Understanding Essential Physics of the MJO

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Acknowledge Fei Liu
OUTLINE

1. Current status and science issues
2. Observed MJO characteristics
3. A unified theoretical model
4. The model simulated MJO
5. Critical roles of the Frictional Convergence (FC) feedback
6. Roles of moisture feedback
7. Propagation mechanism
8. Instability mechanism
9. Conclusion and discussion
1. Current status of modeling and understanding of MJO
Vertical Structure and Diabatic Processes of the MJO: *Global Model Evaluation Project*
MJO Task Force/YOTC and GASS 2012

Lag-regression of rainfall with Indian Ocean base point (70-90E; 5S-5N)
20-100day filtered dash line – 5 m/s

Jiang et al. 2015
MJO Theories

- Equatorial Wave-CISK (Lau and Peng 1987; Hendon 1988)
- Evaporation-wind feedback (Emanuel 1987; Neelin et al 1987, Wang 1988a)
- Moisture mode theory (Raymond and Fuch 2009, Sobel and Maloney 2012, 2013)
Processes/mechanisms

Shallow convection-BL circulation interaction (Johnson et al. 1999, Lin et al. 2004, Kikuchi and Takayabu 2004);


The diverging views presented above suggest that our knowledge and understanding the essence of the MJO remains elusive.

What are the essential features of the MJO that a theory must explain?
2. Observed MJO Characteristics:
Defining theoretical targets
1. Wave number one zonal circulation coupled with large scale of convective anomalies.
2. Slow eastward propagation gives rise to a 40-50 day spectral peak
3. Development over IO and decay east of dateline
4. Low SLP leads convective anomalies

Madden and Julian 1972, reproduced by McPhaden
Idealized MJO Animation


Courtesy: Jon Gottschalck
Observed structure of MJO

(a) Observation (EC Interim)

850 hPa

(d) Observation (EC Interim)

200 hPa
The models-simulated MJOs were made by 7 best propagating models and 7 worst propagating models selected from the 24 GCMs that participate in the MJOTS/GASS global model assessment project (Jiang et al. 2015).
Three-Dimensional Structure of the MJO

A mixed R-K wave structure and PBL convergence leading major convection

Wang (2005)
Observed MJO Characteristics
(Theoretical Targets)

1. Coupled convection and mixed Kelvin and Rossby waves structure. Horizontal structure: Coupling mechanism
2. Slow eastward propagation leading to irregular 30-60 days oscillation. Oscillation mechanism
3. Amplification/decay over the warm (cold) ocean. Instability mechanism
4. Backward tilted baroclinic structure with PBL moisture convergence leading convective anomalies. Vertical structure
5. Planetary scale circulation and a large scale of convective complex. Scale selection.
6. Coupling with ocean mixed layer Air-sea interaction
(a) Why does the MJO possess a mixed Kelvin-Rossby wave structure and how could Kelvin and Rossby waves, which propagate in opposite directions, couple together with convection and select eastward propagation?

(b) What gives rise to slow eastward propagation speed (about 5 m/s) and yield the 30-60 day periodicity?

(c) What mechanisms intensify MJO in the warm oceans against dissipation?
3. A Unified Theoretical Model for Essential Dynamics of MJO

--Hoskins and Wang 2006: Large scale dynamics, Chapter 9 in “Asian Monsoon”, Ed. B. Wang, Praxis-Springer
Physical Consideration

(1) The model must be derived from the first principles with reasonable/justifiable assumptions.

(2) The model is designed to include only the essential processes to MJO dynamics.

(3) The coupled convection and Kelvin-Rossby wave structure implies the free tropospheric wave dynamics and interactive heating should be described by the model.

(4) The eastward shift of the BL convergence compared to free tropospheric convective heating indicates the necessity to include BL dynamics.
Fundamental Large-Scale MJO dynamics

- Low-Frequency Equatorial Waves
- Convective Latent Heating
- Moisture Feedback
- Boundary Layer Dynamics
- Moisture (MSE) Distribution

Table:

<table>
<thead>
<tr>
<th>Land-sea Distribution</th>
<th>Climatological SST</th>
<th>Surface Heat Flux</th>
</tr>
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<tbody>
<tr>
<td>Lower boundary forcing</td>
<td></td>
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</table>
The unified model extends the Matsuno-Gill model by incorporating moisture feedback to precipitation heating and a trio-interaction among low-frequency equatorial waves, boundary layer dynamics, and precipitation heating described by a suit of simplified convective parameterization.
Vertical structure: Two-layer free atmosphere with a barotropic PBL

\[ \omega_0 \]

\[ \begin{align*}
\Delta p & \quad u_1, v_1, \phi_1 & \quad \bar{q}_1 \\
\Delta p & \quad u_3, v_3, \phi_3 & \quad \bar{q}_3 \\
\text{PBL} & \quad u_b, v_b & \quad \bar{q}_e
\end{align*} \]

\[ P_0 = 100mb \]
\[ P_1 = 300mb \]
\[ P_2 = 500mb \]
\[ P_3 = 700mb \]
\[ P_e = 900mb \]
\[ P_s = 1000mb \]

\[ - yv_b = -\phi_{bx} - Eu_b \]
\[ yu_b = -\phi_{by} - Ev_b \]
\[ \frac{H_b}{H_T} (u_{bx} + v_{by}) + w_b = 0 \]

PBL equations
One and half layer model for MJO (nondimensional)

\[ u_t - yv + \phi_x = -\varepsilon u \]

\[ yu + \phi_y = 0 \]

\[ \phi_t + u_x + v_y = -\mu \phi - P \]

\[ q_t + \tilde{Q}(u_x + v_y) = +\bar{Q}_s W_b - P + Ev \]

Boundary layer Ekman Pumping:  \( \text{(Wang and Rui 1990)} \)

\[ W_b = \frac{H_b}{H_T} (d_1 \nabla^2 \phi + d_2 \phi_x + d_3 \phi_y) \]
Three types of simplified cumulus parameterization

Simplified Betts-Miller parameterization (Frierson et al. 2004):

\[ P_r = \frac{(q + a_0 F)}{t} \]

Simplified Kuo- parameterization (Wang 1988):

\[ P_r = b(\overline{QD} + \overline{Q_b} dD_b) \]

Wave activity flux parameterization (Majda and Stechmann 2009):

\[ P_t = rq \]

Two types of model structure: Without and with PBL frictional convergence feedback
Climatological mean 1000 hPa specific humidity (shading) and sea surface temperature (SST, contour). The specific humidity is scaled by $10^{-3}$.
The absolute humidity over tropical ocean decays exponentially with a water vapor scale height $H_1$ (about 2.2 km) (Tomasi 1984).

$$q(p) = q_s \left( \frac{p}{p_s} \right)^m$$

$$m = \frac{H}{H_1}$$

Wang 1988

Observed over EIO, EWP and EEP. The black curve shows the vertical profile used as basic-state specific humidity in the unified model when the surface specific humidity is the same as that over the EIO.
Basic state MSE: Energy source for MJO motion

Tomasi (1984): basic-state atmospheric absolute humidity decays exponentially with height with a water vapor scale height $H_1$ (normally about 2.2 km).

\[ q(p_1, p_2) = q_0 \frac{(p_2^m p_1^m)}{m(p_2^m p_1^m)} \quad m = \frac{H}{H_1} \]

\[ q_0(SST) = (0.94 \ SST(°C) \ 7.64) \times 10^{-3} \]

Wang (1988)
The model framework integrate the following known mechanisms/processes

- **Equatorial Wave-convection interaction** (Lau and Peng 1987; Hendon 1988)


- **Evaporation-wind feedback** (Emanuel 1987; Neelin et al 1987, Wang 1988a)

- **Convection-moisture feedback** (or moisture mode) (Raymond and Fuchs 2009, Sobel and Maloney 2012, 2013)

4. The MJO simulated by the unified model
Numerical Methods

1. Initial value solution with nonlinear heating. The model is solved in an aqua-planet channel between 40°S and 40°N on a spherical coordinate. The typical values for the model parameters used in numerical calculations are listed in Table 1. The numerical scheme derived by Lin and Rood (1997) is adopted. Transient BL is used.

2. Normal mode solution with linear heating. For zonally propagating modes using meridional expansion of parabolic cylinder functions, N=3. Only the Kelvin and Rossby waves are kept in this model. Sensitivity experiments show that inclusion of higher meridional modes does not affect the results appreciably. The eigenvalues and eigenvectors are calculated through the matrix inversion for each wavenumber.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Typical value utilized here</th>
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<tbody>
<tr>
<td>$p$</td>
<td>Half-pressure depth of the free atmosphere</td>
<td>400 hPa</td>
</tr>
<tr>
<td>$P_2$</td>
<td>Pressure at level 2</td>
<td>500 hPa</td>
</tr>
<tr>
<td>$C_0$</td>
<td>Dry gravity wave speed of the baroclinic mode</td>
<td>50 m s$^{-1}$</td>
</tr>
<tr>
<td>$R$</td>
<td>Gas constant for dry air</td>
<td>287 J K$^{-1}$ kg$^{-1}$</td>
</tr>
<tr>
<td>$L_c$</td>
<td>Latent heat of condensation at 0 °C</td>
<td>$2.5 \times 10^6$ J kg$^{-1}$</td>
</tr>
<tr>
<td>$<em>^</em>$</td>
<td>Dimensional Horizontal diffusion coefficient</td>
<td>1.0 $10^5$ m$^3$ s$^{-1}$</td>
</tr>
<tr>
<td>$<em>^</em>$</td>
<td>Dimensional Reighley friction</td>
<td>(7 day)$^{-1}$</td>
</tr>
<tr>
<td>$<em>^</em>$</td>
<td>Dimensional Newtonian cooling coefficient</td>
<td>(7 day)$^{-1}$</td>
</tr>
<tr>
<td>$<em>^</em>$</td>
<td>Convective adjustment time</td>
<td>2.0 h</td>
</tr>
<tr>
<td>$E^*$</td>
<td>Dimensional Ekman number in the boundary layer</td>
<td>3 $10^5$ s$^{-1}$</td>
</tr>
<tr>
<td>$m$</td>
<td>Density scale height/water vapor density scale height</td>
<td>3.45</td>
</tr>
<tr>
<td>$SST$</td>
<td>Sea surface temperature</td>
<td>29.5 °C</td>
</tr>
<tr>
<td>$b$</td>
<td>Precipitation efficiency coefficient</td>
<td>0.9</td>
</tr>
<tr>
<td>$d$</td>
<td>Nondimensional boundary layer depth</td>
<td>0.25</td>
</tr>
<tr>
<td>$\bar{Q}$</td>
<td>$\bar{q}_3/(d_0)$</td>
<td>1.00</td>
</tr>
<tr>
<td>$\bar{Q}_e$</td>
<td>$\bar{q}_e/(d_0)$</td>
<td>2.03</td>
</tr>
<tr>
<td>$d_0$</td>
<td>$d_0 = \frac{2P_2C_pC_0^2}{pRL_c}$</td>
<td>0.008</td>
</tr>
</tbody>
</table>

Table. Parameters and their standard values used in the experiments.
Linear wave oscillation for the FC (dark), MF (blue), and FC-MF (red) models, respectively.
Horizontal structure of eastward-propagating wave one

Precipitation, pressure & Ekman pumping anomalies

a) FC model

b) MF model

c) FC-MF model

Shading:
Normalized precipitation anomalies
Contours: lower tropospheric pressure anomalies with positive
Blue thick contours the upward Ekman pumping with amplitude of 0.8.
MJO simulated with nonlinear heating in (a) Kuo- and (b) B-M Schemes

- Vertical structure: At the equator BL convergence leads precipitation.
- Propagation speeds:
  - Kuo: 11.84 m/s,
  - B-M: 3.02 m/s.
- The basic state SST is uniform 29.5°C.

BL divergence (color shading), lower troposphere geopotential height (dashed contours) and precipitation (solid contour).
Horizontal structure of simulated MJO

Coupled Kelvin-Rossby wave structure (The Gill pattern)

winds (vectors), zonal wind (contours) and precipitation rate (shading).
Three-Dimensional Structure of the MJO

A mixed R-K wave structure and
PBL convergence leading major convection

Wang (2005)
The unified model, under two different cumulus parameterization schemes, produces the same essential characteristic of the MJO: An equatorial planetary scale unstable system moving eastward slowly (3~11 m/s) with a coupled Kelvin-Rossby wave structure and BL convergence leading precipitation.

To a large extent, the MJO mode can be perceived as a convectively coupled Kelvin-Rossby wave package.
5. Critical roles of the FC feedback in MJO structure and eastward propagation
Could the moisture feedback process make the Kelvin and Rossby waves couple together and propagate eastward?
The PBL frictional feedback (a) couple Kelvin and Rossby waves; (b) makes the damping moisture modes growing and (c) moving eastward slowly.
Equatorial boundary layer Dynamics

\[
\frac{\partial u_b}{\partial t} + \beta y v_b = -\frac{\partial \phi_e}{\partial x} - E u_b \\
\frac{\partial v_b}{\partial t} - \beta y u_b = -\frac{\partial \phi_e}{\partial y} - E v_b
\]

Barotropic boundary layer model

\[
D = -\frac{E}{E^2 + \beta^2 y^2} \left( \nabla^2 \phi_e + \beta u_b + \frac{\beta^2}{E} y v_b \right)
\]

- Due to change of sign of the Coriolis force at the equator, equatorial boundary layer dynamics differs from the quasi-geostrophic Ekman theory.
- The equatorial frictional convergence is determined by the Laplacian of the pressure at the top of the boundary layer and the strengths of the eastward and poleward surface winds.
Boundary layer convergence associated with Kelvin Wave and Rossby Wave

- Both $K$ and $R$ waves create a **unified boundary layer convergence** field
  1. In the easterly phase, leading the major convective heating,
  2. creating east-west moisture asymmetry, and
  3. Resulting in vertical backward tilted structure.
How could Kelvin and Rossby waves, which propagate in opposite directions, be coupled together with convection and select eastward propagation?

Analysis of the BL moisture convergence reveals that when convective heating excites Rossby wave westerly to its west and Kelvin wave easterly to its east, both the Rossby wave and Kelvin wave induce BL convergences to occur at the easterly phase, thereby the combined BL moisture convergence field yields a maximum located to the east of the major convective heating center.

The BL moisture convergence feeds back to convection and couples the Kelvin and Rossby waves together, selecting eastward propagation.
6. Important roles of moisture feedback
In the presence of the frictional feedback, the moisture feedback tends to slow down the eastward propagation, and reduce the growth rate.
Horizontal structure of simulated MJO

- MJO shape parameter: the ratio of the zonal extent of the MJO easterly versus westerly averaged between 5°S and 5°N. 3:1
- MJO Westerly intensity parameter: the ratio of the maximum low-level westerly speed $U_{max}$ vs. the maximum easterly speed $abs(U_{min})$ averaged over 5°S and 5°N. 1.3 vs 0.64

winds (vectors), zonal wind (contours) and precipitation rate (shading).
In the presence of the frictional feedback, the moisture feedback tends to
(a) reinforces the Kelvin and Rossby wave coupling, resulting in a more realistic horizontal structure,
(b) enhance the Rossby wave response, slow down the eastward propagation, and
(c) reduce the growth rate.
7. MJO propagation speed
When SST increases, the basic state moisture content and wave-induced precipitation heating rate increase, thus the effective static stability decreases. 50 to 14 at SST = 30°C.

The coupling of the Kelvin and Rossby waves by FC feedback provides a mechanism to further slow down the eastward propagation. 14 to 8 m/s.
Dependence of MJO eastward propagation speed on MJO westerly strength

Enhanced Rossby wave component further reduce the eastward propagation speed
8. MJO Instability Mechanism
The MJO instability in both the Kuo- and B-M simulations depends on the basic state SST or basic state moist static energy, which is the ultimate heating energy source for the MJO instability.
Energy generation and precipitation-BL convergence relationship

potential energy (gpe), low-level geopotential height (z), precipitation (pr), boundary layer convergence (BL_cv) and moisture anomalies (q).

- The generation of EAPE is determined by the negative covariance between Pr and z.
- Pr occurs in the negative z and BL convergence, which leads Pr.
- The growth rate is inversely related to the phase difference between the maximum BL convergence and maximum precipitation in the B-M scheme.
Conclusion

1. The unified model produces the essential large-scale characteristic of the observed MJO: An equatorial planetary scale unstable system moving eastward slowly (~5 m/s) with a rearward tilted, coupled Kelvin-Rossby wave structure.

2. It is the BL Frictional Convergence (FC) feedback that couples Kelvin and Rossby waves with convective heating and selects a preferred eastward propagation.

3. In the presence of the FC feedback, the moisture feedback in the B-M scheme enhances the Rossby wave response, thereby slowing down eastward propagation and leads to a more realistic horizontal structure.
Conclusion

4. The eastward propagation speed is related to the relative intensity of the MJO westerly and the SST that controls effective static stability through altering convective heating.

5. MJO intensification/decay is fundamentally controlled by the SST or basic-state moist static energy. The FC feedback generates CAPE and EAPE, intensifying MJO, while the moisture feedback tends to reduce the growth rate by decreasing the CAPE releasing rate.

6. Model representation of the interaction between the convection and BL FC may hold key to realistic simulation of MJO. The cumulus parameterization scheme may affect propagation through changing the MJO horizontal structure.
How could Kelvin and Rossby waves, which propagate in opposite directions, be coupled together with convection and select eastward propagation?

Analysis of the BL moisture convergence reveals that when convective heating excites Rossby wave westerly to its west and Kelvin wave easterly to its east, both the Rossby wave and Kelvin wave induce BL convergences to occur at the easterly phase, thereby the combined BL moisture convergence field yields a maximum located to the east of the major convective heating center.

The BL moisture convergence feeds back to convection and couples the Kelvin and Rossby waves together, selecting eastward propagation.
What gives rise to slow eastward propagation speed (about 5 m/s) that yields the 30-60 day oscillation?

The slow eastward propagation is primarily attributed to:
(a) warm sea surface temperature (SST),
(b) the degree of coupling of Kelvin and Rossby waves,
(c) the relative intensity of the Rossby wave wetserly.

The eastward propagation speed is found to be inversely related to the relative strength of the Rossby vs. Kelvin wave component in its horizontal structure.

The moisture feedback in the B-M parameterization can slow down eastward propagation because it favors precipitation heating occurring further away from the equator that would enhance the vorticity generation and Rossby wave response.
What mechanisms intensify MJO in the warm oceans against dissipation?

SST or basic-state moist static energy has a fundamental control on MJO intensification/decay.

The growth rate in the B-M simulation is inversely proportional to the phase difference between the maximum precipitation and the maximum BL moisture convergence.

Cumulus parameterization scheme and the parameters embedded in the schemes can change the phase relationship between the BL convergence and precipitation, thus changing the growth rate.

The FC feedback generates Convective Available Potential Energy (CAPE) and eddy available potential energy for a developing MJO mode, while the moisture feedback can reduce the growth rate by decreasing the releasing rate of CAPE.
Implications

The MJO propagation and amplification are sensitive to the cumulus parameterization. Even within the same parameterization scheme (B-M), they depend on parameters (such as the convective adjustment time).

This is because different schemes (parameters) may produce different horizontal and vertical structures of the MJO.

This may explain why a variety of MJO behaviors have been produced in the GCMs and tuning parameters or change of cumulus parameterization often works well to improve the MJO simulation.
END
Any Comments?
Skeleton Model:

Heating parameterization: wave activity flux

\[ u_t - yv + \phi_x = 0 \]
\[ yu + \phi_y = 0 \]
\[ \phi_t + u_x + v_y = -P \]
\[ q_t + \tilde{Q}(u_x + v_y) = -P + Q_s W_p \]
\[ P_t = rq \]

P is proportional to synoptic wave activity.

Majda and Stechmann 2009:
Wave activity parameterization
No PBL dynamics.
Two family of Neutral modes, one eastward and other westward.
Nearly non-dispersive.
Frictional Skeleton model
(effects of frictional convergence feedback)

\[ u_t - yv + \phi_x = 0 \]
\[ yu + \phi_y = 0 \]
\[ \phi_t + u_x + v_y = -P \]
\[ q_t + \tilde{Q}(u_x + v_y) = -P + \tilde{Q}_s W_b \]
\[ P_t = rq \]

\[ W_b = \frac{H_b}{H_T} (d_1 \nabla^2 \phi + d_2 \phi_x + d_3 \phi_y) \]

Liu and Wang 2012:
Skeleton model with PBL
The CFC mechanism generate unstable modes, select aestward propagation
Preferred planetary scale
MJO – a Dynamic Definition

An equatorial planetary scale circulation system coupled with a multi-scale convective complex moves eastward slowly with a rearward tilted, mixed Kelvin-Rossby wave structure.

MJO also has remarkable seasonality, couples with ocean mixed layer, and involves multi-scale interaction in its convective complex.
Roles of Frictional moisture feedback

(a) couples K and R waves and convection heating, explaining MJO horizontal structure;
(b) Creates upward and westward tilt of vertical motion (vertical structure)
(c) generates E-W moisture asymmetry that establishes convective instability to the east of MJO convection, selecting eastward propagation.
(d) generates instability in a stable regime to wave-CISK.
(e) slowing down eastward propagation due to coupling Rossby and Kelvin waves.

Other mechanisms for slow eastward propagation: reduction of effective static stability, air-sea interaction
Comparison of the simulated MJO with the B-M scheme (a) without and (b) with boundary layer dynamics. Precipitation rate (color shading) and lower troposphere geopotential height (contours). The contours start from -0.1 with an interval 0.1. The basic SST is uniform 29.5°C.
The triangular wedge-shape precipitation coincides with the regions of positive column integrated moisture anomaly, which is well correlated with the BL moisture convergence.
Moisture Feedback  
(Betts-Miller parameterization)

\[ u_t - yv + \phi_x = 0 \]
\[ yu + \phi_y = 0 \]
\[ \phi_t + u_x + v_y = -P \]
\[ q_t + \tilde{Q}(u_x + v_y) = -P + E + \tilde{Q}_s W_b \]

\[ P_r = \frac{1}{\tau} (q + \alpha \Phi) \]

\[ W_b = \frac{H_b}{H_T} (d_1 \nabla^2 \phi + d_2 \phi_x + d_3 \phi_y) \]

- A simplified Betts-Miller parameterization:
- Inclusion of moisture mode
- With or without PBL dynamics

\[ P_r = \frac{\delta}{\tau} (q - \tilde{q}(T)) \]
\[ \tilde{q}(T) = \alpha \frac{C_p dp}{L_c g} T \]
Moisture-mode model
(Sobel and Maloney 2013)

Assumption: no wave dynamics
P is proportional to q

\[ u = \psi + \phi_x = F^U - c \eta \]

\[ yu + \phi_y = 0 \]

\[ \phi_t + u_x + v_y = -P + F^\psi - \mu \phi \]

\[ \int [q_t + \tilde{Q}(u_x + v_y) = -P + F^q + \tilde{Q}_x W_x + M(q)] \]

Instability: Zonal advection
Eddy Frictional PBL

[\frac{\partial W}{\partial t} + U \frac{\partial W}{\partial x} = -\tilde{M} P + E - (1 - \tilde{M}) R + k_w \frac{\partial^2 W}{\partial x^2} - \frac{\partial}{\partial y} u'' W'' \cdot]

\( k_w = 0 \)

0.02
0.01
0
-0.01
-0.02
0
5
10
15
20
growth rate (1/d)
zonal wave number

growth rate
phase speed

FIG. 2. Phase speed and growth rate for zonal moisture diffusivity (left) \( k_w = 0 \) and (right) \( k_w = 1 \times 10^4 \text{ m}^2 \text{ s}^{-1} \).
Frictional coupled moist K-R wave model: Simplified Kuo parameterization

\[ u_t - yv + \phi_x = 0 \]
\[ yu + \phi_y = 0 \]
\[ \phi_t + u_x + v_y = -P \]
\[ q_t + \tilde{Q}(u_x + v_y) = -P + E + \tilde{Q}_s W_b \]
\[ W_b = \frac{H_b}{H_T} (d_1 \nabla^2 \phi + d_2 \phi_x + d_3 \phi_y) \]

- PBL dynamics and Convection-Frictional Convergence (CFC) feedback included,
- A simplified Kuo-type parameterization: Moisture conservation
- No moisture feedback mode

Wang and Rui 1990, Linear Instability
Wang and Li 1994. Positive only (nonlinear) heating, initial value solution.
Frictionally coupled moist K-R wave instability

(a) Growth Rate (1/day)
(b) Phase Speed (m/s)
(c) Upward motion at $p_e$
(d) Observed winds & convergence

Coupled K-R Structure
BL upward motion leads convection

Slow eastward movement

Hendon and Salby 1994
Horizontal structures of equatorial Kelvin wave (left) and most trapped equatorial Rossby wave (right) in the presence of boundary layer damping: (upper) geopotential and (lower) boundary layer divergence. The vectors in upper panel denote the zonal wind near the equator. See Wang and Rui (1990) for details of calculation.
PBL-Moistening creates convectively unstable stratification ahead of MJO convection

MJO equivalent potential temp.

\[ \theta'_e \ 1000 \text{~hPa} - \theta'_e \ 500 \text{~hPa} \]

Hsu and Li, 2012