Impact of Latent Heat Flux Modifications on the Reproduction of a Madden–Julian Oscillation Event during the 2015 Pre-YMC Campaign Using a Global Cloud-System-Resolving Model

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Abstract

We show that a modification to the latent heat flux (LHF) formulation in Non-hydrostatic Icosahedral Atmospheric Model (NICAM) impacts the representation of a Madden–Julian oscillation (MJO) event during the Pre-Years of the Maritime Continent (Pre-YMC) field campaign in 2015. First, we compare the LHFs computed by the standard NICAM setting with those estimated from the ship observation during Pre-YMC. In this comparison, the NICAM LHF is smaller than observation in the low wind speed region and larger in the high wind speed region. Consequently, the MJO signal weakens when it passes over the Maritime Continent (MC). Next, sensitivity experiments are conducted with a modification to the threshold minimum wind speed in the bulk formula, to enhance the LHFs in the low wind speed region. With this modification, propagation of the MJO is better simulated over the MC, although a bias still remains without corrections in the high wind speed regions. Result indicates that increasing the LHF in the low wind speed region likely contributes to a more effective accumulation of moisture over the eastern MC region and consequently allows the MJO to pass over the MC in the model.

(Citation: Matsugishi, S., H. Miura, T. Nasuno, and M. Satoh, 2020: Impact of latent heat flux modifications on the reproduction of a Madden–Julian oscillation event during the 2015 Pre-YMC campaign using a global cloud-system-resolving model. SOLA, 16A, 12–18, doi:10.2151/sola.16A-003.)

1. Introduction

The Madden–Julian oscillation (MJO; Madden and Julian 1971, 1972) is a phenomenon in which packets of organized clouds propagate eastward from the Indian Ocean (IO) to the central Pacific. It is the most prominent intraseasonal event in the tropics and has a substantial impact on tropical and global weather (Zhang 2013). When the MJO propagates over the Maritime Continent (MC), the weakening and blocking of the MJO is known as “Barrier Effect” (Zhang and Ling 2017). Despite recent developments in forecasting models, forecasting MJO propagation over the MC remains difficult (Vitert 2017; Kim et al. 2018). Of the possible model limitations, this study examines the influence of the latent heat flux (LHF). It is thought that the propagation and activation of the MJO are closely related to the LHF. For example, the LHF can destabilize the troposphere, as shown by moist static energy budget analyses in the IO (Sobel et al. 2014) and the MC (Yokoi and Sobel 2015). In addition, LHF and precipitation anomalies have positive covariance on intraseasonal timescale (Aralligidad and Maloney 2008) and there are contribution of LHF to the MJO propagation from the theoretical framework (Sobel and Malony 2012). Therefore, the quality of LHF representations in simulations is expected to affect the reproducibility of the MJO.

A global cloud-system-resolving model, Non-hydrostatic Icosahedral Atmospheric Model (NICAM; Tomita and Satoh 2004; Satoh et al. 2008, 2014), can reproduce the MJO relatively well (Miura et al. 2007; Miyakawa et al. 2014). The model settings for studying the MJO (e.g. Miyakawa et al. 2014, Miura et al. 2015; Nasuno et al 2016) were different from standard climate settings of NICAM (e.g. Kodama et al. 2015). Because insufficient LHF in lower surface wind condition, which might be critical to the MJO propagation (e.g. Takasuka et al. 2015), was expected in the standard settings, a larger threshold of lower limit of the surface wind speed in the LHF formulation was assumed to enhance LHF. However, simulated LHFs have not been compared with in-situ observations, nor their impacts on MJO representations using global cloud-system-resolving models have been examined. In this study, we evaluate the simulated LHF in NICAM by comparison with an in-situ observation taken during “Pre-Years of the Maritime Continent (Pre-YMC)”, and examine the impacts of the LHF settings in the model on the reproducibility of the MJO. The Pre-YMC aimed for improving the representation of the MJO by increasing the LHF in lower surface wind condition, which might be critical to the MJO propagation and its relationship with the large-scale. The research vessel (R/V) Mirai was deployed in the western Sumatra Island (see detail in Wu et al. 2017 and Yokoi et al. 2017), and simulations using NICAM were conducted for the campaign period (Nasuno 2019). First, we compare the LHFs in NICAM simulation for the Pre-YMC campaign period with the LHFs estimated based on the R/V Mirai observations. Second, we examine whether a more consistent LHF representation can contribute to a better representation of an MJO event during this period. We will demonstrate that LHFs in the low wind speed region impact the propagation of the MJO over the MC in NICAM.

2. Data and simulation

We used the observational data obtained by the R/V Mirai from 23 November to 17 December 2015 at 4°S, 102°E. The surface meteorological datasets and sea surface temperature (SST) were used to estimate the LHF with an 11-min running average. The LHFs were estimated using the COARE 3.0 bulk flux algorithm (Fairall et al. 2003). This algorithm estimates tracer coefficients based on an application of the Monin–Obukhov similarity theory and is widely accepted in the air–sea interaction research community. For comparison with the NICAM outputs, 3-h averages of the estimated LHFs were used. To diagnose the large-scale features of the MJO, precipitable water (PW) and wind from the ERA-interim (Dee et al. 2011), the NOAA interpolated outgoing longwave radiation (OLR), and the LHF of the objectively analyzed air–sea flux (OAFlux; Yu and Weller 2007) were used.

We conducted three-member 30-days ensemble simulations using NICAM with a 14-km mesh size. The simulations were initialized at 0000 UTC on 1, 2, and 3 December 2015. The detail of model configuration of control experiments (CTL) is given in Supplement 1 and Nasuno (2019). The cloud microphysics settings were tuned for the MJO simulations, following Miyakawa et al. (2014) and Miura et al. (2015), while the LHF settings were unchanged from the standard settings (Kodama et al. 2015).
The COARE algorithm adopts a gustiness effect ($U_g$), and Miura et al. (2015) set USMIN to 1.9 m s$^{-1}$. Meanwhile, Miyakawa et al. (2014) found that the MJO were reasonably represented but with some specific biases (Kikuchi et al. 2017). An AMIP-type premise that higher resolution models may represent turbulent-scale turbulence in the 14-km resolution model. In order to examine how this modification affects the simulated MJO, we conducted sensitivity experiments with the USMIN value of 1.9 m s$^{-1}$.

For the low wind speed region, which is our primary focus, the COARE algorithm adopts a gustiness effect ($U_g$) that permits non-zero fluxes to be reproduced as the wind speed approaches zero by assuming the effects of boundary layer-scale eddies (Godfrey and Beljaars 1991). $U_g$ is considered for all the U ranges. In NICAM, this effect is approximately included by setting a parameter USMIN, a lower limit of $U$ (Eq. 2). The same formulation is also applied to the sensible heat flux.

In the CTL, USMIN was set to 0.001 m s$^{-1}$ based on the premise that higher resolution models may represent turbulent structures more realistically near the surface. An AMIP-type simulation (Kodama et al. 2015) with this setting, climatology of the MJO were reasonably represented but with some specific biases (Kikuchi et al. 2017). Meanwhile, Miyakawa et al. (2014) and Miura et al. (2015) set USMIN to 1.9 m s$^{-1}$. They believed that larger value was required to account for the effect of sub-grid scale turbulence in the 14-km resolution model. In order to examine how this modification affects the simulated MJO, we conducted sensitivity experiments with the USMIN value of 1.9 m s$^{-1}$ and other settings same as CTL (referred to as U19).

3. Overview of the MJO event and LHF comparison between the observation and NICAM

Figure 1a shows the time–longitude cross-section of OLR. Here we define the MJO signal by an envelope of the 7-day running-mean OLR. In the first half of December 2015, convec-
tion was inactive in the MC around 120°E. Prior to the propagation of the MJO (from the November until mid-December), the convective activity was continuously enhanced in the IO. During this period, the LHF was large (over 120 W m$^{-2}$) in the west side of the active convection over the IO and small in the convectively inactive areas over the MC, respectively (Fig. 1c). Meanwhile, the PW gradually increased around the MC (Fig. 1b). After this period (i.e., since around 12 December), the MJO convective envelope started moving eastward, as seen in OLR, PW, and 850 hPa zonal wind (U850), and the LHF was significantly enhanced over the MC.

Figure 2 compares the surface wind speeds observed on the R/V Mirai and the estimated LHFs and those in the CTL. The observed wind speed and the LHF increased sharply around 13 December when the MJO passed over the observation point. The OAFlux reproduced this feature. The CTL marginally reproduced the increase in the surface wind speed, but its timing was delayed by approximately three days, and the amplitudes of the wind perturbations were smaller than those observed.

To compare the wind–LHF relationships of the observation and the CTL, the scatter plots of the LHFs and wind speeds are shown in Fig. 3. For wind speeds lower than 2 m s$^{-1}$, the simulated LHFs (blue marks in Fig. 3b) tend to be smaller than the observational estimates (black marks in Fig. 3a) and are larger for wind speeds higher than 8 m s$^{-1}$. This trend is similar to that found in the comparisons with tropical buoy data (figures not shown).

As $\Delta q$ did not significantly depend on $U$ in the observation or simulation (figures not shown), the model bias in the slope of the relationship (i.e., the absence of air–sea interactions). The latter is expected to be more critical in higher wind speed regions than in lower wind speed regions. Another bias is found in the y-intercept in Fig. 3. The LHF obtained from observations using the COARE algorithm was greater than zero even when the wind speed was close to zero (Fig. 3a), whereas that from the CTL was nearly zero due to the small USMIN value. The above result indicates that the use of such a small USMIN is not suitable at least for the current simulation. The results of the U19 are compared with those of the CTL and observation in Figs. 2 and 3. Increases in the wind speed and LHF for the U19 from those in the CTL were found in early December (Fig. 2), although the changes were not significant.
sufficient to remove the biases in the CTL. Figure 3c shows that the U19's LHFs were closer to the observational estimates for the lower wind speed ranges with non-zero values (Fig. 3d). This fact supports that U19 should be reasonable in the 14-km resolution model.

4. Impacts of the LHF modifications on a MJO simulation

In this section, we show how LHFs modification impacts on the MJO propagation in the simulation. In the CTL (Figs. 4a–4d), the active convection and moistening in the IO were reasonably simulated in the early stage of the simulation before 8 December.

The MJO convective envelope and associated westerly wind anomalies (Fig. 4d) started moving eastward around 12 December, but stagnated around 120°E after 16 December.

In the U19 (Figs. 4e–4h), the convective region remained in the eastern part of the IO before 11 December, which was similar to the observations and the CTL. The onset of the eastward propagation of convective envelope from the IO to the MC was reproduced at the same timing (around 12 December) as that in the CTL. However, a distinct difference between the U19 and the CTL was found over the MC. In the U19, the convective envelope continuously traveled eastward across the MC and approached near the dateline. The corresponding signal in PW and U850 was also captured, although the signal was still weaker than in the observations, and with spurious persistent convection remaining over the IO.

The LHF was oversupplied in the high wind speed regions (e.g., the west side of convective regions over the IO), while it was insufficient in the low wind speed regions (e.g. around 120°E on 6–11 December; Figs. 1c and 4c). This is consistent with the LHF bias on the observation point (Section 3). This steep gradient in the LHFs between the IO and the MC likely prevented the MJO from moving eastward over the MC. The LHF gradient across the IO and the MC in the U19 was smaller than that in the CTL (Fig. 4g), although it was still larger than that in the OAFlux.

The improvement in the MJO representation was also clear in the horizontal distribution of moisture (Figs. 5, S1, and S2). In the observed MJO, prior to 8 December, dry air from the south of the MC penetrated into the eastern side of the MC (Figs. 5b, S1b, and S2b). The dry intrusion is not usual but was observed in approximately half of the MJO events (DeMott et al. 2018). This region was gradually moistened and recovered to its condition prior to the dry intrusion (Fig. 5d); subsequently, the convective envelope passed over the MC on 18 December (Figs. 5e and S1f). Compared with ERA-Interim, the high humidity associated with the MJO stagnated over the MC in the CTL (Fig. S1e), while that in the U19 moved across the MC, although there were still moist/dry biases in the IO/WP after 20 December (Figs. S2e and S2f).

Next, we further investigate what processes were related to such differences. Figures 6a–6c show the time series of the PW in three regions: IO, eastern MC, and the western Pacific (WP). The observations (Fig. 6a) show that the eastern MC was in a dry condition on 8 December; then, it gradually became wetter. Finally, upon the arrival of the convective envelope at the MC on
18 December, its wettest state was achieved. In the CTL (Fig. 6b), the recovery of moisture in the eastern MC was slow; therefore, the PW in the IO remained larger than that in the MC. Conversely, in the U19 (Fig. 6c), the moistening was faster than that in the CTL during 10–18 December; subsequently, the PW amounts in the MC overtook those in the IO and WP. It appears that the dry intrusion in the eastern MC prevented the propagation of the MJO in the CTL. This event was not critical to the MJO in the observation and the U19 with a rapid moisture recovery.

In the following, we discuss the difference between the CTL and the U19 in the moistening process over the MC. Figure 6d shows the column-integrated water budget terms over the MC (in energy dimensions). The budget equation is:

\[
\frac{\partial PW}{\partial t} = LHF - LP - \int P \cdot \nabla q dp / g, \tag{3}
\]

where \(P\) is the precipitation, \(V\) is the horizontal winds, \(P_s\) is the surface pressure, and \(g\) is the acceleration of gravity. The last term of RHS was calculated as a residual. The absolute value of each term in NICAM has biases in comparison with reanalysis (e.g., Hannah and Maloney 2014; Fig. S3) due to the LHF biases remaining in the high wind speed regions, even though the MJO propagation was better represented in the U19 than CTL. Then we focus on the difference between the CTL and U19. The difference of LHFs did not explain the total difference in the moisture tendency via directly increasing moisture (Fig. 6d). The increase in PW in the U19 was primarily caused by the moisture convergence (especially after 15 December), a major part of which was consumed by the enhanced convective activity (Figs. 4a and 4e). The LHFs in the U19 were larger than those in the CTL since early December (Fig. 4g). The larger moisture in the lowest level enhanced low level vertical velocity via latent heat release, and likely contributed to the subsequent enhancement of the large-scale circulation (reduced zonal divergence over the MC during 10–15 December; Figs. 4d and 4h). This facilitated convective organization over the MC (Figs. S2e and S2f, but not in S1e and S1f), leading to a further increase in the moisture convergence after 15 December, as in the ERA-interim (Fig. 6d). These process selectively worked over the MC, where the wind speed was originally low and the ratio of the increase in LHF to the total amount was relatively high. The above results indicate that larger LHFs could provide a favorable environment for the eastward propagation of the MJO by enhancing moisture build up.
through the development of the large-scale circulation associated with the MJO (i.e. moisture–convection feedback) and by directly increasing the local LHF's.

5. Summary and conclusions

We compared the NICAM-simulated LHF's with those of the observational estimates during the Pre-YMC campaign. We found that the simulated LHF's tended to be underestimated/overestimated in the low/high wind speed regions. We tested a larger threshold value in the bulk LHF formula; an improvement in the MJO reproducibility was achieved via this modification, although there were still some biases in the IO. The area in the east of the MJO recovered from dryness faster owing to the increase in the LHF's via an enhancement of the large-scale circulation as well as through its direct effects in the U19. The weak development of the circulation might increase the negative effects of the dry intrusion over the MC in the CTL.

Our result suggests that LHF's in the low wind speed regions play an important role in preconditioning the MJO propagation: to reduce the LHF gradient between the high and low wind speed
regions, which affects the large-scale circulation. However, biases still remain because no correction was made in the high wind speed regions in this study. The total improvements of the bulk formula of NICAM are left for forthcoming studies.

Acknowledgments

The authors thank the crew of the R/V Mirai. The R/V Mirai data are archived at http://www.jamstec.go.jp/ymc/index.html. All simulations were run using the Earth Simulator of JAMSTEC. The authors appreciate ECMWF (https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era-interim), NOAA (https://www.esrl.noaa.gov/psd/data/grid/datasets/), and WHOI (http://oaflux.whoi.edu/) for providing reanalysis and observation data. This work was supported by JSPS Grant-in-Aid for Scientific Research (B) 25287119 and (B) 16H04048. This work was supported by MEXT as “Program for Promoting Researches on the Supercomputer Fugaku” (Large Ensemble Atmospheric and Environmental Prediction for Disaster Prevention and Mitigation).

Edited by: K. Yasunaga

Supplements

Supplement 1 describes the details of model setup. Supplement 2 shows same as Figure 5 but in the simulations. Supplement 3 shows the column-integrated moist static energy budget terms in the ERA-Interim and U19.

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Manuscript received 11 February 2020, accepted 3 May 2020

SOLA, 2020, Vol. 16A, 12–18, doi:10.2151/sola.16A-003

SOLA, https://www.jstage.jst.go.jp/browse/sola/