MJO Simulation in CMIP5 Climate Models: Understanding Model Behavior using the Moisture Mode Framework

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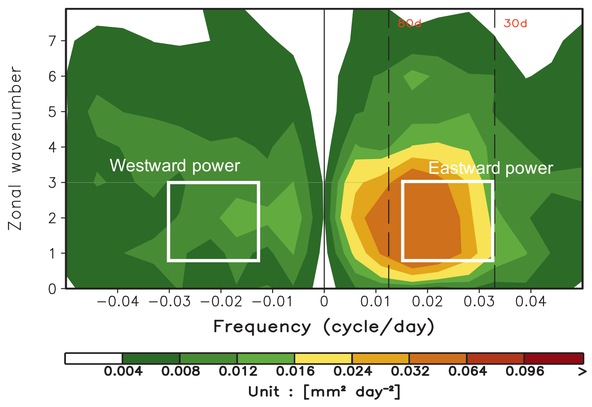
Part I. How well do the CMIP5 models represent the Madden-Julian oscillation (MJO)?

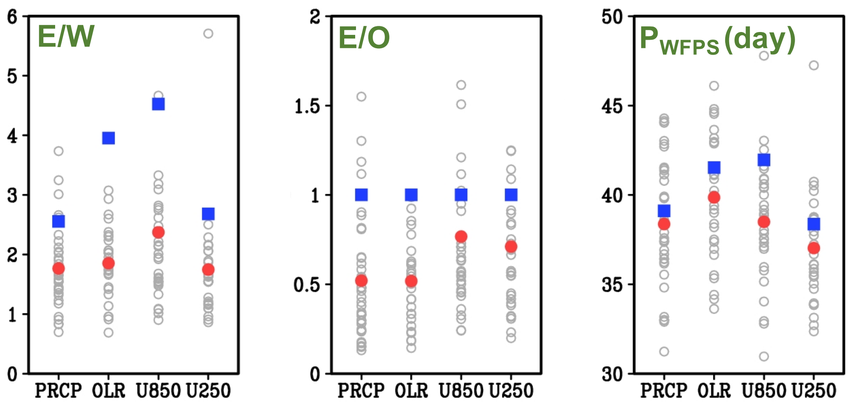
1. MJO skill metrics from wavenumer-frequency power spectra



*MJO band period: 30-60 days wave number: 1-3

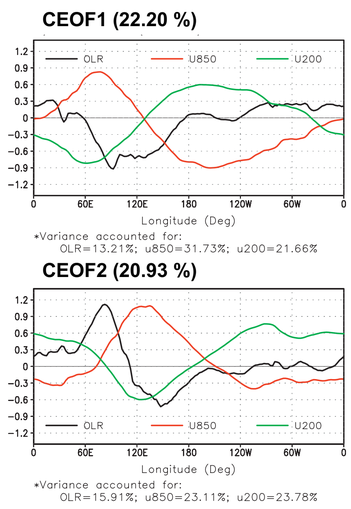
- **E/W** : (eastward power)/(westward power)
- **E/O** : (model eastward power)/(obs eastward power)
- **P_{WFPS}** : 1/(power-weighted average of frequency)

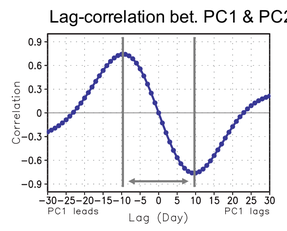
CMIP5 model results



- **Most CMIP5 models underestimate MJO amplitude, especially when OLR is used in the evaluation, and exhibit too fast phase speed. Models show a wide variety of MJO simulation skill.**

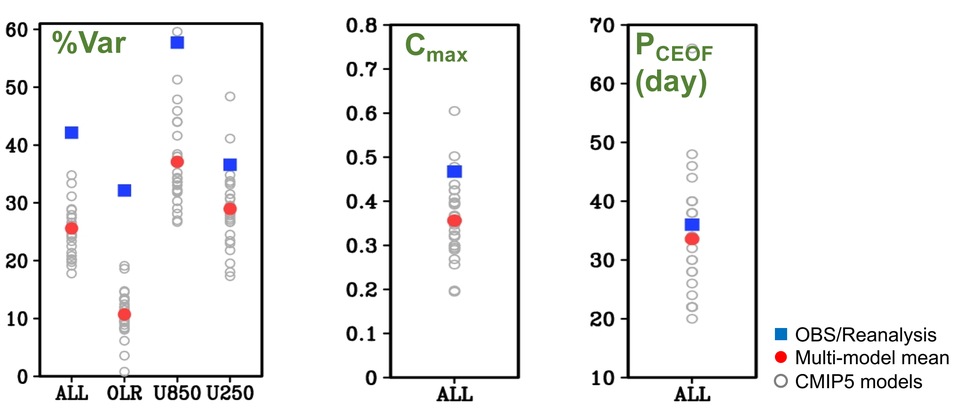
2. MJO skill metrics derived from the combined EOF analysis





- **%Var**: percentage variance of combined or each variable explained by the leading pair of combined EOF (MJO mode)
- **C_{max}**: maximum cross correlation between PC1 and PC2
- **P_{CEOF}**: period estimated from the lag-correlation between PCs of the two leading combined EOF modes

CMIP5 model results



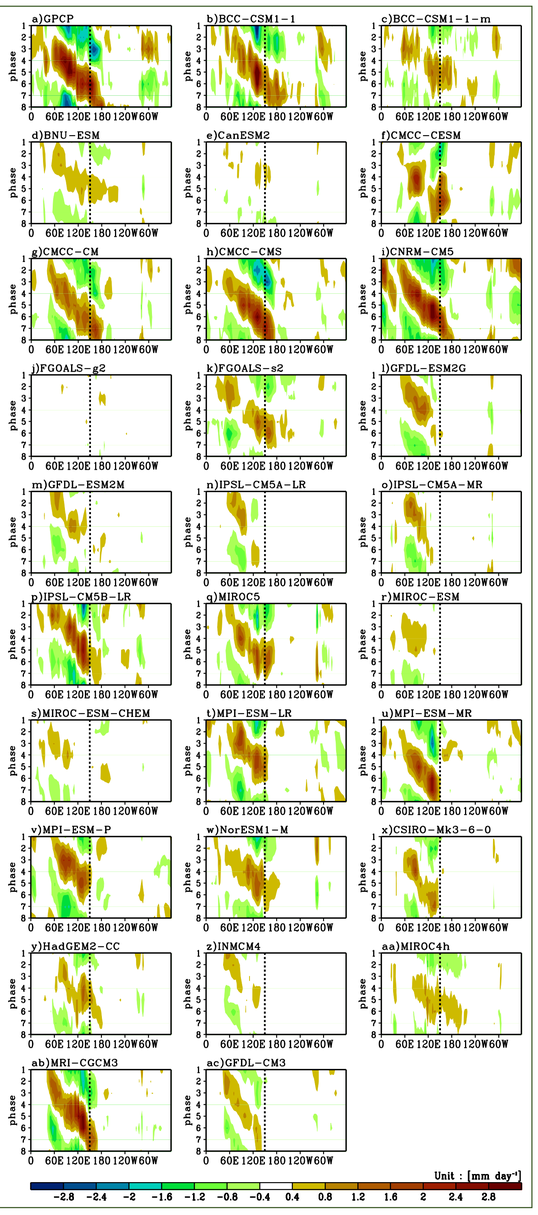


Figure (➔) Hovmöller diagrams of MJO phase composited 20-100-day precipitation averaged between 10°S-10°N. The MJO phase composites are based on the PC time series formulated by projecting the 20-100-day filtered anomaly data onto the CEOF's eigenvectors. The vertical dotted lines in each plot indicate the 150°E longitude.

Part II. Why are some models better than others? - testing theory-driven hypotheses

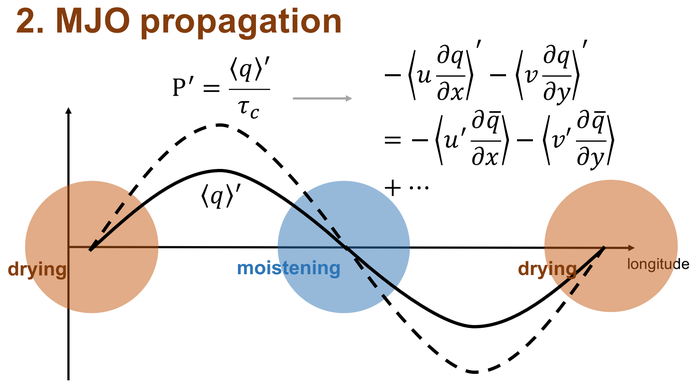
1. Moisture mode

A recent growing body of thoughts regard the MJO as a '**moisture mode**' on an equatorial beta-plane [*Neelin and Yu,* 1994; *Raymond,* 2001; *Sobel and Maloney,* 2012, 2013; *Adames and Kim,* 2016]. Under the moisture mode framework, which is based on the tight coupling between moisture and convection [e.g., *Bretherton et al.,* 2004] and the smallness of buoyancy perturbations in the tropics [*Charney,* 1963; *Sobel et al.,* 2001], **the evolution of large-scale, low-frequency anomalies of convection associated with the MJO is explained by those of moisture anomalies**. The column-integrated moisture and moist static energy budget of the MJO have been examined using reanalysis and model simulations to understand propagation and maintenance mechanism of the MJO.

MJO propagation: Horizontal moisture advection, especially **the advection of the mean moisture by the MJO-related anomalous winds**, has been identified as the process that is key to the MJO propagation [*Kiranmayi and Maloney* 2011; *Andersen and Kuang* 2012; *Adames and Wallace* 2015]. *Gonzalez and Jiang* [2017] showed that GCMs' MJO simulation performance has a tight relationship with their ability to simulate realistic basic state moisture distribution over the Indo-Pacific warm pool, emphasizing the role of the mean state simulation.

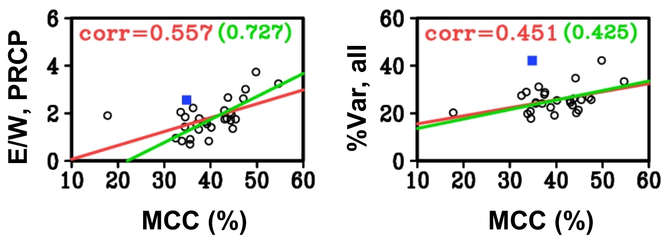
MJO maintenance: The **normalized gross moist stability**, indicative of the efficiency of a convective atmosphere for exporting moist static energy out of the column, has shown a tight relationship with MJO simulation fidelity in previous model intercomparison studies [*Benedict et al. 2014; Jiang et al. 2015; Ahn et al. 2017].* The **longwave cloud-radiation feedback** process has been suggested as the key process for MJO maintenance [*Kiranmayi and Maloney* 2011; *Andersen and Kuang* 2012; *Adames and Kim* 2016]. *Kim et al.* [2015] showed that GCMs with a stronger longwave cloud-radiation feedbacks tend to simulate more pronounced MJO variability.

2. MJO propagation



Anomalous heating (P') is tightly coupled to anomalous moisture (<q>') and the anomalous heating induces low-level circulation anomalies (Matsuno-Gill response), which then redistribute moisture

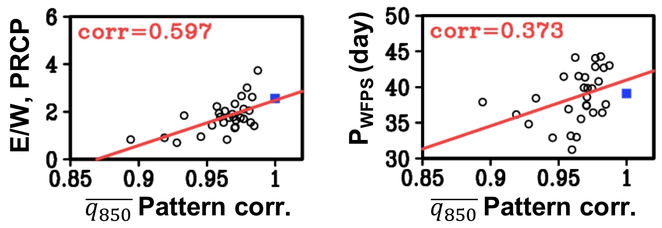
Hypothesis I: models with a tighter moisture-convection coupling would produce a stronger MJO propagation



$$\mathrm{MCC} = \overline{RH_{LT}}^{top\ 10\%} - \overline{RH_{LT}}^{bottom\ 20\%}$$

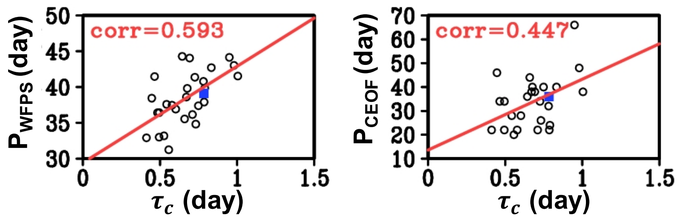
Moisture-convection coupling (MCC): lower tropospheric relative humidity difference between top 10% and bottom 20% rain events

Hypothesis III: models with a more realistic low-level mean moisture pattern (hence gradient of it) would produce a better MJO propagation



Low-level mean moisture skill: pattern correlation of model boreal winter 850-hPa specific humidity field and observations

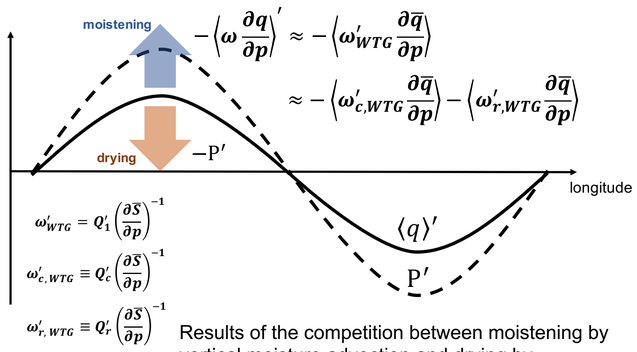
Hypothesis II: models with a longer convective adjustment time scale would produce a slower MJO propagation



$$P' = \frac{\langle q \rangle'}{\tau_c} \qquad \tau_c = \frac{Cov\,(\langle q \rangle', P')}{Var(P')}$$ Jiang et al. (2016)

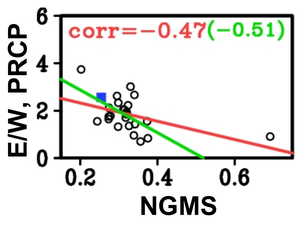
Convective adjustment time scale (τ_c): the time scale at which anomalous convection restores humidity anomalies back to its climatological value

3. MJO maintenance



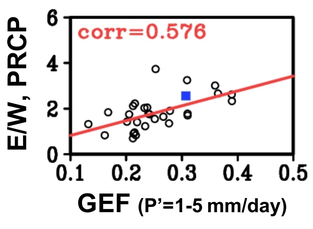
Results of the competition between moistening by vertical moisture advection and drying by precipitation determines whether the positive moisture anomalies would develop further or decay.

Hypothesis IV: models with a lower NGMS would produce a stronger MJO



Normalized gross moist stability (NGMS): the ratio of column-integrated vertical advection of MSE to that of dry static energy

Hypothesis V: models with a stronger GEF would produce a stronger MJO



Greenhouse Enhancement Factor (GEF): the ratio of column-integrated anomalous radiative heating to column-integrated anomalous condensational heating

- **Moisture move view provides useful guidance toward understanding the inter-model spread in MJO performance**
  - tighter **moisture-convection coupling** ➔ stronger MJO
  - shorter **convective adjustment time scale** ➔ faster MJO
  - steeper **mean meridional moisture gradient** ➔ stronger, faster MJO
  - lower **normalized gross moist stability** ➔ stronger MJO
  - stronger **cloud-radiation feedbacks** ➔ stronger MJO
- **The theory-driven, process-oriented diagnostics/metrics could be utilized to accelerate model development**

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