Moisture Transport over the Western Maritime Continent during the 2015 and 2017 YMC Sumatra Campaigns in Global Cloud-System-Resolving Simulations

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Abstract

Transport of moisture over the western Maritime Continent (MC) was examined using global cloud-system-resolving simulations for the Years of the Maritime Continent (YMC) field campaigns in 2015 and 2017, under peak El Niño and moderate La Niña conditions, respectively. We focused on the role of high- and low-frequency variability in the moistening over land and ocean, and their relationship with intraseasonal oscillation (ISO) events.

The period-mean profiles indicate moistening by low-frequency upward motion in the deep troposphere and drying (moistening) in the lower (middle and upper) troposphere by high-frequency variability. The advection over ocean was greater in 2017 than in 2015, with the opposite occurring over land with smaller interannual differences. Over ocean, the roles of the high-frequency variability in the ISO life cycle, namely, the lower-to-middle-tropospheric moistening (enhanced upward transport of moisture) during the preconditioning (active) phases of the ISO, were common in both years, while over land, the high-frequency effects were nearly in phase (not correlated) with the ISO in the 2015 (2017) case. These results highlight clear land-ocean contrasts in the sensitivity of local convection to the background state and its link with the ISO life cycle.

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1. Introduction

The Maritime Continent (MC) is known to have the highest convective activity globally (Ramage 1968), where local processes associated with complicated land-ocean distribution and steep orography account for a large part of the precipitation (Mori et al. 2004; Ogino et al. 2017). It is expected that the upscale effects of local convection on large-scale fields are significant over the MC. For example, by analyzing satellite observation data, Zhang and Ling (2017) demonstrated that Madden-Julian Oscillation (MJO), Madden and Julian (1971, 1972) or intraseasonal oscillation (ISO) episodes often terminated over the MC. Hagoes et al. (2016) conducted sensitivity experiments for a typical ISO episode in 2011 and concluded that the ISO signal was enhanced by extinguishing the diurnal variations of convection over the MC. By contrast, Ichikawa and Yasunari (2007) and Kubota et al. (2015) reported cases where local convection over the MC contributed to robust propagation of the ISO by intensifying convective systems within the ISO, or initiation of the ISO by increasing moisture transport through activation of wave disturbances. Thus, the scale interactions over the MC are still uncertain, with a wide range of variation.

To understand the impacts of local processes over the MC on global climate, the Years of the Maritime Continent (YMC) is being conducted as a combination of multinational intensive observations and modeling studies. As subprojects of the YMC, field campaigns were conducted in southwest Sumatra during the boreal winters of 2015 and 2017. Numerical simulations for the campaign periods were also executed using a global cloud-system-resolving model (CSRM). One useful aspect of such high-resolution modeling is the availability of three-dimensional variables, including diabatic heating and vertical velocity with dense areal coverage, which allows a direct calculation of heat and moisture budgets and scale interactions. These are indirectly diagnosed from in-situ observations (e.g., Yanai et al. 1973, 2000; Katsumata et al. 2011; Johnson et al. 2015) or implicitly represented in global analysis systems (e.g., Nasuno et al. 2015; Tseng et al. 2015). Nasuno et al. (2017), who directly calculated heat and moisture budgets using global CSRM simulation outputs for a field campaign over the equatorial Indian Ocean, detected pronounced upward transport of moisture by high-frequency variability (e.g., cumulus clouds), especially during the active period of the ISO events. Vincent and Lane (2018) examined the diabatic heating around Sumatra and its relation with the ISO in 10-year regional CSRM outputs, and argued that convective (stratiform) heating is maximized prior to (during) the active period of the ISO, which is consistent with the observation that peak precipitation over the MC precedes the main body of the ISO convection (Fujita et al. 2011; Peatman et al. 2014). However, they did not mention much about moisture tendency, which is thought to be more essential for accurate prediction of ISO than is diabatic heating (Klingaman et al. 2015). Considering the diversity of the ISO behavior over the MC, accumulation of detailed case studies and long-term analyses are both necessary for comprehensive understanding.

The purpose of the present study is to quantify and gain insights on the effects of local high-frequency variability on large scales, by using the global CSRM outputs for the YMC campaigns. We focus on moisture tendency, in particular, advection, and examine contributions from different scales (cf. Nasuno et al. 2017). Attention is also given to the land-ocean contrast, which is another key factor in the relationship between the ISO and local convection over the MC (Fujita et al. 2011; Peatman et al. 2014; Birch et al. 2016; Vincent and Lane 2017; Zhang and Ling 2017).

2. Data and analysis methods

Seven-day long outputs of global 7-km mesh simulations using Nonhydrostatic Icosahedral Atmospheric Model (NICAM; Satoh et al. 2014) were analyzed. The model settings were similar to those in Nasuno et al. (2016) (Table S1). Moist convection was calculated explicitly using a single-moment cloud microphysics scheme (NSW6; Tomita 2008), without applying a cumulus parameterization scheme. The simulations were initialized using the National Center for Environmental Prediction (NCEP) final analysis at 0000 UTC on each day during the periods 1 November−25 December 2015 and 15 November 2017−15 January 2018. Sea surface temperature (SST) was given as the sum of the daily climatology and the initial anomalies. Six-hourly snapshots (3-hour averages) for multi-level (single-level) variables were used.

To examine the contributions of local convection and large-scale fields, the advection terms of the moisture tendency equation...
were calculated by separating each variable \(X\) into the 7-day mean (low-frequency, \(X\)) and deviation (high-frequency, \(X'\)), in the same manner as Nasuno et al. (2017) (Eq. S2).

For evaluation of the simulation results, the 0.1° grid Global Satellite Mapping of Precipitation (GPM-GSMaP Ver. 6) near-real-time products (Okamoto et al. 2005) and the 1.0° grid European Center for Medium Range Forecasts (ECMWF) Reanalysis (ERA-Interim (Dee et al. 2011) were used.

3. Convective activity during the 2015 and 2017 campaigns

3.1 Precipitation

Figure 1 shows time-longitude cross-sections of precipitation for the 2015 and 2017 campaign periods. On average, precipitation selectively occurred over the Indian Ocean (the MC–western Pacific) in 2015 (2017) under peak El Niño (moderate La Niña) conditions (Figs. 1a, 1b and S3). In 2015, westward migration of diurnal precipitation was pronounced over the eastern Indian Ocean, particularly in November (Wu et al. 2017; Yokoi et al. 2017). In 2017, the Indian Ocean was rather clear, and eastward-propagating disturbances over the MC were more abundant. ISO episodes developed around the MC in mid-December 2015, late November 2017, and early January 2018, as seen in 7-day running-mean large-scale convective envelopes (Fig. 1, contour lines). Here, the active (inactive) phases of the ISO over the western MC (90°E–120°E, 12°S–8°N) are defined by positive (negative) anomalies in the 7-day running-mean precipitation relative to those averaged over the campaign periods, and the pre-conditioning phase by a positive tendency before the active phase (Fig. 1, right panels).

The composite simulation time series (i.e., the average of the seven outputs with different initial dates on the same valid date, as in Nasuno et al. [2017]) generally reproduced these observed features, except for a few deficiencies, such as more persistent precipitation in the western Pacific in late December 2015 and early January 2018.

3.2 Period-mean fields

Differences in the vertically integrated water vapor (i.e., the averages for 2017 minus those for 2015) over the analysis domain

![Figure 1](image-url)
of the present study (90°E–120°E, 12°S–8°N) is presented in Fig. 2a. The areal fractions of land and ocean are 29% and 71%, respectively. Overall, the western (eastern) part of the domain was more humid in 2015 (2017), consistent with the zonal distribution of precipitation (Fig. 1). The total amount of water vapor was greater in 2017 than in 2015, while the land area was more humid in 2015 than in 2017.

Figures 2b and 2c show vertical profiles of the average vertical velocities over land and ocean areas. Over ocean, the upward motion was stronger in 2017 than in 2015 throughout the troposphere. The difference was less distinct over land, but with stronger upward motion in 2015 than in 2017 in the lower troposphere. Considering the bottom-heavy distribution of water vapor, this accounts for the greater tropospheric moisture over land in 2015 than in 2017 (Fig. 2a). The period mean characteristics described above were reasonably captured in the simulations with some quantitative exaggeration.

Based on the above evaluations of the reproducibility of basic aspects, the following sections discuss moisture advection over the target domain using the simulation outputs.

4. Moisture advection

4.1 Period-mean profiles over the western MC

Figure 3 shows the period mean profiles of the moisture advection associated with unfiltered ($-\omega \frac{\partial q}{\partial z} - \nabla \cdot \nabla q$), low-frequency ($-\nabla \cdot \frac{\partial q}{\partial z} - \nabla \cdot \nabla q$), and high-frequency ($-\omega \frac{\partial q}{\partial z} - \nabla \cdot \nabla q$) components, where $q$, $V$, and $w$ are the specific humidity, and horizontal and vertical velocities, respectively, in 2015 and 2017. The vertical advection accounted for the dominant part, largely in balance with condensation (cf. Yanai et al. 1973; Nasuno et al. 2017), and the horizontal advection made secondary contributions (Figs. 3a and 3b). The vertical profile of each component shows similar structure between the two years with greater magnitude in 2017 than in 2015 (Figs. 3a and 3b), as expected from the mean upward motion (Figs. 2b and 2c). The nonlinear effects of the high-frequency components reduced (increased) moisture in the lower (middle and upper) troposphere. In other words, the high-frequency variability associated with individual convection (e.g., diurnal variation, short-lived convective systems, cumulonimbus, etc.) transported lower-tropospheric moisture accumulated by large-scale slow upward motion (e.g., intraseasonal variability, seasonal mean motion, etc.).

The relative strength of the advection over land compared with that over ocean showed opposing signs for the two years; it was greater over land than over ocean in 2015 with pronounced lower-tropospheric moistening over land (Figs. 3c and 3e), while the reverse was seen in 2017 with greater lower-tropospheric moistening over ocean (Figs. 3d and 3f). This can be explained by the period-mean vertical velocity (Figs. 2b and 2c), and is suggestive of the impacts of the different background large-scale circulation (e.g., lower tropospheric convergence, Walker circulation) as a response to the SST anomaly distribution (Fig. S3) associated with the El Niño–Southern Oscillation (ENSO).

4.2 Relationship with the ISO life cycles

The dependence of the convective activity on the ISO life cycle over land and ocean is an important aspect of the local convection and ISO interactions in the MC (Fujita et al. 2011; Peatman et al. 2014; Birch et al. 2016; Vincent and Lane 2017). Figures 4 and 5 show the time-height cross-sections of the anomalous moisture advection in 2015 and 2017, respectively, with the corresponding precipitation time series.

In 2015, precipitation over the MC was relatively suppressed, although it was enhanced in the western part with pronounced diurnal variations during the inactive period before 5 December (Figs. 1a and 4e). Correspondingly, moistening in the lower and middle troposphere occurred over land during the inactive period by both low- and high-frequency variability (Figs. 4b and 4d). These were followed by deep moistening associated with the main body of the ISO and a subsequent switch to anomalous drying (Figs. 4a and 4b). Over ocean, the contrast between the inactive and active periods was more distinct (Fig. 4, right panels). During the inactive phase, anomalous moistening concentrated near the surface (middle troposphere) by high-frequency variability (low-frequency horizontal variability) occurred, whereas during the active phase, high-frequency variability enhanced moistening (drying) in the middle and upper (lower) troposphere (Fig. 4d). Modulation in precipitation with an approximately 5-day period was also notable over ocean (Fig. 4e). The reasons for such marked land-ocean contrast in 2015 are discussed in Section 5.

In 2017, convection over the target domain was overall more active than in 2015 under increased low-level convergence associated with the La Niña condition (Fig. S3) with two ISO active periods (Fig. 1), which are identified in the low-frequency moisture advection over both land and ocean (Figs. 5a and 5b). More synoptic-scale convective disturbances passed over the target domain even during the inactive period of the ISO (e.g., tropical cyclones in 18–25 December 2017), with diurnal precipitation coexisting over land (Figs. 1b and 5e). Over ocean, moisture transport by high-frequency variability was enhanced during the ISO active phases (Fig. 5d) in a similar manner as that in 2015 (Fig. 4d) and in the ISO events over the open Indian Ocean (Nasuno et al. 2017). Again, anomalous moistening occurred near the surface during the inactive phase (3–29 December 2017), accompanied by deeper anomalous moistening on 15–31 December 2017. The modulation of precipitation with a 5–10-day period also appeared after 20 December 2017 over ocean (Fig. 5e). Over land, moisture advection associated with high-frequency variability did not well correspond to the ISO (Fig. 5d), implying strong control
by local processes, although it was not the primary component in the total advection (Figs. 1b, 1d, 5a, and 5b).

4.3 Diurnal variation

The large amplitude of the diurnal precipitation, especially over land (Figs. 4e and 5e), suggests its significant role in high-frequency moisture advection. Figure 6 shows the composite diurnal variations in the simulated moisture advection. The average of the profiles at four local times (LTs) corresponds to the unfiltered profiles in Fig. 3. The diurnal variations were clearer over land than over ocean, with peak moistening in the evening (morning) over land (ocean), consistent with the observations (Mori et al. 2004; Yokoi et al. 2017; Wu et al. 2017). Over land, vertical extension of moistening (with a peak at 2-km altitude at 1300 LT and maximized at 1900 LT with a peak at 4.5 km altitude; Figs. 6a and 6b) might have contributed to the middle and upper tropospheric moistening associated with high-frequency variability even under the relatively suppressed condition in 2015 (Fig. 4d) and regardless of the ISO phase in 2017 (Fig. 5d). Over ocean, the anomalous moistening confined near the surface might be associated with the 5−10-day period variability (presumably associated with low-top precipitation for 2015), and contributions from the diurnal variations do not seem to be essential for either 2015 or 2017 (Figs. 4e, 5e, 6c, and 6d).

Transport of moisture over the western MC was examined using global CSRM outputs for the YMC Sumatra campaigns in 2015 and 2017. We focused on the role of high- and low-frequency variability in the moistening over land and ocean areas, and their
Fig. 4. Time-height cross-section of the anomalous vertical moisture advection averaged over the total (left panels), land (center panels), and ocean (right panels) areas of the analysis domain (Fig. 2a) associated with (a) total, (b) low-frequency vertical, (c) low-frequency horizontal, and (d) high-frequency variability in the 2015 simulation. (e) Time series of the 7-day running-mean precipitation averaged over the total (black line), land (thick red line, center panel) and ocean (thick blue line, right panel) areas of the analysis domain, with unfiltered precipitation (thin lines). In (a)–(d), deviations from the period-mean profiles (Fig. 3) are shown. Vertical lines depict the beginning of the pre-conditioning (dotted), active (solid), and inactive (dashed) phases of the intraseasonal oscillation (ISO) events (defined in Fig. 1).
relationships with the ISO.

The period-mean profiles over the western MC indicate moistening by low-frequency upward motion in the deep troposphere and drying (moistening) in the lower (middle and upper) troposphere by high-frequency variability. The advection over ocean was greater in 2017 than in 2015, but the opposite occurred over land with significant bottom-heavy moistening in 2015. These can be related to relatively suppressed (enhanced) upward motion over ocean under the strong El Niño (moderate La Niña) conditions during 2015 (2017). Over land, the responses of the local circulation to the SST anomalies (Jiang and Li 2018) might have been responsible for the anomalous moisture transport.
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Supplement

Supplement 1 (Table S1) describes the model settings for the simulations.

Supplement 2 describes the moisture tendency equation (Eq. S2).

Supplement 3 (Fig. S3) presents the period-mean distributions of sea surface temperature anomaly in NOAA_OI_SST_V2 and wind fields in ERA-Interim.

Supplement 4 (Fig. S4) shows real-time multivariate MJO diagrams for the 2015 and 2017 campaign periods.

References


Fig. 6. Composite vertical profiles of the moisture advection at 0000 UTC (0700 LT, blue solid line), 0600 UTC (1300LT, red dashed line), 1200 UTC (1900 LT, red solid line), and 1800 UTC (0100 LT, blue dashed line), averaged over the (a) (b) land and (c) (d) ocean areas of the analysis domain (Fig. 2a) in the (a) (c) 2015 and (b) (d) 2017 simulations.

Another point of concern is the location of the ISO convective center. In the 2015 case it was located over the IO during the inactive period over the western MC (Fig. 1a), although its magnitude was not large in the real-time multivariate MJO index (Wheeler and Hendon 2014; Fig. S4a). The convection over the land area of the MC and its diurnal variation are most enhanced during this phase of the ISO life cycle under strong thermal instability with small large-scale cloud coverage (Fujita et al. 2011; Peatman et al. 2014; Birch et al. 2016; Vincent and Lane 2017). For the 2017 case, by contrast, the ISO convection and associated circulation traveled over the western Pacific and western hemisphere during the inactive phase over the western MC (Figs. 1b and S4b). During these phases, the convection over the land area of the MC is most suppressed after the large-scale convective activity (Fujita et al. 2011; Birch et al. 2016). Thus, both the ENSO and ISO phases favored convection over land in the 2015 campaign period compared with 2017. The relative importance of these two factors will be investigated in forthcoming studies.

Regarding the major contributor of the high-frequency variability to the moisture advection, an important role of diurnal variation in the inactive period before the ISO event over land was suggested for the 2015 case, whereas that in the 2017 case appeared less significant. In the 2017 case, moisture advection associated with synoptic-scale disturbances seems to have been more pronounced during the inactive phase especially over ocean, which might not necessarily be linked to the ISO convective organization. The roles of local diurnal variation and other convective disturbances are important targets for further investigations.

This case study will serve as a step towards more comprehensive understanding of the multi-scale interactions over the MC under the influence of various background conditions (e.g., Tung et al. 2014; Son et al. 2017).


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