Effects of Surface Orography and Land–Sea Contrast on the Madden–Julian Oscillation in the Maritime Continent: A Numerical Study Using ECHAM5-SIT

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ABSTRACT

This study uses the atmospheric general circulation model (AGCM) ECHAM5 coupled with the newly developed Snow–Ice–Thermocline model (ECHAM5-SIT) to examine the effects of orography and land–sea contrast on the Madden–Julian oscillation (MJO) in the Maritime Continent (MC) during boreal winter. The ECHAM5-SIT is one of the few AGCMs that realistically simulate the major characteristics of the MJO. Three experiments are conducted with realistic topography, without orography, and with oceans only in the MC region to evaluate the relative effects of orography and land–sea contrast. Orography and land–sea contrast have the following effects on the MJO in the MC: 1) a larger amplitude, 2) a smaller zonal scale, 3) more realistic periodicity and stronger eastward-propagating signals, 4) a stronger southward detour during the eastward propagation, 5) a distorted coupled Kelvin–Rossby wave structure, and 6) larger low-level moisture convergence. The existence of mountainous islands also enhances the mean westerly in the eastern Indian Ocean and the western MC, as well as the moisture content over the MC. This enhancement of mean states contributes to the stronger eastward-propagating MJO. The findings herein suggest that theoretical and empirical studies, which are largely derived from an aquaplanet framework, have likely provided an over-simplified view of the MJO. The effects of mountainous islands should be considered for better understanding and more accurate forecast of the MJO.

1. Introduction

The warm pool in the tropical western Pacific, including the Maritime Continent (MC), is one of the most convective regions on Earth. It contributes substantial energy to drive the atmospheric general circulation and global climate system. Within the warm pool, the MC plays a critical role in influencing the fluctuations in global atmospheric energy and hydrological cycles by inducing tropical heating and exciting poleward-emanating Rossby waves (Neale and Slingo 2003). The complex land–sea contrast and orography in the MC also exerts effects on the prominent tropical phenomenon such as the Madden–Julian oscillation (MJO), an intraseasonal fluctuation (Madden and Julian 1972;

Matthews (2000) and Hsu and Lee (2005) reveal that the MC, the Andes, and the East African highlands act as orographic barriers to block and delay low-level Kelvin waves. In addition, the MJO modulates the variability in rainfall, diurnal cycle amplitude, and land-based rainfall peaks over the MC (Rauniyar and Walsh 2011; Peatman et al. 2014; Birch et al. 2016). Inness and Slingo (2003) show that convective precipitation tends to split into two centers as the MJO crosses the MC: one moving northward into the South China Sea and another moving across northern Australia and into the South Pacific convergence zone. Consequently, the MJO often weakens when it passes over the MC (Inness and Slingo 2006; Kim et al. 2017). The studies also show that the eastward propagation of the MJO is sometimes disrupted over the MC (D. Kim et al. 2014; Feng et al. 2015; Kim et al. 2017; Zhang and Ling 2017). Furthermore, models tend to poorly simulate and predict the MJO over the MC (Vitart et al. 2007; Zhang et al. 2013; H.-M. Kim et al. 2014; Wang et al. 2014; Peatman et al. 2015).

A variety of mechanisms have been proposed to describe the effect of the MC on the MJO. Some studies suggest that the MC weakens the convection and delays the propagation of the MJO. First, orography can block the eastward propagation of the low-level Kelvin wave signals embedded in the MJO (Hsu and Lee 2005; Inness and Slingo 2006; Wu and Hsu 2009; Zhang and Ling 2017). Second, the island masses might weaken the air–sea interaction (Sobel et al. 2010; Takasuka et al. 2015), which is suggested to enhance the eastward propagation of the MJO (Flatau et al. 1997; Klingaman and Woolnough 2013; Tseng et al. 2015). Weakened air–sea interaction might hinder the eastward propagation. Finally, the diminishing diurnal cycle of precipitation over the MC consumes less moist static energy (MSE), which is required to trigger both diurnal and intraseasonal convection. Thus, the existing diurnal cycle could play a marked role in weakening the MJO in model simulation (Bladé and Hartmann 1993; Oh et al. 2012, 2013; Hagos et al. 2016). By contrast, a local strengthening effect has also been reported. Some studies (e.g., Hsu et al. 2004; Hsu and Lee 2005; Wu and Hsu 2009) argue that the lifting and frictional effects caused by orography and the land–sea contrast in the MC might enhance the near-surface moisture convergence east of the topography, thus developing a new deep convection region. A sudden shift in the deep convection is observed from one region to another when the MJO passed over the MC. Thus, the MJO is characterized by downstream development of deep convection at specific longitudes, such as 95°, 110°, 120°, and 145°E, over the MC, where mountainous islands, such as Sumatra, Borneo, Sulawesi, and New Guinea, are located.

The effect of the MC on the MJO has been evaluated through climate model simulations. Inness and Slingo (2006) demonstrate the orographic weakening effect of the MC on MJO convection using an atmospheric general circulation model (AGCM) in an aquaplanet setting, which is forced by the prescribed MJO-like moving SST. However, this AGCM poorly simulated the MJO and could not resolve the complex orography and land–sea contrast in the MC because of a very coarse model resolution. Takasuka et al. (2015) conduct high-resolution model simulations with and without flat land in the MC and suggest that the land–ocean zonal contrast of latent heat flux is the major reason for the slower eastward propagation of the MJO in the land experiment. Overall, many leading GCMs have difficulty in realistically simulating the major MJO characteristics (Slingo et al. 1996; Lin et al. 2006; Kim et al. 2009; Hung et al. 2013) and therefore are unsuitable for evaluating the effects of orography and land–sea contrast on the MJO. However, previous studies have suggested that successful simulations of the MJO over the MC can be achieved by resolving the topography (Inness and Slingo 2006; Miura et al. 2007; Wu and Hsu 2009; Birch et al. 2016) and atmosphere–ocean coupling (Zhu et al. 2010). The present study uses the newly developed ECHAM5-SIT model (described in section 2), one of the few GCMs that realistically simulate the MJO (Tseng et al. 2015; Jiang et al. 2015), to address this unresolved concern. Three experiments are conducted to delineate the relative effects of land–sea contrast and orography in the MC on the MJO and address the following questions: 1) How does the MC influence the intensity of MJO convection? 2) How does the MC influence eastward propagation? 3) What are the relative contributions of orography and land–sea contrast?

The model and methodology are described in section 2. Section 3 presents the results and is followed by a discussion in section 4.

2. Data, methodology, and model

The precipitation data are from Global Precipitation Climatology Project (GPCP) (Adler et al. 2003). The other parameters are retrieved from NCEP Climate Forecast System version 2 (CFSv2) 6-hourly products (Saha 2011). The CLIVAR MJO Working Group diagnostics package (Waliser et al. 2009) is used to isolate and analyze the intraseasonal (20–100 day) variability. MJO phase composites are computed based on the
Real-Time Multivariate MJO index (Wheeler and Hendon 2004).

We use the ECHAM5.4 (Roeckner 2003) AGCM coupled with the Snow-Ice-Thermocline (SIT) one-column ocean model (Tu and Tsuang 2005; Tsuang et al. 2009) to simulate the influences of orography and land–sea contrast on the MJO. The ECHAM5.4 has 31 vertical layers with the model top at 10 hPa. A high horizontal resolution of T213 (approximately 0.5°) is chosen to resolve the major structure of the mountain ranges in the MC. The details of the model setting for SIT and its coupling with ECHAM5.4 are the same as in Tseng et al. (2015). Readers are referred to Tseng et al. (2015) for the details.

Three sets of experiments are conducted: realistic MC (CTL), aqua MC (AQUA), and flat MC (FLAT). Realistic land–sea contrast and orography in the MC are retained in the control experiment CTL, whereas the island grid points in AQUA are replaced by 200-m-depth ocean grid points in the region of 11°S–8°N, 90°–160°E. In FLAT, the land grid points are retained but the orography is reduced to zero over 11°S–8°N, 90°–160°E. Figure 1 shows the topography in the MC, demonstrating that the T213 resolution (approximately 50 km) can describe the outlines and rough shapes of the terrain although the height and steepness of the mountains are still underrepresented. Table 1 presents the experimental details. The analysis focuses on the boreal cool season (November–April) when the eastward propagation tendency of the MJO is most evident. The simulation length of each experiment is 21 years, and the outputs of the last 20 years are analyzed.

3. Results

a. Mean state

The mean atmospheric state is known to affect MJO simulations (Inness and Slingo 2003; Inness et al. 2003; Sperber et al. 2005; Zhang et al. 2006; Watterson and Syktus 2007; Kim et al. 2009; Maloney 2009; Kim et al. 2011; Ray et al. 2011). The effects of orography and land–sea contrast on the mean 850-hPa zonal wind and precipitation over the MC are estimated based on the differences between the CTL experiment and the FLAT and AQUA experiments (Fig. 2). The observations are also shown in Figs. 2a and 2b for comparison. Orography and land–sea contrast enhance the 850-hPa westerly (i.e., westerly anomaly) in the western MC and the eastern Indian Ocean and weaken the westerly (i.e., easterly anomaly) to the east of the MC (Figs. 2c,e,g). These differences are more substantial in the AQUA experiment than in the FLAT experiment (Figs. 2e,g), indicating that land–sea contrast plays a more dominant role than orography in modifying the mean flow. The existence of islands contributes to the east–west contrast
in the low-level zonal winds, suggesting that the zonal wind distribution would be more homogeneous if the MC were submerged in the ocean. Altogether, the existence of mountainous islands enhances the precipitation on the windward side of the mountains and reduces the precipitation on the lee side (Figs. 2f,h); however, the changes are more evident in the AQUA experiment (Fig. 2h). A comparison with the observed climatology (Fig. 2b) confirms that the existence of mountainous islands results in the strong geographical dependence of precipitation. A comparison between the CTL and FLAT experiments indicates that the net influence of mountains is highly complicated and varied with the mountain range (e.g., a decrease over Sumatra Island compared with an increase over Java Island). This complexity is likely due to the different characteristics (e.g., height, steepness, and orientation relative to the flow) of individual mountain ranges. Notably, islands are more efficient than orography in enhancing precipitation in our simulations. These are intriguing topics that are beyond the scope of this study.

The cross section of apparent heat source (Q1; i.e., estimated diabatic heating defined as the residual of thermodynamic equation by plugging observed atmospheric motion and temperature into the equation; Yanai et al. 1973) and vertical overturning circulation changes at the equator (Fig. 3) further illustrates the effects of mountainous islands on simulated convection and circulation. In accordance with the change in precipitation, heating increases on the windward sides of the mountain ranges in Sumatra, Boneo, Sulawesi, and the northwestern corner of New Guinea (Fig. 3d). Notably, this contrast is more evident in the AQUA experiment than in the FLAT experiment, confirming that the existence of islands (even flat) has a greater effect on the mean circulation than that of orography. If the MC were submerged in the ocean, a large area of deep convection with fewer geographical variations would cover the region. The existence of mountainous islands enhances the deep convection and heating in the western and eastern edges of the MC (Figs. 3c,d). Therefore, the overturning circulations (e.g., the Walker circulation over the Pacific and the reversed Walker circulation over the Indian Ocean) are strengthened compared with those in the AQUA experiment (Fig. 3d), indicating that mountainous islands affect the characteristics of the observed tropical mean state not only in the MC but also in the Indian Ocean and the western Pacific. The spatial distribution of vertically integrated Q1 from 1000 to 200 hPa is shown in Figs. 4a–c. The heating surrounding islands is markedly larger in the CTL and FLAT experiments, although weaker cooling is identified over islands. As a result, the area-averaged diabatic heating is significantly enhanced by the mountainous island, with the largest in the CTL followed by the FLAT and AQUA. The existence of islands can enhance the peak heating between 500 and 300 hPa by about 1 K day−1 (not shown) in the MC (e.g., 10°S–0, 120°–150°E). Moisture content also exhibits markedly differences between experiments. The change in vertically integrated specific humidity mean state from 850 to 200 hPa is shown in Figs. 4d–f. Compared with the minor difference between CTL and FLAT (Figs. 4d,e), the moisture is distinctly reduced in the AQUA experiment (Fig. 4f) over the MC, especially over islands. In summary, the existence of the orography and land–sea contrast in the MC enhances the mean heating, moisture, and overturning circulation in the surrounding regions. The zonal moisture gradient has recently been proposed as an important characteristic of the mean state in inducing eastward propagation of the MJO (Sobel et al. 2008; Maloney 2009). The weakened westerly in the eastern Indian Ocean and relatively homogeneous moisture distribution in the AQUA experiment are consistent with the confinement of the eastward propagation to the east of 110°E in the same simulation, which will be shown later.

b. MJO simulations

1) MJO CHARACTERISTICS

The simulated MJO characteristics in the CTL, FLAT, and AQUA experiments are compared in this
Figure 5 presents the wavenumber–frequency spectra of simulated 850-hPa zonal wind and precipitation anomalies. The CTL experiment demonstrates that the ECHAM5-SIT model realistically reproduces the observed spectral characteristics and strength of the eastward propagation at wavenumbers 1 to 2 in 850-hPa zonal wind and wavenumbers 2 to 4 in precipitation with a periodicity of 30–80 days (Figs. 5a,b). In the FLAT experiment, the MJO exhibits a similar wavenumber structure and amplitude but a longer periodicity (Fig. 5c) relative to the CTL experiment, suggesting slower eastward propagation. By contrast, the AQUA experiment shows substantially weaker magnitudes in both 850-hPa zonal wind and precipitation (Fig. 5d) at the longer periodicity part of the 30–80-day band. The shift of peak spectra toward the lower-frequency part is observed in the FLAT and AQUA experiments, respectively, which are also plotted in (c) for comparison. The area within the black lines indicates the westerly wind zone. Differences within the green lines are significant at the 5% level.
In the AQUA experiment, the spectrum appears to be more concentrated on wavenumber 1, but it is more evenly distributed within the 30–80-day band. Moreover, the wavenumber-1 scale is more consistent with the scale-selection mechanism reported in theoretical studies (Lau and Peng 1987; Wang and Rui 1990; Zhang 2005), which suggest the dominance of the largest-scale (e.g., wavenumber-1) perturbation in the MJO because of the largest growth rate. However, the scale dependence is weaker when orography and land–sea contrast are considered, thus indicating that orography and land–sea contrast induce perturbations in smaller zonal scales. Figure 6 is the Hovmöller diagrams of correlation between the MC (10°S–5°N, 120°–150°E) precipitation and 10°N–10°S averaged precipitation (color) and 10-m zonal wind (contour) on intraseasonal time scales. The disruption of eastward propagation, evidently caused by stronger geographically locked component, is clearly seen in

Fig. 3. (a) Observed and (b) simulated winter mean states and its differences between the (c) CTL and FLAT experiments and (d) CTL and AQUA experiments at the equator. Colors represent apparent heating (Q1; K day⁻¹). Vectors denote vertical wind (10⁻² Pa s⁻¹) and zonal wind (m s⁻¹).

Fig. 4. Simulated climatological means of (left) vertically integrated Q1 (1000–200 hPa; W m⁻²) and (right) specific humidity (850–200 hPa; g kg⁻¹) for the (top) CTL, (middle) FLAT, and (bottom) AQUA experiments.
the CTL and FLAT experiments, whereas much smoother eastward propagation with little disruption is simulated in AQUA. Correlations are also generally weaker in AQUA, suggesting that the convection–circulation coupling is enhanced with the existence of the mountainous islands. The aforementioned findings reveal the potential effects of complex orography and land–sea contrast in the MC, namely 1) shifting of intraseasonal perturbations to a smaller spatial scale but a more confined periodicity band and 2) enhancement of MJO strength.

2) CIRCULATION: HORIZONTAL AND VERTICAL

Figure 7 presents the composites of MJO cycles from phases 3 to 6. The CTL experiment realistically simulates the observed effects of mountainous islands (Figs. 7a,b), such as the flow bifurcation around Sumatra, Java, Borneo, Sulawesi, and New Guinea in phases 3–6 and the convergence in the eastern side of New Guinea in phase 5, followed by additional eastward propagation over the western Pacific in phase 6. The major convection region also shifts southward while reaching Sumatra and continues eastward propagation over the oceanic channel in the southern MC. The flow bifurcation and southward-shifted propagation route are also evident in the FLAT experiment (Fig. 7c), except that the near-surface flow is stronger over the land, particularly over New Guinea where the high mountains in the CTL experiment are removed. During phases 3 and 4 in the CTL and FLAT
experiments (Figs. 7b,c), an elongated convection and easterly belt, which is generally symmetric to the equator and exhibits the characteristics of an equatorial Kelvin wave, is also observed in the equatorial western Pacific. Furthermore, traces of an equatorial Rossby wave to the west of the deep convection region are observed. When islands and mountains are removed, the signatures of equatorial Kelvin and Rossby waves are more evident in the AQUA (Fig. 7d) experiment than in the CTL (Fig. 7b) and FLAT (Fig. 7c) experiments. Evidently, the eastward propagation is more clearly simulated without the interruption of islands and mountains. Eastward propagation of the major convection region occurs south of the equator where high SSTs are observed (Zhu et al. 2010). In the CTL and FLAT experiments (Figs. 7b,c), the more southward detour may be partially attributed to the deflection of the low-level flow caused by islands and mountains (Wu and Hsu 2009).

The effect of the MC is further demonstrated in the vertical structure of the MJO (Fig. 8). Shown here are the diabatic heating and vertically overturning circulation averaged over 0°–10°S in phases 3 and 6 when the deep convection is over the western and eastern MC, respectively. In the observation and CTL experiment (Figs. 8a,b), the deep convection over the MC in phase 3 exhibits a strong geographical association with orography and mountainous islands, characterized by enhanced deep convection near the mountainous islands and weaker convection over the oceans. For example, an isolated deep convection region near 135°E (west of the mountain ranges in western New Guinea) is particularly evident in phase 6 (Fig. 8b). In addition, geographical dependence, despite being weaker, is also evident in the FLAT experiment (Fig. 8c). By contrast, separation into isolated regions of enhanced convection is not as evident in the AQUA experiment (Fig. 8d). The enhancement of convection over orography and islands also has a strong effect on the zonal scale of the deep convection region; it is the smallest in the CTL experiment in phase 3 and larger in the FLAT and AQUA experiments.

Near-surface moisture convergence east of the deep convection region is considered one of the key factors leading to the MJO eastward propagation as discussed in the introduction. A comparison of the phase 3 composites among the three experiments reveals a marked contrast in the low-level moisture convergence; it is the strongest in the CTL experiment, weaker in the FLAT experiment, and the weakest in the AQUA experiment (Figs. 8b–d, blue contours). As suggested by Wu and Hsu (2009),
Frictional and lifting effects associated with surface orography and land–sea contrast likely enhanced low-level moisture convergence. A comparison between phases 3 and 6 support the aforementioned finding (Fig. 8). For example, no obvious contrast is observed for phase 6 among the three experiments when the convection is located in the central Pacific, where there are no mountains or islands. By contrast, in phase 3, low-level moisture convergence east of the deep convection is particularly evident in the CTL experiment.

c. Mechanisms

The possible mechanisms underlying the effects of the MC on the MJO are discussed as follows.

1) OBSTACLE EFFECT

Topographic effects, such as flow bifurcation over mountainous islands and lee-side moisture convergence, are identified in the CTL experiment (Fig. 7). These features are similar to the observations reported in.
previous study (Wu and Hsu 2009). The distribution of mountainous islands in the MC likely helps result in the southward detour of the eastward-propagating MJO convection and the sudden eastward shift of the deep convection from one region to another (e.g., the positive heating west of Papua New Guinea shifting to the east between phase 4 and 5 in Figs. 7a and 7b). This phenomenon, referred to as the obstacle effect, has certain similarities with the theoretical characteristics of the flow around an idealized obstacle in the low Froude number condition (Hunt and Snyder 1980; Smolarkiewicz and Rotunno 1989; Sha et al. 1998), which demonstrate the existence of leeside vortex and convergence. The topographic effect is further demonstrated by the evolution of 10°S–0° averaged vertically integrated Q1 (1000–200 hPa; colors, Fig. 9) and moisture convergence (1000–700 hPa; contours, Fig. 9) in the eight phases. The integrated Q1 and moisture convergence indicate fluctuations in deep and shallow convection, respectively. In contrast to the smooth eastward propagation in the AQUA experiment (Fig. 9d), eastward propagation in the CTL experiment (Fig. 9b) tends to stall at longitudes with mountains and islands. In the CTL experiment, the eastward propagation through the MC is divided into three stages separated by weakened convergence: before reaching (west of 120°E) the MC, at 120°E–150°E, and after leaving the MC (east of 150°E). This evolution is characterized by a series of weakened-in-the-west and reemerging-in-the-east convergence (and convection) through the complicated land–sea contrast, ocean channels, and mountains. The FLAT experiment (Fig. 9c) has a more continuous eastward propagation than the CTL experiment; however, stagnation and delay are evident in the longitudes where islands existed. By contrast, the convergence in the AQUA experiment is not affected by the stagnation effect of islands and mountains and has a

Fig. 8. The 10°S–0° averaged cross section of Q1 in phases 3 and 6: (a) observation, (b) CTL, (c) FLAT, and (d) AQUA. Colors represent heating (Q1; K day⁻¹). Vectors denote zonal wind (m s⁻¹) and vertical speed (omega; 10⁻² Pa s⁻¹). Blue contours indicate moisture convergence (10⁻⁶ g kg⁻¹ s⁻¹; interval, 8). A positive value denotes convergence (solid line) and a negative value denotes divergence (dashed line).
smooth eastward propagation (Fig. 9d). Interestingly, the major eastward propagation in the AQUA occurs mainly in the east of 110°E. This contrast is consistent with the effect of mean flow discussed below.

Notably, a weaker (stronger) Q1 and moisture convergence to the west (east) of 135°E, respectively, are observed in the FLAT and AQUA experiments compared with the CTL experiment. The enhancement and weakening of the mean westerly flow to the west and east of 135°E, respectively, caused by mountainous islands likely contributed to this contrast, which is particularly evident between the CTL and AQUA experiments. In the AQUA experiment, the stronger westerly mean flow is located farther to the east compared with the other experiments, thus leading to stronger convection to the east of the MC. This finding is consistent with previous theoretical studies that report stronger MJO convection in the stronger westerly mean flow (Kiladis et al. 1994; Zhang and Dong 2004; Zhang 2005; Maloney 2009). By contrast, mountainous islands induced stronger mean westerly flow in the eastern Indian Ocean and the western MC in the CTL experiment, resulting in stronger MJO convection in these regions.

The effect of the Sumatran mountain ranges might also have contributed to the larger convection west of 100°E in the CTL experiment (phase 3; Fig. 7b). The blocking effect of the Sumatran mountain ranges leads to upstream near-surface convergence near 90°E and consequently stronger convection in the CTL experiment; this feature is clearly demonstrated in Wu and Hsu (2009). Notably, this phenomenon is similar to the stagnation of the mesoscale convection system revealed in observational and theoretical studies (e.g., Reeves and Lin (2007). However, the applicability of this analog to MJO convection warrants further research. The preceding discussion implies that land–sea contrast and mountains affect convection and circulation through the obstacle effect locally in the MC and remotely upstream and downstream of the MC.

2) FRICTIONAL EFFECT

Near-surface convergence located east of the major convection is considered one of the main factors contributing to the eastward propagation of the MJO through the frictional wave–conditional instability of the
second kind (CISK) mechanism (Wang and Rui 1990; Hendon and Salby 1994; Maloney and Hartmann 1998; Hsu et al. 2004; Kang et al. 2013). As shown in Fig. 8, the existence of mountainous islands evidently contributes to the occurrence of near-surface moisture convergence. This is further demonstrated in Fig. 10, which shows moisture convergence averaged over 10°S–0°, 120°–150°E. Phase leading of the near-surface convergence relative to the deep convection is most evident in the CTL experiment. As the MJO is an eastward-propagating phenomenon, the shallow convective phases occur to the east of deep convective phases and hence, the horizontal (phase) axis can be considered as the zonal direction (Kim et al. 2009). Thus, the moisture convergence exhibiting a westward titling structure is consistent with the low-level convergence preconditioning deep convection during the eastward propagation. Wu and Hsu (2009) suggest that the existence of topography and islands enhances the frictional and near-surface lifting effects, and consequently the near-surface convergence. Figure 11 illustrates the vertical profile of MSE at four longitudes throughout the MJO life cycle. In the CTL experiment (Fig. 11a), at a 90°E oceanic point to the west of the MC, the MSE began to develop at phase 1, reaches its maximum during phases 2–3, and weakens at phase 6. The profile is characterized by an upright deep structure extending to the upper troposphere, which is typical of deep convection. A similar deep profile but with much smaller amplitude and a secondary maximum is also simulated in the FLAT and AQUA experiments (Figs. 11e,i). The low-level MSE is the strongest in the CTL experiment, despite of the lack of a secondary maximum as in the FLAT and AQUA experiments, and the weakest in the AQUA experiment. This contrast in strength is consistent with the stronger near-surface moisture convergence in the regions depicted in Fig. 8b. At 120°E, an island location in the CTL experiment (Fig. 11b), the MSE develops a near-surface maximum during phases 2–3 and weakens thereafter, but extends upward to exhibit a deeper vertical structure. This feature is consistent with the preconditioning of deep convection. This development from a shallow to deep structure is much less evident in the FLAT and AQUA experiments (Figs. 11f,j). At 135°E, a bottom-heavy structure is highly evident in the CTL experiment (Fig. 11c). By contrast, MSE exhibits a higher and homogeneous structure in the FLAT experiment and a top-heavy structure in the AQUA experiment.
At 155°E, a location with leeside convergence (Fig. 8b; Wu and Hsu 2009), the MSE tilting structure is similar in all three experiments, but with relatively stronger tilting in the CTL experiment (Fig. 11d) than in the FLAT and AQUA experiments (Figs. 11h,l). This variation in the vertical structure among the three model settings, consistent with the results shown in Fig. 8, confirms the enhancement in low-level moisture convergence due to the near-surface frictional and lifting effects of orography and land. Therefore, the frictional wave–CISK mechanism becomes more dominant with the existence of topography and islands.

3) INFLUENCE OF MEAN STATE

The mean state influences the MJO. The intraseasonal variability in the lower troposphere is stronger in the westerly belts, particularly in the Pacific (Kiladis et al. 1994; Zhang and Dong 2004). Maloney (2009) suggests that climate models must have realistic basic-state distributions of the lower-tropospheric zonal wind and specific humidity to simulate realistic intraseasonal variability. In our simulations, the existence of mountainous islands enhances the zonal variation of the mean states: the westerly wind increase in the western MC and
the eastern Indian Ocean and decrease east of the MC, and the stronger zonal moisture gradient between the MC and the eastern Indian Ocean. Figure 9 shows that the convection is stronger over the Indian Ocean and weaker over the western Pacific in the CTL experiment compared to those in the FLAT and AQUA experiments. The relationship between the changes in the mean westerly flow and moisture with and without mountainous islands and changes in the MJO convection strength revealed in the experiments are consistent with the findings of previous studies.

4. Conclusions and discussion

The effect of the MC on the MJO is an important and yet relatively unexplored mechanism, partly because the current state-of-the-art GCMs are unable to realistically simulate the MJO. This study uses a newly developed coupled GCM, ECHAM5-SIT, which realistically simulates the major characteristics of the MJO, to examine the effect of the MC on the MJO. Three experiments are conducted: CTL (realistic orography and land–sea contrast), FLAT (without orography), and AQUA (land grid points replaced with a 200-m deep ocean) in the region 11°S–8°N, 90°–160°E. T213 spatial resolution is adopted to effectively resolve the orography.

4a. Effects on the MJO

Comparing the results of the three experiments reveals that orography and land–sea contrast in the MC affect the simulated MJO in the following manner:

1) Larger amplitude: The wavenumber–frequency spectrum reveals an overall increase in the amplitude with the MC present; in the AQUA experiment, the amplitudes of the intraseasonal frequencies are substantially smaller than those in the CTL and FLAT experiments. The existence of land, rather than mountainous terrain, appears to be the major factor enhancing the overall amplitudes in the wavenumber domain. However, the effect on the local amplitude in the MC is geographically dependent. The amplitude (e.g., Q1, vertical motion, MSE, and zonal wind) is larger (weaker) west (east) of approximately 135°E, compared with the case when both orography and land are removed. Both orography and land–sea contrast contributes to this east–west contrast.

2) Smaller zonal scale: The wavenumber–frequency spectrum indicates that energy dispersion to the higher zonal wavenumbers is caused by the land–sea contrast, whereas in the AQUA experiment the energy is mainly concentrated in wavenumber 1, which is consistent with the scale selection mechanism proposed in previous theoretical studies. Evidently, the existence of mountainous islands results in more complicated structures of the MJO. As expected, convection and circulation exhibit a much more complicated spatial distribution according to the atmospheric local responses to orography and land–sea contrast (e.g., stronger convection in the windward side of mountains and the jump of convection from the west to the east of the New Guinea Island between phases 4 and 5 in Figs. 7 and 8) in comparison with the more homogeneous distribution in the AQUA experiment.

3) More realistic periodicity and stronger eastward propagating signals: A larger variance ratio in the 30–80-day periodicity is observed in the CTL experiment. Removing orography shifts the spectral peak toward longer periods. The ratio of the eastward-propagating and westward-propagating variance is the largest in the CTL experiment and the smallest in the AQUA experiment. The existence of mountains and islands causes inhomogeneous eastward propagation, which is characterized by a sudden shift in the major convection from one mountainous island to another caused by the obstacle effect of mountainous islands. This characteristic is consistent with previous findings that MJO propagation through the MC is a combination of a mountain-locked stationary component and eastward-propagating component. By contrast, the eastward propagation from the Indian Ocean to the central Pacific is steadiest in the AQUA experiment. A comparison between the three experiments suggests that orographic forcing is the major contribution to this contrast.

4) Stronger southward detour during the eastward propagation: Both convection and low-level flow shift southward when the MJO approaches the MC from the Indian Ocean. Furthermore, the southward shift is also observed in the AQUA experiment because of the higher SST south of the equator, but the shift is more enhanced in the CTL and FLAT experiments. This enhancement can be attributed to the existence of mountains and the land–sea contrast. Flow bifurcation often occurs upstream of mountainous islands. This phenomenon is particularly evident around New Guinea: the MJO westerly anomaly bifurcates west of the island, flows around it, and converges east of the island. Our experiments reveal that this effect is partially caused by the land–sea contrast. Friction is a likely cause of the bifurcation effect on the low-level flow in flat-island settings.

5) Distorted coupled Kelvin–Rossby wave structure: The theoretical Kelvin–Rossby wave structure is...
6) Larger low-level moisture convergence in the MC: Lifting and frictional effects due to orography and land–sea contrast result in larger low-level moisture convergence. The lead–lag relationship between shallow and deep convection, which is often referred to as the westward-tilting vertical structure and is the basis for the frictional wave–CISK mechanism, is much more evident in the CTL experiment. A similar relationship can be partially attributed to the mountainous island-related effects of the MC.

b. Effects on mean states

In addition, the mountains and islands in the MC modify the long-term mean state beyond the MC both upstream and downstream. The mean westerly flow is stronger in the eastern Indian Ocean and the western MC and weakens east of the MC. The existence of the islands of Sumatra and New Guinea enhances the convection at the western and eastern edges of the MC, respectively. Therefore, the induced westerly and easterly anomalies lead to the enhancement and weakening of the mean westerly to the west and east of the MC, respectively. Theoretical studies have revealed that the MJO is enhanced (weakened) in a stronger (weaker) westerly mean state. The mountainous islands in the MC modify the mean westerly by inducing east–west contrast and lead to a stronger and weaker MJO in the eastern Indian Ocean and east of the MC, respectively. The existence of the islands also increases the moisture over the MC, especially over the islands, due likely to the enhanced low-level convergence and deep convection over islands although the land surface evaporation is likely reduced. This enhancement enlarges the zonal gradient of moisture between the eastern Indian Ocean and the MC and contributes to the more notable eastward propagation of the MJO from the eastern Indian Ocean to the MC.

This study reveals the crucial effects of the mountains and land–sea contrast in the MC on the MJO. The eastward propagation of the MJO is interrupted by mountainous islands; its amplitude is intermittently weakened and enhanced according to the atmospheric responses to local topography. These effects have largely been ignored in the previous theoretical and statistical MJO studies. Although the MJO is complicated by mountains and land–sea contrast in reality, theories developed in an aquaplanet framework have been adopted to explain the observed characteristics (e.g., structure, strength, period, and propagation speed) of the MJO in the MC. Wu and Hsu (2009) demonstrate that the effects of mountainous islands cannot be empirically removed through strong spatial smoothing or time averaging, suggesting that these effects are intrinsic to the observed MJO. Detailed exploration of the effects of the mountainous islands in the MC will provide a clearer understanding and more accurate forecast of the MJO. The present findings are obtained from a single model. Future studies using other MJO-resolving GCMs are required to verify whether our results are model dependent. In addition, a systematic model comparison study will help resolve this critical issue.

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