Impacts of Cloud Microphysics Modifications on Diurnal Convection and the ISO over the Maritime Continent: A Case Study of YMC-Sumatra 2017

Tomoe Nasuno
Japan Agency for Marine-Earth Science and Technology, Yokohama, Japan

Abstract

Relationship between diurnal convection and the intraseasonal oscillation (ISO) over the western Maritime Continent (MC) was investigated by a case study of an ISO event that occurred during the Years of the Maritime Continent (YMC)-Sumatra 2017 campaign. Two sets of global cloud-permitting simulations using cloud microphysics settings for ISO prediction (CTL) and for climate simulation (MOD) were performed to clarify their impacts. CTL had biases of weaker diurnal variation and smaller precipitation amounts over land than in observations; these were reduced in MOD by higher probabilities of local intense convection in the middle troposphere and higher precipitation efficiency. The enhanced convection over land coincided with suppressed convection over the surrounding ocean, especially at the diurnal peak time of land convection. Exception is the onset period of the ISO convection, when upward moisture advection and precipitation increased also over ocean in MOD than in CTL at the diurnal peak time of oceanic convection. These results suggest that the enhancement of local convection over the MC by the cloud microphysical processes basically hinders the ISO convection by the activation of land convection, but it also favors the ISO convection development over ocean during the onset period.

(Citation: Nasuno, T., 2021: Impacts of cloud microphysics modifications on diurnal convection and the ISO over the Maritime Continent: A case study of YMC-Sumatra 2017. SOLA, 17, 16−23; doi:10.2151/sola.2021-003.)

1. Introduction

The tropical intraseasonal oscillation (ISO) is a major target of subseasonal to seasonal prediction due to its marked impacts on global weather (Zhang 2013; Vitart et al. 2017); however its accurate prediction over the Maritime Continent (MC) has been challenging (Vitart and Molteni 2010; Kim et al. 2016; Wang et al. 2019; Ahn et al. 2020). The MC is characterized by diurnally forced active convection that is driven by local processes associated with complex land-ocean distribution and steep orography (Yang and Slingo 2001; Mori et al. 2004). Active local convection over the MC affects the ISO intensity and propagation (Innes and Slingo 2006; Kim et al. 2014; Zhang and Ling 2017). Hagos et al. (2016), by sensitivity experiments with and without the diurnal insolation cycle, highlighted the blocking effects of diurnal convection on the ISO propagation. To improve the prediction of the ISO over the MC, adequate representation of local and large-scale convective processes is essential.

The development of general circulation models (GCMs) has led to remarkable progress in reproducing the ISO propagation over the MC (Wang et al. 2019; Ahn et al. 2020). Ahn et al. (2020) demonstrated that the models participated in Coupled Model Intercomparison Project Phase 6 (CMIP6) outperform those in Phase 5 (CMIP5) by reducing mean moisture field bias due to updates in convection schemes. On the other hand, the latest GCMs still exhibit biases in the simulation of diurnally forced MC convection (Branowski et al. 2019; Argüeso et al. 2020). Regional cloud-permitting models are useful for studying the MC convection, including its dependence on the ISO (Hagos et al. 2016; Vincent and Lane 2017, 2018; Argüeso et al. 2020), while they tend to overpredict diurnal convection over land. Appropriate modeling of cloud microphysics and shallow convection is a key issue (Argüeso et al. 2020). In addition, scale interactions in regional models are restricted by their domains. With this respect, global cloud-permitting models have an advantage (Miura et al. 2007, 2015; Miyakawa et al. 2014; Fujita et al. 2011; Nasuno et al. 2017; Nasuno 2019).

The international project Years of the Maritime Continent (YMC) was conducted to improve our understanding and prediction of the global MC impacts; one YMC campaign collected field data in Sumatra in 2017 (Yoneyama and Zhang 2020), for which near-real-time forecasts were executed using a global 7-km mesh model. Nasuno (2019) used this simulation dataset to quantify the moisture transport in the ISO, and found that the high-frequency variabilities contributed to the ISO-scale moistening in the preconditioning phase of the ISO over ocean, whereas such relationship was not clear over land. However, the role of diurnal variation could not be thoroughly examined due to the single simulation setup and model biases.

In the present study, two series of simulations, each with different cloud microphysics settings, were performed, and the resulting systematic differences in diurnal convection over the MC were examined to clarify how the model physics altered the behavior of local convection and its effects on the simulated ISO.

2. Data and methods

2.1 Simulation setup

In this study Nonhydrostatic Icosahedral Atmospheric Model (NICAM, Satoh et al. 2014) was used with a horizontal mesh size of 7 km globally. Moist convection was explicitly calculated using a six-category single-moment bulk cloud microphysics scheme (NSW6, Tomita 2008) without operating implicit convection schemes. The details of the model configurations for the near-real-time forecasts (CTL) are provided in Nasuno (2019). The simulations were initialized daily at 0000 UTC throughout the YMC-Sumatra 2017 campaign period using the National Centers for Environmental Prediction (NCEP) final operational global analysis (NCEP FNL). In this study, 5-day outputs for the period between 9 November and 9 December 2017, covering the full life cycle of an ISO event, were analyzed. For the sensitivity simulations (MOD), the model configurations were based on the climate simulations (Kodama et al. 2021) and initialized using the same data as used in CTL. The most significant difference between the two setups was in the cloud microphysics settings; other minute changes had little impacts on the week-long simulation results (Supplement 1).

In the CTL settings, the terminal velocities of the precipitating condensates (i.e., snow, graupel and rainwater) were reduced to avoid excessively intense, sporadic precipitation and to facilitate large-scale organization of convection, which were valid for the month-long ISO simulations (Miyakawa et al. 2014; Miura et al. 2015). In the MOD settings, the modification of NSW6 proposed by Roh and Satoh (2014), which was based on evaluation of cloud...
microphysics processes by a satellite simulator, were employed, with parameter tuning for global cloud climatology (Kodama et al. 2015). The MOD settings decelerated conversion of cloud ice to snow and growth of graupel, which led to increased (reduced) amount of ice (graupel) with lower peak level of snow in MOD than in CTL (Fig. 1d). These changes in the ice condensates were accompanied with little changes in latent heat release, but some increase (decrease) in latent heating (water vapor content) occurred accordingly (Figs. 1b and 1c).

3.2 Moisture advection

The essential role of the moisture variability in the ISO dynamics has been well established (Fuchs and Raymond 2005; Raymond and Fuchs 2009; Sobel et al. 2001; Sobel and Maloney 2013; Nasuno et al. 2015, 2017). In this study, sum of the horizontal and vertical components of moisture advection terms were calculated (Supplement 3) using these time series; the ISO-scale components were extracted using a 7-day running average. For comparisons, precipitation data from the Climate Prediction Center morphing method (CMORPH) products (Joyce et al. 2004) and atmospheric data from the European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis (ERA-Interim and ERA5; Dee et al. 2011; Hersbach et al. 2020) were used.

3. Results

3.1 Precipitation

The period-mean distribution and time series of simulated precipitation over the MC are presented in Fig. 2 and Fig. 3, respectively. Large precipitation amounts over the western MC (Fig. 2a) were associated with the ISO event that occurred in this period (i.e., averaging outputs initialized on different dates for each valid time), and horizontal and vertical components of moisture advection terms were calculated (Supplement 3) using these time series; the ISO-scale components were extracted using a 7-day running average. For comparisons, precipitation data from the Climate Prediction Center morphing method (CMORPH) products (Joyce et al. 2004) and atmospheric data from the European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis (ERA-Interim and ERA5; Dee et al. 2011; Hersbach et al. 2020) were used.

Fig. 1. Vertical profiles of (a) temperature, (b) water vapor content, (c) diabatic heating rate by latent heat release (black), short wave (red) and long wave (blue) radiation, (d) cloud ice (light blue), snow (blue), graupel (purple), cloud water (yellow), and rainwater (red) in CTL (solid lines) and MOD (dashed lines). Averages of the 5-day data initialized on 5, 10, 15, and 20 November 2017 (all day for the target period) in the target domain (90°E−120°E, 12°S−8°N) are shown in (c) and (d) ((a) and (b)).
Fig. 2. Mean precipitation (left) and diurnal difference (right) in (a) (b) CMORPH, (c) (d) CTL, (e) (f) MOD, and (g) (h) the difference (MOD – CTL), averaged between 9 November and 9 December 2017. The diurnal difference is defined by subtracting the precipitation at 0000 UTC (0700 LT) from precipitation at 1200 UTC (1900 LT). In (h), magnitude of the difference is drawn. Box indicates the target domain of analysis.

Fig. 3. Time series of the ISO-scale (7-day running average; thick lines) and unfiltered (thin lines) precipitation averaged in the land (red) and ocean (blue) area of the target domain for (a) CMORPH, (b) CTL, and (c) MOD. (d) Column integrated moisture advection (black), precipitation (gray), and precipitation minus surface moisture flux (green) for MOD [in water mass tendency per unit area]. Vertical dotted, solid, and dashed lines indicate the beginning of the pre-conditioning, active, and inactive phases of the ISO, respectively, according to the definitions in Nasuno 2019. The periods of averages in Fig. 5 are also indicated.
To more clearly see the responses of the land-ocean contrast to the microphysics modifications, time-averaged moisture advection and its diurnal differences were calculated (Fig. 5). Differences between MOD and CTL mainly appeared at height (z) of 4−10 km, with enhanced (reduced) moistening over land (ocean) (Figs. 5a, 5b, and 5c). These trends were more evident at the diurnal peak time of land convection, especially in the suppressed period prior to the ISO convection onset (Fig. 5d). The moistening tendency (MOD – CTL) over land continued to increase during the ISO convection onset period (21−25 November; Figs. 5f and 5g), and then decreased during the latter active period (26 November to 2 December; Figs. 5h and 5i).

Over ocean, the drying tendency (MOD – CTL) was more pronounced, reflecting intensification of compensating subsidence via enhanced upward motion over land. The exception was the ISO convection onset period, when the moistening tendency also appeared over ocean at the diurnal peak time of oceanic convection (Fig. 5g). In both simulations, the continuous increase in the moistening was robust over ocean, in contrast to the reduction in the latter active period over land (Fig. 5h). Such land-ocean contrast is supporting of the known precipitation variation associated with the ISO (e.g., Peatman et al. 2014).

### 3.3 Decomposition of vertical motion

Given the compensating relationship between convection over land and ocean in the western MC (Fig. 5), a question arises which change (e.g., intensity, area) of the upward/downward motion by the cloud microphysics modifications was the major factor. Vertical motion $W$ over the target domain can be decomposed as follows:

$$W = W_u + W_d = a_l W_{ul} + a_u W_u + a_d W_{dl} + a_d W_d,$$

where $a_l + a_u + a_d = 1.0$; $a$ and $w$ stand for the areal fraction and the mean vertical velocity of each component; and the subscripts $l$, $u$, $d$, and $o$ denote land, ocean, upward, and downward, respectively.
respectively. The period-mean profiles of \( a \) and \( w \) of each component are shown in Fig. 6, together with \( w_l \) and \( w_s \) in the ECMWF reanalyses. The difference between \( w_l \) and \( w_s \) was greater in ERA5 than in ERA-Interim, and those in the simulations were within the realistic range (Figs. 6a and 6b). The following paragraphs discuss the differences between MOD and CTL.

On average, \( w_l \) (\( w_s \)) [red (blue) lines] increased (decreased) below \( z = 10 \) km by the cloud microphysics modifications (Fig. 6b), elucidating the difference in moisture advection (Fig. 5). In all components, \( w_l \) [red] and \( w_s \) [blue] were greater (smaller) in MOD [broken lines] than in CTL [solid lines] below (above) \( z = 10 \) km (Fig. 6d). The increase in \( w_l/w_s \) [red/blue lines] was especially pronounced in \( w_{ul} \) and \( w_{us} \) in the middle troposphere (\( z = 4-10 \) km) [positive side in Fig. 6d], which accounted for the enhanced late evening land convection and the morning oceanic convection during the ISO onset period (Figs. 5f and 5g). These were accompanied with decrease in \( a_u \) (increase in \( a_d \)) (Fig. 6c), indicating compensation between the upward and downward motion within the target domain. The reduction in \( a_{us} \) and increase in \( w_{ds} \) accounted for the mean decrease in \( w_s \) [blue lines in Fig. 6b] and moisture advection over ocean [blue lines in Fig 5a]. The intensification of \( w_u \) was mainly attributable to the reduction of

Fig. 5. Vertical profiles of moisture advection for CTL (solid lines) and MOD (dashed lines) averaged over land (red) and ocean (blue) in the target domain for (a) all day mean and composites at (b) (d) (f) (h) 1200 UTC, and (c) (e) (g) (i) 0000 UTC. Averages for (a)–(c) the total period, (d) (e) November 9–20, 2017 (suppressed period), (f) (g) November 21–25, 2017 (onset period), and (h) (i) November 26 to December 2, 2017 (latter active period).
and reduction in a dvection. In CTL, indicating the weaker sustainability of the organized convection. In the latter active period, decreases in a, and W were more significant in MOD than in CTL, indicating the weaker sustainability of the organized convection.

4. Conclusions

In this study, two series of global cloud-system-resolving simulations with different cloud microphysics settings, for ISO prediction (CTL) and for climate simulation (MOD), were examined to clarify the effects of the cloud microphysics modifications on local convection and their linkage with the ISO.

Intense upward motion with latent heat release in the middle troposphere occurred more frequently in MOD than in CTL, owing to the reduced drag force of precipitating condensates (Figs. 6 and S1-2). These led to enhanced local diurnally forced convection and a resultant increase in the mean precipitation over land (Figs. 2 and 3), accompanied by systematic differences in moisture advection (Figs. 4 and 5). The enhancement of upward motion selectively occurred in the convectively active regions (e.g., over the MC, tropical continent, and inter tropical convergence zone), without significant changes in the global circulation (Fig. S5). Thus, compensating subsidence was rather constrained around the neighboring domains. As a result, the upward motion and moisture transport were suppressed over the surrounding ocean within the western MC, through the intensification of mean downward motion and reduction in the fractional area of upward motion. In terms of bulk moisture balance, the enhanced precipitation in MOD with little change in moisture gain led to higher precipitation efficiency (Supplement 3). Changes in the lower troposphere (reduced fractional area of downward motion and intensification of mean downward motion) and in the upper troposphere (increased ice clouds with slower upward motion and broader coverage) also appeared, although their impacts on changes in moisture advection and precipitation were secondary.

In view of the impacts on the ISO, the temporal variation of moisture advection showed generally opposite tendencies over land and over ocean, consistent with the above analysis. The exception was the ISO onset period, when anomalous upward moisture advection with enhanced diurnal variation occurred over ocean. This can be attributed to stronger radiative forcing over the ocean with less cloud amount in MOD (Fig. 1c), as well as gradual development of large-scale circulation associated with the ISO. This result implies that the MOD settings enhance interactions between ISO and diurnal variation over ocean, with anomalous moistening by the latter (e.g., Nasuno et al. 2015; Tseng et al. 2015). Responses of the radiative forcing associated with the ISO convection (e.g., stronger/weaker surface insolation in the convectively inactive/active period) to the microphysics modifications,
in light of the moisture mode concept (Fuchs and Raymond 2005; Sobel and Maloney 2012), are the topic of forthcoming investigations.

The enhancement of local deep clouds in MOD, which selectively appear over land, was consistent with the dominance of convective precipitation over land in observations (Sakaeda et al. 2017, 2020) and in regional cloud-permitting simulations (Vincent and Lane 2018), whereas the development of stratiform clouds, which accounts for the major body of the ISO convection especially over ocean, was less evident in MOD than in CTL, despite the general improvement of the representation of the upper-level clouds (Kodama et al. 2021; Roh and Satoh 2014). The results of this study suggest that more realistic settings lie between the two settings, which is pursued in forthcoming investigations, as well as better understanding of scale interactions, including the long-term responses of the large-scale conditions through extended-range simulations.

Acknowledgements

The author acknowledges Ms. Mikiko Ikeda for executing the simulations. The Earth Simulator was used for the simulations. The author acknowledges the ECMWF for providing the ERA-Interim and ERA5 dataset, the NCEP for providing the NCEP FNL and the CMORPH. The author was supported by JSPS KAKENHI Grant Number JP19H04248, JP20H01386, and JP20H05172. The author sincerely acknowledges two anonymous reviewers for their insightful comments.

Edited by: T. Takemi

Supplements

Supplement 1: Additional information of the cloud microphysics.
Supplement 2: Details of the cloud microphysics settings.
Supplement 3: Definitions and results of the moisture budget analysis.
Supplement 4: Summary of the vertical motion decomposition analysis results.
Supplement 5: Additional information of the large-scale vertical motion.

References

Ahn, M.-S., D. Kim, D. Kang, J. Lee, K. R. Sperber, P. J. Gleckler, X. Jiang, Y.-G. Ham, and H. Kim, 2020: MJO propagation across the Maritime Continent: Are CMIP6 models better than CMIP5 models? Geophys. Res. Lett., 47, e2020GL087250.
Argüeso, D., R. Romero, and V. Homar, 2020: Precipitation features of the Maritime Continent in parameterized and explicit convection models. J. Climate, 33, 2449−2466.
Baranowski, D. B., D. E. Waisser, X. Jiang, J. A. Ridout, and M. K. Flatau, 2019: Contemporary GCM fidelity in representing the diurnal cycle of precipitation over the Maritime Continent. J. Geophys. Res. Atmos., 124, 747−769.
Duce, D. P. and co-authors, 2011: The ERA-interim reanalysis: Configuration and performance of the data assimilation system. Quart. J. Roy. Meteor. Soc., 137, 553−597.
Fuchs, Z., and D. J. Raymond, 2005: Large-scale modes in a rotating
Nasuno, T. 2015: Moistening processes before the convective initiation of Madden-Julian Oscillation events during the CINDY2011/DYNAMO period. *Mon. Wea. Rev.*, 143, 622−643.

Nasuno, T., K. Kikuchi, M. Nakano, Y. Yamada, M. Ikeda, and H. Tamiguchi, 2017: Evaluation of the near real-time forecasts using a global nonhydrostatic model during the CINDY2011/DYNAMO. *J. Meteor. Soc. Japan*, 95, 345−368, doi:10.2151/jmsj.2017-022.

Peatman, S. C., A. J. Matthews, and D. P. Stevens, 2014: Propagation of the Madden-Julian oscillation through the Maritime Continent and scale interaction with the diurnal cycle of precipitation. *Quart. J. Roy. Meteor. Soc.*, 140, 814−825.

Raymond, D. J., and Z. Fuchs, 2009: Moisture modes and the Madden-Julian oscillation. *J. Climate*, 22, 3031−3046.

Roh, W., and M. Satoh, 2014: Evaluation of precipitating hydrometeor parameterizations in a single-moment bulk microphysics scheme for deep convective systems over the tropical central pacific. *J. Atmos. Sci.*, 71, 2654−2673.

Sakaeda, N., G. Kiladis, and J. Dias, 2020: The diurnal cycle of rainfall and the convectively-coupled equatorial waves over the Maritime Continent. *J. Climate*, 33, 3307−3331.

Sakaeda, N., G. Kiladis, and J. Dias, 2017: The diurnal cycle of tropical rainfall and cloudiness associated with the Madden-Julian oscillation. *J. Climate*, 30, 3999−4020.

Sato, M., H. Tomita, H. Yashiro, H. Miura, C. Kodama, T. Seiki, A. T. Noda, Y. Yamada, D. Goto, M. Sawada, T. Miyoshi, Y. Niwa, M. Hara, Y. Ohno, S. Iga, T. Arakawa, T. Inoue, and H. Kubokawa, 2014: The non-hydrostatic iccsahedral atmospheric model: Description and development. *Prog. Earth Planet. Sci.*, 1, doi:10.1186/s40645-014-0018-1.

Sekiguchi, M., and T. Nakajima, 2008: A k-distribution-based radiation code and its computational optimization for an atmospheric general circulation model. *J. Quant. Spectrosc. Radiat. Transf.*, 109, 2779−2793.

Sobel, A., J. Nilsson, and L. M. Polvani, 2001: The weak temperature gradient approximation and balanced tropical moisture waves. *J. Atmos. Sci.*, 58, 3630−3665.

Sobel, A., and E. Maloney, 2012: An idealized semi-empirical framework for modeling the Madden–Julian oscillation. *J. Atmos. Sci.*, 69, 1691−1705.

Sobel, A., and E. Maloney, 2013: Moisture modes and the eastward propagation of the MJO. *J. Atmos. Sci.*, 70, 187−192.

Sui, C.-H., X. Li, and M.-J. Yang, 2007: On the definition of precipitation efficiency. *J. Atmos. Sci.*, 64, 4506−4513.

Sui, C.-H., M. Satoh, and K. Suzuki, 2020: Precipitation efficiency and its role in cloud-radiative feedbacks to climate variability. *J. Meteor. Soc. Japan*, 98, 261−282.

Tomita, H., 2008: New microphysics with five and six categories with diagnostic generation of cloud ice. *J. Meteor. Soc. Japan*, 86A, 121−142.

Tseng, K. C., C. H. Sui, and T. Li, 2015: Moistening processes for Madden-Julian Oscillation during DYNAMO/CINDY. *J. Climate*, 28, 3041−3057.

Vincent, C. L., and T. P. Lane, 2017: A 10-year Austral summer climatology of observed and modeled intraseasonal, mesoscale and diurnal variations over the Maritime Continent. *J. Climate*, 30, 3807−3828.

Vincent, C. L., and T. P. Lane, 2018: Mesoscale variation in diabatic heating around Sumatra, and its modulation with the Madden-Julian oscillation. *Mon. Wea. Rev.*, 146, 2599−2614.

Vitart, F., and M. Satoh, and K. Suzuki, 2020: Precipitation efficiency and its role in cloud-radiative feedbacks to climate variability. *J. Meteor. Soc. Japan*, 98, 261−282.

Vitart, F., and co-authors, 2017: The Subseasonal to Seasonal (S2S) prediction project database. *Bull. Amer. Meteor. Soc.*, 98, 163−173.

Yang, G.-Y., and J. Slingo, 2001: The diurnal cycle in the tropics. *Mon. Wea. Rev.*, 129, 784−801.

Yoneyama, K., and C. Zhang, 2020: Years of the Maritime Continent. *Prog. Earth Planet. Sci.*, 7, 10.1186/s41038-020-00019-9.

Yoneyama, M. Hara, Y. Ohno, S. Iga, T. Arakawa, T. Inoue, and H. Kubokawa, 2014: The non-hydrostatic iccsahedral atmospheric model: Description and development. *Prog. Earth Planet. Sci.*, 1, doi:10.1186/s40645-014-0018-1.

Zhang, C., and J. Ling, 2017: Barrier effect of the Indo-Pacific Maritime Continent on the MJO: Perspectives from tracking MJO precipitation. *J. Climate*, 30, 3439−3459.

Manuscript received 1 October 2020, accepted 10 December 2020

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