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Tropical wave modes modified by semi-empirical parameterizations of moisture

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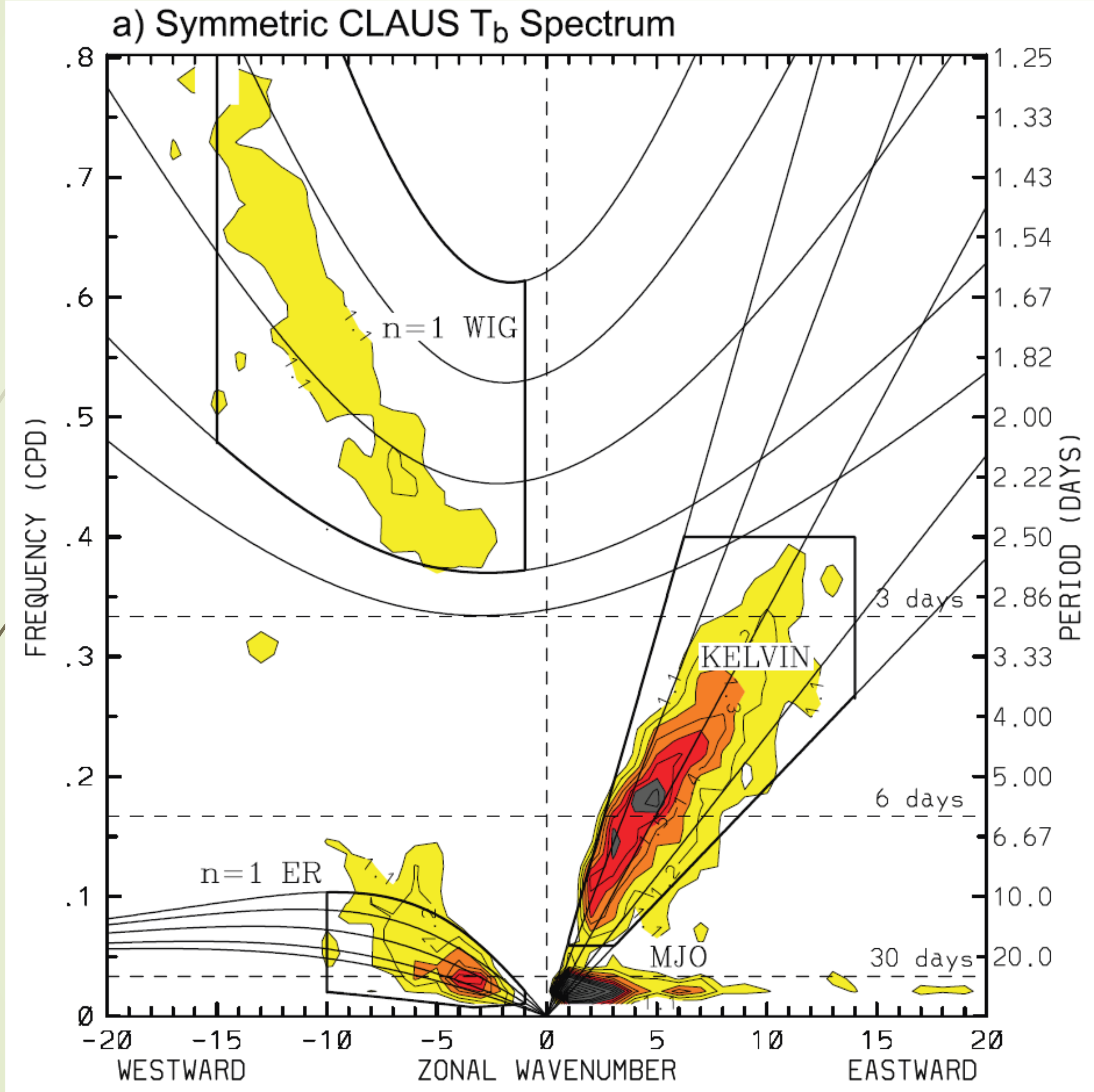
“Separation” between MJO and classical waves



Kiladis et al. 2009

Modified dynamic modes

- Moisture processes are considered in the dynamic equations

  convergence in the planetary boundary layer; surface heat flux;

  convectively coupled Kelvin-Rossby wave; multi-scale interaction;

  ocean-atmosphere interaction; …

- Take Kang et al. (2013) as an example

$$\frac{\partial u}{\partial t} - \beta y v + \frac{\partial \phi}{\partial x} = -\kappa \nabla^2 u; \qquad \beta y u + \frac{\partial \phi}{\partial y} = 0$$

$$\frac{\partial \phi}{\partial t} + C_0^2 \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right) = \boldsymbol{Q} - N\phi$$

The heating term
Related to moisture processes

Moisture mode

- The modes determined by the moisture tendency
- Take Sobel and Maloney (2012) for an example

Time tendency of moisture

↓

$$\frac{dW}{dt} = \boldsymbol{\frac{\partial W}{\partial t}} + u\frac{\partial W}{\partial t} = -\widetilde{M}P + E - (1 - \widetilde{M})R + k_W\frac{\partial^2 W}{\partial x^2}$$

$$\hat{u}(x,t) = \int G(x|x')[P(x',t) - R(x',t)]dx'$$

Motivation

- Tropical wave modes under the influence of dynamical processes and the moisture processes;
- The momentum tendency and the moisture tendency are both considered in a uniform theoretical framework;

Shallow-water system

$$\frac{\tilde{\partial}\vec{u}}{\tilde{\partial}t} + \beta y\vec{k} \times \vec{u} = -\nabla\phi,$$

$$\frac{\tilde{\partial}\phi}{\tilde{\partial}t} + c^2\nabla \cdot \vec{u} = Q,$$

$$\frac{\tilde{\partial}W}{\tilde{\partial}t} + u\frac{\partial\overline{W}}{\partial x} + v\frac{\partial\overline{W}}{\partial y} - M\nabla \cdot \vec{u} = m_b + E - P,$$

$\vec{u}$ is the horizontal velocity, ϕ is the geopotential,
c is the gravity wave speed, M is the moisture stability.

E denotes evaporation, P denotes precipitation
$W = \int \frac{q}{g} dp$, Q=Q(P).

m_b is the moisture source due to Ekman pumping.

Parameterization for evaporation

The traditional bulk formula

$$E = \rho_0 C_d |\overline{U} + u| (q_s - q_a)$$

Assuming a dominant mean westerly wind (positive $\overline{U}$) in the background, for ex., from the tropical Indian Ocean to the western Pacific Ocean, $\overline{U}$ is positive and overwhelms u. Thus, $|\overline{U} + u| = \overline{U} + u$, regardless of the direction of u.

$$E = bu,$$

$$b = \rho_0 C_d (q_s - q_a)$$

Parameterization for precipitation

- convective precipitation due to the moisture transfer from the PBL

$$-\mu \cdot \nabla \vec{\mathrm{u}}_b \cdot \overline{W}$$

- large-scale precipitation proportional to the water vapor content in the air column

$$d_3 W$$

- precipitation due to convectively available potential energy

$$d_4 \phi$$

Parameterization for precipitation

$$\mathrm{P} = -\mu \nabla \vec{u}_b \cdot \overline{W} + d_3 W + d_4 \phi,$$

According to Wang and Li (1994)

$$\nabla . \vec{\mathrm{u}}_b = -\frac{(\nabla^2 \phi + \beta u + \beta \delta v)}{\epsilon (1 + \delta^2)},$$

Finally, $P = -d_1 u - d_2 v + d_3 W + d_4 \phi,$

P is related to all state variables.

$$\mathrm{d}_1 = \frac{(1-\mu)\overline{W}\beta}{\epsilon(1+\delta^2)} \text{ and } \mathrm{d}_2 = \frac{(1-\mu)\overline{W}\beta\delta}{\epsilon(1+\delta^2)}.$$

Parameterized shallow-water system

$$\frac{\tilde{\partial} u}{\tilde{\partial} t} - \beta y v = -\frac{\partial \phi}{\partial x},$$

$$\frac{\tilde{\partial} v}{\tilde{\partial} t} + \beta y u = -\frac{\partial \phi}{\partial y},$$

$$\frac{\tilde{\partial} \phi}{\tilde{\partial} t} + c^2 \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) = -\delta_1 u - \delta_2 v + \delta_3 W + \delta_4 \phi,$$

$$\frac{\tilde{\partial} W}{\tilde{\partial} t} + u \frac{\partial \overline{W}}{\partial x} - M\nabla \cdot \vec{u}(x, y, t) = (b + d_1)u + d_2 v - d_3 W - d_4 \phi,$$

where $\delta_i = \frac{\mu}{\mu - 1} \gamma L d_i,\ i = 1, 2$ and $\delta_i = \gamma L d_i,\ i = 3, 4.$

Eigen-value problem

$$(1+i)\frac{\partial^2 V}{\partial y^2} + \left[\frac{\delta_1 y}{d_3 c} + i\left(\frac{\delta_3 \mathrm{b}}{c^2\beta}y + \frac{\delta_2}{c\sqrt{\beta c}}\right)\right]\frac{\partial V}{\partial y} - \left[(1+i)y^2 - \frac{\delta_4}{d_3}y^2 + i\frac{\delta_2 y}{c\sqrt{\beta c}}\right]V = \Lambda V,$$

$$\Lambda = -(1+i)\left(\omega^2 - k^2 + \frac{k}{\omega}\right) + \left[\gamma L\left(\frac{\delta_1\omega}{\delta_3 c} - \frac{Mk}{c^2}\right) + i\frac{\delta_3(b - \overline{W}_x)}{\omega\beta c^2}\right]\left(k - \frac{1}{\omega}\right) + \gamma L\frac{\delta_4\omega^2}{\delta_3}.$$

$$\Lambda = \Lambda_{\mathrm{d}} + \Lambda_{\mathrm{m}},$$

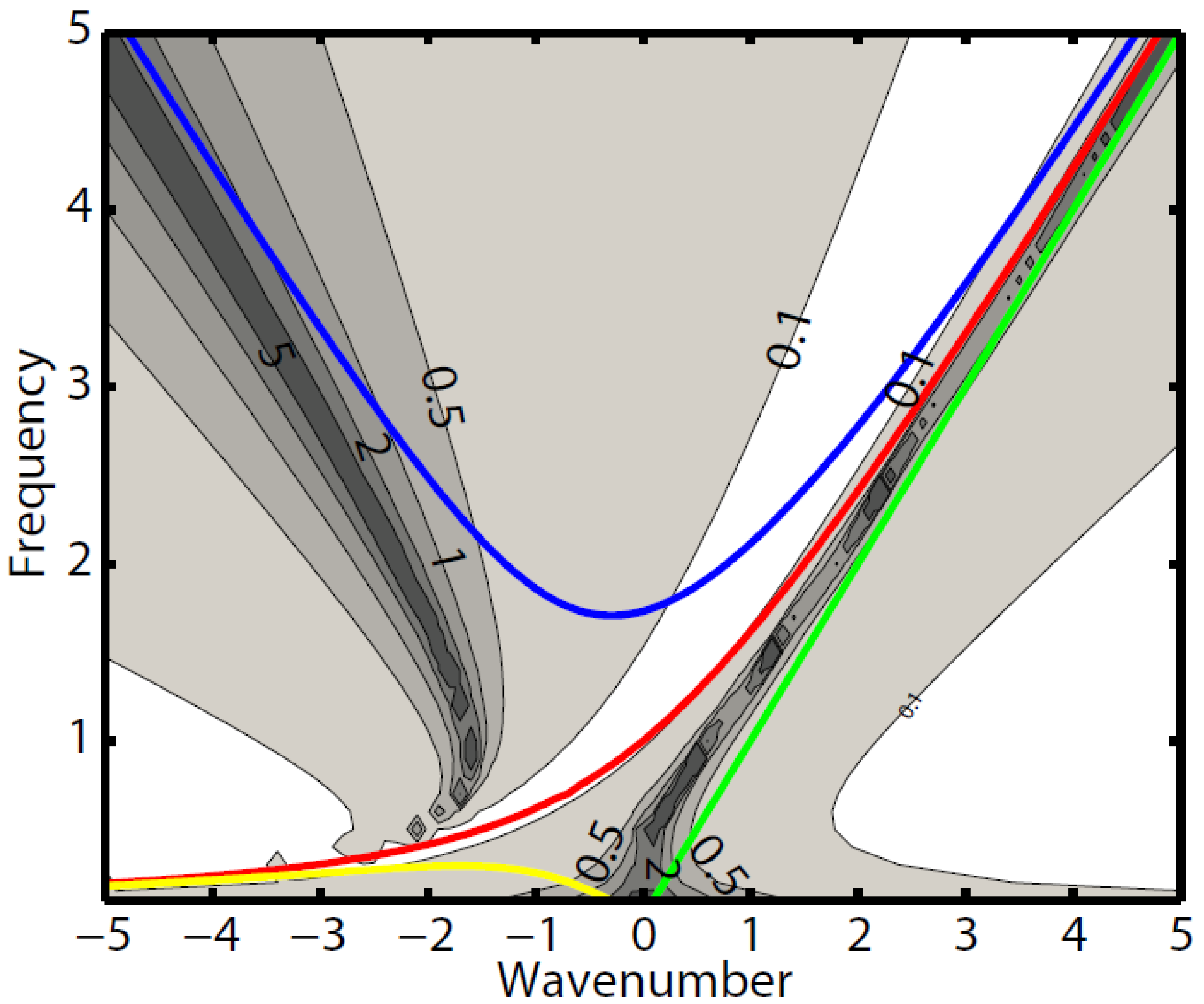
$$\Lambda_{\mathrm{d}} = -(1+i)\left(\omega^2 - k^2 + \frac{k}{\omega}\right),$$

$$\Lambda_{\mathrm{m}} = \left[\gamma L\left(\frac{\delta_1\omega}{\delta_3 c} - \frac{Mk}{c^2}\right) + i\frac{\delta_3(b - \overline{W}_x)}{\omega\beta c^2}\right]\left(k - \frac{1}{\omega}\right) + \gamma L\frac{\delta_4\omega^2}{\delta_3}.$$

Parameters

Parameter	Value	Parameter	Value
M	-3×10^{-5} kg m^{-2}	**b**	2.3×10^{-7} kg m^{-3}
c	50 m s^{-1}	$\bar{W}_x$	-4.4×10^{-8} kg m^{-3}
β	2.3×10^{-11} m^{-1} s^{-1}	$\bar{W}_y$	-1.7×10^{-6} kg m^{-3}
d_1	1.6×10^{-5} kg m^{-3}	δ_1	2.3×10^{-3} m s^{-2}
d_2	1.2×10^{-5} kg m^{-3}	δ_2	1.7×10^{-3} m s^{-2}
d_3	1.4×10^{-4} s^{-1}	δ_3	0.02 kg^{-1} m^{4} s^{-3}
d_4	2.7×10^{-7} kg m^{-4} s	δ_4	3.9×10^{-5} s^{-1}

Importance of moisture processes



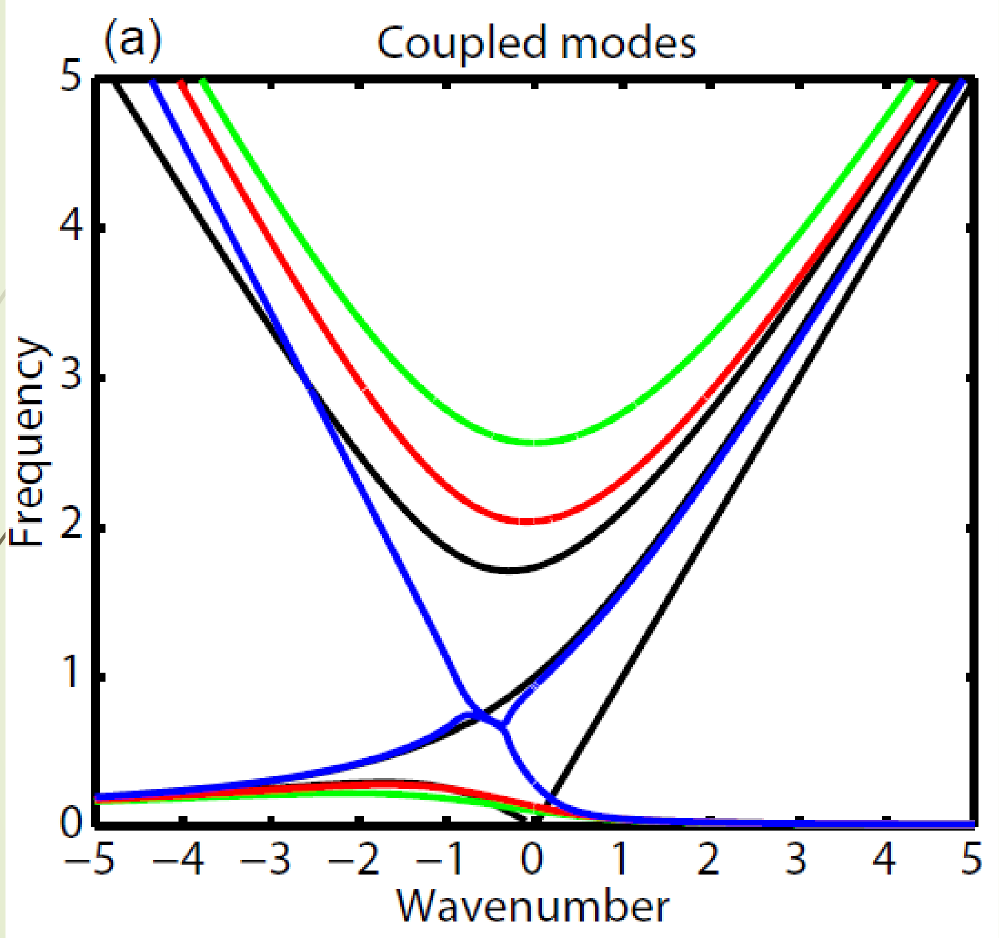
$$\Lambda = \Lambda_{\mathrm{d}} + \Lambda_{\mathrm{m}},$$

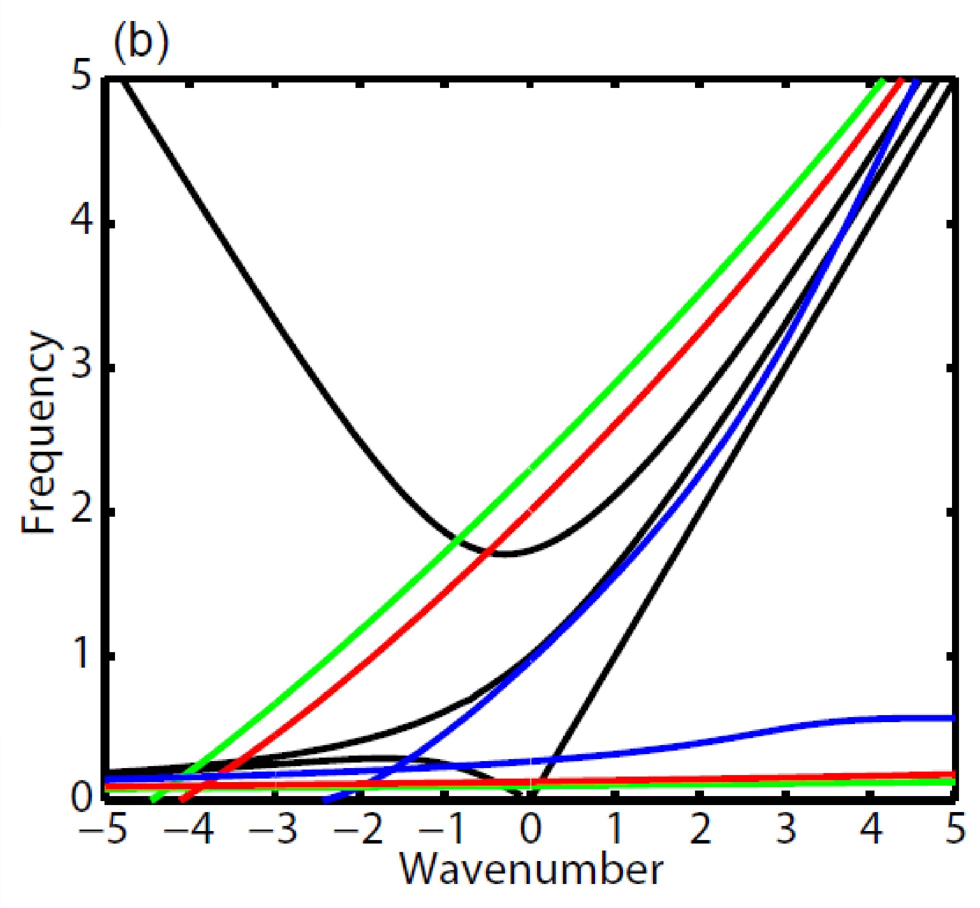
The ratio of

$$|\Lambda_m| \backslash |\Lambda_d|$$

When the ratio is large, moisture processes dominate

Dispersion relation

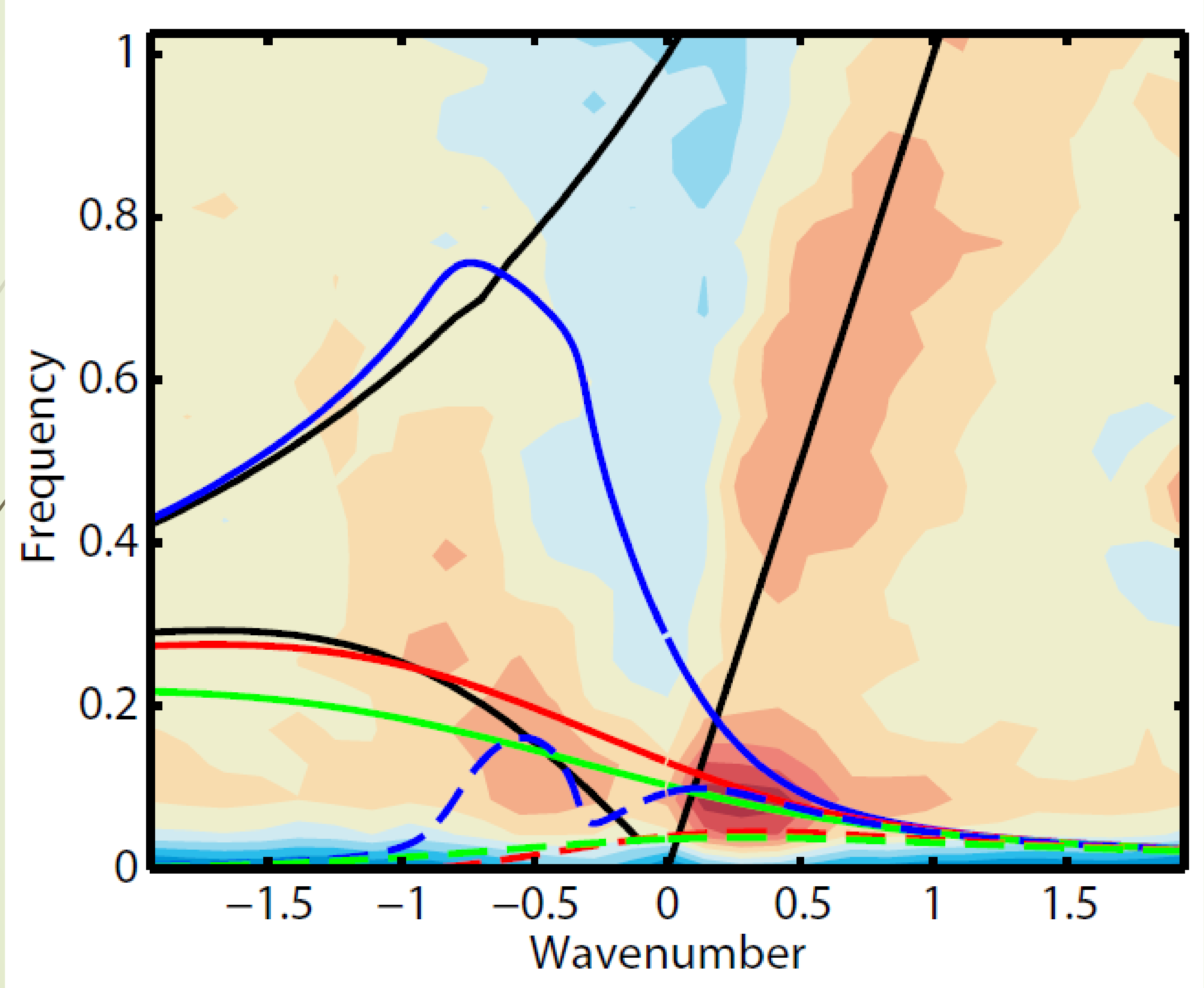




Black lines: classical dynamical waves;
Red lines: The second mode;

Blue lines: the first mode;
Green lines: the third mode.

The MJO domain



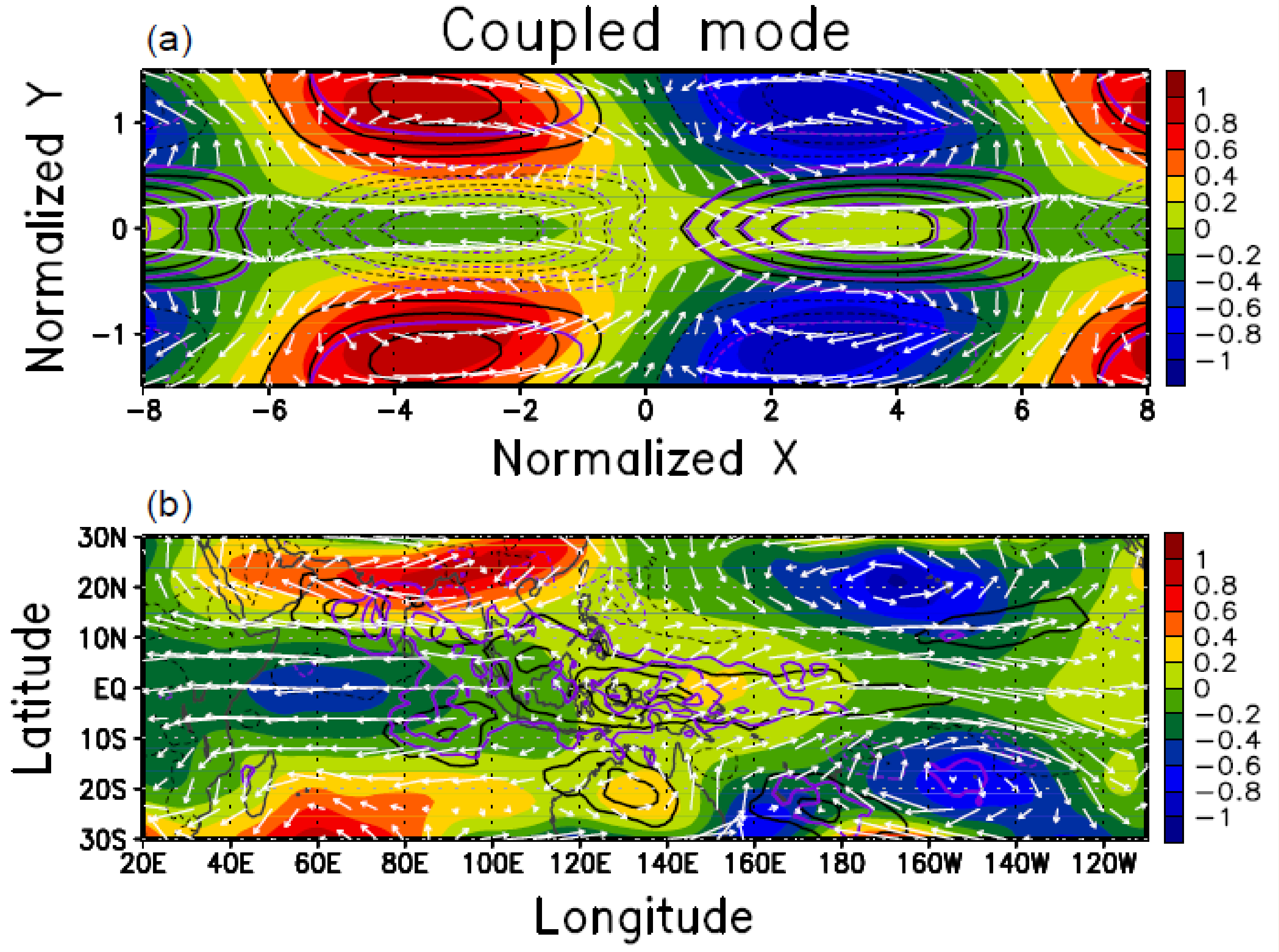
Black lines: classical dynamical waves

Blue lines: the first mode;

Red lines: The second mode;

Green lines: the third mode

Plan-view of the coupled mode



Colors ~ φ

Black contours ~ W

Purple contours ~ precipitation

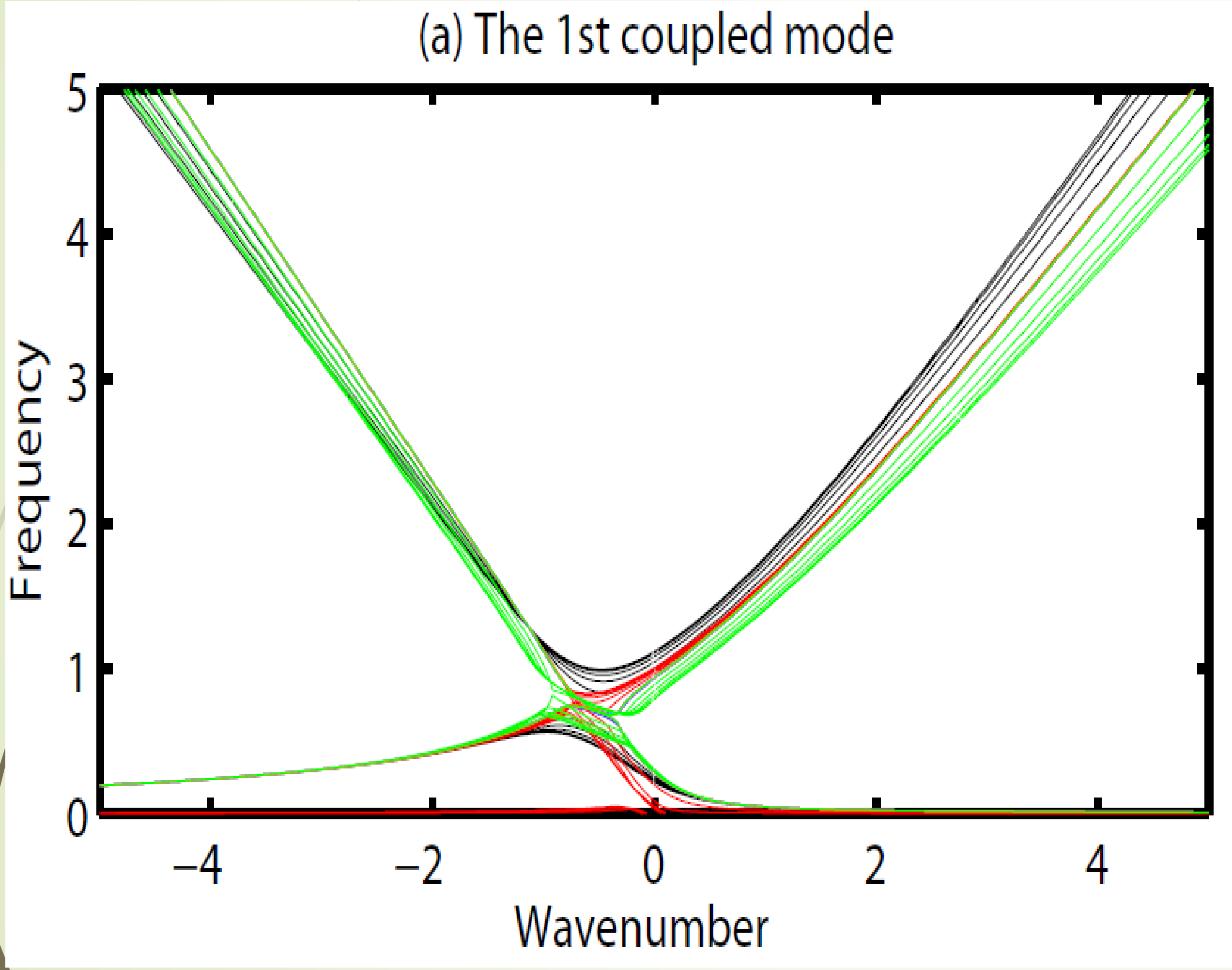
vectors ~ $\vec{u}$

Solid contours stand for positive anomalies

Dashed contours stand for negative anomalies

All variables are normalized with their own maximum

Parameter sensitivity



A parameter is perturbed by ±50% (from -50% to 50% with an interval of 10%) off their base values listed in the previous table.

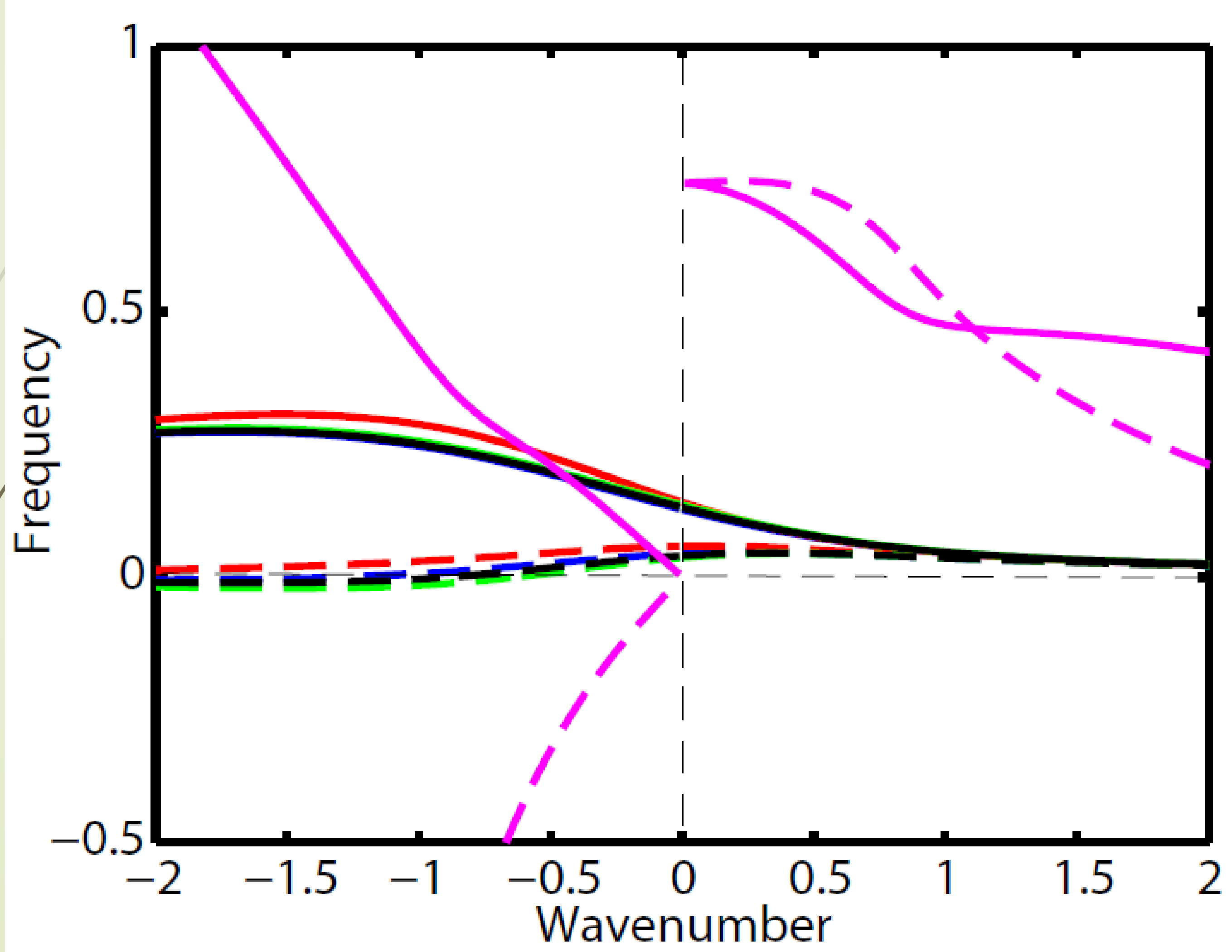
Black curves ~ d_1, δ1

Blue curves ~ d_2, δ_2

Red curves ~ d_3, δ_3

Green curves ~ d_4, δ_4.

Influence of different parameter



Black lines show the dispersion relation with all parameters.

Blue lines: d_1 and δ_1 are zero

Red lines: d_2 and δ_2 are zero

Purple lines: d_3 and δ_3 are zero

Green lines: d_4 and δ_4 are zero

Conclusions

- With an ideal and linearized shallow water system, the effect of moisture on tropical wave modes is analytically studied;
- The moisture tendency and the momentum tendency are both explicitly considered;
- The coupled dynamic-moisture mode is consistent with the observed MJO in both the spectral and physical domains;
- New modes related to moisture processes occur when the moisture tendency is considered.

Thanks!