A Systematic Relationship between Convectively Coupled Equatorial Wave Activity and the Madden-Julian Oscillation in Climate Model Simulations

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with collaboration from
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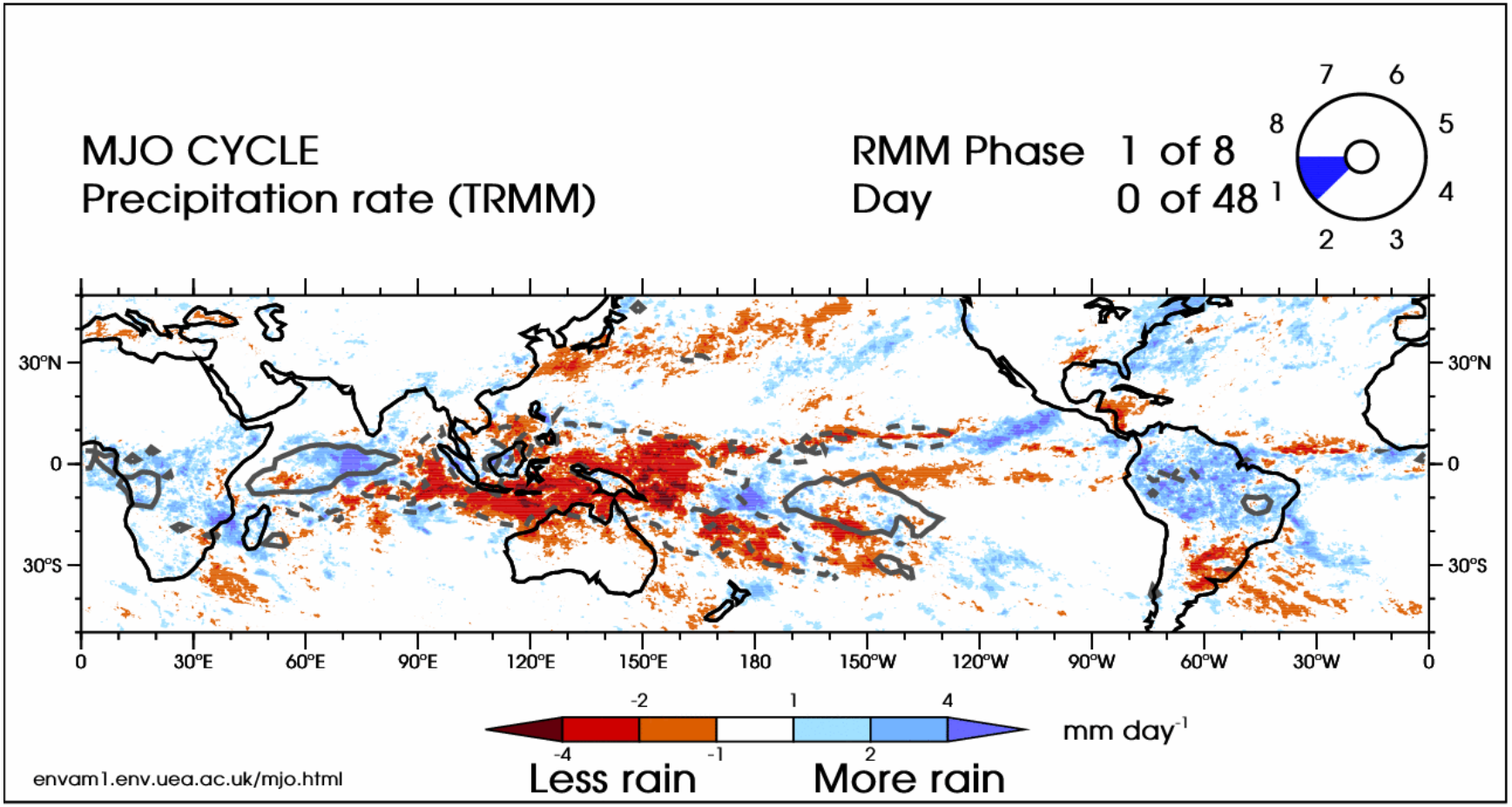
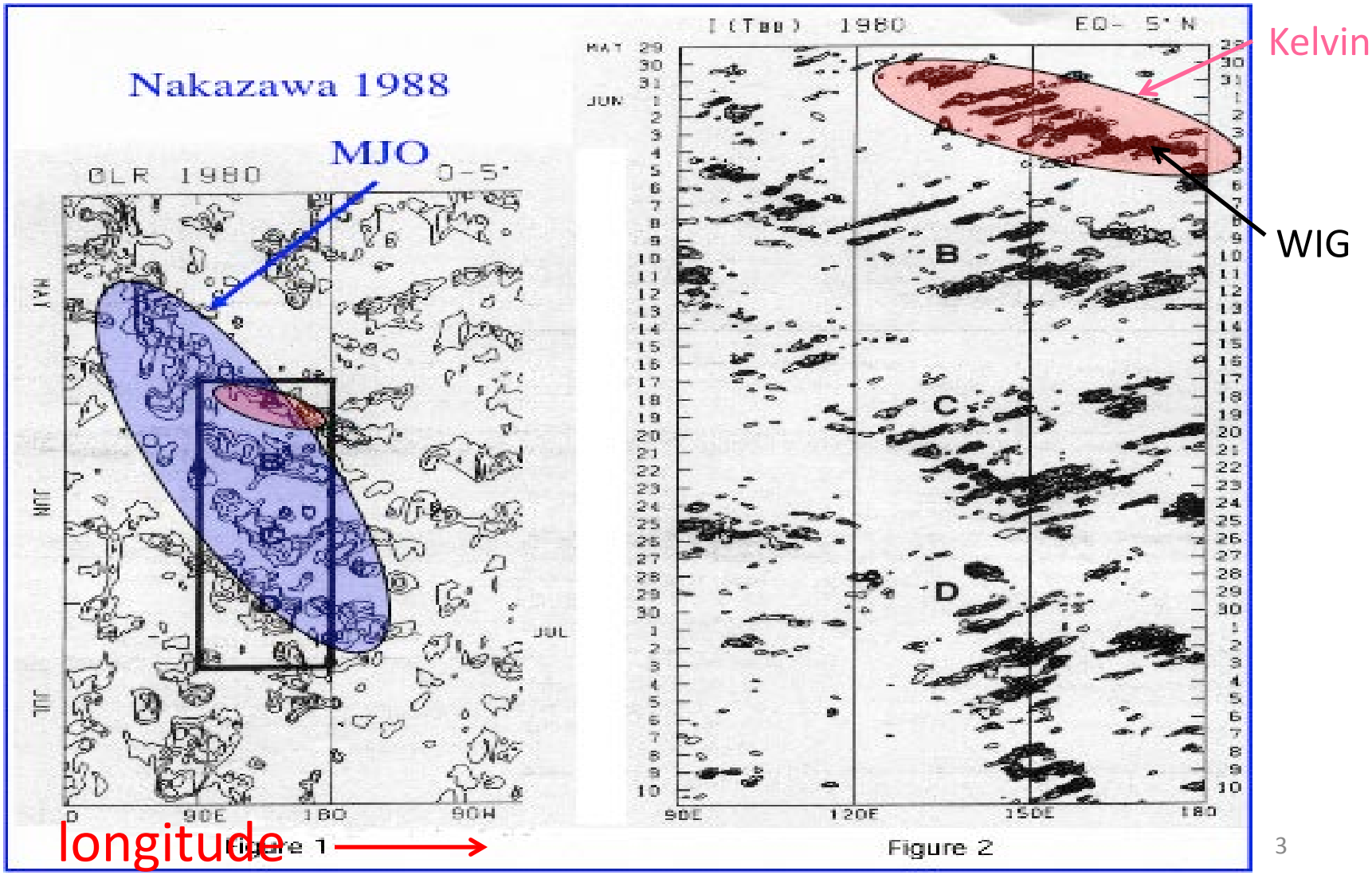
The Madden-Julian Oscillation (Madden & Julian, 1971, 1972)

- planetary scale
- slow eastward propagation
- intraseasonal



Multi-scale structure of the MJO

- MJO can be regarded as the large scale envelope of embedded convectively coupled equatorial waves



Convectively Coupled Equatorial Waves (CCEWs)

- Kelvin
- equatorial Rossby (ER)
- mixed-Rossby-gravity (MRG)
- westward &eastward propagating Inertio-gravity waves (WIG & EIG)

They are theoretical wave solutions of the shallow water equation over the tropics that couple with the convection;
important tropical modes on the synoptical scale
(~several days, ~10^3 km, except ER wave)

- The simulation of MJO and CCEWs in GCMs is far from satisfaction.
- Previous studies have evaluated the performance of the MJO and CCEWs in GCMs (CMIP3, CIMP5…), **but separately**.

In this study, we will examine possible relationships between MJO and CCEW using models from a recent multi-agency effort: the MJOTF/GASS MJO inter-comparison project.

Vertical Structure and Diabatic Processes of the MJO: *Global Model Evaluation Project*

MJO Task Force/YOTC and GASS

http://yotc.ucar.edu/mjo/vertical-structure-and-diabatic-processes-mjo

	Model Experiment	Science Focus	Exp. POC
I.	**20 Yr Climatological Simulations** (1991-2010 if AGCM) 6-hr, Global Output Vertical Structure, Physical Tendencies	Model MJO Fidelity Vertical structure Multi-scale Interactions: (e.g., TCs, Monsoon, ENSO)	**UCLA/JPL** X. Jiang D. Waliser
II.	**2-Day MJO Hindcasts** YOTC MJO Cases E & F (winter 2009)* Time Step, Indo-Pacific Domain Output Very Detailed Physical/Model Processes	Heat and moisture budgets Model Physics Evaluation (e.g. Convection/Cloud/BL) *Short range Degradation*	**Met Office** P. Xavier J. Petch
III.	**20-Day MJO Hindcasts** YOTC MJO Cases E & F (winter 2009)* 3-hr, Global Output Elements of I & II	MJO Forecast Skill State Evolution/Degradation Elements of I & II	**NCAS/Walker in.** N. Klingaman S. Woolnough

*DYNAMO Case TBD

Commitments: About 30 Modeling Groups with AGCM and/or CGCM

Participating GCMs for Climate Simulation Component

	Model	Horizontal Resolution	Vertical Resolution	References	Notes
1	01_NASAGMAO_GEOS5	0.625° lon x 0.5° lat	72	Molod et al., 2012	
2	03a_SPCCSM (CAM3 + POP)	T42 (~2.8°)	30	**Super-parameterization** (Stan et al., 2010)	
3	03b_SPCAMP_AMIP	T42	30	(Khairoutdinov et al 2008)	1986-2003
4	04_GISS_ModelE2	2.5° lon x 2° lat	40	(Schmidt et al. 2014)	
5	05_EC_GEM	~1.4°	64	(Cote et al, 1998)	
6	07_MIROC	T85 (~1.5°)	40	(Watanabe et al. 2010)	AMIP SST 1986-2005
7	10_MRI-GCM	T159	48	(Yukimoto et al, 2012)	
8	11_CWB_GFS	T119 (~1°)	40	(Liou et al., 1997)	
9	14_PNU_CFSv1	T62 (~2°)	64	(Saha et al. 2006)	
10	16_MPI_ECHAM6 (ECHAM6 + MPIOM)	T63 (~2°)	47	(Stevens et al, 2013)	
11	17_MetUM_GA3	1.875° lon x 1.25° lat	85	(Walters et al. 2011)	
12	21_NCAR_CAM5	1.25° lon x 0.9° lat	30	(Neal et al, 2012)	
13	22_NRL_NAVGEMv.01	T359 (37km)	42	(Hogan et al. 2014)	
14	24_UCSD_CAM	T42 (~ 2.8°)	30	(Zhang & Mu 2005)	
15	27_NCEPCPC_CFSv2	T126 (~ 1°)	64	(Saha et al. 2013)	
16	31a_CNRM_AM	T127 (~1.4°)	31	(Voldoire et al. 2013)	
17	31b_CNRM_CM (CNRM_AM+ NEMO)				
18	31c_CNRM_ACM				
19	34_CCCma_CanCM4	2.8°	35	(Merryfield et al. 2013)	
20	35_BCCAGCM2.1	T42 (~2.8 deg)	26	(Wu et al 2010)	
21	36_FGOALS2.0-s	R42 (2.8°lonx1.6°lat)	26	(Bao et al . 2013)	
22	37_NCHU_ECHAM5-SIT	T63	31	(Tseng et al. 2014)	
23	39_TAMU_Modi-CAM4 (CCSM4)	2.5 ° lon x 1.9 ° lat	26	(Lappen & Schmumacher 2012)	Idealized tilted vertical heating
24	40_ACCESS (modified METUM)	1.875° lon x 1.25° lat	85	(Zhu et al. 2013)	
25	43_ISUGCM	T42 (~ 2.8°)	18	(Wu and Deng 2013)	
26	44_LLNL_CAM5ZMMicro	1.25° lon x 0.9° lat	30	(Song & Zhang 2011)	
27	45_SMHI_ecearth3	T255(80km)	91	IFS cy36r4	

DATA

- Precipitation is used as the proxy of the convection

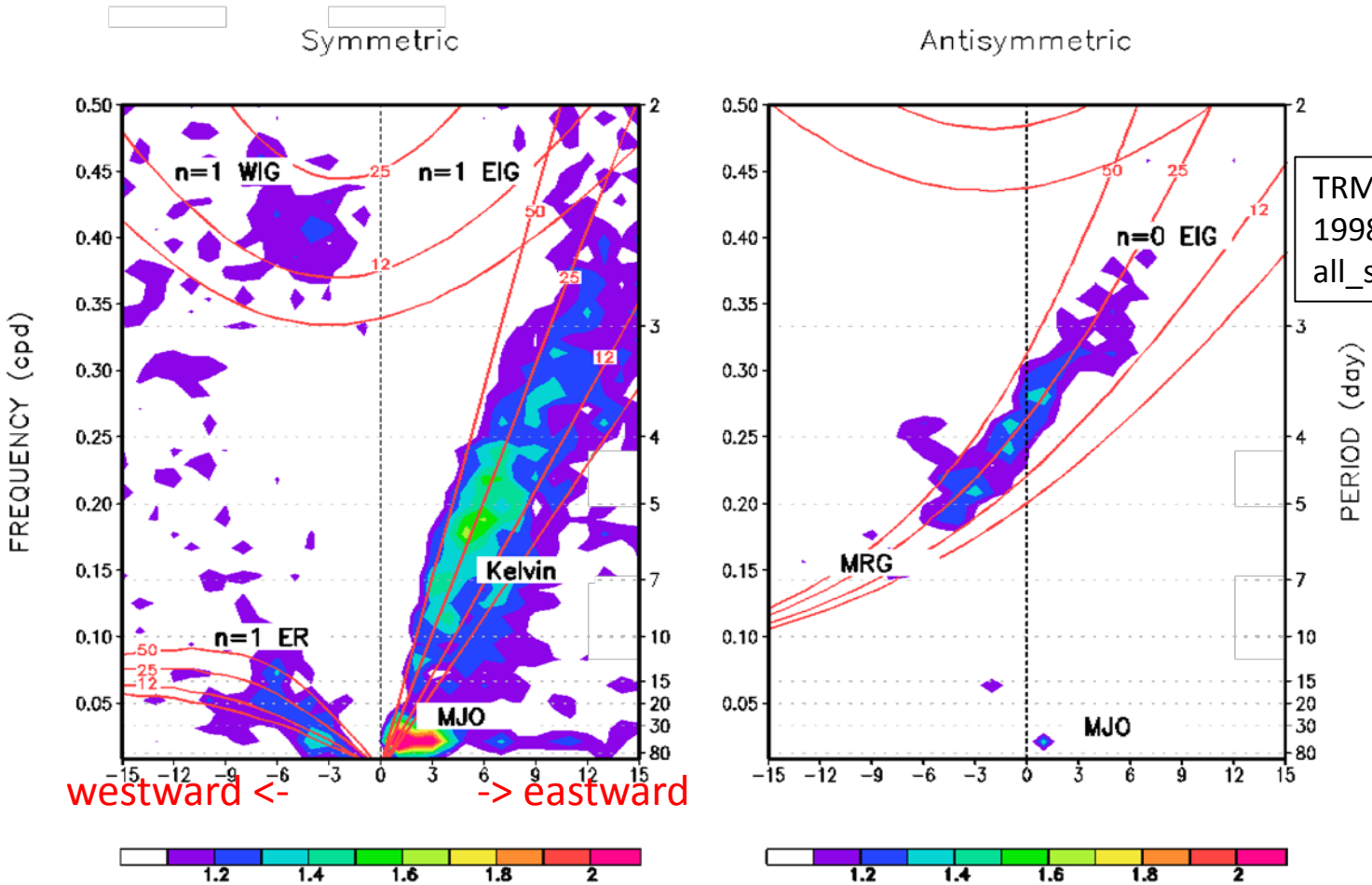
- TRMM rainfall: 1998-2012

- Model precipitation: 20 year (1991-2010) from 26 models

daily, and on 2.5°x2.5° resolution

Wavenumber–frequency Analysis

Wheeler and Kiladis (1999)



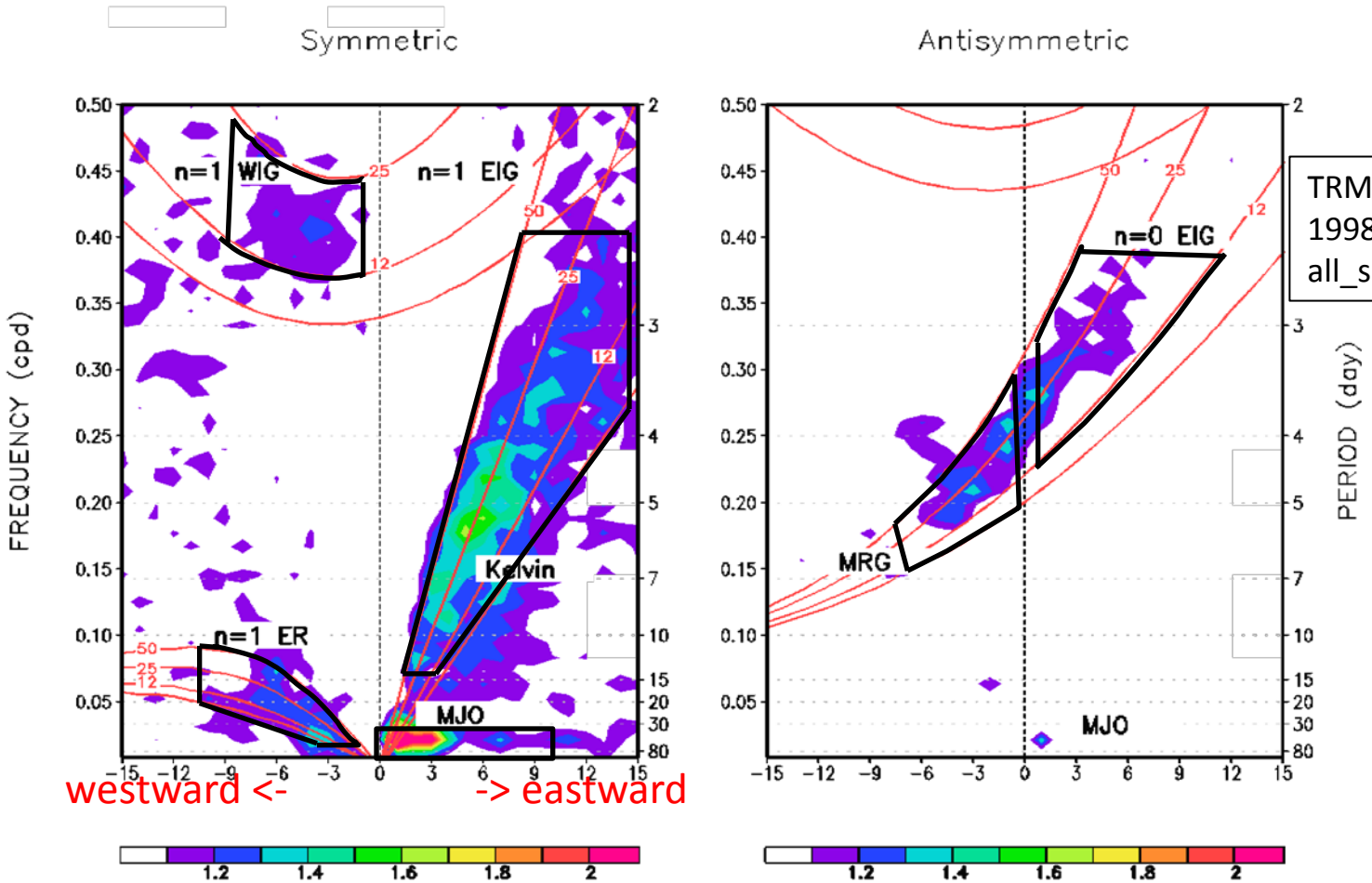
TRMM, 15S-15N, 1998-2012, all_season

Red curves: dispersion lines of the theoretical wave solutions

- Spectral peaks coincide with the theoretical solutions of the equatorial waves

Wavenumber–frequency Filtering to Isolate CCEWs

Wheeler and Kiladis (1999)

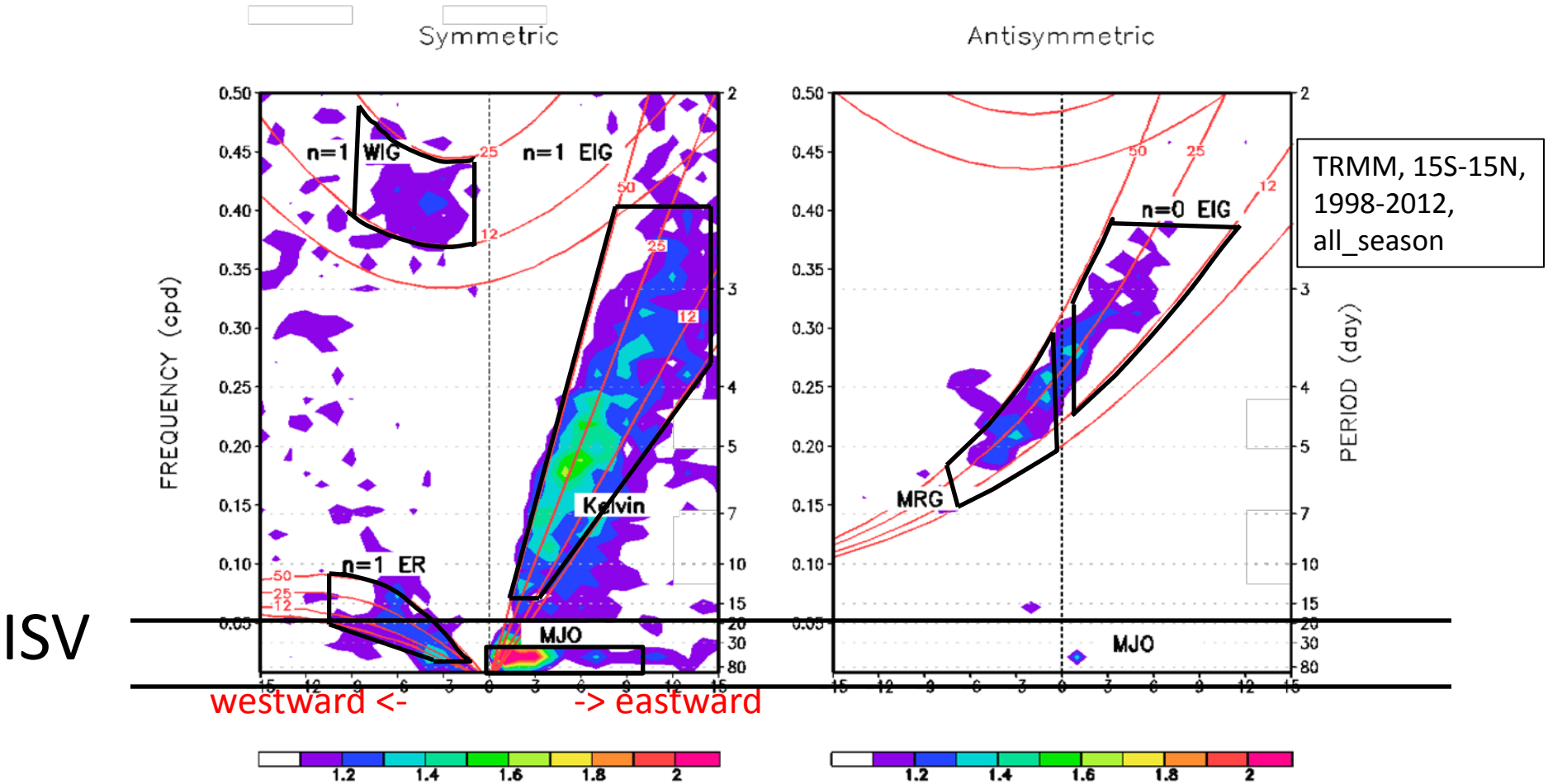


TRMM, 15S-15N, 1998-2012, all_season

- Extract a wave by retaining the specific spectra corresponding to it

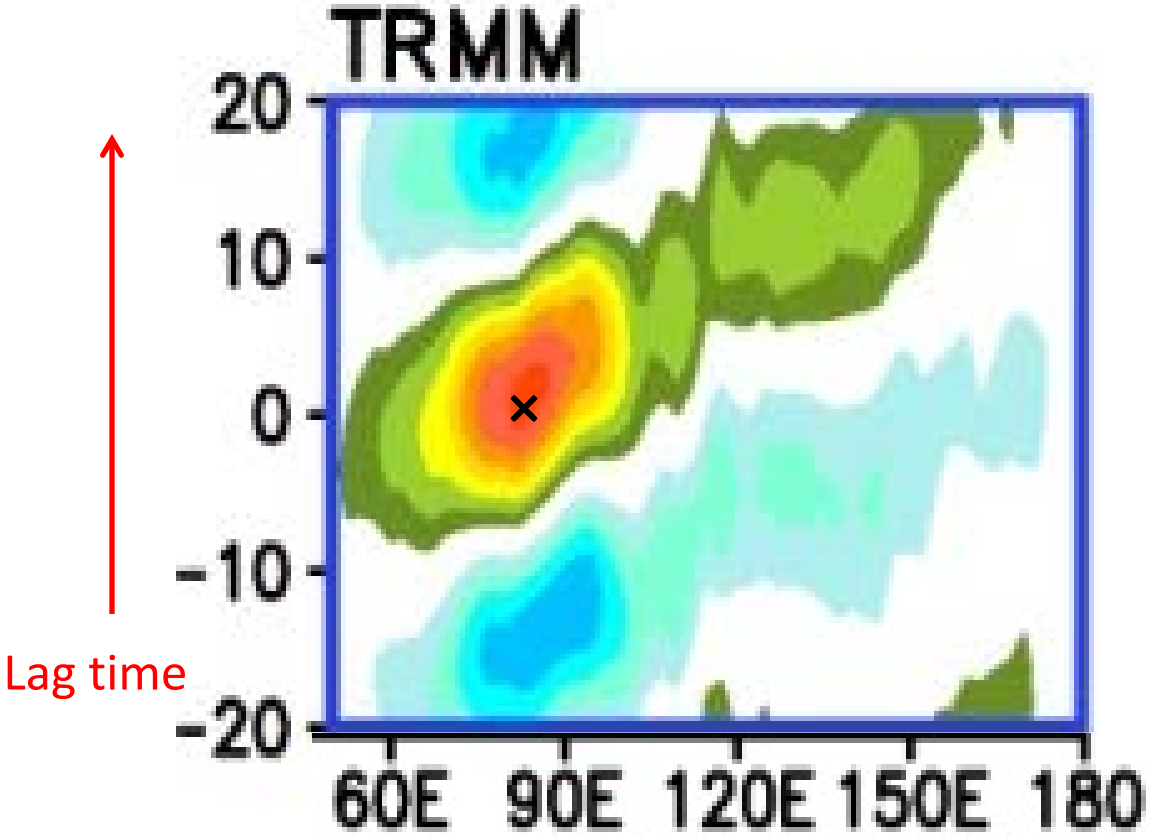
Wavenumber–frequency Filtering to Isolate CCEWs

Wheeler and Kiladis (1999)



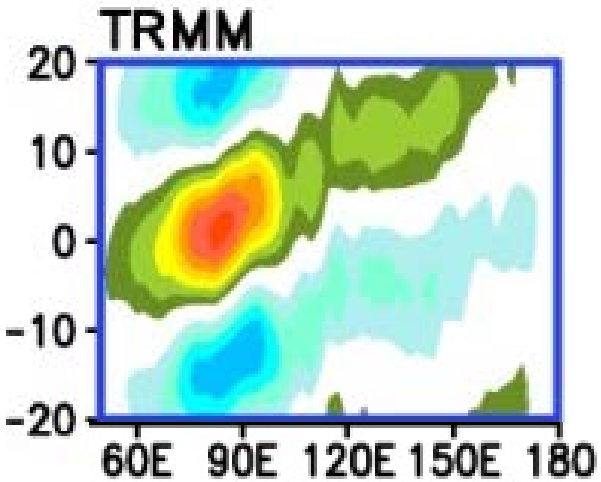
Intraseasonal variability (ISV): 20-100-day bandpass filtered

Determination of the MJO Score of a GCM by lag regression



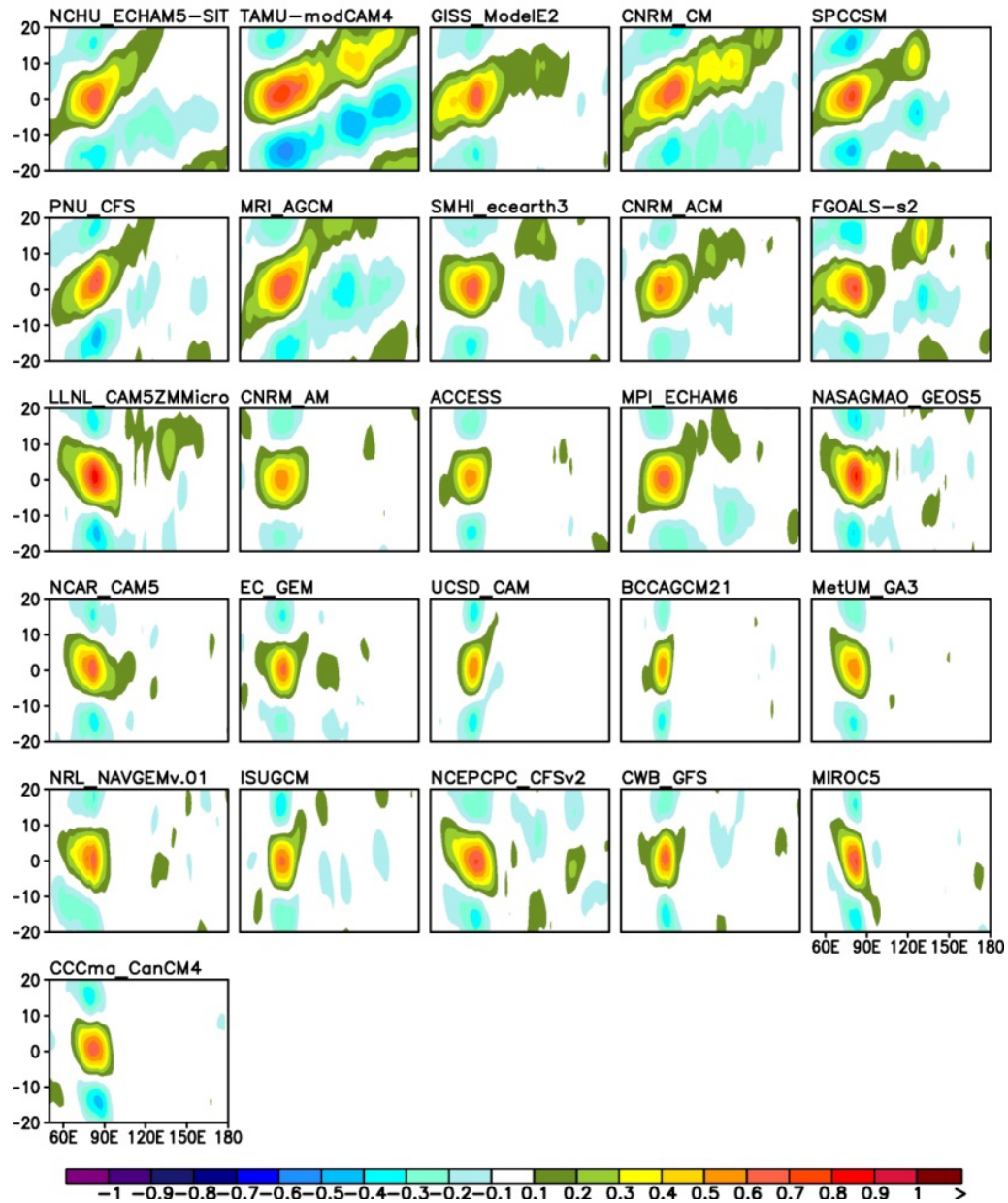
- Lag-regression of 14-year daily ISV anomalies with itself at an Indian ocean base point
- Large-scale eastward propagation pattern revealed in this Hovemoller-like diagram: MJO signal

Determination of the MJO Score of a GCM by lag regression



MJO score: pattern correlation between model and TRMM

Good MJO models:
eastward propagation pattern
Bad MJO models:
Stationary or even westward propagation



Part I: MJO Performance and Climatology of CCEW Activity

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Low-frequency variability

ISV, MJO

~ER~

Kelvin, MRG, IG (High-frequency)

>100d

intraseasonal

~ 10day

Precipitation spectrum

Part I: MJO Performance and Climatology of CCEW Activity

Low-frequency variability | ISV, MJO | ~ER~ | Kelvin, MRG, IG (High-frequency)

>100d | intraseasonal | ~ 10day

Precipitation spectrum

- Prominent problem in the precipitation simulation

- too weak CCEW variance ("weak CCEW" bias)

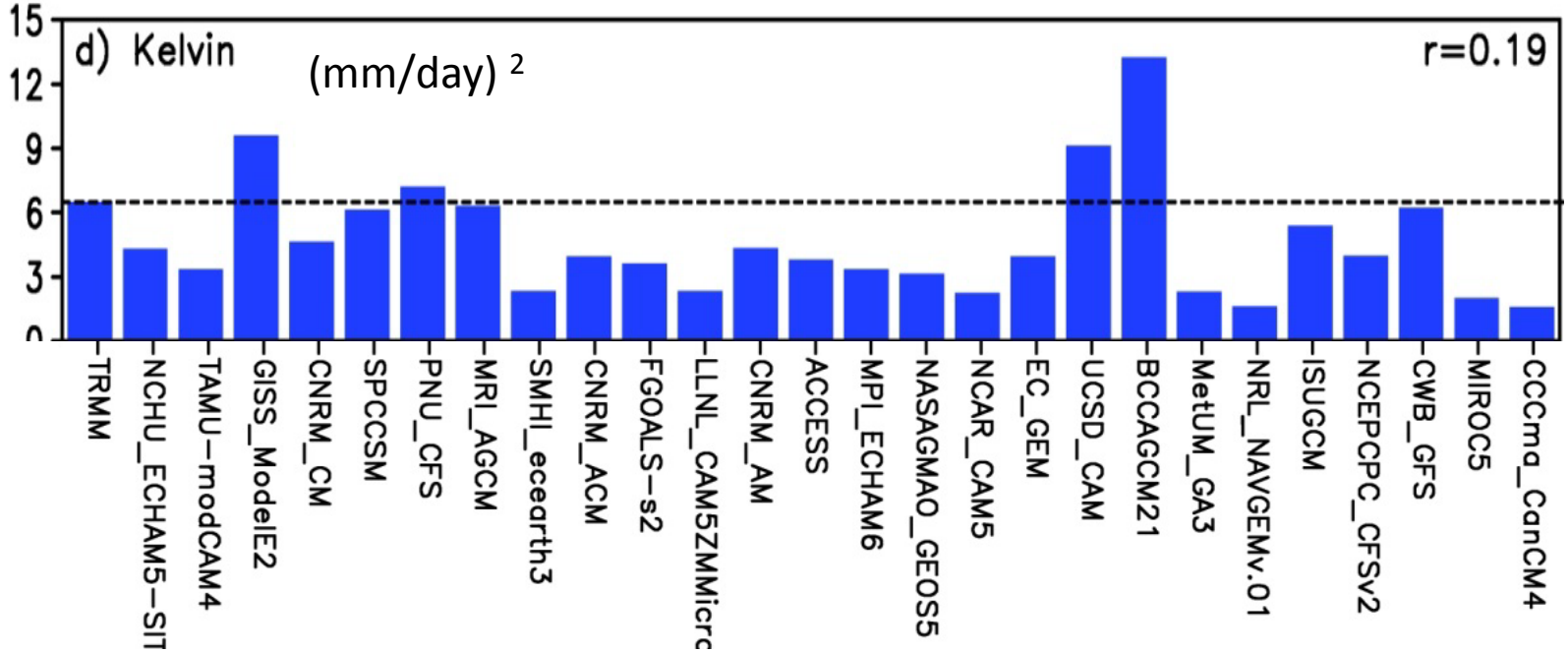
- too strong variance in the low-frequency variability ("over-redden" bias)

Climatology of Kelvin Wave Activity

Procedure:

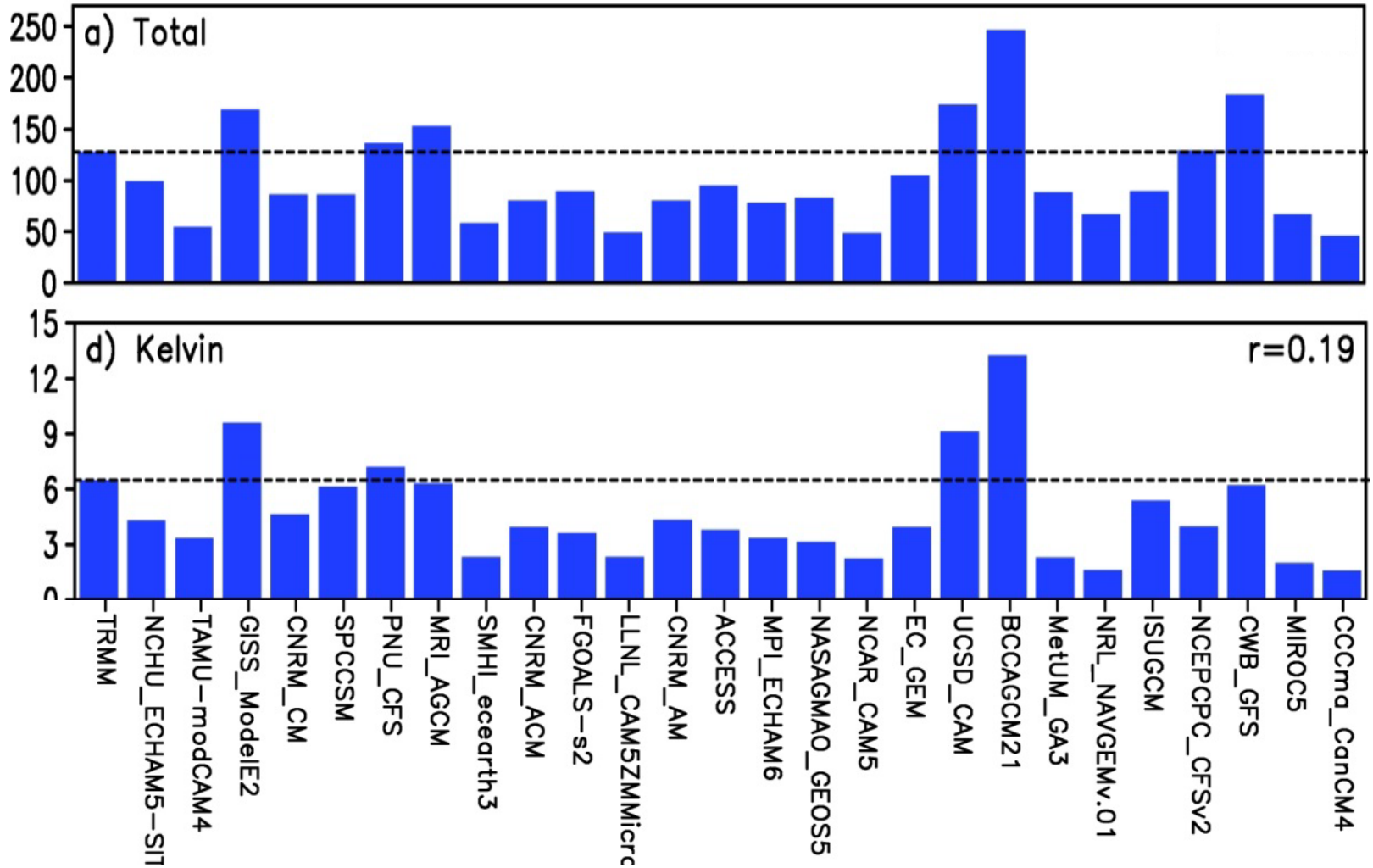
step 1: Climatological Kelvin wave activity (wave variance): 2-D

step 2: averaged over Indian-west Pacific region: one single value for each model



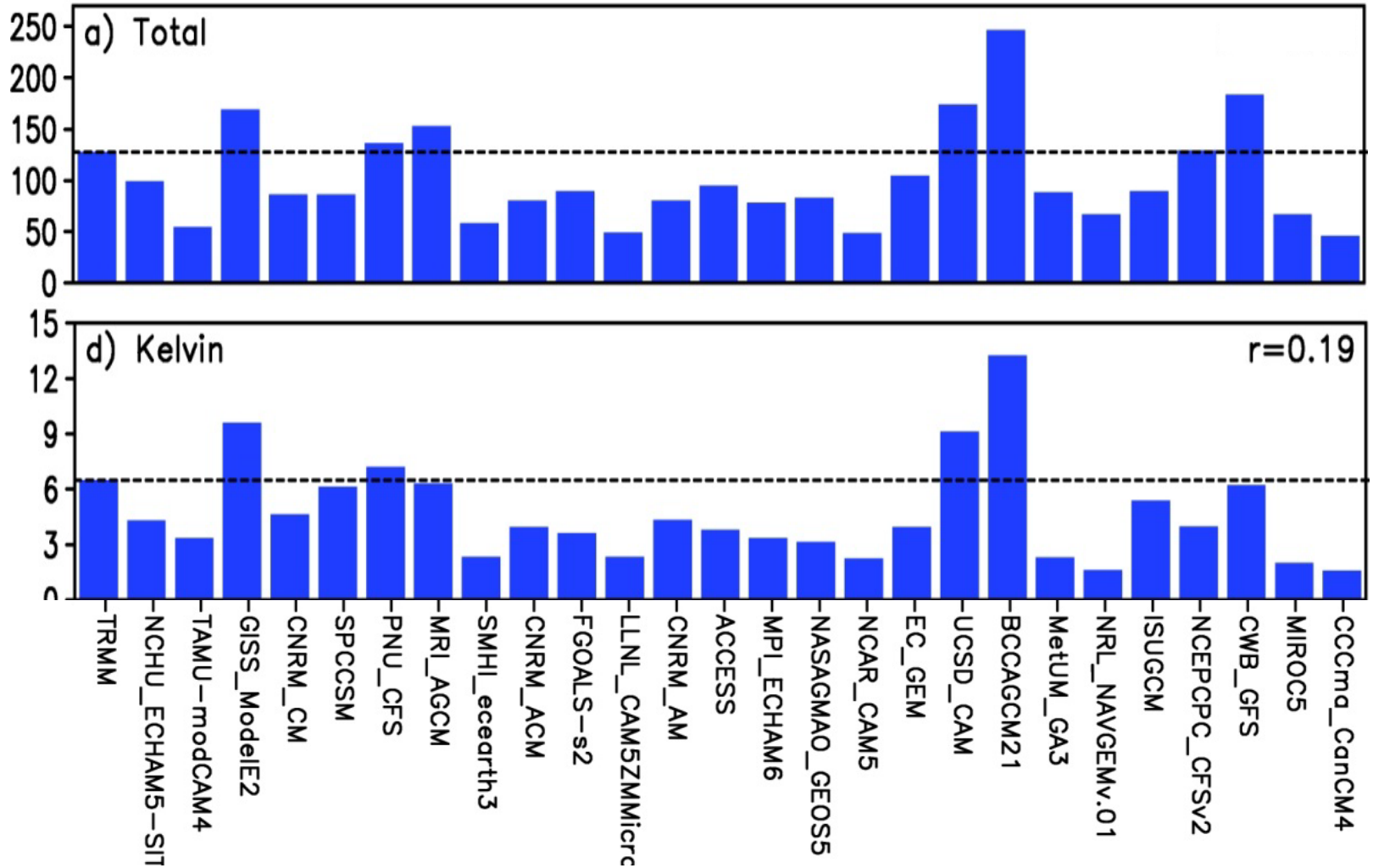
- Some positive correlation, but not significant

Climatology of Kelvin Wave Activity



- A model's Kelvin wave variance is largely dependent on its "total" wave variance

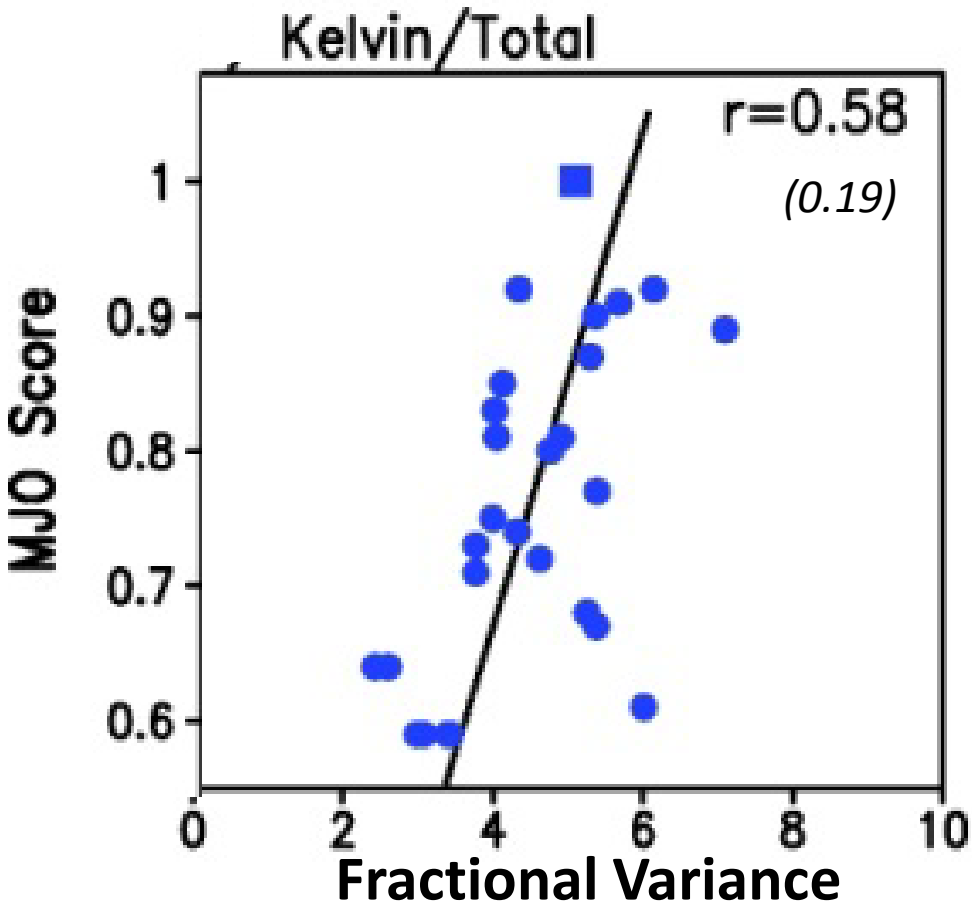
Climatology of Kelvin Wave Activity



- **Fractional variance**: the fraction of CCEW variance relative to the "total" variance

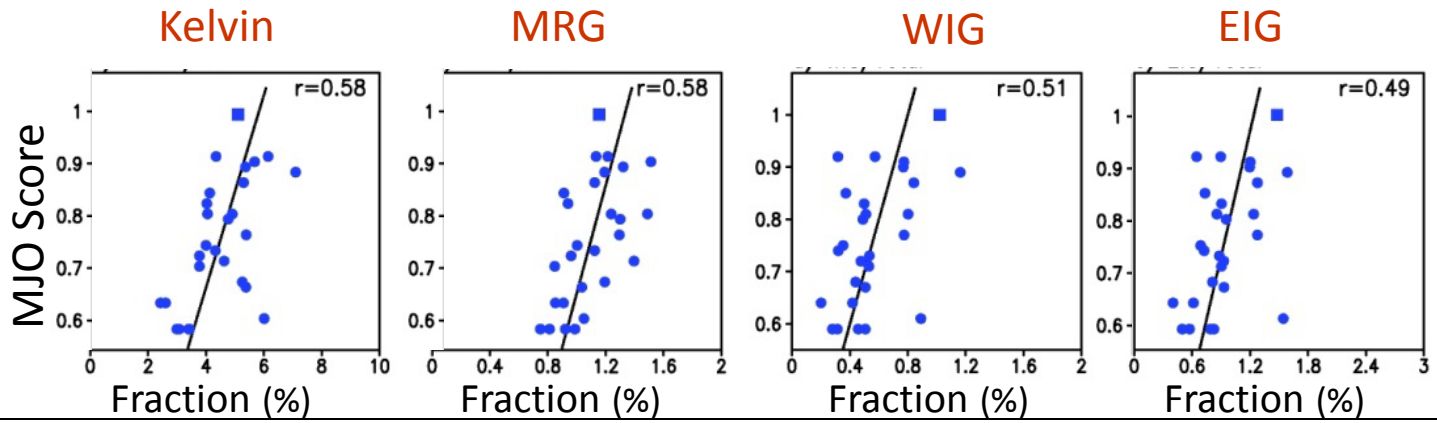
  - to eliminate the model-to-model difference due to difference in "total" variance

Climatology of Kelvin Wave Activity



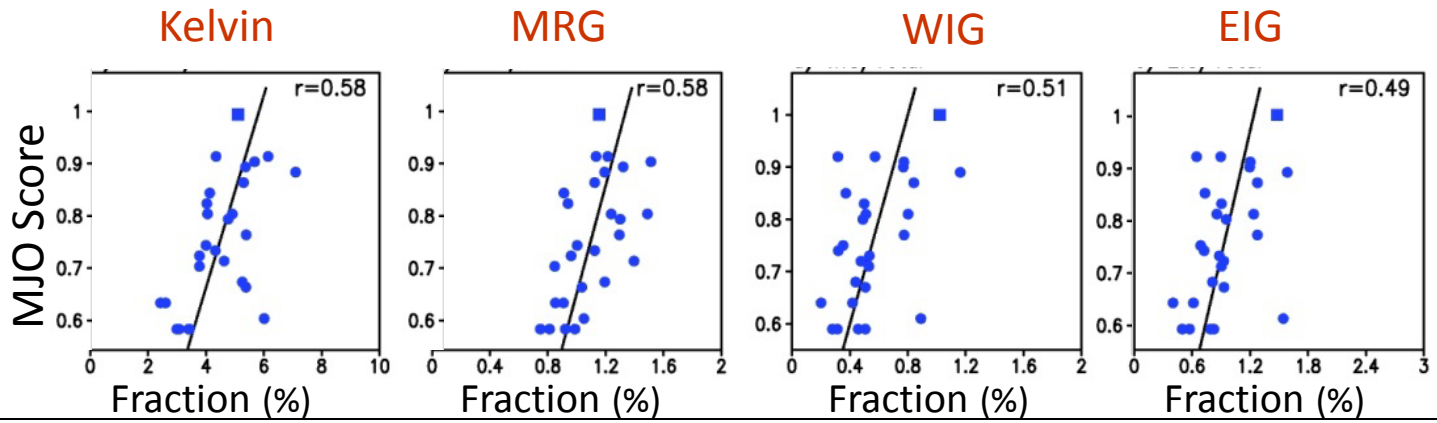
- **Strong positive correlation**: better MJO models tend to have stronger fractional variances for Kelvin wave

Kelvin, MRG, WIG, and EIG (high-frequency CCEWs)



- **Strong positive correlation** found for other high-frequency CCEWs

Kelvin, MRG, WIG, and EIG (high-frequency CCEWs)



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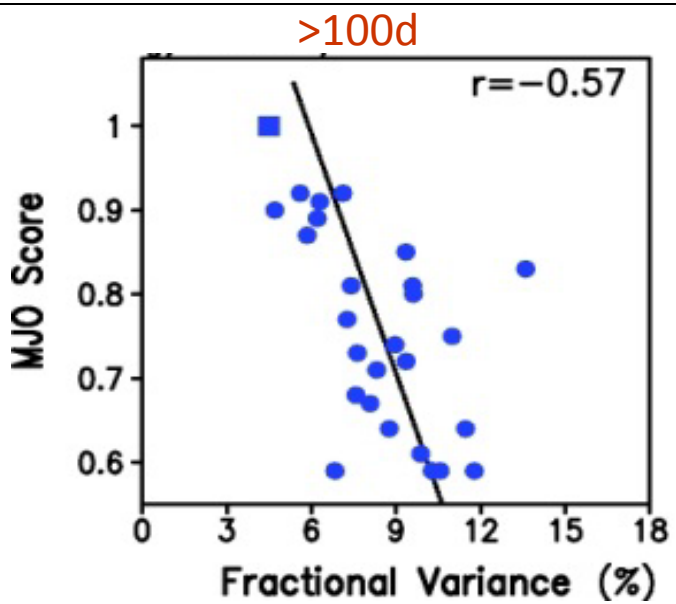
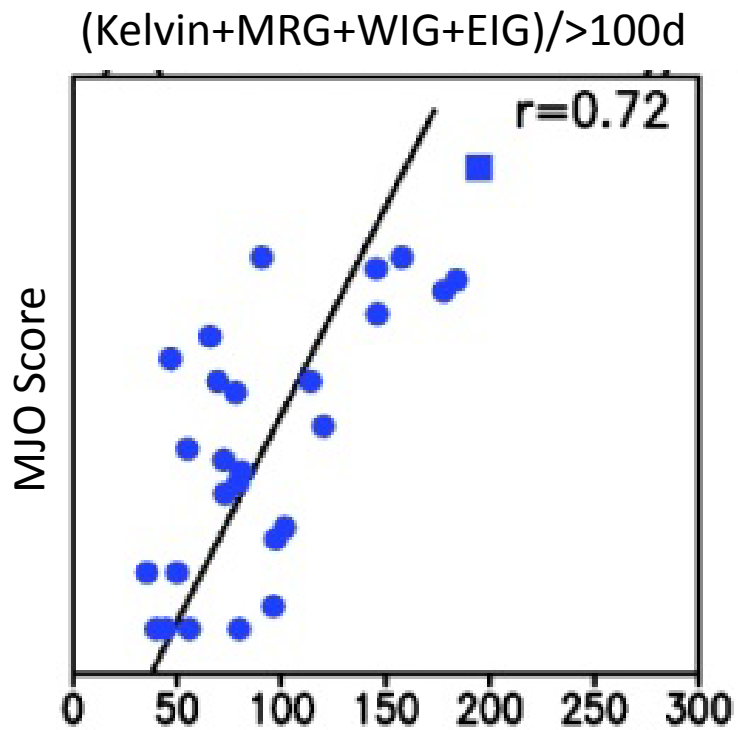


- **Strong negative correlation** found for low-frequency variability

MJO performance and the alleviation of "weak CCEW/over-redden" bias



- Better MJO models tend to simulate stronger precipitation variance at the high-frequency spectrum end (Kelvin, MRG, WIG, and EIG), while weaker variance at the low-frequency end
- This corresponds to the alleviation of a longstanding problem in simulating precipitation: too weak precipitation variance in high-frequency part, and too strong variance in low-frequency part ("over-reddened spectrum")

Part II: MJO Performance and the Degree of Coherence of MJO-CCEW Interaction

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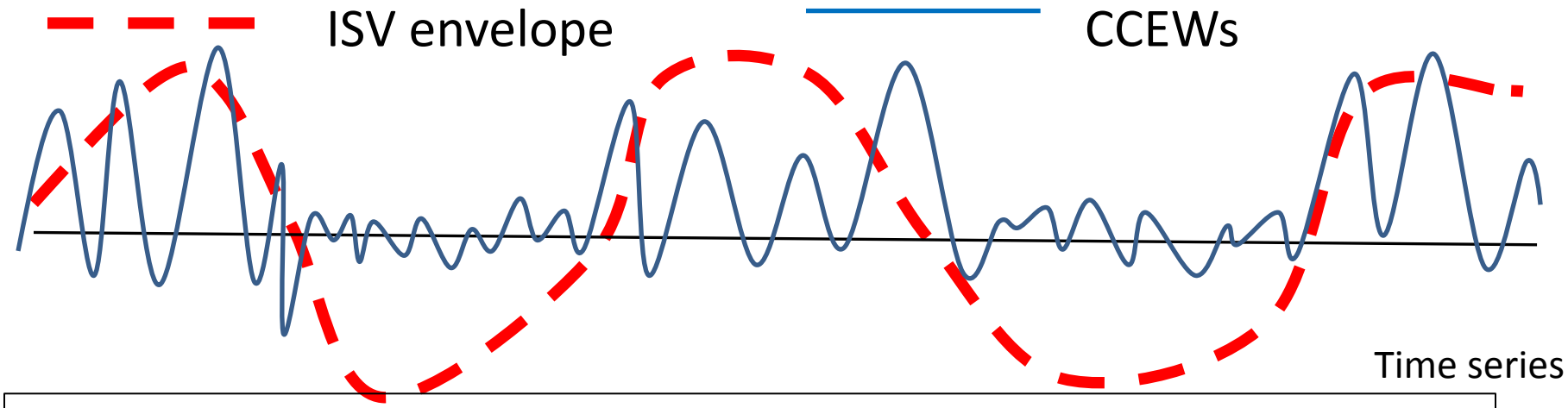
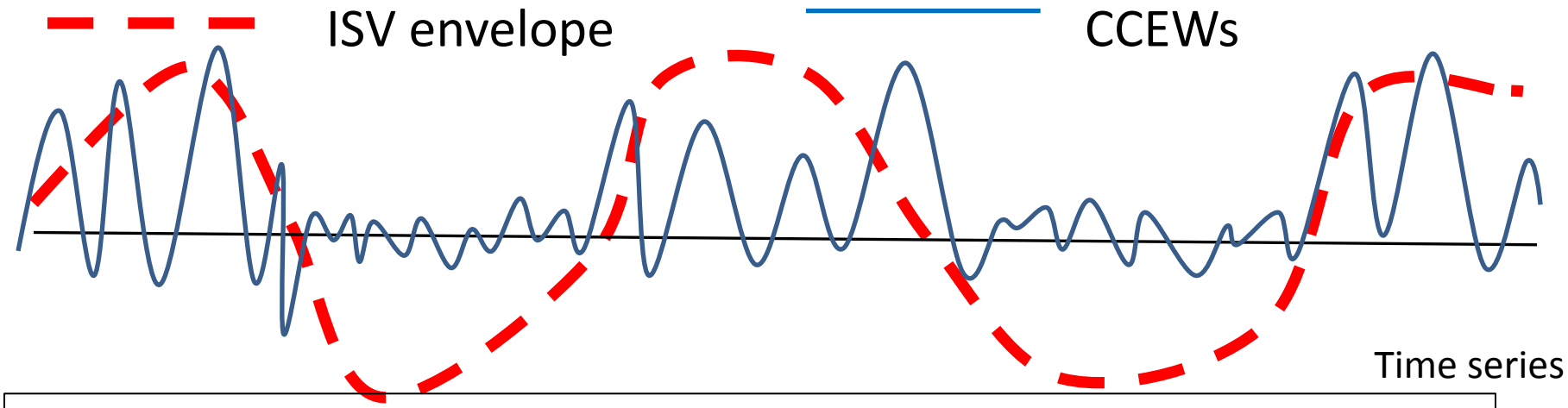


- Enhancement/suppression of Kelvin wave activity in association with active/suppressed ISV convection

Part II: MJO Performance and the Degree of Coherence of MJO-CCEW Interaction

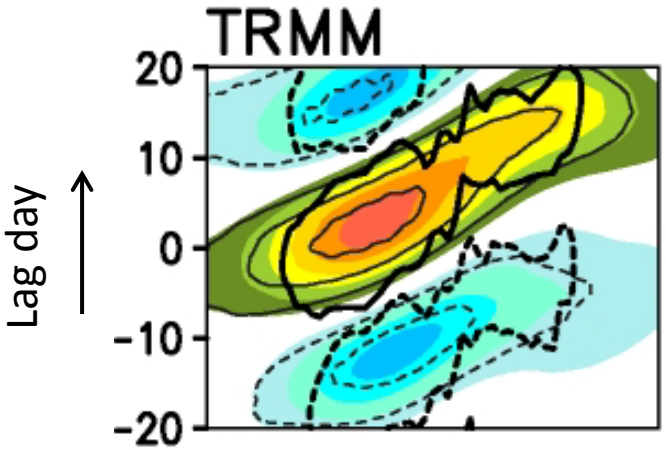


- Enhancement/suppression of Kelvin wave activity in association with active/suppressed ISV convection

- Regress the time series of the squared Kelvin wave anomalies against the ISV index: **regressed variance**

- *Larger regression suggests better coherence between MJO and CCEW interaction*

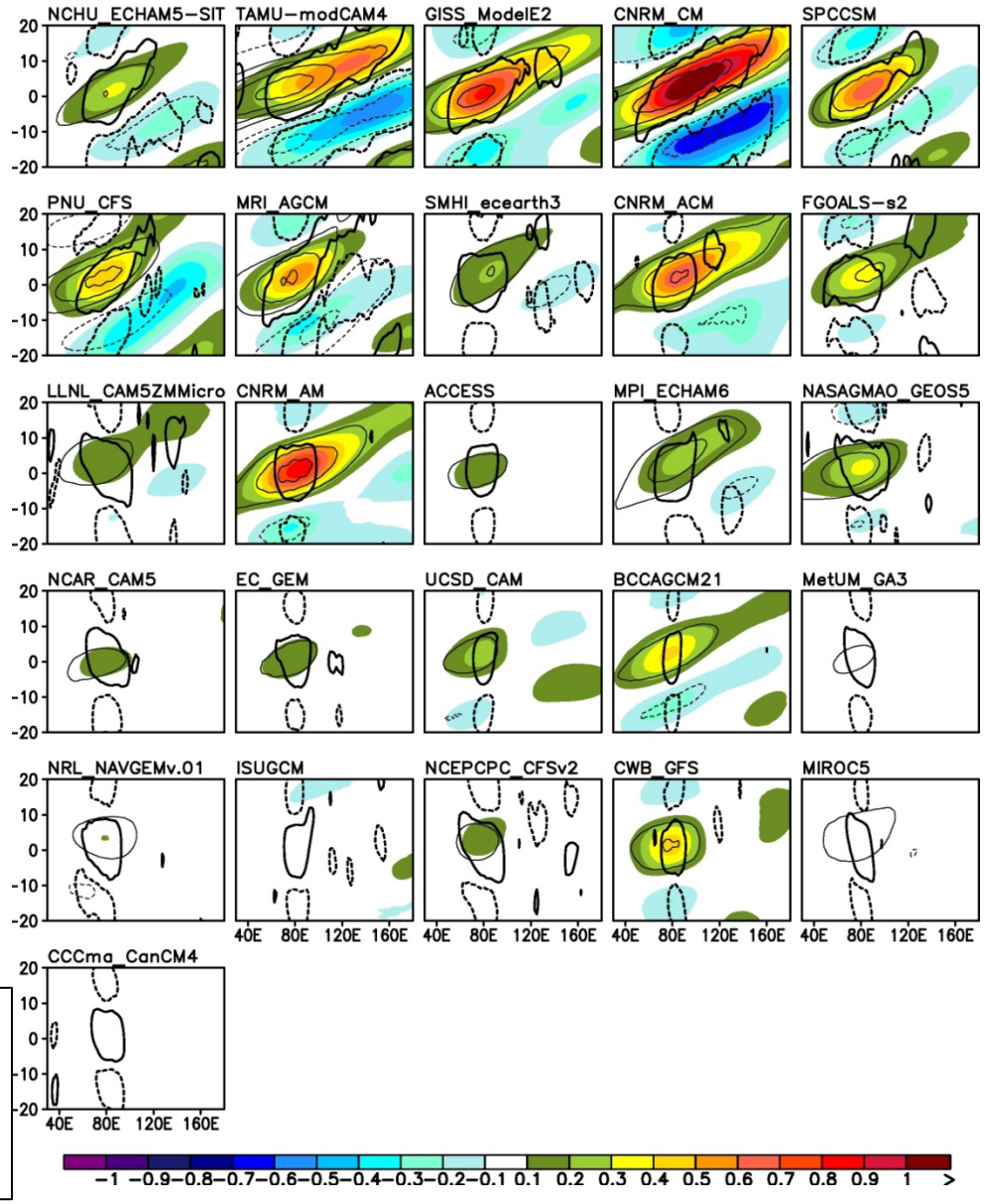
Lag Regression of Kelvin Variance against ISV Index



Shade:
wave variance

Thick contour:
ISV envelope

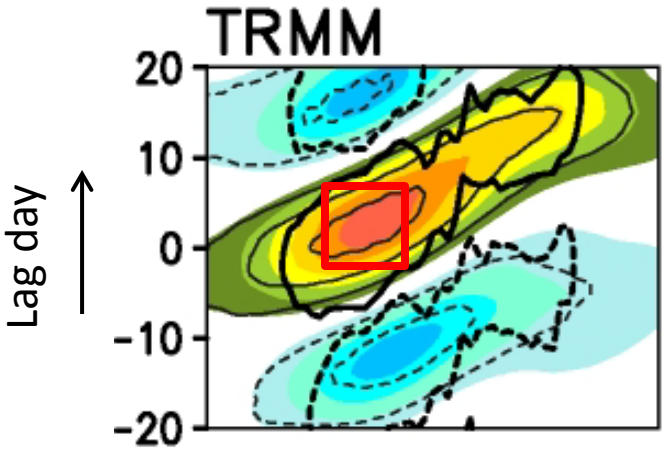
Thin contour:
Corr coefficient



- Larger regression in better MJO models:

- Better MJO-CCEW interaction

Lag Regression of Kelvin Variance against ISV Index



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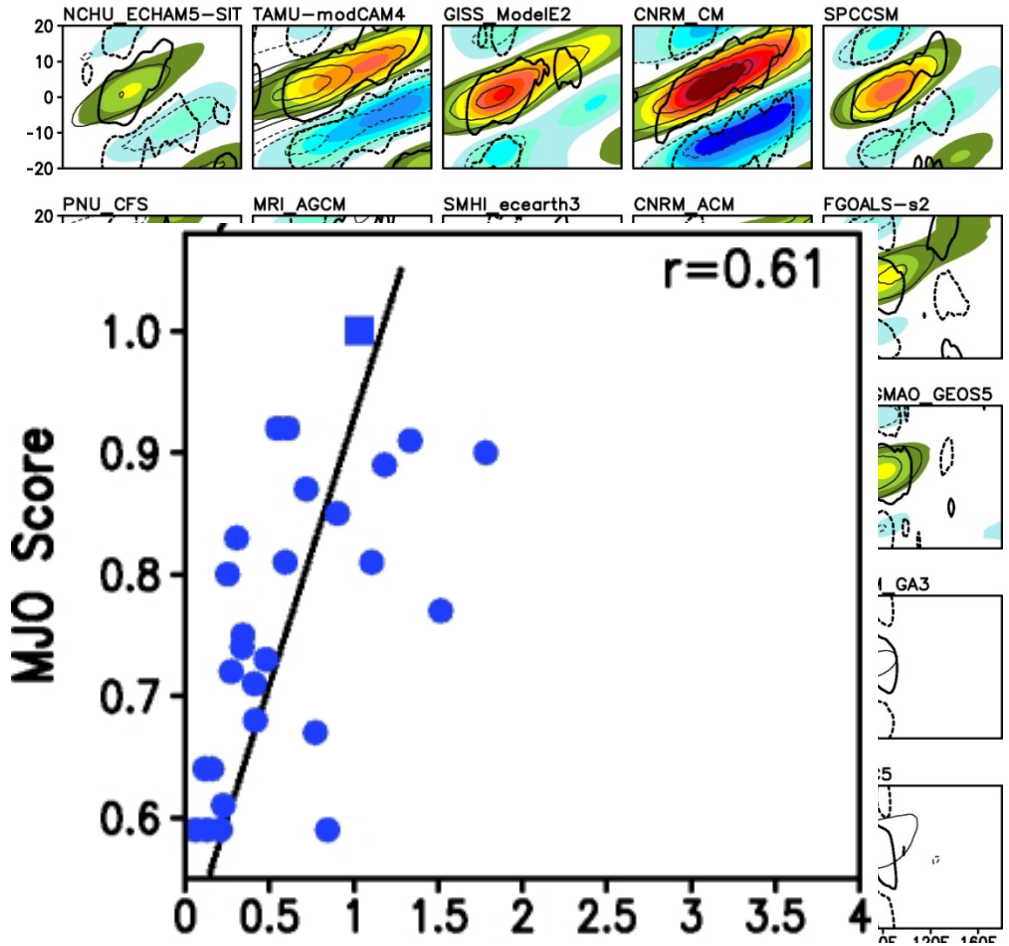
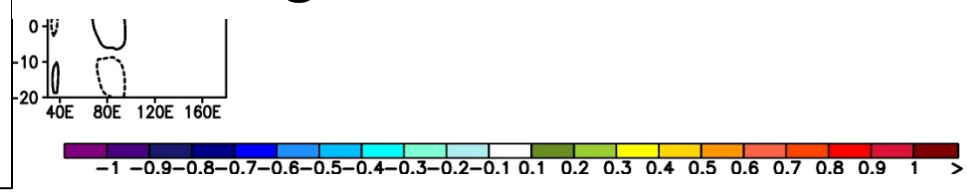


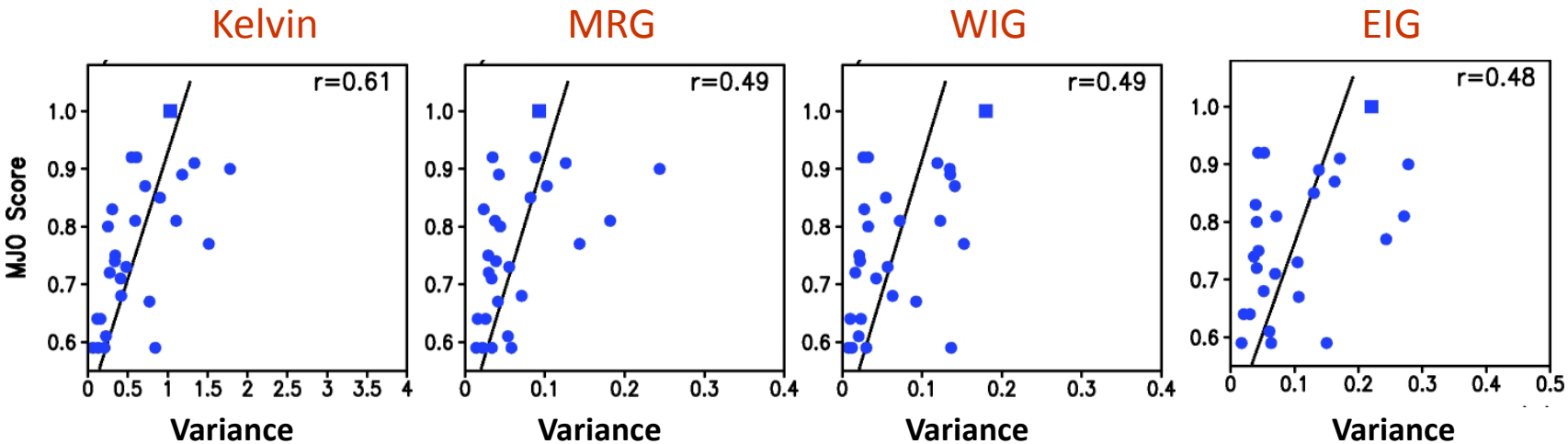
Regressed Variance *(mm/day)²*



- Larger regression in better MJO models:

- Better MJO-CCEW interaction

MJO score V.S. Regressed CCEW variance



- **Also true for MRG, WIG, and EIG:**

- Better MJO models tend to simulate stronger CCEW (Kelvin, MRG, WIG and EIG) variance associated with the ISV envelope, suggesting better coherence and stronger interactions between these CCEWs and the ISV envelope in the good MJO models.

Conclusions

- Results based on 26 GCMs suggest that better MJO models tend to:

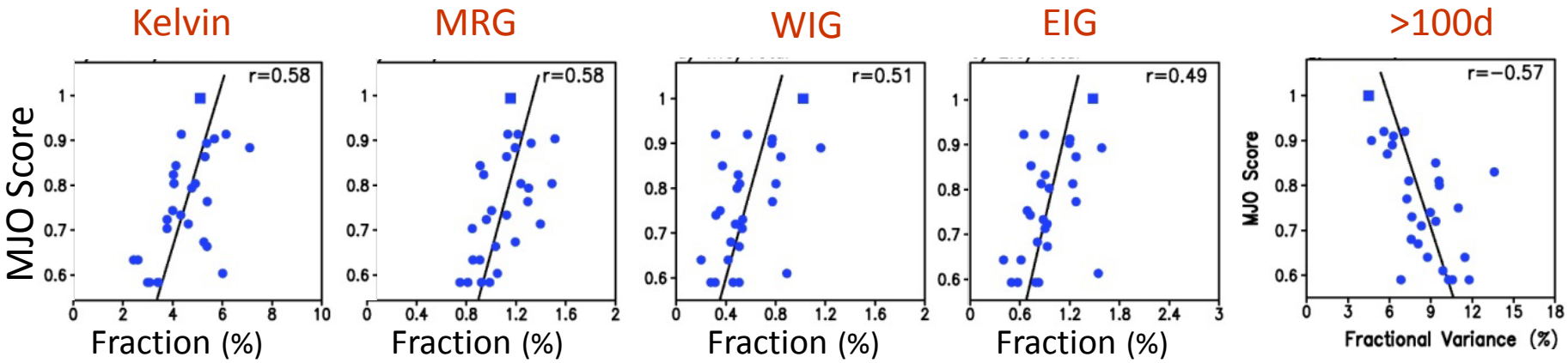
1) have stronger fractional variances for high-frequency wave modes (Kelvin, MRG, WIG, and EIG), while weaker variances at the low-frequency end, which corresponds to more realistic distribution of the tropical precipitation spectra.

2) exhibit better coherence and stronger interactions between the MJO and these CCEWs

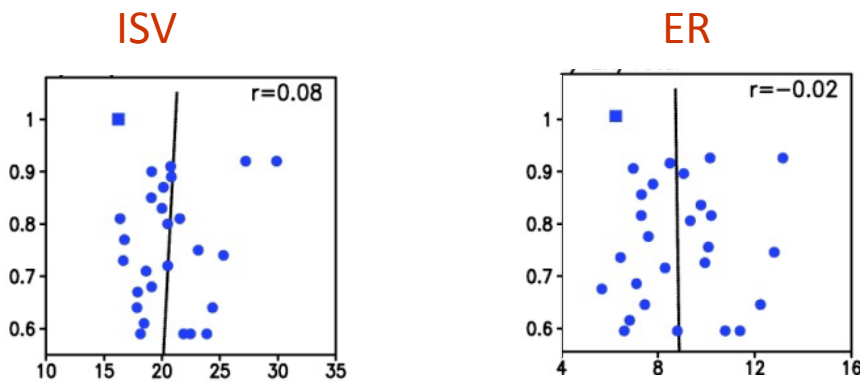
- Our results suggest improved representation of one would lead to improved representation of the other, suggesting that improved predictability and prediction skill on both intraseasonal and synoptical scale could be achieved at the same time.

Guo, Waliser, and Jiang (2014, J. Climate, under revision)

MJO score V.S. Fractional CCEW variance



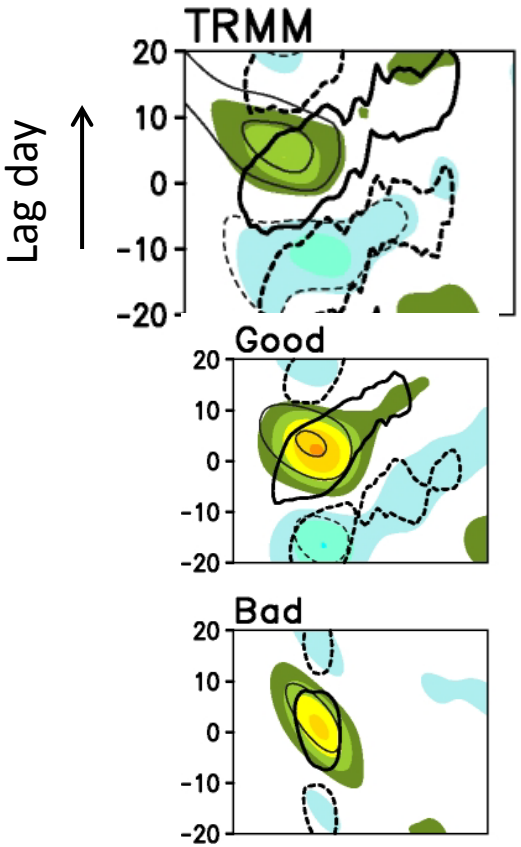
- Better MJO models tend to have higher fractional variances for various high-frequency wave modes (Kelvin, MRG, WIG, and EIG)



- Little correlation is found between the MJO performance and the strength of the ISV and ER variances. Note: ER overlaps with the westward part of the ISV

Lag Regression of ER Variance against ISV Index

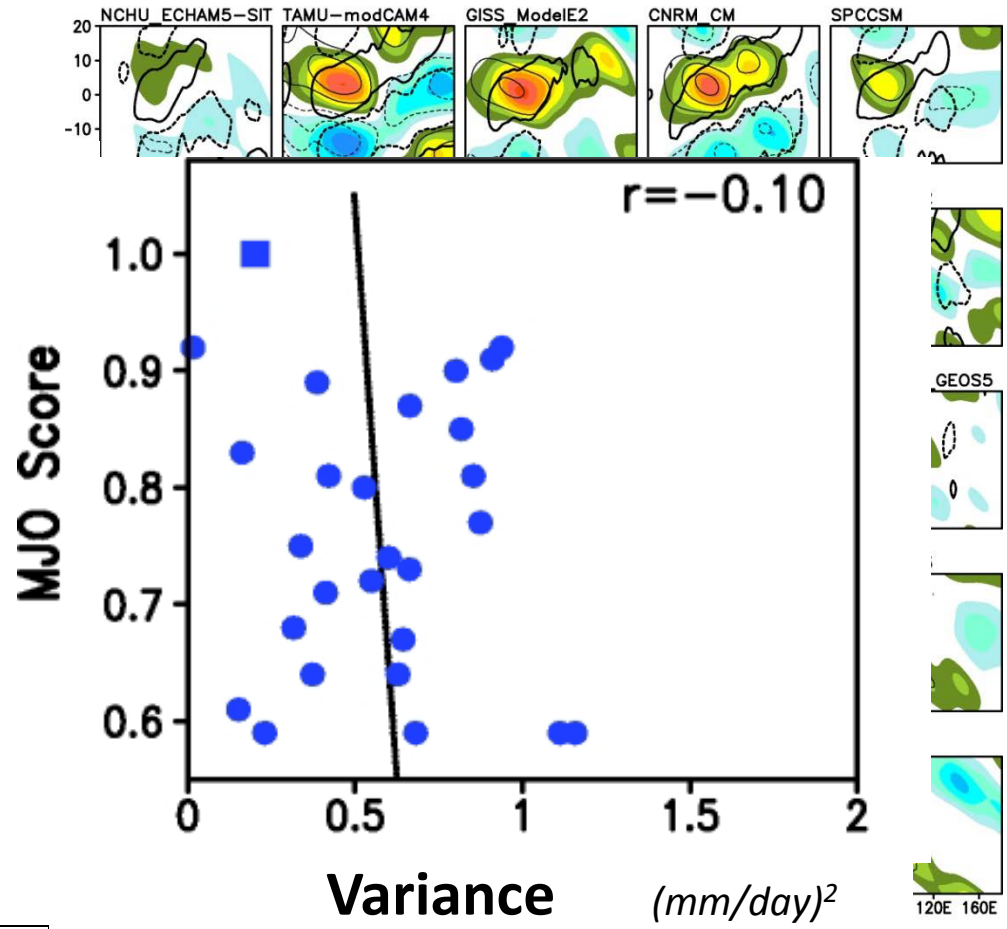
ER variance lead-lag regressed against Indian ocean ISV index



Shade: wave variance

Thick contour: MJO envelope

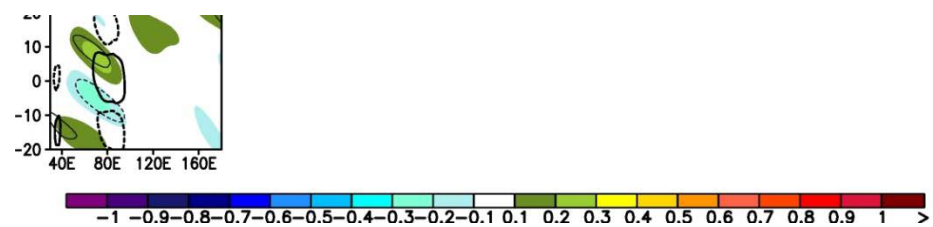
Thin contour: Corr coefficient



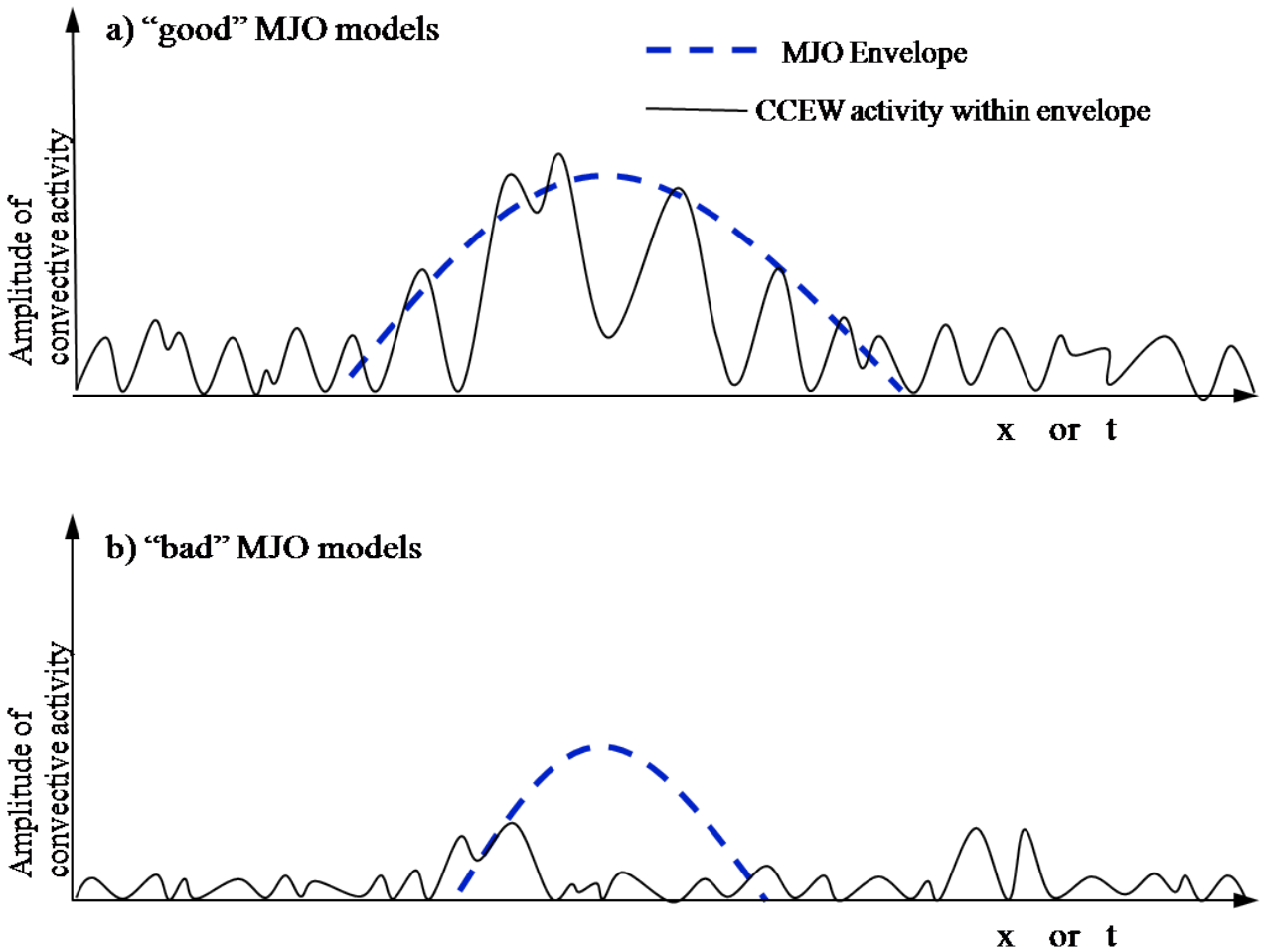
Bad MJO models:

In association with quasi-stationary "MJO" envelope, the ER variance moves only westward

Note: ER overlaps with the westward part of the ISV



Schematic Illustration of Multiscale Structure of the MJO



- Good MJO models: stronger CCEW (Kelvin, MRG, WIG and EIG) climatology; better coherence and stronger interactions between CCEW and MJO
- Vice versa for bad MJO models

Convectively Coupled Equatorial Waves (CCEWs)

they are theoretical wave solutions of the shallow water equation over the tropics, including

- Kelvin
- equatorial Rossby (ER)
- mixed-Rossby-gravity (MRG)
- westward &eastward propagating Inertio-gravity waves (WIG & EIG)

Two-way interactions between the MJO and the CCEWs

- MJO modulates CCEWs through modulating the large scale wind shear and moisture content *(e.g., Guo, Jiang, and Waliser, 2014)*
- CCEWs feedback to MJO through upscale transports of momentum, temperature and moisture *(e.g., Hendon and Liebmann, 1994)*