# A Revised Real-time Multivariate MJO Index

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# Outline

- ◊ Review of MJO and its indices
- ◊ Spectral analysis vs. EOF
- ◊ CEOF for real-time monitoring
- ◊ Higher-order CEOF modes
- ◊ How to revise the RMM
- ◊ Comparison of RMM-r & RMM

# Review of MJO and its indices

- *Tropical modes*

  Diurnal cycle
  Synoptic waves (Kelvin; Rossby; Easterly wave; 1-20 days)
  Intraseasonal variability (20-100days)
  Annual cycle (yearly)
  Inter-annual variability (ENSO; TBO; QBO)
  Decadal and longer-term variability

- *Madden-Julian oscillation (MJO)*

  "Detection of a 40-50 day oscillation in the zonal wind in the tropical Pacific" (J. Atmos. Sci., 1971)
  "Description of global-scale circulation cells in the tropics with a 40-50 day period (J. Atmos. Sci., 1972)

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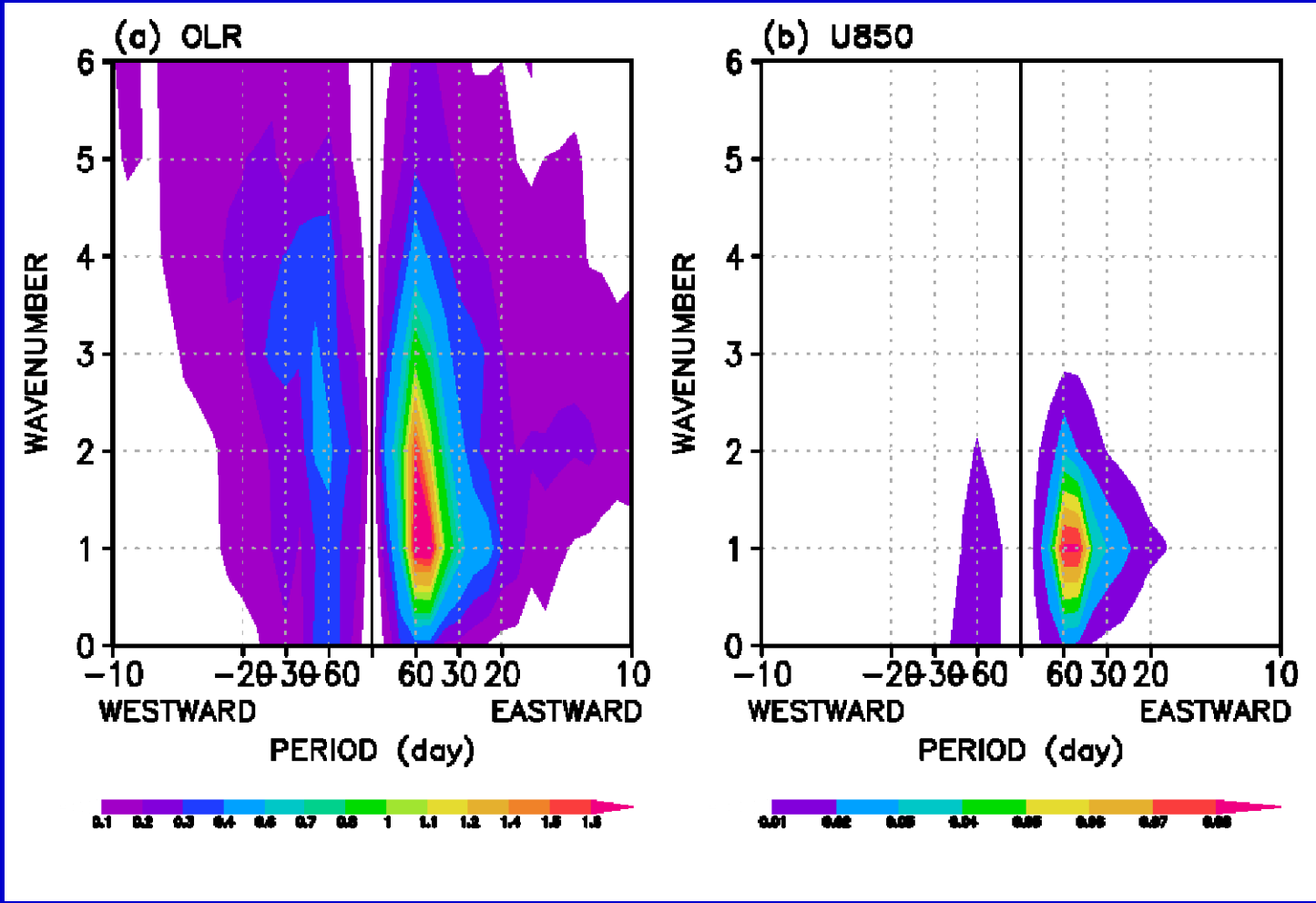
# Spectral: OLR 1979-2012



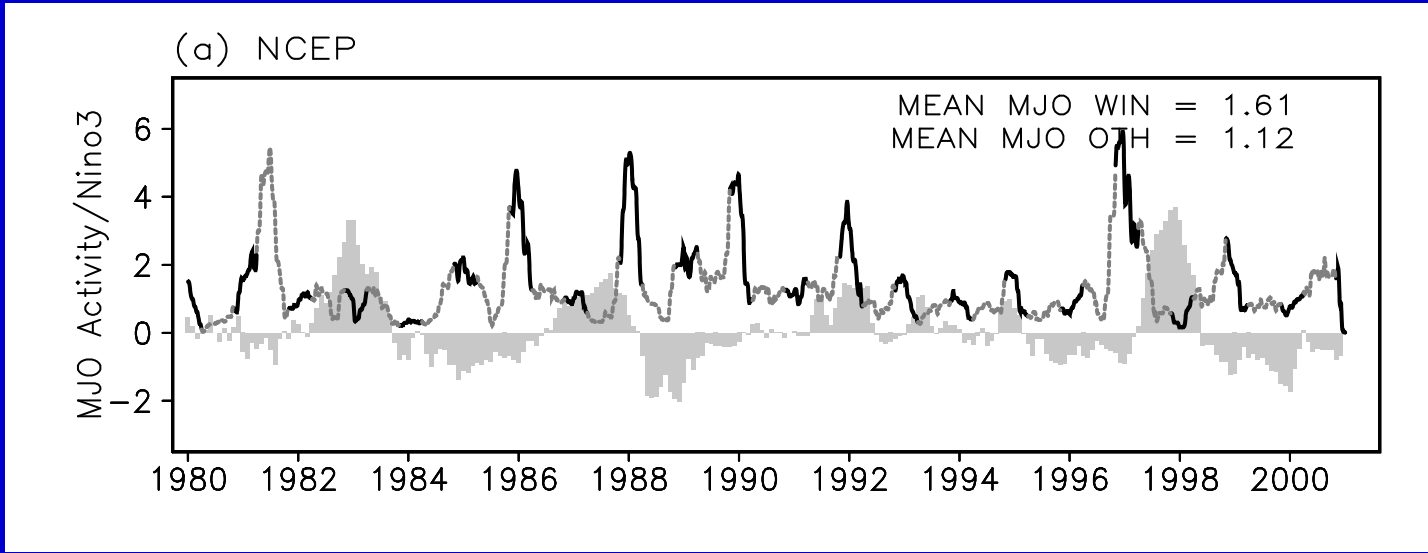
# MJO detection – spectral analysis

"Space-time spectral analysis and its applications to atmospheric waves" (JMSJ; Hayashi 1982)

-- Overall MJO spectral features

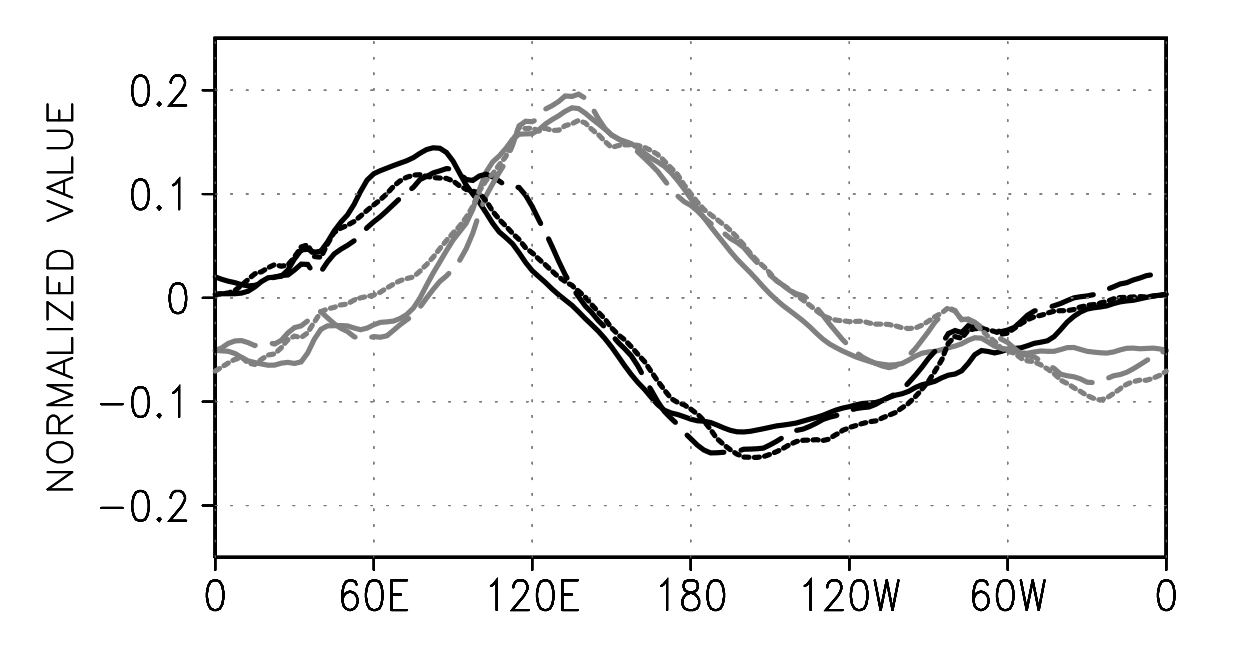
# MJO detection – band-pass filter

- Slingo et al. (1996) used 20-100-day filtered zonal mean zonal wind at 200 hPa to represent the MJO interannual activity.



# MJO detection – BPF + EOF

- The first two eigenvectors of U850 can well disclose the salient structures of an MJO (Maloney and Hartmann 1998).



# MJO detection – BPF + EOF

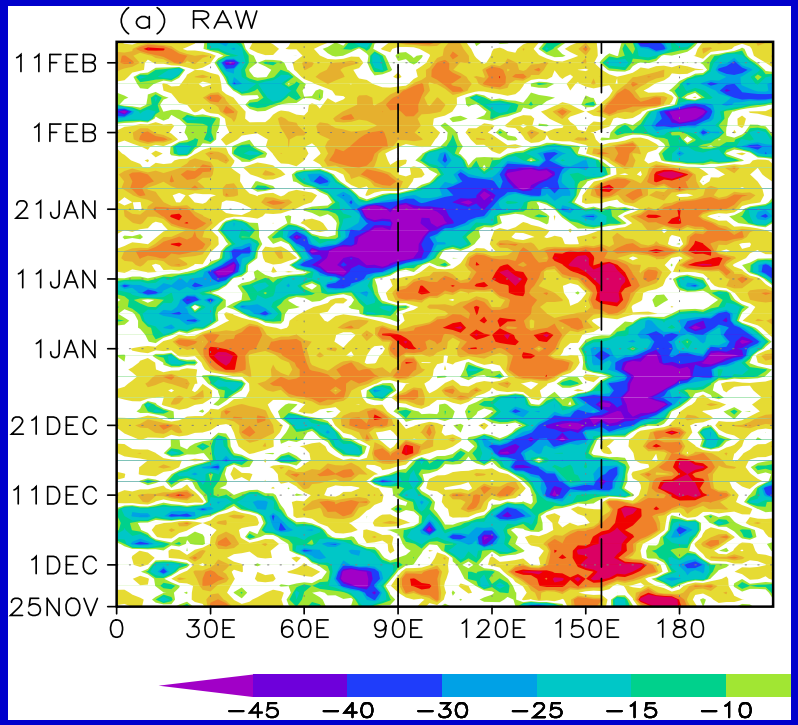
- An MJO index

$$IND(t)=PC1(t)+[PC2(t+2)+PC2(t+3)]/2$$

is thus defined to make a composite life cycle of MJO

# MJO detection – Real time

- Spectral approach is less ideal for its “edge effect”
- Individual event is quite episodic – TOGA-COARE



# Real-time Multivariate MJO (RMM) index

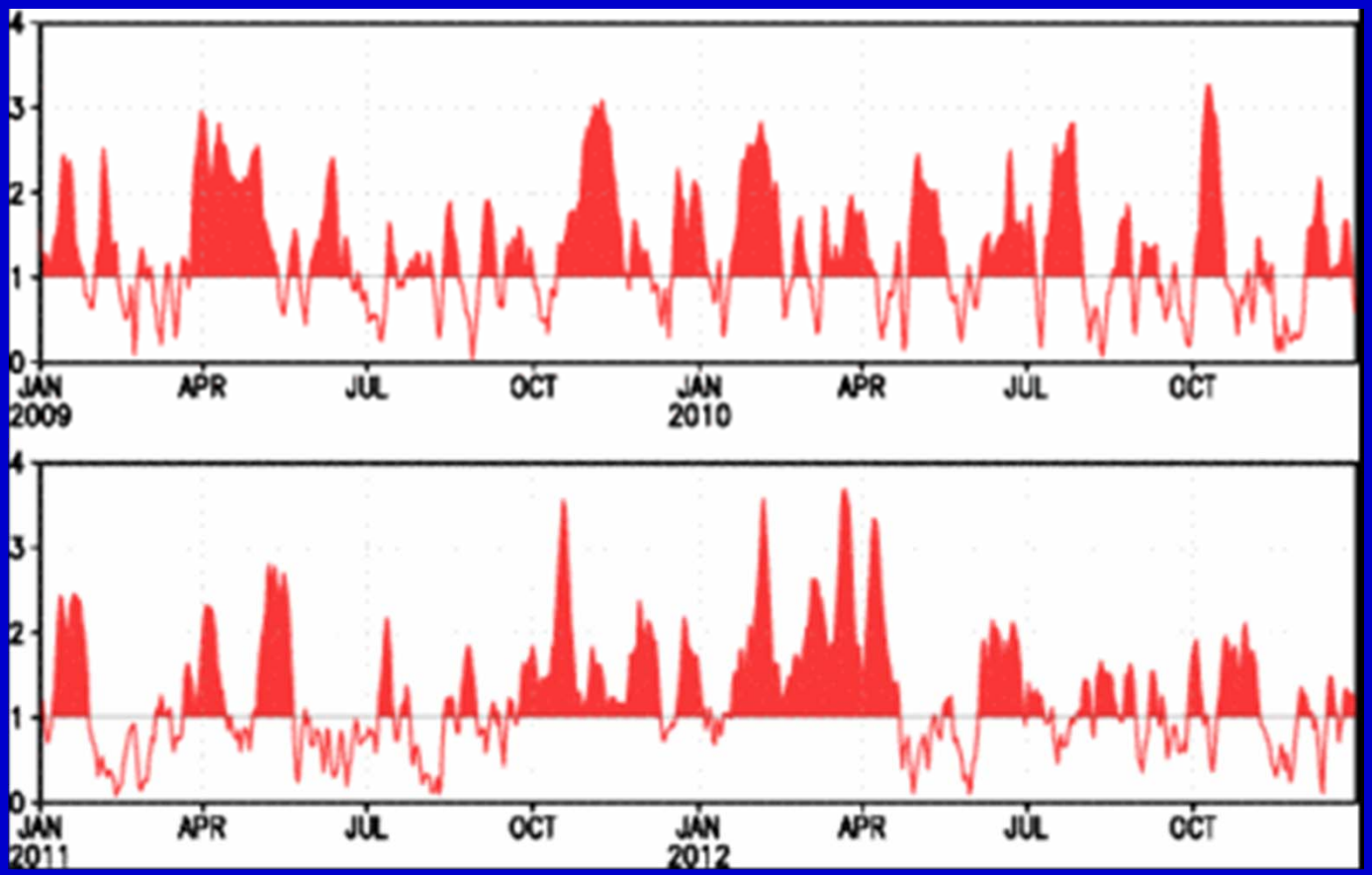
- Combined EOF (CEOF) of daily anomalies in OLR, U850 and U200 (Wheeler and Hendon 2004). Special steps to prepare the anomalous data.

# RMM index

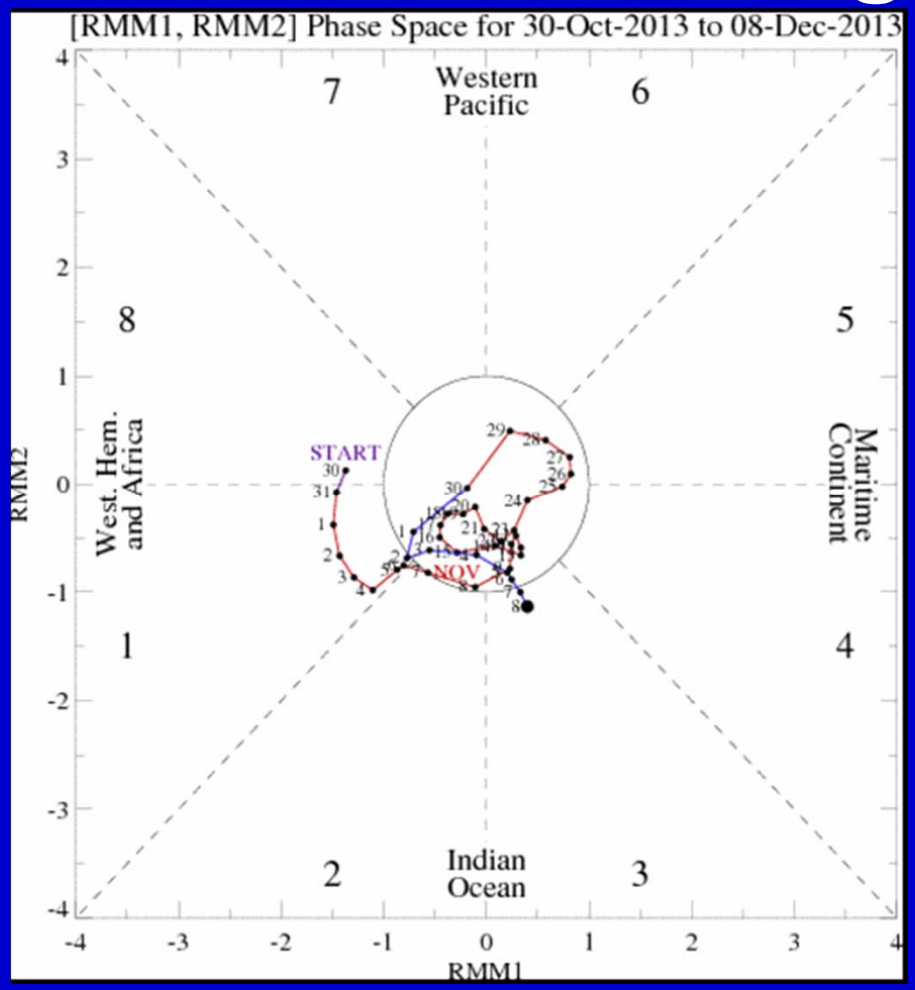
- Diurnal cycle: daily mean
- Seasonal cycle: 1st 4 modes of annual cycle
- Synoptic waves: 15°S – 15°N average for a substantial reduction
- *Interannual variability:*
  *ENSO SSTA mode: EOF – REOF – Regression – Interpolation to daily*
- Linear trend and lower-than-interannual variability
  retrospective 120-day mean; it is also effective to remove interannual and longer-scale variability (Lin et al. 2008)
- **Normalize each with its global-average STD for equal contribution**
- CEOF: first two principal components as RMM1 and RMM2

# RMM Framework - amplitude

$$\sqrt{RMM1^2 + RMM2^2}$$



# RMM Framework - diagram

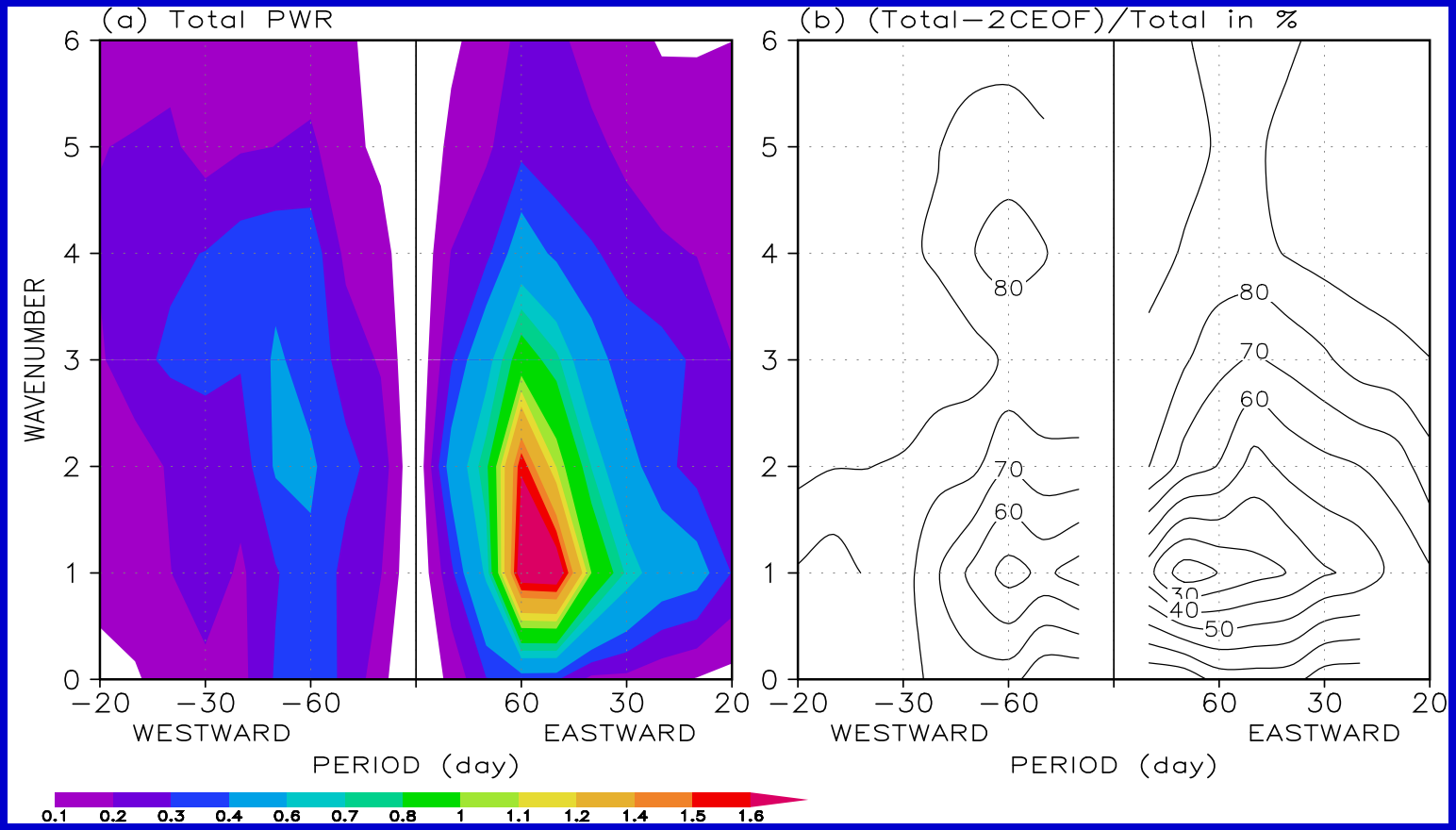


# Issues with the RMM

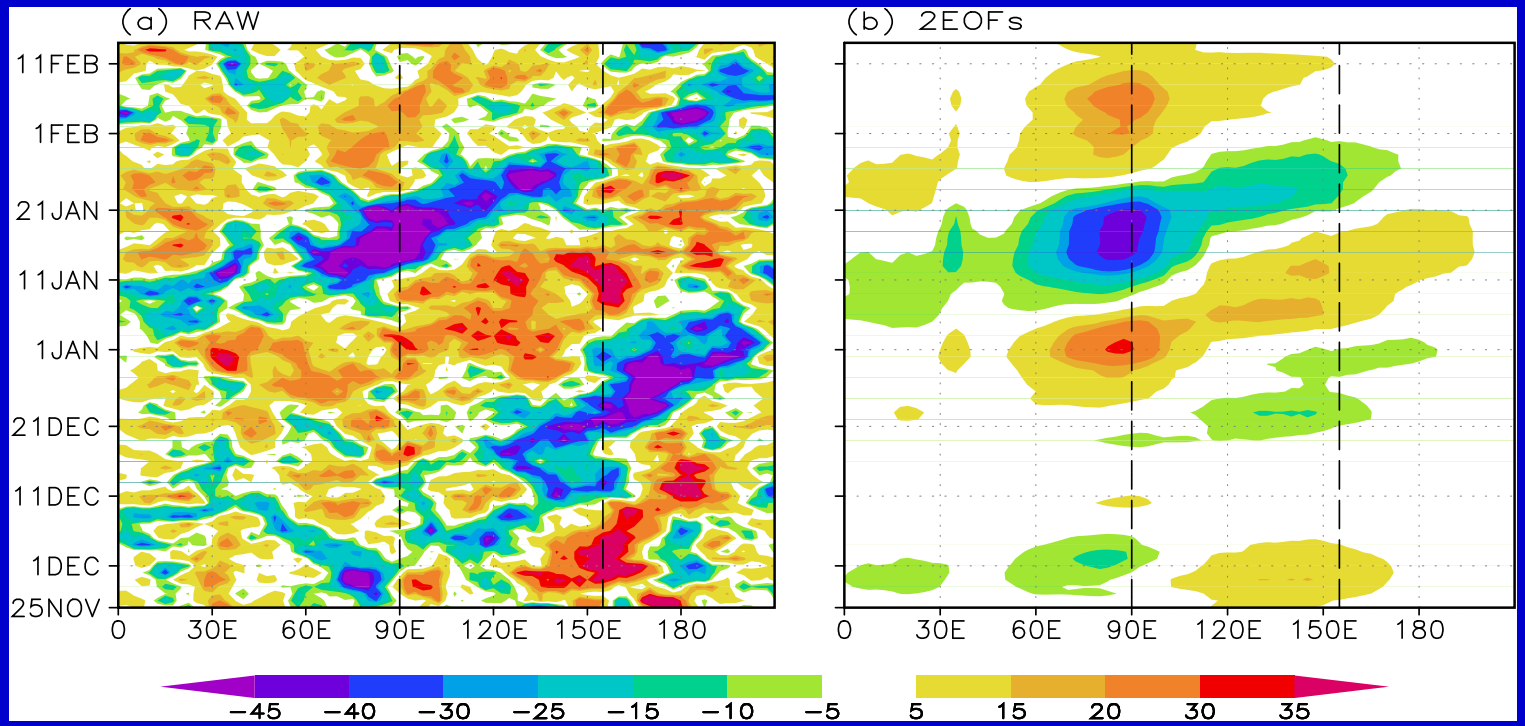
OLR/convection is systematically weak;
RMM is more like a dynamical index.

-- e.g., Straub (2013); Liu (2014)

# Spectral leakage at WN 2-5

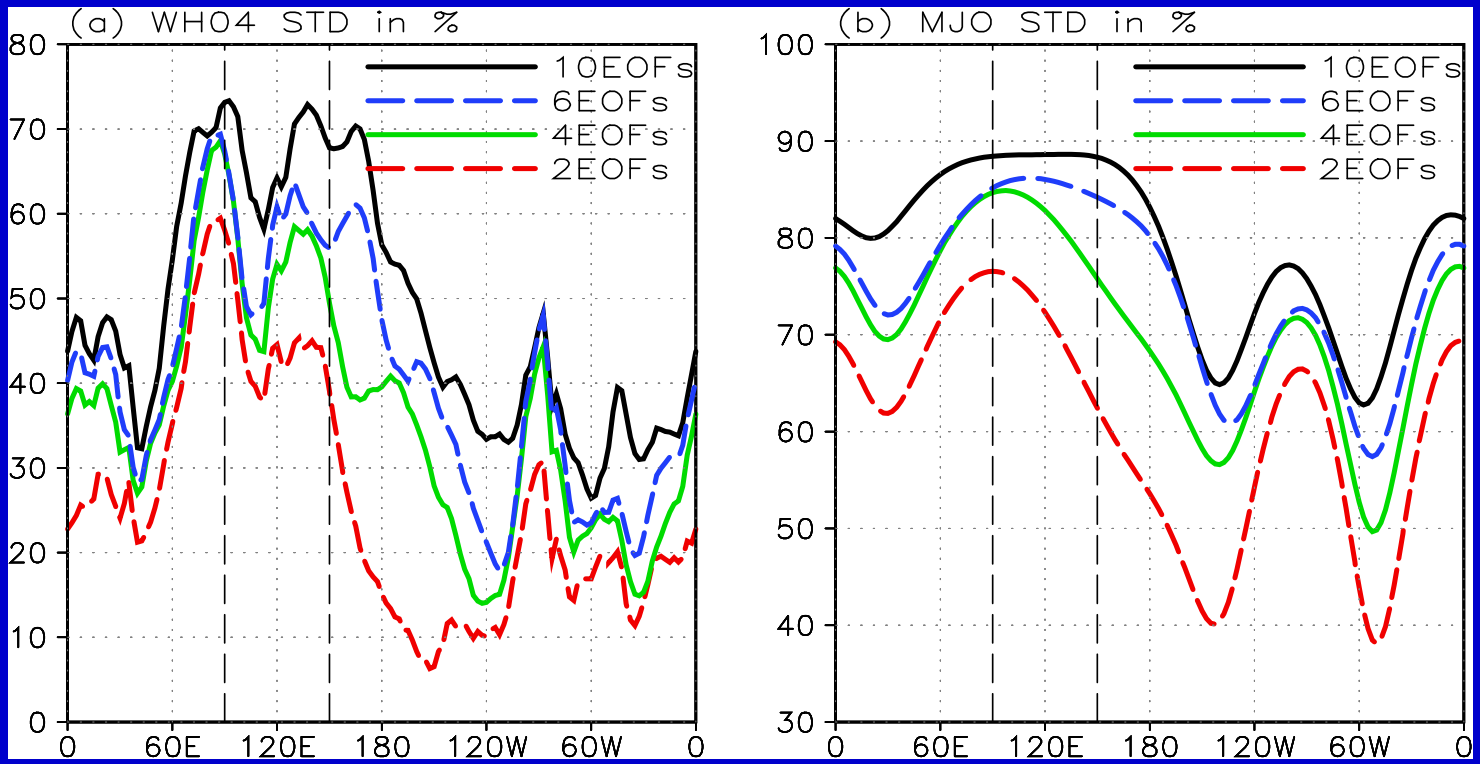


# TOGA-COARE events



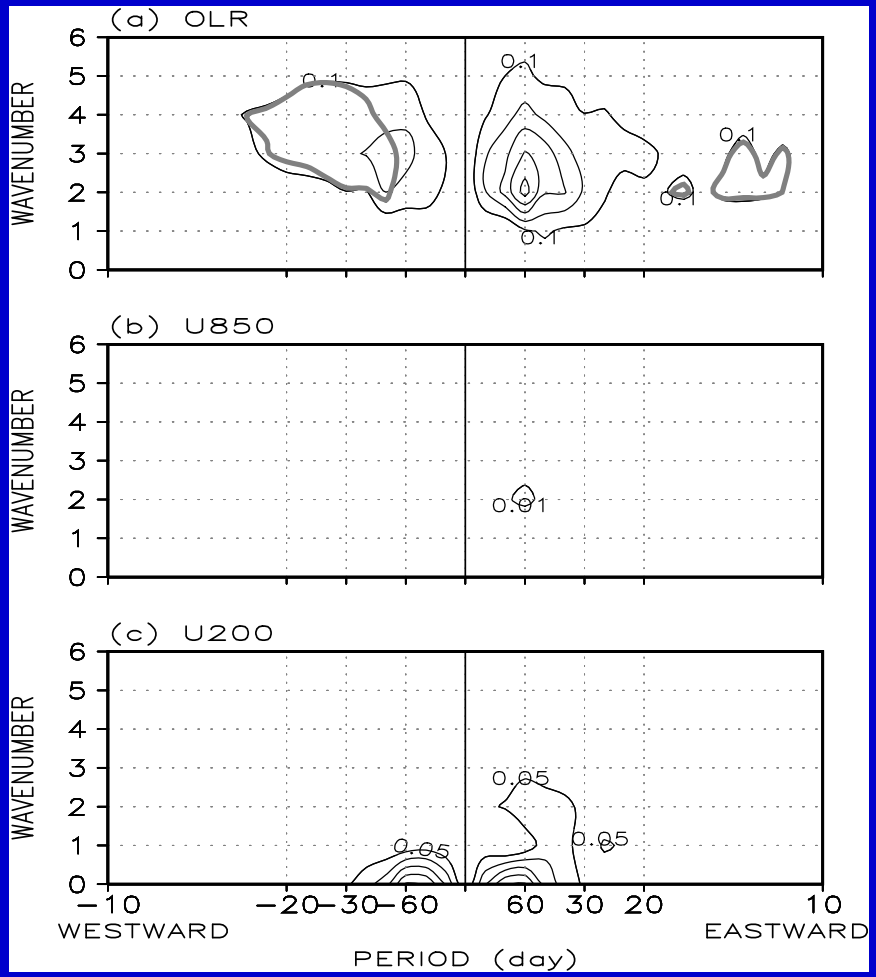

OLR; underestimated amplitude and structure in the Western Pacific

# Way to Improve – 10 CEOFs

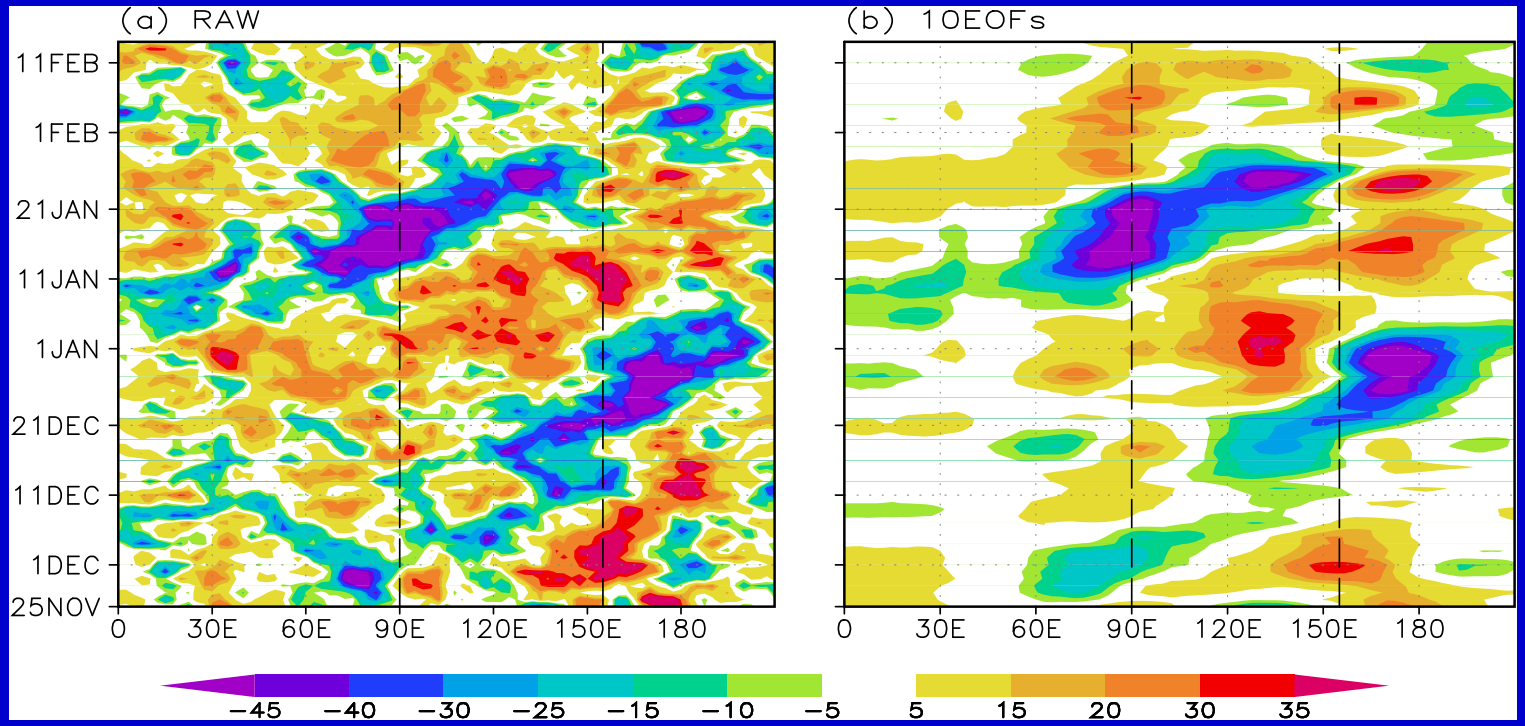



Liu 2014, Climate Dynamics

# Way to Improve – 10 CEOFs



# Way to Improve – 10 CEOFs



# Issues with 10 CEOFs

Difficult to incorporate the 10 modes to the RMM phase diagram.

Go back to the steps for RMM.

# Pre-steps for RMM

- Each field was normalized by its globally averaged STD (15.3 W $m^{-2}$ for OLR, 1.8 $m^{-1}$ for U850 and 4.9 m $s^{-1}$ for U200) for an equal contribution

Is this justified mathematically and physically?

# Covariance and Correlation

Covariance $cov(X,Y) = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{n-1}$, where X, Y are two time series on a pair of grids.

Correlation $cor(X,Y) = cov(X,Y)/\sigma_X\sigma_Y$, where $\sigma$ is the standard deviation (STD) – normalized

- Scaled by its own STD of a time series

# Correlation Matrix – guarantee equal contribution

$$COR = \begin{pmatrix} 1 & cor_{1,2} & \dots & cor_{1,n} \\ cor_{2,1} & 1 & \dots & cov_{2,n} \\ & & \vdots & \\ cor_{n,1} & cor_{n,2} & \dots & 1 \end{pmatrix}$$

# Covariance Matrix

$$COV = \begin{pmatrix} var_{1,1} & cov_{1,2} & \dots & cov_{1,n} \\ cov_{2,1} & var_{2,2} & \dots & cov_{2,n} \\ & \vdots & & \\ cov_{n,1} & cov_{n,2} & \dots & var_{n,n} \end{pmatrix}$$

Dividing the variances with the global averaged variance is a scaling. An equal contribution cannot be guaranteed.

# Covariance Matrix – equal contr.

$$COV = \begin{pmatrix} var_{1,1} & cov_{1,2} & \dots & cov_{1,n} \\ cov_{2,1} & var_{2,2} & \dots & cov_{2,n} \\ & \vdots & & \\ cov_{n,1} & cov_{n,2} & \dots & var_{n,n} \end{pmatrix}$$

The equal contribution from each field is depended on the same summation of the variance for each field then, suppose as a, b and c.

# Covariance Matrix – equal contr.

We need to seek

$$a/x=b/y=c/z=(a+b+c)/3$$

A unique solution exists and is
$x=3a/(a+b+c)$, $y=3b/(a+b+c)$, $z=3c/(a+b+c)$
We can compute them from observational data as $\sqrt{x}$ = 1.64, $\sqrt{y}$ = 0.19, and $\sqrt{z}$ = 0.52. Roughly 10 times smaller than the three numbers in WH04.

The matrix WH ~ correlation

# Four matrices

Covariance (COV)
Correlation (CORR)
WH04 (RMM)
RMM-r (RMM-r)

*RMM-r: scaled by (2,1,1) after a series of tests*

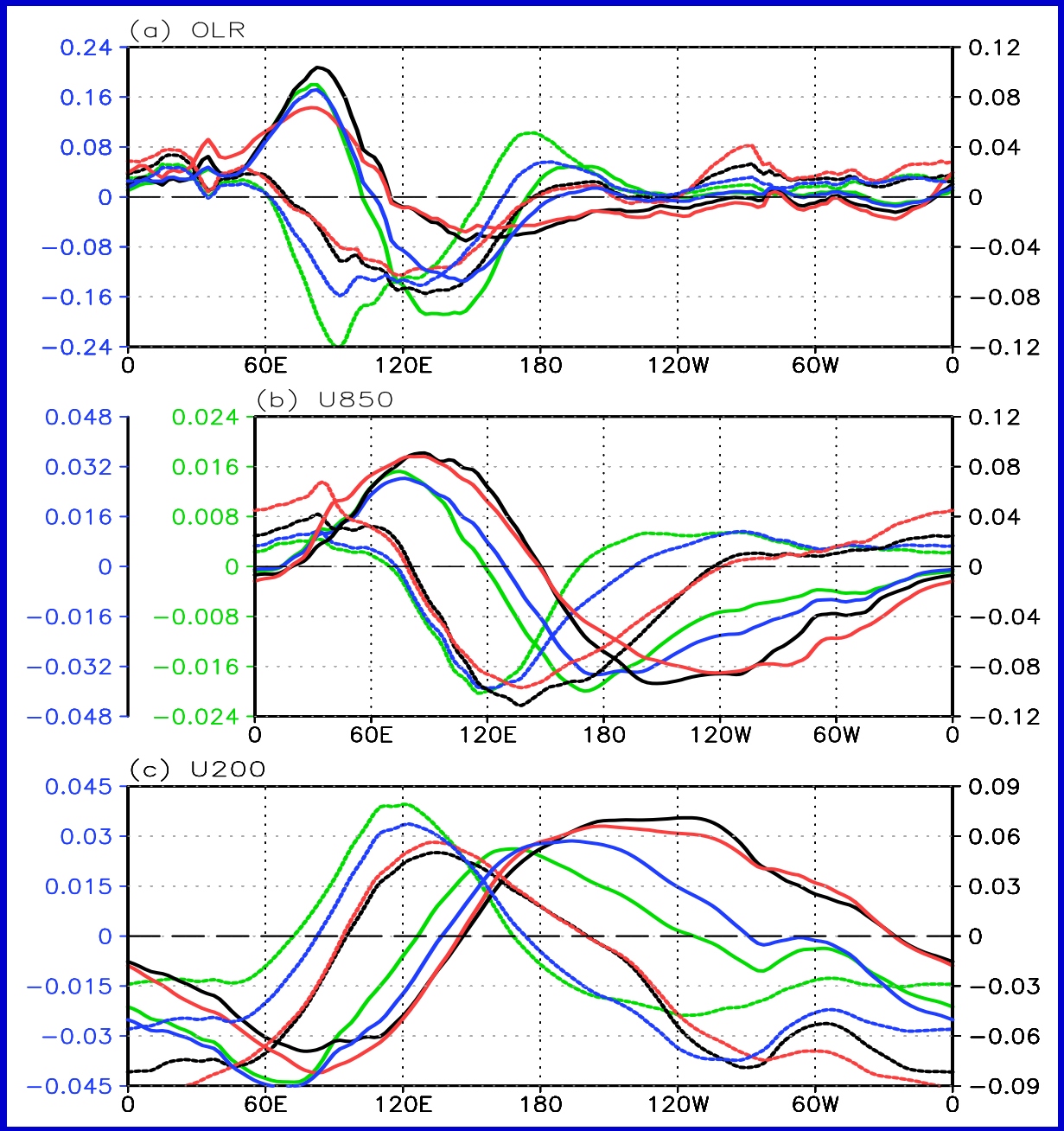
# EOF structures

Correlation (CORR) & WH04 (RMM)
Covariance (COV) & RMM-r (RMM-r)

The scaled matrix is close to a correlation matrix; both over-scaled the OLR.

RMM (black), CORR (red), COV (green), and RMM-r (blue)

RMM-r more balanced



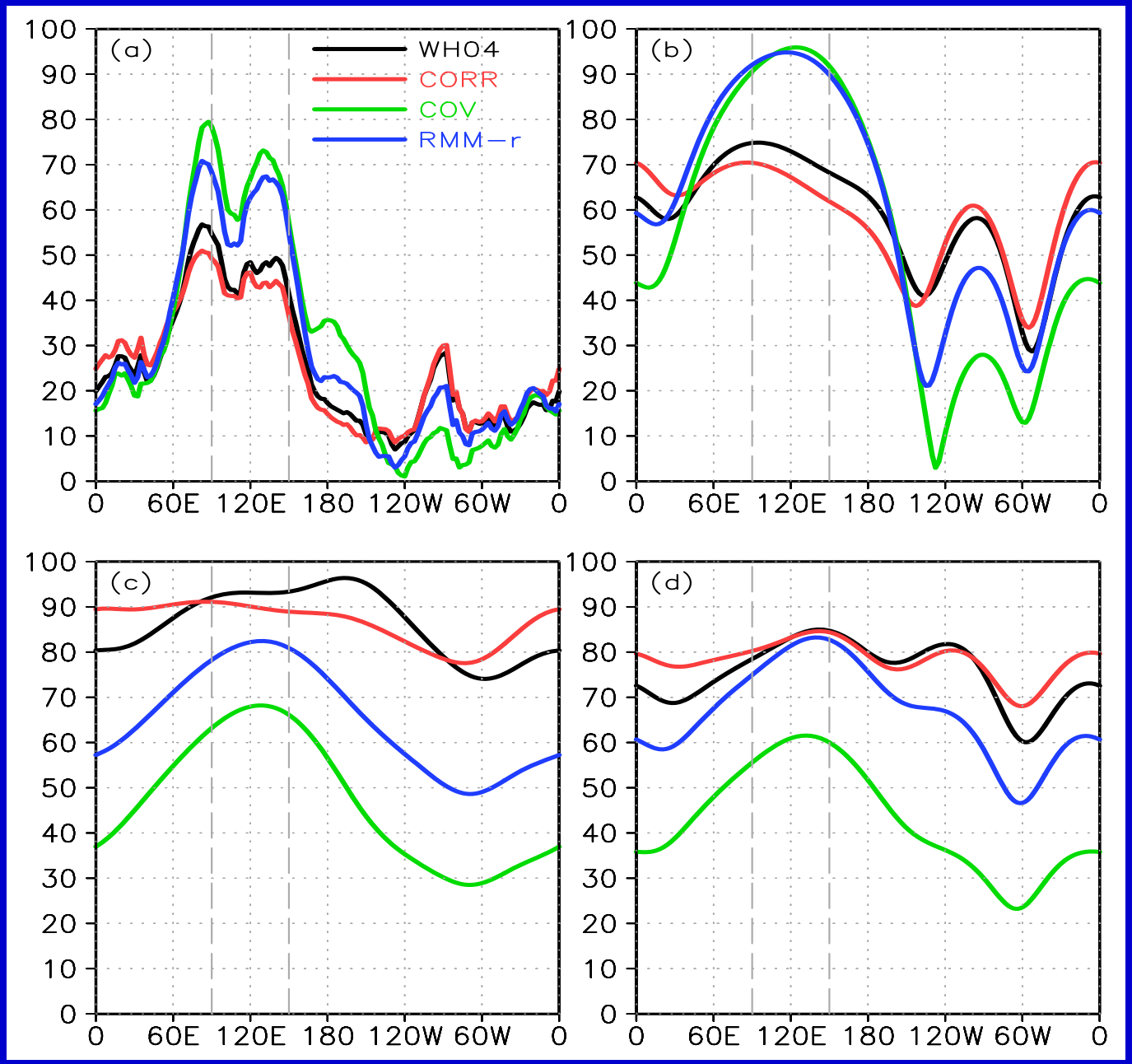
# STD contribution

Correlation (CORR) & WH04 (RMM)
Covariance (COV) & RMM-r (RMM-r)

The scaled matrix is close to a correlation matrix; both over-scaled the OLR.

RMM (black), CORR (red), COV (green), and RMM-r (blue)

(a) Total OLR
(b) First two OLR
(c) U850
(d) U200



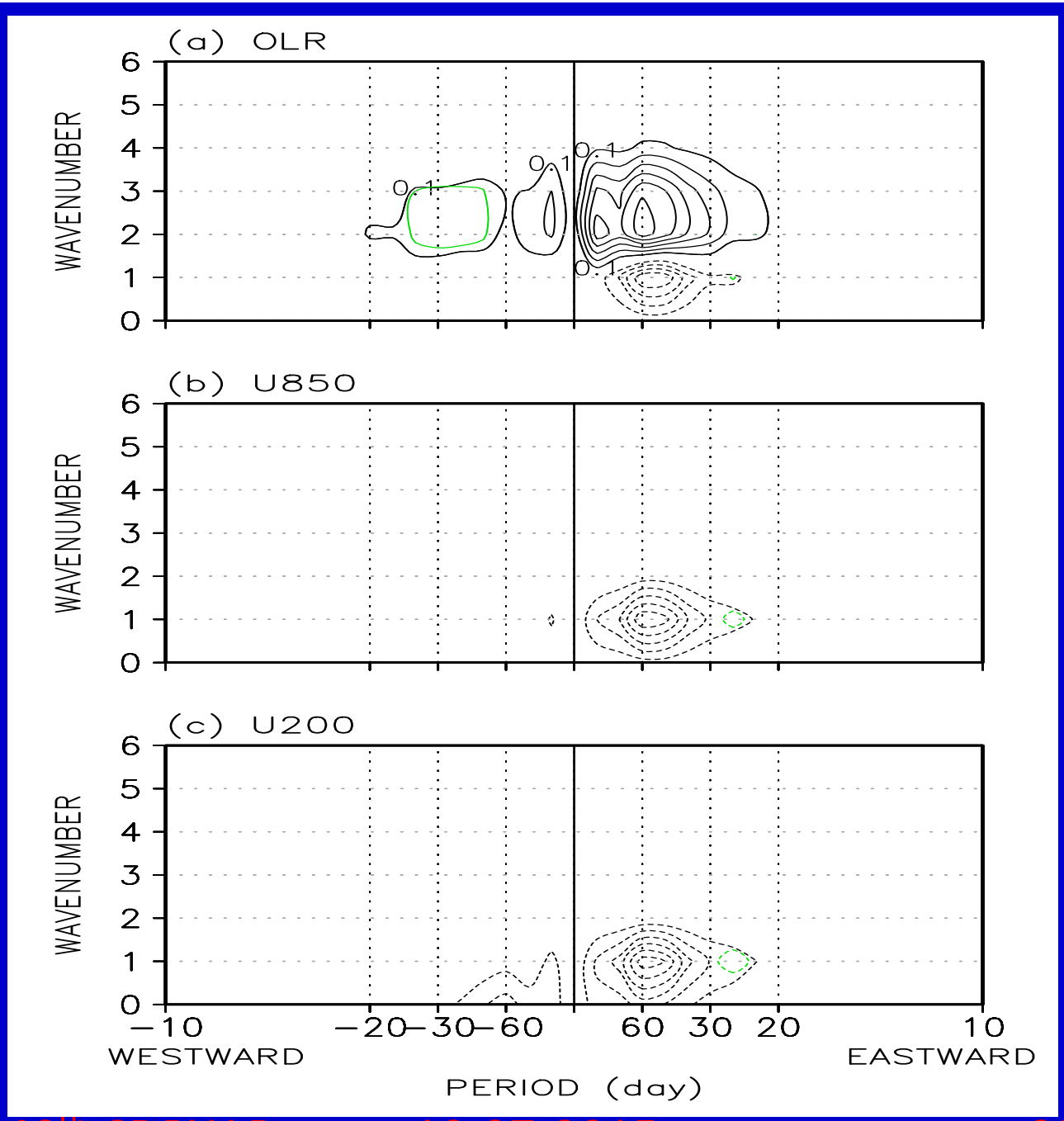
# Power Spectra

COV - RMM

COV-RMM in power spectra

Similar in COV-CORR

Over reduced U850 & U200

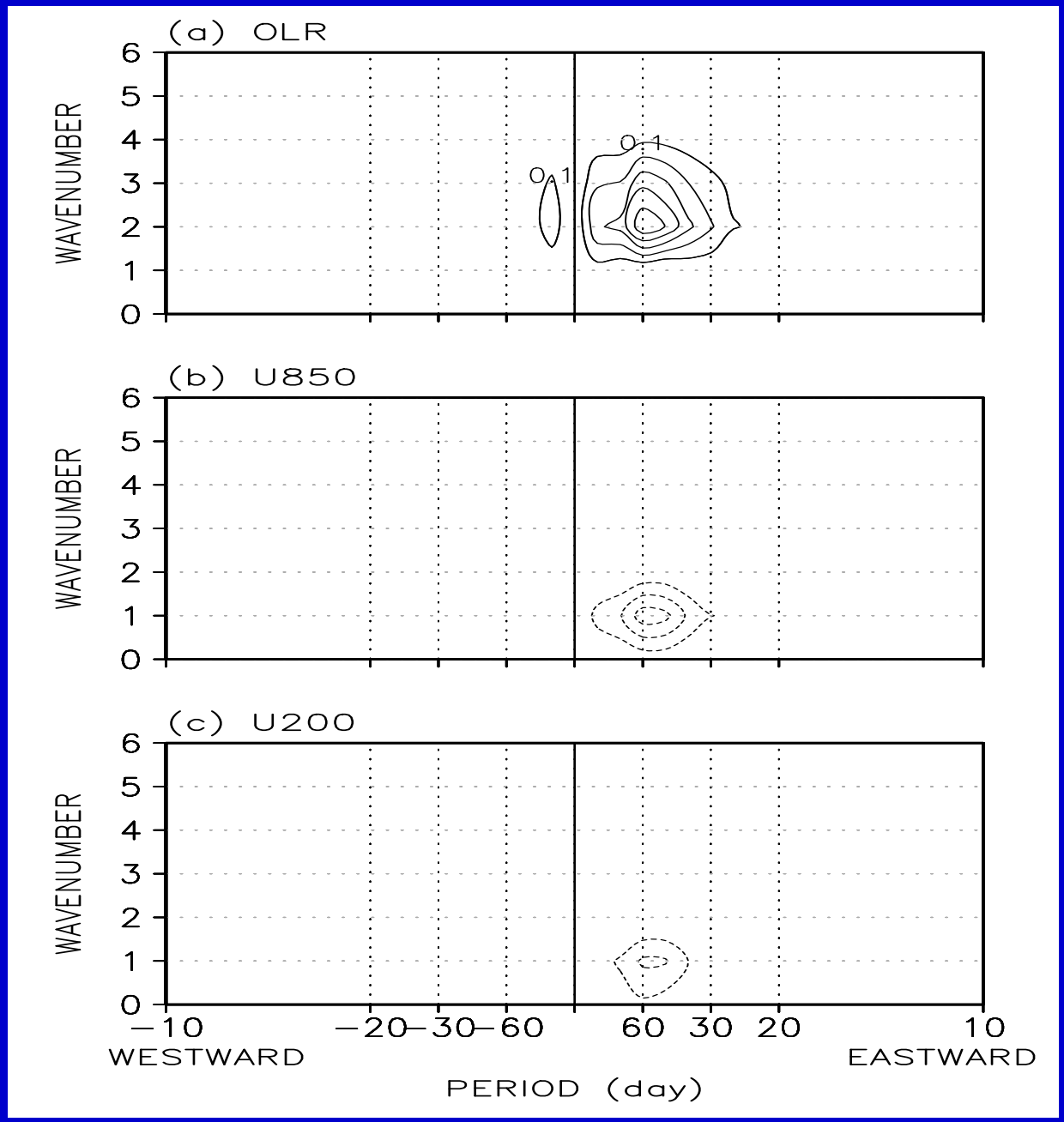


# Power Spectra

RMM-r - RMM

RMM-r-RMM in power spectra

improvement



# Strong MJO Convective Peaks

Table 3 Intensity and location of strong MJO convective peaks

| | longitudes in 2.5 – 100°E | | longitudes in 100 – 180°E | |
|---|---|---|---|---|
| | $OLR_m$ (W $m^{-2}$) | Longitude (degree) | $OLR_m$ (W $m^{-2}$) | Longitude (degree) |
| Raw | -21.0 | 89.4 | -24.2 | 131.4 |
| RMM | -12.6/60% | 90.0 | -12.2/50.4% | 127.4 |
| **RMM-r** | **-17.0/81.0%** | **91.6** | **-18.2/75.2%** | **128.0** |
| RMM-Raw | 8.4 | 0.6 | 12.0 | -4.0 |
| **RMM-r - Raw** | **4.0** | **2.2** | **6.0** | **-3.4** |

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# Strong MJO Phases
# RMM-r vs. RMM

Table 4 Total number (#) of occurrences and average intensity (AI.) for strong MJO phases with RMM magnitude exceeding two normalized units

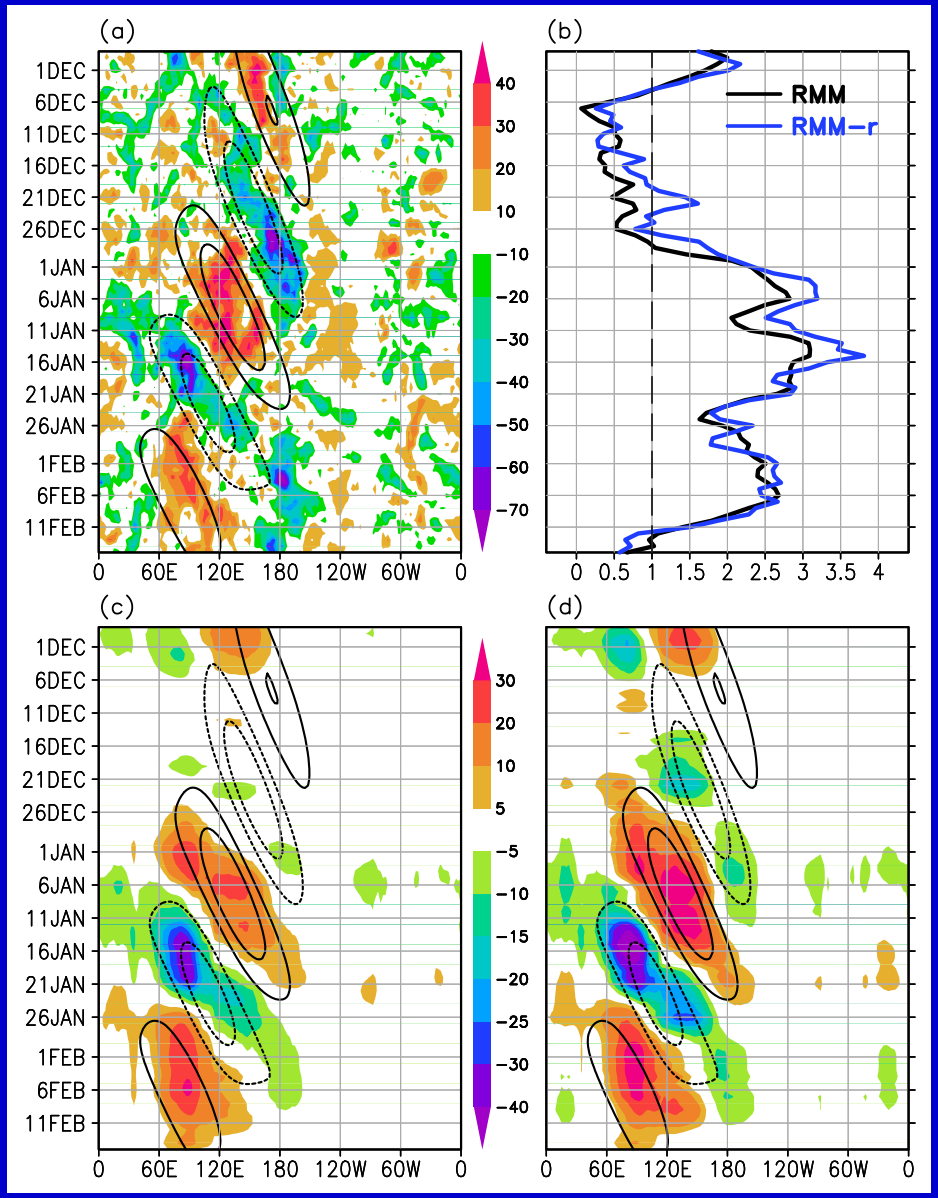
| | #RMM | #RMM-r | #DIFF% | AI.RMM | AI.RMM-r | AI.DIFF | AI.T-test |
|---|---|---|---|---|---|---|---|
| Phase 1 | 217 | 219 | 0.9 | 2.36 | 2.51 | 0.15 | **3.79 \| 99.9%** |
| Phase 2 | 183 | 227 | **24.0** | 2.38 | 2.40 | 0.02 | 0.51 |
| Phase 3 | 232 | 269 | **16.0** | 2.45 | 2.44 | -0.01 | 0.59 |
| Phase 4 | 171 | 186 | 8.8 | 2.48 | 2.51 | 0.03 | 0.18 |
| Phase 5 | 204 | 242 | **18.6** | 2.50 | 2.53 | 0.03 | 0.32 |
| Phase 6 | 204 | 212 | 3.9 | 2.38 | 2.43 | 0.05 | 1.18 |
| Phase 7 | 235 | 231 | -1.7 | 2.44 | 2.41 | -0.03 | 1.22 |
| Phase 8 | 230 | 292 | **27.0** | 2.47 | 2.54 | 0.07 | **1.74 \| 90%** |

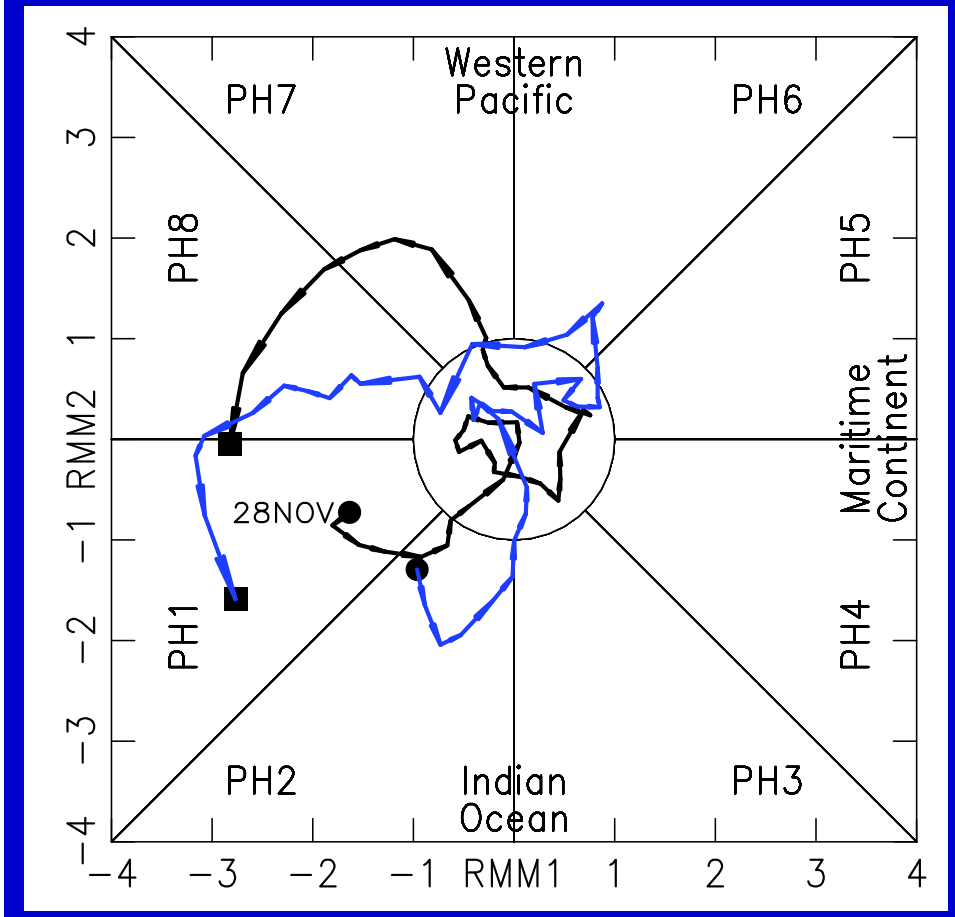
# Several Cases
# RMM-r vs. RMM

TOGA-CORE

RMM-r vs RMM

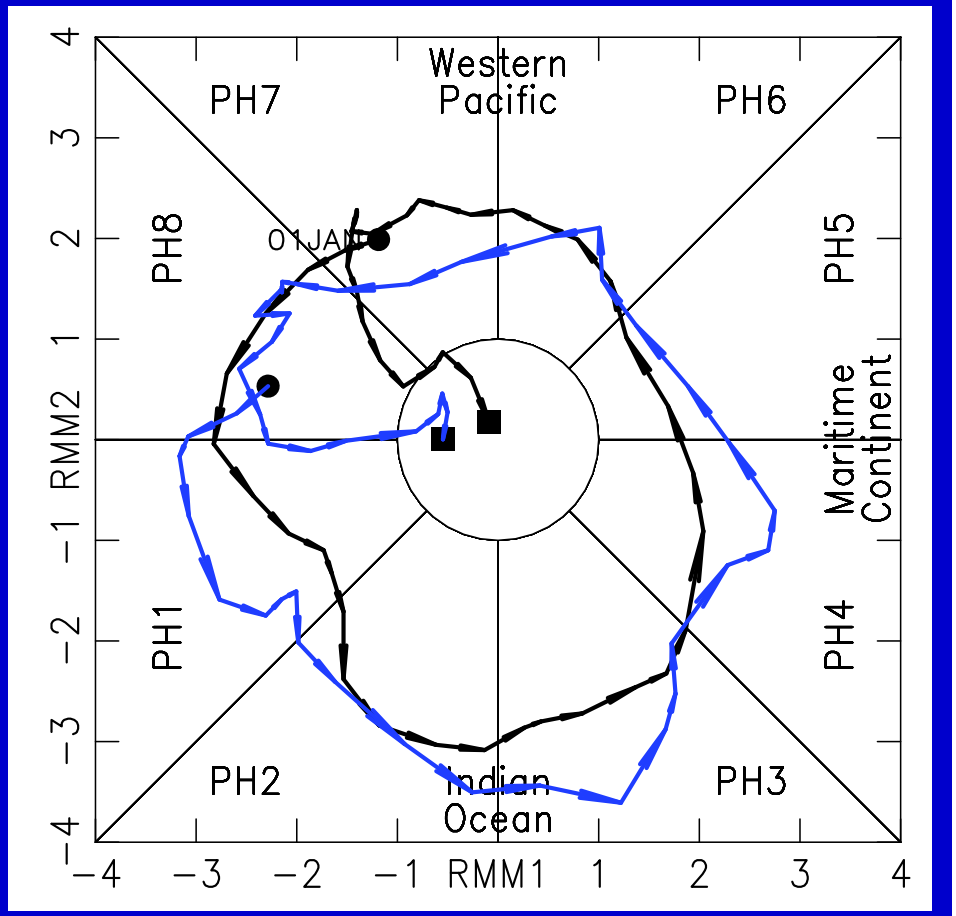
In intensity, duration






1st TOGA-COARE event

2nd TOGA-COARE event

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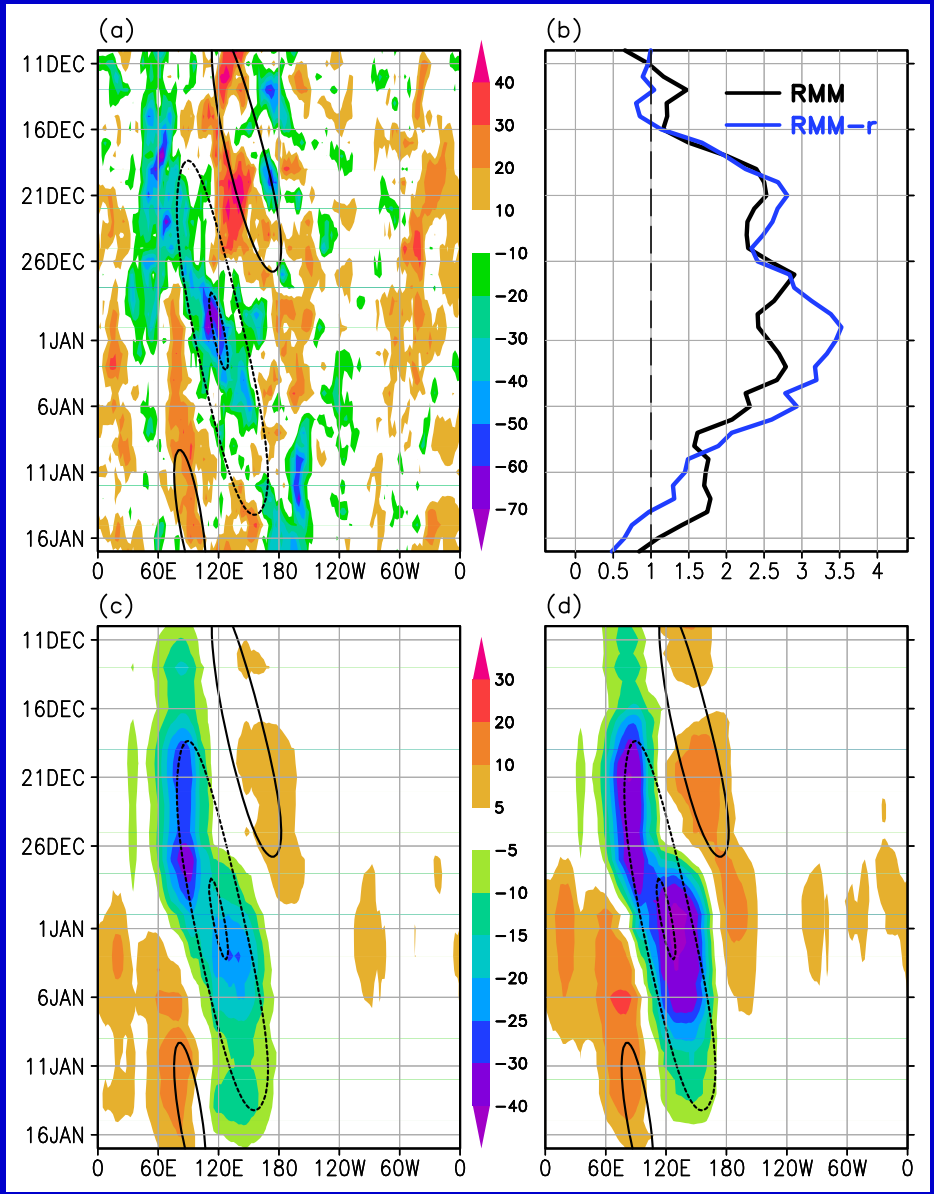
# 2006-07 Event
# RMM-r vs. RMM

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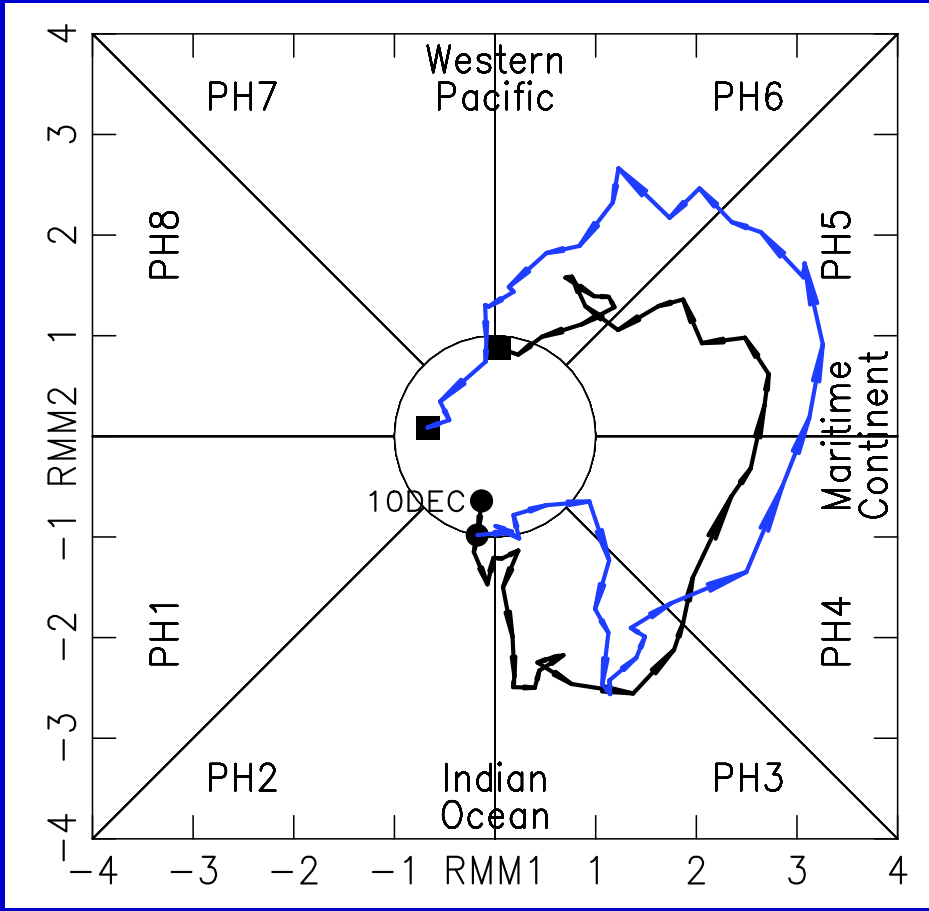
PH8
PH7
Western
Pacific
PH6
PH5
Maritime
Continent
PH4
PH3
Indian
Ocean
PH2
PH1
10DEC
RMM2
RMM1
4
3
2
1
−1
−2
−3
−4
−4
−3
−2
−1
1
2
3
4

# Summary

. More balanced contributions from the three fields to the RMM-r

. Better representation in MJO convection

. Better detecting MJO evolution in real time

. Using the RMM-r to calibrate and evaluate the GEFS reforecasts/forecasts at weeks 2-4

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