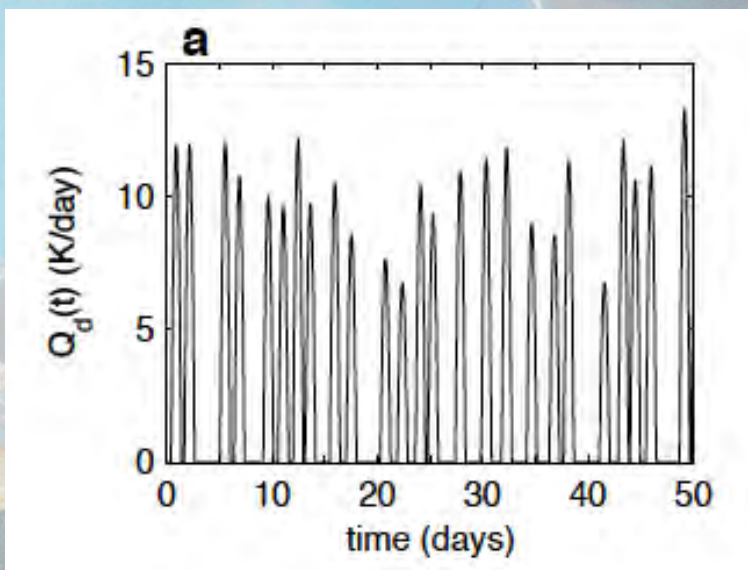
Column model

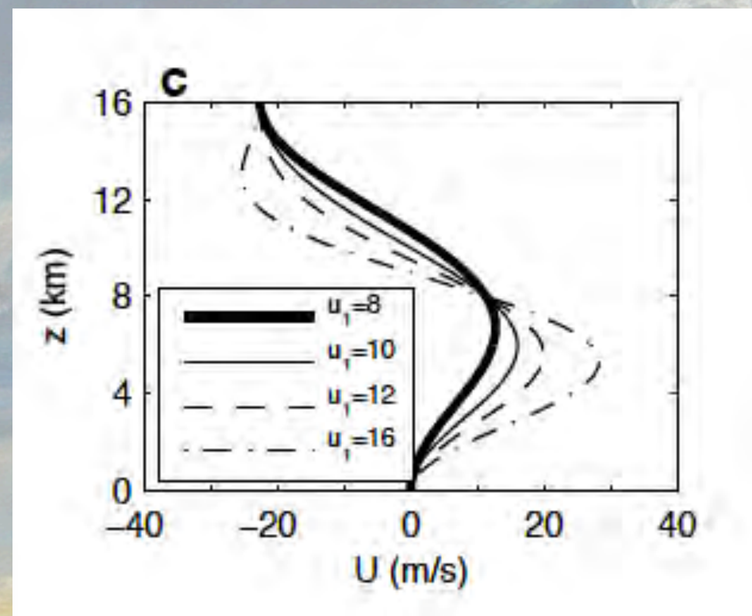
$$\frac{\partial u}{\partial t} = F_{CMT}$$

initially:

$$u_1 = 10\ m/s, u_2 = 10\ m/s; u_3 = 0;$$

Prescribed random heating





Stochastic CMT model; Majda and Stechmann (2008)

The ``mean field'' CMT model

- Strong baroclinic wind environment enhance formation of large stratiform anvils lagging deep convection (Lin and Mapes, 2000) resulting in mesoscale convective systems tilted in the direction of upper-level wind

- Tilted structures induce acceleration of wind in opposite direction at low-level

- In suppressed conditions, we have cumulus friction

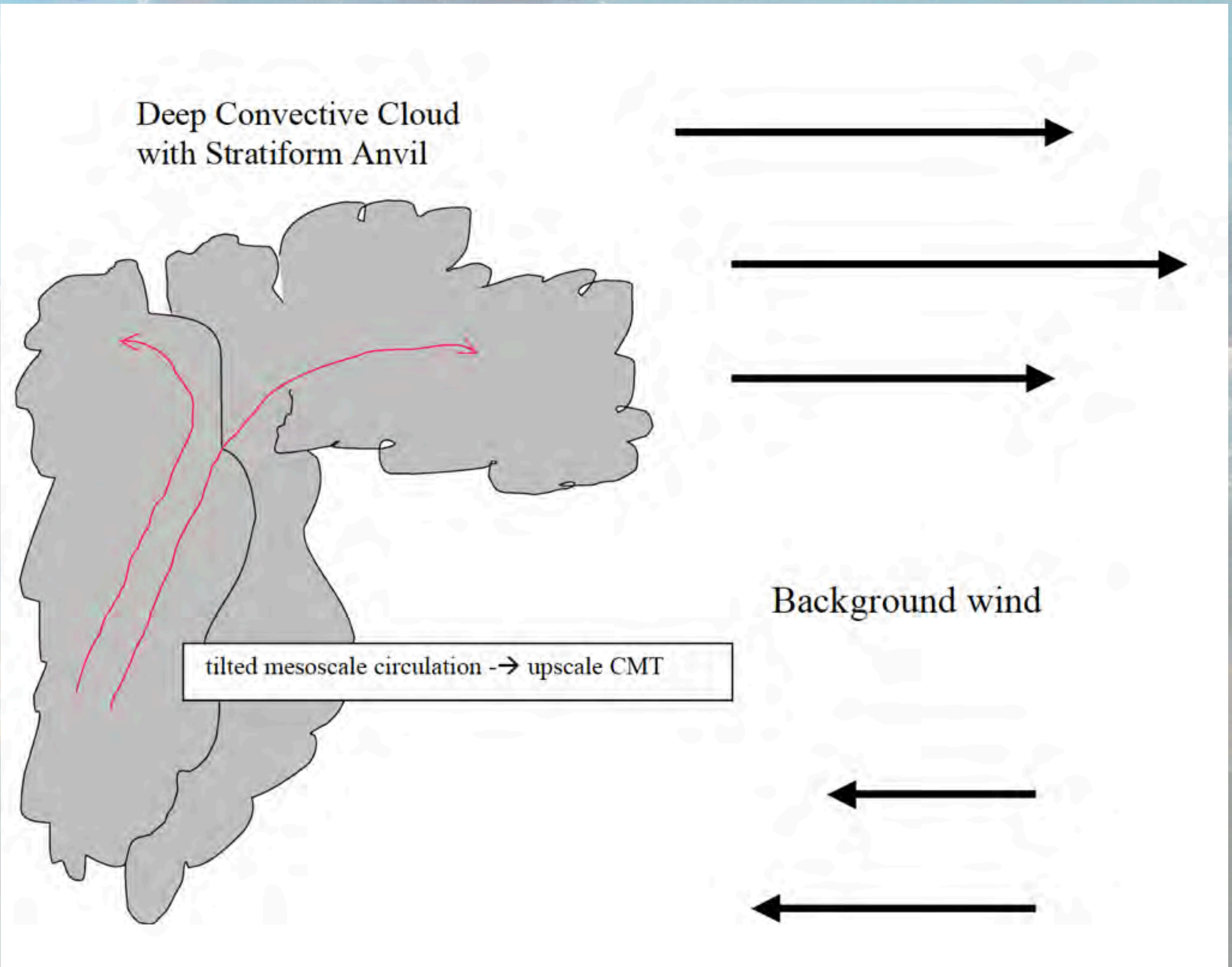
$$\partial_t V + V \cdot \nabla V + \beta y V^{\perp} = -\nabla P + F_{CMT}$$

$$F_{CMT} = -(1 - e^{-V_T/V^*}) d(V - V_0) + e^{-V_T/V^*}(-(V'w')_z)$$

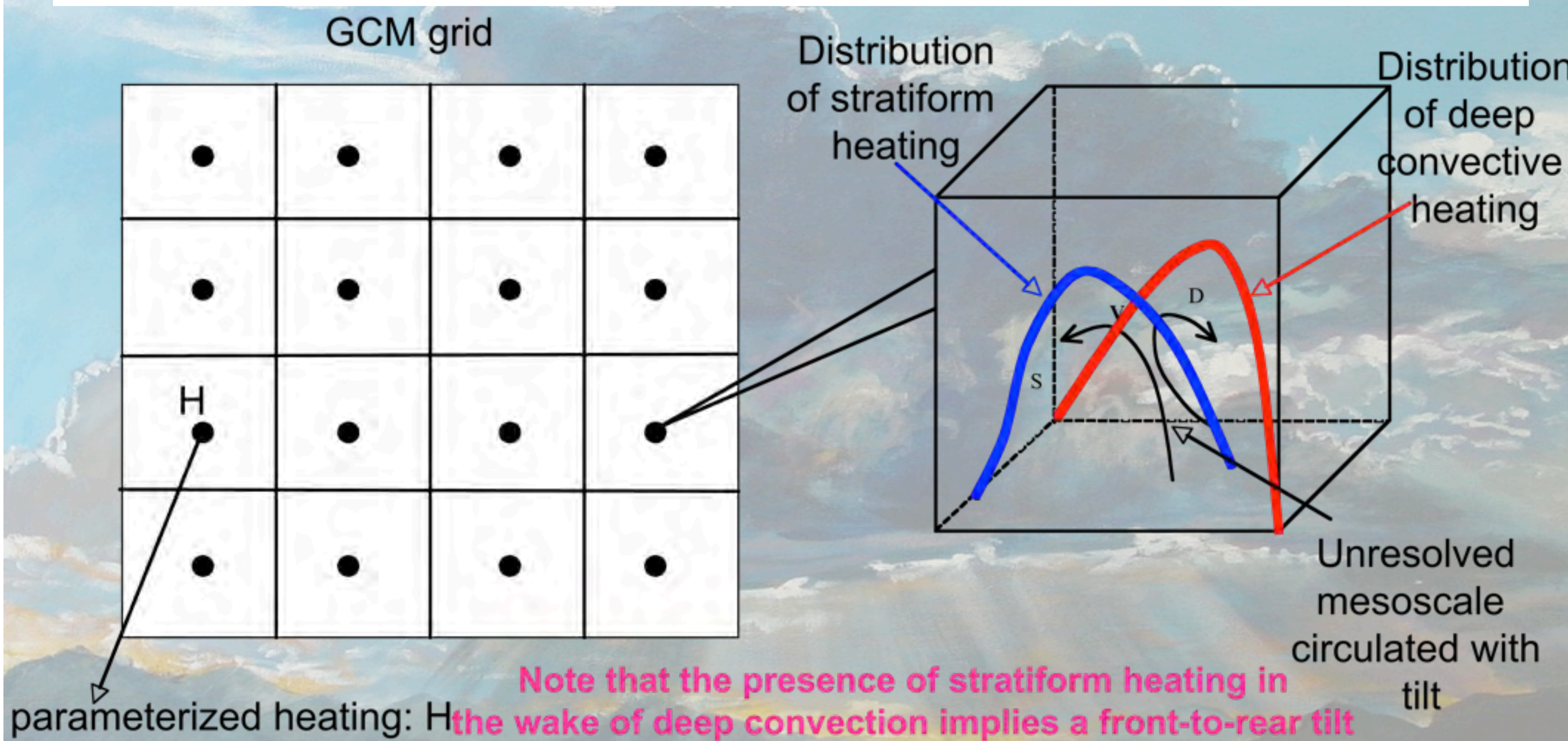
$V_T =$ wind strength in the upper troposphere
$V^* = 2$ m/s; typical turbulence scale
$d = 3$ days; damping rate

Mesoscale circulation model

Parametrized deep heating is extended with stratiform anvil in the direction of upper level shear



Parametrized deep convective heating is extended to include a stratiform anvil and redistributed within GCM grid-box to induce a sub-grid circulation



Note that the presence of stratiform heating in the wake of deep convection implies a front-to-rear tilt of the implied mesoscale circulation which is important for CMT. Without the tilt , CMT is zero

- Weak-Temperature Gradient at mesoscale (Majda 2007)

$$w = D\sin(z) + S\left(\sin(z) - \frac{\sin(2z)}{2}\right)$$

- Potential Flow

$$u' = \Phi_x(x,y,z), \quad v' = \Phi_y(x,y,z), \quad \Phi_{xx} + \Phi_{yy} = -w_z$$

$$D = \frac{H}{\sigma^2} e^{-(x^2+y^2)/2\sigma^2}; S = \frac{\alpha H}{\sigma_v^2} e^{-((x-L)^2+y^2)/\sigma_v^2};$$

x is the coordinate in wind direction

$\sigma = 75$ km $\quad \sigma_v = 1.5\sigma e^{V_T/V} \quad L = V_T\tau,\ \tau = 3$ hours

Mesoscale CMT flux

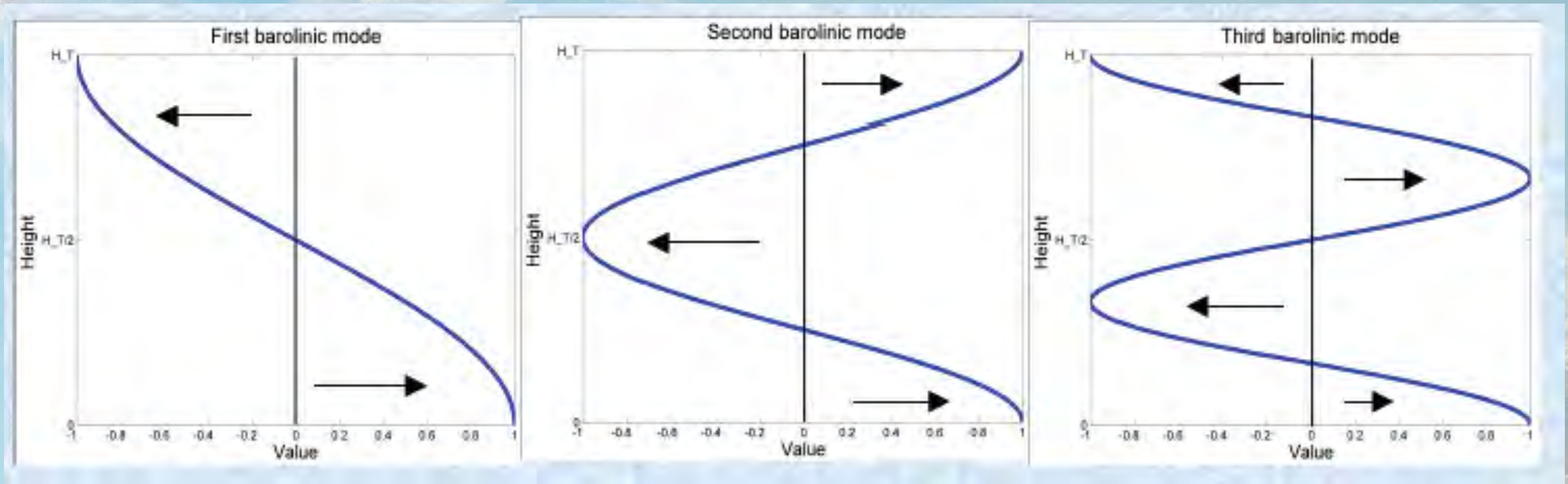
$$-(\overline{u_p'w'})_z \approx \frac{D_0^2\alpha}{L_*^2}\left[(\frac{G}{2\sigma^2}-\frac{F}{4\sigma_v^2})\cos z + \cancel{(\frac{G}{\sigma^2}+\frac{F}{\sigma_v^2})\cos 2z} - 3(\frac{G}{2\sigma^2}+\frac{F}{4\sigma_v^2})\cos 3z\right]$$

$$F = \sqrt{2\pi}\pi\sigma_v e^{\frac{-L^2}{2\sigma_v^2}}\left[e^{\frac{L^2}{4\sigma_v^2}} I_{1/2}(\frac{L^2}{4\sigma_v^2}) - \frac{1}{\sqrt{1+\sigma_v^2/\sigma^2}} e^{\frac{L^2}{4\sigma_v^2}\cdot(\frac{1}{1+\sigma_v^2/\sigma^2})} I_{1/2}(\frac{L^2}{4\sigma_v^2}\frac{1}{1+\sigma_v^2/\sigma^2})\right]$$

$$G = -\sqrt{2\pi}\pi e^{\frac{-L^2}{2\sigma^2}}\sigma\left[e^{\frac{L^2}{4\sigma^2}} I_{1/2}(\frac{L^2}{4\sigma^2}) - \frac{1}{\sqrt{1+\sigma^2/\sigma_v^2}} e^{\frac{L^2}{4\sigma^2}\cdot(\frac{1}{1+\sigma^2/\sigma_v^2})} I_{1/2}(\frac{L^2}{4\sigma^2}\frac{1}{1+\sigma^2/\sigma_v^2})\right]$$

- Mesoscale CMT forces 1st and 3rd baroclinic modes
- Horizontally uniform heating induces zero CMT
- Including stratiform downdrafts doubles CMT flux but doesn’t change its form

Effect of Mesoscale CMT on Background Wind

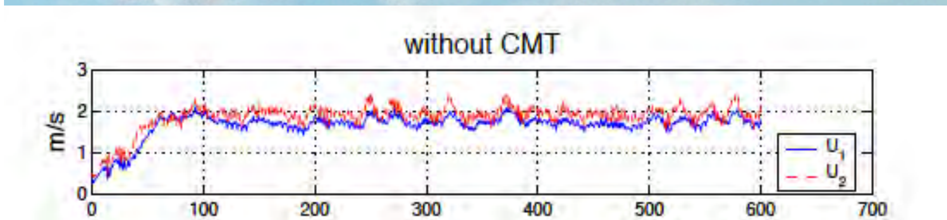


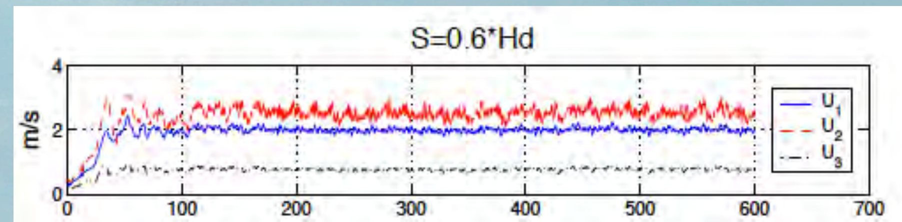
Accelerates U_1 Neutral on U_2 Decelerates U_3

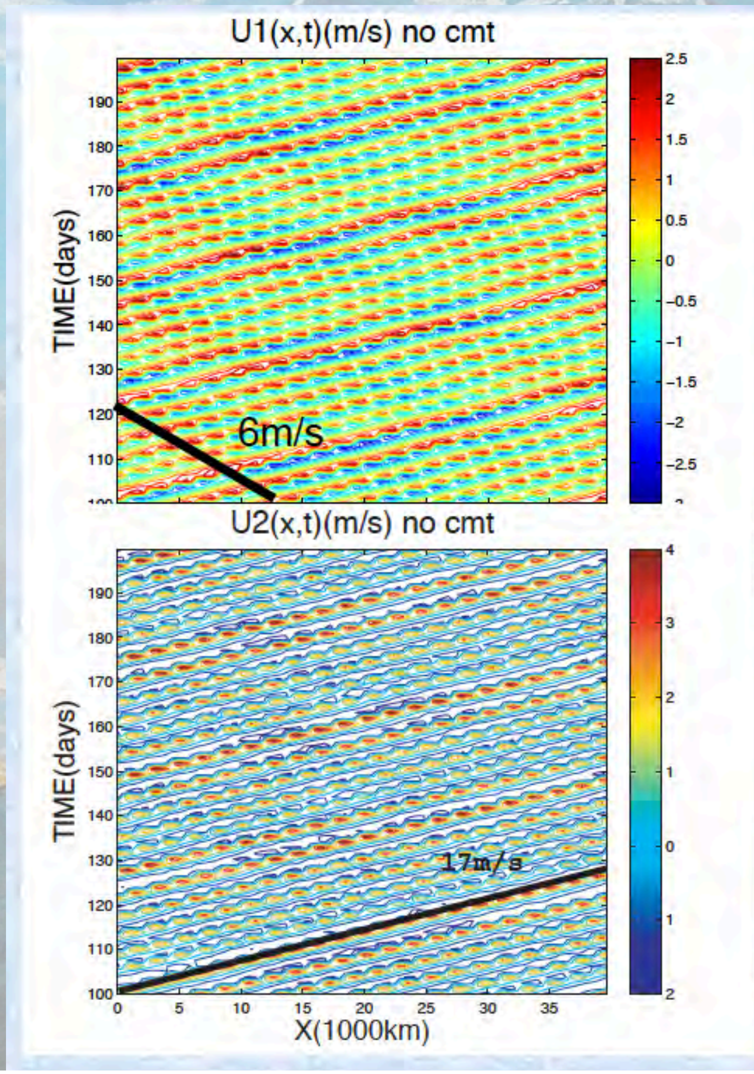
- This would create a low-level shear, which rises a chicken-and-egg problem
- Implies enhanced of lower tropospheric convergence which has an impact on convectively coupled waves

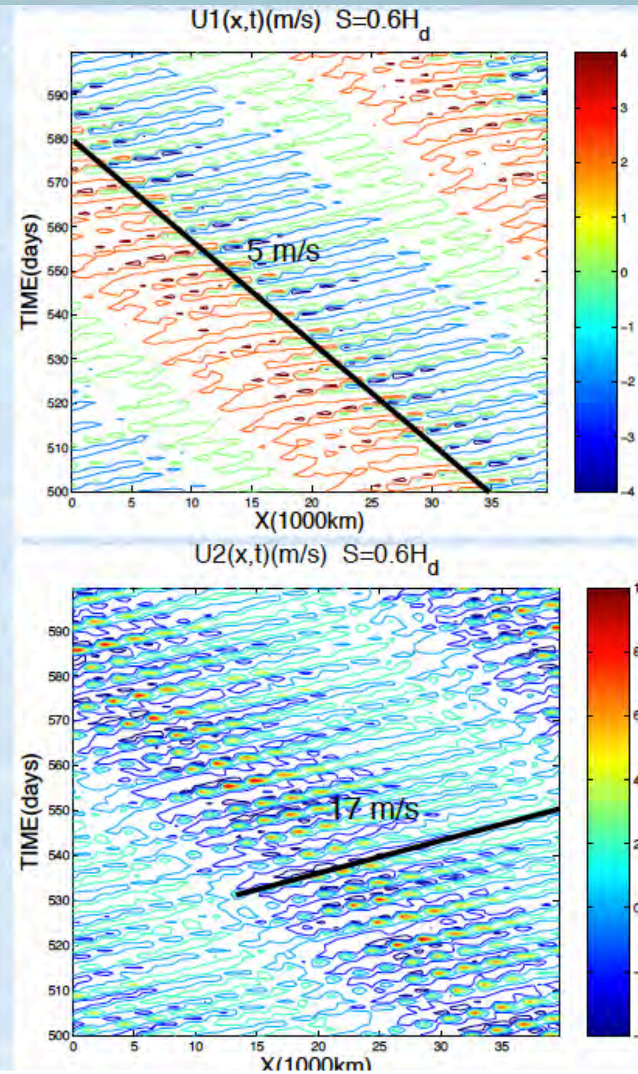
Without CMT

With Mesoscale CMT



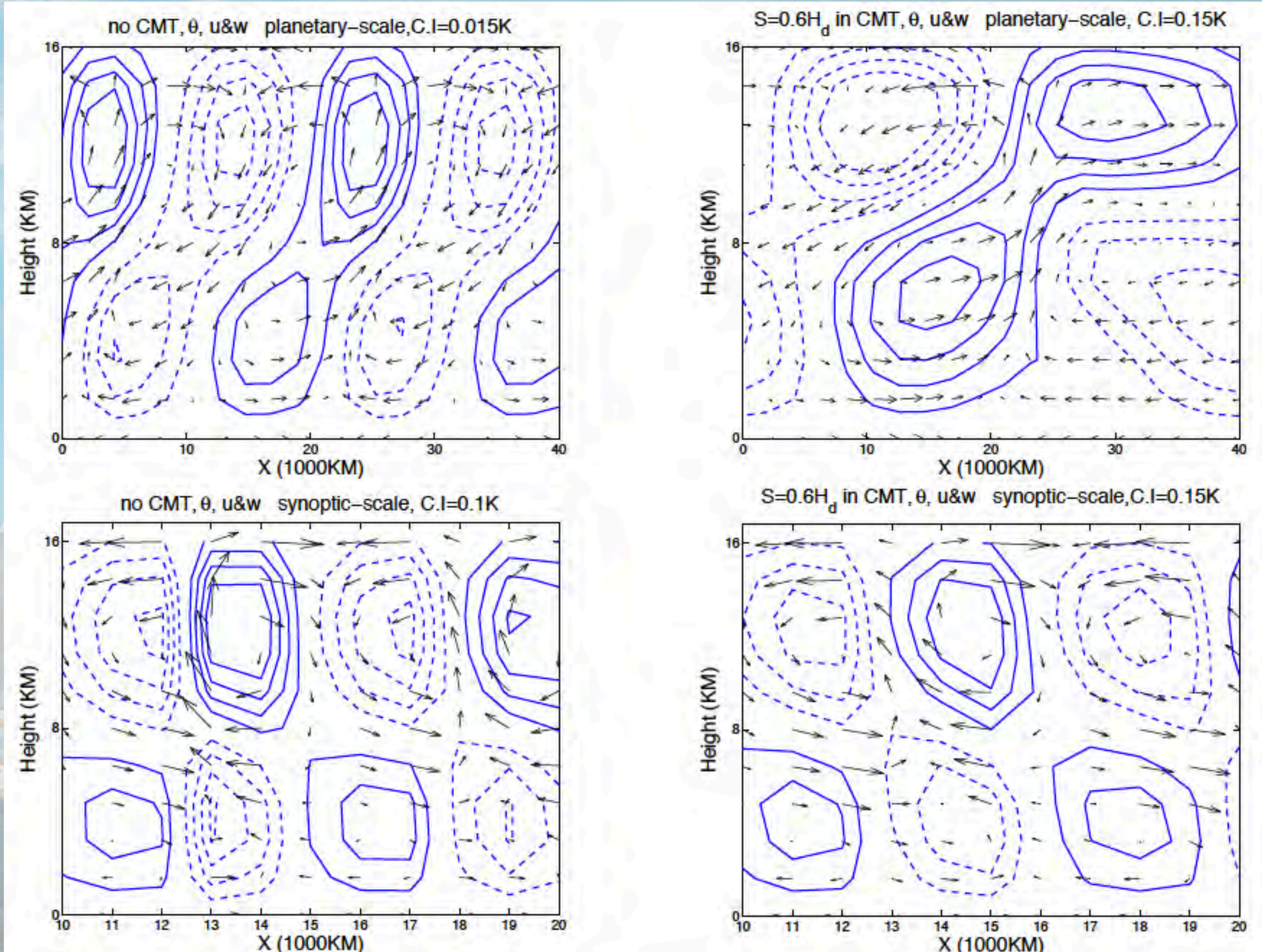






Without CMT

With Mesoscale CMT



Summary

- ✦ Mesoscale CMT intensifies convective organization at both synoptic and planetary scales--affects both amplitude and wavelength.
- ✦ Mechanisms at work are not well understood. One speculation would be that mesoscale CMT enhances low-level moisture convergence by strengthening low-level easterlies/westerlies in front/back of the wave.
- ✦ Key parameters are (1) threshold for large-scale shear that controls CMT forcing v.s. damping distribution function and the lag between stratiform anvils and deep convection, (2) strength of deep convection, and (3) third baroclinic moisture convergence (a pure CMT by-product).

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Multiscale waves in the MJO background

- Behaviour of convectively coupled waves within the MJO envelope
- Han and K. (2010) used two baroclinic mode approximation
- Synoptic wave CMT excites a third baroclinic velocity through CMT. What is the feedback of this 3rd mode on the waves?
- Majda and Stechmann 2009: Two-way interactions between background wind and waves in an asymptotic model both undergoing oscillations on the intra-seasonal time scales?

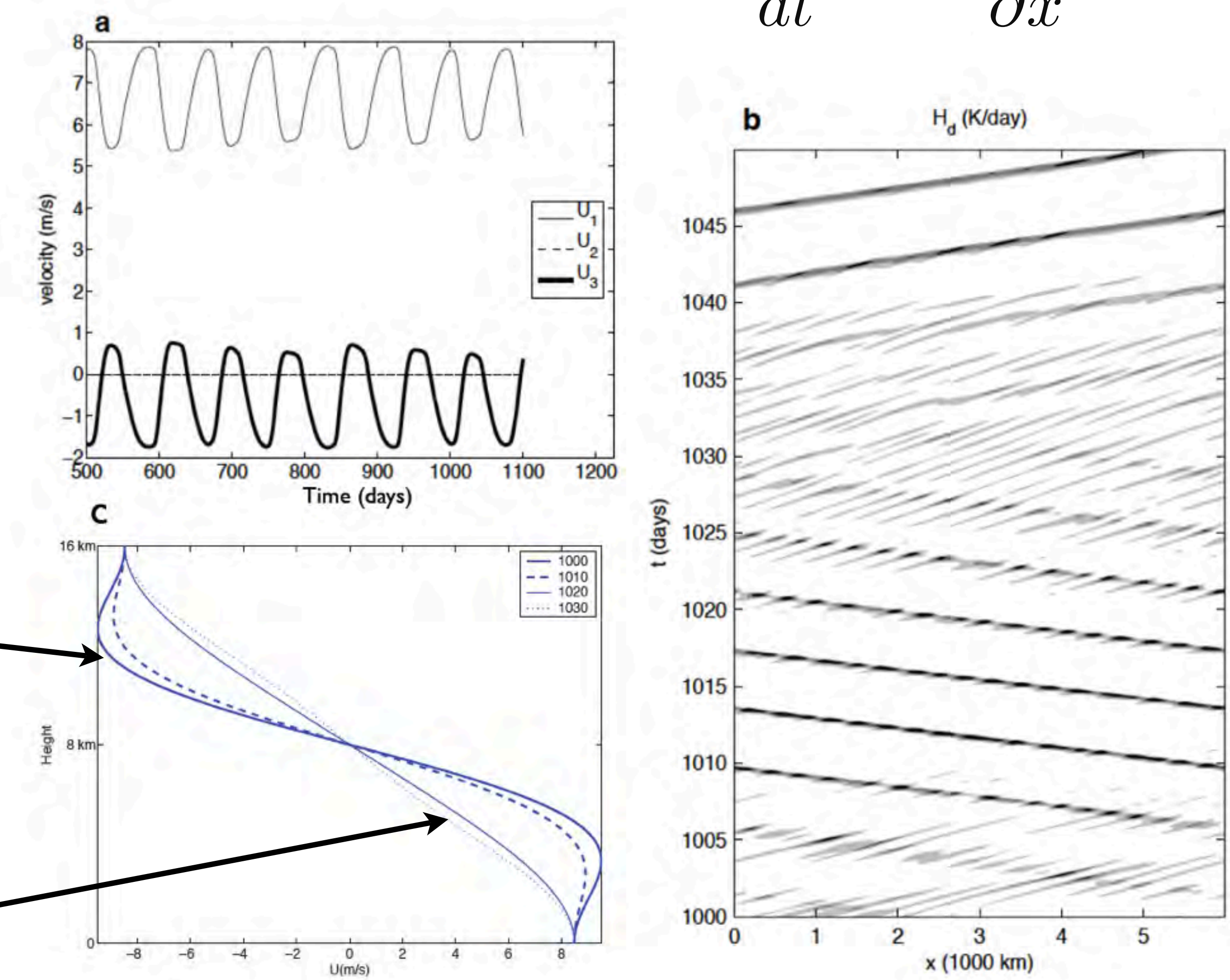
Asymptotic model of Majda and Stechmann (2009)

Multicloud model without rotation

$$u(x,y,z,t) = U(\epsilon^2 t, z) + \epsilon\, u'(x,y,z,t)$$

$$\frac{\partial U}{d\tau} = -(u'w')_z; \quad \tau = \epsilon^2 t;$$

$$\frac{\partial u'}{dt} + U\frac{\partial u'}{\partial x} + w'\frac{\partial U}{\partial z} + \cdots$$



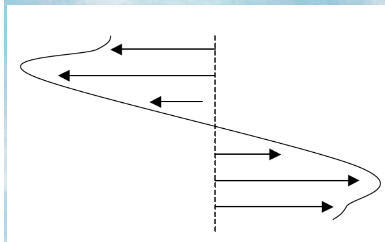
Favours Westward moving waves

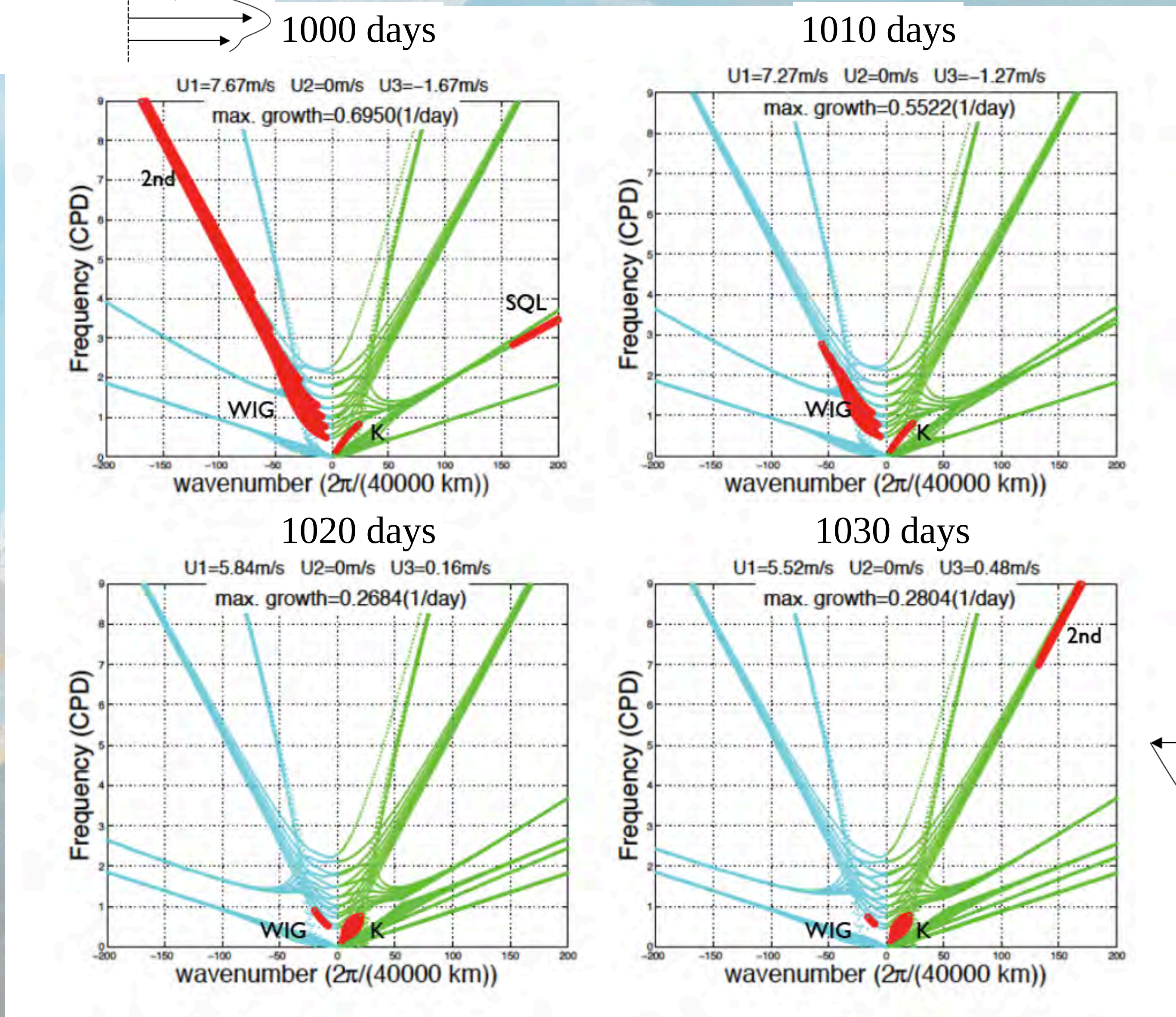
Favours Eastward moving waves

Accelerate low-level westerly shear

Decelerate low-level westerly shear

MS09 Background used to force beta-plane multicloud equations: WWB region of MJO

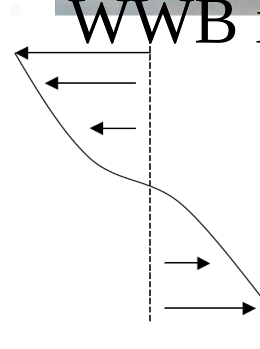




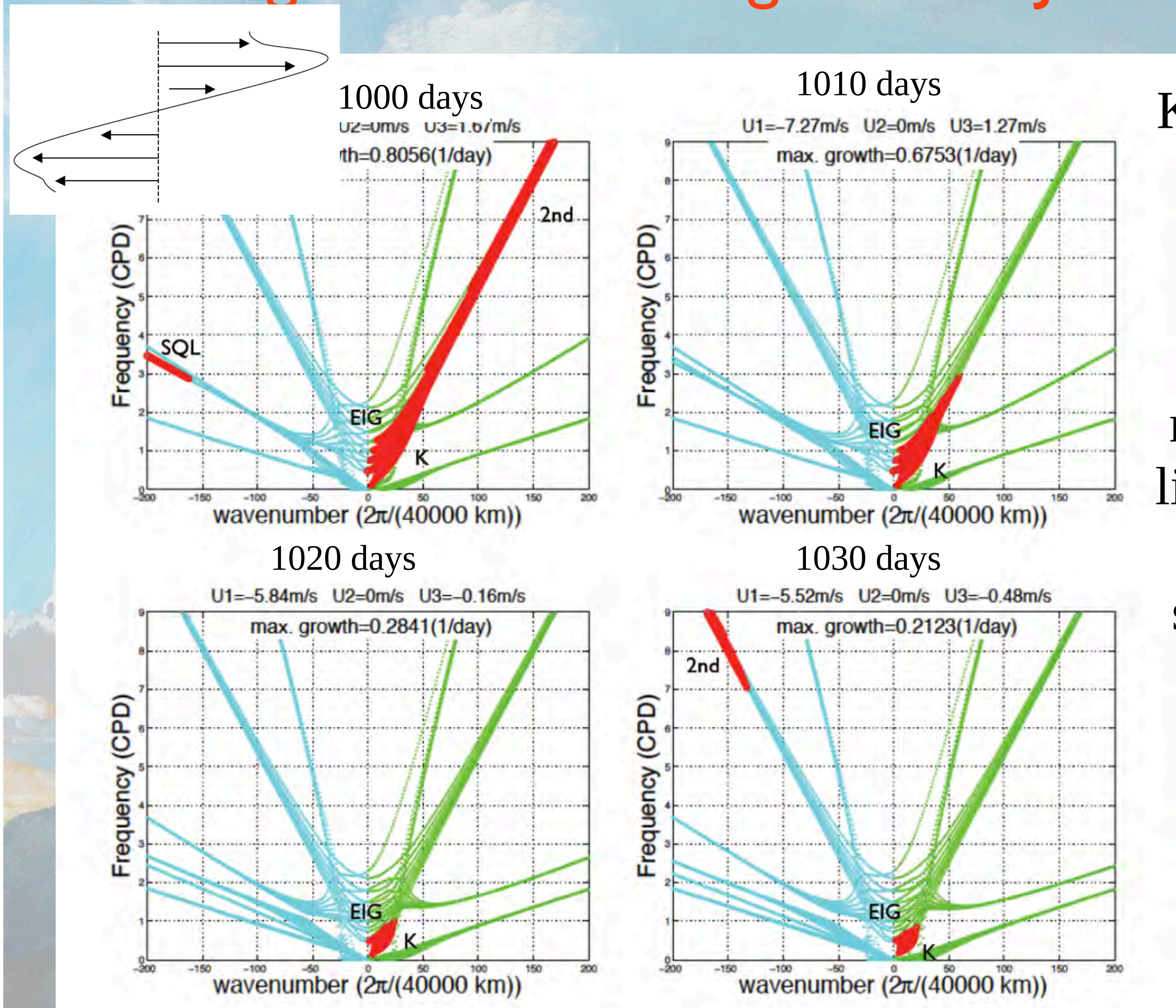
Results are consistent with rotation-less model.

Kelvin Waves when WWB is weak

WIG Waves and Westward Squall lines when WWB is strong



Inverting the MS09 Background: MJO onset region



Kelvin and EIG waves al the time.

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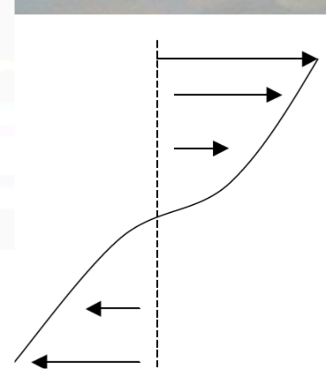
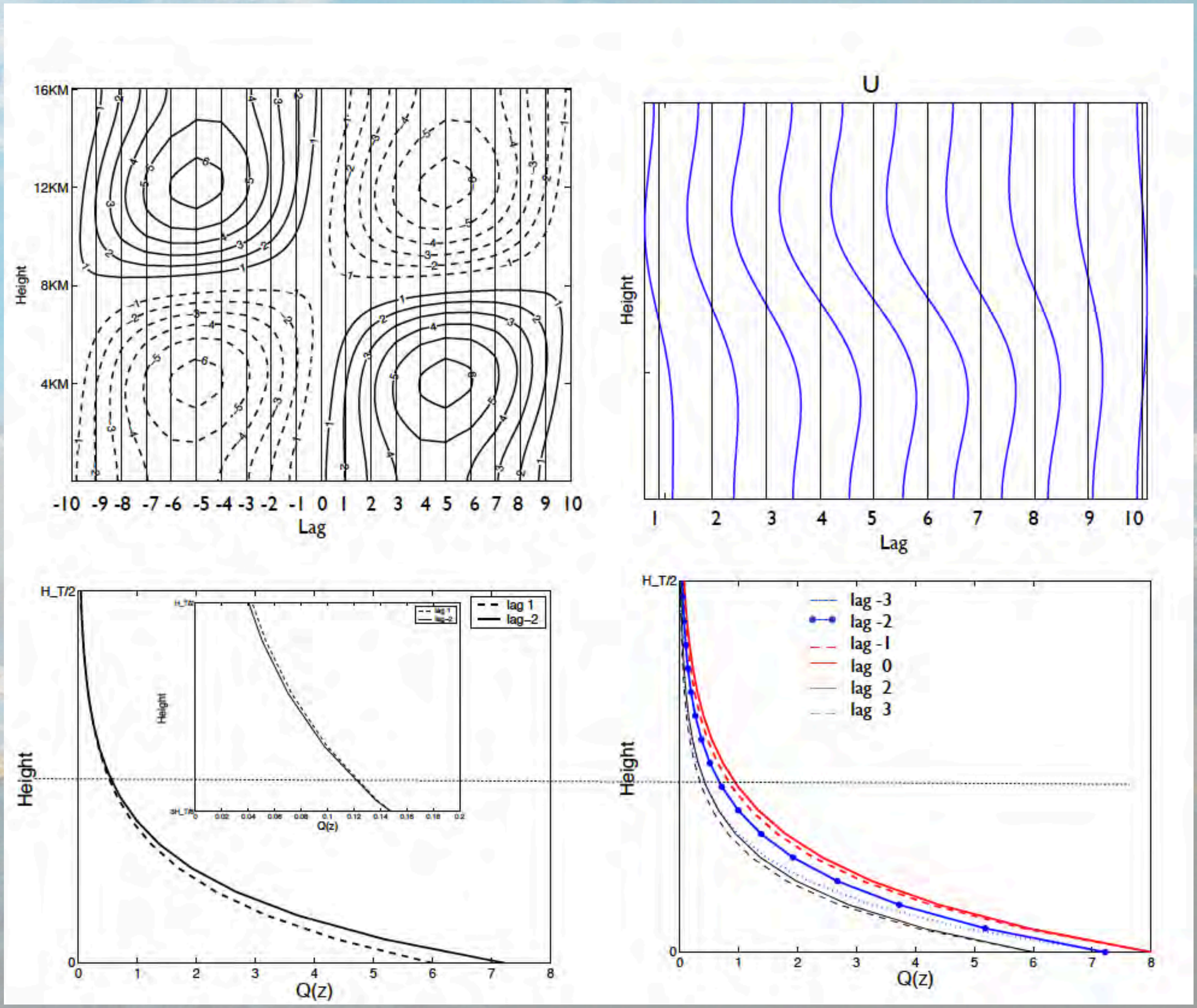
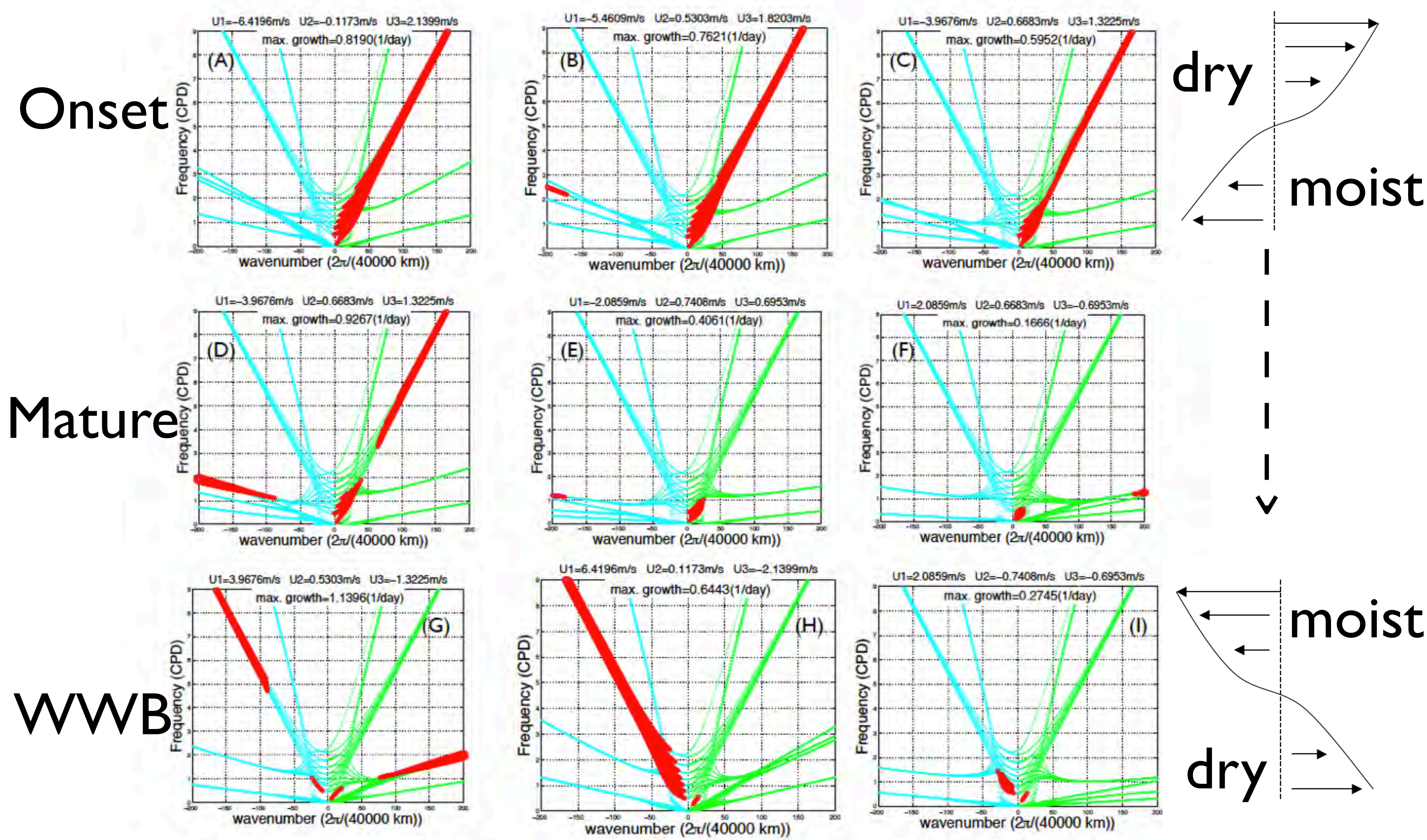
Westward moving Squall lines when low-level easterly shear is strong



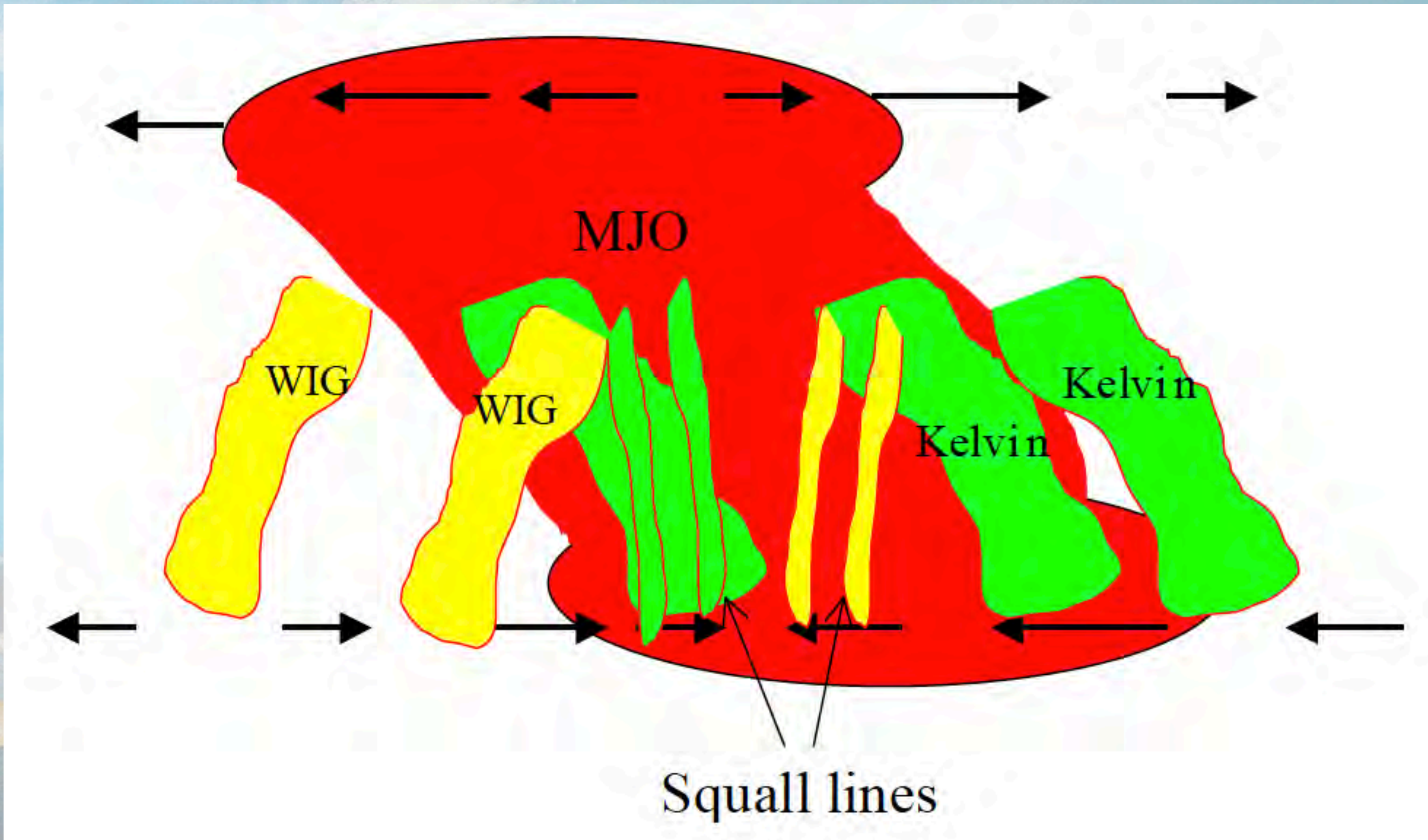
Realistic MJO: Changing both Wind and Moisture Background



Multiscale waves inside the MJO envelope



Multiscale waves inside the MJO envelope



Implication it terms of CMT feedback

MJO Phase / Waves	Onset: (A)–(C)	East of Core: (D)–(E)	West of Core: (F)–(G)	Mature WWB (H)	Decaying WWB (I)
WIG	NA	NA	NA	Deceleration	Deceleration
Kelvin	Deceleration	Deceleration	Acceleration	Acceleration	Acceleration
SQLN	Acceleration	Acceleration	Acceleration	Acceleration	NA
Total CMT effect	Deceleration of Easterlies by Kelvin waves	Neutral	Acceleration of WWB by Kelvin waves and squall lines	Deceleration of WWB by WIG waves	Deceleration by WIG waves continues and would potentially trigger acceleration of Easterlies for next MJO event.

Suggest that CMT from the embedded synoptic and mesoscale waves cooperates with MJO initiation, intensification, and propagation