A Comparison of the Madden-Julian Oscillation Simulated by Different Versions of the MIROC Climate Model

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Abstract

A pair of 20-year simulations by two different versions of MIROC (Model for Interdisciplinary Research on Climate) was examined by using a standardized set of Madden–Julian Oscillation (MJO) diagnostics. One of the major differences between version 4 (MIROC4) and version 5 (MIROC5) of MIROC is the cumulus parameterization scheme. MIROC4 uses a prognostic Arakawa-Schubert scheme, whereas MIROC5 uses the Chikira scheme. MIROC5 reproduced the MJO better than MIROC4: a stronger signal in the wavenumber–frequency diagram, a slower and more noticeable eastward movement in the lag-correlation plot, and a better phase relationship between outgoing longwave radiation and zonal winds.

To investigate the impact of mid-tropospheric humidity on cumulus development in MIROC5, the atmosphere-only version of MIROC5 was used for a series of sensitivity runs, each with different entrainment parameter values. The entrainment parameter settings significantly influenced the simulated MJO. Large-scale cloud systems tended to move westward with smaller entrainment parameter values, accompanied by a pair of rotations with quasi-symmetry about the equator in the lower troposphere, whereas eastward movements were faster, with larger entrainment parameter values.

1. Introduction

Ever since the discovery of the Madden–Julian Oscillation (MJO; Madden and Julian 1971), many researchers have struggled to understand its physical mechanisms and to simulate or predict it. The MJO occurs mainly over warm waters of the Indian and western Pacific oceans, where it strongly influences precipitation (e.g., Zhang 2005). Besides its significant influence in the intraseasonal time scale, the basic physical mechanisms of the MJO are not well understood, and most atmospheric and atmosphere–ocean coupled general circulation models (GCMs) cannot simulate the MJO’s life cycle realistically (e.g., Slingo et al. 1996). Even the MJO representations of most of the modern atmosphere–ocean coupled GCMs used by the Coupled Model Intercomparison Project-3 (CMIP3) are inadequate (Lin et al. 2006).

Recently, better MJOs have been reproduced by a few GCMs with cumulus parameterizations (e.g., Sperber et al. 2005) and by a superparameterized Community Atmosphere Model, which uses a two-dimensional cloud-resolving model instead of a cumulus parameterization in each vertical column (Khairoutdinov et al. 2005). These studies may imply that the MJO can be simulated with a relatively coarse resolution (T42 or more) if the columnar physics parameterizations can realistically represent heat and moisture transport by deep or shallow clouds. Another approach to improving MJO simulations is high-resolution cloud-resolving modeling that directly computes the development and decay of deep convection (e.g., Miura et al. 2007).

With these improvements, a need has emerged to use GCMs to investigate the physical mechanisms responsible for the MJO and to simulate future changes in MJOs under climate change. A prerequisite for such advanced applications is a standardized set of MJO diagnostics for evaluating GCM simulations and tracking model improvements in a coherent manner. The U.S. Climate Variability and Predictability (CLIVAR) MJO Working Group (2009) has proposed such a set of MJO diagnostics, and Kim et al. (2009) used those diagnostics to examine the ability of eight GCMs to simulate the MJO. Because the MIROC (Model for Interdisciplinary Research on Climate) (Watanabe et al. 2010; W10 hereafter) was not one of those eight GCMs, its evaluation with that set of diagnostics would be informative for researchers who intend to use MIROC for an MJO study.

The MIROC was recently upgraded from version 4 (MIROC4), which uses almost the same physics schemes as version 3 (MIROC3.2) but with higher horizontal and vertical resolutions, to version 5 (MIROC5). W10 has described MIROC5’s improved representation of precipitation, zonal mean atmospheric fields, equatorial ocean surface fields, and the El Niño–Southern Oscillation. The cumulus parameterization in MIROC5 uses the Chikira scheme (Chikira and Sugiyama 2010) instead of the variant of the prognostic Arakawa-Schubert (AS) scheme used in MIROC4 (Pan and Randall 1998; Emori et al. 2001). Because cumulus parameterization may have a dominant influence on how well GCMs represent the MJO (e.g., Tokioka et al. 1988; Maloney and Hartmann 2001), it is interesting to investigate whether the MJO representation is improved in MIROC5.

We were thus motivated to use the standard diagnostics of the U.S. CLIVAR MJO Working Group to compare MJO simulations between MIROC4 and MIROC5. In this work, we provide evidence that the MJO representation of MIROC5 is superior to that of MIROC4. We also conducted sensitivity tests to gain insight into the mechanism of the improvement.

2. Data and analysis methods

2.1 Model simulations

We analyzed daily means of outgoing longwave radiation (OLR), upper (200 hPa) and lower (850 hPa) tropospheric zonal winds (denoted as U200 and U850, respectively), and specific humidity in a pair of 20-year simulations performed by MIROC4 and MIROC5. The selected period constitutes a latter part of a simulation that was conducted for more than 100 years to obtain the initial condition for the 20th century simulation for CMIP5. The settings for MIROC4 and MIROC5 are the same as those used for the CMIP5 runs. For MIROC4, the horizontal resolution and number of vertical levels were T213 and 56, respectively, and T85 and 40, respectively, for MIROC5. Both atmospheric models are coupled with an ocean model. As described in section 1, MIROC4 uses a prognostic AS scheme with cumulus inhibition under drier environments, and MIROC5 uses the Chikira scheme for cumulus parameterization. In addition, MIROC5 uses new parameterizations for radiation (Sekiguchi and Nakajima 2008) and turbulence (Nakanishi and Niino 2004).

The major difference between the AS and the Chikira schemes is the entrainment rate (ε). In the AS scheme, ε is constant for each cloud type and is related to the vertical change in the normalized mass flux (η) as follows:

\[
\varepsilon = 1 - \frac{\partial \eta}{\eta \partial z}.
\]

In the Chikira scheme, ε is proportional to buoyancy (B) and...
inversely proportional to vertical velocity squared ($w^2$):

$$\varepsilon = \frac{\alpha B}{w^2}$$  \hspace{1cm} (1)

where $\alpha$ is buoyancy efficiency and $\lambda$ is a parameter that controls the strength of entrainment. The Chikira scheme allows cumulus enhancement in more humid environments and cumulus inhibition in drier environments.

### 2.2 Observation and reanalysis data

The simulations were validated against OLR observations by the Advanced High Resolution Radiometer (AVHRR) (Liebmann and Smith 1996) and against U200, U850, and specific humidity data from the National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR) reanalysis (Kalnay et al. 1996). We used data from 27 years (1979 to 2005).

### 2.3 Diagnostics

To save space, we show only OLR wavenumber–frequency diagrams, lag-correlation plots of OLR and U850, and the first two modes of the combined empirical orthogonal function (CEOF) analysis of OLR, U200, and U850. We used the tools provided by the CLIVAR MJO Working Group (2009) and analyzed the data during boreal winter (November–April). The 20–100-day bandpass-filter was applied before the analyses, except in the wavenumber–frequency analysis.

### 3. Analysis results

#### 3.1 Mean state and variance

We compared simulations of mean surface precipitation with Climate Prediction Center Merged Analysis of Precipitation (CMAP) data (Xie and Arkin 1997) and found that MIROC5 was more realistic overall than MIROC4 (Supplement Figs. S1a, S1c, and S1e). Although MIROC5 exaggerated the Intertropical Convergence Zone (ITCZ) compared with CMAP, the double ITCZ structure noticeable in MIROC4 was absent.

To see the magnitude and spatial distribution of intraseasonal variability, we examined the 20–100-day bandpass-filtered variance of OLR (Supplement Figs. S1b, S1d, and S1f). As with mean precipitation, the MIROC4 showed a double ITCZ structure as an unrealistic pair of parallel bands, one on each side of the equator, with the band south of the equator (over northern Australia and the South Pacific Convergence Zone), having stronger power. In contrast, the spatial distribution was similar between MIROC5 and observations. Although MIROC5 showed relatively strong power in the eastern Indian Ocean, around the maritime continent, and in the western Pacific, overall the variances were weaker than observations, especially over the eastern Indian Ocean and the western Pacific. Land–sea contrasts were also simulated well.

#### 3.2 Wavenumber–frequency spectra

To see the characteristic spatial and temporal scales of cloud systems in the tropics, we calculated wavenumber–frequency power spectra for the symmetric and anti-symmetric components of OLR, following the procedure proposed by Wheeler and Kiladis (1999) (Fig. 1). The AVHRR data show well-isolated signals that are likely associated with equatorial Rossby and Kelvin waves and the MJO. In MIROC4, the signal corresponding to Kelvin waves is as strong as in AVHRR, but its maximum power is shifted to a lower frequency and a larger horizontal scale. The signal corresponding to the MJO is unclear. In MIROC5, the Kelvin wave signal is less pronounced than in MIROC4, but the MJO and the Rossby-wave signals are as strong as in AVHRR, although their frequencies are lower and their spatial scales are smaller. In plots of the raw spectra (Supplement Fig. S2), the features of the MJO signal were the same.

In terms of the anti-symmetric components, the signals corresponding to inertia-gravity and mixed Rossby-gravity waves are considerably weaker in both MIROC4 and MIROC5 than in AVHRR. We speculate that this is due to insufficient interactions between clouds through boundary layer processes in the models. Obtaining realistic anti-symmetric power spectra is a task for future model development.

#### 3.3 Lag-correlation maps

To examine the movement of cloud systems, we calculated the lag correlation of OLR and U850 (Fig. 2). Bandpass-filtered data were averaged over 10°S–10°N prior to the analysis, and the correlation was computed between the zonal averages over 75°E–100°E and the lagged values. The AVHRR OLR and NCEP U850 data show that large-scale convective systems develop over the Indian Ocean at about 60°E, move eastward at about 5 m s$^{-1}$, and decay near the dateline.

The lag correlations in MIROC4 and MIROC5 are considerably lower than those of the observations. Cloud systems appear to develop at about 60°E, but they decay over the maritime continent (around 120°E). The eastward-moving speed is obviously greater than
5 m s\(^{-1}\). The lag correlations in MIROC5 are only slightly lower than those in AVHRR, but the eastward extension of the signal is still insufficient. In MIROC5, large-scale cloud systems form over the western Indian Ocean, move eastward slowly, and decay around the maritime continent, before reaching the dateline. As suggested by the wavenumber–frequency diagram, the eastward-moving speed is even slower than the observed speed. Therefore, although unresolved issues remain, MIROC5 appears to have a better ability to simulate the observed slow eastward movement of cloud systems than MIROC4.

### 3.4 MJO modes from the CEOF analysis

To isolate the MJO modes, we used the multivariate CEOF technique proposed by Wheeler and Hendon (2004). OLR, U850, and U200 were processed simultaneously to extract the convective and baroclinic zonal wind structures. In the observational data, the first mode (Fig. 3a, upper panel) captures the strong convective activity and strong low-level westerly wind over the Indian Ocean. The westerly maximum is located slightly to the west of the OLR minimum. In the second mode (Fig. 3a, lower panel), both the OLR minimum and the westerly maximum are shifted to the western Pacific. The phase of the upper-level zonal wind is almost opposite to that of the lower-level zonal wind in both modes, reflecting the baroclinic structure. The first and second modes explain more than 43% of the filtered variance.

The pattern of the first mode of MIROC5 (Fig. 3c, upper panel) is quite similar to the observation pattern, although the spatial extent of the stronger signal is too small. In the second mode, however, the OLR minimum is very weak and the baroclinic structure is unclear although the pattern of the low-level zonal wind is similar to the observed pattern. The first and second modes explain about 23% of the filtered variance (i.e., slightly more than half of that explained by the first and second modes of the observation). This smaller contribution may be associated with a smaller variance (Supplement Fig. S1f) and the insufficient eastward extension of the cloud system (Fig. 2c). The first and second modes of MIROC4 explain nearly 29% of the variance, but the OLR minimum is less clear and the patterns in the second mode are shifted eastward comparing to the observation and MIROC5. This eastward shift is possibly due to the faster eastward movement of cloud systems (Fig. 2b). The spatial relationships among OLR, U850, and U200 are better reproduced by MIROC5 than by MIROC4.

### 4. Sensitivity test

The results presented so far show that MIROC5 can more realistically represent the MJO than MIROC4 in various ways. Chikira and Sugiyama (2010), who just replaced the modified AS scheme in MIROC4 with the Chikira scheme, demonstrated a similar improvement in the wavenumber–frequency analysis.
result. Therefore, although further investigations of the impacts of the new radiation and turbulence parameterizations of MIROC5 are needed, it is reasonable to consider that the use of the Chikira scheme dominantly explains the better representation of the MJO by MIROC5. To gain insight into the impact of the entrainment formulation given by Eq. (1), we conducted sensitivity tests with different values of $\lambda$.

### 4.1 Settings

We used only the atmosphere-only model of MIROC5 and reduced the horizontal resolution to T42 to lessen the need for computer resources. We performed three 10-year simulations with $\lambda = 0.39$ ($\lambda_{39}$), 0.52 ($\lambda_{52}$), or 0.65 ($\lambda_{65}$) under climatological conditions and analyzed the last 9 years. The seasonal cycle of the sea surface temperature (SST) was given. We also performed a supplemental 6-year simulation with $\lambda = 0.0$ ($\lambda_{0}$) and analyzed the last 5 years. Note that the default setting of MIROC5 is $\lambda = 0.52$.

### 4.2 Results and discussion

The OLR wavenumber–frequency spectra (Supplement Fig. S4) show that signals associated with the equatorial Rossby and equatorial Kelvin waves are strengthened when $\lambda$ is greater. It is interesting that eastward-moving signals are more sensitive to $\lambda$ than westward-moving signals. As $\lambda$ increases, the Kelvin waves slow and apparently behave more like convectively coupled Kelvin waves. The MJO signal is most obvious in $\lambda_{52}$. In $\lambda_{65}$, the Kelvin wave signal is more pronounced than the MJO signal.

Lag-correlation plots of OLR and U850 (Fig. 4) indicate that organized systems have a tendency to move westward on an intra-seasonal timescale when the entrainment is weaker ($\lambda_{0}$ and $\lambda_{39}$). In contrast, eastward movement appears when the entrainment is stronger ($\lambda_{52}$ and $\lambda_{65}$). Note that the coherence between OLR and U850 and their eastward movement is relatively weaker in $\lambda_{52}$ than in Fig. 2c. The reason may be the shorter simulation period, the lower horizontal resolution, or the use of the climatological SST. Notably, the eastward-moving speeds are roughly related as $u_{\lambda_0} < u_{\lambda_{39}} < u_{\lambda_{52}} < u_{\lambda_{65}}$, where $u_{\lambda_0}$ and $u_{\lambda_{39}}$ are negative. It will be interesting to investigate in the future whether this change relative to $\lambda$ is continuous or whether some criterion causes a discontinuous separation of the westward and eastward movements.

When we shifted the reference domain from the Indian Ocean area ($75^\circ$E–$100^\circ$E and $10^\circ$S–$5^\circ$N) to the Western Pacific ($160^\circ$E–$185^\circ$E and $5^\circ$S–$20^\circ$N), we found similar westward movement for $\lambda_{0}$ and $\lambda_{39}$, but the signals starting around the date line became insignificant before it reached the Indian Ocean (not shown). This fact and Fig. 4 may suggest a weak relationship between the westward moving cloud systems, one in the Indian Ocean and the other in the Western Pacific, in MIROC5.

To examine low-level wind fields relative to cloud systems, we used the CEOF technique to determine the phases of cloud systems and then constructed composite diagrams of OLR and low-level winds during the phase when OLR was at a minimum in the eastern Indian Ocean (Fig. 5). The organization of the convection is weak in $\lambda_{0}$. In $\lambda_{39}$, a pair of cyclonic vortices to the west...
and a pair of weaker anti-cycloonic vortices to the east of the OLR minimum emerge. The $i=52$ plot is similar to the $i=39$ plot, but the anti-cycloonic vortices are less clear. In $i=65$, both the cyclonic and anti-cycloonic vortices are weak, and convergence of zonal winds dominates instead.

These results suggest that cloud systems are more strongly coupled to eastward-moving rotational motions at smaller $i$ and to eastward-moving divergent motions at greater $i$. Under stronger convective inhibition, organized cloud systems may prefer stronger forcing by divergent motions, whereas, under weaker inhibition, destabilization by sensible and latent heat flux along rotating motions may be more allowed to develop cloud systems to balance radiative cooling. This hypothesis can explain why a realistic representation of the MJO in MIROC5 requires a proper range of $i$ to balance westward and eastward motions. The weaker eastward movement in $i=52$, however, indicates that we need to perform longer simulations with higher horizontal resolution to derive more robust conclusions.

5. Summary

We used diagnostics of the CLIVAR MJO Working Group to compare MJO representations between MIROC5 and MIROC4. The results clearly showed that MIROC5 has a better ability to simulate the MJO than MIROC4, although unresolved issues remain. The sensitivity study demonstrated that the entrainment parameter setting is key to the proper incorporation of mid-tropospheric humidity and better reproduction of the MJO in MIROC5. Changing the entrainment parameter in the cumulus parameterization scheme causes remarkable and systematic changes in the spatial structure of convection–circulation coupling that controls eastward movement of the simulated MJO. In the future, we will analyze model results for evidence supporting the frictional-convergence feedback (e.g., Wang 1988), wind-evaporation feedback (e.g., Sobel et al. 2010), and moisture modes (e.g., Maloney et al. 2010) theories of eastward propagation, following Benedict and Randall (2007). The current results suggest, at least, that not only eastward-moving divergent systems but also westward-moving rotational systems play an important role in enabling MIROC5 to represent the slow eastward movement of the MJO. To derive more robust conclusions, longer simulations with higher horizontal resolution are needed. Finally, we mention that this work is a concise summary of the master’s thesis of Maeda (2012), where more figures and a more detailed discussion can be found.

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Supplement

Figure S1. Spatial distribution of mean precipitation (a, c, e) and the intraseasonal variance of OLR (b, d, f): (a) CMAP, (b) AVHRR, (c, d) MIROC4, and (e, f) MIROC5.

Figure S2. Raw OLR spectra for (a) AVHRR, (b) MIROC4, and (c) MIROC5. Note that the wavenumber and frequency axes are reversed from Fig. 1, following the format of the standard diagnostics.

Figure S3. Composite diagram of the vertical distribution of specific humidity (upper) and OLR anomaly (lower) for the phase when the OLR minimum was in the eastern Indian Ocean: (a) NCEP/NCAR and AVHRR, (b) MIROC4, and (c) MIROC5.

Figure S4. Wavenumber–frequency diagrams of the OLR symmetric component: (a) $i=0$, (b) $i=39$, (c) $i=52$, and (d) $i=65$.

References


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SOLA: http://www.jstage.jst.go.jp/browse/sola