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Propagation Characteristics of Madden Julian Oscillation in the Indonesian Maritime Continent: Case Studies for 2020-2022

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ABSTRACT

Madden-Julian Oscillation (MJO) can affect weather and climate variability in the Indonesian Maritime Continent. MJO propagation is not always the same, previous research has classified MJO into 4 categories: slow, fast, stand, and jump. The objective of this study is to investigate the differences in MJO propagation and the factors that impact it. Daily data for variables such as Outgoing Longwave Radiation (OLR), zonal wind, and sea surface temperature are utilized in this research. The collected data is processed using composite methods based on the 8 MJO phases, with a specific focus on the years 2020, 2021, and 2022. The research findings suggest that warm sea surface temperatures in the Pacific Ocean and zonal winds dominated by Kelvin waves are favorable for MJO propagation. Conversely, cooling sea surface temperatures in the Pacific Ocean and zonal winds dominated by equatorial Rossby waves can hinder MJO propagation. Future researchers are expected to examine the impact of MJO propagation during extreme rainfall occurrences in several regions of Indonesia, as well as the application of machine learning and deep learning methods to predict MJO propagation in the future.

KEYWORDS

Madden Julian Oscillation, Indonesian Maritime Continent, propagation characteristics, weather phenomena, sea surface temperature

INTRODUCTION

The Madden-Julian Oscillation (MJO) is an intraseasonal phenomenon that spans from the Indian Ocean to the Pacific Ocean over a period of 30-60 days (Madden and Julian, 1972, 1971; Zhang, 2013). The MJO is detected through the movement of convective clouds from west to east and can influence weather and climate variability along the equator (Birch et al., 2016; Lu et al., 2019; Zhang, 2013, 2005). However, not all MJOs follow the same path, and some MJOs fail to reach the Pacific Ocean due to weakening and loss of propagation when crossing the Maritime Continent (Barrett et al., 2021; Chen et al., 2020; Feng et al., 2015; Kim et al., 2014). When the MJO cannot cross the Maritime Continent, it falls into two categories. The first category is called "jump", which refers to cases where the MJO jumps over the Maritime Continent or stops on its western side before re-emerging in the western Pacific Ocean.

The second category is called "stand" which describes cases where the MJO halts on the western side of the Maritime Continent (Wang et al., 2019). Possible causes for the MJO's inability to cross the Maritime Continent include external and internal factors related to the Maritime Continent. An external factor that hinders MJO propagation is the presence of Rossby waves propagating from east to west, which impedes the eastward movement of the MJO (Feng et al., 2015; Haertel, 2022; Li et al., 2021; Liu and Wang, 2017). The second factor is the barrier effect of the Maritime Continent itself, which can disrupt MJO propagation (Kerns and Chen, 2020; Zhang and Ling, 2017; Zhang and Han, 2020). One mechanism that can cause the occurrence of a barrier effect on the Maritime

Continent is the diurnal cycle, which traps convection on land, preventing the formation of Mesoscale Convective Systems (MCs) over the Maritime Continent (Hagos et al., 2016; Ling et al., 2019; Majda and Yang, 2016; Zhang and Ling, 2017). The diurnal cycle is related to sea surface temperature (Webster et al., 1996) and ocean-atmosphere interactions (Brilouet et al., 2021). If there is a strong sea surface temperature anomaly in the Pacific, the MJO will propagate rapidly (Marshall et al., 2016). However, if this anomaly weakens, the MJO will stall over the Maritime Continent (Wang et al., 2019).

Based on the information provided, it is clear that multiple factors can influence MJO propagation, resulting in variations in its behavior. Therefore, this study aims to analyze the characteristics of MJO propagation in the years 2020, 2021, and 2022 and investigate the factors contributing to differences in MJO propagation. The selection of this year's period is based on the MJO RMM graph (Figure 1), which indicates distinct patterns among these three years, warranting further investigation.

RESEARCH METHODS

Data Source and Study Area

This research focuses on studying the Maritime Continent, also known as the MC region, in Indonesia. The MC region spans from 80°E to 180°E longitude and 15°S to 15°N latitude, making it a significant area of investigation. To gather the necessary information, we will utilize daily NOAA data for Interpolated Outgoing Longwave Radiation (OLR) (Liebmann and Smith, 1996), zonal and meridional winds (Kalnay, 1996), and sea surface temperature (SST) anomaly data from CMEMS (Good et al., 2020). These datasets provide valuable insights into the climate patterns of the MC region. The OLR and wind data will be available at a resolution of 2.5°×2.5°, while the SST anomaly data will be at a higher resolution of 0.05°×0.05°. Our analysis will cover the period from December 2019 to April 2022, allowing us to capture a comprehensive view of the climate dynamics.

Data Source

To enhance our understanding of the climate phenomena in the MC region, we will incorporate the Real-Time Multivariate MJO (RMM) index (Wheeler and Hendon, 2004). This index enables us to identify and analyze the different phases of Madden-Julian Oscillation (MJO) events. By compositing the OLR, zonal and meridional wind data, and SST anomaly data based on the MJO phases using the RMM index, we can gain deeper insights into the relationships between these variables.

1. OLR Composite: Composite OLR is used to observe the propagation of the Madden-Julian Oscillation (MJO). It is composited based on the phases of the RMM index, which include 8 phases from December to April in the years 2019 to 2022. Composite OLR for each phase is calculated as follows:

$$\text{OLR Composite} = \frac{\sum_{i=1}^{i=n} \text{OLR}}{\text{n}} \quad (1)$$

2. Wind Composite: Wind composite for each MJO phase is used to observe wind movements during each phase. The wind variables used are zonal wind (u) and meridional wind (v). Both variables are composited using the RMM index for the period from December to April in the years 2019 to 2022. Wind Composite for each phase is calculated as follows:

$$\text{Zonal Wind Composite} = \frac{\sum_{i=1}^{i=n} u}{n} \quad (2)$$

$$\text{Meridional Wind Composite} = \frac{\sum_{i=1}^{i=n} v}{n} \quad (3)$$

3. SST Anomaly Composite: SST Anomaly composite is used to observe anomalies during each phase of the MJO. It is composited based on the phases of the RMM index, which include 8 phases from December to April in the years 2019 to 2022. SST Anomaly Composite for each phase is calculated as follows:

$$\text{SST Anomaly Composite} = \frac{\sum_{i=1}^{i=n} SST\ Anomaly}{n} \quad (4)$$

Symbol 'n' represents the number of MJO events in each phase. These two variables are then visualized using the 'quiver' package in Python to obtain wind direction and speed values.

Hovmöller Plots: MJO propagation can be visualized by plotting OLR and zonal wind values against time and longitude from December to April in 2019 to 2022. The results of these plots will be compared with Hovmöller plots of atmospheric waves from NCICS to support our analysis and provide a comprehensive understanding of atmospheric dynamics in the MC area. Hovmöller plots of atmospheric waves from NCICS can be accessed via the link: https://ncics.org/portfolio/monitor/mjo/. Data processing in this research used Microsoft Excel and Python software. The RMM index data obtained from BoM was processed to obtain the dates of MJO events based on phases using Microsoft Excel. Then, these dates were used to composite data from variables such as OLR, wind, and SST. Subsequently, the composite results were visualized using Python. The limitation of

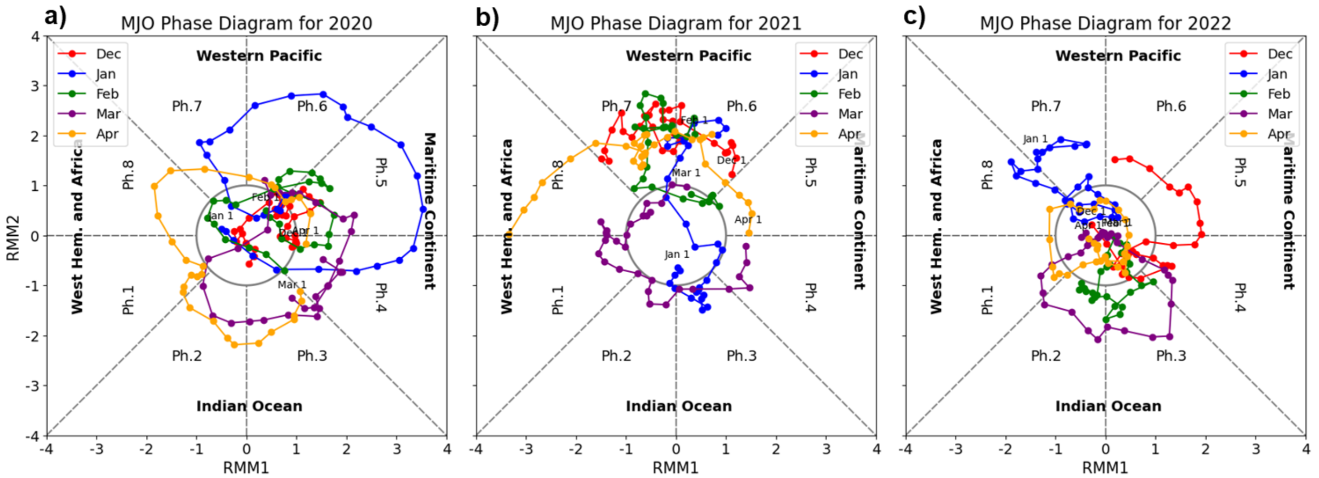

Figure 1. MJO Phase Diagram for the year (a) 2020, (b) 2021, (c) 2022. Red line for December, blue line for January, green line for February, Purple line for March, and yellow line for April.

this study involves examining the MJO during December to April of the years 2020, 2021, and 2022. The study area encompasses the maritime continent (80° E–180° E and 15° N–15° S). The research utilizes the RMM index and incorporates variables such as OLR, zonal and meridional winds, as well as SST anomalies. The MJO categories used are those identified by Wang (2019), namely slow, fast, stand, and jump.

RESULTS AND DISCUSSION

Madden-Julian Oscillation Propagation

The Madden-Julian Oscillation (MJO) can be categorized into eight phases based on the location of its convective center. These phases are used to track the propagation of the MJO. One method to determine the MJO phase is by utilizing the Real Time Multivariate MJO (RMM) index provided by the Australian Bureau of Meteorology (BoM). According to the MJO phase diagram for 2020 (Figure 1a), it was observed that in December 2019, the MJO passed through the Maritime Continent (Phases 4 and 5) with weak intensity (Wheeler and Hendon, 2004). During the months of January, February, and March 2020, the MJO exhibited strong intensity, with values exceeding 1. The highest amplitude was recorded when it crossed the Maritime Continent in early to mid-January. In April, the MJO was only in Phase 5 with strong intensity.

In December 2020, MJO (Figure 1b) displayed weak intensity as it crossed the Maritime Continent in Phase 4, and strong intensity in Phase 5. During the months of January, February, and March 2021, there was weak activity in Phases 4 and 5, except for the end of March when Phase 4 had strong activity. In April, there was only activity in Phase 5 with strong intensity.

In December 2021, the MJO (Figure 1c) crossed the Maritime Continent with very weak intensity in phases 3 and 4, then began to strengthen in phase 5. From January to March 2022, the MJO activity was predominantly weak, except at the end of March when it crossed into Phase 4 with strong intensity. In April, the MJO crossing the Maritime Continent had weak activity.

The propagation of the Madden-Julian Oscillation (MJO) in each phase can also be observed by analyzing its Outgoing Longwave Radiation (OLR) values. Low OLR values indicate the presence of convective clouds, which signify the formation of the MJO (Miyahara et al., 2023; Wahyuni et al., 2020). In the MJO year 2020 (Figure 2a), convective clouds begin to enter Phase 2 and 3. In Phase 4, convective clouds become stronger in almost the entire Indonesian region. Moving into Phase 5, the center of convective clouds shifts eastward, specifically to the east of Papua Island. Similarly, in Phases 6, 7, and 8, the convective center continues to shift further eastward towards the Pacific Ocean. the MJO in 2020 is categorized as "fast propagation".

Analyzing all the phases in DJFMA 2020, the propagation appears to be normal. However, in the year 2021 (Figure 2b), it can be observed that over the Maritime Continent, the propagation pattern is similar to that of the MJO year 2020. In Phase 5, the center of convection is once again drawn westward and located in the western and central parts of Indonesia. Then, in Phase 6, the propagation exhibits characteristics similar to Phase 4, except that convection extends towards the Pacific. As for Phases 7 and 8, the convective center in Indonesia weakens as it moves towards the Pacific. the MJO in 2021 is categorized as "stand" in 150E.

In the MJO year 2022 (Figure 2c), it is observed that during Phase 2, the convection center starts moving into the western side of Sumatra. By Phase 3, convection has spread throughout the entire Indonesian region, forming a convection pattern resembling a horse saddle in the northern Pacific Ocean

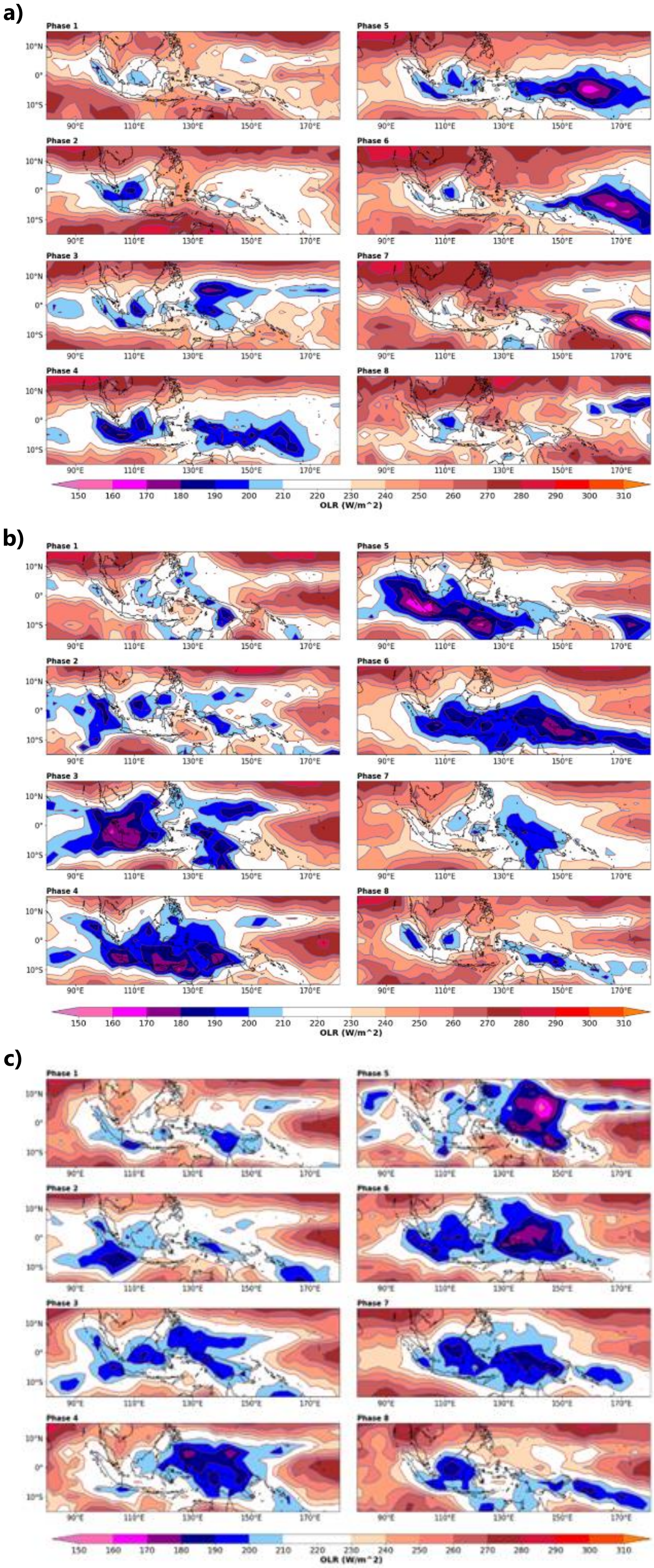

Figure 2. Spatial plot of OLR for each MJO phase during DJFMA in the year (a) 2020, (b) 2021, (c) 2022.

and Papua. Moving into Phase 4, the convective center strengthens and moves northward towards Papua. In Phase 5, the center of convective activity once again strengthens and gathers in the northern Papua region. It is worth noting that the convective center does not move eastward towards the Pacific. Therefore, the MJO in 2022 is categorized as "stand" (Wang et al., 2019).

In 2020 (Figure A1a), the first indication of the MJO occurred from December 29, 2019, to January 22, 2020. During this period, there were convective clouds (low OLR values) and westerly winds (positive zonal winds), indicating the eastward movement of convective clouds. The second MJO event occurred from early February to February 18, 2020, with convective clouds detected at 120°E and westerly winds observed from 110°E. The third MJO event took place from February 27, 2020, to March 10, 2020, and was detected between longitudes 110°E and 170°E.

Atmospheric Phenomena that Influence Madden-Julian Oscillation Propagation

To study the atmospheric phenomena that influence the propagation of the Madden-Julian Oscillation (MJO), such as equatorial Rossby waves, Kelvin waves, and tropical cyclones, we require Hovmöller data from the NCICS website. In Figure A1b, it is evident that strong Kelvin waves supported all MJO propagation during DJFMA 2020. This can be observed by the weakening of equatorial Rossby waves when they encountered the Kelvin waves. However, there were also hindrances to MJO propagation, such as tropical cyclones (Claudia, Tino, Damien, and Harold) in the Southern Hemisphere and some equatorial Rossby waves.

In the MJO year 2021 (Figure A2a), convective clouds and westerly winds ceased at 150°E. Only three events managed to cross this point: the first occurred from December 10 to December 17, 2020, the second from January 22 to February 10, 2021, and the third from March 20 to April 20, 2021. The atmospheric wave patterns (Figure A2b) suggest that the occurrence of equatorial Rossby waves at 150°E on these three occasions might have caused the cessation of outgoing longwave radiation (OLR) and zonal wind propagation at that point.

Furthermore, only a few Kelvin waves reached the Maritime Continent, which hindered the eastward propagation of the MJO. In 2022 (Figure A3a), convective clouds mostly ceased at 160°E, and westerly winds stopped at 140°E. Based on the observations of OLR and westerly winds, there were three potential MJO events: the first occurred from December 17, 2021, to January 10, 2022, the second from February 10, 2022, to early March 2022, and the third from March 11 to early April 2022. The atmospheric wave patterns (Figure A3b) indicate that the Kelvin waves were weakly formed, while equatorial Rossby waves dominated, resulting in the cessation of MJO propagation at 160°E.

Wind Circulation

Wind circulation at the 850 hPa level based on the MJO phases in 2020 (Figure 3a) shows weak westward winds across the Maritime Continent (MC). During Phase 4, there is a vortex to the west of Sumatra. The convective center forms between the wind divergence (winds turning from east to east), and this divergence shifts further towards the ocean as the MJO propagates towards the Pacific.

In 2021 (Figure 3b), wind circulation indicates stronger westerly and easterly winds compared to 2020. Two vortices appear to the west of the MC, and the convective center is also located within the wind divergence. For 2022 (Figure 3c), westward winds are slightly weaker compared to 2021. The easterly winds are quite strong, which hinders the movement of the convective center towards the Pacific. A relatively strong vortex forms during Phase 5 to the west of the MC.

Sea Surface Temperature Anomaly

The plot of SST anomalies in 2020 filtered based on MJO phases (Figure 4a) indicates positive or warming SST anomalies in the Pacific Ocean, categorizing it as fast propagation (Wang et al., 2019). Meanwhile, in 2021 (Figure 4b) and 2022 (Figure 4c), there are weakening or cooling SST anomalies in the Pacific Ocean, categorizing them as stand (Wang et al., 2019).

Based on the SST anomaly plot for DJFMA 2020 filtered by MJO phases (Figure 4a), it was found that the difference between phases one and two occurred in the South China Sea. Subsequently, during phases 3, 4, and 5, SST increased in the eastern part of Indonesia extending to the western Pacific due to the concentration of convection in Indonesia. During phases 6, 7, and 8, SST in Indonesia started decreasing, especially in the South China Sea area and the southern side of Papua. Overall, there was a positive SST anomaly in the western Pacific throughout the phases, indicating that the MJO in 2020 represented a fast propagation MJO (Wang et al., 2019). In 2021 (Figure 4b), during the first phase, there was a positive SST anomaly north of Papua, which then intensified in the second phase. However, in the third phase, a change occurred in the negative SST anomaly. The South China Sea, the western part of Sumatra, and the western Pacific experienced cooling again. Typically, during phase 3, the convection center starts moving into Indonesia, causing the Indian Ocean to experience a decrease in SST and the Pacific Ocean to experience an increase However, the Pacific Ocean cooled instead of warming,

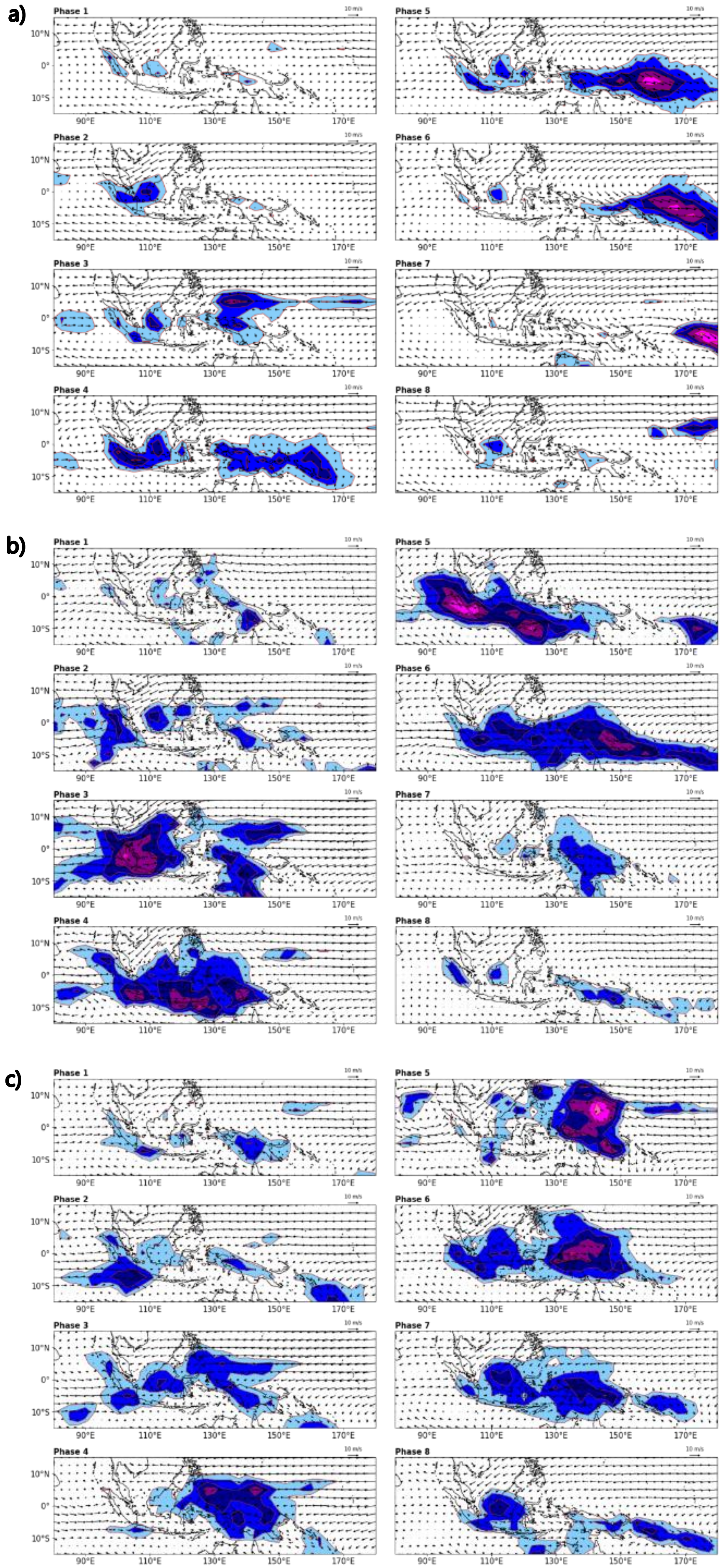

Figure 3. Spatial plot of 850 hPa winds for each MJO phase during DJFMA in the years (a) 2020, (b) 2021, (c) 2022.

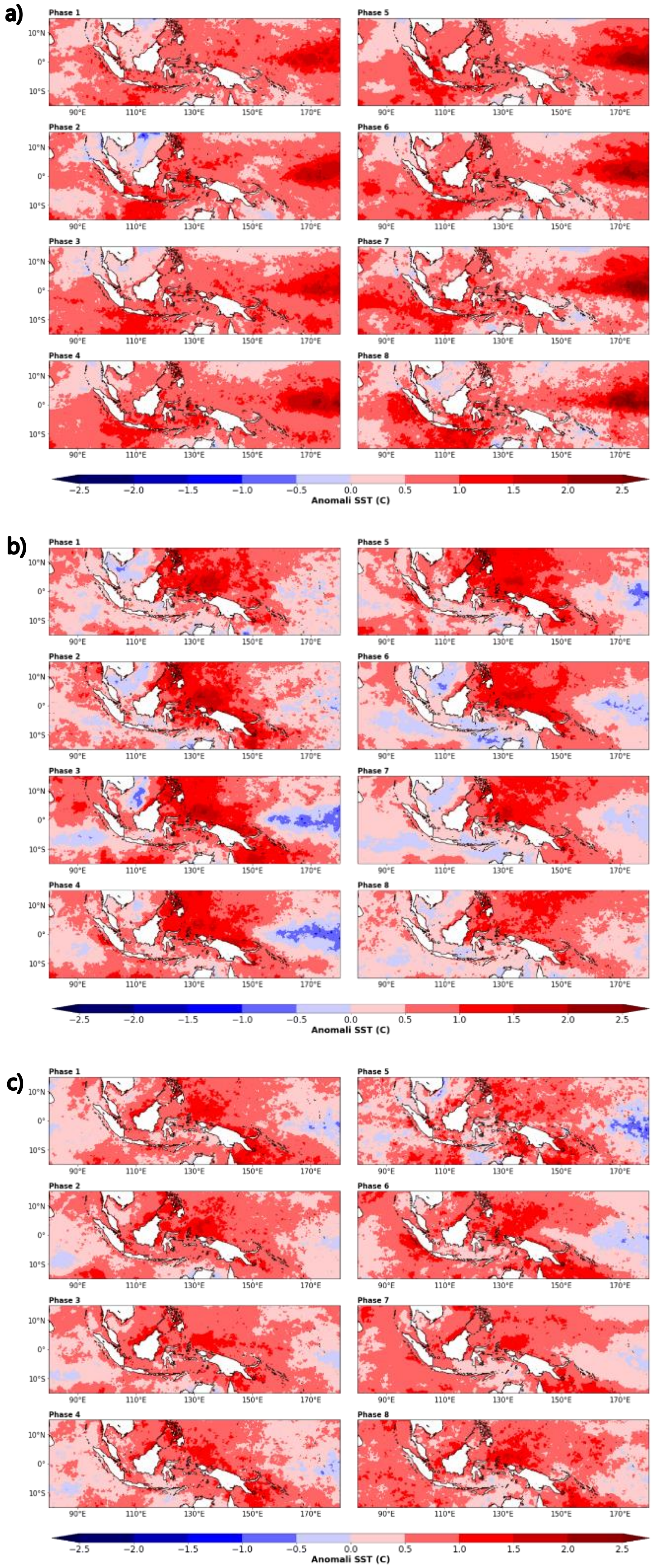

Figure 4. Spatial plot of SST anomalies for each MJO phase during DJFMA in the year (a) 2020, (b) 2021, (c) 2022.

which persisted. Through phases 4 and 5, hindering the convection center's movement towards the Pacific. Phases 6, 7, and 8 exhibited a decrease in SST anomalies in the South China Sea, the western and southern parts of Indonesia, while the Pacific Ocean experienced an increase in SST anomalies. Overall, the SST anomalies in 2021 fell into the MJO stand category according to Wang et al., (2019), specifically halting propagation at 150°E due to the cold SST anomalies in the Pacific Ocean.

The SST anomalies in 2022 (Figure 4c) displayed a pattern almost identical to those in 2021, with the Pacific Ocean experiencing cooling. This cooling hindered the propagation of MJO. The difference from2021 lies in the anomalies' values, which were not too high for both cold and warm SST anomalies. Additionally, the South China Sea in 2022 exhibited positive anomalies. Regarding the SST's connection to propagation, in phase 5, the Pacific Ocean's SST was lower compared to other phases. This circumstance hindered the convective center in the north of Papua during phase 5.

This study attempts to observe the propagation of the MJO in 2020, 2021, and 2022 based on the MJO propagation categories as per Wang et al., (2019), namely slow, fast, stand, and jump. The results indicate different propagation patterns for 2020, 2021, and 2022. In 2020, it shows a "fast propagation" category, while 2021 and 2022 exhibit a "stand" category. This research is currently based on the types of MJO categories rather than on the impacts of different MJO propagations on extreme rainfall. Therefore, it is hoped that future studies can examine the impact of MJO propagation during extreme rainfall occurrences in various regions of Indonesia.

CONCLUSION

This study conducted extensive research on the influence of sea surface temperature (SST) and zonal winds on the propagation of the Madden-Julian Oscillation (MJO) during the years 2020, 2021, and 2022. The comprehensive analysis, based on the Real-time Multivariate MJO (RMM) index, provided valuable insights into the distinct propagation patterns observed in each phase during these three years. In the year 2020, the MJO exhibited a normal propagation pattern, which can be attributed to the increased sea surface temperature in the Pacific Ocean. This increase, coupled with the presence of Kelvin waves, facilitated the rapid propagation of the MJO. However, in contrast, the years 2021 and 2022 displayed a different scenario, with no propagation of the MJO observed. The study findings suggest that in 2020, the MJO falls into the category of fast propagation. This can be attributed to the elevated sea surface temperature in the Pacific Ocean, which provides favorable conditions for the MJO's eastward movement. The presence of Kelvin waves further supports this observation. However, in 2021, a stalled propagation pattern of the MJO is observed.

This can be attributed to the decrease in sea surface temperature in the Pacific Ocean, which hinders the eastward propagation of the MJO. Additionally, the presence of equatorial Rossby waves further contributes to the stalling of the MJO in this year. Similar propagation characteristics are observed in the year 2022, with the MJO displaying patterns consistent with those observed in 2021. These findings highlight the dynamic nature of the MJO and its sensitivity to variations in sea surface temperature and zonal winds. Overall, this study provides significant insights into the complex relationship between sea surface temperature, zonal winds, and the propagation of the Madden-Julian Oscillation. The findings contribute to a better understanding of the mechanisms driving the MJO's behavior and can serve as a foundation for further research in this field.

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ANNEX

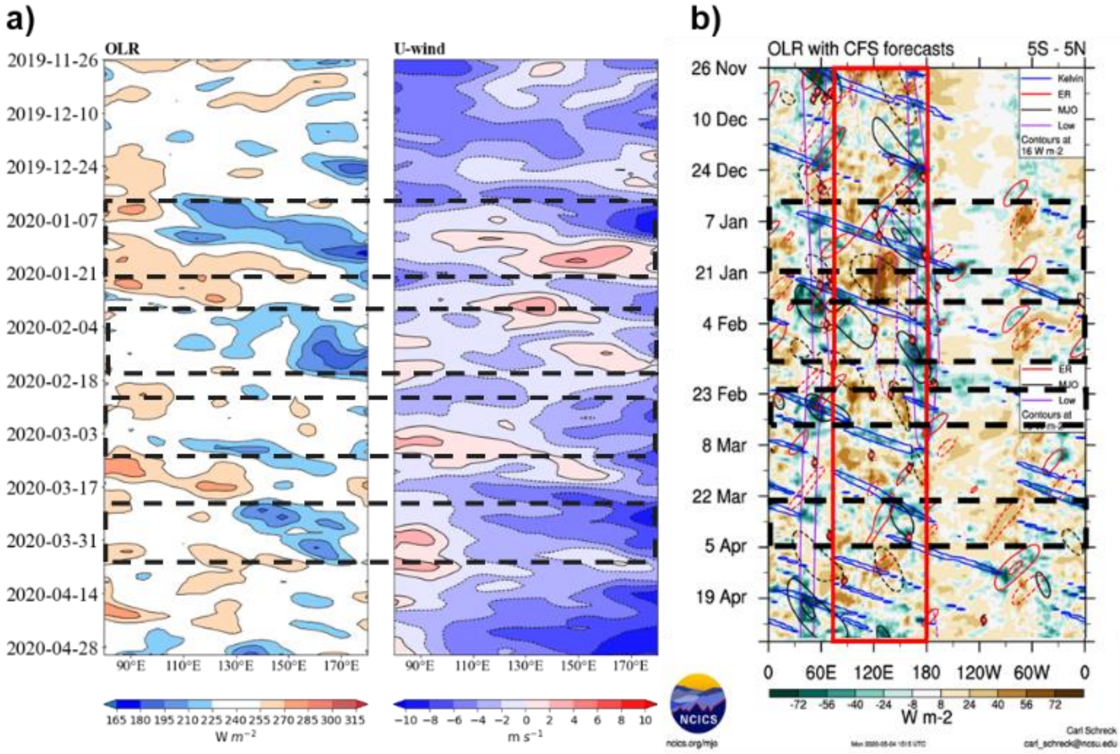

Figure A1. (a) Hovmöller plot of OLR and zonal winds for DJFMA in the year 2020. (b) Hovmöller plot from NCICS for DJFMA in the year 2020 (modified from: https://ncics.org/portfolio/monitor/mjo/). Dashed black box indicate MJO event, and red box indicate the study area.

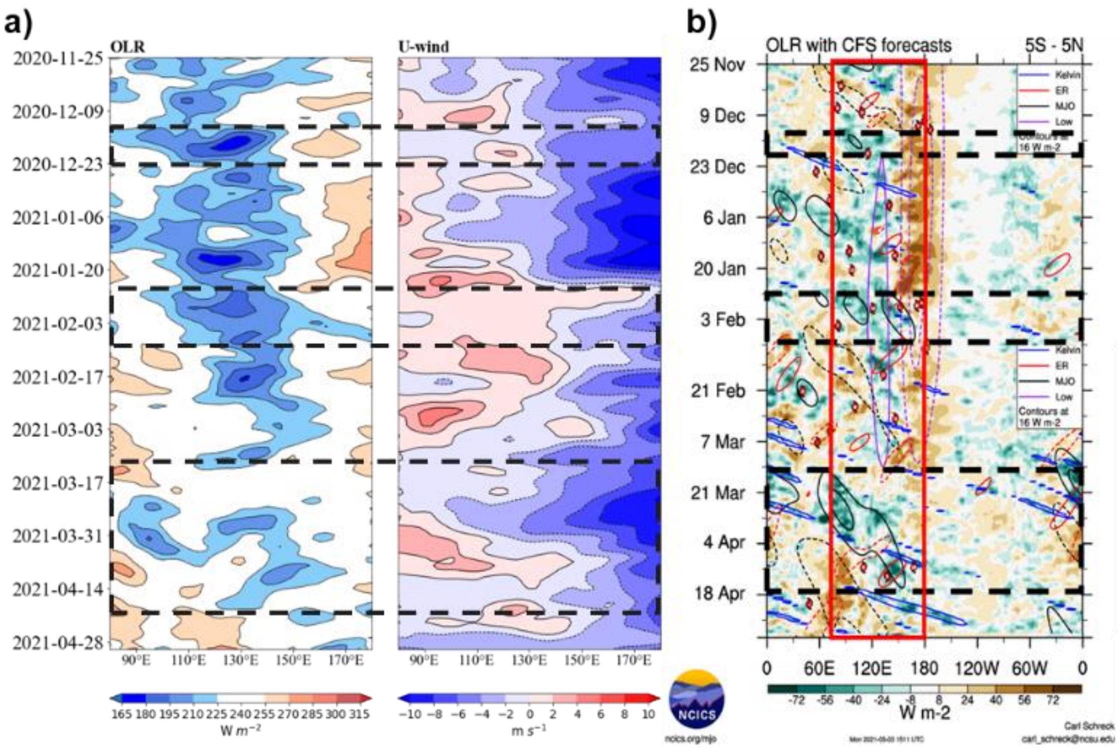

Figure A2. (a) Hovmöller plot of OLR and zonal winds for DJFMA in the year 2021. (b) Hovmöller plot from NCICS for DJFMA in the year 2021 (modified from: https://ncics.org/portfolio/monitor/mjo/). Dashed black box indicate MJO event, and red box indicate the study area.

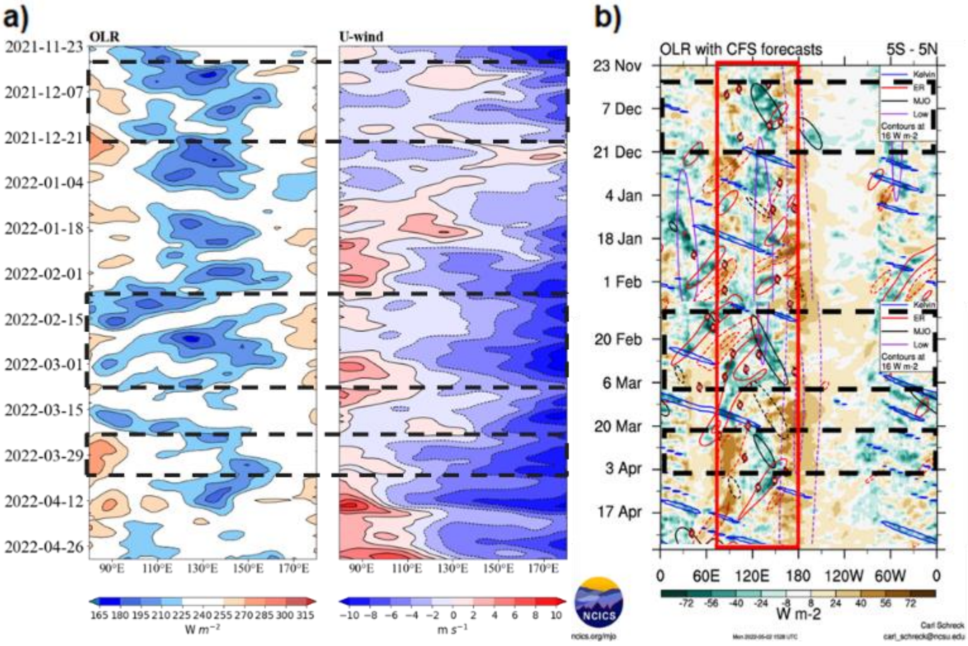

Figure A3. (a) Hovmöller plot of OLR and zonal winds for DJFMA in the year 2022. (b) Hovmöller plot from NCICS for DJFMA in the year 2022 (modified from: https://ncics.org/portfolio/monitor/mjo/). Dashed black box indicate MJO event, and red box indicate the study area.