A Trio-interaction Theory for Madden-Julian Oscillation

Bin Wang

Department of Atmospheric Sciences, University of Hawaii and Earth System Modeling Center, NUIST

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AMS 2018, Austin, 1-8 2018

The trio-interaction theory of MJO

(a) demonstrates the essential MJO physics is rooted in the trio-interaction among atmospheric heating, moisture, and dynamics (equatorial waves and BL);

(b) integrates all major possesses proposed in the existing theoretical MJO models developed over the past three decades and can accommodate a variety of simplified convective schemes;

(c) produces a planetary scale unstable MJO mode that not only propagates eastward slowly with a period of 30–60 days and but also exhibits a coupled Kelvin-Rossby wave structure with its major convection led by boundary-layer (BL) low pressure;

The trio-interaction theory of MJO

(d) **uniquely** reveals (i) MJO structure depends on convective parameterizations, (ii) MJO propagation speed depends on MJO zonal structural asymmetry, and (iii) critical roles of the BL convergence feedback in eastward propagating, planetary scale instability and coupled Kelvin-Rossby wave structure

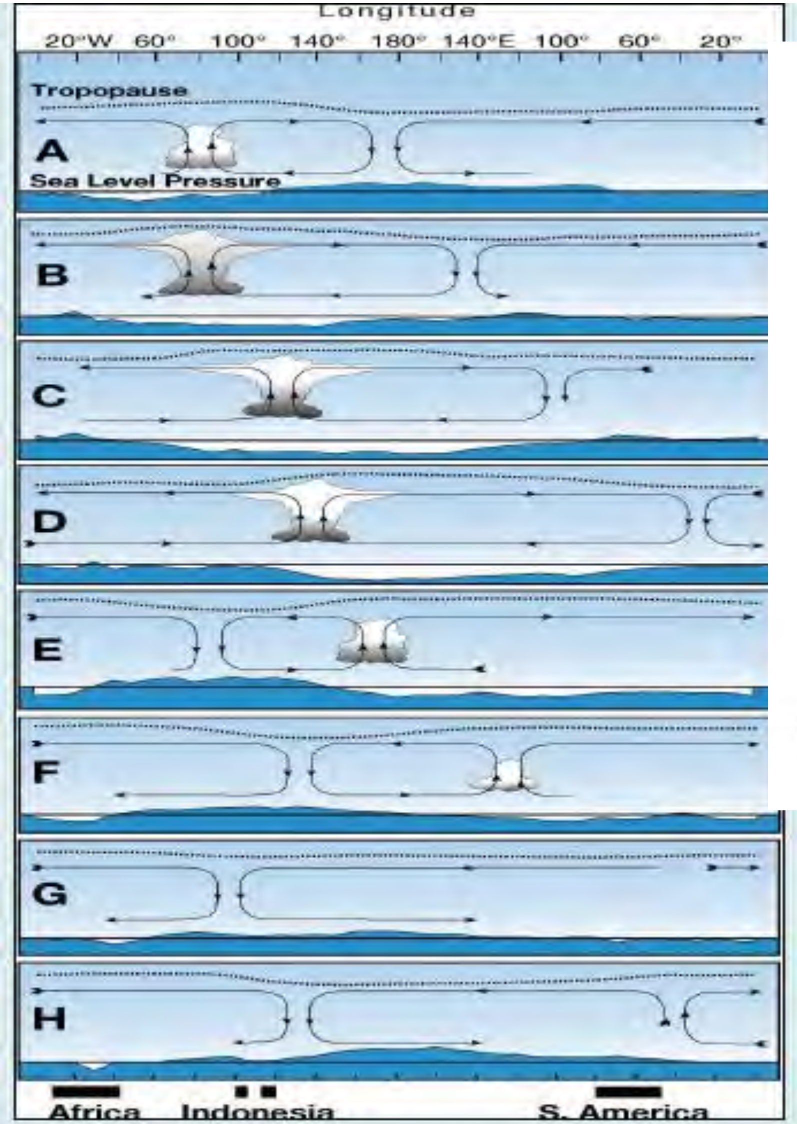
(e) **uniquely** elaborates roles of four major feedback processes: wave feedback, moisture feedback, BL convergence feedback, and cloud-radiation feedback.

(f) **uniquely** explains why the MJO possesses a coupled Kelvin–Rossby wave structure, why the MJO precipitation is led by the BL low pressure, and what controls amplification and decay of MJO.

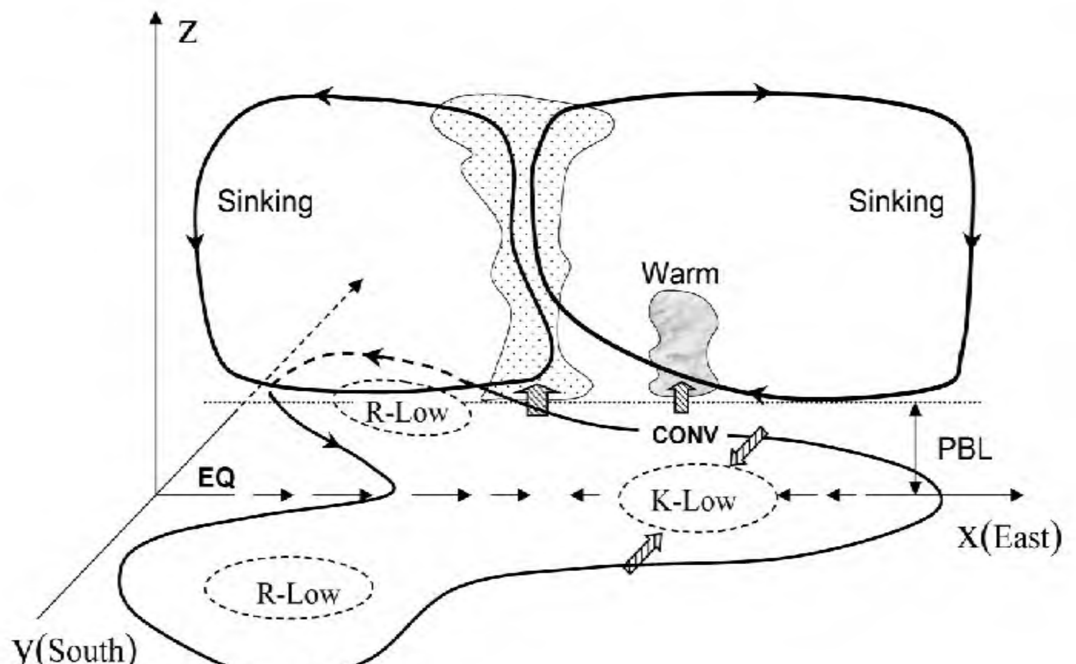
1. Essence of the trio-interaction theory

With Betts-Miller scheme

Essential Properties of MJO- targets for theoretical study



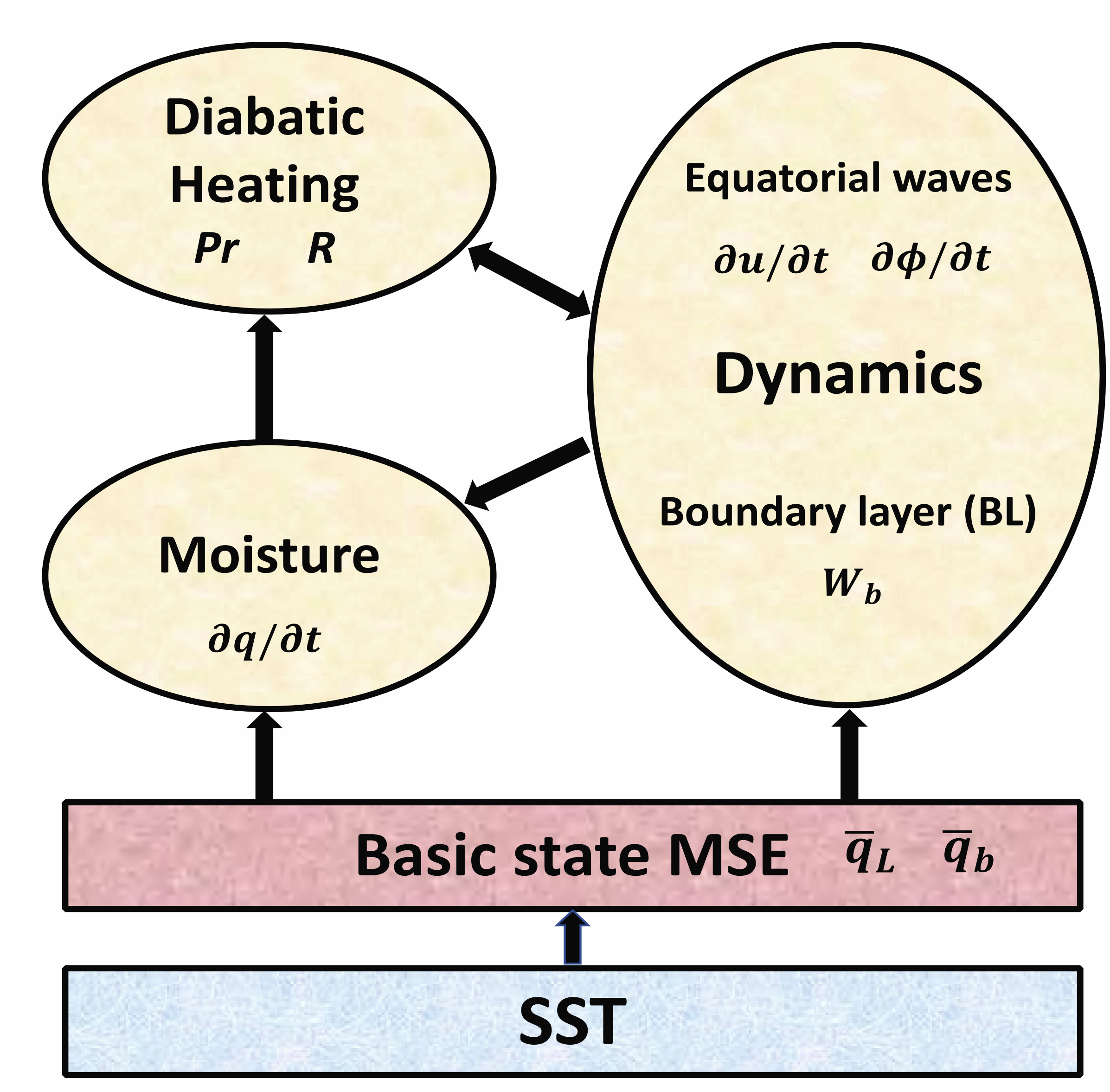
Madden and Julian 1972 ,
reproduced by McPhaden



Wang 2005, Kiladis et al. 2005

1. Planetary scale circulation system.
2. Slow eastward propagation (~5 m/s) from IO to WP, yielding a 40-50 day period.
3. Amplification/decay over warm (cold) ocean.
4. Coupled K-R wave structure.
5. Tilted heating led by BL convergence.

Essence of trio-interaction theory



The essential physics of MJO is rooted in the trio-interaction among heating, circulation and moisture.

2. A general Trio-Interaction Model

Reference:

Wang, B. and G. Chen 2017: **A general theoretical framework for understanding essential dynamics of Madden-Julian Oscillation**, *Climate Dynamics*, **49**, 2309–2328.

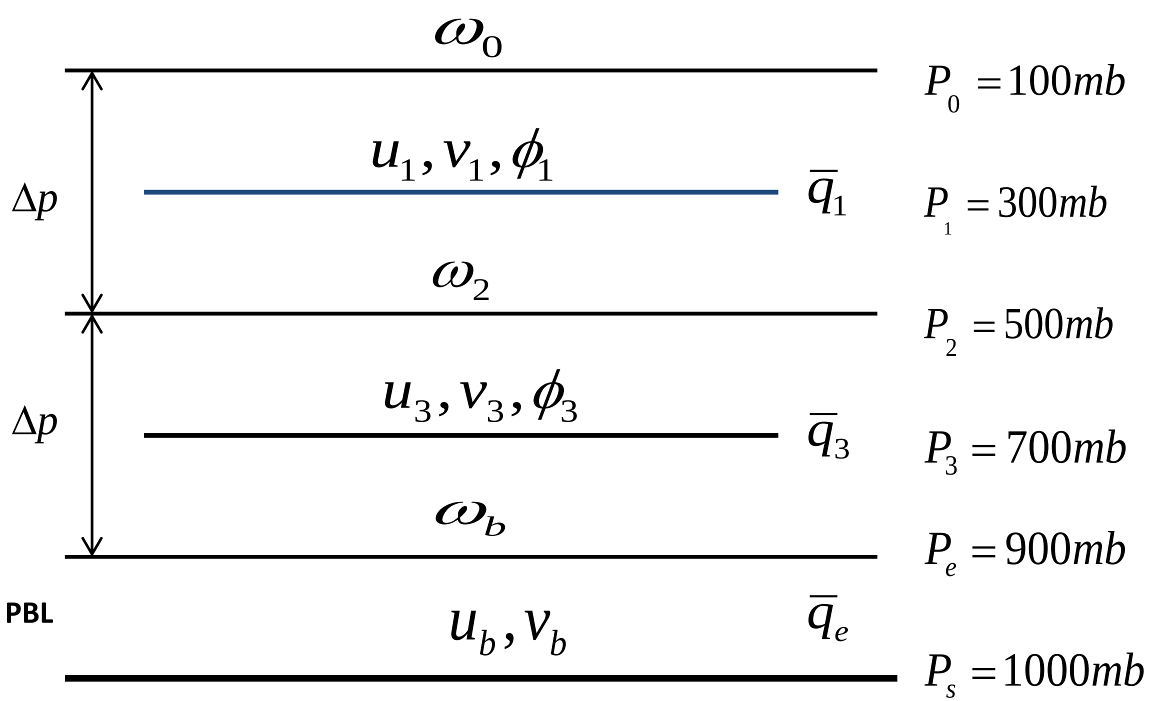
Trio-interaction theory focusses on

Essential Dynamics of MJO

Assumptions/ limitations

1. No atmosphere-ocean interaction
2. Neglect background mean flows
3. Large scale motion ($L>L_R$)
4. Single vertical mode in free troposphere
5. Barotropic BL Ekman effect

Vertical structure: Two-layer free atmosphere with a barotropic PBL



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

--Wang 2012: Theory, Chapter 10 in "Intraseasonal oscillation in the atmosphere and Ocean", Eds. W. Lau and D. Waliser, Praxis-Springer

Governing Equations

$$\frac{\partial u}{\partial t} - yv = -\frac{\partial \phi}{\partial x} - \varepsilon u$$

$$\frac{\partial v}{\partial t} + \mathrm{yu} = -\frac{\partial \phi}{\partial x} - \varepsilon v$$

$$\frac{\partial \phi}{\partial t} + \mathbf{D} + \boldsymbol{W_b} = (\boldsymbol{Pr} - \boldsymbol{R}) - \mu\phi$$

$$\frac{\partial q}{\partial t} + \bar{q}_L \mathrm{D} + \bar{q}_b W_b = Ev - Pr$$

$$W_b = d(\alpha_1 \nabla^2 \phi + \alpha_2 \frac{\partial \phi}{\partial x} + \alpha_3 \frac{\partial \phi}{\partial y})$$

One and half layer model
(non-dimensional)

The general theoretical model for MJO is an extension of the Matsuno-Gill theory by incorporating a trio-interaction among convection, moisture, and wave-boundary layer (BL) dynamics.

The model integrates major existing MJO theories

- Frictional coupled moist K-R wave theory (Wang and Rui 1990, Wang and Li 1994, Kang et al. 2013) which integrates

  Equatorial Wave-CISK (Lau and Peng 1987; Hendon 1988)

  Evaporation-wind feedback (Emanuel 1987; Neelin et al 1987)

  BL Frictional moisture feedback (Wang 1988)

- Moisture mode theory (moisture-convection feedback) (Raymond and Fuch 2009, Sobel and Maloney 2012, 2013, Adames and Kim 2015), also Woolnough et al. 2001, Grabowski and Moncrieff 2004, Bony and Emanuel 2005, Benedict et al. 2014, Adams and Kim 2015)

- Multi-scale interaction theory including Skeleton model with wave activity ensemble scheme (Majda and Biello 2004; Biello and Majda 2005 Majda and Stechmann 2009; Liu and Wang 2012a). Two-way interaction models (Wang and Liu 2011; Liu et al. 2012; Liu and Wang 2012b, 2013b); Multicloud model (Khouider and Majda 2006, 2007); Wave packet model due to high-frequency wave interference (Yang and Ingersoll 2011, 2013);

The general model can accommodate variety of simplified cumulus parameterization schemes

(1). Simplified Betts-Miller (B-M) scheme (Frierson et al. 2004, Wang et al. 2016, Liu and Wang 2017)

$$Pr = (q + \alpha\phi)/\tau$$

(2) Simplified Bretherton scheme (Bretherton et al. 2004, Sobel and Maloney 2012, 2013; Kim et al. 2015, Adames and Kim 2016)

$$P_r = \frac{q}{t}$$

(3). Wave activity ensemble (Majda and Stechmann 2009, Liu and Wang 2012):

$$\partial Pr/\partial t = r_0 q$$

(4). Simplified Kuo- Scheme (Wang and Rui 1990):

$$Pr = -b(\bar{q}_L D + \bar{q}_b W_b)$$

(5) Cloud-radiation feedback (Fuchs and Raymond 2005, 2017); Peters and Bretherton 2005, Sobel and Malony 2013, Kim et al. 2015)

$$R = -rP_r$$

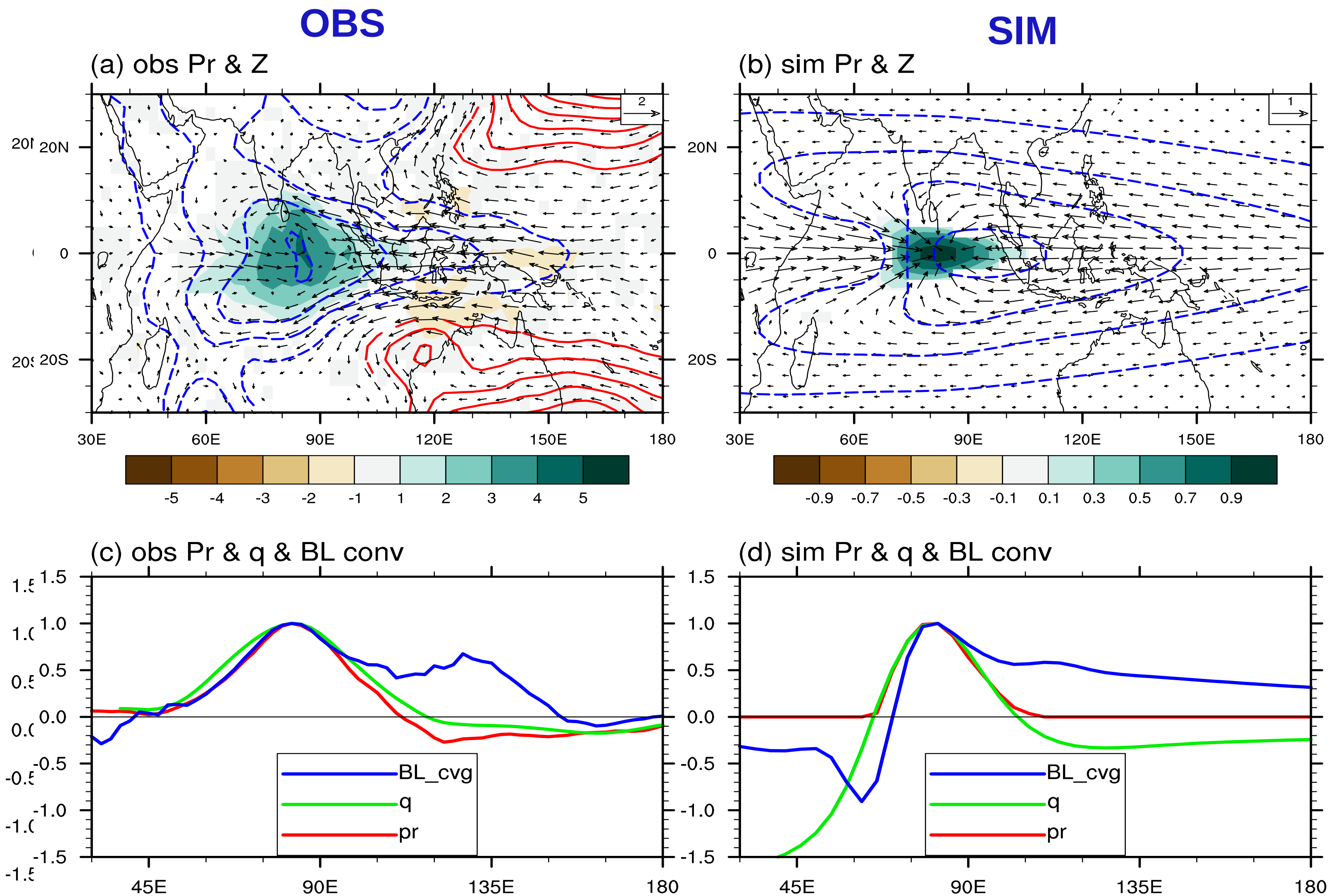
Existing theoretical models are special cases of the general trio-interaction model

Existing Theories	Convective Heating	BLC Feedback	Moisture Feedback	Radiation Feedback	Wave Feedback	Evaporation -wind Feedback
Emanuel (1987)	Evaporation ✓				✓	✓
Wang-Rui (1990)	Kuo ✓	✓			✓	✓
Majda-Stechmann (2009)	Wave-Activity ✓		✓		✓	
Liu-Wang (2012)	Wave-Activity ✓	✓	✓		✓	
Sobel-Maloney (2013)	Bretherton ✓	(✓)	✓	✓		✓
Yang-Ingelsoll (2013)	Triger ✓				✓	
Adames-Kim (2016)	Bretherton ✓	(✓)	✓	✓		✓
Wang-Liu-Chen (2016)	Betts-Miller ✓	✓	✓	✓	✓	✓
Fuchs-Raymond (2017)	Bretherton ✓		✓	(✓)	✓	✓
Liu-Wang (2017)	Betts-Miller ✓	✓	✓	(✓)	✓	(✓)

3. Properties of the trio-interaction mode

Linear and nonlinear heating

Structure of the trio-interaction MJO mode (B-M scheme)

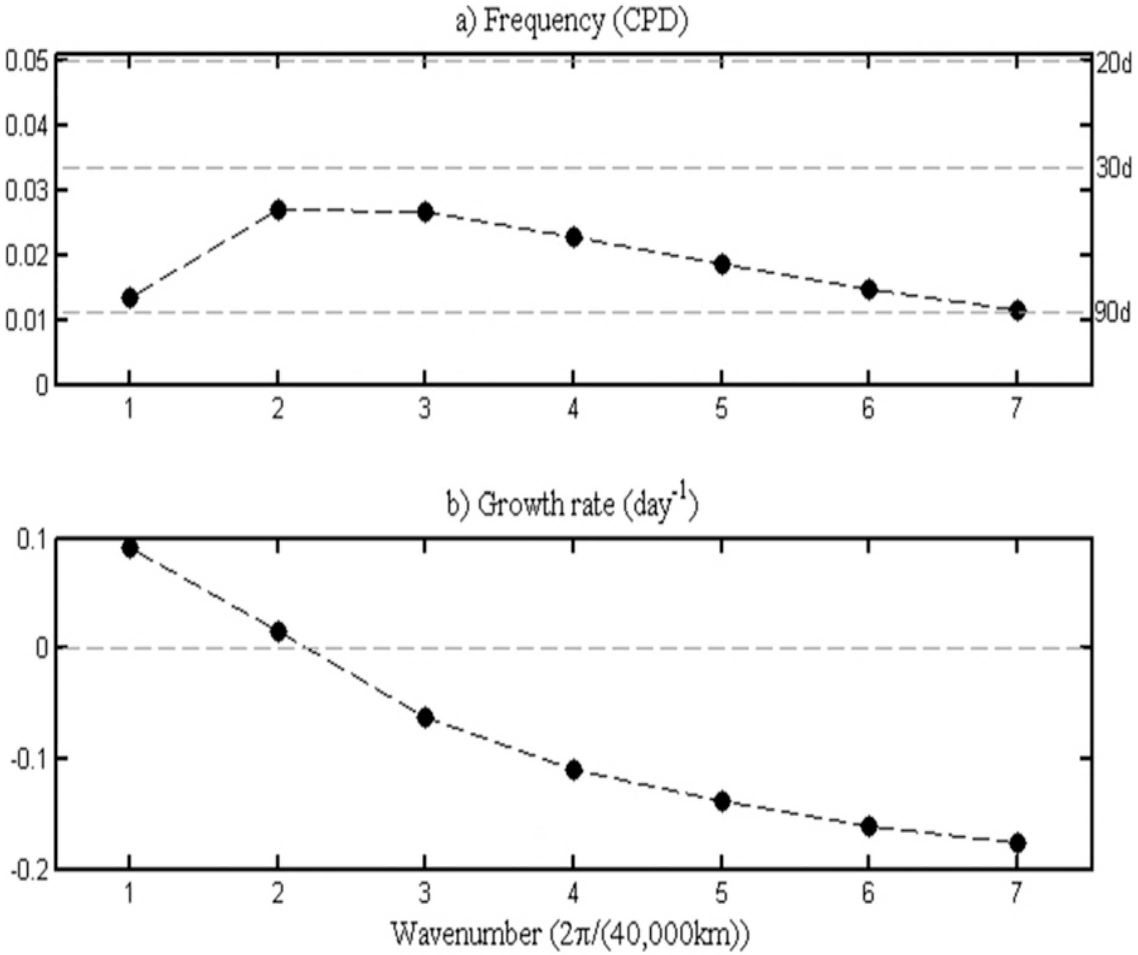


- Coupled Kelvin-Rossby wave horizontal structure
- BL convergence leads major precipitation

Wang et al. 2016

Period and Growth rate vs. wavenumber

Trio-interaction MJO mode (B-M scheme)

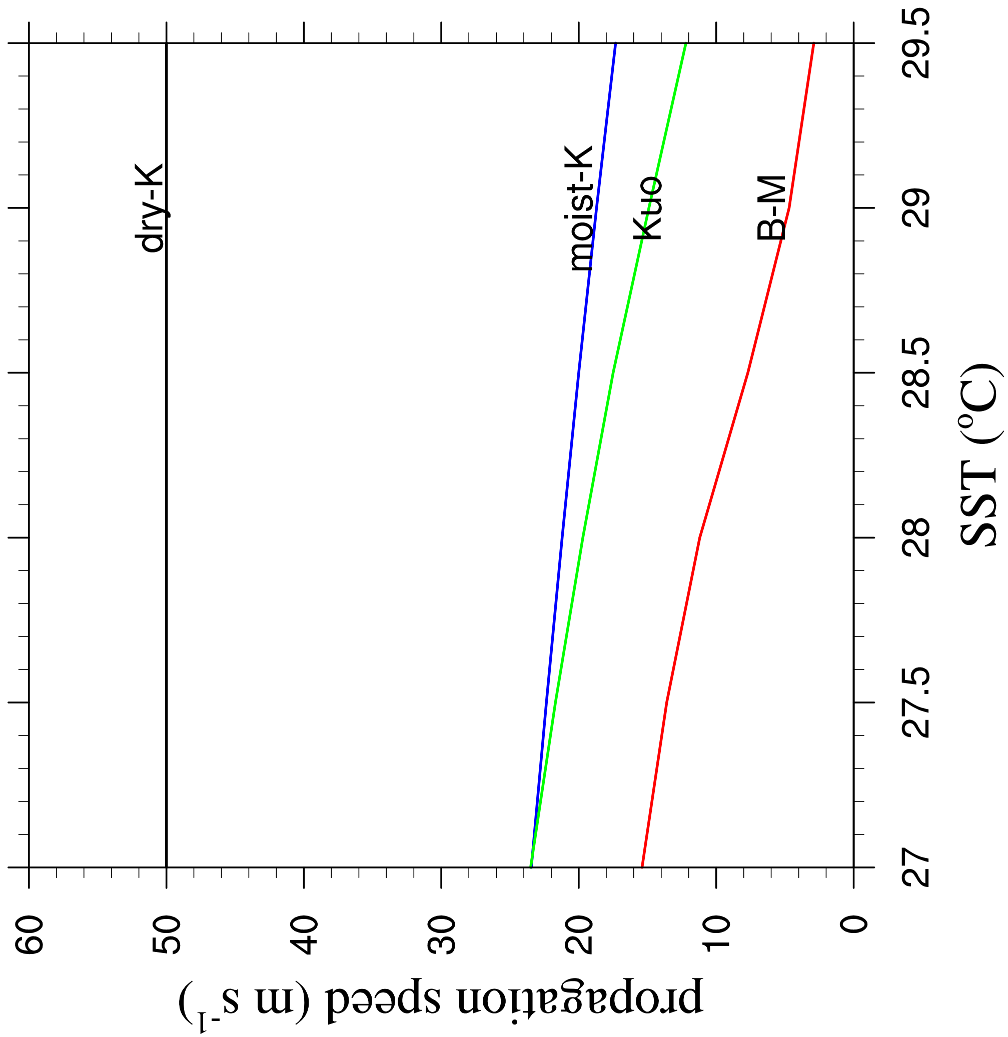


Period within 30-90day
Slow eastward propagation

Wave 1 and 2 are growing modes

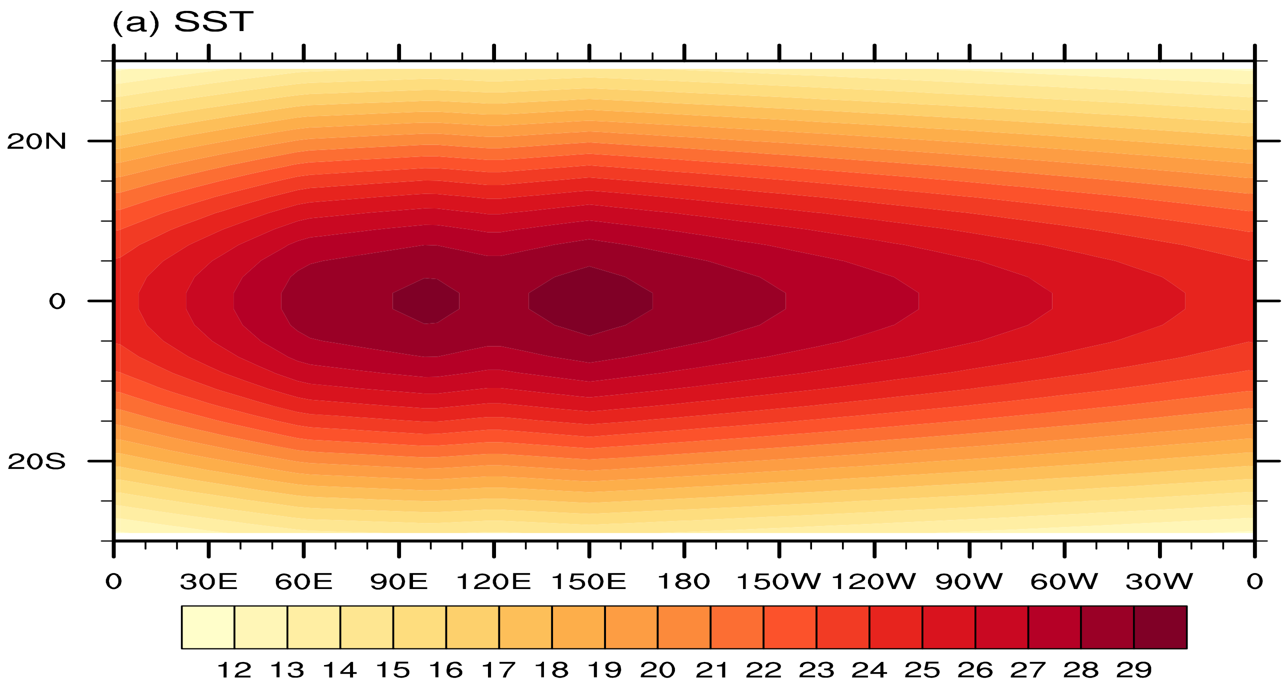
Liu and Wang 2017

Factors controlling propagation speed

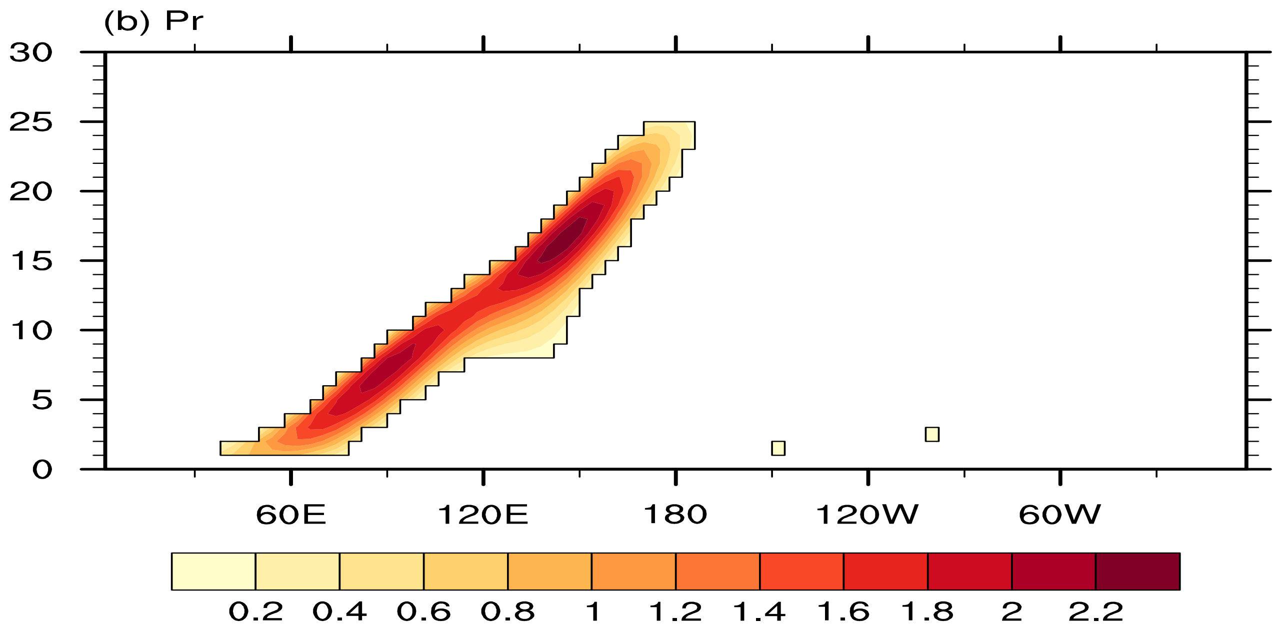


$$\frac{\partial \Phi}{\partial t} + C_0^2 (1 - \overline{q_3} / q_c) \nabla \bullet \vec{v} = 0$$

- SST (basic state MSE) can dramatically reduce propagations speed from 50 to 19 at SST =29 C through reduce the static stability.
- The BLC-induced coupling of Kelvin and Rossby waves slows down E-Prop from 19 to 14 at SST =29C
- The moisture feedback further slows down eastward propagation from 14 to 5 m/s at SST =29C



3. Nonlinear heating with A spatially varying basic state SST



- Amplification over warm pool; Rapid decay passing the date line

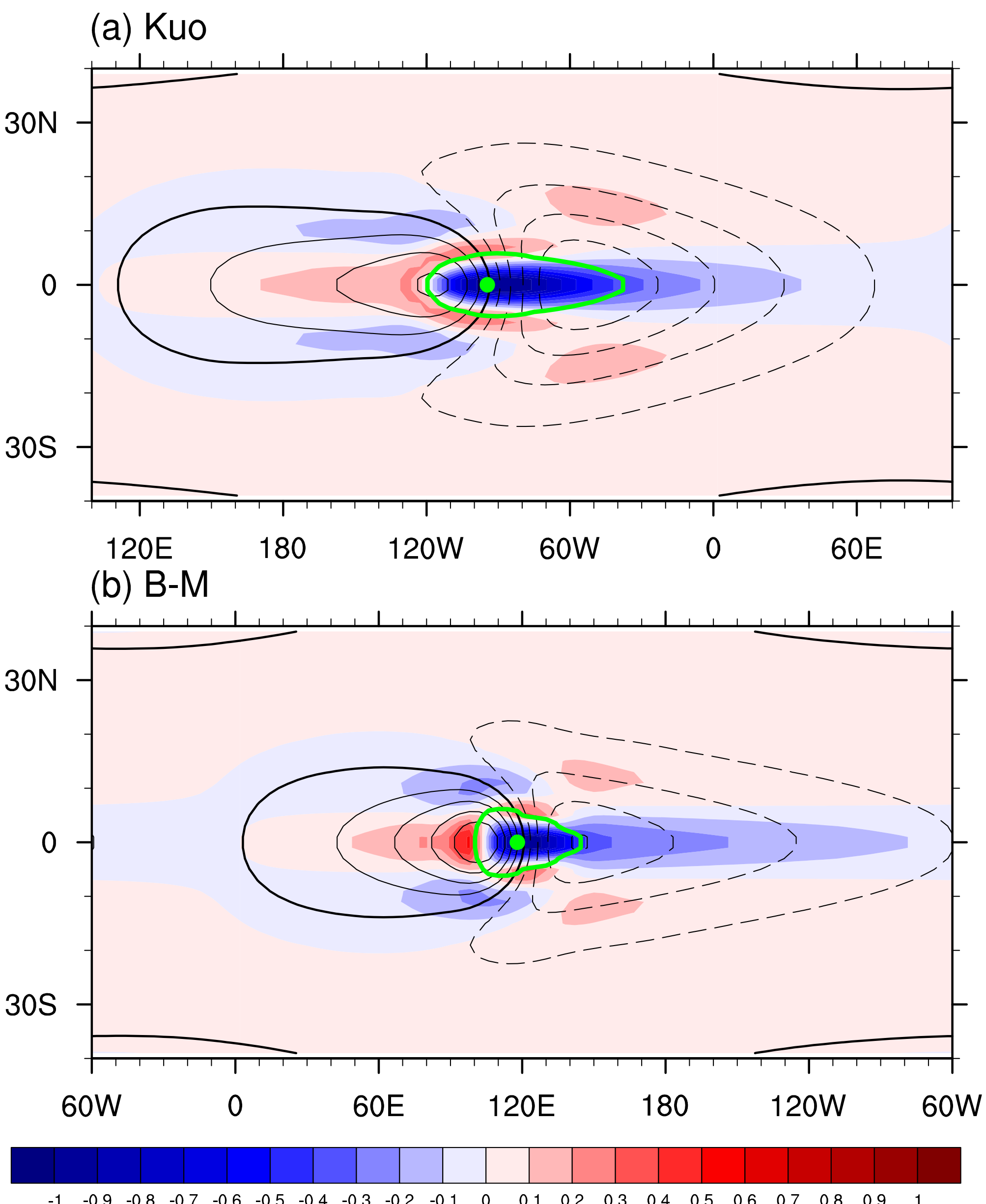
The trio-interaction mode produces robust large-scale characteristics of the observed MJO, including the

- coupled Kelvin-Rossby wave structure,
- slow eastward propagation (~5 m/s) over warm pool,
- planetary (zonal) scale circulation,
- BL low pressure and moisture convergence preceding major convection, and
- amplification/decay over warm/cold SST regions.

4. Novel findings revealed by the trio-interaction theory

- MJO structure depends on convective parameterization scheme
- MJO propagation speed depends on the MJO structure (zonal structural asymmetry)
  (RW vs. KW intensity: R-K ratio)

Dependence of the structure on convective Schemes



U850 (contours)

In Kuo scheme, KW easterly is stronger than RW westerly.

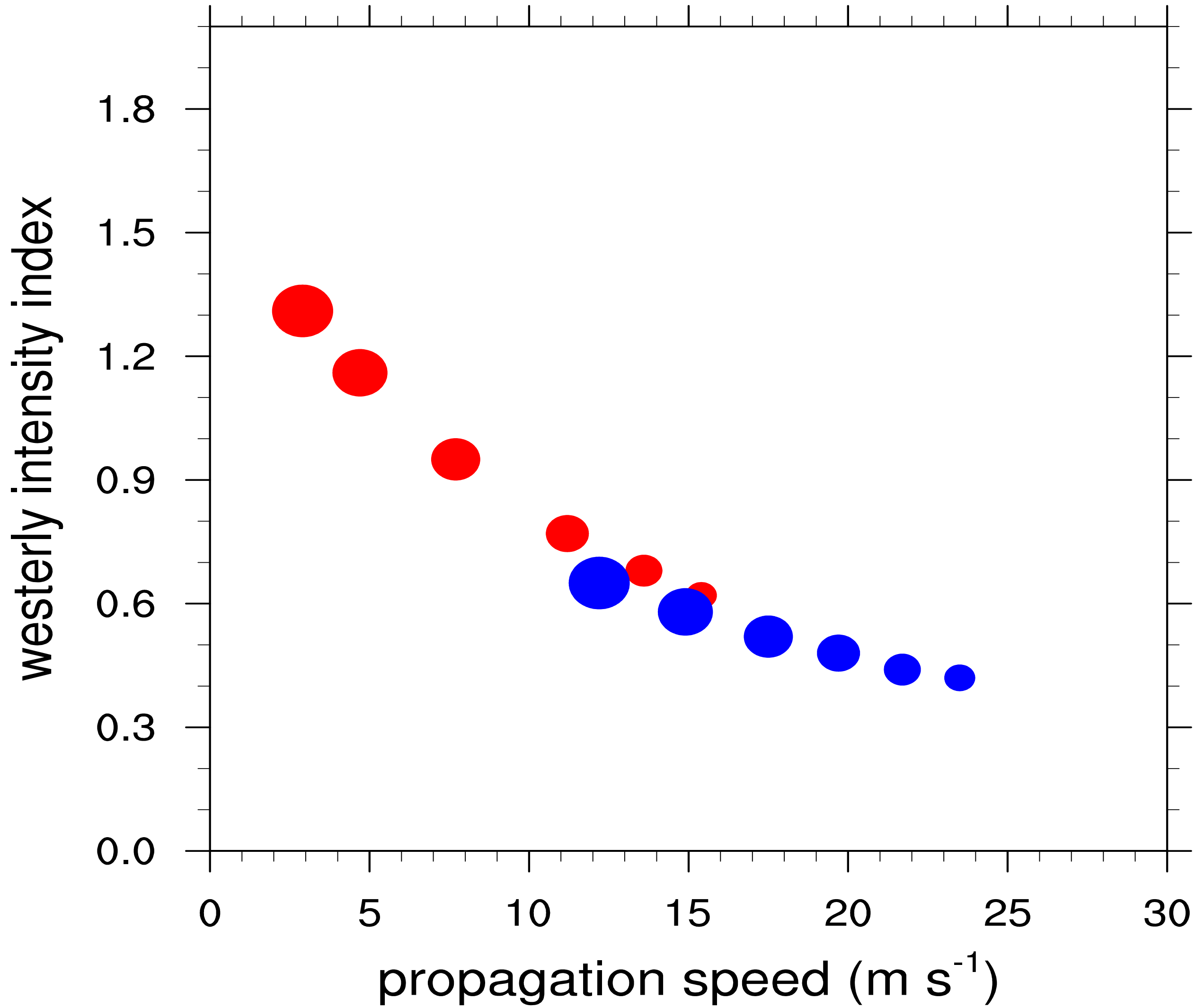
Faster E propagation

In B-M scheme (With moisture feedback) RW westerly is stronger than KW easterly.

Slower E-propagation

Wang and Chen 2017

Dependence of propagation speed on the zonal structural asymmetry (R-K ratio)



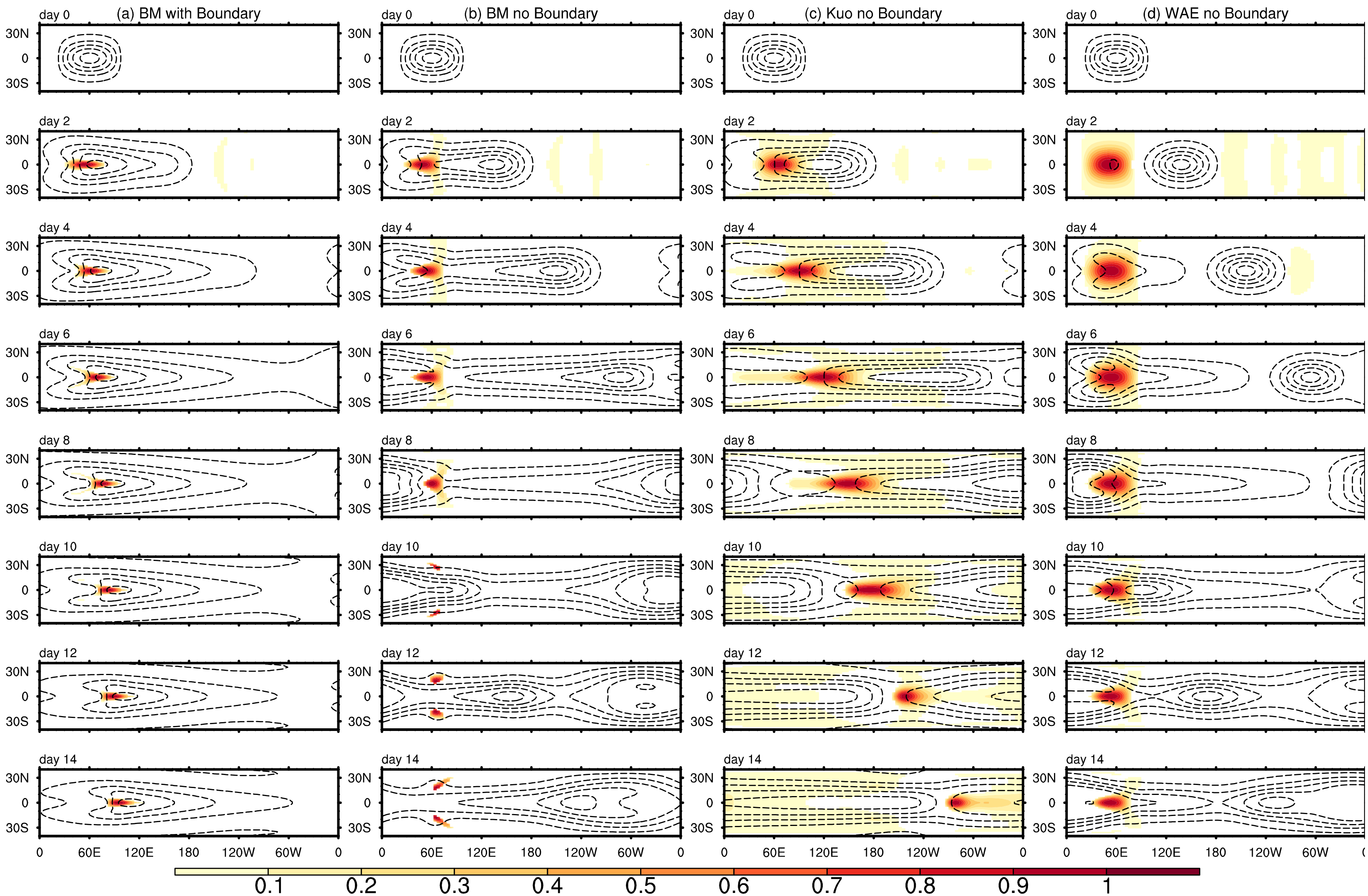
When RW westerly intensity increases the E-propagation becomes slower.

Wang and Chen 2017

5. The trio-interaction theory elaborates the roles of

Moisture feedback,
BLC feedback,
Wave feedback,
Cloud-radiation feedback,
in shaping MJO dynamics

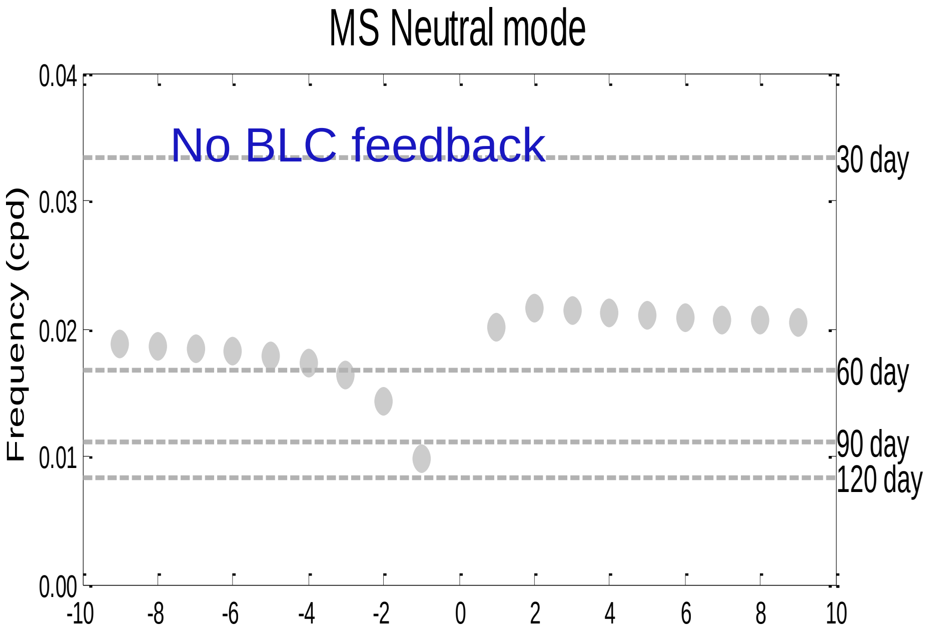
Roles of BLC feedback in shaping MJO propagation/structure



Effects of BLC feedback (Wave activity flux)

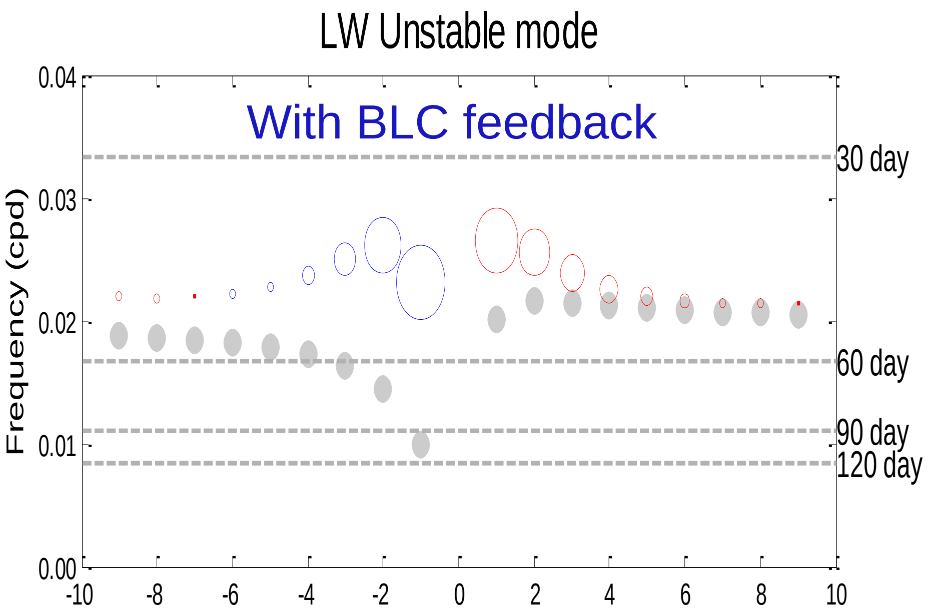
Skeleton Mode

Majda and Stechmann 2009



Frictional skeleton mode

Liu and Wang 2012



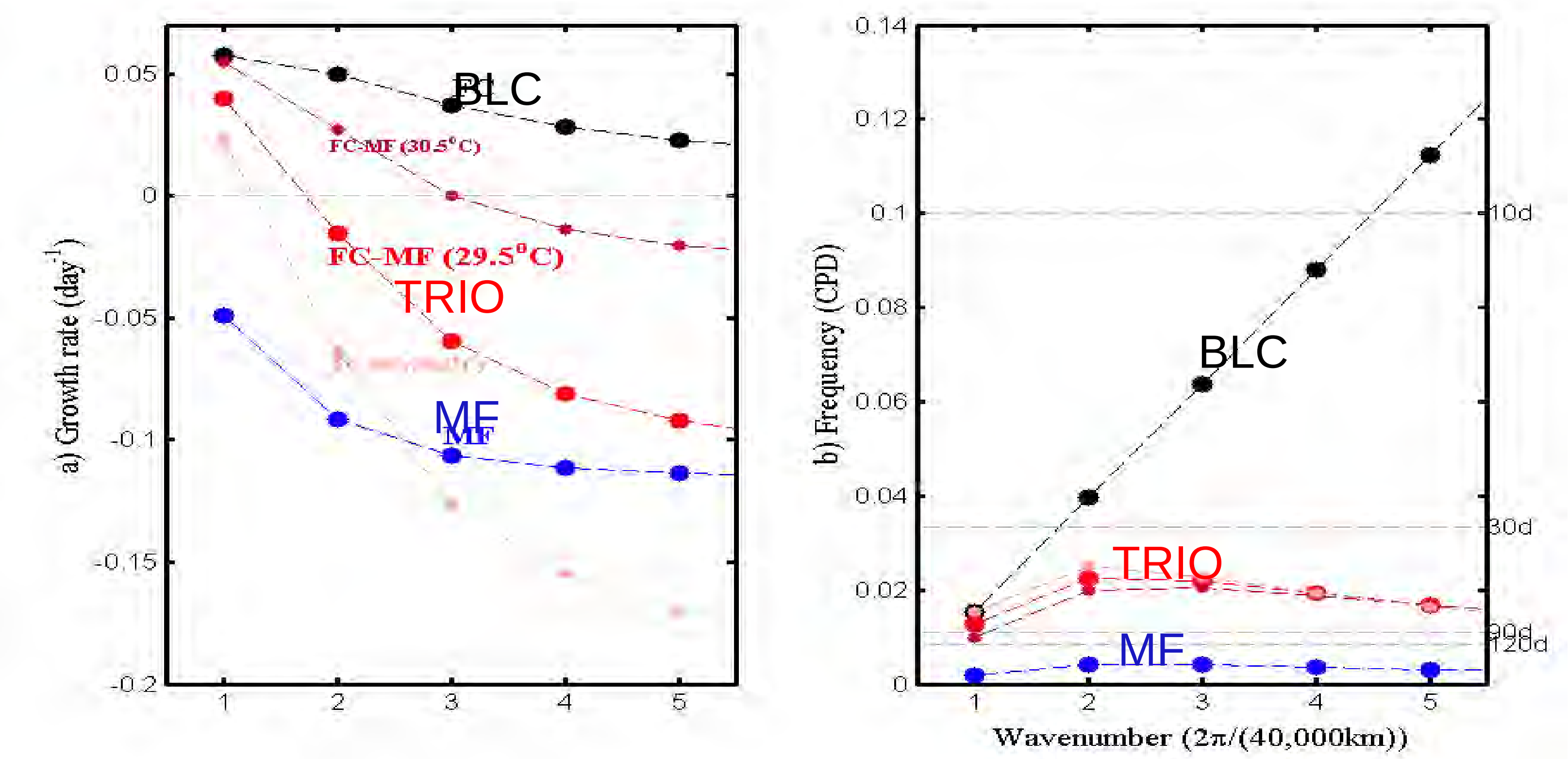
Neutral modes,
Propagates either eastward or westward.

Eastward growing mode,
Westward damping mode,
Select eastward propagation
Preferred planetary scale

Moisture feedback and BLC feedback versus Trio-interaction mode (B-M scheme)

Growth rate

Period



Black: BLC feedback mode
Blue: Moisture feedback mode
Red: Trio-interaction mode

Liu and Wang (2017)

Effects of each feedback process on MJO properties

	Planetary Scale Selection	Eastward Propagation	Propagation Speed	Instability	Coupled Structures
Convective Heating			✓(−)	✓	✓
BLC Feedback	✓	✓	✓(+)	✓	✓
Moisture Feedback			✓(−)		✓
Radiation Feedback	(✓)		✓(−)	✓	✓
Wave Feedback			✓(−)	✓	✓
GW feedback	✓	✓	✓		
Background SST (MSE)			✓(−)	✓	✓

BLC feedback couples Kelvin and Rossby waves with heating, selects preferred eastward propagation and planetary scale instability.
Moisture feedback mainly acts to reduce the propagation speed and growth rate of the short waves, producing a more realistic structure.
Wave feedback plays a large role in slowing down eastward propagation and increasing growth rate for planetary waves.
Cloud-radiation feedback plays the similar roles as those of wave feedback.

6. Mechanisms offered uniquely by the trio-interaction theory

why moves eastward
why has a preferred planetary scale
why exhibits a coupled Kelvin-Rossby wave structure with major convection led by BLC; and
what controls the eastward propagation speed.

Reference: Wang and Chen 2017

Conclusions

1. The essential physics of MJO is rooted in the trio-interaction among heating, circulation and moisture.
2. The general trio-interaction model can represent major existing theories with simplified assumptions.
3. The trio-interaction theory can explain why MJO moves eastward and has a preferred planetary zonal scale and a coupled Kelvin-Rossby wave structure with major convection led by BLC; what controls the eastward propagation speed.
4. The trio-interaction theory can help to elaborate the roles of the Moisture feedback, BLC feedback, Wave feedback, Cloud-radiation feedback, and Evaporation-wind feedback.
5. The theory reveals dependence of the MJO structure on cumulus parameterization schemes and the dependence of MJO propagation on zonal structural asymmetry.

Implications

Different schemes (parameters) may produce different horizontal and vertical structures of the MJO, thus different propagation speed. Therefore, the MJO propagation and amplification are sensitive to the cumulus parameterization and the associated parameters.

The interaction between shallow-congestus cloud heating and BL Frictional Convergence (FC) may be critical to realistic simulation of MJO.

Diagnosis numerical models' problems may focus on the zonal structural asymmetry generated by the BL moisture feedback, the phase leading of the BLMC, pre-moistening, pre-destabilization, and lower tropospheric heating.

Thank You! Any Comments?

References

Wang, Liu, and Chen 2016: **A trio-interaction theory for Madden-Julian Oscillation.** *Geoscience. Lett.* **3**, 34, DOI 10.1186/s40562-016-0066-z.

Wang, B. and G. Chen 2017: **A general theoretical framework for understanding essential dynamics of Madden-Julian Oscillation**, *Climate Dynamics*, **49**, 2309–2328, DOI 10.1007/s00382-016-3448-1

Liu, F., and B. Wang, 2017: **Effects of moisture feedback in a frictional coupled Kelvin–Rossby wave model and implication in the Madden–Julian oscillation dynamics**. *Climate Dyn.*, 48(1-2), 513-522, DOI: 10.1007/s00382-016-3090-y.

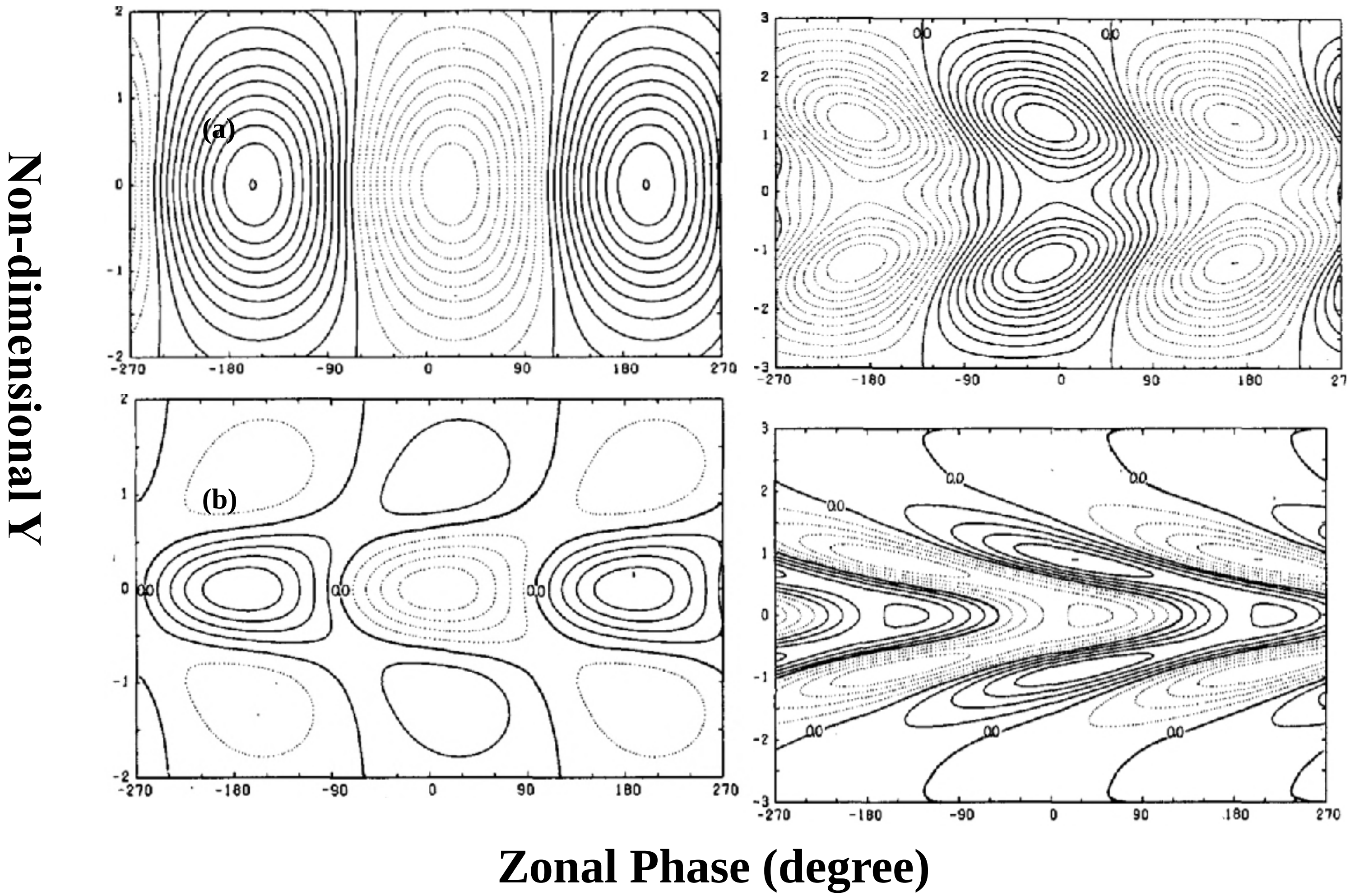
Liu, F., and B. Wang, 2017: **Roles of the moisture and wave feedbacks in shaping the Madden-Julian Oscillation**. *J. Climate*, **30**, 10275-10291, DOI: 10.1175/JCLI-D-17-0003.1

I. Why does the MJO exhibits a coupled Kelvin-Rossby wave structure? How could Kelvin waves and Rossby waved be coupled together and select eastward propagation?

The BL Frictional Convergence (FC) feedback couples Kelvin and Rossby waves with convective heating and selects a preferred eastward propagation.

Boundary layer convergence associated with

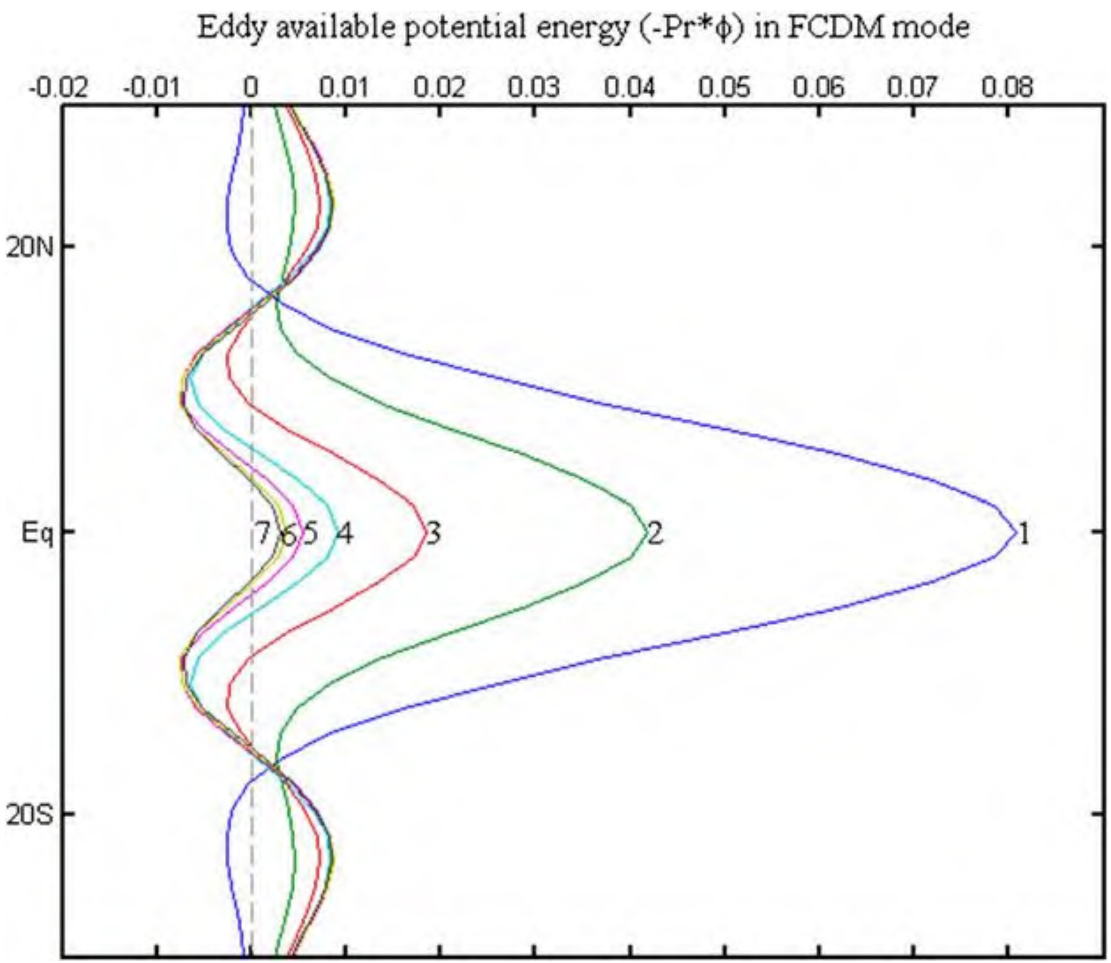
Kelvin Wave / Rossby Wave



•Both K and R waves create a **unified boundary layer convergence** field in the easterly phase, leading the major convective heating, **creating east-west moisture asymmetry**, and resulting in vertical backward tilted structure.

Planetary scale selection

Trio-interaction MJO mode



Wave 1 and 2 have large Eddy Available Potential Energy generation rate

Some guidelines
for establishing theoretical models

(1) Must be derived from the first principles with reasonable/justifiable assumptions.

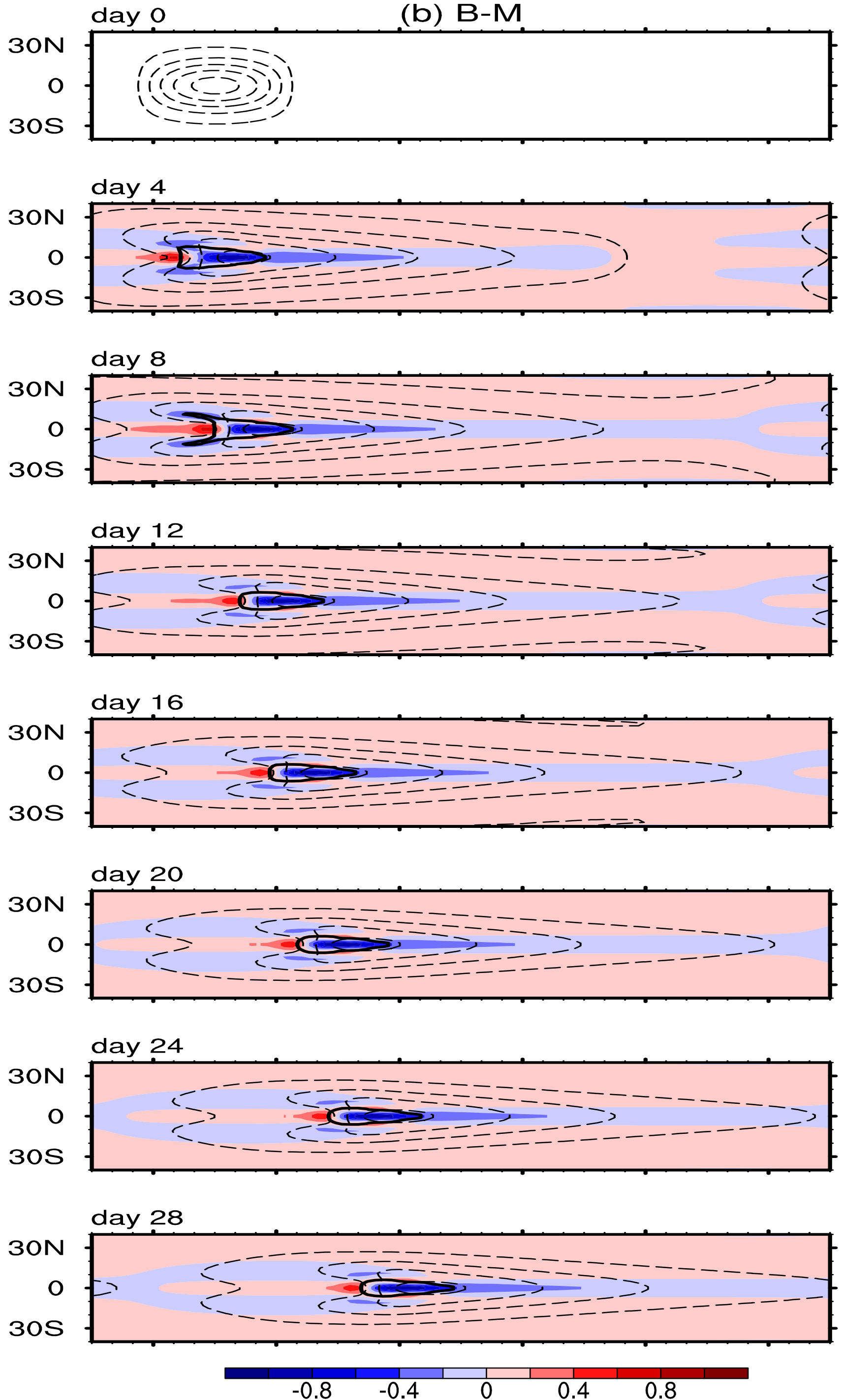
(2) Include only the essential processes of MJO dynamics.

(3) Model results are verifiable against observations.

(4) Capable to explain the fundamental mechanisms at work.

$$\overline{q_3} = q_0(p_e^m - p_2^m)/(m(p_e - p_2))$$

$$\overline{q_b} = q_0(p_s^m - p_e^m)/(m(p_s - p_e))$$



2. Nonlinear heating analysis with a Uniform basic state SST 29.0^{o}C

➢ Slow eastward Propagation speeds: 4.8m/s.

9. Implications to GCM simulation

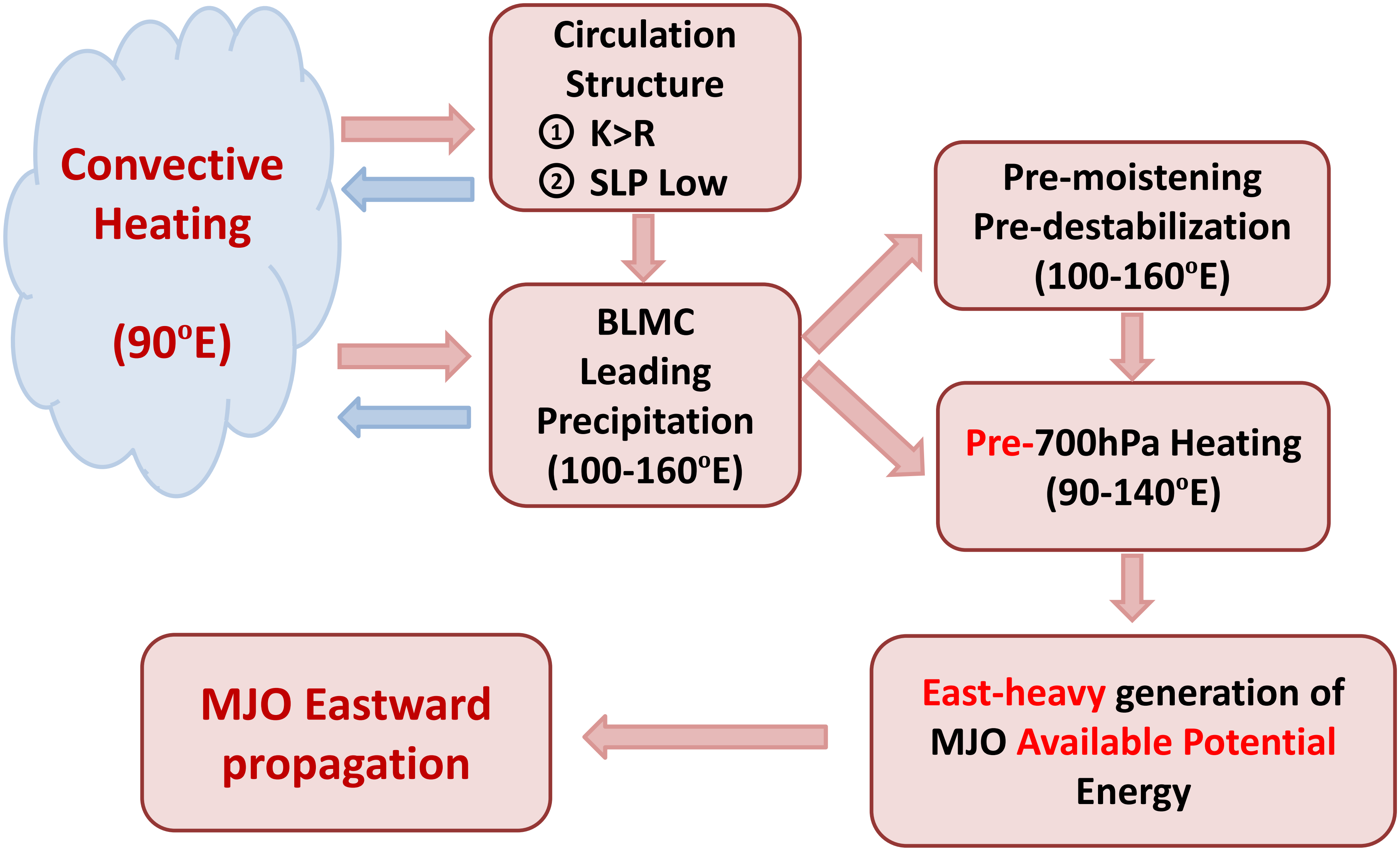


FIG.12 Schematic diagram illustrating the mechanism for MJO eastward propagation.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Dynamic prediction of MJO with GCMs

Dynamical MJO prediction has significantly advanced. The skill has increased from 7 days during 1990s to about 25-30 days (ECMWF and GFDL models) during 2010s (Lee et al. 2016, Vitart et al. 2014, Xiang et al. 2015).

The models still have large room to reach potential predictability limit (Neena et al. 2014, Lee et al. 2015)

Review of basic theories for MJO

- Frictional coupled moist K-R wave theory (Wang and Rui 1990, Wang and Li 1994, Kang et al. 2013) This theory integrated

  Equatorial Wave-CISK (Lau and Peng 1987; Hendon 1988)

  Evaporation-wind feedback (Emanuel 1987; Neelin et al 1987)

  BL Frictional moisture feedback (Wang 1988)

- Moisture mode theory (moisture-convection feedback) (Raymond and Fuch 2009, Sobel and Maloney 2012, 2013, Adames and Kim 2015), also Woolnough et al. 2001, Grabowski and Moncrieff 2004, Bony and Emanuel 2005, Benedict et al. 2014, Adams and Kim 2015)

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Other theory and mechanisms

- Atmosphere-ocean interaction theory (Flatau et. al. 1997, Wang and Xie 1998, Waliser et. al. 1999, Fu and Wang 2004,..)
- The boreal summer ISO theory (Webster et al. 1984, Wang and Xie 1997; Jiang et al. 2004; Drbohlav and Wang 2005, Kang et al. 2010, Booth and Kuang 2010,)
- Shallow convection-BL circulation interaction (Johnson et al. 1999, Lin et al. 2004, Kikuchi and Takayabu 2004);
- Stratiform cloud-wave interaction (Mapes 2000, Kuang 2008, Fu and Wang 2009, Seo and Wang 2010, Holloway et al. 2013);
- Radiation-convection interaction (Hu and Randall 19944, Raymond 2001, Lee et al. 2001, Lin and Mapes 2004, Bony and Emanuel 2005, Anderson and Kuang 2012);
- Moisture transport (Maloney 2009, Maloney et al. 2010, Anderson and Kuang 2012, Hsu and Li 2012, Pitchard and Bretherton 2014, Kim et al. 2014)