Dependence of precipitation on precipitable water vapor over the Maritime Continent and implications to the Madden-Julian Oscillation

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Key Points:

- The dependence of precipitation on precipitable water vapor is stronger over ocean than over the Maritime Continent.
- The MJO modulates the precipitable water vapor over the ocean and over the Maritime Continent by roughly the same amount.
- Weaker precipitation variations over the Maritime Continent between the MJO phases may be explained by the weaker water vapor dependence.

Abstract

The weakening of the Madden-Julian Oscillation (MJO) as it propagates over the Maritime Continent (MC) is often referred to as the MC barrier. Here, we use 3-hourly precipitable water vapor (PWV) data obtained from the Sumatran GPS Array and the ERA5 reanalysis to investigate the role played by the column moisture over the MC. Over Sumatra and the whole MC, we find a stronger dependence of precipitation on PWV over the ocean as compared to both inland and coastal regions. The MJO modulates the PWV over the ocean and over the MC by roughly the same amount, and the weaker precipitation variations over the MC between the MJO phases may be interpreted in terms of its weaker dependence on PWV over the MC. This different precipitation dependence on column moisture between the MC and the ocean may contribute to the MC barrier effect.

Plain Language Summary

The Madden-Julian Oscillation (MJO) is the dominant intraseasonal variability in the tropical atmosphere, and also influences the global climate and weather, including the El Nino-Southern Oscillation and the North Atlantic Oscillation. However, the reason behind why the MJO weakens or terminates as it propagates over the Maritime Continent remains unclear. Based on the idea that the rainfall is highly sensitive to the water vapor in the troposphere, we examine observations and reanalysis data. We find a weaker dependence of rainfall on column water vapor over the Maritime Continent than over the oceans, which may provide a simple interpretation of the smaller changes of rainfall over land associated with the MJO.

1 Introduction

The Madden-Julian Oscillation (MJO) is the dominant component of the intraseasonal (30-90 days) variability in the tropical atmosphere (Madden & Julian, 1971, 1972). In a typical MJO event, a convectively active envelope of precipitation develops over the western Indian Ocean and slowly propagates eastward along equator to the Pacific Ocean. Over the past decades, there have been extensive studies into both the mechanisms of the MJO and its interaction with the extratropical weather, and other large-scale modes of variability [e.g. the Asian monsoon, the El Nino-Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO), etc.] (e.g. Kiladis & Weickmann, 1992; Mo, 2000; Zhang, 2005; Schreck et al., 2013; Zhou et al., 2016; Tippett, 2018; Barrett, 2019; Arcodia et al., 2020).

The Maritime Continent (MC) is a region in the tropics dominated by islands, many of which fall along the path of the MJO (Yamanaka, 2016). The MJO acts to modulate the rainfall and local land-sea circulation over the MC (Tian et al., 2006; Fujita et al., 2011). Recent observational analysis shows that the MC appears to be a barrier to the MJO propagation – some MJO events become weaker over the MC as they propagate into Pacific Ocean, while some terminate over the MC (Rui & Wang, 1990; Zhang & Ling, 2017). Model simulations show relatively low skills in representing this barrier effect (Inness et al., 2003; Seo et al., 2009; Vitart & Molteni, 2010; Weaver et al., 2011;Wang et al., 2019). Rainfall variance associated with the MJO is also markedly lower over the islands compared to their surrounding oceans (Maloney & Sobel, 2004).

Previously proposed mechanisms for this barrier effect involve, for example, local orography and the strong diurnal cycle over land. Maloney & Sobel (2004) attributed the smaller MJO modulation of the rainfall over the islands to the fact that land surfaces have lower sensible and latent heat capacity compared to the ocean. Inness & Slingo (2006) and Wu & Hsu (2009) suggested that the elevated orography over the islands could act to block the propagation of low-level pressure and wind signal, which may disrupt the MJO propagation. Previous studies have also attributed the weakening of the MJO over the MC to the strong diurnal cycle over land and related phenomena (Neale & Slingo, 2003; Rauniyar & Walsh, 2011; Hagos et al., 2016; Majda & Yang, 2016). For example, the strong diurnal cycle of convection over islands increases the cloud cover and decreases surface insolation, which results in the lower precipitation rate over land in the MC (Rauniyar & Walsh, 2011). After removing the diurnal cycle of the incoming shortwave radiation at the top of the atmosphere, it was found through numerical simulations of a MJO event that the MJO could propagate more smoothly through the MC (Hagos et al., 2016).

Our work is motivated by the possibility of interpreting this barrier effect of the MC in the “moisture mode” framework for the MJO (e.g. Raymond, 2001; Andersen & Kuang, 2012; Sobel & Maloney, 2012, 2013; Adames & Kim, 2016). Recognizing the long timescale associated with the MJO compared to that of convectively coupled equatorial waves, the moisture mode framework of the MJO takes the column integrated moisture, instead of temperature or buoyancy, as the central component, and focuses on the processes that modify the column integrated moisture when considering the generation and propagation of the MJO. In terms of the generation, the moisture mode framework postulates that the MJO arises from a positive feedback in which an anomalously moist atmospheric column precipitates more, and the combined effect of anomalous radiative and surface fluxes and anomalous advection due to the resulting circulation further leads to an even moister column, resulting in a positive feedback loop. For a recent review on the moisture mode framework, see Adames & Maloney (2021).

In our paper, we emphasize the first half of the aforementioned feedback loop, namely that an anomalously moist atmospheric column precipitates more. Based on the daily rainfall and PWV derived from microwave measurements, Bretherton et al. (2004) showed an exponential relationship between rainfall and PWV over different tropical ocean areas. While the direction of causation in this relationship is not unambiguous *a priori*, this exponential relationship could be plausibly interpreted in terms of the moisture-convection feedbacks, in which the moister environment reduces the entrainment drying of updrafts and/or precipitation re-evaporation, and thus favors deep convection (Holloway & Neelin, 2009). The gradient of the precipitation-precipitable water curve has also been interpreted as the inverse of a moisture adjustment timescale (Bretherton et al., 2004; Adames, 2017). Based on GCM simulations, Hannah & Maloney (2011) found that both increasing the minimum entrainment parameter and increasing the rain evaporation fraction in the convective parameterization make the dependence of rainfall on column saturation fraction more nonlinear and more consistent with the observed relationship. These arguments taken together may be viewed as an empirical (and partial) support for the “moisture mode” framework. And within this framework, if the dependence of precipitation on PWV is weaker over the MC, e.g., due to a strong diurnal cycle, this weaker dependence may lead to a weaker “moisture mode” and contribute to the barrier effect.

It has been previously established with Tropical Rainfall Measuring Mission (TRMM) rainfall measurements that modulation of rainfall by the MJO is weaker over the MC compared to that over the surrounding oceans (Maloney & Sobel, 2004; Sakaeda et al., 2017). PWV over the MC is not available from the microwave measurements used in Bretherton et al. (2004) owing to the complications associated with land-surface emissivity. Roundy & Frank (2004) used data from the NASA Water Vapor Project (NVAP), but the data may be problematic over the MC (Torri et al., 2019). Bergemann & Jakob (2016) used the ERA-Interim data from 1998 to 2015 to study the rainfall-PWV relationship and found that coastally influence rainfall has a weaker dependence on mid-troposphere humidity than that over the open ocean. However, the accuracy of the ERA-Interim water vapor data over the Maritime Continent has not been well established, and over a substantial portion of the dataset time period, all-weather data such as that from GPS Radio Occultation was not available for assimilation. Torri et al. (2019) used data from the Sumatran GPS Array (SuGAr), a network of ground GPS stations in Sumatra established for geodesic studies (Feng et al., 2015), and found that the MJO modulates the diurnally averaged PWV over the archipelago and coastal stations by similar amounts (Fig. 12 in Torri et al. (2019)). If we take the coastal stations to be more land-like than the archipelago stations, these results imply a weaker dependence of rainfall on PWV over the different MJO phases over Sumatra.

In our work, we extend the work by Torri et al. (2019) in two ways. We first examine the dependence of rainfall on PWV more generally in a manner following the approach of Bretherton et al. (2004). Second, in addition to Sumatra, we extend the analysis to the entire MC region using ERA5 reanalysis data (Hersbach et al., 2020), which assimilates GPS radio occultation (RO) data. The GPS RO data show a good agreement with collocated ground-based GPS measurements in Torri et al. (2019)'s Fig.5. This work also revisits Bergemann & Jakob (2016) and Ahmed & Schumacher (2017) using the SuGAr dataset and the new ERA5 data. The comparison between reanalysis PWV and co-located SuGAr data (Figure 1bc) shows that ERA5 has improved quality compared to ERA-Interim used in the previous work. Also, we divided the Maritime Continent into 4 geographic categories in order to investigate the change in rain-PWV relationship over different regions in more detail, while the MC is regarded as a whole in Ahmed & Schumacher (2017).

In section 2, we will introduce the datasets and methods. In subsections 3.1 and 3.2, we will present the results of the diurnal cycle of rainfall and PWV and relationship between rainfall and PWV. In subsection 3.3, we will investigate how the MJO modulates the PWV and rainfall over MC, and their linkage. In section 4, we will summarize the results and interpret the MC barrier effect using our findings.

2 Data and Methods

In this work, PWV is estimated using ground-based GPS-derived network data over Sumatra and ERA5 reanalysis over the Maritime Continent. We also use the Global precipitation measurement (GPM) rainfall data.

2.1 PWV data from Sumatra GPS Array station (SuGAr)

GPS relies on the transmission of radio wave signals from satellite to receiver in order to obtain precise positions. When these signals travel through the atmosphere, two potential sources of error arise due to refraction of the radio waves – the ionospheric delay, and the tropospheric delay. The delay due to the tropospheric component (tropospheric path delay) in the neutral atmosphere (troposphere and stratosphere) can be further divided into the hydrostatic delay and the wet delay, the latter of which, when mapped to the zenith angle, can be used to obtain precipitable water data (Askne & Nordius, 1987). The relative insensitivity of L-band radio signals to cloud and droplet makes the GPS-PWV product available in all weather conditions. In our study, as in Torri et al. (2019)**,** we use data from 45 GPS stations over Sumatra during the period of 2008-2013 (Feng et al., 2015). We divide the stations into three categories: the small islands west of Sumatra (ocean), the coast along Sumatra (coast), and inland (land) as shown in Fig. 1a.

2.2 PWV data over the MC from ERA5 reanalysis

As for the PWV data over the broader Maritime Continent (10°S-10°N, 90°E-150°E), we utilize ERA5, the latest global atmospheric reanalysis dataset released by the European Centre for Medium-range Weather Forecasts. The Constellation Observing System for Meteorology, Ionosphere, and Climate Version 1&2 (COSMIC1&2) radio occultation measurements, which can provide information on temperature and humidity based on the signal refraction, were assimilated into ERA5 since 2006 and 2020, respectively. The ERA5 reanalysis PWV data compare well with COSMIC1&2 over the Maritime Continent (Fig. S1) and provide a better temporal and spatial coverage. Therefore, we use ERA5 PWV data whose time resolution is 1 hour, and spatial resolution is 0.25°, over the Maritime Continent during 2005-2016. Based on ERA5 land fraction data, we divide the Maritime Continent area into ocean (land fraction<0.1), coast (0.1<land fraction<0.8) and land (land fraction>0.8) grids, which is similar to the three categories of SuGAr stations. As PWV is the integral of column of water vapor above the ground, a higher elevation means a shorter integration path and a naturally lower PWV value. Therefore, we exclude grids where the elevation is higher than 150 meters from the three categories above and reclassify them as mountainous regions, so that regions remain classified as “land” and “coast” can better compare with the “ocean”.

2.3 Rainfall data from Global Precipitation Measurement

The Global Precipitation Measurement (GPM) is the successor to TRMM. It has two advanced instruments, Dual-frequency Precipitation Radar and a radiometer called GPM Microwave Imager, which allows GPM to measure precipitation intensity and type through all cloud layers using a wider data swath (Skofronick-Jackson et al., 2018). The Integrated Multi-Satellite Retrievals for GPM (IMERGv6) we use here, is the Level 3 precipitation estimation product of GPM, which intercalibrate, merge, and interpolate satellite microwave precipitation estimates with microwave calibrated infrared (IR) satellite estimates, precipitation gauge analyses at high spatio-temporal resolution of 30 minutes and 0.1°. In order to do a comparison with the PWV data, we average the higher-resolution GPM 0.1° by 0.1º data to a coarser 0.25º by 0.25° grid exported by the ERA5 reanalysis.

2.4 RMM MJO index

Wheeler and Hendon (2004) developed the Real-time Multivariate MJO (RMM) index to compute the state of the MJO using latitudinal averages of outgoing longwave radiation and zonal wind at 200 and 850 hPa in the tropics. This index has become the standard method used to describe the approximate center and phase of the MJO as it propagates along the equator. Based on the rainfall (Fig. S6), we assign RMM MJO phases 2, 3, 4, 5 as active MJO phases and phases 1, 6, 7, 8 as suppressed phases over the MC.

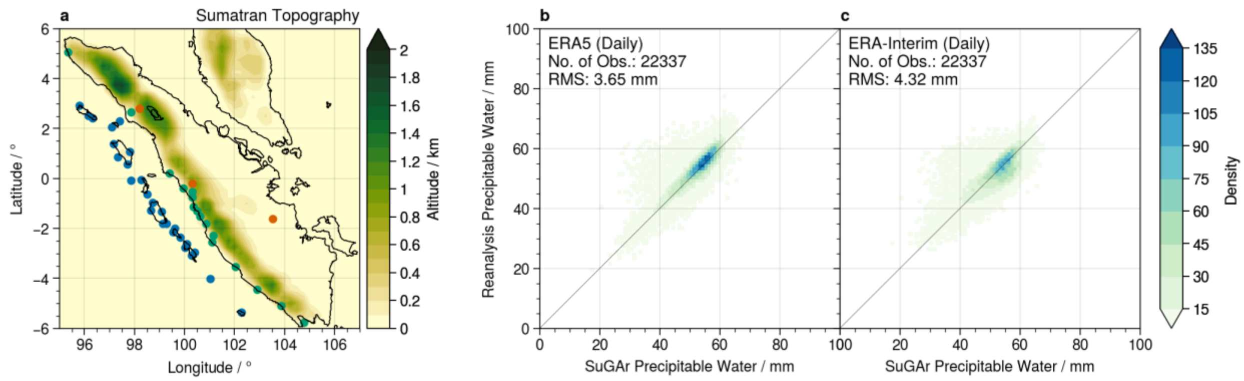

Figure 1. (a) The GPS stations are divided into three categories: ocean (blue), coast (green), land (red). The shading shows the orography. The comparison of PWV (b) between ERA5 and SuGAr and (c) between ERA-Interim and SuGAr.

3 Results

3.1 Modulations of the diurnal cycle of PWV and rainfall by the MJO

Previous studies suggest that the diurnal cycle of precipitation and related sub-MJO-scale features compete with the MJO for moist static energy, which may explain the MC barrier effect (Neale & Slingo, 2003; Sakaeda et al., 2017; Ling et al., 2019). Here we extend the diurnal cycle of PWV over Sumatra investigated by Torri et al. (2019) to the whole Maritime Continent and also include the diurnal cycle of rainfall at different MJO phases. First we examine the diurnal cycle of PWV over Sumatra with more coastal ground-based GPS stations compared to Fujita et al. (2011). Figure S2 indicates that the diurnal cycle of PWV in this work has a clear sinusoidal pattern, with a peak at about 19:00 local time, which is different from the midnight peak time over the coastal stations in Fujita et al. (2011). With 6 years of data, the diurnal cycle of PWV over Sumatra in our Figure S3 compares well with Torri et al. (2019)'s Fig. 11, which used 6 months of data to show that when the MJO transitions from suppressed to active phases, PWV increases by roughly the same amount throughout the day across all surface types. The modulation of the rainfall diurnal cycle by the MJO is substantial over both land and ocean, but is stronger over the ocean than over the land (Figure S4). The diurnal cycles of rainfall and PWV over the whole Maritime Continent (Fig. S5&S6) show a similar behavior.

3.2 Relationship between daily PWV and precipitation over the Maritime Continent

In this section, we examine the relationship between the daily averaged PWV and precipitation over land and ocean.

We first examine this relationship using Sumatra GPS data (Figure 2a). Across all surface types (ocean, coast and land), the precipitation rate is on average below 0.5 mm/h when PWV is below 55 mm. Over ocean, the rain-PWV relationship curve sharply increases when PWV is above 55 mm, which is similar to what Bretherton et al. (2004) found over tropical oceans. At the same time, when PWV is higher than 55 mm the precipitation rate over land is lower than over the coast and much lower than over the ocean. The next question is, is Sumatra representative of the broader MC area?

Figure 2b shows the relationship between PWV and rainfall over the MC using 12 years of ERA5 PWV data and GPM IMERG precipitation data. Precipitation rate over the ocean increases exponentially when PWV is above 55 mm, approaches 2 mm/h when PWV reaches 65 mm, which is similar to the results over Sumatra (Figure 2a). In contrast, the rain-PWV curves over land and coast are less steep than that over ocean. At similar PWV values, the precipitation rate over land is lower than over the ocean, which confirms a weaker rain dependence on PWV over the Maritime Continent.

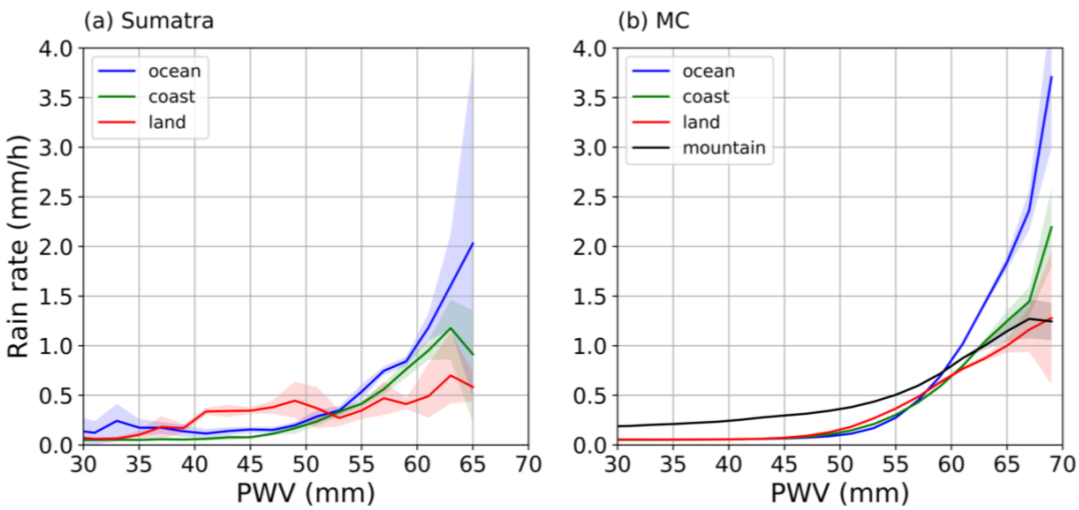

Figure 2. Relationship between daily rainfall and daily precipitable water vapor over (a) Sumatra and (b) the Maritime Continent, for oceanic areas (blue), coastal areas (green), land areas (red) and mountain areas (black). The shadings show the 95% confidence interval of the mean, estimated by using t-test and dividing the data into 5 groups. Data are not shown above 65 mm for Sumatra (69 mm for the MC) due to limited occurrences of such high PWV values.

3.3 PWV and rainfall modulation by the MJO

Figure 3a shows the difference in the probability distribution functions (PDF) of daily-aggregated PWV between MJO active phases (Fig. S7a) and suppressed phases (Fig. S7b) over the Maritime continent. The difference in probability distribution of PWV shows a dipole pattern, corresponding to the PWV values shift between the different MJO phases. Except for the mountain grids, frequencies of PWV below (above) 57 mm decreased (increased), with a peak frequency decrease (increase) at 53mm (61 mm) with enhanced MJO convection. Note that this shift is remarkably similar over ocean, coast and land, except over mountainous regions, where the spectrum shifts to lower PWV values. Therefore the PWV modulation by the MJO is no weaker over the MC land compared to over the ocean.

Figure 3b shows the difference in the distributions of log precipitation rates between the active and suppressed MJO phases. This difference between the active phase and suppressed phase, is positive (negative) when precipitation rate is higher (lower) than about 0.5 mm/hr over all regions, corresponding to the strong convection during the active phase of the MJO over the MC. In contrast, the change in rainfall rate is larger over the ocean than over both land and coastal regions, which means the MJO modulation of precipitation rate is stronger over the surrounding ocean area than the MC. The frequency of high rainfall rates greater than 1 mm/hr is larger over ocean than land during the active MJO phases.

To summarize, the MJO has similar influences on PWV for different surface types, but has a weaker effect on the precipitation rate over land as compared to over the surrounding ocean area. This contrast between land and ocean, which is consistent with the weaker convection modulation over land found by Zhang & Ling (2017) and others, may be interpreted in terms of the difference in the sensitivity of rainfall on PWV between land and ocean.

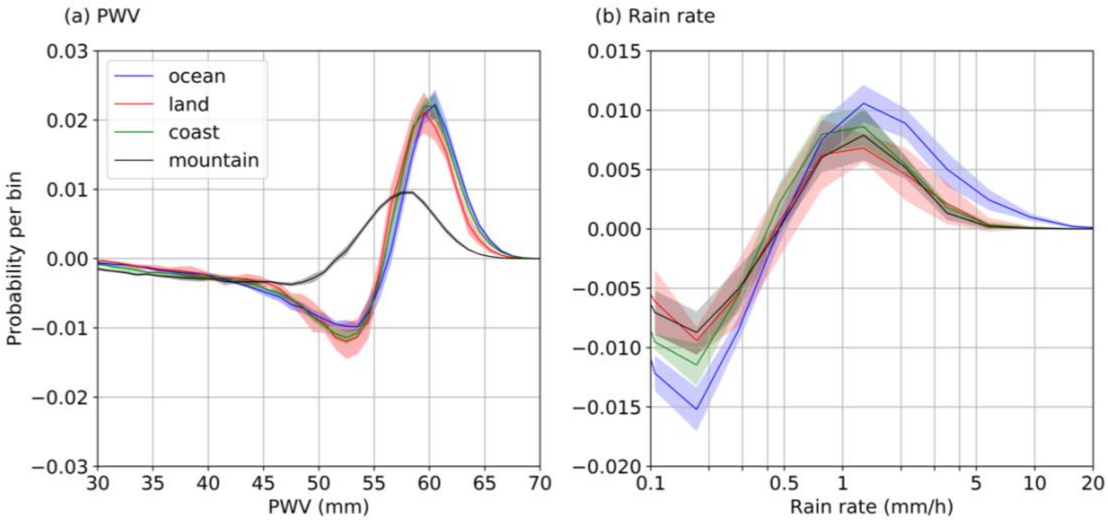

Figure 3. Difference of the distributions of (a) precipitable water vapor and (b) log rainfall rate during the MJO active phases relative to the suppressed phases for ocean grids (blue), coast grids (green), land grids (red) and mountain grids (black) over the MC. Bin size is 1mm for PWV and 0.217 in $\log_{10}$(precipitation rate) scale, respectively. The shadings show the 95% confidence interval of the mean, estimated by using t-test and dividing the data into 5 groups.

4. Summary and discussion

This work is inspired by the “moisture mode” framework, in which a prognostic column moisture equation is the key to the MJO dynamics. One of the supporting evidence of the “moisture mode” theory is the observed exponential rain-PWV relationship over the tropical oceans (Bretherton et al., 2004), which shows that precipitation is highly sensitive to column water vapor (or column relative humidity). In this work, we utilized the PWV derived from ground-based GPS stations over Sumatra, which are relatively unaffected by cloudy and rainy conditions or land-surface emissivity, and extend the study to the whole MC with ERA5, which assimilates GPS radio occultation data and shows good agreement with SuGAr.

We find a clear rain-PWV relationship over all surface types (i.e., ocean, land, and coast areas), which is consistent with previous studies. However, the dependence of rainfall on PWV is weaker over land and coast than over ocean. We also find that the MJO enhances the PWV by roughly similar amounts over land and ocean, and suggest that the weaker modulation of rainfall rate by the MJO over land compared to that over ocean may be a consequence of its weaker dependence of rainfall on PWV. This in turn may lead to a weaker “moisture mode” that partially explains the MC’s barrier effect on the MJO. Whether and how a weaker rain-PWV dependence over land is related to its stronger diurnal cycle will be further investigated through numerical simulations in the future.

The rain-PWV dependence is only one aspect of the MJO dynamics within the moisture mode framework. While our results suggest the weaker rain-PWV dependence over land as a potential factor for the general weakening of the MJO over the MC, other reasons as to why some MJO events stall and some propagate through the MC could be differences in the mean state, or just generally the diversity of MJO events as recently highlighted by Wang et al. (2019). Zhang & Ling (2017) found that the land-to-ocean precipitaion ratio is higher for the non-MC crossing events and proposed that the competition between land and oceanic convection is key to the varying strengths of the barrier effect. Ahn et al. (2020) produced this association in GCMs, provided the interpretation that the weaker MC land convection results in steepening of the vertical and meridional mean moisture gradient over the MC, and the MSE advection further enhances the MJO eastward propagation. It is however also possible that a higher land-to-ocean rain ratio gives land convection, and its weaker PWV dependence, a greater role in the MJO dynamics, consistent with our hypothesis. Many other aspects can affect the MJO propagation through the MC as well. For example, Kim et al. (2014) suggested that whether MJO convection over the Indian Ocean can cross over the MC is closely associated with the dry anomalies over the eastern MC and west Pacific. The positive moisture meridional advection by the anomalous poleward flow, which is interpreted as part of the Rossby wave response to the dry anomaly, moistens the atmosphere to the east of MJO convection, which helps MJO eastward propagation. More generally, the horizontal moisture advection by MJO anomalous wind acting upon the mean state moisture gradient is argued as key to the MJO propagation, with the MJO detouring to the south of the MC during the boreal winter as a good example (Jiang, 2017; Kim et al., 2017). Our suggestion is compatible with these arguments within the moisture mode framework, as various processes modify the column moisture, leading to the strengthening/weakening or propagation of the column moisture anomaly.

Many recent modeling studies suggest that the moisture–convection feedbacks and the MJO variability can be strengthened in GCMs by increasing the sensitivity of the convective scheme to free tropospheric moisture (Waliser et al., 2009; Zhu et al., 2009; Kim & Kang, 2012), e.g.,with the use of a specified convective rain evaporation fraction (Grabowski & Moncrieff, 2004). That modern models tend to exaggerate the barrier effect could therefore be due to poor representations of the mean state moisture (Gonzalez & Jiang, 2017), or overly strong MC land convection (Ahn et al., 2020). Our results suggest that the rain-PWV dependences over land and ocean in the GCMs could be another valuable diagnosis.

Acknowledgments and Data

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https://gpm.nasa.gov/taxonomy/term/1417, and the RMM MJO index is from https://psl.noaa.gov/mjo/mjoindex/.

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