COMPARATIVE ANALYSIS OF DIURNAL AND SEASONAL VARIATIONS IN PRECIPITATION OF MESOSCALE CONVECTIVE SYSTEM AND NON-MESOSCALE CONVECTIVE SYSTEM OVER BORNEO ISLAND

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Received: August 14, 2024 Reviewed: February 22, 2025 Accepted: March 10, 2025

ABSTRACT

Convective storms, which play a critical role in producing severe weather events, are often associated with mesoscale convective systems (MCS). The most favorable tropical regions for MCS development include the Indonesian Maritime Continent (IMC), with Borneo Island being a prominent area. Borneo Island features unique topography and is influenced by the surrounding oceans, resulting in MCS with the largest average size and most extended lifespan compared to other islands within the IMC. Previous studies on MCS focused on occurrence statistics and case studies. However, analyses distinguishing characteristics of MCS and non-MCS precipitation remain limited over the IMC. This study examines the diurnal and seasonal variations and their respective contributions over Borneo Island. MCS identification and tracking were performed using the Flexible Object Tracker (FLEXTRKR) algorithm. The results indicate that MCS precipitation typically occurs from nighttime to early morning, while non-MCS precipitation primarily occurs during the daytime until the evening. Furthermore, MCS precipitation occurs more frequently over the ocean, while non-MCS precipitation is primarily observed over land. Seasonally, MCS precipitation is most prominent during the December–January–February (DJF) season, particularly over the South China Sea, parts of West Kalimantan, Sarawak, Central Kalimantan, and the Java Sea. Conversely, MCS precipitation is less dominant during the June–July–August (JJA) season. The contribution of precipitation produced by MCS exceeds 50% of the total precipitation, whereas non-MCS precipitation contributes approximately 20–40%. The differences in precipitation produced by MCS and non-MCS clouds will affect for soil water content, vulnerability to hydrometeorological disasters, and further understanding of climate and weather.

Keywords: mesoscale convective system (MCS), diurnal and seasonal variabilities, precipitation contribution.

1. Introduction

Convective storms, which can produce severe weather events such as heavy rain, hailstorms, strong winds, and thunderstorms are often associated with mesoscale convective systems (MCS) [1,2]. MCS exhibit various shapes and sizes, including convective and stratiform cloud systems, with precipitation and anvil cloud areas extending 100 km or more. These systems significantly contribute to total rainfall in tropical and mid-latitude regions and influence global large-scale atmospheric circulation, energy balance, and the hydrological cycle [3,4,5]. The extreme weather events associated with MCS can result in economic and social losses, including damage to communication systems, public facilities, transportation systems, and agriculture. [6].

The tropical region is the most favourable area for the development of MCS, particularly in the Intertropical Convergence Zone (ITCZ), the western Pacific warm pool, and the maritime continent, including Borneo Island. [7]. MCS contribute to more than half of the total rainfall in tropical regions, and in certain seasons, precipitation from MCS over land areas can exceed 80% [8]. The main characteristic of MCS is a larger horizontal scale and a most extended lifetime than other convective clouds, persisting for several hours with storms lasting more than a day [9]. Particularly, Borneo Island has an MCS with the largest average size and most extended lifetime compared to other islands in the maritime continent [10].

Research on MCS in the Indonesian Maritime Continent (IMC) primarily focuses on their properties and related case studies [11,12,13,14]. Previous studies of MCS over Borneo Island have concentrated on a specific type of MCS known as Mesoscale Convective Complexes (MCC). The contribution of MCC precipitation in Central Kalimantan and the South China Sea near Kalimantan occurs in all seasons, consistent with the seasonal frequency distribution of MCC [15]. Such conditions may be related to cold surges and the Borneo vortex, which can cause synoptic-scale cyclonic disturbances. The MCC in Central Kalimantan develops in the afternoon by orographic convective interaction with other convective clouds around the MCC. Westerly wind from Sumatra, northerly wind from the South China Sea, and southerly wind from Java interact with sea breezes and the effects of topographic uplift from mountains. MCC reaches its maximum size at midnight and begins to disappear in the morning [16].

Furthermore, MCS has various shapes, sizes, and characteristics that distinguish it from other convective clouds. Its precipitation also differs from that of non-MCS systems. MCS tends to produce higher precipitation with a longer duration. MCS rainfall is more concentrated on a spatial and temporal scale compared to non-MCS rainfall, which is more temporally and spatially distributed. In Central America, MCS rainfall is 7 times heavier than non-MCS rainfall, but its frequency is 3–5 times less frequent on a spatial scale and 2 times less frequent in time [17]. MCS and non-MCS rainfall also have different diurnal cycles, MCS rainfall peaks at night and non-MCS rainfall peaks in the afternoon [1, 2], 3]. It is important to know the characteristics of precipitation because it will have different impacts: continuous moderate-intensity rain will seep into the soil and benefit for plants. In contrast, large amounts of precipitation in a short time can cause floods and landslides [18]. Moreover, this understanding is crucial due to significant impact on groundwater resources, agricultural productivity, hydrometeorological disaster preparedness, and climate resilience. Therefore, understanding the characteristic differences between MCS and non-MCS precipitation is essential, particularly on the island of Borneo, which features unique topography and is influenced by the surrounding ocean. This study aims to examine the contributions of MCS and non-MCS precipitation and to analyze the diurnal and seasonal variations of MCS precipitation over Borneo Island.

2. Data and Methods

Data. This study utilizes satellite data with Brightness Temperature (BT) Global Merged IR V1 parameters [19] and precipitation feature (PF) using Integrated Multi-satellite Retrievals for GPM (IMERG) V06B [20]. These data were collected over the Borneo Island study area during the period 2011–2020. The 10-years datasets were selected for a general comparison that can represent the characteristics of MCS precipitation in the area. Global geostationary satellite BT data, with a temporal resolution of 30 minutes and a spatial resolution of 4 km, are used to identify and track convective clouds associated with MCS [21]. One of the two BT data sets is taken to identify and track deep convective clouds associated with the hourly MCS. GPM IMERG V06B precipitation data is precipitation estimation data originating from a passive microwave (PMW) sensor using a motion vector of water vapor [20] with a temporal resolution of 30 minutes and a spatial resolution of 0.1^o x 0.1^o. The 30-minute IMERG precipitation data were averaged to represent hourly precipitation amounts to reduce computational magnitude. Previous research on tracking MCS using hourly data suggests that such temporal resolution is sufficient to discern MCS [3].

Methods. MCS identification and tracking uses the Flexible Object Tracker (FLEXTRKR) algorithm [22] with BT and PF data to track cloud cold shield (CCS) and precipitation associated with MCS. The FLEXTRKR algorithm enables the comprehensive analysis of the entire life cycle of MCSs, from development to dissipation, thereby allowing the calculation of precipitation produced in all phases of MCS. High-resolution tracking of convective clouds is fundamental to capturing the temporal and spatial development of MCS events and their associated precipitation patterns. The methodology allows for an in-depth examination of MCS behavior and precipitation patterns, providing valuable insights into the dynamics and impact of these systems over Borneo Island. Additionally, the use of high-resolution satellite data and sophisticated tracking algorithms helps to enhance the accuracy of MCS identification and precipitation estimation, thereby contributing to more reliable weather forecasting and climate studies in the region. The comprehensive dataset and advanced analytical techniques employed in this study enable the clear distinction between MCS and non-MCS precipitation, thereby providing a better understanding of their respective contributions and characteristics.

Analysis of the mesoscale convective Systems that often occur in the central United States using geostationary satellite imagery was introduced by [2], namely mesoscale convective complex (MCC). The identification of another type of MCS with different shapes from MCC was carried out by [23], namely persistent elongated convective Systems (PECSs). Based on the shape, area, and duration [26], classified another smaller type, the meso-β circular convective Systems (MβCCS) and meso-β elongated convective Systems (MβECS). Then [24], classified an even smaller type, namely small meso-β circular convective Systems (SMβCCS) and small meso-β elongated convective Systems (SMβECS). Based on the various types of MCS, the author uses the minimum value of the MCS type contained in the studies of [24, 25] so that it meets the following criteria:

1. Interior BT $\leq -52^o$ C and cloud shield $\leq -32^o$ C
2. Cold cloud Systems (CCS) $\geq 3 \times 10^4$ km^2

3. The duration of these two conditions is ≥ 3 hours (the minimum MCS value over the Maritime Continent based on research by [25])

Each type of MCS has a different size and duration, so it has the potential to produce different precipitation intensites. This study focuses on precipitation associated with both MCS and non-MCS convective clouds. The minimum value of convective clouds from the MCS was selected based on the method used in [22], allowing for the inclusion of various MCS cloud types. In this case, we do not categorize the cloud types but instead take the minimum value from the existing MCS classification.

Furthermore, precipitation is categorized as either non-MCS or MCS-related. Non-MCS precipitation refers to rainfall events not associated with Mesoscale Convective Systems. This classification is derived by simply subtracting MCS precipitation from the total precipitation, ensuring a straightforward separation of the two categories.

3. Result and Discussion

Diurnal variability of MCS and non-MCS Precipitation. As shown in Figure 1, the diurnal variability of MCS precipitation over Borneo Island was analyzed by dividing the data into four seasons: December-January-February (DJF), March-April-May (MAM), June-July-August (JJA), and September-October-November (SON). Each plot presents local time on the y-axis and longitude on the x-axis. MCS precipitation is calculated based on the hourly average value at each grid point in longitude. The diurnal amplitude of precipitation is calculated using the amplitude at the first harmonic (n=1), which captures the daily cycle by representing the difference between peak and minimum precipitation values within a 24-hour period.

MCS precipitation during the DJF season is dominant, while JJA shows the least. A distinct diurnal cycle is observed, with precipitation peaks occurring in the early morning or late afternoon, varying across seasons. The highest amplitude consistently occurs between longitudes 112°E and 114°E, indicating that MCS precipitation is concentrated in the central region of Borneo Island, particularly over areas with complex topography such as mountains and plateaus. This aligns with findings from [26, 27], which show that MCS development frequently occurs in mountainous regions due to horizontal pressure gradients and alternating mountain-valley wind systems. These wind systems enhance convective activity, as demonstrated in [28]. Mountain and valley winds, which alternate in diurnal cycles, contribute to convective activity, particularly in regions with complex topographic features, such as Borneo Island [15].

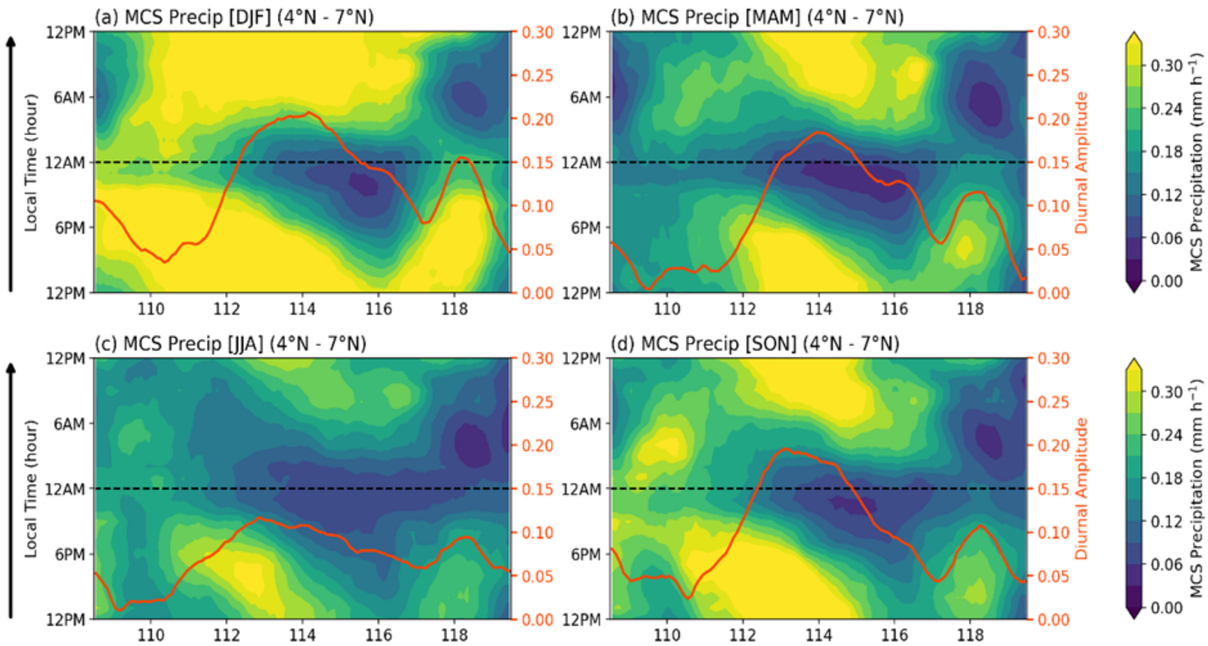

Figure 1. Hovmöller diagram of average MCS precipitation for each season in the latitude range of 9° S – 6° S (Borneo Island). The shading color represents the average MCS precipitation (mm/hour), and the red line represents the precipitation amplitude (mm/hour).

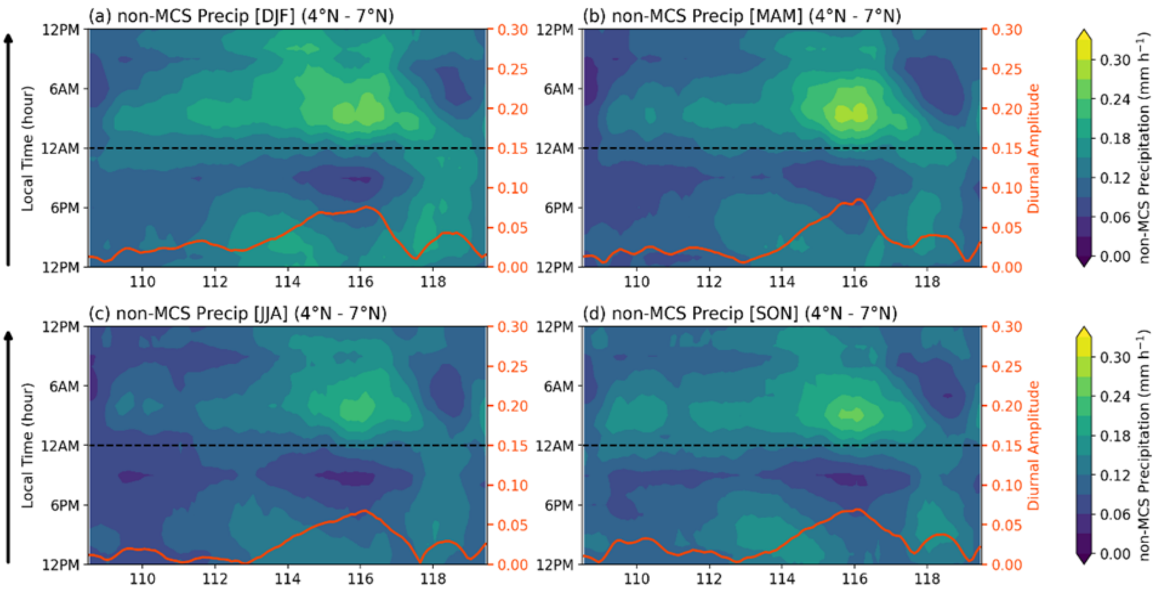

Figure 2. Same as Figure 1, but for non-MCS precipitation.

In contrast, Figure 2 illustrates the diurnal variability of non-MCS precipitation across all seasons. Non-MCS precipitation is generally less dominant overall but occurs more frequently from morning until noon. During the MAM season, non-MCS precipitation peaks, particularly between 115°E and 117°E, while in the DJF season, it appears more evenly distributed but remains less dominant than in MAM. The amplitude of non-MCS precipitation is consistently higher in the 115°E–117°E region across all seasons, suggesting that these areas are more susceptible to localized, short-duration rainfall events.

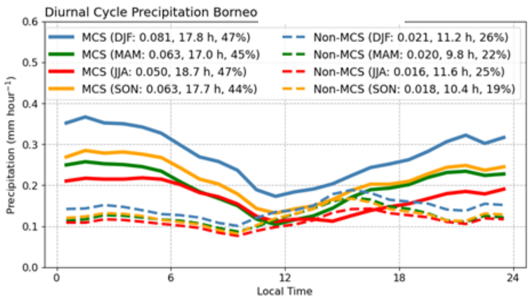

Figure 3. Time series graph of mean precipitation (mm/h) for MCS (thick line) and non-MCS (dashed line) over Borneo Island, covering the latitude range of 4°N to 7°N and the longitude range of 108.5°E to 119.5°E. Each color represents a different season: blue for the DJF season, green for the MAM season, red for the JJA season, and yellow for the SON season. For each season, the statistical analysis includes three key metrics: amplitude (magnitude of variation), phase (timing of peak precipitation), and variance (spread of the data).

Figure 3 compares the diurnal cycles of MCS and non-MCS precipitation, demonstrating that MCS precipitation is significantly more dominant, particularly during the DJF season, when it can be more than double that of non-MCS precipitation. MCS events predominantly occur from night to early morning, like patterns observed in Central America, where MCS precipitation peaks during the same timeframe [29]. Meanwhile, non-MCS precipitation generally peaks from midday to late afternoon. These findings align with previous studies on the mesoscale convective complex (MCC) development process over Kalimantan, where surface wind convergence—comprising westerly winds from Sumatra, northerly winds from the South China Sea, and southerly winds from Java—contributes to convective cloud uplift, with MCC systems reaching their maximum size at midnight and dissipating by morning [16].

Seasonal variability of MCS precipitation. As shown in Figure 4, MCS precipitation over the ocean is more dominant than over land. Precipitation produced by MCS appears dominant in the West Kalimantan, Sarawak, Central Kalimantan, and Java Sea regions, especially in the DJF season with daily precipitation intensity values above 10 mm/day. MCS-related precipitation dominates the South China Sea region near Borneo during the DJF and SON seasons. In Central and West Kalimantan, precipitation predominantly occurs during the DJF (December–January–February) and MAM (March–April–May) seasons compared to other periods. In the JJA season, MCS precipitation is seen to be less dominant than in other seasons.

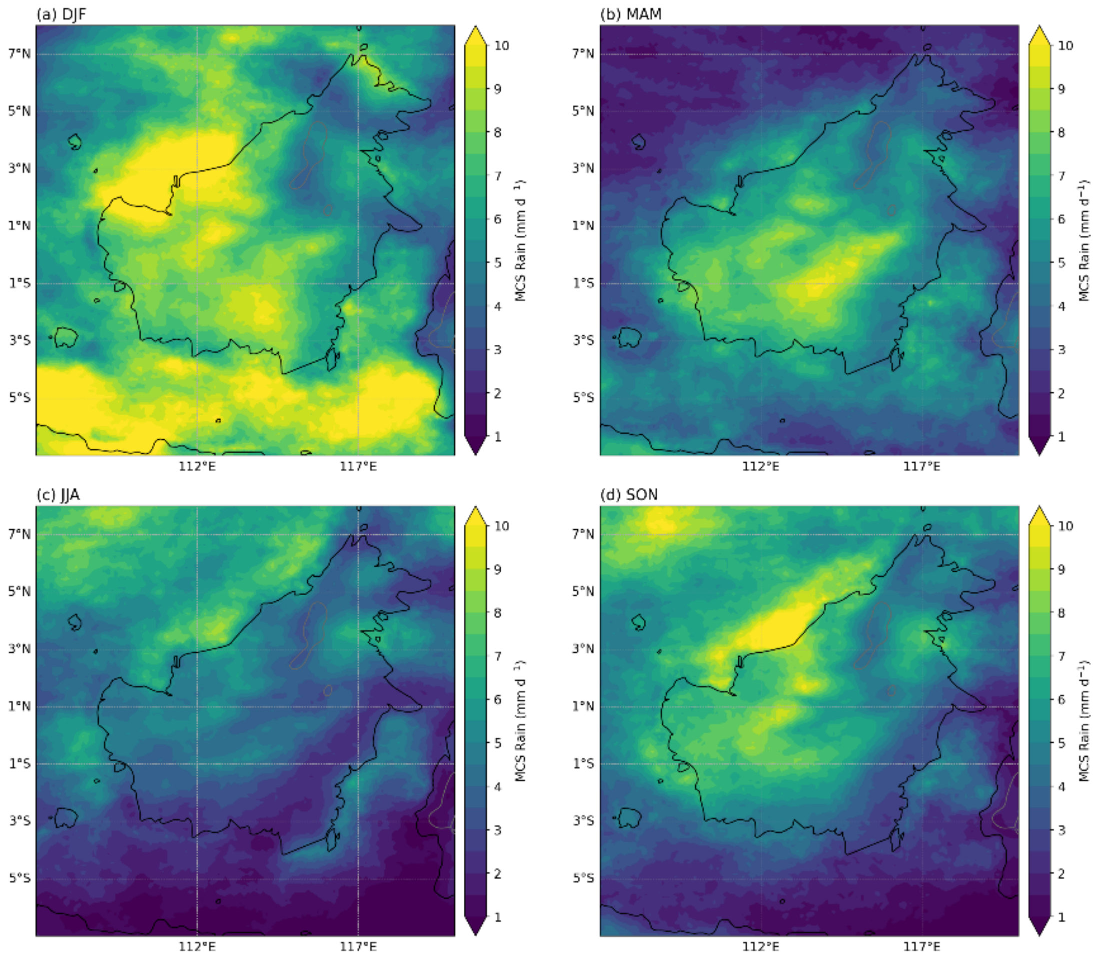

Figure 4. Spatial distribution of average MCS precipitation (shaded, mm/day) each season.

Figure 5 shows the frequency of MCS precipitation, which represents the number of precipitation events generated by MCS. What is calculated here is not the intensity of the precipitation but the number of precipitation events. The frequency of MCS rain on Borneo Island varies greatly depending on the season and location. The frequency of MCS precipitation is dominant in the Central Kalimantan, West Kalimantan, and Sarawak regions throughout the season, except for the JJA season, which is only dominant in the South China Sea. The frequency of MCS rain is highest in the DJF season compared to other seasons in almost all areas of Borneo Island.

During the MAM (March–April–May) season, MCS precipitation is more pronounced over land than over oceanic regions. This aligns with findings from [30], which observed that MCS events occur more frequently over land compared to coastal and open ocean areas. The disparity is linked to synoptic-scale environmental conditions, particularly baroclinic instability prior to the onset of summer—a mechanism also documented in Southern Africa [31] .

The dominance of mesoscale convective system (MCS) precipitation during the DJF season is influenced by the substantial intrusion of air masses from the East Asian landmass, which experiences winter, toward the South China Sea. This monsoonal wind generates strong landward airflow and excessive rainfall along island chains and coastal landmasses. During winter over the Asian continent, the northeast monsoon winds intensify periodically over one to several weeks, enhancing low-level cyclonic vorticity off the northwestern coast of Borneo. Consequently, the Borneo Vortex becomes highly active during the boreal winter [32,33].

Conversely, during the summer season over the Asian landmass, the intrusion of air masses is weaker, resulting in reduced precipitation. Precipitation dominance is primarily observed over inland Borneo, driven by the wake effect, wherein sea breeze circulation is enhanced on the sheltered side of the island, leading to more significant rainfall on the leeward side of mountain ranges exposed to synoptic winds [34].

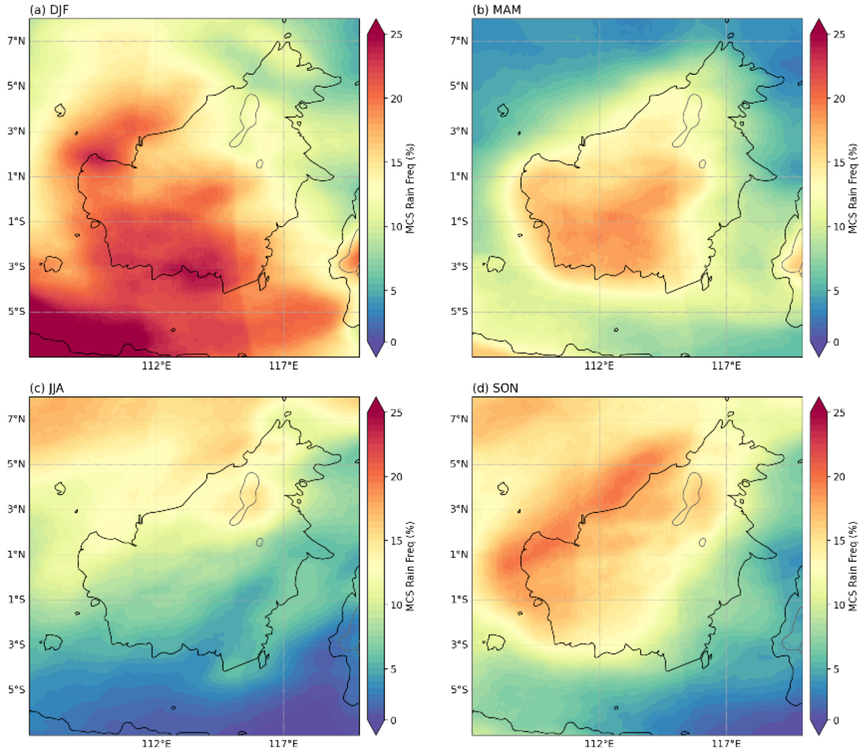

Figure 5. Spatial distribution of MCS precipitation frequency percentage (shaded; percent) each season.

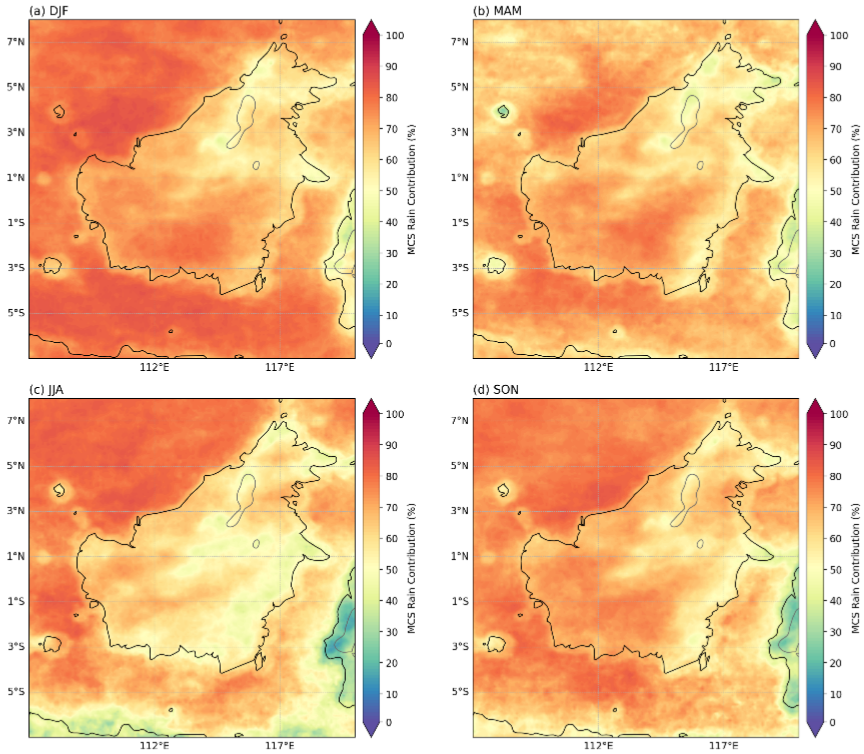

Figure 6. Spatial distribution of MCS precipitation contribution in Borneo Island (shaded; percent) each season.

Contribution of MCS and non-MCS precipitation. Figure 6 highlights the contribution of MCS to total precipitation across Borneo Island. The MCS contribution peaks during the DJF season, with dominant regions including West Kalimantan, East Kalimantan, the South China Sea, Sarawak, South Kalimantan, and North Kalimantan, where MCS precipitation accounts for over 50% of total rainfall. This dominance may be linked to synoptic-scale phenomena such as cold surges and the Borneo Vortex, which enhance MCS cloud development, particularly during cyclonic disturbances near Borneo [35,36].

Non-MCS precipitation refers to the proportion of precipitation produced by non-MCS clouds relative to total precipitation. It is calculated by subtracting MCS precipitation from total precipitation. As shown in Figure 7, the contribution of non-MCS precipitation over Borneo Island generally ranges from 20% to 40%. Non-MCS precipitation tends to be more dominant over the land than the ocean, exhibiting an inverse relationship with MCS precipitation. The highest contribution of non-MCS precipitation occurs during the JJA season across most areas of Borneo Island. In other seasons, non-MCS precipitation is more dominant in specific regions, including parts of Sabah, Sarawak, North Kalimantan, and South Kalimantan.

Although we did not specifically discuss precipitation trends in Borneo Island, it is important to address this topic briefly. As previously discussed, MCS (Mesoscale Convective Systems) precipitation contributes up to 50% of the total precipitation, while non-MCS precipitation accounts for approximately 20-40%. Recent studies highlight a significant warming trend across Borneo, particularly in its eastern regions. Temperature data from 1991 to 2020 show increases of 0.5°C to 2.5°C compared to the baseline period of 1951–1980. This rise in surface temperatures has contributed to shifts in rainfall patterns, including a decline in prolonged light rainfall events and a corresponding increase in short-duration, high-intensity rainfall [37].

Based on simulations conducted by [38] to assess the impact of land use and vegetation changes on rainfall in Borneo Island, the results indicate that deforestation, which converts forests into open land or areas with high albedo, can reduce rainfall. Deforestation decreases evapotranspiration, increases albedo, and suppresses radiative energy and sensible heat, thereby inhibiting convection and reducing the supply of moisture supply to the atmosphere. Consequently, rainfall in Borneo is reduced. Conversely, changes in vegetation type that lower evapotranspiration efficiency without altering albedo can increase rainfall. Enhanced sensible heat and reduced latent heat can promote more active convection and draw in horizontal atmospheric moisture flow. As a result, even though evapotranspiration decreases, rainfall may still increase.

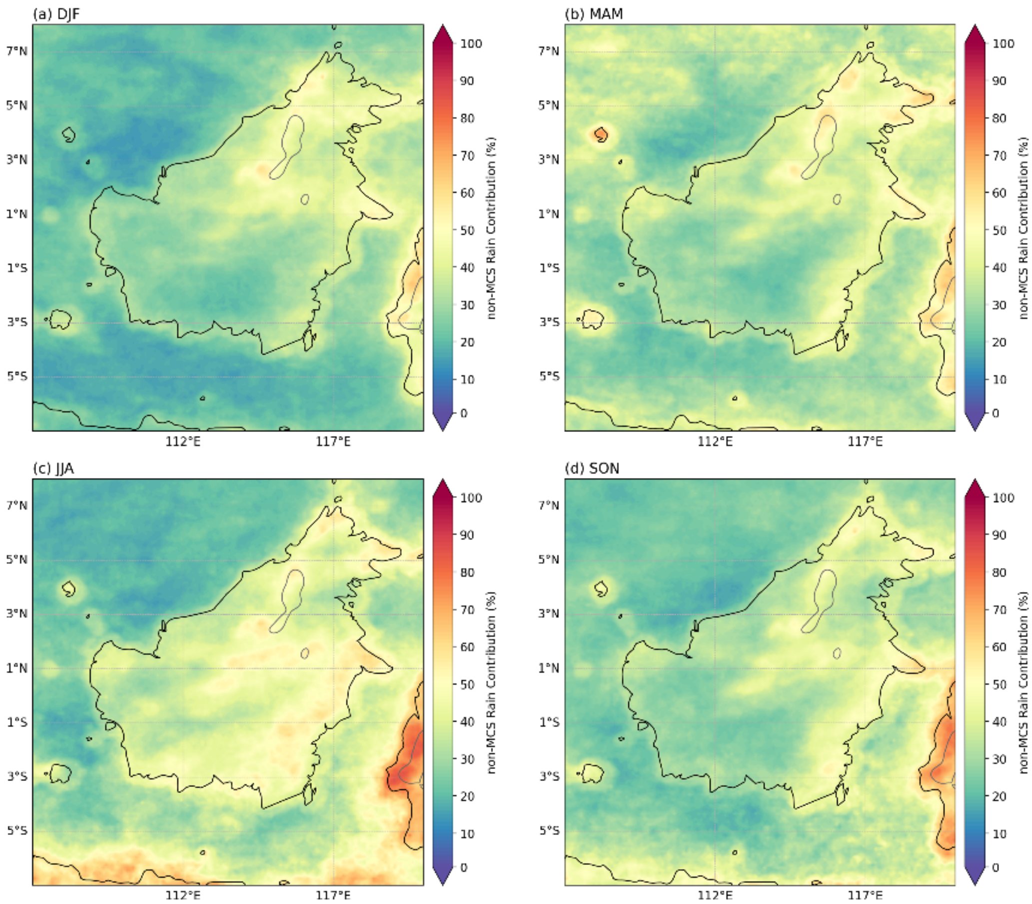

Figure 7. Same as Figure 6, but for non-MCS precipitation.

4. Conclusion

Studies on MCS and non-MCS precipitation characteristics on Borneo Island found different characteristics in diurnal and seasonal variation patterns and their contributions. MCS precipitation shows an apparent diurnal cycle, with peaks at night until early morning. Meanwhile, non-MCS precipitation occurs during the day until the evening. In addition, MCS precipitation is more frequent over oceanic regions than over land, while non-MCS precipitation follows the opposite pattern.

Seasonally, MCS precipitation peaks during the DJF season. The highest intensities are observed in the South China Sea, parts of West Kalimantan, Sarawak, Central Kalimantan, and the Java Sea during DJF, whereas MCS precipitation is less dominant in the JJA season. The contribution of precipitation produced by MCS reaches more than 50%, while non-MCS precipitation only occurs around 20-40% of the total precipitation. Knowledge of the differences in precipitation characteristics produced by MCS and non-MCS clouds is essential for hydrometeorological disaster preparedness, agriculture, and understanding climate and weather.

Acknowledgment

All the authors contribute to the analysis, suggestions, and feedback. We also thank to Dr. Nurjanna Joko Trilaksono (Bandung Institute of Technology, Indonesia). We also thank to the Indonesia Endowment Fund for Education Agency (LPDP) for providing funding for our research and education.

References

[1] R. A. Houze, B. F. Smull, and P. Dodge, “Mesoscale Organization of Springtime Rainstorms in Oklahoma,” *Monthly Weather Review*, vol. 118, pp. 613–654, Mar. 1990.

[2] R. A. Maddox, “Mesoscale Convective Complexes,” *Bulletin of American Meteorology Society*, vol. 61, no. 11, pp. 1374–1387, 1980.

[3] Z. Feng *et al.*, “Spatiotemporal Characteristics and Large-Scale Environments of Mesoscale Convective Systems East of the Rocky Mountains,” *Journal of Climate*, vol. 32, no. 21, pp. 7303–7328, Nov. 2019, doi: 10.1175/JCLI-D-19-0137.1.

[4] R. Yang, Y. Zhang, J. Sun, S. Fe, and J. Li, “The characteristics and classification of eastward-propagating mesoscale convective systems generated over the second-step terrain in the Yangtze River Valley - Yang - 2019 - Atmospheric Science Letters - Wiley Online Library,” *Atmospheric Science Letters*, vol. 20, no. 1, Accessed: Aug. 16, 2024. [Online]. Available: https://doi.org/10.1002/asl.874.

[5] F. Song *et al.*, “Contrasting Spring and Summer Large-Scale Environments Associated with Mesoscale Convective Systems over the U.S. Great Plains,” *Journal of Climate*, vol. 32, no. 20, pp. 6749–6767, Oct. 2019, doi: 10.1175/JCLI-D-18-0839.1.

[6] R. A. Houze, “100 Years of Research on Mesoscale Convective Systems,” *Meteorological Monographs*, vol. 59, p. 17.1-17.54, Jan. 2018, doi: 10.1175/AMSMONOGRAPHS-D-18-0001.1.

[7] X. Huang *et al.*, “A long-term tropical mesoscale convective systems dataset based on a novel objective automatic tracking algorithm,” *Clim Dyn*, vol. 51, no. 7–8, pp. 3145–3159, Oct. 2018, doi: 10.1007/s00382-018-4071-0.

[8] J. Yuan and R. A. Houze, “Global Variability of Mesoscale Convective System Anvil Structure from A-Train Satellite Data,” vol. 23, pp. 5864–5888, Nov. 2010, doi: 10.1175/2010JCLI3671.1.

[9] R. A. Houze, “Mesoscale convective systems,” *Reviews of Geophysics*, vol. 42, no. 4, p. 2004RG000150, Dec. 2004, doi: 10.1029/2004RG000150.

[10] N. S. Putri, H. Iwabuchi, and T. Hayasaka, “Evolution of Mesoscale Convective System Properties as Derived from Himawari-8 High-Resolution Data Analyses,” *Journal of the Meteorological Society of Japan*, vol. 96B, no. 0, pp. 239–250, 2018, doi: 10.2151/jmsj.2018-020.

[11] R. W. S. Saragih, “Identifikasi Karakteristik Mesoscale Convective Complex (MCC) di Wilayah Papua dan Sekitarnya,” *jf*, vol. 12, no. 2, pp. 42–54, Nov. 2022, doi: 10.15294/jf.v12i2.39190.

[12] E. Yulihastin, D. E. Nuryanto, - Trismidianto, and R. Muharsyah, “Characteristics of Mesoscale Convective Complexes that Triggered Heavy Rainfall Related to Severe Flash Flood in Luwu, Sulawesi, Indonesia,” Sep. 06, 2021. doi: 10.20944/preprints202109.0084.v1.

[13] I. F. P. Perdana, Y. I. Rismana, F. A. Prasetya, and A. Mulsandi, “Studi Kejadian *Mesoscale Convective Complex* (MCC) di Wilayah Papua Bagian Selatan pada 9-10 Mei 2018,” *Jurnal Meteorologi Klimatologi dan Geofisika*, vol. 6, no. 1, pp. 58–66, Sep. 2019.

[14] D. E. Nuryanto, H. Pawitan, R. Hidayat, and E. Aldrian, “Characteristics of two mesoscale convective systems (MCSs) over the Greater Jakarta: case of heavy rainfall period 15–18 January 2013,” *Geosci. Lett.*, vol. 6, no. 1, p. 1, Dec. 2019, doi: 10.1186/s40562-019-0131-5.

[15] Trismidianto, E. Yulihastin, H. Satyawardhana, J. T. Nugroho, and S. Ishida, “The Contribution of the Mesoscale Convective Complexes (MCCs) to total rainfall over Indonesian Maritime Continent,” *IOP Conf. Ser.: Earth Environ. Sci.*,

vol. 54, p. 012027, Jan. 2017, doi: 10.1088/1755-1315/54/1/012027.
[16] Trismidianto, E. Yulihastin, H. Satyawardhana, and S. Ishida, “A composite analysis of the Mesoscale Convective Complexes (MCCs) development over the Central Kalimantan and its relation with the propagation of the rainfall systems,” *IOP Conf. Ser.: Earth Environ. Sci.*, vol. 54, p. 012036, Jan. 2017, doi: 10.1088/1755-1315/54/1/012036.
[17] H. Hu, L. R. Leung, and Z. Feng, “Understanding the Distinct Impacts of MCS and Non-MCS Rainfall on the Surface Water Balance in the Central United States Using a Numerical Water-Tagging Technique,” *Journal of Hydrometeorology*, vol. 21, no. 10, pp. 2343–2357, Oct. 2020, doi: 10.1175/JHM-D-20-0081.1.
[18] K. Trenberth, “Changes in precipitation with climate change,” *Clim. Res.*, vol. 47, no. 1, pp. 123–138, Mar. 2011, doi: 10.3354/cr00953.
[19] J. Janowiak, B. Joyce, and P. Xie, “GES DISC Dataset: NCEP/CPC L3 Half Hourly 4km Global (60S - 60N) Merged IR V1 (GPM_MERGIR 1).” 2017. Accessed: Jun. 23, 2024. [Online]. Available: https://disc.gsfc.nasa.gov/datasets/GPM_MERGIR_1/summary/
[20] G. J. Huffman, E. F. Stocker, D. T. Bolvin, and J. Tan, “GES DISC Dataset: GPM IMERG Final Precipitation L3 Half Hourly 0.1 degree x 0.1 degree V06 (GPM_3IMERGHH 06).” 2019. Accessed: Jun. 23, 2024. [Online]. Available: https://disc.gsfc.nasa.gov/datasets/GPM_3IMERGHH_06/summary?keywords=imerg
[21] Z. Feng *et al.*, “Structure and Evolution of Mesoscale Convective Systems: Sensitivity to Cloud Microphysics in Convection-Permitting Simulations Over the United States,” *Journal of Advances in Modeling Earth Systems*, vol. 10, no. 7, pp. 1470–1494, 2018, doi: 10.1029/2018MS001305.
[22] Z. Feng *et al.*, “A Global High-Resolution Mesoscale Convective System Database Using Satellite-Derived Cloud Tops, Surface Precipitation, and Tracking,” *Journal of Geophysical Research: Atmospheres*, vol. 126, no. 8, p. e2020JD034202, 2021, doi: 10.1029/2020JD034202.
[23] C. J. Anderson and R. W. Arritt, “Mesoscale Convective Complexes and Persistent Elongated Convective Systems over the United States during 1992 and 1993,” *Mon. Wea. Rev.*, vol. 126, no. 3, pp. 578–599, Mar. 1998, doi: 10.1175/1520-0493(1998)126<0578:MCCAPE>2.0.CO;2.
[24] X. Yang, J. Fei, X. Huang, X. Cheng, L. M. V. Carvalho, and H. He, “Characteristics of Mesoscale Convective Systems over China and Its Vicinity Using Geostationary Satellite FY2,” *Journal of Climate*, vol. 28, no. 12, pp. 4890–4907, Jun. 2015, doi: 10.1175/JCLI-D-14-00491.1.
[25] Y. Norman and N. J. Trilaksono, “Investigation of Mesoscale Convective Systems over Indonesian Maritime Continent using Geostationary Meteorological Satellite,” *J. Phys.: Conf. Ser.*, vol. 1204, p. 012124, Apr. 2019, doi: 10.1088/1742-6596/1204/1/012124.
[26] W. S. Ashley *et al.*, “Distribution of Mesoscale Convective Complex Rainfall in the United States,” *Mon. Wea. Rev.*, vol. 131, no. 12, pp. 3003–3017, Dec. 2003, doi: 10.1175/1520-0493(2003)131<3003:DOMCCR>2.0.CO;2.
[27] A. G. Laing and J. M. Fritsch, “The Large-Scale Environments of the Global Populations of Mesoscale Convective Complexes,” *Mon. Wea. Rev.*, vol. 128, no. 8, pp. 2756–2776, Aug. 2000, doi: 10.1175/1520-0493(2000)128<2756:TLSEOT>2.0.CO;2.
[28] M. Kawashima *et al.*, “Case Study of an Intense Wind Event Associated with a Mesoscale Convective System in West Sumatera during the HARIMAU2006 Campaign,” *Journal of the Meteorological Society of Japan*, vol. 89A, pp. 239–257, 2011, doi: 10.2151/jmsj.2011-A15.
[29] H. Hu, L. R. Leung, and Z. Feng, “Observed Warm-Season Characteristics of MCS and Non-MCS Rainfall and Their Recent Changes in the Central United States,” *Geophysical Research Letters*, vol. 47, no. e2019GL086783, 2020, doi: 10.1029/2019GL086783.
[30] Trismidianto, “Characteristics of the oceanic MCC, continental MCC, and coastal MCC over the Indonesian maritime continent,” *IOP Conf. Ser.: Earth Environ. Sci.*, vol. 149, p. 012024, May 2018, doi: 10.1088/1755-1315/149/1/012024.
[31] P. D. Tyson and R. A. Preston-Whyte, *The Weather and Climate of Southern Africa*. Oxford University Press, 2000.
[32] Johnson, R. H., and R. A. Houze Jr., 1987: Precipitating cloud systems of the Asian monsoon. Monsoon Meteorology, C.-P. Chang and T. N. Krishnamurti, Eds., Oxford University Press, 298–353.
[33] Chang, C., Z. Wang, J. McBride, and C. Liu, 2005: Annual Cycle of Southeast Asia—Maritime Continent Rainfall and the Asymmetric Monsoon Transition. J. Climate, 18, 287–301.
[34] Qian, J., A. W. Robertson, and V. Moron, 2013: Diurnal Cycle in Different Weather Regimes and Rainfall Variability over Borneo Associated with ENSO. J. Climate, 26, 1772–1790.
[35] T.-C. Chen, J.-D. Tsay, M.-C. Yen, and J. Matsumoto, “The Winter Rainfall of Malaysia,” *Journal of Climate*, vol. 26, pp. 936–958, Feb. 2013, doi: 10.1175/JCLI-D-12-00174.1.

[36] P. Wu, Y. Fukutomi, and J. Matsumoto, "An Observational Study of the Extremely Heavy Rain Event in Northern Vietnam during 30 October-1 November 2008," *Journal of the Meteorological Society of Japan. Ser. II*, vol. 89A, pp. 331–344, 2011, doi: 10.2151/jmsj.2011-A23.

[37] Hamed, M.M., Al-Sakkaf, A.S., Rady, M. and Shahid, S. (2024), Temperature and Precipitation Extremes Over Borneo Island: An Integrated Climate Risk Assessment. Int J Climatol, 44: 6040-6064.

[38] Takahashi, A., T. Kumagai, H. Kanamori, H. Fujinami, T. Hiyama, and M. Hara, 2017: Impact of Tropical Deforestation and Forest Degradation on Precipitation over Borneo Island. J. Hydrometeor., 18, 2907–2922.