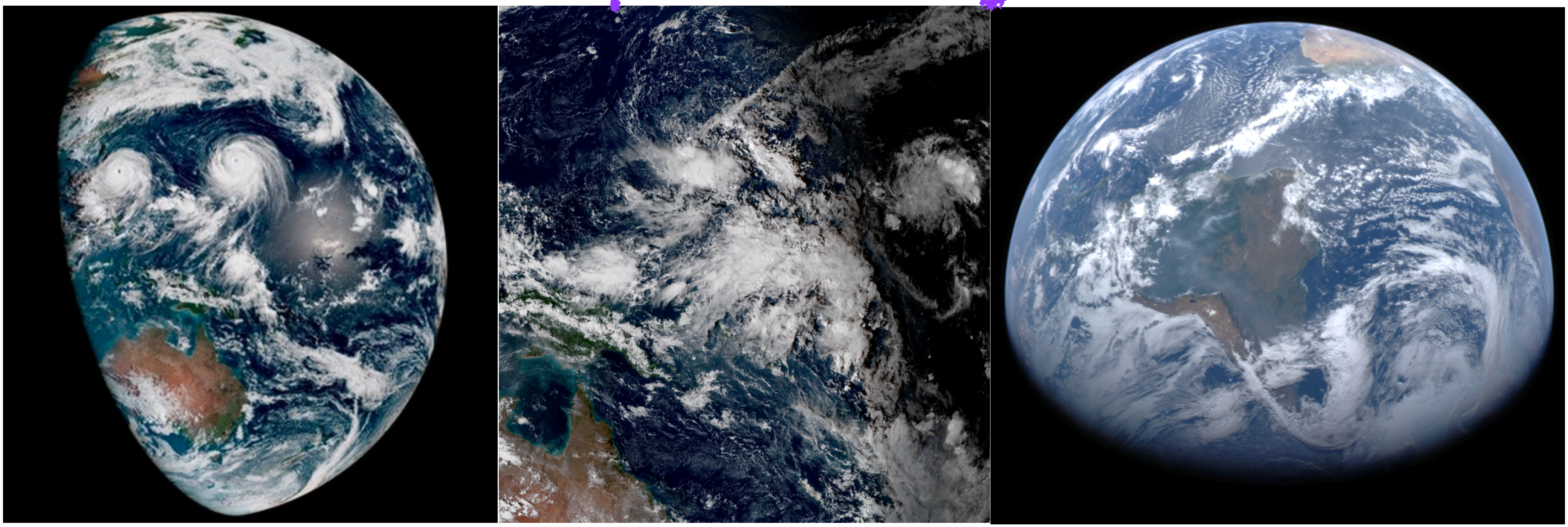
Observations of Convection Organization

at the planetary scale



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with slides from: Angel Adames — Adam Sobel — Da Yang

many more adapted from: George Kiladis — Chidong Zhang

“convection organization”

WHAT DO WE MEAN BY ORGANIZATION?

- organization by the boundary
- self - organization of the atmosphere
    - through (dry) dynamics
    - through moisture

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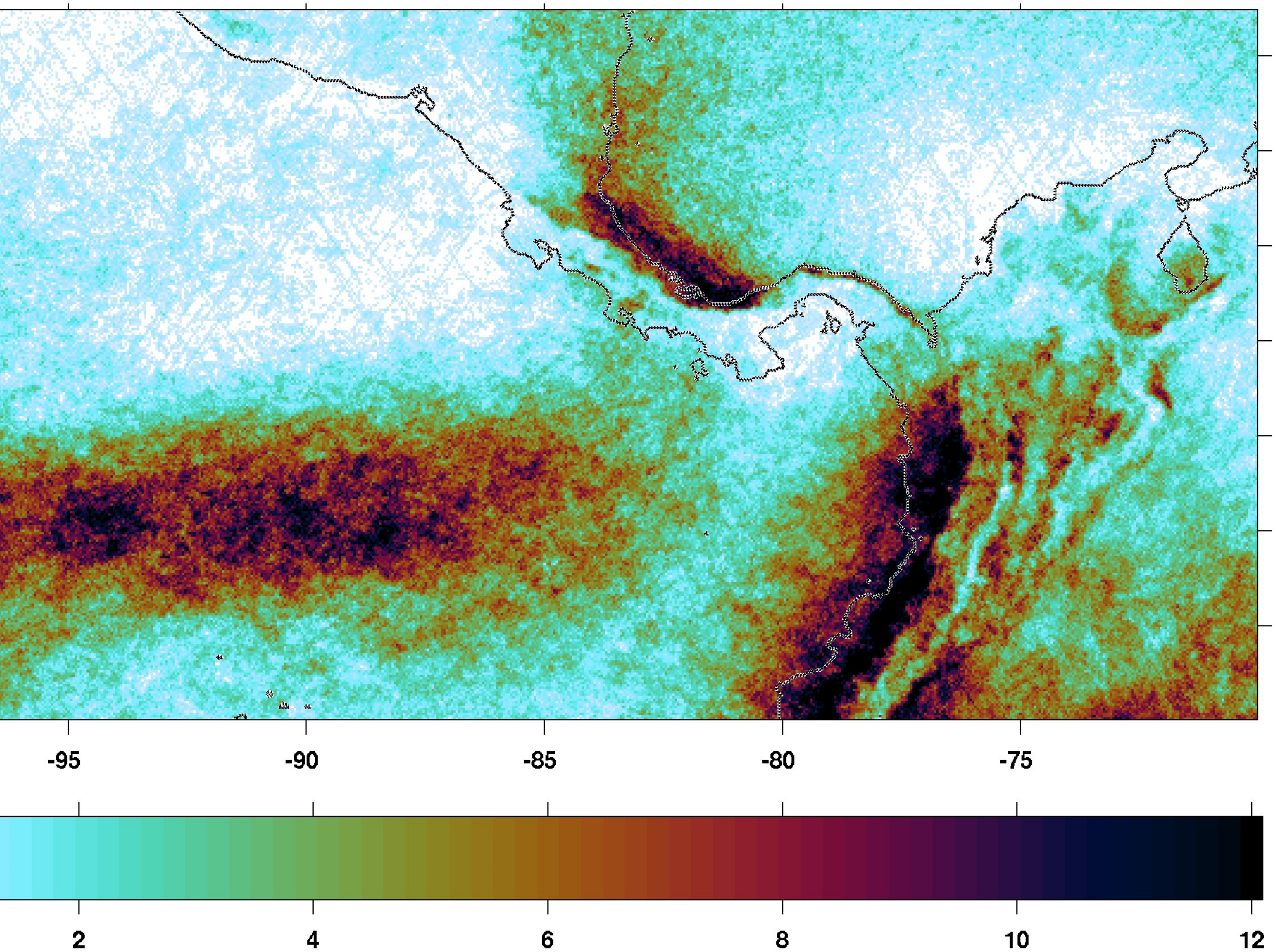
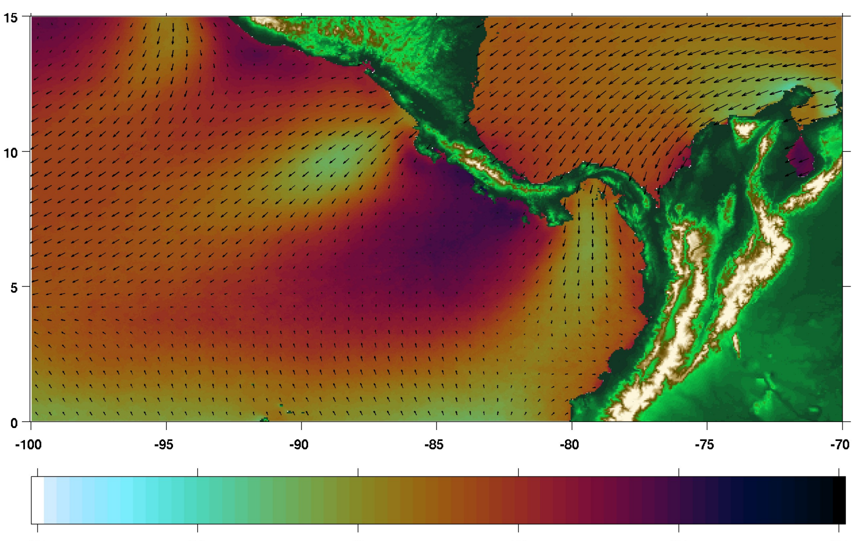
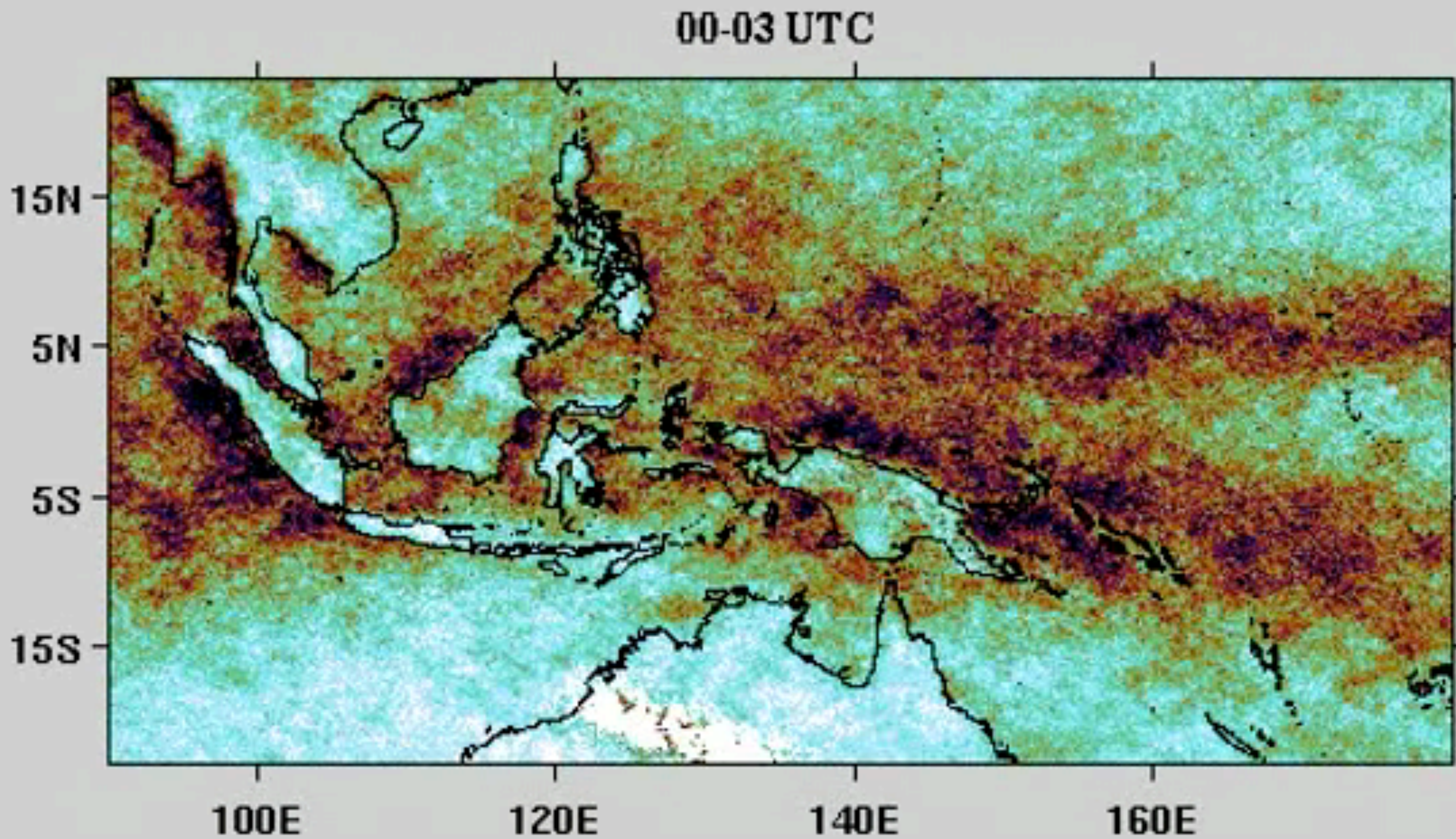


by the boundary

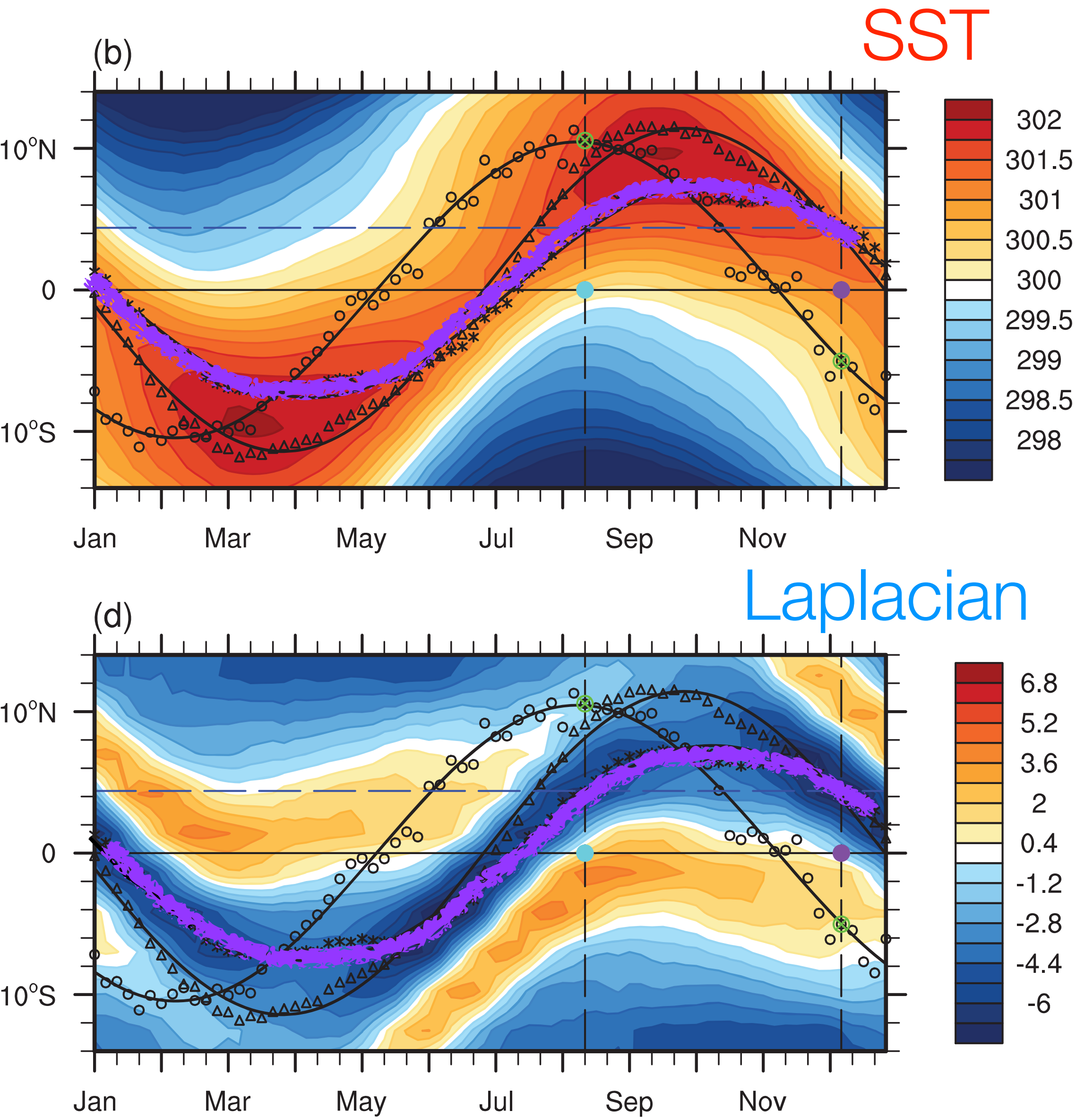
- orography
  - barrier
  - lift
- patterns in enthalpy fluxes
  - SST
  - wind speed
- patterns in surface convergence
- diurnal circulations (rectified)



diurnal circulations



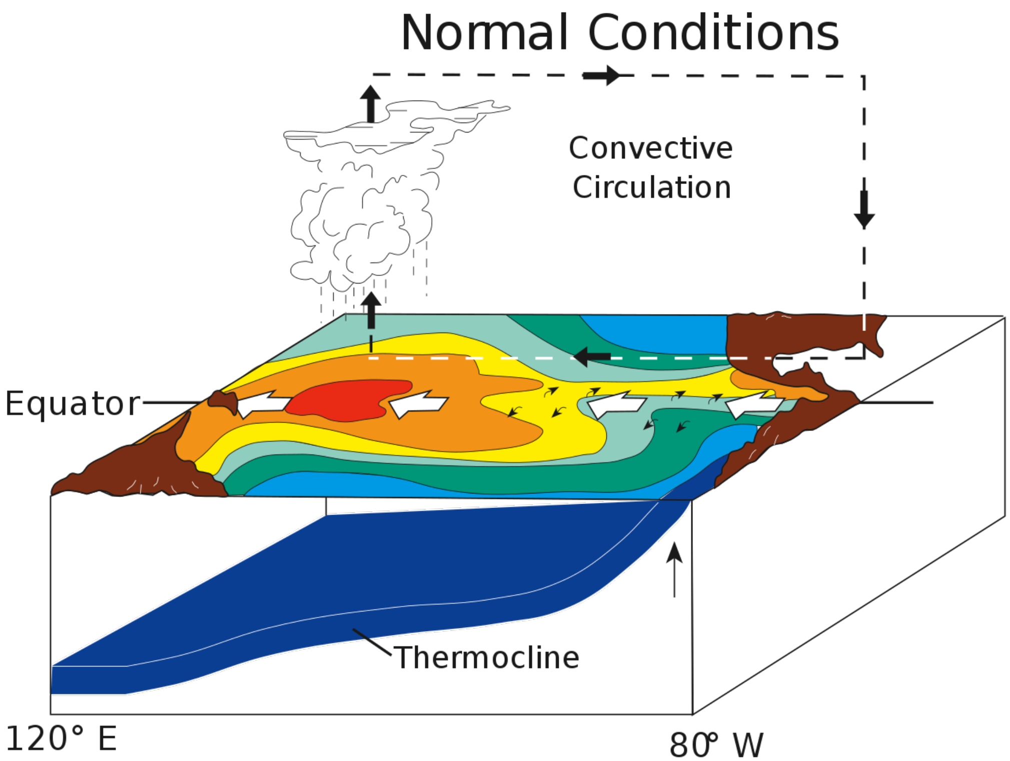
at seasonal to interannual (& longer) scales organization is from the boundary

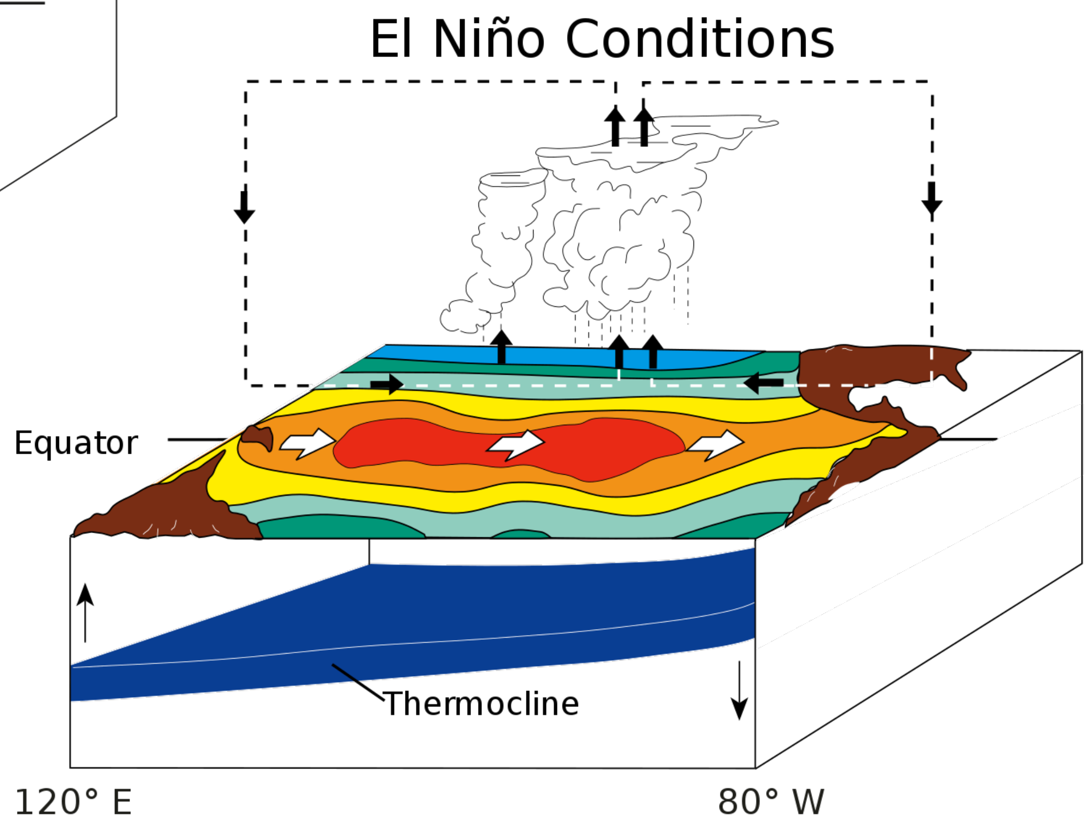


wei and bordoni (2018)

The seasonal excursion of an **Aquaplanet ITCZ** follows the (Laplacian) of SST

at seasonal to interannual (& longer) scales organization is from the boundary





NOAA

“convection organization”

WHAT DO WE MEAN BY ORGANIZATION

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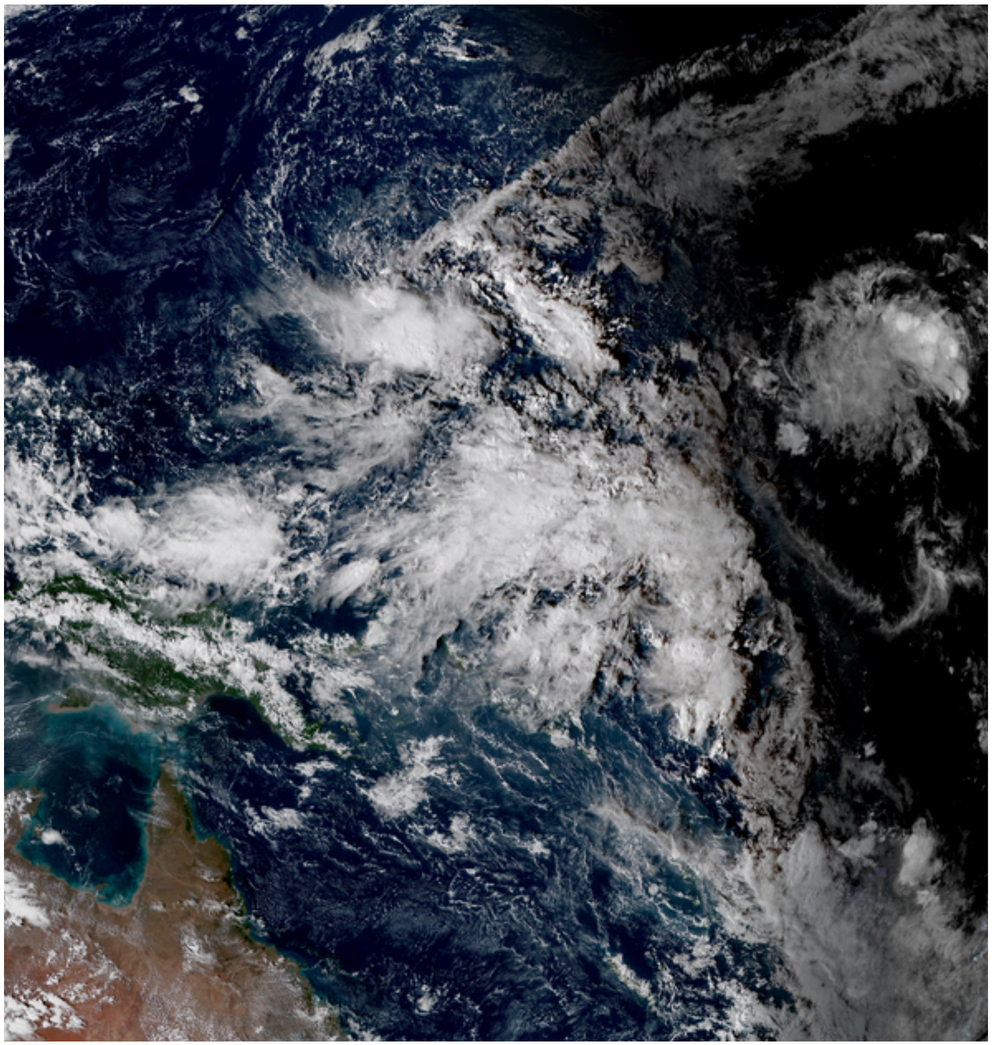
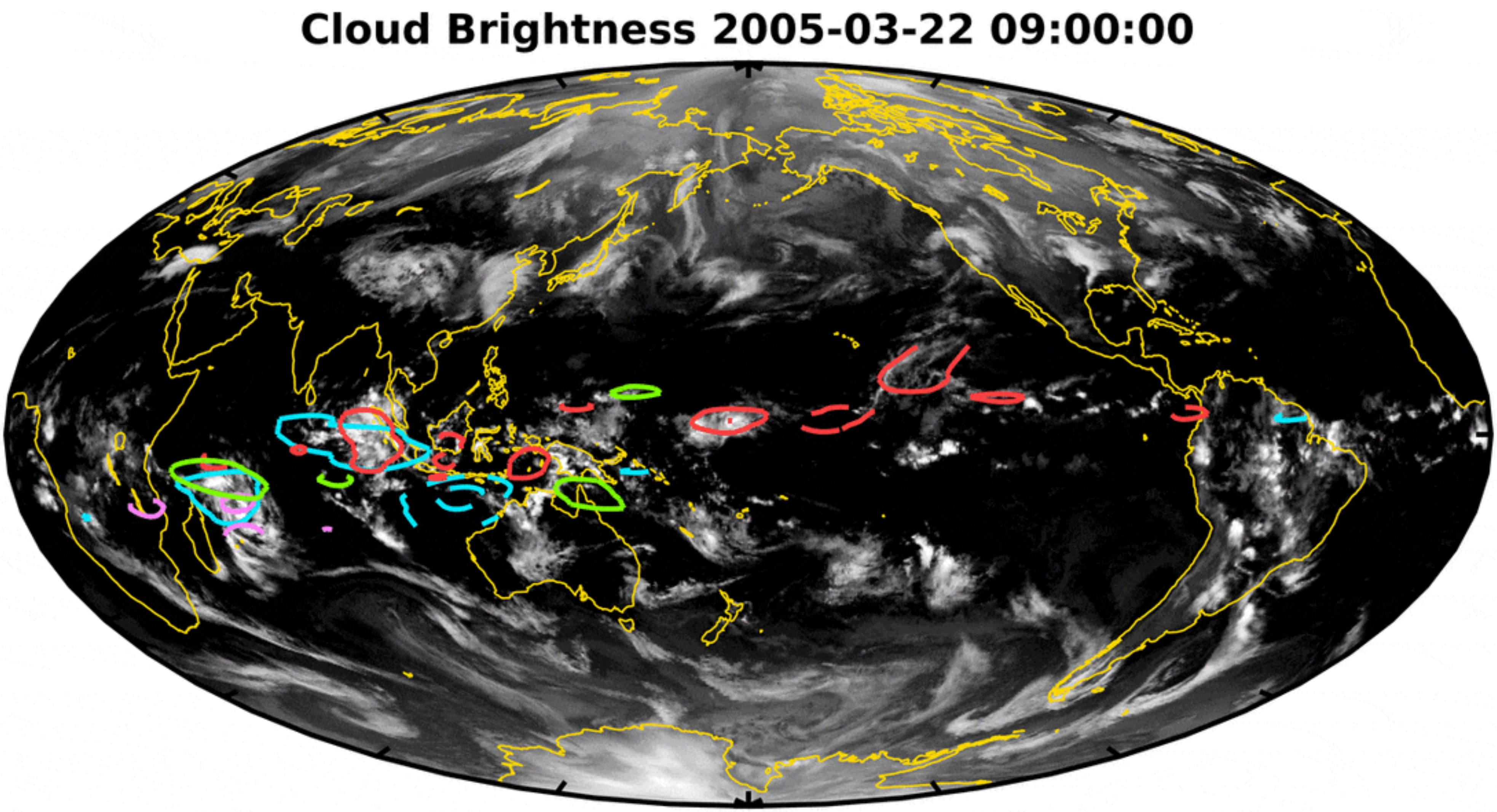
self-organization of the atmosphere

- through (dry) dynamics: Equatorial Waves
- through (maybe) moisture: The MJO



- (mostly) away from land
- sub-seasonal

A diversity of convectively-coupled waves and modes



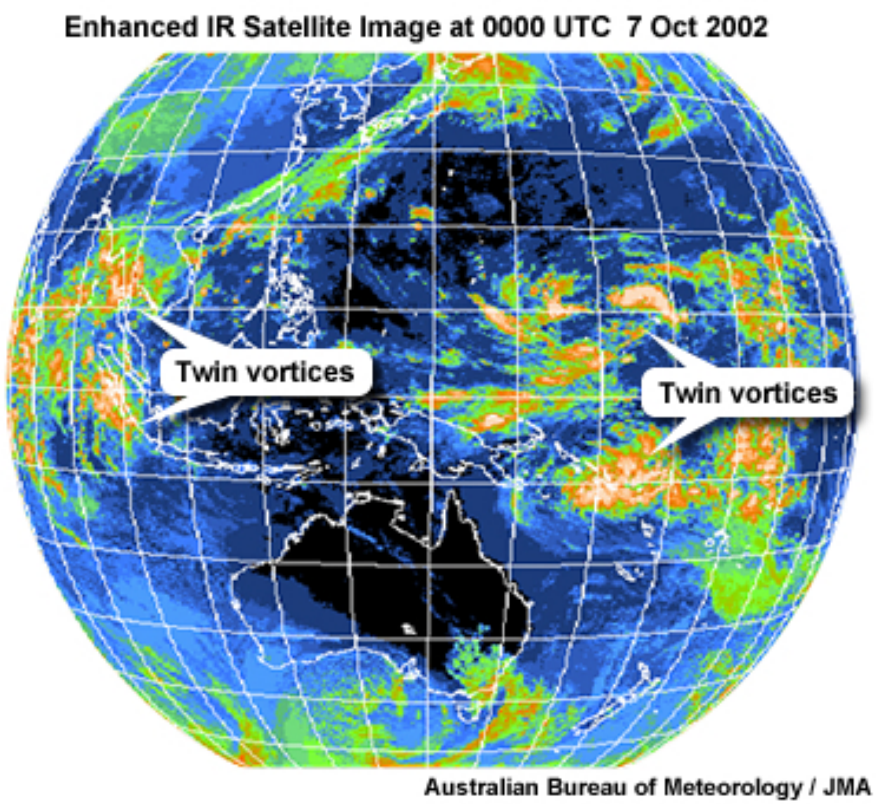
MJO Eq. Rossby Kelvin MRG

Ángel F. Adames
University of Michigan

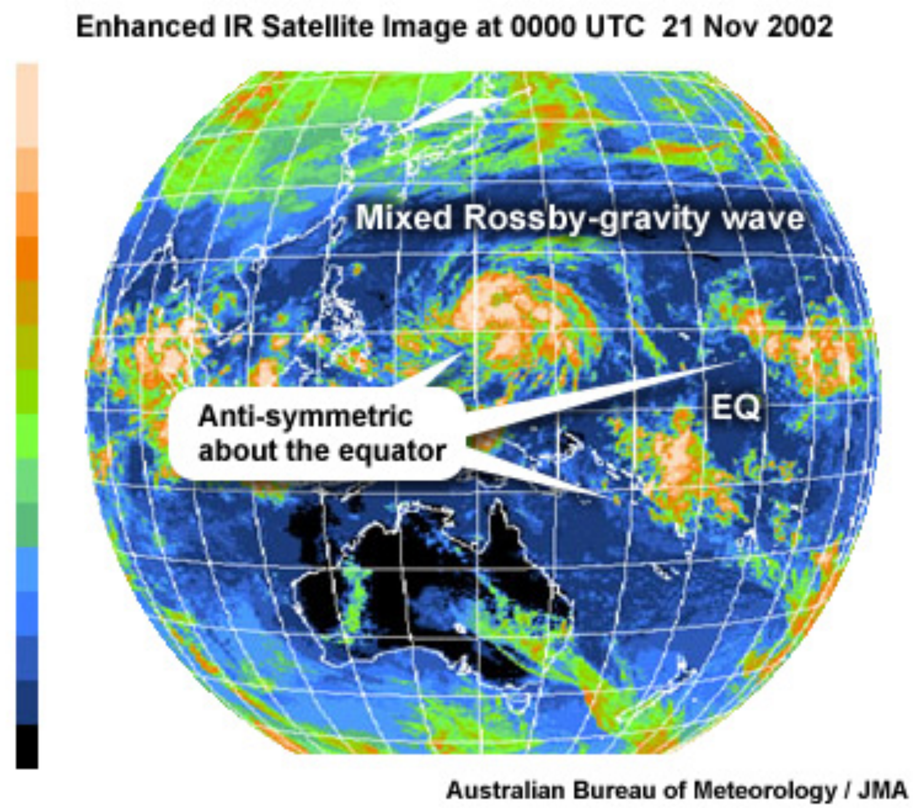
How to diagnose tropical waves: the Wheeler and Kiladis diagram (1/5)

1. Decompose (IR) into components that are symmetric and anti-symmetric about the equator. (This takes care of the y-direction)

Symmetric



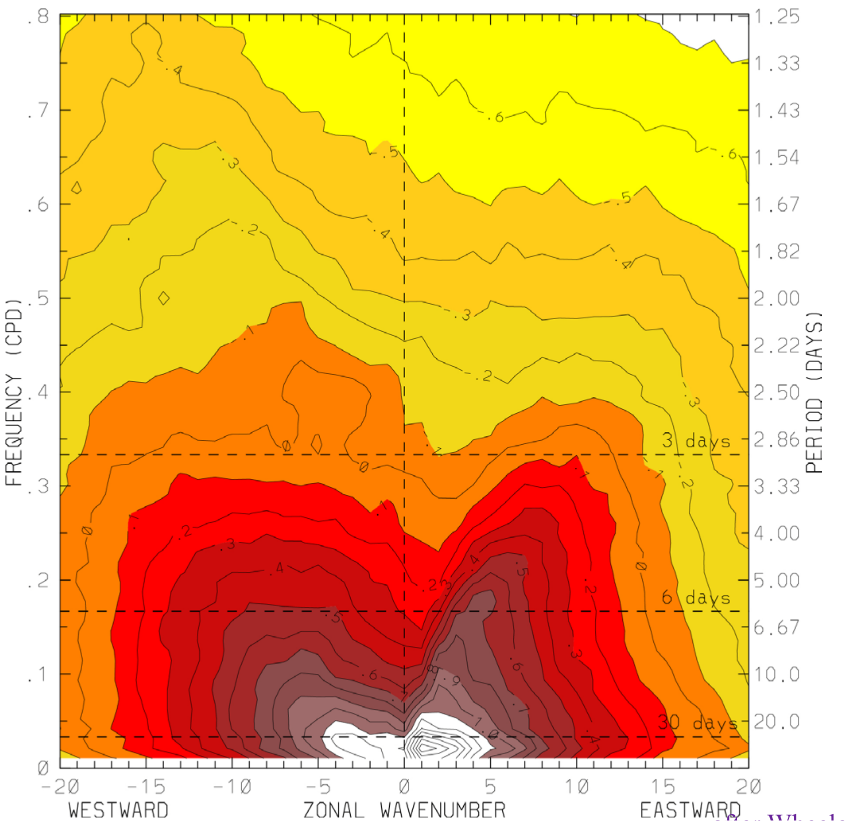
Anti-symmetric



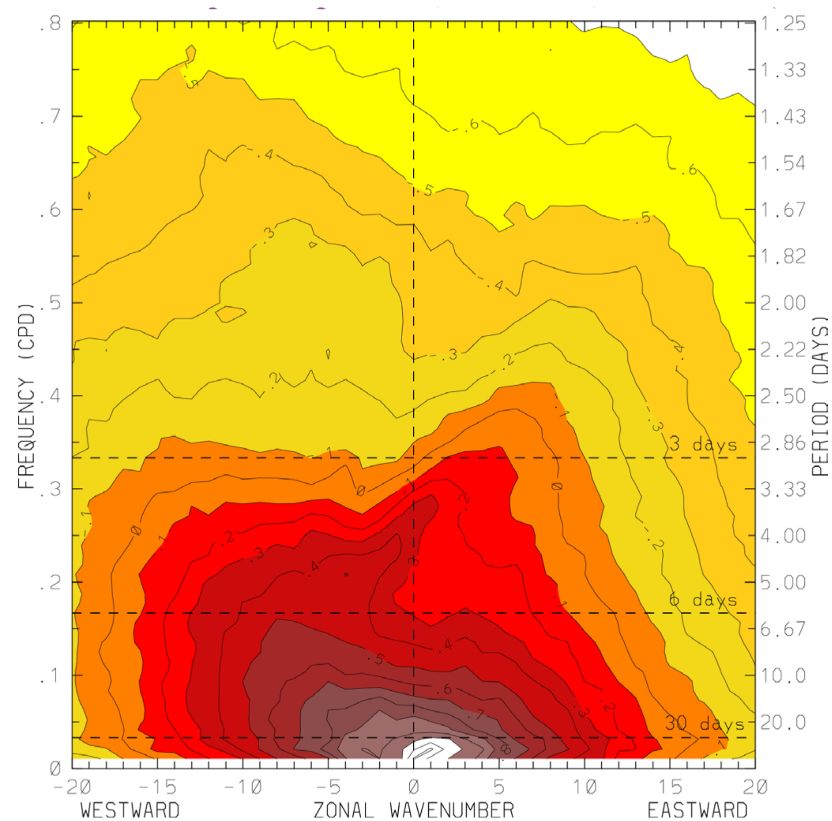
How to diagnose tropical waves: the Wheeler and Kiladis diagram (2/5)

2. Take 2-D Fourier transformation of a(x, t) ⟶ A(k, n)
3. Plot $A^2(k, n)$: Power spectrum

Symmetric



Antisymmetric



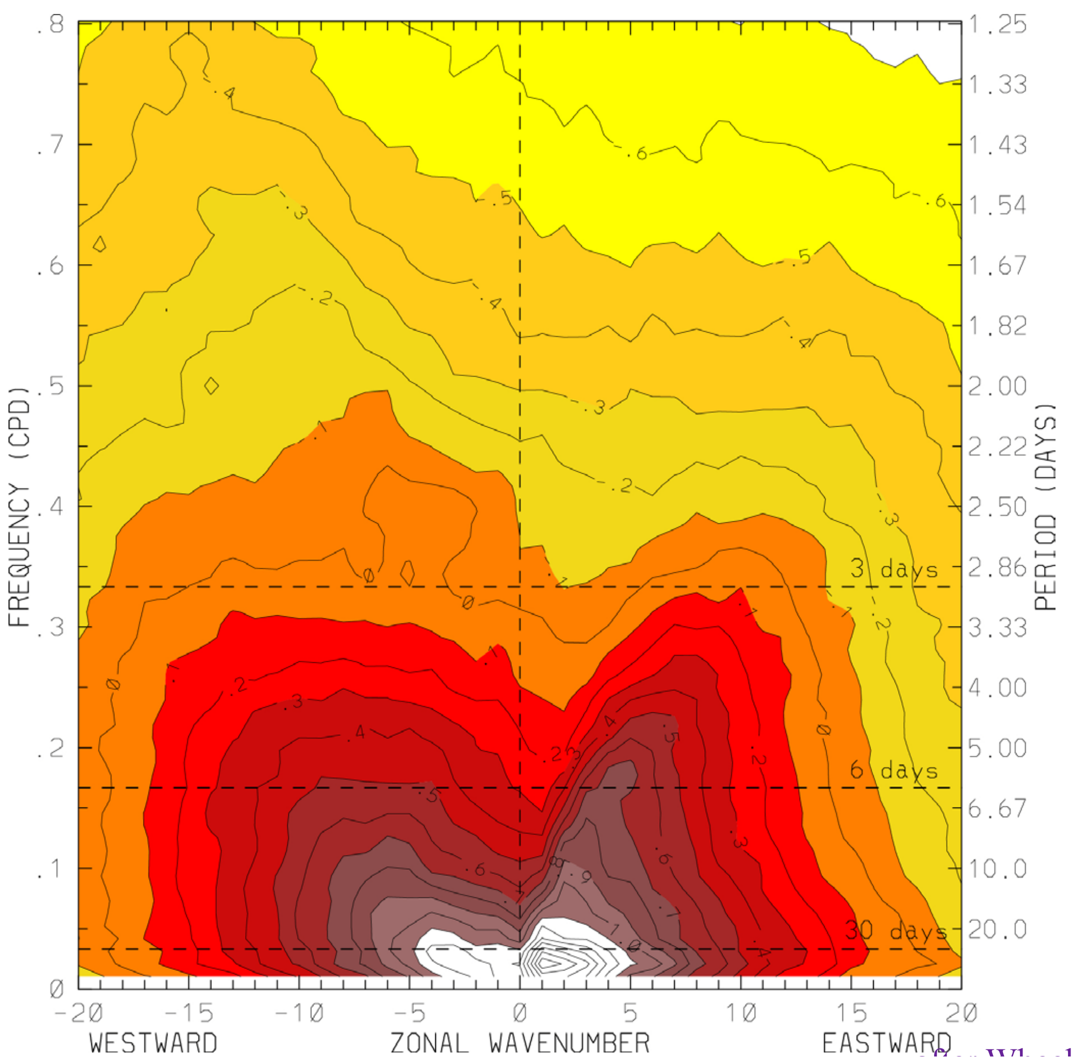
CLAUS Tb power spectrum, 15°S-15°N, 1983–2006 (after Wheeler and Kiladis, 1999).

How to diagnose tropical waves:
the Wheeler and Kiladis diagram (3/5)

↑ faster ↑

↑ faster ↑

30 days



←smaller smaller →

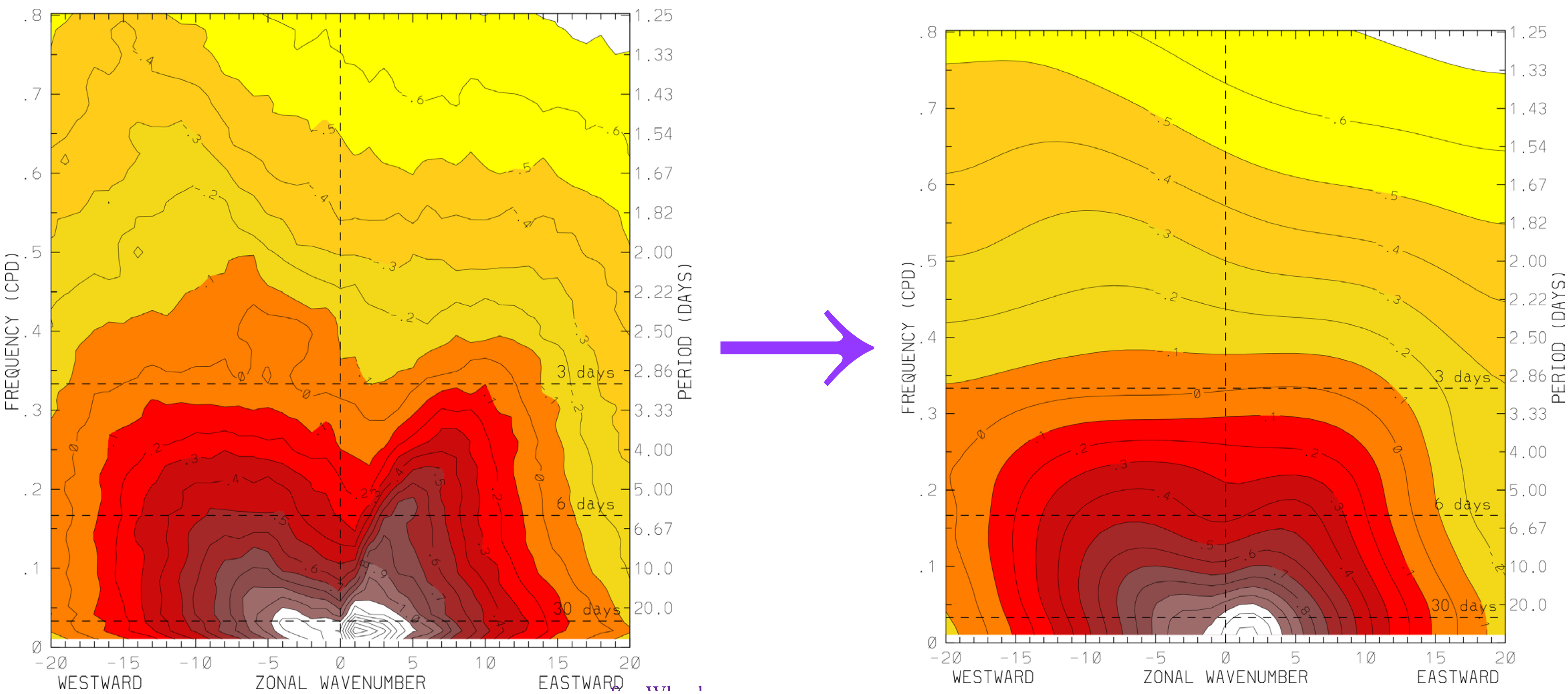
WESTWARD EASTWARD

larger frequency
==
faster time scale

larger wavenumber
==
smaller zonal scale

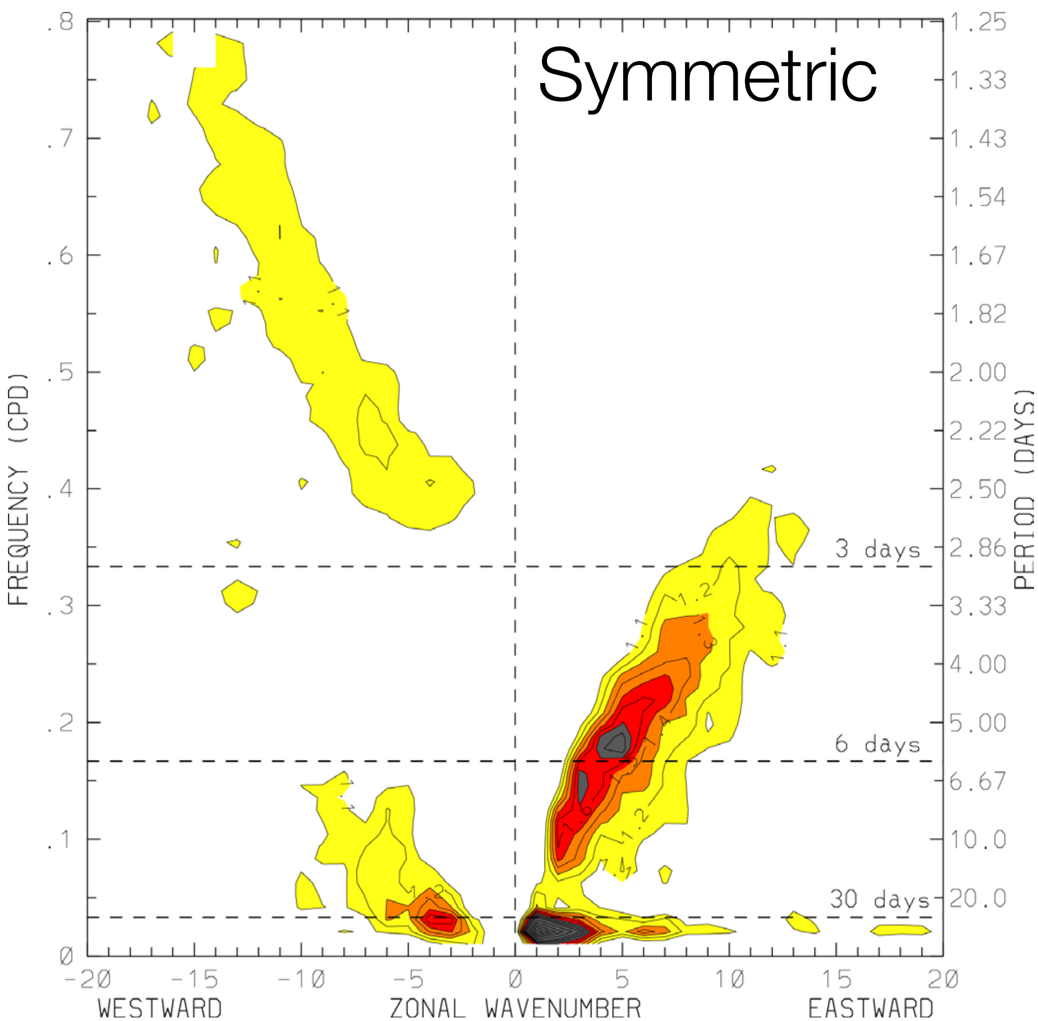
How to diagnose tropical waves: the Wheeler and Kiladis diagram (4/5)

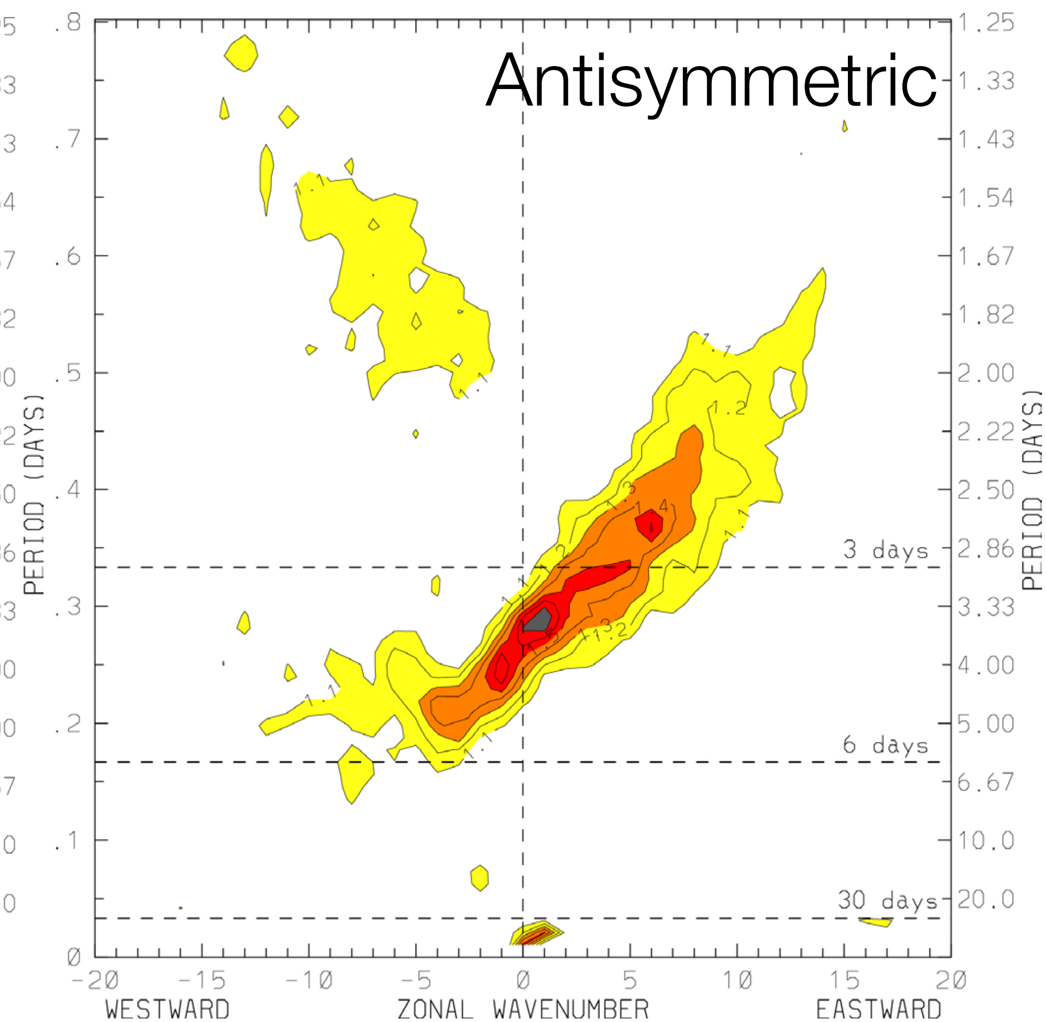
4. Determine “background” spectrum by smoothing raw spectra



How to diagnose tropical waves: the Wheeler and Kiladis diagram (5/5)

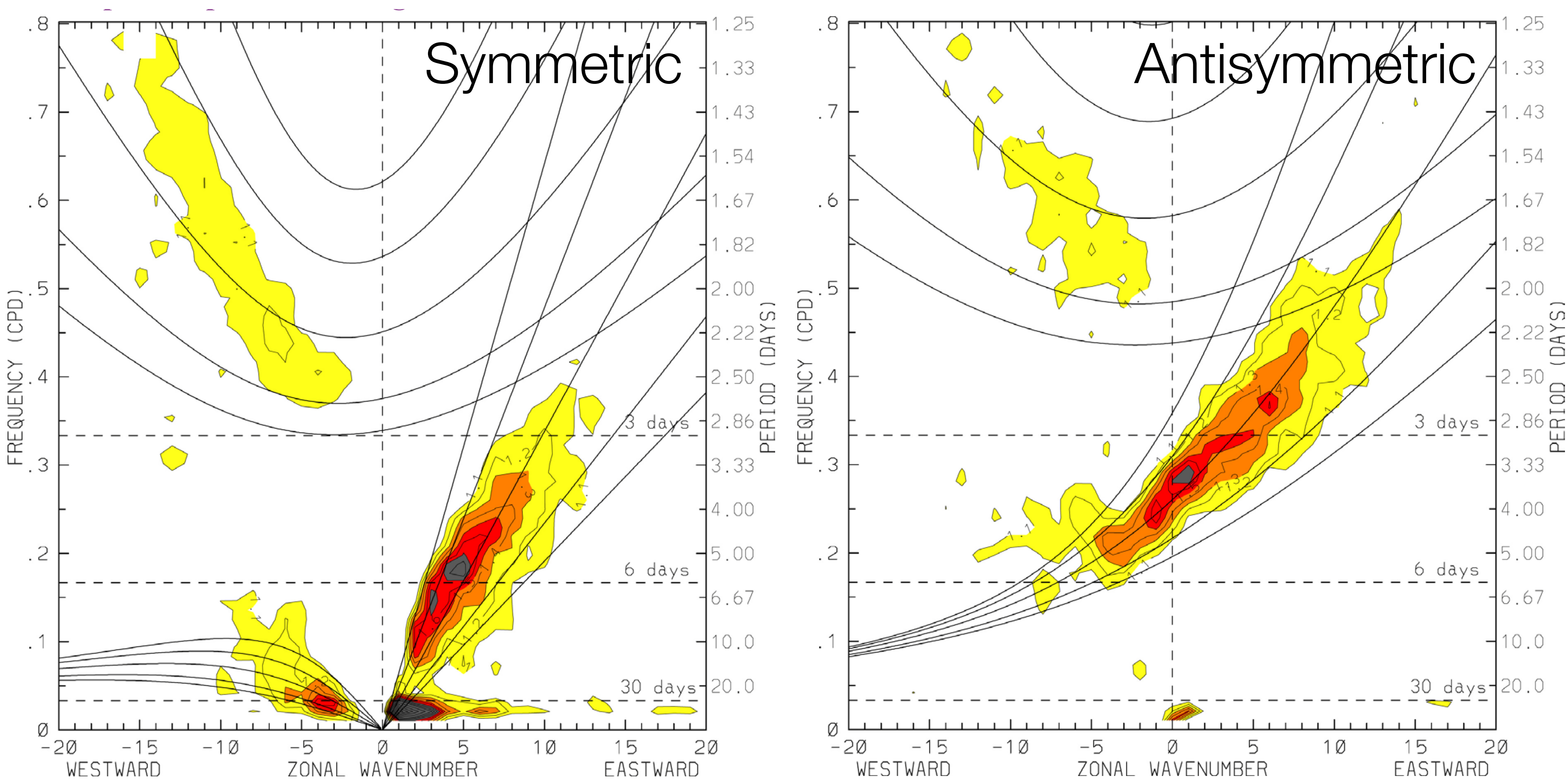
5. Divide raw spectra by background spectra to determine signals standing above the background





Enhanced power in the Wheeler and Kiladis diagram corresponds to known tropical waves

There is a good match to the dispersion relation of dry equatorially trapped waves found by Matsuno (1966)



Equatorial Shallow Water (unforced, undamped)

$$\frac{\partial u}{\partial t} - \beta y v + \frac{\partial \phi}{\partial x} = 0$$

$$\frac{\partial v}{\partial t} + \beta y u + \frac{\partial \phi}{\partial y} = 0$$

$$\frac{\partial \phi}{\partial t} + gh\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) = 0$$

SW:
incompressible
and $L_z >> L_{x,y}$

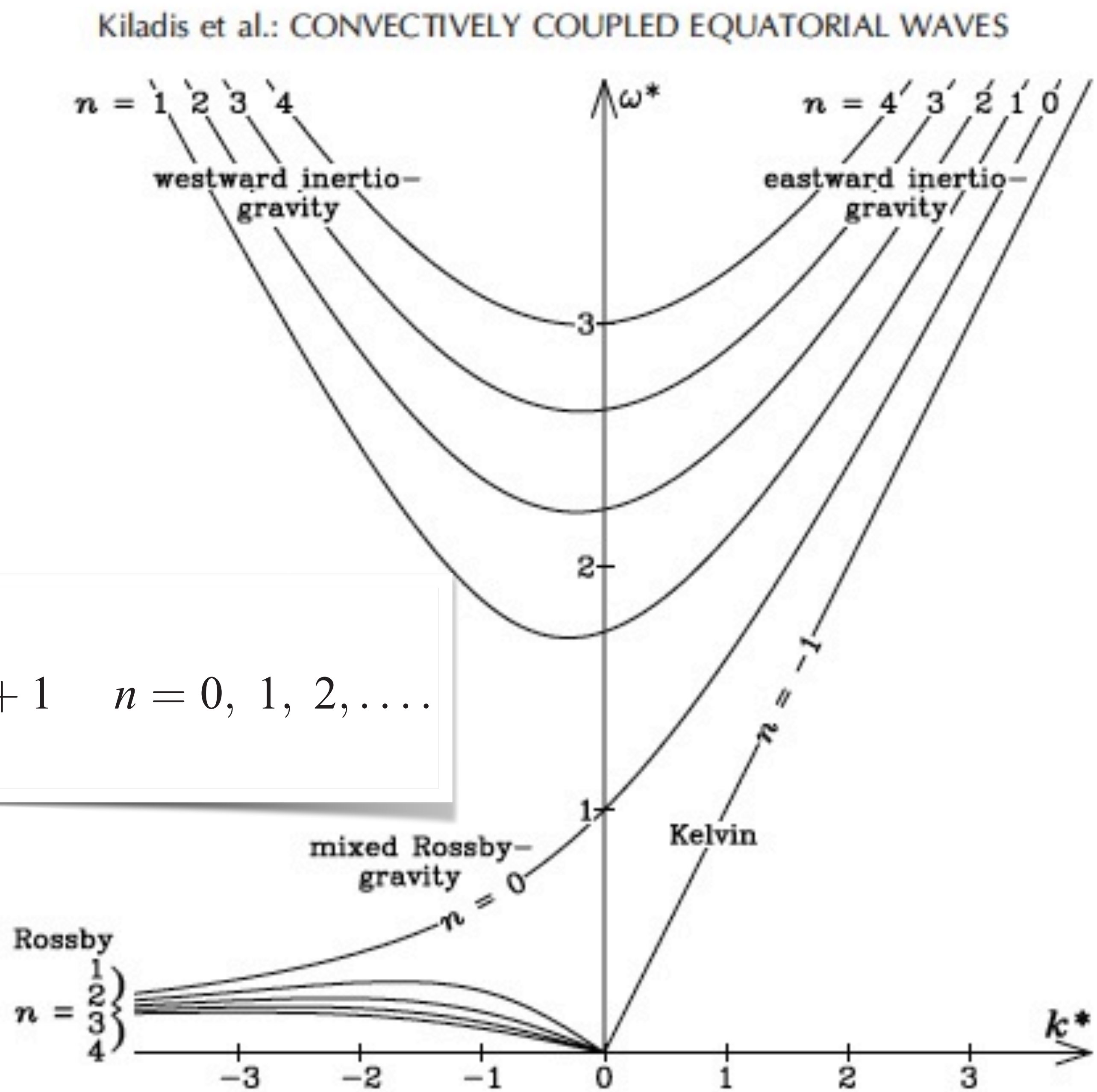
Linearized around a
basic state at rest

Two restoring forces:
Gravity and Rotation
=> wave solution

To the board:

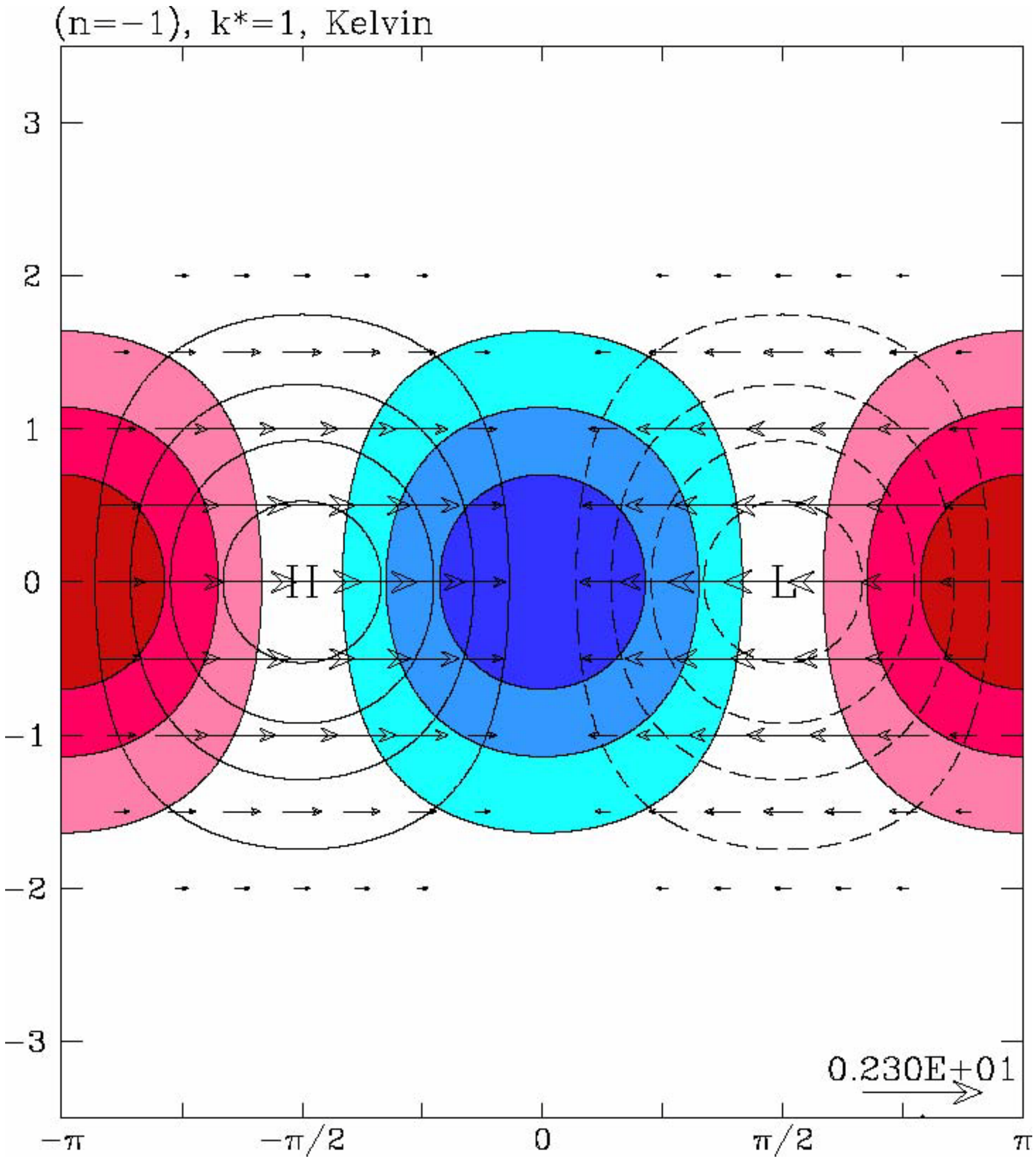
let’s sketch how we get to the wave solutions

The dispersion relation of SW Equatorially Trapped Waves



$$\frac{\sqrt{gh_e}}{\beta}\left(\frac{\omega^2}{gh_e} - k^2 - \frac{k}{\omega}\beta\right) = 2n + 1 \qquad n = 0,\ 1,\ 2, \ldots .$$

Horizontal Structure of the Kelvin Wave



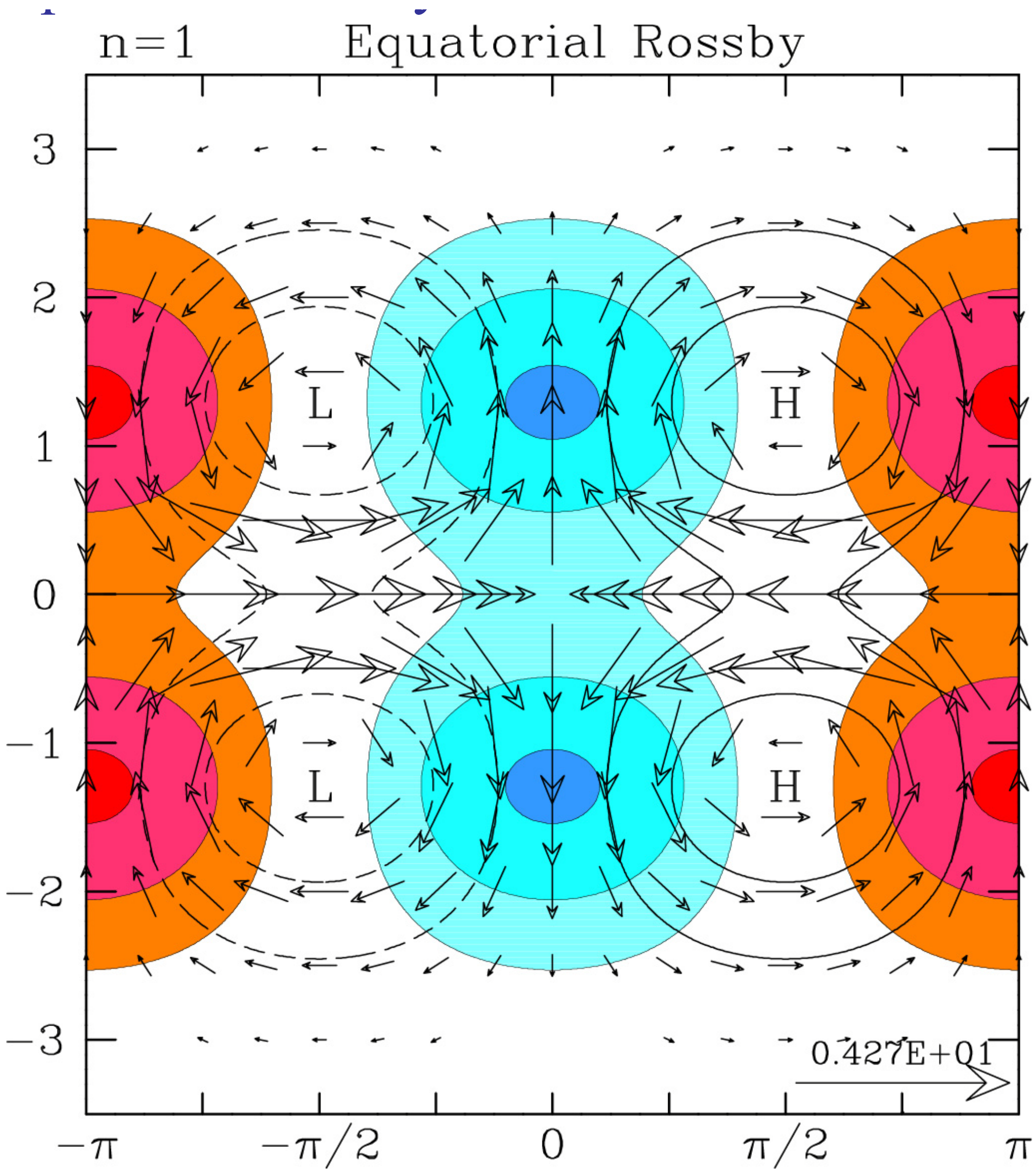
v = 0 everywhere

u = ϕ (contours)

symmetric, decaying

divergent

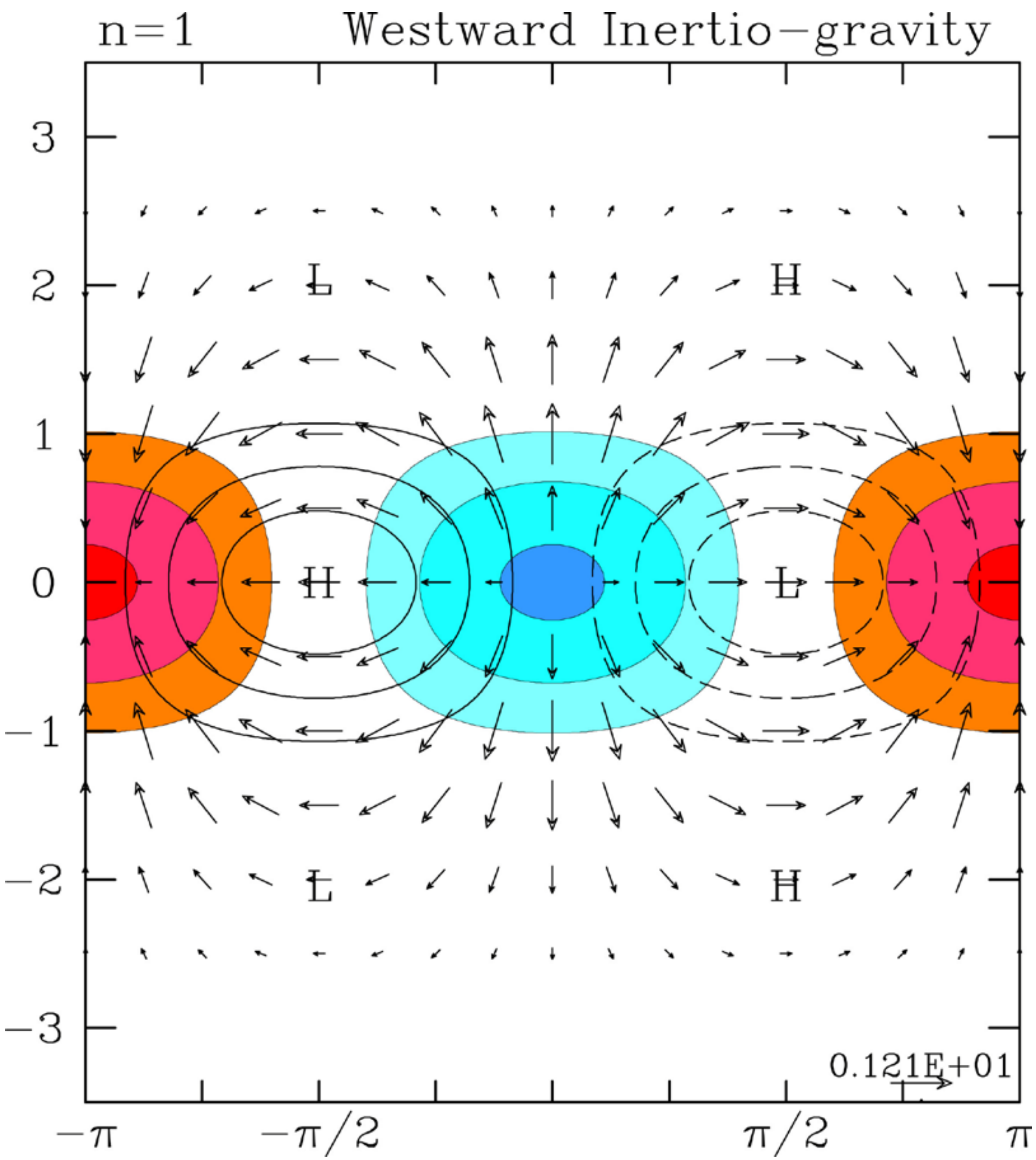
Horizontal Structure of the Equatorial Rossby Wave



symmetric,

rotational

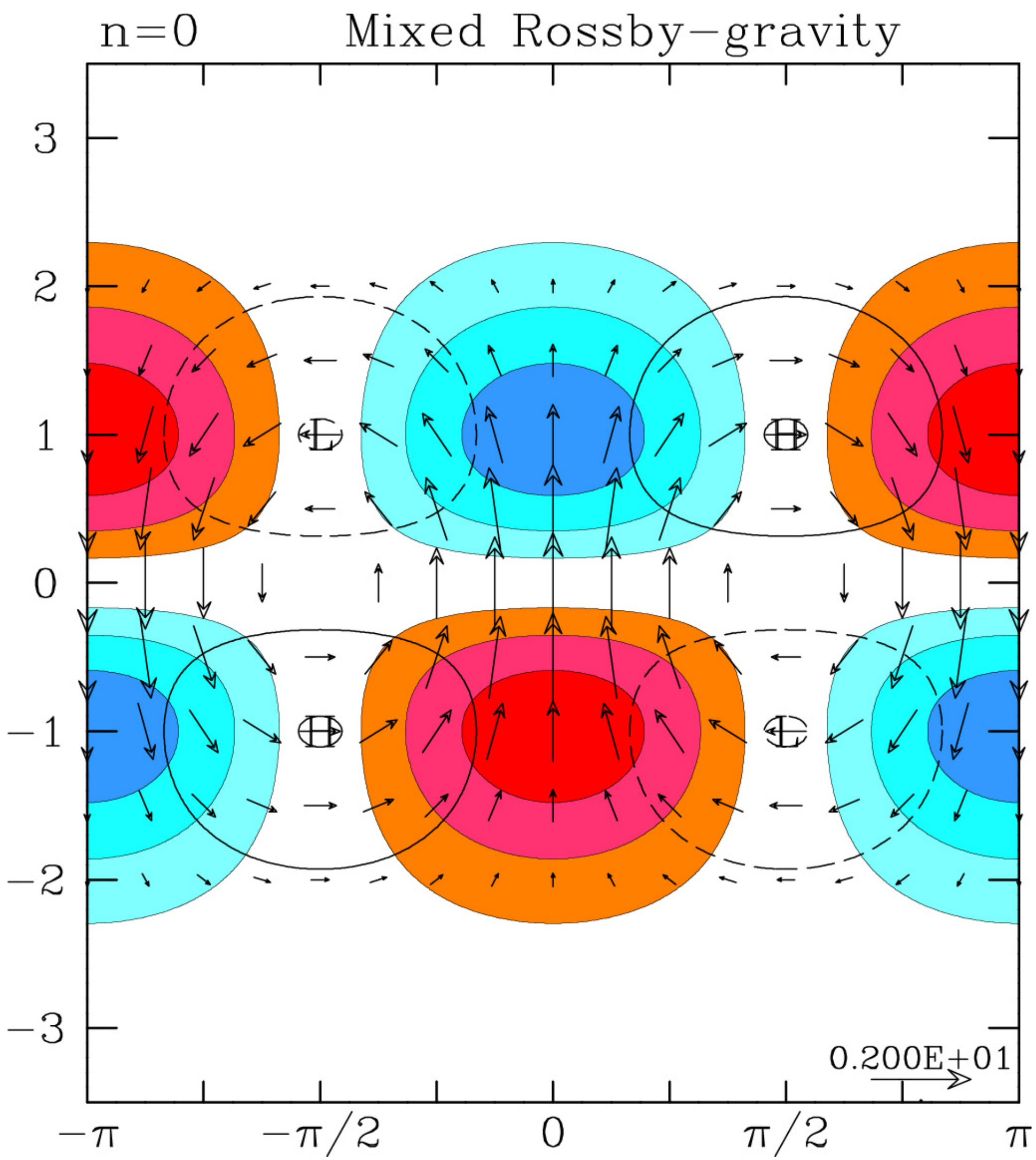
Horizontal Structure of Inertio-Gravity Waves



symmetric,

divergent

Horizontal Structure of Mixed Rossby-Gravity Waves



anti-symmetric,

rotational

Key parameters for the SW Equatorially Trapped Waves

Gravity Wave Speed

$$c = \sqrt{gh}$$

Rossby Radius of Deformation:

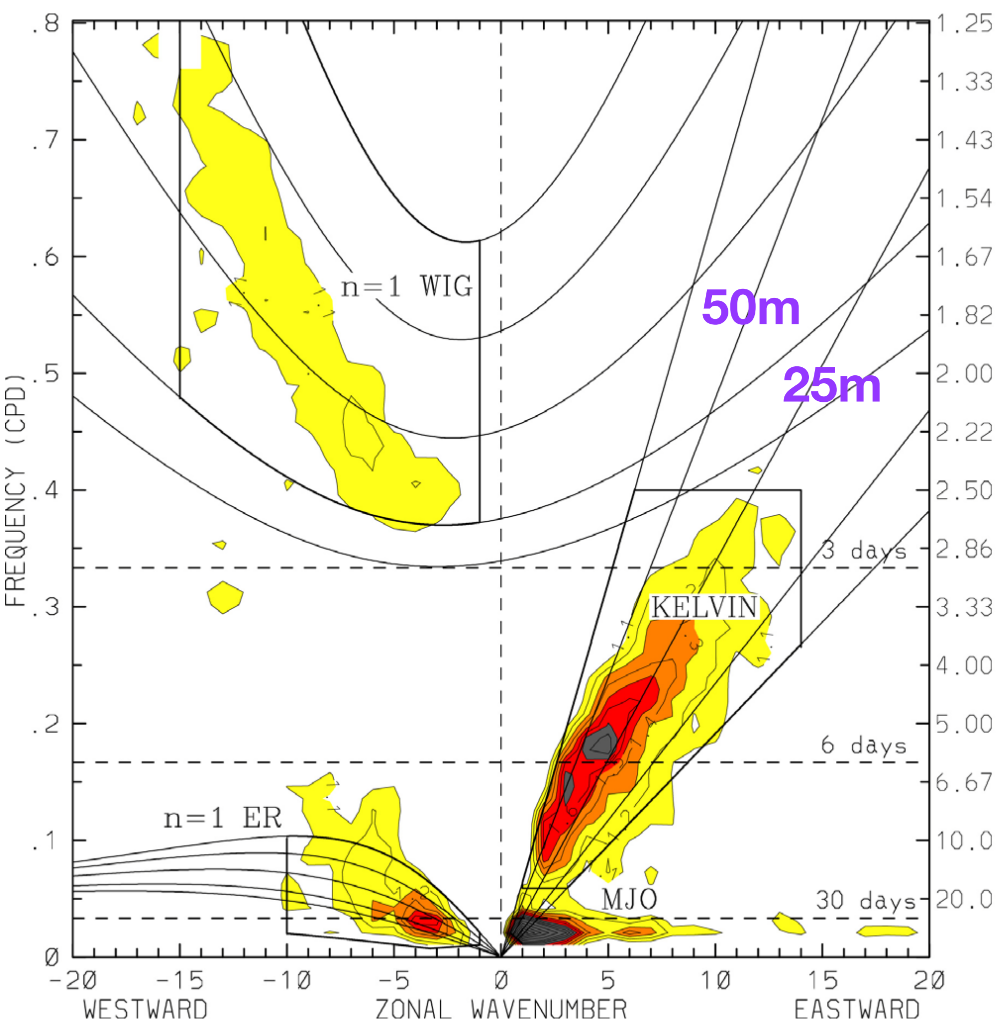
$$R_e = \sqrt{\frac{c}{\beta}}$$

what is h?

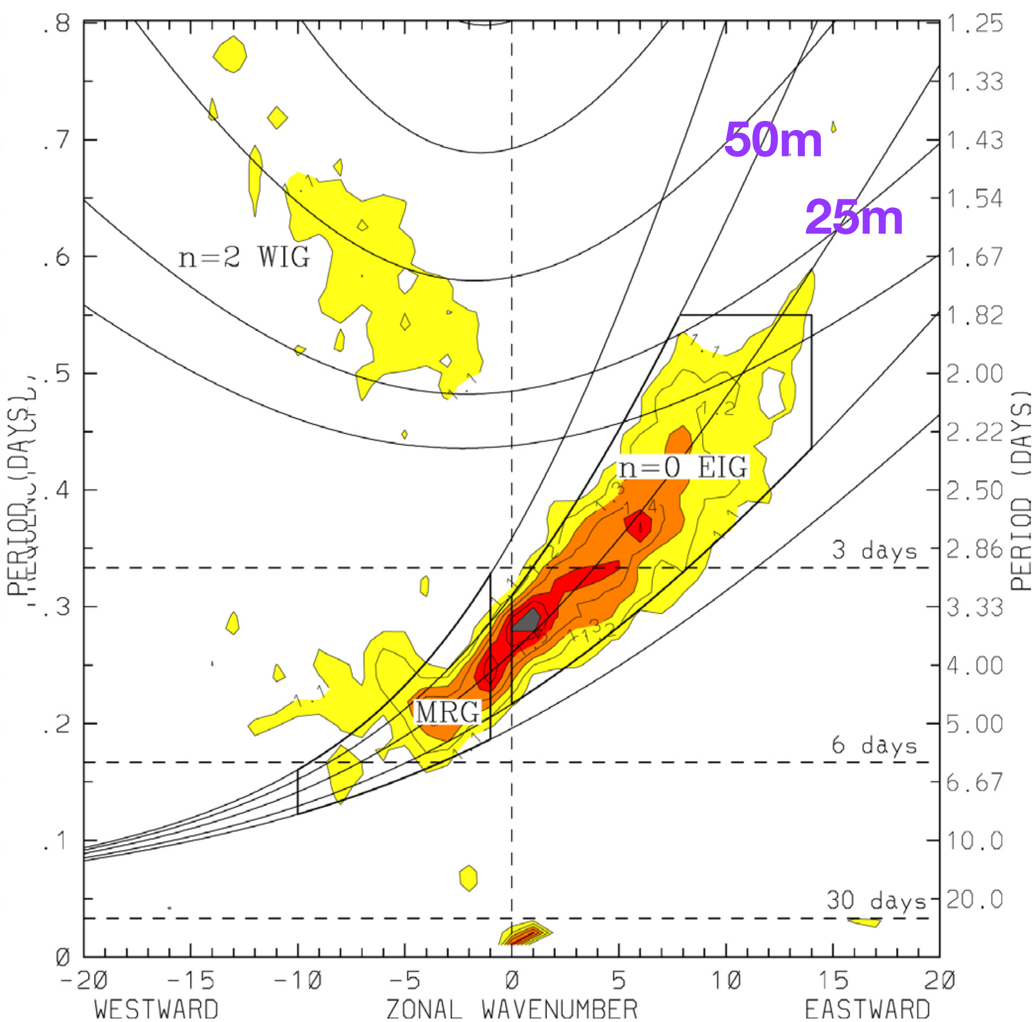
h_e	L_z (km)	$\sqrt{gh_e}$ (m s^{-1})	R_e (Degrees Latitude)
	H = 7.3 km, $dT_0/dz = -7.0$ K km^{-1} (Troposphere)		
10	6.0	9.9	6.0
20	8.5	14.0	7.1
50	13.4	22.1	9.0
100	19.2	31.3	10.7
200	27.9	44.3	12.7
500	47.5	70.0	15.9

Back to the board:
we relax the shallow water assumption

There is a continuum of equivalent depths h_e in the observed CCEW



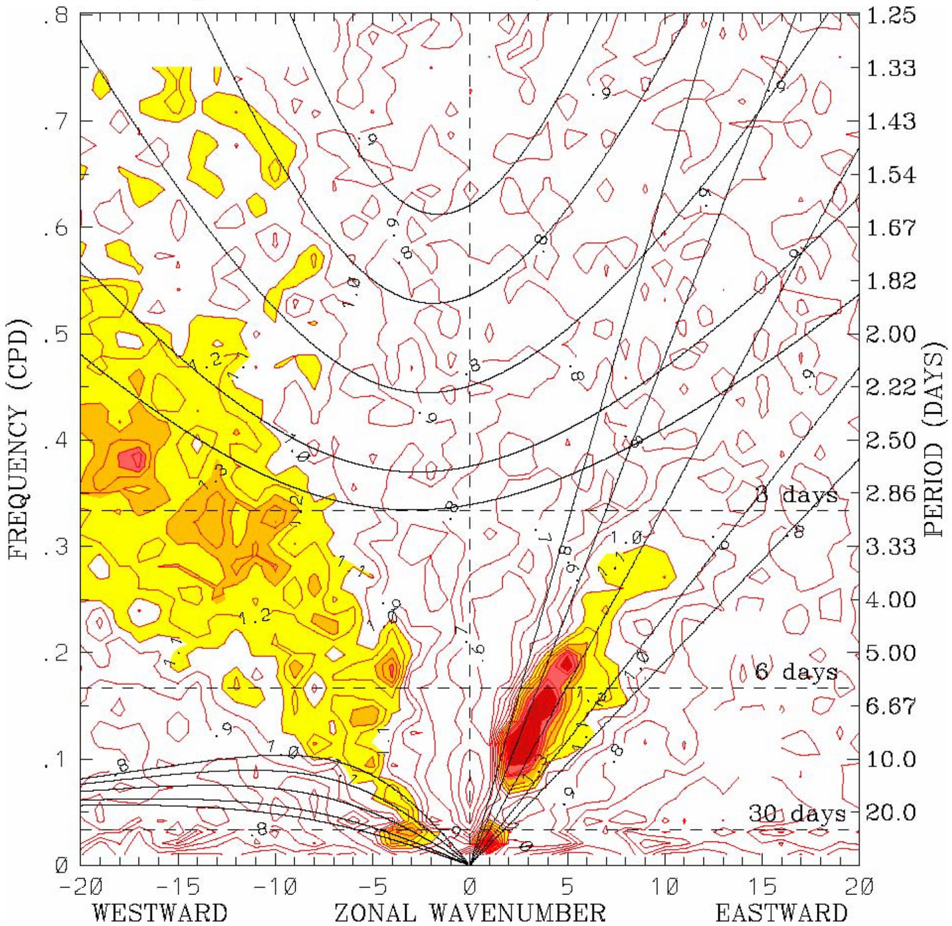
Symmetric



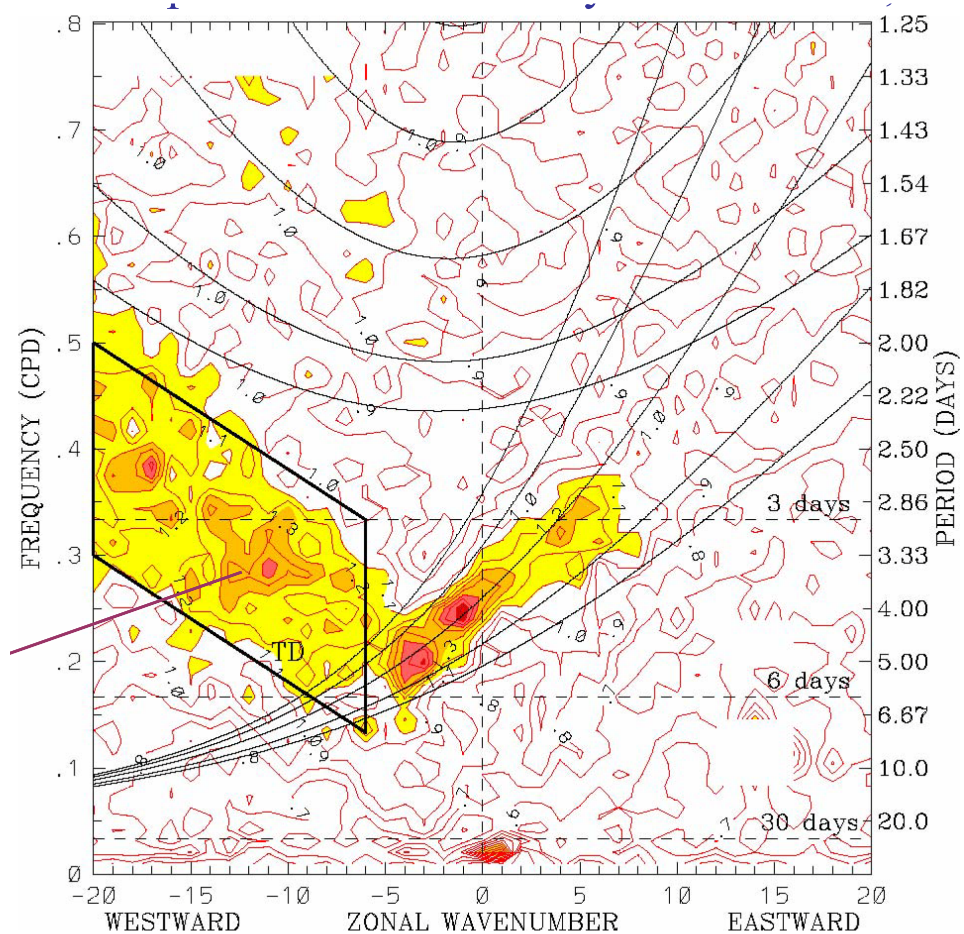
Antisymmetric

One more type of "wave": Tropical Depressions (and Easterly Waves)

JJA Tb



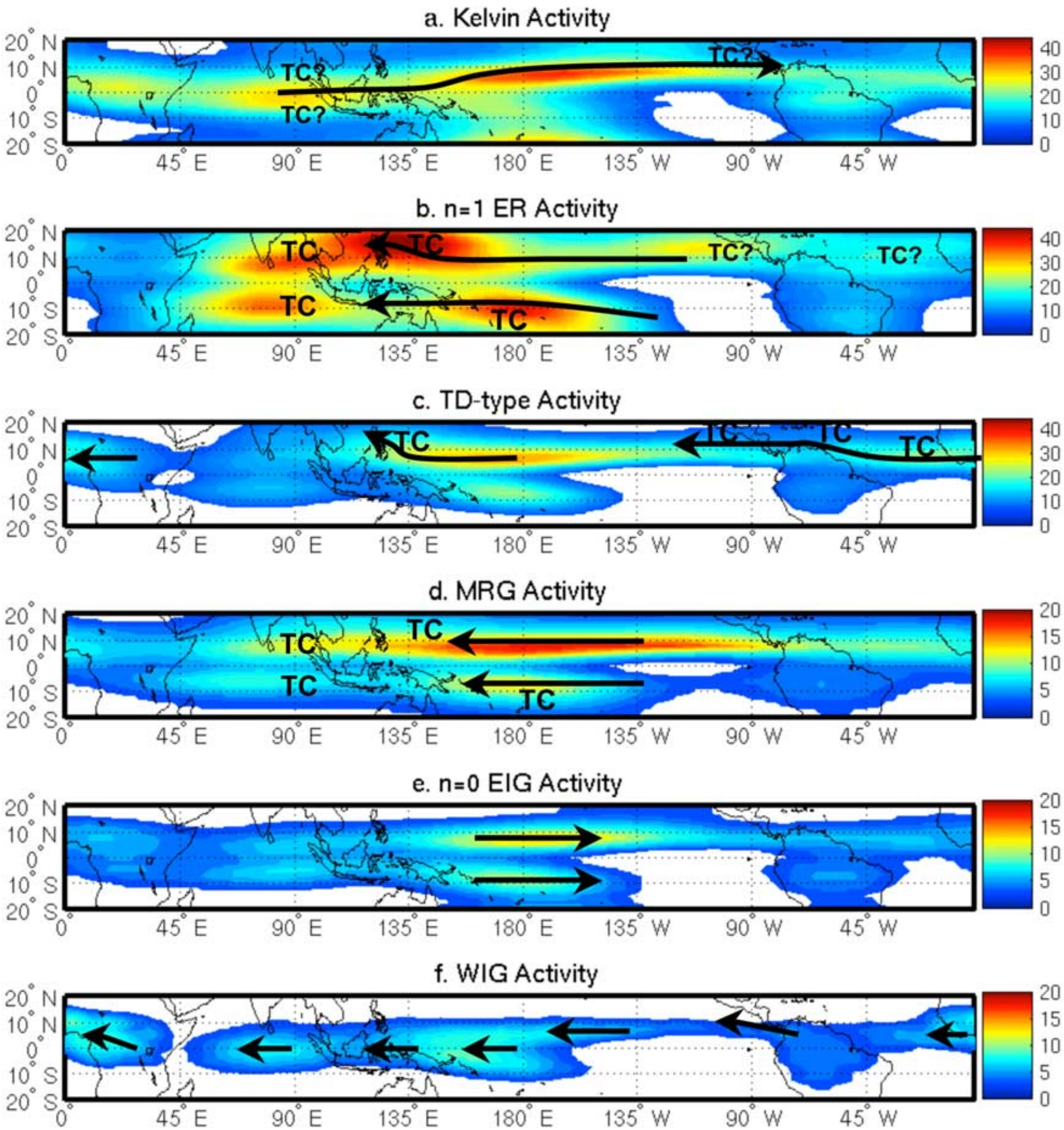
Symmetric



Antisymmetric

Observed Wave Activity

Annual-mean variance in Tb and TC genesis



Kelvin

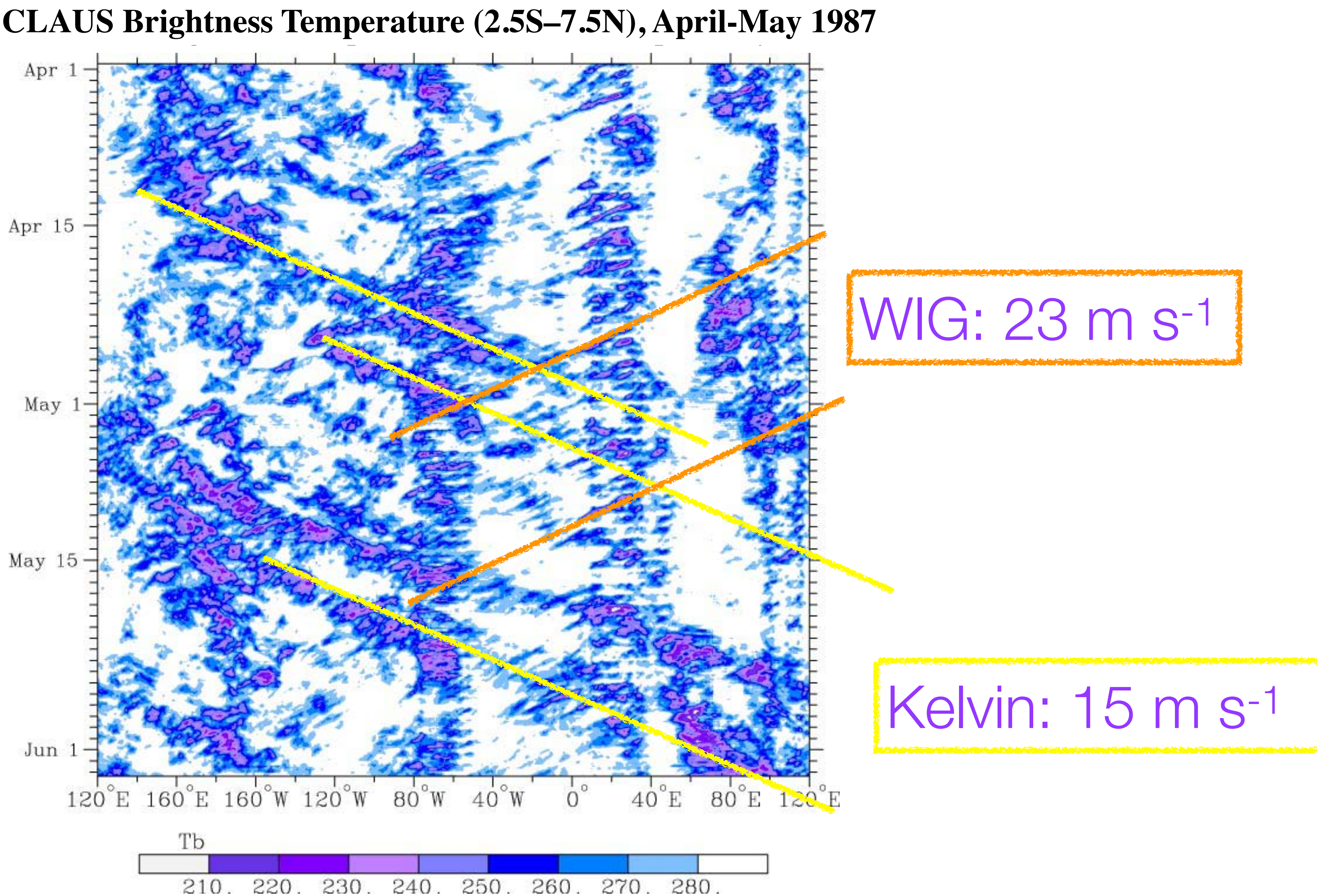
Rossby

TD & AEW

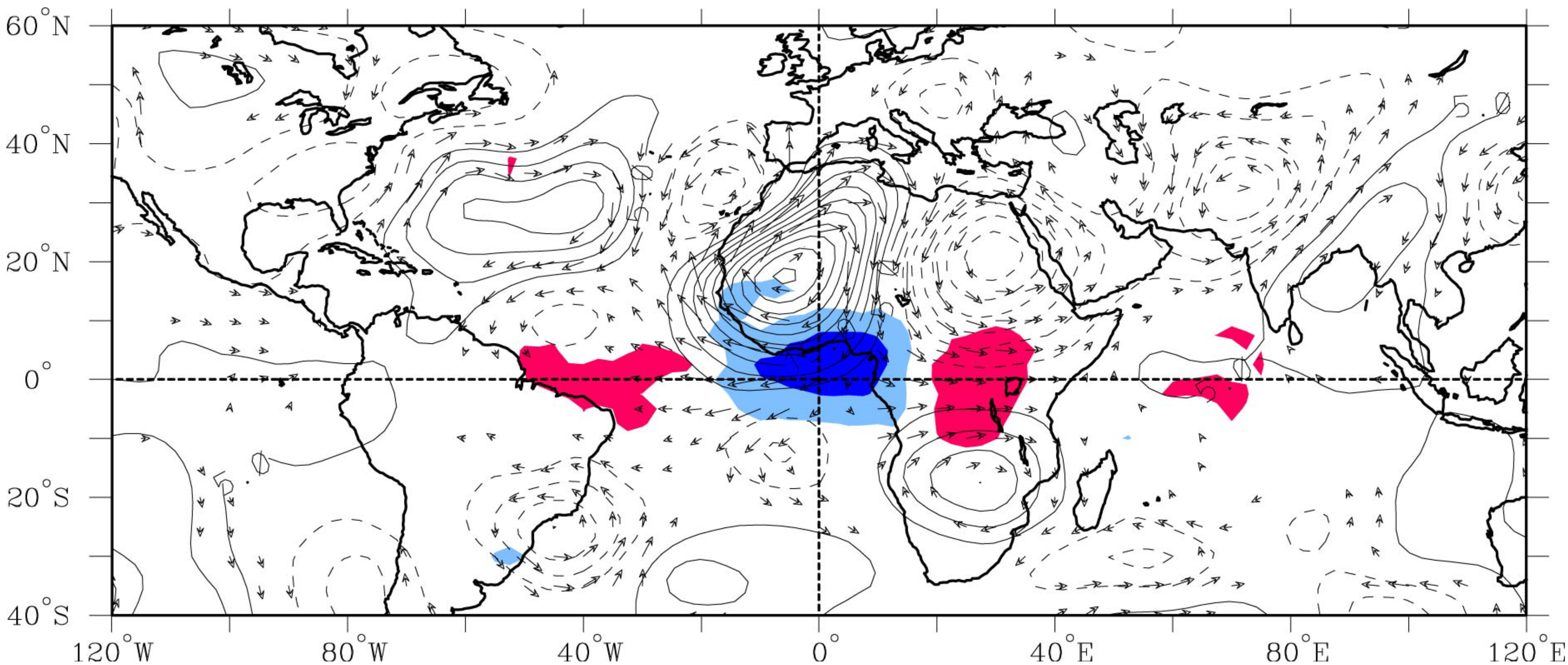
Mixed Rossby-Gravity

Inertia-Gravity

A superposition of criss-crossing CCEW



Horizontal Structure of the observed moist Kelvin Wave(s)



Regression against Kelvin filtered Tb anomalies

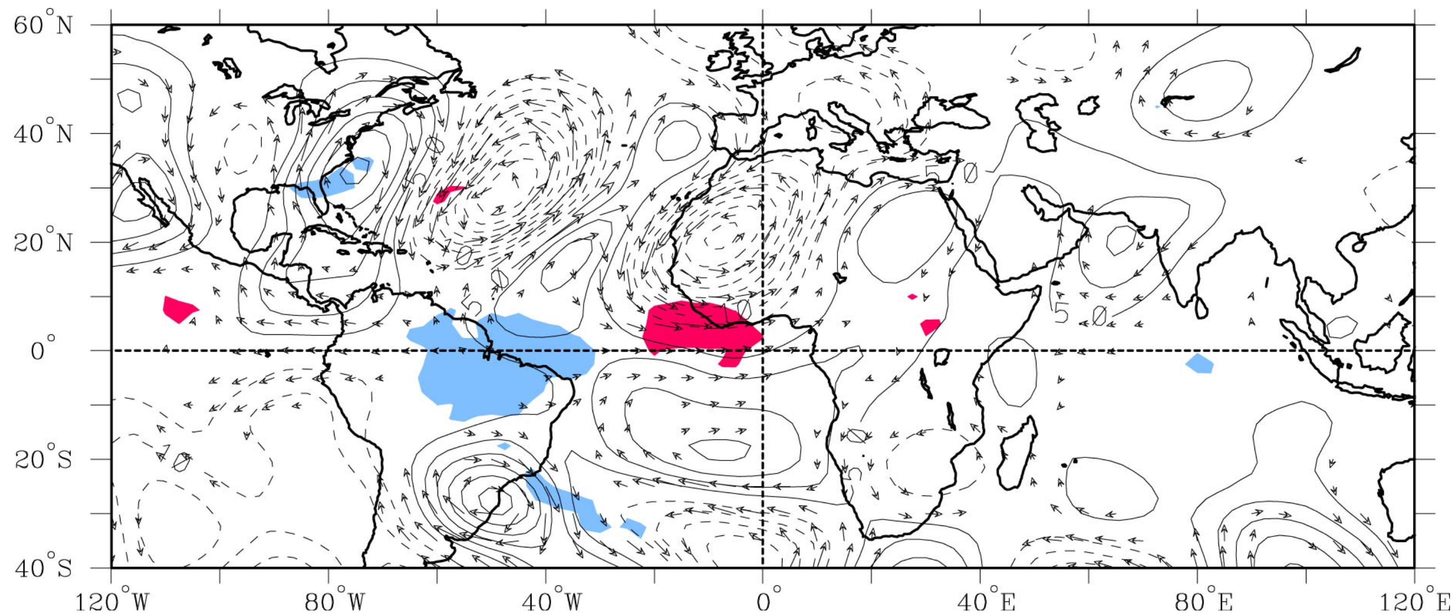
(DAY 0 at 2.5N, 0E, March-May)

200 hPa Streamfunction (contours 5 X 10^5 m^2 s^{-1})

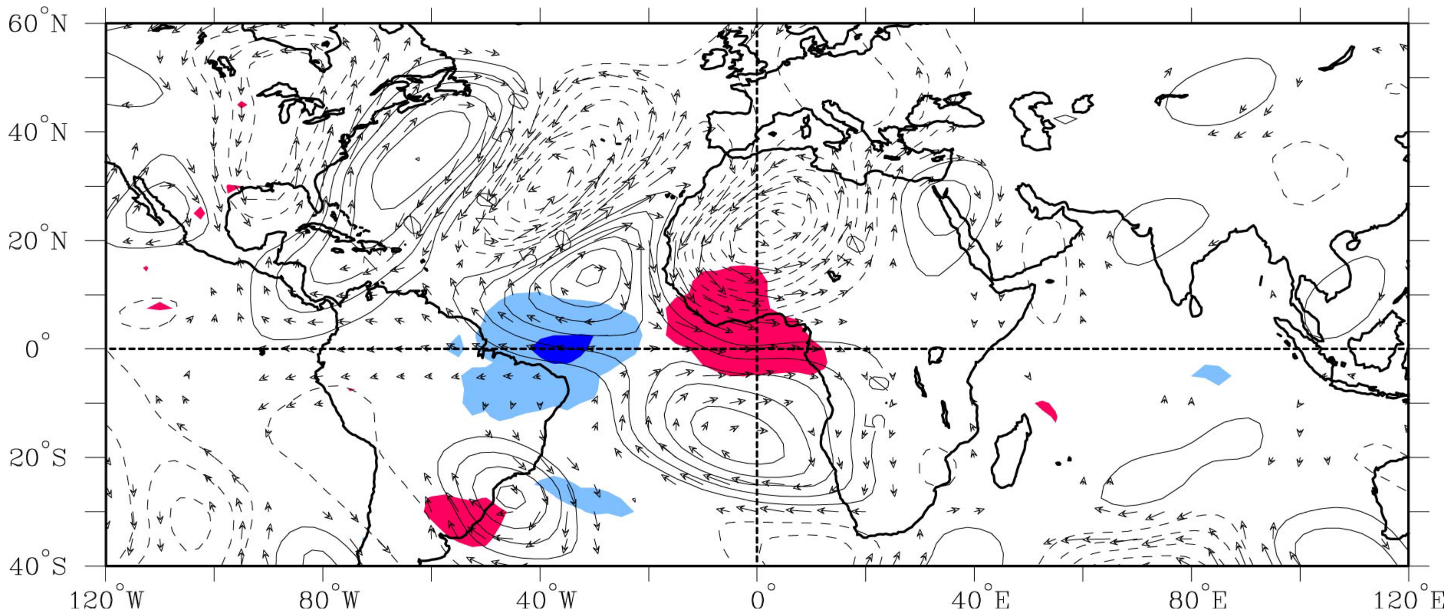
Wind (vectors, largest around 2 m s^{-1})

Tb (shading starts at +/- 4°K), negative blue

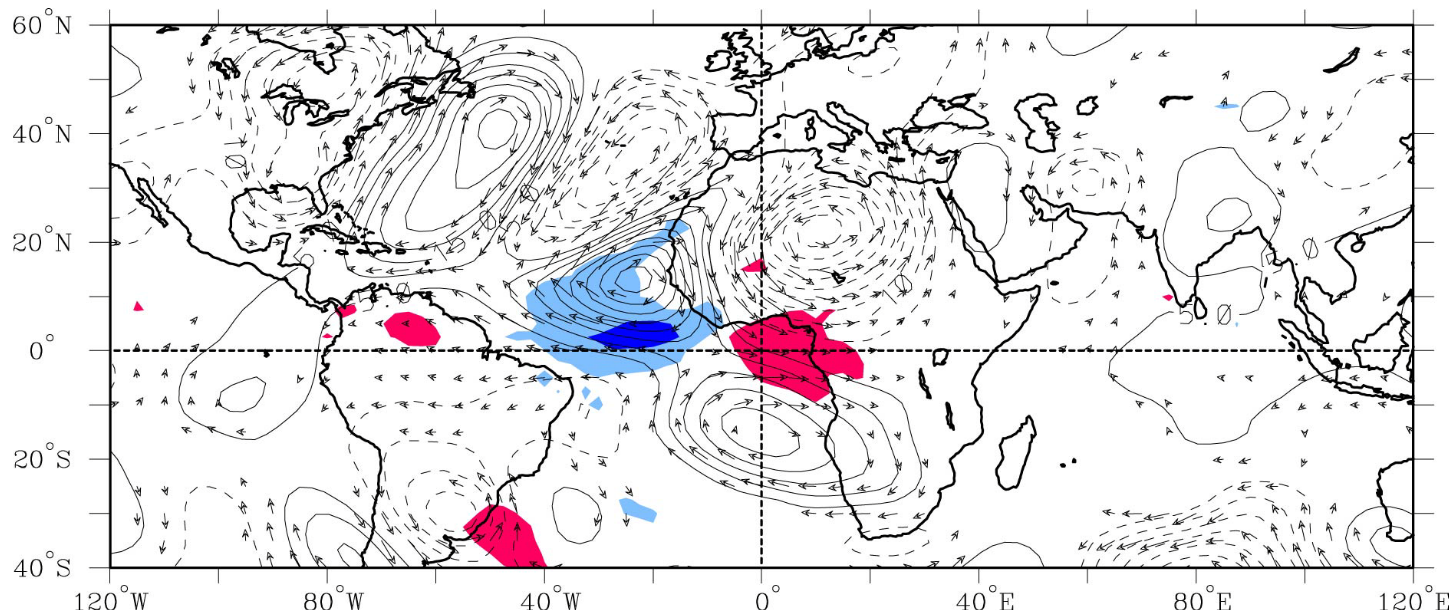
Day-4



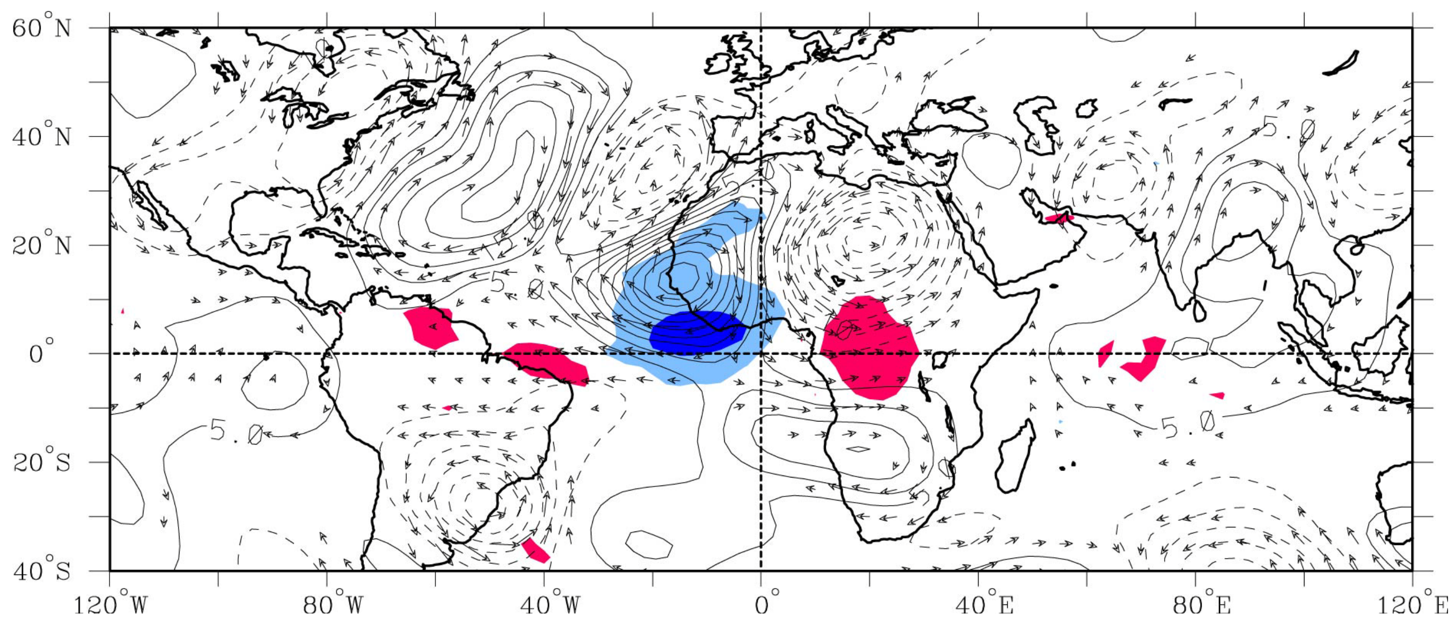
Day-3



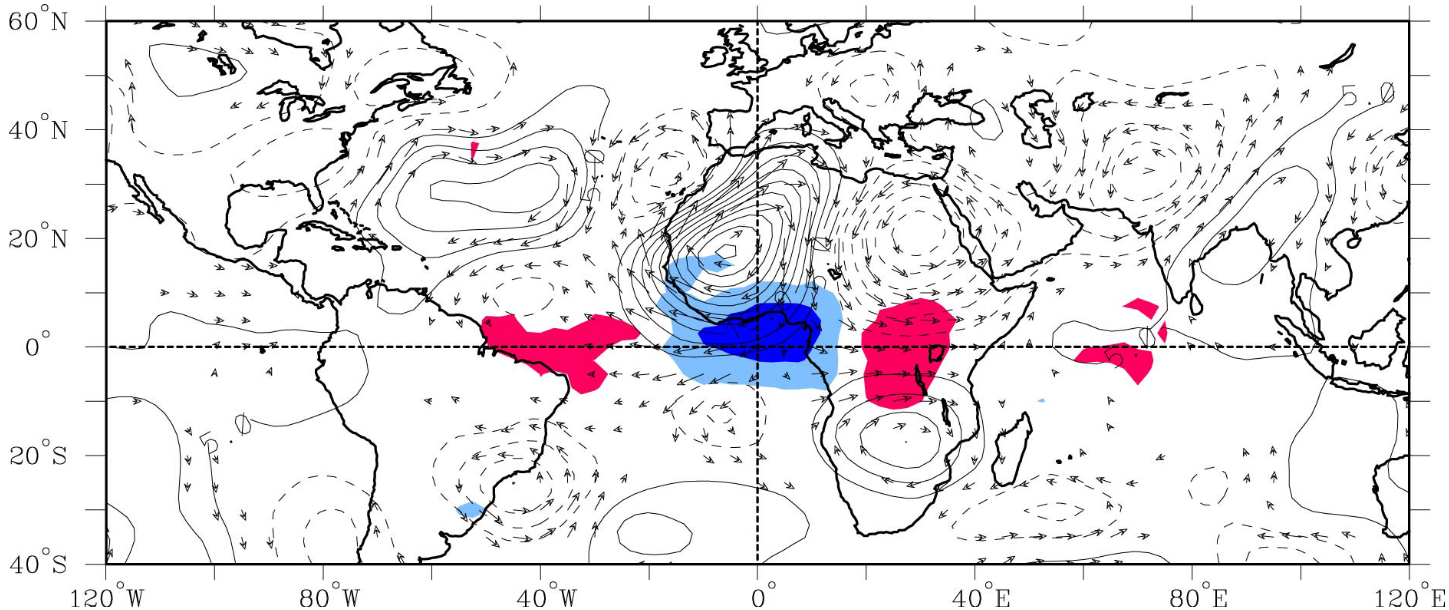
Day-2



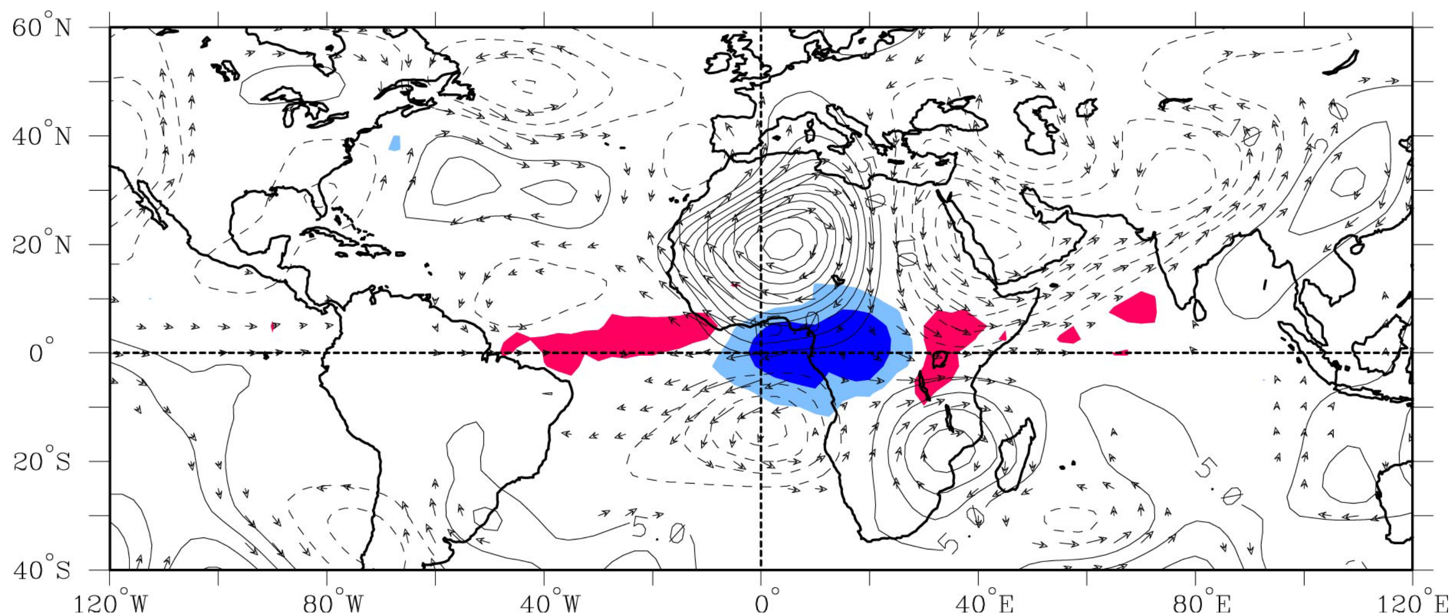
Day-1



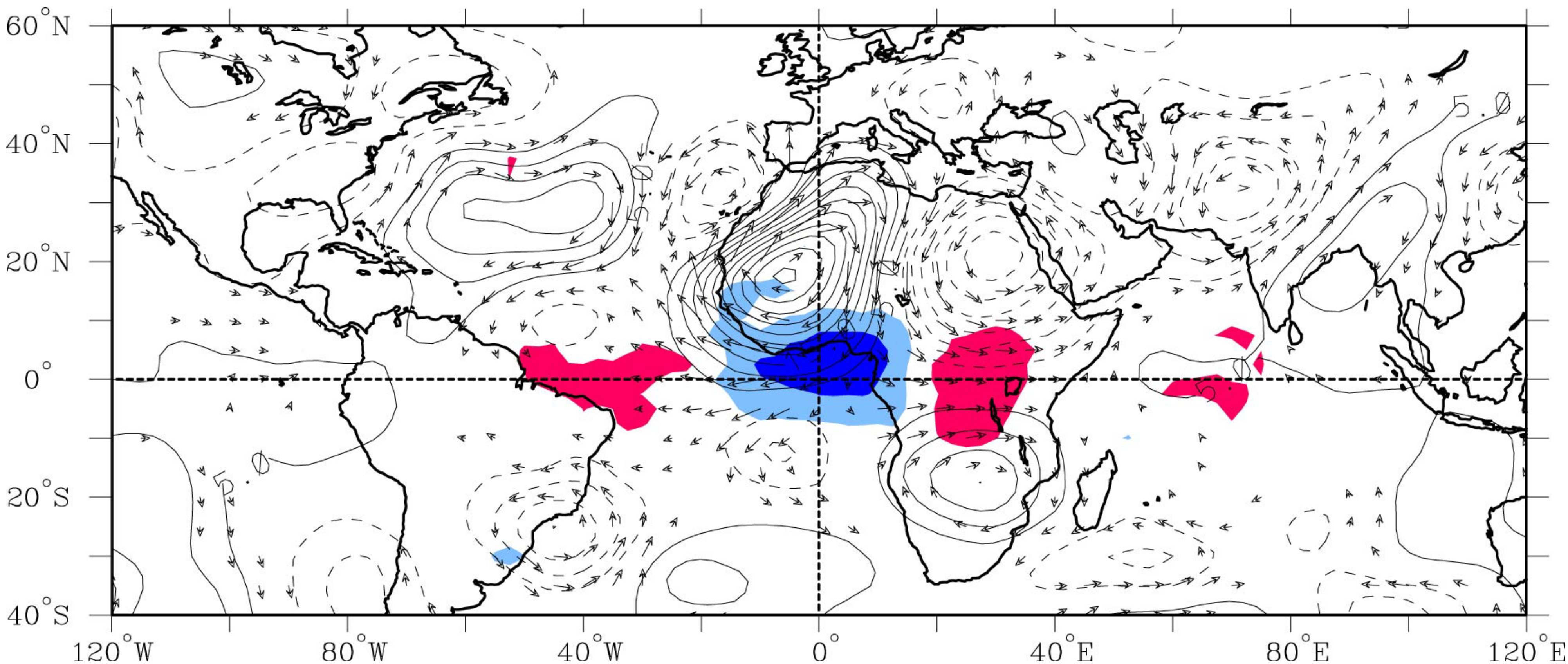
Day 0



Day+1



Horizontal Structure of the observed moist Kelvin Wave(s)



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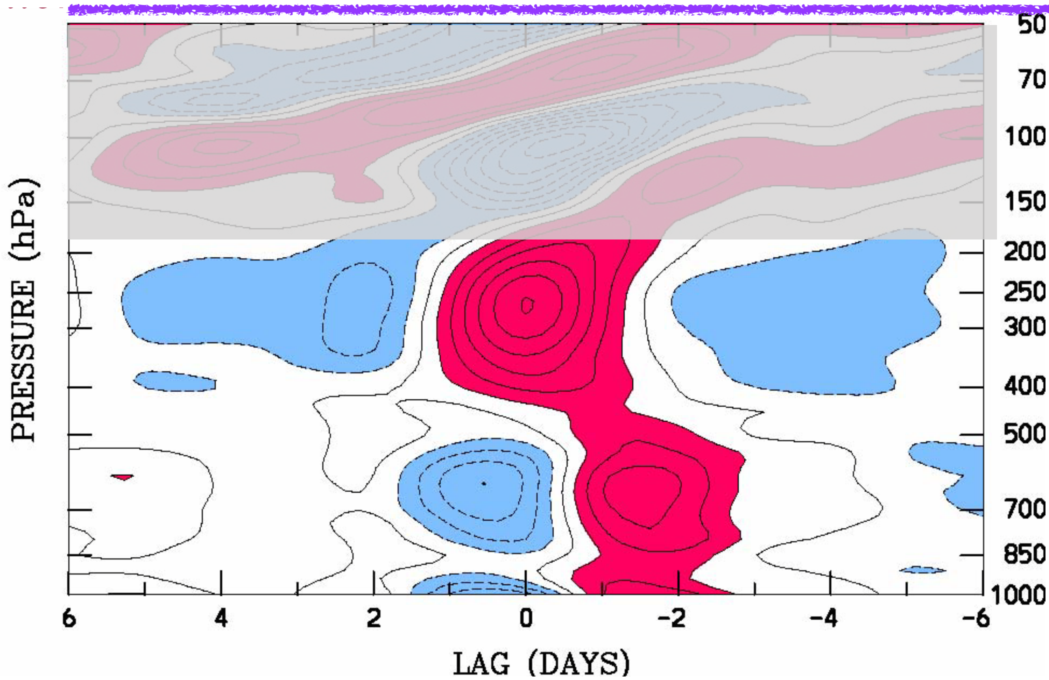
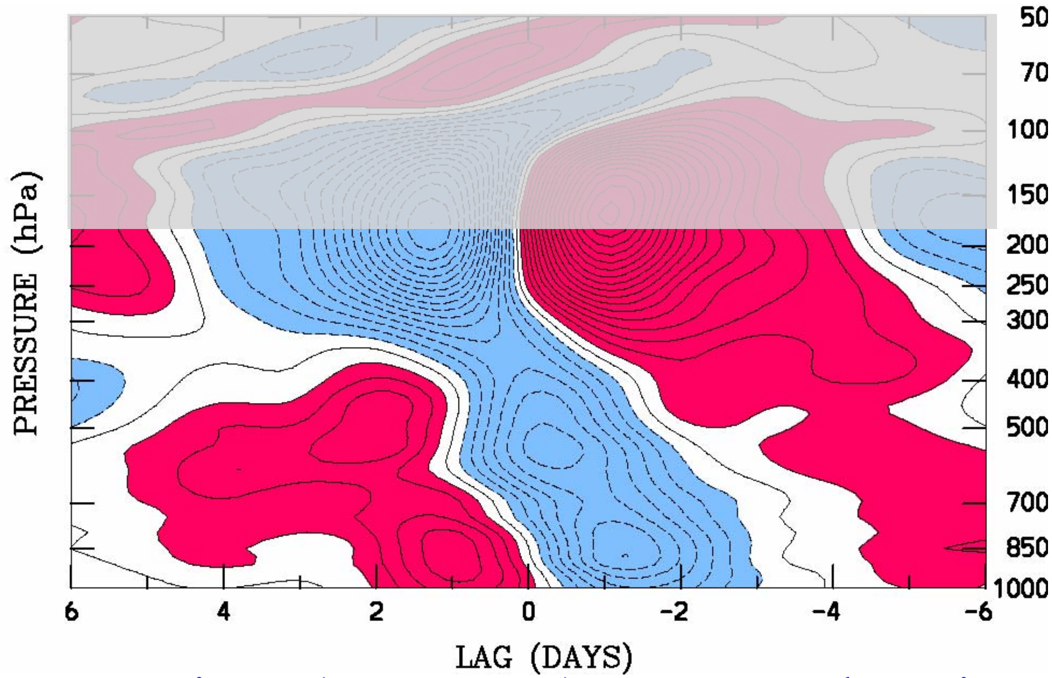
Vertical Structure of the observed moist Kelvin Wave(s)



temperature

(contours, .1 °C), red positive

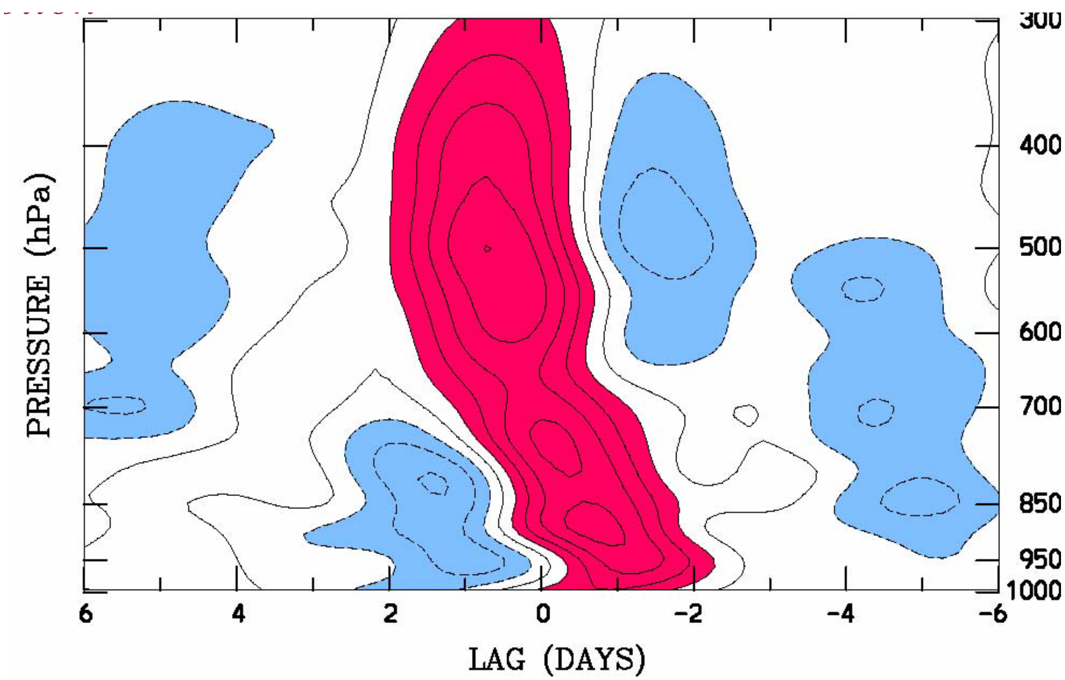


zonal wind

(contours .25 m s-1), red positive

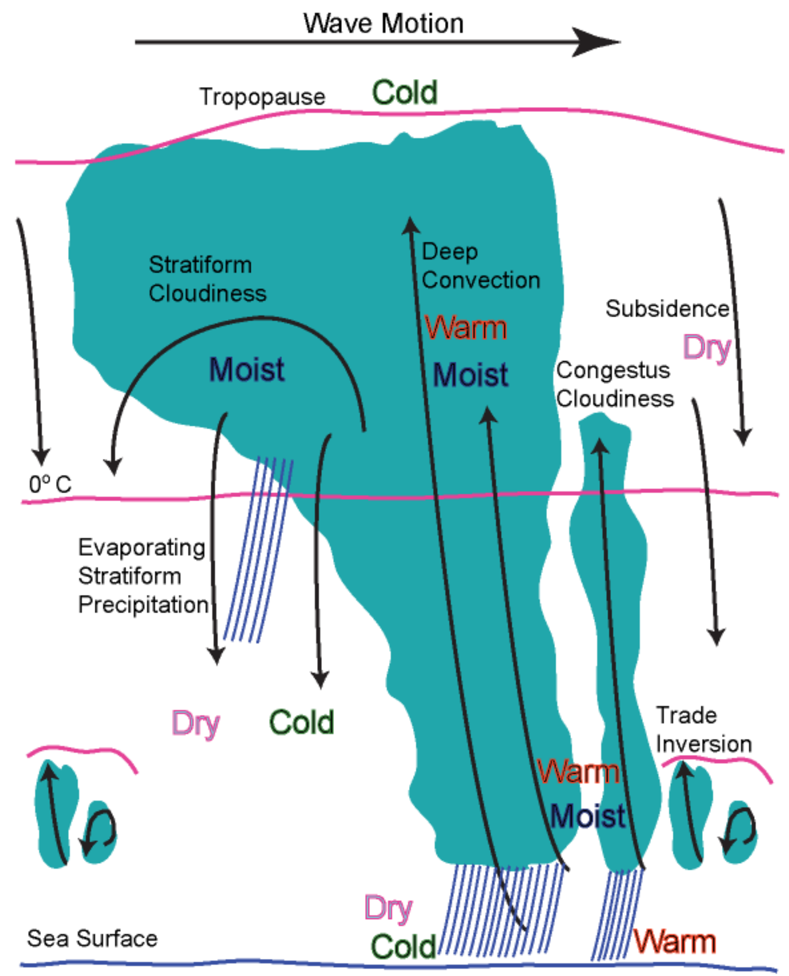
at Majuro (7N, 171E) Regressed against Kelvin-filtered OLR (1979-1999)

Vertical Structure of the observed moist Kelvin Wave(s)



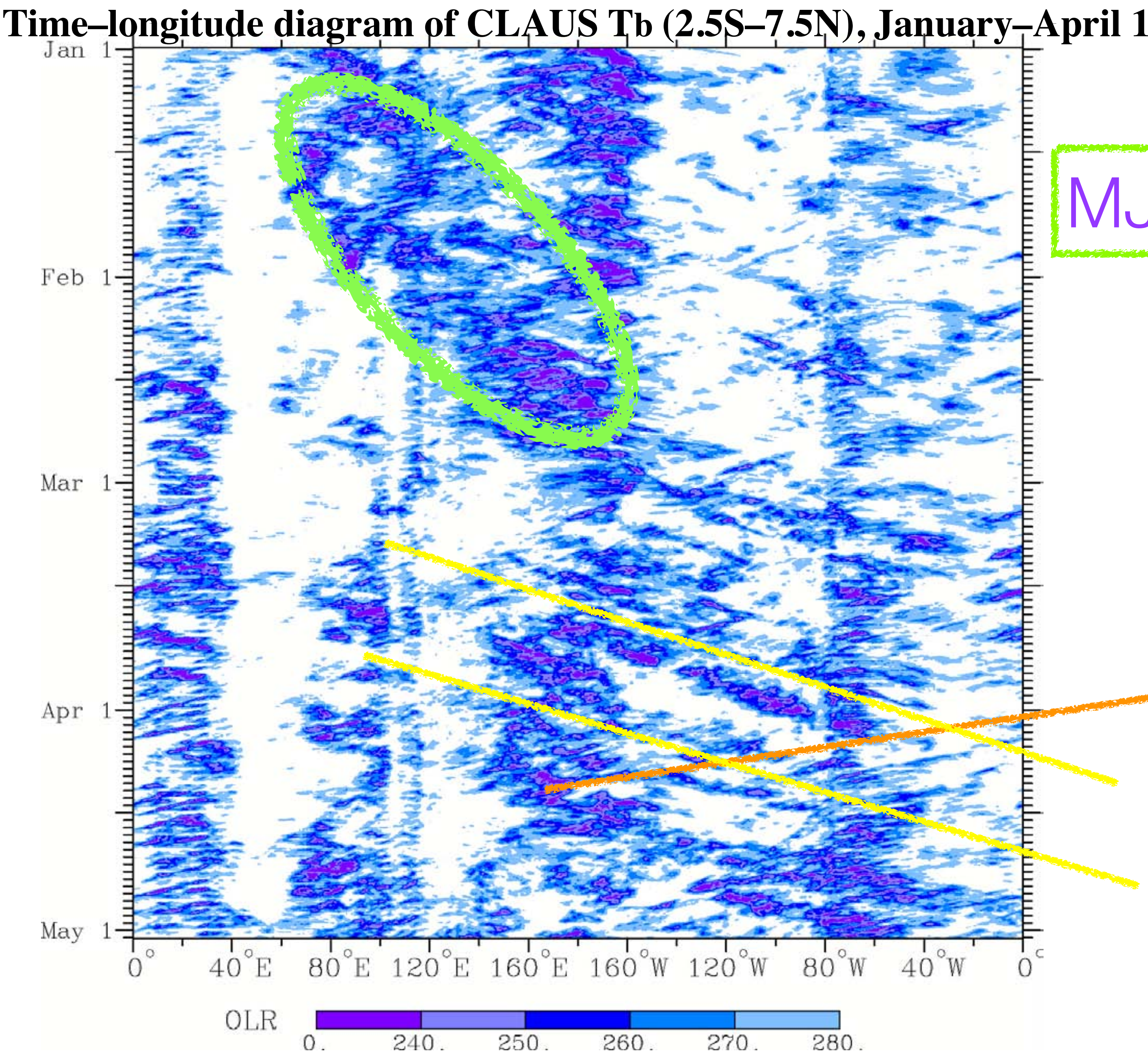
specific humidity

(contours, 1 X 10^{-1} g kg^{-1}), red positive

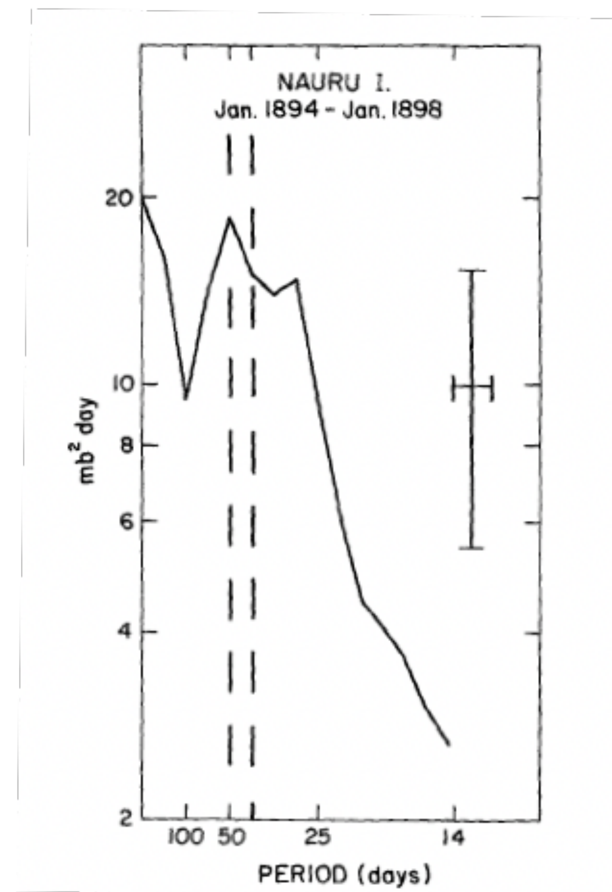


Generalized Evolution of a Convectively Coupled Equatorial Wave (self similar organization?)

The main mode of intraseasonal variability: the Madden-Julian Oscillation (MJO)

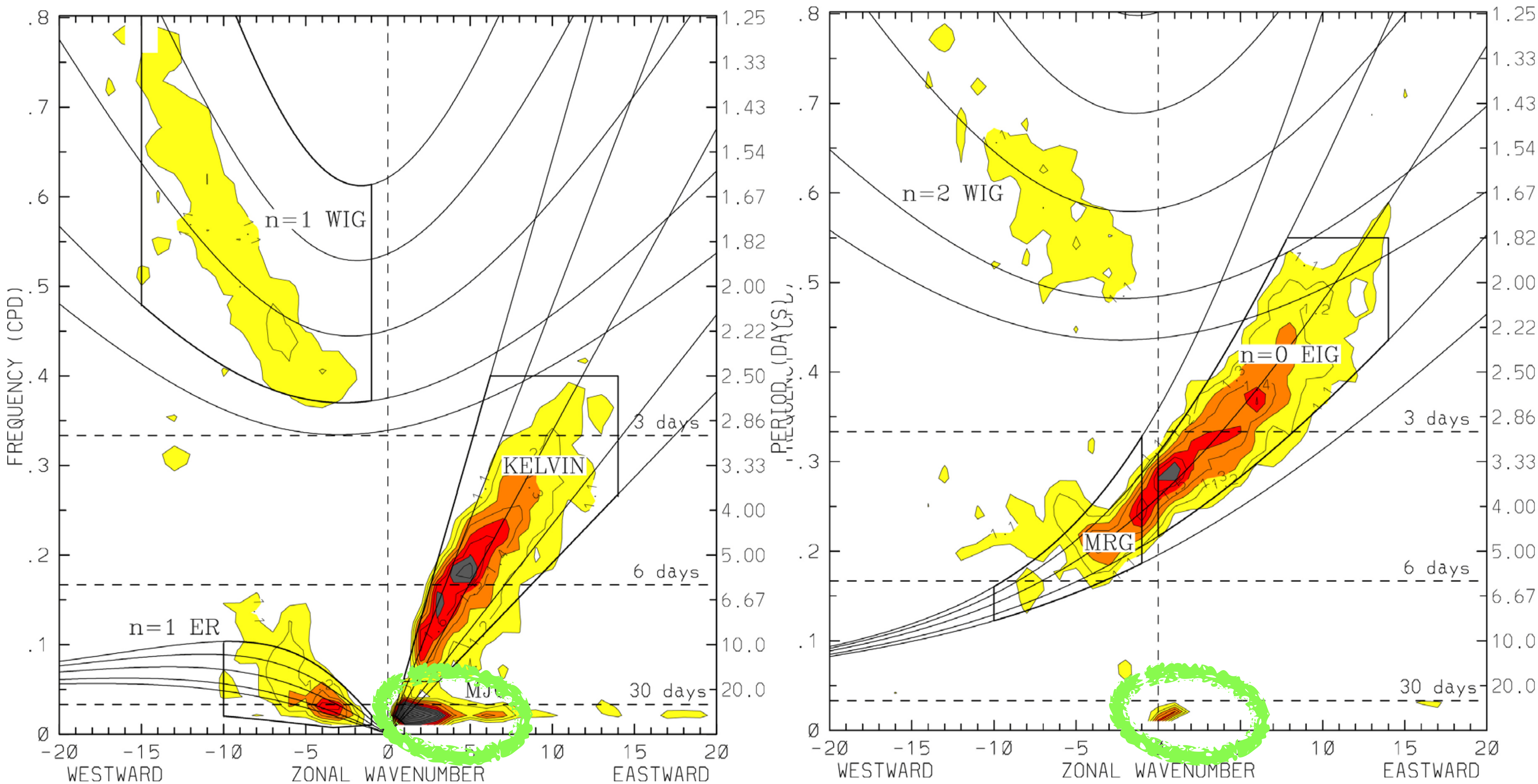


MJO: 5 m s^{-1}



Madden and Julian

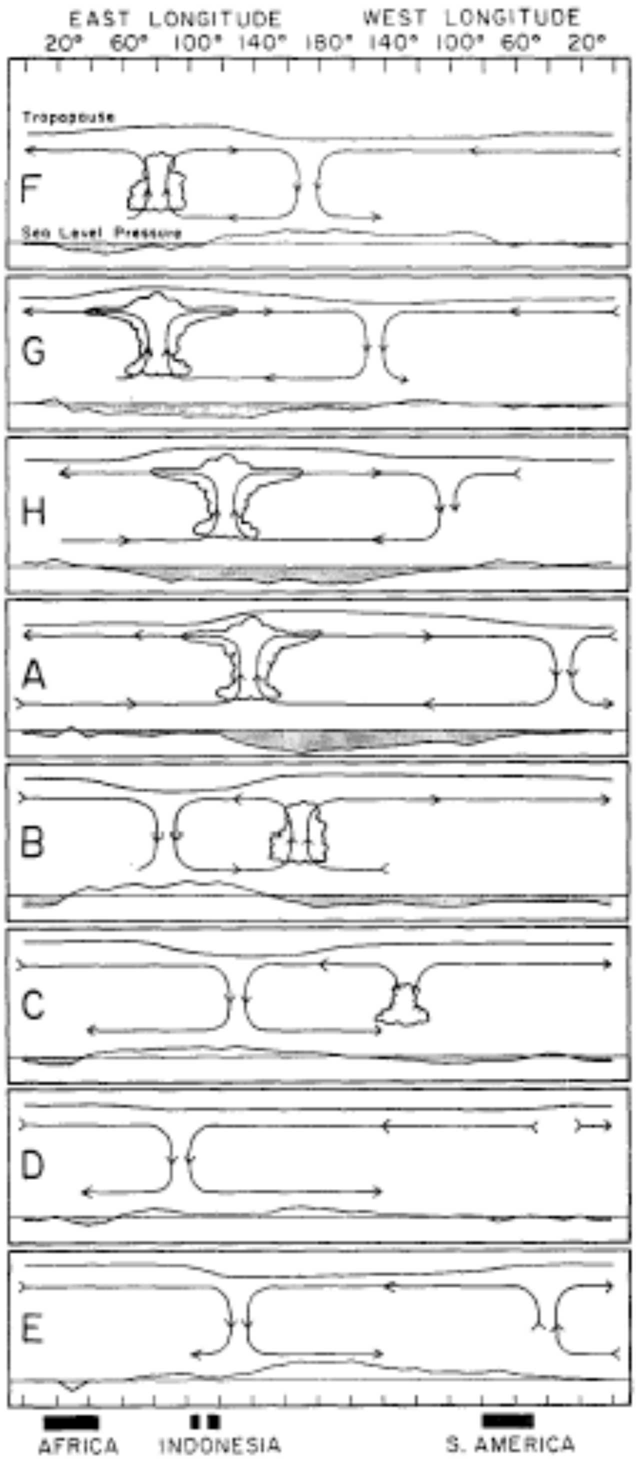
The MJO is slower, hence not a Kelvin Wave



Symmetric

Antisymmetric

Phenomenology of the MJO

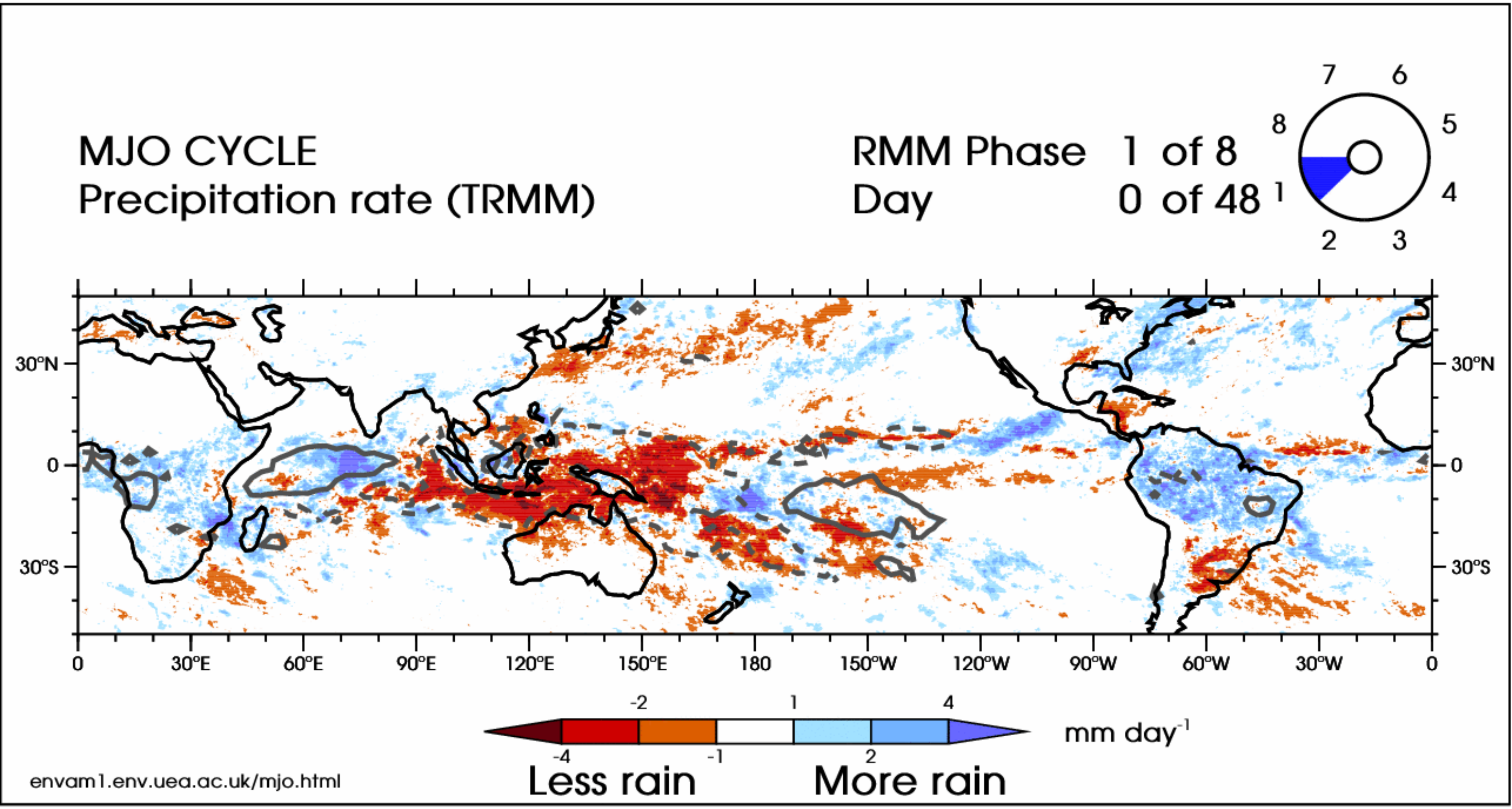


Indian Pacific

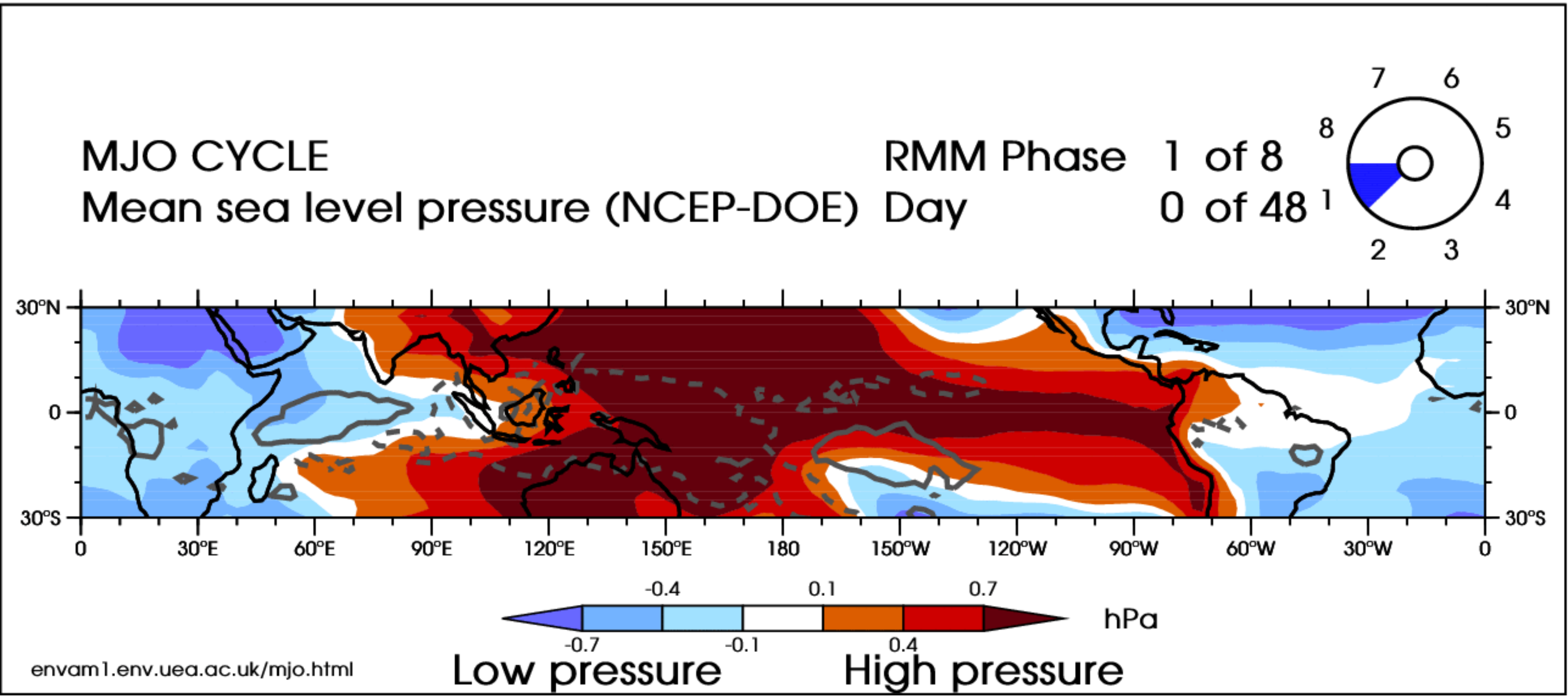
Madden and Julian

- Organized planetary scale system
- Characterized by convectively active and inactive phases
- Convective signal strongest in Indian Ocean and West/Central Pacific.
- Phases connected by deep overturning zonal circulations
- Zonal winds reverse between lower and upper-level
- Dynamic signal seen throughout the tropics.
- Moves eastwards at about 5m/s
- Intraseasonal time scale (30-60 days)

MJO signal in rainfall



MJO signal in sea-level pressure



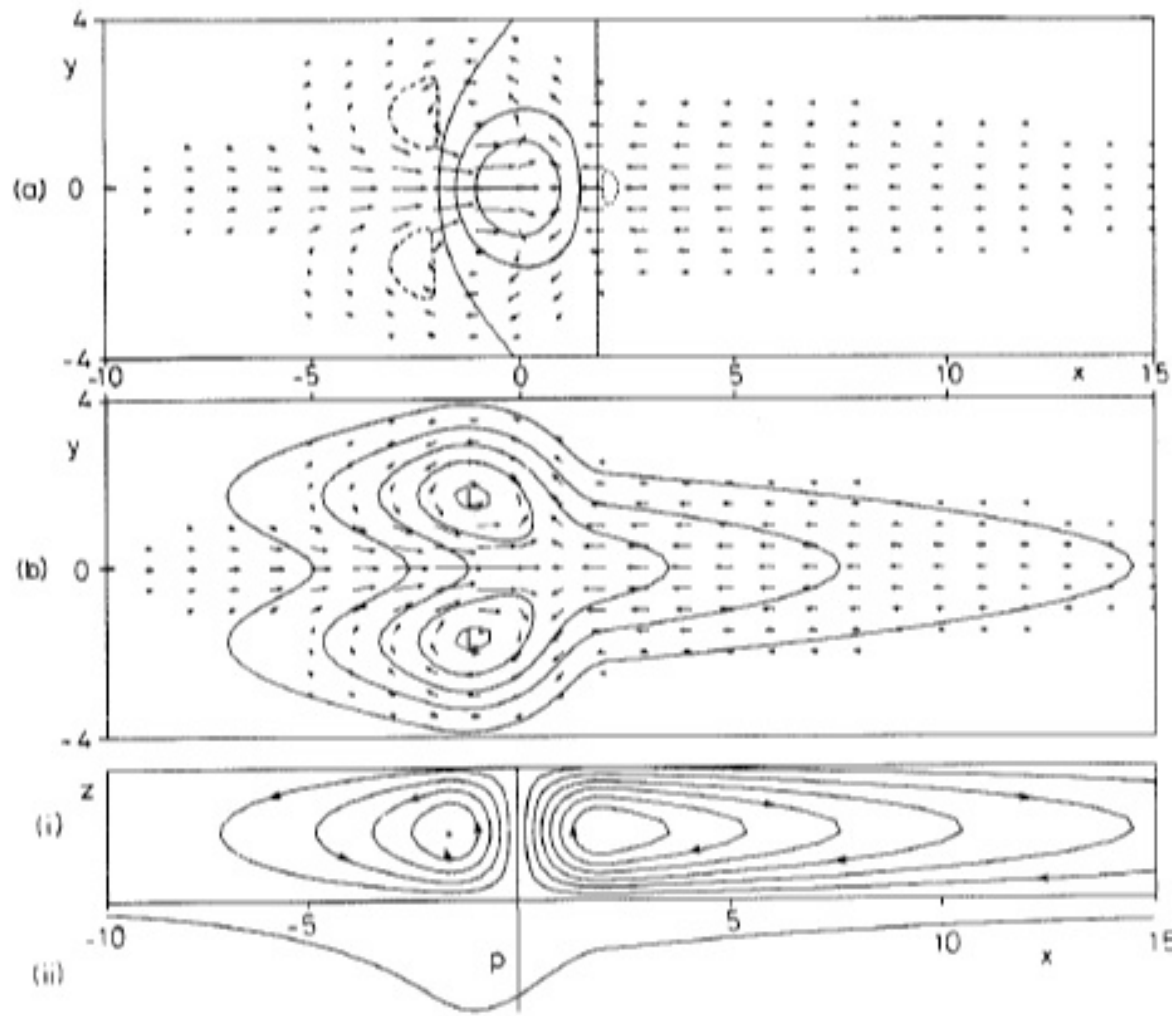
Let's go back to the equations to seek a steady-state (damped, forced) solution

$$-\beta y v = -\frac{\partial p}{\partial x} - \epsilon u$$

$$\beta y u = -\frac{\partial p}{\partial x} - \epsilon v$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = Q - \epsilon_T p$$

Q = single equatorial heating



Gill 1980

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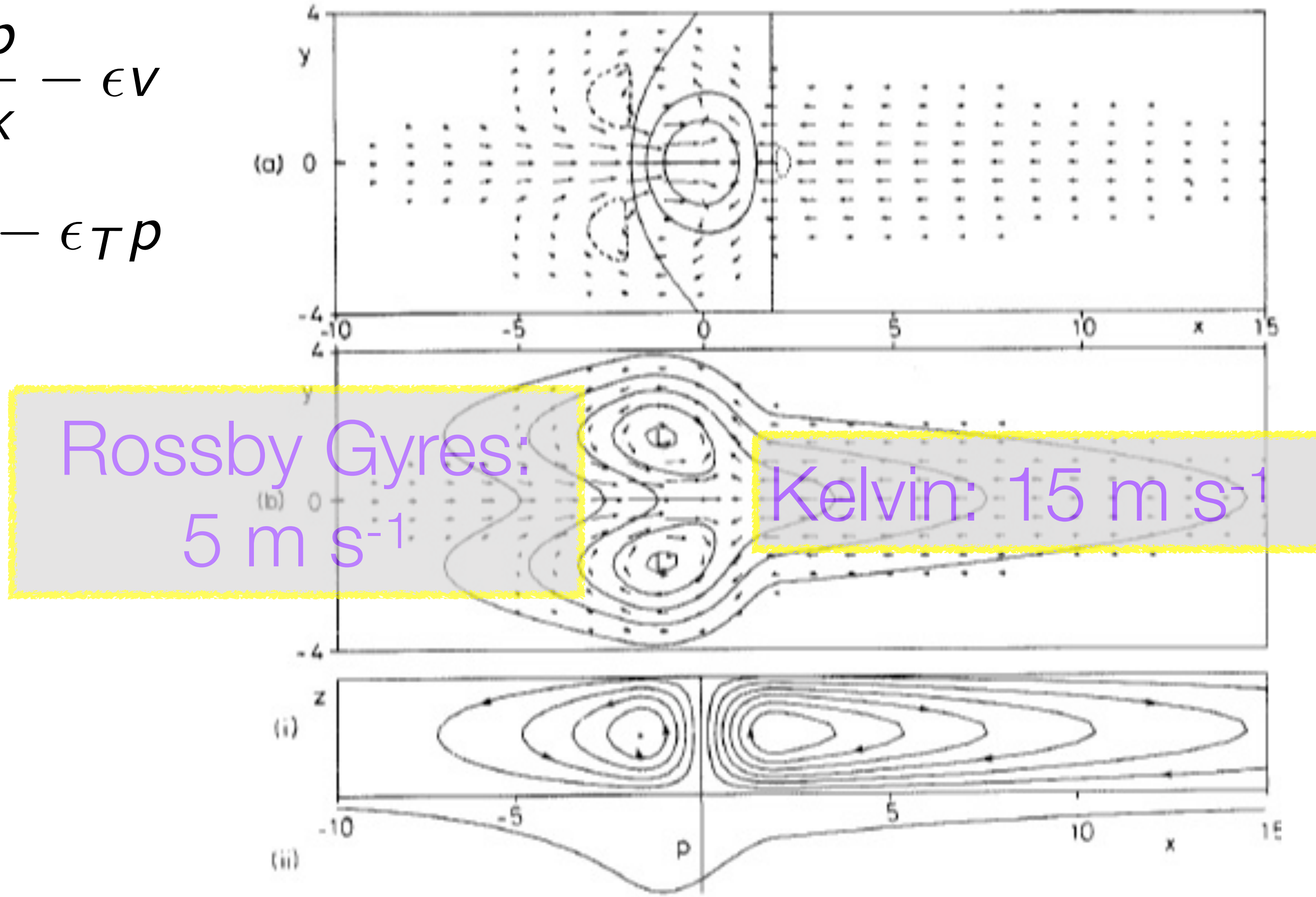


Gill 1980

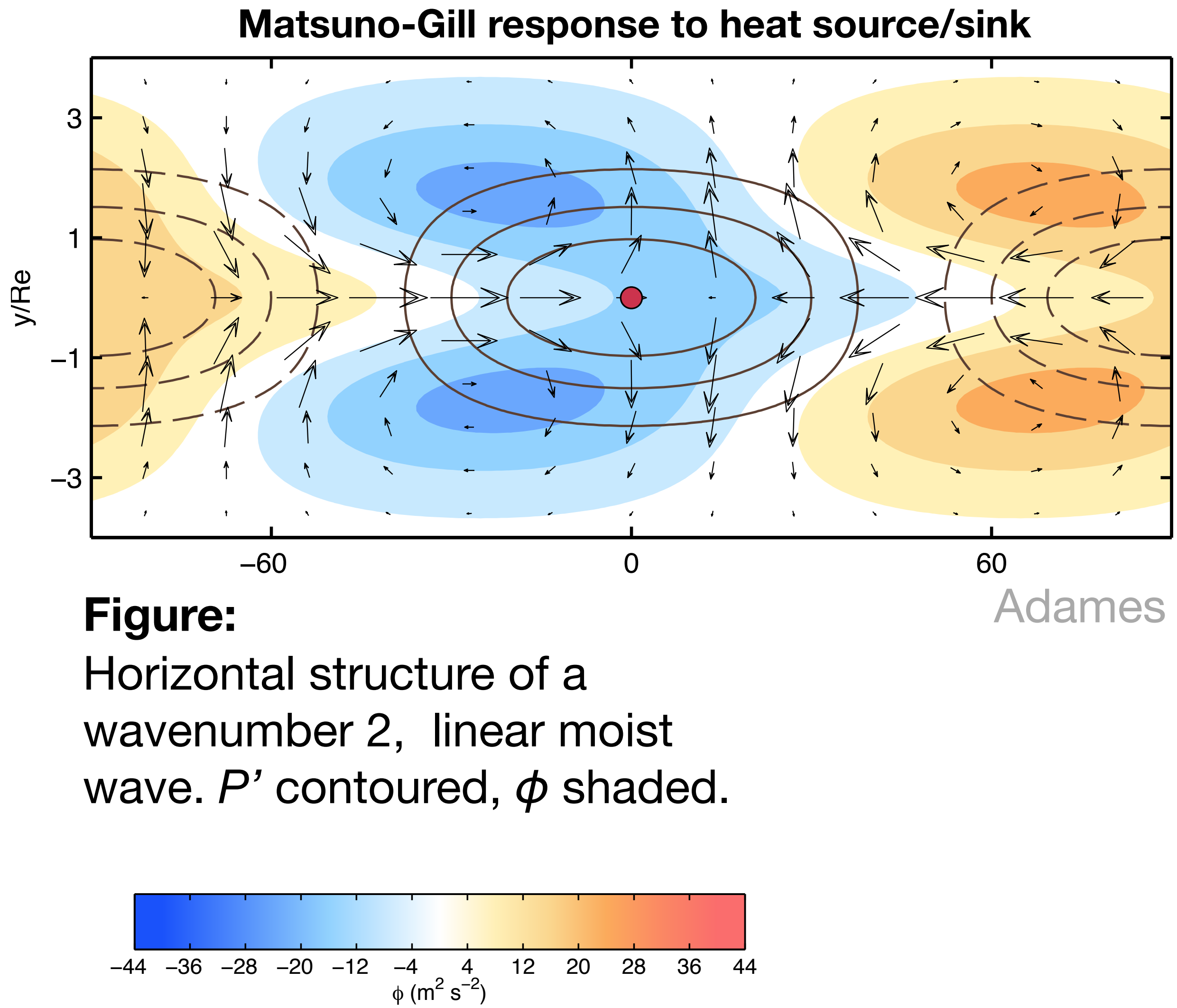
We can superimpose linearly the solutions for different forcings

$$-\beta y v = -\frac{\partial p}{\partial x} - \epsilon u$$

$$\beta y u = -\frac{\partial p}{\partial y} - \epsilon v$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = Q - \epsilon_T p$$

Q = wavenumber 2 equatorial heating



Adames

Figure:
Horizontal structure of a wavenumber 2, linear moist wave. *P'* contoured, ϕ shaded.

Adames

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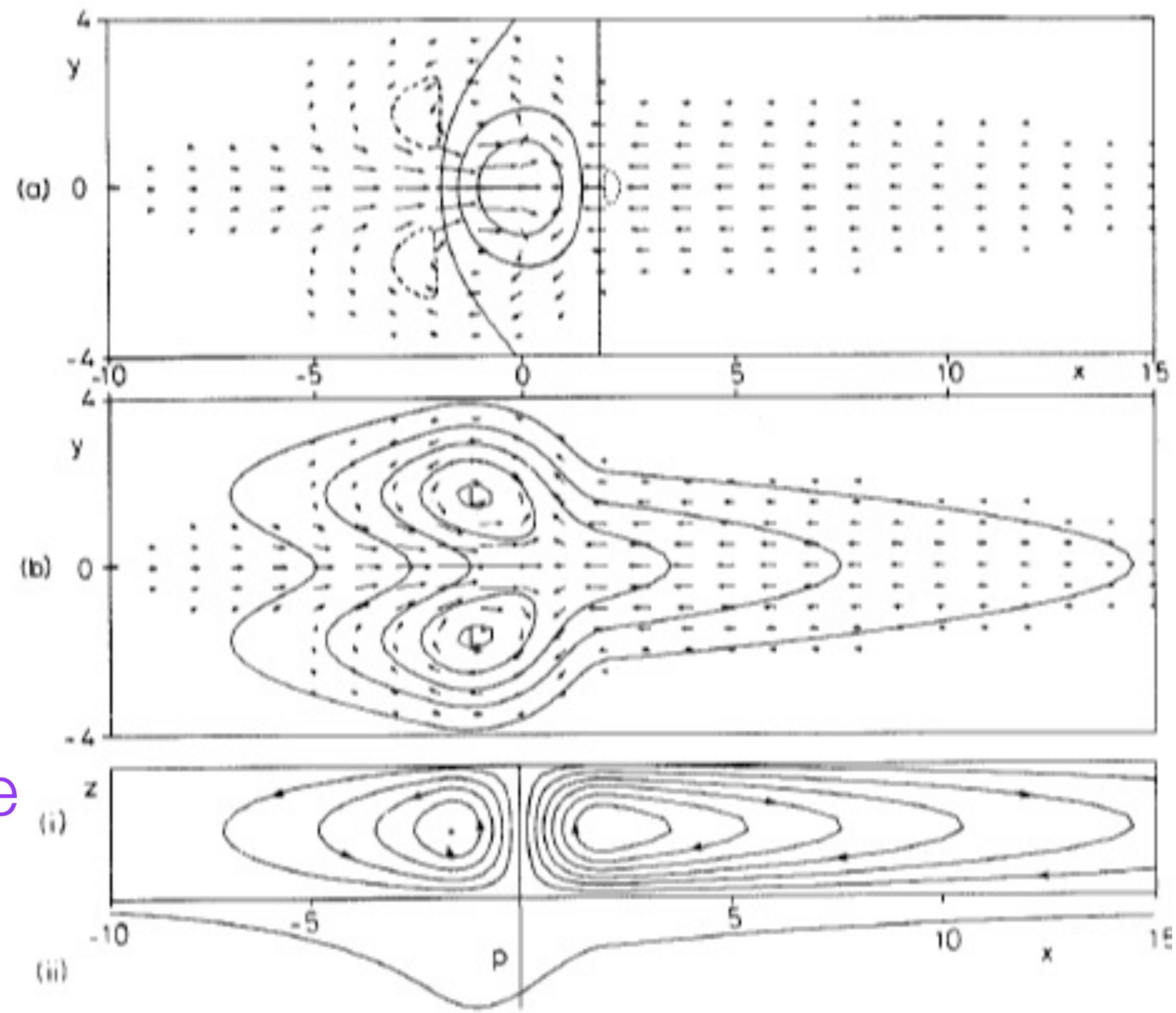
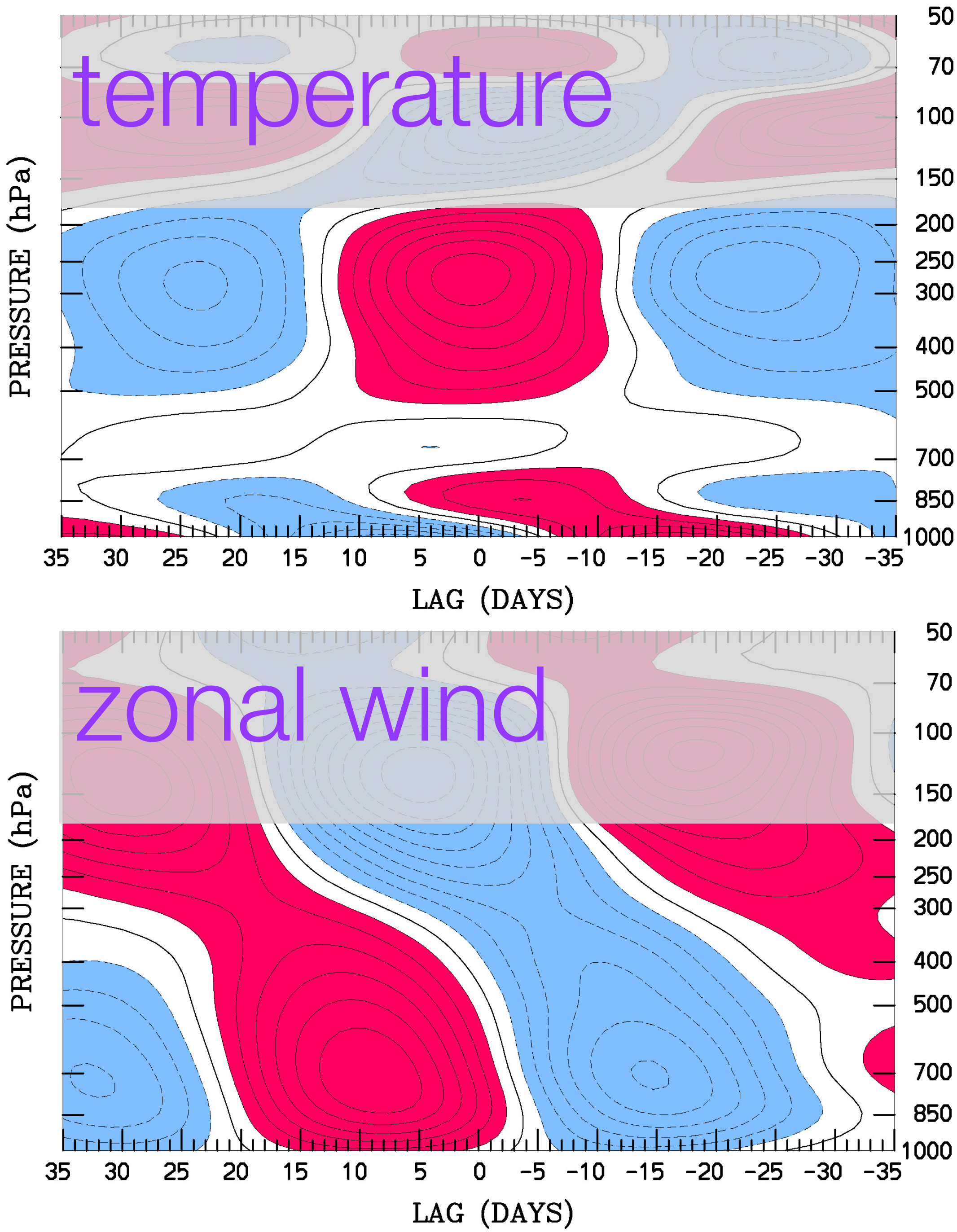
Q = single equatorial heating



deep overturning in the meridional plane

Gill 1980

Observed Vertical Structure of the MJO



consistent with the Gill model

BUT the MJO PROPAGATES!

Building a Theory of the MJO:

- Why does it propagate eastward?

- What sets the propagation speed?
- the spatial scale?
- the intra-seasonal time scale?

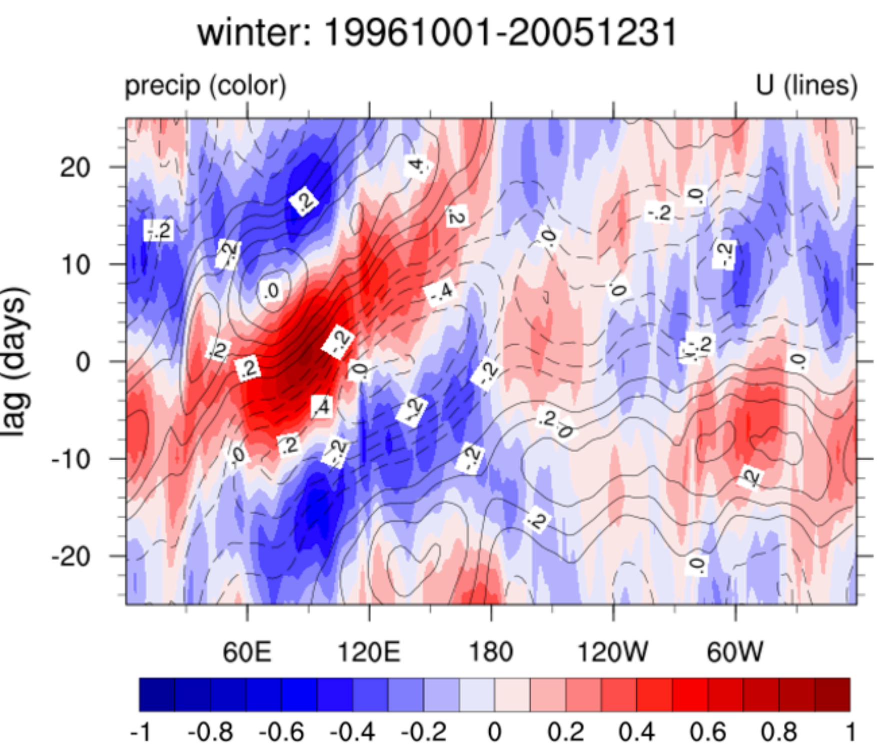
- Why is it much stronger over the Indo-Pacific?
- What is its energy source?

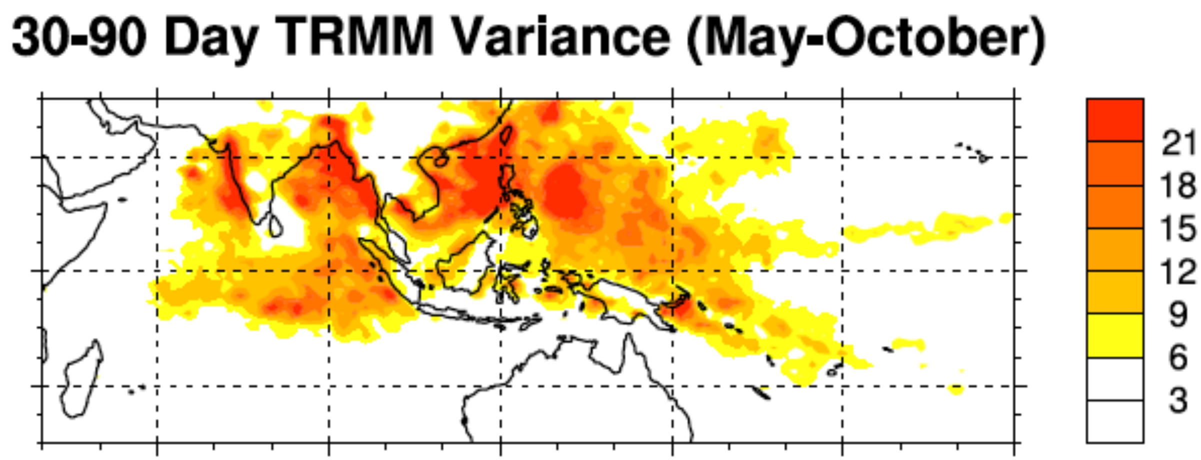
- What is the connection to the embedded fast waves?

A recent review of 4 modern MJO theories

Yang, D., A. Adames, B. Khouider, B. Wang, C. Zhang, 2019: A Review of MJO Theories. The Global Monsoon System, (Eds C. P. Chang et al.). World Scientific Series on Asia-Pacific Weather and Climate, World Scientific, Singapore (in press).

The MJO as a moisture mode. Rationale:



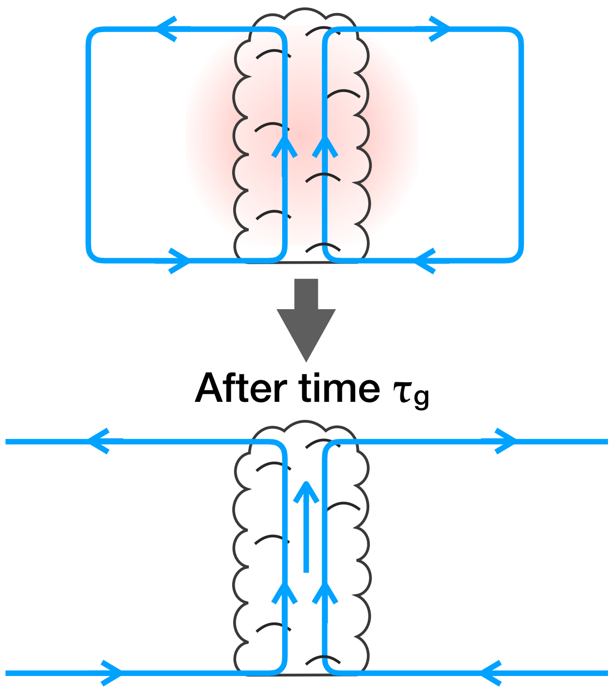


The slow propagation speed is limited to the Warm Pool, where the MJO has a strong convective component

Intraseasonal rainfall variance is greater over warm SST and greater over ocean than land, which suggests a role for net surface heat flux (likely dominated by latent heat flux).

Sobel et al, 2008

The MJO as a moisture mode. Basic Idea:



Adames

A large-scale moist instability. Hence, the timescale is slower than the speed of gravity waves, so that we are in the WTG and CQE regime.

$$\frac{\partial q'}{\partial t} + U\frac{\partial q'}{\partial x} = -MP' + E' - (1-M)R'$$

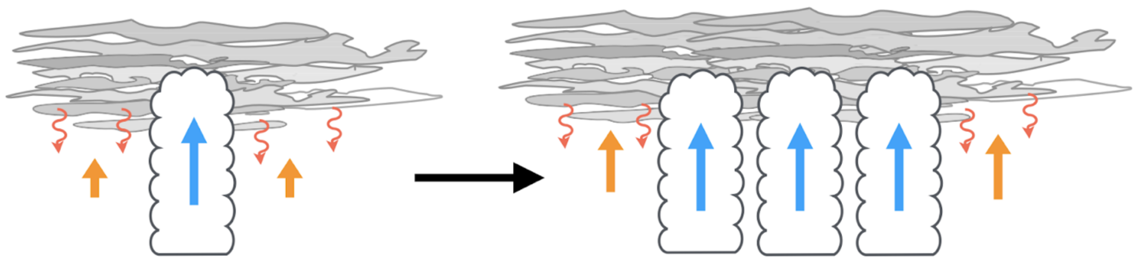
(energy units)

Precipitation is a restoring force

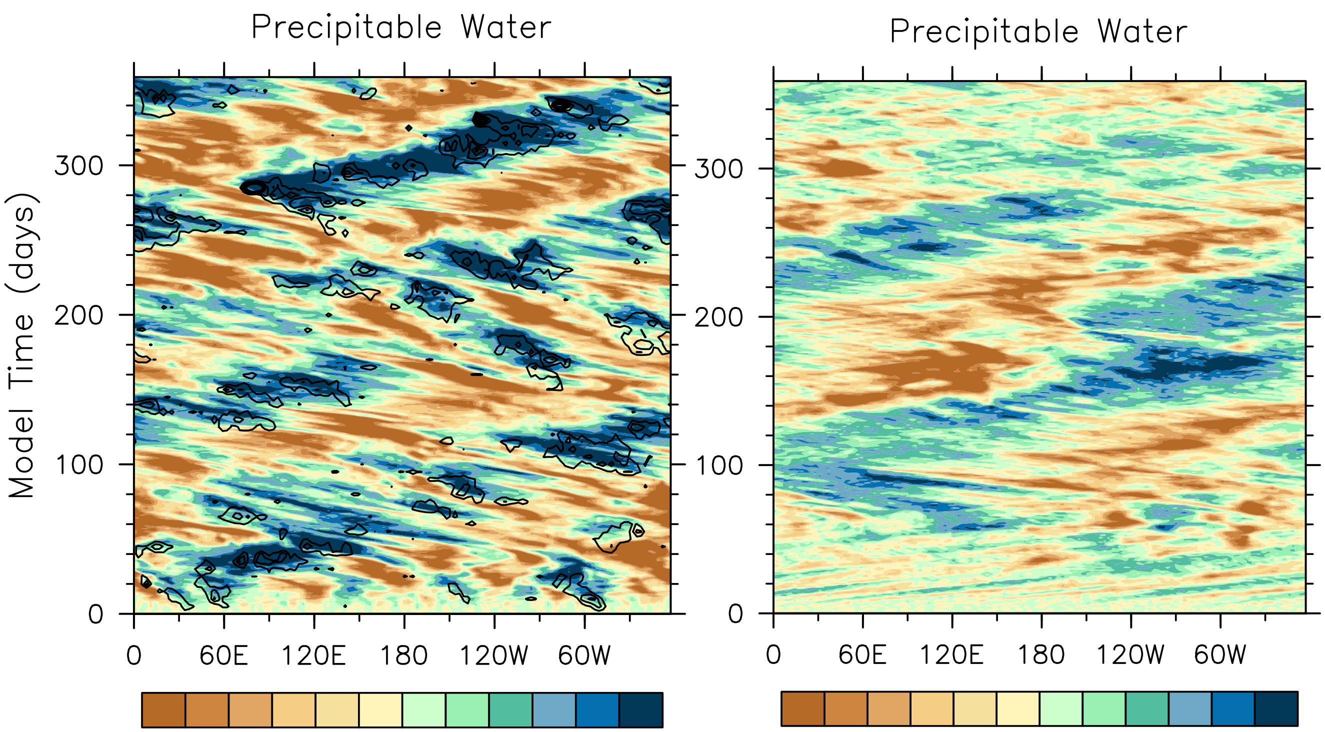
Energy Fluxes are the sources of energy

Sobel and Maloney (2012,2013)

Radiation is the main destabilizing process



Adames



Control simulation

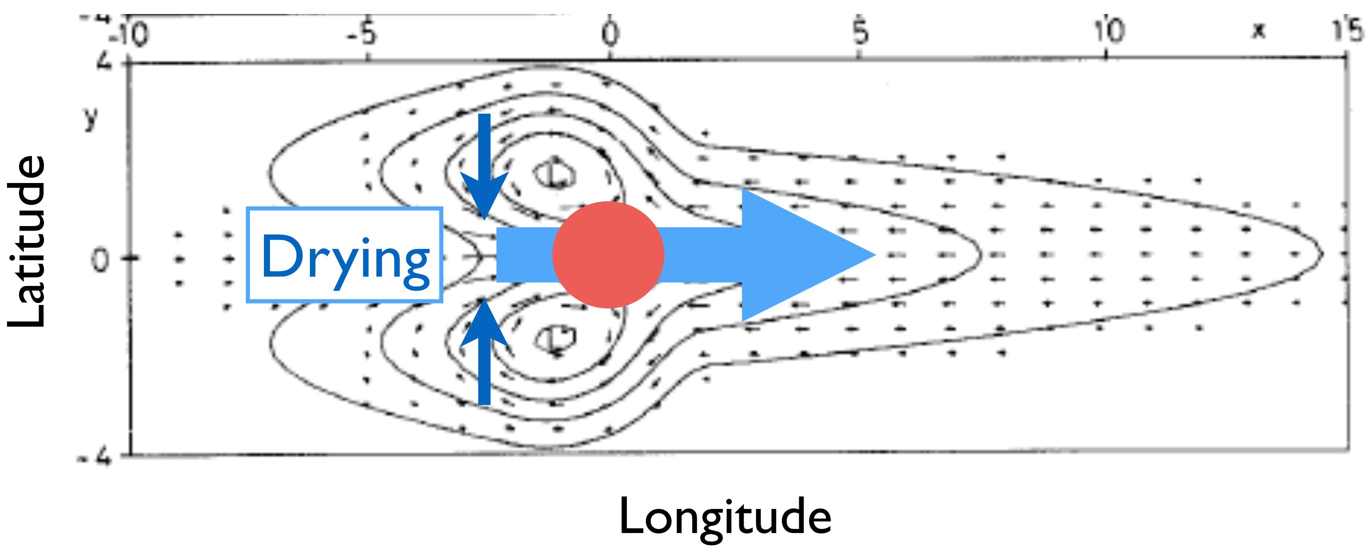
No radiative feedbacks

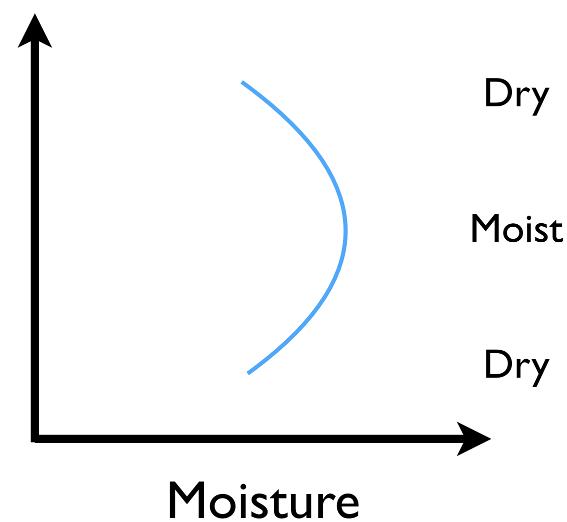
High cirrus in deep convection reduce OLR and causes a net warming, which is balanced by upward motion and moisture import into the free troposphere.

Arnold and Randall 2015 JAMES

Need a better representation of moisture advection for Eastward propagation

Horizontal Advection: meridional advection by the *MJO wind* of the *background moisture gradient*

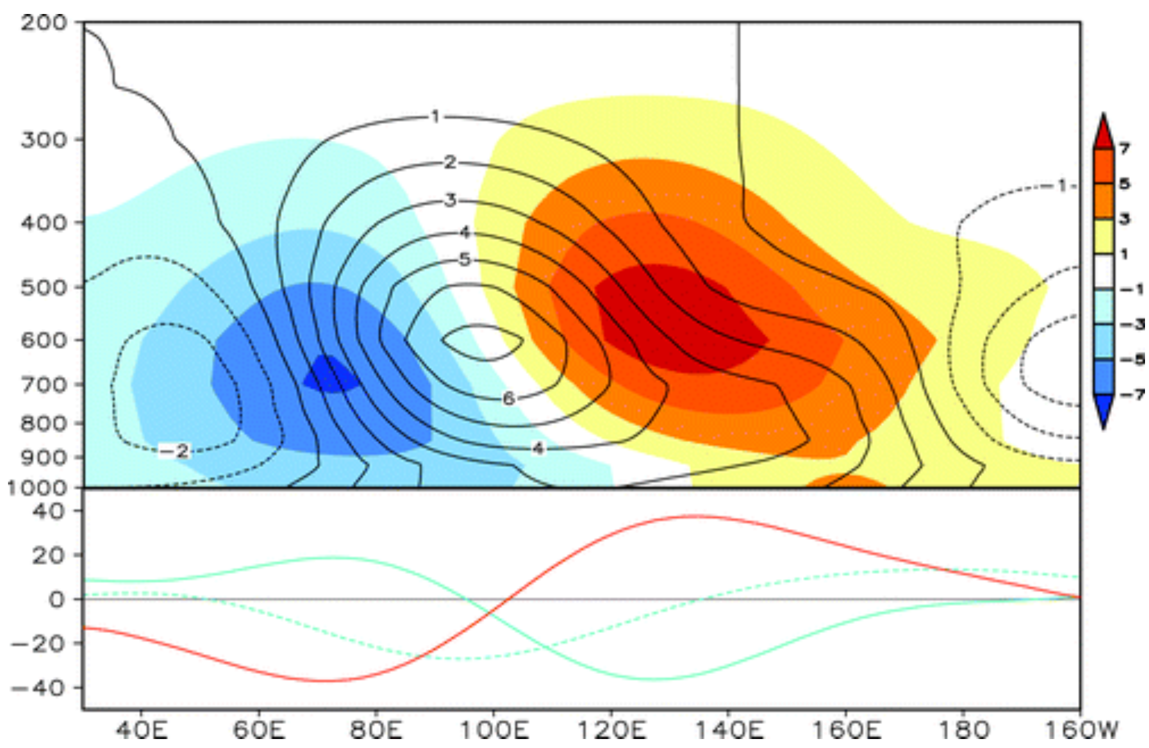




(during DYNAMO, zonal advection did the moistening to the east of the main convection)

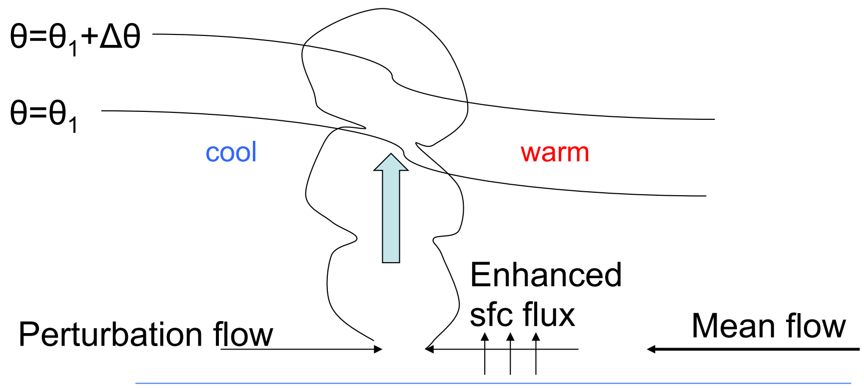
Need a better representation of moisture advection for Eastward propagation

<u>vertical moisture advection</u>*:* Frictional convergence and a shallow circulation to the East create a positive moisture (and MSE) tendency.

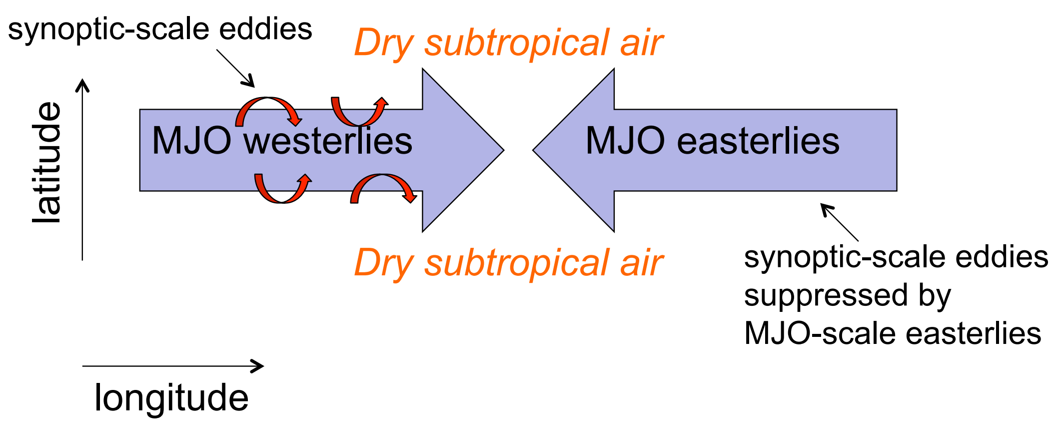


Hsu, P., & Li, T. (2012)

details and add-on's…



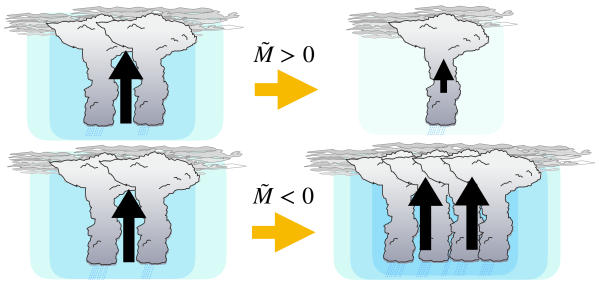
WISHE enhances surface fluxes when u' reinforces the mean wind



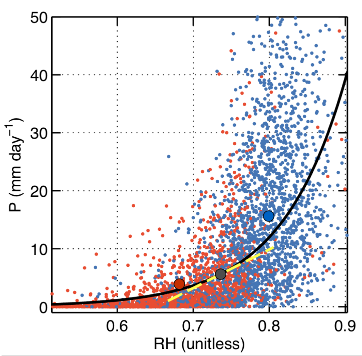
synoptic eddies affect dry/moist advection and help propagate the convective region

(Maloney 2009, Andersen and Kuang 2012,Adames, 2017)

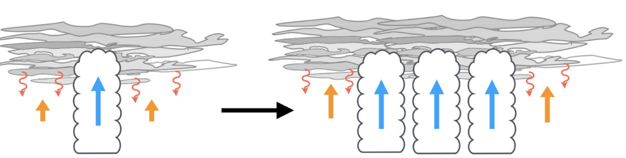
Assumptions and issues with a pure moisture mode:



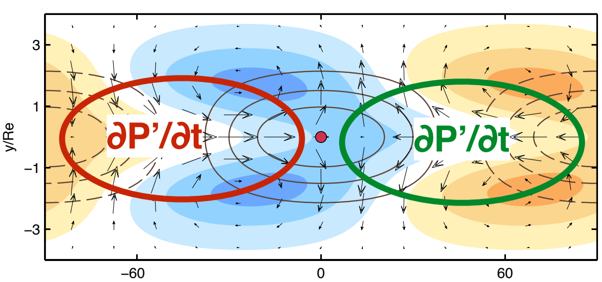
negative GMS needed for circulation to import energy and lead to amplification



precipitation only a function of moisture



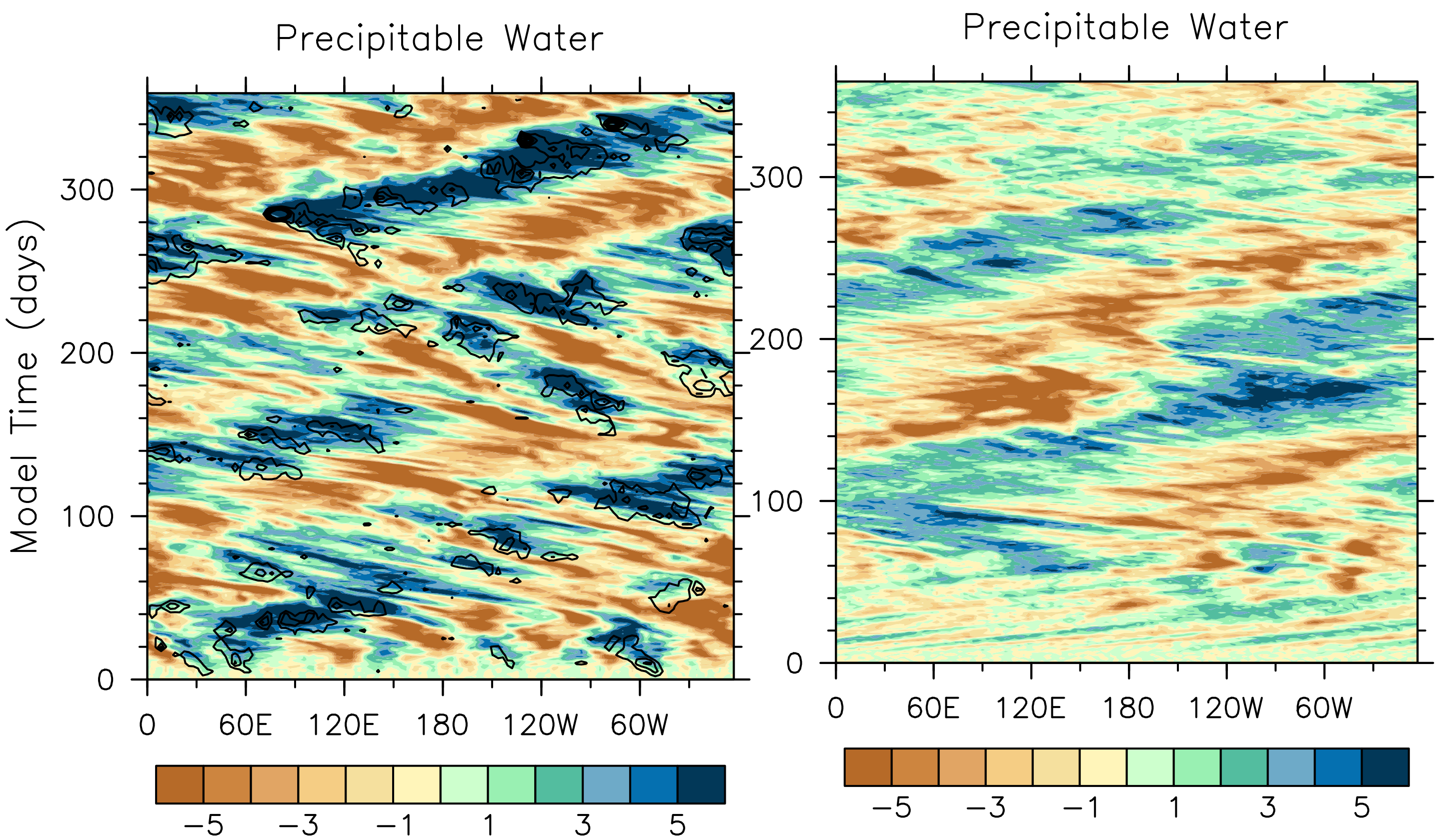
radiative feedbacks need to be scale dependent for the unstable modes to select planetary scale



depends on background moisture gradients for eastward propagation

Issue:

Spatial scale remains unchanged when radiative feedbacks are switched off



Control simulation

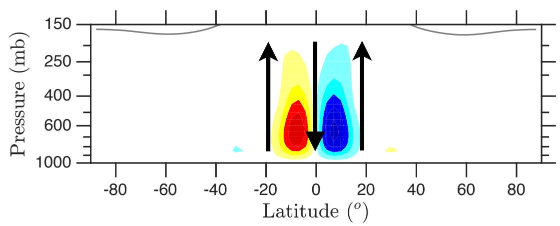
No radiative feedbacks

Amplitudes become smaller

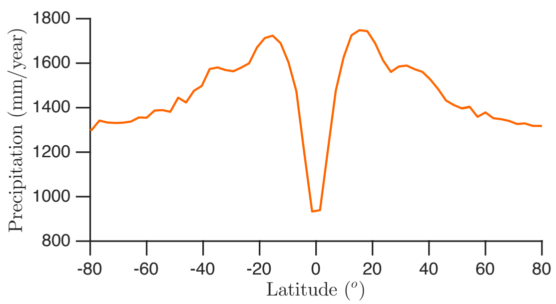
Arnold and Randall 2015 JAMES

Issue:

The “MJO” eastward propagation is not always sensitive to horizontal moisture advection

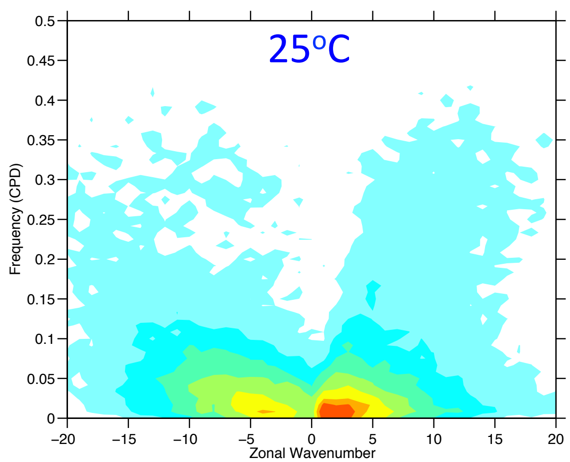


Anti-Hadley circulation emerged



Two tropical rainfall peaks

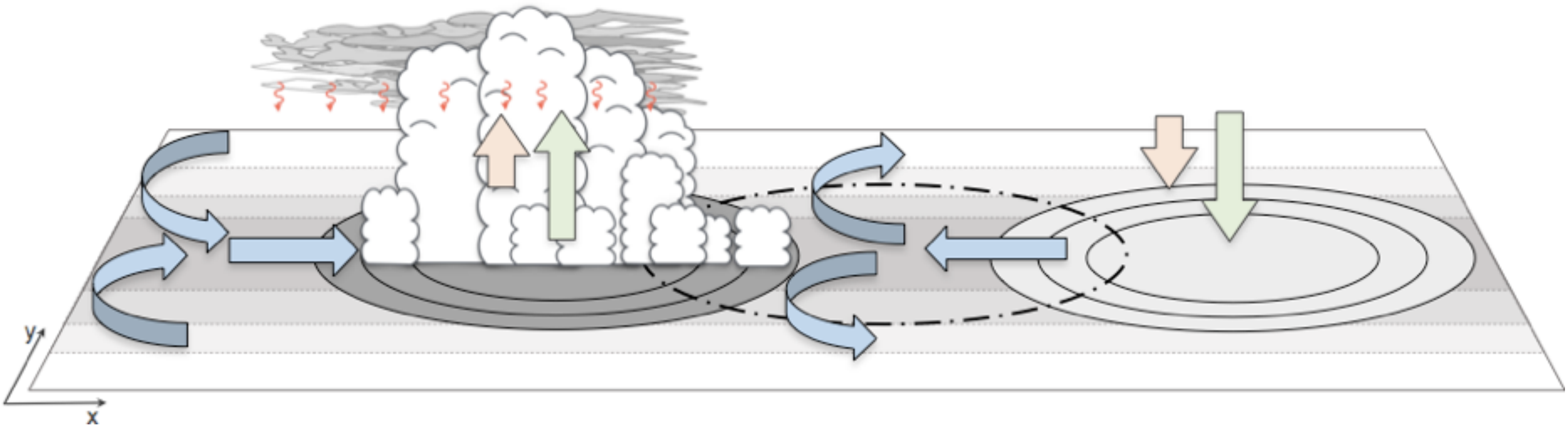
Tropics is dry; subtropics is humid



The MJO still propagates to the east

Pritchard and Yang 2016, J. Climate

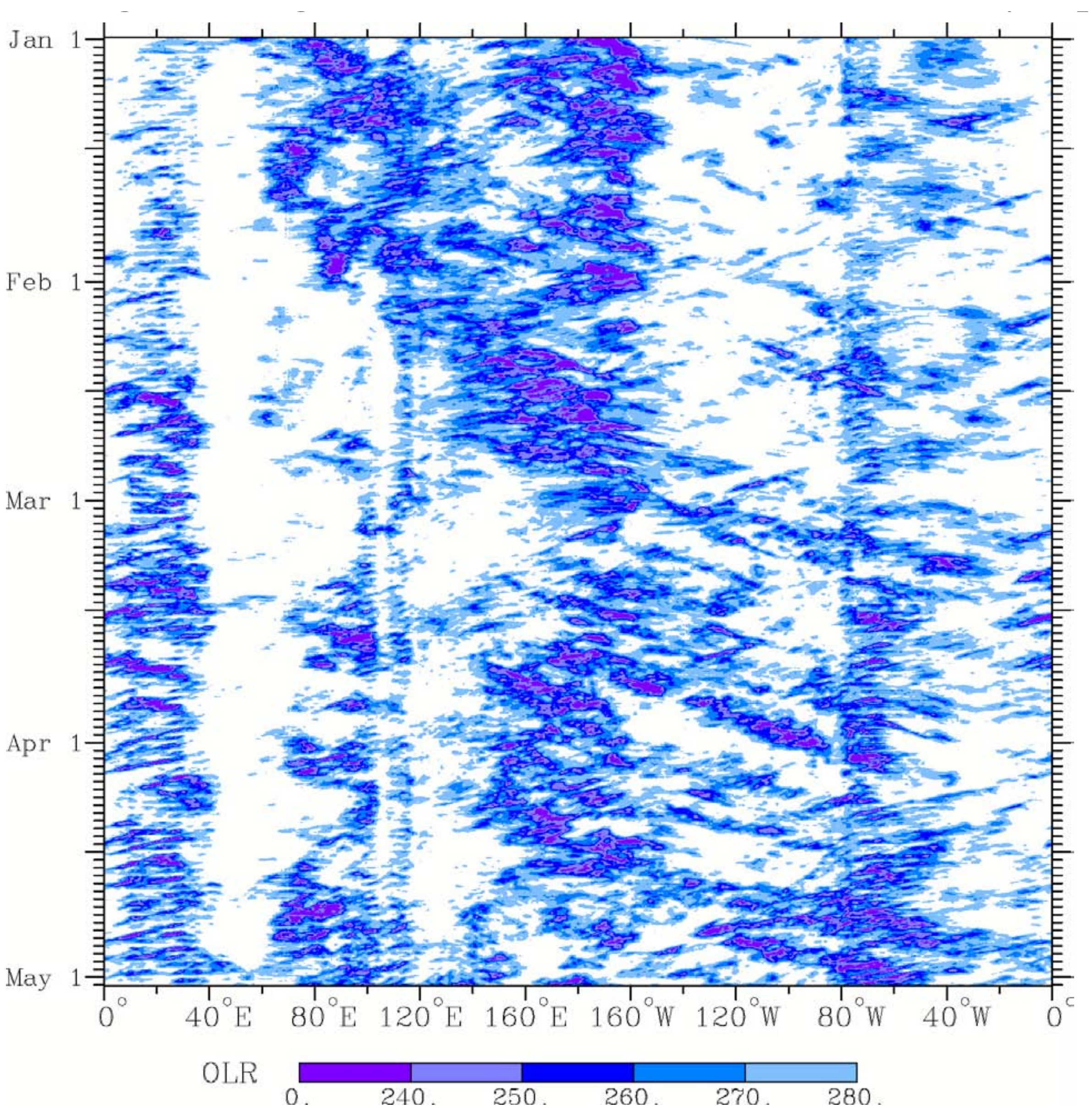
The MJO as a moisture mode. Summary:

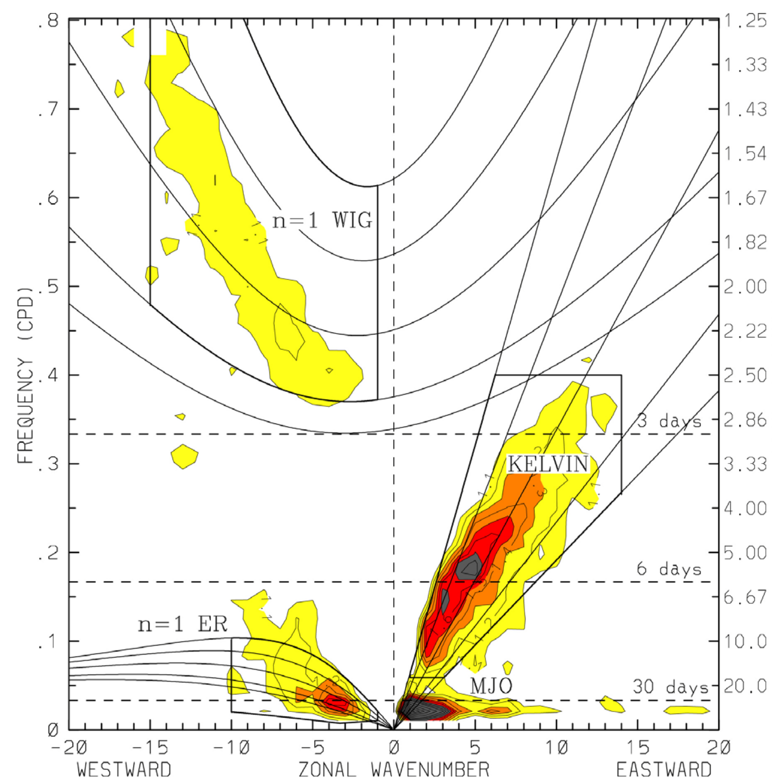


- Distinct (but can co-exist) with buoyancy-driven (gravity) modes. Flow dominated by rotational component.
- Destabilized (at least partly) by moisture mode instability. Instability can occur from: cloud radiation feedbacks, negative gross moist stability, and air-sea interaction.
- Exhibit slow or no propagation.
- The processes that change column moisture determine propagation of the disturbance.

Adames; Yang et al 2019

Another kind of self organization:
The MJO as an envelope of interfering WIG s and EIGs

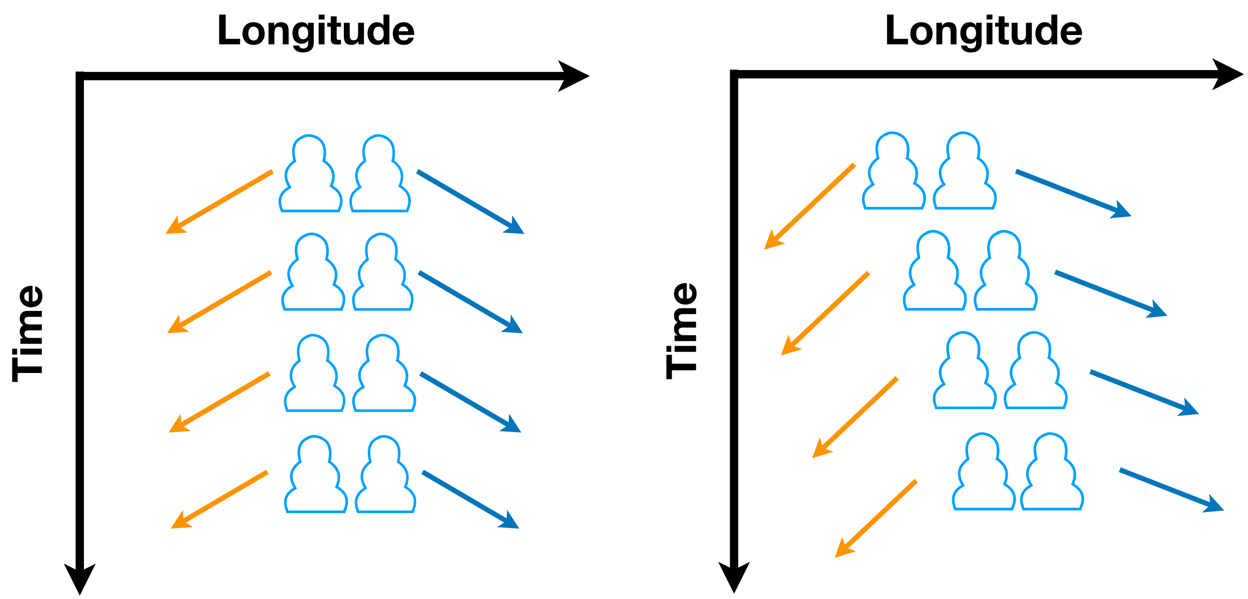




The gravity-wave model

A multi-scale theory: The MJO is a large-scale envelope of small-scale high-frequency eastward and westward inertia-gravity (IG) waves.

Convection excites a quasi standing IG wave, which triggers more convection events in the vicinity of recent convection events. Because of the non-linearity of the trigger mechanism, convection excites a range of frequencies.

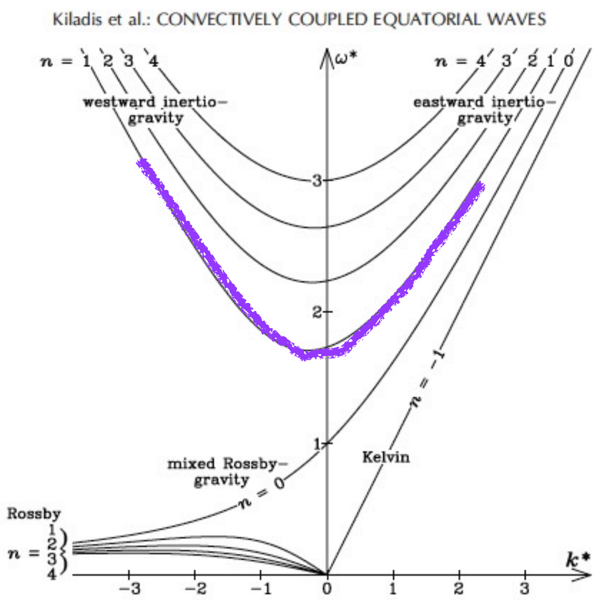


$c_W = c_E \Rightarrow c_{MJO} = 0$

$c_W < c_E \Rightarrow c_{MJO} > 0$

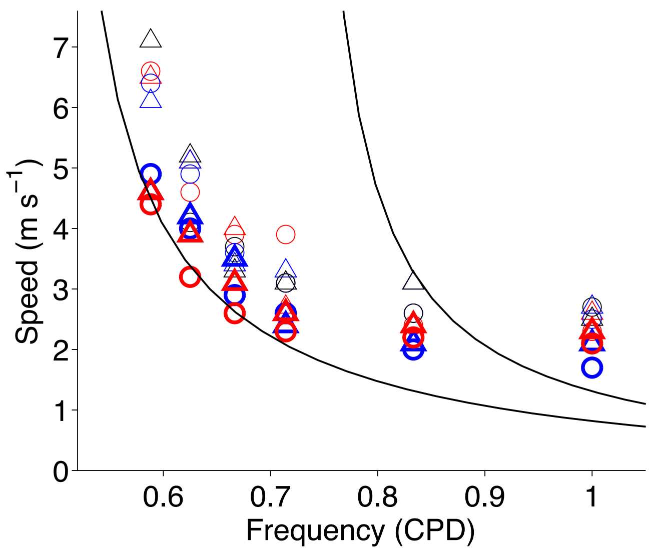
Yang and Ingersoll 2013, 2014

The gravity-wave model



The zonal asymmetry of IG waves set the propagation speed of the MJO:

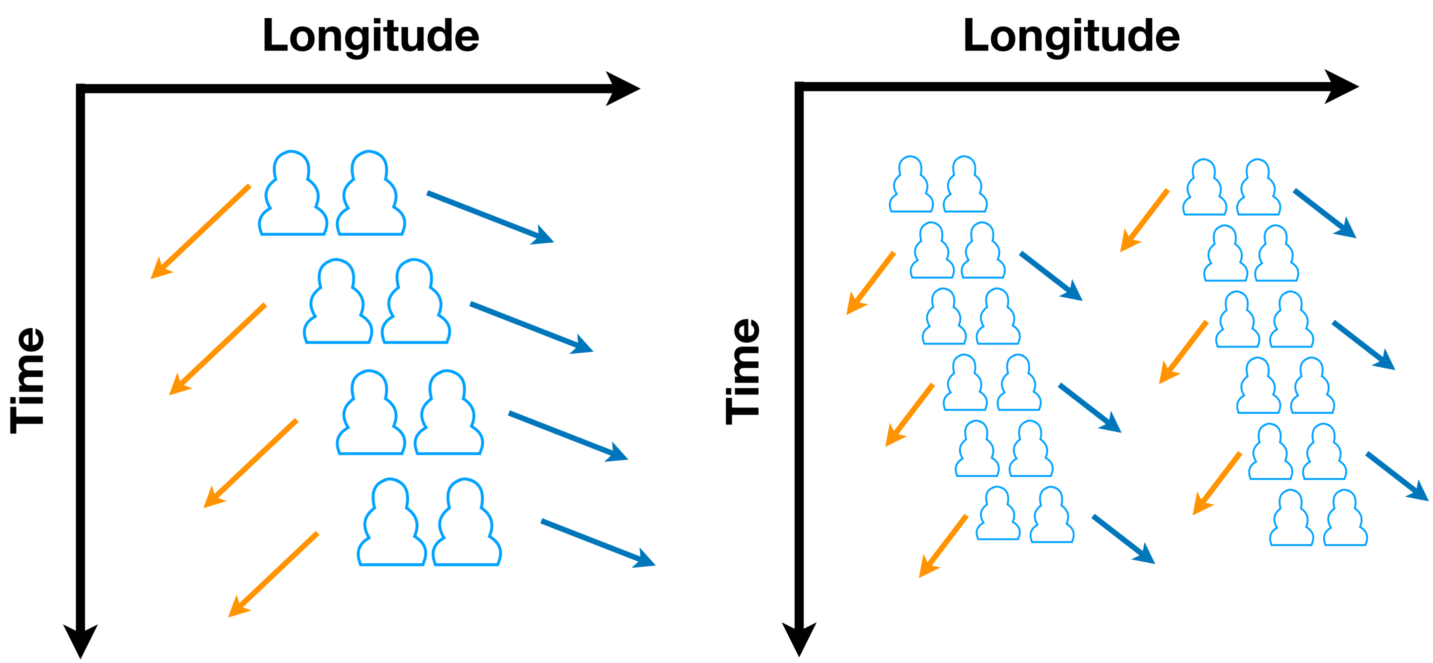
$$c = 0.5(c_E - c_W)$$



This figure presented 60 simulations with a wide range of parameter values. Each marker represents a simulation. The curves correspond to the theoretical MJO speed. The lower one is associated with the lowest meridional structure.

The gravity-wave model

The zonal scale is set by the mean free path (MFP) of gravity waves



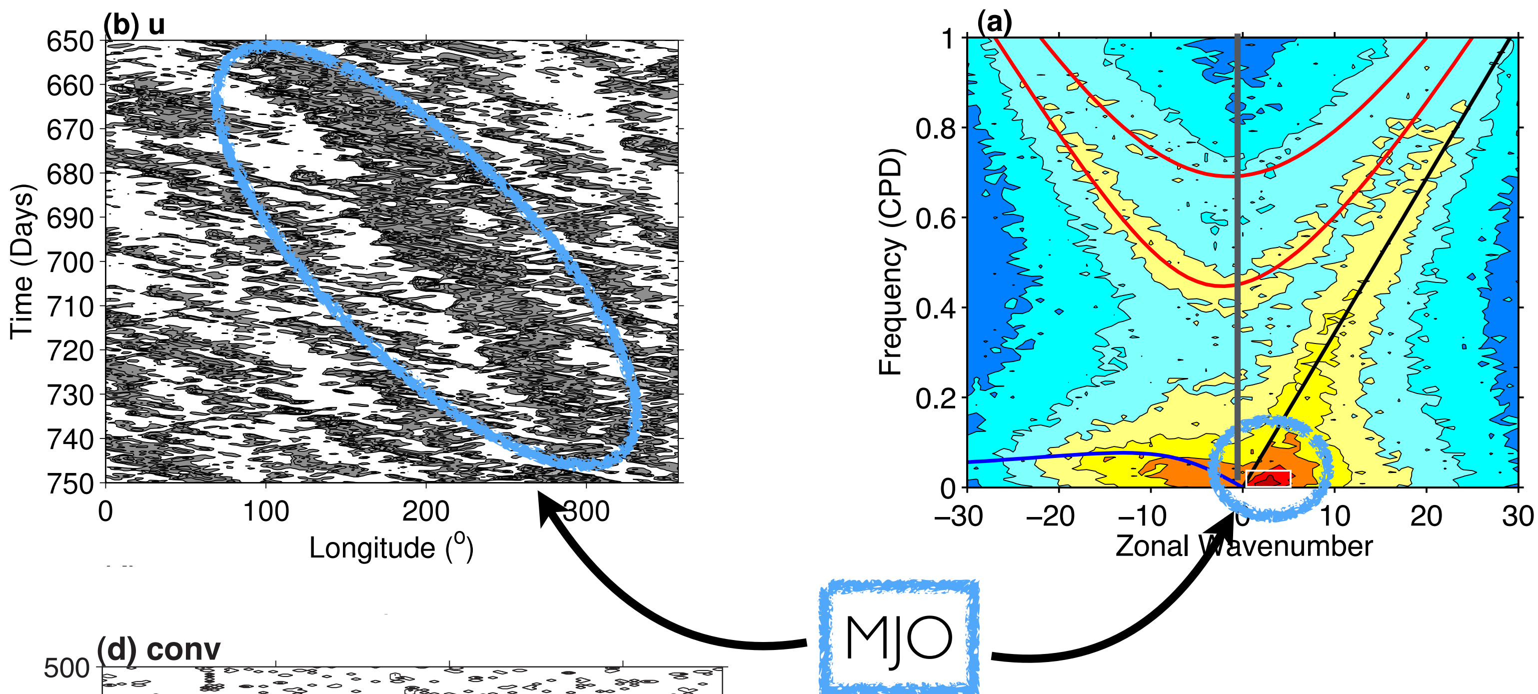
Fewer, stronger storms (large MFP) lead to large zonal scale of the MJO

Faster gravity waves (small MFP) lead to small zonal scale of the MJO

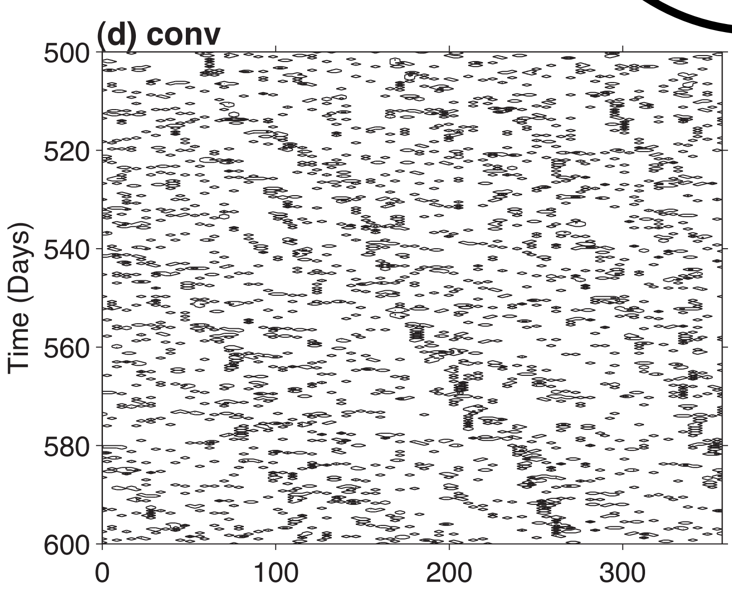
=> faster, bigger, and stronger MJOs in warmer climates.

The gravity-wave model

Results from a one-layer atmosphere model (shallow water model)



Dynamic Field (U)



convection

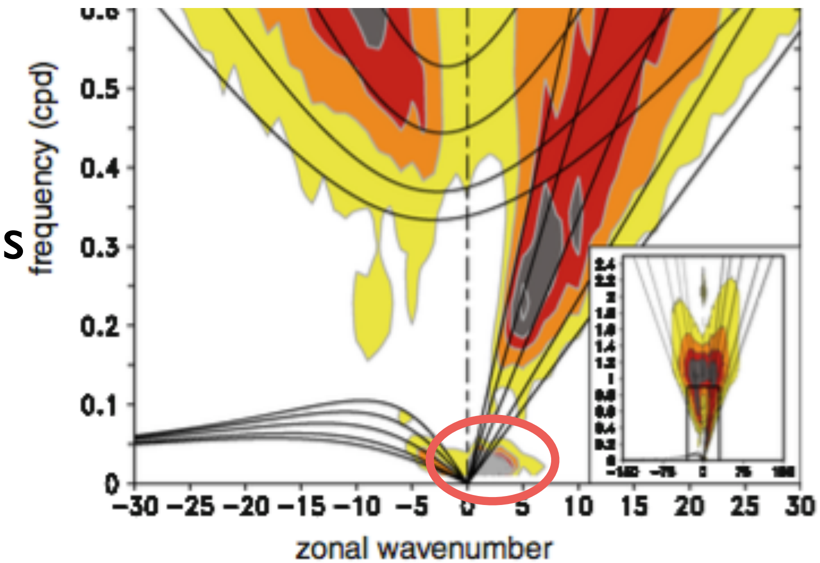
Yang and Ingersoll 2013, *JAS*

Validating the gravity-wave model:

Observation supports the multi-scale theory (in spectral — but not physical — space)

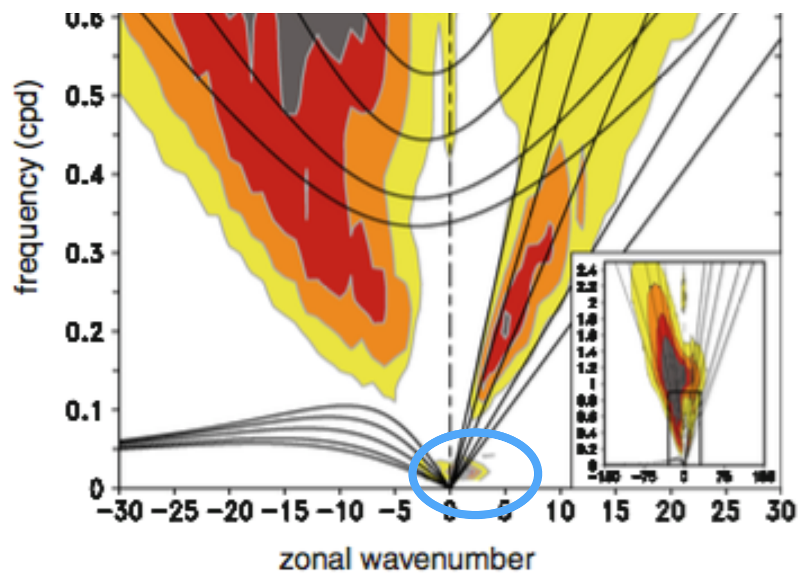
Strong MJO

Eastward & westward waves



Weak MJO

No eastward waves

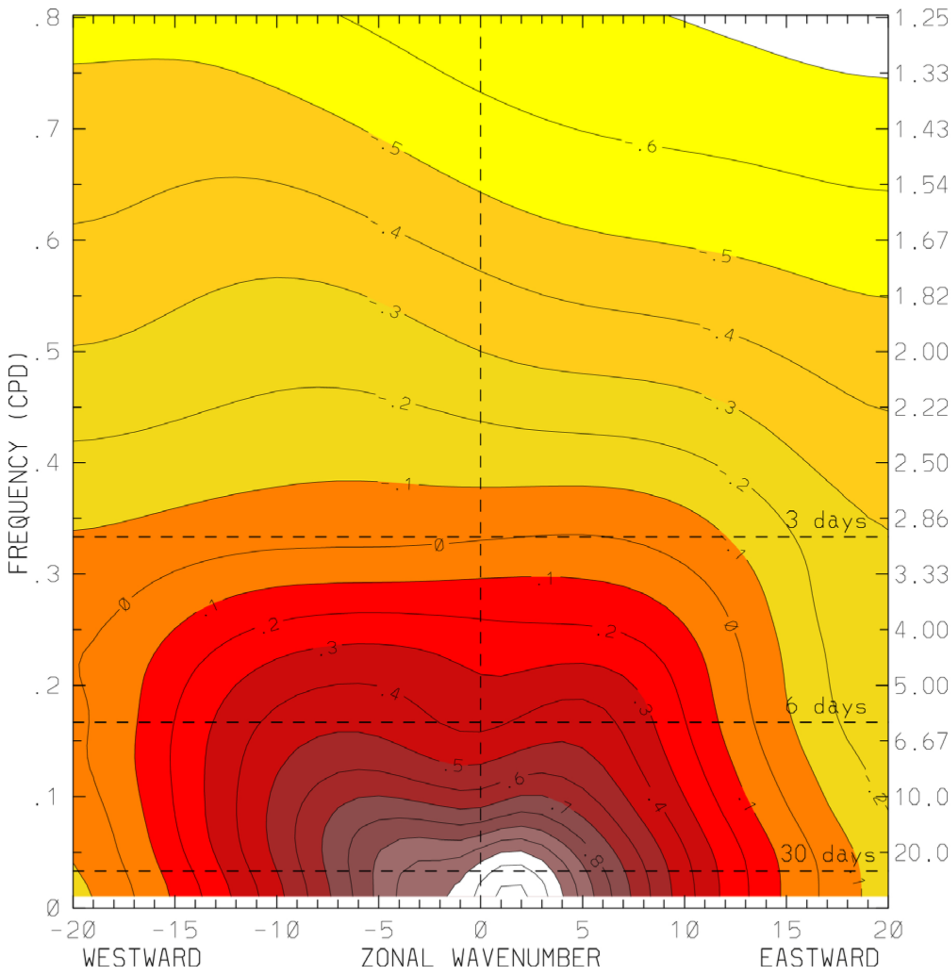


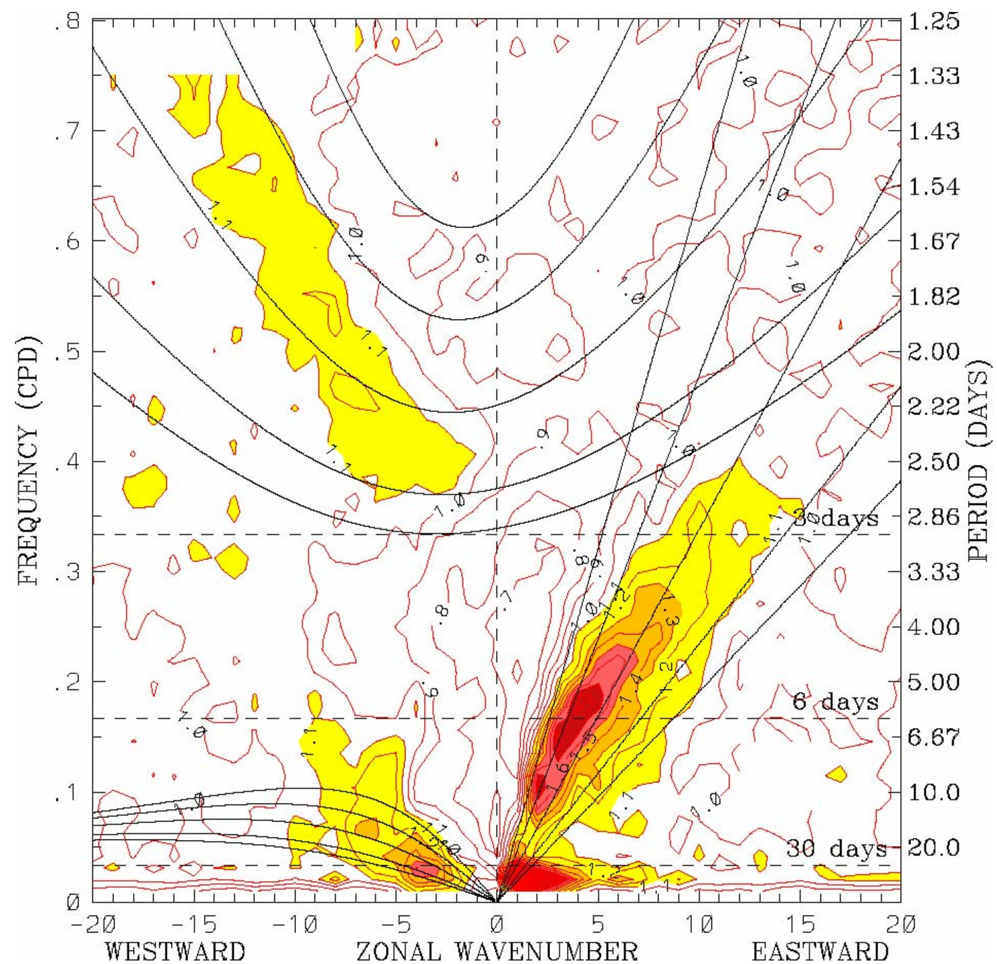
Kikuchi 2010

Conclusions:

- The tropical atmosphere self-organizes at sub-seasonal and intraseasonal time scales.
- All CCEWs have dry-atmosphere counterparts (gravity, and rotation are their restoring forces), but are slowed down by moist convection.
- The MJO is (probably, partly) a moisture mode: convection in near-balance with the L-S flow destabilized by radiation, surface fluxes, and GMS propagating because of moisture advection
- The MJO could be lots of other things… (combining Equatorial Waves, Convection, Radiation, and Boundary Layer Processes)
- Tropical Cyclones are a whole other ball of wax…

CAVEAT: What about the background?





“convection organization”

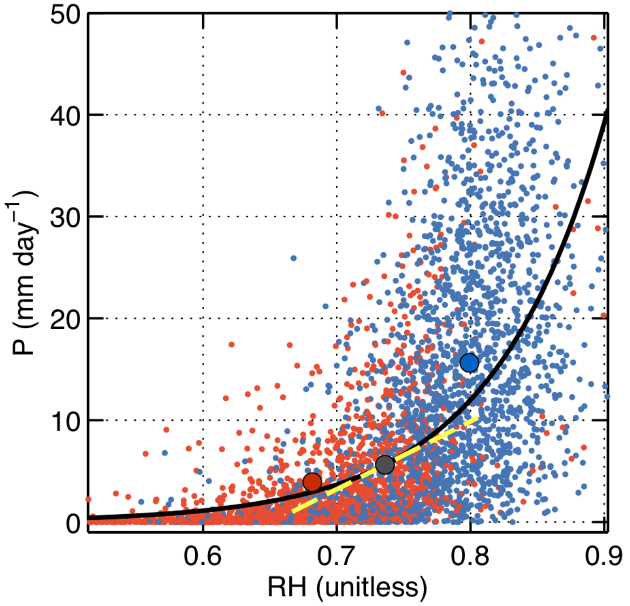
WHAT DO WE MEAN BY ORGANIZATION?

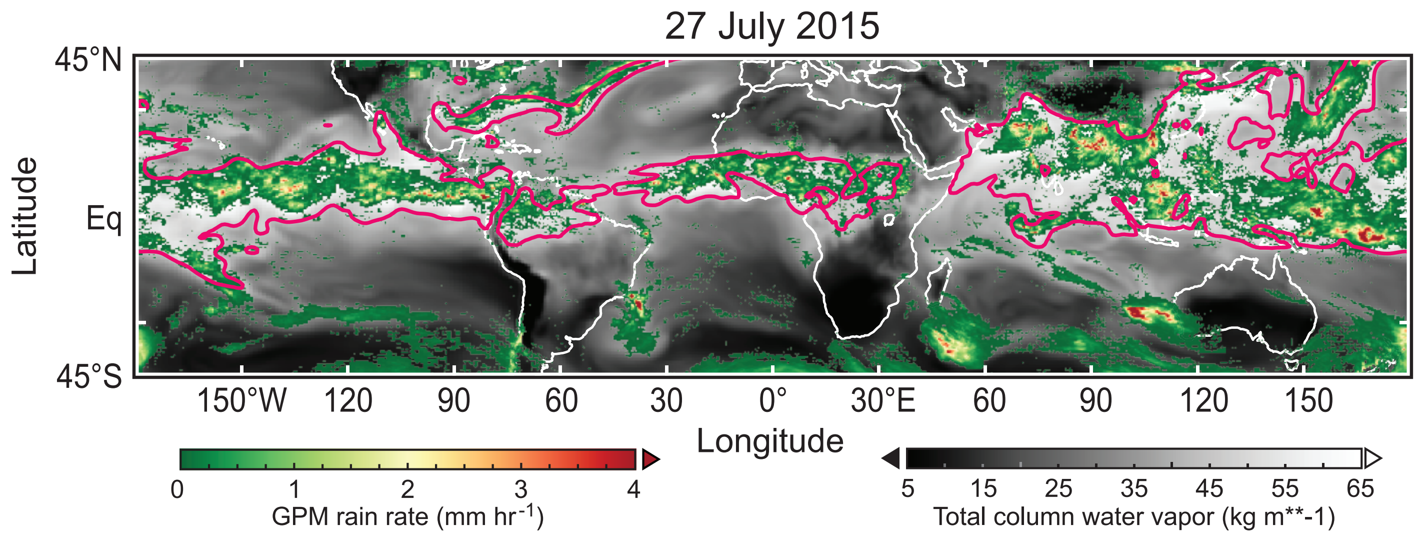
- organization by the boundary
- self - organization of the atmosphere
  - through (dry) dynamics
  - through moisture

WHAT DO WE MEAN BY CONVECTION?

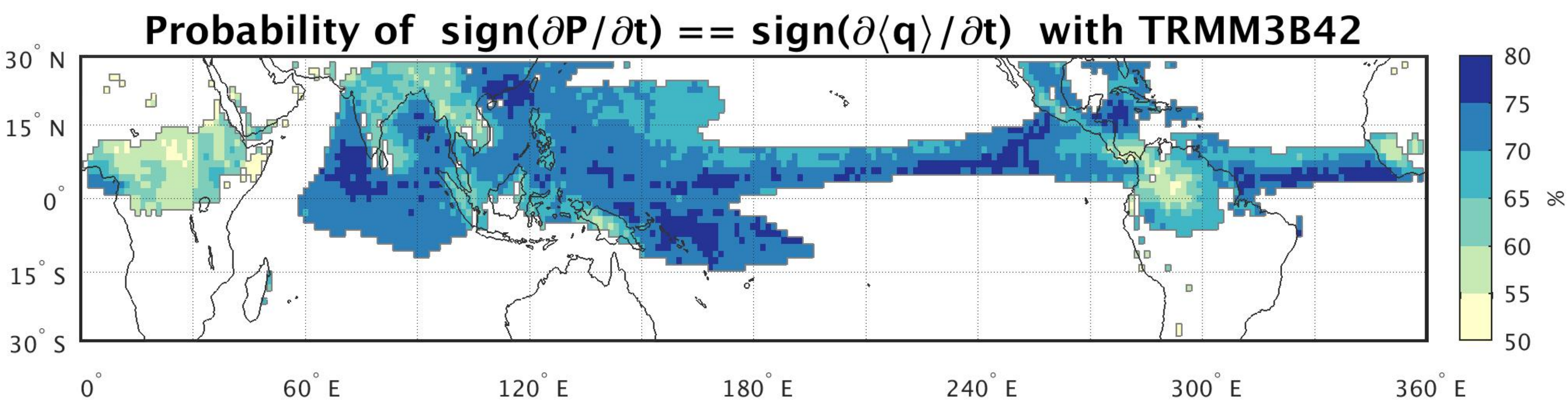
- deep clouds? rainfall? PW?

We have assumed that <q> and P are tightly linked:

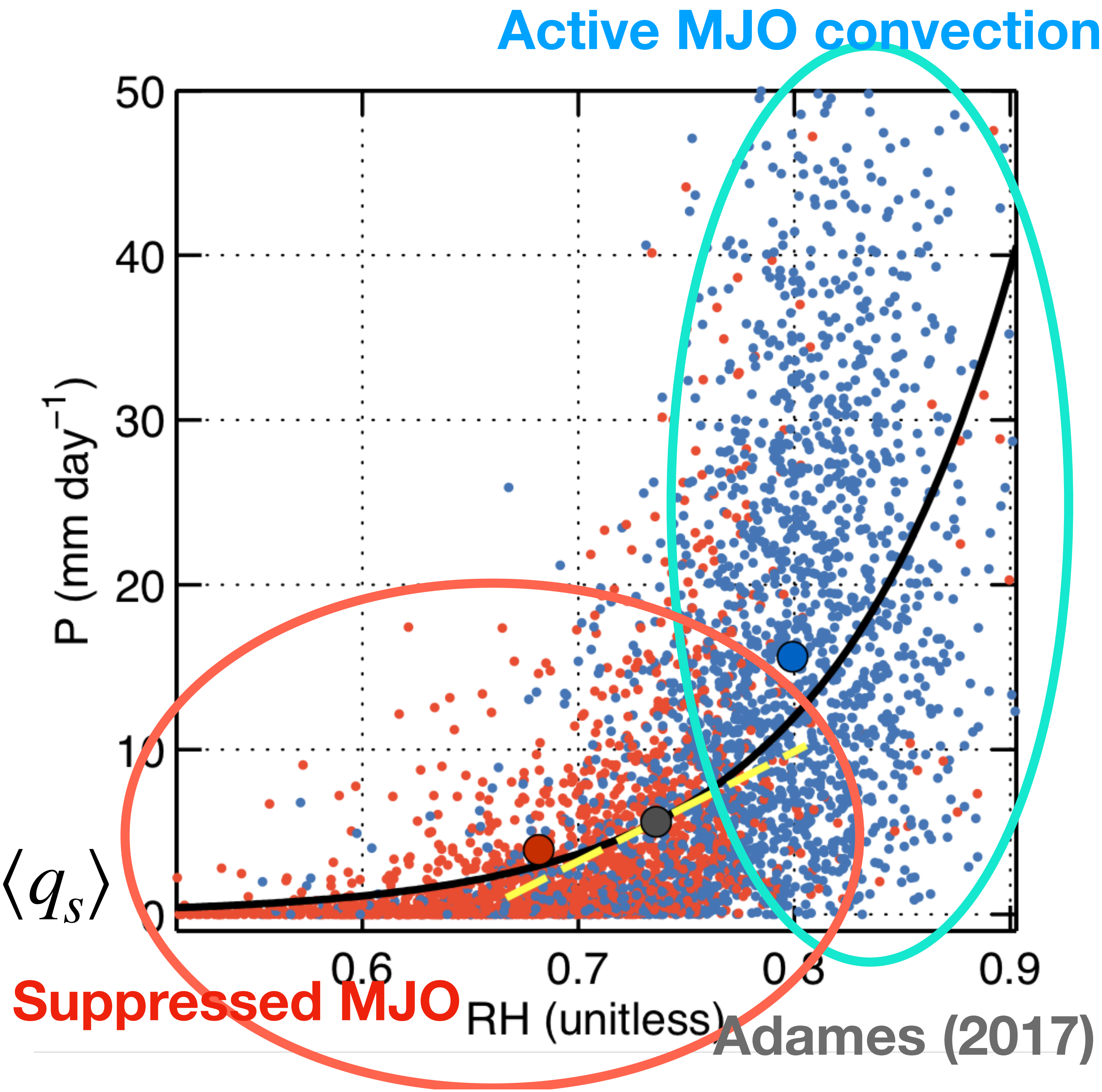




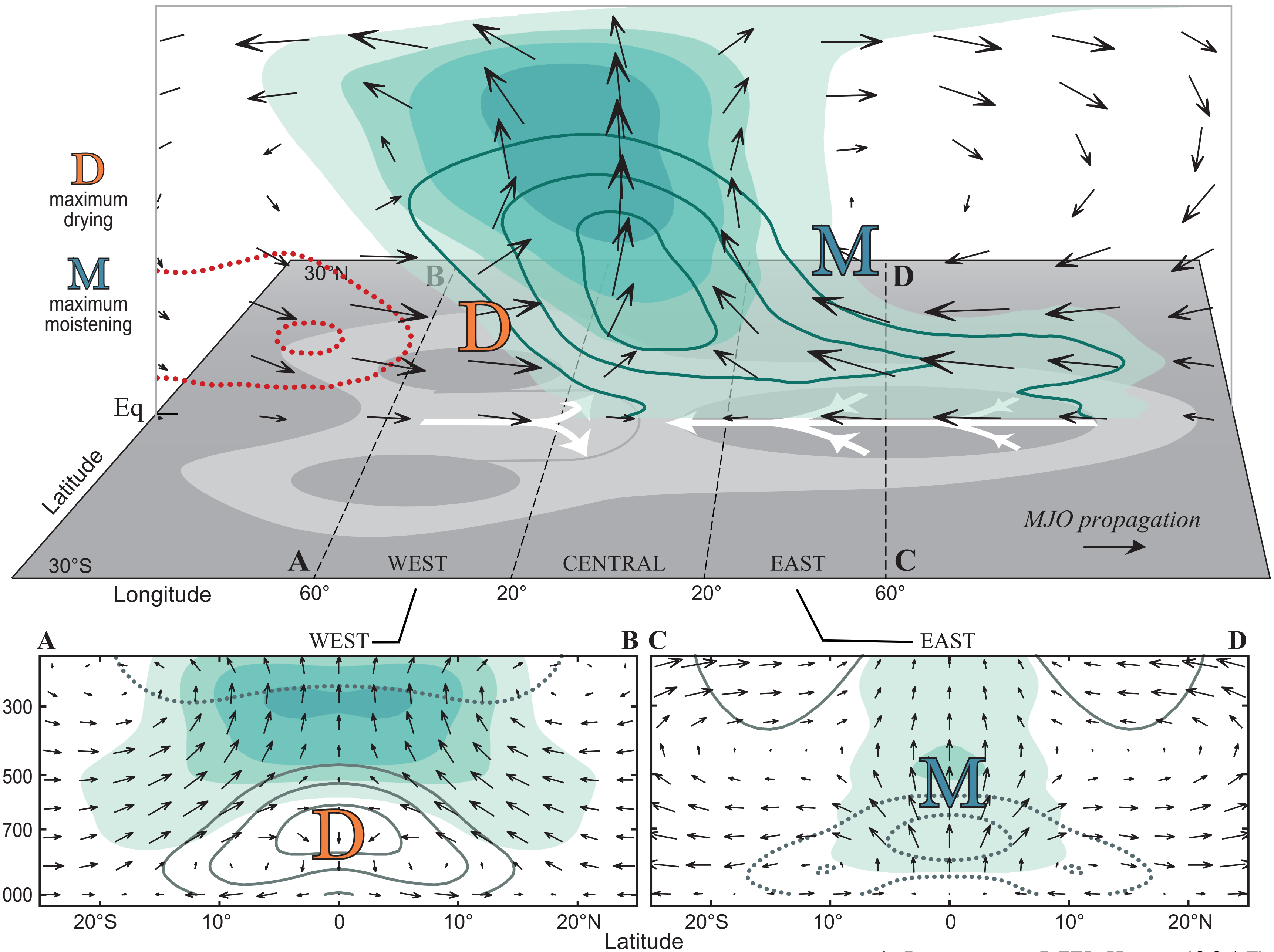
is that so over land?



Kuni Inoue (in prep)

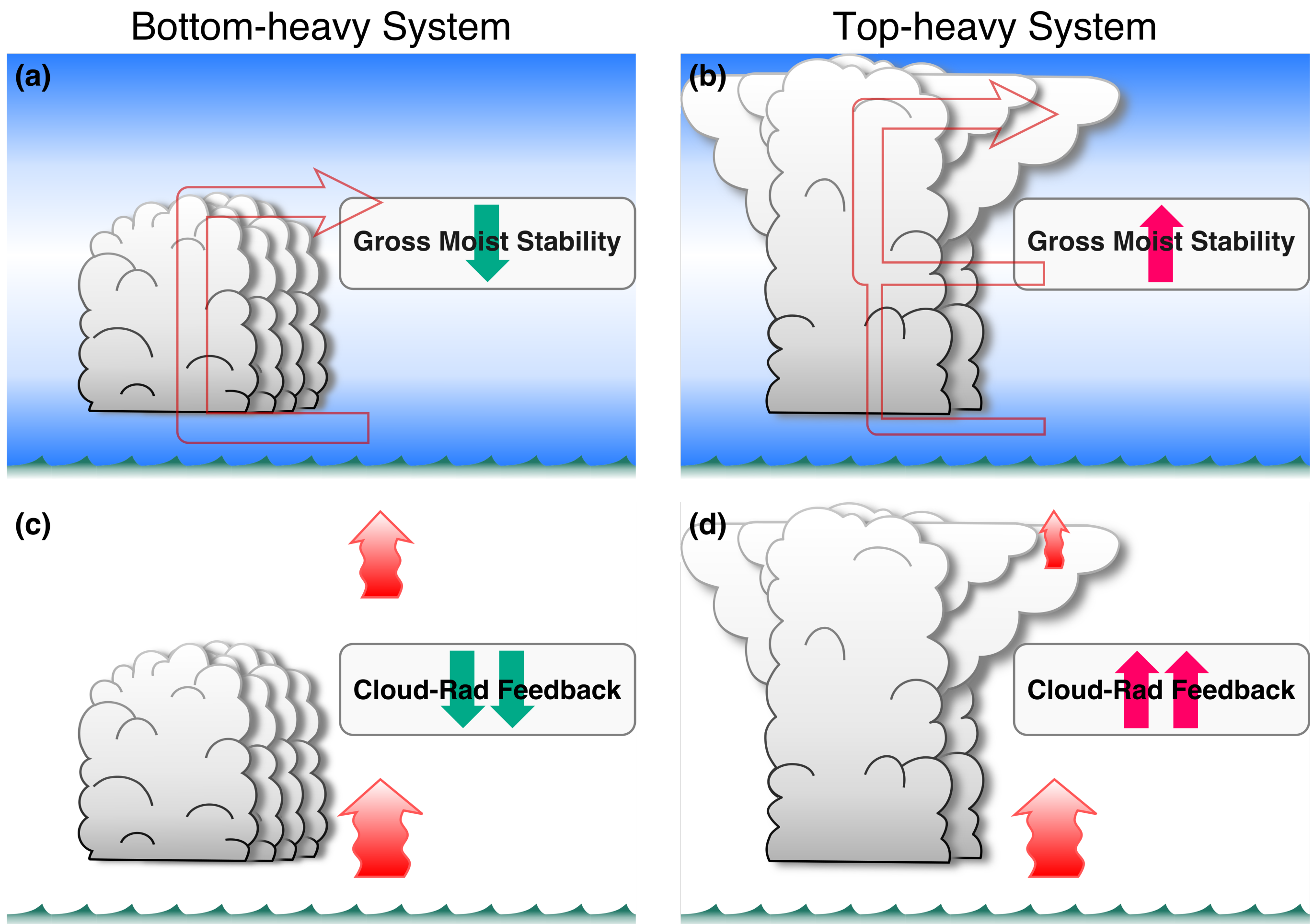


$$RH = \langle q \rangle / \langle q_s \rangle$$



Adames and Wallace (2015)

Radiation and GMS in the MJO



TCs as moisture modes.

Montgomery et al. (2010, *Atmos. Chem. Phys.* **10**, 9879-

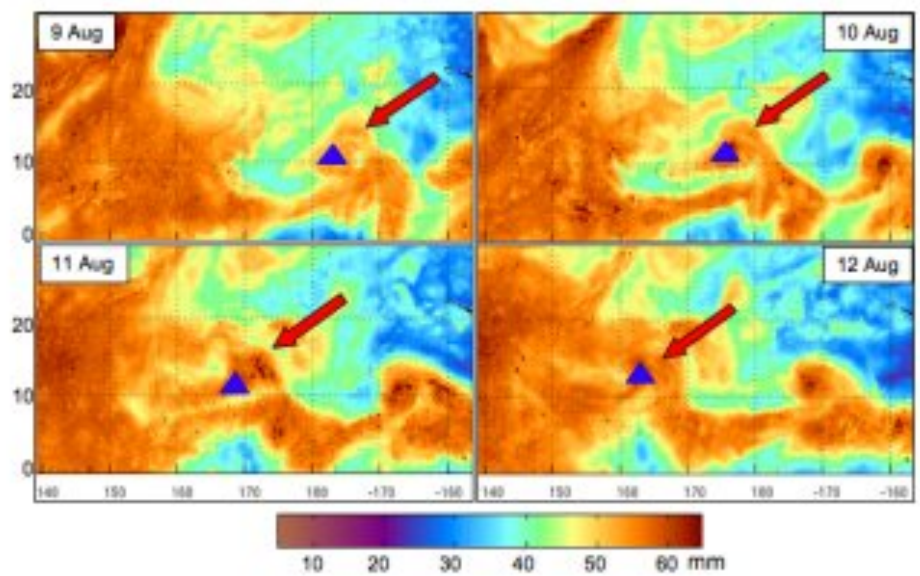


Fig. 6. Four-day time series of CIMMS Morphed TPW valid at 12:00 Z each day. Red arrows point towards the cat's eye region of the easterly wave (i.e., the wave pouch), which is hypothesized by DMW09 to be an area of increased moisture in the low to mid-troposphere and which helps protect the proto-vortex from lateral intrusions of dry air. The blue triangles indicate the position of the sweet spot as diagnosed in the GFS FNL at the 925 hPa level.

A current theory of tropical cyclogenesis, known as ”marsupial” (Dunkerton et al. 2009, Atmos. Chem. Phys) holds that the incipient cyclone is essentially a blob of moist air that needs to be protected by closed streamlines against dry air advection.