Madden-Julian Oscillation and Convectively Coupled Equatorial Waves
Simulated in the NCEP Global Forecast System and
Climate Forecast System Models

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1. Introduction

While some of the major MJO characteristics can indeed be simulated by atmospheric models with prescribed sea surface temperatures (SST), the results from many studies suggest the importance of air-sea interaction in the MJO dynamics. Observational and modeling diagnoses have shown coherent variations in surface heat fluxes, SST, and convection associated with the MJO, indicating that interactive air-sea coupling needs to be included in numerical models to obtain a reasonable representation of the MJO.

In reality, however, improvements in the general circulation model (GCM) for the MJO simulation and forecast by this inclusion are considerably limited and dependent upon a GCM (Waliser et al. 1999; Hendon 2000; Inness and Slingo 2003; Lin et al. 2006; Seo et al. 2007; Fu et al. 2008). The recent study of Lin et al. (2006) demonstrates that only two models out of 14 coupled GCMs participating in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) are able to simulate the MJO variance and pronounced 30-60-ay period spectral peak comparable to the observations.

The deficiencies apparent in MJO simulation can be attributed to many factors not limited to the above mentioned air-sea coupling. The applied deep convection scheme is seemingly one of the most sensitive elements. Another factor is model resolutions. Time mean basic-state circulation and wind shear over the tropics are also believed to be important controlling elements for the correct MJO simulation (e.g., Inness et al. 2003). Furthermore, the appropriate representation of mean state sea surface temperature (SST) is considered a prerequisite for the improved MJO simulation since a cold SST bias adversely affects convective activity (e.g., Inness and Slingo 2003). As noted above, moisture convergence plays a crucial role in developing and sustaining the MJO. The ultimate key to the MJO simulation is dependent upon whether models accurately simulate the persistent interaction of lower-level circulation waves and deep convection, as revealed by many previous observational and modeling studies (e.g., Maloney and Hartmann 1998; Waliser et al. 1999; Seo and Kim 2003).

Recently, an atmosphere-ocean coupled Climate Forecast System (CFS) model with the horizontal resolution of T62 was developed by NCEP. Several coupled CMIP simulations using this version have been performed along with an atmosphere-alone AMIP simulation. Additionally, the higher resolution CFS model adopting a T126 grid system was run to produce long-term integrated data. Furthermore, the CFS T126 model run that employs a different deep convection scheme has been also conducted to test the impact of the cumulus scheme on various climate oscillations and teleconnections. All these simulations have made it possible to evaluate the effects of air-sea interaction, model resolution and deep convection scheme on the MJO. In addition, comparison of these runs provides an opportunity to investigate key factors for the proper MJO simulation.

In addition to the MJO evaluation, other dominant convectively coupled equatorial waves (e.g., Kelvin, equatorial Rossby (ER), mixed Rossby-gravity (MRG), inertio-gravity waves) identified theoretically by Matsuno (1966) and observationally by Wheeler and Kiladis (1999) are diagnosed in the NCEP climate model runs.
2. The simulations and data

The AMIP simulation is performed using the GFS model with T62 resolution (referred to hereafter as GFS T62) that is forced with the observed monthly mean SST from 1982-2002. Among several CMIP long-term simulations that are conducted with the CFS model, two CMIP runs with a resolution of T62 and T126 are executed to test the sensitivity to the horizontal resolution (referred to hereafter as CFS T62 and CFS T126, respectively). This simulation is initialized from the observed analyses of 1 January 2002 and run for 21 years. The above AMIP and CMIP simulations are based on the simplified Arakawa-Schubert (SAS) cumulus parameterization scheme. Therefore an additional coupled T126 run is performed with the relaxed Arakawa-Schubert (RAS) scheme to examine the impact of the deep convection scheme. This simulation is called CFS T126RAS and is run from 2002 to 2016.

The observational data used in this study comprise NCEP/DOE Reanalysis-2 (R2), CMAP, and daily AVHRR OLR from 1982 to 2002. Calculations for the MJO are based on 20-100-day bandpass filtered anomalies using a Lanczos filter.

3. Results

3.1. The MJO

Fig. 1 shows the power spectra of the OLR anomalies averaged over the tropical Indian Ocean area [75°-95°E and 10°S-10°N], where the MJO convection is developed and strengthened. The observed spectrum (Fig. 1a) measured by the smoothed periodogram (thick line) illustrates that a higher power exists in the intraseasonal band of 30-80-day periods with a center around 40-55 days. However, GFS T62, CFS T62 and CFS T126 (Figs. 1b, 1c, and 1d) do not show any significant spectral peaks associated with the MJO. In contrast to the model simulations using the SAS cumulus scheme, CFS T126RAS (Fig. 1e) produces statistically significant spectral peaks in the MJO band. Several peaks exist in the 30-80-day band.

Fig. 2 shows the two leading EOF modes of tropical convection-circulation fields. In these simulations (i.e., GFS T62, CFS T62, and CFS T126), the explained variance is more than 35% weaker than the observation. However, the CFS T126RAS run (Figs. 2i and 2j) shows some improved results. In particular, the strength of the MJO convection and circulation is greatly enhanced for both EOF1 and EOF2.
Fig. 2. Spatial structures of combined empirical orthogonal functions (EOFs) of 20-100-day filtered OLR, u850, and u200. EOF1 & EOF2 from (a) and (b) observations, (c) and (d) GFS T62, (e) and (f) CFS T62, (g) and (h) CFS T126 and (i) and (j) CFS T126RAS, respectively. OLR, u850, and u200 are plotted in solid, dashed, and dotted lines, respectively. The percentage value above each panel is the variance explained by each mode and scaled against the observations. All variables are normalized by the averaged value of global variance (9.06 Wm\(^{-2}\) for OLR, 1.25 ms\(^{-1}\) for u850, and 3.51 ms\(^{-1}\) for u200).

Fig. 3 shows the lag correlations between the PC time series of EOF2 (or PC2) and the individual fields (u850, precipitation rate, OLR, surface latent heat flux, downward solar radiation flux, surface temperature, 1000-hPa moisture convergence). GFS T62 produces less pronounced precipitation and OLR anomalies (Fig. 3b). Meanwhile, CFS T62 (Fig. 3c) shows a much stronger convection signal and greater spatial coherence between the convection and surface fluxes, and SST over the Indian Ocean. The CFS T126 run (Fig. 3d) exhibits basically the same features as CFS T62 with the strong “propagation barrier” appearing over the Maritime Continent and western Pacific. This propagation barrier has also been noticed in forecast data (Seo...
et al. 2005) and even a CFS T62 simulation with flux adjustment (Seo et al. 2007). By contrast, CFS T126RAS exhibits much improved propagation characteristics (Fig. 3e). The MJO convection signal (shown as precipitation and OLR anomalies) is very vigorous and this tends to penetrate into the Maritime Continent and western Pacific.

Fig. 3. Lag correlation coefficient between PC2 and u850, precipitation rate, OLR, surface downward solar radiation flux, downward latent heat flux, surface temperature, and 1000-hPa moisture convergence for (a) observations, (b) GFS T62, (c) CFS T62, (d) CFS T126, and (e) CFS T126RAS. The moisture convergence is defined as $-\nabla \cdot (Vq)$, where $V$ is the velocity vector and $q$ is the specific humidity. Only statistically significant regions at the 95% level are shaded.

3.2. Factors for the MJO simulation

Only CFS T126RAS has demonstrated a capability to simulate the correct MJO. This section presents the important factors for successfully simulating the MJO.

(a) Air-sea interaction: The air-sea coupling improves the coherence between convection and circulation and other surface fields (Fig. 3).

(b) Model horizontal resolution: The current CFS model runs demonstrate that an increase in the resolution from T62 (which corresponds to ~209 km) to T126 (~105 km) does not help improve the MJO simulation; however, a higher model resolution than T126 remains to be tested.

(c) Basic-state vertical easterly wind shear: Zhang and Geller (1994) showed that vertical easterly shear favors eastward propagating waves. Fig. 4 shows the annual mean vertical easterly shear (u200-u850) over the Maritime Continent and the western Pacific (120°E-170°E, 7.5°S-7.5°N) for the observation and model
simulations. The vertical wind shear in CFS T126RAS is less than one third that of the observation. These results imply that the background vertical easterly wind shear does not play a major role in the MJO simulation.

(d) Basic-state easterly low-level zonal wind along the tropics: Fig. 5 shows the annual mean zonal wind at 850 hPa in the observation and simulations. Westerlies or weak easterlies are observed over the tropical Indian Ocean, Maritime Continent and western Pacific (Fig. 5a), where the major development and propagation occur. Although the easterly bias in CFS T125RAS (Fig. 5d) is slightly decreased over the Maritime Continent and far western Pacific Ocean compared to the other CFS simulations, the westerlies remain weak over the central-eastern Indian Ocean and the easterly wind prevails over the Maritime Continent. These suggest that the basic-state easterly bias along the tropics may not be a major factor for the MJO simulation.

(e) SST: The SST bias, defined as model SST minus observed SST, is presented in Fig. 6 for the coupled simulations. A warm bias of ~0.5-1.0 °C appears over the western Indian Ocean, while a cold bias prevails over the eastern Indian Ocean and the western Pacific. CFS T126RAS shows that even if a cold bias exists over the tropical western Pacific, the MJO eastward propagation is greatly enhanced (Fig. 6c). In combination, these results suggest that in the absence of a huge SST bias, other factors may be more effective.

(f) Deep convection parameterization: The current analysis demonstrates that an apparent improvement when the NCEP coupled model utilizes the RAS scheme for cumulus parameterization. The active convective activity along the tropics over the warm pools in this model enhances the lower-level circulation, which in turn helps maintain the MJO convection. The positive feedback between the convection and circulation induces the continued eastward propagation across the Maritime Continent.

(g) Lower-level moisture convergence: To explicitly display the relationship between the MJO
convection and lower-level moisture convergence in the CMIP runs, the correlation coefficients presented in Fig. 3 are averaged over the Indian Ocean and the western Pacific regions (Fig. 7). In both regions, enhanced convection follows the moisture convergence with a ~2-5-day lag (Fig. 7a). CFS T126 shows a weak moisture convergence signal, which is about half of the observed convergence (Fig. 7b). However, the CFS T126RAS run (Fig. 7c) has a stronger moisture convergence that leads the enhanced convection by ~2-5 days, which is similar to the observations. The phasing and magnitude of the lower-level moisture convergence is a key factor for the development and propagation of the MJO and only the persistent interaction between the MJO convection and circulation waves ensures the MJO maintenance.

3.3. Global response to tropical heating of the MJO

To examine the global circulation patterns induced by MJO convective forcing, OLR and 200-hPa streamfunction anomalies are regressed onto PC1 and PC2. To represent the circulation response to the strong enhanced or suppressed MJO convection events, the regression is performed with respect to a deviation of PC1=2 and PC2=2, as in Matthews et al. (2004). Fig. 8 shows the regression maps of the observed wintertime (November through March) OLR and streamfunction anomalies at 6-day intervals. An anticyclonic (cyclonic) flow couplet off the equator is located to the west of or collocated with the enhanced (suppressed, respectively) convection anomalies, and the westerly (easterly) anomalies along the equator appear to the east of the enhanced (suppressed) convection. This is indicative of a Rossby-Kelvin wave response to the MJO heating (e.g., Matthews 2000; Seo and Kim 2003). At t=0 and t=6, a westward retraction of the east Asian jet appears along ~30°N and the Pacific-North American (PNA)-like wave pattern is formed. Over the eastern Pacific, the Rossby wave propagation to the southern hemisphere through the westerly duct (Hoskins and Ambrizzi 1993) is seen from t=0 to t=12. A weak wave train in the southern hemisphere emanates from the Indian Ocean

Fig. 6. Annual mean SST bias for (a) CFS T62, (b) CFS T126, and (c) CFS T126RAS.

Fig. 7. Relationship between OLR and surface moisture convergence averaged over [60-90°E, 10°S-10°N] for (a) observations, (b) CFS T126, and (c) CFS T126RAS, and averaged over [130-160°E, 10°S-10°N] for (d) observations, (e) CFS T126, and (f) CFS T126RAS.
through the east of the date line, as shown at t=0 (Fig. 8a) and more clearly at t=6 (Fig. 8b).

Figs. 9 and 10 represent the corresponding circulation response to the intraseasonal tropical heating in CFS T126 and CFS T126RAS. The convective anomalies in the CFS T126 simulation are much weaker than those in the observations, and thus the streamfunction anomalies are also weak. Meanwhile, CFS T126RAS (Fig. 10) successfully simulates the eastward propagation of the MJO convection. The actual pattern correlation between the regressed streamfunction in CFS T126RAS and the observation ranges from 0.84 to 0.91, which is much higher than the correlation of 0.47-0.78 between CFS T126 and observation. If the MJO convection over the Pacific is better simulated, the simulation of circulation and precipitation variations in the downstream region, including the Americas, will be much improved.

3.4. Intraseasonal convectively coupled equatorial waves

Fig. 11 shows the space-time spectra for the observation, and the NCEP CMIP runs. Also plotted are the theoretical dispersion curves corresponding to three equivalent depths of 12, 25 and 50 m. In the spectra of the antisymmetric component (Fig. 11), MRG and EIG modes are dominant and are connected to each other in the wavenumber-frequency space. For the symmetric component of the equatorial waves, the westward moving ER and WIG waves exist while much stronger eastward MJO and Kelvin waves are identified. All these waves are aligned along the equivalent depths in the range of ~25 m (middle phase lines in Fig. 11).

Figs. 12 and 13 show the space-time spectra of CFS T126 and CFS T126RAS, respectively. In these model runs, statistically significant peaks associated with MRG and EIG waves are not generated. Moreover, all models tend to produce too excessive synoptic scale variability associated with the westward disturbances with periods less than 5 days in the symmetric component of the OLR spectra. CFS T126RAS reveals the
strongest power for Kelvin waves among all models. The isolated spectral peaks appear only in CFS T126RAS.

4. Conclusions

This study shows that the interactive air-sea coupling greatly improves the coherence between convection, circulation and other surface fields. A higher horizontal resolution run (CFS T126) does not show any significant improvements in the intensity and structure. In fact, GFS T62, CFS T62, and CFS T126 all yield weaker 30-60-day variances that are not statistically distinguishable from the background red noise spectrum. Their eastward propagation is stalled at the “barrier” over the Maritime Continent and far western Pacific, which is similarly to that in many other climate models. In contrast to the model simulations using the SAS cumulus scheme, CFS T126RAS produces statistically significant spectral peaks in the MJO spectral band and the strength of MJO convection and circulation is greatly improved. Most of all, the ability of the MJO convection signal to penetrate into the Maritime Continent and western Pacific is demonstrated. Especially, the surface moisture convergence signal in this model is comparable to the observation and propagates across the Maritime Continent region. The moisture convergence is located persistently to the east of the enhanced convection and induces the frictional convergence mechanism. Furthermore, this study demonstrates that the improved MJO simulation in CFS T126RAS improves the simulation of extratropical circulation anomalies and hence can extend the predictability over Asia and North America.

At least in this study, the deep convection scheme, convection-circulation interaction, and frictional moisture convergence are found to be more important. More active convective activity along the tropics in the CFS T126RAS model enhances lower-level circulation and moisture convergence to the east of the enhanced convection, which in turn feeds back to the expansion of the MJO convective entities to the east. The persistence interaction between the convection and circulation gives rise to the continued eastward propagation across the Maritime Continent.

References


Fig. 11. Space-time spectra of tropically averaged OLR anomalies for observation. The dispersion curves of the equatorial waves are superimposed for the three equivalent depths of 12, 25, and 50 m.

Fig. 12. As in Fig. 11 except for CFS T126.

Fig. 13. As in Fig. 11 except for CFS T126RAS.