MJO AND CONVECTIVELY COUPLED WAVES IN A COARSE RESOLUTION GCM WITH A SIMPLE MULTI-CLOUD MODEL

University of Victoria

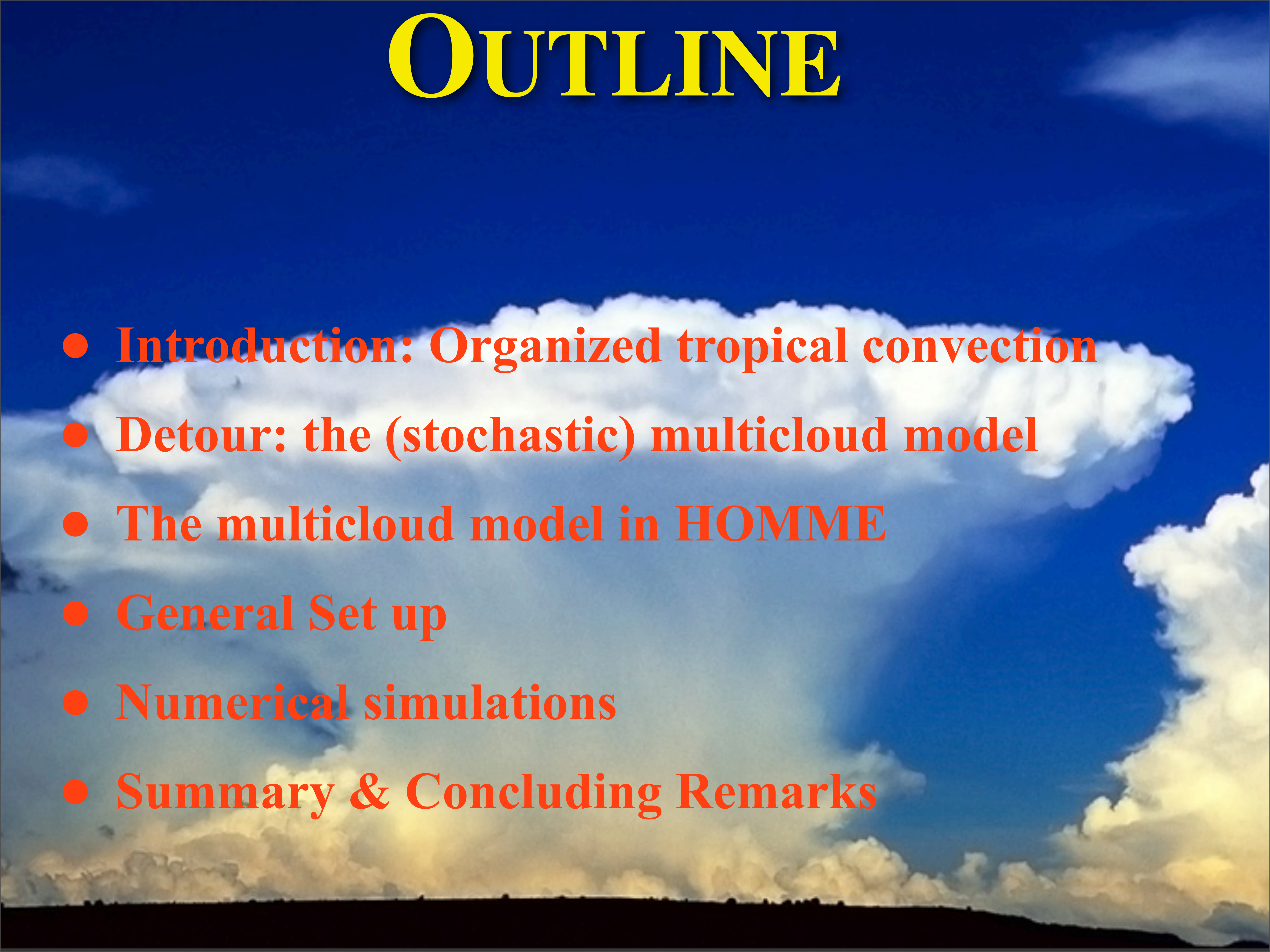
BOUALEM KHOUIDER (UNIVERSITY OF VICTORIA)

ANDREW J. MAJDA (COURANT INSTITUTE)

AMIK ST CYR & JOSEPH TRIBBIA (NCAR)

Acknowledgment: Natural Sciences and Engineering Research Council of Canada (NSERC) and The Canadian Foundation for Climate and Atmospheric Sciences (CFCAS)

OUTLINE



- Introduction: Organized tropical convection
- Detour: the (stochastic) multicloud model
- The multicloud model in HOMME
- General Set up
- Numerical simulations
- Summary & Concluding Remarks

Related Papers (some)

❖Deterministic Multicloud model

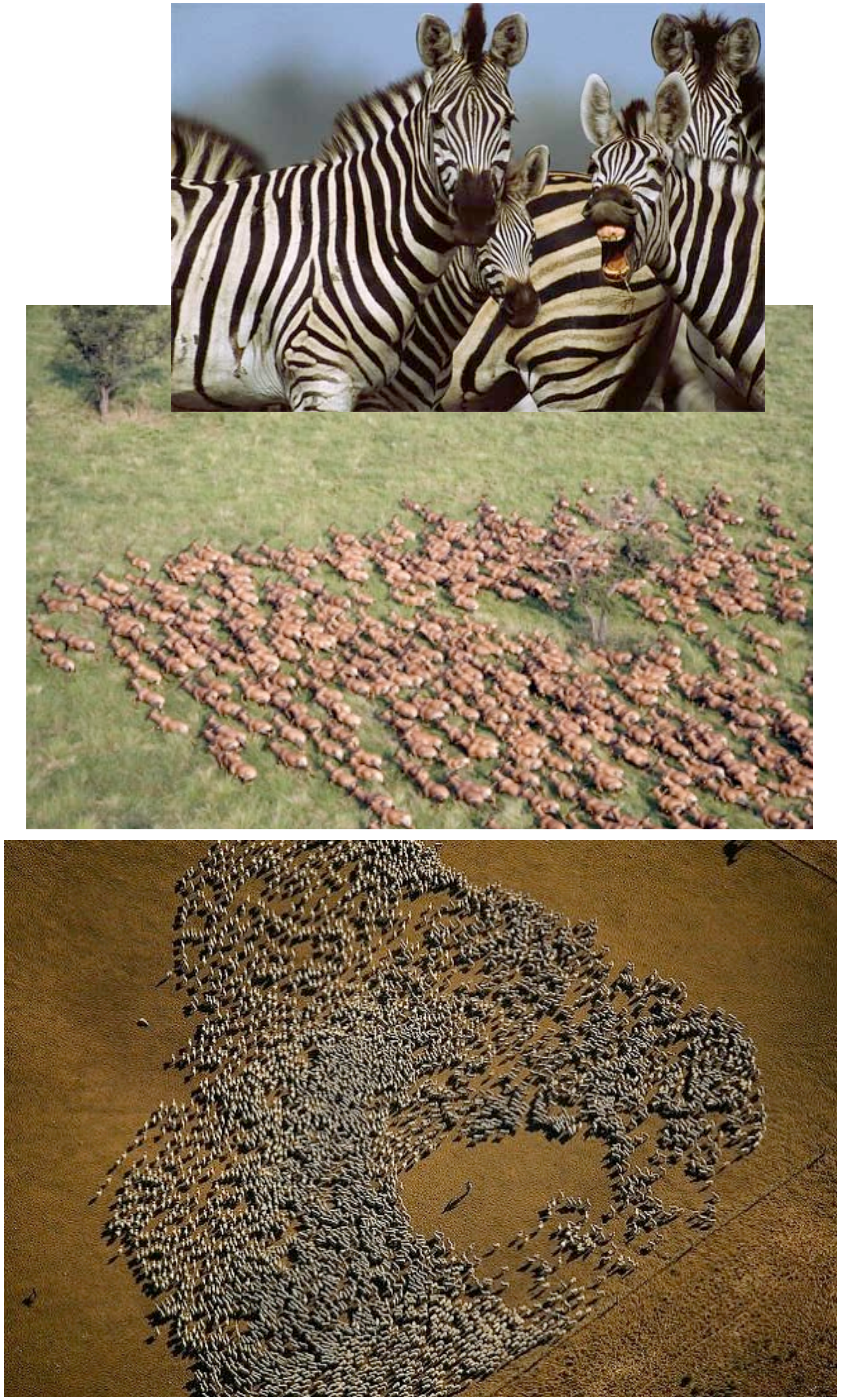
- ✓ K. and Majda, J. Atmos. Sci. (2006, 2007, 2008, 2008)
- ✓ Majda, Stechmann, and K., PNAS (2007): MJO analog
- ✓ Majda and Stechmann (2009): gravity waves-mean shear interactions and CMT
- ✓ Waite and K., J. Atmos. (2009): Boudary layer dynamics
- ✓ Han and K., J. Atmos. (2010): CCW's in sheared environment
- ✓ K., St Cyr, Majda, and Tribbia, J. Atmos. Sci. (2010): MJO and CCW's in HOMME

❖Stochastic Models for convection

- ✓ Majda and K., PNAS, (2001): Mesoscopic and Stochastic models for CIN
- ✓ K., Majda and Katsoulakis, PNAS (2003): Coarse-grained stochastic models for CIN,
- ➡ Being implemented in Zhang&McFarlane parametrization (Ian Ross).
- ✓ K., Biello, and Majda, CMS, (2009): Stochastic multicloud model, 2009

INTRODUCTION

- Convection is tropics organized on a hierarchy of scales
  - ✓ individual clouds (hrs, 1-10, km),
  - ✓ mesoscale clusters (1-2 days, 500 km),
  - ✓ superclusters (2-5 days, 2000 km)--convectively coupled waves,
  - ✓ planetary scale envelopes--Madden Julian oscillation (40 days, 20,000 km)



Satellite Observations: OLR

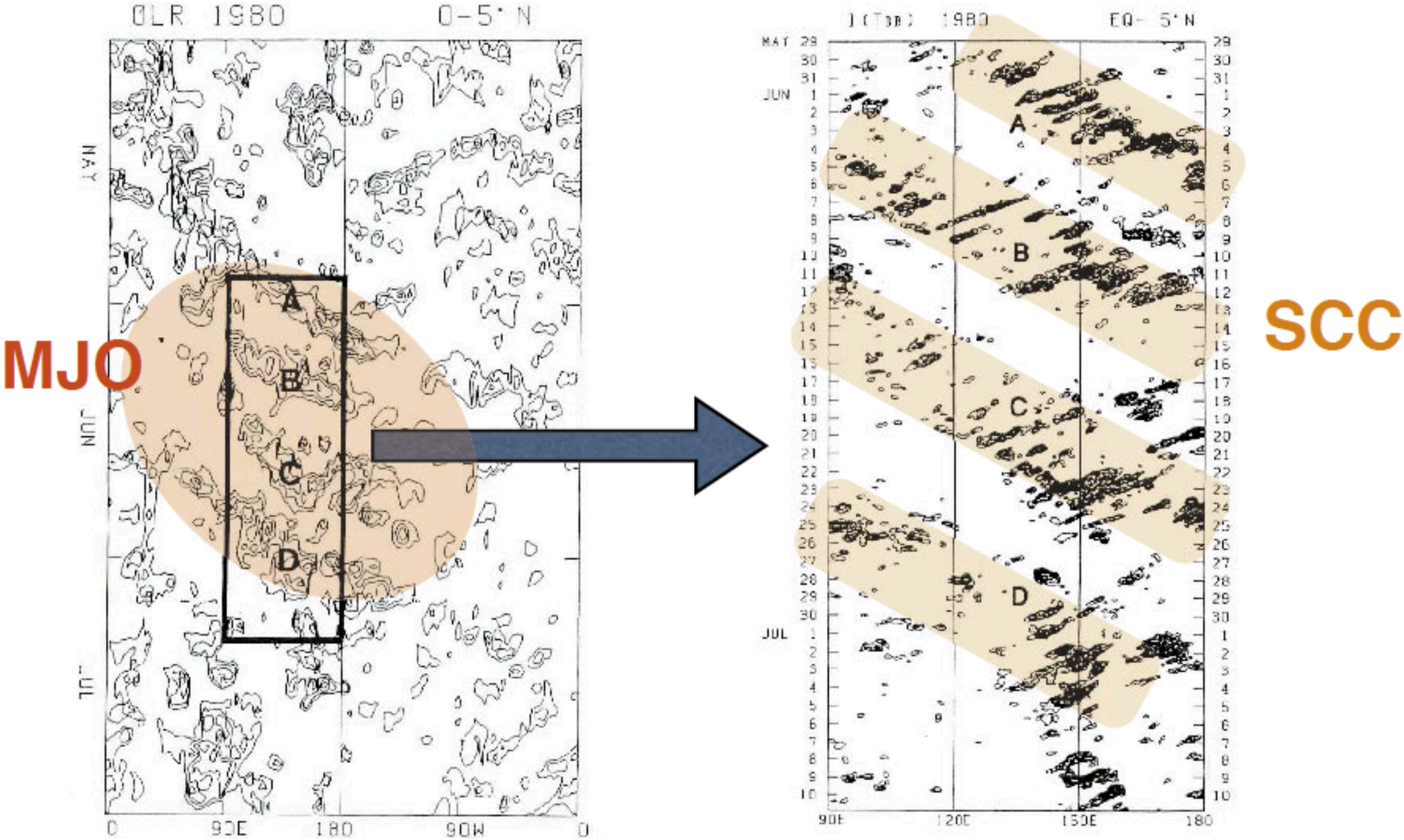
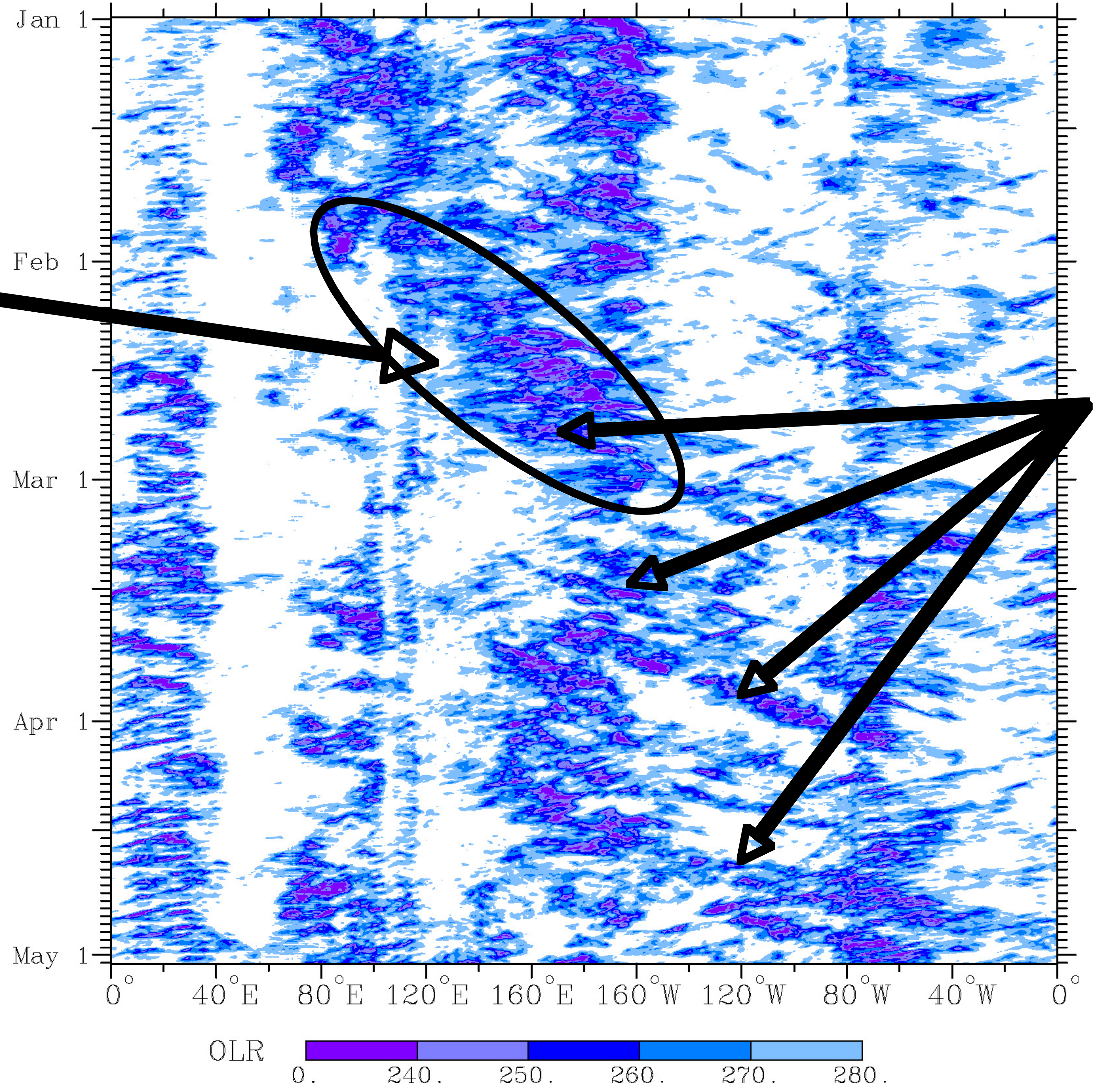


Fig. 1: MJO consists of Super Cloud Clusters (Nakazawa, 1988)

OBSERVATIONS OF KELVIN WAVES AND THE MJO

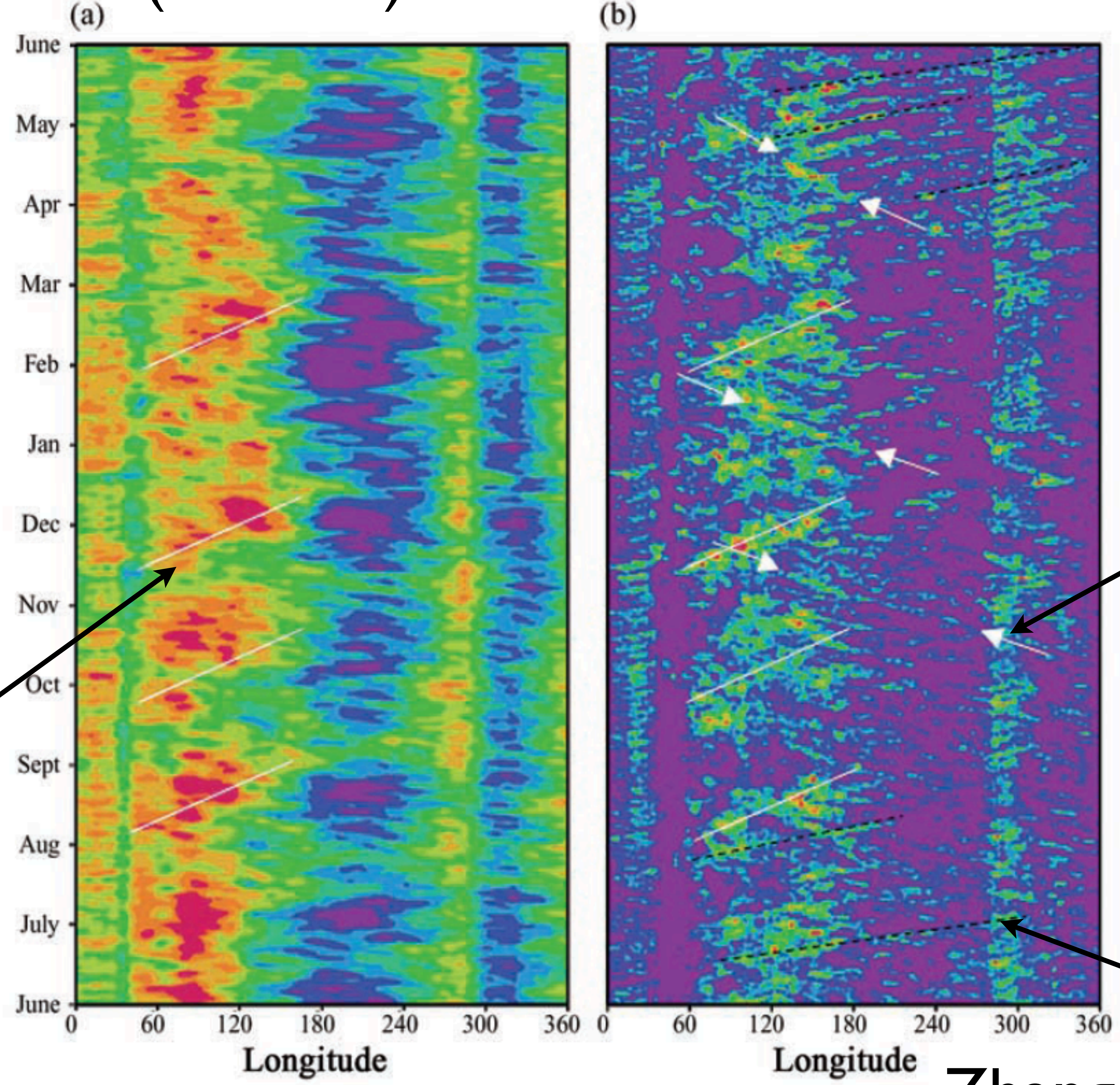
Time–longitude diagram of CLAUS Tb (2.5S–7.5N), January–April 1987



MJO
($5\ m\ s^{-1}$)

Kelvin waves
($15\ m\ s^{-1}$)

G. Kiladis



U (850 hPa)

Precipitation

MJO

Rossby or MRG

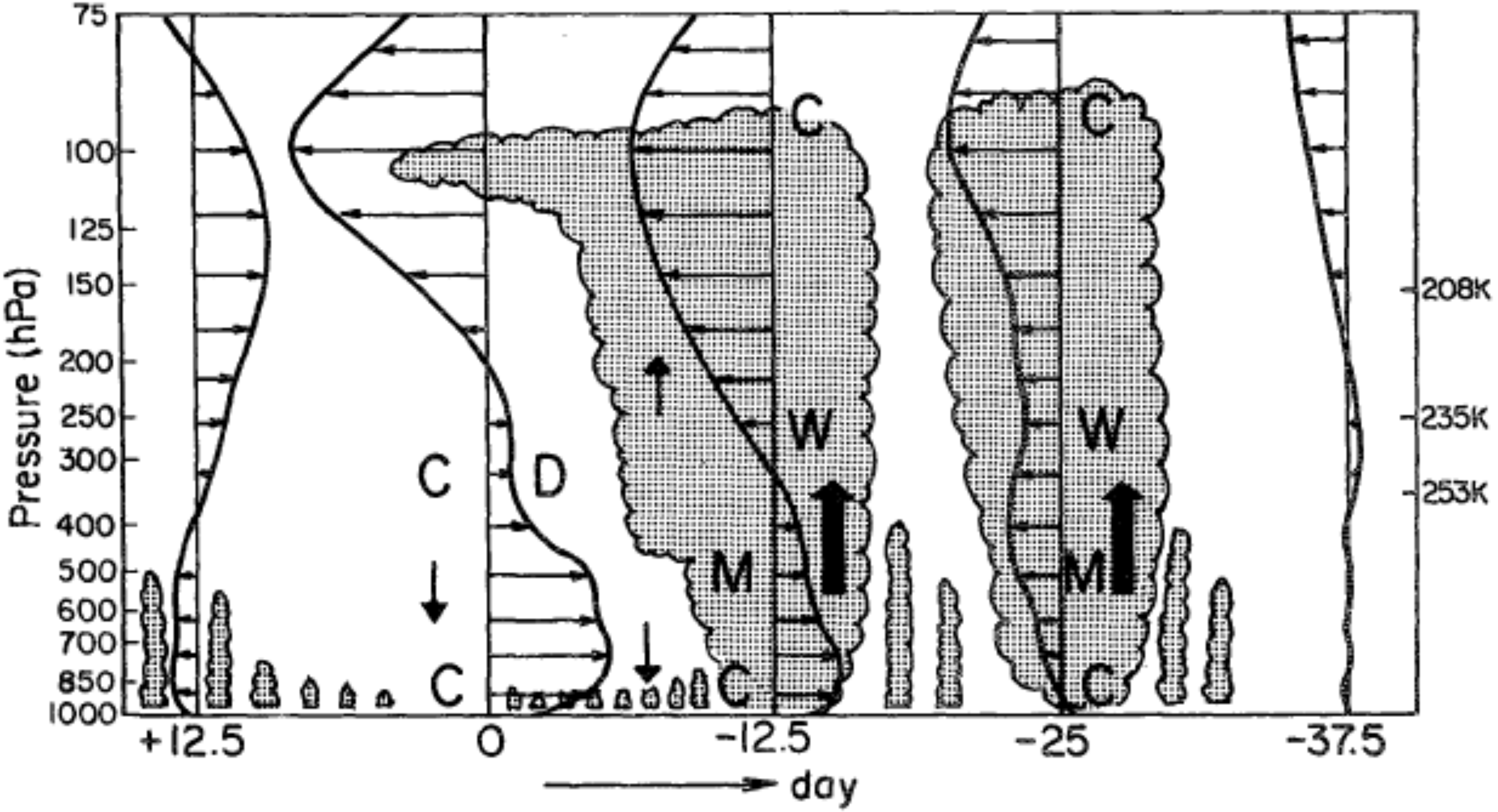
Kelvin

Zhang (2005)

INTRODUCTION (CTND)

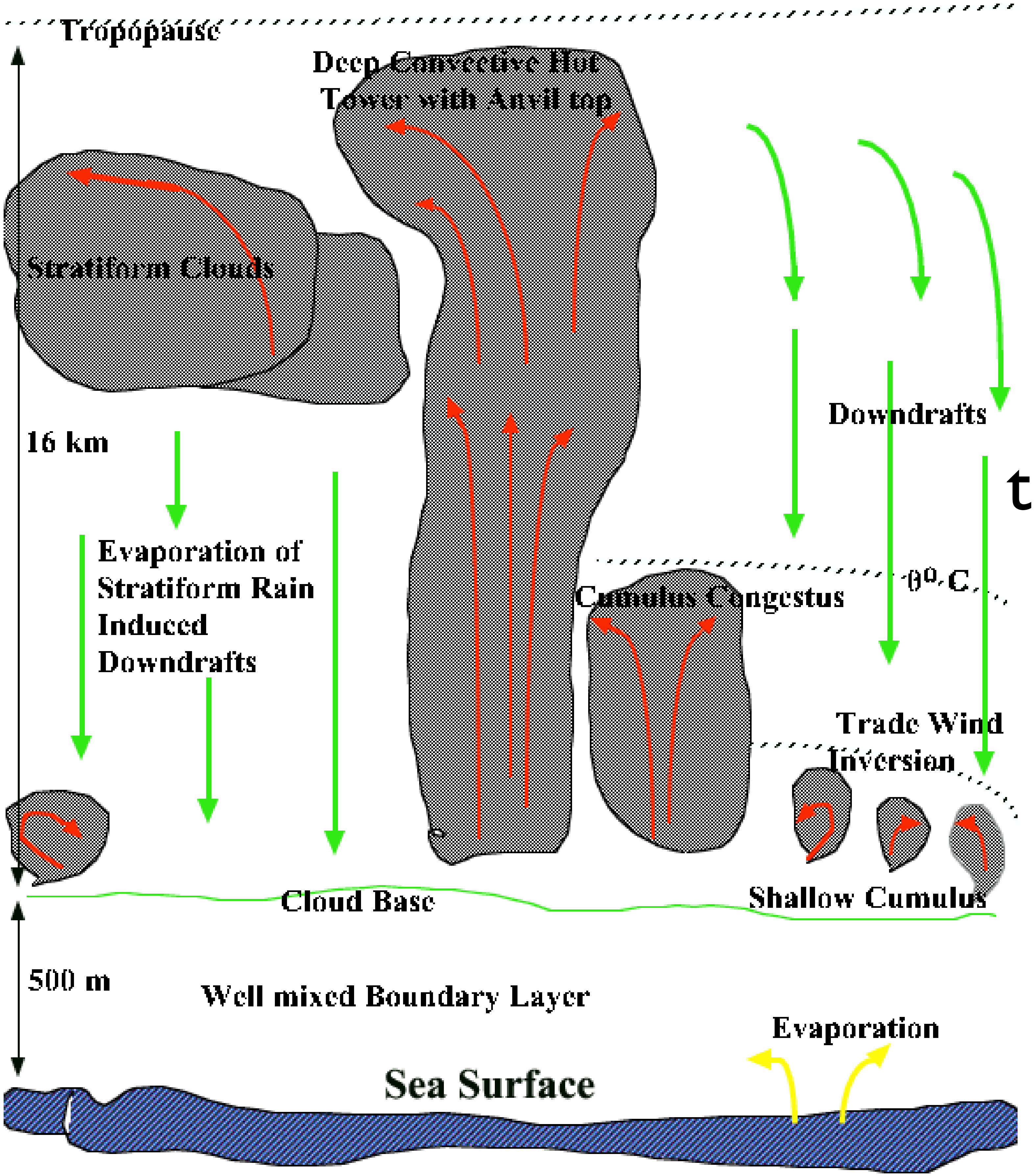
- MJO affects tropical and extra-tropical climate and weather patterns: monsoons, ENSO, & extratropical weather patterns.
- GCMs represent poorly MJO and CCW's due to inadequate treatment of organized convection
- Superclusters are moist analogues of the equatorially trapped waves but with important differences (Takayabu 1994, Wheeler & Kiladis 1999).
- Multicloud model convectively coupled waves
- Multicloud model used here as cumulus parameterization in next generation NCAR GCM (HOMME)

Physical and dynamical structure of MJO



Lin and Johnson 1996

CARTOON VIEW OF THE MULTICLOUD MODEL

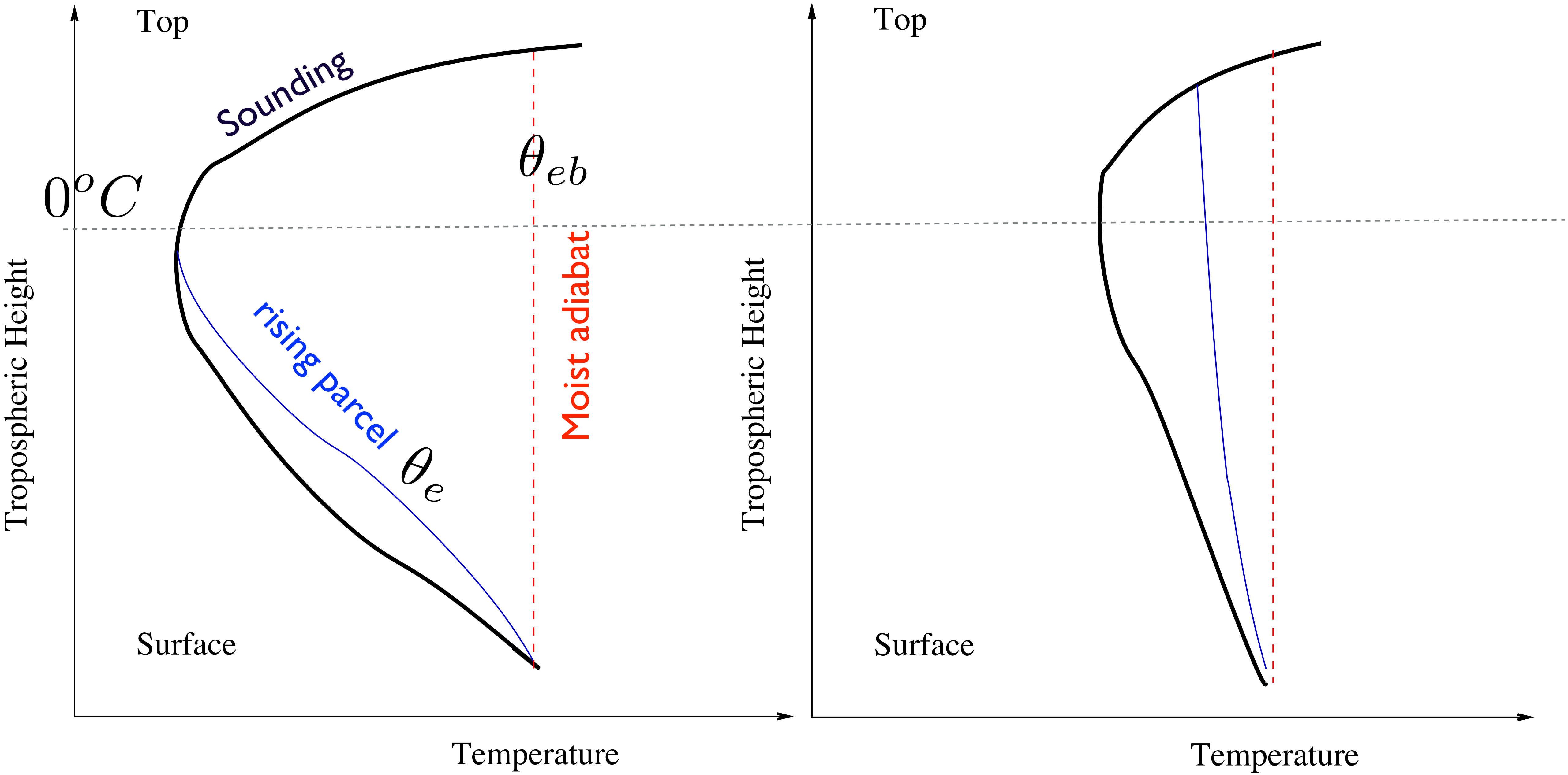


Self-similarity of tropical convective systems

Dilute parcel lifting

Dry environment

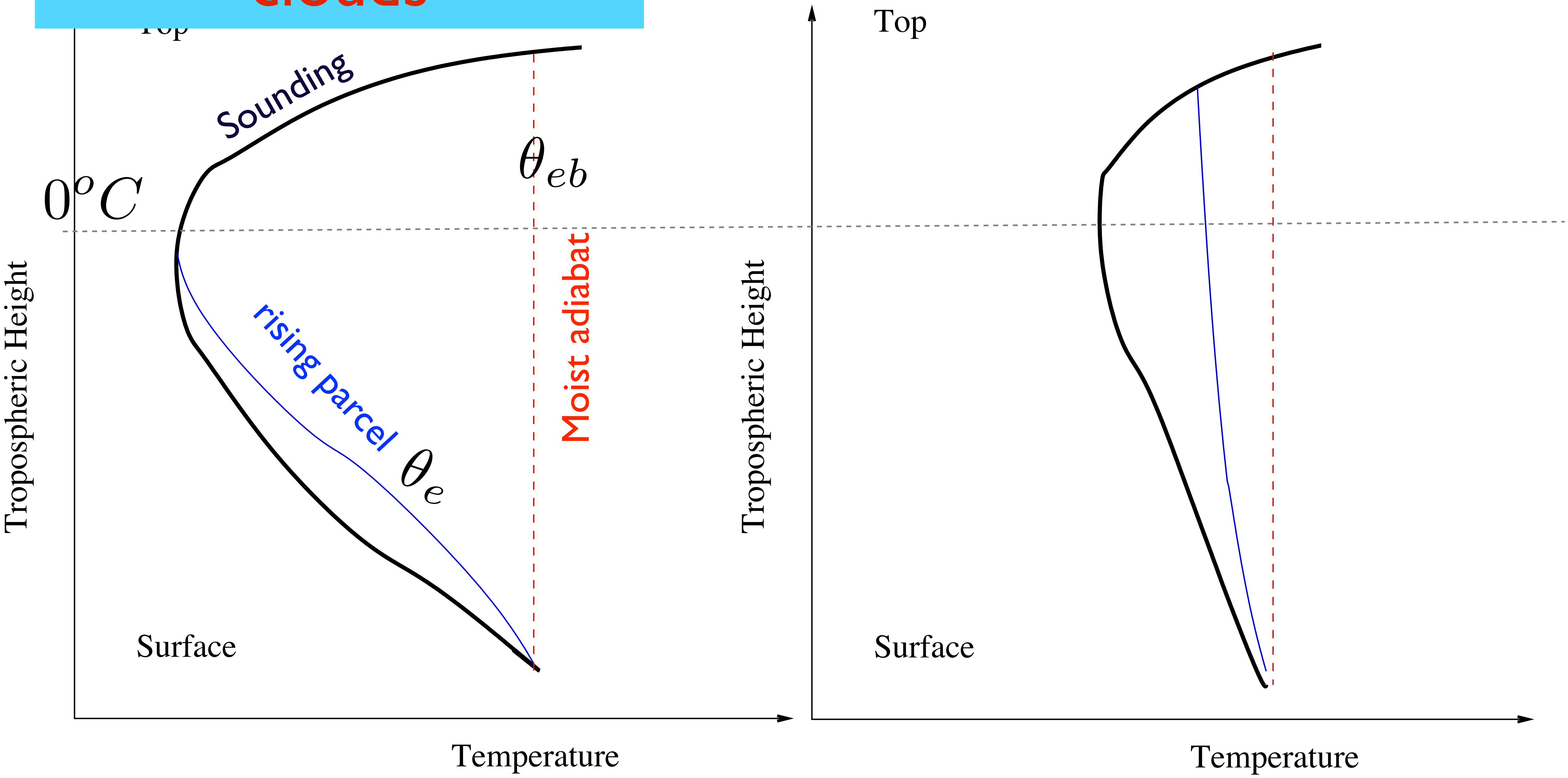
Moist environment



Dilute parcel lifting

Dry troposphere with positive CAPE will favor congestus clouds

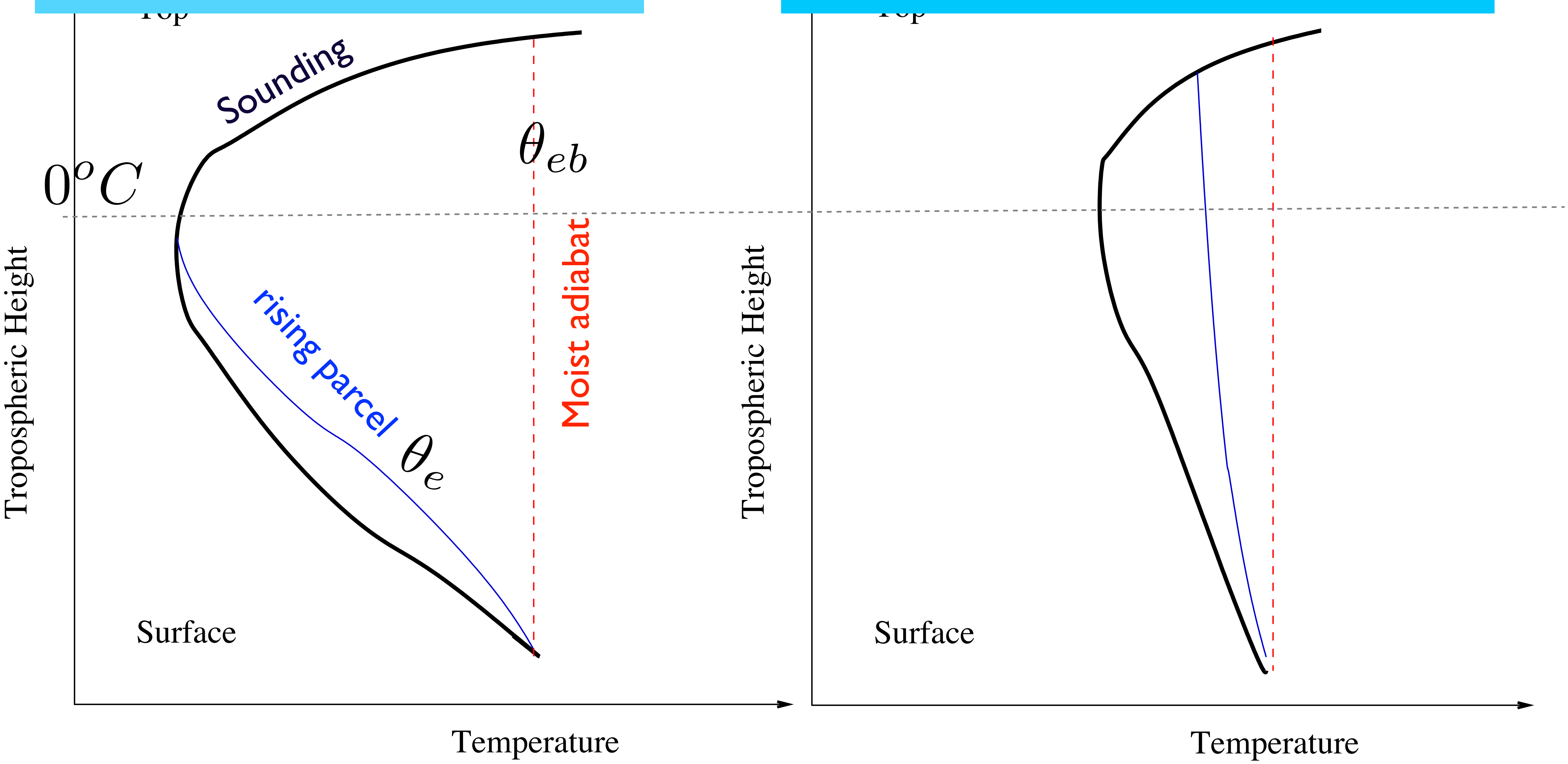
Moist environment



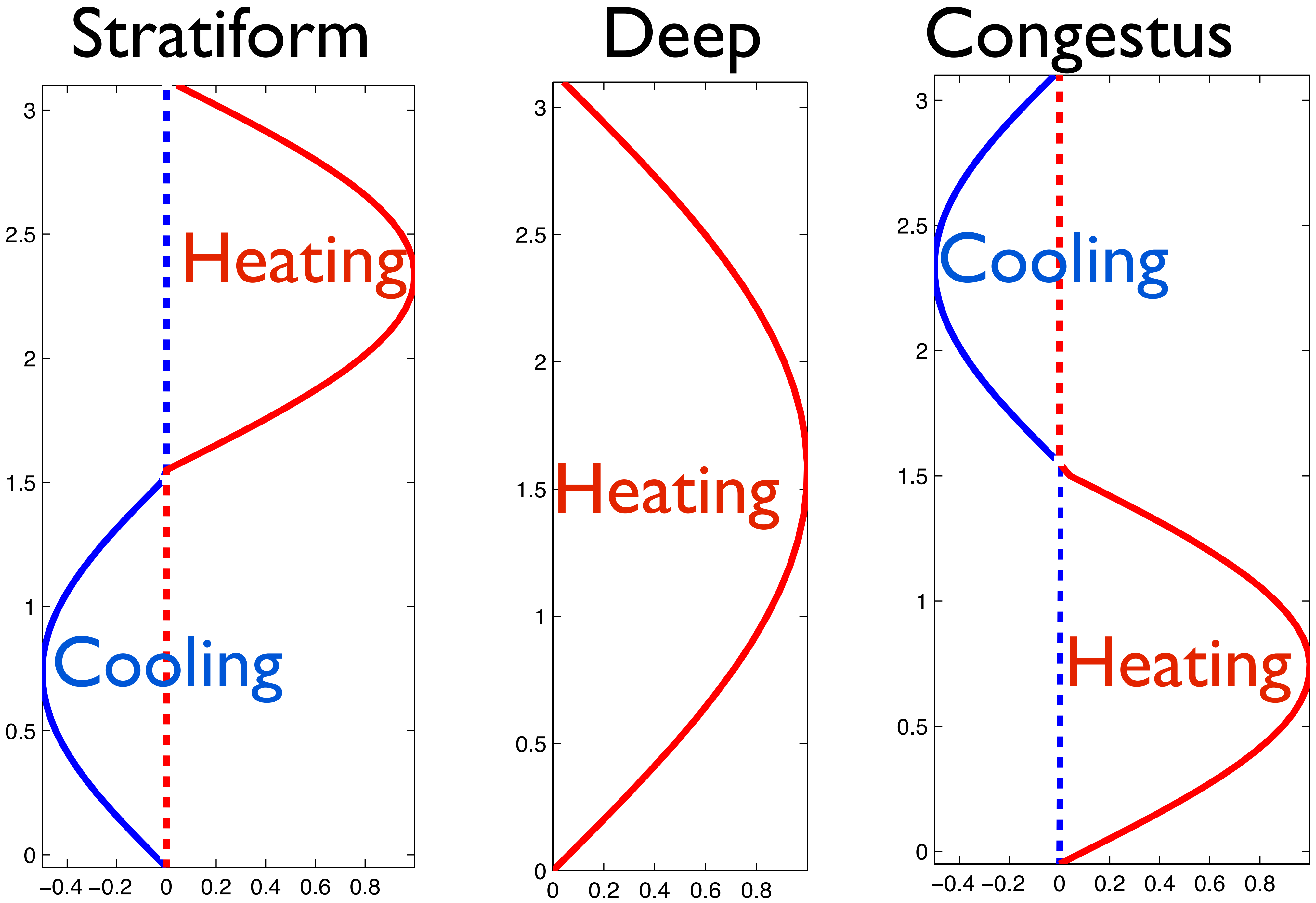
Dilute parcel lifting

Dry troposphere with positive CAPE will favor congestus clouds

Deep convection is allowed (beyond freezing level) when troposphere is moist



Idealized heating profiles

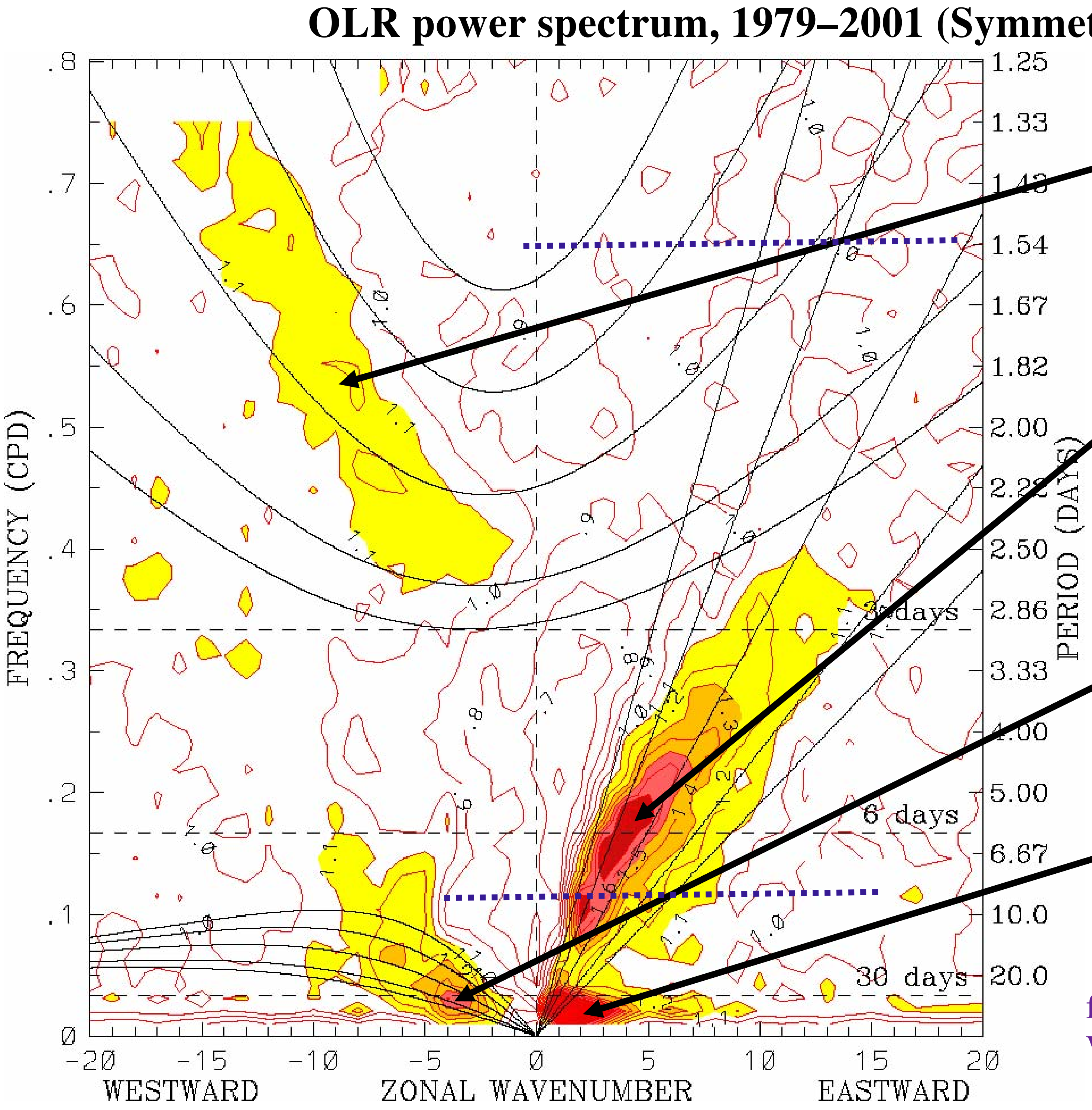


Stratiform

Deep

Congestus

Linear Instabilities and Waves


OLR power spectrum, 1979–2001 (Symmetric)

Westward Inertio-Gravity

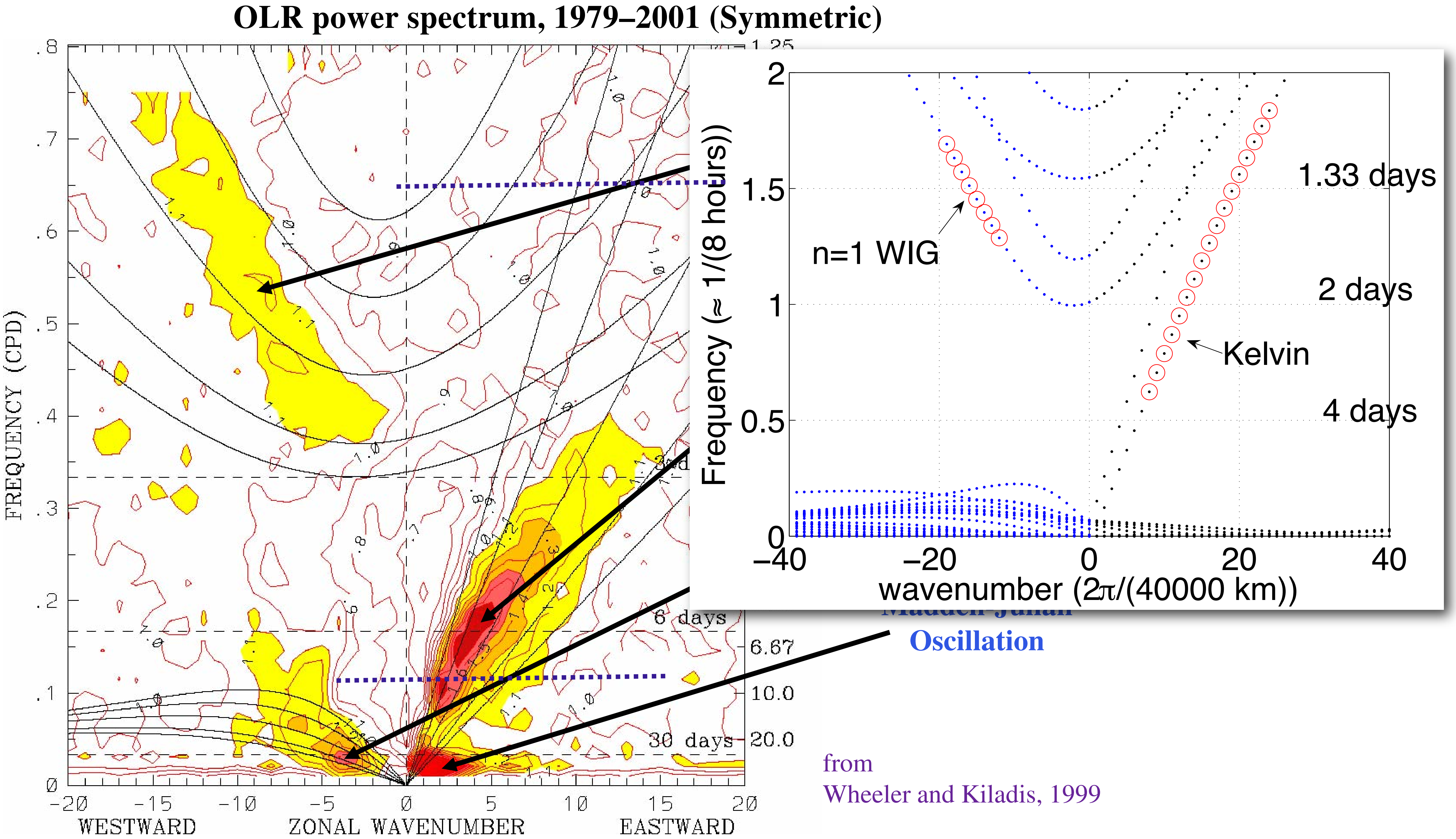
Kelvin

Equatorial Rossby

Madden-Julian Oscillation

from
Wheeler and Kiladis, 1999

Linear Instabilities and Waves



Madden-Julian Oscillation

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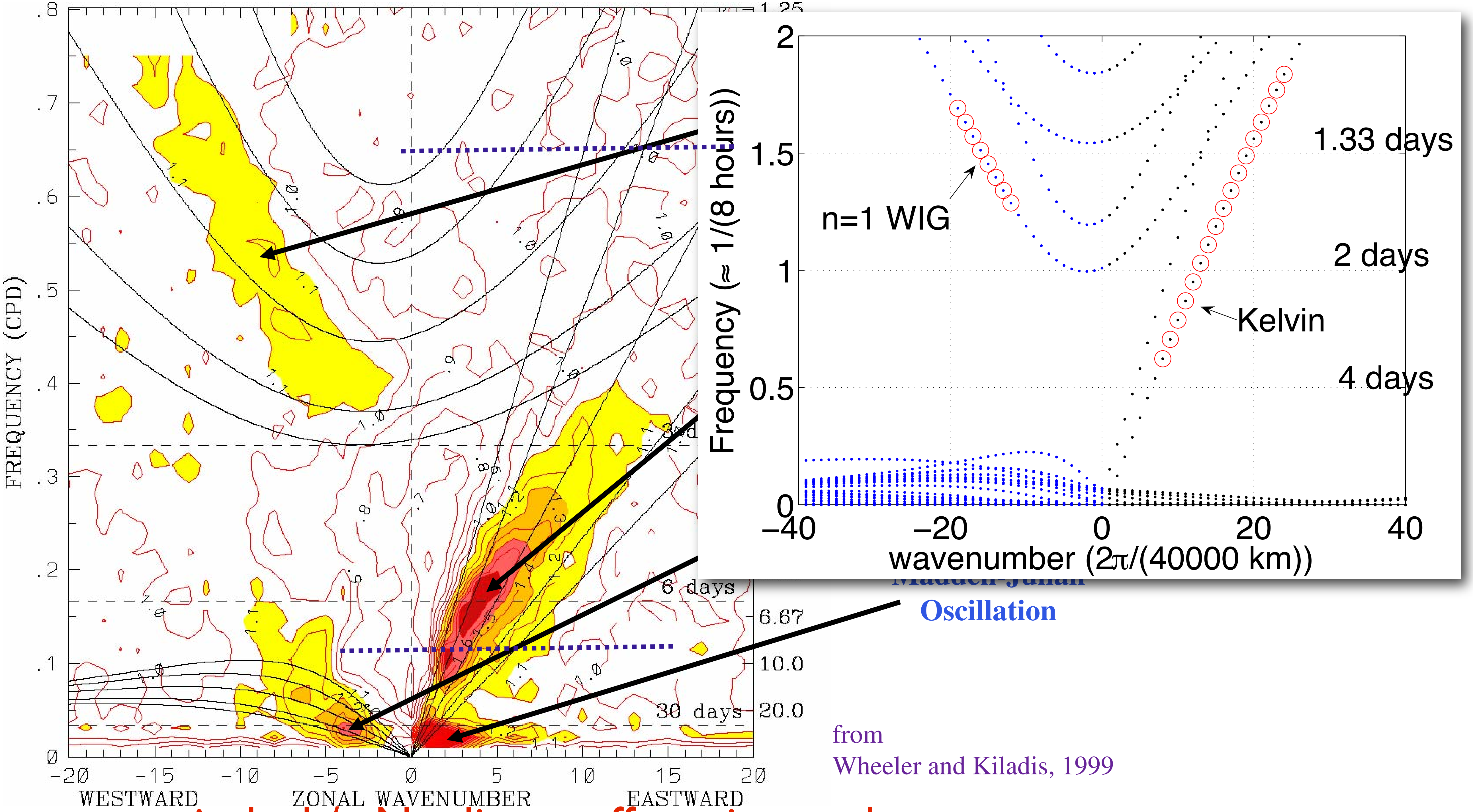
Linear Instabilities and Waves

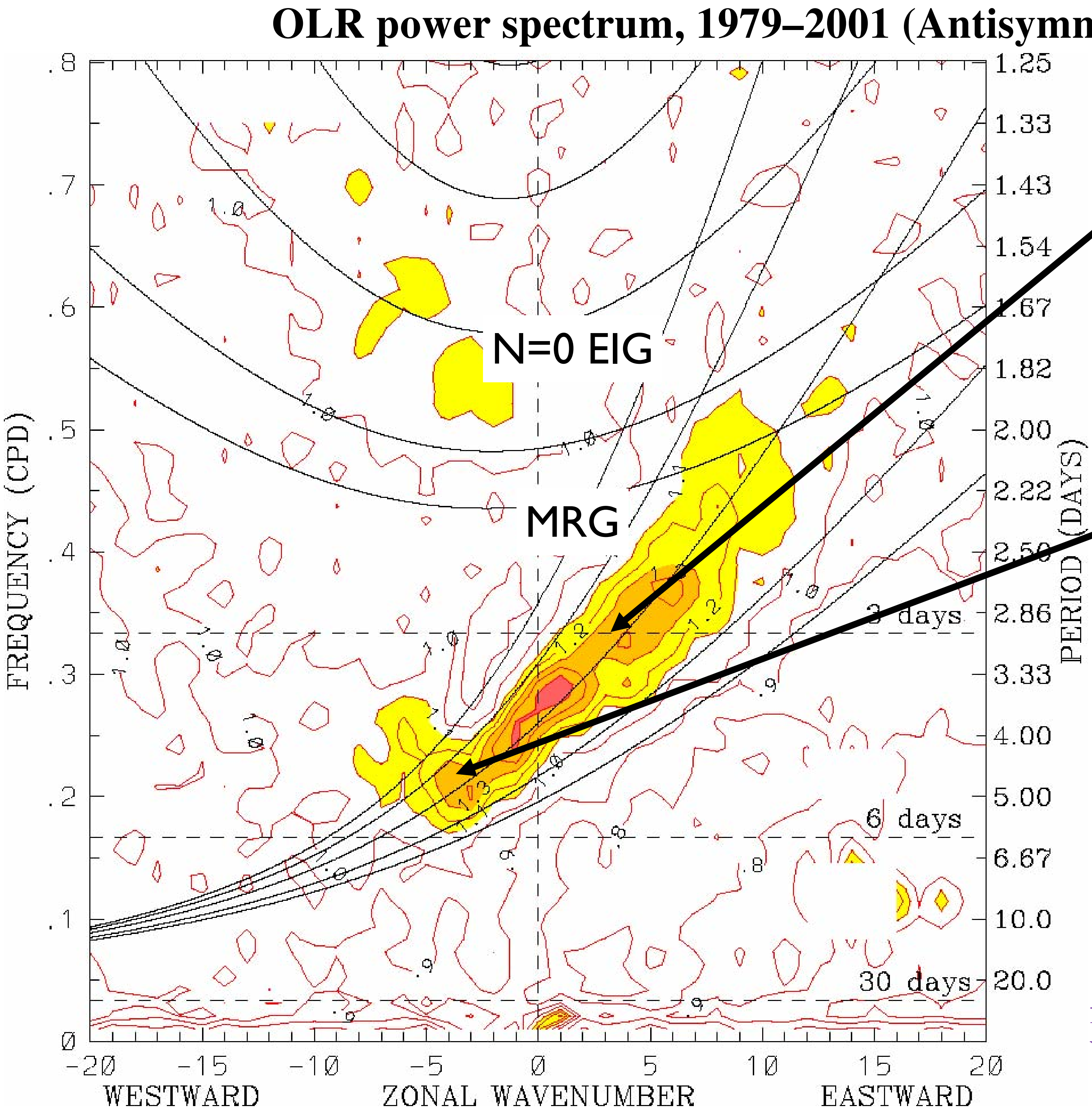
OLR power spectrum, 1979–2001 (Symmetric)



from
Wheeler and Kiladis, 1999

Shorter periods b/c Nonlinear effects ignored.
Model has no Rossby wave instability due to Lack of barotropic flow (Han and K. 2010), GCM results presented next.

Waves and Instabilities: Anti-symmetric

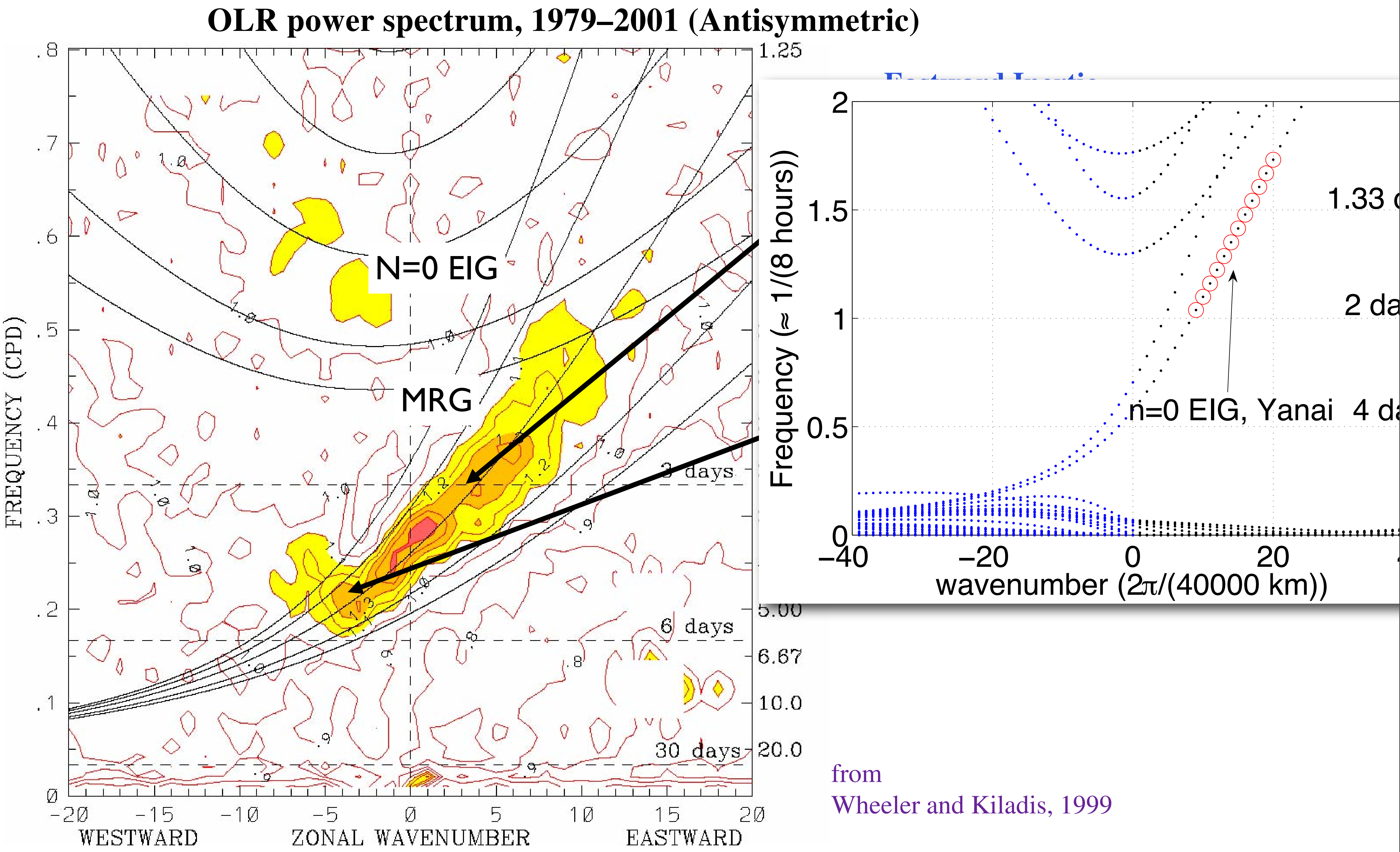


Eastward Inertio-Gravity

Mixed Rossby-Gravity

from
Wheeler and Kiladis, 1999

Waves and Instabilities: Anti-symmetric

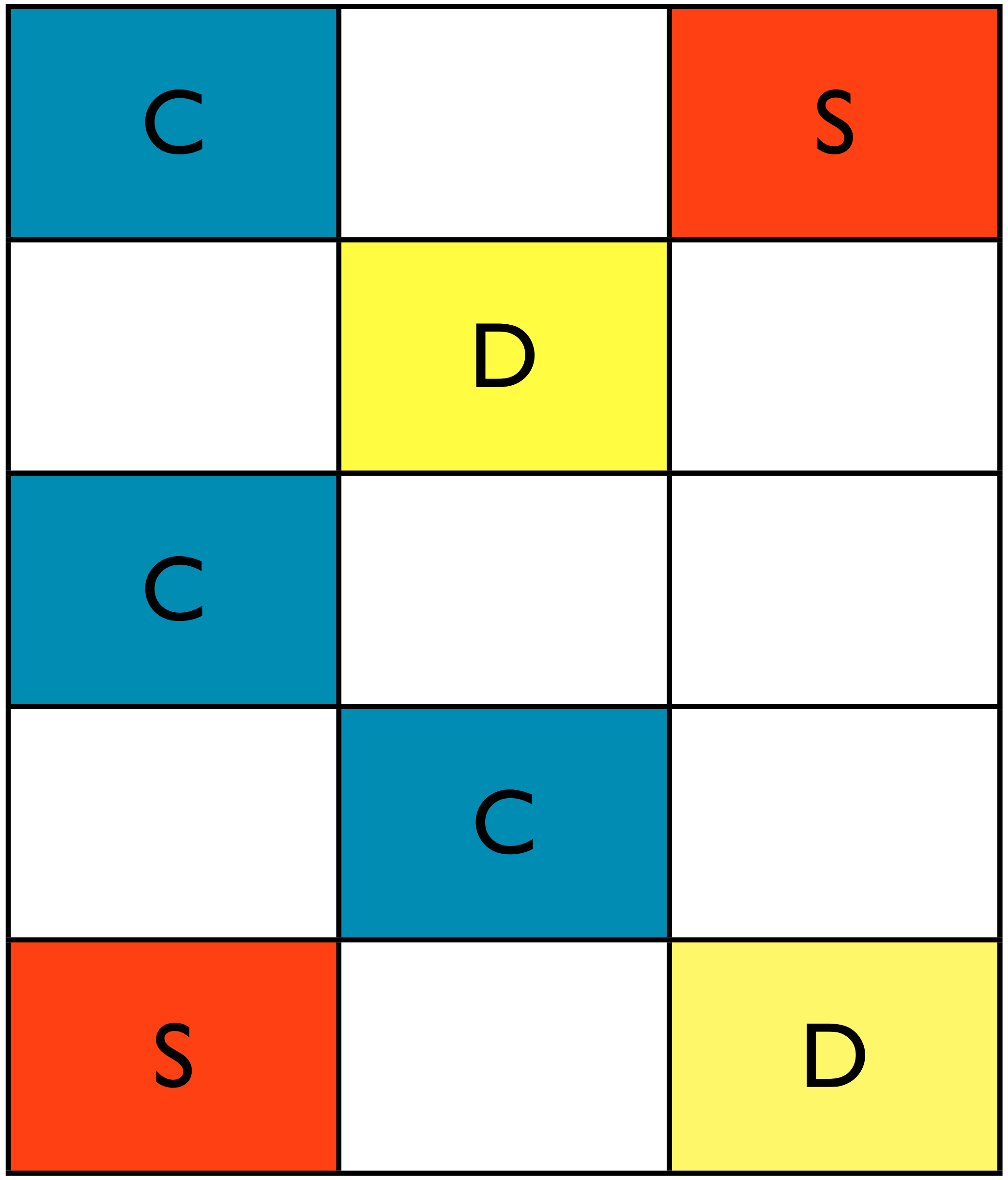


from
Wheeler and Kiladis, 1999

Stochastic Multicloud Model

As a way of modeling/capturing randomness of cloud-cloud complex interactions and transitions.

- Lattice points take values 0,1,2, or 3 ==> a Four state Markov chain
- Three order parameters c,d,s taking values 1 or 0, at a given lattice point according to whether there is a congestus, a deep, a stratiform cloud or none: multivariable stochastic process



C		S
	D	
C		
	C	
S		D

✓ K., Biello, and Majda, CMS 2009

Intuitive transition rules

- A clear sky site turns into a congestus site with high probability if CAPE>0 and middle troposphere is dry.
- A congestus or clear sky site turns into a deep site with high probability if CAPE>0 and middle troposphere is moist.
- A deep site turns into a stratiform site with high probability.
- All three cloud types decay naturally according to prescribed decay rates.

Transition probabilities

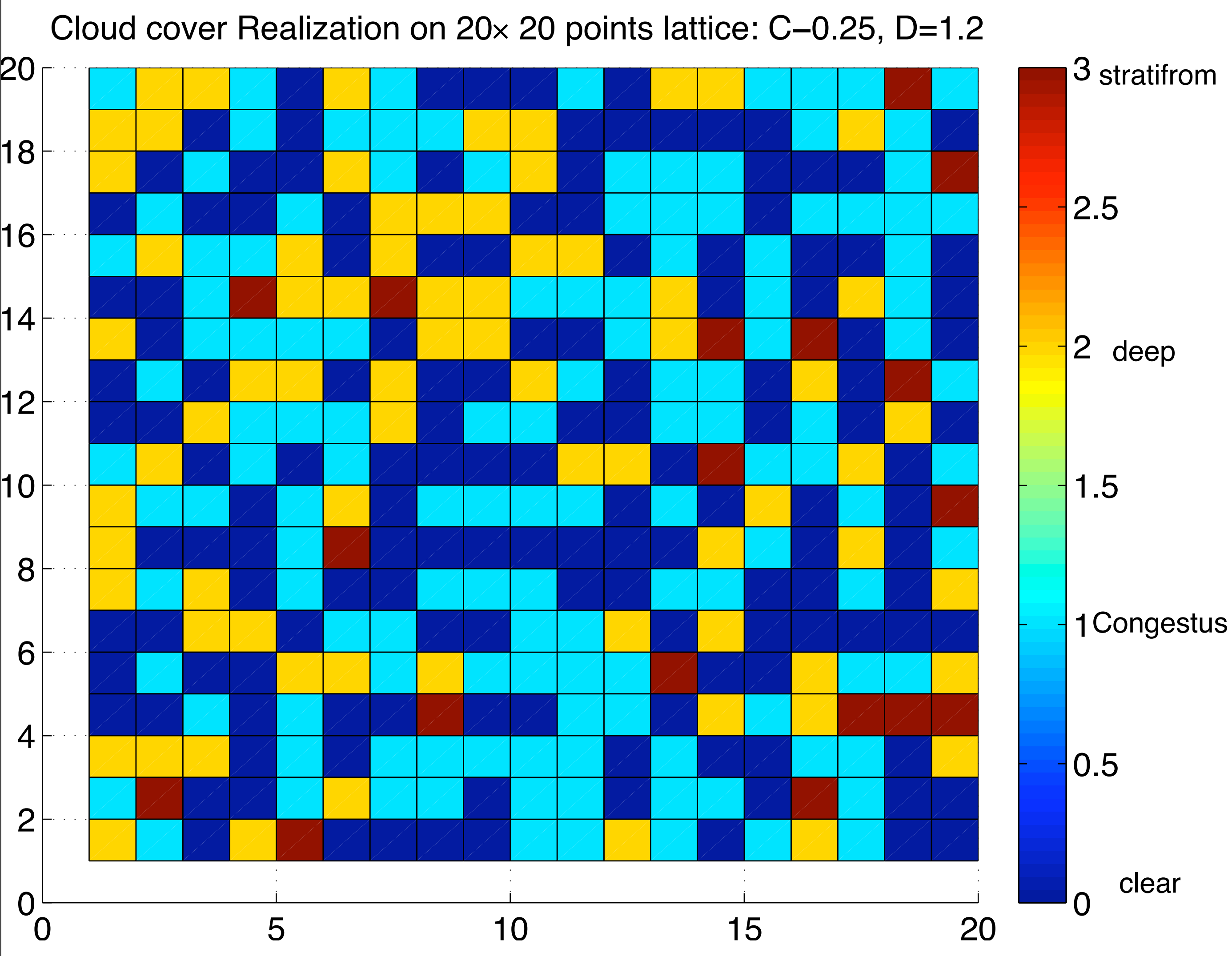
- Four state Markov chain at given site

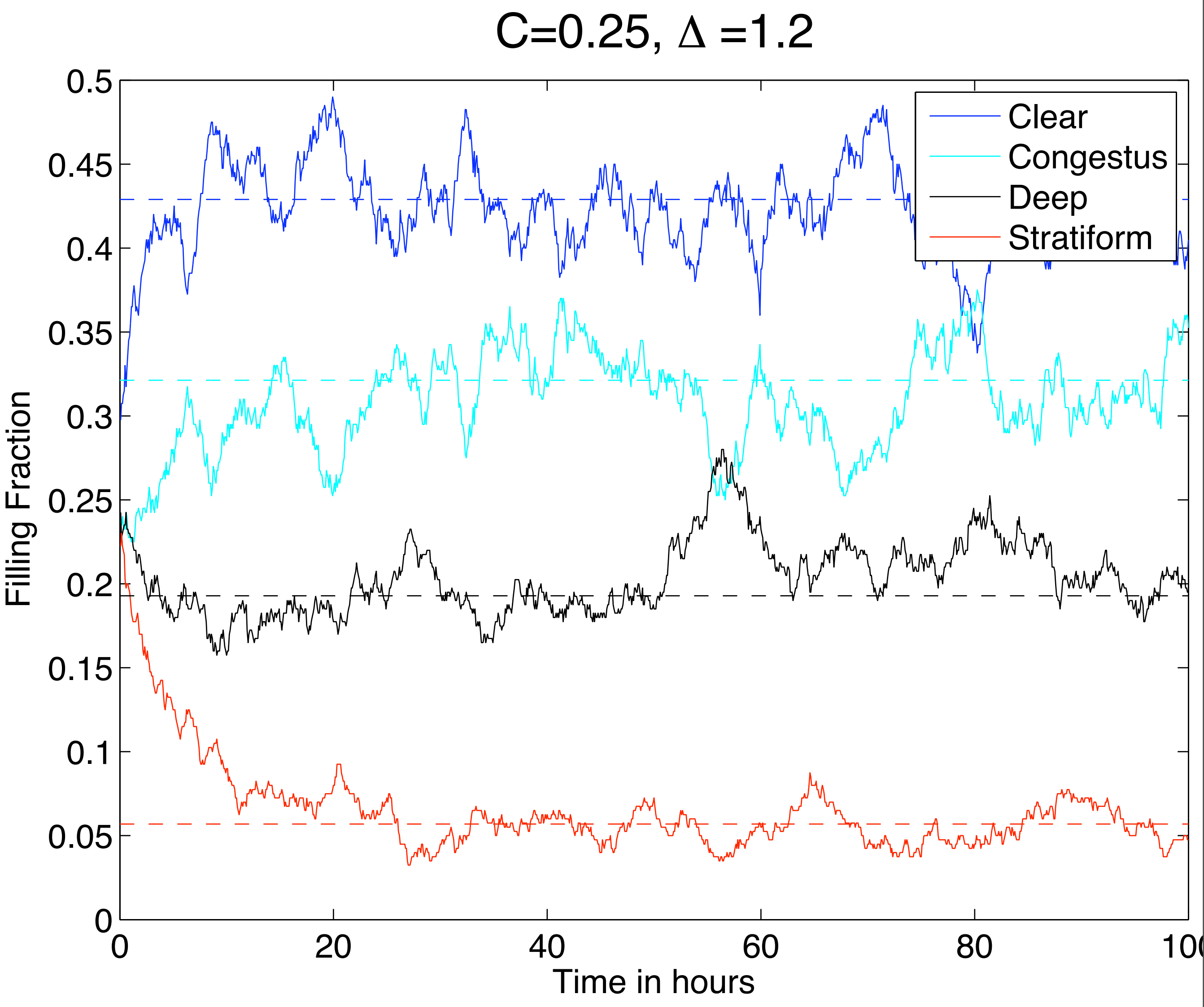
$$X_t = \begin{cases} 0 & \text{at clear sky site} \\ 1 & \text{at congestus site} \\ 2 & \text{at deep site} \\ 3 & \text{at statiform site} \end{cases}$$

- Prob{ $X_{t+\Delta t} = k / X_t = l$} = $R_{lk}\Delta t + O(\Delta t^2), l \neq k$
- Transition probability matrix, $\text{with } P_{lk} = R_{lk}\Delta t$

$$M = \begin{bmatrix} 1 - P_{01} - P_{02} & P_{01} & P_{02} & 0 \\ P_{10} & 1 - P_{10} - P_{12} & P_{12} & 0 \\ P_{20} & 0 & 1 - P_{20} - P_{23} & P_{23} \\ P_{30} & 0 & 0 & 1 - P_{30} \end{bmatrix}$$

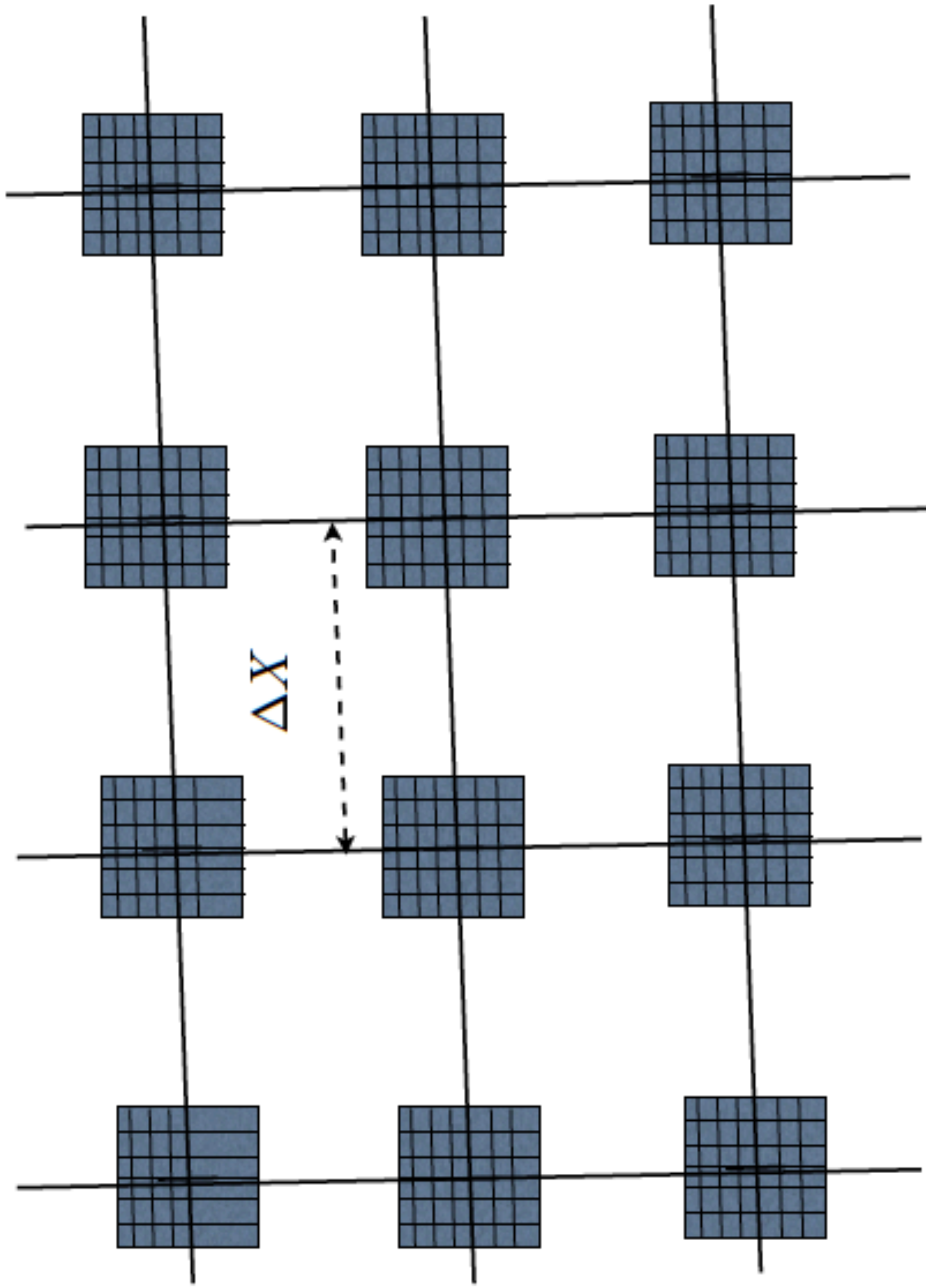
Time evolution and statistics of filling fraction



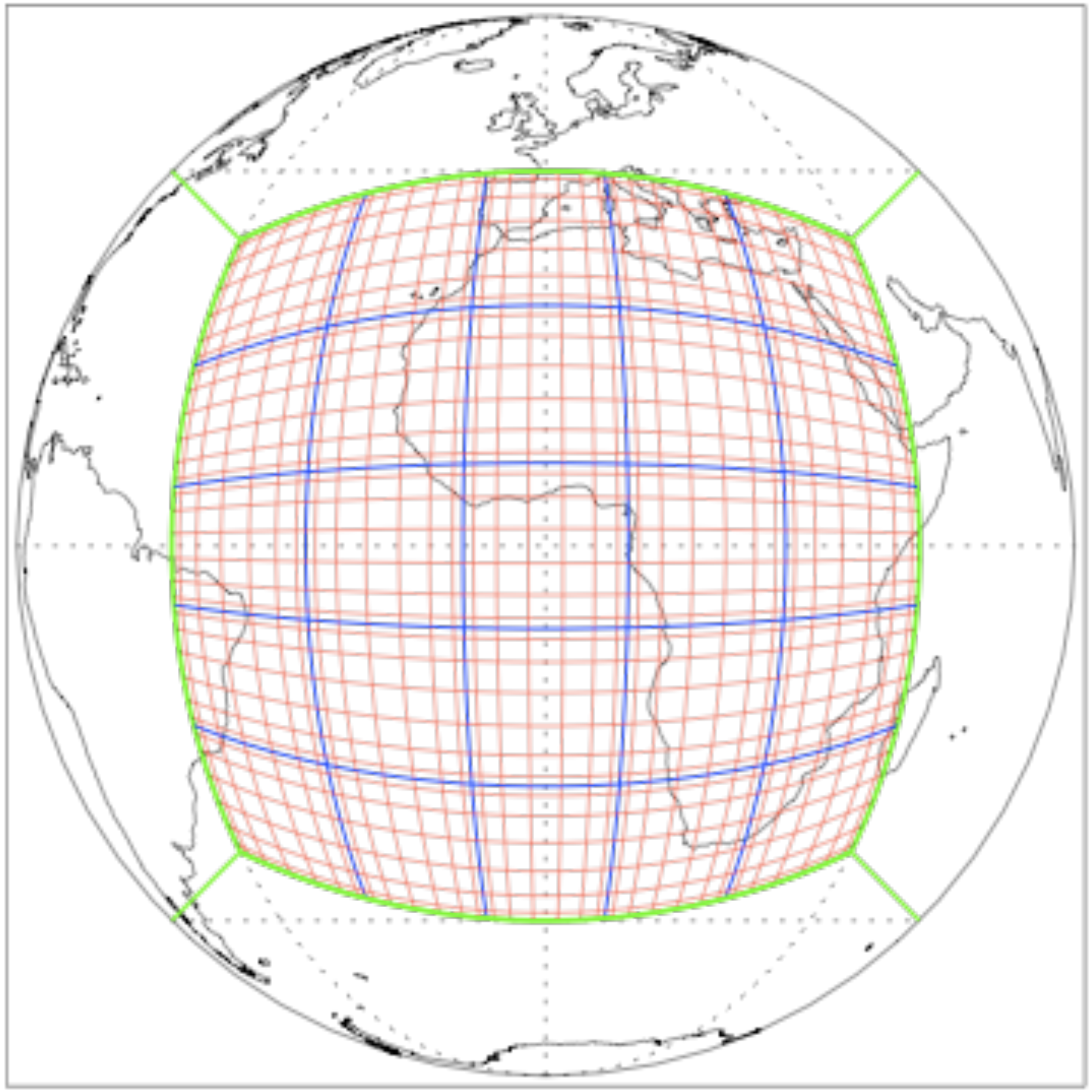


Coupling to deterministic Multicloud Equations

- Couple stochastic multicloud model to deterministic convective parametrization-- based on such cloud-type population
- A lattice of convective sites is imbedded within each coarse grid cell
- Filling fractions modify strength of heating/cooling associated with each cloud type



HOMME: Next generation NCAR AGCM



- **HOMME:** High-Order Methods Modelling Environment
- Spectral elements, Continuous or discontinuous Galerkin on cubed sphere
- Explicit or semi-implicit time integration
- Vertical discretization: finite-differences (CAM)
- Proven to be highly scalable on MP systems O(90000) cpus

Extract vertical modes from initial sounding GATE

- Vertical normal mode expansion (Kasahara & Puri,1981)

$$\mathbf{u}(x,y,p,t) = \sum_n \mathbf{u}_n(x,y,t)\phi_n(p)$$

$$-\frac{d}{dp}\left(p^2 N^2 \frac{d\phi_n}{dp}\right) = \frac{1}{c_n^2}\phi_n,$$

- Vertical velocity

$$\omega(x,y,p,t) = \sum_n \omega_n(x,y,t)\psi_n(p)$$

$$\psi_n(p) = -\frac{1}{p_B - p_T}\int_{p_T}^{p} \phi_n(p')dp'$$

Heating profiles from GATE background

$$\mathcal{H}^{tot} = \mathcal{H}_d \tilde{\psi}_1(p) + (\mathcal{H}_c - \mathcal{H}_s)\tilde{\psi}_2(p).$$

$$\psi_j(p) = -\int_{p_T}^{p} \phi_j(p')dp'$$

Heating profiles from GATE background

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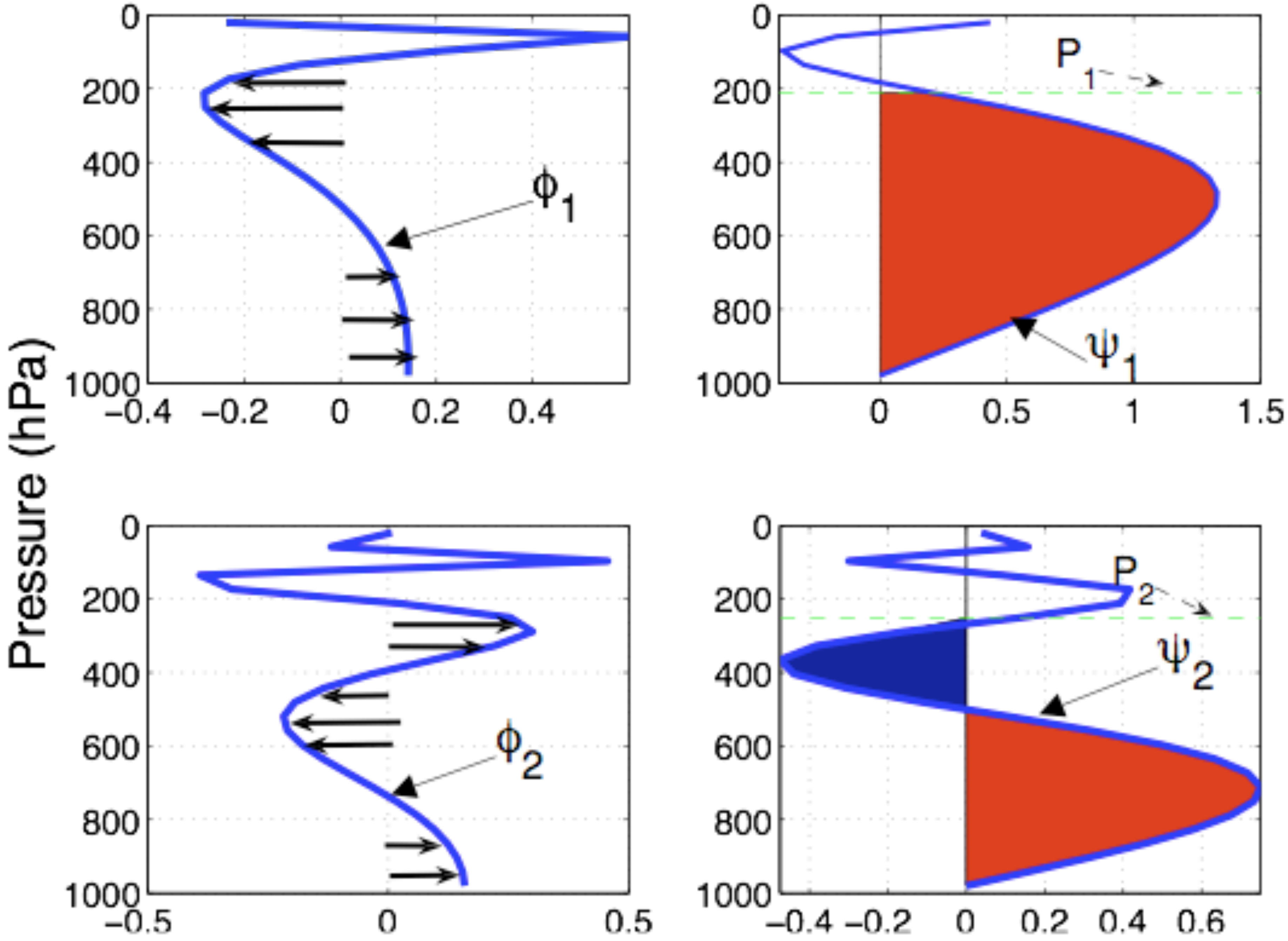

Heating profiles from GATE background

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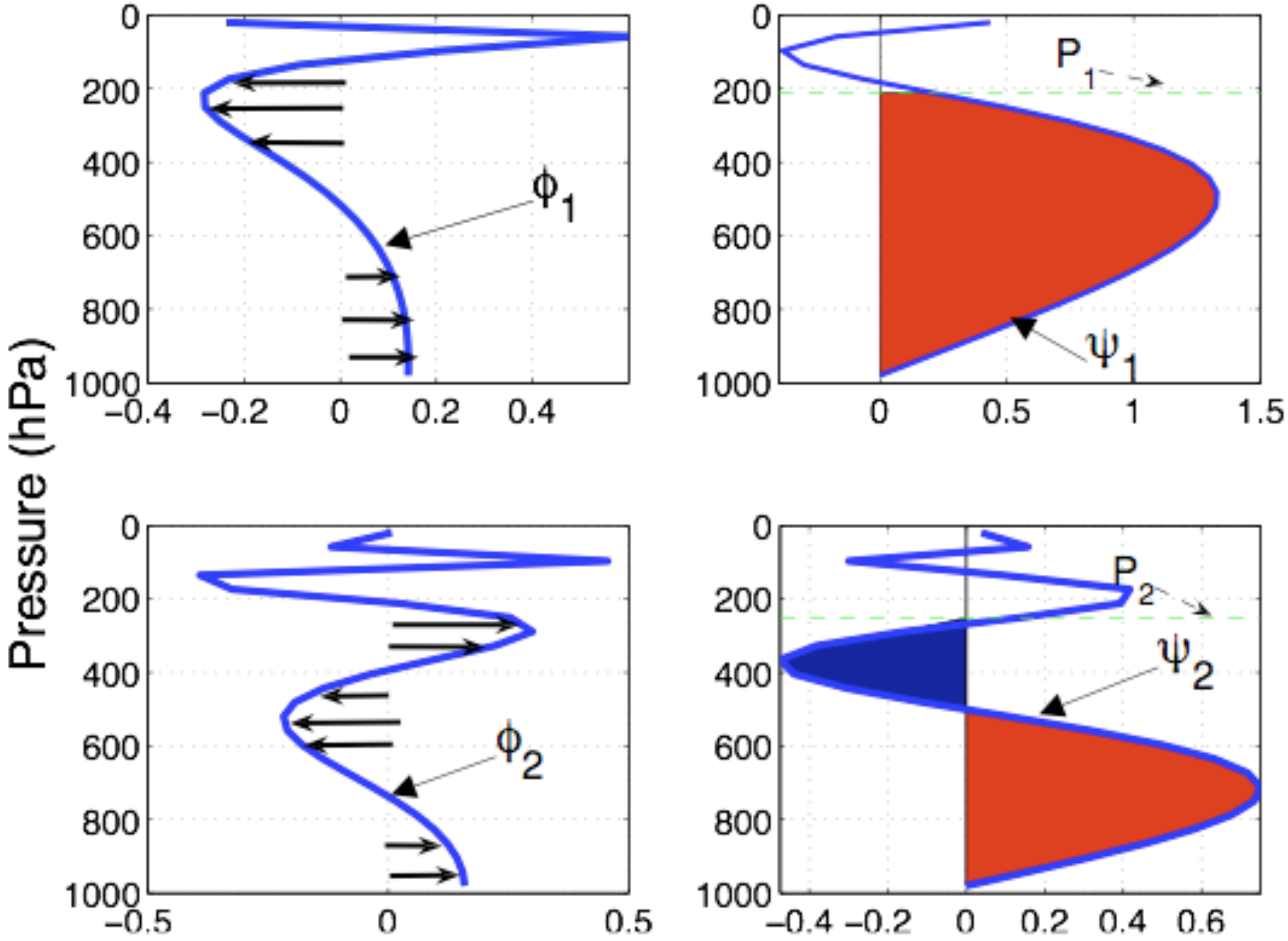


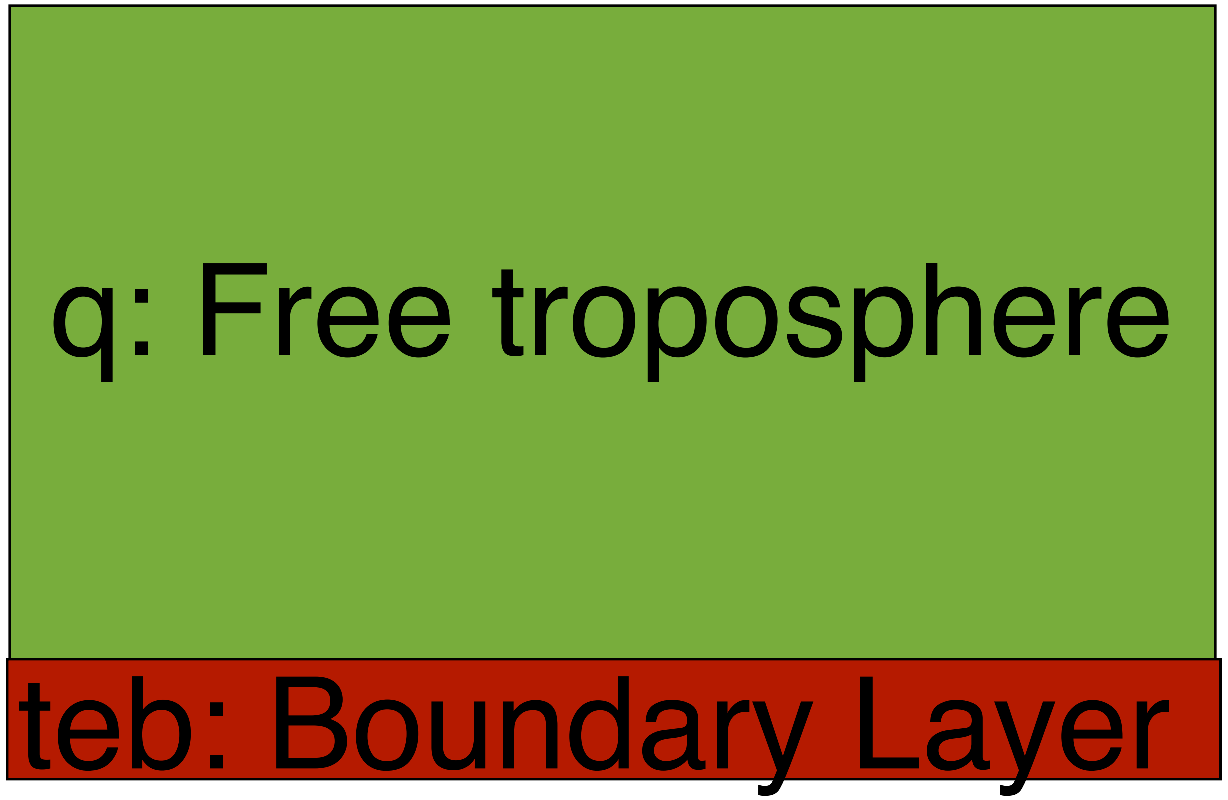
Note: Here switch between cloud types is deterministic!

Moist Thermodynamics

- Vertical average moisture equation:

$$\frac{\partial q}{\partial t} + \nabla \cdot (q(\bar{\mathbf{u}} + \mathbf{u}_1 + 0.1\mathbf{u}_2)) + \tilde{Q}_1 \nabla \cdot \mathbf{u}_1 + \tilde{Q}_2 \nabla \cdot \mathbf{u}_2 = -P + \langle E \rangle$$

$$\tilde{Q}_j = \int_{p_T}^{p_B} \frac{d\tilde{Q}}{dp} \psi_j(p) dp, j = 1, 2.$$


q: Free troposphere

teb: Boundary Layer

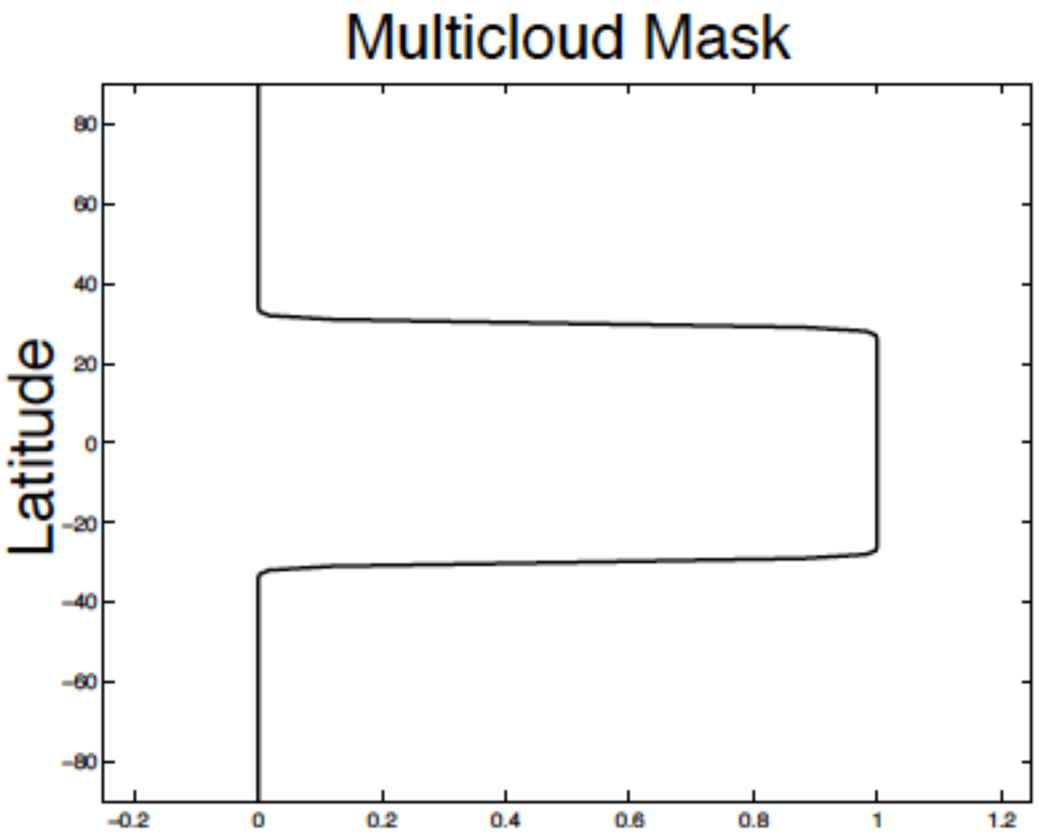
- Boundary layer theta_eb

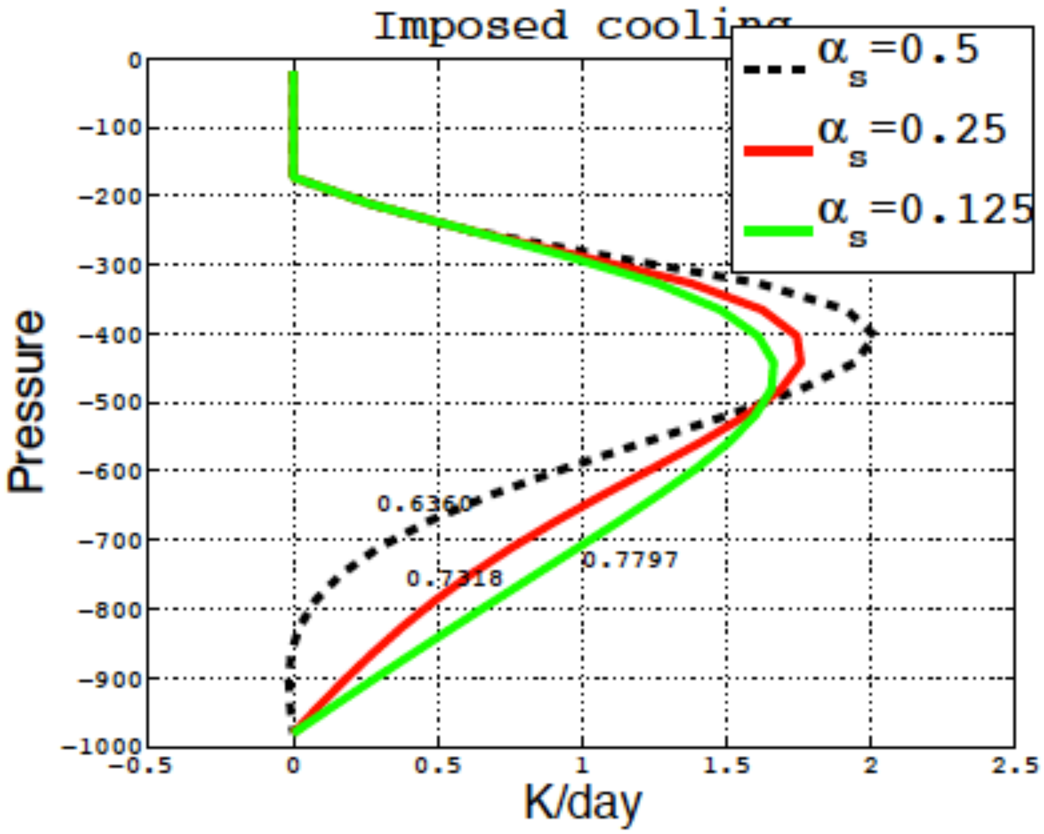
$$\frac{\partial \theta_{eb}}{\partial t} + \mathbf{u}(x, y, p_1, t) \nabla \theta_{eb} = \frac{1}{h_b} E_s - \frac{1}{h} D$$

General Set up

- Background: GARP-GATE
- Imposed Cooling has profile of heating for RCE solution to exist
- Aquaplanet (sea everywhere)
- Tropical mask for heating

- Resolution: equiv. to 167 km
- 26 vertical levels
- Time step: 30 seconds

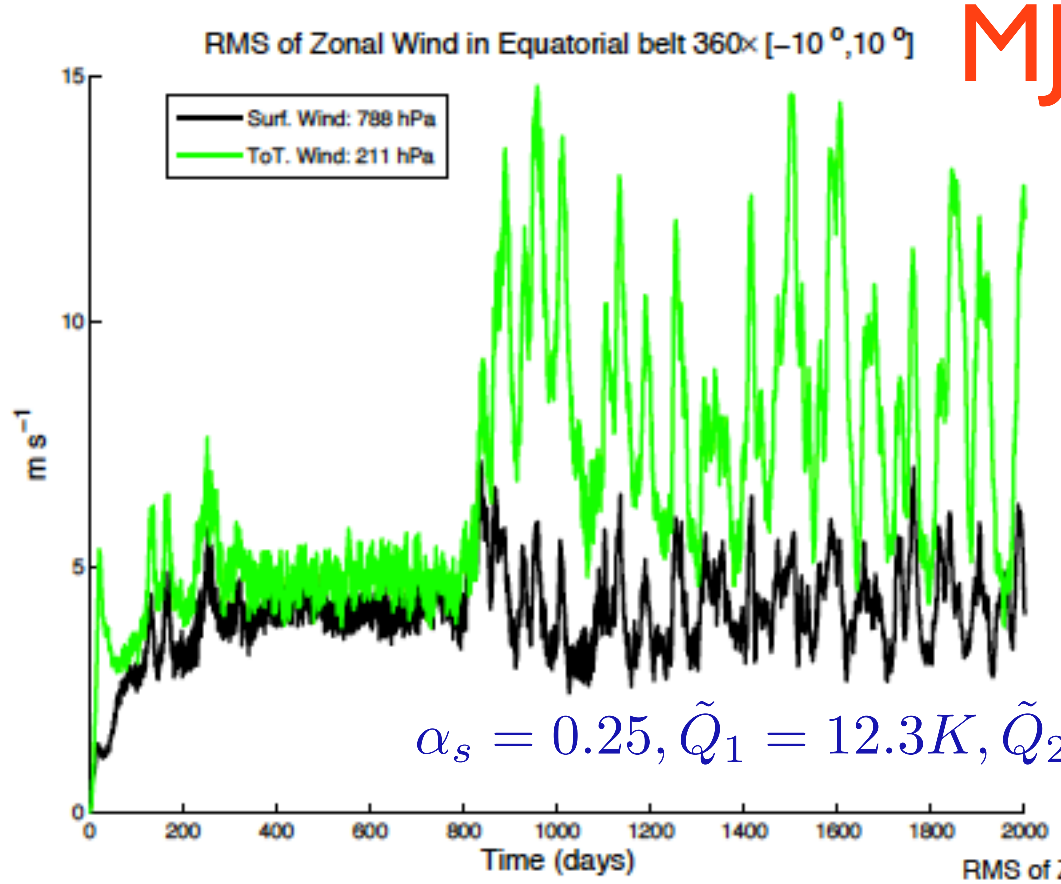

Multicloud Mask


Imposed cooling

Results: Simulate Three Regimes

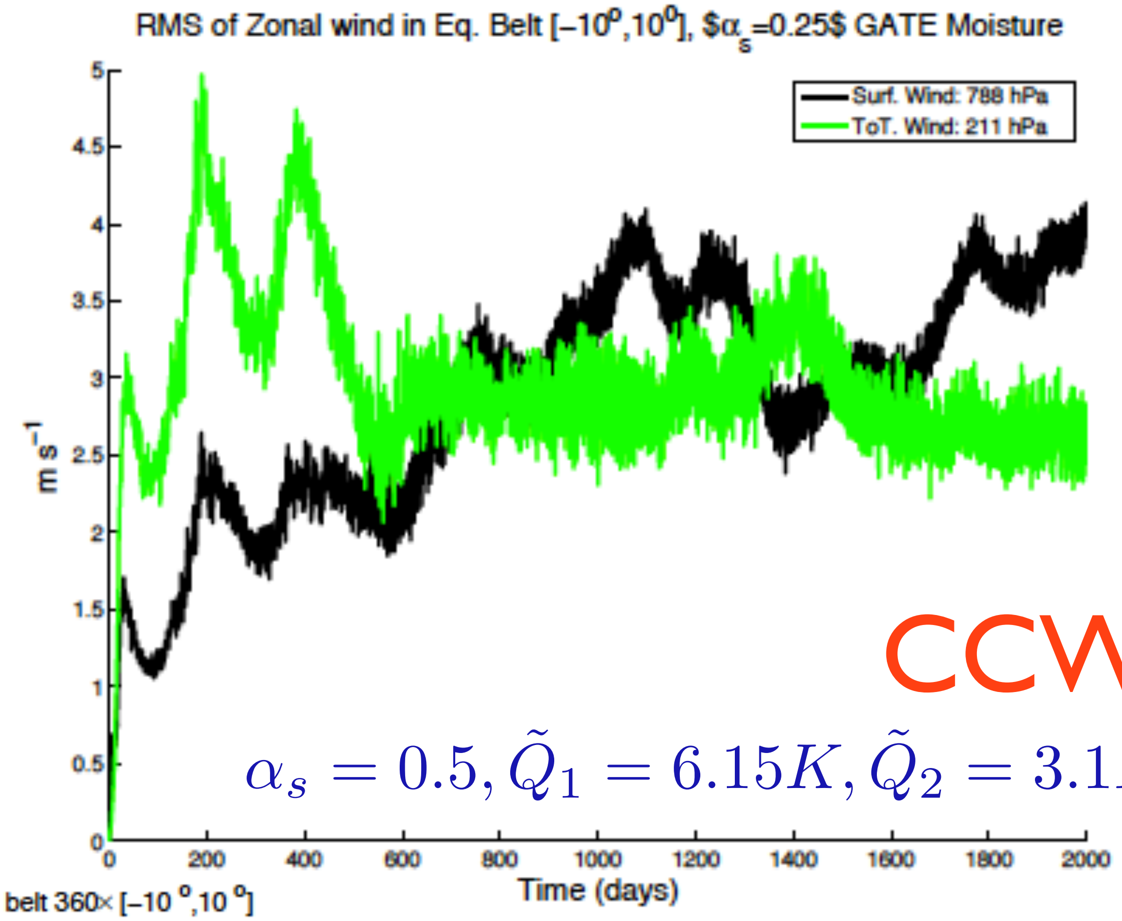
Stratiform fraction	Background moisture gradient ➡ Strength of vertical advection of moisture	Solution
Small (0.25)	2xGATE	MJO
Large (0.5)	GATE	Convectively Coupled Waves
Small (0.25)	GATE	Fast Kelvin

Zonal Wind RMS



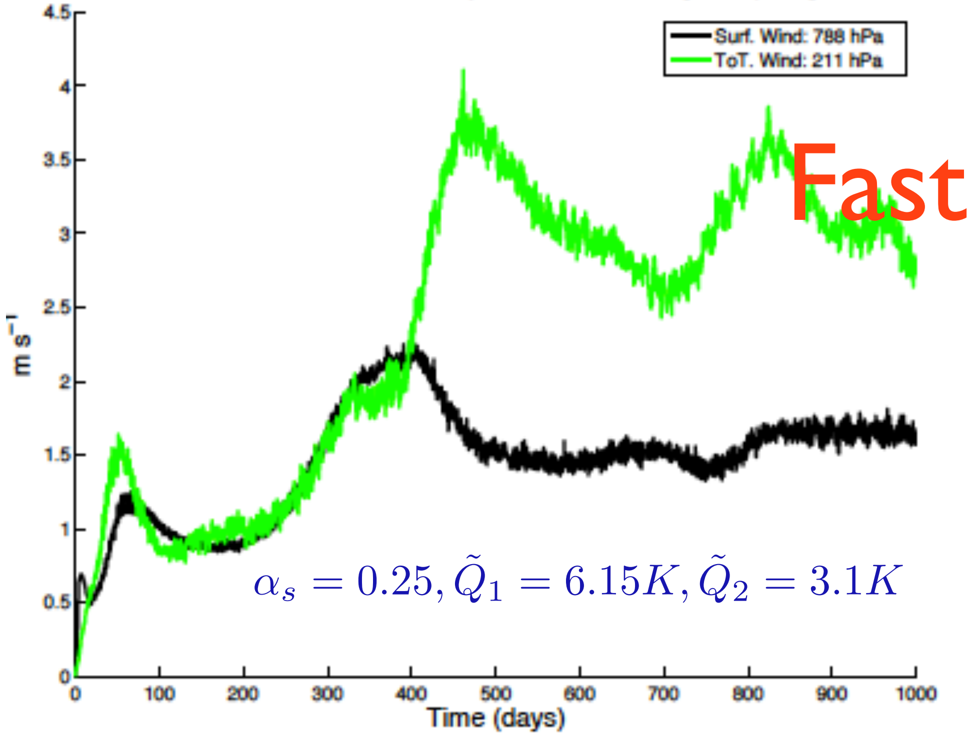
MJO

$\alpha_s = 0.25, \tilde{Q}_1 = 12.3K, \tilde{Q}_2 = 6.13$



CCWs

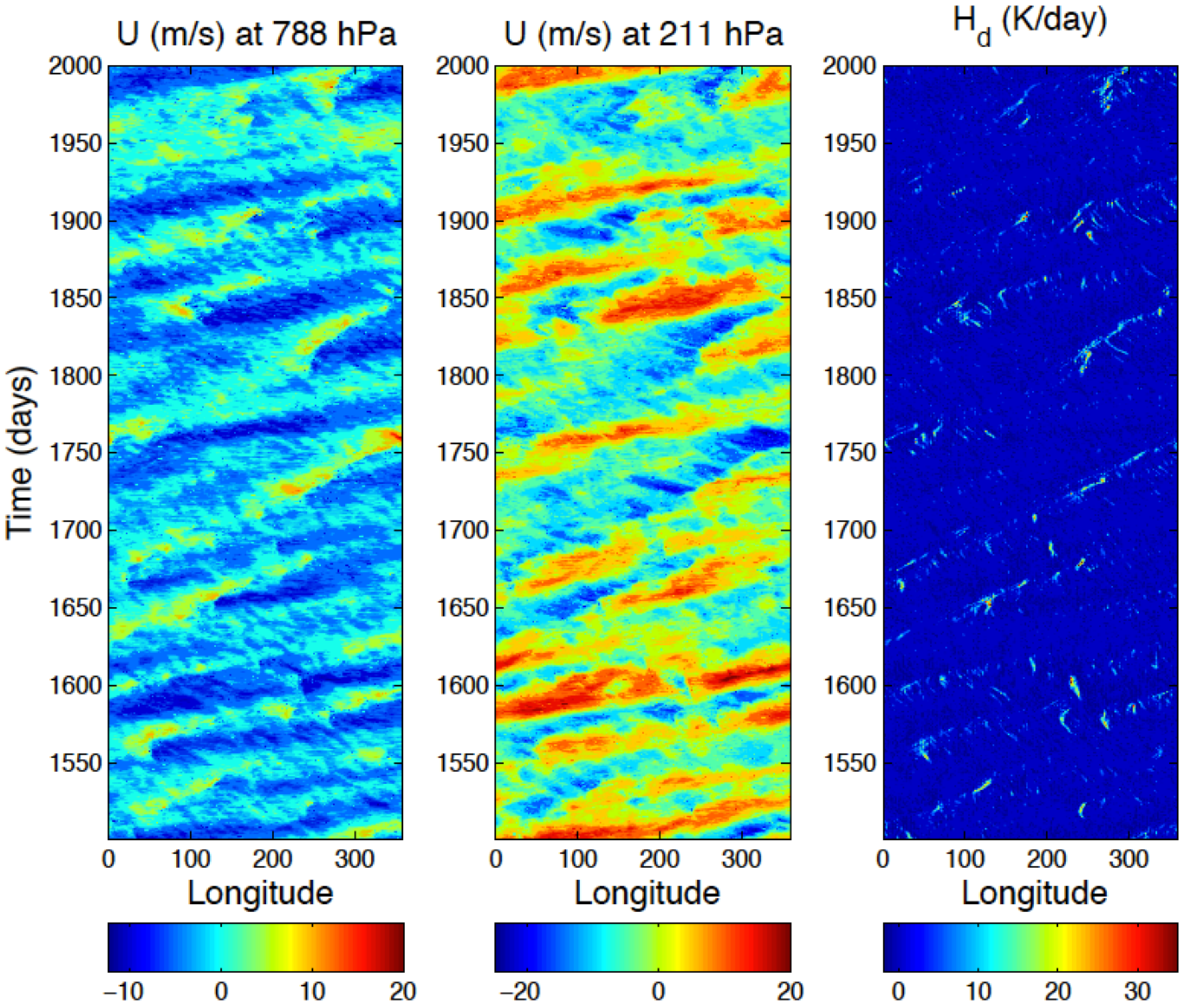
$\alpha_s = 0.5, \tilde{Q}_1 = 6.15K, \tilde{Q}_2 = 3.1K$



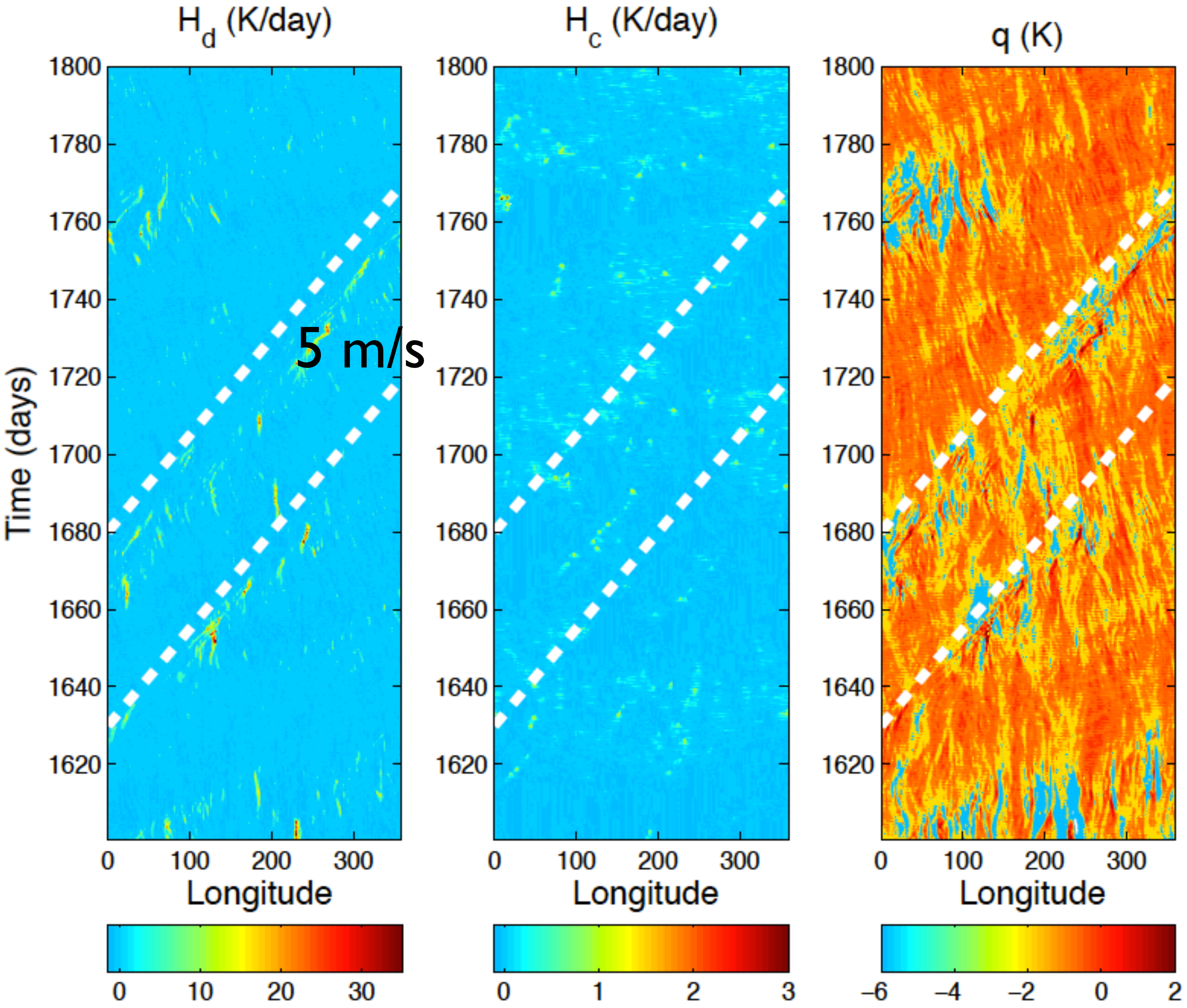
Fast Kelvin

$\alpha_s = 0.25, \tilde{Q}_1 = 6.15K, \tilde{Q}_2 = 3.1K$

Hovmoller diagram (North-South Average): MJO

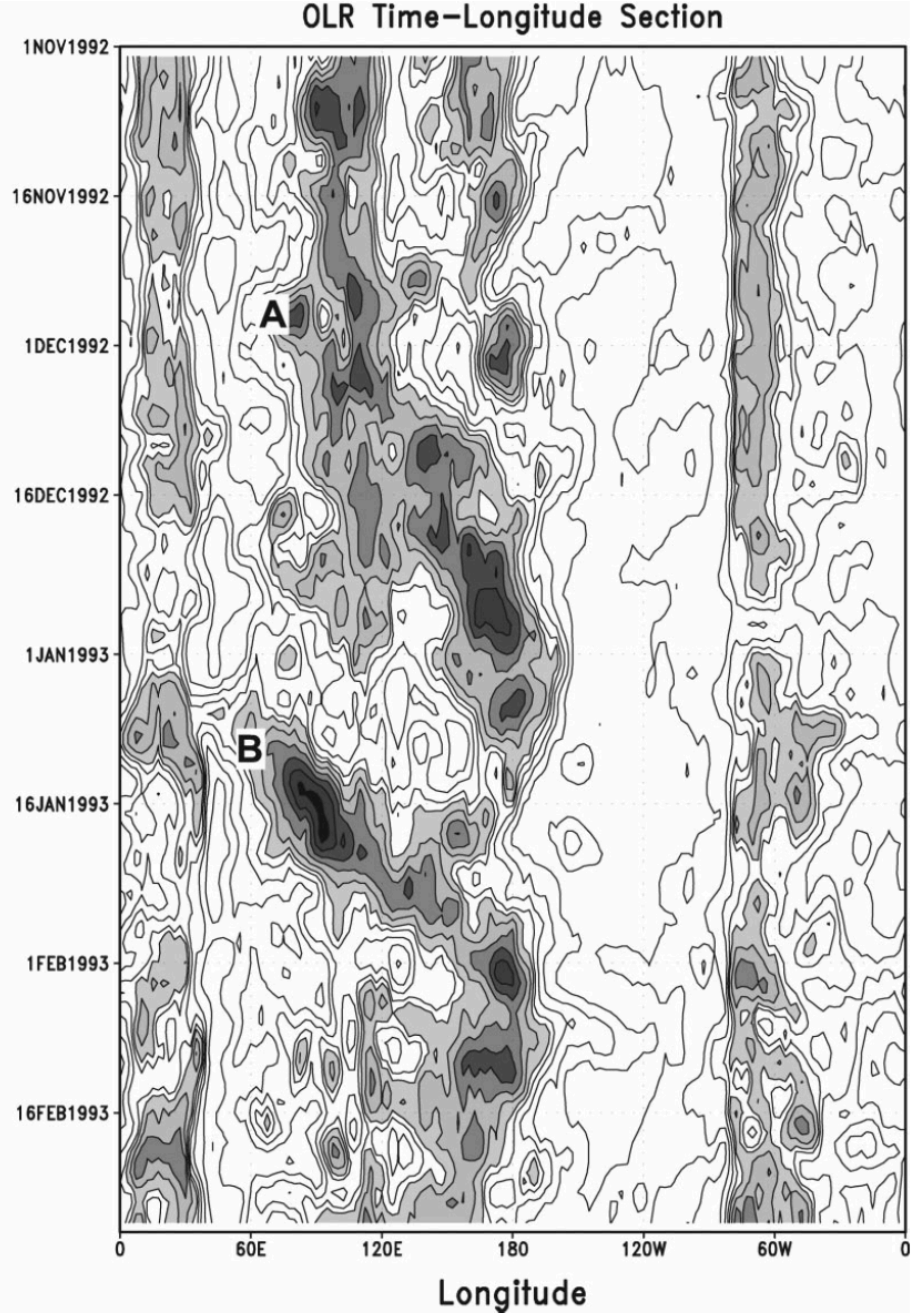


Focussing on two MJO events



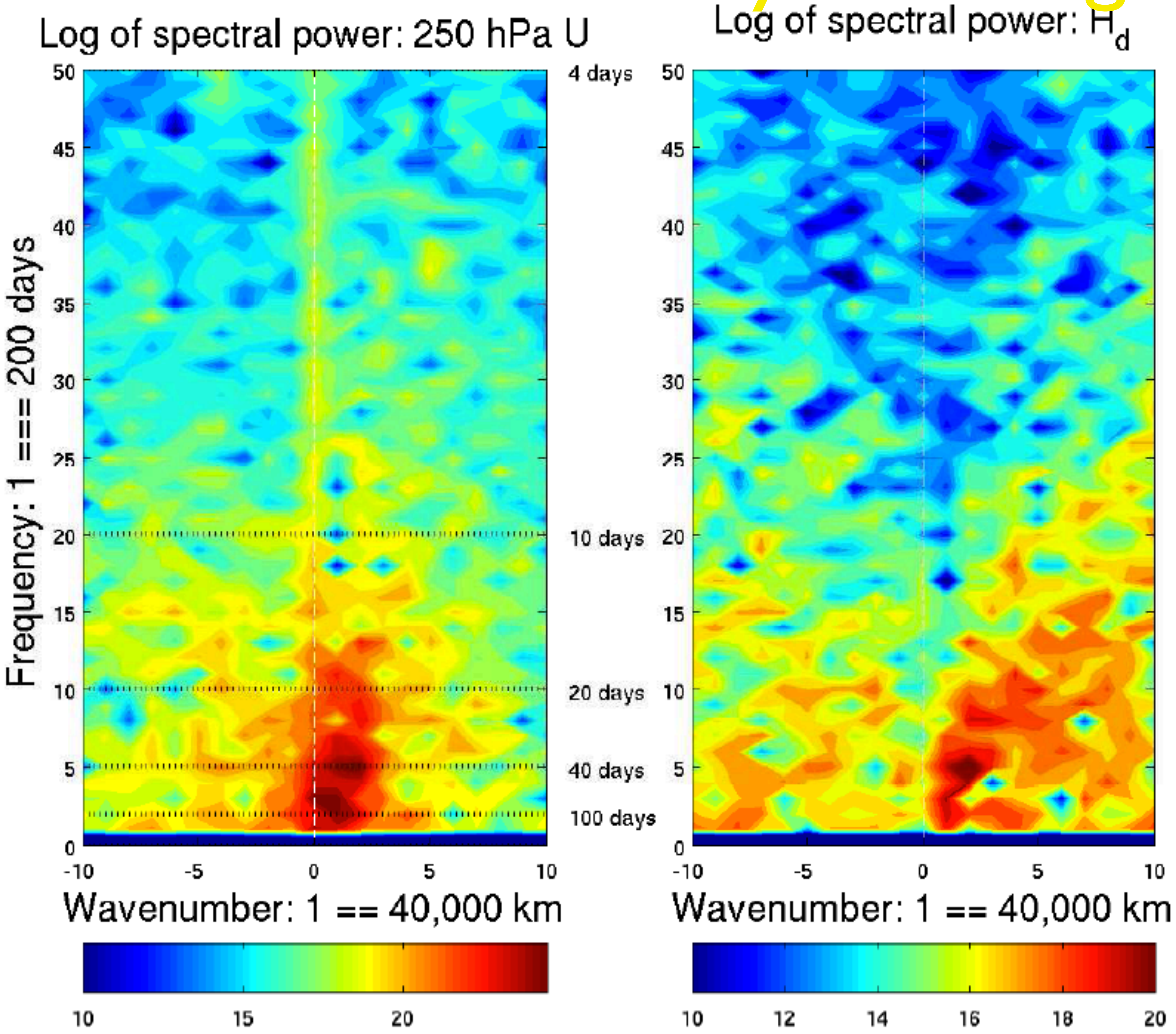
Standing spikes of deep convection reminiscent of zero group velocity of MJO. Deep convective event eresonate with moisture variation as in Harmonic Osillator like model of Majda and Stechmann (2009)

...as seen in TOGA-COARE data

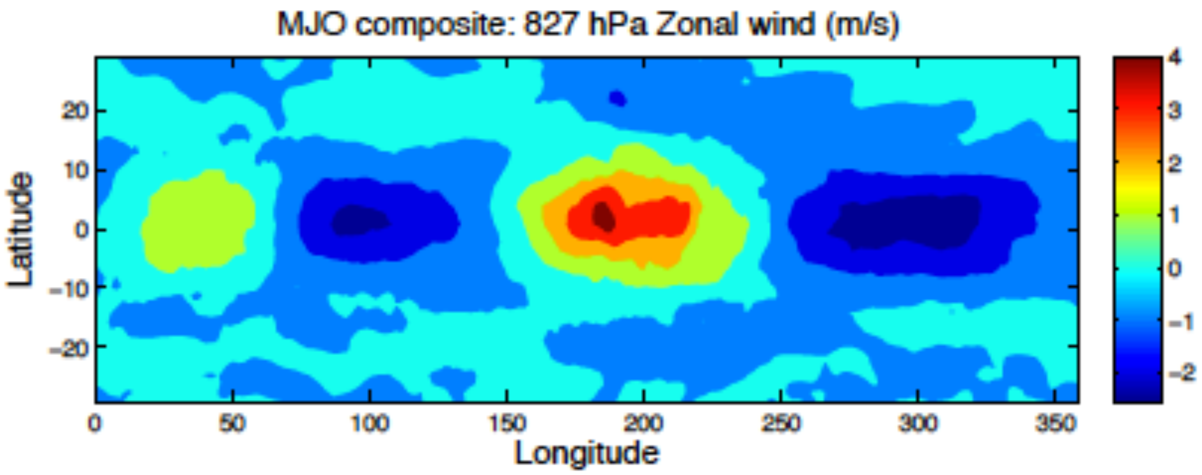


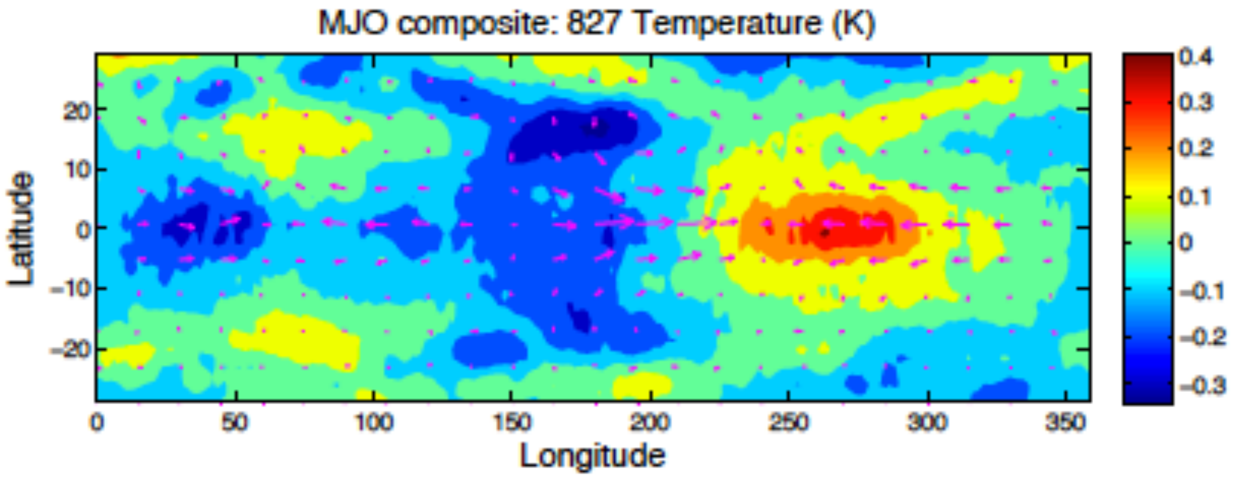
Yanai et al. 2000

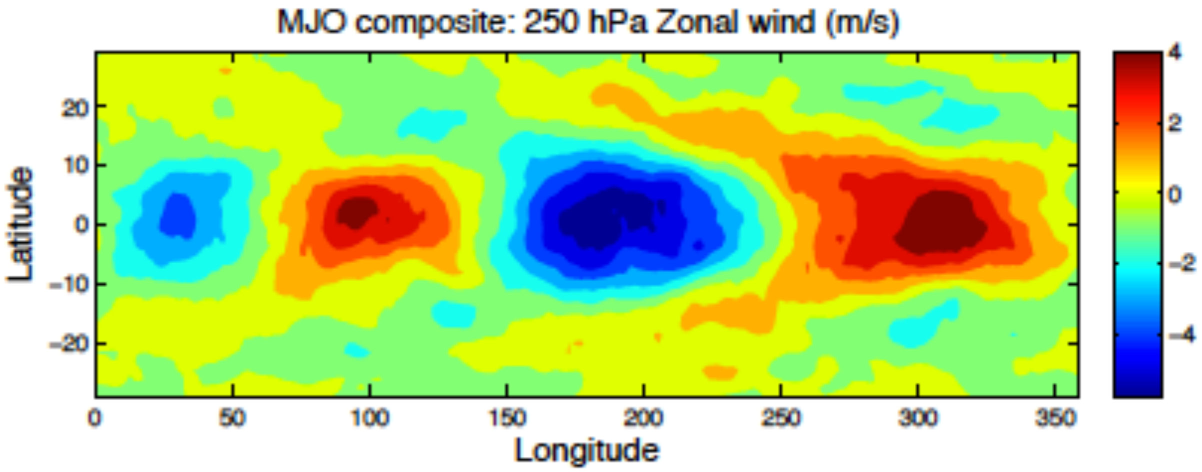
Wheeler-Kiladis-Takayabu Diagram

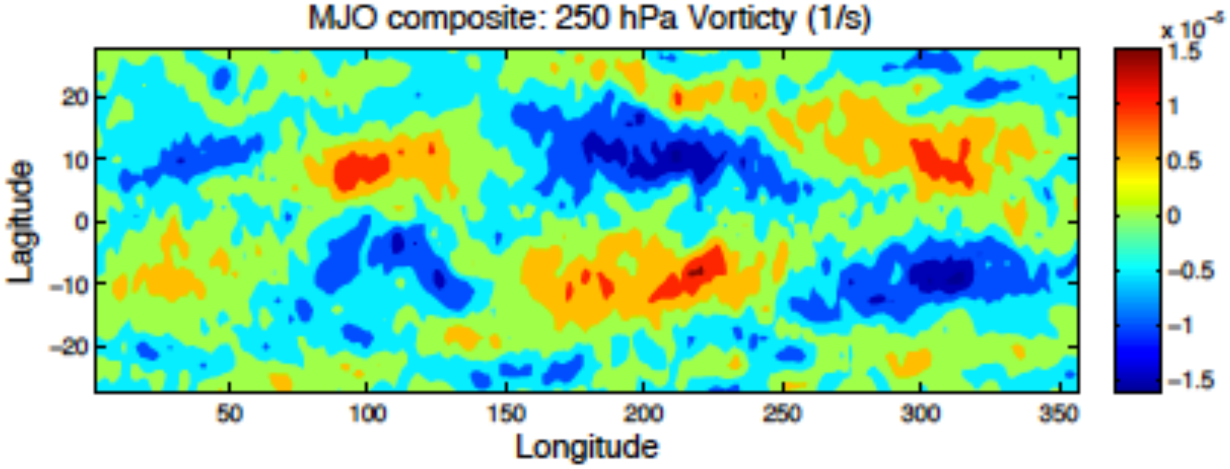


MJO Filtered Horizontal Structure

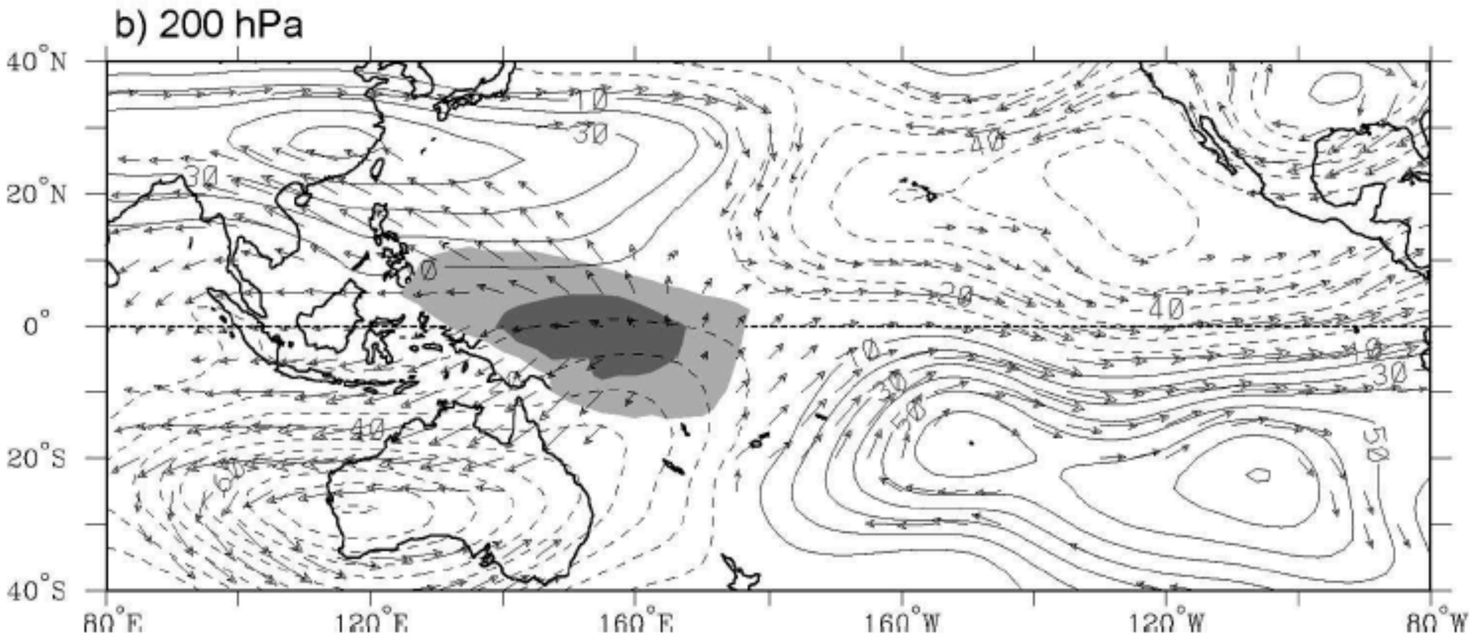

MJO composite: 827 hPa Zonal wind (m/s)


MJO composite: 827 Temperature (K)


MJO composite: 250 hPa Zonal wind (m/s)

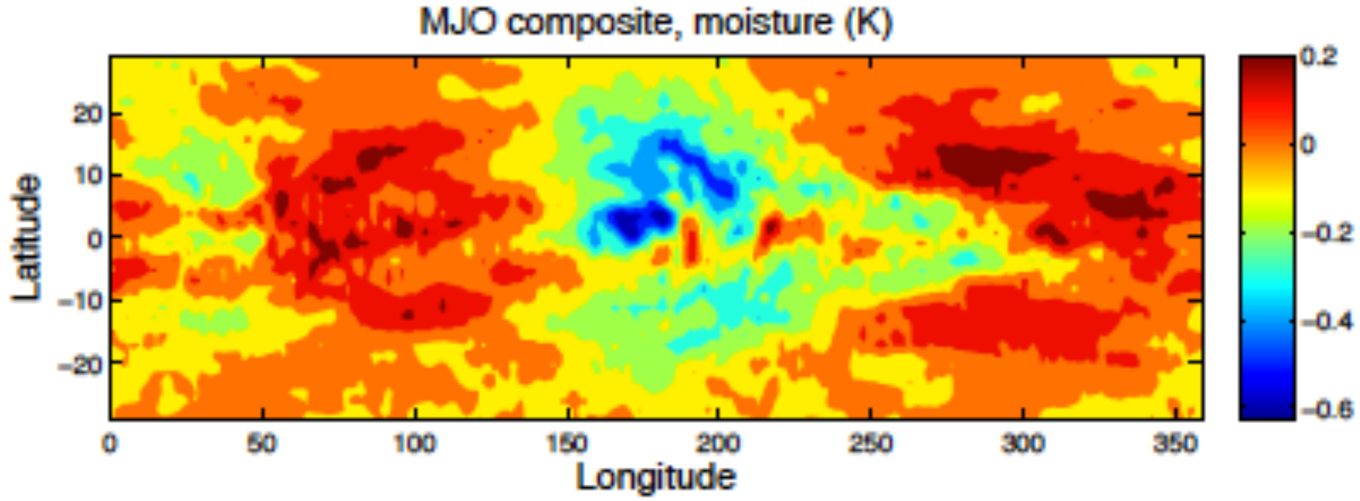

MJO composite: 250 hPa Vorticty (1/s)

Obs. Kiladis et al. 2005

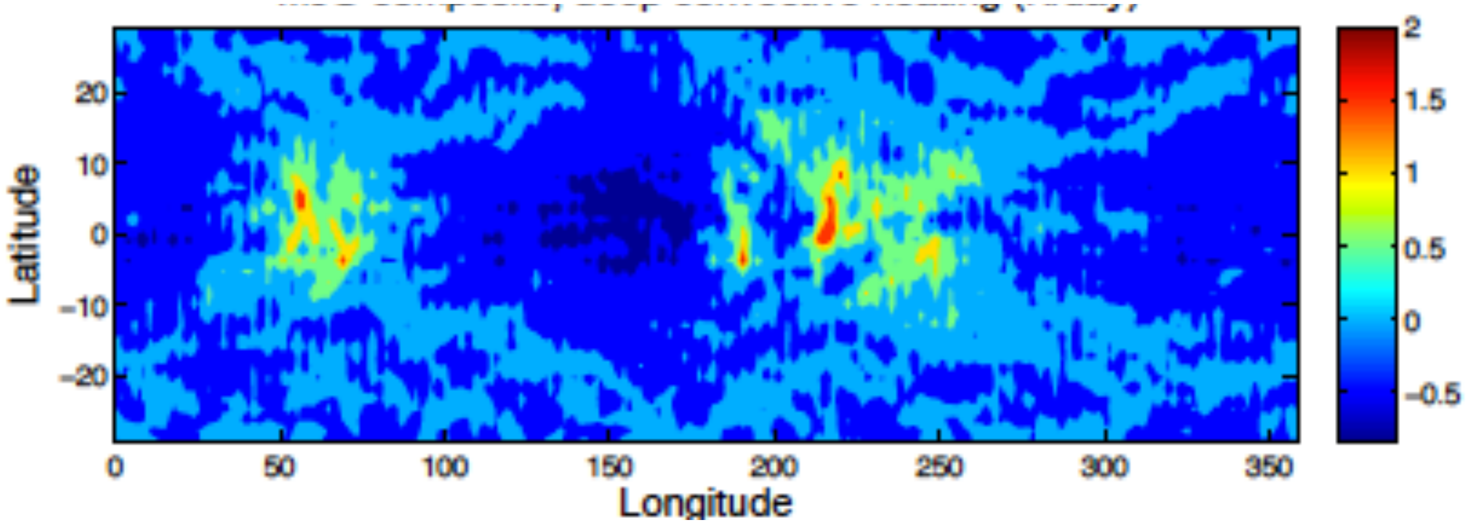

b) 200 hPa

MJO Filtered Heating and Moisture Cycle

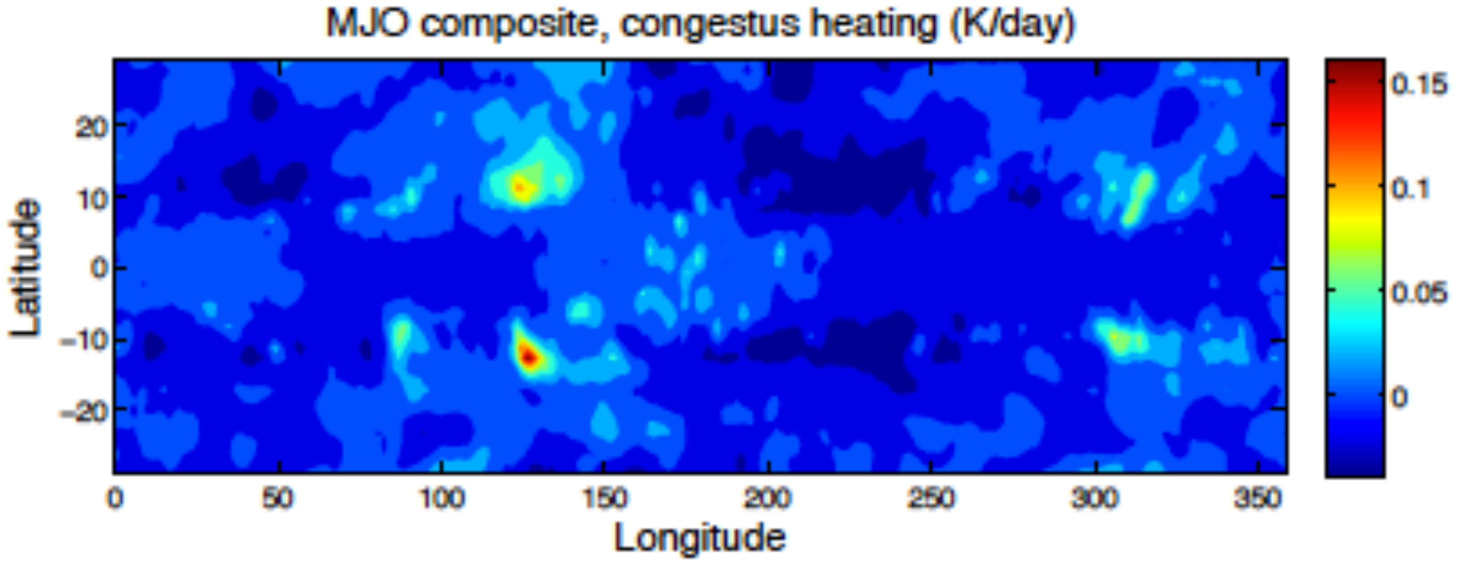
Moisture leads convection

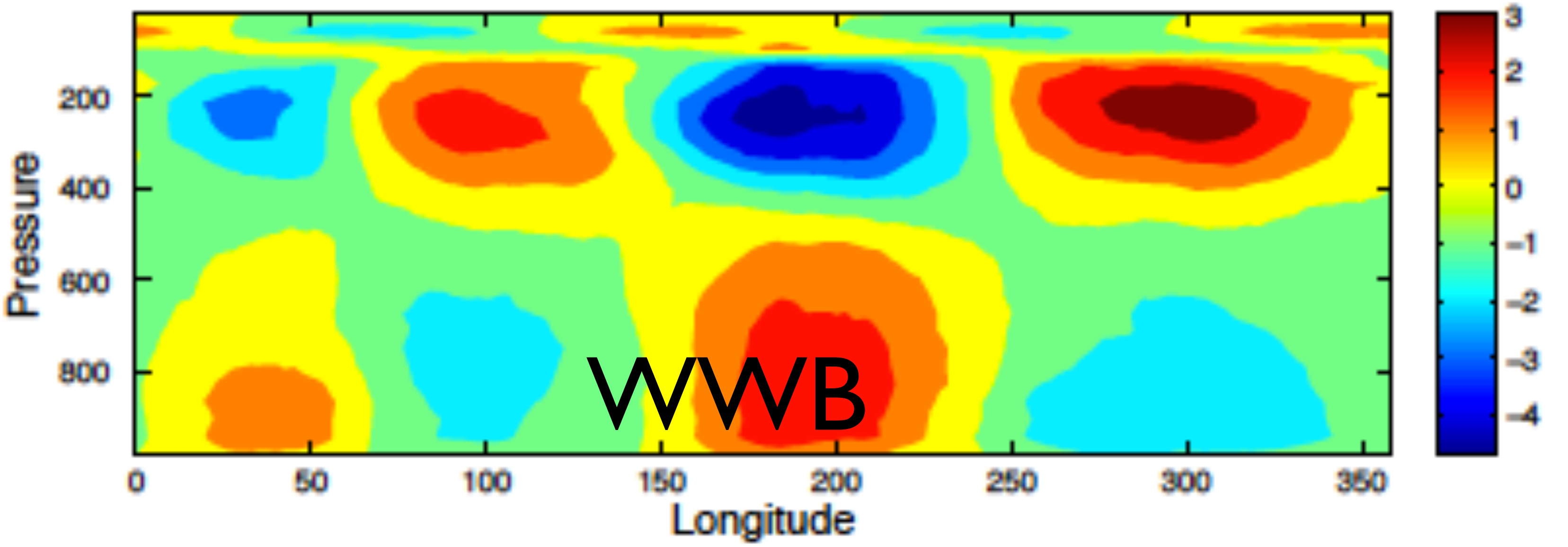

MJO composite, moisture (K)

Deep Convection drives the circulation and dries environment through pricipitation



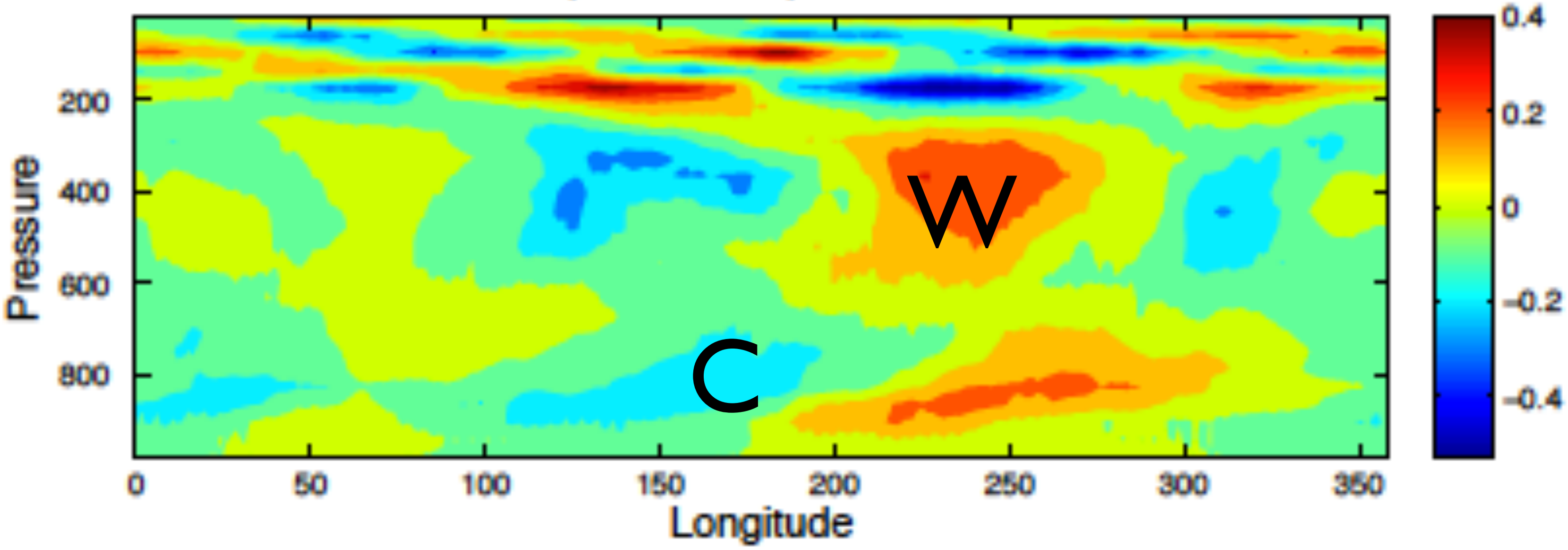
Congestus on the flanks remoistens environment for next MJO event


MJO composite, congestus heating (K/day)



MJO composite: Zonal wind anomalies averaged over [−10 deg , 10 deg]

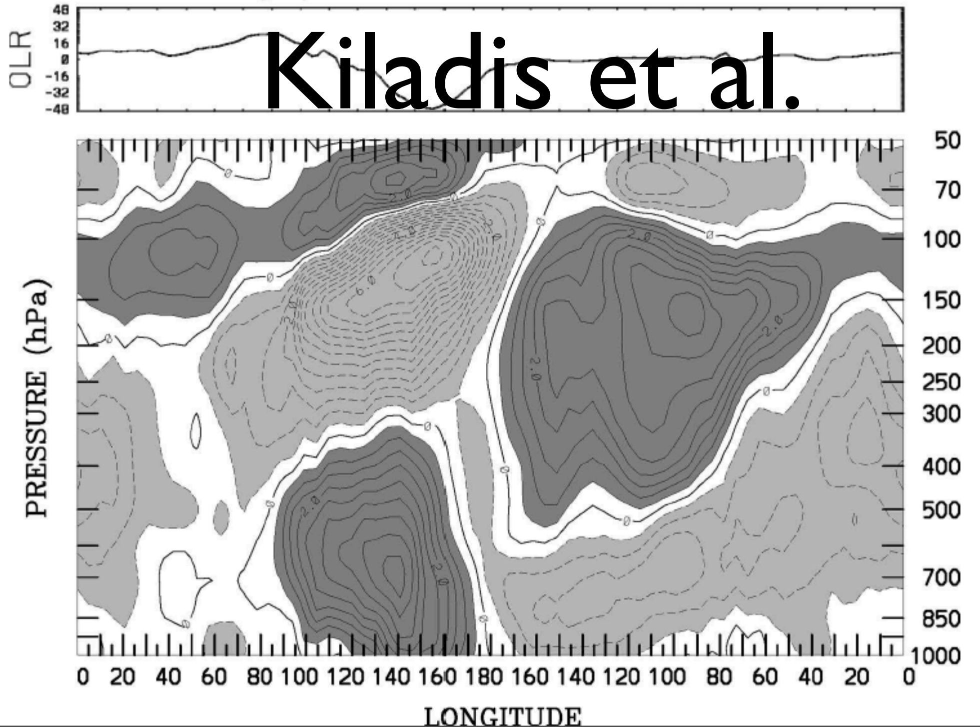
WWB



MJO composite: Temperature anomalies

W

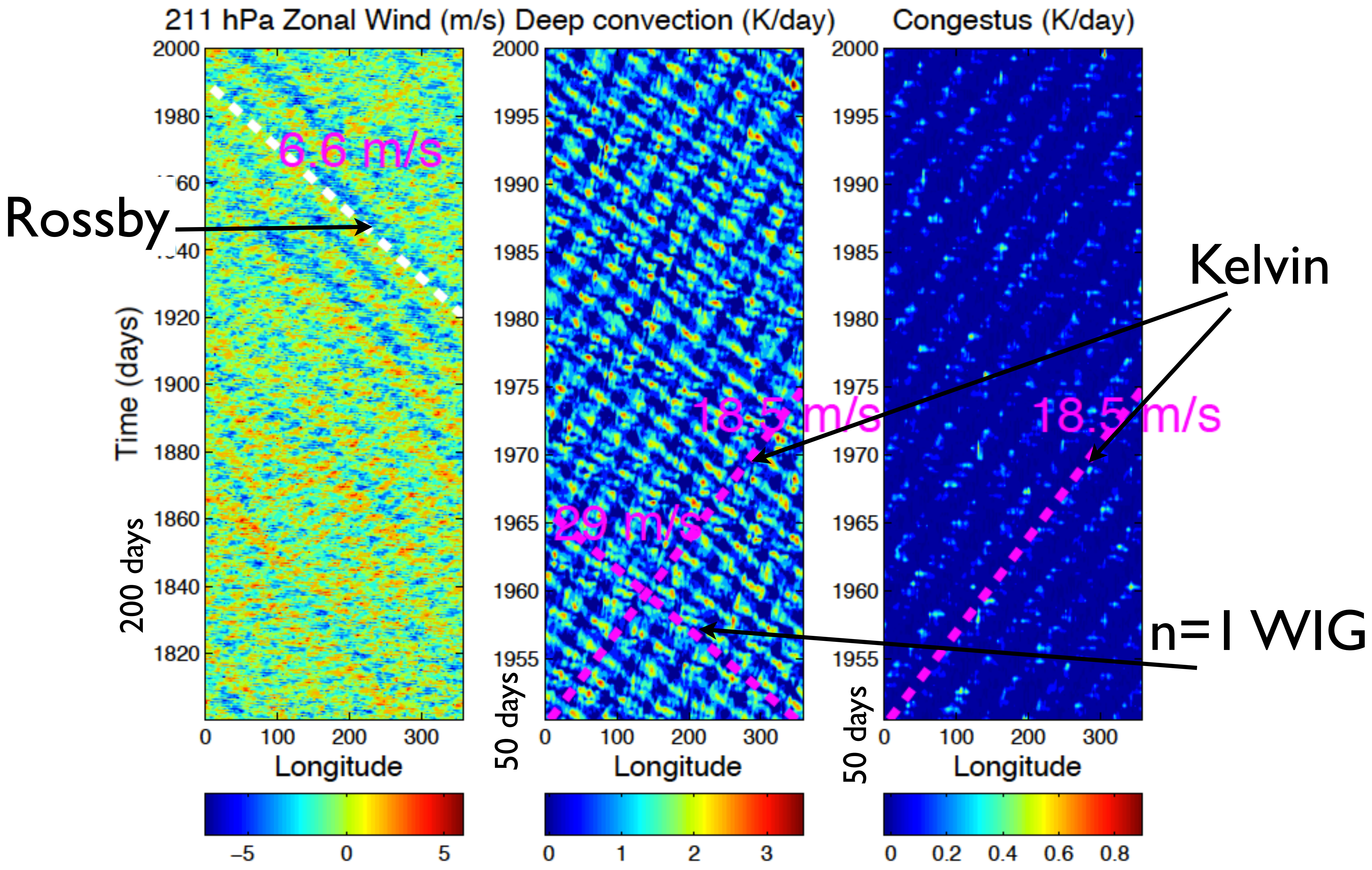
C



Zonal Wind along Equator

Kiladis et al.

Convectively Coupled Waves Regime



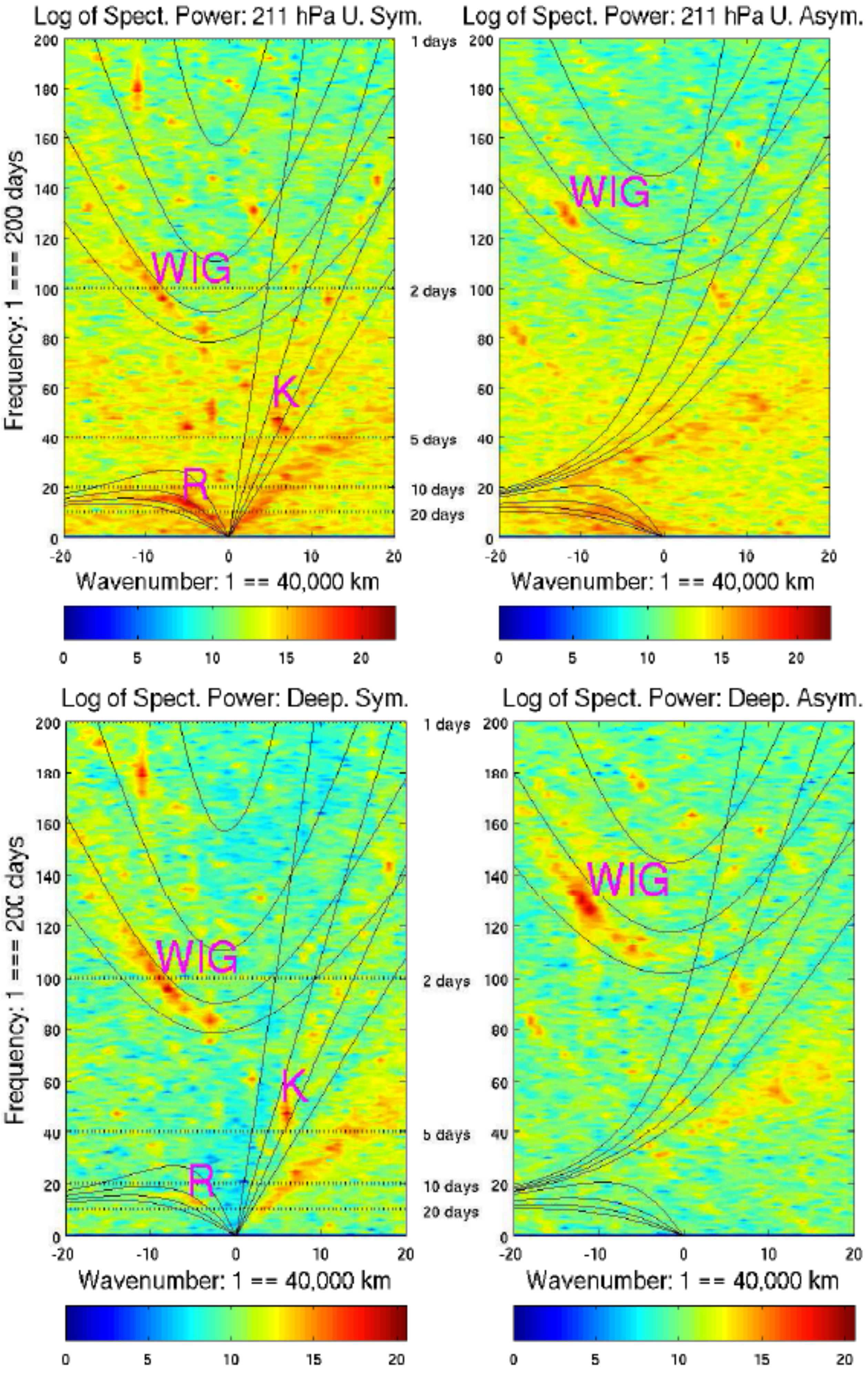
211 hPa Zonal Wind (m/s) Deep convection (K/day) Congestus (K/day)

Rossby

Kelvin

n=1 WIG

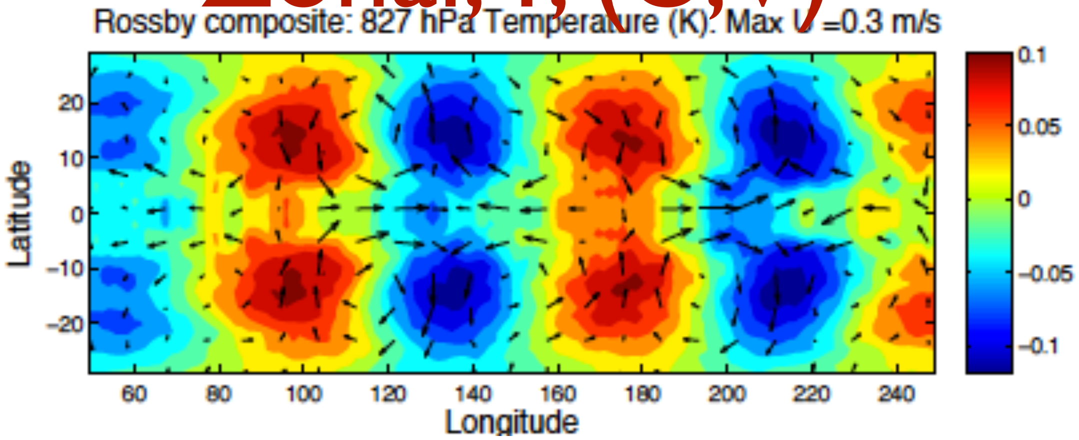
- Rossby (& Kelvin) waves dominate Zonal wind power
- n=1 WIG waves dominate the power of deep convection
- Rossby and Kelvin waves are large-scale envelopes of WIG waves
- WIG waves play role of MCS's at such coarse resolution

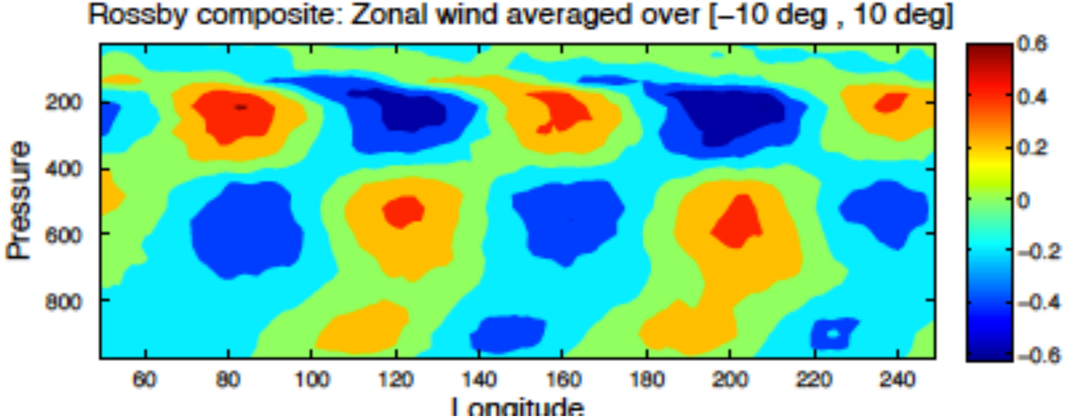


Zonal, T, (U,V)

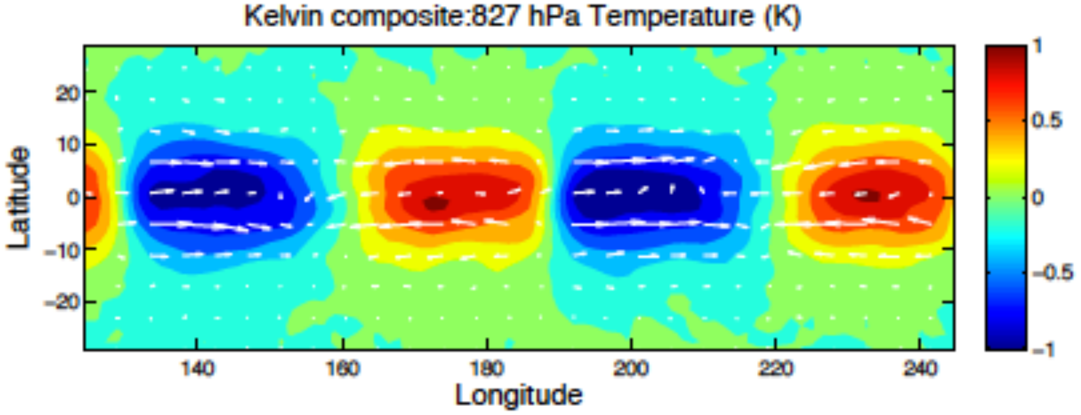
Vertical, U

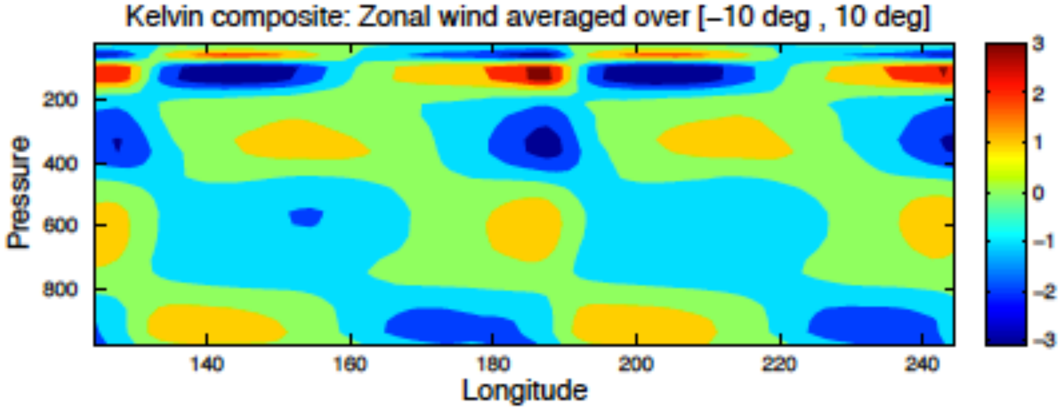
Rossby


Rossby composite: 827 hPa Temperature (K): Max U =0.3 m/s

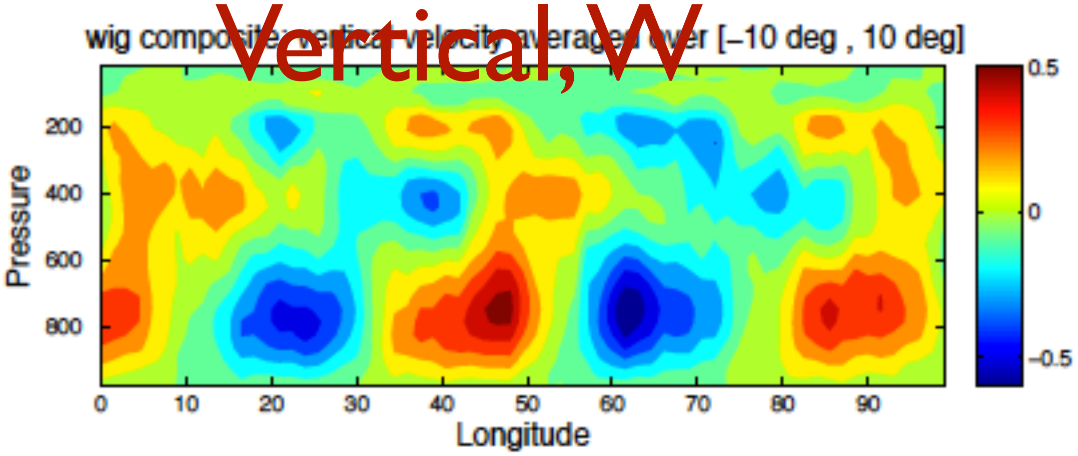

Rossby composite: Zonal wind averaged over [−10 deg , 10 deg]

Kelvin

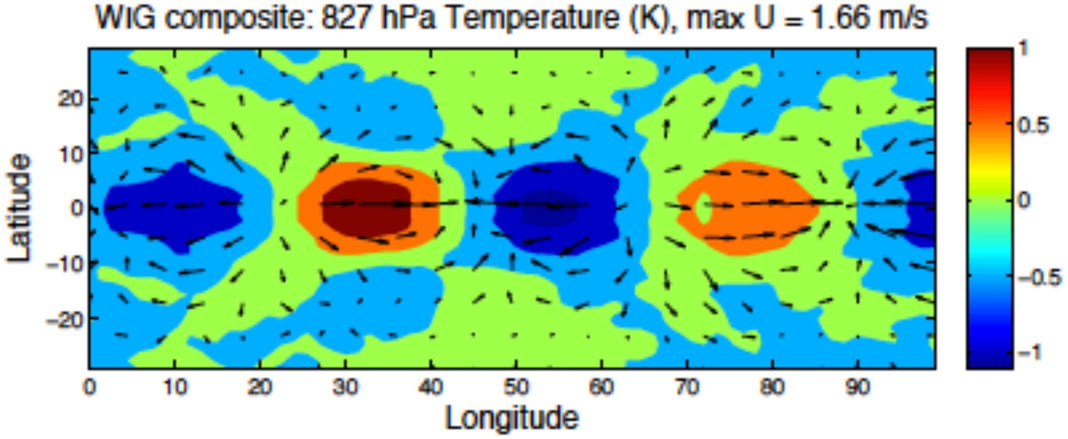

Kelvin composite:827 hPa Temperature (K)


Kelvin composite: Zonal wind averaged over [−10 deg , 10 deg]

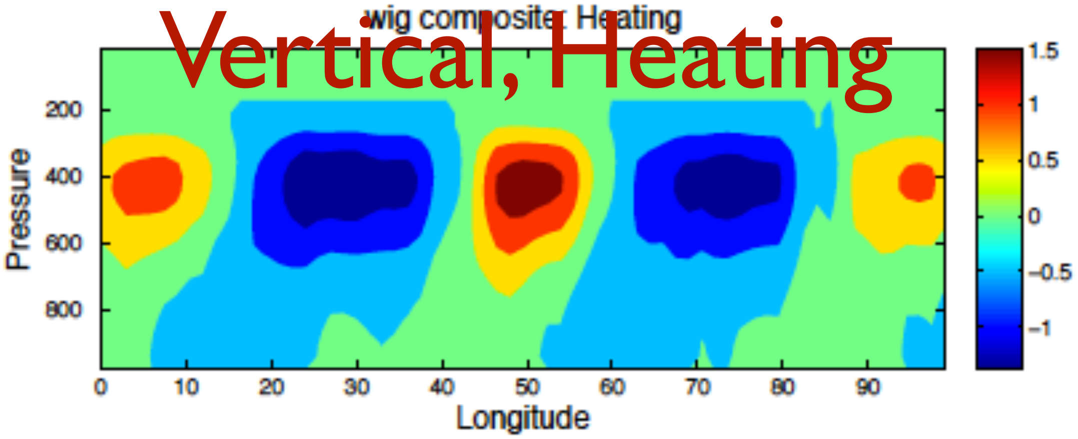
Vertical, W


wig composite: vertical velocity averaged over [−10 deg , 10 deg]

n=1 WIG

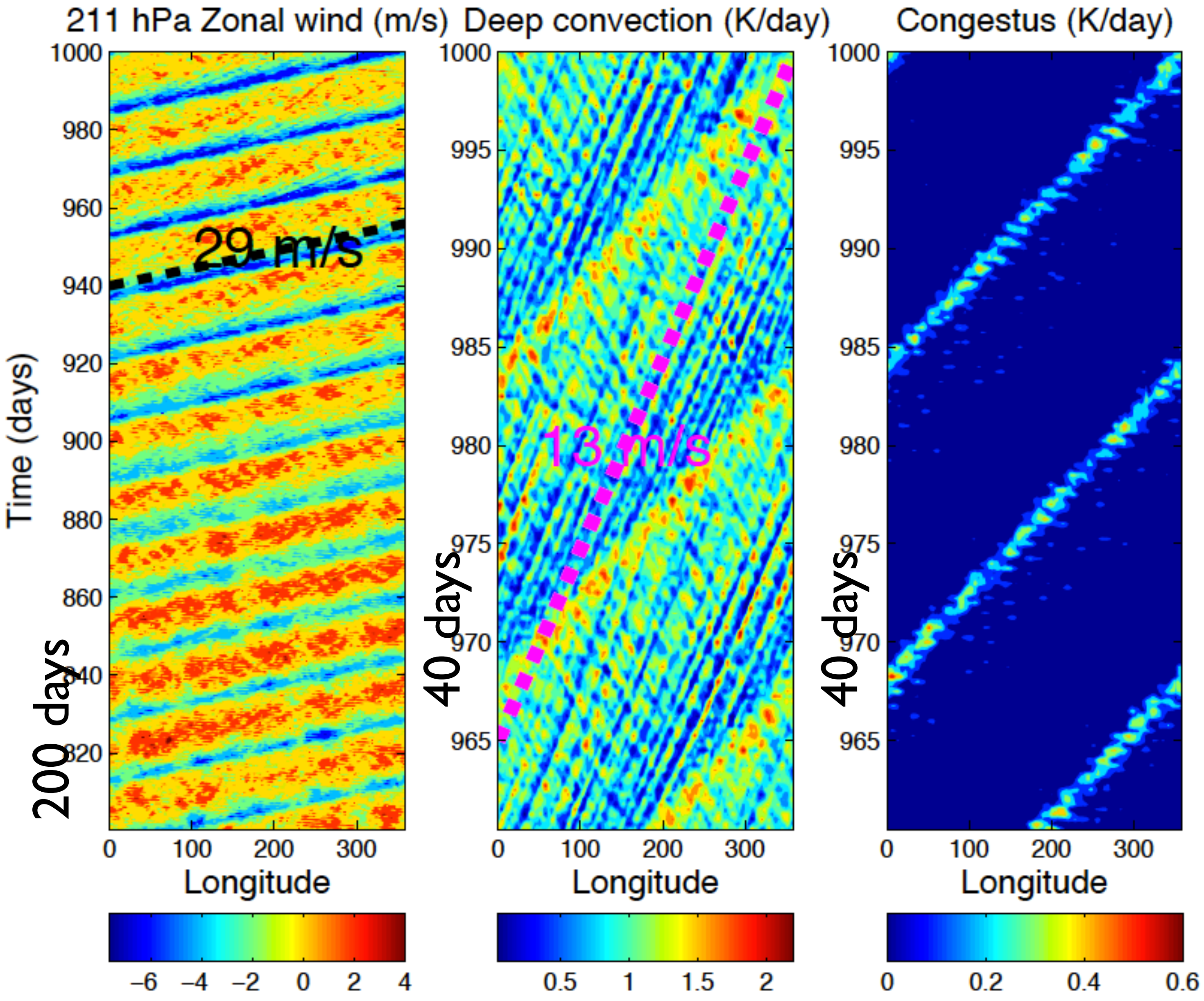

WIG composite: 827 hPa Temperature (K), max U = 1.66 m/s

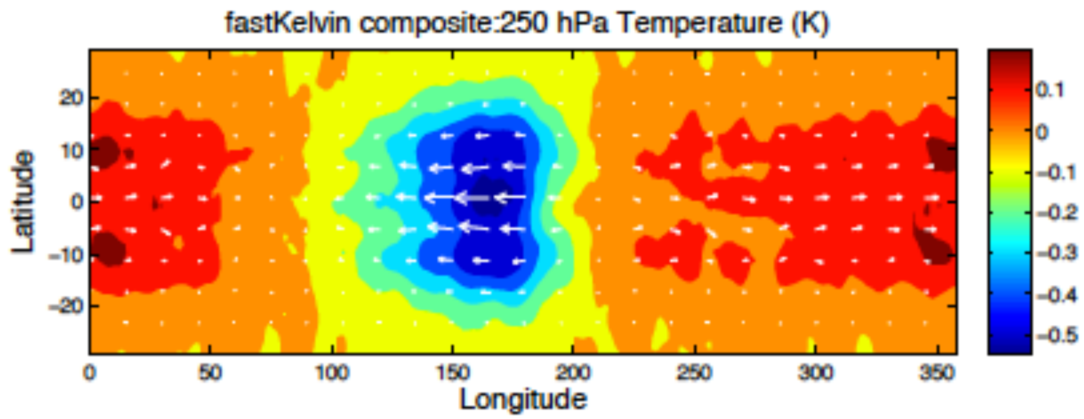
Vertical, Heating

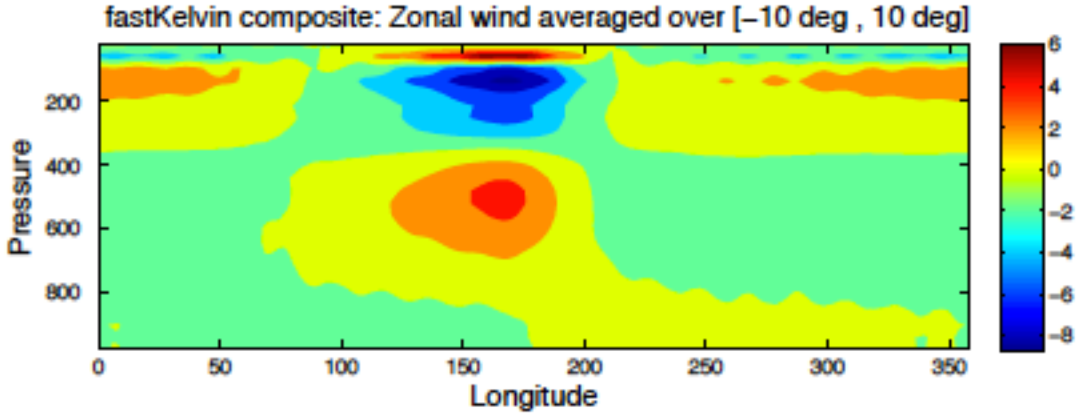

wig composite: Heating

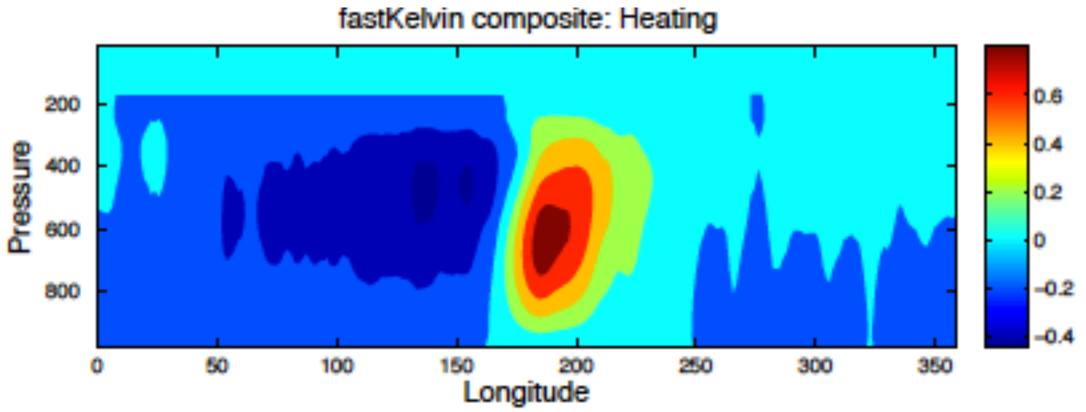
Tilt in WIG important for CMT that drives Rossby waves

Fast Kelvin Wave--Example of Bad MJO simulation


211 hPa Zonal wind (m/s) Deep convection (K/day) Congestus (K/day)

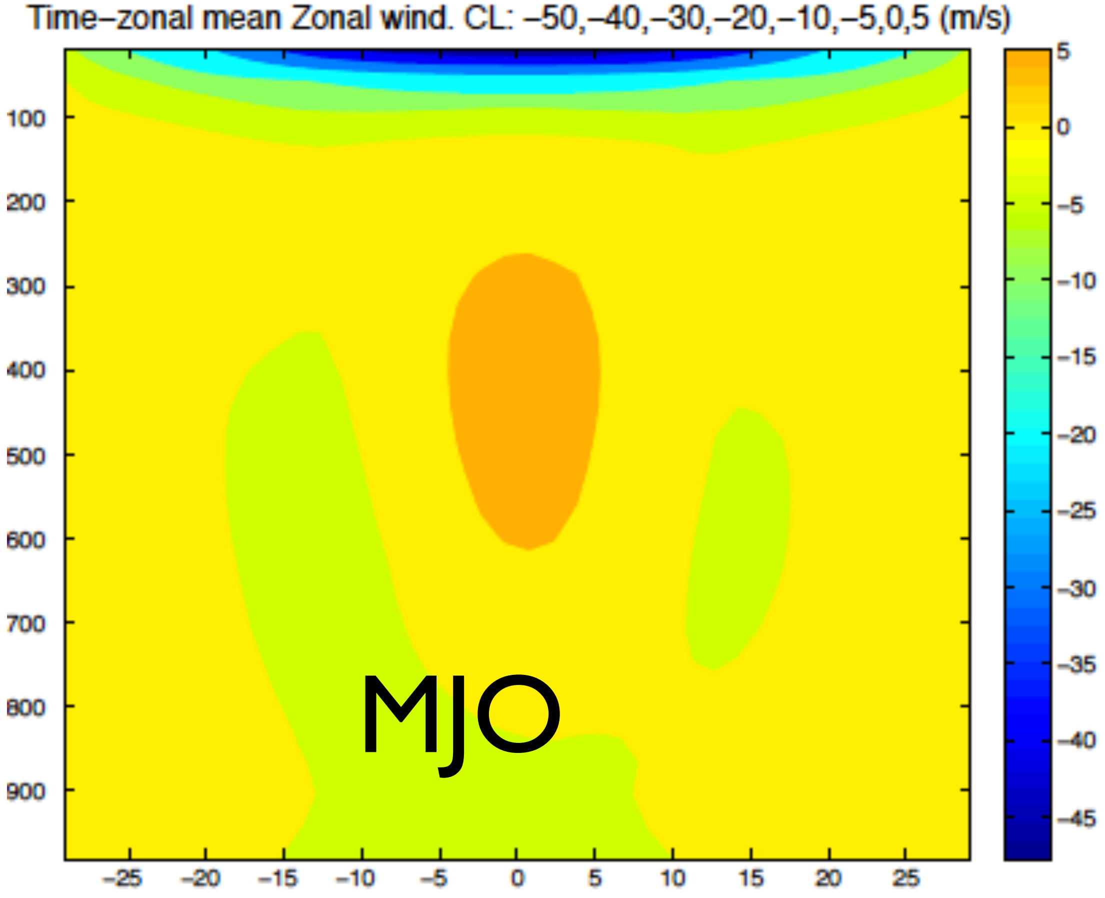

fastKelvin composite:250 hPa Temperature (K)

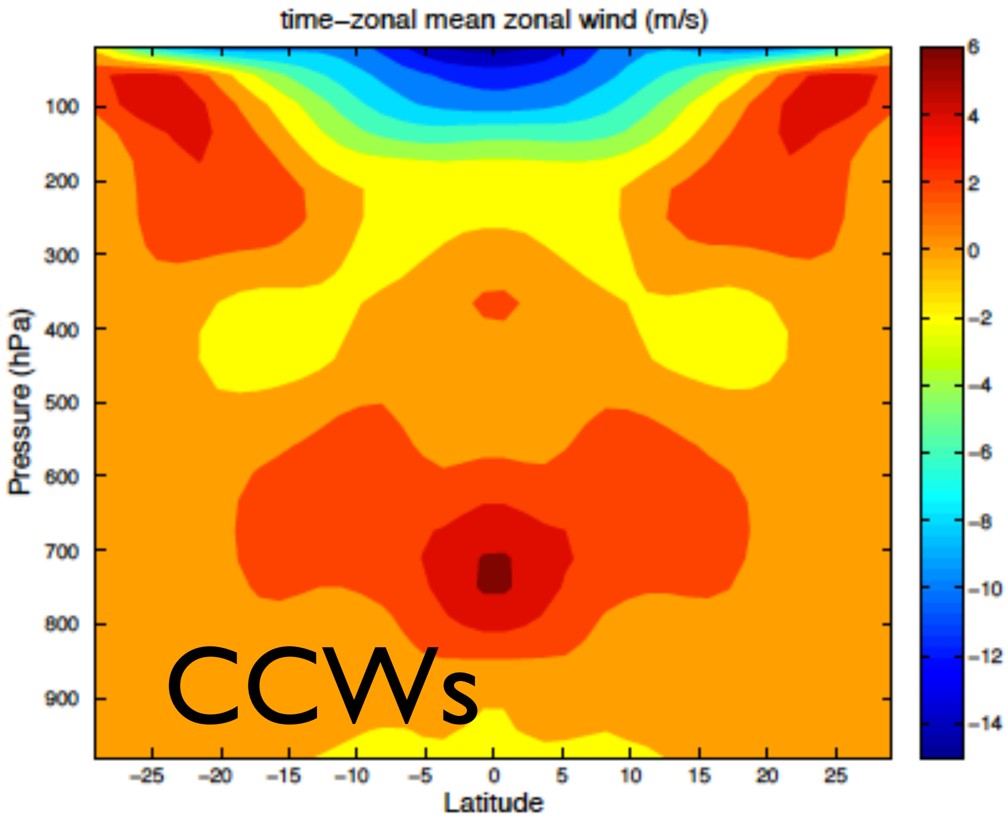

fastKelvin composite: Zonal wind averaged over [−10 deg , 10 deg]


fastKelvin composite: Heating

Congestus driving 2nd baroclinic Kelvin wave! Strong jet in mid-troposphere, low-level heating, tilted in wrong direction!

Mean Climatology & Superrotation





- MJO creates mean state that allows it to propagate.
- MJO as Gill response to moving heat source as in Biello&Majda's kinematic model (2005).
- Mean westerlies is due to MJO induced super-rotation (Biello, Majda& Moncrieff 2007).
- CCWs superrotation has amore barotropic westerly wind, weak in mid-to-upper troposphere. No MJO signal.

Summary & Concluding Remarks

- Simulations of tropical convective systems in HOMME with simple multicloud model
- Multicloud model based on three cloud types, designed to capture key features of CCW's
- Multicloud model coupled to GCM through clever use of vertical normal modes
- Simulations in 3 different parameter regimes: MJO, CCWs,
- Moisture vertical flux & Stratiform fraction are key param
- If such regimes exist in nature, what sets transitions?
- Shortcomings: Imposed vertical profiles & moisture background, fixed stratiform fraction

➡ Multicloud ideas easily extensible into comprehensive parametrization---under consideration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Thank you!