Meridional Migration of Diurnal Heavy Rainfall during Extreme Events over Java and Surrounding Waters and Its Relation to Madden Julian Oscillation

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Abstract. In this study, meridional migration characteristic of diurnal heavy rainfall (DHR) over Java and surrounding waters and its relation to Madden Julian Oscillation (MJO) during extreme events was investigated. The rainfall data was the Climate Prediction Centre Morphing (CMORPH) V1.0 in the December-January-February (DJF) wet season of the 1998-2019 period. The thresholds of extreme events were based on the 95% percentile of daily rainfall area average of mountainous area (MA), northern plain area (NPA), northern waters (NW), southern plain area (SPA), and southern waters (SW) that were based on Global Land One-kilometer Base Elevation (GLOBE) Digital Elevation Model. We analyzed meridional migration of DHR through composite and the Hovmoller diagram. To get the MJO signal, we used the Wheeler-Kiladis wavenumber-frequency domain to filter outgoing longwave radiation (OLR). The results showed that DHR was stationary over the mountains, migrated to the Java Sea (The Indian Ocean), and was stationary over the Java Sea (Indian Ocean) in conjunction with migration from Java to the waters when extreme events occur over MA, NPA (SPA), and NW (SW), respectively. Based on a comparison of MJO-OLR during extreme events period of MA, NPA, SPA, NW, and SW, it seems that MJO had a stronger impact on the DHR of NW and SW than the others, but it must be examined based on significant test in the further study.

1. Introduction

The Java Island is one of the largest islands with mountains stretching from west to east in the maritime continent which of course has a diurnal rainfall migration that is different from other islands with northwest to southeast-oriented mountains such as Sumatra and northeast to southwest-oriented such as Kalimantan. Sumatra has a peak rainfall migration to the northeast part of Sumatra and southwest (mostly the Indian Ocean) as far as 200 km and 400 km from Bukit Barisan at midnight to early morning at speeds of 7.4 m/s and 11.1 m/s as a result of the self-replicating mechanism and the gravity wave [1]. With the X-band weather radar, Mori et al. [2] found that in the migration of rainfall from western Sumatra to the Mentawai Strait with a speed of 4 m/s. This nocturnal pattern was also found in Teo et al. [3] study with a phase speed of 8-13 m/s. With Weather Radar observation data that has a better resolution, Yokoi et al. [4] found that the average speed of southward migration on the western part of Sumatra Island was 3.3 m/s that was lower than the migration in the Indian Ocean at a speed of 8 m/s. Meanwhile, the diurnal rainfall migrates northwestward at a speed of 3 m/s in northeastern Kalimantan and the South China Sea in the easterly (EE) regime and migrates...
southeastward at a speed of 7 m/s in southwest Kalimantan and the Makassar Strait [5]. Teo et al. [3] found that average speed of northwest migration was 15 m/s, which was faster than the result of Ichikawa and Yasunari [5], and southeast migration only occurred in mainland Kalimantan because the westward migration from Sulawesi Island extended which was also stated by Wu et al. [6]. In the Cendrawasih Bay and the Tolo Bay, the diurnal rainfall migrates from the mainland to the north and west at a speed of 4.6 m/s and 6.1 m/s [7]. The migration of diurnal rainfall in the mountains of New Guinea also speeds up to 2-6 m/s and it becomes faster at speeds of 3.7-8 m/s in northeastern waters [3], [8], [9]. In Jakarta and its surroundings, diurnal rainfall migration is northward (southward) at night (day) at a speed of 5 m/s (2 m/s) caused by a front land-breeze (sea-breeze)-like [10].

In the intraseasonal scale, Madden Julian Oscillation (MJO) is the most dominant atmospheric phenomenon. MJO is associated with large-scale coverage of clouds and convection that propagate from the Indian Ocean to the Pacific Ocean with a period of 30-90 [11]. MJO weakens when it reaches maritime continent (MC) [12] and some cases of MJO do not propagate across the MC at all [13]. It appears to produce the largest diurnal precipitation over the Java island compared to other islands in the active MJO period [14]. When MJO is active, morning rainfall in the Java Sea becomes more intense, but terrestrial rainfall shows a minimum value [12]. Vincent and Lane [15] concluded that diurnal rainfall was significant before (when) MJO was active in Java Island (waters around Java Island). There is also another influence of convectively coupled equatorial waves (CCEWs) to the diurnal rainfall over Java that increase amplitude of diurnal rainfall and delay its phase [16].

There were studies about DHR over Java, such as the study of Wu et al. [17] who identified that downflow from the mountain slope produced wind convergence over the northern plains of Java island and precipitation moved northward in the flood event of late January and early February 2007, Trilaksono et al. [18] who found that heavy precipitation moved southward from the Java Sea to Jakarta on 31 January-2 February 2007 with the peak of rainfall in the morning in Jakarta, Wu et al. [19] who stated that southward precipitation propagation over the Java island from the nighttime to early morning in the flood event of middle of January 2013, and Yulihasrin et al. [20] who found landward movements that were preceded by seaward movements to form early morning precipitation over the coastal. Generally, these studies only focus on the DHR migration over the north coast of western Java, so that a comprehensive study covering Java island and its surrounding waters is necessary to increase our literacy.

2. Data and Method
We used CMORPH V1.0 [21] with a resolution of 8 km in the December-January-February (DJF) of the 1998-2019 period (21 years). In DJF, there was more rainfall over southern MC [22]. We made an hourly accumulation of 30 minutely data. accuracy of hourly CMORPH was about 85.5-90.67 % over East Java in the period of 2010-2014 [23]. For heavy rainfall intensity, we used a threshold of >4 mm/h [24] and >8 mm/h for maximum rainfall as it was double of heavy rainfall threshold. Over Java, the diurnal rainfall was higher in the mountainous area than the plain area [22] and the extreme rainfall of daily accumulation (mm/day) has more impact to the community life than an hour rainfall accumulation (mm/h), so the tresholds of extreme events were calculated based on 95% percentile of the daily rainfall area average of mountainous area (MA), northern plain area (NPA), northern waters (NW), southern plain area (SPA), and southern waters (SW). These areas were classified based on Global Land One-kilometer Base Elevation (GLOBE) Digital Elevation Model [25] with 0 m for NW and SW, 0.1-300 m for NPA and SPA, and >300 m for MA (figure 1).

To understand meridional migration, we analyzed the meridional hovmoller diagram and the the spatiotemporal contour map of CMORPH (figure 2-4). We made the lines (blue or red) in the middle of rainfall contour in the hovmoller and calculate the meridional range of lines (y-axis) devided by the time (x-axis) as Hassim et.al [9] made.
To show the relation between MJO and DHR, we filtered the outgoing longwave radiation anomaly (OLRA) data with a Wheeler Kiladis filter (WK99) [26] to obtain an MJO signal with a wave number and a period of 0-9 and 30-96 days [27] then we composite the MJO signal at the extreme events in each of the area.

![Image](Java and its surrounding waters MA (red), NPA (yellow), SPA (green), NW (blue), and SW (light blue) and the extreme thresholds are 49, 48.9, 49.97, 58.5, and 53.4 mm/day, respectively. The topography contour (black) is 300, 500 m.)

**Figure 1.** Java and its surrounding waters, MA (red), NPA (yellow), SPA (green), NW (blue), and SW (light blue) and the extreme thresholds are 49, 48.9, 49.97, 58.5, and 53.4 mm/day, respectively. The topography contour (black) is 300, 500 m.

### 3. Result and Discussion

Based on the 95% percentile of daily rainfall accumulation, we get extreme thresholds of each area are 49, 48.9, 49.97, 58.5, and 53.4 mm/day. All thresholds are lower than the result of Supari et al. [28] and Wicaksono and Hidayat [29]. It is maybe caused by rainfall underestimate of satellite [30].

![Image](21-years climatology of diurnal rainfall and Hovmoller diagram of diurnal rainfall climatology overlaid by the topography over Java and surrounding waters.)

**Figure 2.** (a) 21-years climatology of diurnal rainfall and (b) Hovmoller diagram of diurnal rainfall climatology overlaid by the topography over Java and surrounding waters.

Based on the climatology of diurnal rainfall in figure 2.a, rainfall >1.5 mm/h occurs in mountains at 14-21 LT and in the Java Sea at 22-10 LT which has a similar pattern to the research of
Qian [22]. Rainfall >3 mm/h only occurs around the mountains of central Java and parts of the lowlands of eastern Java. The Hovmoller diagram (figure 2.b) shows that rainfall >0.8 mm/h formed in the mountains of Java and tends to be stationary for 6 hours (13-19 LT) then migrated northward at a speed of 4.54 m/s. and southward with a speed of 3.08 m/s but with a lower intensity. There is no clear difference between the speed of migration on land and at sea. The migration speed is close to the result of the study by Mori et al. [10] with a value of 5 m/s using weather radar caused by a land-breeze-like front. Land-Sea breeze itself is a form of internal gravity wave [31].

![Figure 3](image)

*Figure 3.* Composite of DHR in the extreme event over (a) MA, (b) NPA, and (c) NSA and Hovmoller diagram of heavy and maximum rainfall in the extreme event over (d) MA, (e) NPA, and (f) NSA.
Figure 4. Composite of DHR in the extreme event over (a) NW and (b) SW and Hovmoller diagram of heavy and maximum rainfall in the extreme event over (c) NW and (d) SW.

During the extreme event in MA, DHR occurred around the mountainous area and plain area at 11-23 LT and the maximum rainfall was around the mountains of central Java in figure 3.a. Figure 3.d also shows that diurnal rainfall tends to be stationary around the mountains at 11-23LT. It may relate to the longer time of wind convergence to occur than its climatology that enhances large amount of precipitation. During the extreme event at the NPA in figure 3.b, DHR initially formed around the northern mountains at 12-15 LT and migrated to northern plain area around 16-22 LT and then to the coastal and northern waters of western Java around 23-06 LT which is early morning precipitation [18], [20]. The heavy rain in these northern waters is also influenced by the westward migration of heavy rainfall from southern Sumatra which is also found in the research of Nuryanto et al. [32]. The maximum rainfall occurs in the northern lowlands of central and eastern Java. Figure 3.e displays only the northward migration of rainfall from mountains to the Java Sea at a speed of 4.7 m/s. This northward migration may relate to the gravity waves but faster than the climatology. There is no DHR that migrates southward because it may be blocked by the mountains. DHR in figure 3.c initiates around the southern mountains at 12-20 LT, moves to the southern coast of central Java, and a small part of it migrates to the Indian Ocean at 22-01 LT. The maximum rainfall occurred in the plain area of southern central Java during the extreme events of SPA. Based on figure 3.f, there is a migration of rainfall from the mountains to the south-east at a speed of 3.25 m/s that is faster than climatology. The gravity waves may relate to the south-eastward migration but the northward migration is blocked by the mountains. DHR occurs in the Java Sea all-day in figure 4.a during extreme events in NW. While
on land, DHR also appeared around the mountains of central Java which migrated to the Java Sea at 13-05 LT. The maximum rainfall is only in the northern waters of western Java. In figure 4.c, DHR appears occurs stationary all-day in the Java Sea and migrates from the northern mountains to the Java Sea at a speed of 5.58 m/s that is faster than the climatology. The northward migration increases the intensity of rainfall to >4 mm/h in the Java Sea at 23-05LT or early morning precipitation [18], [20]. In figure 4.b, DHR occurs in the Indian Ocean all-day although the intensity is smaller at 12-17 LT. DHR also occurs around the mountains of central and eastern Java at 15-16 LT and an only small part of DHR migrates to the Indian Ocean because the southern coastline of central Java is less curved than the northern coastline. The more curved coastline can produce stronger land breeze convergence at night [7]. Figure 4.d described that the rainfall migrates from mountains to the Indian Ocean at 15-07 LT with a speed of 5.4 m/s which increases the rainfall intensity in the Indian Ocean to be >4 mm/h at 01-05 LT. Based on the comparison of Figure 3-4, the migration of DHR from the mountains to the Java Sea and the Indian Ocean during extreme events in NPA, SPA, NW and SW is faster than the climatological pattern in figure 2.b.

**Figure 5.** Composite of MJO-filtered daily OLRA (W/m²) during the extreme events over (a) MA, (b) NPA, (c) SPA, (d) NW, and (e) SW.

During the extreme events in MA and SPA, daily OLRA of about -1 W/m² was only observed over western Java and surrounding waters (figure 5.a and 5.c) and 1 W/m² was in the eastern Java and surrounding waters (figure 5.a). Daily OLRA of about -1 W/m² was over large parts of Java island and the Java Sea during the extreme event in NPA (figure 5.b). It is different when the extreme event in
NW and SW, MJO appears to have a role in increasing the rainfall intensity because OLRA ranges from -5 to -2 W/m² (figure 5.d) and -8 to -3 W/m² (figure 5.e). This is in line with the results of research by Vincent and Lane [15] which states that the heaviest rainfall on the Java island occurs when real-time multivariate MJO index (RMM) in phase 2-3 and over waters in phase 4. By using the WK99 filter, Sakaeda et al. [33] also found that MJO only has a significant relationship with the diurnal rainfall amplitude over waters of the Maritime Continent because the diurnal amplitude of middle, high and deep cloud fractions increase over ocean and the diurnal amplitude of low cloud fractions decrease over land within enhanced MJO convection.

4. Conclusion
The study of heavy rainfall migration during extreme events in 5 areas, namely MA, NPA, SPA, NW, and SW was carried to determine the pattern of heavy rainfall migration in Java and its surrounding waters. We found that DHR tends to be stationary in the mountains during extreme events in MA, migrating northward (southward) from Java Island to surrounding waters during extreme events in the NPA (SPA), and tends to be stationary in the Java Sea (Indian Ocean) in conjunction with migration from Java to the waters during the extreme event at NW (SW). All of these migrations are faster than climatology. The maximum rainfall can only be found on the island of Java during the extreme events in MA, NPA, and SPA and in the western Java Sea during the extreme event in NW. We also studied the relationship of MJO with these extreme events. The MJO signal is obtained from OLRA filtered with WK99. The results show that only the extreme events in NW and SW appear to be more influenced by the MJO than others.

Because we only study the relation of rainfall migration with MJO, studies regarding the significant connection between rainfall migration and MJO and other atmospheric phenomena in the research area are needed for further studies.

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