Linkages of Active and Weakening MJO events to Seasonal Variations over the Maritime Continent

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Abstract. The Madden-Julian Oscillation (MJO) is a large-scale phenomenon of air-sea intra-seasonal variability in the equatorial area, particularly in the Maritime Continent (MC). This research focused on the analysis of the MJO propagation process in association with rainfall events and sea surface temperature anomaly (SSTA) during seasonal variations, i.e., November, December, January February, and March (NDJFM), and May, June, July, August September (MJJAS). MJO events from 2010 to 2019 were classified as MJO active or MJO weakening according to propagation characteristics and amplitude changes in the RMM index. This research uses a dataset of 10-year series of daily Tropical Rainfall Measuring Mission (TRMM) (3B42 V7 derived) measurements for detecting rain rates. Daily OLR data from the NOAA Physical Sciences Laboratory and SSTA daily data from Physical Oceanography Distributed Active Archive Centre (PODAAC) NOAA are considered for analysing MJO propagation. Composites of outgoing longwave radiation (OLR) were also identified differences between the two events; active MJO events had consistently higher negative OLR anomalies than weakening MJO events. Active MJO events during NDJFM had a higher rain rate and positive SSTA than weakening MJO events. Furthermore, composite rain rates distribution over MC during NDJFM are mainly located in the south of the equator, contrarily when MJJAS are north of the equator.

1. Introduction

The Madden-Julian Oscillation (MJO) is an intraseasonal phenomenon that influences the tropics of the maritime continents (MC). The MJO is a zonal wind oscillation cell that propagates eastward with an average speed of 5 m/s along the equator from the Indian Ocean to the Pacific Ocean at altitudes of 850 hPa 200 hPa with a period of 30-60 days [1]. The MJO phenomenon is characterized by strong convection and high precipitation intensity for the area it passes. The influence of the MJO on weather variability in the tropics could cause changes in air-sea variable variations, namely, variations in Sea Surface Temperature (SST), evaporation, advection, and wind speed and direction in the upper and surface layers [2].

The occurrence of MJO was classified using the empirical analysis method orthogonal function (EOF's) from OLR data and the average zonal wind in the 850-hPa and 200-hPa layers. From the EOF analysis, the principal component (PC) time series pairs are obtained, namely Real-time Multivariate MJO series 1 (RMM1) and 2 (RMM2) [3]. The PCs time series is used to calculate the MJO Index and is used as a reference to determine MJO events:

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Furthermore, research on the relationship between marine parameters and the MJO phenomenon found an increase in maritime activity caused by the MJO as an increase in evaporation due to a positive SST anomaly before MJO convection [3]. Active MJO events have a larger index amplitude than weaker events. The difference in amplitude appears on day 3 in the Real-time Multivariate MJO (RMM) index and remains up to lead days (+15) in both indices (day-0 marks the day the event enters MC).

Finally, MJO intensity and propagation over the MC are linked to the changing intensity of the ocean-atmosphere variable. This study emphasizes the characteristics of the ocean-atmosphere parameters generated by the active and weakening MJO intra-seasonal phenomena in rainfall propagation and SST based on their effect on MC. MJO classification method [3] is using RMM index in characterize the MJO phenomenon. Analysis of the effect of MJO classification is observed based on the monsoon cycle. The monsoon influences southeast Asia’s weather system but also affects areas in tropical latitudes. The two main monsoon regimes are specifically selected the northeast monsoon (boreal winter monsoon) from November to March (NDJFM) of the following year and the southwest monsoon (boreal summer monsoon) from late May to September (MJJAS). In addition, October and April are categorized as a transition phase from the southwest monsoon season to the northeast monsoon season [4]. The results are expected to advance our understanding of the MJO propagation process and examine the relationship between atmospheric variables, particularly longwave radiation (OLR), wind, and precipitation, with ocean parameters, such as the sea surface temperature (SST) during the phase active and weakening MJO.

2. Data and Methods

In this study, a real-time multivariate MJO index (RMM) was used to measure the intensity and position of the MJO [3]. The researcher [3] conducted a study on identifying MJO events using empirical orthogonal functions (EOF's) analysis methods from OLR data and the average zonal wind in the 850 hPa. From the EOF's analysis, the principal component (PC) time series pairs are obtained, namely Real-time Multivariate MJO series 1 (RMM1) and 2 (RMM2), which are freely available from the Bureau of Meteorology of Australia. The MJO affects the MC area in phases 3, 4, and 5; with phase 3, the MJO affects the western part of the MC.

![Figure 1. The study area for MJO propagation](image)

The study area of this research covers latitude 12° N - 12° S and longitude 90° E -141° E, which is part of the MJO oscillation area over MC. The data used in this study uses ten years, starting from January 1, 2010, to December 31, 2019. In understanding the characteristics of the MJO, an analysis
was carried out using Gridded daily OLR data obtained from the National Center for Atmospheric Research (NCAR) with temporal interpolation resolution $0.25^\circ \times 0.25^\circ$. Data for daily zonal wind with pressure level $850 \text{ hPa}$ with $2.5^\circ \times 2.5^\circ$ global grids are obtained from NCEP/NCAR reanalysis data to get lower-level wind characteristics. To represent precipitation over tropical regions, daily Tropical Rainfall Measuring Mission (TRMM) (3B42 V7 derived) measurements are used to detect rain rates. This research referred to the TRMM user handbook produced by the National Space Development Agency of Japan (NASDA) for detailed dataset documentation. MJO characterization is carried out to monitor MJO activity based on the classification of active and weakening MJO and its relationship with marine parameters in SST anomalies. SST anomaly can be accessed from A Group for high-resolution sea surface temperature (GHRSSST) Level 4 data with temporal resolution coverage of $0.25^\circ \times 0.25^\circ$.

The method used in this study is using a bandpass filter which is limited by two cut-off frequencies. The data filter applied in this study is a bandpass filter with a period of 20-100 days to determine the MJO propagation [5], with a low-frequency cut-off value of 0.01 (representing 100 days) to a high frequency of 0.05 (representing 20 days). Furthermore, the bandpass filter will discard signal oscillations with periods below 20 days and above 100 days. This filtering is expected to limit the impact of interannual, annual, and seasonal phenomena. The time series equation used is as follows:

\[
Y_t \sum_{k=\infty}^{k=\infty} \bar{w}_k X_{t-k} = \bar{w}_k
\]

\[
\bar{w}_k = \left( \frac{\sin 2\pi f c_1 k}{\pi k} - \frac{\sin 2\pi f c_2 k}{\pi k} \right) \sigma, k = -n, ..., 0, ..., n
\]

which:
- $\bar{w}_k$ : Signal weight at 95% confidence interval
- $f c_1$ : first frequency cut-off
- $f c_2$ : second frequency cut off which gives a “0” response to the Nyquist frequency.

In classifying MJO based on active and weakening MJO, it is done using RMM index analysis. To be classified as an active MJO event, the MJO must propagate from phase 3 to phase 5 with an RMM index amplitude of 1.0 and exhibit a counterclockwise progression in each phase area [6]. In contrast, the MJO weakening event is defined as an MJO propagation event that crosses the phase 4 area with an RMM index amplitude of 1.0 (similar to active) but weakens and exits phase 5 with an RMM index of 1.0.

3. Result and Discussion

This study aims to determine the effect of MJO classification on atmospheric-ocean dynamics in the MC region. The results of this study are as follows:

3.1 Active and weakening MJO events

An analysis of the frequency of MJO events was conducted to compare the number of active and weakening MJO events in the NDJFM and MJAS seasons. From 2010 to 2019, 48 MJO events were identified above the MC (Table 1) that entered phase 4 RMM with an amplitude greater than 1.0. Of the index RMMs, 30 events exited phase 5 with an amplitude greater than 1.0 (and thus classified as active MJO), and 18 exited phase 5 with an amplitude less than 1.0 (thus classified as weakening MJO). During the transition period, seasonal variations occurred in 4 cases, referring to October and April. This analysis indicates that the boreal winter monsoon dominates the highest frequency of MJO events.
Table 3.1 Number of active and weakening MJO events in the RMM indices from 2010 to 2019, for the entire year and for each seasonal variation.

| RMM Index  | Active MJO | Weakening MJO | Total     |
|------------|------------|---------------|-----------|
| All Seasons| 30         | 18            | 48 cases  |
| NDJFM      | 17         | 7             | 24 cases  |
| MJJAS      | 10         | 10            | 20 cases  |
| Transition | 3          | 1             | 4 cases   |

Furthermore, the frequency of MJO events is divided based on the month of occurrence, starting from January to December. In Figure 2, it can be seen that there is a phase of the highest number of days (>40 days) when the highest active MJO is dominated successively in December, September, March, and June, while when the weakening MJO, the most increased occurrence only occurs in September. The less frequent MJO events occur in July, August, and October for active MJO, February, June, April, and December to weaken MJO. The statistical frequency shows that MJO occurs more frequently during the boreal winter season (24 cases) than the boreal summer monsoon (20 cases).

![Figure 2. Number of day events both active and weakening MJO events in the RMM indices from 2010 to 2019.](image)

3.2 MJO propagation

The OLR parameter shows MJO propagation in Figure 3. Convection activity is moving towards eastern Indonesia, and the influence of the MJO in the lead day (day +8) is decreasing in some areas such as Sumatra, Java, and Kalimantan. After the bandpass filter is performed, all data per timestep is combined into composite data for each parameter based on MJO classification and seasonal variations. In identifying further variation between active and weakening MJO events, composite OLR is examined through the MC region. MJO propagation on the lag day (day -8) showed a negative OLR anomaly, moving from 90° E in the active and weakening MJO phases. However, in Figure 3’, we can see that the active phase of the MJO shows a stronger and more pronounced negative anomaly than the weakening MJO, which gradually propagates towards the MC. Furthermore, on day 0, it is seen that in the active MJO phase, the negative OLR has covered the MC with a more vigorous intensity than the weak MJO phase. Then on day +8, the difference between active and weakening MJO is more visible at 120° E - 150° E. A strong negative anomaly still occurs in the active MJO, while the weakening MJO experiences a decrease in convection, as indicated by a negative OLR anomaly.
Figure 3. Composite anomalies of OLR for a–d day – 8, b–e day 0, and c–f day+8. Active MJO are shown in the left column (a, b and c); weakening MJO are shown in the right column (d, e and f).

From this section, we can indicate that the intensity of the convection strength in the Indian Ocean region when the MJO is formed will determine the formation of an active and weakening MJO. Strong convection characterized by a negative OLR anomaly (Figure 3a) in the lag day contributed to an active MJO. Conversely, a weak negative OLR anomaly at the lag day in the Indian Ocean would form a weakening MJO (Figure 3d).

3.3 Wind 850 hPa and MJO propagation
Furthermore, MJO propagation is also identified by the wind speed and direction at the 850 hPa layer to prove MJO propagation over MC. The results of the OLR propagation analysis with 850 hPa layer winds indicate that the OLR propagates to the east at a speed of 4 m/s. MJO is evidenced by a negative OLR anomaly that moves at a propagation speed of 3 - 7 m/s [5]. OLR propagation is classified based on the incidence of active and weakening MJO, which is then carried out by OLR composites for further analysis on a seasonal scale. In the active and weakening MJO phase, the negative OLR is intensive in the boreal winter season, especially in the eastern Indian Ocean region and south of the equator. Compared to the boreal summer season, the OLR anomalies tend to have weaker, with negative OLR centered in the north equator. It also occurs in the boreal summer monsoon during the weakening phase of the MJO. The weakening phase of the MJO shows a random distribution of OLR anomalies. It is dominated by positive OLR anomalies, which indicate weak convection, compared to the active phase of the MJO, which is dominated by strong convective anomalies (negative OLR anomalies).
3.4 Precipitation and MJO propagation

In the central and western regions of MC, boreal winter monsoons significantly affect MC [8]. Boreal summer monsoon can cause some areas in Indonesia to experience a dry season [11]. This condition is also detected by Figure 5 in the boreal summer season, which has a smaller rainfall intensity than the boreal winter monsoon. Based on the average daily rain rates throughout 2010-2019 in the boreal winter monsoon, rainfall > 18 mm/day spread over the MC. The boreal winter monsoon during MJO has a more robust impact because the ITCZ is closer to the equator and Indonesia experiences wet monsoon season during this time, which enhances moisture transports to most parts of Indonesia. ITCZ moves north in the summer in the northern hemisphere (July) and the south in the southern hemisphere (in January), following the location of maximum solar heating. The ITCZ significantly affects monsoon activity and rainfall at rainfall on the equator [12]. The dominant occurs in the Indian Ocean, northern and southern Java Seas, and Karimata Strait. The reasonably high intensity of rainfall generally occurs during the active phase of MJO events compared to the weakening MJO events, which typically experience a distribution of high rainfall intensity only in certain areas. Furthermore, in the boreal summer monsoon, intense rainfall occurs to the north of the equator, with dominant rainfall clusters on Papua Island and the Pacific Ocean.

An exciting phenomenon and other regions that do not experience is high rainfall during the boreal summer season. This is due to the existence of boreal summer intra-seasonal oscillation (BSISO), which plays an essential role in the intra-seasonal variability of a wide range of weather and climate phenomena across the region modulated by the Asian summer monsoon system [9]. BSISO also influences the Madden-Julian Oscillation (MJO) phenomenon along the equator. It is characterized by a BSISO mode with prominent northward propagation and significant variability in the monsoon trough regions outside the equator. In the boreal summer, the BSISO disturbance tends to spread to the northeast and significantly affects the fluctuations in active and/or break monsoon rainfall. The disturbance associated with the BSISO causes the MJO to have a less direct impact on rainfall over the equatorial continent.
Figure 5. Composite anomalies of OLR and wind direction over MC during active and weakening MJO in boreal summer (MJJAS) and boreal winter (NDJFM) monsoon phases.

3.5 SST Anomaly and MJO propagation
Analysis of the linkages between SST and MJO was carried out by dividing the composite data in the boreal winter and boreal summer monsoons, which were then identified based on day -8, day 0, and day +8. In the boreal summer phase (day -8), the positive SST anomaly was quite strong in the western Indian Ocean during weakening MJO compared to active MJO events. However, in the eastern Indian Ocean region, weakening MJO events were more dominated by negative SST anomalies than the active phase of MJO, which had positive SST anomalies. Furthermore, on day 0, both active and weakening MJO, positive SST anomalies dominate the MC region, with the highest intensity of positive SST anomalies occurring in the 115° E – 150° E region (SSTA > 0.3). Furthermore, on the lead day (day +8), the condition of the SST anomaly still dominates, but there is a decrease in the intensity of the SST anomaly compared to day 0.

Figure 6. Day -8 through day +8 lags of MJO propagation during active MJO associated with SST anomaly for boreal summer (MJJAS) and boreal winter (NDJFM) monsoon phases over MC.
Figure 7. Day -8 through day +8 lags of MJO propagation during weakening MJO associated with SST anomaly for boreal summer (MJJAS) and boreal winter (NDJFM) monsoon over MC.

In the boreal winter monsoon, during the active MJO phase, the positive SST anomaly is more stable distributed than in the weakening phase of the MJO, which is spread randomly, both on the lag, the day 0, and the lead day. The weakening of the MJO is strongly dominated by negative SST anomalies, which are quite strong compared to when the MJO is active, especially in the Southern Hemisphere. There is a positive SST anomaly in the day -8 phase, which is quite intensive compared to the conditions of day 0 and day +8. Furthermore, the value of positive SST anomalies is gradually decreased in both MJO phases in the lead day.

The results show that intensive positive SST is dominant in the southern region during the boreal winter monsoon. In contrast, in boreal summer monsoon, positive SST anomalies are quite focused on the Indian Ocean waters compared to boreal winter, where negative SST dominates. These results agree with research that states that the MJO variance is concentrated in the southern MC during boreal winter [10]. Contrarily, in boreal summer, the monsoon is more dominant in the north, including North Sumatra.

Figure 8. Meridional profiles of sea sea surface temperature anomaly
Furthermore, the results of the meridional profile of the SST anomaly are shown in Figure 8. The results show that SST tends to be lower during the lag day compared to day 0. On day 0, the SST anomaly increases from north to south of the equator. On the lead day, the SST anomaly tends to raise more than the conditions at day 0, with significantly higher values occurring near the equator. This shows that the area traversed by the MJO will experience an increase in SST along with the passage of wind direction to the east. This further causes a warmer SST in the Indonesian Sea during the MJO suppression phase prompting the MJO convective phase to spread eastward over the maritime continent (MC).

4. Conclusion
From the 48 total MJO events during 2010-2019, the highest MJO events occurred during the active MJO phase, as many as 30 cases, with the most MJO cases occurring during the boreal winter season was 24 cases. MJO propagation can be easily represented by the negative OLR anomaly propagation, supported by the eastward zonal wind at the 850 hPa layer. The analysis of ocean-atmosphere parameters during active and weakening MJO based on seasonal time periods produces different responses. During the boreal summer monsoon, the active period and weakening MJO events did not experience a significant difference over MC, with weaker intensity occurring in the weakening MJO phase. Negative OLR anomalies and rain rates will increase in intensity in the northern part of the equator. In contrast, positive SST anomalies will generally be centered at 115° E – 150° E. Unlike during the boreal winter season, there is quite a varied response to each active phase and weakening of the MJO. Negative OLR anomalies and rain rates indicate that the highest intensity is more dominant in the south of the equator and the Indian Ocean when the MJO is active. In contrast, positive SST anomalies have similarities with boreal summers centered in the 115° E – 150° E region. Contrarily, in the weakening MJO phase, generally, the parameter intensity will be weaker and unevenly distributed of intensity. The area traversed by the MJO will experience an increase in SST along with the passage of MJO propagation to the east. The analysis results show a fairly close relationship between parameter variations based on the characterization of the MJO against seasonal variations, which can then be used to understand the response of ocean- atmosphere parameters to the active and weakening of the MJO at certain phases and times.

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