Comparison of Moist Static Energy and Budget between the GCM-Simulated Madden–Julian Oscillation and Observations over the Indian Ocean and Western Pacific

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ABSTRACT

The moist static energy (MSE) anomalies and MSE budget associated with the Madden–Julian oscillation (MJO) simulated in the Iowa State University General Circulation Model (ISUGCM) over the Indian and Pacific Oceans are compared with observations. Different phase relationships between MJO 850-hPa zonal wind, precipitation, and surface latent heat flux are simulated over the Indian Ocean and western Pacific, which are greatly influenced by the convection closure, trigger conditions, and convective momentum transport (CMT). The moist static energy builds up from the lower troposphere 15–20 days before the peak of MJO precipitation, and reaches the maximum in the middle troposphere (500–600 hPa) near the peak of MJO precipitation. The gradual lower-tropospheric heating and moistening and the upward transport of moist static energy are important aspects of MJO events, which are documented in observational studies but poorly simulated in most GCMs. The trigger conditions for deep convection, obtained from the year-long cloud-resolving model (CRM) simulations, contribute to the striking difference between ISUGCM simulations with the original and modified convection schemes and play the major role in the improved MJO simulation in ISUGCM. Additionally, the budget analysis with the ISUGCM simulations shows the increase in MJO MSE is in phase with the horizontal advection of MSE over the western Pacific, while out of phase with the horizontal advection of MSE over the Indian Ocean. However, the NCEP analysis shows that the tendency of MJO MSE is in phase with the horizontal advection of MSE over both oceans.

1. Introduction

Convection, precipitation, and cloud processes are key components of the global climate system and operate on a wide range of time and space scales. The formation and growth of clouds and precipitation are associated with water-phase changes between vapor, liquid, and solid in the atmosphere. Convective clouds affect local thermodynamics, large-scale circulations, and wave disturbances through the release of latent heat, the redistribution of heat, moisture and momentum, and precipitation. The organized convection coupled with the large-scale circulation is a major feature of the intraseasonal Madden–Julian oscillation (MJO) with the moist convection initiating over the equatorial Indian Ocean and propagating eastward at a speed of −5 m s⁻¹ through the Pacific Ocean (Madden and Julian 1972, 1994). Myers and Waliser (2003) presented a composite analysis of the three-dimensional structure and evolution of moisture associated with the MJO events selected using the Xie–Arkin bandpassed pentad rainfall data (Xie and Arkin 1997). They found that during the life cycle of MJO, the lower-tropospheric water vapor leads precipitation over the Indian Ocean and western Pacific, and the upper-tropospheric water vapor lags the precipitation peak for its moistening following intense convection.

Tian et al. (2006) examined the Atmospheric Infrared Sound (AIRS) data through a composite analysis based on Tropical Rainfall Measuring Mission (TRMM) data...
and showed that the MJO convection is preceded by a lower-tropospheric moist anomaly and followed by a lower-tropospheric dry anomaly. With the MJO deep convection events selected from the spectrally filtered TRMM and Global Precipitation Climatology Project (GPCP) data, Benedict and Randall (2007) suggested that the moist precondition of the MJO deep convection includes the vertical transport of moisture related to the shallow convection, while the dry process behind the MJO deep convection may be related to the mesoscale process. Maloney (2009) analyzed the moist static energy (MSE) budget of composite MJO events in a general circulation model (GCM) and observations, and demonstrated that the energy recharge process occurs in advance of the MJO precipitation with the lower-tropospheric easterlies and the discharge process during and after precipitation with the westerly anomalies. The horizontal advection of MSE and the surface latent heat flux are the leading contributors to the energy budget. The importance of horizontal advection by the low-level wind to eastward propagation is further supported by the sensitivity tests conducted using an aquaplanet atmospheric general circulation model (Maloney et al. 2010). Sobel and Maloney (2012) constructed an idealized semiempirical model and illustrated the strong influence of horizontal advection of moisture on the MJO-like disturbance. Analyzing the MSE budget of MJO-like disturbances in the atmosphere of a zonally symmetric aquaplanet simulated by a GCM with the inclusion of cloud-resolving models as the convection and cloud parameterization, Andersen and Kuang (2012) showed that the eastward propagation of the MJO-like disturbance is mainly due to the MSE generation by the column-integrated horizontal and vertical advection of MSE.

Theoretical studies have shown that the MJO is an atmospheric response to forcing sources that includes the tropical localized thermal forcing and stochastic forcing. The tropical response to the stationary intraseasonal oscillating heat source or the randomly varying heating profiles, such as the convective activity associated with the Asian monsoon and the convective disturbance within the intertropical convergence zone (ITCZ), produces some observed features of the MJO (e.g., Yamagata and Hayashi 1984; Anderson and Stevens 1987; Salby and Garcia 1987). However, the theory does not provide the mechanism responsible for the origin of low oscillation frequency and eastward movement of the heating source. Hu and Randall (1994, 1995) suggested that the low-frequency and localized convective heat source is due to the nonlinear interactions among radiation, cumulus convection, and surface moisture fluxes. Bladé and Hartmann (1993) introduced a discharge–recharge mechanism to determine the period of the low-frequency oscillation of convective heating by the discharge time of convective stabilization together with the recharge time of moist static instability. Maloney and Hartmann (1998) also suggested that the drying of the atmosphere occurs rapidly after the passage of convection with the onset of 850-mb westerly perturbations, and the moistening process in front of convection may set the time scale for the reinitiating of convection over the Indian Ocean and the western Pacific. The discharge–recharge mechanism was further supported by Kemball-Cook and Weare (2001) through an observational study over a radiosonde station. The MJO events appeared to begin with the destabilized atmosphere through a combination of low-level moist static energy buildup, which is controlled by a corresponding increase in the low-level moisture.

Due to the uncertainties in representing the convection and clouds in GCMs and numerical weather prediction (NWP) models, the simulation and prediction of MJO have long been a challenging problem. Impacts of convection schemes on the MJO simulations have been investigated by increasing numbers of studies (e.g., Tokioka et al. 1988; Wang and Schlesinger 1999; Maloney and Hartmann 2001; Liu et al. 2005; Zhang and Mu 2005). Recently, Deng and Wu (2010) showed that the MJO simulations are improved when changes to the deep convection scheme based on results from theoretical, observational, and cloud-resolving modeling studies are included. It was shown that the convection closure assumption plays a key role in the eastward propagation of MJO; the convection trigger condition helps produce less frequent but more vigorous moist convection and enhanced amplitude of MJO, and the convective momentum transport (CMT) contributes to more coherent structure for the MJO convection and the related atmospheric variances. Deng and Wu (2011) further applied the kinetic energy budget to examine the physical processes responsible for the evolution and development of simulated MJOs over the Indian Ocean, the western Pacific, and the central-eastern Pacific.

The objective of this paper is to understand the mechanisms and physical processes affecting the MJO simulation through the examination of the MSE budget. In the next section, GCM MJO simulations and observational datasets are briefly described. In section 3, the MJO events are selected based on the analysis of 850-hPa zonal wind. The phase relationships between the 850-hPa zonal wind, precipitation, and surface latent heat flux will be analyzed for the composite MJOs over the Indian Ocean and western Pacific. In section 4, the impacts of revised convection closure, convection trigger, and CMT on the MSE budgets of composite
MJOs will be compared and investigated over these two regions. The summary and our conclusions will be given in section 5.

2. GCM simulations, observational datasets, and general feature of intraseasonal variability

The Iowa State University GCM (ISUGCM) simulations with the observed monthly sea surface temperatures presented in Deng and Wu (2010, 2011) are analyzed in this paper. ISUGCM is based on a version of the National Center for Atmospheric Research’s (NCAR) Community Climate Model (CCM3; Kiehl et al. 1998) but with three major modifications to the deep convection scheme, which is a bulk mass flux scheme (Zhang and McFarlane 1995) with the closure assumption based on convective available potential energy (CAPE). 1) The revised closure relates convection to the destabilization of the tropospheric layer above the planetary boundary layer by the large-scale processes (Zhang 2002). 2) The trigger conditions obtained from the CRM simulations activate deep convection when the rate of CAPE change due to the large-scale forcing exceeds a certain threshold \([70 \text{ J kg}^{-1}\text{ h}^{-1}; \text{ Wu et al. (2007a)}]\). 3) The CMT parameterization validated by the cloud-resolving simulations takes into account the role of the perturbation pressure field generated by the interaction of convection with large-scale circulation in the vertical momentum transport (Zhang and Cho 1991; Wu and Yanai 1994; Wu et al. 2003, 2007b; Zhang and Wu 2003). Four sets of 10-yr (1979–88) simulations (Table 1) were conducted using the horizontal resolution of T42 (a roughly \(2.8^\circ \times 2.8^\circ\) Gaussian grid) and 18 hybrid vertical levels extending from the surface to 4 hPa. The control simulation (CTL) is using ISUGCM with the original deep convection scheme as in the standard CCM3, and ISUCCM3 simulation was performed with the inclusion of all three modifications in the convection scheme. NOCMT simulation is the run with no CMT but includes the revised closure and trigger conditions in the convection scheme. The NOTRI simulation does not have the CRM-derived trigger conditions and CMT but applies the revised closure in the convection scheme.

The pentad (5-day mean) precipitation product of the Climate Prediction Center (CPC) Merged Analysis of Precipitation (CMAP) is used to evaluate the climate simulations. Observations from rain gauges and precipitation estimates from several satellite-based algorithms (infrared and microwave) are merged by the technique described in Xie and Arkin (1996, 1997). The Atmospheric Infrared Sounder (AIRS) version 5, level 3, standard gridded daily products are used during the period 2002–08 (Parkinson 2003). The AIRS instrument suite is designed to measure the water vapor and temperature profiles on a global scale based on the Aqua mission. The National Centers for Environmental Prediction (NCEP)–NCAR reanalysis data (Kalnay et al. 1996), including the wind, OLR, precipitation, vertical velocity, latent heat flux, and specific humidity, are used in this study. These datasets are gridded to T42 resolution for the comparison with the model output. The basic feature of intraseasonal variability over the Indian Ocean and the western Pacific is presented in Fig. 1, which shows the lag correlations of 30–90-day bandpassed daily 850-hPa zonal wind and precipitation onto daily 850-hPa zonal wind time series at 90° and 155°E. The NCEP–NCAR zonal wind anomaly shows a coherent eastward propagation of MJO across the Indian and Pacific Oceans, with phase speeds of 5 and 10 m s\(^{-1}\), respectively (Figs. 1a,b). The positive peak of the precipitation anomaly appears before the wind anomaly peak at around 90°E over the Indian Ocean (Fig. 1a), but is in phase with the wind anomaly around 155°E over the western Pacific (Fig. 1b). ISUCCM3-simulated MJOs exhibit similar eastward propagation as is seen in the observations, and the phase relationships between the precipitation and zonal wind anomalous positive peaks are similar to those in NCEP–NCAR (Figs. 1c,d). But the amplitude of the MJO over the Indian Ocean is larger than in the observations, and becomes smaller as the MJO propagates across the Maritime Continent and the western Pacific (Fig. 1c), which leads to a weaker eastward propagation than is found in the observations. The amplitude of intraseasonal variability over the western Pacific (Fig. 1d) is higher than in the observations for both zonal wind and precipitation. Despite these deficiencies, the ISUCCM3 MJO simulation is clearly improved from CTL, which produces westward-propagating intraseasonal variability over the Indian Ocean and the western Pacific (Figs. 1e,f).

Table 1. The four ISUGCM simulations.

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Description</th>
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<tr>
<td>CTL</td>
<td>Control simulation with the original convection scheme of CCM3</td>
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<tr>
<td>ISUCCM3</td>
<td>ISUGCM simulation with the revised convection closure assumption, convection trigger conditions, and CMT</td>
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<tr>
<td>NOCMT</td>
<td>ISUGCM simulation with the revised convection closure assumption and convection trigger conditions</td>
</tr>
<tr>
<td>NOTRI</td>
<td>ISUGCM simulation with the revised convection closure assumption</td>
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3. Characteristics of the composite MJO

Following previous studies (e.g., Maloney 2009), the MJO events are identified using the 30–90-day band-passed 850-hPa zonal wind during 1979–88 averaged from 5°N to 5°S at 90°E (the Indian Ocean) and 155°E (the western Pacific). The MJOs are selected during October–April with positive maxima larger than one standard deviation of the 850-hPa zonal wind time series. There are 24 events for ISUCCM3 over the Indian Ocean (Fig. 2a) and 27 events over the western Pacific (Fig. 2b) during October–April 1979–88. For the NCEP data and the CTL, NOCM, and NOTRI simulations, there are 25, 27, 19, and 22 MJOs over the Indian Ocean and 30, 23, 25, and 26 MJOs over the western Pacific, respectively.

Figure 3 presents the composite intraseasonal precipitation and surface latent heat flux as a function of lag relative to the 850-hPa zonal wind averaged between 5°N and 5°S over the Indian Ocean and the western Pacific. In NCEP, the precipitation peak at 90°E leads the 850-hPa zonal wind anomalous peak by about 7 days (Fig. 3a), while the precipitation peak at 155°E is in phase with the zonal wind maximum (Fig. 3b). These findings are consistent with the phase relationship of precipitation and the wind anomalous peak in Figs. 2a and 2b. These results were documented by previous observational studies (e.g., Zhang and Anderson 2003), which showed the convection and precipitation center more often is located between the surface westerlies and easterlies over the Indian Ocean, but collocates with the prevailing westerlies over the western Pacific. Unlike the precipitation, the observed latent heat flux peaks are in phase with the 850-hPa zonal wind peak over both the Indian Ocean and the western Pacific (Figs. 3a,b).

The ISUCCM simulation with the modified convection scheme (ISUCCM3) reproduces some of the
observed features. Over the Indian Ocean, the precipitation peak leads the 850-hPa westerly peak by 9 days and the surface latent heat flux is in phase with the zonal wind, but ISUCCM3 simulates a larger amplitude for the intraseasonal precipitation (1.5 mm day$^{-1}$) and zonal wind (3.2 m $s^{-1}$) than the NCEP precipitation (1.0 mm day$^{-1}$) and zonal wind (2.7 m $s^{-1}$) (Fig. 3c). Over the western Pacific, ISUCCM3 has the precipitation peak leading the westerly peak by 4 days but has the same phase in the surface latent heat flux and wind, and it also produces larger amplitudes of wind, precipitation, and surface flux than NCEP (Fig. 3d). The impact of the modified convection scheme on the simulations of phase relation and the amplitude of the intraseasonal variability can be readily identified by comparing ISUCCM3 with CTL. The ISUGCM with the original convection scheme (CTL) simulates much smaller amplitudes for the intraseasonal precipitation and surface flux over both oceans (Figs. 3e,f), and poor phase relation between the precipitation, surface flux, and zonal wind over the western Pacific (Fig. 3f).

The impact of each modification in the modified convection scheme on the phase relation and MJO amplitude is further illustrated by two sensitivity experiments (i.e., NOCMT and NOTRI). The positive peak of precipitation shifts from day $-9$ in ISUCCM3 (Fig. 3c) to day $-14$ in NOCMT (Fig. 3g) over the Indian Ocean. Similar shifting of the precipitation peak also occurs over the western Pacific (Figs. 3d,h). So the inclusion of CMT in the convection scheme simulates the phase relationship of precipitation anomalies relative to the zonal wind anomalies closer to the observed. The convection-induced momentum tendency tends to produce the upscale kinetic energy transfer, which helps enhance the westerly wind anomalies below 800 hPa and produce more in-phase MJO zonal wind and precipitation (e.g., Tung and Yanai 2002; Deng and Wu 2011). The NOTRI simulation, which removes the modification of the trigger conditions from the NOCMT simulation, produces a smaller amplitude of intraseasonal variability in precipitation, zonal wind, and surface latent heat flux over both oceans (Figs. 3i,j) than do the NOCMT simulations (Figs. 3g,h). As suggested in Deng and Wu (2010), the CRM-derived convection trigger conditions add more constraints to the release of available potential energy and lead to more vigorous convection and stronger MJO amplitude. In addition to the enhancement of amplitude, the use of CRM-derived trigger conditions also affects the phase relationship of surface latent heat flux anomalies relative to the zonal wind anomalies over the western Pacific, which is in phase for NOCMT (Fig. 3h) but out of phase for NOTRI (Fig. 3j). The NOTRI, which includes only the revised convection closure assumption, shows enhanced intraseasonal variability in precipitation and surface latent heat flux over the Indian Ocean (Fig. 3i) when comparing with the CTL simulation (Fig. 3c), and produces an out-of-phase relationship between the precipitation and zonal wind over the western Pacific, as in the CTL simulation (Figs. 3f,i). The analyses of these sensitivity experiments illustrate the impacts of important factors and physical processes of convection parameterization on the MJO simulations. Next, the vertical structure of composite MJO will be examined by analyzing the observed and modeled MSE.

The MSE is defined as $c_pT + gz + Lq$, where $c_p$ is the specific heat at constant pressure, $T$ the temperature, $g$ the gravitational acceleration, $z$ the height, $L$ the latent heat, and $q$ the specific humidity. Since the contributions from the temperature anomalies ($c_pT$) and geopotential height anomalies ($gz$) are small, only the composite intraseasonal MSE anomalies and moisture anomalies ($Lq$) between 1000 and 300 hPa will be presented in the following analysis. The composite anomalies are averaged between 5°N and 5°S as a function of lag in days with respect to the zonal wind events. In addition to the NCEP–NCAR reanalysis, the 7-yr (2002–08) AIRS datasets are used for comparison with model simulations. There are 17 MJO events selected for AIRS during October–April at 90°E and 15 MJOs at 155°E. Over the Indian Ocean, the AIRS MSE and $Lq$ positive anomalies appear near the surface around day $-20$ and develop upward, with the peak near 500 hPa around

![Fig. 2. The variability of 850-hPa zonal wind (m s$^{-1}$) for ISUCCM3 at (a) 90°E and (b) 155°E during 1979–88 after 30–90-day bandpass filtering averaged between 5°N and 5°S. The reference line represents one positive standard deviation of the 850-hPa zonal wind time series after 30–90-day bandpass filtering.](image-url)
FIG. 3. Composite intraseasonal 850-hPa zonal wind (solid, m s\(^{-1}\)), precipitation (dotted, mm day\(^{-1}\)), and latent heat flux (dashed, 10 W m\(^{-2}\)) for NCEP at (a) 90\(^\circ\) and (b) 155\(^\circ\)E averaged between 5\(^\circ\)N and 5\(^\circ\)S, as a function of lag in days relative to the zonal wind events. As in (a)–(b), but for (c)–(d) ISUCCM3, (e)–(f) CTL, (g)–(h) NOCMT and (i)–(j) NOTRI.
lated by CTL over both oceans. The moisture anomalies observed precondition of MJO convection is not simu-
vertical tilt of MSE and the moisture anomalies and different from those in CTL (Fig. 4d). The westward distributions of MSE in ISUCCM3 (Fig. 4c) are largely to the higher moisture anomalies center. The vertical are generally higher than the observations, which is due to the more vertically stacked (Fig. 4b). There is no obvious low-level moisture preconditioning in NCEP compared to AIRS, especially over the Indian Ocean. Since the observational data in this region are sparse, the NCEP–NCAR reanalysis may largely rely on the model physical processes. The uncertainties in the representation of these processes could explain the difference between NCEP and AIRS (e.g., Tian et al. 2006).

The observed recharge–discharge process of MSE is simulated by the ISUCCM3 (Fig. 4c) with a 50-day period at 90° and 155°E, but both the positive and negative MSE anomalies start earlier in the lower troposphere, which suggests an earlier precondition of the MJO convection. In addition, the locations of the MSE maxima are generally higher than the observations, which is due to the higher moisture anomalies center. The vertical distributions of MSE in ISUCCM3 (Fig. 4c) are largely different from those in CTL (Fig. 4d). The westward vertical tilt of MSE and the moisture anomalies and observed preconditions of MJO convection is not simulated by CTL over both oceans. The moisture anomalies appear in the upper troposphere and not at the surface, and the MSE positive anomalous peak shows up after the wind anomalous peak over the western Pacific. The contributions of each modification in the convection scheme to the vertical structure of intraseasonal variability are further illustrated by comparing with two sensitivity simulations of NOCMT and NOTRI. The revised closure reshapes the moisture distribution and helps the preconditioning of the MJO convection in NOTRI (Fig. 4f), which is missing in CTL (Fig. 4d). The initial signal of moisture in NOTRI begins from the surface presenting the lower-troposphere moisture convergence in front of the MJO convection over the western Pacific. The enhancement of the MSE recharge–discharge process is mainly contributed by the convection trigger conditions over the Indian Ocean and the western Pacific through the moisture anomalous process, which is demonstrated in NOCMT (Fig. 4e) against NOTRI (Fig. 4f). The explanation is that the more robust deep convection due to the convection trigger conditions enhances the moisture convergence and transfer from the boundary layer to the upper troposphere. Comparing NOCMT (Fig. 4e) and ISUCCM3 (Fig. 4c), it can be seen that the impact of CMT through the moisture distribution results in a generally higher and later MSE anomalous peak. More coherent structure between the surface westerly wind center and the convection and precipitation center is simulated over the Indian Ocean and western Pacific in the simulation with the CMT. This is in agreement with the more coherent structure of MJO-related wind and precipitation maxima due to the CMT in Figs. 3c,d and 3g,h.

4. Moist static energy budget

To further understand the physical processes responsible for the improved simulation of the intraseasonal moist static energy, low-level wind field, and precipitation, the vertically integrated MSE budget (e.g., Maloney 2009) is analyzed:

\[
\frac{\partial \text{MSE}}{\partial t} = - \langle \omega \frac{\partial \text{MSE}}{\partial p} \rangle - \langle \mathbf{v} \cdot \nabla \text{MSE} \rangle + LH + SH + \langle LW \rangle + \langle SW \rangle. \tag{1}
\]

Term A presents the MSE tendency, term B the vertical advection of MSE, term C the horizontal advection of MSE, term D the latent heat flux, term E the sensible heat flux, term F the longwave heating rate, and term G the shortwave heating rate. In addition, \( \omega \) is the vertical pressure velocity and \( \mathbf{v} \) the horizontal wind vector.

Composite intraseasonal vertically integrated (1000–100 hPa) moist static energy budget anomalies are shown in Fig. 5. The sum of the latent and sensible heat fluxes are presented as the latent heat flux is dominant among them. The shortwave heating rate is small and not shown in the plot. In calculating each term in Eq. (1) using the
FIG. 4. Composite intraseasonal (top) MSE and (bottom) moisture anomalies for (a) AIRS at (left) 90°E and (right) 155°E averaged between 5°N and 5°S as a function of lag in days relative to the zonal wind events. As in (a), but for (b) NCEP, (c) ISUCCM3, (d) CTL, (e) NOCMT, and (f) NOTRI. The contour interval is 100 J kg$^{-1}$, starting at 50 J kg$^{-1}$. Areas greater (less) than 50 (−50) J kg$^{-1}$ are dark (light) shaded.
output variables from NCEP and the models, the sum of the terms on the right-hand side will not balance with the tendency term on the left-hand side. The residual is negligibly small for the models. But the residual is present in the MSE budget from the NCEP–NCAR reanalysis. Since the data assimilation is used to produce the NCEP product, an analysis increment that nudges the model toward observations (e.g., Mapes

FIG. 4. (Continued)
Fig. 5. Composite intraseasonal vertically integrated (1000–100 hPa) moist static energy budget anomalies for NCEP at (a) 90°E and (b) 155°E averaged between 5°N and 5°S as a function of lag in days relative to the zonal wind events. As in (a), (b) but for (c), (d) ISUCCM3, (e), (f) CTL, (g), (h) NOCMT, and (i), (j) NOTRI. The unit is W m⁻². The gray, green, red, blue-dashed, and orange lines are for longwave heating, latent and sensible heat fluxes, horizontal advection, vertical advection, and moist static energy tendency, respectively.
and Bacmeister 2012) could contribute to the residuals. Over both the Indian Ocean and the western Pacific, the charging of MSE in NCEP appears before the latent heat flux (Figs. 5a,b), precipitation (Figs. 3a,b), and longwave heating rate anomalous peak, and the discharging process is during and after (e.g., Maloney 2009). The NCEP MSE tendency is dominated by the vertical advection of MSE, but the horizontal advection of MSE is more in phase with the MSE tendency than the vertical advection of MSE over the Indian Ocean and the western Pacific. The surface heat fluxes and longwave heating are out of phase with the NCEP MSE tendency over both oceans.

Over the western Pacific, the recharge process of MSE in ISUCCM3 is similar to the observations, while the MSE tendency is more in phase with the horizontal and vertical advectios of MSE, but out of phase with the surface heat fluxes and longwave heating (Fig. 5d). While the amplitude of MSE tendency is similar to that in NCEP, note that the amplitude of each term in the MSE budget is larger in ISUCCM3 than NCEP (Figs. 5d,b). Over the Indian Ocean, a major difference is found between the ISUCCM3 and NCEP MSE budgets. ISUCCM3 produces an out-of-phase relationship between the MSE tendency and the horizontal advection of MSE (Fig. 5c), but NCEP shows an in-phase relationship (Fig. 5a). The ISUCCM3 MSE tendency is largely controlled by the vertical advection of MSE over the Indian Ocean (Fig. 5c). CTL shows a weak MJO signal (Figs. 5e,f), and both the horizontal and vertical advectios work negatively during the MSE recharge process, except for the horizontal advection over the Indian Ocean. The impact of three modifications enhances the MJO signal and reverses the contributions of the horizontal and vertical advectios to the MSE recharge process over the Indian Ocean and the western Pacific.

The inclusion of revised closure leads to the positive contributions of the horizontal and vertical advectios to the MSE tendency (Figs. 5i,j and 5e,f) before the MJO deep convection (Figs. 3i,j), but the amplitude of the MJO signal does not change much. In fact, the amplitude enhancement of MJO is due to the use of convection trigger conditions, which lead to more robust deep convection (Figs. 5g,h). The vertical advection plays a more important role in the MSE recharge process than does the horizontal advection over the Indian Ocean when the trigger conditions are added into the scheme (Figs. 5g,i). The impact of CMT over the western Pacific (Figs. 5d,h) during the MSE recharge process leads to the enhanced vertical advection positive peak (from 6 to 21 W m$^{-2}$) and later to the horizontal advection positive peak (from day $-18$ to day $-11$), which interact with each other, illustrating a later recharge process (from around day $-30$ to around day $-18$). Corresponding to the shift of the precipitation and MSE anomalous maximum from around day $-12$ to around day $-4$ (Figs. 3h,d and 4f,d), the later MSE recharge process favors the more coherent structure of the MJO convective center and the prevailing westerly anomalies over the western Pacific in ISUCCM3. Over the Indian Ocean, a later MSE recharge process is evident, due to the CMT impact (Figs. 5c,g), which is also helpful in building up a more coherent structure.

5. Summary and conclusions

MJO variability and coherent eastward propagation across the Indian and Pacific Oceans in ISUGCM is strongly affected by the modified convection scheme. The amplitude of the MJO-related variance for the 850-hPa wind in ISUGCM with three modifications (revised closure, trigger, and CMT) to the deep convection scheme is stronger than that in the control run with the original convection scheme and is comparable to the observations. Also, the observed coherent eastward-propagating structure where the convection and precipitation center leads the surface westerlies anomalous peak over the Indian Ocean and collocates with the prevailing westerlies over the western Pacific is simulated better with the modified scheme than the original scheme.

With the composite analyses, the lag (in phase) relationships between MJO 850-hPa zonal wind, precipitation, and surface latent heat flux are simulated over the Indian Ocean (western Pacific) in ISUGCM, which are greatly influenced by the convection closure, trigger, and CMT. The moist static energy builds up from the lower troposphere 15–20 days before the peak in MJO precipitation, and reaches the maximum in the middle troposphere near the peak of the MJO precipitation. The gradual lower-tropospheric heating and moistening and the upward energy transport are important aspects of MJO events, which are documented in observations such as AIRS, but poorly simulated in most GCMs. With the modifications in the convection scheme, ISUGCM produces a better MJO recharge–discharge process of moist static energy than does the original GCM. The CRM-derived trigger conditions for deep convection contribute to the striking difference between ISUGCM and the control run with the original convection scheme. It plays a major role in the improved MJO simulation through the horizontal and vertical advectios of moist static energy. Imaging we are in a boat watching the movement of the MJO convection, ISUGCM with the CRM-derived trigger conditions will produce much
more vigorous convective clouds than the original model due to the accumulation of moist static energy through the gradually upward energy transport. The quick release of the energy when the convective available potential energy exceeds a threshold in the original model allows much too frequent light precipitation but less heavy precipitation (e.g., Wu et al. 2007a).

The inclusion of the revised closure helps build up the precondition of the MJO convection with the redistribution of moisture through the positive contribution of the horizontal and vertical advection of moist static energy before the onset of MJO convection. The impact of CMT through the interaction between horizontal and vertical advection of moist static energy helps the more coherent atmospheric structure over the Indian Ocean, and favors more collocation of the MJO convective center and the prevailing westerly anomalies over the western Pacific. In addition, the budget analysis for ISUGCM with the modifications shows the increase in MSE is in phase with the horizontal advection of MSE over the western Pacific, while out of phase with the horizontal advection of MSE over the Indian Ocean. However, the NCEP analysis shows that the tendency of MJO MSE is in phase with the horizontal advection of MSE over both oceans. Due to the lack of observations, the characteristics of convection and cloud population are poorly understood for the initiation and evolution of the MJO over the Indian Ocean. The Dynamics of the Madden–Julian Oscillation (DYNAMO) field experiment ran from October 2011 to early February 2012 over the equatorial central Indian Ocean and provides unique observations to facilitate the cloud-resolving simulations of cloud systems over this region. CRM simulations forced by the large-scale temperature and moisture advection obtained during DYNAMO can be compared with those forced by the large-scale condition from the Tropical Ocean Global Atmosphere Coupled Ocean–Atmosphere Response Experiment (TOGA COARE) for examining the characteristics of MJO convection and cloud population over this region. CRM simulations forced by frictional moisture convergence in a composite life cycle of the Madden–Julian oscillation: A review.

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