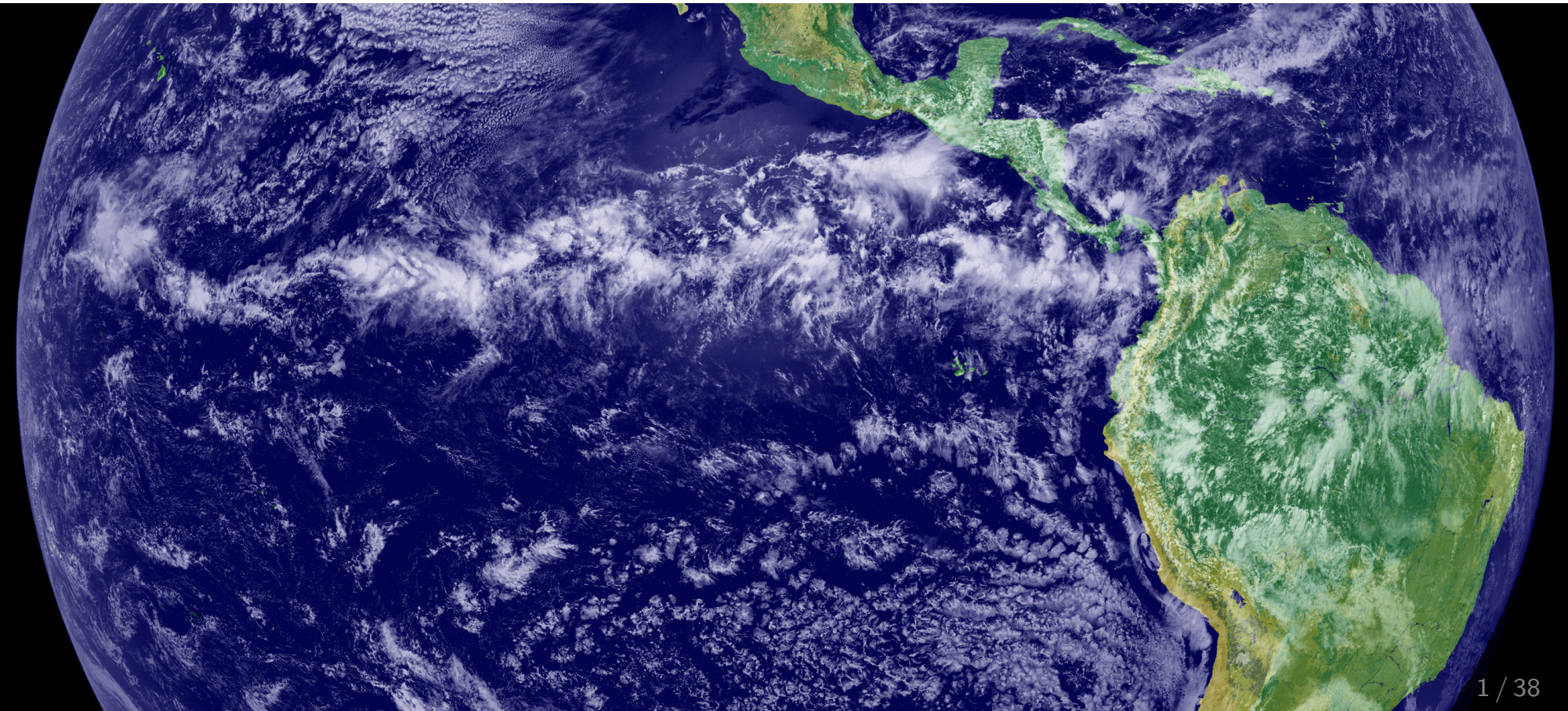
Multi-scale Models for the Scale Interaction of Organized Tropical Convection

Qiu Yang

Center for Atmosphere Ocean Science, Courant Institute, New York University

Thesis Defense, April 27th, 2017



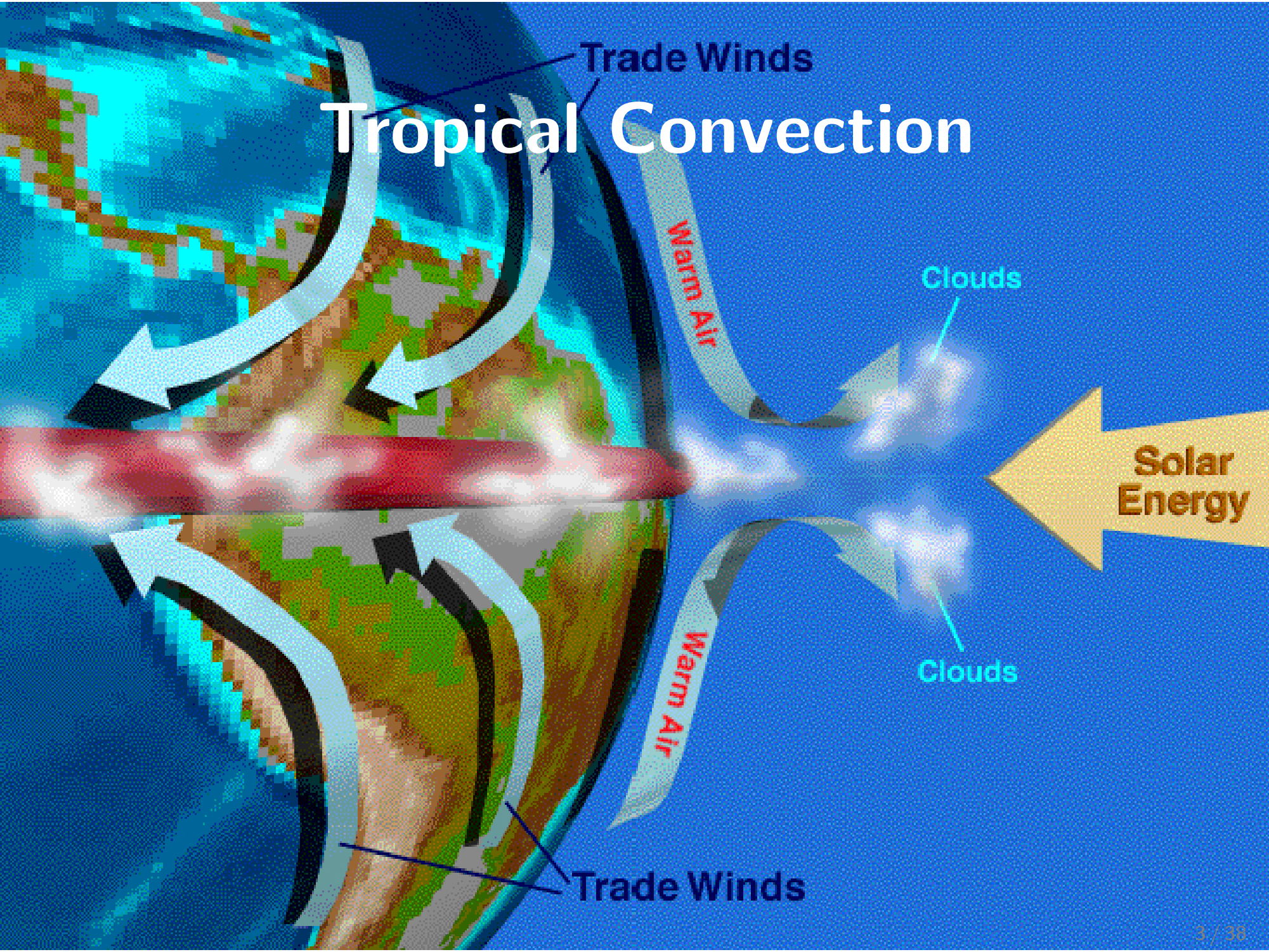
Special gratitude to my advisor **Prof. Andrew Majda**!

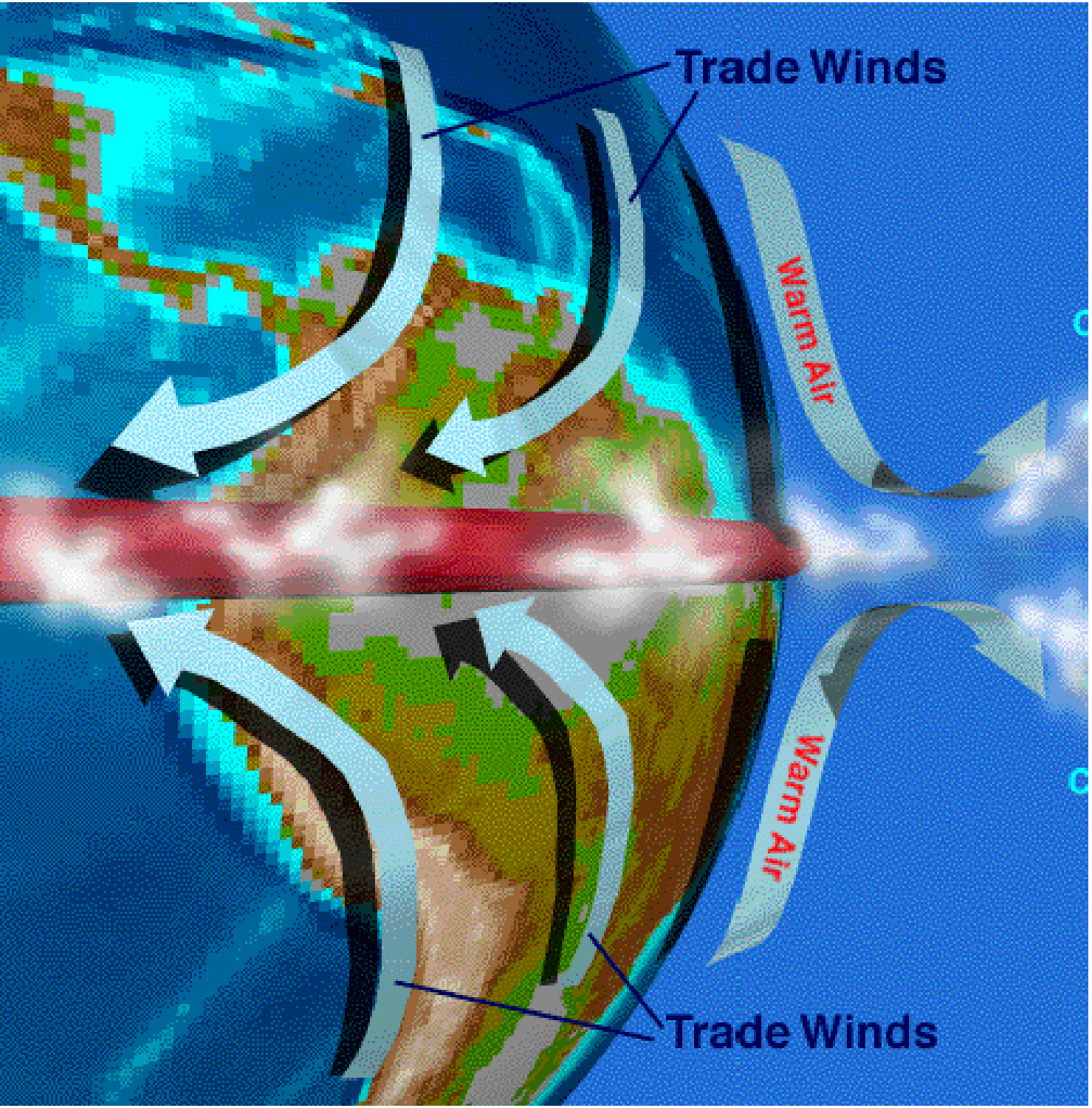
Thesis committee: Prof. Boualem Khouider, Olivier Pauluis, Edwin Gerber, Dimitris Giannakis.

Friends at Courant: Sulian Thual, Nan Chen, Jim Thomas, Noah Brenowitz, Yuanxun Bao and Di Qi.

My parents.

In Grateful Appreciation

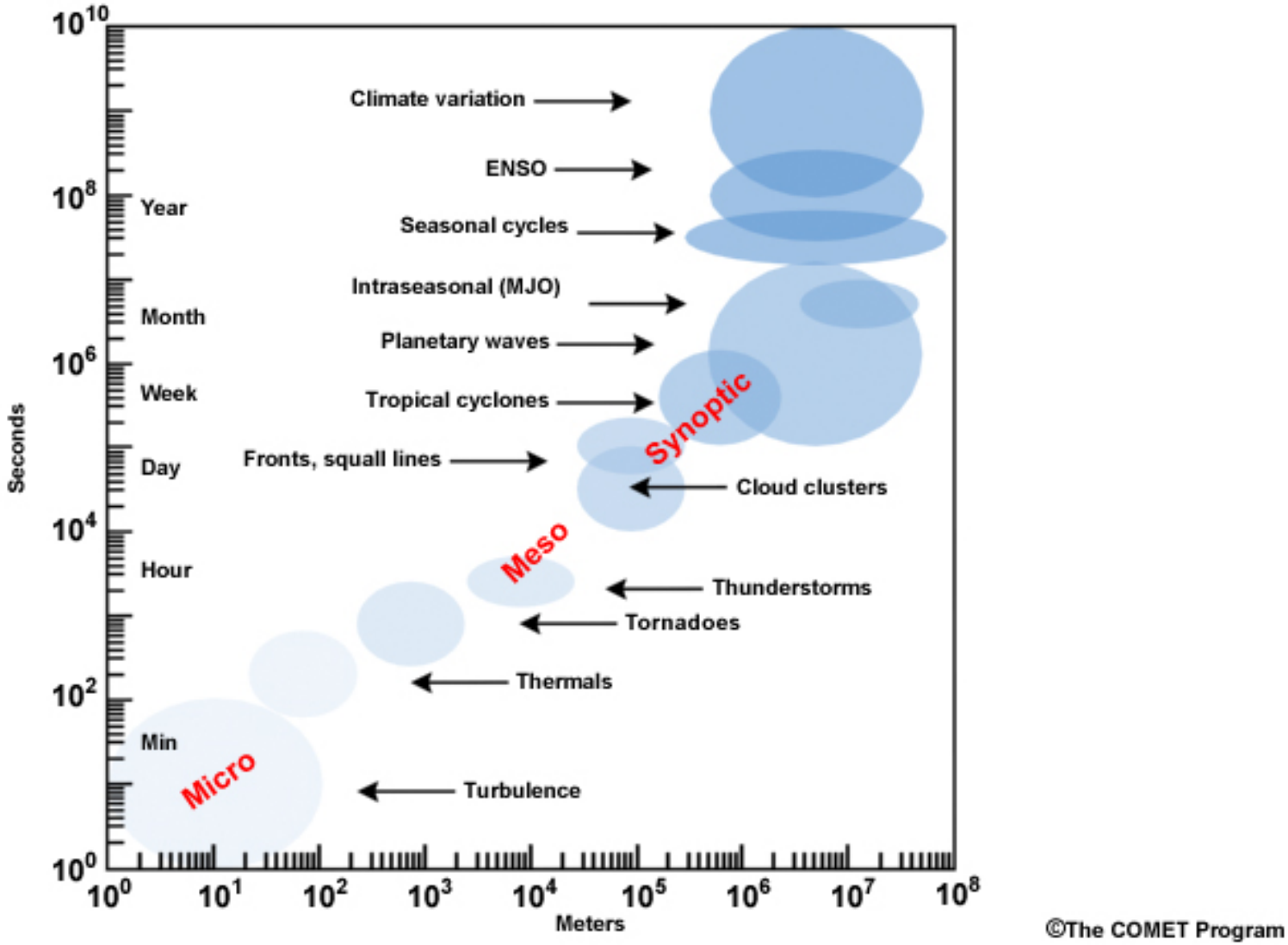

Trade Winds
Tropical Convection
Warm Air
Clouds
Solar Energy
Clouds
Warm Air
Trade Winds

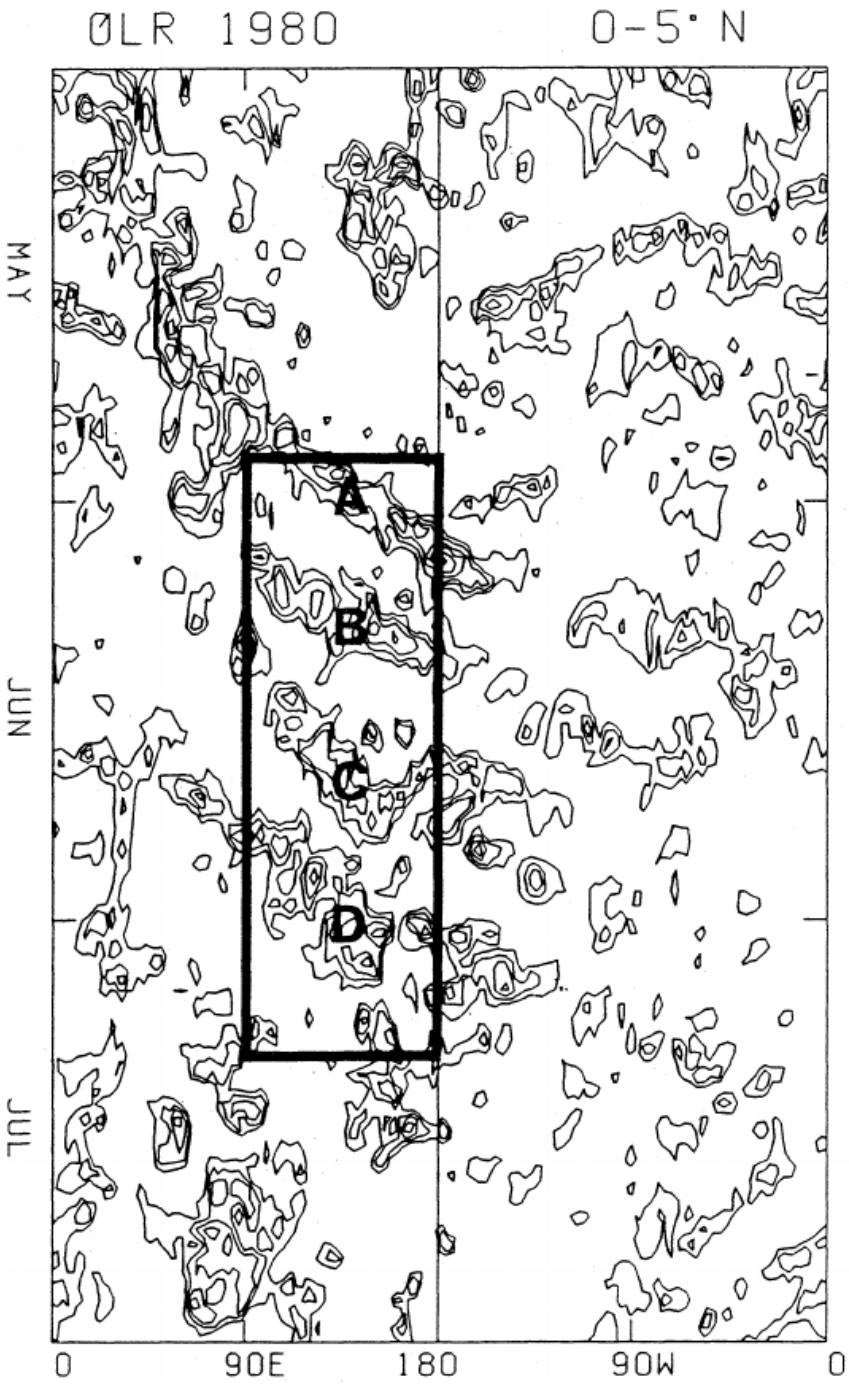


Coriolis force

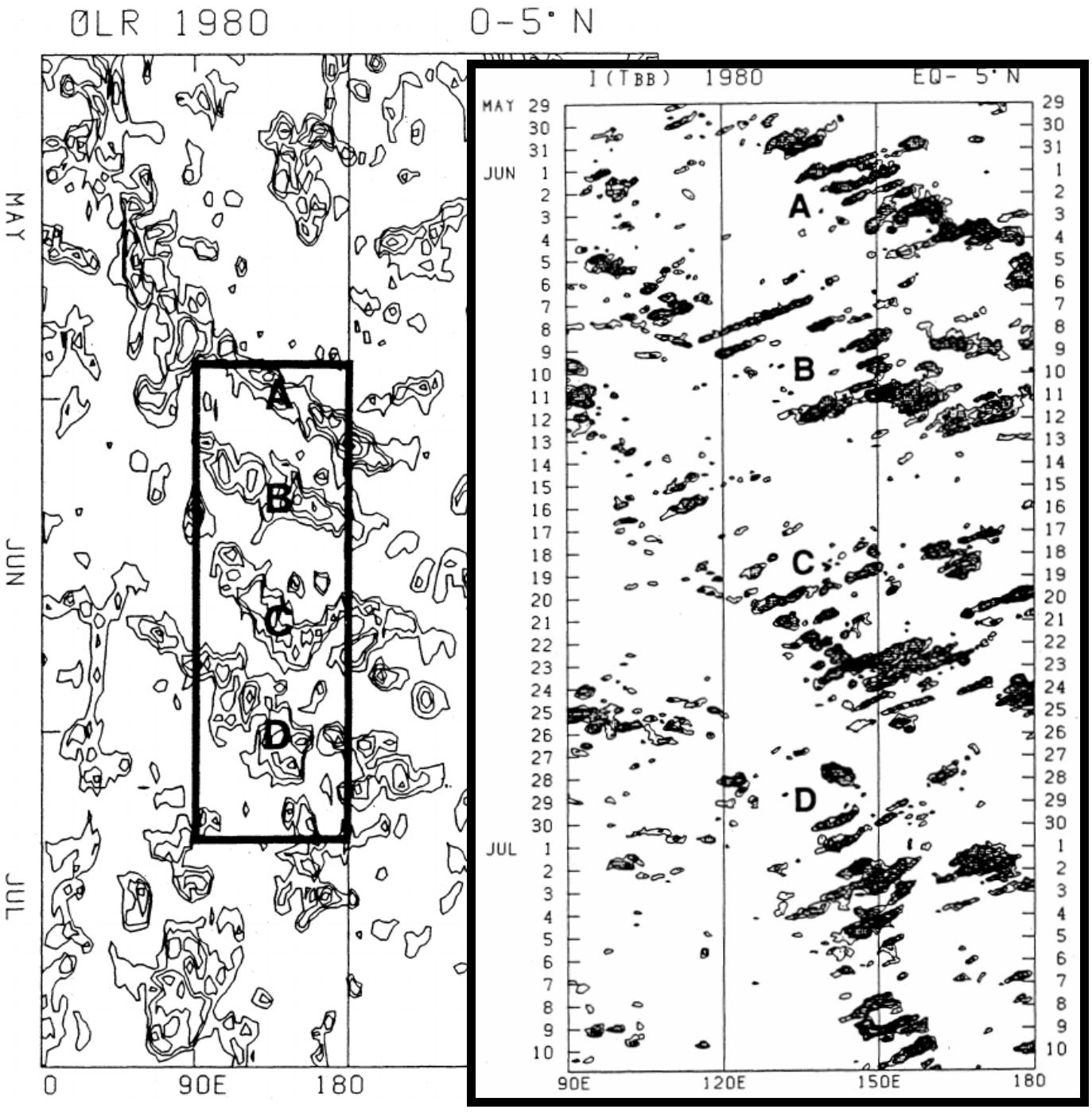
Water vapor

Tropical Convection across Multiple Scales

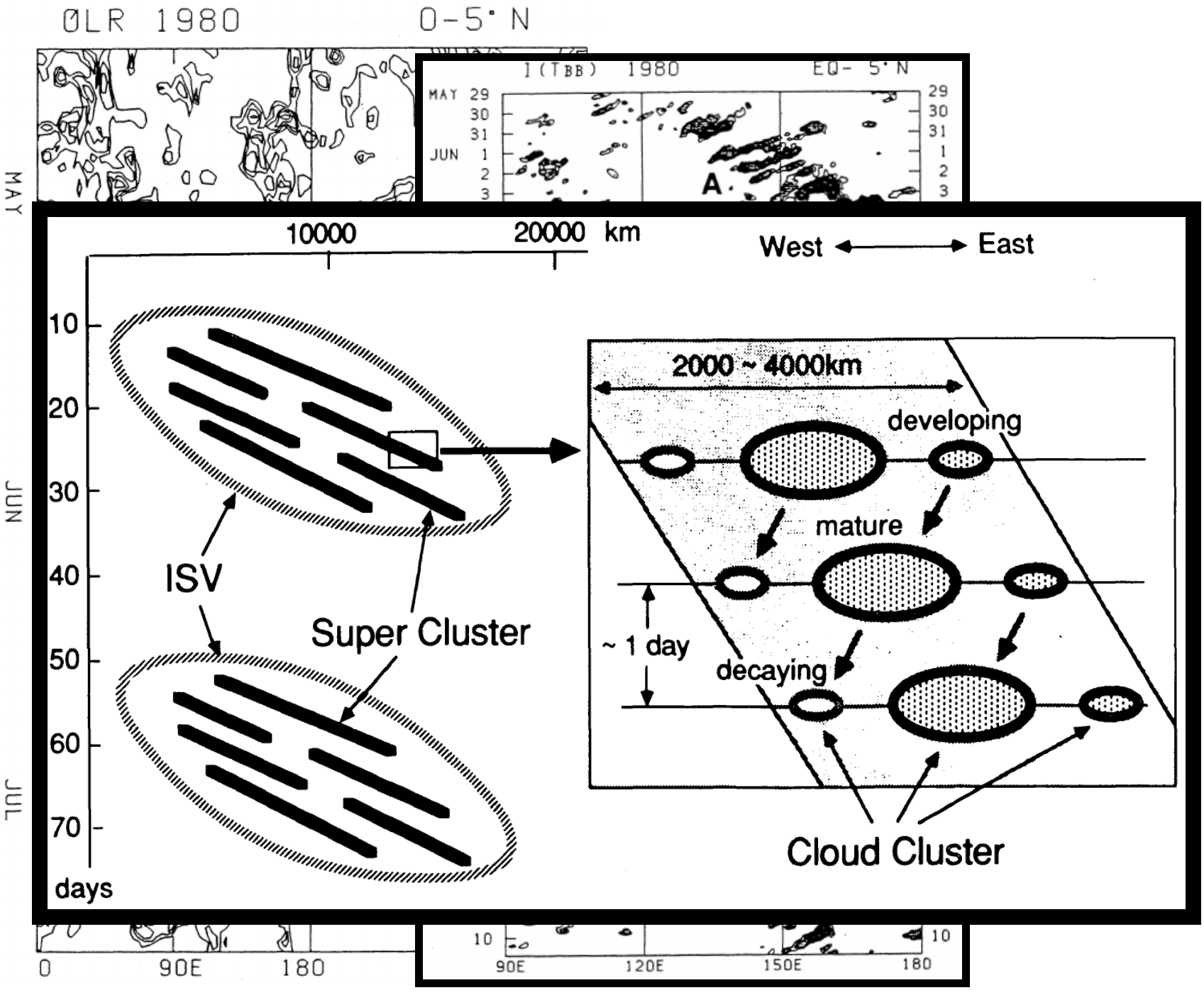




(Nakazawa,1988)



(Nakazawa,1988)



(Nakazawa,1988)

Multi-scale models for tropical convection

- 2003 *"Systematic multiscale models for the tropics"*.
  (Majda and Klein, 2003)
- 2004 Multi-scale models for Madden-Julian Oscillation.
  (Majda and Biello, 2004; Biello and Majda, 2005, 2006)
- 2007 *"New multiscale models and self-similarity in tropical convection"*. (Majda 2007)
- 2007 *"Multiscale models with moisture and systematic strategies for superparameterization"*. (Majda 2007)
- 2010 Multi-scale models for hurricane embryo, squall lines.
  (Majda et. al., 2010; Majda and Xing, 2010)
- 2012 Multiscale models for synoptic-mesoscale interactions in the ocean. (Grooms et. al., 2012)
- 2013 Multi-scale models for ITCZ. (Biello and Majda, 2013)

Outline

Chapter 1&2: A Multi-Scale Model for the Intraseasonal Impact of the Diurnal Cycle over the Maritime Continent on the Madden-Julian Oscillation

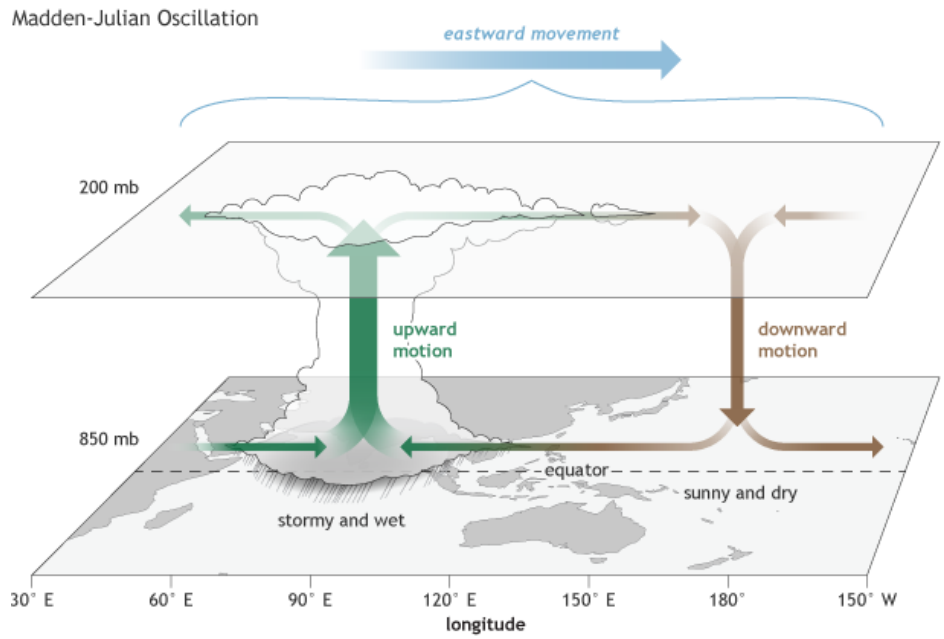
Chapter 3: ITCZ Breakdown and Its Upscale Impact on the Planetary-Scale Circulation over the Eastern Pacific

Outline

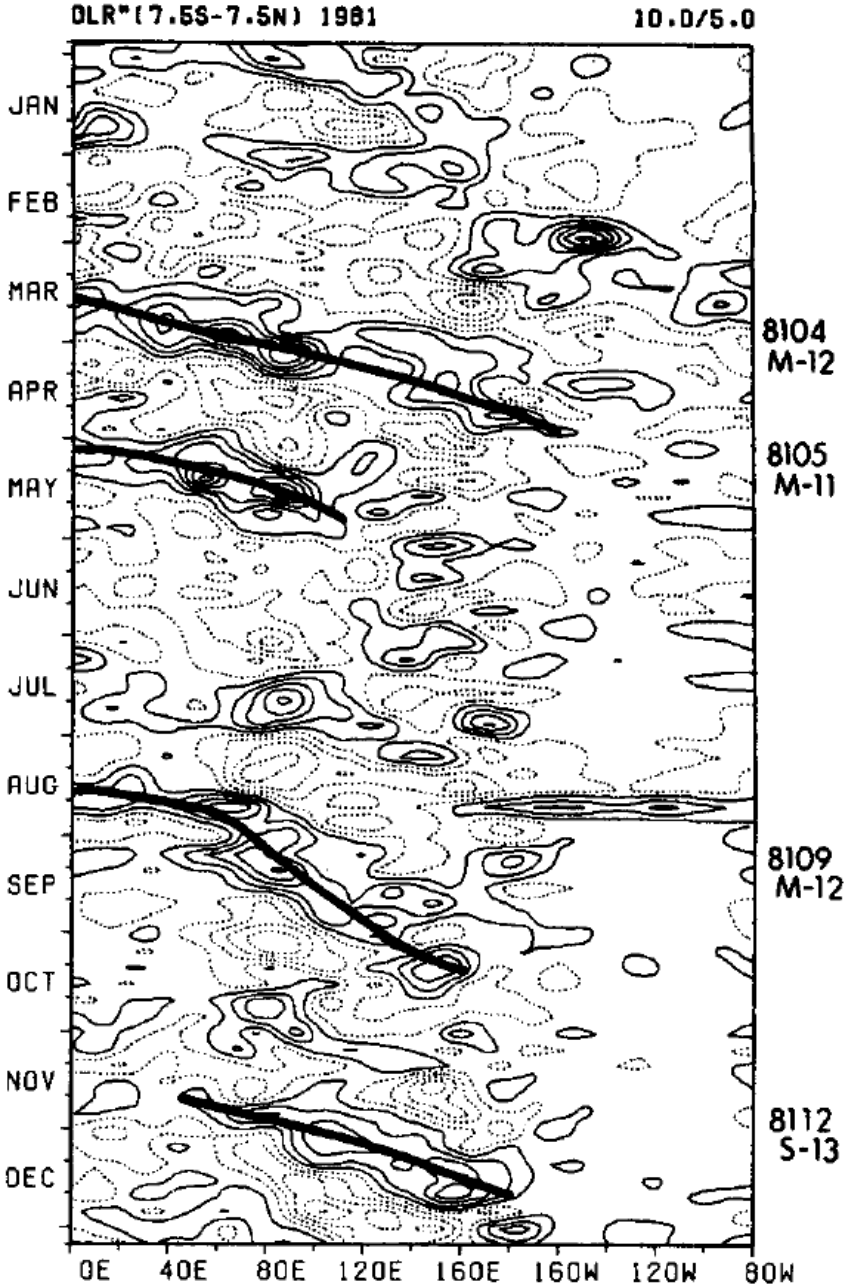
Chapter 1&2: A Multi-Scale Model for the Intraseasonal Impact of the Diurnal Cycle over the Maritime Continent on the Madden-Julian Oscillation

Chapter 3: ITCZ Breakdown and Its Upscale Impact on the Planetary-Scale Circulation over the Eastern Pacific

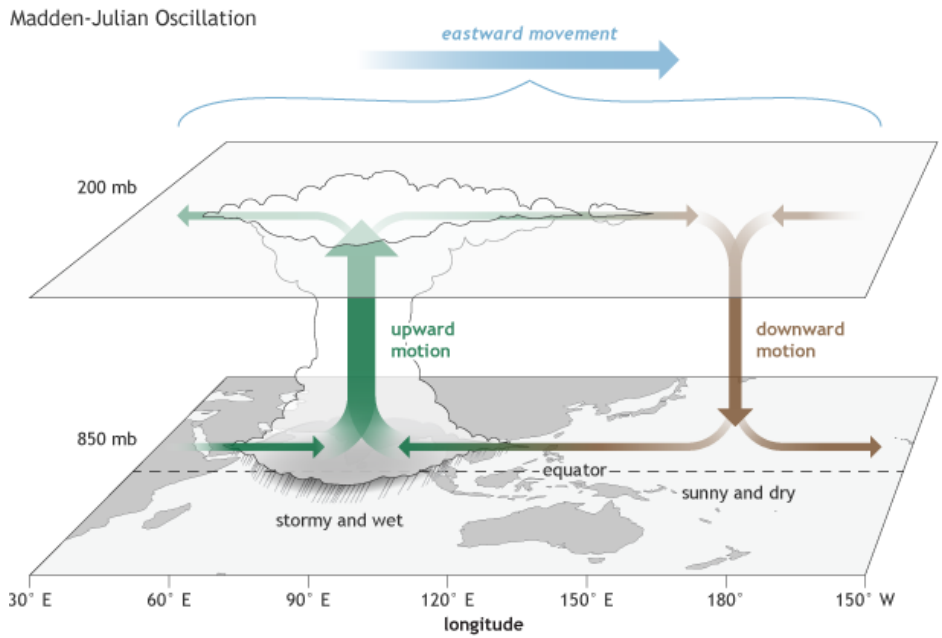
Madden-Julian Oscillation (MJO)



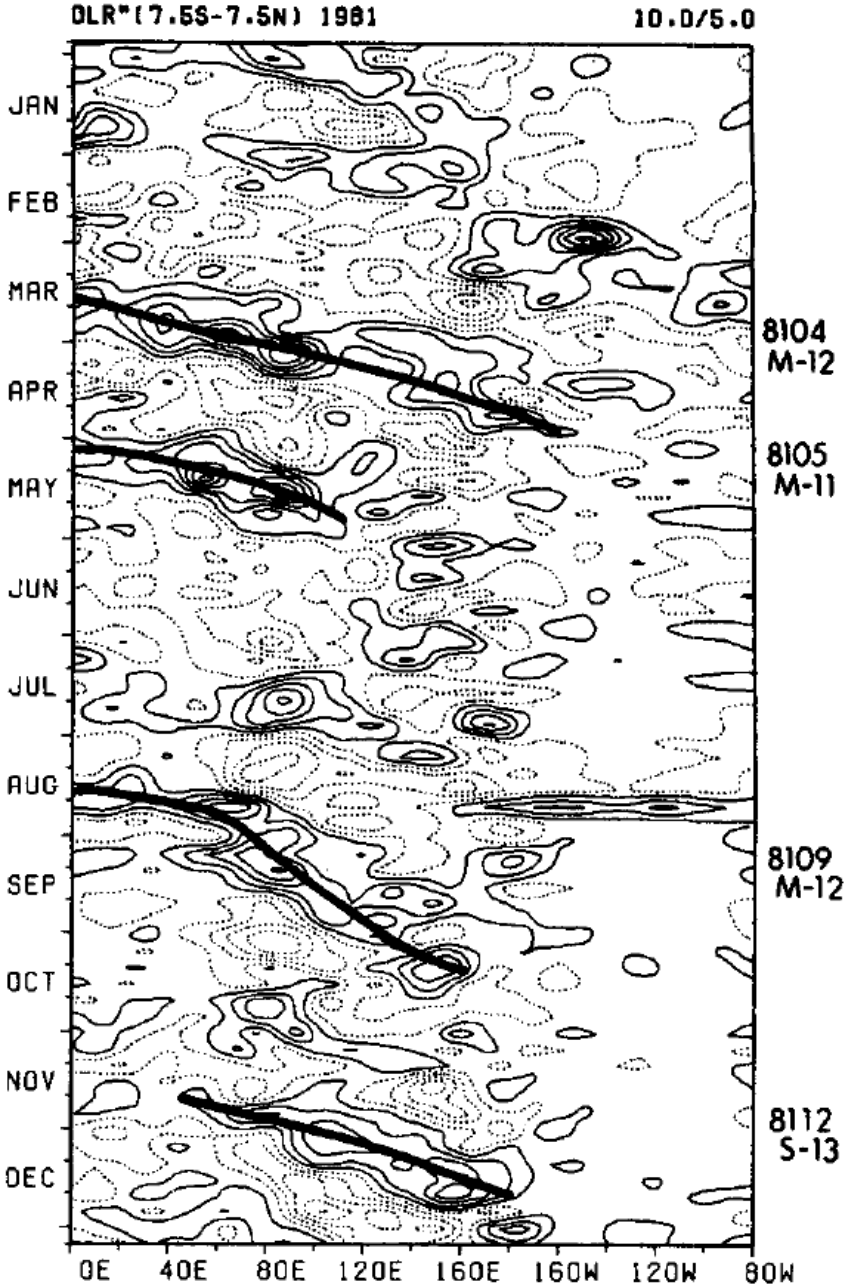
Madden-Julian Oscillation (MJO)



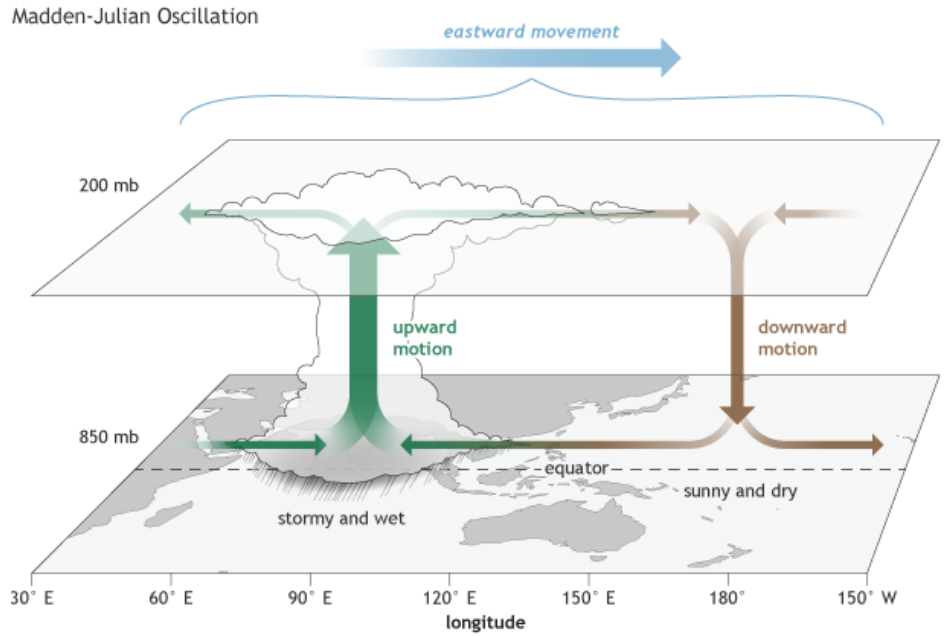
(Rui and Wang, 1990)



Madden-Julian Oscillation (MJO)



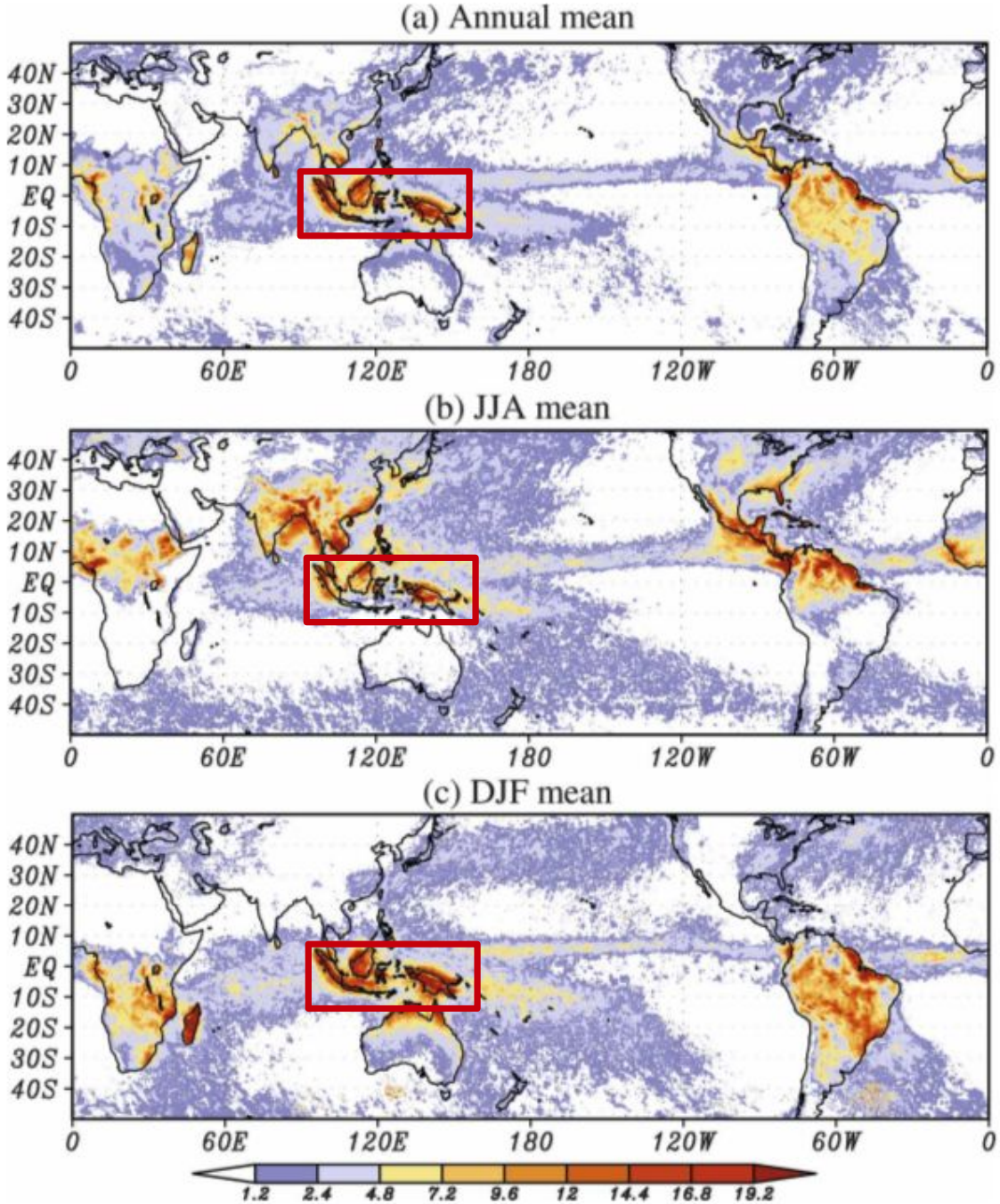
(Rui and Wang, 1990)



Maritime Continent is a barrier for eastward propagating MJO.

(Tung, Giannakis and Majda, 2014)

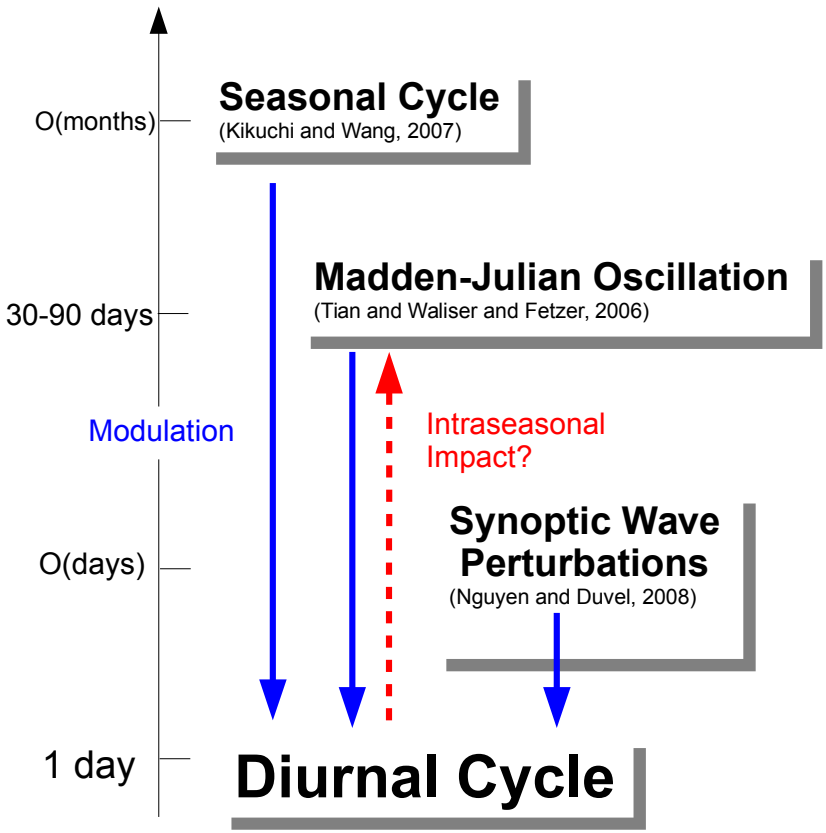
Diurnal cycle?



Color: diurnal precipitation (TRMM datasets)

Diurnal Range:
climatological daily maximum precipitation-daily minimum precipitation

kikuchi and Wang (2007)



Challenge:
GCMs poorly represent MJO and diurnal precipitation over the Maritime Continent.
(Inness and Slingo 2003;Stratton and Stirling 2012)

Hypothesis:
The inadequate treatment of the diurnal cycle and its scale interaction with the MJO.

Our work:
"A multi-scale model for the intraseasonal impact of the diurnal cycle over the maritime continent on the MJO". (Majda and Yang, 2016; Yang and Majda, 2014)

Hagos et. al., (2016) says

> *"Majda and Yang [2016] show that planetary-scale diurnal variability of diabatic heating can have an upscale effect on intraseasonal variability...cancel temperature anomalies associated with the MJO diurnal cycle"*

Derivation

The primitive equations on an equatorial β-plane

$$\frac{D}{Dt}u - \beta yv = -\phi_x - du$$
$$\frac{D}{Dt}v + \beta yu = -\phi_y - dv$$
$$\frac{D}{Dt}\theta + N^2 w = -d_\theta \theta + S_\theta$$
$$\phi_z = \theta$$
$$u_x + v_y + w_z = 0$$

momentum dissipation for cumulus drag $-du, -dv$, $d \approx \frac{1}{5day}$ (Lin et al.,2005)

radiative cooling $-d_\theta\theta$, $d_\theta \approx \frac{1}{15day}$ (Mapes et al., 1995)

Step 1: Nondimensinalization

Froude number	0.1	ϵ
synoptic	$1,500km$	x, y
daily	$8.3h$	t
planetary	$15,000km$	X
intraseasonal	$3.5d$	T

Step 2: Asymptotic expansion, e.g.

$$u = \epsilon[\tilde{u}(t, T) + U(T)] + \epsilon^2 u_2 + \mathcal{O}\left(\epsilon^3\right)$$

Step 3: Collect Terms on the same order

A multi-scale model for the intraseasonal impact of diurnal cycle

A model for diurnal cycle

$$\begin{aligned}
\tilde{u}_t - y\tilde{v} &= 0 \\
\tilde{v}_t + y\tilde{u} &= -\tilde{p}_y \\
\tilde{\theta}_t + \tilde{w} &= \tilde{S}_\theta \\
\tilde{p}_z &= \tilde{\theta} \\
\tilde{v}_y + \tilde{w}_z &= 0
\end{aligned}$$

where $\tilde{S}_\theta$ is diabatic heating. All variables are on daily time scale.

A model for planetary/intraseasonal circulation

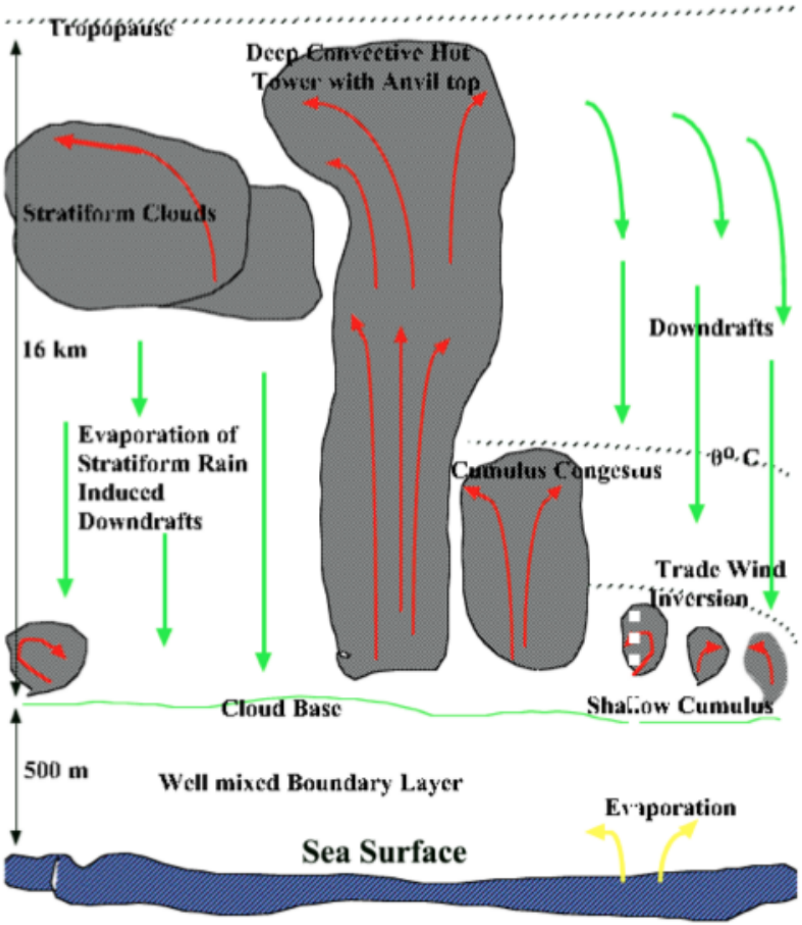
$$\begin{aligned}
U_T - yV &= -P_X - dU + F^u \\
yU &= -P_y \\
\Theta_T + W &= -d_\theta \Theta + F^\theta \\
P_z &= \Theta \\
U_X + V_y + W_z &= 0
\end{aligned}$$

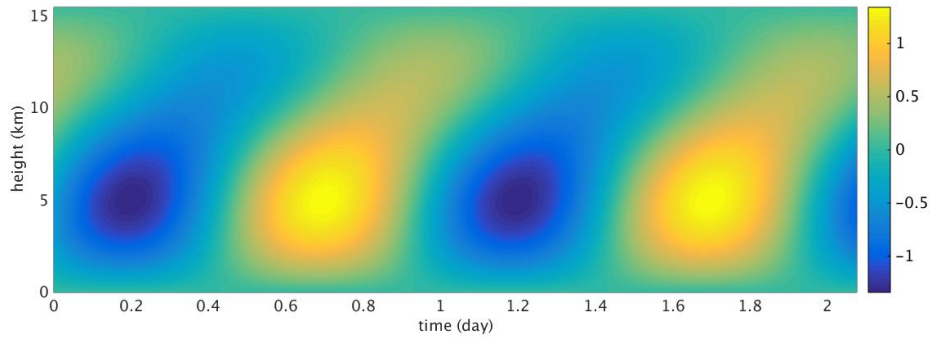
where

$$\begin{aligned}
F^u &= -\frac{\partial}{\partial y}\langle \tilde{v}\tilde{u} \rangle - \frac{\partial}{\partial z}\langle \tilde{w}\tilde{u} \rangle \\
F^\theta &= -\frac{\partial}{\partial y}\langle \tilde{v}\tilde{\theta} \rangle - \frac{\partial}{\partial z}\langle \tilde{w}\tilde{\theta} \rangle
\end{aligned}$$

Modeling diurnal heating

$$\tilde{S}_\theta = F(X)\,H(y)\,[\sin(kX+\omega t)\sin(z)+\alpha\sin(kX+\omega t+\beta)\sin(2z)]$$

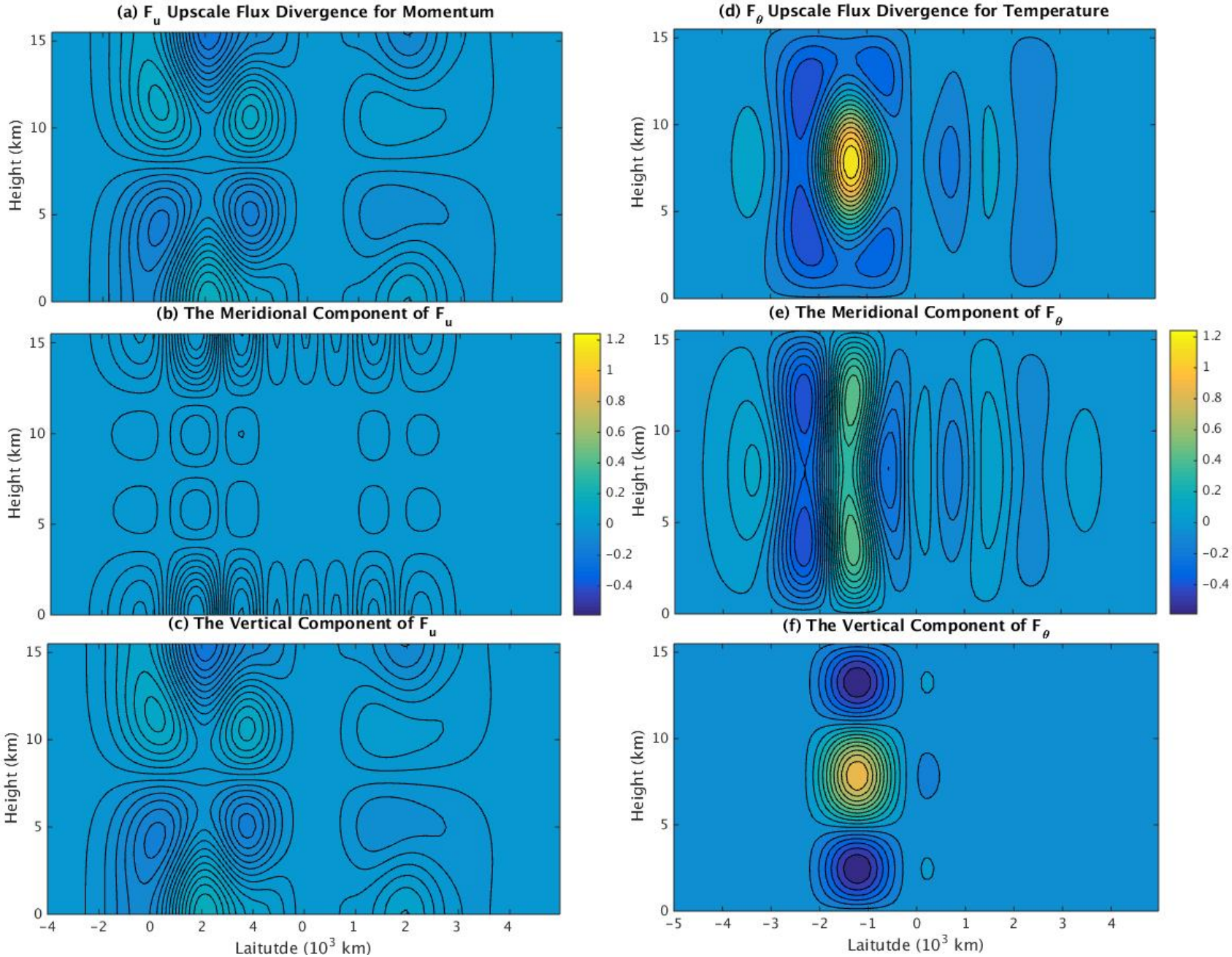




$F(X)$ is planetary-scale envelope function (Maritime Continent)

$H(y)$ Gaussian function centered at $12^0 S$ (Boreal Winter)

(Khouider and Majda, 2008)

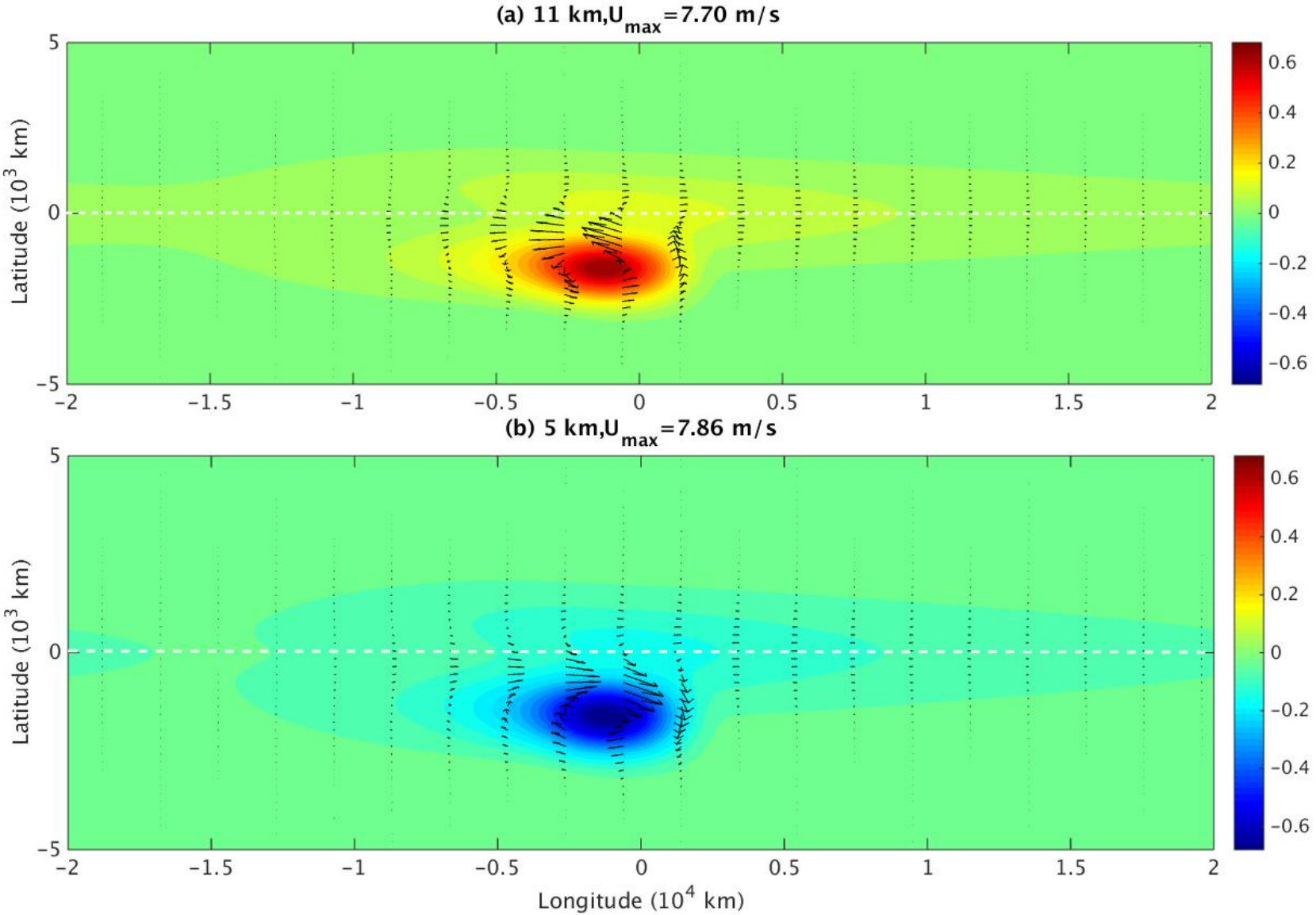


$$F^u = -\frac{\partial}{\partial y}\langle \tilde{v}\tilde{u}\rangle - \frac{\partial}{\partial z}\langle \tilde{w}\tilde{u}\rangle,$$

$$F^\theta = -\frac{\partial}{\partial y}\langle \tilde{v}\tilde{\theta}\rangle - \frac{\partial}{\partial z}\langle \tilde{w}\tilde{\theta}\rangle$$

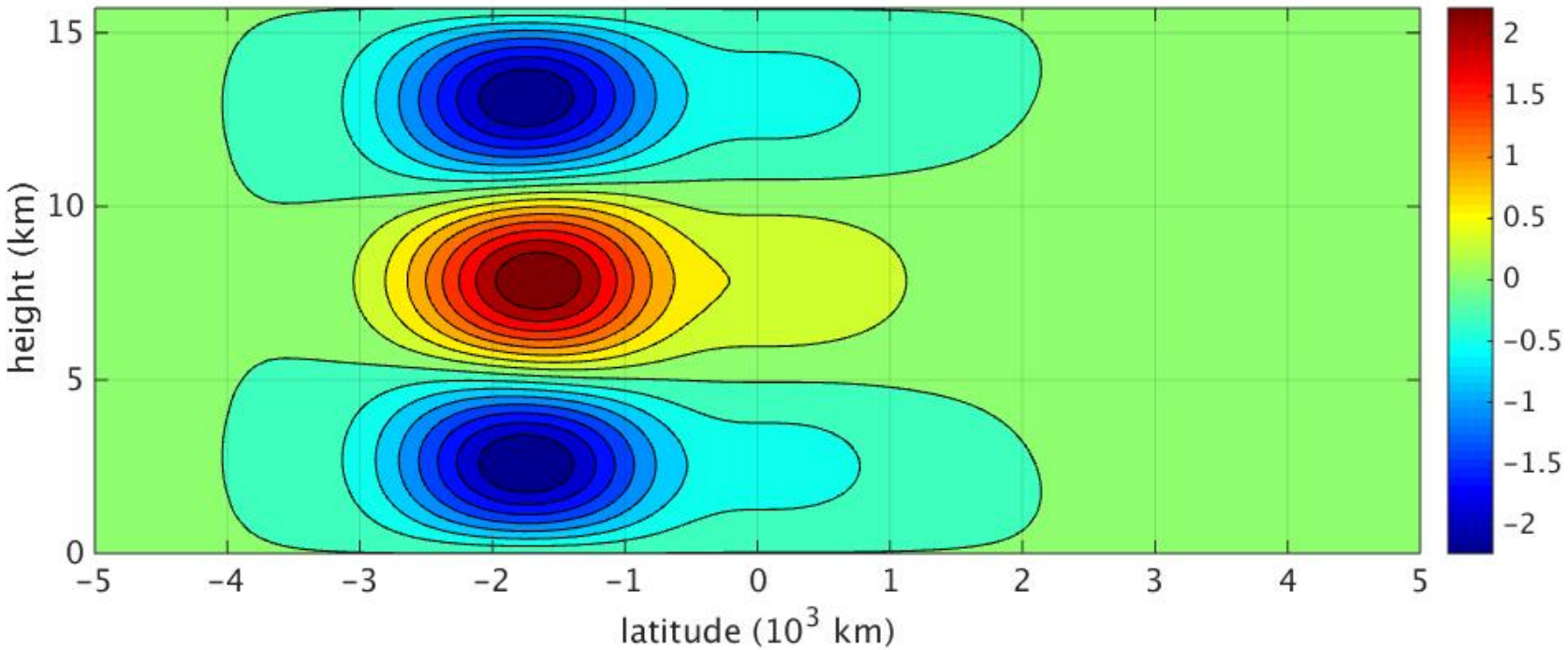
Intraseasonal Impact of Diurnal Cycle:

horizontal velocity (arrow) and pressure perturbation (color)



Intraseasonal Impact of Diurnal Cycle:

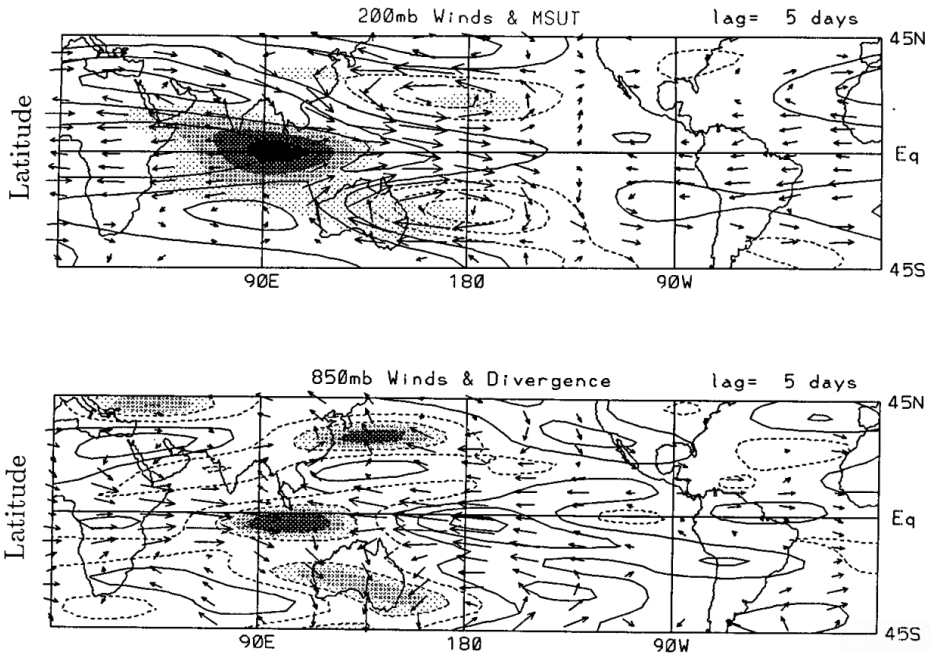
potential temperature anomalies Θ (K)



Introduce a MJO event with quadruple structure

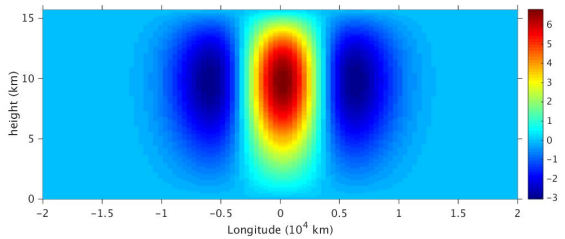
A model for planetary/intraseasonal circulation

$$U_T - yV = -P_X - dU + F^u$$
$$yU = -P_y$$
$$\Theta_T + W = -d_\theta \Theta + F^\theta + S^\theta_{MJO}$$
$$P_z = \Theta$$
$$U_X + V_y + W_z = 0$$

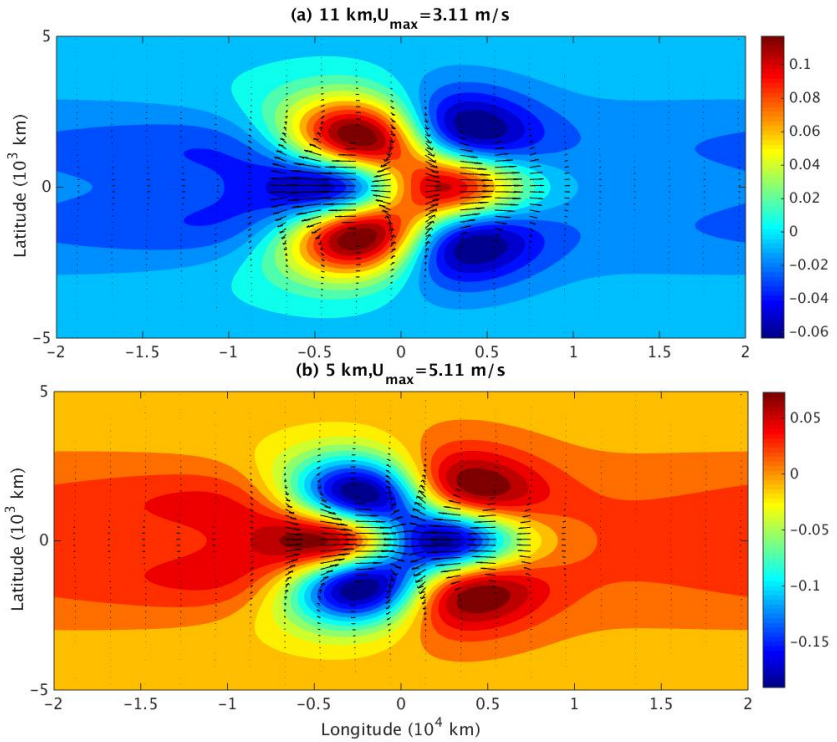


(Hendon and Salby, 1994)

Planetary-scale heating from MJO

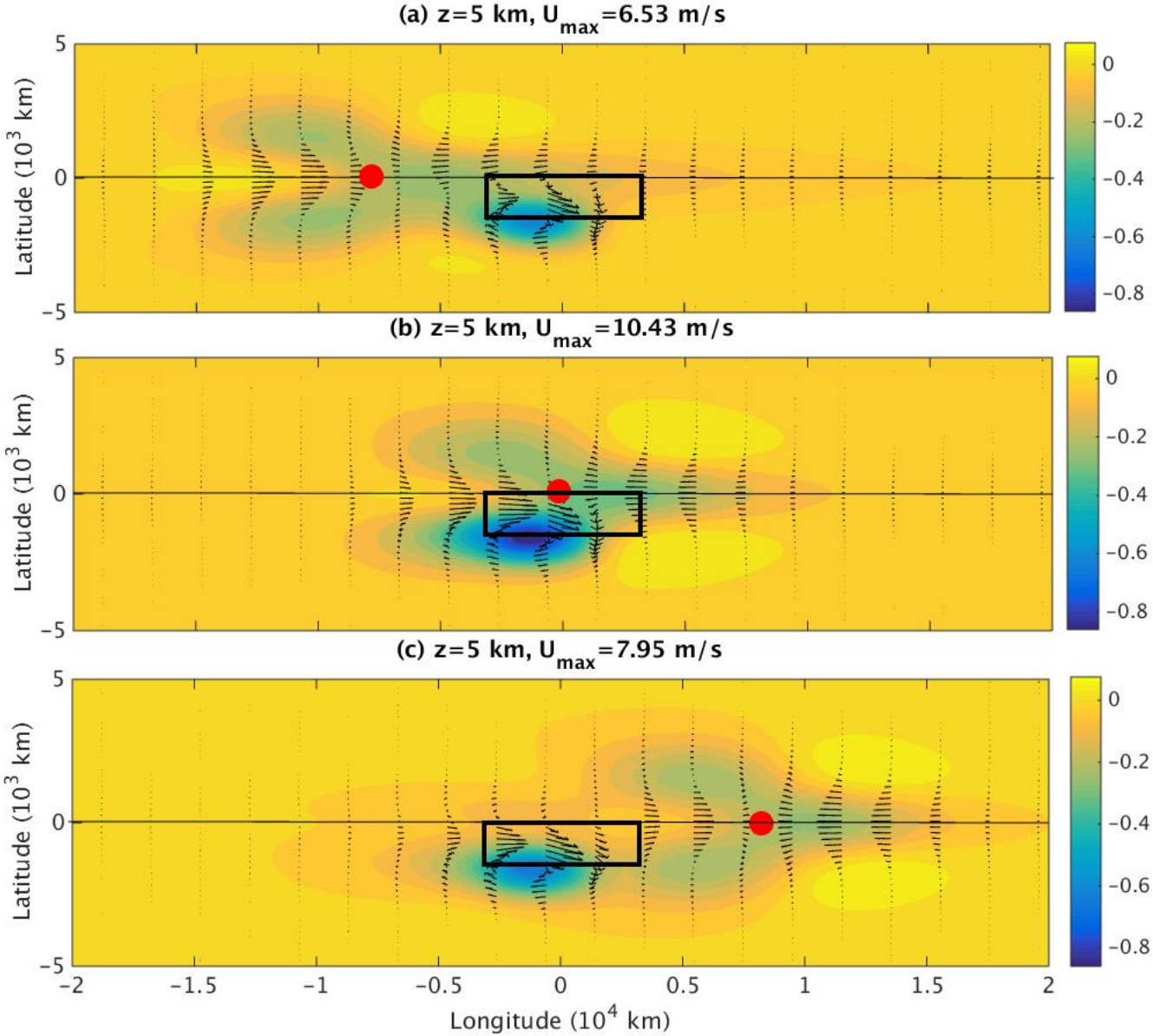


horizontal velocity, pressure (color)



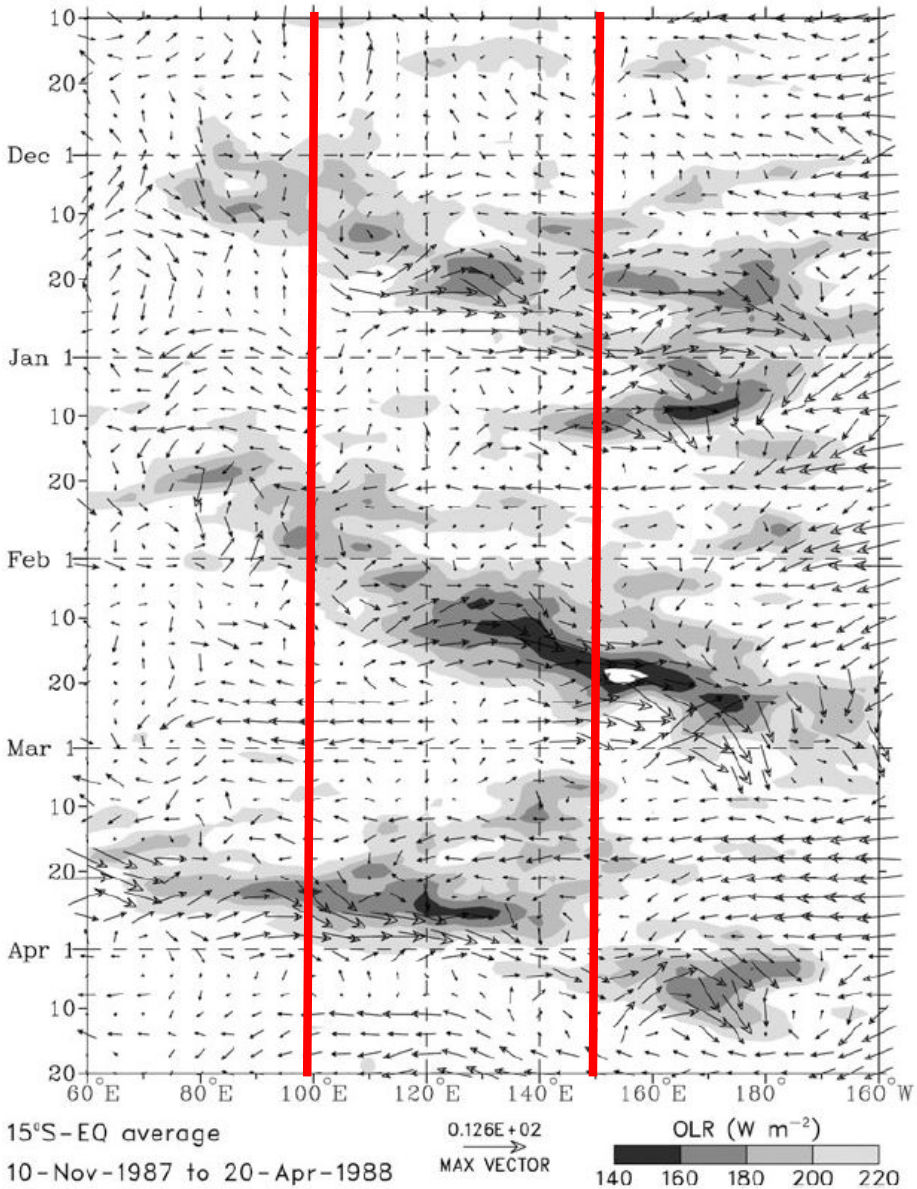
Intraseasonal Impact of Diurnal Cycle on MJO

Persistent low-level westerly winds over Maritime Continent



Intraseasonal Impact of Diurnal Cycle on MJO

Persistent low-level westerly winds over Maritime Continent



(Wheeler and McBride, 2012)

Introduce a MJO event driven by two-scale heating

A model for planetary/intraseasonal circulation

$$
\begin{aligned}
U_T - yV &= -P_X - dU + F^u + \tilde{F}^u \\
yU &= -P_y \\
\Theta_T + W &= -d_\theta \Theta + F^\theta + \tilde{F}^\theta + S^\theta_{MJO} \\
P_z &= \Theta \\
U_X + V_y + W_z &= 0
\end{aligned}
$$

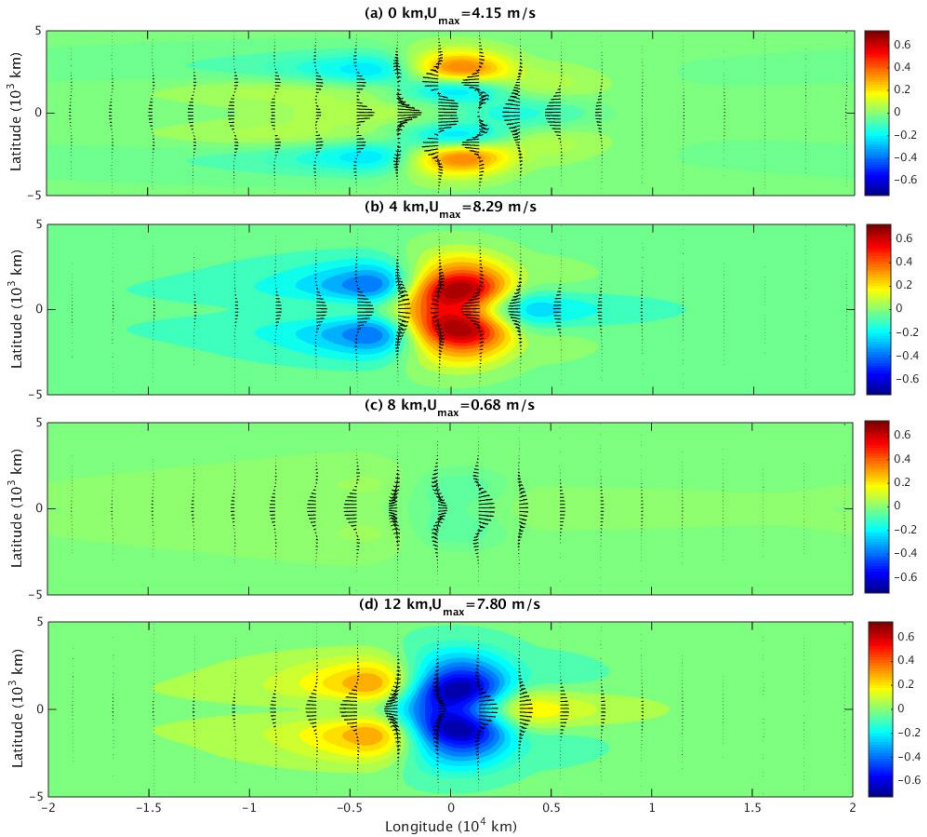
where

$$
\begin{aligned}
\tilde{F}^u &= -\overline{(u'v')}_y - \overline{(u'w')}_z \\
\tilde{F}^\theta &= -\overline{(\theta'v')}_y - \overline{(\theta'w')}_z
\end{aligned}
$$

involve synoptic-scale fluctuations.

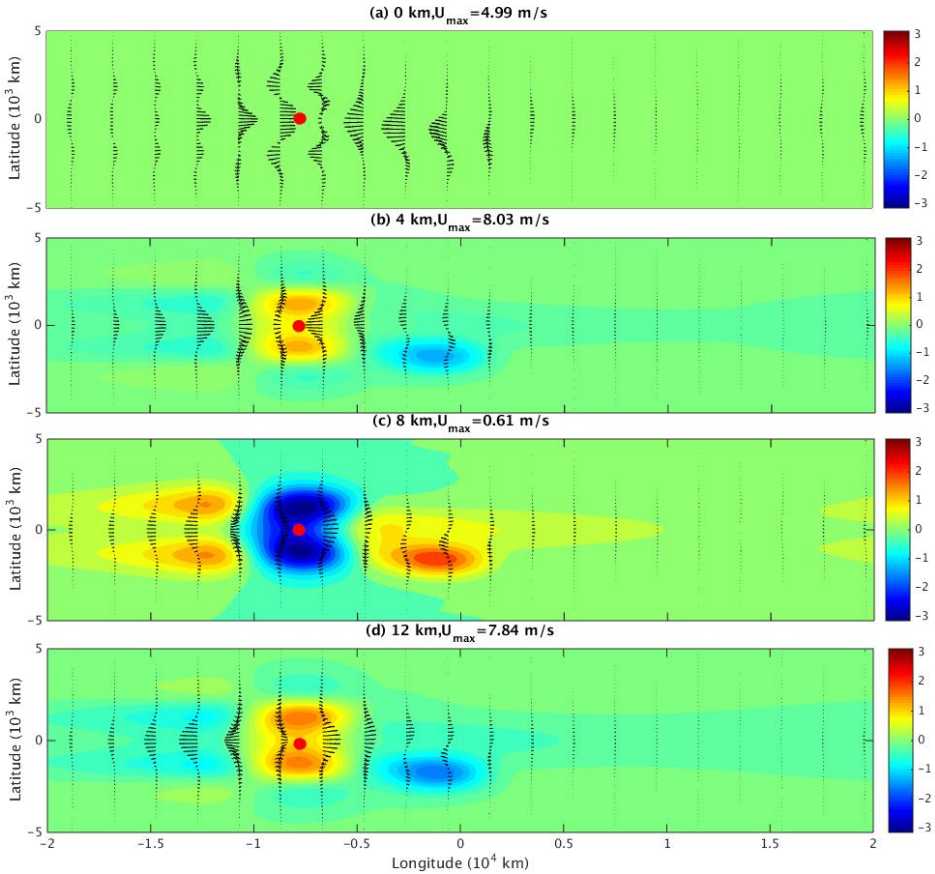
(Biello and Majda, 2005)

horizontal velocity, pressure (color)

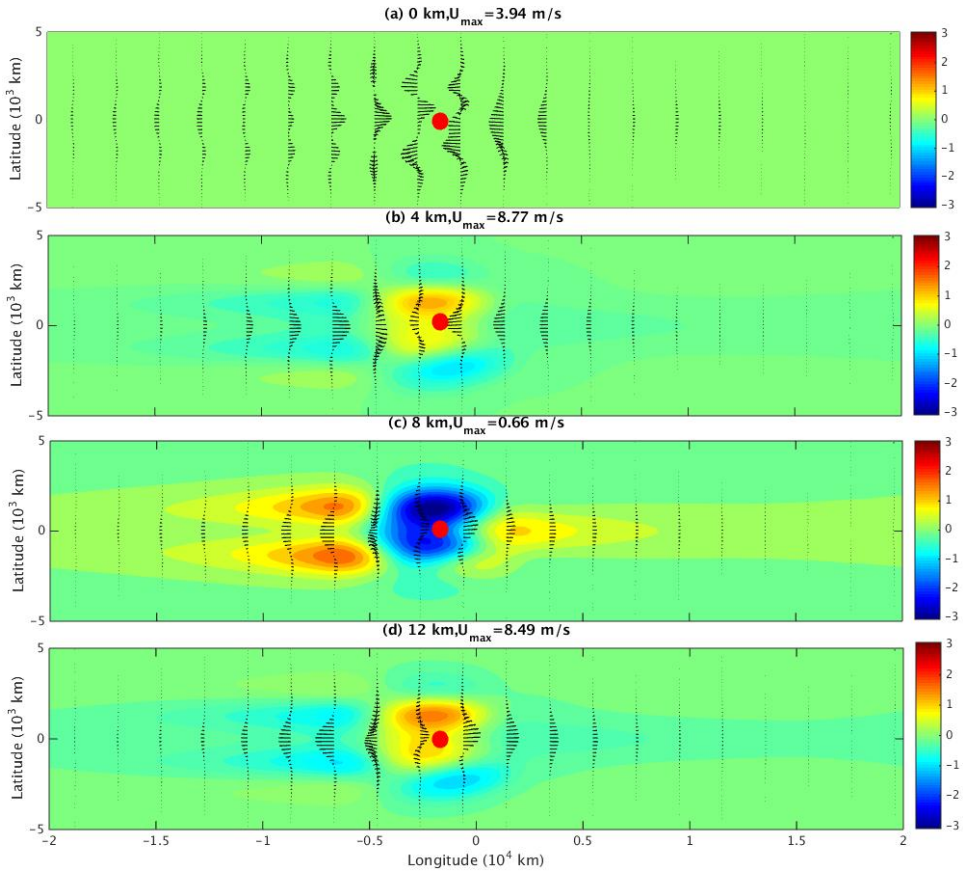


Intraseasonal Impact of Diurnal Cycle on MJO

potential temperature cancellation over Maritime Continent



before the MJO passage



during the MJO passage

Summary

Intraseasonal impact of diurnal cycle on MJO

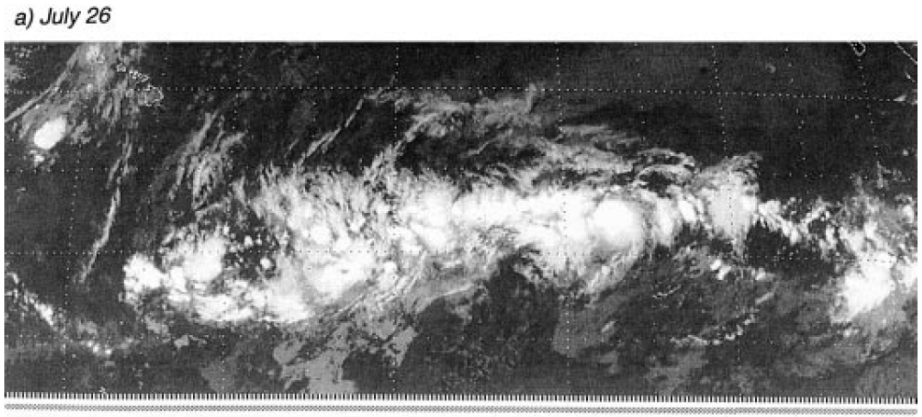
- Persistent westerly winds in the lower troposphere.
- Potential temperature cancellation explains MJO weakening and stalling over the Maritime Continent.

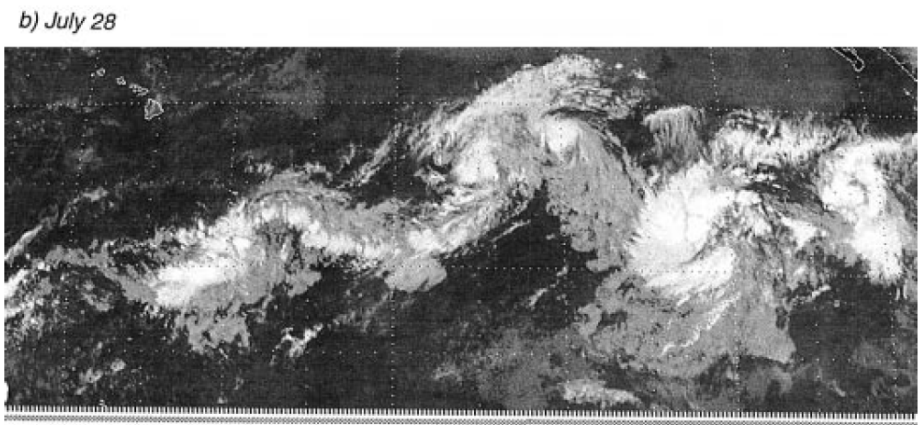
Outline

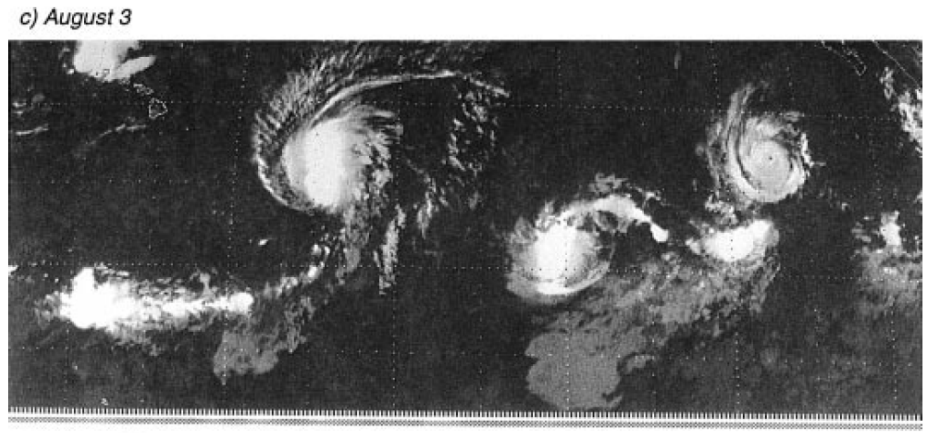
Chapter 1&2: A Multi-Scale Model for the Intraseasonal Impact of the Diurnal Cycle over the Maritime Continent on the Madden-Julian Oscillation

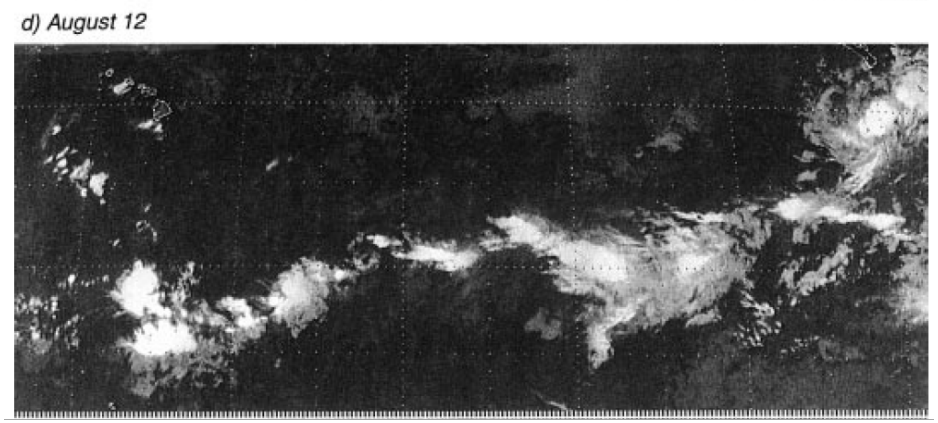
Chapter 3: ITCZ Breakdown and Its Upscale Impact on the Planetary-Scale Circulation over the Eastern Pacific

ITCZ Breakdown







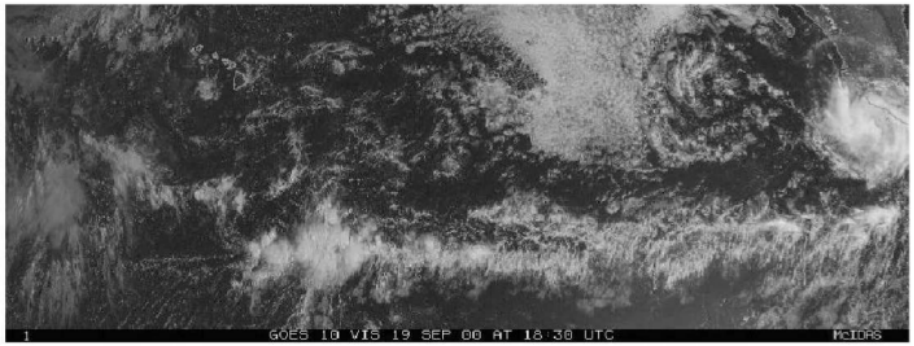


(Ferreira and Schubert, 1997)

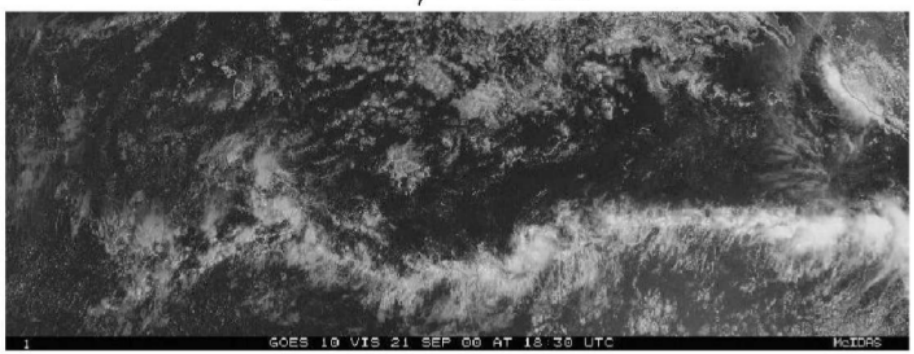
Possible Mechanisms (Wang and Magnusdottir, 2005)

(1) The Vortex Rollup Mechanism

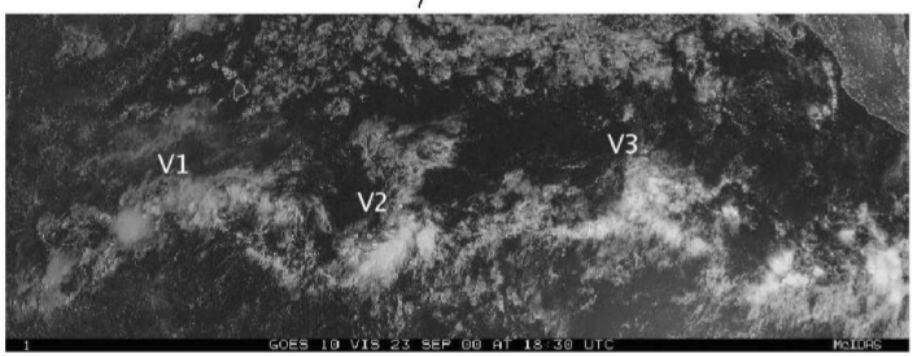
SEP/19 9:00



SEP/21 9:00

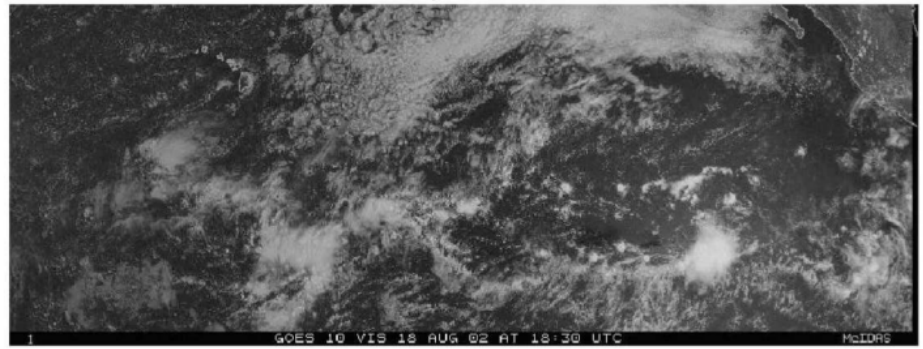


SEP/23 9:00

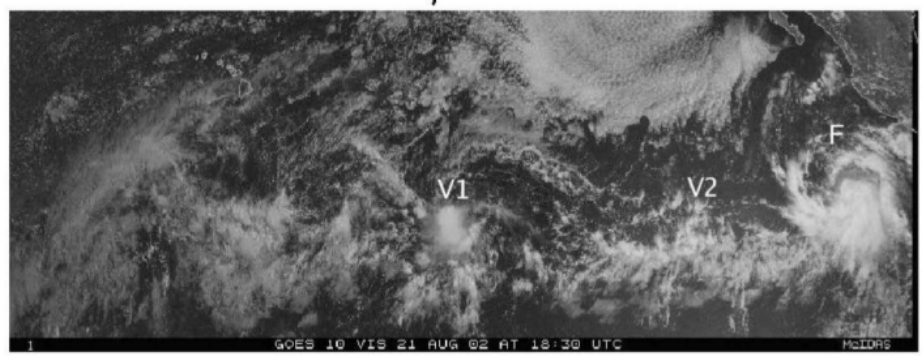


(2) Westward-propagating Disturbances

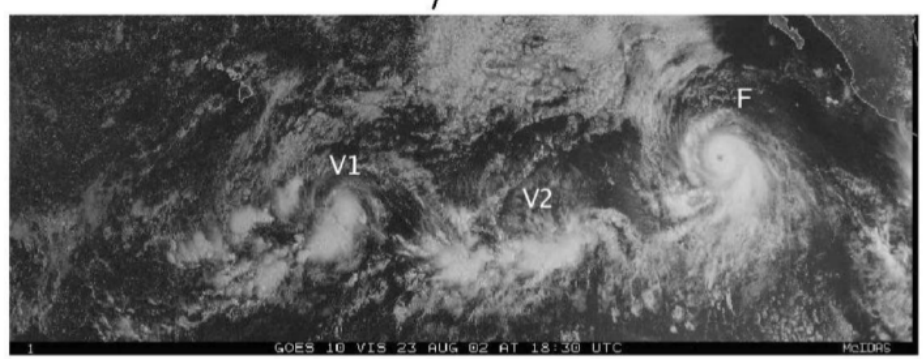
AUG/18 9:00



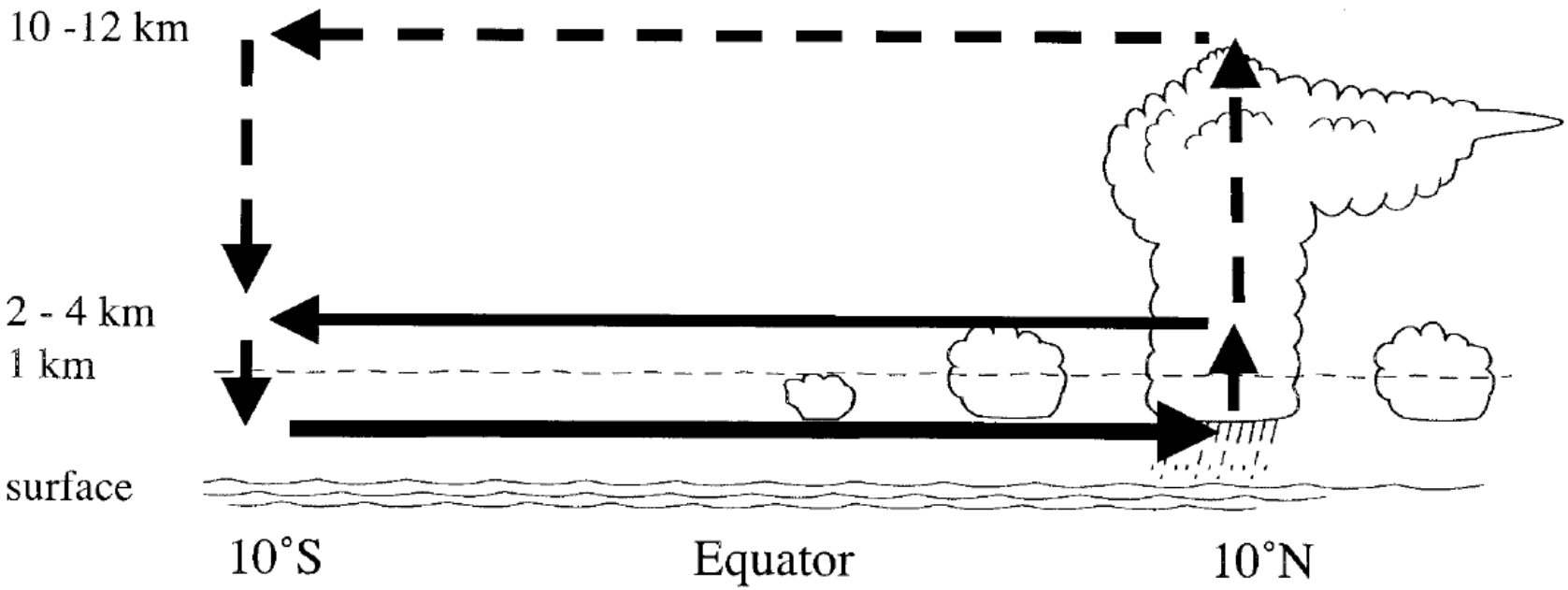
AUG/21 9:00



AUG/23 9:00

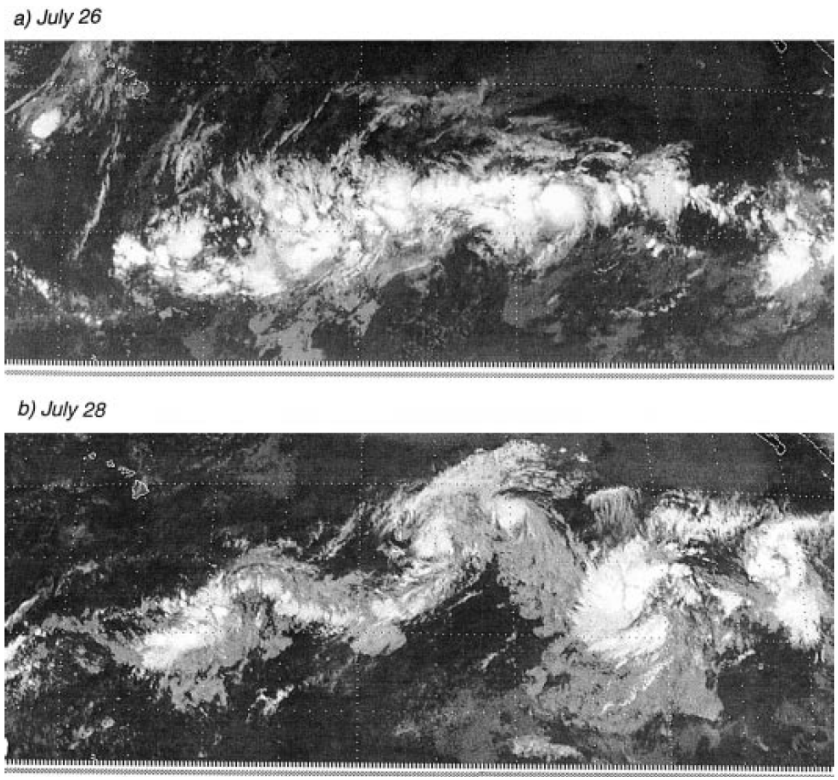


Deep and Shallow Meridional Circulation



(Zhang and Mcgauley, 2003)

Motivation



Q1: What is upscale impact of mesoscale fluctuations during ITCZ breakdown on planetary-scale circulation?

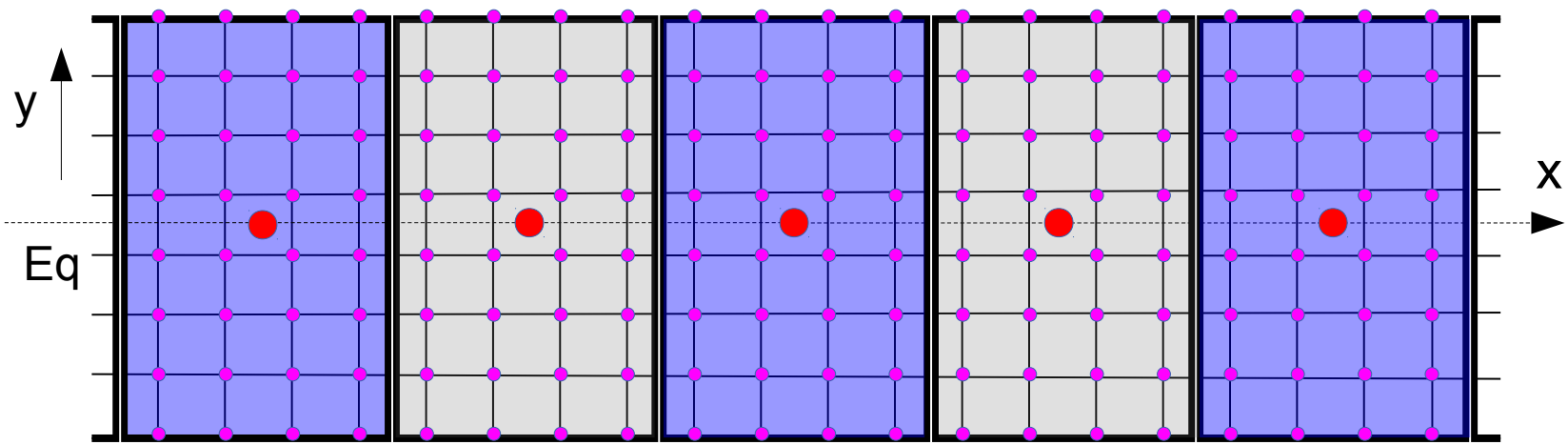
Q2: What is the difference between deep and shallow cases?

The Modulation of the ITCZ equations (M-ITCZ)

$$\frac{Du}{Dt} - yv = -p_x - \Pi_X - du$$
$$\frac{Dv}{Dt} + yu = -p_y - dv$$
$$w = S^\theta$$
$$u_x + v_y + w_z = 0$$
$$\Pi_x = \Pi_y = 0,\ \Pi_z = \Theta$$
$$\Theta_t + W = 0$$
$$[\langle \bar{u} \rangle - U]_X + W_z = 0$$

planetary	$5000km$	X
mesoscale	$500km$	x, y
time	$1d$	t
horizontal velocity	$5ms^{-1}$	u, v
potential temperature	$3.3K$	Θ
diabatic heating	$33Kday^{-1}$	S^θ

(Biello and Majda, 2013)

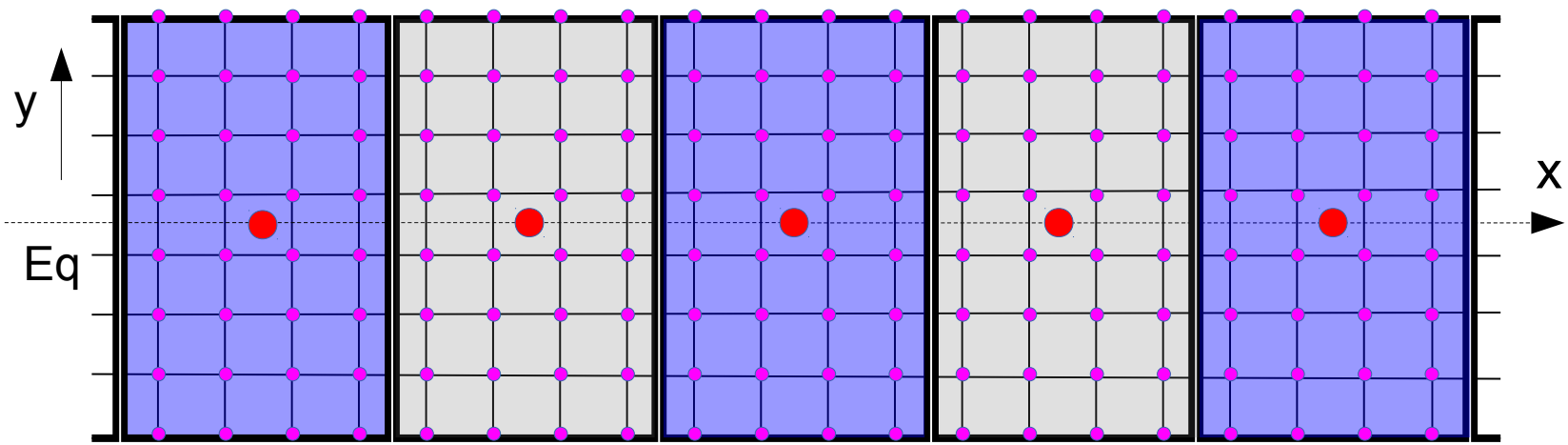


The Modulation of the ITCZ equations (M-ITCZ)

$$\frac{Du}{Dt} - yv = -p_x - \Pi_X - du$$
$$\frac{Dv}{Dt} + yu = -p_y - dv$$
$$w = S^\theta$$
$$u_x + v_y + w_z = 0$$
$$\Pi_x = \Pi_y = 0, \ \Pi_z = \Theta$$
$$\Theta_t + W = 0$$
$$[\langle \bar{u} \rangle - U]_X + W_z = 0$$

planetary	$5000km$	X
mesoscale	$500km$	x, y
time	$1d$	t
horizontal velocity	$5ms^{-1}$	u, v
potential temperature	$3.3K$	Θ
diabatic heating	$33Kday^{-1}$	S^θ

(Biello and Majda, 2013)



The Modulation of the ITCZ equations (M-ITCZ)

$$\frac{Du}{Dt} - yv = -p_x - \Pi_X - du$$

$$\frac{Dv}{Dt} + yu = -p_y - dv$$

$$w = S^\theta$$

$$u_x + v_y + w_z = 0$$

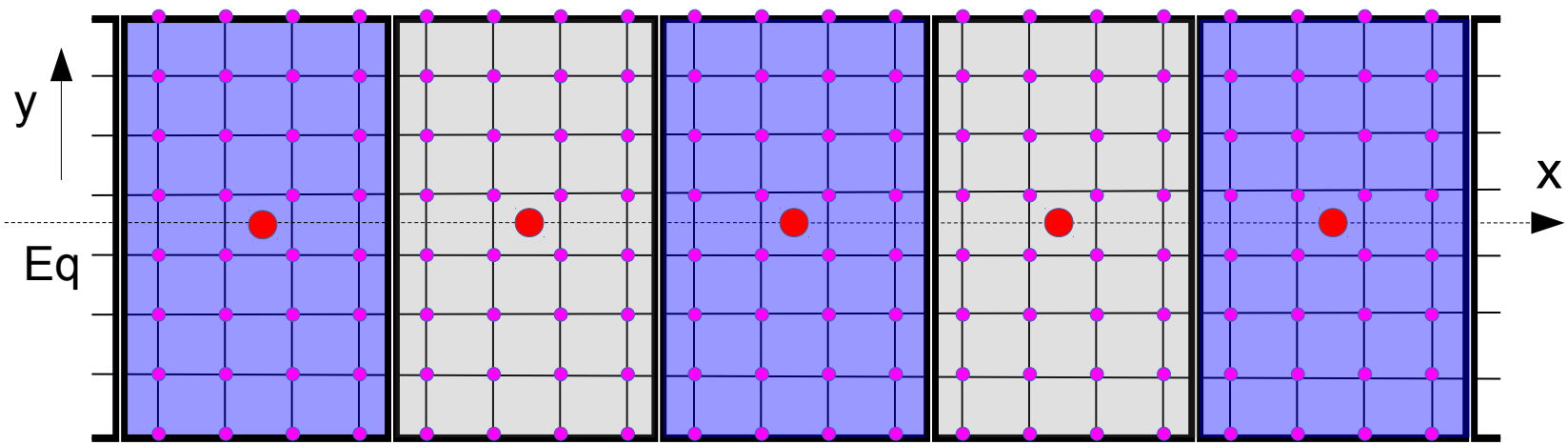
$$\Pi_x = \Pi_y = 0, \ \Pi_z = \Theta$$

$$\Theta_t + W = 0$$

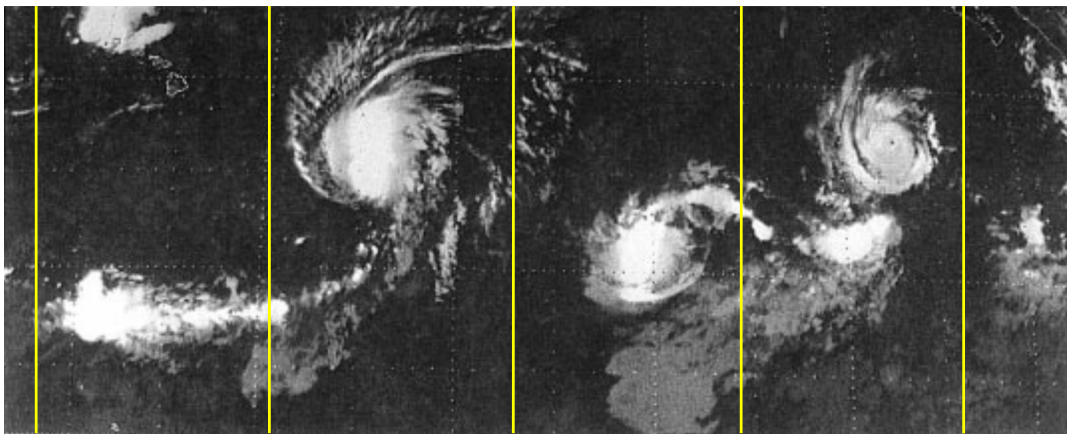
$$[\langle \bar{u} \rangle - U]_X + W_z = 0$$

planetary	$5000km$	X
mesoscale	$500km$	x, y
time	$1d$	t
horizontal velocity	$5ms^{-1}$	u, v
potential temperature	$3.3K$	Θ
diabatic heating	$33Kday^{-1}$	S^θ

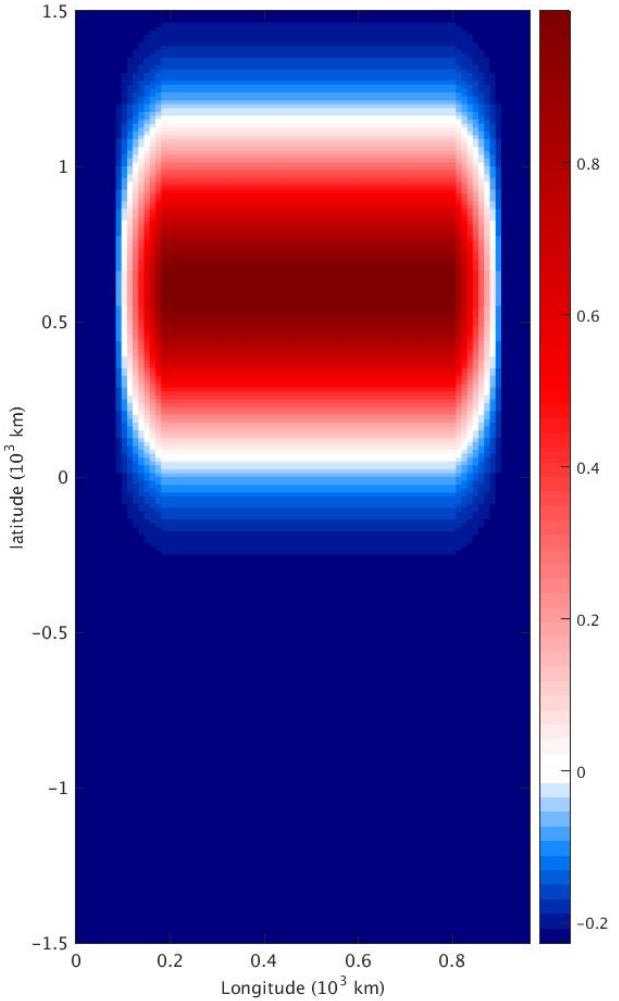
(Biello and Majda, 2013)



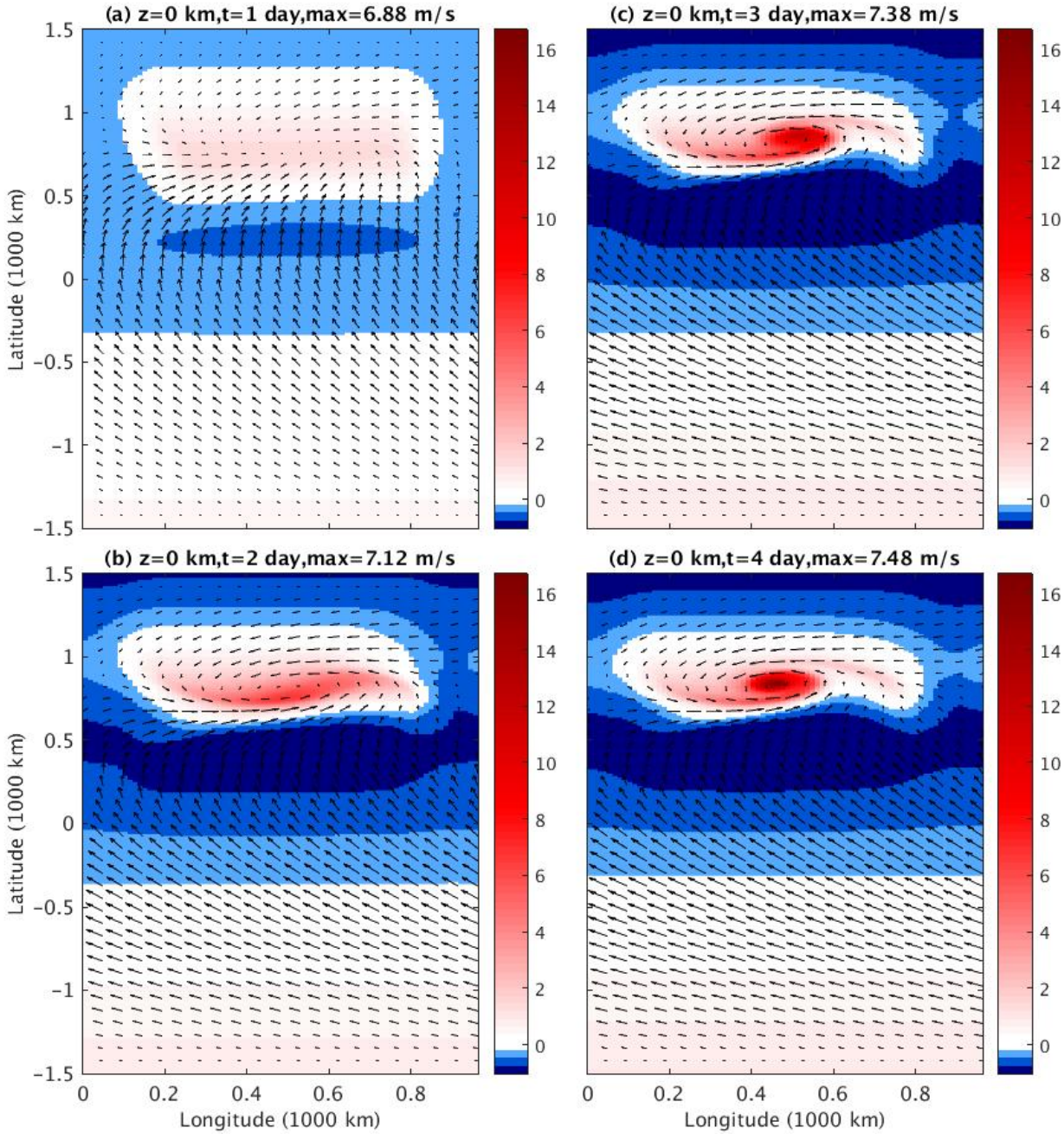
Zonally Symmetric ITCZ on the Planetary Scale

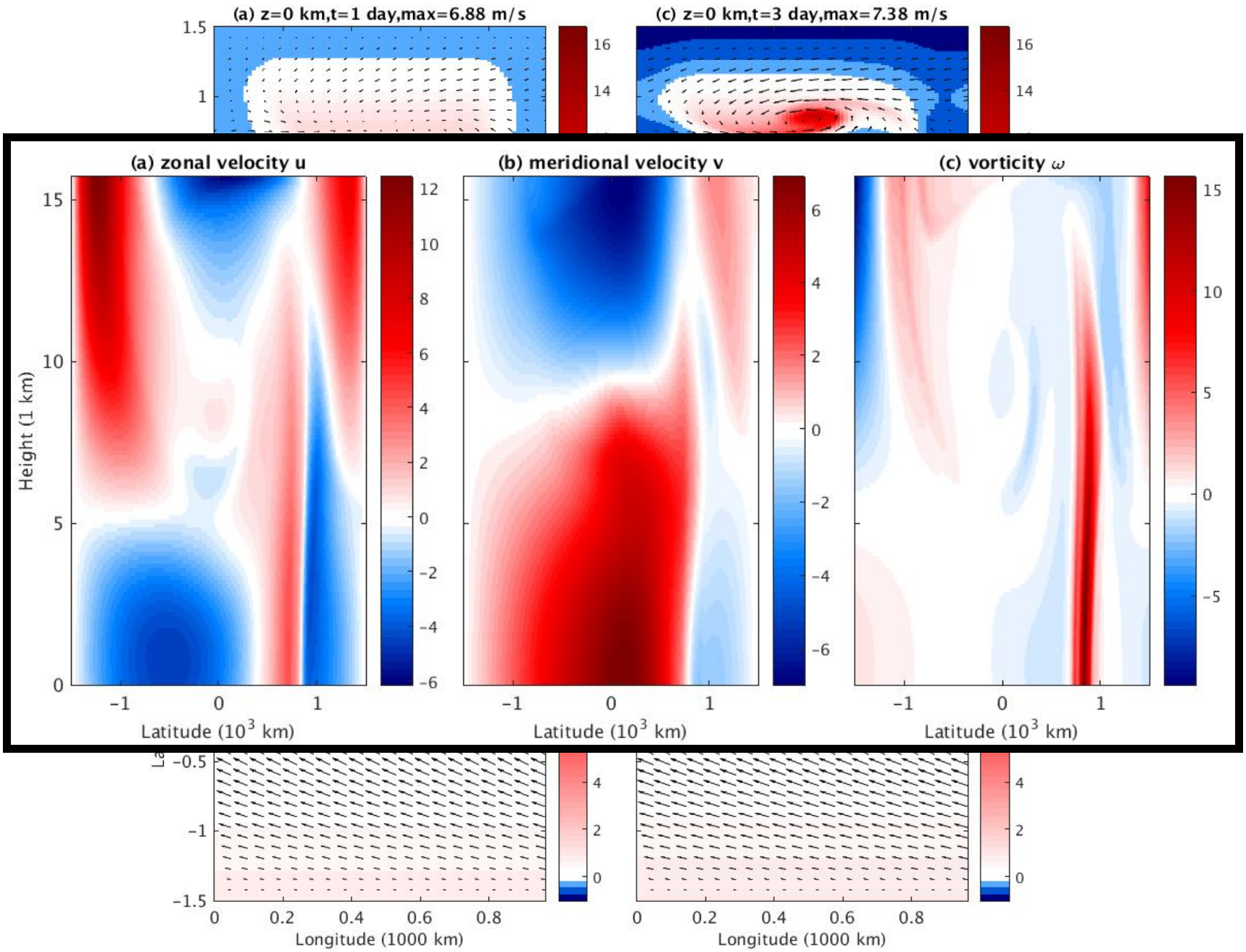


prescribed mesoscale heating



surface-level vorticity (color)




(a) z=0 km,t=1 day,max=6.88 m/s
(c) z=0 km,t=3 day,max=7.38 m/s
(a) zonal velocity u
(b) meridional velocity v
(c) vorticity ω
Height (1 km)
Latitude (10^3 km)
Longitude (1000 km)

Q1: Upscale Impact of ITCZ breakdown on the Planetary-Scale circulation

(1) zonal momentum Equation

$u_t + uu_x + vu_y + wu_z - yv = -p_x - du$

Q1: Upscale Impact of ITCZ breakdown on the Planetary-Scale circulation

(1) zonal momentum Equation

$u_t + uu_x + vu_y + wu_z - yv = -p_x - du$

(2) planetary-scale zonal momentum

$$\bar{u}_t + \bar{v}\bar{u}_y + \bar{w}\bar{u}_z - y\bar{v} = -d\bar{u} - \left(\overline{v'u'}\right)_y - \left(\overline{w'u'}\right)_z$$

eddy flux divergence of zonal momentum (m/s/day)

Q1: Upscale Impact of ITCZ breakdown on the Planetary-Scale circulation

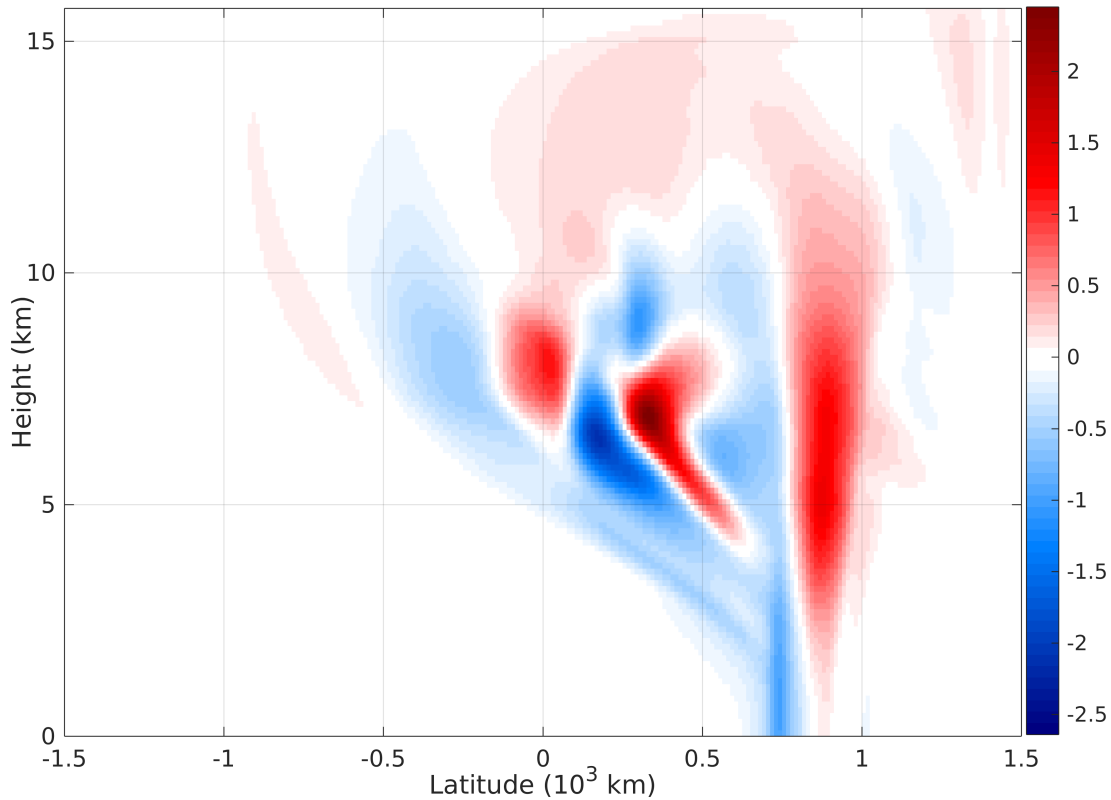
(1) zonal momentum Equation

$$u_t + uu_x + vu_y + wu_z - yv = -p_x - du$$

(2) planetary-scale zonal momentum

$$\bar{u}_t + \bar{v}\bar{u}_y + \bar{w}\bar{u}_z - y\bar{v} = -d\bar{u} - \left(\overline{v'u'}\right)_y - \left(\overline{w'u'}\right)_z$$

eddy flux divergence of zonal momentum (m/s/day)



Q1: Upscale Impact of ITCZ breakdown on the Planetary-Scale circulation

(1) zonal momentum Equation

$u_t + uu_x + vu_y + wu_z - yv = -p_x - du$

(2) planetary-scale zonal momentum

$$\bar{u}_t + \bar{v}\bar{u}_y + \bar{w}\bar{u}_z - y\bar{v} = -d\bar{u} - \left(\overline{v'u'}\right)_y - \left(\overline{w'u'}\right)_z$$

eddy flux divergence of zonal momentum (m/s/day)

(3) kinetic energy

$$\left(\frac{\bar{u}^2}{2}\right)_t + \ldots = \left[-\left(\overline{v'u'}\right)_y - \left(\overline{w'u'}\right)_z\right]\bar{u} + \ldots$$

acceleration/deceleration effects ($m^2 s^{-2} day^{-1}$)

Q1: Upscale Impact of ITCZ breakdown on the Planetary-Scale circulation

(1) zonal momentum Equation

$u_t + uu_x + vu_y + wu_z - yv = -p_x - du$

(2) planetary-scale zonal momentum

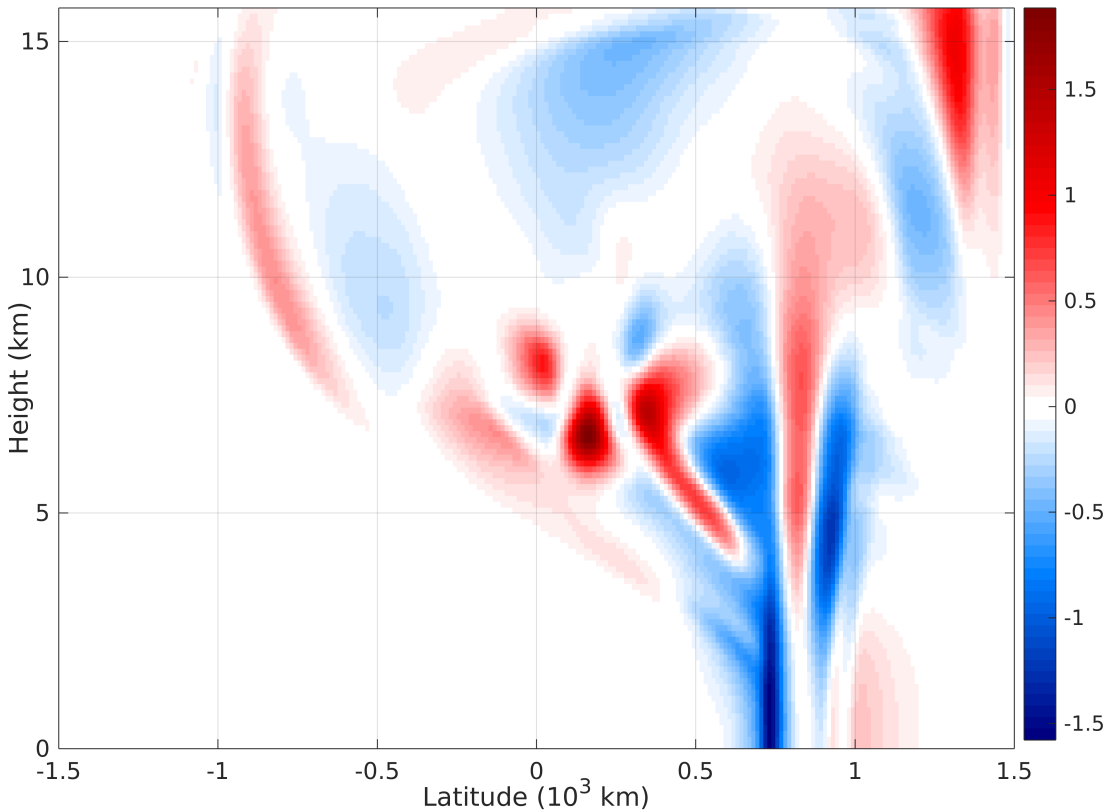
$$\bar{u}_t + \bar{v}\bar{u}_y + \bar{w}\bar{u}_z - y\bar{v} = -d\bar{u} - \left(\overline{v'u'}\right)_y - \left(\overline{w'u'}\right)_z$$

eddy flux divergence of zonal momentum (m/s/day)

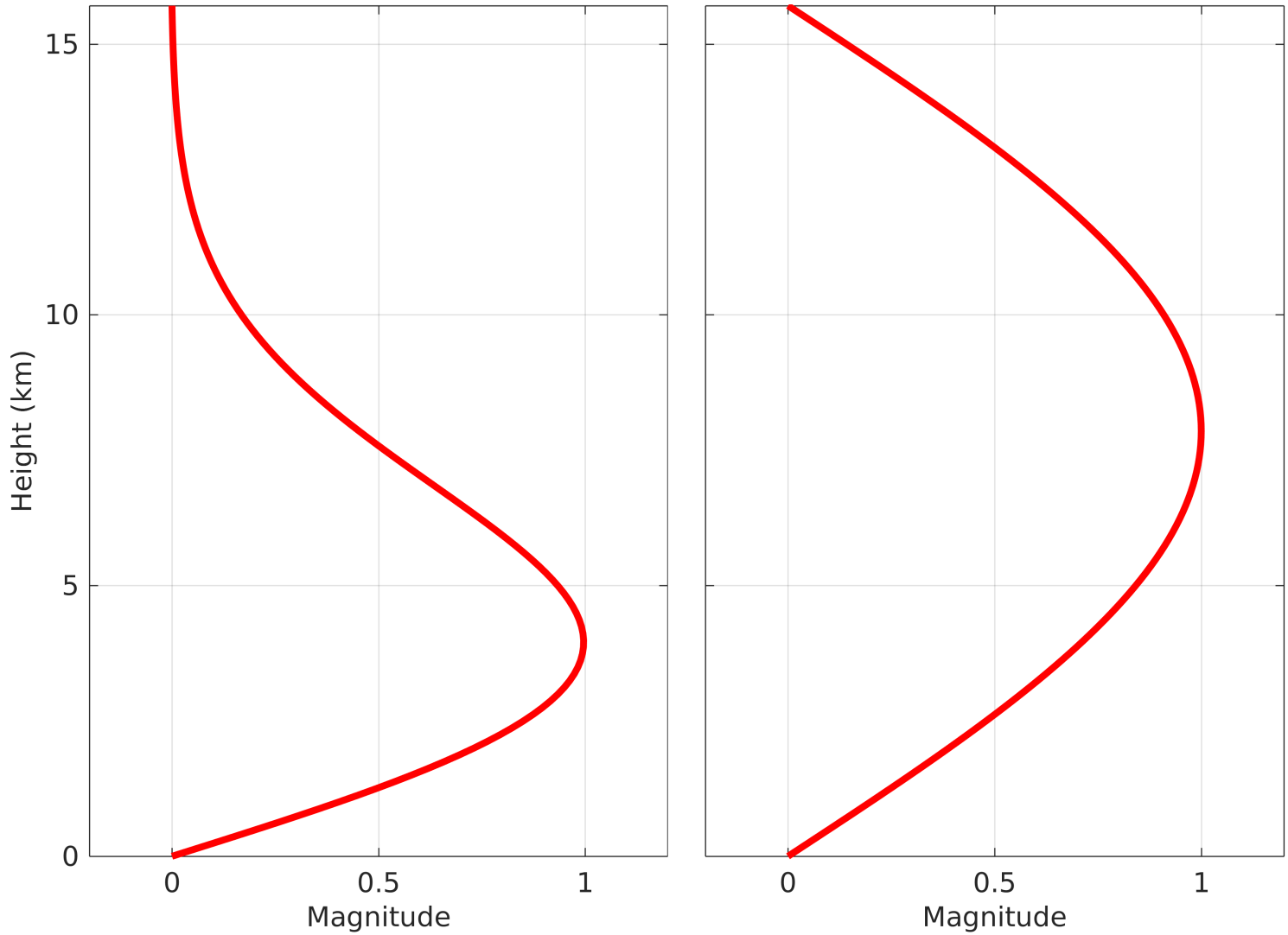
(3) kinetic energy

$\left(\frac{\bar{u}^2}{2}\right)_t + \ldots = \left[-\left(\overline{v'u'}\right)_y - \left(\overline{w'u'}\right)_z\right]\bar{u}$ -

acceleration/deceleration effects ($m^2 s^{-2} day^{-1}$)



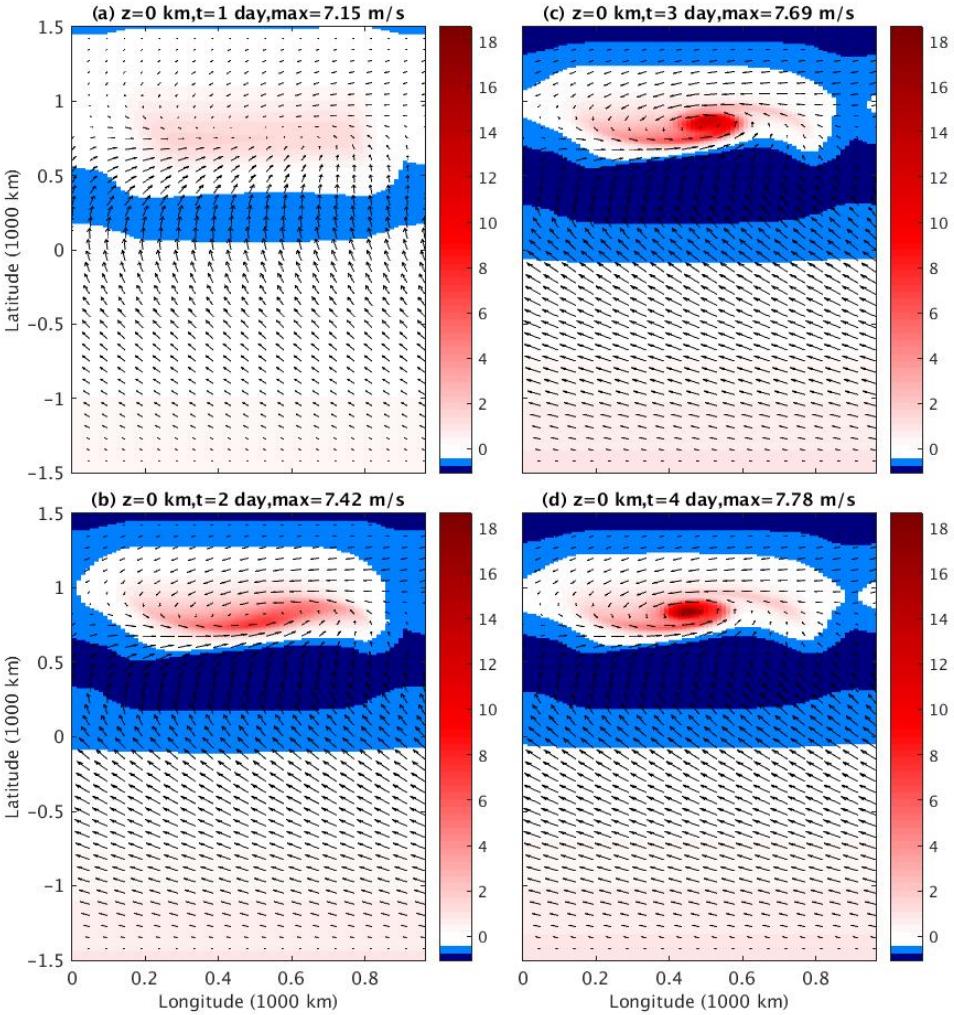
Q2: Difference between shallow and deep heating cases



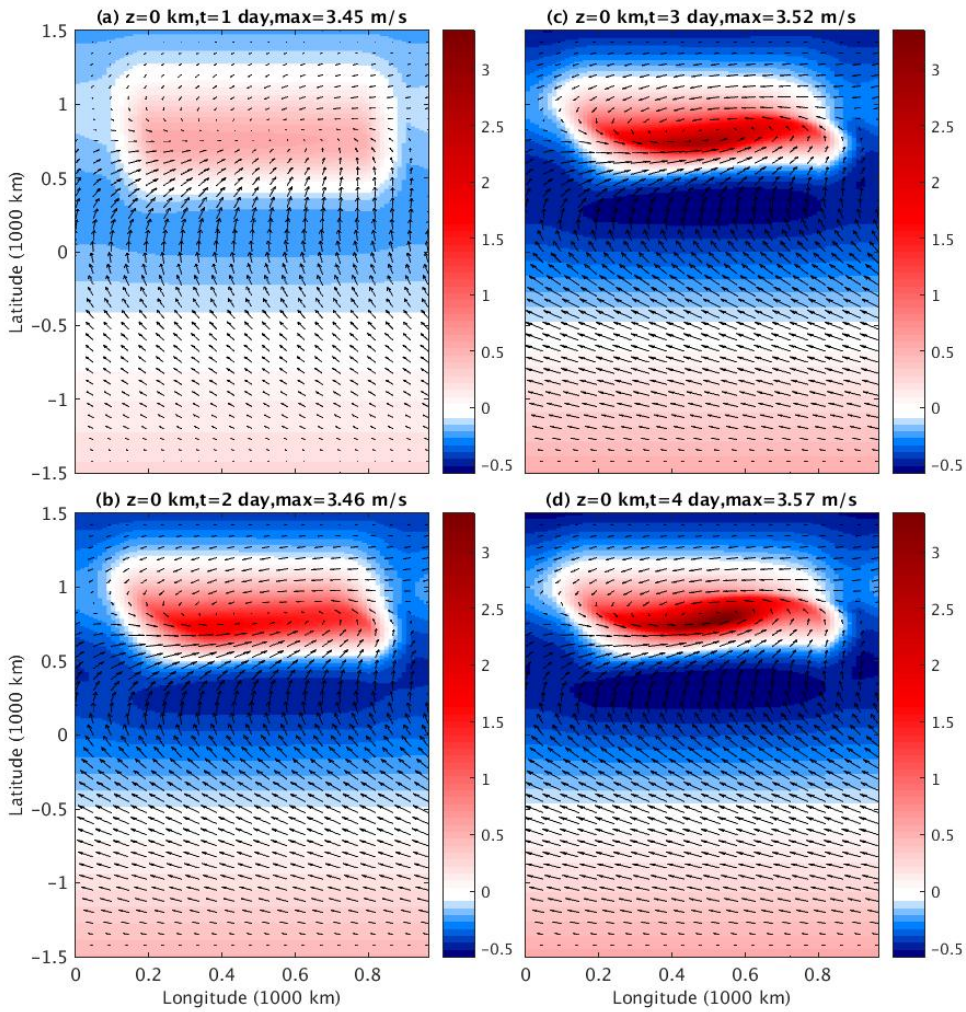
shallow

deep

Surface-level vorticity

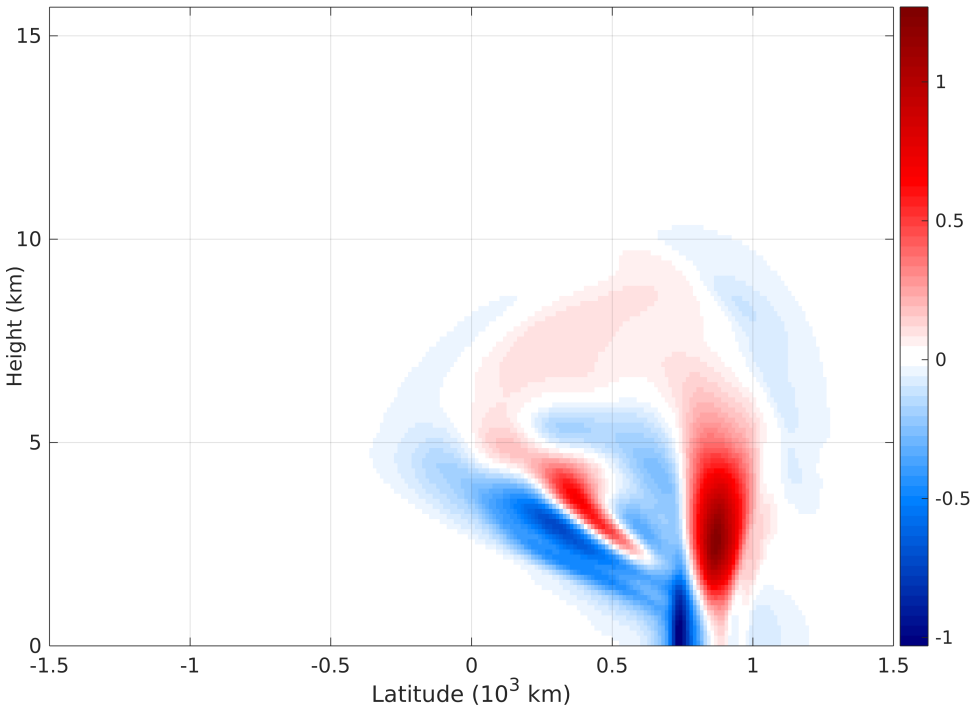


shallow

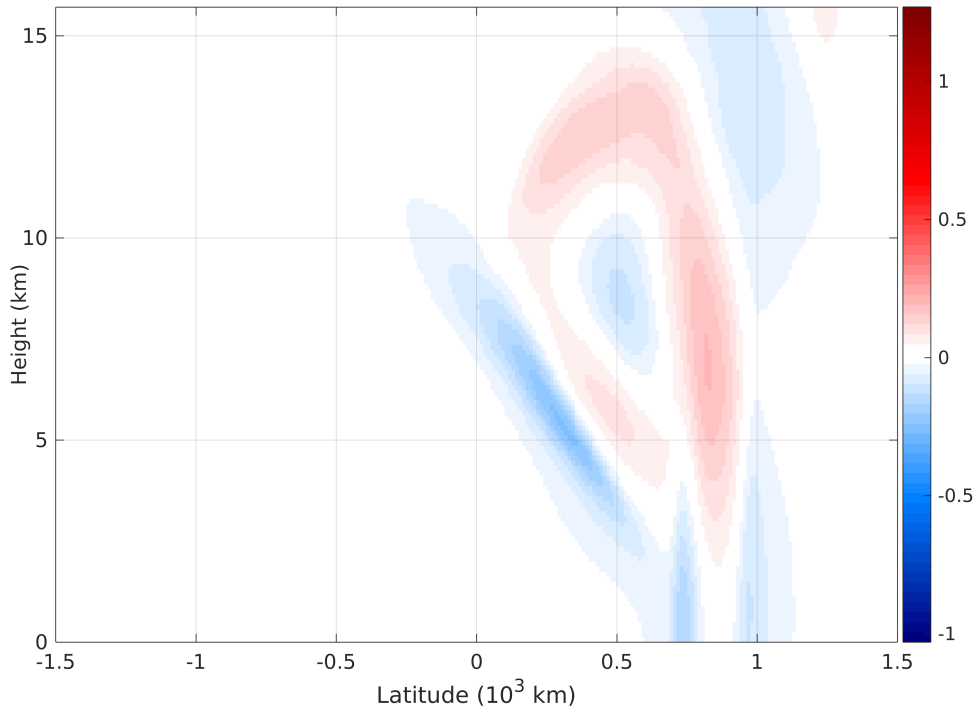


deep

Eddy Flux Divergence of Zonal Momentum $-\left(\overline{v'u'}\right)_y - \left(\overline{w'u'}\right)_z$

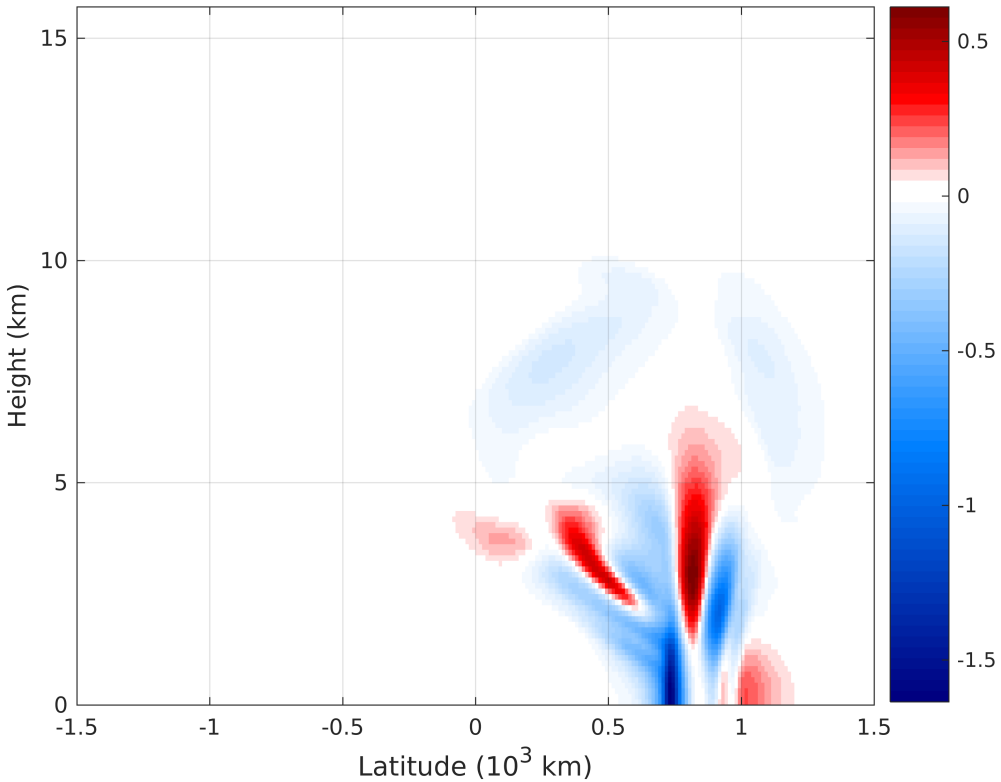


shallow

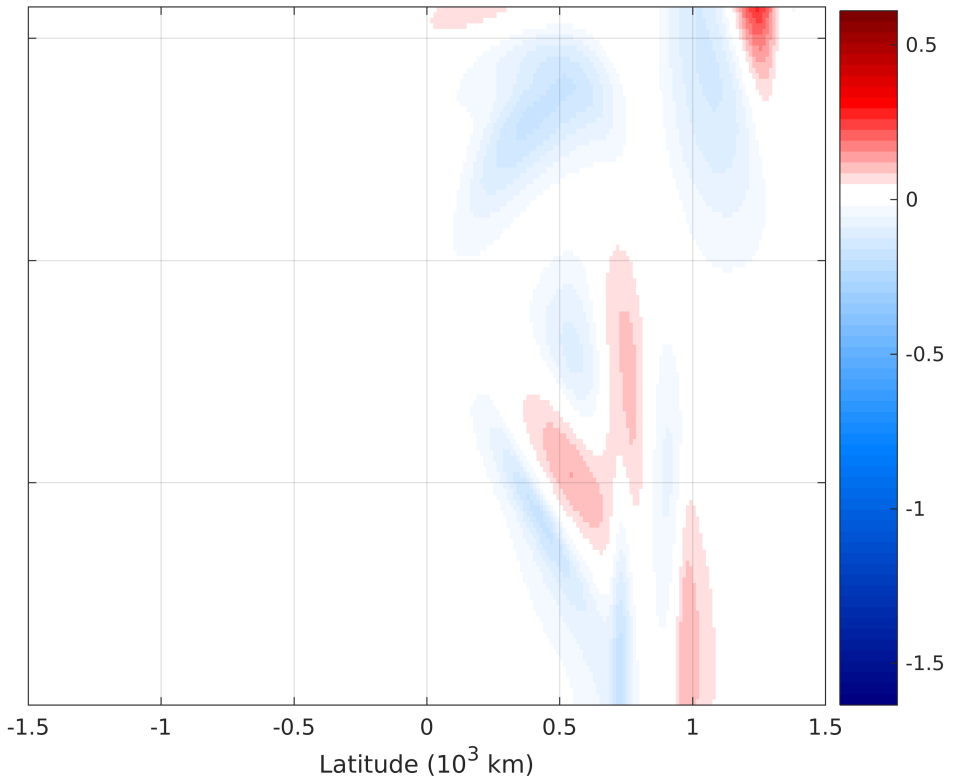


deep

Acceleration/deceleration $\left[-\left(\overline{v'u'}\right)_y - \left(\overline{w'u'}\right)_z \right] \bar{u}$



shallow

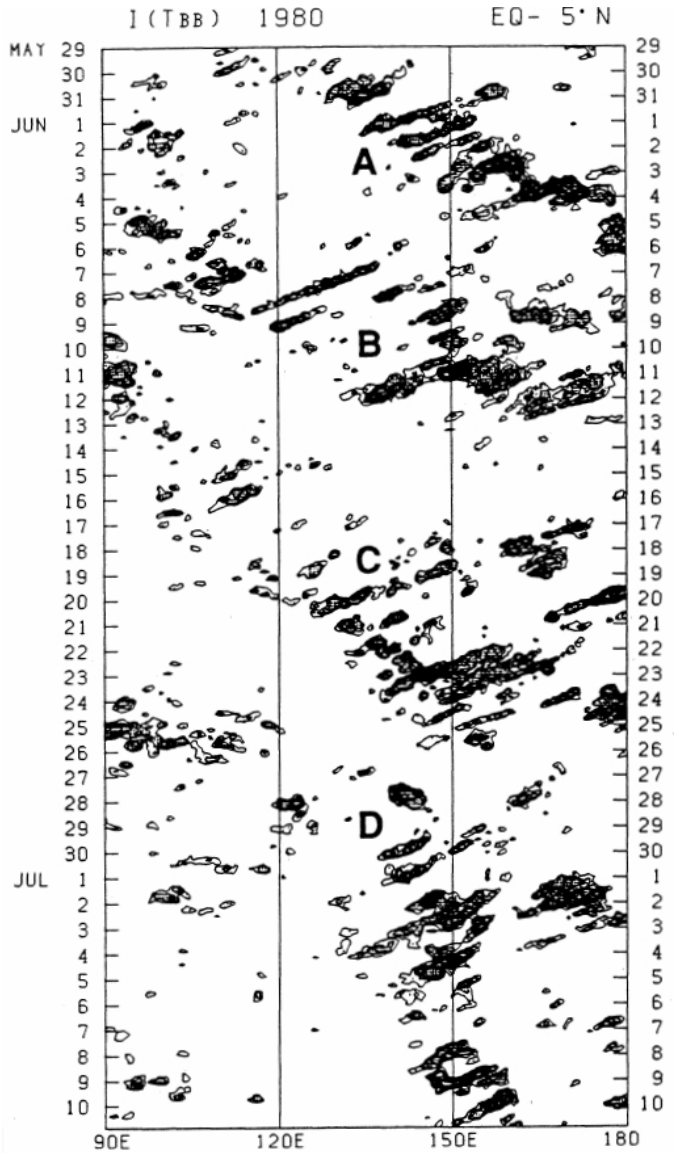


deep

Summary

- Baroclinic aspects of ITCZ breakdown.
- ITCZ breakdown induce significant eddy flux divergence of zonal momentum and accleration/deceleration effects on the planetary-scale zonal jets.
- Shallow heating Induce stronger vorticity and winds at the surface, stronger eddy flux divergence of zonal momentum and acceleration/deceleration effects.

Current and Future Research (not in thesis)



(Nakazawa,1988)

Mesoscale Equatorial Synoptic Dynamics model (MESD), (Majda, 2007)

Its 2D version, "*Upscale Impact of Mesoscale Disturbances of Tropical Convection on Synoptic-Scale Equatorial Waves in Two-Dimensional Flows*", manuscript submitted to JAS.

Its 3D version...

Thank you!

References

[1] Majda, A. J. (2007). New multiscale models and self-similarity in tropical convection. Journal of the atmospheric sciences, 64(4), 1393-1404.

[2] Yang, Q., & Majda, A. J. (2014). A multi-scale model for the intraseasonal impact of the diurnal cycle of tropical convection. Theoretical and Computational Fluid Dynamics, 28(6), 605-633.

[3] Majda, A. J., & Yang, Q. (2016). A Multiscale Model for the Intraseasonal Impact of the Diurnal Cycle over the Maritime Continent on the Madden-Julian Oscillation. Journal of the Atmospheric Sciences, 73(2), 579-604.

[4] Yang, Q. & Majda, A. J. & Khouider, B. (2017). ITCZ Breakdown and Its Upscale Impact on the Planetary-Scale Circulation over the Eastern Pacific. Submitted to Journal of the Atmospheric Sciences. In revision.

[5] Yang, Q. & Majda, A. J. (2017). Upscale Impact of Mesoscale Disturbances of Tropical Convection on the Synoptic-Scale Equatorial Waves in Two-Dimensional Flows. Submitted to Journal of the Atmospheric Sciences.