Simulating the MJO in a 3D model with a convection threshold

leading to intermittency

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Abstract

It is still a challenge today to simulate the Madden-Julian Oscillation (MJO) in a 3D general circulation model (GCM) even though the MJO was first discovered 40 years ago. Here we simulate the MJO in an idealized GCM focusing on intermittent convection and high-frequency waves, which we suggest are essential to the MJO. We carry out four different experiments. We use the default GCM setup as the control simulation, and there is no MJO. We then make convection more intermittent by separately raising the convection threshold in three different variables: column integrated precipitable water, convective available energy (CAPE), and convection inhibition (CIN). The MJO emerges from each of these simulations with the observed drift rate and spatial structures, and the high-frequency waves are stronger in these simulations than in the control simulation. This is consistent with the Yang and Ingersoll (2013, 2014) hypothesis that the triggered convection and high-frequency waves are important to the MJO. This study has broader implications on improving GCM convection parameterizations.
1. Introduction:

There are two distinct schools of MJO theories. One school considers the MJO as a large-scale, low-frequency unstable mode in the tropics, e.g., a moisture mode. It arises from moisture-convection feedback, i.e., positive feedbacks between convection and the source of moist static energy (MSE) (e.g., Neelin and Yu, 1994; Sobel et al., 2001; Fuchs and Raymond, 2002, 2005, 2007; Maloney, 2009; Raymond and Fuchs, 2009). Evidence comes from the fact that making deep convection sensitive to free troposphere moisture improves the MJO simulations in general circulation models (GCMs) (e.g., Grabowski, 2003; Bechtold et al., 2008; Holloway et al., 2013). Then convection is usually treated as a quasi-equilibrium (QE) process by emphasizing its effect on large-scale, slowly varying circulations. However, GCMs significantly underestimate the MJO variability, and simple models do not agree on the basic mechanisms.

The other school emphasizes the role of high-frequency, small-scale waves (e.g., Moncrieff 2004; Biello and Majda 2005; Majda and Stechmann 2009, 2011; Yang and Ingersoll 2011; Solodoch et al. 2011). Yang and Ingersoll (2013, 2014, hereafter YI13 and YI14) consider that the MJO is a large-scale, long-lasting envelope of small-scale high-frequency waves, and convection is a set of intermittent energetic events that are triggered when a certain threshold in the environment is exceeded. YI13 and YI14 suggest that the intermittency of precipitation is key to simulating the MJO. YI13 develop a 2D shallow water model of the MJO that emphasizes the role of triggered convection and high-frequency waves. Convection is parameterized as a short-duration localized mass source and is triggered when the layer thickness falls below a critical value. Radiation is parameterized as a steady uniform mass sink. Over a wide range of
parameters, they observed MJO-like signals with the observed drift rate and horizontal structures. Based on their simulation results, YI13 propose that the MJO could be an interference pattern of the westward and eastward inertia gravity (WIG and EIG) waves. The propagation speed of the MJO is approximately equal to one-half the phase speed difference between the EIG and WIG waves. YI14 present a 1D $\beta$-plane model that successfully simulates the MJO using the same governing mechanism as in the 2D YI13 model. Using this 1D model, they derive a scaling theory for the MJO horizontal wavenumber by assuming that each MJO event is in radiative-convective equilibrium (RCE). As a result, the MJO horizontal scale is the distance that the temperature anomaly can be effectively smoothed by gravity waves. This scaling theory says that the MJO wavenumber increases with the number density of precipitation events, and decreases with the Kelvin wave speed. This scaling theory further predicts that the MJO becomes stronger and larger in a warmer climate. This prediction is qualitatively consistent with recent superparameterized Community Atmosphere Model (SPCAM) simulation results (Arnold et al. 2013). In addition to the above theoretical studies, there is also growing observational evidence suggesting that the intermittency of precipitation and high-frequency waves might be important to the MJO (e.g., Nakazawa 1988; Tung and Yanai 2002; Kikuchi and Wang 2010; Zuluaga and Houze 2013).

In this paper, we will use a 3D GCM to further test if the intermittency of precipitation and high-frequency waves are important to the MJO. In section 2, we describe our model configuration and experiment setup. In section 3, we show our simulation results. In section 4, we present our conclusions, discussions, and plans for future work.
2. Model and experiment setup:

We use a 3D moist GCM similar to those described by O’Gorman and Schneider (2008) and Frierson (2007). This GCM is based on the Geophysical Fluid Dynamics Laboratory (GFDL) spectral dynamical core and has a slab ocean as the lower boundary condition. There are no continents or solid surfaces. This GCM uses a gray radiation scheme and a simplified Betts-Miller convection scheme. This convection scheme relaxes temperature and moisture with a time constant of 2 hours to reference temperature and moisture profiles, which are calculated by assuming a pseudoadiabatic process with a fixed relative humidity of 0.8. In the control simulation, deep convection happens when both the convective available potential energy (CAPE) and the column water excess ($\delta q$) are positive with respect to the reference moisture profile. In the original setup, this GCM cannot simulate the MJO (Frierson, 2007).

To test our hypothesis, we make precipitation more intermittent by raising the convection threshold in three different ways, i.e., convection only happens when $\text{CAPE} > \text{CAPE}_o$, when $\delta q > \delta q_o$, and when $\text{CIN} < \text{CIN}_o$, where CIN is convective inhibition—the minimum amount of energy to activate convection. Each of the above methods can make precipitation more intermittent, and we implement them separately. The simulations have uniform short wave incoming radiation and globally uniform optical depth. This heavily reduces the meridional temperature gradient and therefore reduces the meridional moisture gradient.

3. Simulation results:
Figure 1 shows the Hovmoller diagram of precipitation averaged over 10°S to 10°N. In the control experiment (Fig. 1a), there are both eastward propagating Kelvin waves and westward propagating equatorial Rossby waves, and most strong precipitation events propagate westward. The equatorial waves seen here are the convectively coupled waves. The Kelvin wave speed is \( \sim 20 \) m/s and is significantly slower than the dry Kelvin wave speed, which is about 50 m/s. This reduction in speed has been documented in Frierson (2007) and is due to the reduction of effective static stability by moist convection. The MJO, however, is absent in this experiment. In the \( \delta q \) experiment (Fig. 1b), short-lived precipitation events mainly propagate westward, but the large-scale envelope of these precipitation events propagate eastward at \( \sim 2.3 \) m/s and show wavenumber 3 structure. These large-scale envelopes are the MJO-like signals, and raising the precipitable water threshold can improve the MJO simulation. In the CAPE experiment (Fig. 1c), the large-scale long-lasting precipitation events are the dominant signals and propagate eastward at \( \sim 3.1 \) m/s. There is a strong MJO event that loops the equator from day 600 to day 750. There are also weak ones with the same drift rate. According to this experiment, raising the CAPE threshold can improve the MJO simulation. In the CIN experiment (Fig. 1d), MJO-like signals dominant the precipitation. They show wavenumber 2 structure and propagate at \( \sim 3.9 \) m/s. This suggests that raising the CIN threshold can also improve the MJO simulation. We have so far improved the MJO simulation in one GCM with three different methods. One method—the \( \delta q \) experiment—has elements in common with the moisture-convection feedback, but the other two experiments do not. Since all three experiments can simulate the MJO, this suggests that the moisture-convection feedback is not essential to the MJO. The similarity in the above three methods is to make convection more intermittent and energetic. According to YI13 and YI14,
such convection events will excite high-frequency waves that form the large-scale envelope of the MJO. This hypothesis puts these three different experiments in a coherent picture.

Figure 2 shows the 2D power spectra of the symmetric components of precipitation averaged over 10°S to 10°N with the background spectra removed following Wheeler and Kiladis (1999). In the control experiment (Fig. 2a), there are both Rossby and Kelvin wave signals along the corresponding dispersion curves, but there is no MJO. In the $\delta q$ experiment (Fig. 2b), the Rossby and Kelvin wave signals are weak along the corresponding dispersion curves, and there is a spectral peak within the white box in the low wavenumber and low frequency region. This spectral peak is associated with the MJO that we observed in Fig. 1b. In both the CAPE and CIN experiments (Figs. 2c and d), the Rossby and Kelvin wave signals are weak along the corresponding dispersion curves, and there are spectral peaks associated with the MJO. Compared to the control experiment, the CAPE and CIN experiments have weaker westward power and stronger eastward power in total. Figure 2 illustrates that, in the spectral domain, the experiments with raised convection threshold have better MJO simulations than the control experiment.

The MJO signals show similar spatial structures in all three experiments. Figure 3 shows the horizontal and vertical structure of the MJO composite in the CAPE experiment. The composites shown here are based on a widely used linear regression method (e.g., Anderson and Kuang 2012; Arnold et al., 2013), in which we filter the MJO precipitation signal by taking the Fourier coefficients within the white box (Fig. 2c) and transferring it back to the physical domain. Then we get the MJO composite in precipitation and use the precipitation time series at 180° longitude
as the reference time series in regressing other fields. Figure 3a shows the upper level map view of the MJO composite. The active precipitation envelope of the MJO occupies ~ 100° of longitude. The associated wind intrudes from the subtropics, diverges around the convective center along the equator and forms off-equatorial cyclonic and anticyclonic vortices to the east and west, respectively. This structure is consistent with the observed MJO horizontal structures (Kiladis et al. 2005). Figure 3b shows the vertical wind and specific humidity structures associated with the MJO. The wind anomalies show the first baroclinic structure—lower level convergence and upper level divergence—around the convective center. Consistent with observations (e.g., Kiladis et al., 2005), the specific humidity shows a significant tilting structure with height, and there are positive specific humidity anomalies to the east of the MJO convective center at 180° longitude.

We have simulated MJO-like signals with the observed drift rate and the observed horizontal and vertical structures in $\delta q$, CAPE, and CIN experiments. The common feature of these experiments is raising the threshold for convection and increasing the intermittency of precipitation. Now we further test our hypothesis by examining if these simulations have stronger high-frequency waves compared to the control simulation, in which there is no MJO signal. Figure 4 shows the power spectra with MJO signals normalized by the control simulation power spectrum in the 10-based logarithm scale. There are three striking common features of these simulation results. First, relative to the control, there are strong high-frequency wave signals associated with IG waves in all three experiments. This supports the idea that the MJO is a large-scale envelope of high-frequency IG waves and is consistent with simple model simulation results in YI13 and YI14. It suggests that better simulating the high-frequency waves helps to improve the MJO simulations.
Second, there are strong eastward propagating signals with frequencies below 0.5 CPD and wavenumbers from 10 to 40, labeled with white boxes. These signals do not fit in the equatorial wave dynamics, and the phase speeds of these signals are similar to the MJO speed. We interpret these enhanced signals as a by-product of the MJO. The MJO convection envelope provides a large-scale environment that favors convection, and the slowly eastward propagating convection variability is enhanced by the MJO envelope. Third, the Rossby and Kelvin wave signals are weaker than or similar to those in the control experiment. This suggests that Rossby and Kelvin waves are not essential to the MJO.

4. Conclusion and discussions:

We have simulated MJO signals through raising the convection threshold in three different ways in an idealized GCM. We find that the intermittent convection excites high-frequency waves, and these high-frequency waves are much stronger in the simulations with MJOs. This is consistent with the hypothesis in YI13 and YI14 and suggests that high-frequency waves are essential to the MJO.

This study implies that departures from QE convection are important. The importance of such departures has been recognized, and superparameterization has been used to capture departures from QE by including a small-scale cloud-resolving model in each GCM grid box (Grabowski 2001; Randall et al. 2003). Recent studies (e.g., Benedict and Randall 2009) with SPCAM show improved MJO simulations. Our next objective is to develop a convection scheme that accounts for the departures from the QE and can simulate the MJO.
This study is in contrast to previous studies that consider the MJO as a moisture mode, in which the moisture-convection feedback is essential. Recent moisture-mode studies investigate the MSE budget of the MJO and conclude that cloud-radiation feedback is the leading component of the MSE budget and is essential to the MJO (e.g., Anderson and Kuang, 2012; Arnold et al., 2013). Our simulations do not have cloud-radiation feedback, and yet they have an MJO-like signal. In addition, Anderson and Kuang (2012) suggest that drying to the west of the MJO convection center due to advection of subtropical dry air is important to the eastward propagation. However, our simulations have the same degree of moisture-convection feedback as in the control experiment, and yet the control experiment does not have an MJO-like signal. Further our GCM is in the aquaplanet setup and is forced by grey radiation uniformly distributed in latitude. There is no meridional temperature gradient and no significant moisture gradient, and yet we still simulate the MJO. Our results suggest that cloud-radiation feedback, moisture-convection feedback, and the meridional moisture gradient, as identified in previous MSE budget analyses, are not essential to the existence and propagation of the MJO. This further suggests that the underlying mechanism of the MJO has not been revealed through the MSE budget analysis. Instead of driving the MJO, the anomalous MSE associated with the MJO might be a response of the already existing eastward propagating MJO.

We have, so far, only tested our hypothesis in this particular GCM. To further test the Yang and Ingersoll models, we will implement similar thresholds in other GCMs with different convection schemes and examine if the MJO simulation has been improved. In our $\delta q$, CAPE, and CIN experiments the equatorial Rossby waves and Kelvin waves are suppressed. Similar deficiencies...
have been found in other MJO simulations with simple convection schemes as well (e.g., Ajayamohan et al., 2013). We will investigate what process suppresses the equatorial Rossby and Kelvin waves in our model and use these tests to improve our convection scheme.

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Reference:


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Figure 1. Hovmoller diagram of precipitation anomalies (kg/m²/s) averaged over 10°S to 10°N. (a) Control experiment, (b) \(\delta q\) experiment, (c) CAPE experiment, (d) CIN experiment. The precipitation anomaly has been multiplied by 3 to illustrate in the same color scale.
Figure 2. Power spectra of the symmetric component of precipitation averaged over 10°S to 10°N in 10-based logarithm scale. Background spectra have been removed. (a) Control experiment, (b) δq experiment, (c) CAPE experiment, (d) CIN experiment. The colors represent the spectral power density, and solid lines show the dispersion relations of the lowest order symmetric equatorial waves at 15 m equivalent depth. The black line represents the Kelvin wave, the red line represents the Rossby wave, and the blue line represents the IG wave. The white box contains the MJO signal.
Figure 3. Horizontal and vertical structure of the MJO composite. (a) Map view of the MJO precipitation anomalies \((10^{-4} \text{ kg/m}^2/\text{s}, \text{colors})\). Vectors represent the MJO horizontal wind anomalies at ~ 200 hPa. (b) Vertical cross section of the MJO. The color shows the correlation between the specific humidity and the MJO precipitation anomaly. The color interval in both panels is 0.1385, and white indicates zero correlation.
Figure 4. Normalized power spectrum of (a) the δq experiment, (b) the CAPE experiment, (c) the CIN experiment and (d) the CAPE experiment with zoomed in wavenumber and frequency range. Normalization means relative to the control experiment (Fig. 2a). The contour interval is 0.25 with a 10-based logarithm scale, and the zero line is labeled by the blue contour. The black line represents the Kelvin wave dispersion relation with equivalent depth as 15 m. The blue lines represent the IG wave dispersion relations with equivalent depths of 15 m and 250 m. The red lines represent the corresponding Rossby waves.