Impacts of Insolation and Soil Moisture on the Seasonality of Interactions Between the Madden-Julian Oscillation and Maritime Continent

Samson Hagos1, Chidong Zhang2, L. Ruby Leung1, Oluwayemi Garuba1, Casey D. Burleyson1, and Karthik Balaguru1

1Pacific Northwest National Laboratory, Richland, WA, USA, 2NOAA Pacific Marine Environmental Laboratory, Seattle, WA, USA

Abstract This study investigates the seasonality of the interaction of the Madden-Julian Oscillation (MJO) with the Maritime Continent (MC). Beside their seasonal east-west migration with the monsoons, observations show that the MJO amplitude and precipitation over the MC islands exhibit semiannual variability, with apparent strengthening of MJO signal during March and September, when solar insolation is strongest over the MC region. Furthermore, during the high-insolation months, soil moisture shows wetter conditions during the early phases of the MJO. Motivated by these results, a series of regional convection permitting simulations are performed for the November 2014 MJO event as a case study under the following conditions: (i) increased solar insolation to mimic the local summer, (ii) reduced initial soil moisture, and (iii) the two conditions combined to isolate their local effects from their impacts on the large-scale circulation. Results show that increased insolation increases precipitation including that associated with MJO moisture convergence over the MC region. On the other hand, decreased initial soil moisture slightly increases precipitation over the MC islands and reduces it over the surrounding waters, but such effect is short lived as the increased precipitation gradually restores the soil moisture to wetter conditions. Using a moisture budget analysis that isolates the MJO and non-MJO signals and additional idealized simulations, the MJO response to high insolation is demonstrated to be related to an increase in the basic state moisture over the MC region rather than a direct response of the MJO to the insolation.

1. Introduction

Limitations in understanding and simulating the propagation characteristics of the MJO across the Indo-Pacific Maritime Continent (MC) have been an impediment to MJO prediction. Some MJO events propagate across the MC relatively unaffected while others are weakened, strengthened, or stalled (Kerns & Chen, 2016). Several studies have documented this behavior and proposed mechanisms for the variability. These studies have progressed along two lines of inquiry, one emphasizing the role of precipitation processes and the other the influence of the diurnal cycle on the propagation of MJO convection across the MC.

Using TRMM satellite data, Peatman et al. (2014) found that as MJO events approach the MC, a vanguard of precipitation appears over the MC islands in an otherwise relatively dry large-scale environment ahead of the main convective envelope, allowing a rapid response in the diurnal cycle that rectifies onto the lower-frequency MJO. These results were confirmed by regional climate model simulations by Birch et al. (2016), who showed that the vanguard convection is sustained by sea breeze convergence. Furthermore, in these simulations, the cloud cover increases, and surface insolation decreases during the phases of peak local MJO convection, which weaken the strength of the mesoscale circulations and reduce land-based rainfall. In another study the influence of the diurnal cycle on the propagation of MJO convection across the MC was investigated using cloud-permitting regional model simulations and observations (Hagos et al., 2016). A pair of ensembles of control and no-diurnal-cycle simulations were performed for an MJO event. In the control simulations, propagating MJO precipitation is weakened over the MC, with much of its convection stalling over the large islands of Sumatra and Borneo. In the no-diurnal-cycle simulations, the incoming shortwave radiation at the top of the atmosphere is maintained at its daily mean value, and the signal in MJO convection propagating across the MC is enhanced. Examination of the surface energy fluxes in the
simulations indicates that surface down-welling shortwave radiation is larger in the presence of the diurnal cycle, primarily because clouds preferentially form well after peak insolation. Subsequently land-surface processes related to MJO events that propagate versus blocked were systematically examined by Zhang and Ling (2017). Using a precipitation-tracking method to identify MJO events that propagate across the MC and those that are blocked by the MC, they showed that most of the precipitation associated with the events that cross the MC is over the seas, while the precipitation for the blocked events is mainly over the land. Thus, they suggested that inhibiting convective development over the sea could be a possible mechanism for the barrier effect of the MC. In a follow up study, Ling et al. (2019) used satellite observations to show that the crossing events are associated with the strong vanguard of precipitation over islands when their convection centers approach the MC. Subsequently, soil moisture increases, the diurnal amplitude of land convection is reduced, and precipitation dominates over water by nondiurnal convection as the MJO convection centers move over the MC.

As noted above, several other studies emphasize the role of the large-scale environment and its zonal or meridional movement in the variability of the strength of MJO events as they cross the MC. For example, according to Kim (2017), the path of MJO events shift southward when they cross the MC during austral summer along with the seasonally enhanced convective activity over the southern part of the MC. They explained this shift as a response of the column-integrated moist static energy of the MJO to the seasonal change in the zonal gradient in background moisture associated with the onset of the Australian monsoon. Similarly, DeMott et al. (2018) separated the boreal winter MJO events into events with convective anomalies that propagate or not propagate across the MC and identified transient dry precursors that compete with the MJO moist static energy anomalies. They further suggested that ENSO influences the transient dry precursors by modifying the background moisture. Using ERA5 reanalysis, Jiang et al. (2019) showed that MC topography interrupts the moistening that supports eastward propagation of the MJO by modifying the seasonal mean zonal distribution of moisture and the associated advection moistening. In another recent study, Hagos et al. (2019) estimated the moisture flux convergence directly from precipitation and showed the slow eastward migration of zonal moisture flux convergence between the Asian and Australian monsoon convergence centers from summer to winter. They found that the strengths of individual MJO events vary as they propagate across this zonally and seasonally varying monsoonal moisture convergence. MJO events starting in February–April tend to be weak over the eastern Indian Ocean, but they strengthen as they propagate into the moisture convergence region over the western Pacific. During May–July, the moisture convergence pattern is reversed, and MJO events weaken as they propagate into moisture divergence region in the western Pacific. Winter MJO events are most likely to be strong over the MC region, particularly when the Australian monsoon is strong.

The two sets of results highlighting the role of precipitation over the islands and the role of the large-scale environment on MJO propagation through the MC might be related to each other. This study aims to provide insights into the seasonality of the interactions of MJO events with the MC and thereby connect the two sets of findings. We first use observations to develop hypotheses through examining the seasonality of MJO strength, precipitation, and soil moisture over the MC region during the passage of MJO events (section 2). We then use convection permitting model simulations to test the hypotheses (sections 3 and 4).

2. Observed Seasonality of MJO-MC Interactions

In order to understand the seasonality of interactions of the MJO with the MC, we examine the seasonality of MJO strength, mean precipitation over the MC islands and the surrounding seas, and soil moisture over the MC islands during different MJO phases. The daily Real-time Multivariate MJO (RMM) index of Wheeler and Hendon (2004) is used to identify MJO events. Total precipitation during a given RMM phase of the MJO is compared using daily precipitation from two sources. They are the Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (PERSIANN; Ashouri et al., 2015) and Tropical Rainfall Measuring Mission (TRMM 3B42; Huffman et al., 2007) rainfall estimate. Because of the lack of reliable observations, soil moisture from four global reanalysis products is used and compared for their consistency. They are the NCEP-DOE reanalysis (NCEP2; Kanamitsu et al., 2002), ERA5 (Copernicus Climate Change Service (C3S), 2017), Modern Era reanalysis (MERRA; Rienecker et al., 2011), and the Japanese reanalysis (JRA25; Onogi et al., 2007).
In starting the analysis, the Wheeler and Hendon (2004) RMM amplitude is normalized by the standard deviation. Events for which this normalized RMM amplitude is greater than 1.0 continuously for more than 10 days are defined as MJO events. This definition of the MJO is commonly used but arbitrary, whether the RMM amplitude is normalized or changing the threshold number of days has little impacts on the results and the subsequent conclusions. For the period between January 1979 and December 2017, 242 such events are identified. Figures 1a and 1b show the seasonal cycle of the monthly averaged amplitude of the MJO events and their total number of days in each RMM phase. In this figure and others to follow, statistical significance of the difference between the mean value of the variables in each bin and the whole sample is determined based on the Student t test, and values that are significant at 95th percentile confidence level are marked by small green circles. Large mean amplitudes are apparent during Phase 3 in January and March and Phase 5 in September, when MJO events are on the western and eastern sides of the MC region. Figure 1b shows a clear seasonal propagation in the amount of time MJO events spend in each phase. This progression is consistent with the progression of monsoon zonal moisture convergence flux discussed in Hagos et al. (2019). That is, MJO events spend more time in the Indian monsoon region (Phases 1 and 2) during boreal summer and in the Australian monsoon region (Phase 7) during austral summer where moisture is abundant. However, the focus of this study is the clear deviation from this seasonal cycle especially in March in RMM Phase 4 and September in RMM Phase 5 when MJO events tend to be strong over the MC region.

In a similar framework, the total mean precipitation over the MC islands and the surrounding seas is shown in Figure 2 as a function of calendar months and RMM phases. The total precipitation shown in Figure 2 for a given RMM phase of the MJO should not be confused with the MJO precipitation. Precipitation specifically associated with MJO-scale temporal variability in moisture and/or wind will be analyzed in the context of modeling results in section 4. Consistent between the PERSIANN and TRMM data, precipitation over the islands shows a clear peak in March in Phases 3 and 4, but no such March peak is apparent over the surrounding seas (Figure 2). Figure 3 shows the seasonal variation in soil moisture from four global reanalysis products displayed in the same framework. Despite differences in the thickness of the soil layers between NCEP2 and ERA5, soil moisture in the four reanalysis data sets more or less closely tracks the observed precipitation with strong seasonal cycle, showing wet soil condition in Austral summer during essentially all the phases and dry condition between August and November. However, modulation of soil moisture by variability in the MJO phases is also apparent, with relatively wet condition in the first four phases occurring between January and March, but the wet conditions are shifted to the later phases in November and December as well as April and May when precipitation crosses the MC region during its southward and northward seasonal migration.

The rainfall peak (Figure 2) and wet soil conditions (Figure 3) between February and March over the MC islands are interesting in that they are distinct from the monsoonal migration that affects the MC islands.
and surrounding seas in the same manner. Processes related to solar insolation and soil moisture may explain these results. First, the apparently strong MJO in March and September in the MC region (Figure 1a) and the strong precipitation over the maritime islands during the active phase of the MJO in March might be related to the maximum insolation during these months, which preferentially warms up the land surface relative to the ocean because of its low heat capacity. Second, stalling of the MJO in Phase 5 in September (Figure 1b) might be related to the relatively dry soil conditions combined with the higher insolation during that month. Thus, we forward a hypothesis that the seasonal migration of MJO amplitude following the seasonal migration of moisture convergence associated with Asian and Australian monsoons (Hagos et al., 2019) might be modulated by the variations of insolation and soil moisture conditions over the MC region. More specifically, high insolation and dry soil might enhance moisture convergence and precipitation over the MC islands, apparently disrupting the otherwise smooth propagation and monsoon modulated seasonality. The following two sections describe the model simulations designed to test this hypothesis and the results.

3. Model Simulations

3.1. Design of the Simulations

The MJO event selected for the modeling case study is one observed in November and December of 2014. Its RMM phase diagram is shown in Figure 4. The event is particularly strong and propagates rather smoothly across the MC. The model used in this study is the Weather Research and Forecasting (WRF) model Version 3.8.1 (Skamarock et al., 2005). Details of the model setup are provided in Table 1. The simulation domain covers the region between 10°S to 10°N and 80–160°E (Figure 5). All simulations are performed at 3 km
grid spacing without a cumulus parameterization. Lateral and initial atmospheric conditions as well as surface boundary conditions are obtained from the ERA-Interim reanalysis (Dee et al., 2011) and are updated every 6 hr. Sea surface temperatures are also prescribed and updated every 6 hr. Four ensembles of simulations are performed with a realistic setup. The purpose of the numerical experiments is to isolate the local effects of insolation and soil moisture from their impacts on large-scale circulation features such as the monsoons. This is achieved by keeping the lateral and lower boundary conditions that represent the large-scale circulation the same while changing the insolation and soil moisture within the model domain in each set of simulations. The first ensemble of simulations is control (CONTROL), with members of the ensemble differing only by the physics parameterization choices as listed in Table 2. The simulations are initialized by ERA-Interim reanalysis soil moisture and the insolation corresponds to 18 November, when the Sun declination angle is S19°05′. Figure 5a shows the top of the atmosphere downwelling shortwave radiation flux for the CONTROL simulations on the first day at local noon of the center of the domain.

In the second ensemble the initial solar declination angle is set to 0.0, which amounts to starting the simulation on 20 March while keeping all surface and lateral boundary conditions the same. This results in maximum insolation at the equator, so the simulations are referred to as HINSOL for high insolation. Figure 5b shows the difference in top of the atmosphere downwelling shortwave radiation between HINSOL and CONTROL at local noon of the first simulation day. In the third ensemble of simulations, the initial soil moisture over the MC region is reduced to 0.1 m^3/m^3 and then allowed to adjust to the soil and vegetation conditions on the first day. This ensemble is hereafter referred to as DRYSOIL. The initial condition in soil moisture of CONTROL is shown in Figure 5c, and the deviation of the DRYSOIL initial condition from it is shown in Figure 5d. On the first day the soil moisture in the DRYSOIL case is about half of that of CONTROL. The final ensemble of simulations features the combination of dry soil initial condition...
and high insolation, so it is referred to as DSHINSOL for dry soil and high insolation. The design of the HINSOL and DSHINSOL simulations is motivated by the seasonality of soil moisture discussed above (Figure 3). With high insolation and wet and dry soil conditions, the two ensembles of simulations are meant to approximate the March and September conditions, respectively. For each ensemble of simulations, we present results based on the ensemble mean of each four-member run with different physics options. A separate set of simulations is also run with the boundary conditions kept as that of the first day for the duration of the length of the simulation to examine the effects of higher insolation and initial dry soil moisture on the basic state in the absence of MJO. This additional set of simulations is discussed in section 4.

4. Simulation Results

4.1. Impact on Precipitation

Before we assess the sensitivity of precipitation to increased insolation and decreased initial soil moisture, we present a brief evaluation of the temporal evolution of precipitation in CONTROL. The top panels of Figure 6 show the evolutions of precipitation from CONTROL and the observations. Precipitation is filtered by 8-day running mean to highlight intraseasonal signals. While the overall precipitation patterns are similar, precipitation from CONTROL is rather weak; over the western MC region, the simulated precipitation is about half of the observed. This is related to the fact that the model domain excludes Australia by design. Thus, while moisture is advected in and out of the domain, propagating precipitating signals from the Australian monsoon are not allowed into the domain, so all the simulated precipitation is produced inside the domain. The bias is a small price to pay for avoiding the decision to impose the changes in the insolation and soil moisture over northern Australia or introduce unrealistic gradients, both confounding the interpretation of the results. Furthermore, the smaller domain keeps the computational cost affordable, allowing us to run multiple ensemble members. Nonetheless, one must keep this in mind in interpreting the results. The middle and bottom panels of Figure 6 show the sensitivity simulations and their deviations from the CONTROL. Increased insolation has two effects: increases in precipitation over Sumatra and Borneo persist throughout the simulation period, but the largest increase appears first to the west (Sumatra) and then moves eastward all the way to New Guinea and over the western Pacific (Figure 6g). The effect of dry soil initialization on the propagation characteristics is rather small, and the positive effect does not last beyond the first week. In fact, dry soil conditions have a weakening effect on the propagating signal (Figure 6h). The combined effect of high insolation and dry soil appears to enhance the precipitation over the islands especially during the first 10 days (Figure 6i).

In order to better understand these effects, we consider the spatial distribution of the changes in precipitation averaged over the period of the simulations. Figure 7 shows the difference between the three sensitivity experiments and CONTROL. Both increased insolation and reduced soil moisture initial conditions have similar effect in that they increase the precipitation over the MC islands, with the effect of increased insolation being stronger. But there is an important difference in that a drier soil initial condition reduces rainfall over the surrounding water both north and south of the islands. This is consistent with its weakening effect on the propagating signal (Figure 6h). The effect is strongest when increased insolation and a dry soil moisture initial condition are combined (Figure 7c). Before examining the processes that led to the changes in precipitation, a brief look at the effects of the changes in precipitation on soil moisture is warranted. Figure 8 shows the evolution of soil moisture in the top 7-cm layer averaged over all MC islands for the four ensembles of

| Table 1 |
| **Configuration Common to All Simulations** |
| Parameterization, parameters, or conditions | Configuration |
| Horizontal grid spacing | 3 km |
| Cumulus parameterization | None |
| Longwave radiation | The Rapid Radiative Transfer Model (Mlawer et al., 1997) |
| Shortwave radiation | The Rapid Radiative Transfer Model (Iacono et al., 2008) |
| Surface, initial, and boundary | ERA-Interim, updated every 6 hr |
| Number of vertical levels | 30 |
| Model top | 50 hPa |

Figure 4. The phase diagram of the 2014 November–December MJO event. This event is selected for the regional convection permitting modeling case study.
simulations. Soil moisture in DRYSOIL and DSHINSOL partially recovers and reaches a semisteady state after the first 10 days, which explains its weaker and short-lived impact on precipitation over the MC islands. Another feature is that increased insolation increases the soil moisture as expected from the changes in precipitation. The relatively wet soil conditions in the early phases of the MJO in February and March (Figure 3) are therefore related to this effect, and the MJO and increased insolation might help

![Figure 5](image)

**Table 2**

| Ensemble member | Model physics |
|-----------------|---------------|
| Member 1        | Thompson Microphysics (Thompson et al., 2008), MYNN 2.5 level TKE scheme (Nakanishi & Niino, 2004) Community Land Model Version 4 (CLM4), adapted from CAM (Lawrence et al., 2011) Thompson Microphysics (Thompson et al., 2008) MYNN 2.5 level TKE scheme Monin-Obukhov (Janjic) scheme (Janjic, 2001) Noah Land surface model (Ek et al., 2003) |
| Member 2        | WRF double moment microphysics 6-class scheme Shin-Hong PBL scheme Noah Land-Surface model (Ek et al., 2003) |
| Member 3        | WRF double moment microphysics six-class scheme Univ. of Washington PBL scheme (Bretherton & Park, 2009) Community Land Model Version 4 (CLM4), adapted from CAM (Lawrence et al., 2011) |
4.2. MJO and non-MJO Signals

As noted above, the behavior of precipitation variability over the MC region is rather complicated as multiple processes acting on a broad range of spatial and temporal scales are involved. In this subsection we use a multiscale moisture budget analysis to isolate the MJO and non-MJO signals and subsequently examine the contributions of various multiscale interactions to the MJO signal and how those processes are affected by increased insolation and reduced soil moisture. To do that, we partition the hourly water vapor mixing ratio and horizontal winds into contributions from multiple temporal scales for the MJO, diurnal cycle, and the background. We define MJO moisture and wind signals \( q_{\text{mjo}}, v_{\text{mjo}} \) based on the 8-day running mean of the raw hourly signals and subtracting the mean over the length of the simulation. The 8-day running mean is chosen because the full lifecycle of the MJO event in this case study is about 24 days and it spends about 8 days roughly equally over Indian Ocean, MC, and western Pacific (Figure 4). The diurnal cycles \( q_{\text{dc}}, v_{\text{dc}} \) maintain soil moisture over the MC region during what would otherwise be a drier period when the monsoon precipitation is farther south.

Figure 6. (a) Hovmoeller diagram of ensemble mean of precipitation from the CONTROL simulations and (b) and (c) that from the two observational data sets; (d), (e), and (f) depict that of HINSOL, DRYSOIL, and DSHINSOL simulations; and (g), (h), and (i) their respective deviations from the CONTROL. All are averaged between 10°S and 10°N. In (g), (h), and (i) statistically significant differences are marked by green circles.
are defined as the deviations of the hourly values from the daily means and the rest of the signals that include the mean state and the variability between diurnal and MJO scales are considered background (\(q_{bg}, v_{bg}\)). Thus, the total moisture and total wind at any hour are given by the sum of the three components (Equations 1 and 2).

\[
\begin{align*}
q &= q_{mjo} + q_{dc} + q_{bg} \\
v &= v_{mjo} + v_{dc} + v_{bg}
\end{align*}
\]

Given Equations 1 and 2, the total hourly vertically integrated moisture convergence can be written as

\[
-\langle \nabla \cdot (qv) \rangle = \left[ -\langle -\nabla \cdot (q_{mjo} v_{mjo}) \rangle + \langle -\nabla \cdot (q_{mjo} v_{dc}) \rangle + \langle -\nabla \cdot (q_{dc} v_{mjo}) \rangle \right] + \left[ -\langle -\nabla \cdot (q_{bg} v_{mjo}) \rangle \right] + \left[ -\langle -\nabla \cdot (q_{bg} v_{dc}) \rangle \right] + \left[ -\langle -\nabla \cdot (q_{dc} v_{bg}) \rangle \right] + \left[ -\langle -\nabla \cdot (q_{dc} v_{dc}) \rangle \right]
\]

The angle brackets represent vertical integration over the atmospheric column between the surface and 50 hPa. The moisture convergence terms involving the MJO-scale moisture or MJO-scale circulation inside the first square bracket in Equation 3 are defined as “MJO” moisture convergence signal, and the terms that do not involve either the MJO-scale moisture or MJO-scale circulation inside the second square bracket are considered as “non-MJO.” All the terms are conditioned by precipitation greater than 0 mm/day to quantify their contributions to the hourly precipitation. Figure 9 shows the evolution of “MJO” and “non-MJO” moisture convergence in ERA5 and in the CONTROL simulation. While the signals from the CONTROL simulation are weaker than those from ERA5, in both cases the “MJO” moisture flux convergence signal is strongest over Sumatra and Borneo during the first 5 days, and it shifts to west of New Guinea by the third week with the well-known weakening in between which has been found to be related to MC topography (Jiang et al., 2019). The non-MJO signals are essentially standing over the MC islands.
Now that the MJO signal is separated from the background, we can ask how the various multiscale processes contribute to the MJO moisture budget. Figure 10 shows the MJO moisture convergence signals partitioned into contributions from interactions with the background, interactions with the MJO itself, and interactions with the diurnal cycle according to Equation 3. The result indicates that much of the change can be explained by the interaction of the MJO with the background (second column). Interactions involving MJO-scale moisture and circulation (third column) and the contribution of direct interaction of the MJO with the diurnal cycle are comparatively smaller (right column). This brings us to the question of how the changes in insolation and soil moisture affect the background state, which is the subject of our analysis in the next subsection.

4.3. Effect of Increased Insolation and Dry Soil on the Mean State

The above analysis shows that much of the MJO moisture convergence is related to the interactions with the background state. Therefore, we ask how the mean state responds to increased insolation and decreased initial soil moisture. Specifically, we examine the deviations of the difference between HINSOL and DRYSOIL from CONTROL already discussed above and perform another set of simulations where the lateral boundary conditions are kept perpetually as that on the initial day of 18 November 2014 during which the MJO signal was absent. The simulations are denoted by “-PLB” for perpetual lateral boundary conditions. These simulations, CONTROL_PLB, HINSOL_PLB, and DRYSOIL_PLB, are run for 25 days with the exact same boundary and surface conditions. To reduce computational cost, only one simulation is performed for each case with physics parameterization choices identical to the first ensemble member (Table 1) of the simulations with updated lateral boundary conditions. For both simulations with realistic and perpetual boundary conditions, we calculate the differences between the corresponding sensitivity and control simulations in column integrated precipitable water and the effective wind responsible for moisture transport. The effective wind is calculated first by obtaining the vertically integrated moisture flux over each column and dividing it by the total column integrated precipitable water in the column. Figure 11 shows the
Figure 10. Hovmoeller diagrams of contributions to the total “MJO” moisture flux convergence in ERA5 and in CONTROL ensemble (left column) from interactions with background (second column), MJO variability (third column), and interactions with diurnal cycle (right column). All are averaged between 10°S and 10°N.

Figure 11. (a) The difference in column integrated precipitable water from HINSOL and CONTROL (shadings) and that for the moisture weighted wind (arrows) and (b) for the perpetual lateral boundary (PLB). (c and d) The same but for the difference between DRYSOIL and CONTROL cases and for the corresponding PLB simulations. All are averaged over the simulation period. Only differences of 95 percentile statistical significance level are shown.
The difference in total precipitable water and the effective wind in the realistic case, where the MJO is present (left panels), and in the idealized (perpetual) case, where the MJO is absent (right panels). In both cases, increased insolation increases the column integrated precipitable water over the MC region. Similarity between the realistic and perpetual lateral boundary condition (no MJO) cases further confirms that the increased precipitable water is primarily the response of the basic state rather than that of the MJO signal and the effect on the MJO is due to this change in the background state as discussed above. Similarly, the response of PW distribution to dry soil initial condition is also reflected in the idealized case. Decreased soil moisture over the MC islands shifts the precipitable water to the islands, leaving the surrounding waters relatively dry. Again, the effect of initial dry soil moisture is weaker for it is neutralized by the precipitation response.

Finally, the seasonality of precipitable water in ERA5 is examined. Figure 12 shows how the 38-year (1979–2017) climatological column integrated precipitable water varies with the MJO phase and months of the year over the MC islands and the surrounding waters. Again, as shown with precipitation and soil moisture, the prominent signal is the monsoonal variation, with the region being at its wettest in January and driest in July. However, as expected from the results of the simulations discussed above, there is a secondary peak in the precipitable water in March over both land and water. Although one would expect a similar effect in September, it is apparent that the seasonal cycle, specifically the Asian monsoon (Hagos et al., 2019), overwhelms the moistening effect of local insolation.

5. Conclusions

Understanding the processes that affect the propagation of the MJO across the MC has been of recent interest because of the relevance to prediction. Several mechanisms including physical blocking by topography and interactions involving diurnal cycle and the background large-scale moisture have been proposed to influence the propagation behavior. In this study we examine a hypothesis that seasonal variation in insolation and/or soil moisture could modulate the interaction and, hence, determine whether MJO events would get stronger over the MC or not. This hypothesis is motivated by observations of the seasonality of MJO amplitude and precipitation, and soil moisture over the MC region. In addition to the seasonal zonal movement of MJO peak amplitude along with monsoon precipitation discussed in Hagos et al. (2019), MJO RMM amplitude has peculiar peaks over the MC region in March in RMM Phase 3 and in September in RMM Phase 5 (Figure 1). But there is a clear difference in the behavior of precipitation between March and September due to the seasonal cycle. Precipitation during the active phases of the MJO over the MC islands is strongest in March but very weak in September (Figure 2). This difference is also reflected in the soil moisture in global reanalyses. In September, well before the onset of the Australian monsoon, the land surface in the MC region is dry, while in March at the end of the Australian monsoon, the soil is wet (Figure 3).
With the above results revealed from observational analysis as the backdrop, a hypothesis that MJO strength over the MC region is modulated by seasonal variations in insolation and soil moisture is proposed and tested in a modeling case study using convection permitting simulations. A strong MJO event observed in November 2014 is chosen for the case study. The case study includes an ensemble of control simulations, and sensitivity experiments with increased insolation, decreased initial soil moisture, and their combination. The simulations show that increased insolation indeed strengthens the moisture convergence signal and precipitation over the MC region during the passage of the MJO. Dry initial soil conditions also lead to similar effect, but that effect is weak and short lived as soil moisture recovers in response to the increased precipitation (Figure 8). A multiscale moisture budget analysis of the simulations and ERA5 reanalysis indicates that increased insolation increases the background precipitable water and low-level wind convergence over the MC region. This altered background state favors strengthening of the MJO moisture convergence and hence the precipitation signal over the MC region (Figure 11).

Several studies have framed the interaction of the MJO with the MC as propagation or disruption of MJO signals. From that perspective, as discussed above, some studies emphasize the role of diurnal cycle (Hagos et al., 2016; Ling et al., 2019), while others emphasize the role of background moisture (DeMott et al., 2018, Jiang et al., 2019; Kim, 2017). Our findings are consistent with both in that MC islands ultimately regulate the basic state moisture distribution with which MJO events interact. The key difference between this study and other studies is the focus on MJO amplitude and associated precipitation rather than explicitly defining MJO disruption or propagation. Peaking of the MJO over the MC region during the high insolation months implies weakening, in a relative sense, as the MJO events propagate away from the MC (Figure 1). In other words, the concentration of moisture over the MC due to high insolation implies sharper decreasing moisture to the east, which is unfavorable for MJO propagation. Recently, by tracking the precipitation features associated individual MJO events, Kerns and Chen (2016) also show that disruption of MJO propagation is most common during spring and autumn in agreement with the mechanism proposed in this study. Another important point to note is that the combined effect of the MJO and insolation is to increase precipitation over the MC islands during the otherwise drier period when the monsoon is further south or north (Figure 2, top panels). Unlike the monsoonal processes discussed in Hagos et al. (2019), the effect of insolation is semiannual. Therefore, modulation of the relative strength of these two effects, for example, by ENSO, could result in diverse MJO propagation characteristics. Such modulated interference between annual and semiannual cycles could potentially provide a framework for understanding variations in the predictability of MJO events.

Acknowledgments
This is work is supported by the National Oceanic and Atmospheric Administration (NOAA) Oceanic and Atmospheric Research, Program Climate Program Office (CPO), under NOAA Grant NA17OAR4310263 as well as U.S. Department of Energy Office of Science Biological and Environmental Research as part of the Atmospheric Systems Research Program and Global and Regional Modeling and Analysis Program. Computing resources for the model simulations are provided by the National Energy Research Scientific Computing Center (NERSC). Pacific Northwest National Laboratory is operated by Battelle for the U.S. Department of Energy under Contract DE-AC05-76RLO1830, PMEL Contribution 4850. The daily time series of the RMM index is available online (at http://www.bom.gov.au/climate/mjo/graphics/rmm/740Realtime.txt) (accessed on 13 January 2019).

References
Ashouri, H., Hou, K., Sorooshian, S., Braithwaite, D. K., Knapp, K. R., Cecil, L. D., et al. (2015). PERSIANN-CDR: Daily Precipitation Climate Data Record from Multisatellite Observations for Hydrological and Climate Studies. Bulletin of the American Meteorological Society, 96, 69–83. https://doi.org/10.1175/BAMS-D-13-00068.1
Birch, C. E., Webster, S., Peatman, S. C., Parker, D. J., Matthews, A. J., Li, Y., et al. (2016). Scale Interactions between the MJO and the Western Maritime Continent. Journal of Climate, 29, 2471–2492.
Bretherton, C. S., & Park, S. (2009). A new moist turbulence parameterization in the Community Atmosphere Model. Journal of Climate, 22(12), 3422–3446. https://doi.org/10.1175/2008JCLI2556.1
Copernicus Climate Change Service (C3S) (2017). ERA5: Fifth generation of ECMWF atmospheric reanalyses of the global climate. Copernicus Climate Change Service Climate Data Store (CDS). https://cds.climate.copernicus.eu/cdsapp#!/home
Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., et al. (2011). The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. Quarterly Journal of the Royal Meteorological Society, 137(656), 553–597. https://doi.org/10.1002/qj.828
DeMott, C. A., Wolding, B. O., Maloney, E. D., & Randall, D. A. (2018). Atmospheric mechanisms for MJO decay over the Maritime Continent. Journal of Geophysical Research: Atmospheres, 123, 5188–5204. https://doi.org/10.1002/2017JD026979
Elk, M. B., Mitchell, K. E., Lin, Y., Rogers, E., Grumman, P., Koren, V., et al. (2003). Implementation of Noah land surface model advances in the National Centers for Environmental Prediction operational mesoscaleEta model. Journal of Geophysical Research, 108(D22), 8851. https://doi.org/10.1029/2002JD002926
Hagos, S., Zhang, C., Leung, L. R., Burleyson, C. D., & Balaguru, K. (2019). A zonal migration of monsoon moisture flux convergence and the strength of Madden-Julian Oscillation events. Geophysical Research Letters, 46, 8534–8562. https://doi.org/10.1029/2019GL085468
Hagos, S. M., Zhang, C., Feng, Z., Burleyson, C. D., de Mott, C., Kerns, B., et al. (2016). The impact of the diurnal cycle on the propagation of Madden-Julian Oscillation convection across the Maritime Continent. Journal of Advances in Modeling Earth Systems, 8, 1552–1564. https://doi.org/10.1002/2016MS000725
Huffman, G. J., Bolvin, D. T., Nelkin, E. J., Wolff, D. B., Adler, R. F., Gu, G., et al. (2007). The TRMM Multisatellite Precipitation Analysis (TMPA): Quasi-Global, Multiyear, Combined-Sensor Precipitation Estimates at Fine Scales. Journal of Hydrometeorology, 8, 38–55. https://doi.org/10.1175/JHM560.1
Iacono, M. J., Delamere, J. S., Mlawer, E. J., Shephard, M. W., Clough, S. A., & Collins, W. D. (2008). Radiative forcing by long-lived greenhouse gases: calculations with the AER radiative transfer models. *Journal of Geophysical Research, 113*, D13103. https://doi.org/10.1029/2008JD009944

Janjic, Z. I. (2001). Nonsingular implementation of the Mellor-Yamada level 2.5 scheme in the NCEP Mesoscale. NOAA/NWS/NCEP of fi ce note 437, 61.

Jiang, X., Su, H., & Waliser, D. (2019). A damping effect of the maritime continent for the Madden-Julian Oscillation. *Journal of Geophysical Research: Atmospheres, 124*, 13,693–13,713. https://doi.org/10.1029/2019JD031503

Kanamitsu, M., Ebisuzaki, W., Woollen, J., Yang, S.-K., Hnilo, J. J., Fiorino, M., et al. (2002). NCEP-DOE AMIP II Reanalysis (R-2). *Bulletin of the American Meteorological Society, 83*, 1631–1643.

Kerns, B. W., & Chen, S. S. (2016). Large-scale precipitation tracking and the MJO over the Maritime Continent and Indo-Pacific warm pool. *Journal of Geophysical Research: Atmospheres, 121*, 8755–8776. https://doi.org/10.1002/2015JD024661

Kim, H. M. (2017). The impact of the mean moisture bias on the key physics of MJO propagation in the ECMWF reforecast. *Journal of Geophysical Research: Atmospheres, 122*, 7772–7784.

Lawrence, D. M., Oleson, K. W., Flanner, M. G., Thornton, P. E., Swenson, S. C., Lawrence, P. J., et al. (2011). Parameterization improvements and functional and structural advances in version 4 of the Community Land Model. *Journal of Advances in Modeling Earth Systems, 3*, M03001. https://doi.org/10.1029/2011MS000045

Ling, J., Zhang, C., Joyce, R., Xie, P.-p., & Chen, G. (2019). Possible role of the diurnal cycle in land convection in the barrier effect on the MJO by the Maritime Continent. *Geophysical Research Letters, 46*, 3001–3011. https://doi.org/10.1029/2019GL081962

Mlawer, E. J., Taubman, S. J., Brown, P. D., Iacono, M. J., & Clough, S. A. (1997). Radiative transfer for inhomogeneous atmospheres: RRTM, a validated correlated-k model for the longwave. *Journal of Geophysical Research, 102*(D14), 16,663–16,682. https://doi.org/10.1029/97JD002337

Nakanishi, M., & Niino, H. (2004). An improved Mellor-Yamada level-3 model with condensation physics: Its design and verification. *Boundary-Layer Meteorology, 112*(1), 1–31. https://doi.org/10.1023/B:BOUN.0000020164.04146.98

Onogi, K., Tsutsui, J., Koide, H., Sakamoto, M., Kobayashi, M., Hattori, R., et al. (2007). The JRA-25 reanalysis. *Journal of the Meteorological Society of Japan, 85*(3), 369–432. https://doi.org/10.2151/jmsj.85.369

Peatman, S. C., Matthews, A. J., & Stevens, D. P. (2014). Propagation of the Madden-Julian oscillation through the Maritime Continent and scale interaction with the diurnal cycle of precipitation. *Quarterly Journal of the Royal Meteorological Society, 140*, 814–825. https://doi.org/10.1002/qj.2161

Rienecker, M. M., Suarez, M. J., Gelaro, R., Todling, R., Bacmeister, J., Liu, E., et al. (2011). MERRA: NASA's modern-era retrospective analysis for research and applications. *Journal of Climate, 24*(14), 3624–3648. https://doi.org/10.1175/JCLI-D-11-00015.1

Skamarock, W. C., Klemp, J. B., Dudhia, J., Gill, D. O., Barker, D. M., Wang, W., et al. (2005). A description of the Advanced Research WRF version 2. NCAR Tech. Note NCAR/TN-4681STR, 88 pp.

Thompson, G., Field, P. R., Rasmussen, R. M., & Hall, W. D. (2008). Explicit Forecasts of Winter Precipitation Using an Improved Bulk Microphysics Scheme: Part II: Implementation of a New Snow Parameterization. *Monthly Weather Review, 136*, 5095–5115. https://doi.org/10.1175/2008MWR2387.1

Wheeler, M. C., & Hendon, H. H. (2004). An all-season real-time multivariate MJO index: Development of an index for monitoring and prediction. *Monthly Weather Review, 132*(8), 1917–1932. https://doi.org/10.1175/1520-0493(2004)132%3C1917:AAMMPI%3E2.0.CO;2

Zhang, C., & Ling, J. (2017). Barrier effect of the Indo-Pacific Maritime Continent on the MJO: Perspectives from tracking MJO precipitation. *Journal of Climate, 30*(9), 3439–3459. https://doi.org/10.1175/JCLI-D-16-0614.1