Impacts of the Madden–Julian oscillation on precipitation extremes in Indonesia

Fadhlil R. Muhammad1,2 | Sandro W. Lubis3 | Sonni Setiawan2

1School of Earth Sciences, The University of Melbourne, Melbourne, Australia
2Department of Geophysics and Meteorology, IPB University, Bogor, Indonesia
3Rice University, Houston, Texas

Abstract
The influence of the Madden–Julian oscillation (MJO) on the precipitation extremes in Indonesia during the rainy season (October to April) has been evaluated using the daily station rain gauge data from 1987 to 2017 and the gridded Asian Precipitation–Highly Resolved Observational Data Integration Towards Evaluation of Water Resources (APHRODITE) from 1998 to 2015 for different phases of the MJO. The results show that MJO significantly modulates the frequency of extreme precipitation events in Indonesia, with the magnitude of the impact varying across regions. Specifically, the convectively active (suppressed) MJO increases (decreases) the probability of extreme precipitation events over the western and central parts of Indonesia by up to 70% (40%). In the eastern part of Indonesia, MJO increases (decreases) extreme precipitation probability by up to 50% (40%). We attribute the differences in the probability of extreme precipitation events to the changes in the horizontal moisture flux convergence induced by MJO. The results indicate that the MJO provides the source of predictability of daily extreme precipitation in Indonesia.

Keywords
extreme precipitation, extreme probability, intraseasonal variability, MJO

1 | INTRODUCTION

Madden–Julian oscillation (MJO) is the major intraseasonal (30–60 days) variability in the tropics, characterized by the eastward propagation of cloud clusters and precipitation from the Indian Ocean to the western Pacific Ocean (Madden and Julian, 1971). The peak MJO signals are located over the Indian Ocean (eastern Pacific Ocean) during boreal winter (boreal summer) and are dominated by mean westerlies or weak mean zonal winds at 850 hPa and the surface (Zhang and Dong, 2004). During boreal winter, the interaction of MJO and topography causes the MJO to propagate eastward and southward in the Maritime Continent (MC) before it reaches the western Pacific Ocean (Inness and Slingo, 2006; Peatman et al., 2013). MJO brings in organized convection and associated circulation favouring a region for rainy or dry conditions depending on its phase. Previous studies have shown that MJO can influence the frequency and intensity of global precipitation and temperature events (Seto et al., 2004; Barlow et al., 2005; Barlow and Salstein, 2006; Jeong et al., 2008; Wheeler et al., 2009; Lin et al., 2010; Lu et al., 2012; Zhou et al., 2012; Ren and Ren, 2017).

Precipitation in Indonesia exhibits substantial variability at the synoptic to intraseasonal time scales (Kripalani and Kulkarni, 1997; Aldrian and Dwi Susanto, 2003; Hendon, 2003; Aldrian et al., 2004; Moron et al., 2010; Qian et al., 2010; As-syakur et al., 2013; Yanto et al., 2014).
2016). On the interannual time-scales, El-Nino Southern Oscillation (Aldrian and Dwi Susanto, 2003; Hendon, 2003; Hamada et al., 2012; Rakhman et al., 2017) and Indian Ocean Dipole (Hamada et al., 2012; Nur’utami and Hidayat, 2016; Muhammad et al., 2019) are the largest contributors to monthly precipitation variance, while the southeast and northwest monsoons strongly influence seasonal precipitation variance in Indonesia (Hamada et al., 2002; Aldrian and Dwi Susanto, 2003). The monsoonal precipitation is mostly observed over the Indonesian regions with a rainy (dry) season starting from November to February (June to August) (Aldrian and Dwi Susanto, 2003). On the daily to intraseasonal time-scales, the variability of precipitation in Indonesia is explained by MJO and convectively coupled equatorial waves (CCEWs). MJO that contributes up to 50% of the total variance (Waliser et al., 2009), while CCEWs contribute up to 12% of the total variance (Lubis and Jacobi, 2015).

The influence of the MJO on Indonesian precipitation variability has been generally discussed by several authors (Jones et al., 2004; Hidayat and Kizu, 2010; Xavier et al., 2014). A detailed explanation of the influences of the MJO on precipitation in Indonesia has been demonstrated by Hidayat and Kizu (2010). They showed that during austral summer, the MJO increases (decreases) Indonesian precipitation by up to 5 mm day$^{-1}$ during Phases 2–4 (Phases 6–8). In terms of precipitation extremes, the convectively active phases of MJO increase extreme precipitation events in the tropical precipitation as part of a global response by approximately 15–20% (Jones et al., 2004). More recently, Xavier et al. (2014) quantified the probability changes in the extreme precipitation over Southeast Asia and its relationship to large-scale circulation during boreal winter. They found that the MJO increases (decreases) the probability of extreme precipitation by up to 30–50% on Phases 2–4 (10–20% on Phases 6–8). While Xavier et al. (2014) have provided a general view on the MJO impacts on extreme precipitation over Southeast Asia, a detailed analysis of such links on the spatial distribution of “regional” precipitation extremes over the land regions Indonesia remains unclear and is worthy for further investigation. Understanding the impact of MJO on regional precipitation extremes in Indonesia is essential, owing to the different nature of MJO characteristics over different parts of Indonesia (Hidayat and Kizu, 2010). The two main questions we would like to address in this study are as follows:

1. What are the effects of the MJO on regional precipitation extremes in Indonesia?
2. What is the underlying dynamics of the MJO impacts on regional precipitation extreme events in Indonesia?

The data sets and methods are described in Section 2. Results and discussions are presented in Section 3. The conclusions of the study are offered in Section 4.

2 | DATA AND METHODS

To study the impact of the MJO on extreme daily precipitation in Indonesia, we use gridded precipitation data from Asian Precipitation - Highly Resolved Observational Data Integration Toward Evaluation of Water Resources (APHRODITE) (V1901, Yatagai et al., 2012) from 1998 to 2015, with a spatial resolution of 0.25° x 0.25°. APHRODITE comprises data collected from 12,000 rain-gauge stations across the globe. The interpolation was done by taking the topography effects into account, resulting in a more accurate representation of the precipitation over the mountainous regions (Schake, 2004). Furthermore, in order to support the results obtained from APHRODITE, we also use an extensive high-quality rain-gauge database operated by BMKG for the period of 1987 to 2017, from 63 stations in Indonesia (Figure 1b). We only select the rain-gauge stations with data having less than 20% of missing observations.

To understand the dynamical links between extreme precipitation events and large-scale circulations, we use interpolated outgoing longwave radiation (OLR) as a proxy for convection obtained from NOAA/NESDIS (Liebmann and Smith, 1996). Furthermore, we also use the relative humidity, horizontal and vertical wind, and air temperature data at various levels (1000–100 hPa) obtained from the National Center for Environmental Prediction R-2 (NCEP/DOE Reanalysis 2) (Kanamitsu et al., 2002) with a spatial resolution of 2.5 × 2.5° for the period of 1998–2015.

The MJO events are defined based on Real-time Multivariate MJO Index (RMM) (Wheeler and Hendon, 2004). The multivariate EOF is calculated from the zonal wind anomalies at 850 and 200 hPa, and OLR anomalies. The two leading principal components of the multivariate EOF are then defined as the real multivariate MJO indices (RMM1 and RMM2). These indices are then used to calculate the amplitude of the MJO events as $\sqrt{(RMM1^2 + RMM2^2)}$. The MJO is considered as a strong (weak) event if the amplitude is higher (less) than 1. Furthermore, the MJO event is divided into eight phases, where each phase of the MJO indicates the location of the MJO convective center. The convective center of the MJO propagates eastward from west Africa (Phase 1) to the east, passing over the Indian Ocean (Phases 2 and 3), MC (Phases 4 and 5), migrating to the western Pacific (Phases 6 and 7) and decaying at Phase 8.

In order to examine the probability changes of extreme precipitation, we use a probability composite analysis, as described in the study by Wheeler et al. (2009). First, we select the data for the period of the rainy season (from
October to April) and then categorize the ‘strong’ MJO events for each phase, as in the study by Wheeler and Hendon (2004). Second, we calculate the cumulative probability of daily precipitation events that exceed the 95th percentile of precipitation for all wet days in the season ($P_{\text{WETDAYS}}$) and each phase of the MJO ($P_{\text{MJO}}$). Finally, we calculate the probability changes as (Ren and Ren, 2017):

$$\Delta P = \frac{P_{\text{MJO}} - P_{\text{WETDAYS}}}{P_{\text{WETDAYS}}} \times 100\%,$$

where $\Delta P$ is the probability changes in extreme events for each phase of MJO.

To elucidate the underlying dynamics of the MJO’s impact on precipitation extremes, we also analyse the composites of OLR, vertical wind component ($\omega$), vertically integrated moisture flux convergence (VIMFC), and vertical moisture advection anomalies for each phase of MJO. The moisture flux convergence and vertical moisture advection are derived from the moisture budget equation defined as (Banacos and Schultz, 2005):

$$\frac{\partial q}{\partial t} \bigg|_{\text{local moisture tendency}} - \left( \nabla \cdot (q \mathbf{u}_H) \right) \bigg|_{\text{horizontal moisture flux convergence}} - \left( q \frac{\partial w}{\partial p} \right) \bigg|_{\text{vertical moisture convergence}} - \left( w \frac{\partial q}{\partial p} \right) \bigg|_{\text{vertical moisture advection}} = (P_r - E) \bigg|_{\text{sources and sinks}},$$

FIGURE 1 (a) Mean and (b) 95th percentile of daily precipitation superimposed with 850-hPa horizontal wind during the rainy season (Oct to Apr). Circles denote the location of in situ measurements of precipitation [Colour figure can be viewed at wileyonlinelibrary.com]
where $q$ is the specific humidity, $p$ is the pressure, $u_H$ is the horizontal component of wind, $\omega$ is a vertical component of wind, $E$ is evaporation, and $P_a$ is precipitation. The primes denote filtered anomaly fields with a high-frequency cutoff of 20 days and a low frequency of 100 days to retain the MJO signals. In order to obtain the VIMFC, the horizontal moisture flux convergence term is then vertically integrated as follows (van Zomeren and van Delden, 2007):

$$
\text{VIMFC} = -\frac{1}{g} \int_{1000 \text{ hPa}}^{100 \text{ hPa}} \left[ -\left( \vec{V} \cdot (q \vec{u}_H) \right) \right] dp,
$$

where $g$ is the gravity (9.81 ms$^{-2}$). Due to the lack of specific humidity data in NCEP/DOE Reanalysis 2, we calculate the specific humidity from this formulation:

$$
q = q_s \times \text{RH},
$$

where RH is the relative humidity and $q_s$ is the saturated specific humidity calculated as:

$$
q_s = \frac{(0.622 \times e_s)}{(p - 0.378 \times e_s)},
$$

where $p$ is the pressure and $e_s$ is the saturated pressure, which can be calculated using the Clausius–Clapeyron formula as:

$$
e_s = 6.11 \text{ mb} \times \left( \frac{1}{273.15} - \frac{1}{T} \right),
$$

where $l_{wv} = 2.5 \times 10^6 \text{ Jkg}^{-1}$ is the latent heat of transformation of water to vapour, $R_v = 461.5 \text{ Jkg}^{-1} \text{ K}^{-1}$ is the specific gas constant for water vapour, and $T$ is the temperature.

The significant test for each composite is done by using a bootstrap method (Wilks, 2006). In this method, for each phase of the MJO, we generate 1,000 synthetic composites by randomly selecting samples of events to derive a bootstrapped mean and confidence limits. The 1,000 synthetic composites are then sorted to find the 2.5th and 97.5th percentiles for a two-tailed test, with significance at 95% level, or fifth and 95th for significance at a 90% level. Then, we compare the real composites for each phase of the MJO with the percentile levels of the synthetic composites.

### 3 RESULTS AND DISCUSSIONS

#### 3.1 MJO impact on extreme precipitation in Indonesia

#### 3.1.1 Spatial distribution of precipitation anomalies

We begin our analysis with an examination of the MJO impact on the spatial distribution of precipitation anomalies over Indonesia. Figure 1 shows the composite of APHRODITE precipitation anomalies (in mm/day) at each of the MJO phases during the rainy season. In general, the increase in precipitation tends to reach their maxima over the large landmasses of Indonesia during Phases 2–4 (Figure 2b–d). In Phases 5–8 (Figure 2e–h), the variation of precipitation anomalies exhibits a pattern similar to those in Phases 1–4 (Figure 2a–d), but with the opposite sign. The average increases (decreases) of precipitation in Phases 2–4 compared to Phases 5–8 is about 2–6 mm-day$^{-1}$, approximately 20–30% of the seasonal mean precipitation (Figure 1a). In addition, it is clearly seen that the positive precipitation anomalies due to the MJO has already been observed in Indonesia during Phases 1 and 2, while the MJO convective center is still located over the Indian Ocean. This leaping ahead of the MJO envelope is known as a “vanguard” effect of precipitation (Matthews et al., 2013; Peatman et al., 2013). This effect is seen only over the MC and is mainly triggered by the diurnal cycle of convective activity ahead of the MJO envelope and by the enhanced topographic frictional moisture convergence associated with the Kelvin and Rossby waves (Matthews et al., 2013; Peatman et al., 2013).

The variation of the MJO-induced precipitation anomalies obtained from the APHRODITE (Figure 2) is consistent with the observed precipitation data from the rain-gauge stations (Figure 3). In particular, the MJO tends to increase (decrease) the precipitation during Phases 2–4 (Phases 5–8), by which the average increase (decrease) of precipitation anomalies is about 1–4 mm-day$^{-1}$. In addition, the precipitation response from the rain-gauge stations is more inhomogeneous compared to that of the APHRODITE. This inhomogeneous response could be due to strong local effects in some regions in Indonesia, such as over the western and central part of Java (Hidayat and Kizu, 2010).

In summation, the results show that the influence of the MJO on the precipitation over Indonesia is robust in both the rain-gauge data and gridded precipitation data, especially during Phases 2–4 (Phases 6–8) for the positive (negative) anomalies. Next, we will examine how the MJO influence the likelihood of extreme precipitation events in Indonesia.
3.1.2 Spatial distribution of precipitation extremes

Figure 1 shows the distribution of mean and 95th percentile precipitation at each grid point during the rainy season (October to April). The 95th percentile precipitation is used as a threshold to determine extreme precipitation events (Wheeler et al., 2009; Xavier et al., 2014). We quantify the impact of MJO on extreme precipitation as the percentage change of the cumulative probability of extreme events ($P_{\text{MJO}}$) relative to the baseline probability ($P_{\text{WEITDAYS}}$) (see Equation (1)).

Figure 4 shows the percentage of changes in extreme precipitation probability for each phase of the MJO from the observed gridded precipitation data. In general, the changes in the probability of extreme events due to the MJO are consistent with the distribution of MJO-induced precipitation anomalies (Figures 2 and 3), in which the Phases 2–4 (Phases 6–8) produce significantly increased (decreased) extreme precipitation probabilities over the region (see Figures 4 and 5). A cursory inspection of Figure 4 shows that the increase in the probability of extreme events over the land regions on Phase 2 is up to 60% over the west of Sumatra and Borneo during the rainy season (Figure 4b). The maximum increase is observed during Phase 3 (Figure 4c,d) by up to 100% over the western coast of Sumatra and 70–80% over Java and Papua (Figure 4c). On the other hand, the increase in the probability during Phase 4 is higher over Borneo and Sulawesi compared to that of Phase 3. However, the increase is significantly lower over Sumatra and Java (Figure 4c,d). During Phase 5, the MJO decreases the probability of extreme events over most of the western part of Indonesia (e.g., Sumatra and west of Borneo),
while increases the probability over the southeastern part of Indonesia (Figure 4e). Finally, as the suppression phases of the MJO becomes dominant during Phases 6–8 (Figure 4f–h), the MJO mainly decreases the probability of extreme events by up to 80% over Sumatra, the northwestern part of Papua, Maluku, and north of Sulawesi during Phase 6, over the western part of Borneo, Central Java, and the coastal island to the west of Sumatra during Phase 7, and the southern part of Borneo, Sulawesi, and southeastern part of Indonesia during Phase 8.

In order to validate the results obtained from APHRODITE over the land regions, we also examine the impact of the MJO on extreme precipitation events based on rain-gauge data. Figure 5 shows the probability composites of extreme events observed by rain-gauge stations for each phase of the MJO. We find that the impact of the MJO on extreme events observed by rain-gauge stations is generally consistent with the APHRODITE (Figure 4). The increase (decrease) in the probability of extreme events is evident at Phases 2–4 (Phases 6–8) (Figure 5b–d, f–h). The strongest impact is observed during Phases 3 and 4, which increases the probability of extreme precipitation events by more than 50% (Figure 5c,d). During Phases 6–8, the MJO mainly decreases the probability of extreme precipitation events in Indonesia (Figure 5f–h), except over the western and central parts of Java during
Phase 7 or 8 that could be affected by the local effects, such as topography (Hidayat and Kizu, 2010) and the effect of diurnal cycle (Peatman et al., 2013).

To better understand the impact of the MJO on regional extreme precipitation events, we further calculate the average percentage of changes in the probability for four sectors in Indonesia, including the West, North, South, and eastern parts of Indonesia based on their geographical locations (Figure 6). In general, it can be clearly seen that the impact of the MJO is the strongest over the western part of Indonesia, with a maximum probability of around 70% or about 20% higher than the other regions. In particular, the increase (decrease) in extreme probability over the western part of Indonesia begins from Phases 1–4 (5 to 1), with the maximum increase (decrease) up to 70% (40%) during Phase 3 (Phase 5) (Figure 6). Furthermore, as the convective envelope of the MJO propagates further eastward, the associated impact also migrates to the northern and southern parts of Indonesia. Both sectors experience an increase in the probability of extreme events during Phases 2–4, with the maximum by up to 50% during Phase 3. In the southern (northern) part of Indonesia, the maximum decrease occurs during Phase 1 (Phase 7) by up to 50% (35%). On the other hand, the increase (decrease) of extreme probability over the eastern part of Indonesia occurs from Phases 3 to 5 (Phases 6 to 2), with the maximum increase (decrease) by about 50% (40%) during Phase 4 (Phase 1).

Overall, the results indicate that the impact of the MJO on extreme precipitation events is robust and varying across regions in Indonesia. The probability of extreme precipitation increases (decreases) on the days when the MJO wet (dry) phase is occurring. In the next

**FIGURE 4** Percentage changes in the probability of extreme events during different phases of MJO (a–h). Dots indicate values significant at 90% confidence level [Colour figure can be viewed at wileyonlinelibrary.com]
section, we will investigate the underlying mechanisms that are responsible for elucidating such impacts.

3.2 | Dynamical links between precipitation extremes and MJO

To understand the dynamical factors contributing to the MJO-induced extreme precipitation events, we examine two important processes that are responsible for modulating the precipitation anomalies, namely the vertical moisture flux convergence of moisture (Banacos and Schultz, 2005; van Zomeren and van Delden, 2007; Adames and Wallace, 2014; Adames, 2017; Kirshbaum et al., 2018; Wu et al., 2020) and the vertical advection of moisture (Benedict and Randall, 2007; O’Gorman and Schneider, 2009; Adames and Wallace, 2014; Ren and Ren, 2017).

Figure 7 shows the composite anomalies of OLR (shading) and VIMFC (contour) for each phase of the MJO during the rainy season. It is shown that the enhanced (suppressed) convective activity and moisture convergence (divergence) are linked to the positive (negative) changes in precipitation anomaly and extreme precipitation probability. During Phases 1 and 2, the enhanced moisture

![FIGURE 5 Percentage changes in the probability of extreme events observed by rain gauges (triangle) and the APHRODITE (shading). Filled triangle and dots indicate values significant at 90% confidence level for the rain gauge data and the APHRODITE data, respectively.](Colour figure can be viewed at wileyonlinelibrary.com)
convergence has already extended over the western and northern parts of Indonesia (Figure 7a,b), although the enhanced convection associated with the MJO has not reached these regions yet. This enhanced moisture convergence contributes to an increase in precipitation anomaly and extreme precipitation probability (Figures 2, 3a,b, and 4-6a,b), which is likely to be associated with topography-enhanced Kelvin wave responses over those regions (Matthews et al., 2013; Peatman et al., 2013). Furthermore, we observed strong convergence over the western part of Indonesia during Phase 3 (Figure 7c), which is overall consistent with an increase in the precipitation anomaly and probability of extreme precipitation (Figures 2, 3c, 4, 5c, and 6a). As the convectively active phase of the MJO moves eastward over to the MC during Phase 4 (Figure 7d), we observed moisture convergence extending over most regions in Indonesia, but with weaker convective activity compared to the Phase 3. The moisture convergence and convective activity during Phase 4 are consistent with
enhanced precipitation and extremes over most regions in Indonesia. During Phases 5–8 (Figure 7e–h), the variation of VIMFC and OLR anomalies exhibits a pattern similar to that of Phases 1 through 4 (Figure 7a–d), but with the reversed sign. This indicates that the decrease in precipitation anomalies and extreme events are caused by a decreased horizontal moisture flux convergence induced by the MJO (Figures 2, 3e–h, 4m, and 5e–h).

The enhanced (suppressed) VIMFC and OLR in each phase of the MJO are consistent with enhanced (suppressed) upward (downward) motion of moist air over the region. Figure 8 shows a cross section of vertical moisture advection anomalies (colour shading), and wind velocity (vectors) for each phase of the MJO averaged over 11°S–11°N. It can be clearly seen that an increase (decrease) of precipitation and extremes is linked to an increase of upward (downward) moisture advection in the troposphere during the rainy season. In particular, during Phases 2 through 4 (Figure 8b–d), the upward motion of moist air favours moisture entrainment at low to the middle-level troposphere. This supports the development of convection over the MC, consistent with previous findings (Benedict and Randall, 2007; Xavier et al., 2014). In contrast, the downward advection of moisture to the east of central convection of the MJO depletes water vapour at the mid-level troposphere (Wang et al., 2019). During Phase 3, we observe enhanced vertical moisture advection from 90°E to 120°E over the western parts of Indonesia (Figure 8c). It is seen that the strongest advection is observed over the western part of Sumatra (90–95°E) between 1,000 and 300 hPa level, while a downward advection is observed between 1,000 and 700 hPa level over the eastern parts of Indonesia (135–145°E). This strong advection accompanied by the convergence of westerly wind burst and local easterly mountain wind over Sumatra (Figures 7c and 8c) further induces a strong MJO impact on the precipitation over Sumatra (Figures 2, 3c, 4, and 5c) (Wu et al., 2017). As
the upward moisture advection moves eastward during Phase 4, the increase in the precipitation and extreme events is observed over most regions in Indonesia (Figures 2, 3d,f, 4, and 5d). During Phase 5, we observe enhanced upward moisture advection over 120–140°E (Figure 8e). This upward vertical motion is noticeably...

**FIGURE 8** Vertical cross section of vertical moisture advection ($\times 10^{-6}$ kg kg$^{-1}$ s$^{-1}$) (shading) and wind (vector) anomalies during different phases of MJO. Shaded values are significant at the 95% level [Colour figure can be viewed at wileyonlinelibrary.com]
strong at 135°E and between 1,000 and 300 hPa, consistent with high precipitation over the eastern part of Indonesia (Figures 4, 5e, and 6c). Finally, throughout Phases 6–8 (Figure 8f–h), a similar pattern is observed as in Phases 2–4 (Figure 8b–d), except with reversed signs. During these phases, the downward moisture advection occurred across most regions in Indonesia and is consistent with relatively drier days in these regions.

To sum up, we find that the enhanced (suppressed) moisture flux convergence induced by the MJO is the key mechanism that contributes to the increased (decreased) precipitation anomaly and extreme precipitation events over Indonesia during different phases of the MJO. This enhanced (suppressed) VIMFC is consistent with enhanced (suppressed) upward (downward) motion of moist air over these regions.

4 SUMMARY AND DISCUSSION

We have examined the impact of the MJO on the frequency of precipitation extremes in Indonesia during the rainy season (October to April) using the high-quality daily rain gauge data from 63 stations and the gridded precipitation APHRODITE data. We found that MJO can significantly modulate the frequency and intensity of extreme precipitation events in Indonesia. A detailed analysis of the impacts of the MJO on extreme precipitation in Indonesia reveals the following key results:

1. The convectively active phases of the MJO increase the probability of extreme precipitation events by more than 50% over most areas in Indonesia during Phases 3 and 4.
2. The convectively suppressed phases of the MJO decrease the probability of extreme precipitation events by about 40–70% over Sulawesi and Papua during Phases 1 and 2, and over Java, Sumatra, and Borneo islands during Phases 5 and 6.
3. The western part of Indonesia experiences the strongest impact of the MJO, while the impact over the southern part of Indonesia is relatively weaker due to strong interference with local effects.
4. The impact of the MJO on extreme precipitation over Indonesia can be explained through the changes in the moisture flux convergence and the vertical advection of the moist air. The increase (decrease) in MJO-induced moisture flux convergence leads to a high (low) likelihood of extreme precipitation in Indonesia.

It is noteworthy that the impacts of the MJO on extreme precipitation events are largely inhomogeneous over the land regions. It is possible that this is caused by a unique interaction between MJO-induced circulation and lower boundary forcing, such as topography and local effects (Hsu and Lee, 2005; Wu and Hsu, 2009; Hidayat and Kizu, 2010; Kim et al., 2017) and also with the convectively coupled equatorial waves (Lubis and Jacobi, 2015; Baranowski et al., 2020). In addition, the role of other large-scale atmospheric variabilities can also affect the extreme precipitation in some regions of Indonesia. For example, the quasi-biweekly oscillation is partly responsible for the increase of extreme precipitation probability over the western part of Sumatra (Wen and Zhang, 2008), while the influence of cold surge and Borneo vortex can modulate the extreme precipitation probability over the western and northern parts of Borneo (Chang et al., 2005; Lim et al., 2017). Moreover, according to the previous studies, the amount of precipitation over some regions in Indonesia (e.g., Java, Borneo, and Sumatra) have an increasing trend, meaning that the probability of the extreme precipitation may increase in the future (Avia, 2019; Siswanto et al., 2015; Tangang et al., 2020). A detailed examination of the impact on different propagation characteristics of MJO over the MC, as well as the underlying mechanisms of the inhomogenous impact of the MJO on precipitation extremes due to the diurnal cycle, are subjects for a future study.

Overall, the results indicate that the MJO provides the source of predictability of extreme precipitation in Indonesia. This suggests that the skill in probabilistic prediction of extreme daily precipitation in Indonesia would be dependent on the prediction skill of the MJO in the operational weather models and the modelled relationship between MJO and convection.

ACKNOWLEDGEMENTS

The authors are grateful for the generous and insightful comments of Eddy Hermawan, Givo Alsepan, Rahmat Hidayat, Matthew Wheeler, and three anonymous reviewers. This work was supported by Ikatan Alumni Fakultas Ekonomi dan Bisnis Universitas Indonesia (ILUNI FEB UI) Scholarship, Direktorat Jenderal Pendidikan Tinggi (DIKTI) under PPA Scholarship, and Lembaga Pengelola Dana Pendidikan (LPDP) Scholarship. More detailed information about the data can be found at the APHRODITE web page (http://aphrodite.st.hirosaki-u.ac.jp/products.html) and BMKG data online web page (http://dataonline.bmkg.go.id/home).

CONFLICT OF INTEREST

The authors report that they have no conflict of interest.

ORCID

Fadhlil R. Muhammad https://orcid.org/0000-0003-1250-4663
Sandro W. Lubis https://orcid.org/0000-0001-6615-9880
REFERENCES

Adames, A.F. (2017) Precipitation budget of the Madden–Julian oscillation. *Journal of the Atmospheric Sciences*, 74, 1799–1817. https://doi.org/10.1175/jas-d-16-0242.1.

Adames, A.F. and Wallace, J.M. (2014) Three-dimensional structure and evolution of the MJO and its relation to the mean flow. *Journal of the Atmospheric Sciences*, 71, 2007–2026. https://doi.org/10.1175/JAS-D-13-0254.1.

Aldrian, E., Dümenil-Gates, L., Jacob, D., Podzun, R. and Gunawan, D. (2004) Long-term simulation of Indonesian rainfall with the MPI regional model. *Climate Dynamics*, 22, 795–814. https://doi.org/10.1007/s00382-004-0418-9.

Aldrian, E. and Dwi Susanto, R. (2003) Identification of three dominant rainfall regions within Indonesia and their relationship to sea surface temperature. *International Journal of Climatology*, 23, 1435–1452. https://doi.org/10.1002/joc.950.

As-syakur, A.R., Tanaka, T., Osawa, T. and Mahendra, M.S. (2013) Indonesian rainfall variability observation using TRMM multisatellite data. *International Journal of Remote Sensing*, 34, 7723–7738. https://doi.org/10.1080/01431161.2013.826837.

Avia, L.Q. (2019) Change in rainfall per-decades over Java Island, Indonesia. *IOP Conference Series: Earth and Environmental Science*, 374, 012037. https://doi.org/10.1088/1755-1315/374/1/012037.

Banacos, P.C. and Schultz, D.M. (2005) The use of moisture flux convergence in forecasting convective initiation: historical and operational perspectives. *Weather and Forecasting*, 20, 351–366. https://doi.org/10.1175/WAF858.1.

Baranowski, D.B., Flatau, M.K., Flatau, P.I., Karnawati, D.I., Barabasz, K., Labuz, M., Latos, B., Schmidt, J.M., Paski, J.A.I. and Marzuki, M. (2020) Social-media and newspaper reports reveal large-scale meteorological drivers of floods on Sumatra. *Nature Communications*, 11, 1–10. https://doi.org/10.1038/s41467-020-16171-2.

Barlow, M. and Salstein, D. (2006) Summertime influence of the Madden-Julian Oscillation on daily rainfall over Mexico and Central America. *Geophysical Research Letters*, 33, L21708. http://dx.doi.org/10.1029/2006GL027738.

Barlow, M., Wheeler, M., Lyon, B. and Cullen, H. (2005) Modulation of daily precipitation over Southwest Asia by the Madden--Julian oscillation. *Monthly Weather Review*, 133, 3579–3594. https://doi.org/10.1175/MWR3026.1.

Benedict, J.J. and Randall, D.A. (2007) Observed characteristics of the MJO relative to maximum rainfall. *Journal of the Atmospheric Sciences*, 64, 2322–2354. https://doi.org/10.1175/JAS3968.1.

Chang, C.P., Harr, P.A. and Chen, H.-J. (2005) Synoptic disturbances over the equatorial South China Sea and western maritime continent during boreal winter. *Monthly Weather Review*, 133, 489–503. https://doi.org/10.1175/MWR2686.1.

Hamada, J.-I., Yamanaka, M.D., Matsumoto, J., Fukao, S., Winarso, P.A. and Sribinimawati, T. (2002) Spatial and temporal variations of the rainy season over Indonesia and their link to ENSO. *Journal of the Meteorological Society of Japan. Ser. II*, 80, 285–310. https://doi.org/10.2151/jmsj.80.285.

Hamada, J.-I., Mori, S., Kubota, H., Yamanaka, M.D., Haryoko, U., Lestari, S., Suliastiyowati, R. and Syamsudin, F. (2012) Interannual rainfall variability over northwestern Jawa and its relation to the Indian Ocean dipole and El Niño-southern oscillation events. *SOLA*, 8, 69–72. https://doi.org/10.2151/sola.2012-018.

Hendon, H.H. (2003) Indonesian rainfall variability: impacts of ENSO and local air-sea interaction. *Journal of Climate*, 16, 1775–1790.

Hidayat, R. and Kizu, S. (2010) Influence of the Madden–Julian oscillation on Indonesian rainfall variability in austal summer. *International Journal of Climatology*, 30, 1816–1825. https://doi.org/10.1002/joc.2005.

Hsu, H.-H. and Lee, M.-Y. (2005) Topographic effects on the eastward propagation and initiation of the Madden–Julian oscillation. *Journal of Climate*, 18, 795–809. https://doi.org/10.1175/1175-JCLI-3292.1.

Inness, P.M. and Slingo, J.M. (2006) The interaction of the Madden–Julian oscillation with the maritime continent in a GCM. *Quarterly Journal of the Royal Meteorological Society*, 132, 1645–1667.

Jeong, J.-H., Kim, B.-M., Ho, C.-H. and Noh, Y.-H. (2008) Systematic variation in wintertime precipitation in East Asia by MJO-induced extratropical vertical motion. *Journal of Climate*, 21, 788–801. https://doi.org/10.1175/2007JCLI1801.1.

Jones, C., Waliser, D.E., Lau, K.M. and Stern, W. (2004) Global occurrences of extreme precipitation and the Madden–Julian oscillation: observations and predictability. *Journal of Climate*, 17, 4575–4589. https://doi.org/10.1175/1175-JCLI-3238.1.

Kanamitsu, M., Ebisuzaki, W., Woollen, J., Yang, S.-K., Hnilo, J.J., Fiorino, M. and Potter, G.L. (2002) NCEP–DOE AMIP-II Reanalysis (R-2). *Bulletin of the American Meteorological Society*, 83, 1631–1643. https://doi.org/10.1175/BAMS-83-11.

Kim, D., Kim, H. and Lee, M.-I. (2017) Why does the MJO detour the maritime continent during austal summer? *Geophysical Research Letters*, 44, 2579–2587. https://doi.org/10.1002/2017GL072643.

Kirshbaum, D.J., Adler, B., Kalthoff, N., Barthlott, C. and Serafin, S. (2018) Moist orographic convection: physical mechanisms and links to surface-exchange processes. *Atmosphere*, 9, 1–26. https://doi.org/10.3390/atmos9030080.

Kripalani, R.H. and Kulkarni, A. (1997) Rainfall variability over Southeast Asia—connections with Indian monsoon and ENSO extremes: new perspectives. *International Journal of Climatology: A Journal of the Royal Meteorological Society*, 17, 1155–1168. https://doi.org/10.1002/(SICI)1097-0088(19970917):11<1155::AID-JOC188>3.0.CO;2-B.

Liebmann, B. and Smith, C.A. (1996) Description of a complete interpolated outgoing longwave radiation dataset. *Bulletin of the American Meteorological Society*, 77, 1275–1277.

Lim, S.Y., Marzin, C., Xavier, P., Chang, C.-P. and Timbal, B. (2017) Impacts of boreal winter monsoon cold surges and the interaction with MJO on Southeast Asia rainfall. *Journal of Climate*, 30, 4267–4281. https://doi.org/10.1175/JCLI-D-16-0546.1.

Lin, H., Brunet, G. and Mo, R. (2010) Impact of the Madden–Julian oscillation on wintertime precipitation in Canada. *Monthly Weather Review*, 138, 3822–3839. https://doi.org/10.1175/2010MWR3363.1.

Lu, J., Ju, J., Ren, J. and Gan, W. (2012) The influence of the Madden–Julian oscillation activity anomalies on Yunnan’s extreme drought of 2009–2010. *Science China Earth Sciences*, 55, 98–112. https://doi.org/10.1007/s11430-011-4348-1.

Lubis, S.W. and Jacobi, C. (2015) The modulating influence of convectively coupled equatorial waves (CCEWs) on the variability of tropical precipitation. *International Journal of Climatology*, 35, 1465–1483. https://doi.org/10.1002/joc.4069.
Madden, R.A. and Julian, P.R. (1971) Detection of a 40–50 day oscillation in the zonal wind in the tropical Pacific. *Journal of the Atmospheric Sciences*, 28, 702–708. https://doi.org/10.1175/1520-0469(1971)028<0702:DOADO>2.0.CO;2.

Matthews, A.J., Pickup, G., Peatman, S.C., Clewes, P. and Martin, J. (2013) The effect of the Madden-Julian oscillation on station rainfall and river level in the Fly River system, Papua New Guinea. *Journal of Geophysical Research: Atmospheres*, 118, 10–926. https://doi.org/10.1002/jgrd.50865.

Moron, V., Robertson, A.W. and Qian, J.-H. (2010) Local versus regional-scale characteristics of monsoon onset and post-onset rainfall over Indonesia. *Climate Dynamics*, 34, 281–299. https://doi.org/10.1007/s00382-009-0547-2.

Muhammad, F.R., Lubis, S.W., Tiarni, I. and Setiawan, S. (2019) Influence of the Indian Ocean dipole (IOD) on convectively coupled Kelvin and mixed Rossby-gravity waves. *IOP Conference Series: Earth and Environmental Science*, 284, 12012. https://doi.org/10.1088/1755-1315/284/1/012012.

Nur’utami, M.N. and Hidayat, R. (2016) Influences of IOD and ENSO to Indonesian rainfall variability: role of atmosphere-ocean interaction in the Indo-Pacific sector. *Procedia Environmental Sciences*, 33, 196–203. https://doi.org/10.1016/j.proenv.2016.03.070.

O’Gorman, P.A. and Schneider, T. (2009) The physical basis for increases in precipitation extremes in simulations of 21st-century climate change. *Proceedings of the National Academy of Sciences*, 106, 14773–14777. https://doi.org/10.1073/pnas.0907610106.

Petman, S.C., Matthews, A.J. and Stevens, D.P. (2013) 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.

Qian, J.-H., Robertson, A.W. and Moron, V. (2010) Interactions among ENSO, the monsoon, and diurnal cycle in rainfall variability over Java, Indonesia. *Journal of the Atmospheric Sciences*, 67, 3509–3524. https://doi.org/10.1175/2010JAS3348.1.

Rakhman, S., Lubis, S.W. and Setiawan, S. (2017) Impact of ENSO on seasonal variations of Kelvin Waves and mixed Rossby-Gravity Waves. *IOP Conference Series: Earth and Environmental Science*, 54, 012035. https://doi.org/10.1088/1742-6596/755/1/011001.

Ren, H. and Ren, P. (2017) Impact of Madden-Julian oscillation upon winter extreme rainfall in southern China: observations and predictability in CFSv2. *Atmosphere*, 8, 192–216. https://doi.org/10.3390/atmos8010092.

Schaeke, J. (2004) Application of prism climatologies for hydrologic modeling and forecasting in the western U.S. In: *Proceedings of the 18th Conference on Hydrology*. Seattle, WA: American Meteorological Society, p. 5.3.

Seto, T.H., Yamamoto, M.K., Hashiguchi, H. and Fukao, S. (2004) Convective activities associated with intraseasonal variation over Sumatera, Indonesia, observed with the equatorial atmosphere radar. *Annales Geophysicae*, 22, 3899–3916.

Siswanto, S., van Oldenborgh, G.J., van der Schrier, G., Lenderink, G. and van den Hurk, B. (2015) Trends in high-daily precipitation events in Jakarta and the flooding of January 2014. *Bulletin of the American Meteorological Society*, 96, S131–S135. https://doi.org/10.1175/BAMS-D-15-00128.1.

Tangang, F., Chung, J.X., Juneng, L., Supari, S., Salimun, E., Ngai, S.T., Jamaluddin, A.F., Mohd, M.S.F., Cruz, F., Narisima, G., Santisirisomboon, J., Ngo-Duc, T., van Tan, P., Singhru P., Gunawan, D., Aldrian, E., Sopaheluwakan, A., Grigory, N., Remedio, A.R.C., Sein, D.V., Hein-Griggs, D., McGregor, J.L., Yang, H., Sasaki, H. and Kumar, P. (2020) Projected future changes in rainfall in Southeast Asia based on CORDEX-SEA multi-model simulations. *Climate Dynamics*, 55, 1247–1267. https://doi.org/10.1007/s00382-020-05322-2.

van Zomeren, J. and van Delden, A. (2007) Vertically integrated moisture flux convergence as a predictor of thunderstorms. *Atmospheric Research*, 83, 435–445. https://doi.org/10.1016/j.atmosres.2005.08.015.

Walisser, D., Sperber, K., Hendon, H., Kim, D., Maloney, E., Wheeler, M., Weickmann, K., Zhang, C., Donner, L., Gottschalck, J., et al. (2009) MJO simulation diagnostics. *Journal of Climate*, 22, 3006–3030. https://doi.org/10.1175/2008JCLI2731.1.

Wang, B., Chen, G. and Liu, F. (2019) Diversity of the Madden-Julian oscillation. *Science Advances*, 5, eaa0220. https://doi.org/10.1126/sciadv.aax0220.

Wen, M. and Zhang, R. (2008) Quasi-Biweekly oscillation of the convection around Sumatra and low-level tropical circulation in boreal spring. *Monthly Weather Review*, 136, 189–205. http://dx.doi.org/10.1175/2007mwr1991.1.

Wheeler, M.C. and Hendon, H.H. (2004) An all-season real-time multivariate MJO index: development of an index for monitoring and prediction. *Monthly Weather Review*, 132, 1917–1932. https://doi.org/10.1175/1520-0493(2004)132<1917:AMRIMM>2.0.CO;2.

Wheeler, M.C., Hendon, H.H., Cledan, S., Meinke, H. and Donald, A. (2009) Impacts of the Madden–Julian oscillation on Australian rainfall and circulation. *Journal of Climate*, 22, 1482–1498. https://doi.org/10.1175/2008JCLI2595.1.

Wilks, D.S. (2006) *Statistical Methods in the Atmospheric Sciences*, 2nd edition. Cambridge: Elsevier.

Wu, C.-H. and Hsu, H.-H. (2009) Topographic influence on the MJO in the maritime continent. *Journal of Climate*, 22, 5433–5448. https://doi.org/10.1175/2009JCLI2825.1.

Wu, P., Ardiansyah, D., Yokoi, S., Mori, S., Syamsudin, F. and Yoneyama, K. (2017) Why torrential rain occurs on the western coast of Sumatra Island at the leading edge of the MJO westerly wind burst. *SOLA*, 13, 36–40. https://doi.org/10.2151/sola.2017-007.

Wu, Y.C., Yang, M.J. and Lin, P.H. (2020) Evolution of water budget and precipitation efficiency of mesoscale convective systems over the South China Sea. *Terrestrial, Atmospheric and Oceanic Sciences*, 31, 141–158. https://doi.org/10.3319/TAO.2019.11.29.02.

Xavier, P., Rahmat, R., Cheong, W.K. and Wallace, E. (2014) Influence of Madden-Julian oscillation on Southeast Asia rainfall extremes: observations and predictability. *Geophysical Research Letters*, 41, 4406–4412. https://doi.org/10.1002/2014GL060241.

Yanto, Y., Rajagopalan, B. and Zagona, E. (2016) Space-time variability of Indonesian rainfall at inter-annual and multi-decadal time scales. *Climate Dynamics*, 47, 2975–2989. https://doi.org/10.1007/s00382-016-3008-8.

Yatagai, A., Kamiguchi, K., Arakawa, O., Hamada, A., Yasutomi, N. and Kitoh, A. (2012) APHRODITE: constructing a long-term daily gridded precipitation dataset for Asia based on a dense network of rain gauges. *Bulletin of the American Meteorological Society*, 93, 1041–1055. https://doi.org/10.1175/BAMS-D-11-00254.1.
Zhang, C. and Dong, M. (2004) Seasonality in the Madden–Julian oscillation. *Journal of Climate*, 17, 3169–3180.

Zhou, S., L’Heureux, M., Weaver, S. and Kumar, A. (2012) A composite study of the MJO influence on the surface air temperature and precipitation over the continental United States. *Climate Dynamics*, 38, 1459–1471. https://doi.org/10.1007/s00382-011-1001-9.

How to cite this article: Muhammad FR, Lubis SW, Setiawan S. Impacts of the Madden–Julian oscillation on precipitation extremes in Indonesia. *Int J Climatol*. 2021;41:1970–1984. https://doi.org/10.1002/joc.6941