Variability of Jakarta Rain-Rate Characteristics Associated with the Madden–Julian Oscillation and Topography

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ABSTRACT: Research on the interaction between the Madden–Julian oscillation (MJO) and rainfall around Jakarta is limited, although the influence of the MJO on increased rainfall is acknowledged as one of the primary causes of flooding in the region. This paper investigates the local rainfall response around Jakarta to the MJO. We used C-band Doppler radar in October–April during 2009–12 to study rain-rate characteristics at much higher resolution than previous analyses. Results show that the MJO strongly modulates rain rates over the region; however, its effect varies depending on topography. During active phases, MJO induces a high rain rate over the ocean and coast, meanwhile during suppressed phases, it generates a high rain rate mainly over the mountains. In phase 2 of the MJO we find the strongest increase in mean and extreme rain rate, which is earlier in the MJO cycle than most studies reported, based on lower-resolution data. This higher rain rate is likely due to increases in convective and stratiform activities. The MJO promotes more stratiform rain once it resides over Indonesia. In phase 5, over the northwestern coast and western part of the radar domain, the MJO might bring forward the peak of the hourly rain rate that occurs in the early morning. This is likely due to a strong westerly flow arising from MJO superimposed westerly monsoonal flow, blocked by the mountains, inducing a strong wind propagating offshore resulting in convection near the coast in the morning. Our study demonstrates the benefits of using high-resolution radar for capturing local responses to the larger-scale forcing of the MJO in Indonesia.

SIGNIFICANCE STATEMENT: Rainfall in Jakarta and its surroundings is highly variable and often heavy resulting in devastating floods. In this region, in the wet season, rainfall is influenced by large-scale climate variability including the Madden–Julian oscillation (MJO) characterized by eastward propagation of clouds near the equatorial regions on intraseasonal time scales. The MJO has been known to increase the probability of rainfall occurrence and its magnitude, but we show that the impact differs in varying topography. The frequency and intensity of rainfall increase over land areas including mountains even when MJO has not arrived in Indonesia. Meanwhile, once MJO moves through Indonesia, the frequency and magnitude of the rainfall increases over the northern coast and ocean as well as in the west of the radar domain.

KEYWORDS: Maritime Continent; Tropics; Madden-Julian oscillation; Rainfall; Climatology; Radar/Radar observations; Diurnal effects; Intraseasonal variability

1. Introduction

The Madden–Julian oscillation (MJO) has been widely recognized as one of the major climate modes causing rainfall variability around the equatorial Indian and Pacific Oceans (Maloney et al. 2019; Matthews et al. 2013), and the Maritime Continent (MC) (Hidayat and Kizu 2010; Kamimera et al. 2012; Lestari et al. 2019; Muhammad et al. 2020; Oh et al. 2012; Qian 2020; Wu et al. 2017; Wu et al. 2013; Xavier et al. 2014). The impacts of MJO are seen on global weather and climate (Zhang 2013) and across the different parts of the Indonesian MC (IMC) including in rainfall patterns in coastal areas (Bergemann et al. 2015). Previous studies have revealed that in the peak of the rainy season (December–January) (Aldrian and Dwi Susanto 2003), intraseasonal variability of MJO (Wu et al. 2013), monsoon flow (Matsumoto et al. 2017; Wu et al. 2007) play a role in the heavy rainfall that leads to floods in western Java island. However, to date, studies of heavy rain associated with the MJO have largely been conducted using
coarse-resolution products. This is problematic, particularly around Jakarta where there is variable topography and a susceptibility to flooding.

Jakarta, a densely populated region, is situated between coastal areas and steep mountains, typical of many cities of the MC. The complex topography of the MC region has resulted in difficulties for global climate models to simulate the MJO (Matthews et al. 2013; Peatman et al. 2014). Recently, some studies have used high-resolution simulations to understand the variation of diurnal rainfall over the MC, but there is a large difference between models and Tropical Rainfall Measuring Mission (TRMM) 3B42 satellite in capturing the timing and amplitude of rainfall peaks especially over the land (Vincent and Lane 2016, 2017) which highlights the challenges of accurately representing the local convective process in the region (Vincent and Lane 2018).

Satellite data have recently been used to investigate diurnal rainfall variability, for example the Integrated Multi-satellite E Retrievals for GPM (IMERG) is used to capture diurnal rainfall structures over the MC (Tan et al. 2019) but the data have not been applied to understanding MJO-related rainfall variability. Instead, numerous studies have used TRMM 3B42 and found the rainfall peak over the land before the enhanced convective envelope of the MJO arrives over the MC (Birch et al. 2016; Ling et al. 2019; Oh et al. 2012; Qian 2020; Rauniyar and Walsh 2011). Once the MJO resides over the MC, the rain over land is suppressed but intensifies over the ocean. Past research showed that the MJO also modulates the mean and amplitude of the diurnal cycle of rainfall (Lu et al. 2019). Using dual-polarization radar, previous research examined the influence of the diurnal cycle of rainfall events on the development of convection over the ocean during suppressed and active MJO (Rowe et al. 2019). Their study also suggested that a comprehensive analysis of the modulation of rainfall within the diurnal cycle and for different MJO phases was needed. Radar is a powerful tool for characterizing the timing and occurrence of rain in individual phases of the MJO. Nevertheless, there are few radar studies of rainfall over the Indonesian region, partly because of the poor quality of many of the available datasets.

Local topography also plays an important role in the timing and amplitude of the diurnal rainfall peak. By using ERA-5 reanalysis and TRMM, it was reported that topography over the MC modulated the variability of local MJO signals, with mountains in the MC inhibiting the MJO propagation from the East Indian Ocean to the west Pacific (Jiang et al. 2019). Although TRMM and ERA-5 datasets can explain the general diurnal cycle of rain over the IMC during enhanced and suppressed MJO, as well as the dynamical processes of the rain development, it is necessary for future work to revisit these conclusions using higher resolution observational datasets (Jiang et al. 2019). Previous literature has also emphasized that, despite the capability of TRMM data in observing the general rainfall behavior during the passages of the MJO, the dataset has pitfalls in capturing the details of local rainfall especially over steep topography (Matthews et al. 2013) and is too coarse to capture small-scale rain features (Sakaeda et al. 2017). The IMERG data captures the timing and peak of diurnal rainfall variability; however, the data still overestimates light rainfall and underestimates heavy rain relative to ground-based datasets (Tan et al. 2016) and weather radar, particularly over the MC (DaSilva et al. 2021). Thus, denser and finer ground truth data are required to accurately document the nature of local rainfall over the IMC.

Understanding of the nature of rainfall characteristics in all phases of the MJO around Jakarta remains incomplete. In this study, we use a 4-yr dataset of 1-km resolution C-band Doppler radar (CDR) around Jakarta to explore the variability of rain-rate properties with the MJO which then will be compared to the study-period mean. This study analyses the detailed spatiotemporal variation of mean rainfall and rainfall extremes (REs) during the eight strong phases of the MJO, with a focus on the rainfall characteristics over different topography during strong phases of the MJO during October–April. This study improves basic knowledge of the role of local forcings in modulating the influence of the MJO on rainfall. Analysis of the amplitude and timing of the diurnally varying rainfall in each MJO phase is also examined at very high spatial resolution.

2. Methods

The principal dataset used in our study is the C-band Doppler radar from the Agency for The Assessment and Application of Technology (BPPT) Serpong installed as part of the Hydrometeorological Array for Intraseasonal-variation Monsoon Automonitoring (HARIMAU) Project around Jakarta during 2009–12 (Fig. 1). Some CDR missing data are in March–May 2009, December 2011, and September 2012. The quality control of the CDR data has been applied including eliminating noise and nonmeteorological data, calibrating and correcting for attenuation, and masking out areas with strong radar beam blocking (Lestari et al. 2022). The total radar domain with no beam blocking influence used in the analysis was approximately 87.5%. The hourly rain-rate dataset was derived from radar reflectivity at 3.7-km height using the locally derived $Z-R$ (reflectivity–rainfall) relationship $Z = 102.7R^{1.75}$. The $Z-R$ relationship was determined based on 1) 1-min rainfall data ($R$) from the Automatic Weather Station (AWS) located in two stations in the coastal land and low mountain as well as the reflectivity ($Z$) from the CDR, and 2) 1-min disdrometer in Serpong, since the disdrometer can be used to calibrate the radar (Lee and Zawadzki 2006). We combined both disdrometer and CDR to derive the $Z-R$ equation to cover a wide range of variability of rainfall within the radar domain as disdrometer only can cover single elevation. For a detailed description of the radar data processing and derivation of the $Z-R$ relationship, see Lestari et al. (2022).

Over the IMC, the sparsity of high-temporal resolution radar and station data are particularly problematic as the MJO interaction with topography results in strong differences in rainfall variability (Jiang et al. 2019). Thus, CDR used in this study is valuable to analyze the subdaily rainfall record and the detailed spatial structure of rainfall. The CDR datasets
have also been validated using the observational hourly data and both are in a good agreement.

We selected the analysis period from October to April (ONDJFMA) for the MJO analysis following a previous study (Hidayat and Kizu 2010), corresponding with the rainy season. The detailed months that we used in this study were in 2009 (January, February, October, November, December), 2010 (January, February, March, April, October, November, December), 2011 (January, February, March, April, October, November, December), and 2012 (January, February, March, April, October, November, December), as remaining wet season months were missing.

The real-time MJO monitoring (RMM) index was used to define its amplitude and phase (Wheeler and Hendon 2004). The analysis was categorized into two parts:

1) The strong and weak MJO cycles were defined based on the amplitude.

The “strong MJO” was specified when the MJO amplitude > 1 while the “weak MJO” was determined when its amplitude ≤ 1.

2) The distribution of MJO rainfall was analyzed based on phases of the MJO propagation (Fig. S1 in the online supplemental material).

We defined “suppressed” when a strong MJO propagates over the Indian Ocean (phases 2-3), in the western Pacific (phase 7), and in the central Pacific (phases 1 and 8). Meanwhile “active” was defined when a strong MJO resides over the IMC (phases 4-5) and in the western Pacific (phase 6) (Rauniyar and Walsh 2011).

The average rain rate in each strong phase of the MJO was compared to the average rain rate over the full analysis period (study-period mean). The 4-yr record, the strong MJO phases consisted of 33 days (RMM phase 1/MJO 1), 36 days (RMM phase 2/MJO 2), 40 days (RMM phase 3/MJO 3),
48 days (RMM phase 4/MJO 4), 49 days (RMM phase 5/MJO 5), 64 days (RMM phase 6/MJO 6), 68 days (RMM phase 7/MJO 7), and 44 days (RMM phase 8/MJO 8). We focused on exploring: 1) the mean hourly rain rate ($R_h$), 2) the frequency of heavy rain ($R \geq 5$ mm h$^{-1}$), 3) the diurnal variation in hourly rain rate, and 4) the spatial pattern of this variation.

The spatial distribution of maximum and minimum of $R_h$ and daily rain rate during eight phases of strong MJO was plotted. From these maximum and minimum spatial maps, the five regions were selected from five representative pixels (11 km x 11 km) where the rain rate is significantly different between study-period mean and each MJO phase (Fig. 2). To examine how the rain rate changes during strong phases of the MJO, the boxplot of hourly rain rate in each MJO phase was compared to the average boxplot over the whole radar domain (Fig. 3). Further, the rain-rate distribution of each region representing coast, lowland, and low and high mountains as shown in Fig. 2, was also shown in the boxplots.

We employed the two-sample Kolmogorov–Smirnov (K–S test) to assess whether differences between rain-rate distribution for each MJO phase and study-period mean are statistically significant (Dias et al. 2017; Stolz et al. 2017; Wilks 2011).

To capture the majority of the diurnal rain-rate variation, we applied harmonic analysis to obtain information about amplitude and timing (phase) of the diurnal peak of the time series. The diurnal harmonic was fitted to the average diurnal cycle of rain rate at each grid point, for each MJO phase and for the whole study period (Angelis et al. 2004; Wilks 2011). For the analysis, we used a sample size of 24 (h) and starts from $t = 0000$ h to $t = 2300$ h.

The eastward ($u$) and northward ($v$) components of the hourly wind at 850 and 950 hPa, vertical velocity at 500-hPa
FIG. 3. (a) Mean hourly rain rate ($R_h$) in combined mean for all strong MJOs (eight phases) identified throughout the observational record, (b) domain-averaged boxplots of distribution of hourly rain rates for the whole study period/study-period mean (All), the weak MJO periods, and each of the eight strong MJO periods. (c)–(g) As in (b), but averaged over coastal, east lowland, low-mountain, high-mountain, and west lowland areas, respectively, corresponding to labels in (a). There are seven number groups showing the percentile range of the rain rate with the middle range (yellow full lines) showing the median and four black diamonds indicate extremes. Green colors indicate a statistically significant difference in the rain-rate distribution between study-period mean and each phase of strong MJO calculated by the Kolmogorov–Smirnov test. The blue line shows the percentage of rain rate $\geq 0.5$ mm h$^{-1}$ in each condition (study-period mean, weak, and strong MJO).
level, vertical integral of divergence of moisture flux, and convective available potential energy (CAPE) from ERA-5 (C3S 2017) during 2009–12 were used to understand the background process predominantly occurring in each phase of MJO and study-period mean. The horizontal resolution of ERA-5 datasets is 0.25° × 0.25°.

To understand the dominant type of rainfall during different MJO phases, frequency of stratiform and convective rain was examined. Radar reactivity on the 3D cartesian grid was separated into convective and stratiform regions (Steiner et al. 1995). Subsequently, the reactivity was converted to hourly rain rates using our local Z–R (Z = 102.7R^{1.75}). We retrieved the regions of convective and stratiform following the python code available on the manual document of pyart (https://arm-doe.github.io/pyart-docs-travis/API/generated/pyart.retrieve.steiner_conv_strat.html)

3. Results

a. Rain-rate characteristic and its variation in strong phases of the MJO

This section describes the variation of Rh and the spatial distribution of the highest hourly and daily rain rate between the eight phases of the MJO. The analysis includes the boxplot analysis summarizing the rain-rate distribution between each strong MJO phase and study-period mean, which includes hours during both strong and weak MJO conditions. Although we do not consider the study-period mean as true climatology due to the limited time period of the dataset, it is our best estimate of the background conditions during the analysis period. The spatial variation of the hourly rain-rate peak is also examined in detail.

Figure 2 shows color-coded maps of the MJO phase in which the highest and lowest Rh and average daily rain rate occurs. Overall, the spatial patterns of the peaks and troughs of Rh and daily rain rate are similar. But there is marked variation within our relatively small domain of the MJO phases associated with higher and lower rain rates. In general, for the maximum rain, it shows that in the southern part of the radar domain, particularly over the mountains, the peak occurs in suppressed MJO (phases 8, 1, 2, and 3) corresponding to when the peak MJO activity is in the Indian Ocean or central Pacific. Meanwhile, in the northern part of the radar domain, the maximum peak is mostly in phases 4, 5, 6 (active MJO), and 3 (suppressed MJO), found when the MJO resides over the Indian Ocean. Conversely, in the south part of radar domain including the mountainous region, the minimum Rh and daily rain rate is mainly identified in phases 5 and 7 while over the north coast, western and eastern part of radar domain, the minimum rain rate is primarily found in phases 1, 2, and 8.

Notably, there are very few locations where the peak daily or hourly rain rate falls in the phases of the MJO considered as active in the region (phases 4–6) (Rauniyar and Walsh 2011). The heterogeneity of maximum and minimum rain rate with the MJO phases evident in Fig. 2 suggests that there is an interaction between the MJO and local factors generating localized rainfall within the radar domain.

Statistical properties of Rh data were presented as a boxplot with six points: the lower whisker (minimum value of the rain ≥ 0.5 mm h⁻¹, x_min), the lower quartile (25th percentile, Q₁), the median (50th percentile, Q₂), the mean average (X_mean), the upper quartile (75th percentile, Q₃), and the upper whisker (95th percentile, Q₄). We also display four extreme values in the boxplot figures: the 96th, 97th, 98th, and 99th percentiles (Q₀.₉₆, Q₀.₉₇, Q₀.₉₈, Q₀.₉₉, respectively) as suggested by outliers lying above Q₄ (Fig. 3).

In Fig. 3, boxplots of the distribution of Rh (rain ≥ 0.5 mm h⁻¹) for the whole study period (study-period mean), weak and strong MJO periods are shown, for the whole radar domain (Fig. 3b) and for five selected regions with markedly different MJO-scale variation indicated by Fig. 2 (Figs. 3c–g). We selected five relatively small grids to represent rain rate over the coast, west and east lowland, and low and high mountains (Fig. 3a) since choosing larger grids may unintentionally average inhomogeneous rain-rate responses to the MJO.

Overall, in comparison to study-period mean, frequency of rain rate increases significantly when the MJO passes over the Indian Ocean (in phase 2) (Fig. 3b). In contrast, there is a slight decrease in rain rate when the MJO lies over the IMC (phases 4–5) and west Pacific (phase 6) although this is not statistically significant (p value > 0.05) according to the Kolmogorov–Smirnov test (Fig. 3b).

The increased rain rate found in phase 2 over the average of the radar domain is also observed in individual location for the east lowland, low and high mountains (Figs. 3d–f) (except west lowland in phase 1, Fig. 3g), suggesting a high incidence of rainfall over most inland and mountainous regions in phase 2 ahead of the strong MJO arriving in the IMC. The spatial map of Rh during combined mean for all strong MJOs (eight phases) identified throughout the observational record also shows that the highest mean rainfall is mainly observed over the lowland and mountains in the southwestern, southeastern and southern part of radar domain (Fig. 3a). While the domain-average rainfall is typically highest in phase 2, the lowest average rainfall is in phase 4 which corresponds with the large-scale envelope of the MJO being over the region.

Examining across statistical distributions we find the rain rate in suppressed MJO phases (1, 2, and 8) is higher relative to weak MJO and study-period mean (Fig. 3b). Meanwhile, in active MJO (phases 4, 5, and 6), rain rate has a lower distribution relative to study-period mean.

Along with boxplots, we also show the frequency of rain ≥ 0.5 mm h⁻¹ as a percentage (hereafter Wreq/hr) in study-period mean, weak, and strong MJO (Figs. 3b–g). In the whole radar domain, the largest proportion of Wreq/hr is found in phases 4 and 6 of strong MJO (12% and 14%, respectively). This result is in contrast with the fact that the probabilities of heavier rain rate and extreme values in phases 4 and 6 are relatively lower compared to the other strong MJO phases, weak MJO, and study-period mean. During strong MJO in phases 4 and 6, there are more frequent but lighter rain rates compared to the other strong, weak MJO phases and study-period mean.
A consistently high $W_{freq-hr}$ is also observed in phase 6 (Fig. 3b) over the coast, east lowland, low and high mountain regions (Figs. 3c–f), and phases 4 and 6 in west lowland (Fig. 3g), but there are other high peaks of $W_{freq-hr}$ that occur in different MJO phases. For example, A high $W_{freq-hr}$ is observed in phase 2 over the high mountain and is coincident with the high distribution of mean rain rate and extreme rain rate. While over the east lowland and low mountain, the $W_{freq-hr}$ is quite similar in phases 3 and 4 (lowland) and in phase 3 (low mountain), and it is associated with a high extreme rain rate. This finding indicates that during suppressed MJO (phase 2 and 3), ahead of the envelope of active MJO, the high $W_{freq-hr}$ is mainly due to more frequent rain rate with heavier rain rate rather than the lighter rain rate observed in active MJO phases (4 and 6).

From Figs. 4 and 5, we found that in general, there is more MJO-scale variation in stratiform (reaches to ≥7%) than convective rain (only ≥3%). This is shown by more widespread areas with a higher occurrence of stratiform rain that exists in strong MJO phases compared to the study-period mean.

Figure 4 shows that compared to suppressed MJO phases and study-period mean, a higher frequency of stratiform rain-rate event exists during the active phases of MJO (phases 4, 5, and 6) mainly over the lowlands and mountains in the eastern part of the radar domain ($R_i ≥ 7\%$). In phase 6, a slight increase in stratiform rain appears in the western part of radar.
domain. In contrast, the widespread and maximum convective rainfall ($R_c \geq 3.5\%$) occurs in phase 2, ahead of the main MJO envelope, over the lowlands and mountains (Fig. 5). Compared to phase 2, a lower $R_c$ is also found over the lowlands and mountains in the east and south ($2.5\% \leq R_c \leq 3\%$).

In summary, in this section we have demonstrated that rain-rate characteristics are different between suppressed and active MJO phases. During active MJO phases, a more frequent but lighter rain rate is observed whereas rain rate in suppressed MJO phases is less frequent but heavier. Over Sumatera Island, a previous study also found that light rain rates (in phase 5) are a result of rainfall occurring more due to stratiform processes (Marzuki et al. 2016). Our study has added knowledge of the rainfall type occurring over the Jakarta and shown a more detailed spatial distribution of the rainfall type in this complex region. Further analysis of the processes responsible for this lighter rain rate in the active MJO is beyond the scope of our study.

b. Spatial pattern of hourly mean rain rate and rain-rate extremes in eight phases of strong MJO

In this section, we explore the characteristics of hourly rain rate during each phase of MJO and in varying topography. The $R_h$ and $W_{freq-hr}$ are analyzed to examine the difference between mean rain rate and frequency of rain during MJO phases.

The high $R_h$ is observed mainly over the mountain in suppressed phases (1, 2, 3, and 8) ($\geq 1.8$ mm) (Fig. 6). In contrast,
in active phases (4–6), a high $R_h$ is no longer concentrated over the mountain but is found mostly in the western and eastern parts of the radar domain including some of the mountain and lowland, as well as over the coastal region in the northeast. Over the west of the domain, in active phases (4–6), spatial maps of hourly mean vertical velocity and vertical integral of divergence of moisture flux from ERA-5 exhibit lower negative amplitudes relative to other phases. This suggests that in this region, the environment might be conducive to generate convection (Figs. S2 and S3).

The average 850-hPa wind in the study-period mean is predominantly westerly during the extended wet season. It is apparent that the wind has generally followed a typical westerly monsoon particularly existing over the Java region in the wet season (December–February) (Chang et al. 2005; Yoden et al. 2017). In the wet season, the boreal winter with northeasterly winds from the northwest Pacific and the South China Sea exists but for some parts of the IMC, such as Java Island, the westerly wind is more dominant parallel to the topography (Chang et al. 2005; Yoden et al. 2017).

In suppressed MJO phases (1 and 2), ahead of the MJO convective envelope, the wind direction is somewhat different from the wind shown in study-period mean and other MJO phases. Before a strong MJO resides over the IMC,
the northerly low-level wind prevails over the southern region particularly in phase 1. In phase 2, over the southern portion of the radar domain the background wind turns more southerly accompanied by more extensive heavier rain rate over the southern part of radar surrounding the lowland and mountain. In phases 1, 2, and 8, mainly over the lowlands and the mountains in the south, the wind speed is around 0.5–2 m s\(^{-1}\), which is 4–10 times lower than those observed in other phases of MJO. These wind and rainfall features are consistent with previous studies that found that a weak large-scale monsoonal wind with strong diurnal cycle of rain rate might exist particularly over the mountains in the southern coast (Qian et al. 2010) occurring before the MJO passes through the IMC (Qian 2008, 2020).

In phase 1, we observe the anticyclonic circulation. In this phase, the MJO convection and cloud cover initiate over the western Indian Ocean with the easterly wind prevails in the western part of the IMC near Sumatra, Borneo, and the Java Islands (Birch et al. 2016; Oh et al. 2012). However, at the same time, over the west of Java Island near Jakarta, the islands experience maximum heat insolation and surface heating due to less cloud coverage resulting in a strong land–sea-breeze circulation (Peatman et al. 2014; Qian 2020). We speculate that the land–sea-breeze regulates a strong onshore flow originating from the north (ocean) to the south (island) and it has forced the prevailing easterly wind overturns to the south approaching mountainous regions.

In active MJO phases (4 and 5), where a strong MJO moves over the IMC, the westerly wind is still predominant, and is persistent in phases 6 and 7 where the MJO moves to the western Pacific. In phases 5 and 6, the wind speed is the highest (\(>5-8\) m s\(^{-1}\)) compared to all other MJO phases and study-period mean. In phases 5 and 6, the average of 850-hPa wind is westerly along with the westerly monsoonal mean wind, thus this same wind direction increases the wind speed (Qian 2020).

The time–latitude cross section calculated from averaged two transects was also computed (Fig. S4) to examine the dynamics of large-scale during the MJO phases. Compared to other phases, particularly in phase 5, at around 1200–1800 local time (LT), weaker upward vertical velocity and vertical integral of divergence of moisture flux are also observed over the mountains in the south of the radar domain (Figs. S5 and S6). This demonstrates that the large-scale environment might not be favorable to initiate cloud development and convection due to weaker lifting and less moisture convergence. In phase 8, a clear signal of westerly wind gets weaker and is replaced by northwesterly wind coinciding with the development of increasing rain rate in the southern part of radar domain over the land and mountain (Fig. 6).

To understand the behavior of extreme rainfall organization in strong MJO phases, we examine the contribution of the frequency of heavy rain greater than 5 mm h\(^{-1}\) (\(W_{\text{freq-hr}}\)) relative to study-period mean in each phase. Results indicate that the distribution of \(W_{\text{freq-hr}}\) has a similar pattern to the \(R_{\text{f}}\). Over the northeast of the radar domain, including the coast and lowland as well as lowland in the west, a high \(W_{\text{freq-hr}}\) is detected in active MJO phases (4–6) where a strong MJO moves across Indonesia (Fig. 7). Meanwhile, in suppressed MJO phases, the highest frequency of rainfall extremes (\(\geq 7.0\%\)) is found over the southern radar coverage including lowland and mountain areas.

As can be seen when comparing Figs. 6 and 7, during strong MJO conditions, the distribution of mean and extreme rain rate is relatively similar. During the suppressed MJO, heavier rain rate is more apparent over inland (including mountain and lowland) whereas during the active MJO, there is an increase in rain-rate intensity over the north coast and lowland. A detailed analysis of how the MJO and diurnal cycle of rain-rate interaction is described in the next section.

c. Diurnal cycle of rain rate and the MJO

Overall, a pronounced diurnal cycle over Jakarta and the surrounding region is observed with the heaviest rainfall in the afternoon over the land (1600 LT) then migrating to the coast and ocean in the night and early morning (2200–0700 LT) (Katsumata et al. 2018; Sulistyowati et al. 2014). In this section, we will show a more detailed diurnal rain-rate variation with the MJO phases using our radar data.

1) MORNING AND AFTERNOON RAIN RATE WITH THE PASSAGES OF THE MJO

This section aims to identify the influence of the MJO in the development of morning and afternoon rain rate. Here we analyze the difference of rain rate between morning (0000–1100 LT) and afternoon (1200–2300 LT) both in \(R_{\text{m}}\) and \(W_{\text{freq-hr}}\). During suppressed MJO (phases 1–3), \(R_{\text{m}}\) has a similar spatial distribution to that shown in study-period mean (Fig. 8) where the afternoon rainfall is predominant over the southern part of radar including the mountains and lowland. In terms of rainfall extremes, the spatial distribution of \(W_{\text{freq-hr}}\) presents nearly the same patterns to the \(R_{\text{f}}\) (not shown).

Interestingly, in phase 5 when the MJO propagates across parts of the IMC, the diurnal cycle of precipitation in the northwestern part of the radar domain over the coast is dominated by precipitation occurring in the morning. This can be seen by looking at Fig. 8, where the morning rain rate over the northern coast is 0.9 mm h\(^{-1}\) higher than the afternoon rain rate while it is \(\geq 0.9\) mm h\(^{-1}\) higher in the west of radar region.

In phases 7 and 8, when the MJO approaches the central Pacific, the heavier morning rain rate is still observed in the northern part of radar but farther to the north, although this morning peak still can be observed in small areas over the coast. Similar to the study-period mean rain rate, the afternoon rain-rate peak is found in the south of the radar domain (Fig. 8).

2) TIMING AND AMPLITUDE OF THE PEAK OF DIURNAL MEAN RAIN RATE

To examine how the timing of maximum rain rate changes within the day in varying topography, spatial maps of fitted peaks of diurnal rain-rate harmonics have been plotted with 3-h time resolution (Fig. 9). Figure 9 aids Fig. 8 in explaining a more detailed timing of the peak of diurnal rain rate contributing to the morning or afternoon rain rate as shown in
Fig. 8. It is shown that in suppressed phases (1–3 and 7–8) and in active phases (4–6), there is a different spatial signature in the diurnal cycle of rain rate.

Among all phases of MJO, phases 1 and 2 have a similar spatial distribution of the timing of the peak rain rate within the diurnal cycle as seen in study-period mean. For example, the maximum of rain rate in the late evening and morning (1800–0900 LT) exists in the northern part of radar domain over the ocean. In contrast, an afternoon rain-rate peak (mostly at 1200–1800 LT) predominantly exists over the northern coast, the western and southern part of radar domain, and very few areas also show the rain-rate peak at 1200–1500 LT. However, in the study-period mean, the area with the earlier afternoon peak at around 1200–1500 LT is more widespread than that observed in phases 1 and 2 of the MJO (Fig. 9). Here, during the MJO phases 1 and 2, the diurnal peak of afternoon rain rate occurring over the lowlands and mountains in the south (Fig. 9) is consistent with the afternoon rain rate that is also predominant in the south as shown in Fig. 8.

Unlike phases 1 and 2, in phase 3, there are more extensive areas in the western and southwestern part of radar domain and northern coast where the maximum rain rate comes
earlier, at around 1200–1500 LT (Fig. 9). Similar to phases 1–3, in phases 7–8, the morning rain-rate peak is observed in the northern ocean and is slightly found in small areas over the coast. But in phase 8, in the northern coast, some areas experience an earlier maximum rain rate in the early morning (0300–1200 LT).

The different diurnal rain-rate peaks (morning in the north over ocean and afternoon in the south over land and mountain) suggests that during the suppressed MJO (1–3, 8), the land–sea-breeze circulations may play an important role in this different timing of the rain-rate peak, which is consistent with Qian (2020). In phases 1–2, the low-level wind weakens due to opposite direction with the seasonal mean wind favorable for a stronger local thermal inducing diurnal cycle of land-sea breezes circulation (Peatman et al. 2014; Qian 2020), triggering convergence in the afternoon over the mountainous areas (Qian 2008; Wang and Sobel 2017). A strong land–sea breeze also occurs in phase 3 and 8 due to a reduced low-level wind speed (Qian 2020).

From Fig. 9, the most significant feature is that compared to study-period mean and suppressed phases, in active phases (5–6), much earlier morning rain-rate peak initiates in the western part of the radar domain over land and some mountains in the south (2100–0900 and 1200–1500 LT, respectively) and there is a very late rain-rate peak in the evening (1800–2100 LT) occurring in the eastern radar domain in
phase 5. This indicates that land–sea-breeze circulation might not only be involved in the development of rain rate during the active MJO in phases 5 and 6. In these phases, a strong lower-level westerly wind due to MJO that is superimposed with the strong monsoonal westerly wind seems to have an effect on the time difference of the diurnal peak of rain rate (Oh et al. 2012). As a result, there is an increase in wind speed mainly in the Java Sea due to the barrier effect of the mountain. This might initiate the rain-rate production over the Java Sea in the morning (Oh et al. 2012). The differences in the timing of the diurnal peak can be interpreted as the interplay between coastal or oceanic processes with an early morning peak, and continental processes leading to an afternoon peak. The migration of the line separating these competing influences is likely modulated by the background winds and the relative strength of the oceanic and continental processes.

To understand the possible role of land–sea-breeze circulation on the rainfall development, the diurnal perturbation of wind fields from ERA-5 reanalysis datasets were examined. We selected two transects to analyze the diurnal cycle of wind along the transect from high mountain (south radar domain) to the ocean (north Java Island). A wind perturbation was computed based on subtracting the background wind from each observation. We considered a 1-day

FIG. 9. Timing of the peak of the fitted diurnal harmonic in the study-period mean and eight phases of strong MJO. The scale is at a 3-h resolution.
FIG. 10. Hovmöller diagram for meridional wind at 950-hPa level over the west Java Island and sea. Shading indicates speed of wind perturbation with blue showing sea breeze and red showing land breeze. The two vertical lines present the mountainous areas in the south (labeled 1) and coastline in the north (labeled 2).
running wind as the background wind. The perturbation of wind was presented in time–latitude composites of surface $v$ wind speed (Hovmöller diagram) to examine the propagation of the wind anomalies in diurnal time scale (Fig. 10). The Hovmöller was produced by averaging two transects to obtain general features of wind represented along the west Java coast.

Figure 10 indicates that in the study period mean, a typical strong land–sea-breeze circulation exists ($\approx 0.8 \text{ m s}^{-1}$), that is offshore in the morning (around 0000–0800 LT) and onshore in the afternoon (around 1200–1600 LT). The result is consistent with other studies that found the rainfall over the ocean and coast has a peak during midnight to morning while over the mountainous region the peak is in the afternoon (Mori et al. 2018). As for the study period mean, there was a strong onshore wind speed persisting in all phases of MJO; however, in phase 5, the magnitude is getting weaker. This weaker sea breeze might reduce a chance of convective initiation over the mountains or lowlands. This result matches with Fig. 11, that is compared to study-period mean and suppressed phases of MJO, in phase 5, in the afternoon, there is a relatively lower intensity of CAPE over the inland and mountainous region indicating a lower chance of the initiation of convection thus a less chance of rainfall.

From Fig. 10, in the study-period mean and suppressed phases (phases 1–3,7,8), the observed feature is the center of the highest wind speed of the sea breeze that occurs over the lowland and mountains (between lines no 1 and 2). While in phases 4–6, the center of the maximum wind speed of sea breeze is found over the coastline (line no 2) indicating the convection might initiate over the coastal areas.

In addition to the analysis of the timing of the diurnal rain-rate peak, we assess the amplitude of the peak of diurnal rain-rate harmonics. Compared to the peak of $R_b$ (Fig. 6), the spatial feature of the amplitude of diurnal rain-rate peak (Fig. 12) shows that there is a higher intensity of rain rate ($\approx 3.6 \text{ mm h}^{-1}$) over more widespread areas.

A striking feature in Fig. 12 is that there is regular variability that exceeds the average hourly rain rate in many locations across the MJO phases. In comparison to study-period mean, in suppressed MJO, there is a marked increase in the amplitude of the diurnal rain-rate cycle over the southern part of the radar domain mainly to the south of the high mountain ($\approx 3.6 \text{ mm h}^{-1}$) (phase 2). The areas with highest amplitude of diurnal rain-rate cycle grows (phase 2), and migrates to the east of the radar domain over the mountain and land (phase 3). The same pattern with a high peak of the amplitude of diurnal rain rate is also observed during the decaying phases of MJO (7 and 8).

In active MJO phases (4–5), the diurnal peak of land-based rain rate is diminished and moves to the east. Nevertheless, the high amplitude peak of diurnal rain can still be detected near the coast in the northeastern part of the domain and lowland ($\approx 2.2–2.8 \text{ mm h}^{-1}$) even though this magnitude is lower than the observed amplitude in the suppressed MJO.

To examine topographical effects more closely, we analyze the diurnal peak of rain rate in each region over the coastal, lowland, and low–high mountains based on the five pixels from Fig. 3a. Figure 12 highlights the spatial pattern of the high diurnal rain-rate peak. Here, in Fig. 13, we focus on showing the variation of amplitude of diurnal rain-rate peak and the timing.

If we compare the mean of diurnal peak in study-period mean (black line) with the peak during all phases of strong MJO, the MJO seems to be associated with an increase in amplitude of diurnal peak of rain rate with more than doubled amplitude of rain rate over that high mountain and more than tripled over the coast and lowland. However, this analysis needs to be confirmed with larger samples of the data in each MJO phase. Over the high mountain, a clear increase in the peak happens in phases 2 and 3. While for other regions, the increase in rainfall peak varies with the MJO phases from phases 2 to 7.

In general, Fig. 13 shows results that are consistent with Fig. 12. For example, the highest amplitude of the rain-rate peak over the east lowland and mountain is observed in phase 2 ($\approx 9.8$ and 8.2 mm h$^{-1}$, respectively) (Figs. 13b,d). At this phase, over the high mountain (in the southwest), the first peak of rain is one hour earlier (1400 LT) than is found over the low mountain (in the southeast) (1500 LT) (Fig. 13c). The timing of the afternoon peak beginning earlier in the west than the eastern part of the radar domain is also evident in the spatial map from Fig. 9. In phases 4–6, over the west lowland, the morning rain-rate peak exists in the morning between 0000 and 0900 LT (Fig. 13e) and is in agreement with the spatial map of mean $R_b$ (Fig. 6). The different time of the rainfall peak in those regions is likely due to the influence of a combined sea–mountain-breeze convergence (Qian 2008).

Figure 13 also demonstrates that over the low mountain, there is a marked double peak of rain rate beginning from afternoon time at phases 1–3 (Fig. 13c) that is in phase 2 at 1500 and 2000 LT and in phase 3 at 1400 and 1800–1900 LT. In phase 3, a slight double peak is also found in the coastal at 1200 and 1400 LT (Fig. 13a) and east lowland at 1200 and 1400 LT (Fig. 13b). After looking into more detail of the diurnal rain rate in individual MJO event, we find that there are many days with a double rainfall peak during the MJO. Thus, it might explain that although we average the diurnal rain rate across all MJO events, a signature of this double peak still can be observed. The morning peak in phase 5 shown in Fig. 8 is also captured by time series of diurnal rain-rate peak analysis in Fig. 13. It shows that in phase 5, the peak of mean rain rate exists in the early morning (0200–0300 LT) over the northwest coast (Fig. 13a) and at 0200 LT over the west lowland (Fig. 13e). Based on three transects examined over the radar domain (Fig. S7), in phase 5, a similar pattern of morning peak of rain rate over the coast was also observed in the Hovmöller analysis (Fig. S8).

d. Contribution of morning and afternoon rain rate to the mean daily rain rate

In section 3c we have shown that suppressed and active MJO were associated with rain rate occurring at different times of day, in different amounts and that topographical
FIG. 11. Hovmöller diagram for hourly mean of convective available potential energy (CAPE) over the west Java Island and sea. Shading indicates low potential (blue) and high potential of convection (red). The two vertical lines present the mountainous areas in the south (labeled 1) and coastline in the north (labeled 2).
effects were important. In this section, we further explore the contribution in $R_h$ rate between morning and afternoon and how it is responsible for affecting the mean daily rain-rate totals.

The most distinct feature is that the contribution of morning rain rate to mean daily rain rate is predominant in active phases of the MJO (phases 5 and 6). The highest contribution of morning rain rate is observed over the lowlands and mountains in the western part of radar domain and the coastal areas in the north (Fig. 14).

In contrast, the afternoon rain rate (Fig. 15) is responsible for the mean daily rain rate in the study-period mean, in suppressed phases of MJO (phases 1–3, 7–8), and in the early active phase of MJO (phase 4). The highest contribution of afternoon rain rate to the mean daily rain rate (≥12%) was found in MJO phases 1 and 2. In active phases of MJO (phases 5 and 6), a high contribution of afternoon rain rate exists over the mountain and inland regions but only in the east.

Overall, these results suggest that variation of the difference between morning and afternoon rain rate is strongly associated with mean daily rain rate. This indicates that changes of $R_h$ during the MJO are likely attributed to the variability of mean daily rain rate. It is evident that over the northern part of the domain, including ocean and coast, in phase 5, the MJO possibly induces higher morning rain
rates, which are mainly responsible for mean daily rain rate.

4. Discussion and conclusions

To our knowledge, this is the first study that uses high spatial and temporal resolution weather radar data to examine the effect of the large-scale variability of the MJO on rainfall in and around Jakarta. This region includes the most populated city in Indonesia and is prone to floods, mainly associated with heavy rain. Although previous studies have examined the intensity and frequency of extreme rain as factors that generate flooding in Jakarta, there has been little discussion about the individual phase of the MJO and its effect on the development of localized heavy rainfall in Jakarta. In

![Figure 13](image-url)
In fact, a basic understanding of the key drivers of Jakarta’s flooding from meteorological perspective is crucial to help the government formulating adaptation and mitigation plans for flooding but is incomplete due to fundamental knowledge gaps. Here, we have contributed to addressing one such knowledge gap by examining the MJO relationship with extreme rainfall and the diurnal cycle of rain in the region.

This research highlights the importance of the MJO in the enhancement of rainfall over the Jakarta region from October to April. The MJO propagation from phases 1 to 8 has a strong effect on distribution of rain rate and its magnitude. It is found that, on average, over the whole radar domain, there is a higher distribution of intense hourly mean rain rate during suppressed MJO, which is ahead of the MJO convective envelope (phase 2) (Fig. 3b). Meanwhile, there is a slight decrease in rain rate during the active MJO (phase 4–6). In contrast, the frequency of rain rate ≥ 0.5 mm h⁻¹ is found to be higher during active than suppressed MJO. This suggests that when the convective envelope of the MJO is over the region, there is higher chance of light rain rate but a smaller chance of heavier rain rate. This finding is also supported by analysis of spatial characteristics of stratiform and convective rain. It shows that in active phases (4–6), the MJO is likely to generate more stratiform than convective rain rate (Figs. 4 and 5), while the maximum convective rainfall occurs in phases 2 and 6.

This study has provided a new insight of the detailed regions...
receiving stratiform rainfall that so far has not been observed by previous studies.

The results of this study show that the different regions with their own topographic features have a particular response to a single phase of strong MJO. In general, over the mountains and lowland in the southern radar domain, the maximum of mean hourly rain rate ($R_h$) begins in earlier phases (in phases 2 and 3) relative to over the lowland and the coast in the northern part of radar (phases 5, 6) (Fig. 2). This finding is supported by the result of the large-scale condition, that in phases 5 and 6, over the lowlands and mountains in the south, the hourly mean vertical integral of divergence of moisture flux (Figs. S3 and S5), vertical velocity (Figs. S2 and S6) exhibit lower negative values and CAPE shows lower positive amplitudes (Fig. 11) relative to other phases suggesting a less favorable condition for convection. From the low-level wind perspective (Fig. 10), the wind speed also reduces in phase 5 over the lowland and mountain.

By further assessing a detailed distribution of how mean rain rate and rain-rate extremes develop during eight phases of strong MJO (Figs. 6 and 7), it is found that there is an increase of hourly rain rate mainly over the land during suppressed MJO phases (1–3, 7–8) and this finding has supported results from Fig. 2. Previous research suggests that this happens as a result of the enhancement of diurnal cycle due to less cloud coverage and strong shortwave radiation triggering...
the convection over the land (Birch et al. 2016; Hagos et al. 2016; Oh et al. 2012; Qian 2020). By analyzing daily rainfall properties, Hidayat and Kizu (2010) also found that over land in West Java, the peak of daily rainfall occurs in phase 3. By using higher temporal and spatial resolutions of hourly rainfall from radar, our study finds strong spatial heterogeneity in MJO–rainfall relationships. During suppressed MJO periods, previous research also observed that rainfall was generally caused by thermally induced local circulation over southern part of West Java (Ogawa et al. 2017). The heterogeneity of mean rain rate and extreme rain rate peaks over a relatively small area like Java Island, particularly Jakarta, highlights the need for high-resolution observational products and model simulations to understand rainfall processes in the region.

The present finding also shows that the MJO has an effect on the formation of rain rate in the morning and afternoon. In phase 5 where the MJO is active (moves through the IMC), the morning rain rate starts to develop over the northeastern coast and western domain (it is around 1.2 mm h$^{-1}$ higher than the afternoon rain). By using TRMM 3B42, former research also captured that in phase 5, a morning rainfall peak is found over the ocean as well as over the northern coast and west Java Island (Oh et al. 2012), but our study adds information about more specific regions experiencing morning rainfall. A higher morning rain rate over those regions is not found in the mean rain rate (by including study-period mean, Fig. 8) suggesting that the MJO likely plays a role in initiating morning rain over the northern coast and western lowland as well as mountains. During MJO phases 5–6, areas with a high frequency of stratiform rain are located in similar areas with morning rain (Figs. 4, 8, and 9). This suggests that morning rain might be predominantly stratiform in nature. This result supports a previous study that indicated predominance of stratiform rain in the morning (Katsumata et al. 2018), but our study has used longer datasets and specified a detailed spatial distribution of where the stratiform rainfall exists.

In the current research, we found that the MJO might be responsible for delaying and accelerating timing of the diurnal rain-rate peak. During suppressed MJO (phases 1 and 2), some areas in the west and south of the radar domain, over mountains and lowland, the maximum rain rate occurs around 1500–1800 LT (3 h later than study-period mean) (Fig. 9). This finding is also consistent with the highest diurnal rain-rate peak over the lowland and mountain pixels, which also occurs after late afternoon (1500 LT) (Figs. 13a.e). The most distinct feature is that during the active phase (5), an earlier morning peak at 2100–0900 LT is found over the north coast and western part of radar (Fig. 9), which is also observed in maximum diurnal rain rate over the area representing the northwest coast and west lowland (Fig. 13a.e). It is therefore likely that when the MJO is active (over the IMC), the occurrence of rain rate has developed much earlier than in the suppressed MJO. In phase 5, over the eastern radar, the MJO also delays the peak by about 4 h (1800–2100 LT) relative to the study-period mean.

The MJO does not only affect the timing of the rain but also appears to increase the amplitude of the diurnal rain-rate cycle. The largest diurnal peaks are recorded during the suppressed MJO and over the east lowland and mountain in the south of the radar domain. Compared to study-period mean, the peak of rain rate during suppressed MJO has increased by about 2.5 times greater over the mountain (Fig. 13d) and 3 times greater over the lowland and the coast (Figs. 13a,b). In general, over the coast, amplitude of maximum diurnal rain-rate cycle both in the study-period mean and in strong MJO phases is relatively weak compared to other regions (Fig. 13).

Another feature is that when the strong MJO still lies over the Indian Ocean, double peaks of diurnal rain rate are found over the low mountain. A very clear double peak is observed in phase 2 at 1500 and 2000 LT as well as in phase 3 at 1400 and 1800–1900 LT (Fig. 13c). A high-resolution model and CMORPH datasets were also able to capture the signature of the double peaks during strong MJO even though it was very weak (Vincent and Lane 2016). Our study adds to the previous analysis in finding that the MJO is associated with a double peak of rain rate particularly over the land.

In this study, mean hourly rain rate in the afternoon or evening is found to contribute to the amplitude of mean daily rain rate. The most distinct pattern is that, during the active MJO (particularly in phase 5), morning rain rate is mostly responsible for the amplitude of mean daily rain rate over the lowland and mountain in the western part of radar domain, and this signature is not even detected in the other strong MJO phases (Fig. 14).

To conclude, this study demonstrates a vital role of topographical effects in the organization of local-scale rain rate over Jakarta during strong MJO phases. The results extend our knowledge on how each area’s topography is related to rainfall in each phase of strong MJO with distinct features in the timing of the diurnal rainfall peak and its magnitude. The current finding serves a base for future studies. The local effects of the MJO on rainfall are vital to understand for a topographically complex region like the IMC, so useful weather predictions and climate projections of Jakarta rainfall and its impacts may be possible.

Acknowledgments. This research is supported by the Australia Award Scholarship (AAS), Hadi Soesastro Prize, and the Australian Research Council (ARC) Centre of Excellence for Climate Extremes (CLEX) (CE170100023). We thank the Center for Regional Resources Development (PTPSW)-BRIN, Indonesia, together with the Japan Agency for the Marine-Earth Science and Technology (JAMSTEC), Japan for providing C-band Doppler radar from “Hydrometeorological Array for Intraseasonal Variation-Monsoon Automoitoring (HARIMAU)” Project (JFY 2005-2009), and the Science Technology Research Partnership for Sustainable Development (SATREPS) “Maritime Continent Center of Excellence (MCCOE)” Project (JFY 2009-2013) of the Japan Science and Technology Agency (JST)/Japan International Cooperation Agency (JICA). This research was conducted with the assistance of the resources and services from the National Computational Infrastructure (NCI), which is supported by the Australian Ministry of Education, Culture, Sports, Science and Technology (MEXT). This work also benefits from the collaboration with the Global Precipitation Measurement (GPM) Mission Team, the University of Tokyo, and the Japan Agency for Marine-Earth Science and Technology.
government. A. King is supported by the ARC DECRA Fellowship (DE180100638) and C. Vincent is supported by the ARC CLEX (CE170100023).


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