Dynamics-oriented Diagnostics for the Madden-Julian Oscillation

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J. Climate, on Line

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Motivation

To evaluate and track GCMs' simulations of the MJO and identify their major problems, the U.S. Climate Variability and Predictability (CLIVAR) MJO Working Group designed a suite of diagnostics (Waliser et al. 2009).

These diagnostics provide a comprehensive assessment of the simulated MJO properties, but tend to reflect heavily the statistical behavior of the MJO.

From a dynamical standpoint, the large-scale dynamic and thermodynamic structures of the MJO system should be taken into account.

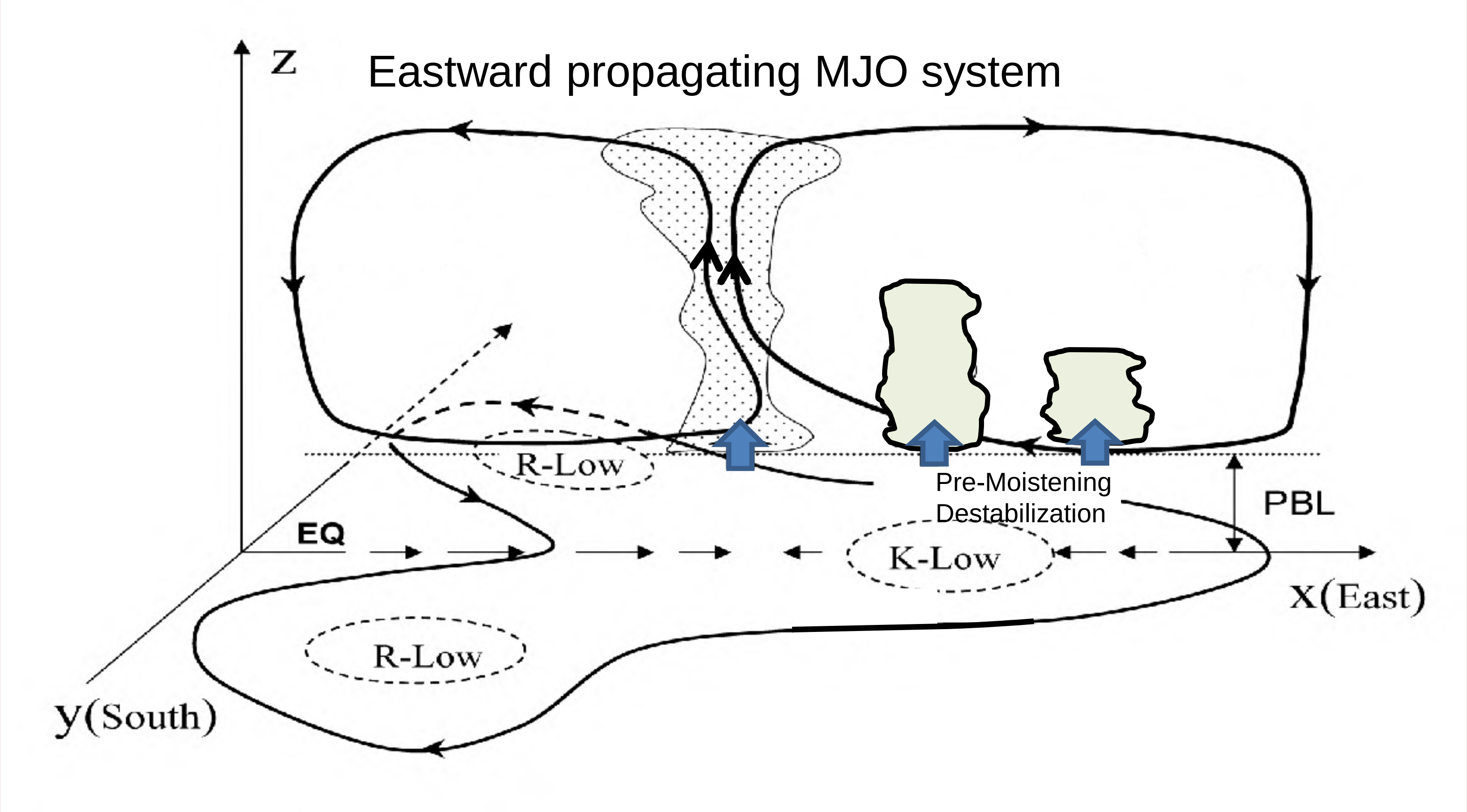
Why?

Results from Observations

Anomalous surface low pressure and boundary layer (BL) moisture convergence (BLMC) precede the major convective center (Madden and Julian 1972; Wang 1988a; Hendon and Salby 1994; Salby et al. 1994; Jones and Weare 1996; Maloney and Hartmann 1998; Sperber 2003; Kiladis et al. 2005; Zhang 2005; Tian et al. 2006).

To the east of the MJO convective center exist gradual deepening of the moist BL (Johnson et al. 1999; Kemball-Cook and Weare 2001; Tian et al. 2006), increasing convective instability (Hsu and Li 2012), and a transition from shallow cumulus, congestus clouds to deep convection and stratiform clouds (Kikuchi and Takayabu 2004; Katsumata et al. 2009; Virts and Wallace 2010; Del Genio et al. 2012; Johnson et al. 2015).

These structural features are arguably critical to the slow eastward propagation of the MJO.



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

Results from Theory

Reference:

Wang, B., F. Liu, and G. Chen 2016: **A trio-interaction theory for Madden-Julian Oscillation.** *Geoscience. Lett.* **3**, 34.

Trio-interaction Theory of MJO

General MJO model

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

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

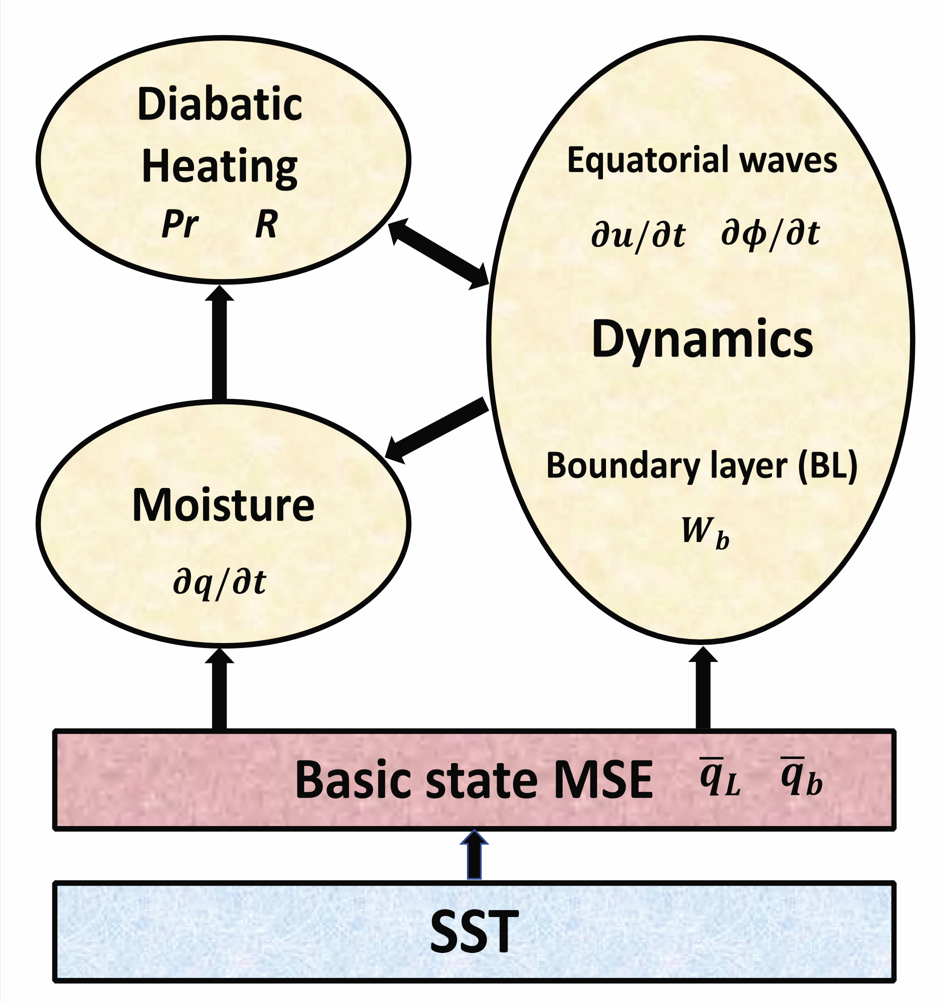
$$\frac{\partial \phi}{\partial t} + \mathbf{D} + \boldsymbol{W_b} = (\boldsymbol{Pr} - \boldsymbol{R}) - \mu\phi$$

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

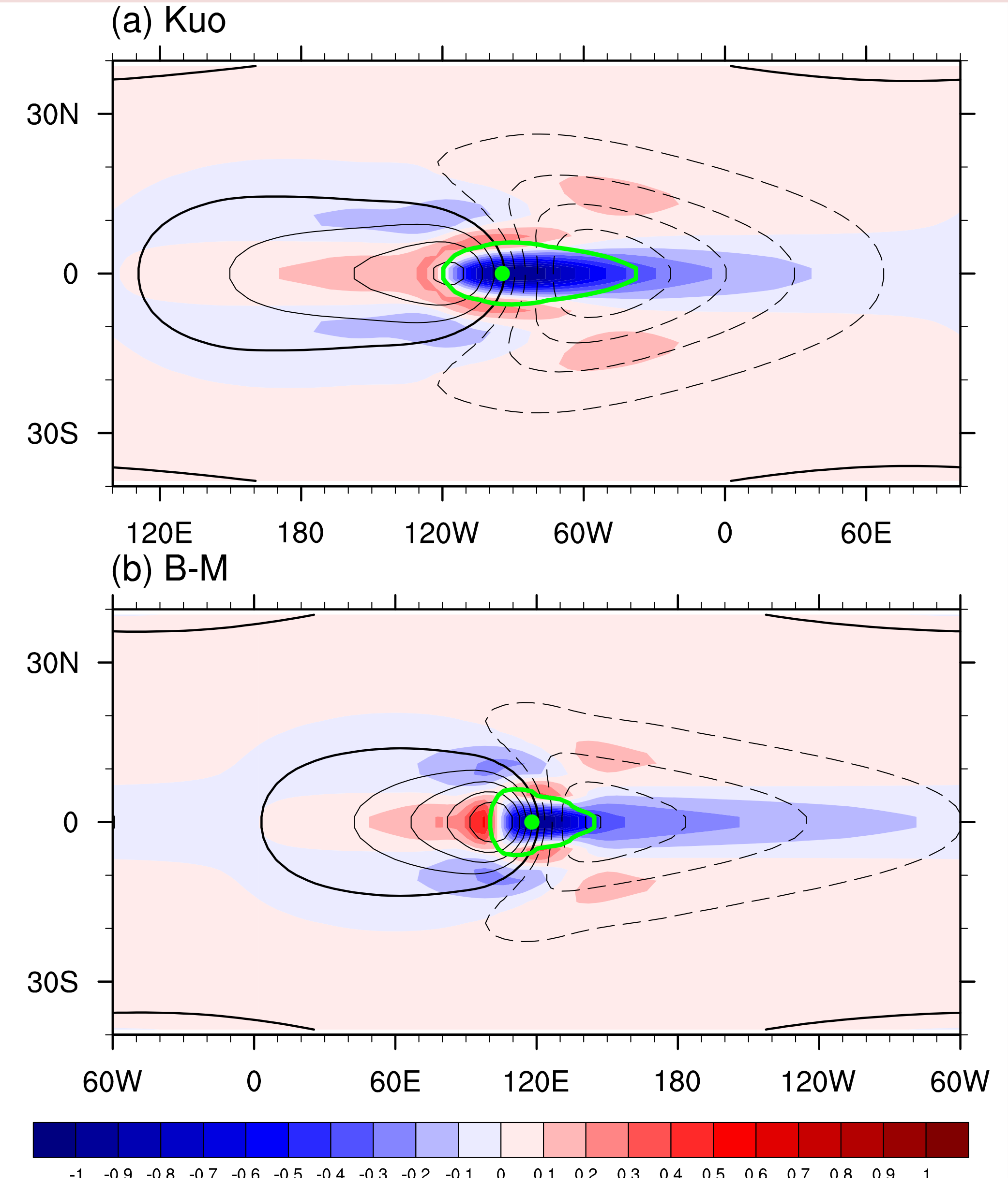
$$W_b = d(\alpha_1 \nabla^2 \phi + \alpha_2 \frac{\partial \phi}{\partial x} + \alpha_3 \frac{\partial \phi}{\partial y})$$

One and half layer model
(non-dimensional)

Essential Physics



Different convective schemes produce different MJO structure



U850 (contours)

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

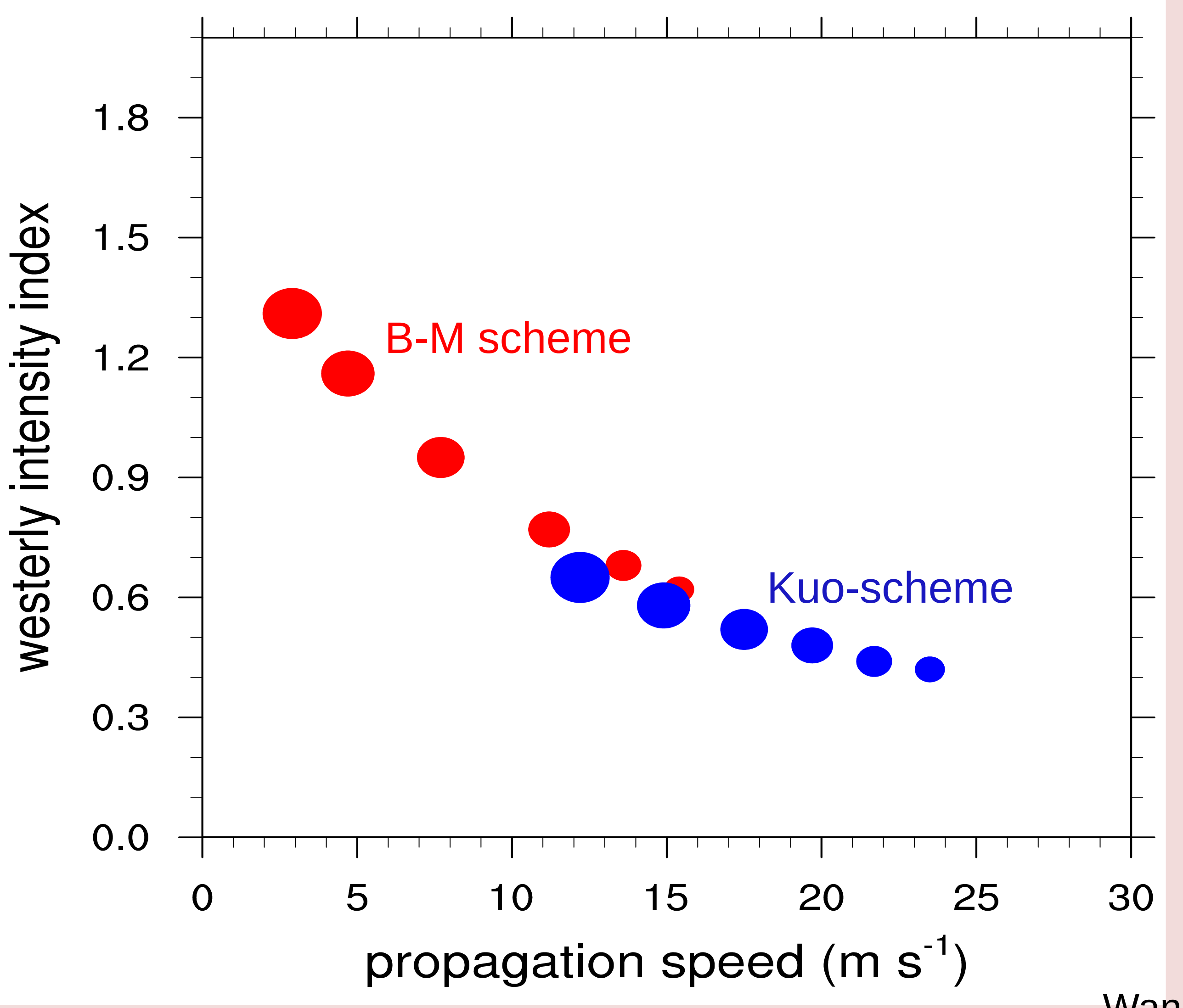
Faster E propagation

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

Slower E-propagation

Wang and Chen 2017

MJO propagation speed depends on the MJO zonal structural asymmetry (R-K ratio)



When RW westerly intensity increases, the Eastward propagation becomes slower.

Wang and Chen 2017

Results from GCM simulations

Reference:

Wang, B. and S.-S. Lee, 2017:
MJO propagation shaped by zonal asymmetric structures: Results from 24-GCM simulations , J. Climate 2017, 30, 7933-7952

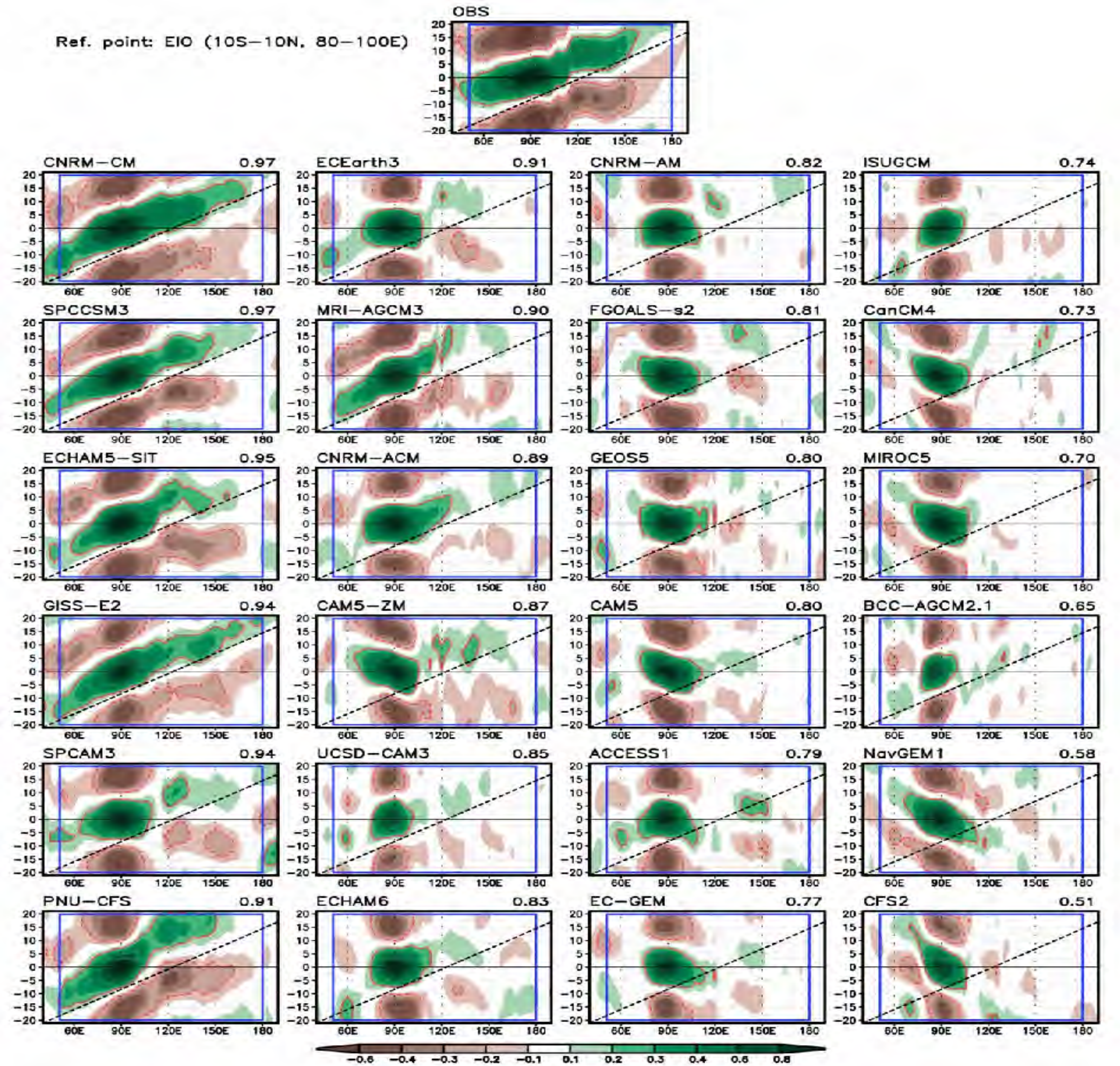
24 GCM simulations

"Vertical Structure and Diabatic Processes of the MJO: A global model evaluation project"

Launched by

WCRP-WWRP/THORPEX MJO Task Force & Year of Tropical Convection (YOTC) and the GEWEX Atmosphere System Study (GASS)

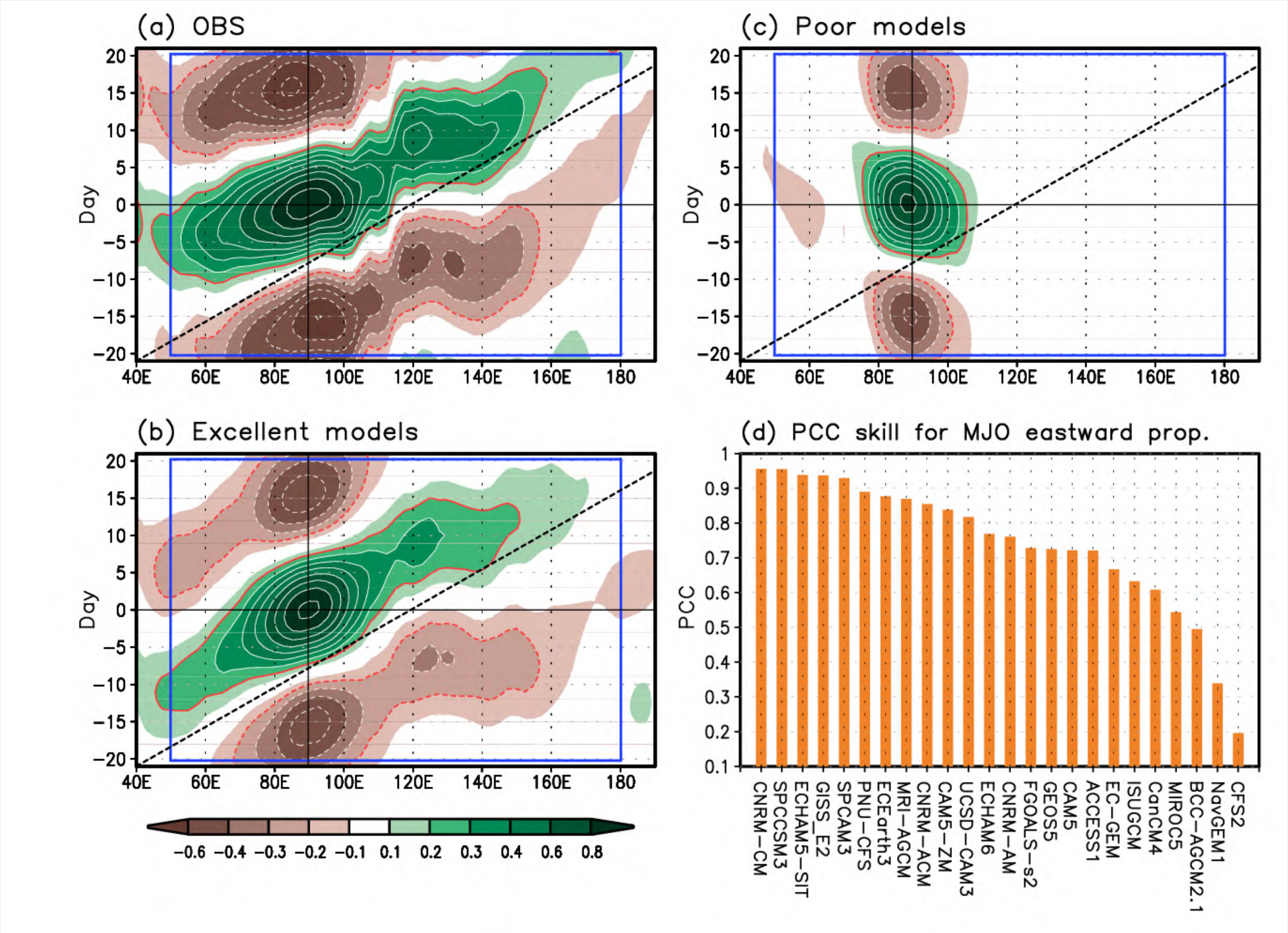
(Klingaman et al. 2015)



Eastward propagation of MJO in observation and 24 GCM simulations

as shown by the lead-lag correlation of 20-70 day band pass filtered precipitation averaged over 10ºS-10ºN with reference to itself over the equatorial Indian Ocean (10ºS-10ºN, 80º-100ºE) for boreal winter (NDJFMA).

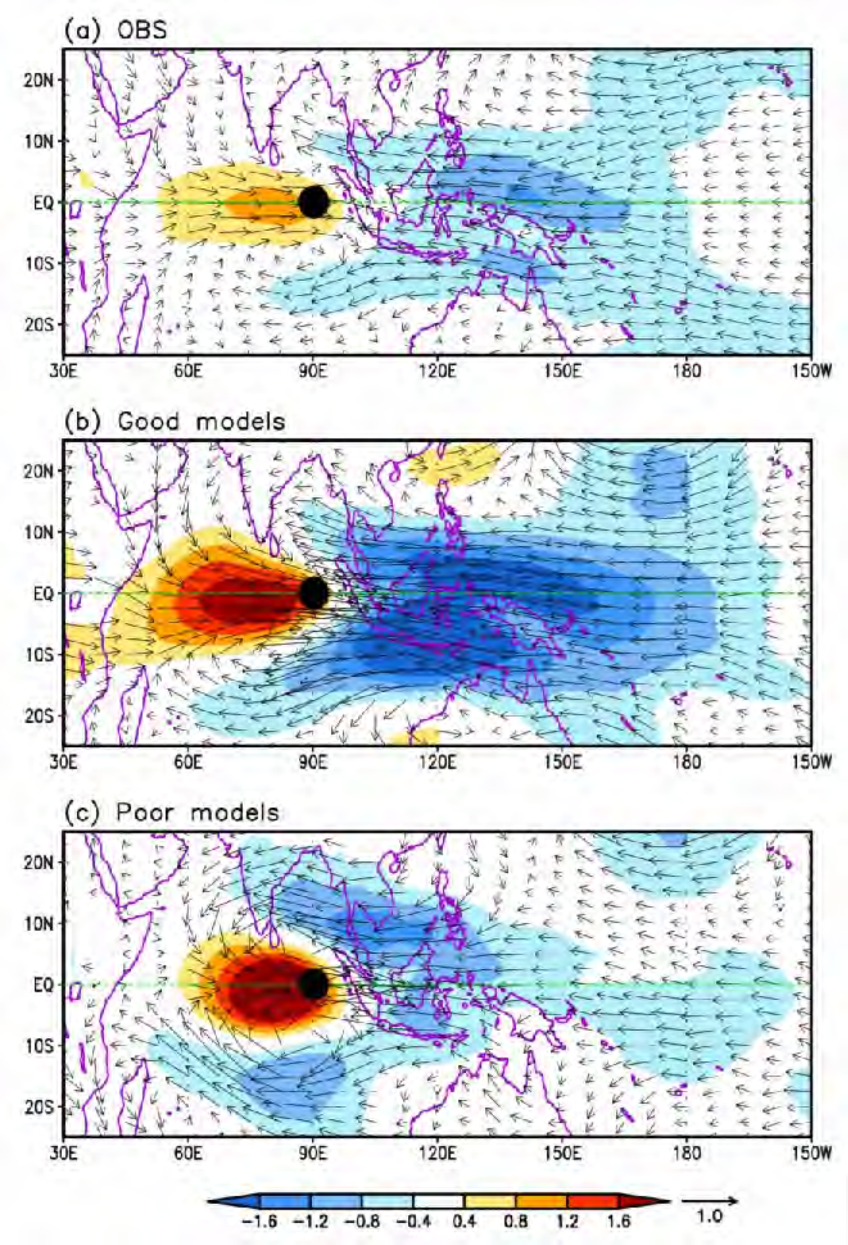
Measure of MJO simulation skill

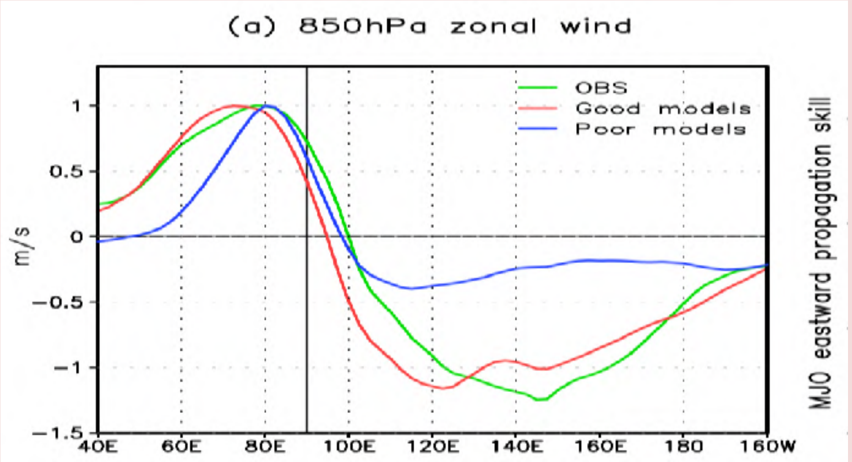


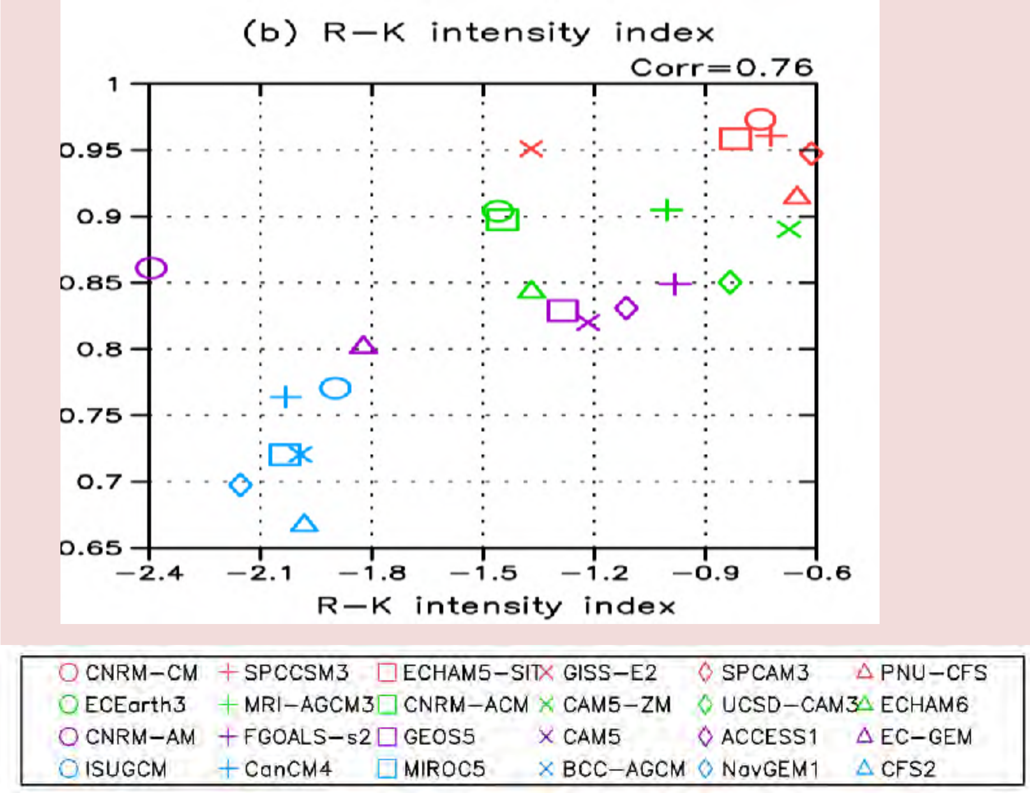
Why do GCMs have diverse performances in simulated MJO propagation?

Hypothesis: the propagation skill may determined by their zonal asymmetry in their dynamic and thermodynamic structures

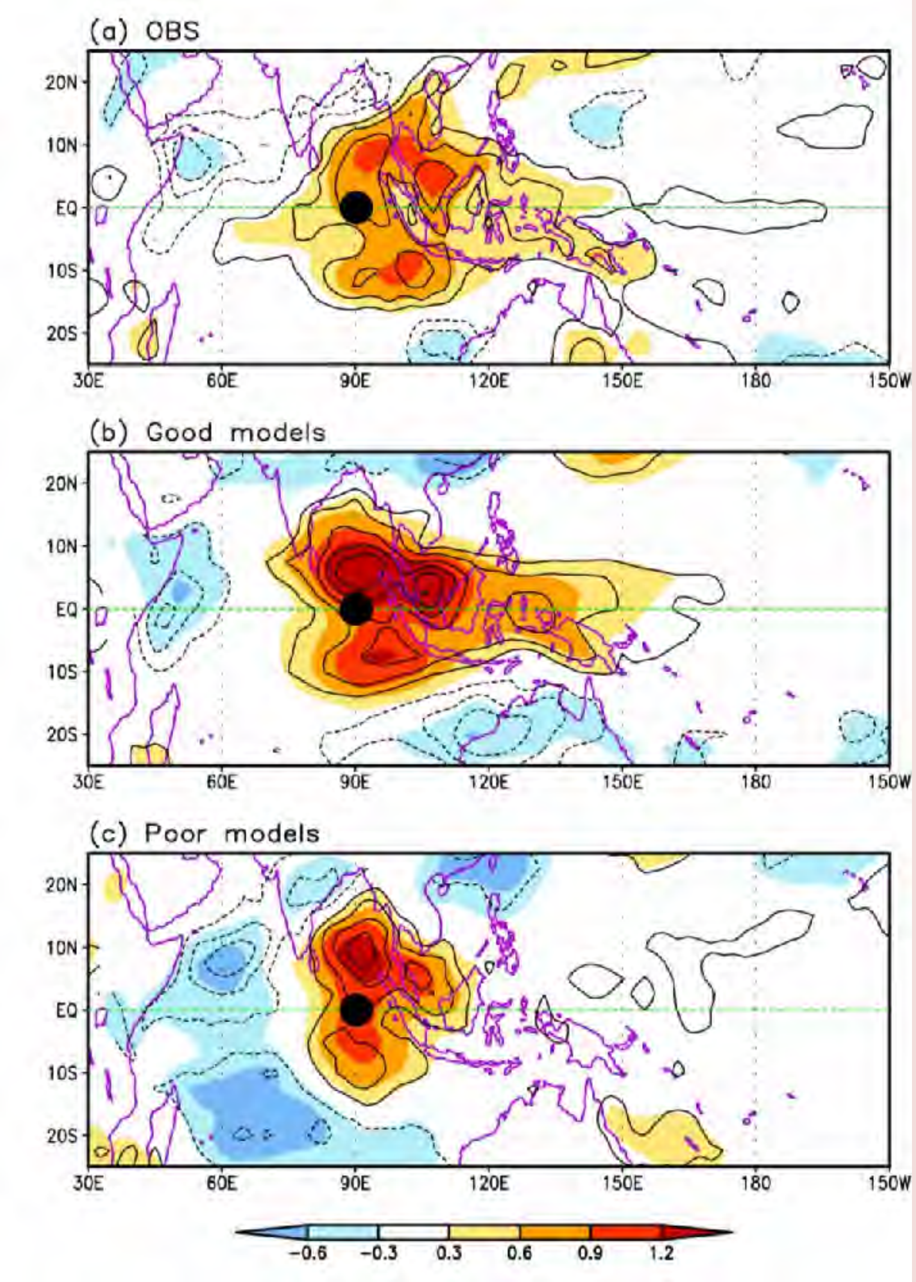
MJO Zonal wind asymmetry and propagation

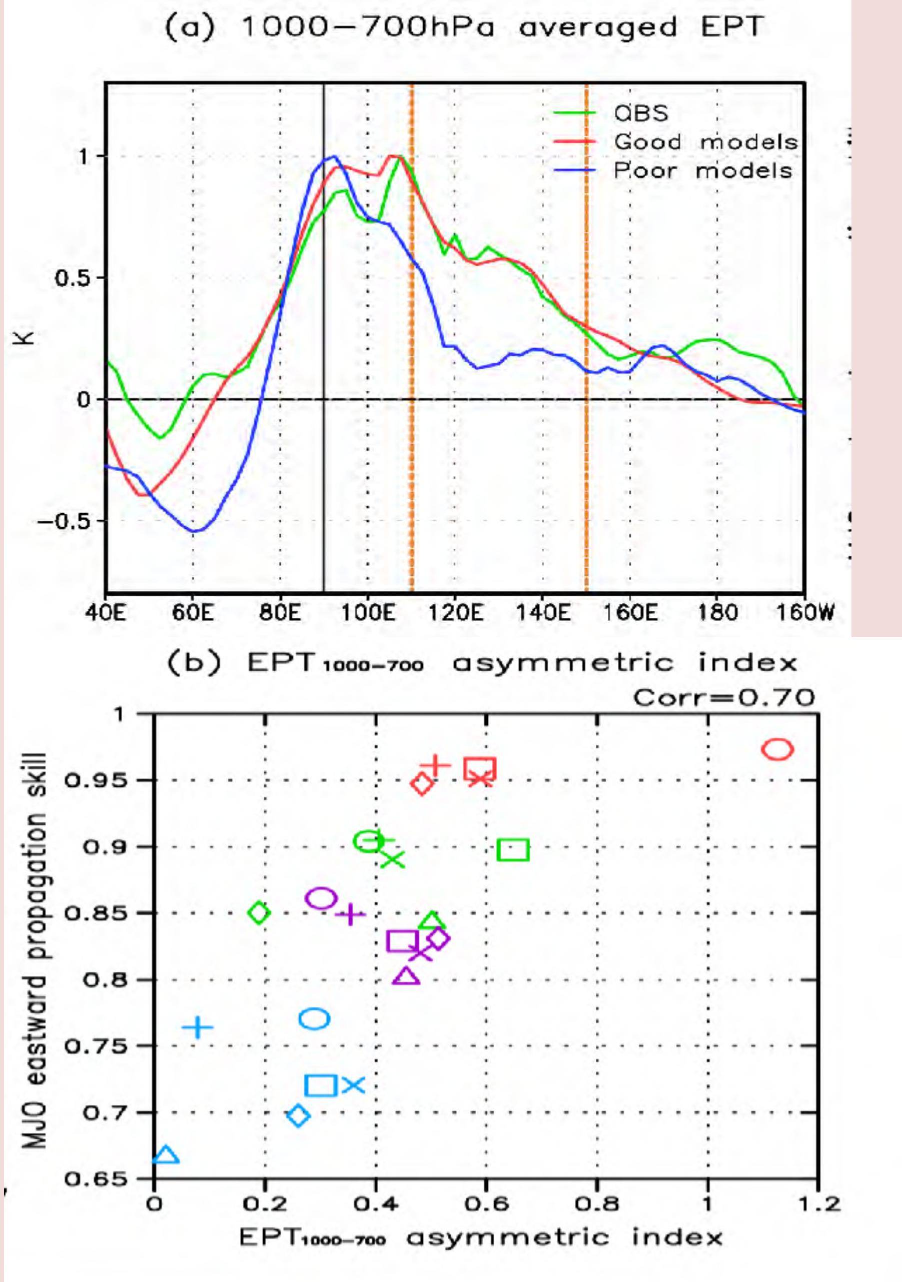




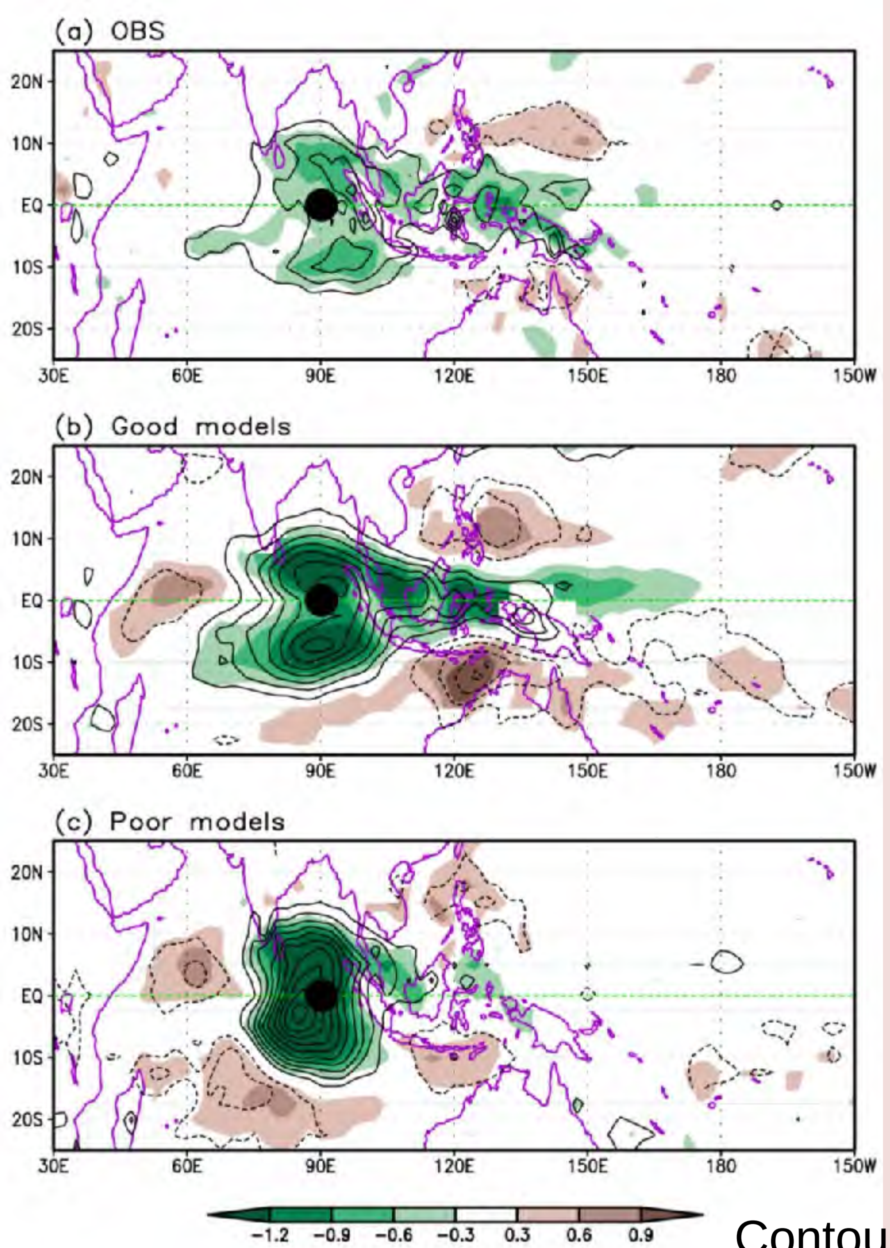


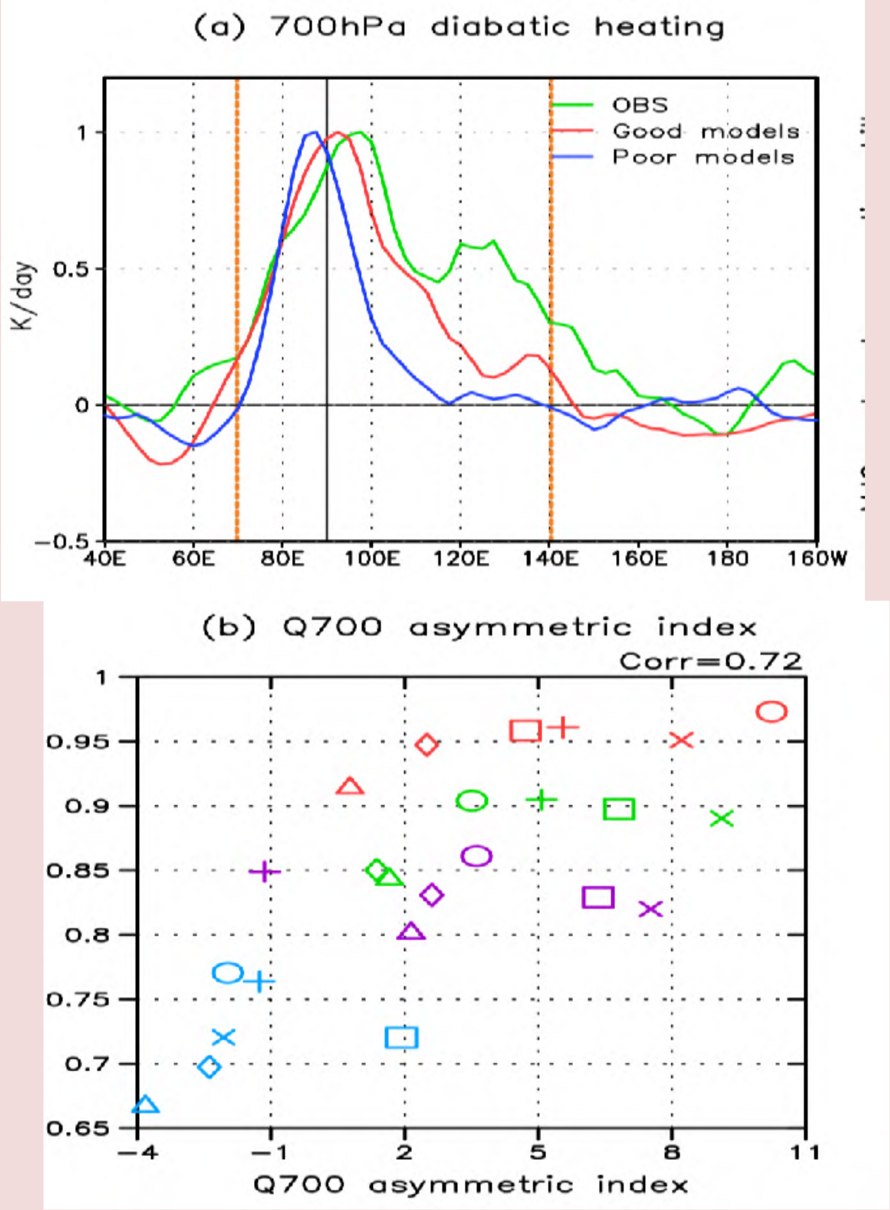
MJO 1000-700 hPa Moist Static Energy





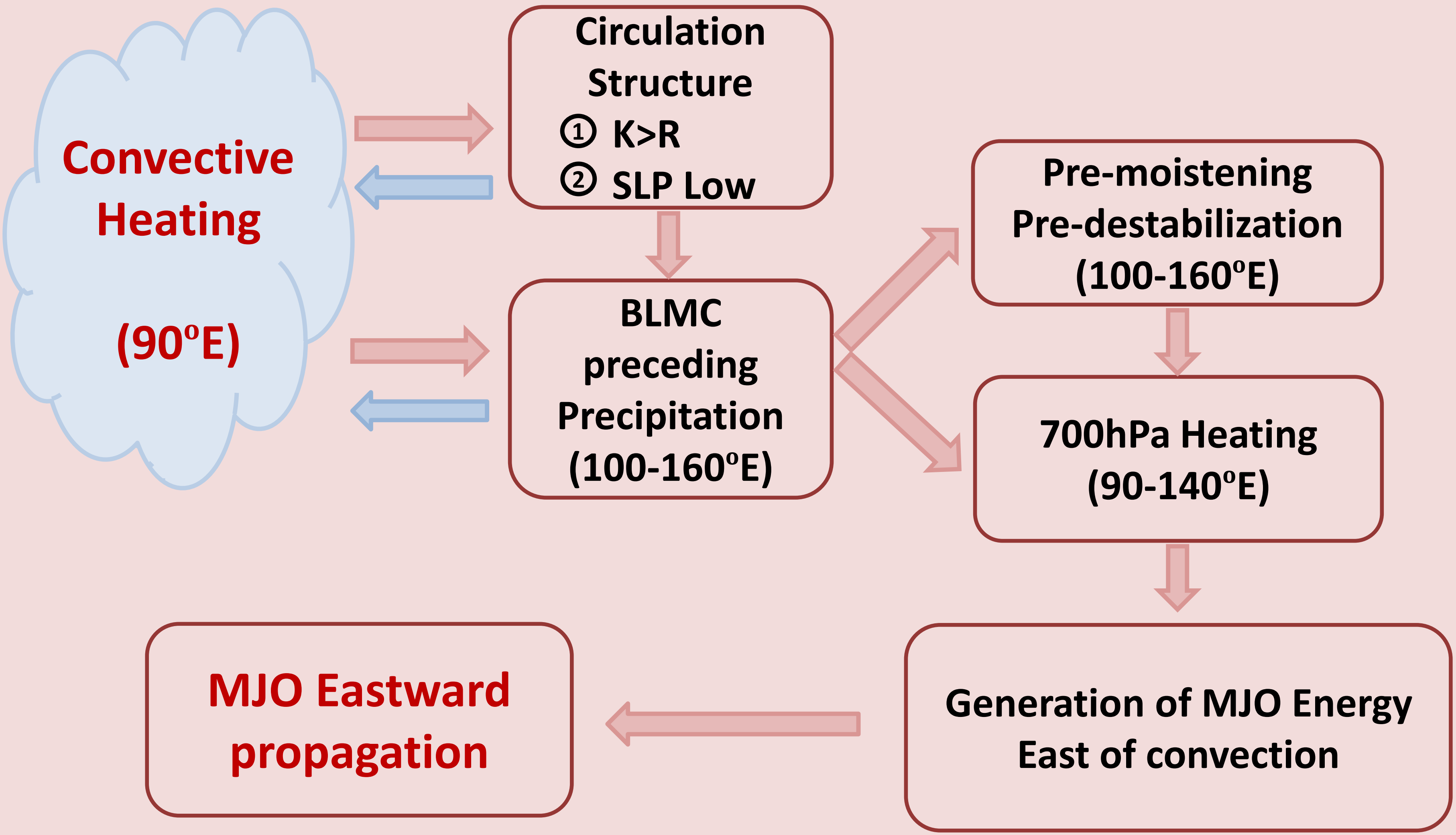
MJO BL convergence and 700 hPa diabatic heating





Contours: heating

Hypothesis



Schematic diagram illustrating the mechanism for MJO eastward propagation

Major points from GCM simulations

- An intrinsic linkage is found between MJO propagation and the zonal structural asymmetry In 24 GCM simulations.
- The MJO structural asymmetry is generated by the trio-interaction among convective heating, moisture, and wave-BL dynamics.
- The BLMC stimulates MJO eastward propagation by pre-moistening and pre-destabilizing the lower troposphere, and by generating lower-tropospheric heating and available potential energy to the east of precipitation center.

Three issues

(I) What are the relationships between MJO structures and propagation in GCM simulation?

(II) How to diagnose GCMs’ problems in MJO simulation? Dynamics-oriented diagnostics for MJO simulation.

(III) How to Improve GCMs’ simulation of MJO?

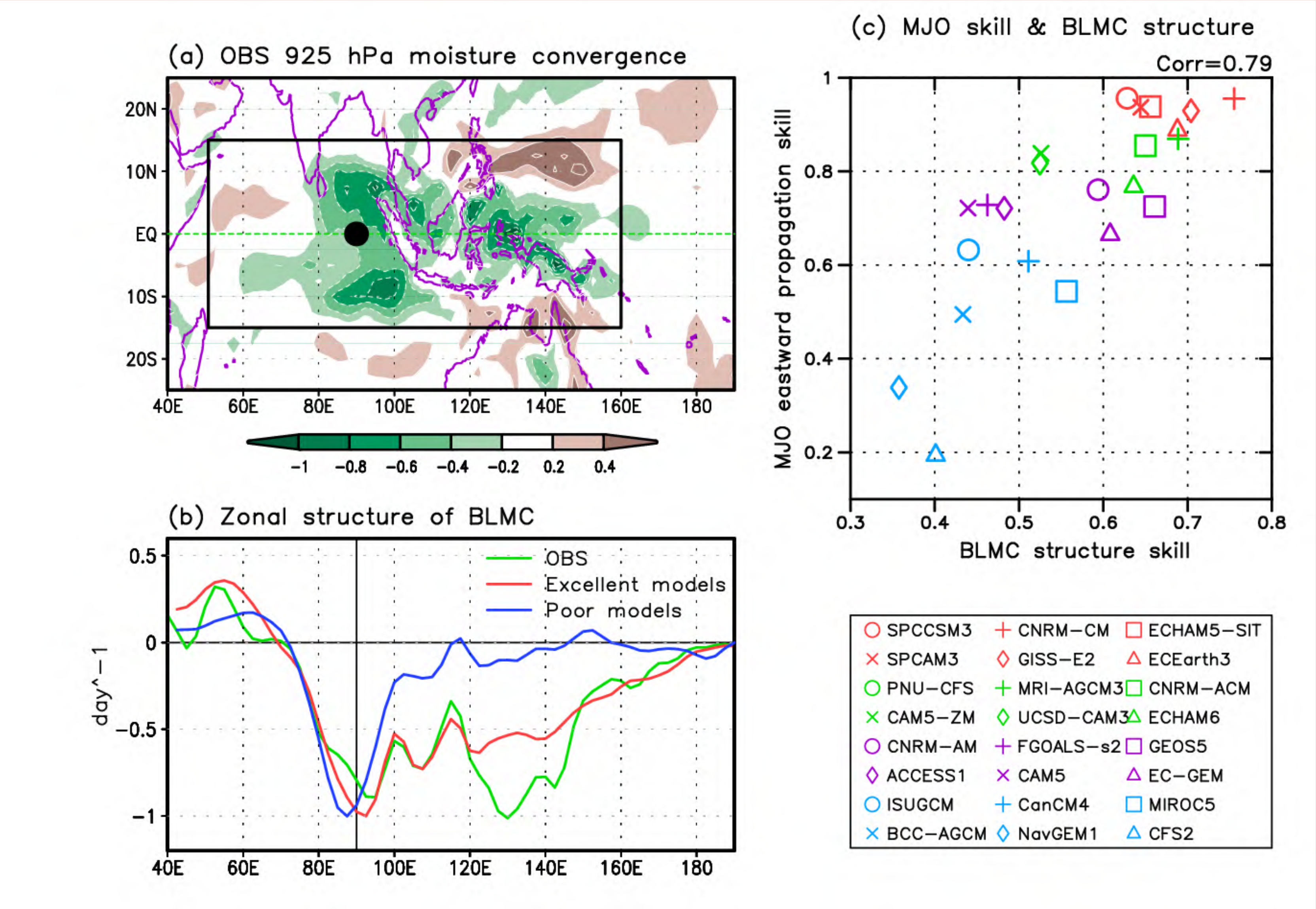
Distinct Features of Dynamics-Oriented Diagnostics

Perception: the MJO is a dynamic system with characteristic dynamic and thermodynamic structures that are intimately related to its propagation and instability.

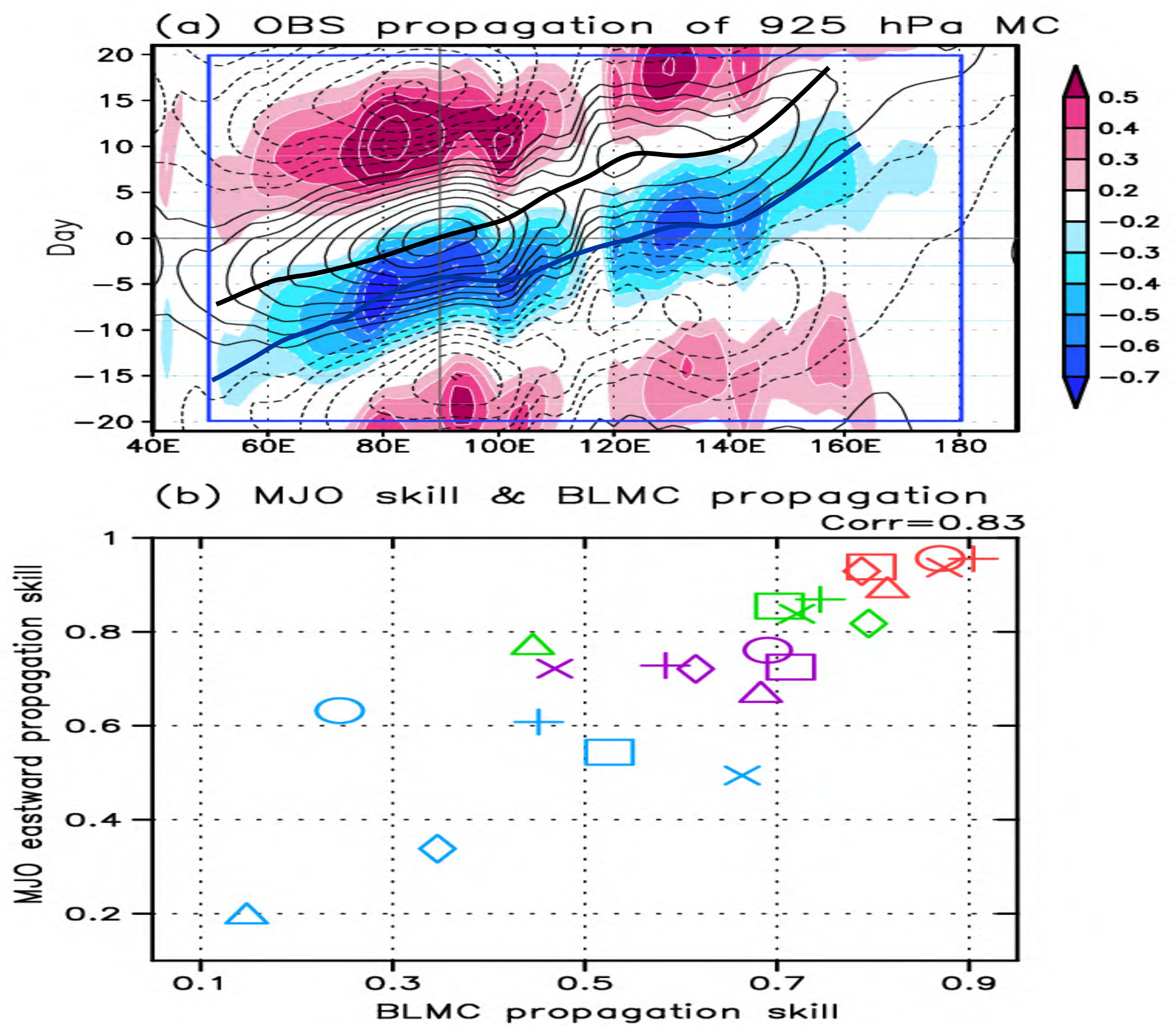
Motivated by observed rudimentary features of the MJO and theoretical understanding of the essential MJO dynamics with specific attention to the processes associated with MJO propagation.

Each proposed diagnostic variable is intended to be physically intuitive, statistically robust, as well as easy to compute in order to quantitatively measure the GCMs’ skill.

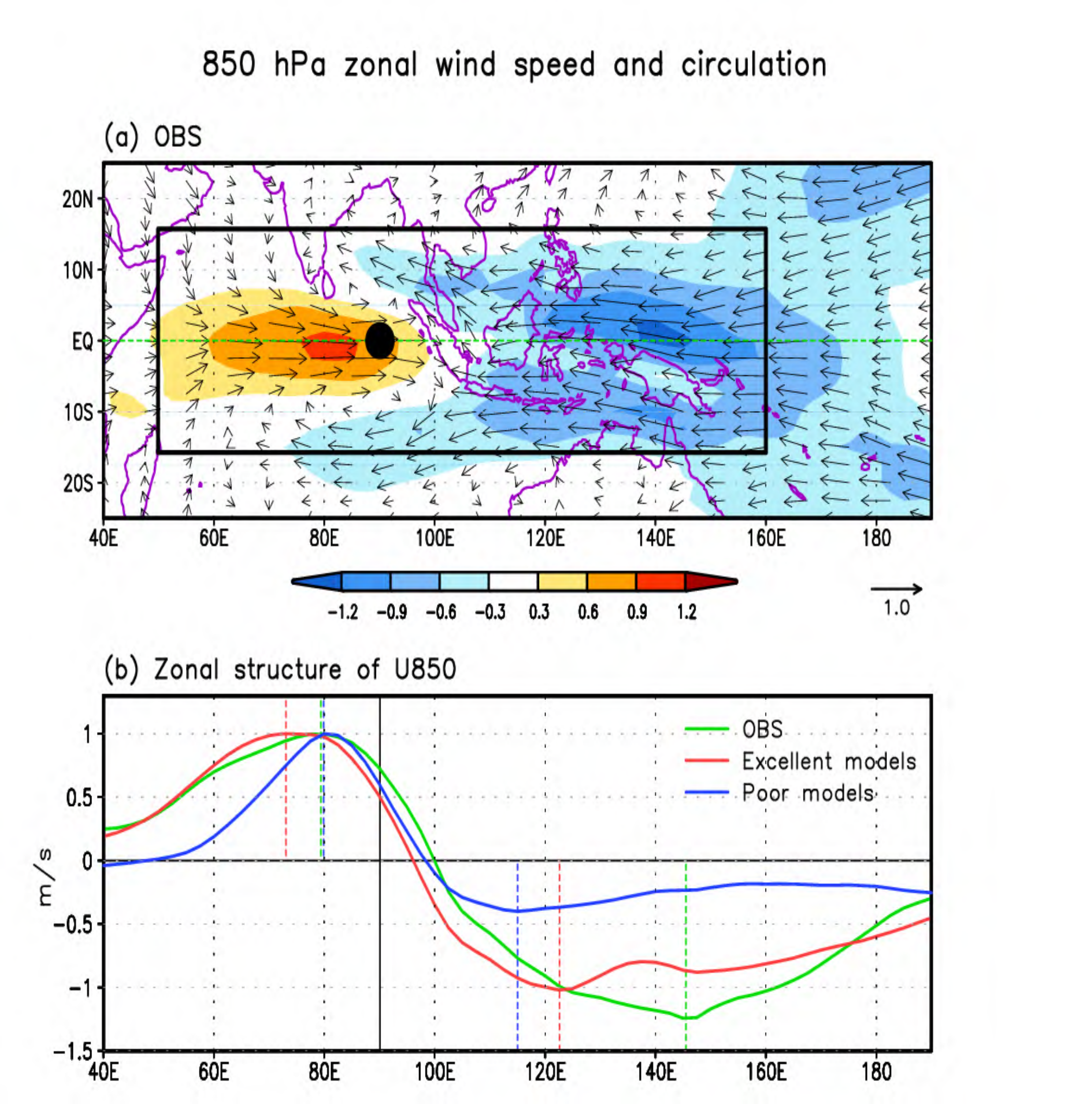
Metric 1:Structure of the BL moisture convergence

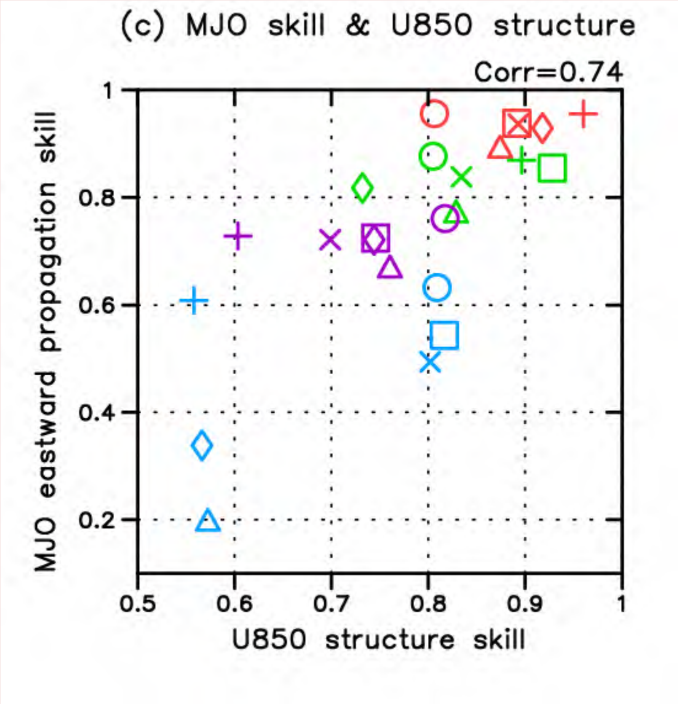


Metric 2: Propagation of BLMC

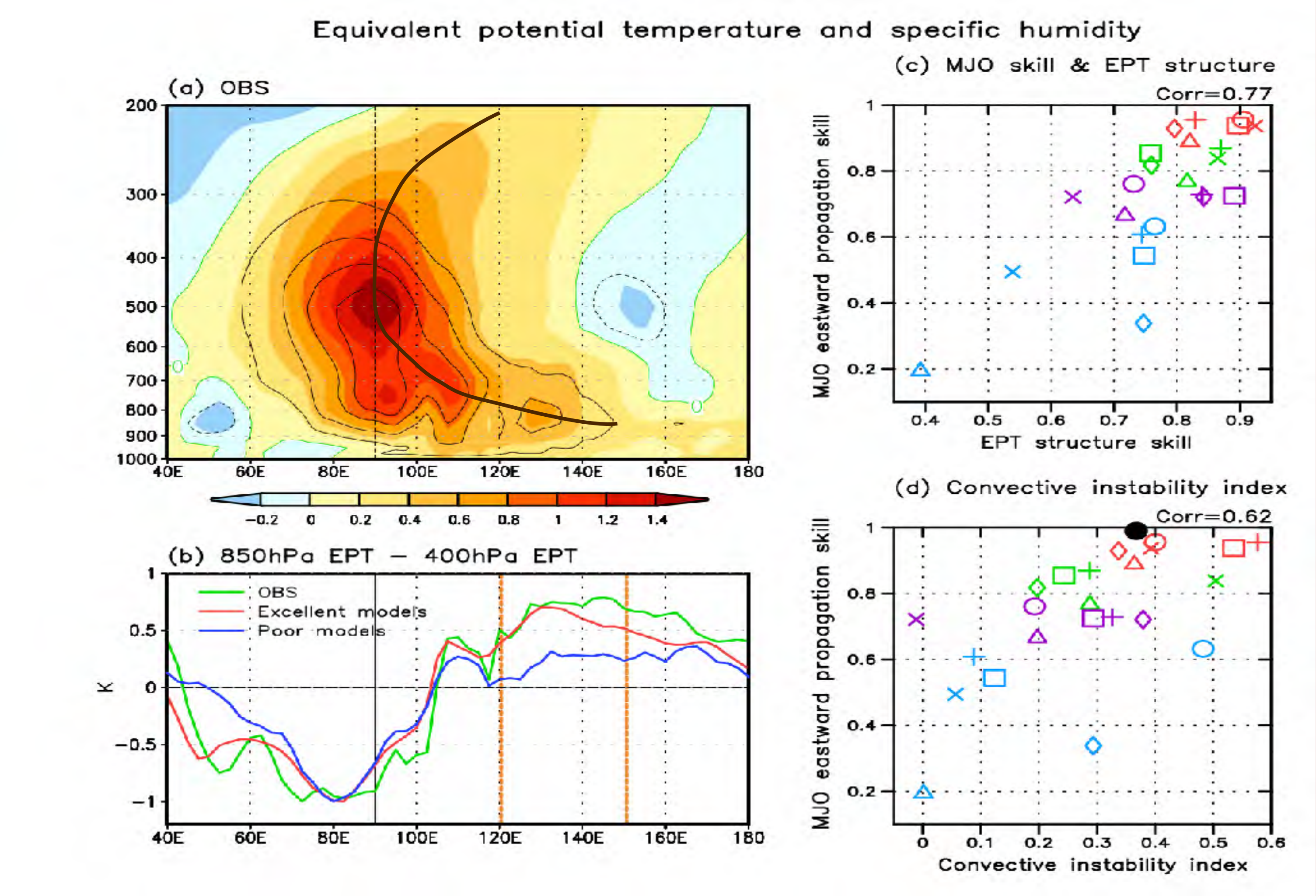


Metric 3: Zonal asymmetry in U850

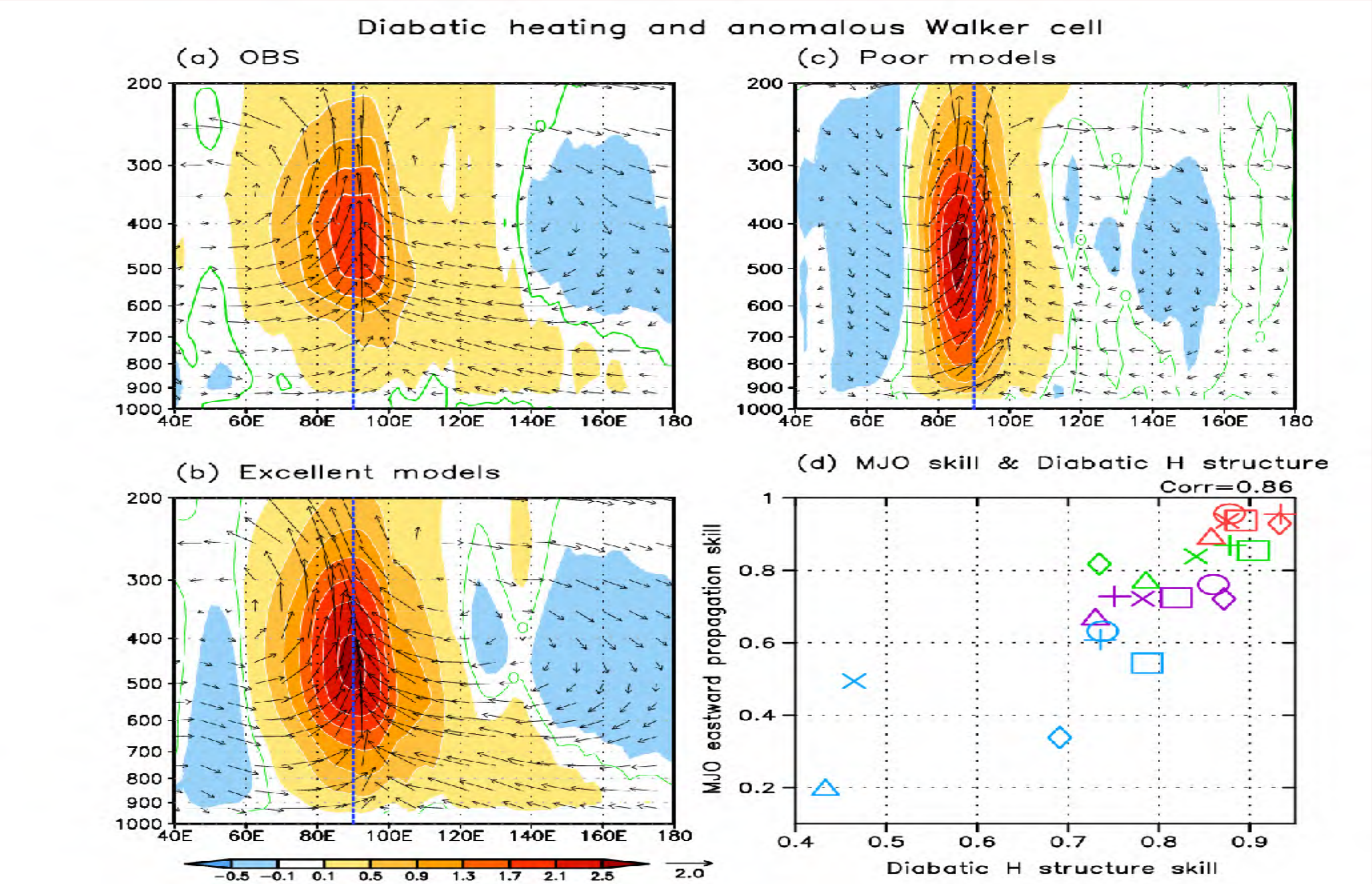




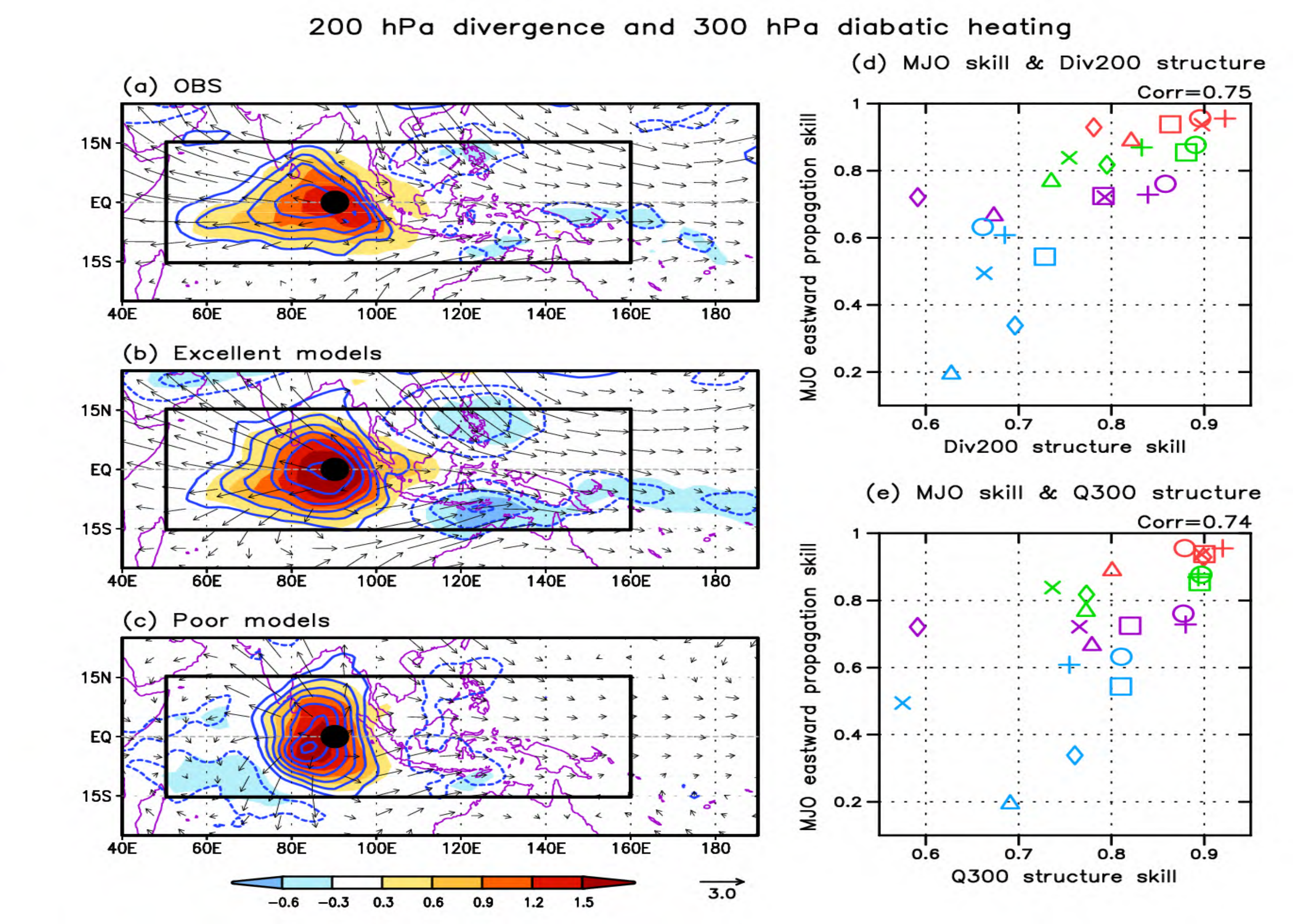
Metric 4: EPT or MSE structure



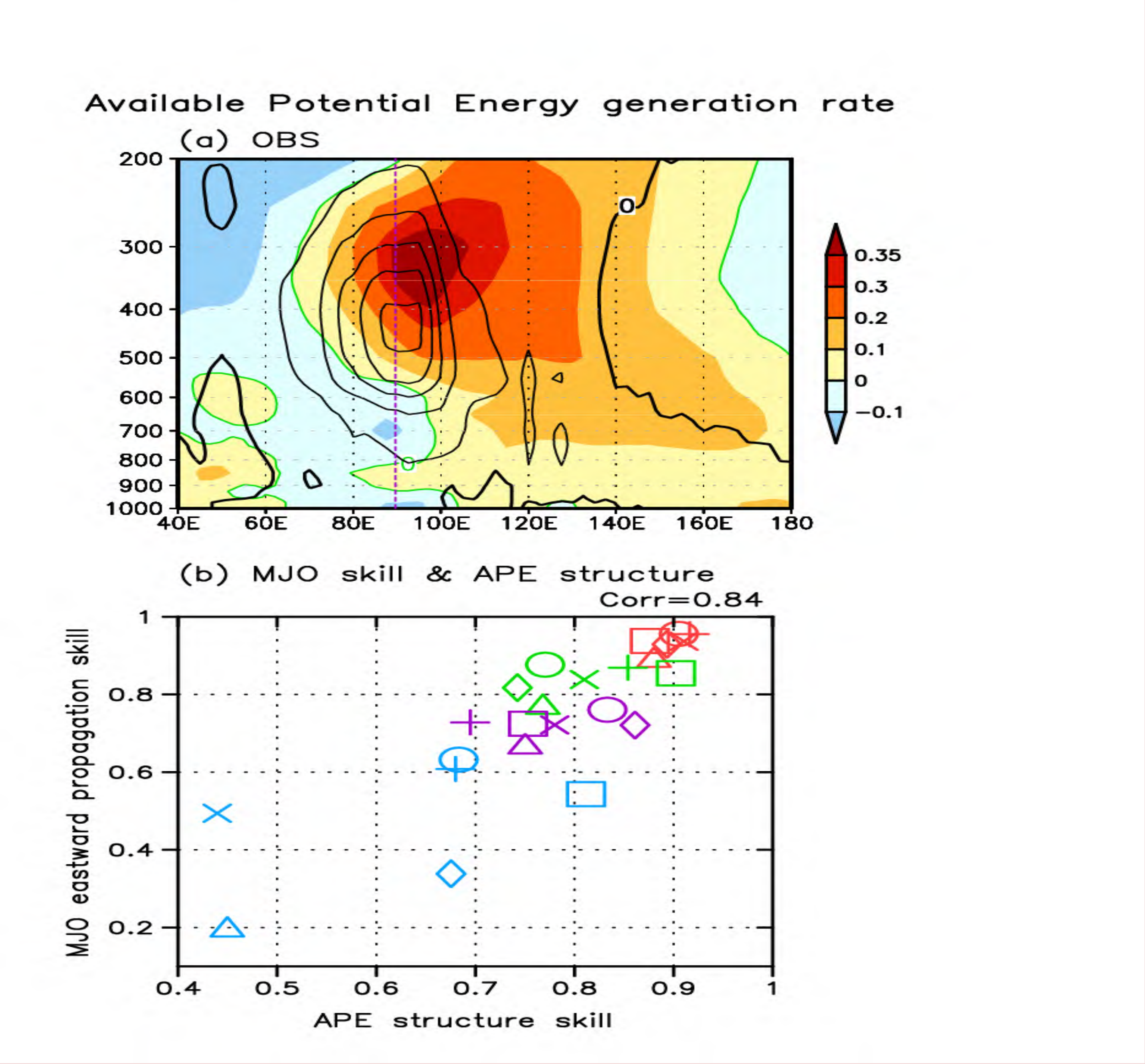
Metric 5: Diabatic heating structure



Metric 6: DIV 200 (contours) and Q300 (Color)



Metric 7: Eddy APE generation rate (contour)



Summary of 24 models' performances in simulation of the dynamics-oriented diagnostics

Diagnostic fields	Model groups (Fig. 1d)			
	Excellent	Good	Fair	Poor
Horizontal structure of BLMC	0.68	0.61	0.54	0.45
Propagation of BLMC	0.84	0.68	0.63	0.40
Horizontal structure of U850	0.89	0.84	0.73	0.69
Vertical structure of EPT	0.86	0.81	0.78	0.66
Vertical structure of diabatic heating	0.89	0.83	0.80	0.64
Horizontal structure of 200 hPa divergence	0.86	0.81	0.76	0.68
Vertical structure of eddy APE generation	0.90	0.81	0.78	0.62

Major points

- The dynamics-oriented diagnostics provide discrimination and assessment of MJO simulations based on the perception that the MJO propagation is shaped by its dynamic structures.
- The diagnostics metrics: (1) horizontal structure of BLMC; (2) the preluding eastward propagation of BLMC; (3) horizontal structure of 850 hPa zonal wind and its equatorial asymmetry (Kelvin easterly vs. Rossby westerly intensity); (4) vertical structure of EPT and convective instability; (5) vertical distribution of diabatic heating that reflects the multi-cloud structure; (6) upper-level divergence that reflects the influence of stratiform cloud heating; and (7) the generation of MJO available potential energy.
- The new dynamics-oriented diagnostics help to evaluate whether a model produces eastward propagating MJO for the right reasons, to identify shortcomings in representing dynamical and heating processes relevant to the MJO simulation and to reveals potential sources of the shortcomings.

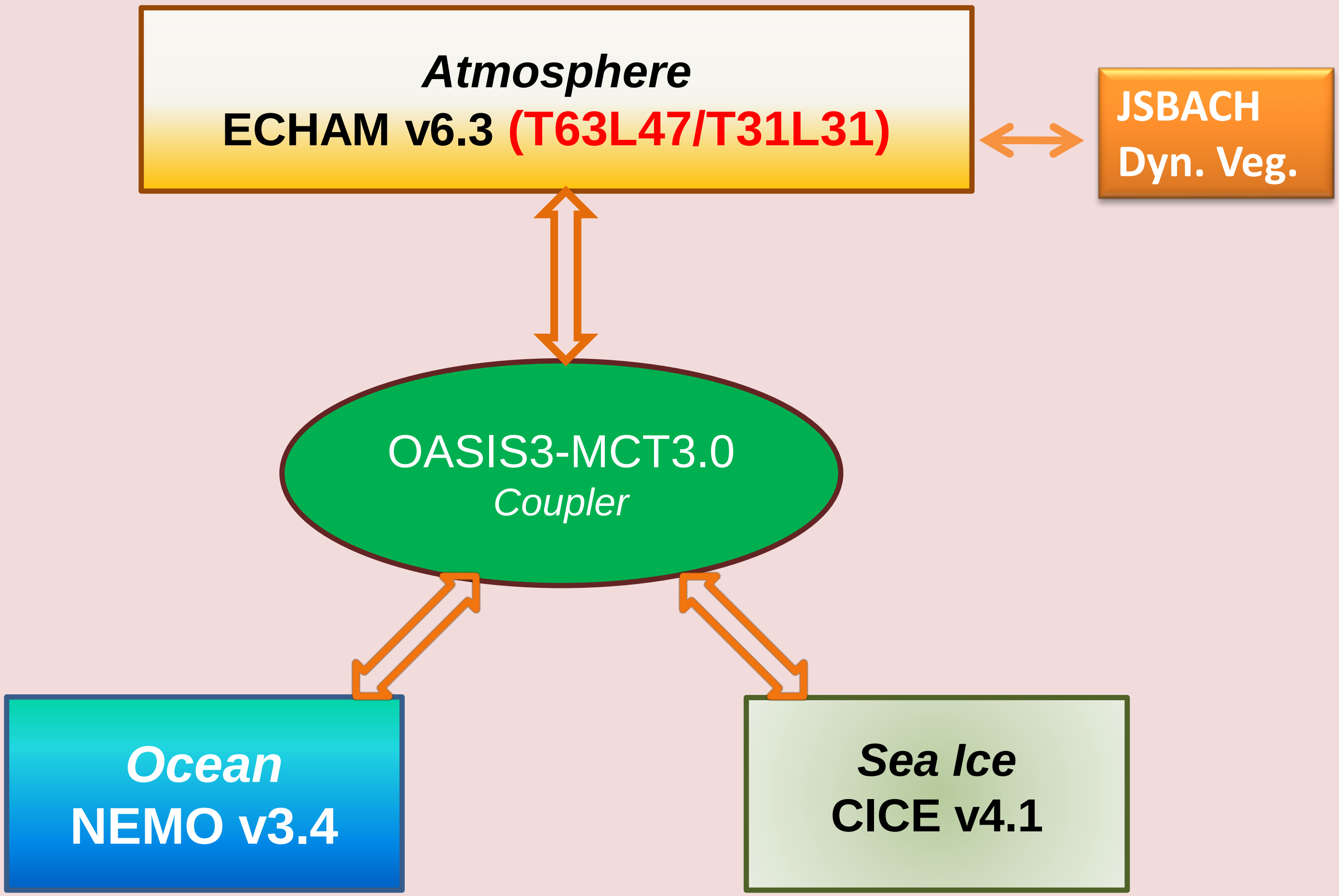
Thanks you!
Any comments?

III. Improving MJO simulation by enhancing lower tropospheric heating - boundary layer convergence feedback

Young-Min Yang and Bin Wang

Submitted to Climate Dynamics

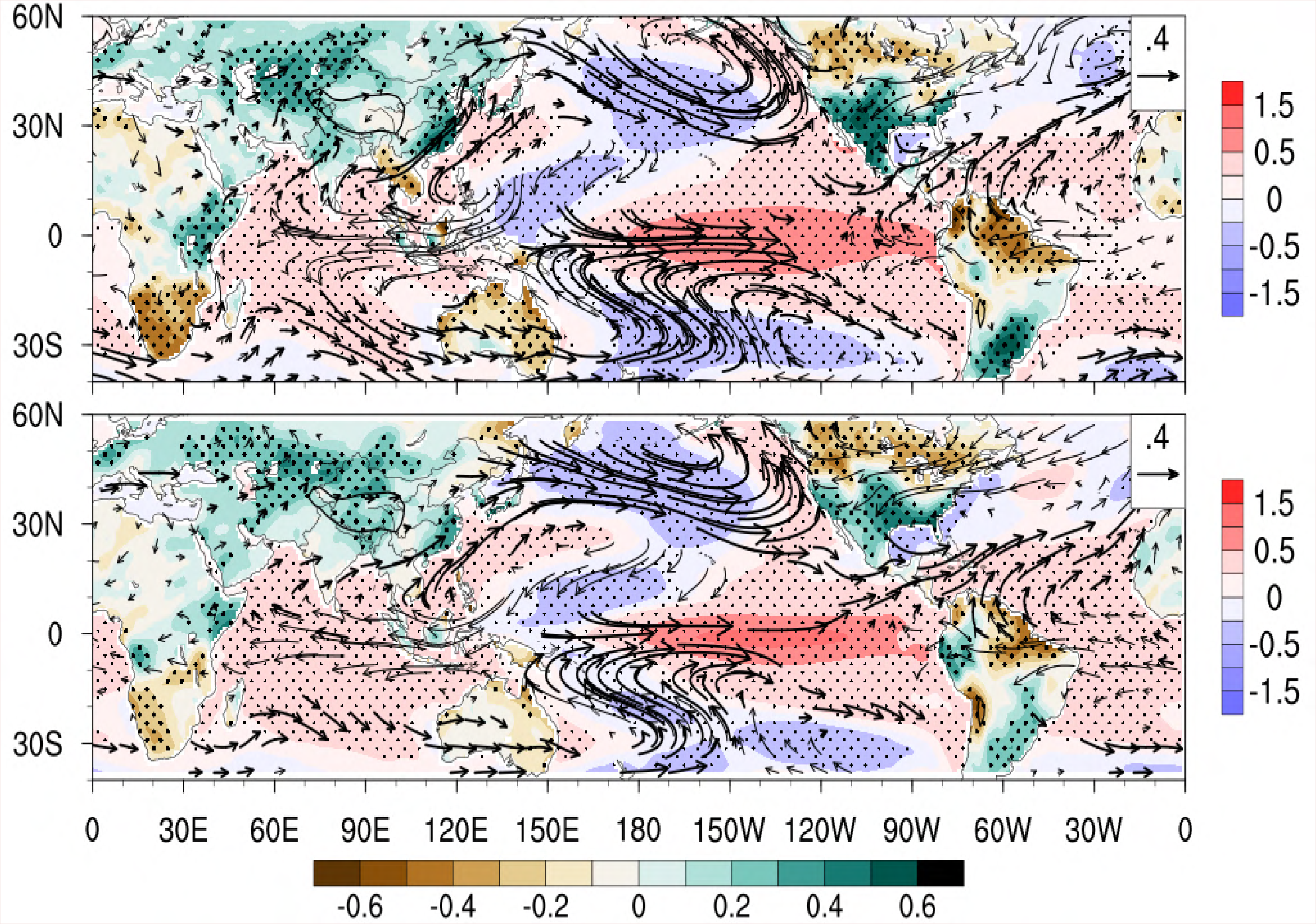
NUIST-ESM V3



Dec. 2016

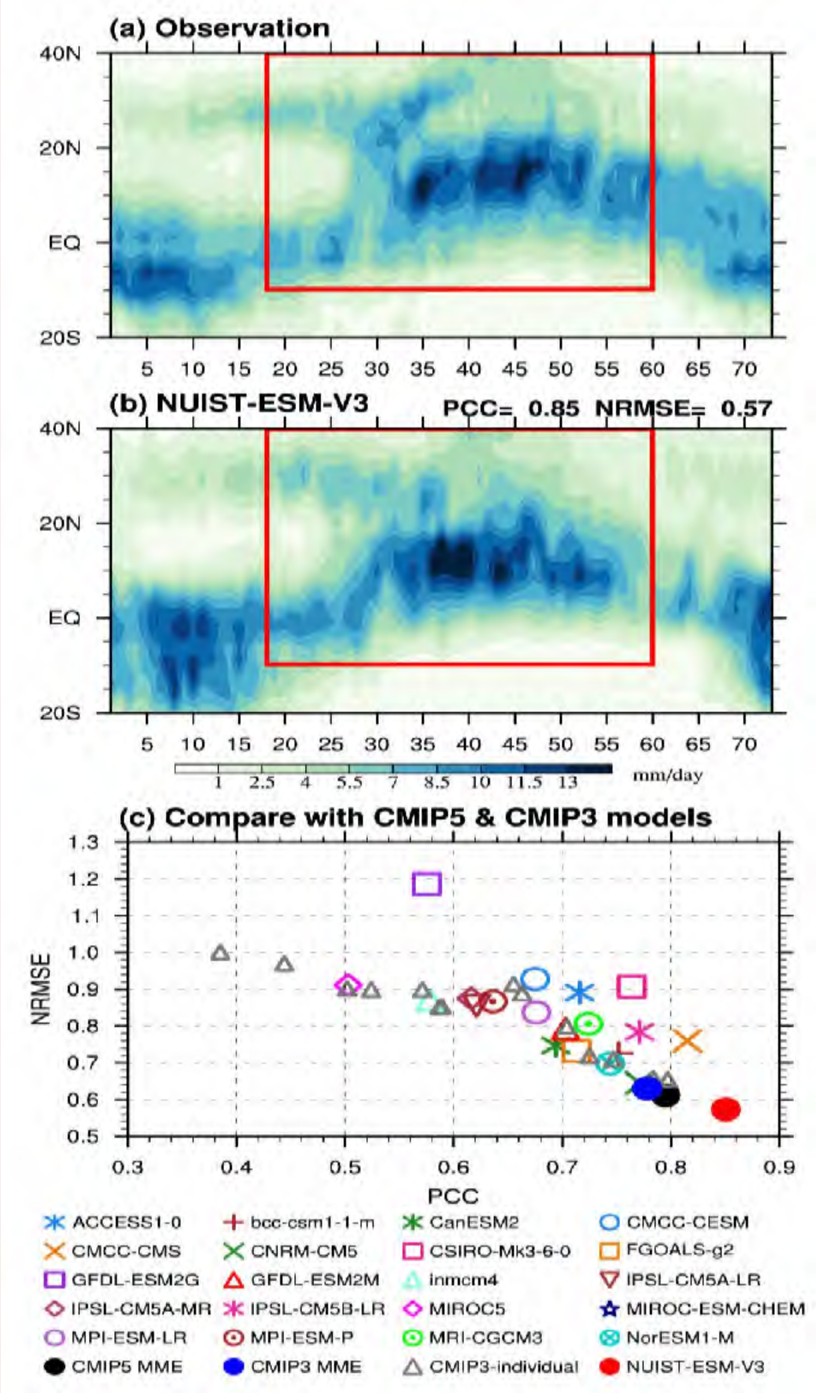
Cao, Wang, Yang et al. 2015, 2017

Correlation map of Land precipitation, SSTA and 850 hPa wind anomalies wrt DJF Nino-3.4 SSTA



OBS (1901-2012)

Historical run (1901-2012)



Seasonal migration of East Asia-WNP precipitation belt

Annual cycle (climatology 1979-2005) for pentad mean precipitation averaged between 110E and 130E from (a) observation and (b) NUIST-ESM-V3 simulation. The PCC and NRMSE skills are calculated over 10S-40N, 18-60 pentad(Apr.-Nov) (red rectangle). (c) Models' performance on simulation of climatological annual cycle of precipitation in terms of PCC and NRMSE.

Summary

How to improve GCM simulation of MJO?

Modification of the convective parameterization schemes:

a) a BL depth-dependent convective trigger (TRG), and

b) a bottom-heavy diffusivity in the shallow convection scheme (SHC), aiming to enhance BLMC feedback on convection.

Results: In the NUIST-ESM, modified Tidtke (M-TDK) Simplified Arakawa-Schubert (M-SAS) convective schemes have significantly improved the quality of MJO simulation.

Why do the modification leads to improved simulation?

Implications: Correct simulation of the heating induced by shallow and/or congestus clouds and its interaction with BL dynamics is critical to realistic simulation of the MJO.

Experiments with modified convective parameterization schemes in the NUIST v3

Exp.	Convective parameterization	Modified scheme
CTL-TDK	Tiedtke scheme (Tiedtke, 1989)	-
TRG	Tiedtke scheme (Tiedtke, 1989)	BL depth-dependent convective trigger function (TRG)
SHC	Tiedtke scheme (Tiedtke, 1989)	Bottom-heavy diffusivity in shallow convection (SHC)
M-TDK	Tiedtke scheme (Tiedtke, 1989)	TRG + SHC
CTL-SAS	Simplified Arakawa-Schubert scheme (Lee et al. 2001)	-
M-SAS	Simplified Arakawa-Schubert scheme (Lee et al. 2001)	TRG +SHC

Improved eastward propagation

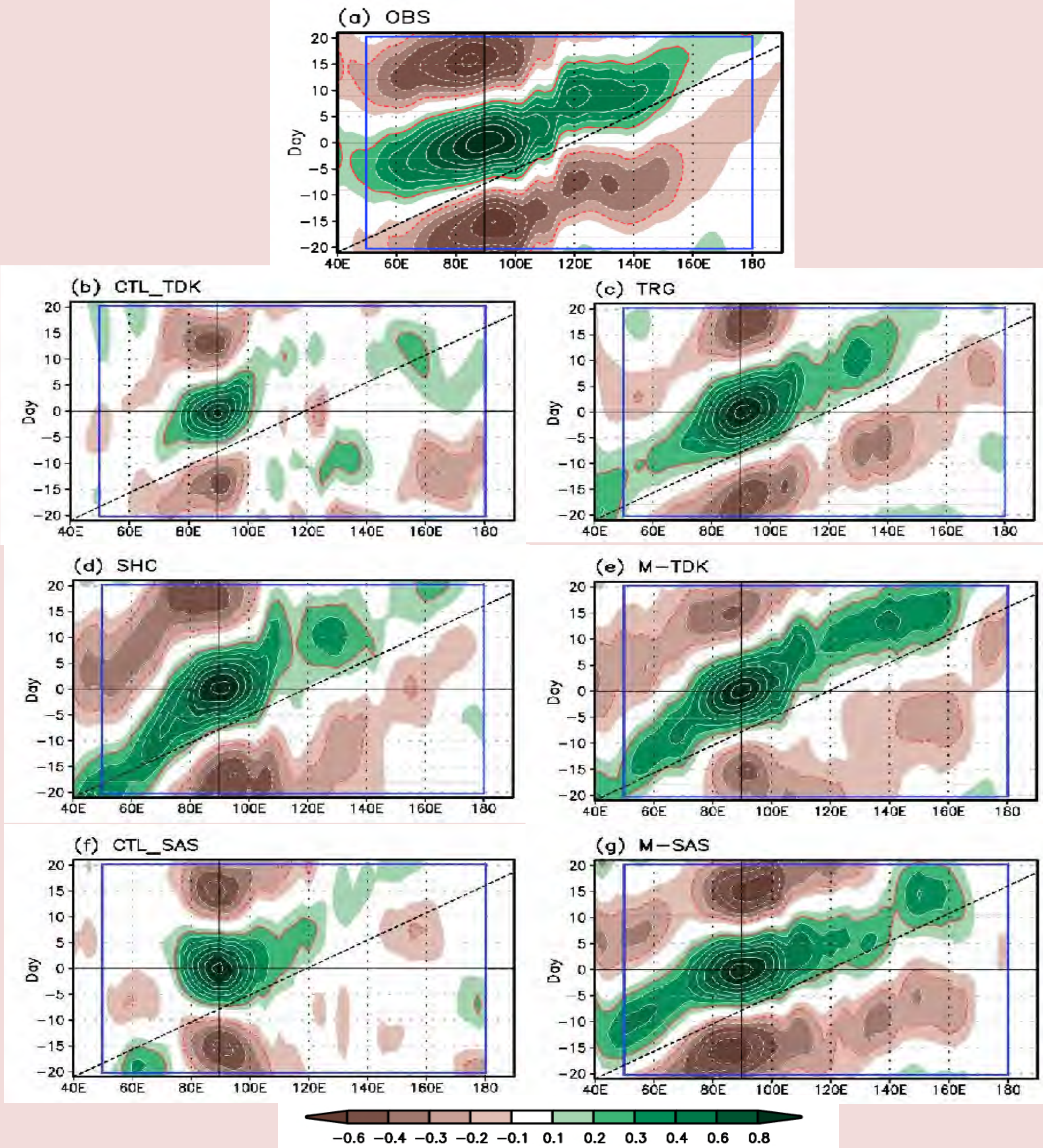
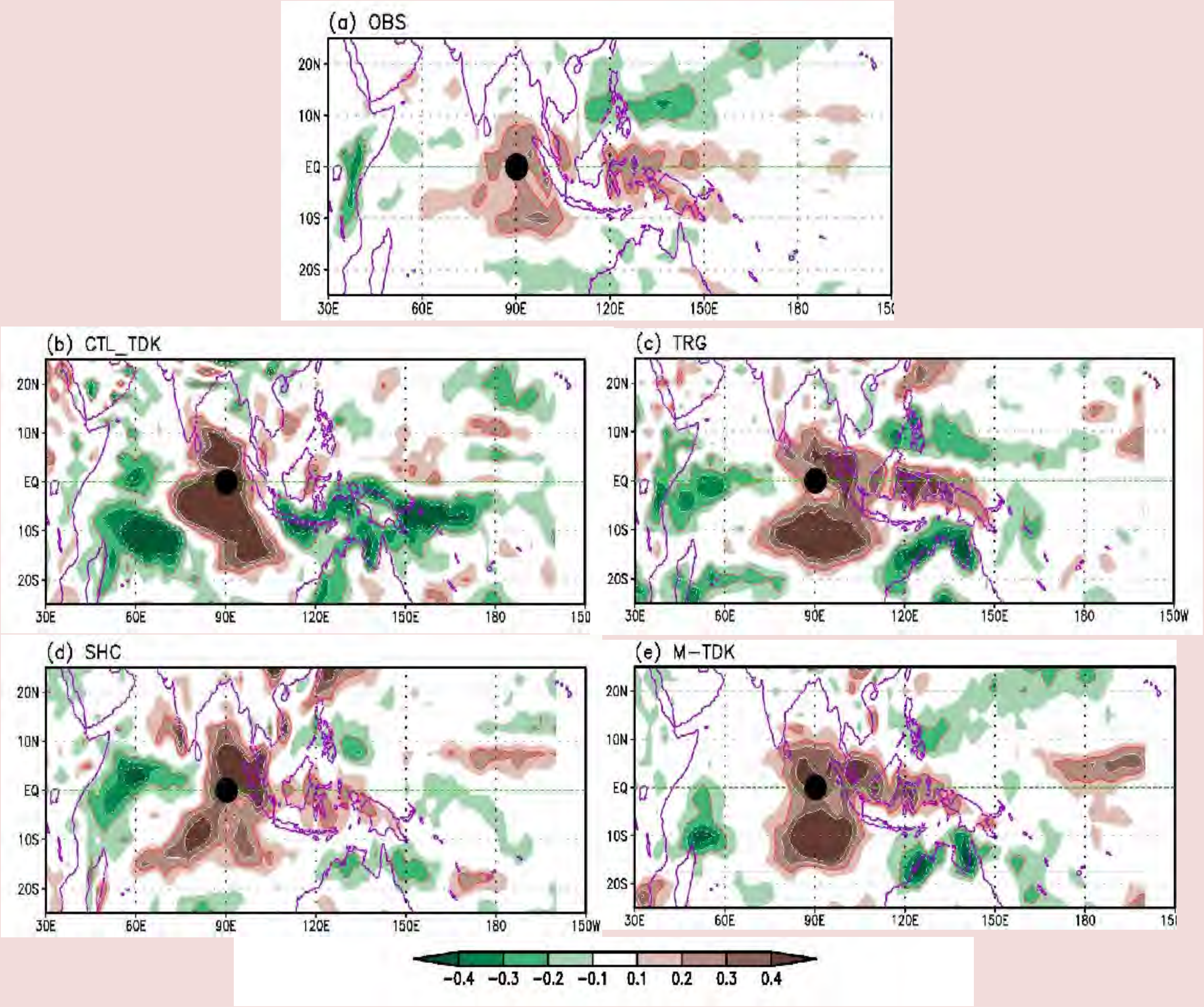
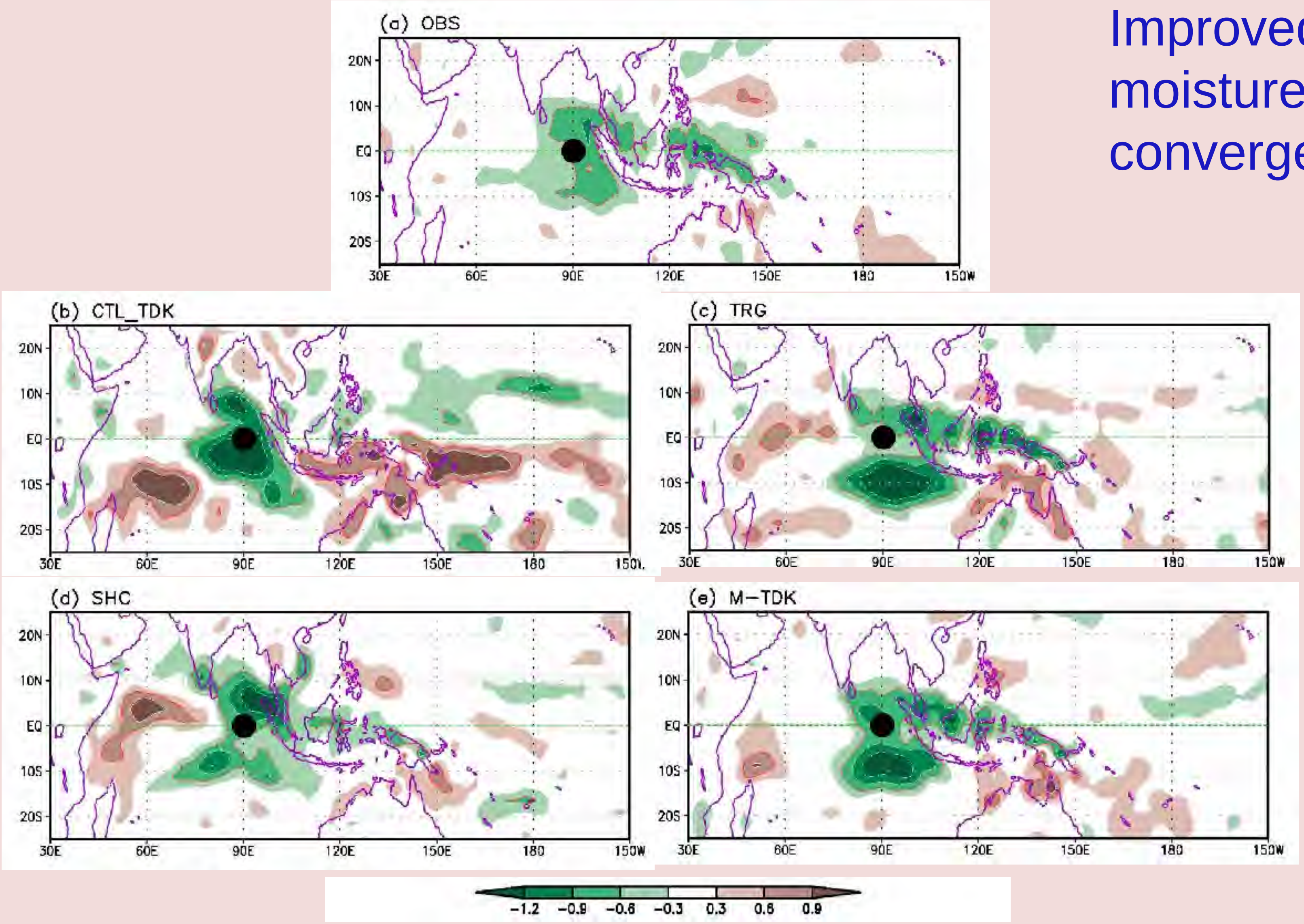


Figure 1. Propagation of MJO precipitation as depicted by the lead-lag correlation of 20-70 day filtered precipitation averaged over 10°S-10°N with reference to the precipitation at the MJO convective center over the equatorial Indian Ocean (10°S-10°N, 80°-100°E) during boreal winter (NDJFMA) derived from (a) observation and model simulations in the experiments of (b) CTL-TDK, (c) TRG, (d) SHC, (e) M-TDK, (f) CTL-SAS and (g) M-SAS. The red contour represents the correlation coefficient of ±0.2. Black dotted lines indicate eastward propagation speed of 5 m s^{-1}.

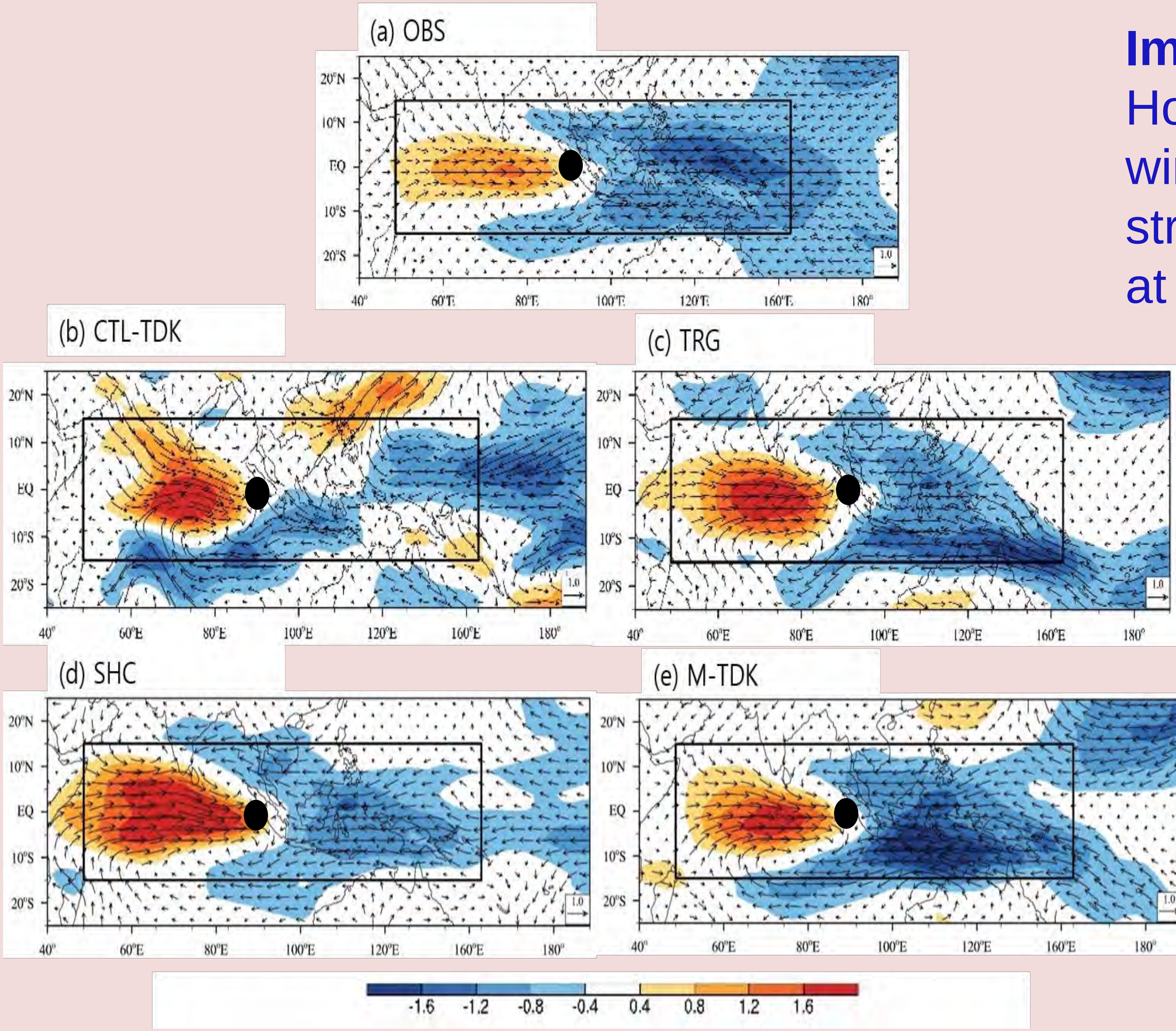
Improved Horizontal structure of diabatic heating at 700hPa

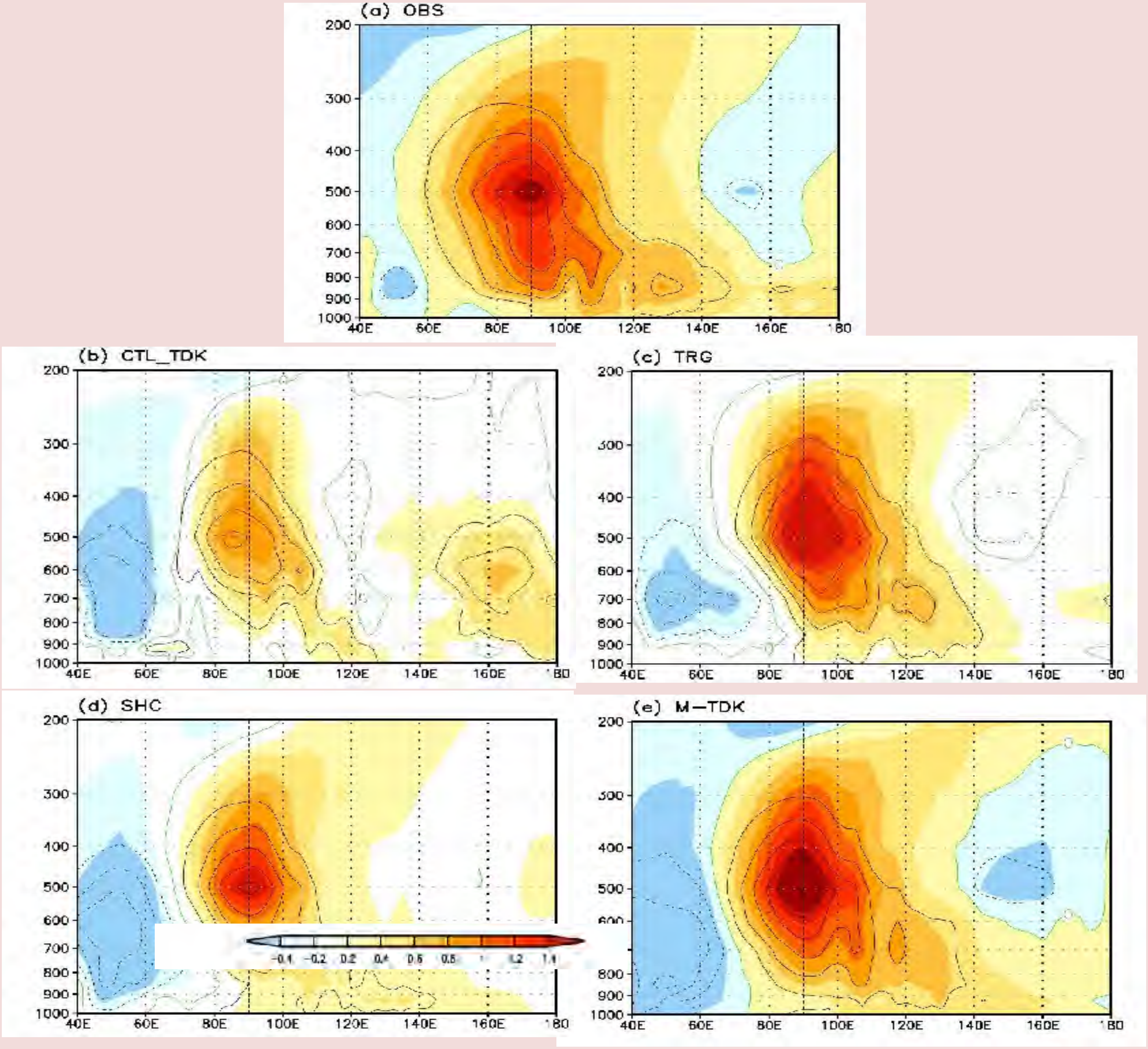


Improved BL moisture convergence



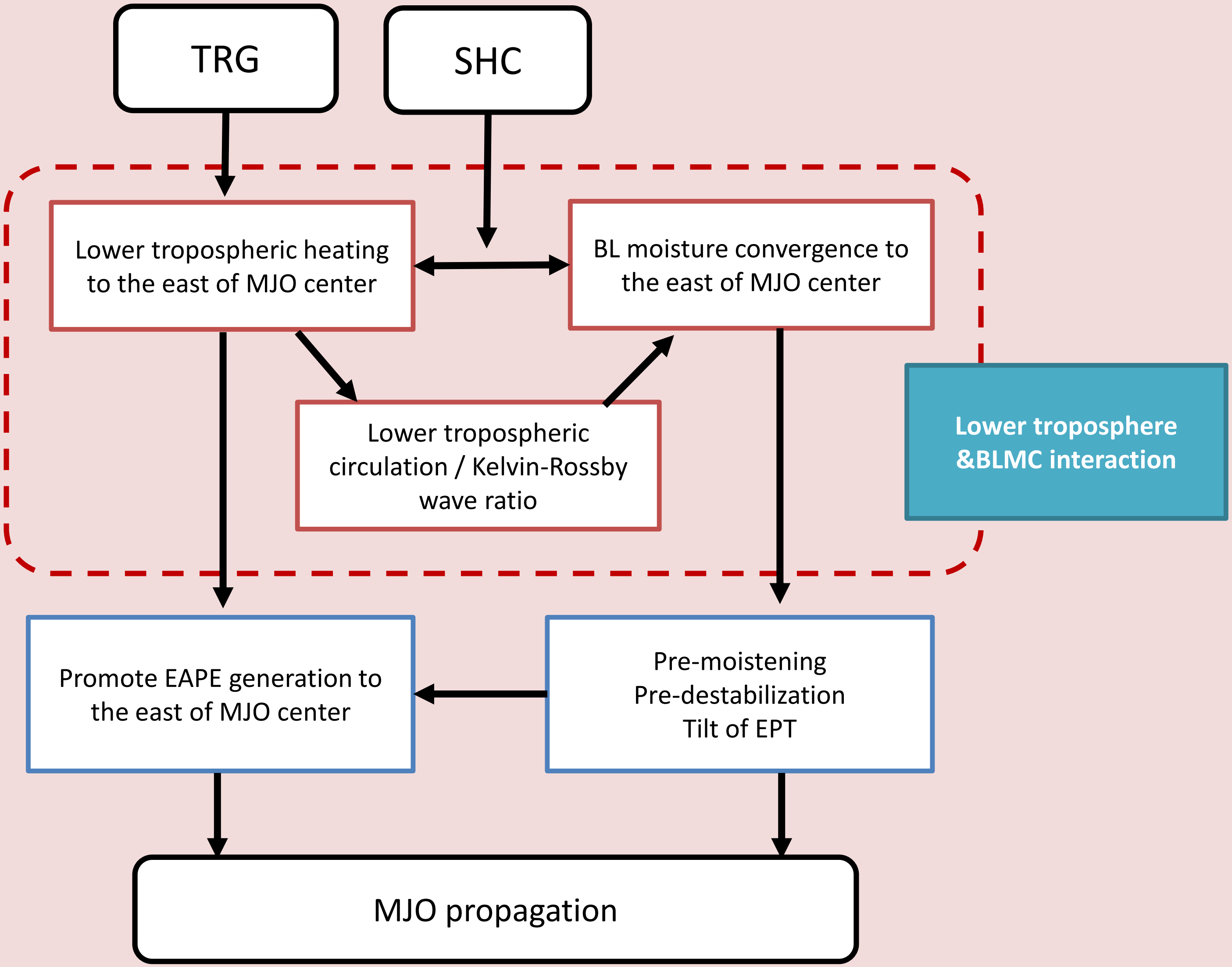
Improved Horizontal wind structure at 850hPa





Improved moistening and destabilization to the east of major convection

Why MODIFICATIONS work



Mechanisms by which the modified cumulus schemes affect MJO structures and improve the MJO eastward propagation.

Three issues

(I) What are the relationships between MJO structures and propagation in GCM simulation?

(II) How to diagnose GCMs' problems in MJO simulation? Dynamics-oriented diagnostics for MJO simulation.

(III) How to Improve GCMs' simulation of MJO?

Table 1. A list of models participating in the 20 year climate simulation (Jiang et al. 2015).

Model name	Institute	References
ACCESS1	Centre for Australian Weather and Climate Research	Zhu et al. (2013)
BCC-AGCM	Beijing Climate Center, China Meteorological Administration	Wu et al. (2010)
CAM5	National Center for Atmospheric Research	Neale et al. (2012)
CAM5-ZM	Lawrence Livermore National Laboratory	Song and Zhang (2011)
CanCM4	Canadian Centre for Climate Modelling and Analysis	Merryfield et al. (2013)
CFS2	Climate Prediction Center, NCEP/NOAA	Saha et al. (2013)
CNRM-AM	Centre National de la Recherche Scientifique/Météo-France	Voldoire et al. (2013)
CNRM-CM		
CNRM-ACM		
ECEarth3	Rossby Centre, Swedish Meteorological and Hydrological Institute	-
EC-GEM	Environment Canada	Côté et al. (1998)
ECHAM5-SIT	Academia Sinica, Taiwan	Tseng et al. (2014)
ECHAM6	Max Planck Institute for Meteorology	Stevens et al. (2013)
FGOALS-s2	Institute of Atmospheric Physics, Chinese Academy of Sciences	Bao et al. (2013)
GEOS5	Global Modeling and Assimilation Office, NASA	Molod et al. (2012)
GISS-S2	Goddard Institute for Space Studies, NASA	Schmidt et al. (2014)
ISUGCM	Iowa State University	Wu and Deng (2013)
MIROC5	AORI/NIES/JAMSREC, Japan	Watanabe et al. (2010)
MRI-AGCM	Meteorological Research Institute, Japan	Yukimoto et al. (2012)
NavGEM1	US Naval Research Laboratory	-
PNU-CFS	Pusan National University	Saha et al. (2006)
SPCAM3	Colorado State University	Khairoutdinov et al. (2008)
SPCCSM3	George Mason University	Stan et al. (2010)
UCSD-CAM3	Scripps Institute of Oceanography	Zhang and Mu (2005)

Diagnostics and modeling of MJO in global climate models

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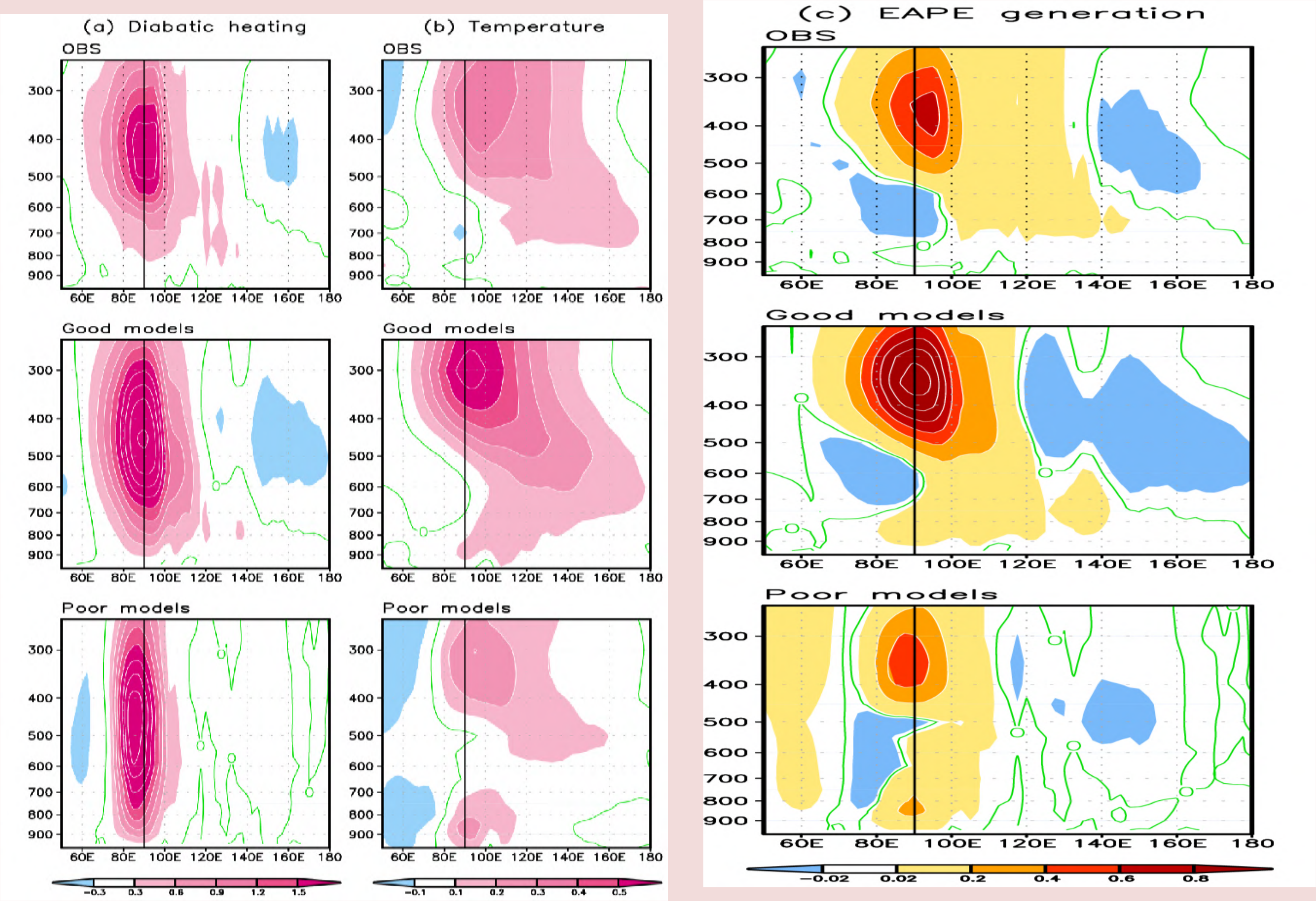
May 15th NUIST 2018

MJO eddy available potential energy generation



Trio-interaction theory revels

(1) MJO convection is led by BLMC.
(2) MJO structure depends on cumulus parameterization schemes and
(3) MJO propagation speed depends on the zonal structural asymmetry (RW vs. KW intensity: R-K ratio)

Can the theoretical results be validated from numerical model simulations?