Topographical Effects on Internally Produced MJO-Like Disturbances in an Aqua-Planet Version of NICAM

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Abstract

The roles of topography on the propagation of the Madden-Julian Oscillation (MJO) are discussed using an aqua-planet of the Nonhydrostatic Icosahedral Atmospheric Model (NICAM) with a 220-km horizontal mesh. Four topographical configurations with different land-sea masks and elevations are tested using a zonally non-uniform fixed-SST distribution. Explicit cloud microphysics is used to obtain MJO-like signals. Broad land cover generally weakens convection because of reduced surface latent heat flux (LHF). Forced lifting because of topography enhances local convection on the upwind side of high topography. It is suggested that the zonal contrasts of LHF are one reason for the delayed eastward propagation of the MJO-like disturbances. When only the eastern portion of the convective envelope is over land where the LHF is small, the LHF becomes rear-heavy, resulting in delayed eastward propagation. As the entire convective envelope proceeds over land, its contrast decreases or even reverses, resulting in faster eastward propagation.

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1. Introduction

The Madden-Julian Oscillation (MJO) (Madden and Julian 1971, 1972) is a dominant intraseasonal variability in the tropics. It affects the tropical rainfall or tropical cyclone genesis and improving its prediction is of great importance for agriculture and disaster prevention in the tropics. Numerical models are useful for understanding or predicting the MJO, but they have not successfully produced MJOs (Slingo et al. 1996; Lin et al. 2006; Zhang et al. 2006) until the mid-2000s. Over the latest decade, models have gradually improved (Hung et al. 2013; Zhang et al. 2013). However, the existence of the Maritime Continent (MC) appears to act as a barrier that degrades the predictability of the MJO in some Global Circulation Models (GCMS), including the best performing operational models (e.g., ECMWF (Vitart et al. 2007) and NCEP (Weaver et al. 2011)). Clarification of the role of the MC currently stands out as a key to improve the MJO prediction performance in GCMS.

Inness and Slingo (2006) discussed the role of the MC using an aqua-planet GCM with the MC. They found that the MC effectively blocks the eastward propagation of Kelvin wave components embedded in the MJO, weakened the convergence to the east of convection in the lower troposphere, and weakened the MJO. The limitation of their study is that the MJO-like disturbances were simulated using forced convection by moving a dipole anomaly of the sea surface temperature (SST) at the constant eastward speed of an observed MJO. Although Woolnough et al. (2001) confirmed that the forced disturbances had similar overall features to observed MJOs, it is not guaranteed that the behavior of the disturbances will represent that of the real MJOs when they encounter an obstacle.

In some recent models, explicitly treating cloud microphysical processes appears to effectively produce MJOs (Miura et al. 2007; Miura et al. 2009; Holloway et al. 2013; Miyakawa et al. 2014). Liu et al. (2009) conducted a detailed analysis of an MJO event simulated by Miura et al. (2007) and suggested that the frictional moisture convergence operated. Furthermore, the latent heat flux (LHF) to the west of the MJO center was enhanced (Miyakawa et al. 2012), which is consistent with observations (Zhang 1996; Lin and Johnson 1996; Zhang and McPhaden 2000). In recent times, it is suggested that this lag between the maximum LHF and convection can help to maintain convection to the west (non-linear WISHE) (Maloney and Sobel 2004; Maloney 2009; Sobel et al. 2010; Sobel and Maloney 2013).

In this study, we provide insight to what factors of the MC are relevant to MJO behavior. We first try to produce MJO-like disturbances internally (i.e., not forced) using an aqua-planet GCM. We run experiments that turn on/off the cumulus parameterization (CP) and use varying SSTs. The influences of the topography on the MJO propagation or structure are subsequently investigated using sensitivity experiments, with differently configured MC-like topography added to the aqua-planet.

We describe the model configurations and our experimental setup in Section 2. The results and their interpretations are discussed and summarized in Section 4.

2. Model configurations and experimental design

We use the Nonhydrostatic Icosahedral Atmospheric Model (NICAM) (Tomita and Satoh 2004; Satoh et al. 2008, 2014) with a coarse resolution 220-km horizontal mesh. The model top is set to 40 km, with 40 vertical layers. The model is first set up as an aqua-planet with fixed-SST, meridionally symmetric ozone distribution, and equinoctial solar forcing with diurnal cycles. Previous studies noted that zonally asymmetric SST distributions may be crucial for realistic eastward MJO propagation (e.g., Miura et al. 2009; Maloney et al. 2010; Yoshizaki et al. 2012a), so the SST field is given as a zonally non-uniform distribution with an added wavenumber 1 and amplitude 2 K anomaly, which promotes internal MJO-like disturbances (see Supplement 1). The aqua-planet experiments were first designed by Hayashi and Sumi (1988) for studying super cloud clusters and are nowadays used for deeper understanding of tropical convective systems (Blackburn and Hoskins 2013). In fact, the aqua-planet experiments of NICAM were extensively performed and analyzed previously by Tomita et al. (2005), Satoh et al. (2005), Miura et al. (2005), Nasuno et al. (2007), Mapes et al. (2008), Kubokawa et al. (2010), Sherwood et al. (2010), Yoshizaki et al. (2012a, b), and Blackburn et al. (2013).

Four different topographical configurations are added to the aqua-planet in subsequent experiments: (1) the MC orography and surface properties (“MARITIME”), (2) flat “MARITIME” (“NUTOPO”), (3) oceanic mountain MC, given the sea surface properties with the same orography as the MC (“MARIOCN”), and (4) big flat rectangular MC (“BIGFLAT”). Topographical configurations are summarized in Fig. 1 (see Supplement 2 for more information). There is a mismatch between the elevation and the land-sea mask in MARITIME because of the low resolution. We discuss the impacts of orography by comparing MARITIME...
waves, have as strong power as them in 2 K SST anomaly experiments (Supplement 4, Figs. S2, S3). Therefore, we use their wavenumbers and periods to identify MJO-like disturbances in this study. Note that for MARIOCN, the strong power is seen more widely in the region of moist-Kelvin waves with frequencies around 0.05−0.15 cpd and wavenumbers of 1−4 compared to AQUA (Figs. S2e, b).

Figures 2a, b, c, d, e show the Hovmöller diagrams of OLR averaged between 5°N−5°S during sampled 6 months (the results for the entire period are shown in Fig. S4 [Supplement 4]). They also include de-trended OLR anomalies filtered for MJO-like signals with the wavenumbers and periods mentioned above. In AQUA (Fig. 2a), active convective envelopes propagate eastward slowly across the warm pool (60°E−180°), and they generally overlap with filtered OLR anomalies of less than −10 W m$^{-2}$. These slowly eastward propagating disturbances are also seen in MARITIME and NOTOPO (Figs. 2b, c). Localized enhancement of convection exists at the east of 120°E and across 140°E−150°E in MARITIME. Such local enhancement is intensified in MARIOCN (Fig. 2d). The localized convection appears to be further enhanced when they overlap with moist-Kelvin wave signals. Note that the enhancement of local convection and excitement of the moist-Kelvin waves (also see Fig. S1e) are not only because of the increased LHF but also partially because of unrealistic sensible heating from the elevated sea surface as mentioned in Section 2. In BIGFLAT (Fig. 2e), differences compared to AQUA are not immediately apparent, except for a tendency to weaker convection between 120°E−150°E.

Before focusing on MJO-like disturbances, we analyze the climatological zonal circulation and convective activities around the warm pool. Figures 3a, b, c, d, e show the Walker circulation averaged over 5°N−5°S for each topographical configuration, which is defined as a deviation of only 5-year mean components from 5-year and zonal mean ones. The zonal SST gradients form the Walker circulation, which has steady low-level westerlies near the equator over the warm pool in all experiments. The different vertical circulations among experiments can be interpreted in conjunction with the mean horizontal fields. Figures 4a, b, c, d, e show the 5-year mean fields of OLR and horizontal winds at z = 625 m in each experiment. In AQUA, the wind convergence occurs uniformly near the equator, and convection is more active where SST is high (Fig. 4a). This corresponds to the upward motion derived from the Walker circulation (Fig. 3a). In MARITIME (Figs. 3b, 4b), the mean strong upward flow is intensified and localized around Sumatra (near 100°E), Sulawesi (near 120°E), and New Guinea (130°E−150°E), which can be attributed to forced convection caused by wind blowing towards high topography (Fig. 1a). NOTOPO does not have this topography-forced convection because the height is 0 m, but convection is weaker over the broad land cover of Borneo (110°E−120°E) and instead intensifies near the west of the land (Fig. 4c). The maxima of the upward motion is also to the west of Borneo (near 90°E, z = 10 km, Fig. 3c). In MARIOCN (Figs. 3d, 4d), the upward motion and forced convection on the upwind side of high topographies are more obvious and active, particularly over Sumatra and New Guinea, when compared to MARITIME. This suggests that the LHF from the sea surface and constant sensible heating at high elevations may intensify convection. In BIGFLAT (Figs. 3e, 4e), convection and near-surface convergence are intensified near the west of the land, and become weaker over inland areas. These features are similar to NOTOPO but have larger amplitudes.

To closer examine the effect of topography on the propagation speed and structures of the MJO-like disturbances, we conduct a lagged composite analysis. We set the reference point (day 0) for the time when the MJO-like disturbances pass the western end of the topography (92°E). The MJO-like disturbances are defined as signals that meet the following two criteria: (a) filtered OLR anomalies are less than −10 W m$^{-2}$ and (b) the average of filtered OLR anomalies within a domain that meets criteria (a) is less than −20 W m$^{-2}$. The zonal position of the MJO-like disturbances to obtain the reference point is defined as the OLR-weighted average of longitudes where filtered OLR anomalies in Fig. 2 are

![Image](image-url)
Fig. 2. Hovmöller diagrams of OLR averaged over 5°N–5°S (W m\(^{-2}\); shading) and OLR anomalies for the filtered MJO-like disturbances (contour lines), for a 6-month sample period. (a) AQUA, (b) MARITIME, (c) NOTOPO, (d) MARIOCN, and (e) BIGFLAT.

Fig. 3. The Walker circulation (zonal wind [m s\(^{-1}\); shading], and vertical wind [cm s\(^{-1}\); contour lines]) in (a) AQUA, (b) MARITIME, (c) NOTOPO, (d) MARIOCN, and (e) BIGFLAT. The Walker circulation is defined as a deviation of only time mean components from the zonal and time mean ones (The values are averaged over 5°N–5°S.).
between 5°N−5°S. Figures 6a, b are for AQUA. The reference distribution of LHF, sensible heat flux (SHF), and OLR averaged and wind anomalies from the 5-year mean fields and the zonal vertical structures of composited temperature, specific humidity, and after its phase speed changes in BIGFLAT, Fig. 6 shows the less than −10 W m$^{-2}$ at each time. Nine MJO-like disturbances pass 92°E in AQUA, 7 pass in MARITIME, 13 pass in NOTOPO, 7 pass in MARIOCN, and 10 pass in BIGFLAT. The horizontal structure of MJO-like disturbances at day 0 in each experiment indicates the Matsuno-Gill pattern (Fig. S5, Supplement 5). Figures 5a, b, c, d, e show Hovmöller diagrams of lagged-composite OLR and zonal winds at $z = 1570$ m averaged over 5°N−5°S. We can regard the main convective envelopes propagating eastward in Fig. 5 as the MJO-like disturbances. In AQUA (Fig. 5a), convective signals associated with the MJO-like disturbances slowly propagate eastward to the vicinity of 120°E. The phase speed along convective centers (shown in Fig. 5a) is about 2.9 m s$^{-1}$ and slower than a typically observed MJO. A faster eastward signal exists over the eastern side of the warm pool, probably a moist-Kelvin wave separated from the MJO-like disturbance judging from its phase speed. In MARITIME and NOTOPO (Figs. 5b, c), convection relatively weakens across 110°E−120°E. One reason for this is the broad land-coverage of Borneo, as seen in Figs. 4b, c. In contrast, the topographically-forced convection near 120°E in MARITIME (Fig. 5b) enhances convection and westerly wind signals. In addition, compared with NOTOPO, the phase speed of the MJO-like disturbances is slightly faster in MARITIME. The localized convection because of topographically-forced lifting in MARIOCN (Fig. 5d) are probably further enhanced because of increased LHF from the surface. Furthermore, the MJO-like disturbance in MARIOCN propagates eastward faster than in the other experiments. A distinct phase speed change occurs in BIGFLAT (Fig. 5e). The MJO-like disturbance slows down as the convective envelope approaches the western end of the land (day −10 to day +10), and then speeds up. We roughly identify phase speeds before and after the MJO-like disturbance reaches the land as 1.3 m s$^{-1}$ and 4.8 m s$^{-1}$, respectively.

To compare the structures of the MJO-like disturbance before and after its phase speed changes in BIGFLAT, Fig. 6 shows the vertical structures of composited temperature, specific humidity, and wind anomalies from the 5-year mean fields and the zonal distribution of LHF, sensible heat flux (SHF), and OLR averaged between 5°N−5°S. Figures 6a, b are for AQUA. The reference points for the composites are the convective centers, which were acquired by regression of the longitude of the minimum OLR averaged over 5°N−5°S on time (red lines in Figs. 5a, e). These points correspond to 0° in Fig. 6. In AQUA, there is convergence/divergence in the lower/upper troposphere (Fig. 6a). We can see the positive temperature anomalies to the east below $z = 4$ km and near $z = 10$ km (Fig. 6b). Furthermore, the positive specific humidity anomaly is larger at $z = 1−5$ km from 0° to −30°, and relatively high below $z = 1$ km from 0° to +30° (Fig. 6b). Theformer reflects the moist signals associated with clouds and the latter reflects the plentiful moisture in the boundary layer to the east of the convective center. Note that the LHF maxima are located to the west of the convective center, indicating a delaying effect on the eastward propagation, as argued in previous studies (e.g., Sobel et al. 2010; Lin and Johnson 1996).

In BIGFLAT, before reaching the land, there is a strong updraft near the convective center and a descending branch to the west (Fig. 6c). The positive/negative humidity anomalies also correspond to the upward/downward motion. The positive temperature anomaly is particularly high below 1 km from +30° to +60°, reflecting enhanced SHF because of the existence of the land to the east of the MJO-like disturbance (Figs. 6c, d). Across this region, the SHF increases and the LHF decreases. However, the SHF is smaller and probably has secondary effects when compared to the reduction of the LHF, so that fluctuations of the surface heat flux mainly depend on increase or decrease in the LHF. The zonal contrast of the LHF is greater than in AQUA, because the LHF is reduced over the land to the east of the convective center. The increased contrast of LHF supports the maintenance of convection to the west of the convective center, which can hinder the eastward propagation of the MJO-like disturbance as one mechanism.

After the impingement (Figs. 6e, f), a descending branch to the west is obvious, and negative humidity anomalies are obvious from $z = 2−6$ km around −40° to the lower layer immediately west of the convective center. This dry area also corresponds to the negative temperature anomalies near $z = 4$ km and near the surface to the west. These moisture and thermal distributions indicate...
Fig. 5. Hovmöller diagrams of lagged composite OLR (W m⁻²; shading) and zonal wind at z = 1570 m (m s⁻¹; contour lines) averaged over 5°N–5°S during the period when the MJO-like disturbances propagate eastward over the warm pool. (a) AQUA, (b) MARITIME, (c) NOTOPO, (d) MARIOCN, and (e) BIGFLAT. OLR in the dotted area is significantly low at the 90% confidence level. The red lines drawn in (a) and (e) are linear regressions of minimum OLR values (convective centers of the MJO-like disturbances).

Fig. 6. Vertical cross sections of the MJO-like disturbance along the convective center for the AQUA experiment: (a) zonal wind and vertical wind speed anomalies (m s⁻¹ and cm s⁻¹; shading and contour lines, respectively). The bottom pannel shows the zonal distributions of LHF and SHF (W m⁻²; red and blue lines, respectively). (b) specific humidity (g kg⁻¹; shading) and temperature anomalies (K; contour lines). The bottom pannel shows the zonal distributions of OLR (W m⁻²). Similar results are shown in (c) (d) and (e) (f) for BIGFLAT before and after impingement. The base of the anomalies in winds, temperature, and specific humidities is the 5-year mean.
that the dry air promotes evaporation and sublimation, which leads to anomalous cooling and subsidence. The anomalous subsidence can contribute to dry intrusion from the mid-troposphere and suppressed convection to the west. With regard to the eastward phase speed, the zonal LHF contrast decreases or even reverses because of the land coverage across the entire convective envelope, resulting in a faster eastward propagation.

4. Summary and discussion

The impact of topography on the propagation and structure of the MJO is examined using an aqua-planet of NICAM with a 220-km horizontal mesh. Four kinds of topography (MC, flat MC, oceanic surface given the elevation of MC, and large flat land) are tested under zonally non-uniform fixed-SST distributions. We obtained an MJO-like disturbance internally only by using an explicit cloud scheme. Mean fields show that convection on the upwind side of high topography is intensified by topographically-forced lifting and that the LHF from the sea surface may contribute to convection enhancements. For broad and low land, convection is intensified near the west of land, and becomes weaker over the inland area because of reduction of LHF. The results of a lagged composite analysis suggest that the broad land mask of Borneo weakens convection associated with the MJO-like disturbance, whereas the topographically-forced lifting enhances it when the MJO-like disturbance approaches high topography. In BIGFLAT, there are distinct differences between the phase speeds of the MJO-like disturbance before and after the impingement on the land (1.3 m s\(^{-1}\) and 4.8 m s\(^{-1}\), respectively). We discuss that the phase speed difference can be attributed to the different zonal contrast of the LHF. The LHF in AQUA is relatively higher to the west of the convective center, suggesting that the nonlinear WISHE helps maintain convection on the rear side and retards eastward propagation (e.g., Sobel et al. 2010). In BIGFLAT, the zonal contrast of the LHF is increased as the convective center approaches land because the LHF to the east is cut-off, which contributes to enhanced convection to the west and slower eastward propagation. As the entire convective envelope proceeds over land, the zonal LHF contrast decreases or even reverses, and the eastward phase speed becomes faster than AQUA. The zonal contrast of the LHF appears to effectively alter the eastward propagation feature of the MJO, although other effects may operate, and quantitative evaluation of the LHF in phase speed change is left for future work. We further believe that downdraft anomalies because of the cold air over land enhances dry intrusion from the mid-troposphere, thereby further suppressing convection to the west of the convective center and resulting in a faster eastward propagation.

The relatively well produced MJO-like disturbances despite the coarse resolution applied in these experiments suggest that the primary mechanism of the MJO propagation may be explained by large scale processes. However, we do not rule out the possibility that multi-scale processes involving smaller scales impact the MJO phase speed and structure. To discuss the similarities and differences between more realistic MJO disturbances with reasonably resolved convective activities and those in this research, it is necessary to conduct at multiple resolutions.

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Supplement

Supplement 1 describes details of SST distributions. Supplement 2 includes more information about topographical configurations. Supplement 3 shows the results of the sensitivity test that turns on/off the CP. Supplement 4 shows Wheeler-Kiladis diagrams (Fig. S3) and Hovmöller diagrams of OLR anomalies (Fig. S4) during the entire period. Supplement 5 shows the horizontal structure of MJO-like disturbances at day 0 in each experiment (Fig. S5).

References


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