How does the air-sea coupling frequency affect convection during the MJO passage?

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Key Points:

- High-frequency air-sea coupling improves the reproducibility of both convection and upper ocean processes
- Low-frequency coupling causes phase-lagging in diurnal cycle
- Higher daytime SST is more important than the daily mean

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Abstract

The importance of air-sea coupling in the simulation and prediction of the Madden-Julian Oscillation (MJO) has been well established. However, it remains unclear how air-sea coupling modulates the convection and related oceanic features on the subdaily scale. Based on a regional cloud-resolving coupled model, we evaluated the impact of the air-sea coupling on the convection during the active phase of the MJO by varying the coupling frequency. The model successfully reproduced the atmospheric and oceanic variations observed by satellite and *in situ* measurements but with some quantitative biases. According to the sensitivity experiments, we found that stronger convection was mainly caused by the higher sea surface temperatures (SSTs) generated in highly coupled experiments, especially when the coupling frequency was 1 hour or shorter. A lower coupling frequency would generate the phase lags in the diurnal cycle of SST and related turbulent heat fluxes. Our analyses further demonstrated that the phase-lagged diurnal cycle of SST suppressed deep convection through a decrease in daytime moistening in the lower troposphere. Meanwhile, in the upper ocean, the high-frequency air-sea coupling helped maintain the shallower mixed and isothermal layers by diurnal heating and cooling at the sea surface, which led to a higher mean SST. In contrast, the barely coupled experiments underestimated SST and therefore convective activities. Overall, our results demonstrated that high-frequency air-sea coupling (1 hour or shorter) could improve the reproducibility of the intensity and temporal variation in both diurnal convection and upper ocean processes.

Plain Language Summary

The Madden-Julian Oscillation (MJO) is one of the important sources of atmospheric variability in tropical regions, however, even the modern numerical models could not well reproduce the MJO. We believe that the underestimation of air-sea coupling may cause some parts of such biases in simulating/predicting the MJO. Therefore, our study is aimed to uncover the impact of the air-sea coupling on convection and the related oceanic feature during the MJO. By varying the air-sea coupling frequency, our results showed that the 1-hour or higher frequency coupled experiments had better performance due to the well-reproduced sea surface temperature (SST), while suppressed convection was found in barely coupled experiments. In general, our study suggested that the high-frequency air-sea coupling could improve the reproducibility of both convection and upper ocean features during the MJO.

1 Introduction

The Madden-Julian Oscillation (MJO) is the chief source of variability in tropical regions on the intraseasonal time scale, which features an eastward propagating convectively active envelope (Madden & Julian, 1972). Over the decades, increasing evidence has shown that the MJO not only influences the global climate system but also many types of extreme weather in the tropics and midlatitudes (e.g., Kayano & Kousky, 1999; Kessler, 2001; Lorenz & Hartmann, 2006; Zhang, 2013; Wang & Moon, 2018). Therefore, it is crucial to obtain the successful simulation/prediction of the MJO for tropical weather systems, extreme weather events, monsoons, and the El Nio-Southern Oscillation (Vitart, 2014; Mishra et al., 2017; Wu et al., 2019).

To successfully simulate/forecast the MJO, numerous studies have been carried out; however, some systematic biases remained even in the state-of-the-art climate and forecast models due to the complexities of the MJO (e.g., Madden & Julian, 2005; Peatman et al., 2014; DeMott et al., 2015; Pilon et al., 2016; Kim et al., 2018). Recent studies found that the moistening processes are crucial to the initiation of the MJO and its maintenance/propagation (e.g., Raymond & Fuchs, 2009; Ruppert & Johnson, 2015; Tseng et al., 2015; Nasuno et al., 2015). For example, based on a regional numerical model, Hagos et al. (2011) demonstrated the important role of the moistening process on stratiform heating and related potential temperature perturbations, and their results also indicated the essence of well-represented shallow- and deep-convection in simulating the MJO. Other studies have mentioned the potential effect of preconditioning moistening on MJO-related rainfall, although the effect may depend on events (e.g., Zermeo-Daz et al., 2015; Chen & Zhang, 2019).

It is now well known that the MJO is a highly air-sea coupled phenomenon from the intraseasonal scale to the subdaily scale (e.g., Waliser et al., 1999; Zhang & Anderson, 2003; DeMott et al., 2015, and the references therein). Numerous studies have demonstrated that the inclusion of air-sea coupling improves the reproducibility of moistening processes during MJO (e.g., Fu et al., 2013; Seo et al., 2014). For example, Kim et al. (2010) suggested that air-sea coupling could improve the intensity and spatiotemporal evolution of the MJO. Seo et al. (2014) further confirmed the improved representation of diurnal sea surface temperature (SST) and the buildup of preconvection warming and moistening in highly coupled models. Based on the *in situ* observations, Ruppert and Johnson (2015) demonstrated that diurnally varying SST could invigorate net column moistening aloft. Some recent studies also suggested that the feedback of SST (hence, air-sea coupling) maintained propagation of the MJO (e.g., Webber et al., 2010; Zhu et al., 2017).

Although the importance of air-sea coupling on convection and the MJO has been well established, few studies have examined detailed modulations on the diurnal scale (e.g., Neale & Slingo, 2003; Crueger et al., 2013; Green et al., 2017). Whats more, some studies have also shown that the air-sea coupling frequency may modulate the reproducibility of the diurnal cycle of SST (e.g., Shinoda, 2005; Seo et al., 2014). It is reasonable to expect that the modulated SST may further influence the subdaily moistening processes and the MJO (e.g., Ruppert & Johnson, 2015; Hagos et al., 2016; Katsumata et al., 2018). However, such modulations on the SST by air-sea coupling were neglected in most studies and, therefore, remained unclear.

Thus, the goal of this study is to evaluate the effect of air-sea coupling (and the coupling frequency) on convective activities and related upper oceanic variations, especially on the subdaily scale. As part of the ongoing Year of the Maritime Continent (YMC) project (Yokoi et al., 2017, 2019; Nasuno, 2019; Wu et al., 2019), we focus on one MJO event (November 26th to December 4th, 2017; Figure 1b) captured during the YMC-Sumatra 2017 field campaign. In this period, a large number of land- and ship-based *in situ* observations are available, providing a great opportunity to validate the capability of our numerical experiments.

This paper is organized as follows. Section 2 includes descriptions of the model setup, data source and sensitivity experimental designs. Section 3 includes validation of the model performance with and without cumulus parameterizations. Section 4 documents the impact of coupling frequencies on the convection and surface conditions, along with analyses of the heat and moisture budgets. In Section 5, the role of the daily mean SST and how the SST was modulated by the coupling frequency are discussed. Finally, a summary of the major findings is presented in Section 6. Results on the cumulus parameterizations and extra experiment for the role of local SST are presented in Sections S1 and S2 in the Supporting Information Section.

2 Model and experiment settings

2.1 Model

In this study, numerical experiments were based on the Coupled-Ocean-Atmosphere-Wave-Sediment Transport (COAWST) Modeling System (Warner et al., 2010), and, for simplicity, we excluded the wave and sediment components and only activated the at-

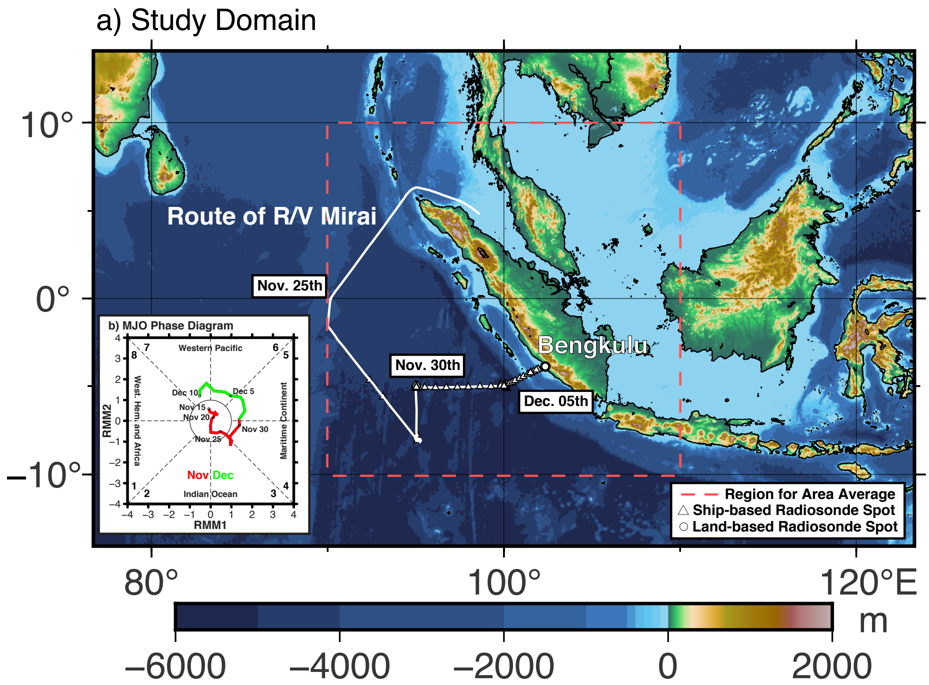

Figure 1. (a) Map of the study domain together with the route of R/V *Mirai* and the locations where the radiosonde was launched. The box enclosed by the red dashed line presents the Sumatra region for area averaging. The inner panel (b) presents the MJO RMM index obtained from the Bureau of Meteorology, Australia.

mospheric (Weather Research and Forecasting Model, WRF V4.1.2) and oceanic (Regional Ocean Modeling System, ROMS svn 980) components. In coupled experiments, WRF uses the SST calculated by ROMS, while ROMS receives heat fluxes, wind stress, surface temperature, relative humidity, and freshwater fluxes. In uncoupled experiments, WRF was activated alone using the satellite-based SST.

The model was designed to cover the region from 78°E to 122°E and 14°S to 14°N, where the center is located at Sumatra Island (0°, 100°E; Figure 1a). All simulations started at 0:00 UTC on November 21st and ran until 0:00 UTC on December 6th, which was 5 days prior to the active phase of the MJO over the Maritime Continent (Phase 4 & 5, Figure 1b).

The horizontal resolution of WRF and ROMS is 7 km with matching grids and land-sea masks (Nasuno 2019). The 30 s Global Multiresolution Terrain Elevation Data 2010 (Danielson & Gesch, 2011) and ETOPO1 (Amante & Eakins, 2009) were used for WRF and ROMS, respectively. WRF has 45 sigma layers from the surface to the top (50-hPa), and ROMS has 50 layers based on the quadratic Legendre polynomial function (Souza et al. 2015) with a larger number of vertical levels in the upper 50 m.

WRF uses the single-moment 7-class microphysics scheme (Bae et al., 2018), the Yonsei University PBL scheme (Hong et al., 2006), the Revised MM5 surface layer scheme (Jimnez et al., 2012), the Unified Noah Land Surface Model (Tewari et al., 2004), the RRTMG Shortwave and Longwave Schemes (Iacono et al., 2008), and the Grell-Freitas Ensemble (GFE) cumulus scheme (Grell & Freitas, 2014). ROMS uses the Mellor-Yamada Level-2.5 closure scheme associated with the third-order upstream horizontal advection, harmonic horizontal mixing, and 4th-order centered vertical advection, and no nudging term is included.

It is worth noting that at a so-called gray zone resolution (Gerard, 2007), the cumulus parameterization does not always enhance the reproducibility in our 7-km model. Therefore, we conducted extra experiments to obtain the best performance, and results can be found in the Supporting Information Section. The schemes we tested included the GFE scheme (Grell & Freitas, 2014), the New Simplified Arakawa-Schubert (NSAS) scheme (Kwon & Hong, 2017), and the Multiscale KainFritsch (MKF) scheme (Zheng et al., 2016). We also tested the New Tiedtke (NT) scheme (Zhang & Wang, 2017), which is not scale-aware but includes both deep and shallow cumulus components. Note that because the NSAS scheme does not have the shallow convection component, which was proved to be important in simulating convection (Pilon et al., 2016), we applied the Global/Regional Integrated Model system (GRIMs) shallow convection scheme (Hong & Jang, 2018) in CP1HC3 following Kwon and Hong (2017).

2.2 Data

In this study, the National Centers for Environmental Prediction (NCEP) Final (FNL) Operational Global Analysis data (NCEP, 2000) and Global Ocean Forecasting System (GOFS) 3.1 (Cummings, 2005) were used as the initial and lateral boundary conditions for WRF and ROMS, respectively. Additionally, in uncoupled experiments, the daily Optimum Interpolation SST (OISST) dataset was used for the lower boundary condition (Banzon et al., 2016; Reynolds et al., 2007). The modeled atmospheric and oceanic properties were saved every 1 hour over the course of each computation in all experiments.

For the model validation, we used precipitation data from the satellite-based hourly Global Rainfall Map (GSMaP) dataset together with ship-based [Research Vessel (R/V) *Mirai*] and land-based (Bengkulu, Indonesia) radiosonde data obtained during the YMC-Sumatra 2017 field campaign (Nasuno, 2019; Wu et al., 2019; Yokoi et al., 2019).

2.3 Sensitivity experiments of coupling frequency

To investigate the influence of the coupling frequency on convection during the MJO active phase, a set of experiments was carried out by varying the coupling interval from 30 minutes to 1 day and an uncoupled experiment (WRF-only). ROMS and WRF were coupled at the first-time step of each experiment and then coupled after the specified interval. For example, the 6-hourly coupled model would exchange atmospheric and oceanic information at 0:00 UTC, 6:00 UTC, 12:00 UTC, and 18:00 UTC. In addition, Three uncoupled (WRF-only) experiments were further conducted to discuss the role of daily mean SST (see subsection 5a and Section S2). Detailed descriptions of the sensitivity experiments can be found in Table 1.

3 Model validation

Figure 2 shows the horizontal distributions of the mean precipitation rates and maximum precipitation time during the active phase of the MJO (Nov. 26th-Dec. 4th) obtained by satellite and CP1HC. The heaviest rain occurred over the Gulf of Thailand near the eastern coast of the Malay Peninsula and the southern Andaman Sea (Burma Sea), along with a weak but widely distributed rainy zone covering the Indian Ocean and the Maritime Continent (Figure 2a). In the Southern Hemisphere, clear rainy zones were observed over the Indian Ocean, south of the equator and south of Java Island, but the precipitation rates were smaller. All the patterns mentioned above were successfully reproduced in CP1HC, although the rainy regions were not as concentrated as the observations in the Southern Hemisphere.

Table 1. Descriptions of sensitivity experiments

Experiment	Settings
CP30MC	30-min WRF-ROMS
CP1HC	1-h WRF-ROMS
CP3HC	3-h WRF-ROMS
CP6HC	6-h WRF-ROMS
CP12HC	12-h WRF-ROMS
CP1DC	1-d WRF-ROMS
NOCPC	WRF-only (OISST)
NOCPC+	WRF-only (OISST & daily mean SST from CP1HC)
NOCPC++	WRF-only (daily mean SST from CP1HC)

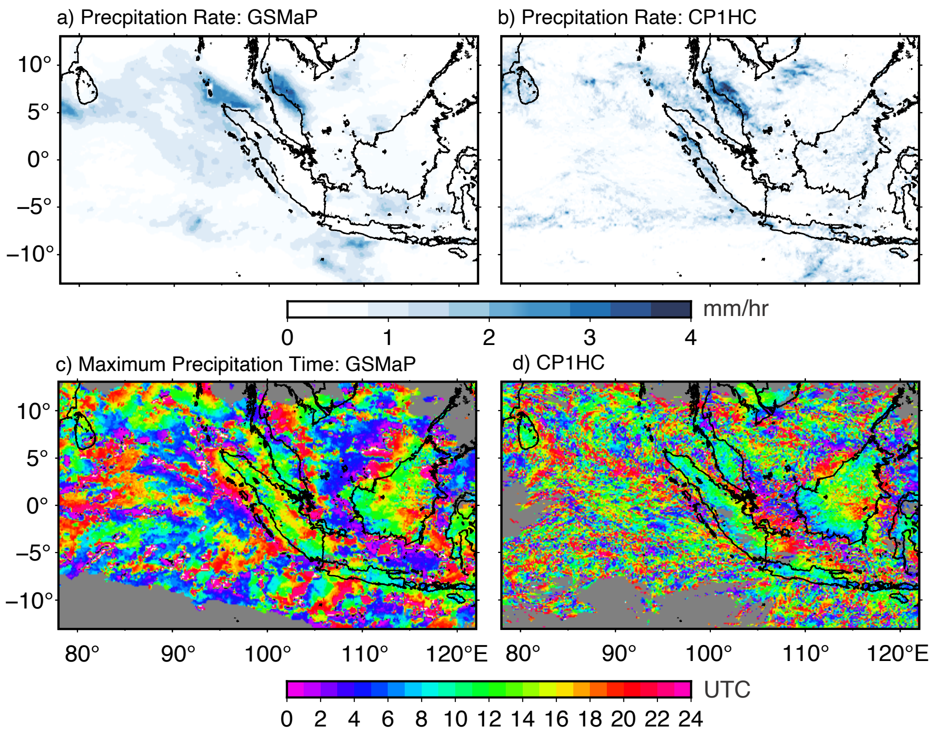

Figure 2. Horizontal distributions of precipitation rates and the time of maximum precipitation obtained from satellite observations (a and c) and CP1HC (b and d).

In addition to the precipitation rate, the time of maximum precipitation can also be regarded as an important indicator representing the diurnal cycle of precipitation. As shown in Figure 2c, the maximum precipitation mainly occurred in the evening near the coastal region and in the early morning inland (see the patterns over Sumatra and Kalimantan). Meanwhile, over the shallow coastal seas, the heaviest rain occurred in the early morning, especially near the Gulf of Thailand and west of Sumatra Island where the heaviest rainfall was observed. In general, the observed diurnal cycle he observed diurnal cycle was consistent with the diurnal cycle revealed in previous studies (Neale & Slingo, 2003; Mori et al., 2004). Moreover, in comparison with the observations, the precipitation in CP1HC reached its maximum rate at the same time (Figure 2d), although the simulated precipitation showed more small-scale features.

In addition, we further compared our model results with the *in situ* radiosonde profiles obtained during the YMC-Sumatra 2017 field campaign (Figure 3; also see Figure 1a for the locations of radiosonde observations). The atmosphere near Sumatra Island was dominated by the westerly wind over the entire active phase of the MJO, which could also be seen in the model. The meridional wind component (v) suggested that a transition of wind field occurred after Nov. 30th, as shown by the opposite meridional wind direction before and after the day. A similar transition of the meridional wind could also be found in our model, but with some underestimations. Moreover, both observations and simulations showed that very high relative humidity (RH) was dominant from the surface to the upper troposphere, indicating the vigorous convective activities occurred in both the model and real atmosphere.

Overall, our model showed good agreement with both satellite-based and *in situ* observations, suggesting that our model is reliable; therefore, we conducted sensitivity experiments of coupling frequencies using the same schemes and settings as CP1HC.

4 Results

4.1 The impact on the atmospheres

To examine the impact of the air-sea coupling frequency on convection, we first focused on the moisture and moisture fluxes in our sensitivity experiments. Figure 4a presents the map of the daily mean precipitable water (PW) and vertically integrated moisture fluxes averaged during the active phase of the MJO (from surface to 300-hPa, November 26th to December 4th) in CP1HC. A large amount of PW was concentrated north of Sumatra Island and the Malay Peninsula, which consists of the location of the heaviest rainfall, as observed by satellite and CP1HC (Figure 2). The cyclonic gyre located in both north and south of the equator, associated with the jet-like moisture fluxes originating from the Indian Ocean to the west (also from the South China Sea), exhibited the existence of vigorous convective activities over the Maritime Continent (i.e., the active phase of the MJO).

In comparison with CP1HC, the differences in the mean PW and moisture fluxes were not obviously changed in CP30MC, CP3HC, or CP6HC. However, unlike the highly coupled experiments (i.e., 6 hours or more coupled), the total amount of PW decreased by 5 mm or more in most regions in the barely coupled models, with the clearest pattern in the uncoupled experiment (NOCPC, Figure 4g). Meanwhile, the moisture flux anomalies showed anticyclonic gyre-like and westward jet-like patterns, indicating greatly suppressed convective activities (Figure 4e-g). Note that although the anticyclonic gyre-like pattern could also be seen in Figure 4d, no westward anomalies were found, suggesting that the convection was weakened in the CP6HC but not as much as that in the barely coupled/uncoupled experiments.

Figure 5a presents the frequency-altitude distributions of RH over the seas near Sumatra Island (red box in Figure 1a; Nasuno et al. 2015). The lower troposphere (sur-

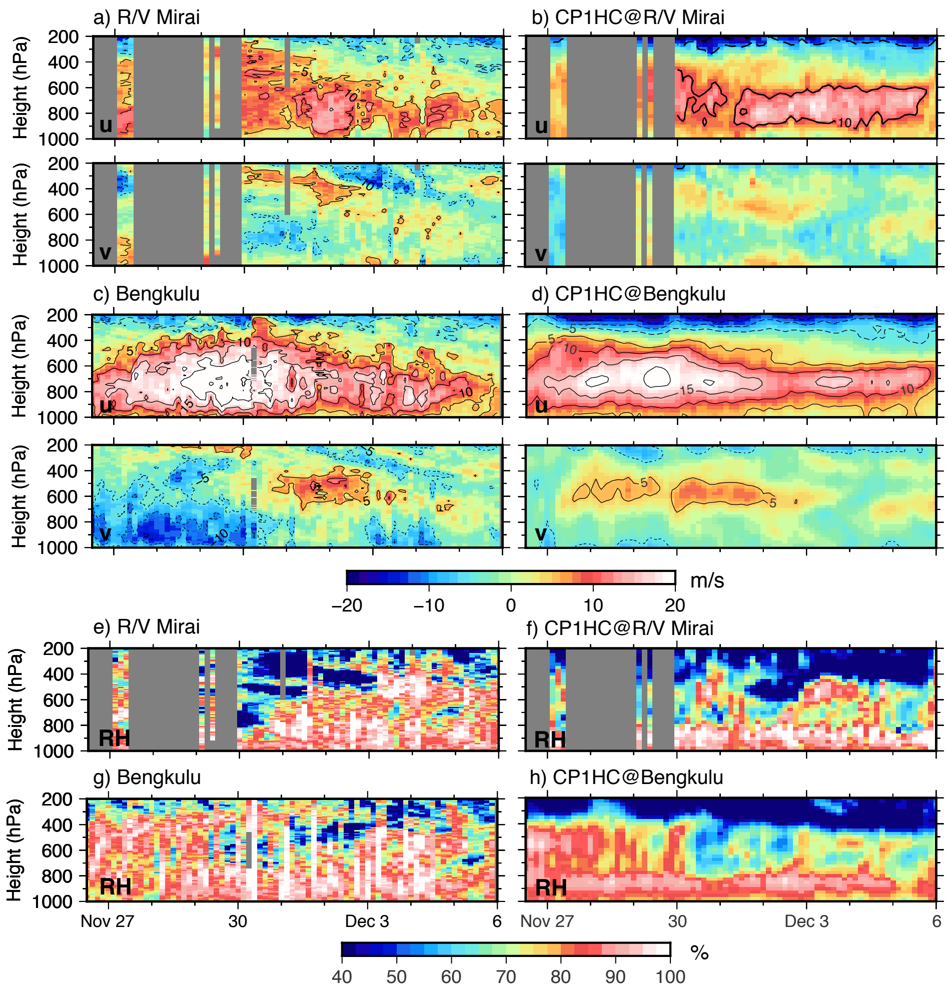

Figure 3. Vertical profiles of wind and relative humidity obtained by CP1HC and radiosonde observations obtained during the YMC-Sumatra 2017 field campaign.

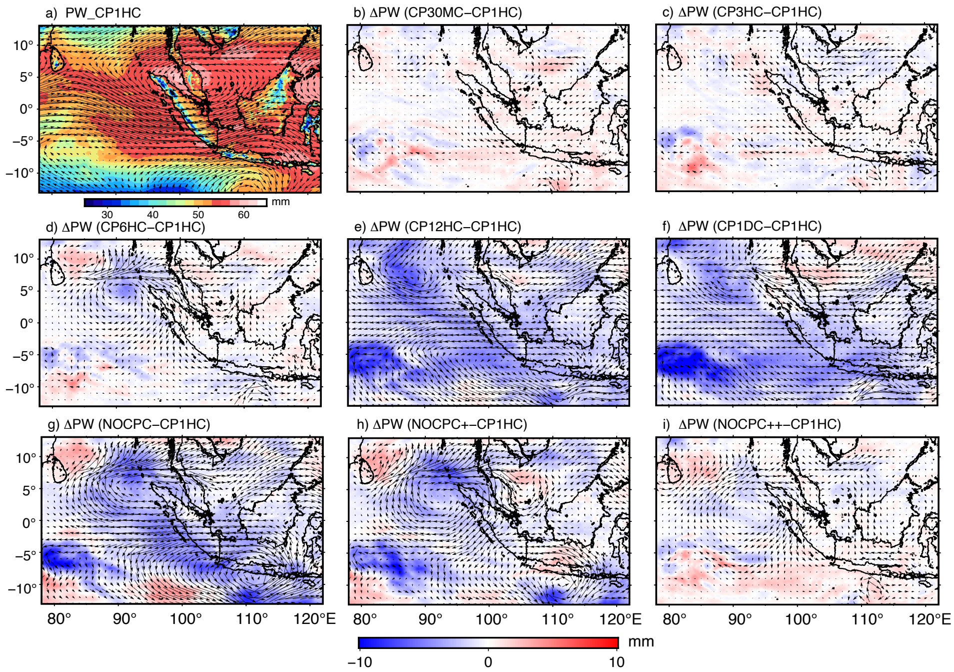

Figure 4. Horizontal distributions of the precipitable water and moisture fluxes integrated from the surface to 300-hPa height during the active phase of the MJO (November 26th to December 4th) in (a) CP1HC and (b-h) the differences between CP1HC and other runs.

face to 800-hPa level) was characterized by frequent occurrences of 80-100% RH. The frequency in the middle troposphere (850-500 hPa) ranged from 50% to 100% RH, where 70-80% RH occurred the most. Above the 500-hPa level, the atmosphere became increasingly dier as the height increased. The other highly coupled experiments showed only small differences (Figure 5b-d) from CH1HC. In the 30-minute coupled experiment, the increased (decreased) frequency of $>$ 70% RH ($<$ 70% RH) suggested that the convective activities were more enhanced. However, this was not the case in the barely coupled/uncoupled experiments. The occurrences of $>$ 70%RH (hereafter, high RH) were greatly reduced from the lower troposphere to the upper levels, and >90% RH was nearly extinct in the midlevels (Figure 5e-g). Accordingly, low RH appeared more frequently in nearly the entire column above the atmospheric boundary layer in the barely coupled/uncoupled experiments, suggesting that convection was greatly weakened.

One may consider that the reduction in high RH may be caused by the modulated preconditioning of the MJO (e.g., Seo et al. 2014). However, our models showed different results. As shown in Figure 6, the occurrences of high RH (>70%) showed no significant differences before the MJO, even at in midlevels (Figure 6c). Nevertheless, the situation started to change only after the MJO entered phase 4 (November 26th-30th, Figure 1b), although the SSTs had already been modulated since the model initiation (see Figure S3 in the Supporting Information). In particular, the atmosphere was greatly moistened in the highly coupled experiments ($>$ 90% occurrence of high RH), which consisted of the vigorous convection during the MJO. Nonetheless, the barely coupled/uncoupled experiments showed relatively lower values, as suggested by the clear separation in the middle troposphere among the experiments. The occurrence of high RH in the barely coupled/uncoupled experiments was approximately 10% lower than that in the highly coupled experiments. As the MJO propagated to the east (after December 1st, i.e., phase 5 of the MJO), convection was suppressed in all experiments (see the descending trend

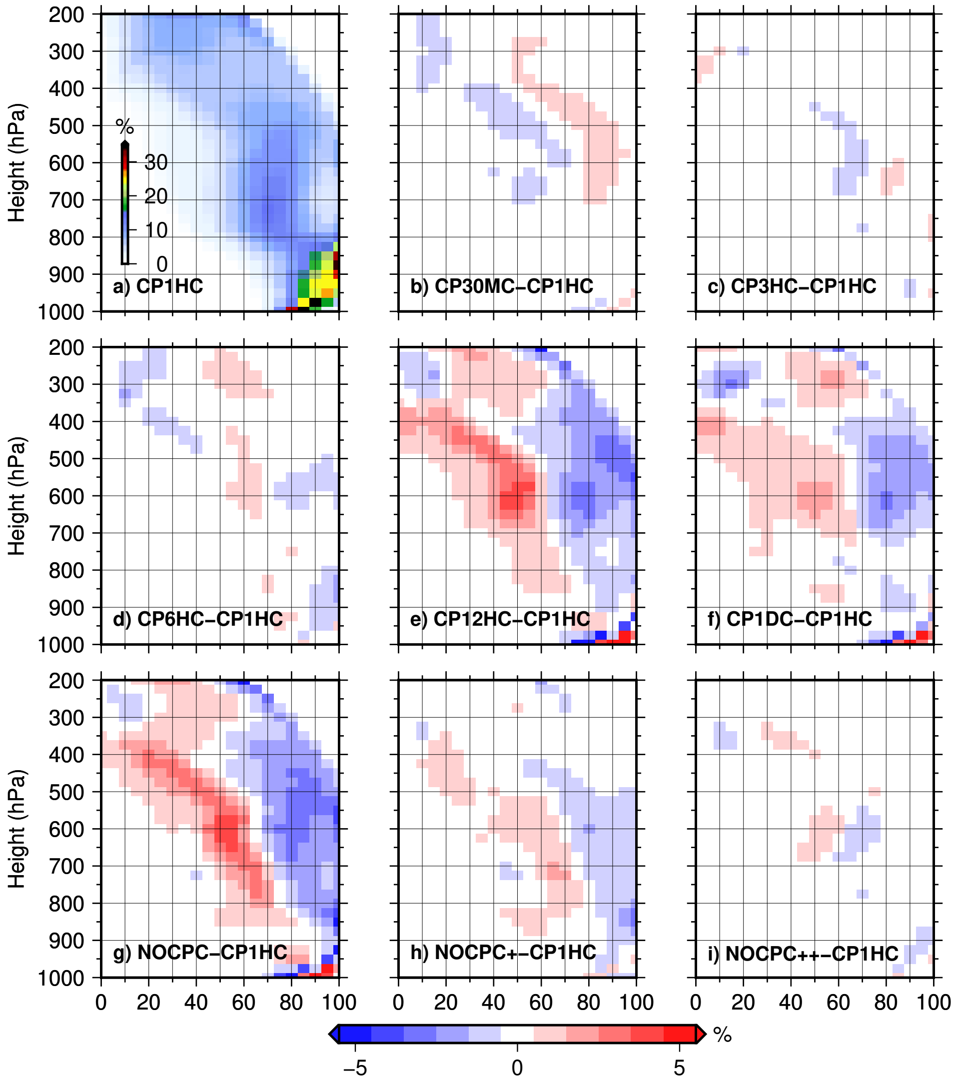

Figure 5. The frequency-altitude distributions of the simulated relative humidity over the seas around Sumatra Island (10°S-10°N, 90°-110°E; red box in Figure 1a).

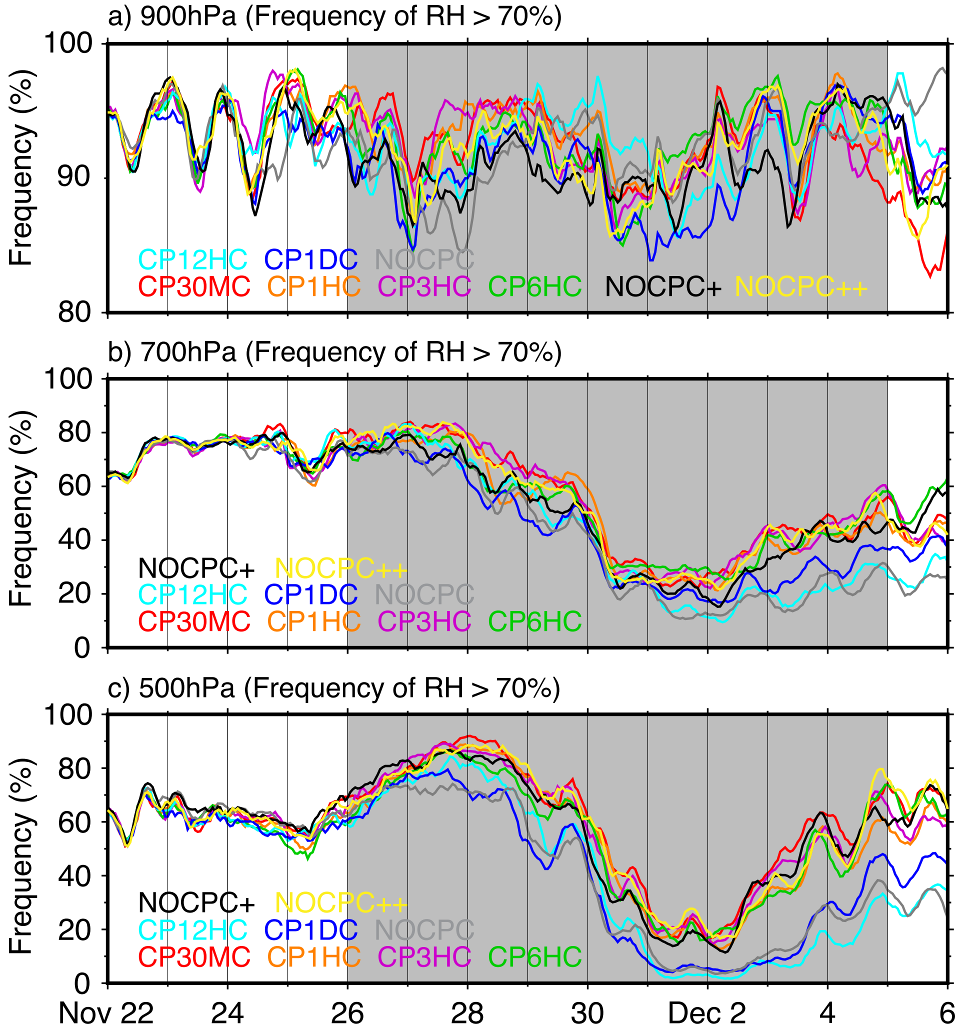

Figure 6. Time series of frequencies (occurrences) of the grid with high relative humidity (> 70%) at the (a) 900-hPa level, (b) 700-hPa level, (c) 500-hPa level, and time series of (d) vertical accumulated divergence of moisture fluxes from the surface to the 800-hPa level.

in Figure 6), but the differences became larger. Overall, our results suggested that the high-frequency air-sea coupling enhanced the convective activities during the active phase of the MJO, and it also helped with the maintenance of the moist atmosphere after the MJO passed.

4.2 Modulated diurnal cycle at the sea surface

Figure 7 represents the diurnal composite of surface variables averaged in the Sumatra region (red box in Figure 1a and ocean only). The SSTs reached over 29.5 °C in the highly coupled experiments, along with a clear diurnal cycle that was absent in the barely coupled/uncoupled experiments. Although the daily mean SST and its diurnal amplitude were nearly identical among the highly coupled experiments (Table 2), the temporal variations were not. In CP1HC and CP30MC, the largest SST appeared at 8:00 UTC, which consisted of a recent study based on buoy data (Morak-Bozzo et al., 2016). However, this was not the case in CP3HC (CP6HC), where the diurnal cycle of SST was de-

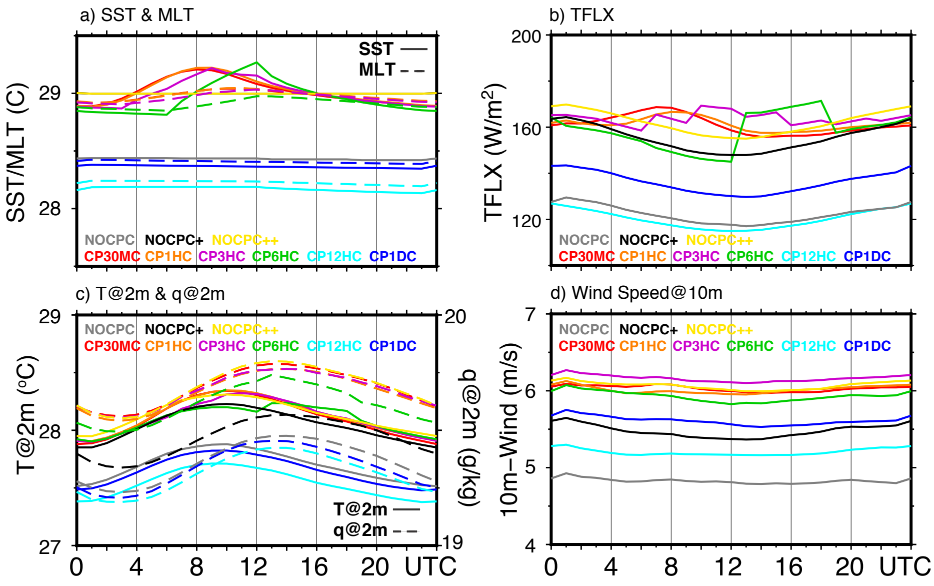

Figure 7. Diurnal composites of (a) sea surface temperature (solid line) and mixed-layer temperature (dashed line), (b) turbulent heat fluxes (the sum of surface sensible and latent heat fluxes, upward positive), (c) surface air temperature (solid line) and specific humidity (dashed line) at 2 m, and (d) surface wind speed at 10 m. Colors represent different experiments. Note that the correspondence of color and experiment is consistent in this paper, except Figure 14.

layed by 1 hour (4 hours). On the other hand, CP12HC and CP1DC did not have any diurnal cycle of SST, and the mean values were also lower than those of highly coupled experiments.

The surface turbulent heat fluxes (TFLX; upward positive), which are mainly controlled by the latent heat flux (see Figure S5 in the Supporting Information), had more complex variations. The TFLX in CP30MC started increasing at 16:00 UTC and finally reached its maximum at 7:00 UTC (14:00 LT in the Sumatra region), followed by a 9-hour decrease. Similar variations could be found in CP1HC, although its largest TFLX appeared 1 hour later and smaller. The lag became larger in CP3HC, along with a 2-hour period fluctuation caused by the different response times of surface air temperature (T2m) and specific humidity (q2m) (Figure 7c; also see Figure 13d for the lead-lag correlation).

Among the highly coupled experiments, CP6HC showed totally different trends: the TFLX monotonically decreased during the daytime and then suddenly increased after 12:00 UTC. Such unrealistic variations were generated by the coupling procedure used in our model. Except for the time step of coupling, both WRF and ROMS used a constant boundary forcing at most of the time steps. For example, in the CP6HC, the increasing SST from 6:00 UTC to 12:00 UTC only occurred in the ocean (ROMS), while WRF used the temporally constant SST (which was obtained at 6:00 UTC) until the next coupling time. Therefore, the underestimation and overestimation occurred continuously due to the constant forcing.

Unlike the SST and TFLX, the surface air temperature (T2m) and specific humidity experienced the same diurnal cycle in all experiments, although they were 0.5 °C and 0.25 g/kg higher in the highly coupled experiments (Figure 7c). Despite the unique vari-

Table 2. Daily Mean SST and TFLX in the Sumatra Region

Experiment	SST (°C)	TFLX (W/m^2)
CP30MC	29.02	161.04
CP1HC	29.02	161.30
CP3HC	29.01	163.85
CP6HC	28.96	158.55
CP12HC	28.17	120.02
CP1DC	28.36	135.95
NOCPC	28.43	122.22
NOCPC+	29.00	155.03
NOCPC++	29.00	161.87

ations in CP6HC, the heating of surface air started at 1:00 UTC, leading to the highest T2m at 9:00 UTC. The increase in q2m started slightly later at 3:00 UTC and then reached its maximum at 13:00 UTC (Figure 7c).

The surface wind speed had nearly no diurnal cycle regardless of coupling frequencies, but it was 1 m/s higher in the highly coupled experiments (Figure 7d). Note that the bimodal variations in T2m and its earlier increase than the SST in the CP6HC were mainly caused by phase-delayed heating from the ocean after 12:00 UTC, which alleviated the nighttime temperature decrease.

Without the diurnally varying surface forcing, the SSTs were nearly constant in the barely coupled experiments. Unlike the increasing trends during the daytime in the highly coupled experiments, their TFLXs decreased during the daytime and increased during the nighttime, following T2m and q2m with an opposite sign (Figure 7c). Such variations were similar to the uncoupled experiment (NOCPC). Note that the higher SST and TFLX in CP1DC were caused by the nonzero solar radiation throughout the day, while the heating was updated to zero in CP12HC after 12:00 UTC (Figure 13c). Moreover, the influence of the mean SSTs and its diurnal cycle can be found in Section 5.

4.3 Heat and moisture budget analysis

To further elucidate the influence of the coupling frequency on subdaily moistening processes, we executed an area-averaged heat and moisture budget analysis. We rearranged the budget equations including the apparent heat source (Q1) and moisture sink (Q2) following Yanai et al. (1973):

$$\frac{\partial s}{\partial t} \equiv Q_1 - \vec{U} \cdot \nabla s - \omega \frac{\partial s}{\partial p}, \tag{1}$$

$$L_v \frac{\partial q}{\partial t} \equiv -Q_2 - L_v \vec{U} \cdot \nabla q - L_v \omega \frac{\partial q}{\partial p}, \tag{2}$$

where $s \equiv c_p T + gz$ is the dry static energy, c_p is the specific heat at constant pressure, T is the temperature, q is the specific humidity, L_v is the latent heat of condensation, and $\vec{U}$ and ω are the horizontal wind vector and the vertical wind component in pressure coordinates, respectively. All terms were calculated based on the hourly output from the model and averaged over the Sumatra region (ocean only, red box in Figure 1a) during the MJO active phase.

Figure 8 represents the diurnal composite time-altitude distributions of the s and q budgets averaged in the Sumatra region during the MJO active phase based on CP1HC. The atmosphere became warmer during the local daytime and cooler during the local nighttime, shifting its phase at 12:00 UTC (Figure 8a). On the other hand, diurnal moistening mainly occurred from 4:00 UTC (11:00 LT) at surface levels, and such moistening generally takes 4-5 hours to extend to the entire lower levels (Figure 8b). Although the positive Q1 could be seen all day long during the MJO, the strong heating started at 16:00 UTC (23:00 LT) in the middle troposphere and reached its maximum at 4:00 UTC (Figure 8c), while the corresponding moisture sink occurred slightly earlier at lower levels before the heating started (Figure 8d). Both Q1 and Q2 were basically balanced by vertical advection (s_{vadv} and q_{vadv}, Figure 8g and 9h, respectively), indicating the existence of vigorous convection, while horizontal moisture advection (q_{hadv}; Figure 8f) tended to dry the atmosphere due to the background eastward moisture fluxes during the MJO (Figure 4a). Note that, in this study, we only focused on the air-sea interaction and convection above the ocean, so that the time evolutions of Q1 and Q2 may include some influences from the diurnal land-sea circulation; however, such influences were neglected during the analyses.

Although the differences between CP6HC and CP1HC were small in the PW and high RH occurrences (Figures 4 and 5), the budget analyses showed more detailed modulations. It is easy to find that the heating (moistening) was stronger (weaker) during the nighttime (daytime) in the CP6HC (Figures 9a and 9b), which was likely due to the phase-lagged SST and related TFLX. In addition to the phase lag in the diurnal processes, both Q1 and Q2 were weakened, associated with the reduced vertical advection of moisture. It is suggested that the phase-delayed diurnal cycle of SST greatly weakened the daytime convection and slightly enhanced the nighttime convection, resulting in a net reduction in daily mean state. Note that the shifted diurnal variations in heat/moisture in the CP6HC not only influenced the convection over the ocean but also overland, inducing an unrealistic diurnal cycle of precipitation (figures not shown).

In the uncoupled run, Q1 and Q2 were significantly reduced over 0.1 K/hr, associated with the weakening in vertical advection (Figure 10). Whats more, the positive anomalies in horizontal moisture advection (q_{vadv}) also indicated that the eastward moisture transport was reduced, which consisted of the easterly moisture flux anomalies, as shown in Figure 4g. As a result, the atmosphere became warmer (cooler) and drier (moister) during the daytime (nighttime) in NOCPC (Figure 10c and 10d). In general, the results shown above suggested that the convection and diurnal heat/moisture processes were greatly modulated when using the daily mean SST; however, to investigate the roles of the mean SST and its diurnal cycle, further experiments were needed (see the discussion section).

5 Discussion

5.1 The role of the daily mean SST

In our model, WRF-only received the SST from ROMS. The SSTs in CP12HC, CP1DC, and NOCPC were >0.6 °C lower than those in the highly coupled experiments, which may therefore be the key factor in the weakened convective activities (e.g., Dipankar et al., 2019). To confirm this, two extra WRF-only experiments were carried out by using the same settings in NOCPC but with modified SSTs. In NOCPC+, we replaced the OISST with the daily mean SST obtained from CP1HC within the Sumatra region (red box in Figure 1a), and such replacement was applied everywhere in the model domain in NOCPC++. One may notice that the SST in NOCPC+/NOCPC++ was slightly lower than that in CP1HC, which induced the linear interpolation of the daily mean SST into the 6-hourly SST, following the same procedure for the OISST in NOCPC. Fortunately, our results show that the biases were small and negligible (~ 0.02 °C, Table 2). Note that we only discussed the role of daily mean SST based on NOCPC++, and readers may refer to Section S2 in the Supporting Information for more results of the local SSTs.

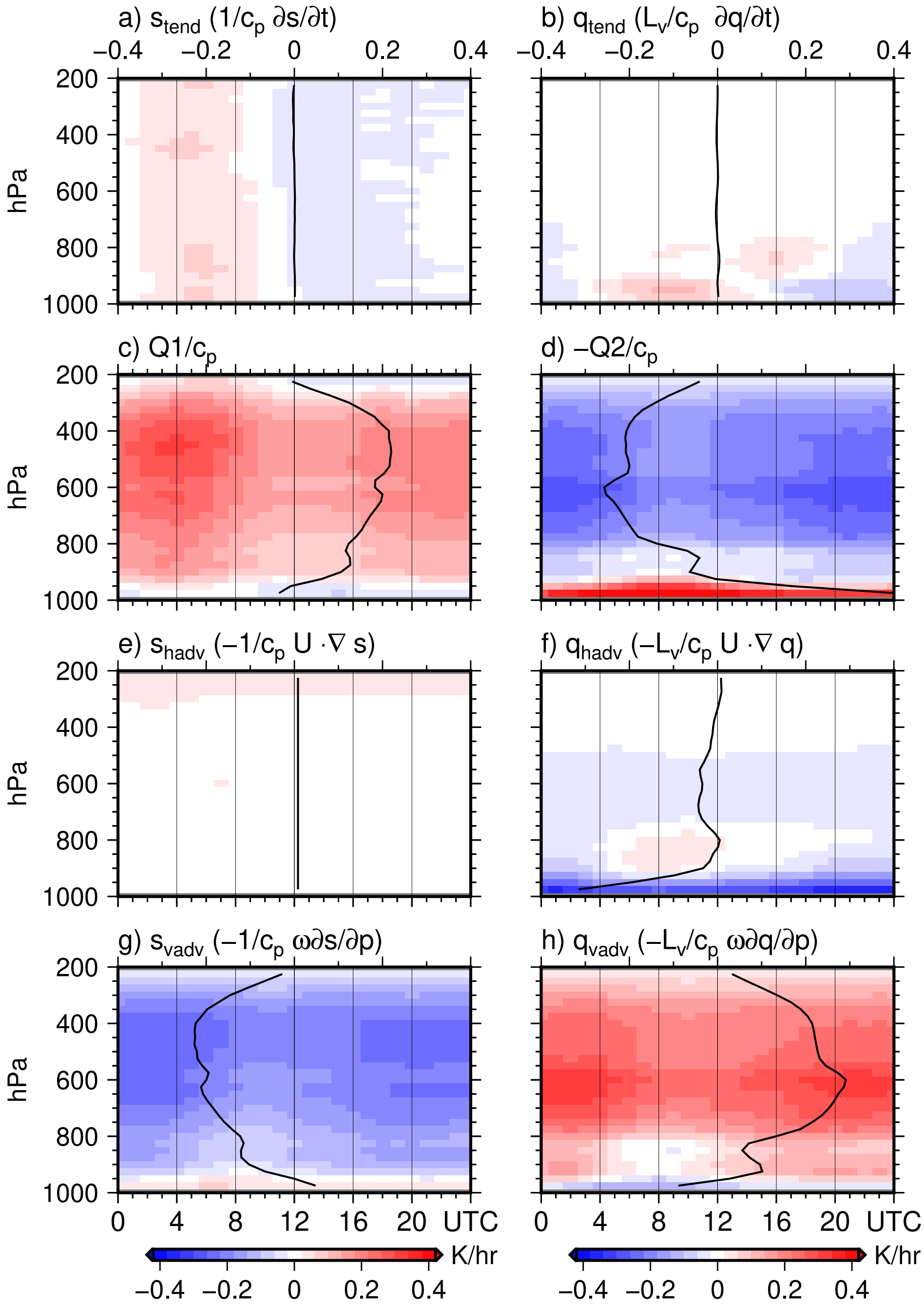

Figure 8. Diurnal composites of (a) tendency term, (c) apparent heat source Q1, (e) horizontal advection term, and (g) vertical advection term. Panels (b), (d), (f) and (h) are the same but for the moisture budget. The vertical distribution of daily mean values is also shown in each panel.

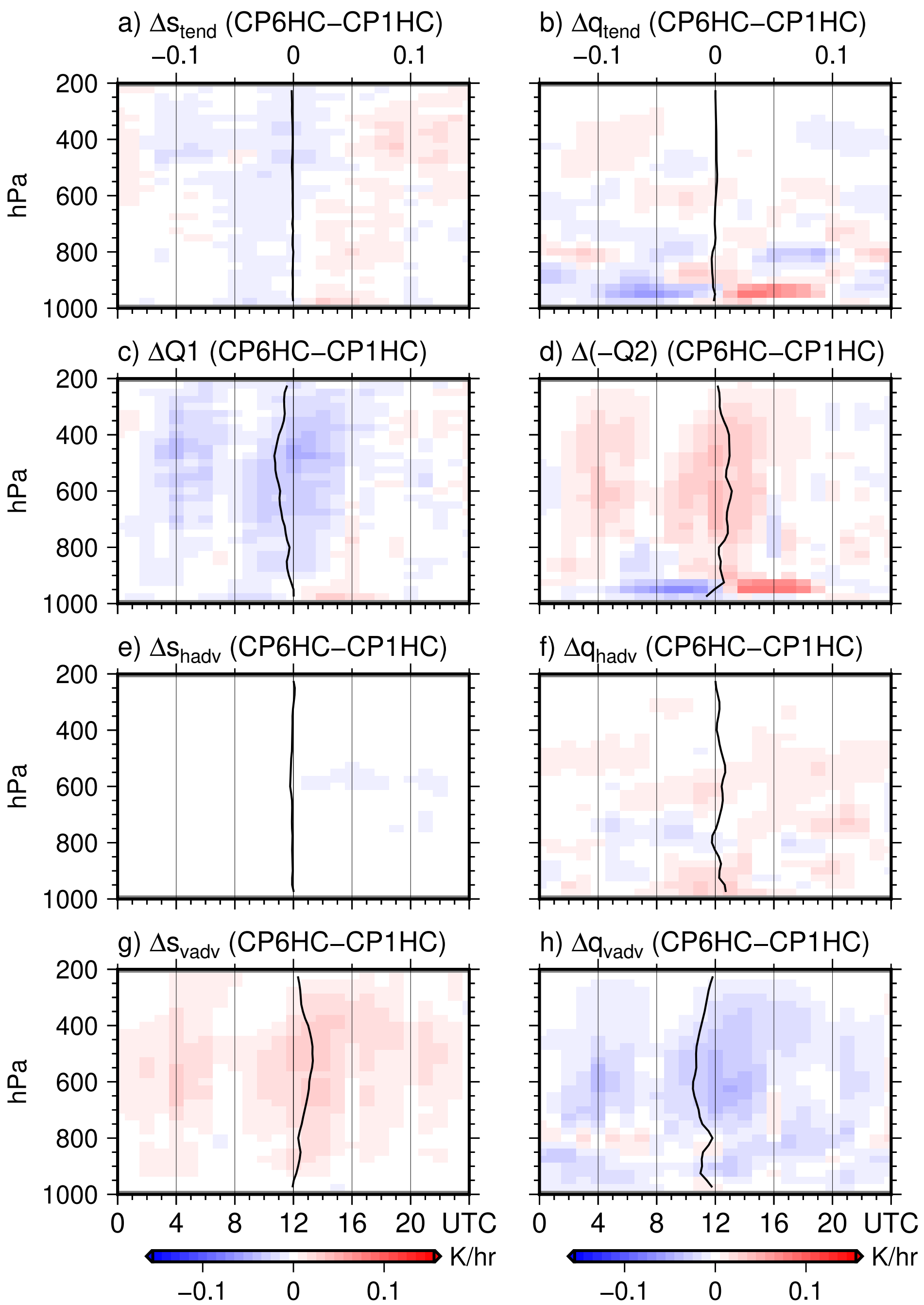

Figure 9. Same as in Figure 8 but for the differences between CP6HC and CP1HC.

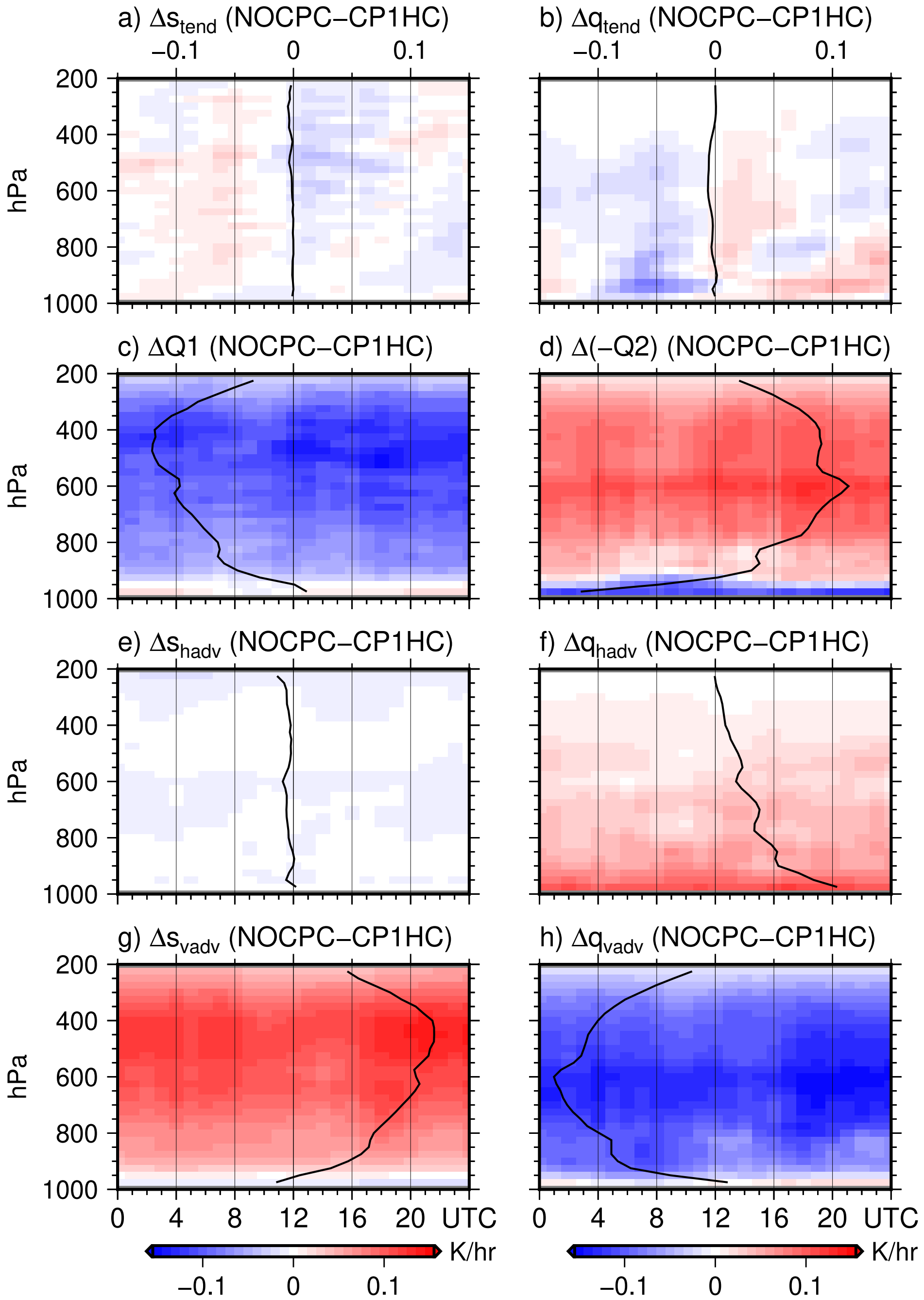

Figure 10. Same as in Figure 8 but for the differences between NOCPC and CP1HC.

In general, the higher SST induced the higher TFLX (Table 2 and Figure 7), more active convection (Figure 6), and therefore a moister atmosphere (Figure 4), which was almost comparable with those in highly coupled experiments. Whats more, with the same daily varying SST, the time evolution of convective activities also showed good agreements with the highly coupled models during the MJO. The anticyclonic gyre-like pattern of moisture flux anomalies remained, along with the small but negative biases in PW, although its center moved to the south. It is suggested that the underestimation of convection remained in NOCPC++, even with the same daily mean SST.

As showed in Figure 11, both Q1 and Q2 had small but nonnegligible negative anomalies from the surface to the midlevels. Moreover, unlike the monotonic reductions in NOCPC, the differences in NOCPC++ showed more subdaily variations. We found that the lower (higher) SST induced a drier (moister) boundary layer in NOCPC++ during the daytime (nighttime). Previous studies suggested that the premoistening of the lower troposphere is an important feature that can promote deep convection (Shinoda & Uyeda, 2002; Katsumata et al., 2018). Therefore, it is likely that this weakened moistening in the lower levels of NOCPC++ (approximately 5:00-12:00 UTC, Figure 11b) suppressed the onset of the subsequent diurnal deep convection, resulting in the negative Q1/Q2 and related vertical advection.

Based on the results of CP6HC and NOCPC++, the daily mean SST did play a dominant role in controlling the convection intensity, while the higher daytime SST (hence, the diurnal cycle of SST) played a smaller but nonnegligible role in daytime moistening and therefore the onset of diurnal deep convection. Figure 12 further demonstrates the above conclusion that while the higher daily mean SST induced larger moisture convergence, small but clear negative biases could be seen after 8:00 UTC in NOCPC++ and CP6HC, exhibiting weakened diurnal convection.

5.2 Modulations in the upper ocean

Since we found that the diurnal cycle of SST played a smaller role than the higher SST, one may ask why the highly coupled experiments had higher SSTs. To answer this question, we focused on the modulations in the ocean by air-sea coupling, especially the dynamics of the oceanic mixed layer and upper isothermal layer.

In this study, we defined the oceanic mixed-layer depth (MLD) in terms of a depth with a density equal to that at the 1 m depth plus an increment in density equivalent to -0.2 °C (Moteki et al., 2018), and therefore, the isotherm depth (ILD) is defined as the depth where the temperature is 0.2 °C lower than that at 1 m depth. Note that the results were not significantly changed when the reference depth was set to 10 m.

As shown in Figure 7c, the mixed-layer temperature (MLT, vertically averaged within the mixed layer) in the highly coupled experiments was approximately 29.0 °C, which was 0.8 °C (0.6 °C) higher than that in CP12HC (CP1DC). Both MLT and MLD had a weak but clear diurnal cycle, indicating the existence of stratification and destratification induced by the surface heating/cooling and mixing processes. The mixed layer became warmer and shallower after the sea surface was heated during the daytime (Figure 13a), and the largest MLT appeared 2 to 3 hours after the SST reached its maximum (Figure 7a), which was the time required by the adjustment processes (Figure 13d). Similar diurnal variations were found in ILDs, although it was generally over 10 m deeper than the MLD in all coupled experiments (Figures 13a).

Our results suggested that the mixed layer dynamics could be greatly modulated with or without high-frequency air-sea coupling. In barely coupled experiments, the MLTs were relatively higher than the SSTs (Figure 7a) because the ocean experienced net heat loss at the sea surface throughout the day (Figure 13c and Table 3). It is reasonable to consider that continuous surface cooling reduced the SST and broke down the upper layer

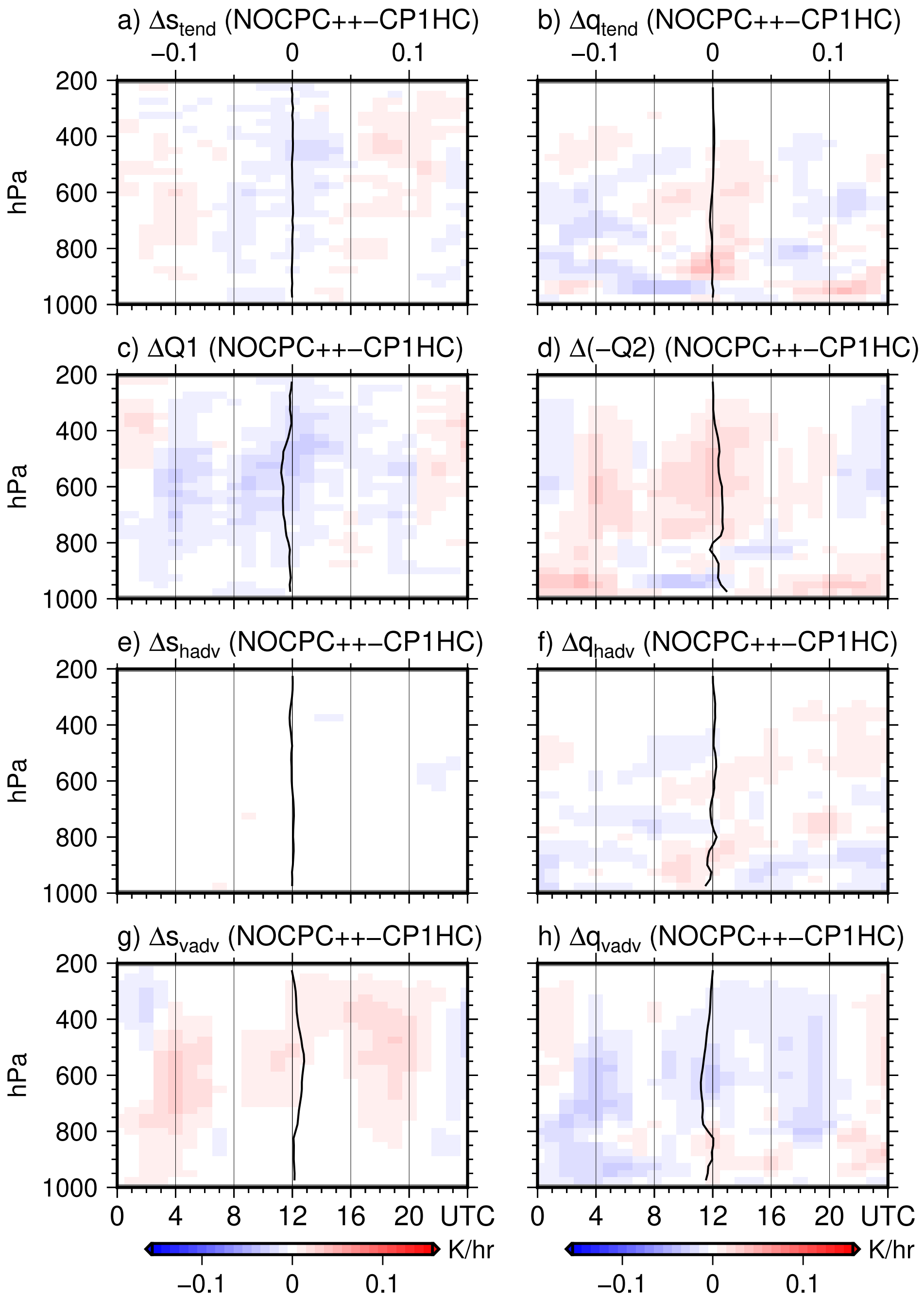

Figure 11. Same as in Figure 8 but for the differences between NOCPC++ and CP1HC.

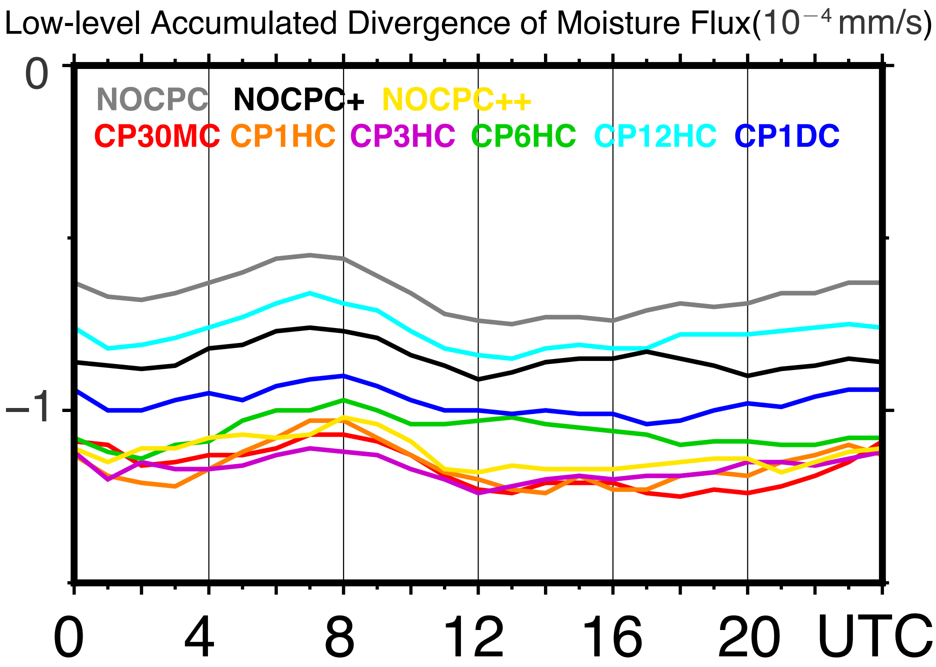

Figure 12. Diurnal composites of frequencies (occurrences) of the high RH (> 70%) around the Sumatra region (90°-110°E, 10°S-10°N; red box in Figure 1) at the (a) 700-hPa level; and (b) 500-hPa level.

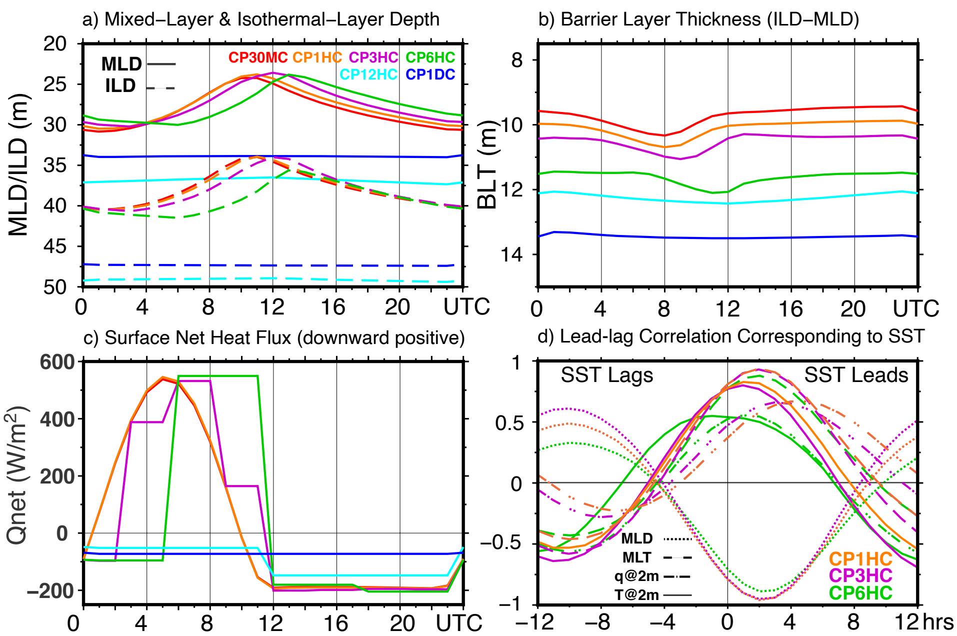

Figure 13. Diurnal composites of (a) the mixed-layer (solid line) and isothermal-layer depth (dashed line), (b) thicknesses of the barrier layer, and (c) the net heat flux at the sea surface (downward positive). (d) The lead-lag correlations of mixed-layer depth (dotted line), mixed-layer temperature (dashed line), surface air temperature (solid line), and specific humidity (dash-dotted line) corresponding to the SST.

Table 3. Daily Mean of Properties in ROMS

Experiment	MLT (°C)	MLD (m)	ILD (m)	BL (m)	Net Heat Flux at Sea Surface (W/m^2)
CP30MC	28.98	28.17	37.89	9.72	27.27
CP1HC	28.98	27.78	37.89	1011	28.15
CP3HC	28.97	27.54	38.05	10.51	24.65
CP6HC	28.91	27.56	39.18	11.62	17.54
CP12HC	28.23	36.86	49.11	12.25	-99.64
CP1DC	28.41	33.90	47.35	13.45	-72.49

instability, inducing strong vertical mixing and therefore the deepening of MLD/ILDs. Whats more, the deeper MLD further reduced the MLT. On the other hand, in highly coupled experiments, the net heat gain during the daytime would raise the SST and enhance the stratification that suppresses the mixing, leading to a shallower MLD/ILD. It is easy to find that the high-frequency air-sea coupling helped to maintain the higher SSTs/MLTs and shallower MLDs/ILDs.

Note that although all highly coupled experiments had similar mixed-layer processes (Figure 15d), the MLD (ILD) became relatively deeper (shallower) when the coupling frequency was higher (Table 3), inducing a thinner barrier layer (Figure 13b).

5.3 The drift of SST

Although the higher mean SST was generated by diurnal surface heating/cooling in highly coupled experiments, the SSTs may still be overestimated because of the positive biases from the OISST (satellite-based). On the other hand, as mentioned in previous studies, the OISST generally underestimates the true SST due to spatial smoothing and the removal of diurnal variations (Reynolds et al., 2007; Clayson & Bogdanoff, 2013). Therefore, it is necessary to compare them with the *in situ* observations. In this study, we used the SST measured by the *Mirai* Surface Meteorological observation (SMet) system at 5-m depth (SBE38, SeaBird Electronics). Details of the ship-based observations can be found in the MIRAI MR17-08 Cruise report (JAMSTEC & BPPT, 2018).

Figure 14 shows the time series of SSTs obtained in our models, satellite, and R/V *Mirai* during the active phase of the MJO, together with the precipitation rate observed by the optical rain gauge (ORG-815DR, Osi). The OISST (NOCPC) showed negative biases most times, while the models overestimated in some periods. The overestimation of SST on November 28th was mainly related to heavy rainfall, while the period from December 3rd was related to the underestimation of convection and its related precipitation (hence, surface cooling) as showed in Figures 3e and 3f. Nevertheless, both OISST and our modeled SSTs generally followed the trend of *in situ* observations in the same order. In addition, despite the slight underestimation of convection, our model showed good agreement with both satellite-based and *in situ* observations over the entire domain. Therefore, our conclusions on the importance of high-frequency air-sea coupling (and the higher and diurnally varying SST generated by that) are robust and reliable.

6 Concluding Remarks

A regional cloud-resolving coupled model was conducted to evaluate the impact of coupling frequency on convective activities during an MJO event captured in the YMC-Sumatra 2017 field campaign. By activating the scale-aware GFE cumulus scheme, the 1-hourly coupled model showed good agreements with both satellite-based precipitation and *in situ* radiosonde observations. Thus, a set of sensitivity experiments was carried

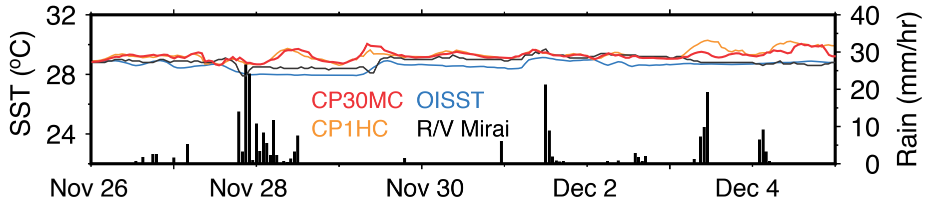

Figure 14. Time series of SSTs simulated/observed during the active phase of the MJO along with the observed precipitation rate by the R/V *Mirai*.

out to investigate the impact of the air-sea coupling frequency on convective activities during the MJO.

By varying the coupling frequency from 30 minutes to 1 day, we found that the PW in the atmosphere was largely reduced in the barely coupled experiments (12-hourly or daily coupled), associated with the westerly moisture flux anomalies (CP12HC and CP1DC; Figure 4). Our analysis indicated that the occurrences of high RH (>70%) were significantly reduced in the barely coupled experiments, especially at the 500-hPa level (middle troposphere), suggesting that deep convection was suppressed. Such a reduction occurred only after the MJO entered its active phase (Figure 6). Similar results were found in the uncoupled (atmosphere-only) model (NOCPC). The analysis of the apparent heat source (Q1) and moisture sink (Q2) budget confirmed that the vertical advection of heat and moisture played the dominant role during the active phase of the MJO, but both were weakened in the barely coupled and uncoupled experiments.

According to our results, high-frequency air-sea coupling is necessary for representing the diurnal cycle and the daily mean of SST. Specifically, in 30-minute and 1-hour coupled experiments (CP30MC and CP1HC), the SST successfully reproduced the diurnal cycle of SST, and the maximum SST appeared at 8:00 UTC, which consisted with observations (Ruppert & Johnson, 2015). However, in CP3HC (CP6HC), the time of the diurnal maximum SST was delayed by 1 hour (3 hours), and such phase lags were also found in surface turbulent heat fluxes (TFLX, Figure 7). The surface air temperature (T2m) and specific humidity (q2m) basically followed the same trend of SST in the highly coupled experiments (with few hours lagged), except in CP6HC where the T2m increased simultaneously with the SST (Figure 7 and 14b). Overall, the SST and TFLX had similar daily means in the highly coupled experiments but became lower in the barely coupled and uncoupled experiments.

To evaluate the role of the daily mean SST and its diurnal cycle, we conducted an extra WRF-only experiment (NOCPC++) by using the same daily mean SST from the 1-hourly coupled model. The results suggested that the mean SST did play the dominant role in promoting convection; however, the higher daytime SST (i.e., the diurnal cycle) also helped in moistening the lower troposphere, which is important for triggering deep convection. As a result, convection was still suppressed in NOCPC++ compared with CP1HC, even with the same daily mean SST.

In addition to the modulations in the atmosphere, our study also revealed the role of the coupling frequency in the upper ocean processes. We found that high-frequency air-sea coupling helped the maintenance of shallower mixed and isothermal layers by diurnal surface heating and cooling, leading to higher surface and upper layer temperatures (e.g., Shinoda 2005) and therefore stronger convection.

Overall, in comparison with previous studies (e.g., Seo et al., 2014), our study presented more detailed information on the subdaily modulations by the air-sea coupling frequency. Our results demonstrated the critical role of high-frequency coupling in representing both diurnal convection and upper ocean features since they were highly coupled with each other. Whats more, although our study focused on one specific MJO event and covered only two weeks, it is reasonable to consider that the impact of air-sea coupling may become more significant in a long-term simulation/prediction. Thus, further examination of long-term simulation and other MJO events will be a topic of ongoing study, together with experiments for resolution dependency (Holloway et al., 2015).

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