PRECURSORS OF MJO-CROSSING (MJO-C) AND MJO-BLOCKING (MJO-B) OVER THE MARITIME CONTINENT BASED ON MOISTURE TRANSPORT

Akhmad Fahim[1]*, Nurjanna Joko Trilaksono[2]
[1]Center for Public Meteorology, Agency for Meteorology, Climatology, and Geophysics, Jakarta, Indonesia
[2]Atmospheric Research Group, Faculty of Earth Science and Technology, Bandung Institute of Technology, Bandung, Indonesia
******E-mail:* Akhmad.fahim.meteo.itb@gmail.com

Article submitted: June 28, 2022 Article revised: January 22, 2024 Article accepted: January 23, 2024

ABSTRACT

Research on MJO propagation that is blocked when crossing the Maritime Continent (MC) is a complex problem. This research aims to determine the precursors of MJO-Crossing (MJO-C) and MJO-Blocking (MJO-B) based on moisture transport analysis. Hovmöller analysis on MJO-C and MJO-B is performed using precipitation data retrieved from the TRMM satellite (3B42v7) in the ONDJFM period 1998-2015 to characterize the propagation of MJO-C and MJO-B. The difference between MJO-C and MJO-B propagation is further investigated using specific humidity and horizontal wind data from ERA-Interim ECMWF to examine the moisture source and vertical structure of specific humidity in MJO-C and MJO-B. Additionally, we conducted wind divergence analysis at 700hPa to identify the characteristics of wind patterns in MJO-C and MJO-B events. Our investigation revealed that during the precursor period (day -15 to -5) or before MJO arrived at the Maritim Continent, there was a weakening of moisture supply in MJO-B events due to the existence of a westward-propagating dry anomaly. This dry anomaly mixed with the moist anomaly of MJO convection could reduce the intensity of moisture and dissipate MJO convection. The westward-propagating dry anomaly indicates the influence of Equatorial Rossby (ER) waves, which can inhibit MJO propagation across the Maritime Continent.

Keywords: MJO propagation, MJO-C, MJO-B, moisture transport.

1. Introduction

The Madden–Julian oscillation (MJO) plays an important role to influence the atmospheric circulation in various time and space scales [1], [2]. The MJO was defined as a dominant mode of intraseasonal variability in the tropics with a period between 30 and 90 days. The MJO was first identified by Madden and Julian [3] using single surface observation station data. Along with the increasing of observation data networks, it provides a better understanding that the MJO is characterized as a large-scale deep convection with the convection center propagating eastward along the equator with an average speed of 4-8 m/s from the Indian Ocean to the Pacific Ocean [4].

Previous studies (e.g., Hsu and Lee [5], Hagos *et al*., [6], Majda and Yang [7], Kim *et al*., [8], Zhang and Ling [9], Feng *et al*.,[10]) have found that some MJO events were blocked in the MC region and could not propagate to the Western Pacific. Based on this phenomenon, MJO events could be classified into two categories that were MJO-Crossing (MJO-C), which can propagate through *(crossed)* the MC region, and MJO-Blocking (MJO-B), which cannot propagate or blocked in the MC region. There are several possibilities that explain why this phenomenon occurs, including reduction of surface latent heat flux in the MC region [5], diurnal cycles of cloudiness and precipitation [6], [7], and large-scale circulations that modulate moisture distributions downstream over the Western Pacific [8], [9], [10].

Research on the mechanism of MJO-C and MJO-B phenomena has been conducted by Zhang and Ling [9]. Based on this research, about half of MJO events that form over the Indian Ocean propagate through the MC region, and most of them (>75%) become weakened when passing through the MC region. In addition, the difference between MJO-C and MJO-B events is their precipitation over the sea versus land. During MJO-C, precipitation is more dominant over the sea than over the land, whereas precipitation over the sea never becomes dominant for MJO-B. This indicates that the MJO event will not successfully pass through the MC region if the development of convective clouds over the sea is inhibited.

One of the methods used to investigate the development of convective clouds is moisture transport analysis. MJO convection will be maintained when there is a continuous supply of moisture from the lower layers (low-level convergence) as the main energy for MJO convection

[11]. When the moisture supply condition is reduced, it will inhibit the development of MJO convection. Previous research in exploring the characteristics of MJO propagation has mostly discussed the moisture conditions in the overall MJO events [12] and has not separated the discussion of moisture conditions for the MJO events that propagate across the Maritime Continent (MJO-C), and those are blocked over the Maritime Continent (MJO-B). Therefore, this research will discuss the characteristics of the precursors of the MJO-C and MJO-B events in terms of moisture transport analysis.

2. Methods

This study utilizes multiple datasets. First, satellite data was obtained from Tropical Rainfall Measuring Mission (TRMM) 3B42 satellite version 7 [13]. This data is used to analyze the characteristics of rainfall propagation in MJO-C and MJO-B events. This data has a resolution of 0.25° × 0.25° with the ONDJFM period 1998-2015. The ONDJFM period was chosen because climatologically the MJO was most active during this period [6]. TRMM rainfall data can be accessed through the following website link: http://disc.sci.gsfc.nasa.gov/giovanni. [14]

Second, the reanalysis data retrieved from ERA-Interim *European Center for Medium-Range Weather Forecasts* (ECMWF) for zonal wind parameters ($\vec{u}$), meridional wind ($\vec{v}$), and specific humidity (q). All data have 27 pressure levels starting from 1000 to 350 hPa with daily temporal resolution and 0.75° × 0.75° spatial resolution. The ECMWF data can be accessed through the link https://apps.ecmwf.int/datasets/data/interim-full-daily/levtype=pl/. [15]

This research emphasizes on the differences between MJO-C and MJO-B precursor conditions in terms of moisture transport analysis. Four stages were carried out to investigate this. First, identify the propagation characteristics of MJO-C and MJO-B. Second, moisture transport analysis of MJO-C and MJO-B is conducted to determine the moisture supply that might provide water vapor to the MC region. Third, the difference in moisture supply from MJO-C and MJO-B over the MC region is then further analyzed using specific humidity parameters to represent the propagation of specific humidity at each level. Finally, analysis of wind divergence analysis at 700hPa was carried out to examine the center of convergence formation during MJO-C and MJO-B events.

The identification of MJO-C and MJO-B phenomena was selected following the research of Kern and Chen [16] during the ONDJFM period 1998-2015. MJO events were identified objectively using the *Large-scale Precipitation Tracking* (LPT) method. LPT is identified using spatially *smoothed* 3-day rainfall accumulations to identify and track rainfall with a minimum size of 300,000 km^2 and a time continuity of at least ten days. The threshold used in LPT can vary from 8 mm/day to 16 mm/day with an average threshold of 12 mm/day. Based on the LPT method, 22 MJO-C events and 18 MJO-B events were obtained.

After identifying the characteristics of MJO-C and MJO-B events based on the LPT method, Hovmöller analysis (average latitude 15°N-15°S) was performed using daily precipitation data to determine day 0 when the peak of connectivity was at 100°E. MJO-C events refer to the eastward propagation of positive precipitation anomalies over 150°E, while MJO-B events are associated with precipitation anomalies that decrease at 100°E until they stop before reaching 150°E [9]. After identifying the characteristics of MJO-B propagation that are blocked in the MC region, moisture transport analysis was subsequently conducted to determine the source of water vapor supply at the lower troposphere, which acts as a fuel for MJO convection. Moisture transport analysis was conducted using *lag* time analysis from day -15 to day +10 for each MJO-C and MJO-B event. Moisture transport indicates the flow of moisture transmission represented by the scalar quantity of specific humidity (q), which is multiplied by the wind vector quantity $\vec{V}$. In this study, moisture transport analysis was carried out from a pressure level of 1000 hPa to a pressure level of 350 hPa, which is expressed by the following equation [17]:

$$\vec{B}_q = \frac{1}{g}\int_{1000}^{350} q\vec{V}dp \qquad (1)$$

Value q is the specific humidity in each layer (g/kg). Value $\vec{V}$ is the horizontal wind speed vector in each layer (m/s). The wind speed vector is obtained by summing the zonal wind component ($\vec{u}$) and meridional wind ($\vec{v}$) from ECMWF Era-Interim data. The value of g is the scalar value of gravitational acceleration (9.8 m/s^2).

A lag time vertical cross-section analysis of the specific humidity anomaly (q) was conducted to further investigate how moisture propagates at each altitude level from 1000 hPa to 350 hPa. The analysis was performed using the lag time method from day -15 to day +10 for each of the MJO-C and MJO-B events. Finally, a time-lag analysis of wind patterns and divergence at 700 hPa was conducted to determine wind circulation patterns and convergence centers formed during MJO-C and MJO-B events. The horizontal wind divergence equation used is as follows [18]:

$$\mathrm{Div}_h = \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) \qquad (2)$$

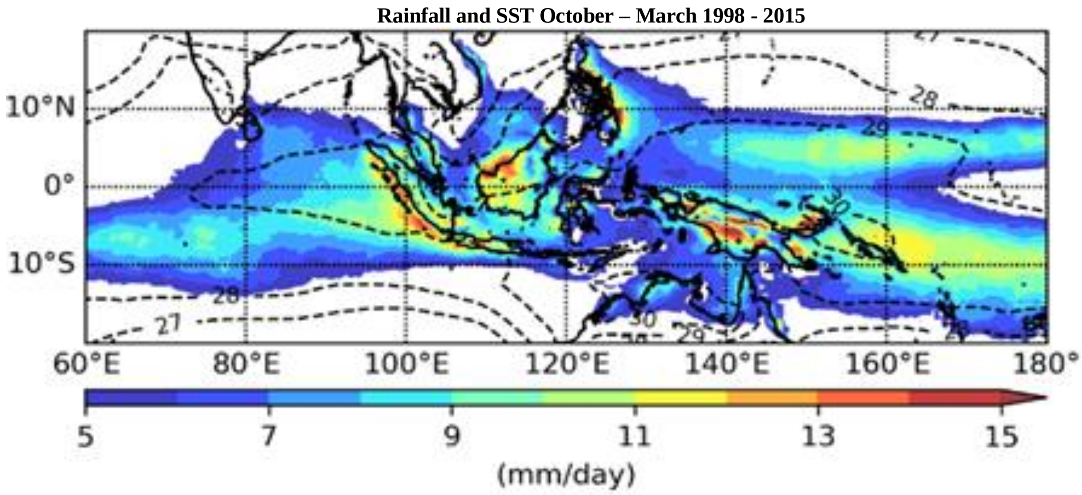

Figure 1. October – March climatology (1998–2015) of rainfall (color shaded; mm d^{-1}) and SST (dash contours labeled every 1°C)

3. Result and Discussion

Characteristics of MJO Propagation. One of the basic components of the MJO phenomenon is a large-scale convection pattern that spans several thousand kilometres and extends eastward along the equator. MJO convection is mostly confined to the Indo-Pacific warm pool with sea surface temperatures (SST) above 28 °C, as shown in Figure 1 in the form of contour plots. Meanwhile, the distribution of average rainfall for the ONDJFM period in 1998-2015 is shown in the *shaded* plot of Figure 1. The high value of rainfall was located along the equator, stretching from the Indian Ocean, the Indonesian Maritime Continent, to the Western Pacific Ocean. The Indonesian Maritime Continent area that receives the highest rainfall includes the Indian Ocean west of Sumatra Island, western Kalimantan, the Philippine Islands, Papua Island, and the western Pacific Ocean.

Figure 2. shows the Hovmöller (time-longitude) plot of the average rainfall anomaly 15°N-15°N. Both MJO-C and MJO-B events show positive rainfall anomalies that propagate eastward from the Indian Ocean (60°E-90° E) towards the MC region, although they differ in terms of amplitude and extent. The positive rainfall anomalies in both MJO-C and MJO-B events begin to decrease when entering the MC region (100°E). In the MJO-C event, the positive rainfall anomaly manages to maintain its amplitude and continues eastward toward the Western Pacific Ocean (140º E - 160º E). Meanwhile, in the MJO-B event, the positive rainfall anomaly fails to recover and weakens continuously until it eventually dissipates before reaching the Western Pacific Ocean. This result is still aligned with Zhang and Ling's research [9].

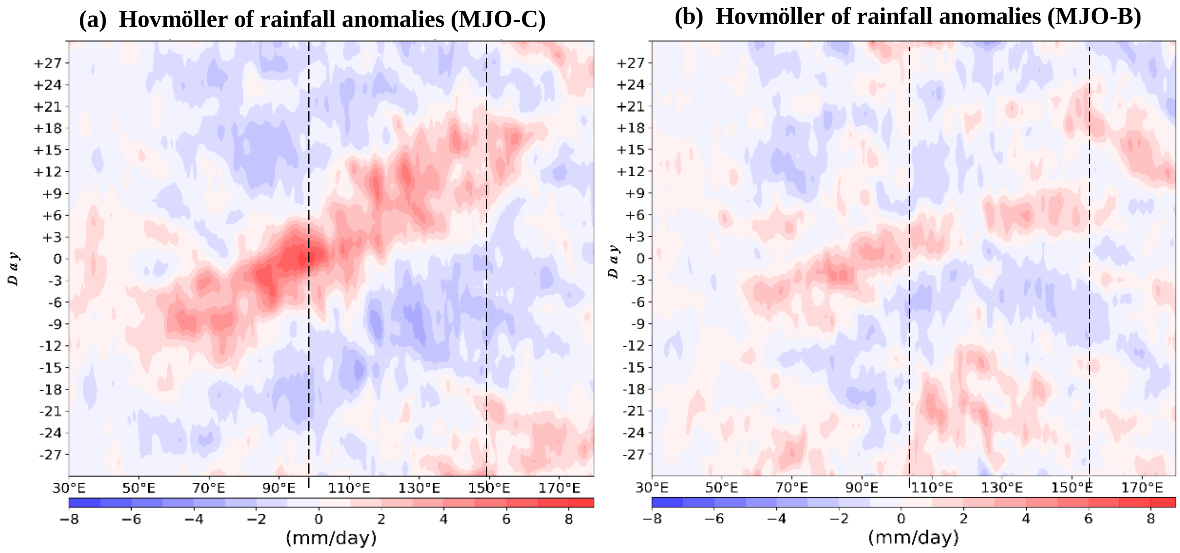

Figure 2. Composite Hovmöller (time-longitude) diagram of rainfall anomalies (unit: mm day $^{-1}$) averaged over 15° S - 15° N for (a) the MJO-C and (b) the MJO-B based on the TRMM data. Day 0 is when their tracks cross 100°E. The black vertical dotted lines indicate the longitude boundaries of 100° E and 150° E.

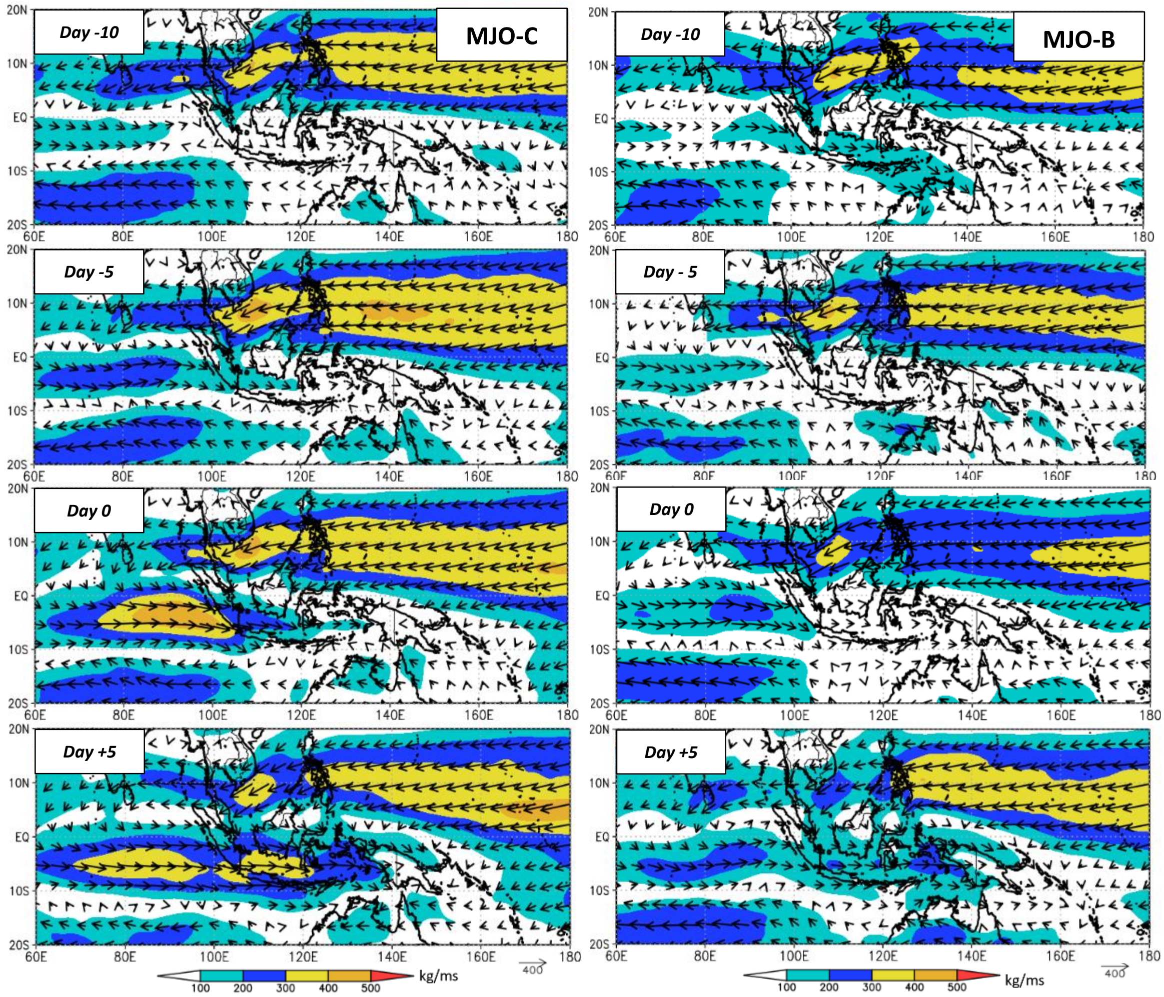

Figure 3. Spatial evolution of Vertical Integrated Moisture Transport (VIMT) for the MJO-C (left) and MJO-B (right) from day -10 to day +5. VIMT magnitude values are shown in shaded and VIMT directions are shown in vectors.

Moisture Transport Analysis of MJO-C and MJO-B. In the tropics, *deep convection* will persist if there is a continuous supply of water vapor from the lower troposphere [2]. Moist atmospheric conditions in the lower troposphere are considered the key to the development of convective clouds and the propagation of MJO through the MC region [17], [18]. Therefore, moisture transport conditions from 1000 hPa to 350 hPa level will be studied to examine the source of water vapor that supplies MJO convection in the MC region during MJO-C and MJO-B.

Figure 3 shows the spatial evolution of moisture transport during MJO-C and MJO-B events. In general, the source of moisture heading towards the MC region comes from three main locations: The South China Sea, the Indian Ocean near Sumatra Island, and the Northwest Pacific Ocean. On day -10 and day -5, moisture transport from the eastern Indian Ocean near Sumatra Island increased to 200-300 kg m^{-1} s^{-1}, as well as in the South China Sea region and the northwestern Pacific Ocean increased to 300-400 kg m^{-1} s^{-1}. These conditions increase the supply of water vapor in the MC region and support the development of MJO convection to be stronger, causing MJO propagation to successfully pass through the MC region.

In contrast to the MJO-B event, the water vapor supply from the three main locations tends to be weaker. On day -10 and day -5, the water vapor supply in the Indian Ocean near Sumatra Island and the South China Sea was not as strong as the MJO-C event. This indicates that the source of water vapor supply from these regions is not significant in supplying moisture to the MC region, resulting in weakened MJO convection propagation when passing through the MC region.

Propagation of Specific Humidity in MJO-C and MJO-B. The investigation into the various sources of water vapor supply in the Maritime Continent (MC) region during MJO-C and MJO-B events will be expanded by examining the propagation of the vertical structure of specific humidity during these events. Figure 4 and Figure 5 show the vertical cross-section of the specific moisture anomalies of MJO-C and MJO-B events averaged from 15°N-15°N. The black line shows the moist anomaly, and the red line shows the dry anomaly. Both MJO-C and MJO-B events show moist anomalies that propagate eastward from the Indian Ocean to the MC region but have differences in terms of amplitude. In the case of the MJO-C event, the amplitude of the moist anomaly appears significantly stronger compared to the MJO-B event. This condition causes the propagation of MJO convection to have enough water vapor to pass through BMI. Meanwhile, in the MJO-B event (Figure 5), day -5, the dry anomaly has strengthened and is present in almost the entire atmospheric column from the low level to the upper level. Meanwhile in the MJO-C event (Figure 4) at the same time (day -5), dry anomalies tend to be only at the 800-400 hPa level. The intrusion of moist anomalies in the upper troposphere can provide a moist environment for MJO convection so that MJO convection can develop properly.

The interesting thing about the comparison of the vertical structure of MJO-C and MJO-B specific humidity is there is a westward propagation of the dry anomaly before the MJO convection arrives at the Maritime Continent (day -15, day -10, day -5) in the MJO-B event. The dry anomaly moves westward from the Pacific Ocean towards the MC region. The dry anomaly will eventually mix with the moist anomaly, reducing the intensity of MJO convection and preventing MJO propagation into the MC region.

The westward propagation wave (WPW) phenomenon has been previously discussed in the research conducted by Feng et al. [10]. Feng argues that WPW represents a dry phase of the Equatorial Rossby (ER) wave, which can travel from the Pacific Ocean toward the MC region. Additionally, the work of DeMott et al. [19] substantiates the existence of a westward-propagating dry anomaly, referring to it as a *"Transient Dry Precursor"* (TDP) signal. Almost half of all MJO events, including both MJO-C and MJO-B, that traverse the MC region encounter this westward-propagating TDP signal. This TDP signal results in a reduction of the moist anomaly and hinders the development of MJO convection, preventing successful eastward propagation of the MJO when passing through the MC region [19].

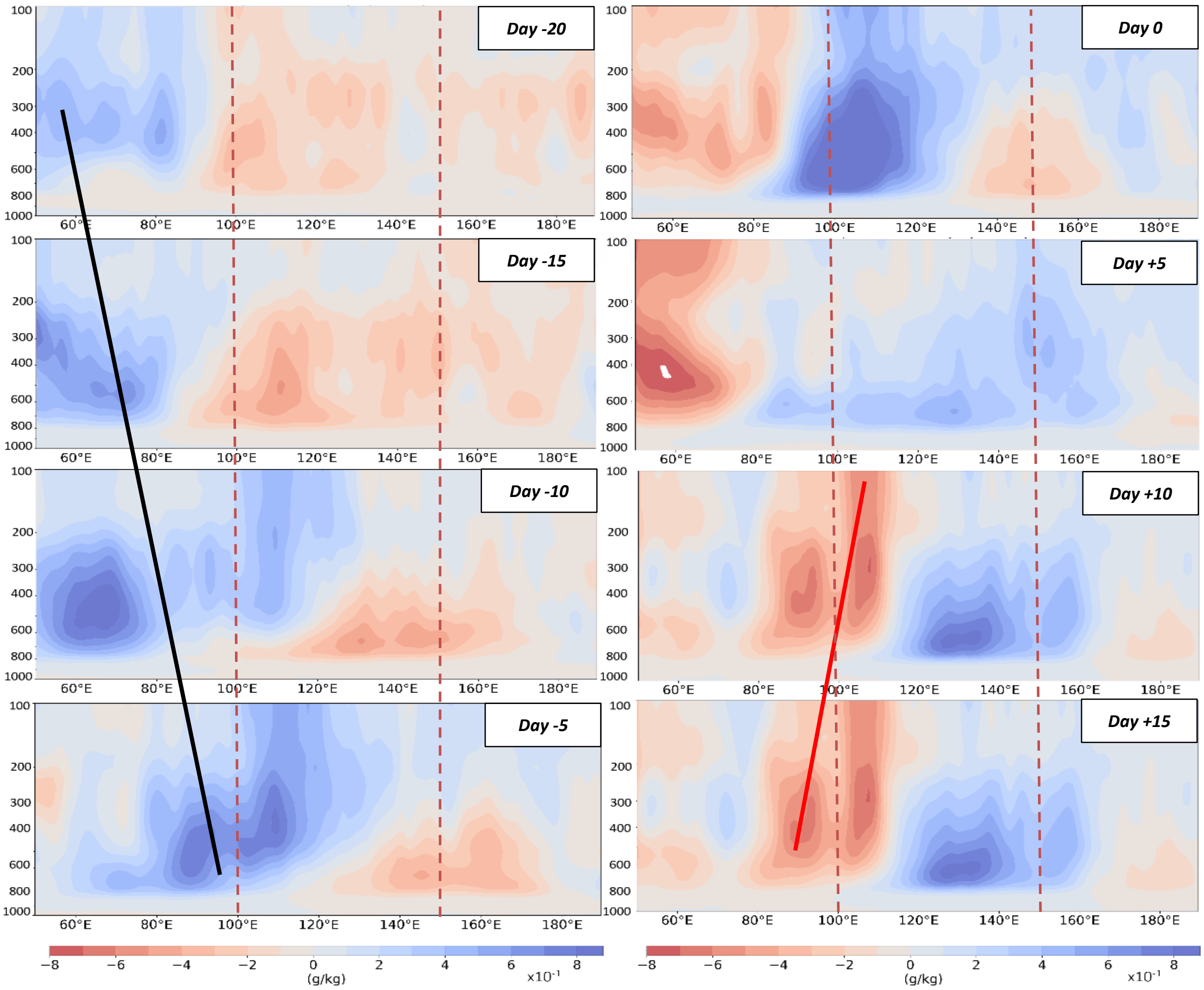

Figure 4. Vertical cross-section of the specific humidity anomaly 15° N-15° S during the MJO-C event. Black lines indicate MJO moist anomalies. Red lines indicate dry anomalies.

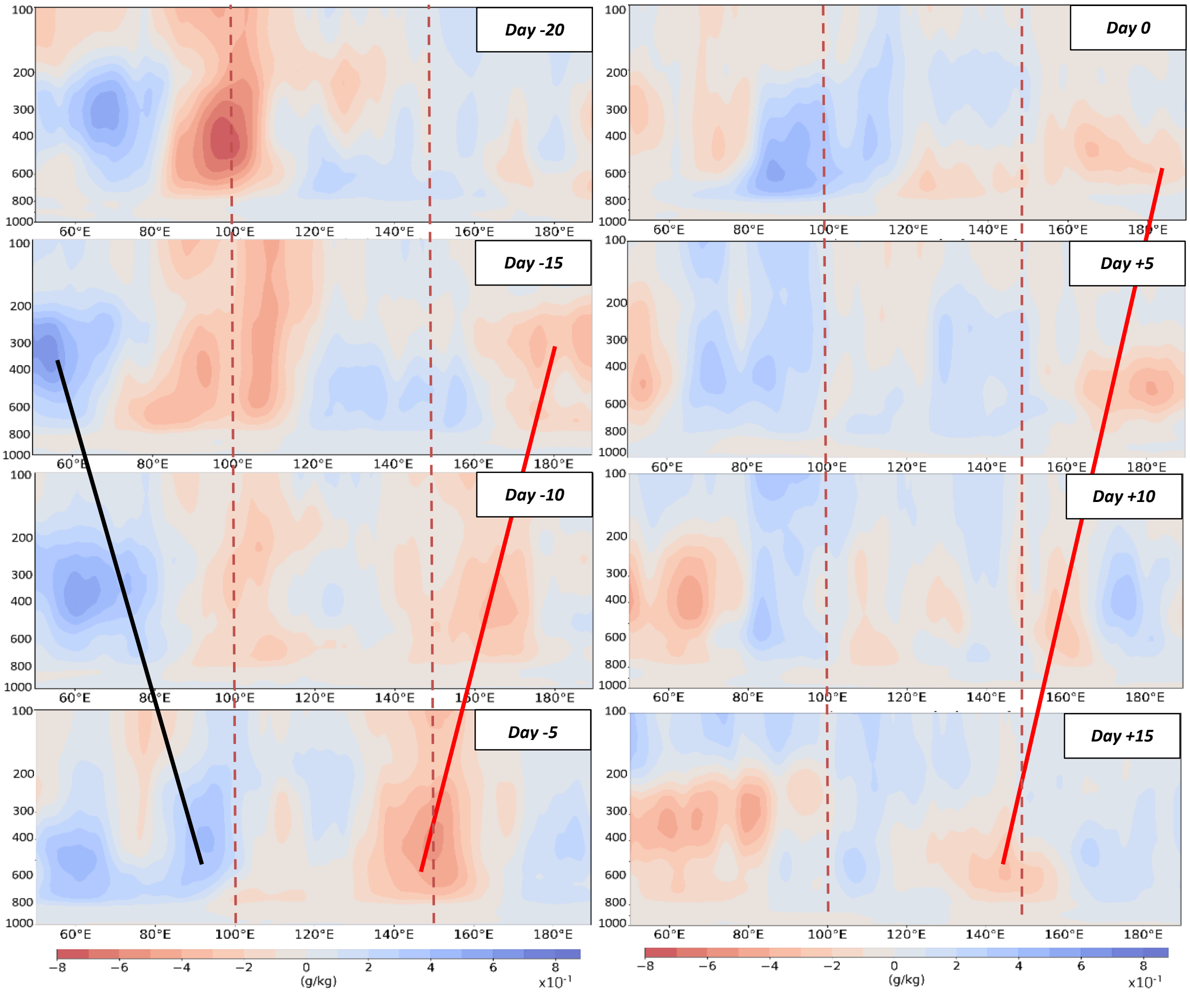

Figure 5. Same as Figure 4 but for the MJO-B event.

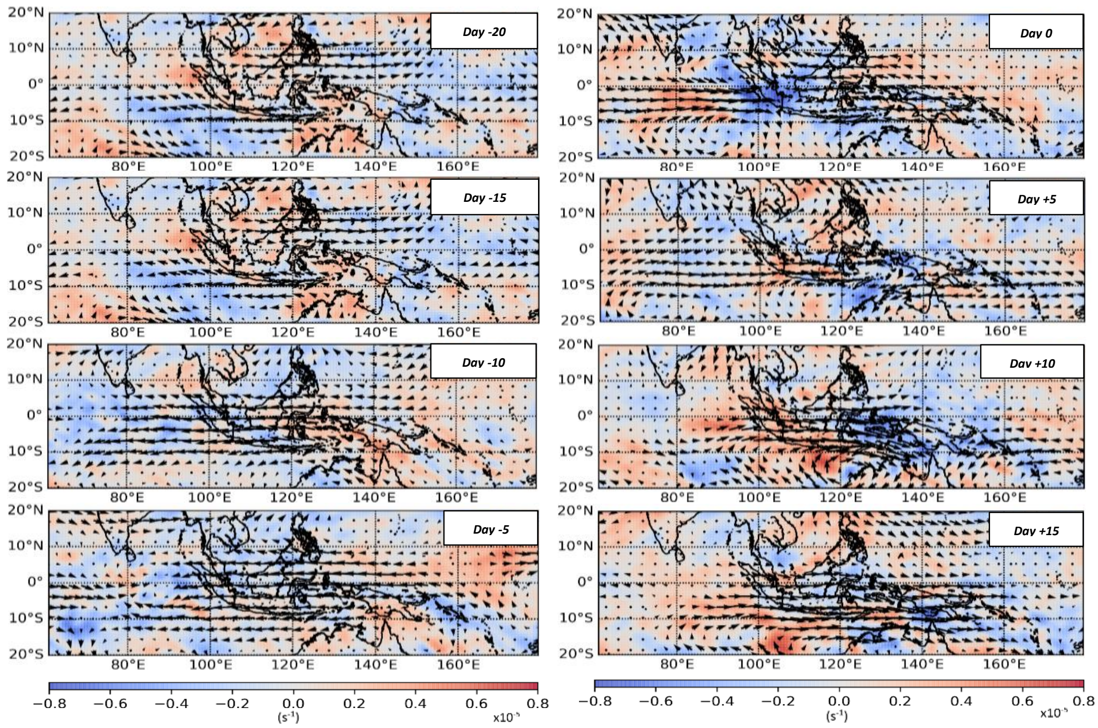

Figure 6. Wind divergence at 700 hPa during the MJO-C event. Divergence (+) and convergence (-) values are shown in shaded and wind direction is shown in vector.

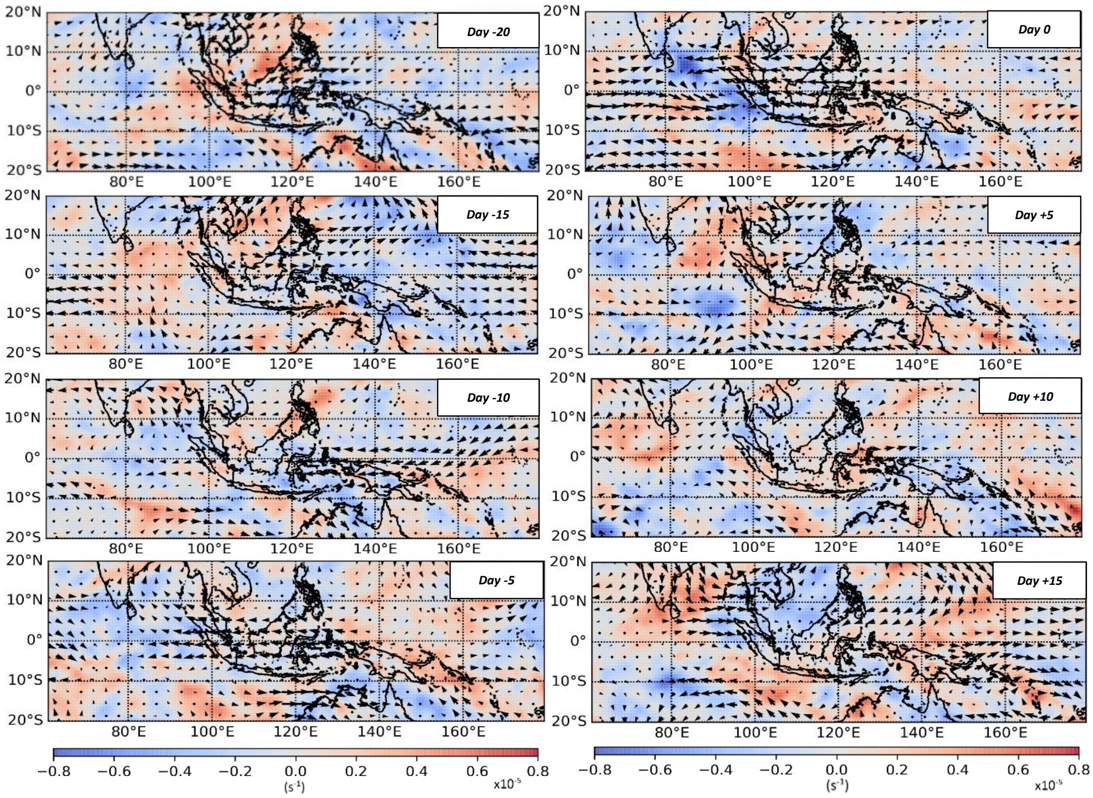

Figure 7. Same as Figure 6 but for the MJO-B event.

Wind Circulation Pattern and Divergence of MJO-C and MJO-B. For a more detailed assessment of the behaviour of westward-propagating dry anomalies and their relationship with *Equatorial Rossby (ER)* waves, an analysis of wind circulation patterns and divergence at 700 hPa altitude in each MJO-C (Figure 6) and MJO-B (Figure 7) event was carried out.

During the MJO-C event from day -15 to day -5, the easterly wind anomaly (Figure 6) is much stronger than the MJO-B event (Figure 7). This intensified easterly wind anomaly facilitates the transportation of water vapor supply from the Maritime Continent and the Western Pacific to the Indian Ocean, thereby enhancing the initiation of MJO convection. Additionally, from day 0 to day +10, there is a reinforcement of the westerly wind, propelling MJO convection eastward beyond the MC region. With the assistance of these westerly winds, MJO convection is effectively sustained past the MC region by taking a southward detour over the sea surface between the MC region and Australia. This aligns with the findings of Kim et al. [8] research on MJO propagation**.** Meanwhile, during the MJO-B event (as shown in Figure 7), there is a tendency for the easterly wind anomaly to be weak from day -15 to day -5, resulting in a reduction of water vapor from the MC region. Furthermore, on day -5 of the MJO-B event, the wind pattern in the southern MC region or in Northern Australia assumes a pattern similar to the Equatorial Rossby (ER) wave, aligning with the findings of Wang et al. [21]. Additionally, a topographic effect is observed in the MC region, contributing to a further reduction in humidity conditions. This effect limits the extent of water vapor reaching the Indian Ocean, which is consistent with the research conducted by Zhang and Ling [9].

4. Conclusion

Moisture transport conditions exhibit distinct differences between the MJO-C and MJO-B events. In the period from 15 days to 5 days before the MJO event (day -15 to day -5), there is a weakening of moisture supply during the MJO-B event. This reduction is attributed to a westward-propagating dry anomaly that propagates from the Pacific Ocean, reaching the MC region. The interaction of this dry anomaly with the MJO moist anomaly results in a decline in moisture intensity and inhibits the propagation of the MJO across the MC region. The phenomenon of westward-propagating dry anomalies indicates the influence of Equatorial Rossby (ER) waves on MJO propagation across the Maritime Continent.

Acknowledgments

The authors would like to thank Dr. Tri Wahyu Hadi, M.Sc and Dr. Rais Abdillah for their advice, input, and suggestions, as well as the Editorial Team of the Journal of Meteorology and Geophysics, Research and Development Center, BMKG.

References

[1] Lau, W. K., dan D. E. Waliser. *Intraseasonal Variability of the Atmosphere-Ocean Climate System*: Springer, New York, 2005.

[2] Zhang, C. Madden-Julian oscillation. *Reviews of Geophysics*, 43 RG2003, 2005.

[3] Madden, R. A., dan P. R. Julian. "Detection of a 40–50 days oscillation in the zonal wind in the tropical Pacific". *Journal of Atmospheric Science*, 28, 702–708, 1971.

[4] Wheeler, M., dan G. N. Kiladis. "Convectively coupled equatorial waves: Analysis of clouds and temperature in the wavenumber–frequency domain". *Journal of Atmospheric Science*., 56, 374–399, 1999.

[5] Hsu, H.H. dan Lee, M.Y. "Topographic effects on the eastward propagation and initiation of the Madden-Julian oscillation". *Journal of Climate*, 18, 795–809, 2005.

[6] Hagos, S.M., Zhang, C., Feng, Z., Burleyson, C.D., De Mott, C., Kerns, B., Benedict, J.J. dan Martini, M.N. "The impact of the diurnal cycle on the propagation of Madden-Julian oscillation convection across the Maritime Continent". *Journal of Advances in Modeling Earth Systems*, 8, 1552–1564, 2016.

[7] Majda, A.J. dan Yang, Q. "A multiscale model for the intraseasonal impact of the diurnal cycle over the Maritime Continent on the Madden-Julian oscillation". *Journal of the Atmospheric Sciences*, 73, 579–604, 2016.

[8] Kim, D., Kug, J.S. dan Sobel, A.H. "Propagating versus non-propagating Madden-Julian oscillation events". *Journal of Climate*, 27, 111–125, 2014.

[9] Zhang, C. dan Ling, J. "Barrier effect of the Indo-Pacific Maritime Continent on the MJO: Perspectives from tracking MJO precipitation". *Journal of Climate*, 30, 3439–3459, 2017.

[10] Feng, J., Li, T. dan Zhu, W. "Propagating and non-propagating MJO events over Maritime Continent". *Journal of Climate*, 28, 8430–8449, 2015.

[11] Wu, Z. "A shallow CISK, deep equilibrium mechanism for the interaction between large-scale convection and large-scale circulation in the Tropics". *Journal of the Atmospheric Sciences*, 60, 377–392, 2003.

[12] Hsu, P.-C., dan T. Li. "Role of the boundary layer moisture asymmetry in causing the eastward propagation of the Madden Julian Oscillation". *Journal of Climate*, 25 (14), 4914-4931, 2012.

[13] Huffman, G., R. Adler., D. Bolvin., G. Gu., E. Nelkin., K. Bowman, Y. Hong., E. Stocker., dan D. Wolff. "The TRMM multisatellite precipitation analysis (TMPA): Quasi-global, multiyear, combined-sensor precipitation estimates at fine scales". *Journal of Hydrometeorol*ogy, 8, 38–55, 2007.

[14] Tropical Rainfall Measuring Mission (TRMM) (2011), "TRMM (TMPA/3B43) Rainfall Estimate L3 1 month 0.25 degree x 0.25 degree V7", Greenbelt, MD, Goddard Earth Sciences Data and Information Services Center (GES DISC), Internet: http://disc.sci.gsfc.nasa.gov/giovanni (accessed on July 10th, 2020)

[15] European Centre for Medium-range Weather Forecast (ECMWF) (2011): The ERA-Interim reanalysis dataset 0.75 degree x 0.75 degree daily product pressure level, Copernicus Climate Change Service (C3S) , Internet: https://apps.ecmwf.int/datasets/data/interim-full-daily/levtype=pl/, (accessed on August 5th, 2020).

[16] Kerns, B. W., dan S. S. Chen. "Large-scale precipitation tracking and the MJO over the Maritime Continent and Indo-Pacific warm pool". *J. Geophys. Res. Atmos.*, 121, 8755–8776, 2016.

[17] Fasullo, J., dan P. J. Webster. "A hydrological definition of the Indian summer monsoon onset and withdrawal. J. Climate, 16, 3200–3211, 2003.

[18] Banacos, P.C. dan Schultz, D.M. "The Use of Moisture Flux Convergence in Forecasting Convective Initiation: Historical and Operational Perspectives". Forecaster's Forum. Weather and Forecasting, 20, 351-366, 2005.

[19] DeMott, C. A., B. O. Wolding, E. D. Maloney, dan D. A. Randall. "Atmospheric mechanisms for mjo decay over the maritime continent". *J. of Geophys Res*. *Atmos.*, 123 (10), 5188–5204, 2018.

[20] Adames, A. F., dan D. Kim. "The MJO as a dispersive, convectively coupled moisture wave: Theory and observations". *Journal of the Atmospheric Sciences*, 73 (3), 913–941, 2016.

[21] Wang, B., G. Chen, dan F. Liu. "Diversity of the Madden-Julian Oscillation". *Science Advances*, 5 (7), 2019.