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The Influence of Madden–Julian Oscillation on Local-Scale Phenomena over Indonesia during the Western North Pacific and Australian Monsoon Phases

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Abstract. In this study, geographical Madden–Julian oscillation (MJO) propagation in association with precipitation rate was obtained using lag correlation applied to empirical orthogonal function (EOF) analysis modes 1 and 2 of filtered MJO data. The precipitation rate over Indonesia was provided at day -10 through day +10 in five-day steps during the December, January, and February (DJF) Western North Pacific (WNP) and July, August and September (JAS) Australian (AU) monsoon phases. Connection with local atmospheric factors was then sought through comparison of local precipitation, represented by 3-hourly precipitation, and dynamical processes, represented by multilevel wind, at seven locations across Indonesia. The results show a global MJO contribution toward local-scale phenomena in Tangerang, Surabaya, and Makassar during the DJF-WNP monsoon phase and in Padang, Medan, Surabaya, Makassar, and Kupang during the JAS-AU monsoon phase. Meanwhile, a lack of MJO contribution toward local factors is presumably due to other local through wider atmospheric-scale phenomena which are suspected to have more influence, particularly in Medan, Padang, Manado, and Kupang during the DJF-WNP monsoon phase, and in Manado and Tangerang during the JAS-AU monsoon phase. This research uses a dataset of 15-year series of daily and three-hourly Tropical Rainfall Measuring Mission (TRMM) (3B42 V7 derived) measurements, 850 hPa zonal wind measurements from 30-year reanalysis data from the ERA-Interim reanalysis dataset, and a 15-year series of 12-hourly observational soundings data from seven stations of the Indonesian Meteorological Climatological and Geophysical Agency (BMKG).

Keywords: MJO, local factors, precipitation rate, multilevel wind.

Abstrak. *Perambatan fenomena Madden – Julian Oscillation (MJO) secara geografis dalam kaitannya dengan laju curah hujan pada hari ke-10 hingga hari +10 dalam rentang lima harian pada fase monsun Pasifik Barat/ Western North Pacific (WNP) bulan Desember, Januari, dan Februari (DJF), serta fase monsoon Australia (AU) bulan Juli, Agustus dan September (JAS) di Indonesia diperoleh menggunakan korelasi lag dari fungsi Emphirical Orthogonal Function (EOF) mode 1 dan 2. Hubungan perambatan fenomena ini dengan faktor atmosfer skala lokal kemudian dicari melalui perbandingan curah hujan lokal dengan menggunakan data curah hujan 3 jam, serta proses dinamis dengan data angin per-lapisan pada tujuh lokasi di Indonesia. Hasil yang diperoleh menunjukkan adanya kontribusi MJO yang berskala global terhadap fenomena skala lokal di Tangerang, Surabaya, dan Makassar selama fase monsun DJF-WNP, serta di Padang, Medan, Surabaya, Makassar, dan Kupang selama fase monsun JAS-AU. Meskipun demikian, lemahnya kontribusi fenomena MJO terhadap faktor lokal di beberapa lokasi diduga disebabkan oleh fenomena atmosfer pada skala lokal hingga skala yang lebih luas lainnya yang memberikan pengaruh lebih besar, terutama di Medan, Padang, Manado, dan Kupang selama fase monsun DJF-WNP, serta di Manado dan Tangerang selama fase monsun JAS-AU. Penelitian ini dilakukan dengan memanfaatkan data pengukuran curah hujan harian dan tiga jam-an dari citra satelit Tropical Rainfall Measuring Mission (TRMM) (3B42 V7) selama 15* *tahun, data angin zonal lapisan 850 hPa dari data reanalisis ERA-Interim selama 30 tahun, serta data pengamatan angin per-lapisan12 jam-an dari tujuh stasiun miliki Badan Meteorologi Klimatologi dan Geofisika Indonesia (BMKG) selama 15 tahun.*

Kata kunci: *MJO, faktor lokal, laju curah hujan, angin per-lapisan.*

1. Introduction

Madden–Julian Oscillation (MJO) is a 40–50-day oscillation phenomenon occurring in tropical areas that can suppress mean sea-level pressure, creating convection over tropical regions, particularly the Maritime Continent of Indonesia (Madden and Julian, 1972). Many studies have demonstrated that MJO has an important influence on the diurnal cycle of precipitation over the Maritime Continent, particularly for Indonesia and Papua New Guinea (Peatman *et al.*, 2014; Peatman *et al.*, 2015; Vincent and Lane, 2016). A previous study suggested that Indonesia is one of the energy sources for extra-tropical circulation over the Maritime Continent because of its ability to produce greater heat energy and water vapour than other tropical regions such as Africa and South America (Ramage, 1968). Thus a progressive study of global-local atmospheric interactions should be carried out to aid understanding of the influence of MJO on local-scale phenomena (Kim *et al.*, 2016).

MJO initiates over the Indian Ocean and dissipates over the dateline, peaking outside the landmass of the Maritime Continent via the Rossby wave response (Zhang and Dong, 2004; Masunaga, 2007; Kim *et al.*, 2016), One study suggests that a barrier effect created by Sumatra weakens the convective process relating to MJO which then increases again after crossing Sumatra (Zhang and Ling, 2017). The peak phase of MJO is weaker during the boreal summer due to the northward and northeastward propagation which predominates in the MJO phase (Rui and Wang, 1990; Masunaga, 2007). Low-level zonal wind (u850) over the Indonesian Maritime Continent during the peak phase of MJO is an eastward-moving wind, while an easterly upper zonal wind (u200) is exhibited over the same region (Wu and Hsu, 2009; Peatman *et al.*, 2015). Meanwhile, an opposite situation occurs over the eastern tropical Pacific, with a westerly upper zonal wind and westward lower zonal wind (Peatman *et al.*, 2015). Beside the purely intra-seasonal eastward propagation (Madden and Julian, 1972), there are other propagation patterns related to MJO, namely north and northeastward intraseasonal propagation over the Indian Ocean and Western Pacific Ocean (Rui and Wang, 1990; Lawrence and Webster, 2002; Masunaga, 2007), and propagation through or blocked by the Maritime Continent (Zhang and Ling, 2017). This study is focused specifically on how this global phenomenon influences local phenomena over Indonesia, without considering these other propagation criteria.

The solar insolation effect over land and sea in the islands of Indonesia is suggested as the main factor in controlling diurnal precipitation over the region, adequate to obscure global-scale factors such as MJO propagation when passing this region (Peatman, 2014). A similar study also revealed that the difference between the active and follow-on period of a lighter wind indicates a dominant topographical factor such as land/sea breeze or mountain/valley breeze rather than MJO propagation. Meanwhile, the lowest diurnal precipitation enhancement exists during MJO phases 6–7 both onshore and offshore over Papua (Vincent and Lane, 2016). Permana *et al.* (2016) reveal that peak enhancement shows an elongated pattern following the high mountain of Jayawijaya (from the west to east of central Papua) during MJO phases 2–3. A complex topography with elongated high mountains through the large islands of the Maritime Continent of Indonesia induces extra lifting/suppression of air in the region (Wu and Hsu, 2009).

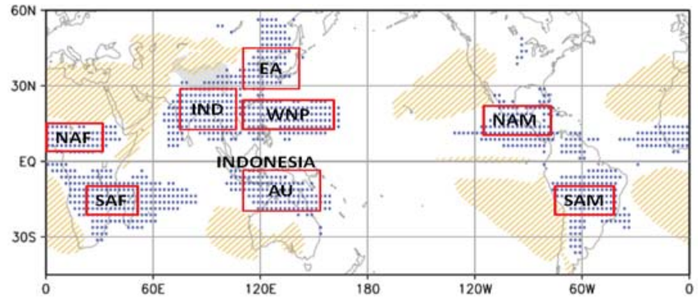

Figure 1. Regional precipitation domains, indicated by abbreviations for each domain (figure adopted from Wang et al., 2012).

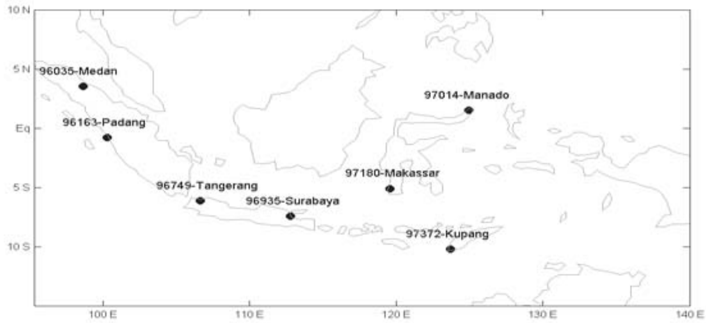

Figure 2. Observational sounding stations from BMKG indicated by WMO number and city name.

There is evidence for MJO intensifying deep convection during an active monsoon from previous studies of the MJO phase within active Australian and Indian summer monsoon onset (Khrisnamurti and Subrahmanyam, 1982; Wheeler and Hendon, 2004). Previous research also suggested that MJO may exist during the WNP monsoon. Although, the study did not describe in detail how these two weather triggers interact (Chen *et al*., 2000) Meanwhile, the Asian and Australian monsoons play a significant role in the Maritime Continent through their ability to cut down westward-moving zonal wind and induce westerly wave propagation (Liebmann and Hendon, 1990; Wheeler and McBride, 2005). This regional-scale circulation is suspected as being a trigger for successive convection related to tropical waves in the Maritime Continent (Wheeler and McBride, 2005; Kiladis *et al*., 2009; Lubis and Jacobi, 2014). A previous study by Wang *et al*. (2012) suggests that, according to seasonal contrast in precipitation variability, there are eight regional monsoon domains, and two of these are the WNP and AU monsoon domains investigated in this study (Figure 1). These two monsoon regions are considered here from two perspectives: first, pattern similarity between climatological annual cycles of precipitation rates of both monsoon regions (Yim et al., 2013: Figure 2) for the Indonesian rainfall annual cycle of climate region A (Aldrian and Susanto, 2003: Figure 3) and second, because WNP and AU are the monsoon domains closest to Indonesia, i.e. they are the monsoon regions bordering the northernmost and southernmost parts of the Indonesia region respectively.

In recognising the importance of MJO in controlling Maritime Continent weather conditions, and given the Asian and Australian monsoons' significant role in determining precipitation peak phase throughout the islands, it is necessary that the connection between these phenomena should be investigated, particularly for the Indonesian Maritime Continent. In this study, the peak of the Asian monsoon is represented by the WNP monsoon index (Wang and Fan, 1999; Wang *et al*., 2008; Yim *et al*., 2013) and the Australian monsoon is represented by the AU monsoon index (Yim *et al*., 2013). The local-scale atmospheric situation for particular areas in this region for precipitation and multilevel wind observations are therefore considered in this paper. This study aims to identify local atmospheric behaviour in association with connections between the Asian and Australian monsoons and MJO phases. The first section of this paper describes various relevant studies, both recently and in the past, related to MJO and monsoon connectivity and linked to local-scale atmospheric circulation over the Maritime Continent. The second section explains the data and methods used to achieve the research objectives, while the third presents the results obtained. The final section presents a discussion of the findings and conclusions.

2. Research Method

Since outgoing longwave radiation is no longer able to be used to represent precipitation over tropical regions, presumably due to a lack of anvil clouds in the diurnal convective clouds of tropical regions (Peatman *et al.*, 2014), precipitation-rate estimates from TRMM 3B42 are used to overcome this problem. A 15-year series of daily and 3-hourly TRMM data (3B42 V7 derived) was used to estimate the tropical precipitation rate from 1 January 2001 through 31 December 2015. TRMM is used because of benefits such as continuous data acquisition, finer resolution (0.25° x 0.25°), its use of comprehensively merged infrared-microwave multi-satellites, and the collection and conversion of all available data into precipitation estimates (Huffman et al., 2006). For detailed documentation about the dataset, this research referred to the TRMM user handbook produced by the National Space Development Agency of Japan (NASDA, 2001). Data for multilevel winds from 12-hourly observational soundings data for the same period as the TRMM data was gathered for seven sounding stations (see Figure 2) from the Indonesian Meteorology Climatology and Geophysics Agency (BMKG), to obtain actual lower- through upper-level wind characteristics that could be used to look for relationships with MJO during each local monsoon regime. Furthermore, 850-hPa zonal wind 30-year reanalysis measurements from the ERA-Interim reanalysis data for 1 January 1986 through 31 December 2015 was used to calculate WNP and AU indices for Asian and Australian monsoon activity, using a method developed by previous researchers already mentioned in the introduction. WNP indices were calculated from U850 (5°N–15°N, 100°E–130°E) minus U850 (20°N–35°N, 110°E–140°E), whereas AU indices were calculated from U850 (0°S–15°S, 90°E–130°E) minus U850 (20°S–30°S, 100°E–140°E).

First, daily satellite precipitation estimates data from TRMM 3B42 was filtered into MJO using the WK99 method devised by Wheeler and Kiladis (1999). A coarser 3B42 grid resolution was used to reduce delays and the costs of running the numerical codes for a long dataset, by applying the inverse distance weight (IDW) method. The equivalent depth (h_e) applied in this study was from 8 to 90 meters and the zonal wavenumber (k) was between -20 and 20 for the whole equatorial globe with a latitudinal window (□) of between 20°N and 20°S. Furthermore, an empirical orthogonal function (EOF) method was applied to affirm the dominant variation in the mode of MJO. A smaller region from 94°E to 140°E and 5°N to 10°S was selected for EOF calculation to seek only the results focused over the Indonesian region. Analyses for both WNP and AU monsoon regimes of MJO were employed to manifest the distribution of its evolution in Indonesia. A filtered wave resulting from space-time spectra analysis was then calculated using the EOF method to exhibit evolution. Subsequently, EOF modes 1 and 2 of the Indonesian domain were calculated to seek the peaks of the normalised unit of expansion coefficient that are above the standard deviation, and these were then collated into one group of data series containing the peak events of the filtered MJO.

The lag correlation was then employed for EOF modes 1 and 2 to obtain the time sequence of the MJO propagation phase, this method adopted from Zhao *et al*. (2013). For both WNP and AU monsoon regimes a comparative analysis was conducted between the spatial analysis of EOF1 and 2 data series, with a spatial variance (figure not shown) in the domain of Indonesia. The most similar EOF mode with this variance was then selected and carried into the next calculation to represent the most appropriate MJO propagation phase. As a result of the EOF1 and two resemblances with its variance (figure not shown), MJO refers to EOF2 for both WNP and AU monsoons, which gives geographical propagation of MJO phases during both monsoon phases as shown in Figure 3.

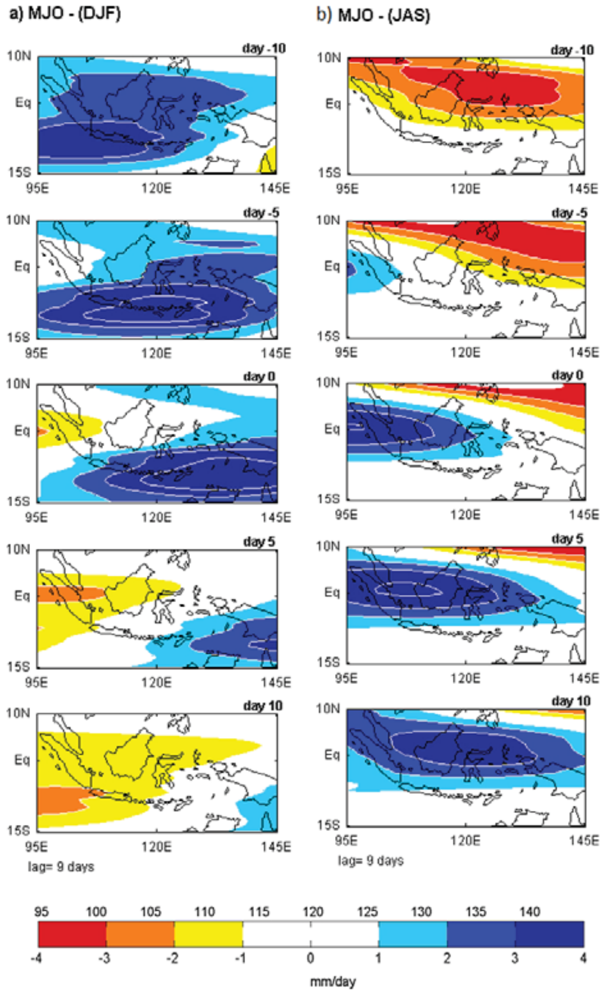

Figure 3. Day -10 through day +10 lags with 5-day steps of MJO propagation referring to EOF 2 using lag correlation for EOF1 and two from 15-year MJO-filtered TRMM-3B42 for DJF-WNP (a) and JAS-AU (b) monsoon phases over Indonesia

After WNP and AU monsoon indices were obtained, the peak of each monsoon month was then collated into one monsoon season based on its monsoon index peak. The calculation result for each monsoon index shows that July, August, and September (JAS) were peak months of the WNP monsoon index, whereas December, January, and February (DJF) are peaks of the AU monsoon index. Since it is broadly known that the naming of monsoon seasons is indicated by the dominant seasonal wind over the region rather than by its peak monsoon index, it will be easier to refer to DJF for the WNP monsoon phase and JAS for the AU monsoon phase (i.e. the dominant wind blowing from the WNP region and the AU regions respectively). Furthermore, to achieve this paper's main aim of determining the MJO phase that corresponds with the WNP and AU monsoon regimes, the times gathered from the MJO propagation phase which coincides with WNP and AU monsoon phase results are then used for local-scale calculations.

A 15-year series of daily 3B42 rainfall estimations were then collated based on daily lags obtained from lag-correlation calculations, representing the MJO propagation phases which coincide with the WNP and AU monsoon phases, as shown in Figure 4. In addition, 3-hourly precipitation-rate estimations from the same data source were plotted against data from seven observation stations over Indonesia, as shown in Figure 2. The IDW method was used, and outputs were plotted for daily lags during the WNP and AU monsoon phases to identify MJO behaviour for local precipitation, as shown in Figure 5. Furthermore, a multilevel wind profile from the same observation stations was plotted for each daily lag at 00Z and 12Z, to seek a local scale of dynamical conditions during MJO active phase coinciding with the WNP and AU monsoon phases (see Figure 6). These near-global and local analyses were performed to exhibit the contribution of the global phenomenon of MJO on complex local-scale phenomena during WNP and AU monsoon phases over the Indonesian region.

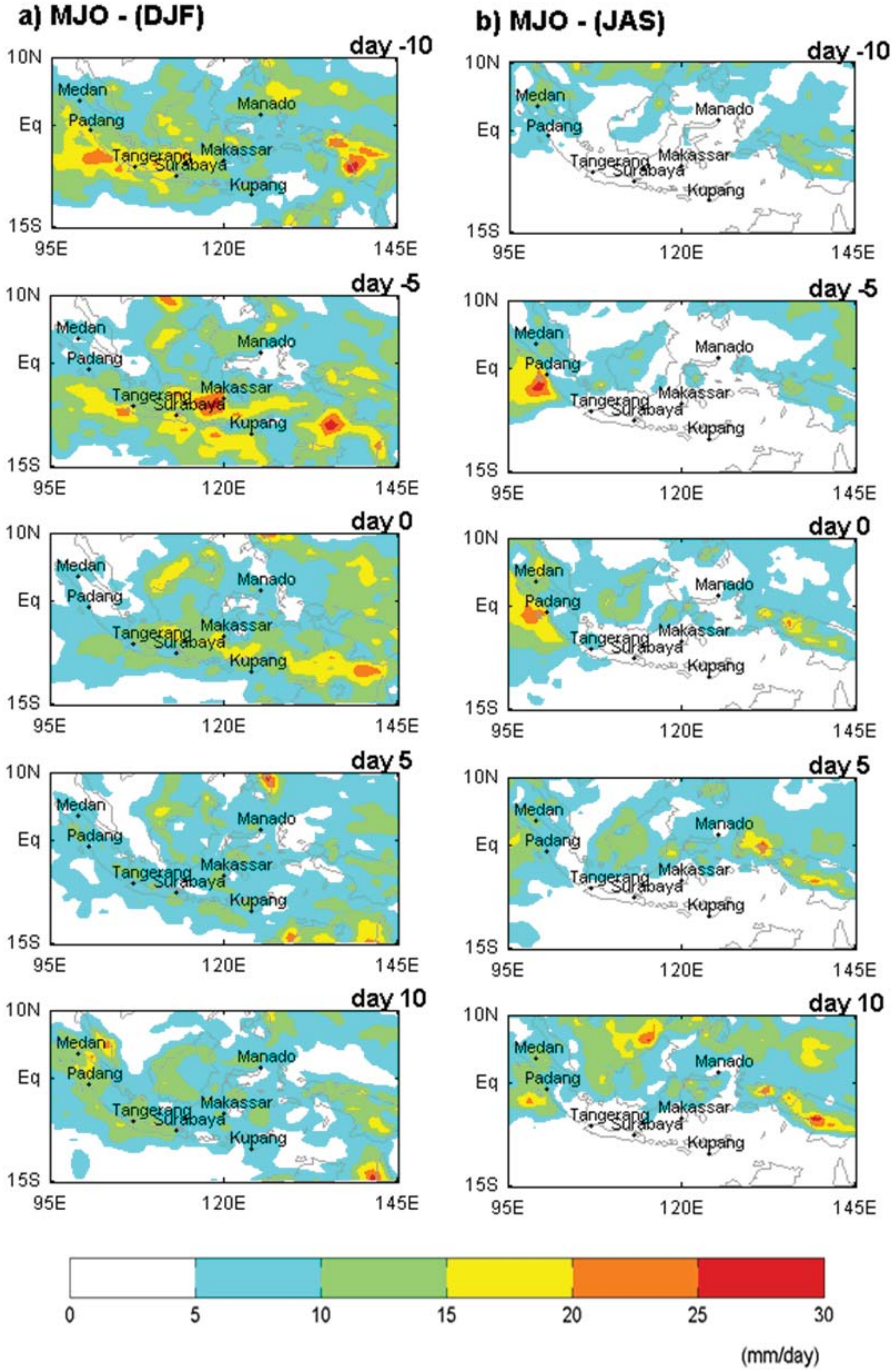

Figure 4. Day -10 through day +10 lags with 5-day steps of MJO propagation associated with precipitation rates for DJF-WNP (a) and JAS-AU (b) monsoon phases over Indonesia

3. Results and Discussion

The geographical data for MJO propagation obtained from the sequential process over Indonesia during the DJF-WNP and JAS-AU monsoon phases reveals a perturbation shift that follows solar radiation shift. This occurs to the north of the equator during JAS and to the south of the equator during DJF. Figure 3-a shows a significant perturbation starting at day 0 over the southern part of Sumatra, Java, Bali, and West Nusa Tenggara, including the Java Sea, which then strengthens eastward at day -5 from east Java to East Nusa Tenggara, and reaches peak perturbation at day 0 over Nusa

Tenggara and the southern part of Papua. After that, the MJO perturbation starts to weaken from day 5 to day 10 and is replaced by a negative perturbation over most of the Indonesian area. Meanwhile, a significant perturbation starts at day -5 during the JAS-AU monsoon phase over the western coast of central Sumatra, which then intensifies eastward at day 0 over Sumatra and expands to the east over western Kalimantan at day 5. At day 10, even though the area covered by the positive perturbation is wider than for previous day lags, this weaker positive perturbation compared with previous day lags indicates the weakness of the MJO phase at this monsoon season, as shown in Figure 3-b.

Meanwhile, a precipitation rate during the DJF-WNP and JAS-AU monsoon season that coincides with MJO propagation exhibits embedded precipitation with a similar pattern, i.e. with positive perturbation coverage except over Papua at day -10 and over North Sumatra at day ten during the DJF-WNP monsoon phase. A further difference occurs over Papua at day -10 through the day -5 during the JAS-AU monsoon phase. Although embedded precipitation along central Papua during both monsoon seasons does not precisely occupy the positive MJO perturbation (more than 1 mm/day), it shows similarity with the conclusions of previous studies (Peatman *et al*., 2014; Peatman *et al*., 2015; Permana *et al*., 2016). However, the results of the present study suggest that this pattern exists as MJO reaches its peak over the Indonesian Maritime Continent, while previous studies suggest that it occurs during MJO phases 2 to 4; that is, over the Indian Ocean and the western Maritime Continent (Wheeler and Hendon, 2004). However, a further question arises related to its static eastward movement, which is presumably due to high mountain topography that allows local factors to dominate precipitation development rather than MJO, particularly at day -10 through the day -5 during the JAS-AU monsoon phase.

In contrast, MJO triggers precipitation at day 0 through day 10 in this region (Peatman et al., 2014; Peatman et al.,2015; Permana et al., 2016; Vincent and Lane, 2016). Meanwhile, embedded precipitation is present over North Sumatra at day ten during the DJF-WNP monsoon phase which resembles the Sumatra squall line (Lo and Orton, 2016) and this needs to be investigated further, given that there is no link between MJO and Sumatra squall formation (He *et al*., 2018). Thus, these embedded precipitation clusters over Sumatra at day ten during DJF and over central Papua at day -10 through the day -5 during JAS seem to be neglected, due to some of the reasons already described.

Figure 4-a shows an intensive precipitation rate at DJF that is clearly observed starting from day -10 over the southernmost part of Sumatra and the Java Sea, with an organised precipitation cluster at day -5 over the Arafura Sea. The dissipation of massive rainfall clusters starts at day 0, remaining as less intensive rainfall in the offshore of the southern part of Papua. Day 5 shows a break phase in intensive precipitation over Indonesia, where a moderate to heavy rainfall which has begun over northern Sumatra at day ten might be abandoned in line with the explanation above.

A less dense precipitation cluster occurs during the JAS-AU monsoon phase, as shown in Figure 4b, with an embedded precipitation cluster developing on the western offshore of central Sumatra at day -5 through day 0, which then diminishes at day 5 and re-forms over the same location at day 10. This embedded precipitation is limited to the western coast and elongated outside the landmass of Sumatra, possibly because of the Sumatra barrier that blocks MJO propagation through this area (Zhang and Lin, 2017). However, this study is limited to all types of MJO propagation criteria without considering the blocking effect near Sumatra, and so further investigation must be conducted to seek evidence for this.

Another intensive precipitation cluster in this monsoon phase is also seen elongated along Papua at day 0, which then strengthens up to day ten as previously described. From this MJO evolution stage during both monsoon phases in Figure 4, it can be seen that a vigorous daily precipitation rate is predominant during the DJF-WNP monsoon phase as compared with the JAS-AU monsoon phase, due to northward and northeastward propagation (Rui and Wang, 1990; Masunaga, 2007). This is in line with a previous study by Wheeler and Kiladis (1999), which was revealed that MJO variance is centralised over the southern Maritime Continent during boreal winter, and is focused further north, including North Sumatra, during boreal summer, with a weaker precipitation rate compared with boreal winter.

Furthermore, rainfall rate plotted locally at seven observation stations shows a distinctive pattern at different places (see Figure5). Observation times from 00Z through 21Z are plotted on the horizontal axis consecutively, where 00Z coincides with the morning at the local time, and 12Z coincides with the evening at the local time. Overall, a peak 3-hourly precipitation accumulation against lag indicates a similar pattern to the daily precipitation rate as shown in Figure 4. This is most likely due to the 3B42 daily precipitation dataset having been obtained from the 3-hourly precipitation calculations from the same dataset (see product description at https://mirador.gsfc.nasa.gov/). The 3-hourly precipitation accumulation rates from DJF and JAS monsoon phases exhibits significant local precipitation occurring during the DJF phase compared with the JAS phase. Significant DJF precipitation exists in Tangerang (96749) for almost all night-time through early morning lags at local time and in Makassar (97180) for lag -10 at early evening. Significant local precipitation at early morning in Tangerang, which is located on the coastal area ahead of Jakarta Bay, indicates a strong local factor controlling cloud development resulting from sea breezes inducing precipitation on coastal areas through offshore at early morning, as shown in Figure 5-a. Another significant 3-hourly precipitation also occurs during the early evening (09 to 12 Z) which is most likely due to convective activity by solar insolation at midday onshore inducing convective precipitation in the same area. This is coherent with previous findings by Peatman (2014). Although precipitation rate at day 0 indicates weaker precipitation than at day -10 and day 10, the early morning precipitation increment is adequate to prove that there is a link between global MJO and local weather conditions. Convective cloud development due to solar insolation at midday (about 09Z) is indicated by a peak of 3-hourly precipitation at day 0 also occurring over Medan (96035) during both monsoon phases and Surabaya (96935) during the DJF-WNP monsoon phase. Although the incremental precipitation rate seems to be lower than in other day lags, this still indicates a significant midday rainfall enhancement compared with other hours. However, based on previous explanations, during the DJF-WNP monsoon phase in Medan (96035), a 3-hourly precipitation pattern in this area during DJF seems to be abandoned. Meanwhile, although a 3-hourly precipitation rate in Makassar exhibits less significance for local precipitation at day 0 compared with day -10 and day -5, yet an embedded precipitation cluster at day -5 (as shown in Figure 4) coincides with positive MJO perturbation shown in Figure3, and so denotes that there is a relationship between global MJO and local precipitation in this region.

A weak 3-hourly precipitation accumulation during the JAS-AU monsoon phase is predominant for almost all stations, except those located in Sumatra, i.e. Medan and Padang (96035 and 96163 respectively), with the weakest precipitation rate at Kupang (97372). This is also consistent with data shown in Figure 4-b and Figure3-b, where an embedded precipitation cluster related to MJO is observed on the western offshore of central Sumatra, while another moderate to heavy precipitation occurs over North Sumatra. Furthermore, the driest atmosphere during this monsoon phase occurs over Java, South Sulawesi, Bali, and Nusa Tenggara, which includes Surabaya, Makassar, and Kupang (96035, 97180, and 97372 respectively), as shown in Figure 5-b. This suggests that there is a link between global MJO during the JAS-AU monsoon phase and local precipitation. However, it is likely that there must be other global factors strongly triggering a dry atmosphere over these regions, particularly regarding the Asian and Australian monsoons represented in this study by the WNP and AU monsoon phases.

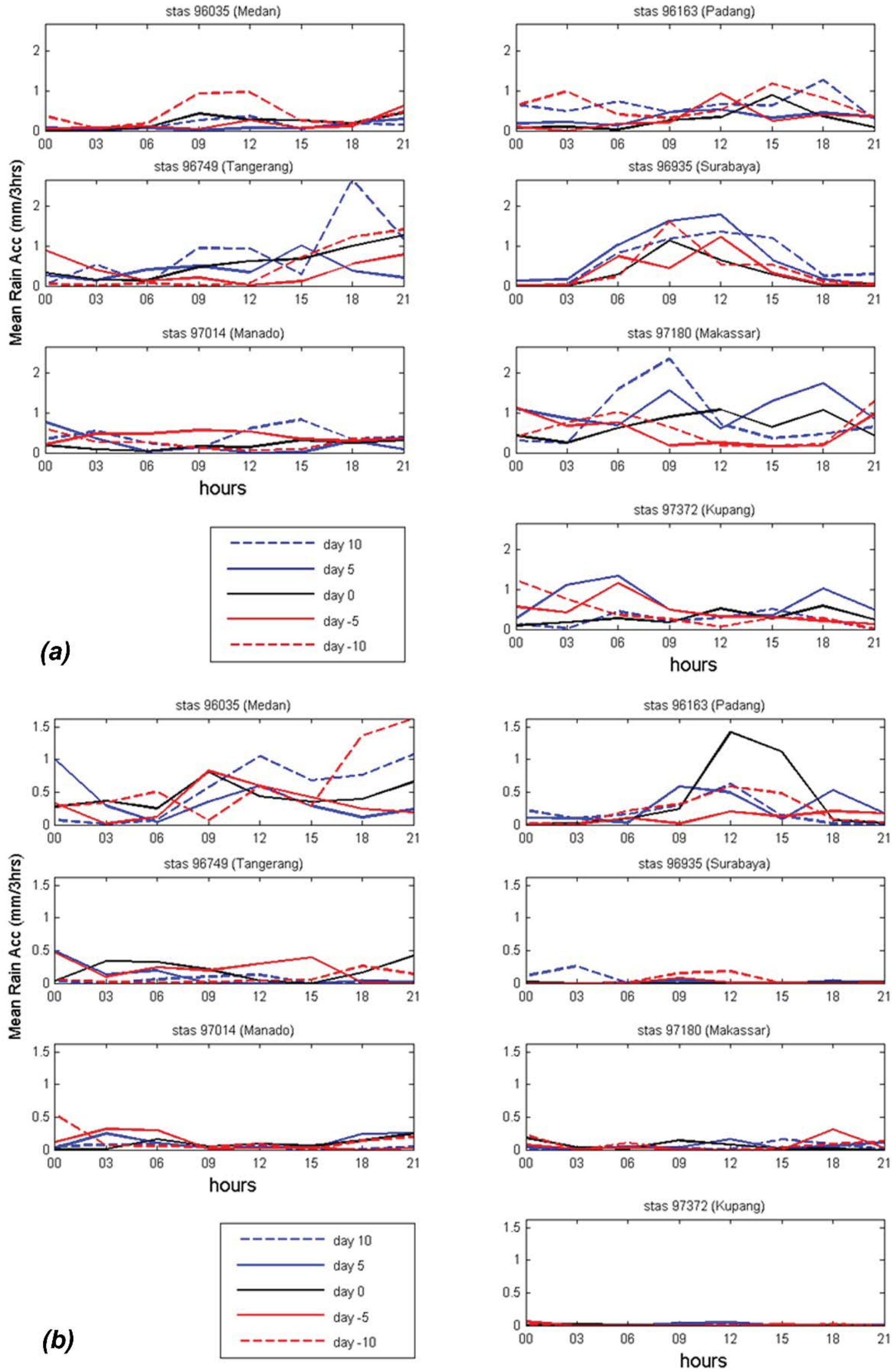

Figure 5. Three-hourly precipitation rate for each day lag (see legend) at seven observation stations (station naming corresponds to WMO number) as shown in Figure 2, (a) DJF and (b) JAS.

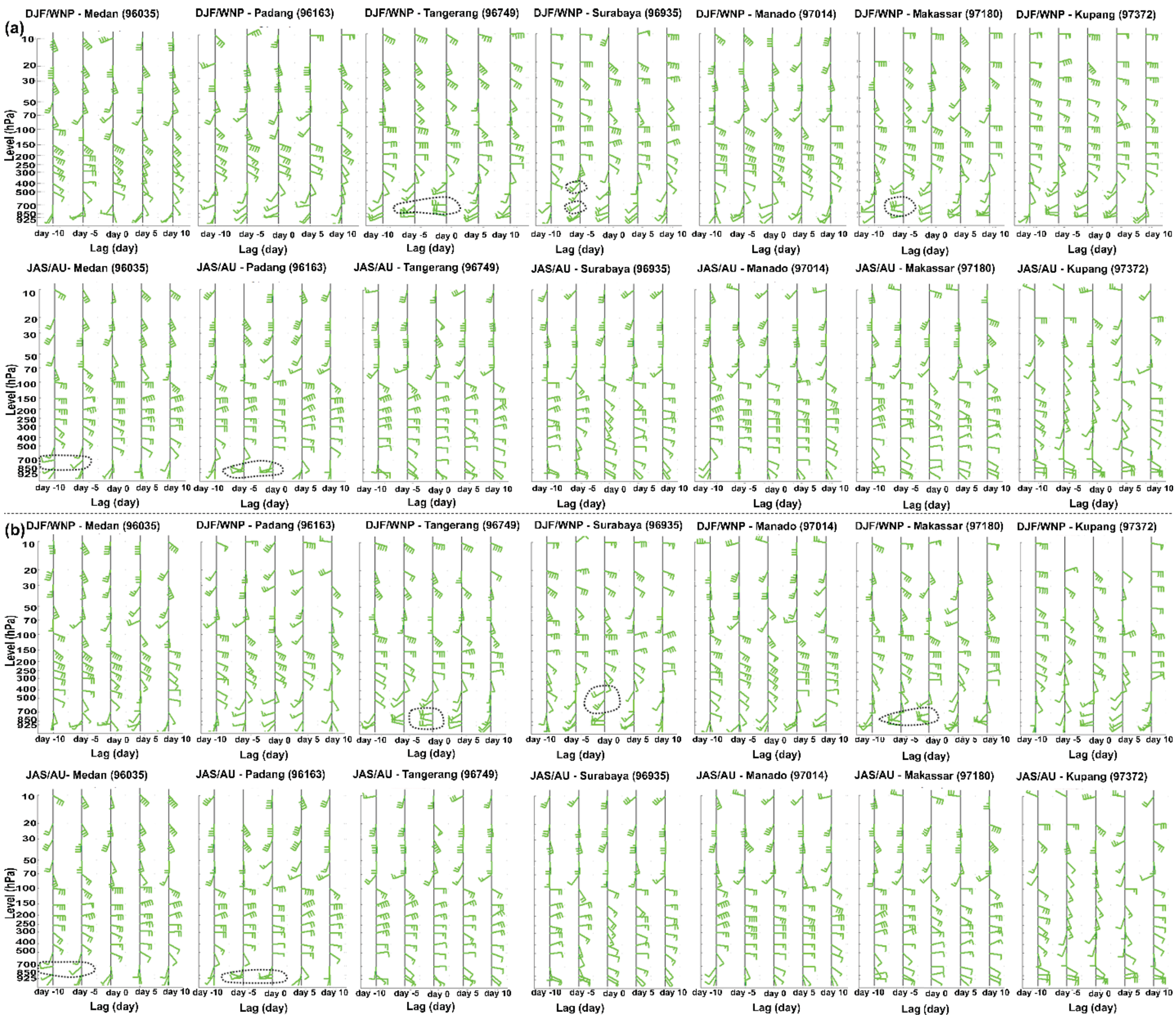

Figure 6. Multilevel wind profile for each day lag (ranged on the horizontal axis) at seven observation stations (similar to Figure 5), for observation time 00Z (a) and 12Z (b). Note that a dashed black contour indicates significant multilevel winds for the range 20 knots (10 knots) for the DJF-WNP (JAS-AU) monsoon phase.

The 3-hourly precipitation pattern in Tangerang during JAS indicates a sea breeze influence at early morning (21Z) and early afternoon (03Z). Although the precipitation rate is quite slight compared with during the DJF monsoon season, this still indicates a significant coastal zone effect in weather formation, and afternoon convection is unable to form during this monsoon phase. Nevertheless, although quite small, a noticeable precipitation pattern at day 0 denotes a relationship between global MJO during the JAS-AU monsoon phase and local precipitation in Tangerang, as shown in Figure 5-b. The correlation of complex terrain with MJO phenomena in Tangerang is in line with the results of Hidayat and Kizu (2010), who suggest that more complex local factors of land-sea distribution are controlling precipitation rather than MJO propagation. On the other hand, by considering the descriptions above, it can be concluded that less significant precipitation in association with MJO phases during the WNP monsoon regime mainly occurs in Medan (96035), Manado (97014), Padang (96163), and Kupang (97372). Only Manado station (97014) indicates the absence of local 3-hourly precipitation about the MJO phase during the AU monsoon regime. Moreover, it should be noted that the MJO evolution phase data in this study is obtained based on EOF one and two focused on the region of Indonesia. Thus a peak 3-hourly precipitation not occurring at day 0 for some places depends on when its positive perturbation reached them. For example, a positive perturbation reaches its peak on Makassar at day-5 and starts weakening the following day as its positive perturbation moves eastward at day 0 (Figure 3).

Figure 6 shows a local dynamical process above surface level represented by the climatological pattern of multilevel wind used to identify the relationship of global MJO with air mass movement on a local scale. From this figure, it can be seen that there is a coherence between the significant precipitation rate (Figures 4 and 5) and the dynamical process associated with MJO, particularly during the DJF-WNP monsoon phase. This is indicated by a strong (≥ 20 knots) lower-mid-level westerly wind during DJF in Tangerang, Surabaya, and Makassar, with an easterly shift mostly at mid-upper-level of 250 hPa (> 10,000 meters) during the DJF monsoon season (Figure 6). Tangerang exhibits a strong (≥ 20 knots) lower-mid-level westerly wind of 400 hPa at day 0, which then shifts into an easterly wind of 250 hPa at day -10 and day 10 during the DJF monsoon season at both 00Z and 12Z observation times. As in Tangerang, a strong (≥ 20 knots) lower-mid-level eastward wind in Surabaya is apparent of 400 hPa at day -5 at 00Z observation time, which shifts into a southwesterly wind of 500–400 hPa at day 0 at 12Z observation times. In Makassar, a stronger (≥ 30 knots) lower-mid-level westerly wind is present of 500 hPa at day -5 and day 0 in the morning, then weakening (≥ 20 knots) in the evening at day 0, with the easterly wind shifting to 300 hPa. A strong (≥ 20 knots) lower-mid-level westerly wind in Kupang at day 0 in the evening does not seem to represent a contribution of global MJO to local dynamical processes, presumably due to the climatological strong wind characteristic at this monsoon phase (Winarso, 2016). This westerly wind at a lower-mid-level of the atmosphere indicates an MJO perturbation as also suggested by a previous study by Yoneyama et al. (2013).

Meanwhile, a rather weak lower-mid-level westerly wind of 700 hPa is apparent in Medan and Padang during the JAS-AU monsoon phase with a predominantly strong easterly mid-upper-level wind from 500 hPa to 100 hPa at both stations, shifting eastward to 70 hPa for both observational times (00Z and 12Z). This climatological pattern of multilevel winds is characteristic of a zonal and vertical structure of MJO as also revealed by Kiladis *et al*. (2005). On the other hand, the lower-mid-level easterly wind that is apparent in Surabaya, Makassar, and Kupang during the JAS-AU monsoon phase confirms a local dynamical process that contributes toward a wet phase of MJO related to the JAS-AU monsoon phase.

4. Conclusion

The geographical distribution of daily precipitation in association with MJO phase during the WNP and AU monsoon regimes (shown in Figure 4) implies that significantly embedded precipitation clouds formed mostly following the MJO propagation area (Figure 3). This is the case except over north Sumatera at day ten during the WNP-DJF monsoon phase and over Papua at day -10 through day five during the AU-JAS monsoon phase. Furthermore, local precipitation represented by 3-hourly precipitation rate reveals that various local factors control rainfall characteristics which then contribute to MJO enhancement during WNP and AU monsoon phases, particularly in Tangerang, Surabaya, and Makassar. Meanwhile, a fairly strong lower-mid-level westerly wind which heightens the MJO contribution toward local-scale formation by a local dynamical process is apparent over these three regions. A significant lower-mid-level westerly wind is also evident over Medan and Padang during the JAS-AU monsoon phase, and this is also supported by a significant 3-hourly precipitation rate at day 0, particularly in Padang. This reveals that there is a connection between local factors and MJO formation in Padang and Medan. In contrast, a drier atmosphere over the negative MJO perturbation area during the JAS-AU monsoon phase in Surabaya, Makassar, and Kupang is obviously indicated by a weak 3hourly precipitation rate and also by a significant lower-mid-level easterly wind over those areas. The absence of intensive precipitation over those areas during the JAS-AU monsoon phase is presumably triggered by a strong Australian monsoon effect that blows non-humid air through the southern region of Indonesia. Meanwhile, an absence of lower-mid-level westerly wind stress during the JAS-AU monsoon phase in Tangerang seems unlikely to favour the MJO dynamical process.

However, a lack of MJO contribution toward local phenomena during WNP and AU monsoon phases in other areas, such as in Medan, Manado, Padang, and Kupang during the DJF-WNP monsoon phase, and also in Manado during the JAS-AU monsoon phase, is suspected to result from other local though wider atmospheric-scale phenomena which have more significant influence over those areas. For example, the DJF monsoon season in Medan at day 10 resembles the Sumatra squall line and embedded precipitation over Papua at the onset of MJO during JAS which follows the elongated Jayawijaya mountain terrain over central Papua. Thus, further investigation using more complex and varied data is needed to seek other phenomena that are the reason for this lack of MJO contribution toward local phenomena. Moreover, denser observational data, particularly for east Indonesia, is needed to obtain more reliable results in the future for this field of research.

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