Impact of Madden-Julian Oscillation on the Diurnal Rainfall Cycle in Peninsular Malaysia

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Abstract. The study investigated the influence of the early phases of Madden-Julian Oscillation (MJO) on the diurnal rainfall cycle in Peninsular Malaysia (PM). The most significant variations in precipitation occurred late evening Malaysia Standard Time. The remote impacts of MJO on PM resulted in changes to the diurnal rainfall patterns during the early MJO phases when the primary MJO convection centre remains over the Indian Ocean. These conditions created a conducive environment for local convection over PM due to the weakening of the southwest monsoon winds. Along the west coast of PM, intensified sea breeze led to anomalous moisture transport fuelling the local convection. In contrast, the eastern coast experienced drier weather due to opposing sea breeze and monsoonal wind patterns, diminishing moisture transport towards the northeastern coastal region.

1 Introduction

The dominant factor driving fluctuations in seasonal rainfall patterns across the Maritime Continent (MC) is widely recognized as the Madden-Julian Oscillation (MJO) [1]. This oscillation profoundly impacts various meteorological parameters such as temperature, wind patterns, and precipitation leading to significant shifts across the MC region [2]. The influence of the MJO and its trajectory exhibits variations influenced by seasonal dynamics across different locations along the equatorial belt [3,4]. Particularly during boreal summer, the MJO's influence intensifies near the northern hemisphere of the equator, spanning from the Bay of Bengal to the South China Sea and extending into the eastern Pacific Ocean [5].

The onset of active MJO convection within the Maritime Continent (MC) typically occurs between Phase 3 and Phase 4 of the Real-time Multivariate (RMM) index [6]. However, past studies discovered that wet weather occurred during the early supressed phases in MC [7,8]. The amplitude of the diurnal cycle demonstrates an increase during the early phases and a decrease during the late phases over the western Maritime Continent [9,10]. Throughout the wet phase, there is a potential for amplification of the diurnal cycle's amplitude by up to 1.5

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times with distinct vertical profiles observed in diurnal heating patterns particularly during morning hours near coastal surface areas [11,12]. Rainfall rates typically reach their peak over land before the convective MJO arrives, while high oceanic rainfall rates coincide with the active presence of the MJO within the Maritime Continent [13]. Across Southeast Asia, the proportion of severe rainfall during active MJO phases can increase by approximately 30% to 50%, while during passive phases, it may decrease by about 20% to 25% [14].

Peninsular Malaysia has a unique topography and intricate terrain lies within the Maritime Continent and bordered by the Strait of Malacca and the South China Sea. The climate of this region is significantly shaped by the Asian-Australian monsoon and the El Niño-Southern Oscillation (ENSO) [15,16]. Additionally, it experiences a pronounced diurnal cycle in deep convection development largely due to the substantial temperature contrast between land and sea and the influence of mountain-valley winds [2,17]. Moreover, the dominance of the diurnal cycle during boreal summer contributes to the intraseasonal variability observed in seasonal patterns. Despite the well-established influence of MJO on seasonal rainfall patterns across the MC, the impact of diurnal rainfall cycle remains underexplored in Peninsular Malaysia. Given the diurnal cycle's crucial role in driving deep convection during the boreal summer, understanding the MJO's influence on these cycles is essential. This study is motivated by the need to fill this knowledge gap by employing the Real-time Multivariate (RMM) index during the early phases of the Madden-Julian Oscillation (MJO) in Peninsular Malaysia to examine the impact of the diurnal cycle of rainfall and wind circulation during this period.

2 Materials and Methods

The rainfall datasets consist of meteorological station data provided by the Malaysian Meteorological Department (MMD) and a gridded datasets from the Global Precipitation Measurement (GPM) project with a 1.0° horizontal resolution were utilised [18]. In order to examine variations in regional air movement, a comprehensive dataset capturing wind circulations at 850 hPa (surface level) was sourced from the fifth iteration of the European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis (ERA5) [19].

To analyse the intraseasonal variations in daily rainfall, anomalies for the early phases of the MJO were calculated utilizing the Real-time Multivariate (RMM) index [6]. This analysis was conducted over a three-month period during boreal summer (June-July-August) covers an 18-year period from 2001 to 2018. Daily rainfall anomaly values were derived by subtracting the seasonal climatological mean of daily rainfall from observed daily rainfall for each MJO phase. The seasonal climatological mean was computed by averaging daily values for boreal summer across the entire 18-year period. Subsequently, composite mean daily anomalies were generated by averaging daily rainfall anomalies across all MJO phases. The statistical significance of these rainfall composites was assessed using a Monte Carlo resampling method [20]. This resampling procedure was repeated 500 times to ensure robust estimations, and the sorted results were evaluated at a 5% significance level using a two-sided test.

3 Results and Discussion

3.1 MJO impact on daily rainfall

The findings suggest a strong association between anomalous daily rainfall and winds at 850-hPa across Peninsular Malaysia and the phases of the MJO (Fig. 1). During the early phases of the MJO, distinct daily rainfall patterns emerge over the west and east coasts of Peninsular

Malaysia. In the northern part of Peninsular Malaysia, some stations experience dry conditions, while the west coast encounters wetter conditions during Phase 1. Phase 2 showcases a noticeable contrast in daily rainfall patterns. The West Coast experiencing wetter conditions while the East Coast records drier conditions. Furthermore, alongside the opposing rainfall anomalies between the east and west coasts, prevalent easterly anomalies dominate Peninsular Malaysia and its surroundings during the early phases. It is indicating a weakening of the south-westerly monsoonal wind. On the contrary, Peninsular Malaysia experiences drier conditions during boreal winter in Phase 1 [7,8].

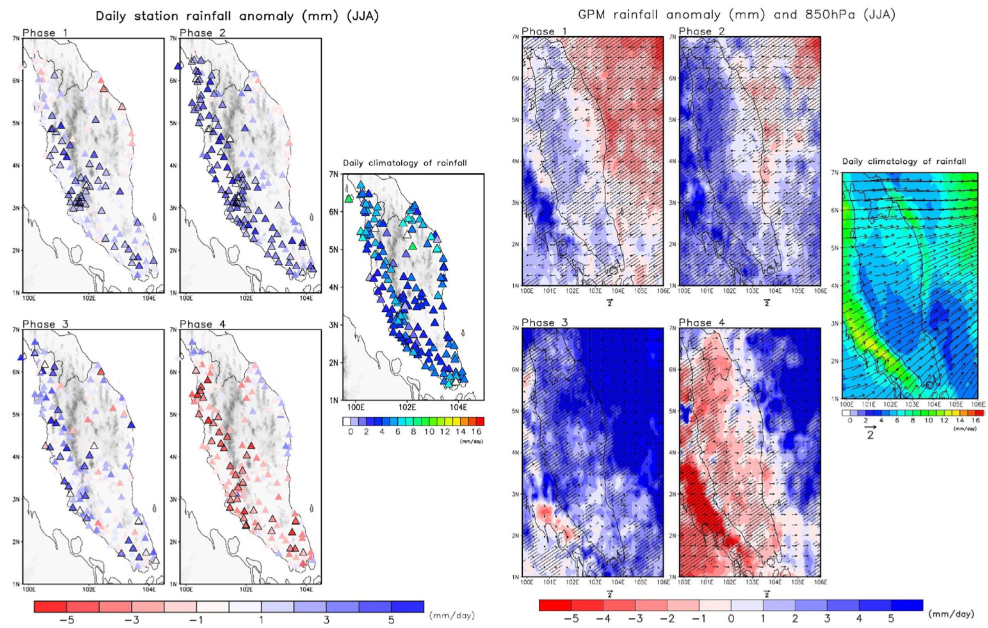

Fig. 1. Composites of daily rainfall anomaly (mm/day) and wind at 850-hPa (m/s) over the Peninsular Malaysia for early MJO phases (phase 1 and 2) and active MJO phases (phase 3 and 4) for data station (left panel) and gridded data (right panel).

Phase 3 shows wet rainfall anomalies covering most of Peninsular Malaysia with weaker MJO signals over land compared to the sea. The number of significant stations decreases throughout the region. The northwesterly winds cross Peninsular Malaysia towards the southern region, while winds remain nearly stationary over the South China Sea near the northeast coast. Rainfall anomalies are more pronounced in the ocean than on land. During Phase 4, weather conditions in Peninsular Malaysia contrast with the early phases, with drier weather on the west coast and wetter weather on the east coast. The westerly wind anomaly strengthens the southwesterly climatological wind from Sumatra, passing through Peninsular Malaysia toward the South China Sea. Generally, the impact is more significant on the west coast than on the east coast during most MJO phases.

3.2 MJO impact on diurnal cycle

The differences in rainfall anomalies can be observed between the sea and land in the morning (05 MST) and in the evening (18 MST) using the GPM rainfall dataset (Fig. 2). According to climatological data, rainfall typically occurs over the ocean during the early morning, particularly in the Strait of Malacca. Rainfall tends to occur over land during the late evening across Peninsular Malaysia with heavy rainfall predominantly observed in the northern region. However, during the early phases of the MJO especially Phase 2, the peak rainfall occurs in the morning in the Strait of Malacca, while the afternoon sees a significant peak in rainfall over the west coast and inland areas of Peninsular Malaysia. Conversely, there is less rainfall observed in the northern part of the east coast including the adjacent South China Sea. This rainfall pattern mirrors that of April, the inter-monsoon season in Malaysia. During Phase 3, the rainfall peak becomes more evenly distributed with reduced rainfall observed across Peninsular Malaysia. As the transition to Phase 4 occurs, distinct wet and dry weather patterns emerge, differing from the earlier stages of the MJO.

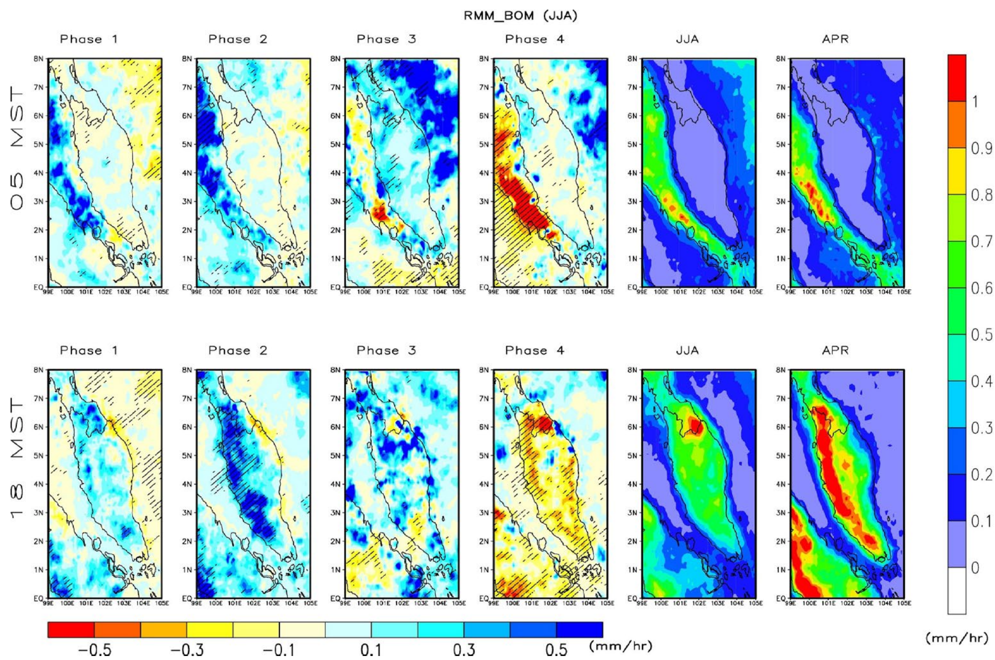

Fig. 2. The anomaly (mm/hr) of the rainfall diurnal cycle at 0200 MST and 1800 MST using GPM datasets for early phases and JJA climatology. Shaded is the significant level at 95%.

4 Conclusion

In Peninsular Malaysia, the impact of rainfall is more significant during the early MJO phases than during the active MJO phases. The early MJO leads to two different weather patterns: i) wet weather in most areas of Peninsular Malaysia, especially in the west coast region, and ii) dry weather in the northern part of the east coast region. Our analysis indicates that the evening peak in rainfall during the early phases of the MJO mirrors that observed during the inter-monsoon period. The fluctuations in the local sea breeze played a crucial role in the alteration of maximum rainfall during Phases 1 and 2. This mechanism resembles the phenomenon observed during the inter-monsoon period, where the convergence of these swift sea breezes and the gap flow originating from mountainous areas triggers a notable surge in rainfall from the afternoon into the late afternoon across the region. The southwesterly monsoonal wind plays a pivotal role in intensifying these sea breezes during this timeframe. A similar mechanism is anticipated in the southern region of the west coast, as it arises from the interaction between the sea breezes originating from both the west and east coasts.

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