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Seasonal Variation of Rainfall in Indonesia under Normal Conditions without ENSO and IOD Events from 1981-2021

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Abstract: This study explores the seasonal rainfall variation in Indonesia under normal conditions, excluding the influence of El-Nino Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) events. Monthly rainfall data is sourced from the CHIRPS dataset, and wind and atmospheric movement data are obtained from the ECMWF ERA-5 dataset. Identification of normal conditions relies on the ONI and DMI indices. Results reveal that the seasonal rainfall patterns during these normal conditions align with previous studies encompassing all atmospheric conditions. Indonesia typically witnesses one or two peaks in rainfall annually, notably in December-January-February (DJF), May-June (MJ), and March-April-May (MAM), consistent with established rainfall zone classifications in earlier research. A nuanced discrepancy emerges in the timing of the May-June peak, previously noted in June-July. The congruence in peak rainfall patterns during normal conditions, as observed in prior comprehensive research, implies a negligible influence of ENSO and IOD on the timing of seasonal rainfall peaks. Although ENSO and IOD may impact the amplitude of seasonal variation, particularly in Indonesia's eastern and western regions, they do not alter the temporal occurrence of rainfall peaks. Consequently, the timing of rainfall peaks in Indonesia predominantly reflects the combined influence of the Asian and Australian monsoons.

Keywords: Normal condition; Rainfall; Seasonal variation

Introduction

Indonesia receives high rainfall throughout the year due to its location near the equator and between the warm Indian and Pacific oceans. Additionally, Indonesia is situated between the vast landmasses of Asia and Australia (Marzuki et al., 2013, 2018). The interaction between the oceans, continents, and the atmosphere also influences rainfall in Indonesia, known as the Asian-Australian monsoon. During June, July, and August (JJA), Indonesia experiences the southeast monsoon, also known as the Australian monsoon, which brings dry air, resulting in a dry season in most parts of Indonesia (Lee, 2015; Pramuwardani et al., 2018). Subsequently, the northwest monsoon (ccccc) occurs in December, January, and February (DJF), bringing moist air and leading to higher rainfall during those months. Additionally, during September-October-November (SON) and March-April-May (MAM), a transitional period between the two monsoons occurs (As-syakur et al., 2013; Sarathchandraprasad et al., 2021). The presence of monsoons causes significant seasonal variations in rainfall in Indonesia. The clear distinction between wet and dry seasons throughout the year is closely related to the movement of monsoonal winds.

Numerous studies have examined the seasonal variation of rainfall in Indonesia. Hidayat & Ando (2014) found that the climatology of rainfall in Indonesia exhibits a maximum during the DJF season, with relatively high rainfall observed in almost all regions of Indonesia, while the minimum rainfall occurs during JJA. Similar results were reported by As-syakur et al. (2013), where high rainfall is observed throughout Indonesia, except for Nusa Tenggara, during the Asian monsoon (November-February). Conversely, low rainfall begins in April and extends until August, covering the eastern regions of Sumatra, Kalimantan, Sulawesi, and southern Maluku.

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Although there have been numerous studies on the seasonal variation of rainfall in Indonesia, most have focused on the associations with El Niño Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) phenomena, making the influence of monsoons less clear. Aldrian et al. (2003) divided the Indonesian region into three rainfall zones, two of which claimed to be influenced by ENSO (Zone C and Zone A). ENSO and IOD are phenomena of atmospheric-ocean interaction that significantly affect global rainfall patterns (Xu et al., 2016). Rainfall tends to decrease during El Niño and positive IOD events, while rainfall increases during La Niña and negative IOD events (Lestari et al., 2018; Puryati et al., 2021; Hadiningrum et al., 2022; Satyawardhana et al., 2022). The influence of ENSO and IOD shows regional variations. Hidayat et al. (2016) found that the western regions of Indonesia, such as Java, are strongly influenced by IOD and minimally affected by ENSO, while the eastern regions, such as Sulawesi, are strongly influenced by ENSO and minimally affected by IOD. These differences will likely affect the seasonal variation of rainfall in each region. This study addresses how the seasonal rainfall variation in Indonesia would occur in the absence of ENSO and IOD (under normal conditions). Does the timing of rainfall peaks in Indonesia shift or remain consistent with previous studies that have focused on ENSO and IOD? To answer these questions, the study analyzes the seasonal rainfall variation in Indonesia during normal conditions (without ENSO and IOD) from 1981 to 2021 using Climate Hazards Group InfraRed Precipitation with Station (CHIRPS) data.

Method

Data

This research utilizes rainfall data from the Climate Hazards Group InfraRed Precipitation with Station (CHIRPS) for 40 years, from 1981 to 2021. CHIRPS is a quasi-global rainfall dataset that combines meteorological station data with infrared data to estimate precipitation (Funk et al., 2015; Harrison et al., 2022). The CHIRPS data can be downloaded from the website https://data.chc.ucsb.edu/products/CHIRPS-2.0/global_daily/. The data used in this study is monthly data with a spatial resolution of 0.05°. CHIRPS covers the region from 50°N to 50°S, but in this research, only the data for Indonesia's region (10S-10N, 90E-145E) are utilized. The topography of the study area can be seen in Figure 1a. In addition to CHIRPS data, surface temperature, vertical wind (ω), and horizontal wind (U and V) data from the fifth-generation reanalysis data (ECMWF ERA-5) are also used. The data used has a spatial resolution of 0.25° and can be downloaded from the website https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels-monthly-means?tab=form. The ERA-5 data period used is the same as CHIRPS, from 1981 to 2021 (40 years).

The data used in this study is data during normal conditions, without ENSO (El Niño-Southern Oscillation) and IOD (Indian Ocean Dipole) events. To determine the ENSO periods, the Niño index is utilized, which can be downloaded from the link https://psl.noaa.gov/gcos_wgsp/Timeseries/. For observing the IOD, the Dipole Mode Index (DMI) is employed, and it can be obtained from the link https://psl.noaa.gov/gcos_wgsp/Timeseries/DMI/. The DMI is determined based on the sea surface temperature anomaly gradient between the Western Tropical Indian Ocean (WTIO) region (50°E - 70°E, 10°S - 10°S) and the Southeastern Tropical Indian Ocean (SETIO) region (90°E - 110°E, 10°S - equator). A detailed description of the DMI index can be found in the paper by (Saji et al., 1999).

Method

The research begins by identifying the months unaffected by ENSO and IOD (normal conditions). The number of months under normal conditions during the 40-year observation period is as follows: January 6, February 7, March 3, April 5, May 8, June 3, July 9, August 7, September 6, October 3, November 3, and December 6. Once the months with normal conditions are identified, an average rainfall mapping is performed for the entire Indonesian region, allowing the spatial rainfall variations to be observed for each month. Additionally, sea surface temperature and horizontal wind patterns are plotted to examine the movement of the Australian and Asian monsoon winds under normal conditions. Furthermore, the anomalies in vertical atmospheric motion are plotted to identify the locations of convection centers during each season. Next, Indonesia's peak months of rainfall are determined for all grid data used. As the maximum number of rainfall peaks in Indonesia is generally two, this study focuses on these two peaks. Before determining the peak rainfall periods, the rainfall data is fitted using harmonic decomposition to reduce irregularities in the time series data as in several studies (Marzuki et al., 2022; Ramadhan et al., 2022c; Szkolka et al., 2023).

Result and Discussion

Climatology of Monthly Rainfall

Figure 1b illustrates Indonesia's average monthly rainfall distribution between 1981 and 2021. Generally, the highest monthly precipitation is observed in the northern region of Kalimantan and the southern part of Papua, surpassing 350 mm/month. Western Java and western Sumatra also experience significant rainfall, averaging around 300 mm/month. Their complex topography is the primary factor contributing to the high rainfall in these areas. Regions with elevated terrain (Figure 1a) tend to receive greater amounts of rainfall. The movement of rain clouds from the Indian Ocean encounters obstacles from the Bukit Barisan, resulting in elevated precipitation levels in the western part of Sumatra (Marzuki et al., 2021). Conversely, the eastern part of Java and northern Sulawesi exhibit lower rainfall, with values below 150 mm/month. Similar patterns of reduced rainfall can be observed in other regions, including Maluku and Nusa Tenggara. These findings align with previous studies on the climatology of average rainfall (Lestari et al., 2018; Ramadhan et al., 2022a; Ramadhan et al., 2022b; Ramadhan et al., 2022d).

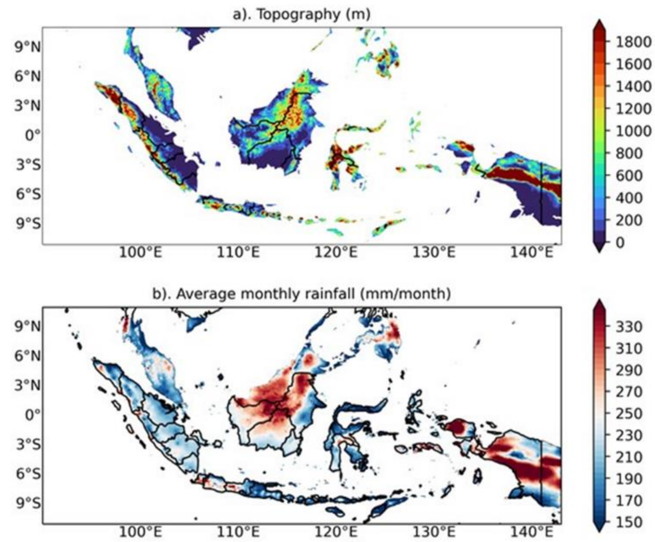

Figure 1. The topography of Indonesia (a), and the average rainfall in Indonesia during normal conditions from 1981-2021(b)

Rainfall during Desember to May

Figure 2 illustrates the rainfall in Indonesia during DJF (December-January-February) and MAM (March-April-May). Both periods exhibit high rainfall. In December, extremely high rainfall (>350 mm/month) occurs in Kalimantan and Java. High rainfall is also observed in eastern Sumatra and southern Papua. Low rainfall (around 150-200 mm/month) is experienced in Sulawesi, Maluku, and western Papua. A similar pattern is observed in January, but the area with high rainfall is narrower compared to December. In February, rainfall ranges from 300-330 mm/month in Java, central Kalimantan, southern Sumatra, and parts of Papua, while other regions receive low rainfall. These findings align with previous research, such as Hidayat et al. (2014), who found high rainfall during the DJF season. Mulyana (2002) also reported similar results, except for increased rainfall in Sulawesi.

During the MAM period, rainfall in Indonesia begins to decrease. In March, rainfall patterns are similar to February, with high rainfall observed in Java, central Kalimantan, southern Sumatra, and parts of Papua. However, other regions, such as northern Sumatra, eastern Java, Sulawesi, and Maluku, experience a decline in rainfall. In April, high rainfall spreads across Papua, Sumatra, Sulawesi, and Maluku, but with lower intensity compared to March. Eastern Java and Nusa Tenggara experienced low rainfall in April. In May, rainfall decreases in Sumatra, while some regions in eastern Indonesia and Kalimantan still receive high rainfall. These findings are consistent with previous research (As-syakur et al., 2013; Hidayat & Ando, 2014) that observed a decrease in rainfall during the MAM season.

The presence of the Asian monsoon winds is evident during the DJF and MAM seasons (Figure 3), as observed in previous studies (As-syakur et al., 2013; Hidayat & Ando, 2014). These monsoon winds bring moist air toward Indonesia, resulting in increased rainfall. The peak of the Asian monsoon winds occurs during the DJF season (Figure 3). The moisture carried by these winds contributes to high rainfall in Indonesia. In contrast, MAM is a transitional period from the Asian monsoon to the southeast monsoon (Anshari, 2023). This transition becomes apparent from April and May, indicating the onset of the southeast monsoon in Indonesia. Due to this monsoon transition, rainfall in Indonesia starts to decrease during MAM, as As-syakur et al. (2013) observed. Additionally, during DJF and MAM, sea surface temperatures in Indonesia tend to be warmer than average (Figure 3), further enhancing higher rainfall in Indonesia.

Seasonal variations in rainfall are also reflected in the patterns of convection. These patterns are represented by the values of vertical air motion (ω) (Figure 4). Negative values indicate upward air movement (updraft) that leads to the formation of rain clouds. In contrast, positive values indicate downward air movement (downdraft), resulting in clear weather in a particular area (Donald & Henson, 2015). Updraft is dominant during the DJF season, especially in December, occurring over the Indonesian region. This leads to high rainfall throughout Indonesia during that month. In January and February, downdraft occurs in western Indonesia, causing low rainfall in western Sumatra. The downdraft from the Indian Ocean gradually shifts towards eastern Indonesia during the MAM season (Figure 4), resulting in lower rainfall.

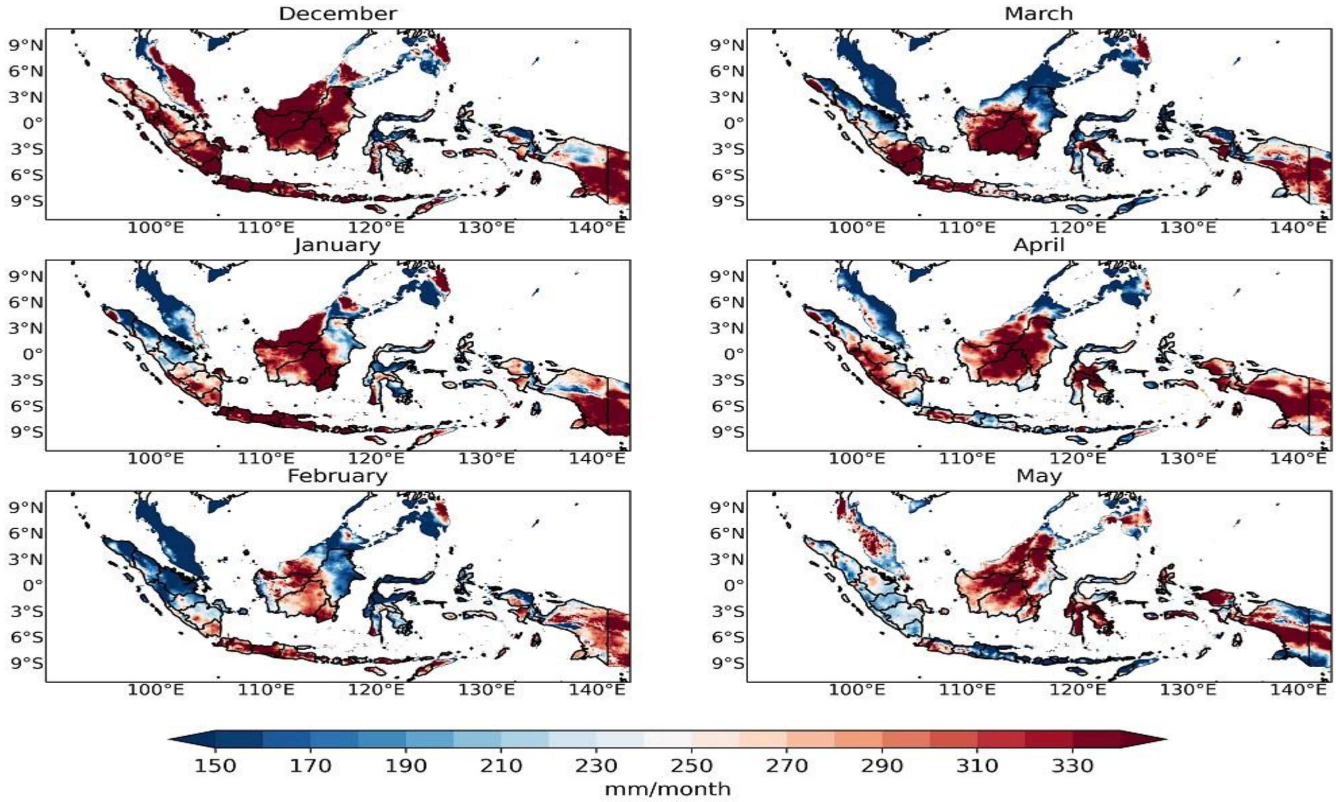

Figure 2. The average monthly rainfall during December-May

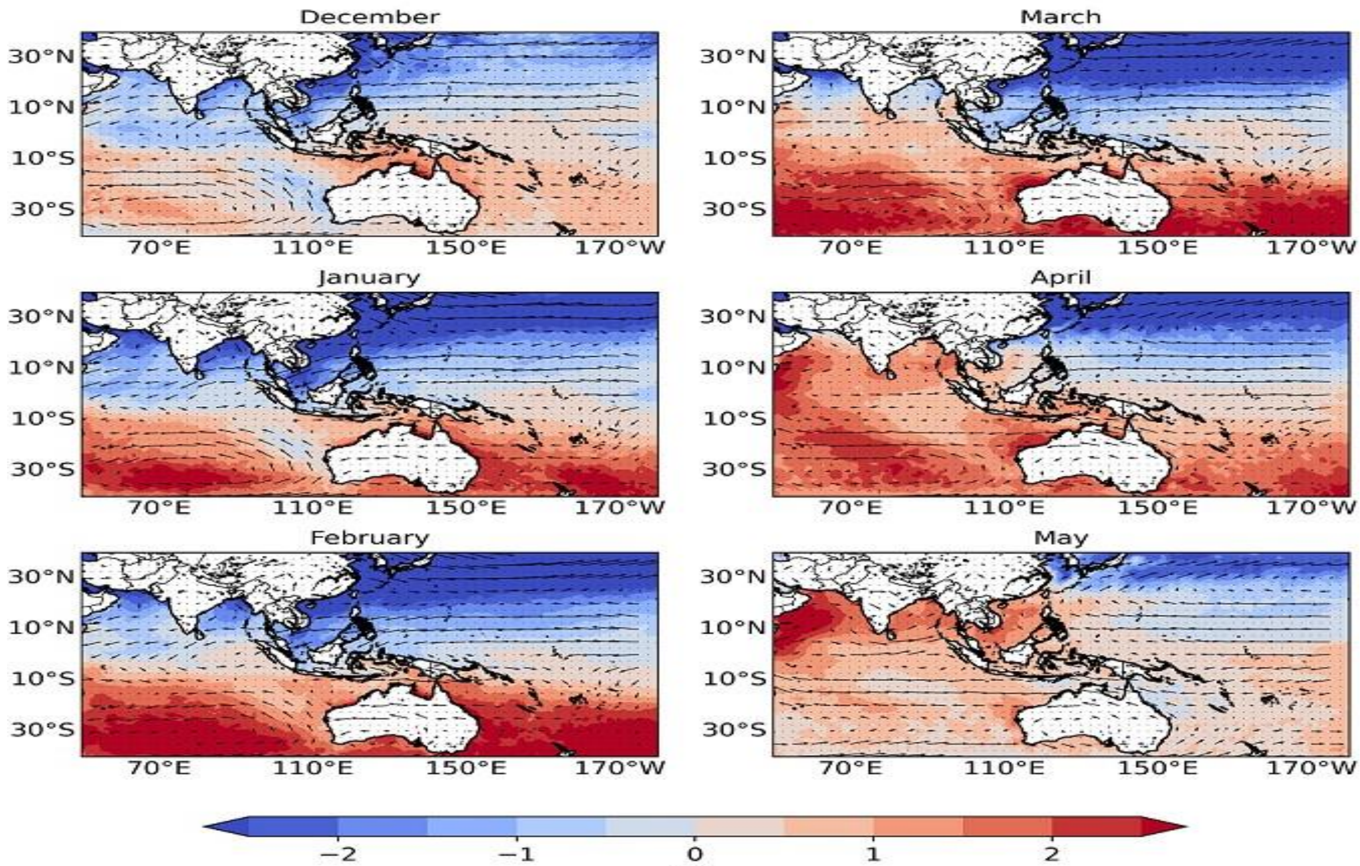

Figure 3. The average monthly sea surface temperature anomaly (background) and wind (quiver plot) during December-May

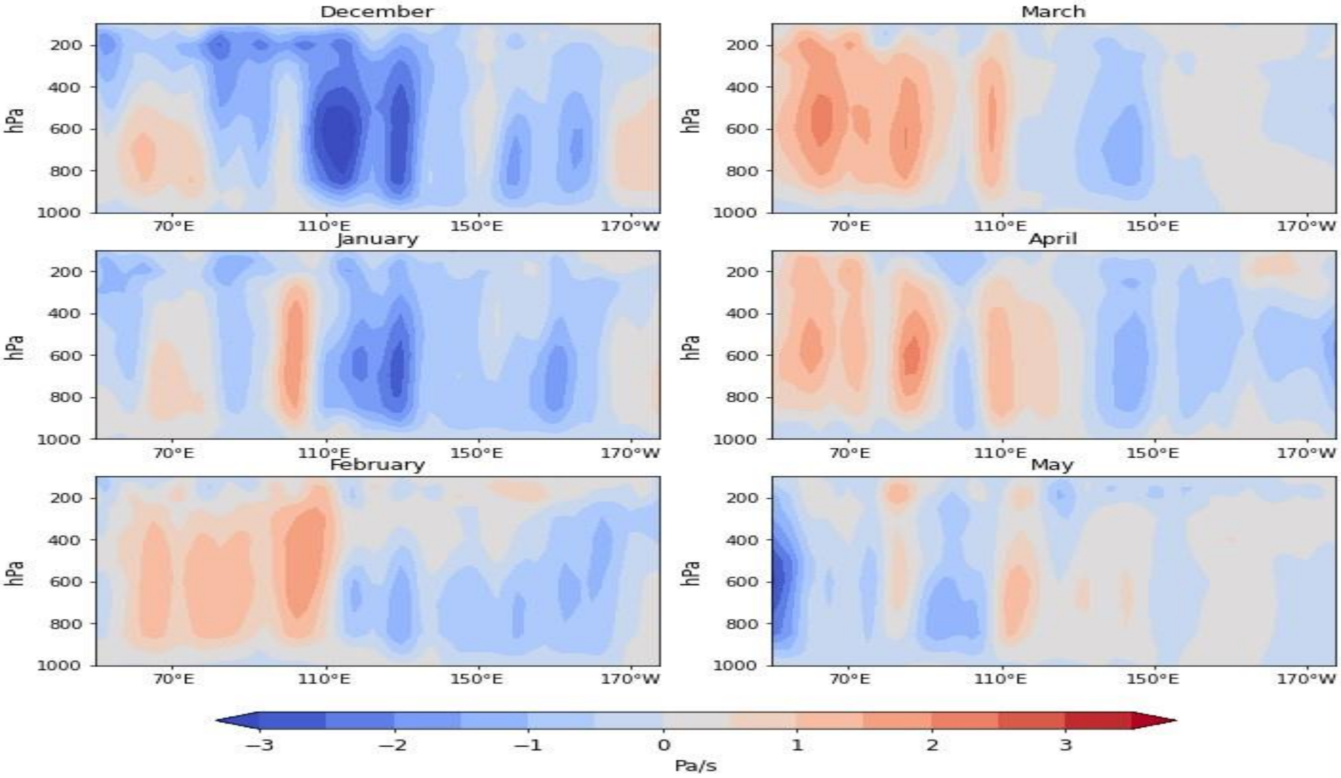

Figure 4. The average monthly vertical motion in the atmosphere during December-May

Rainfall during June –November

Figure 5 shows the monthly rainfall in Indonesia during the JJA (June-July-August) and SON (September-October-November) seasons. Both seasons tend to have below-average rainfall, as Hermawan & Lestari (2007) also found. Rainfall in Indonesia begins to decrease in June. Regions such as Sumatra, Java, and Nusa Tenggara experience low rainfall, below 150 mm/month, while parts of Kalimantan receive around 200 mm/month. However, other regions like Sulawesi, Maluku, and Papua still have high rainfall (>300 mm/month), as also observed by Aldrian & Susanto (2003). The decrease in rainfall peaked in July, as As-syakur et al. (2013) also found. Almost the entire region of Indonesia has rainfall of less than 150 mm/month. Only parts of Papua still experience high rainfall. In August, rainfall in Indonesia remains low but not as low as in July. Purwaningsih et al. (2020) also found similar results, where during the JJA season, rainfall throughout Indonesia is generally low except in the Maluku region and parts of Papua.

During SON, rainfall in Indonesia increases compared to the JJA season. In September, a small part of Sumatra, parts of Kalimantan, and parts of Papua start to experience high rainfall, but other regions still have low rainfall, less than 150 mm/month. In October, the entire region of Sumatra already experienced high rainfall (>330 mm/month). Other regions, such as western Java and western Kalimantan, also have high rainfall. Meanwhile, the eastern part of Indonesia still has low rainfall. Entering November, the western regions of Indonesia, including Sumatra, Java, and Kalimantan, have high rainfall, while the regions of Nusa Tenggara, Sulawesi, and Kalimantan receive around (170-190) mm/month. These findings are consistent with Mulyana (2002), in which high rainfall occurs in western Indonesia during SON while eastern Indonesia experiences low rainfall.

The presence of the Australian monsoon is evident during the JJA and SON periods (Figure 6), as previously observed in research (Hidayat & Ando, 2014). In JJA, the Australian monsoon strengthens, and easterly winds blow across most of Indonesia, except in Sumatra from West Sumatra to the island's northern tip. The easterly winds from Australia pass through Nusa Tenggara, Bali, Java, and the southern tip of Sumatra. Some winds turn north after crossing the equator in Kalimantan. The easterly winds over Irian and northern Sulawesi mainly come from the eastern Pacific Ocean, east of Papua New Guinea. The westerly winds from the Indian Ocean blowing over northern Sumatra are more pronounced than the MAM season. During the transition from the northern summer to winter (SON), the influence of the Australian monsoon on Indonesia gradually diminishes. The wind patterns in Indonesia do not undergo significant changes compared to JJA. Overall, the patterns remain essentially unchanged. However, wind speeds start to decrease, with the easterly winds blowing over Nusa Tenggara, Bali, Java, and the southern tip of

Sumatra, Irian, and Sulawesi and the westerly winds blowing over northern Sumatra. These monsoonal winds carry dry air to Indonesia, leading to reduced rainfall. The decline in rainfall during JJA and SON is also linked to sea surface temperatures, which are relatively lower than average during both seasons, contributing to the decrease in rainfall.

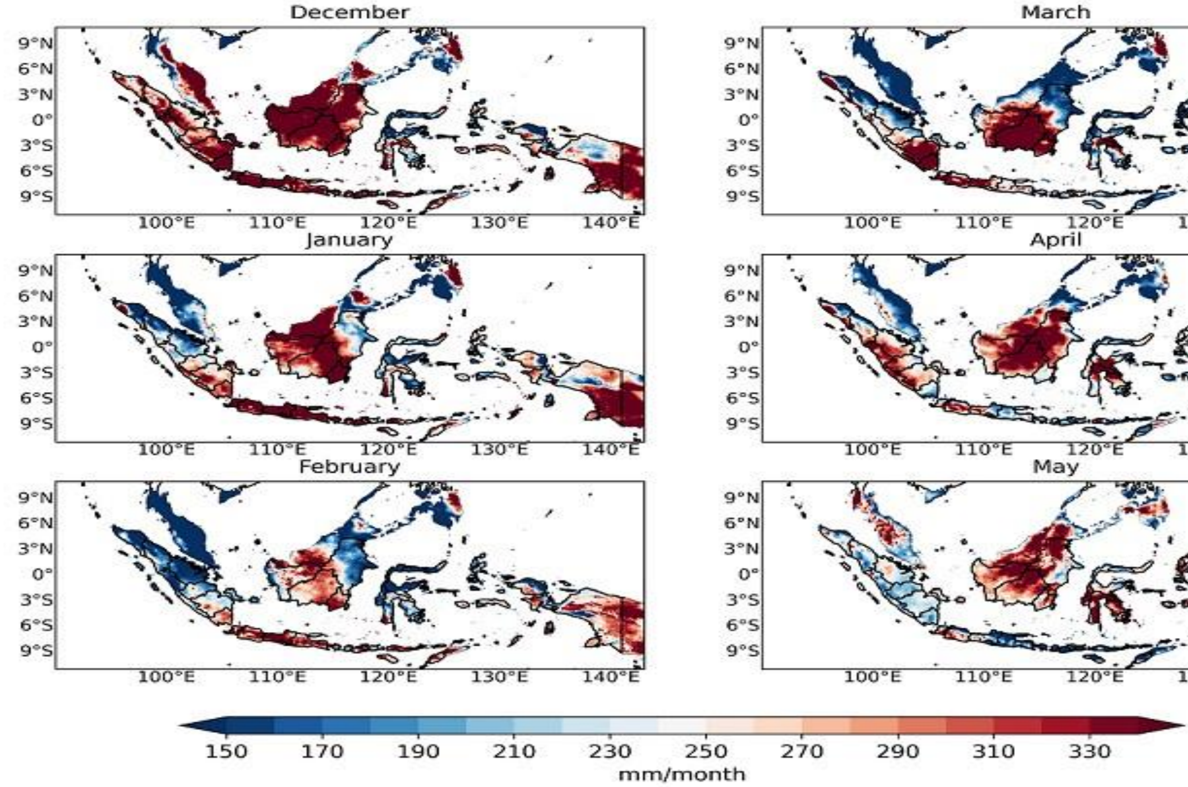

Figure 5. Same as figure 2, but for June-November

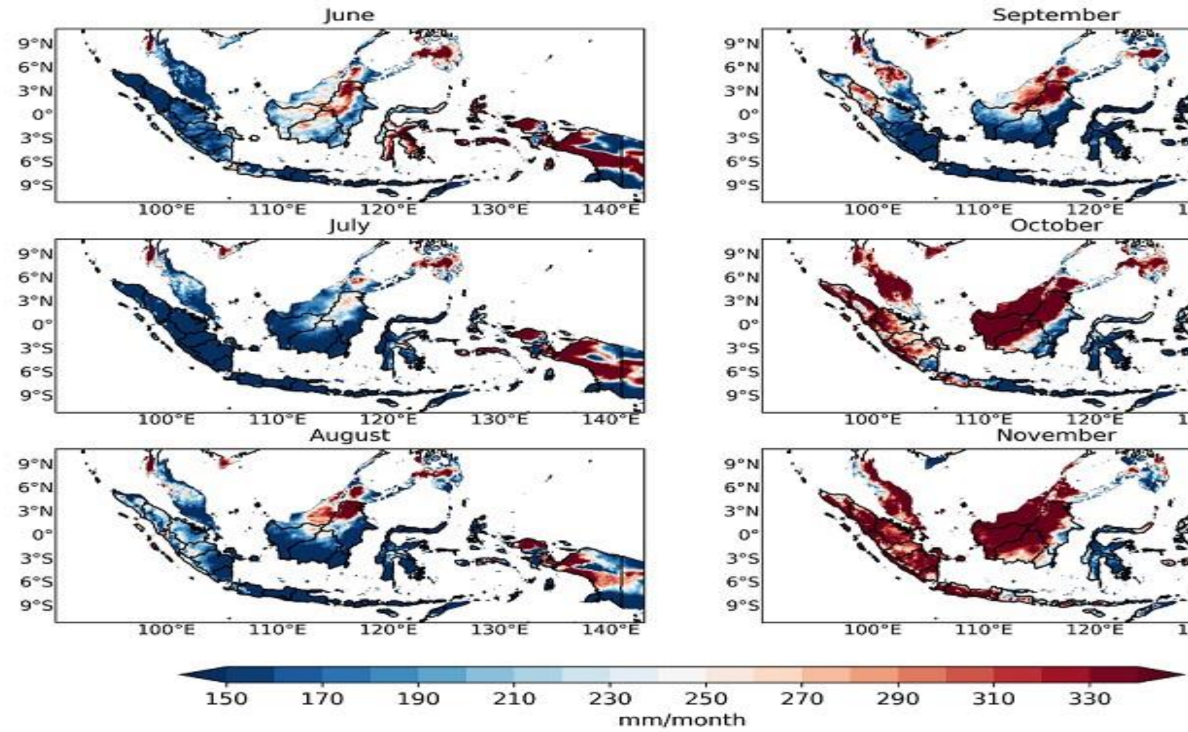

Figure 6. Same as figure 3, but for June-November

The convective patterns during JJA and SON can be observed in Figure 7. In June, there are downdrafts in the western part of Indonesia and updrafts in the eastern part. As a result, the eastern region experiences high rainfall, while the western region has low rainfall during June (Figure 5). In July and August, the downdrafts expand eastward, reducing rainfall across most of Indonesia. During the onset of the SON season, the updrafts from the Indian Ocean continue to shift towards Indonesia and peak in November, causing an increase in rainfall, particularly in the western regions (Figure 5).

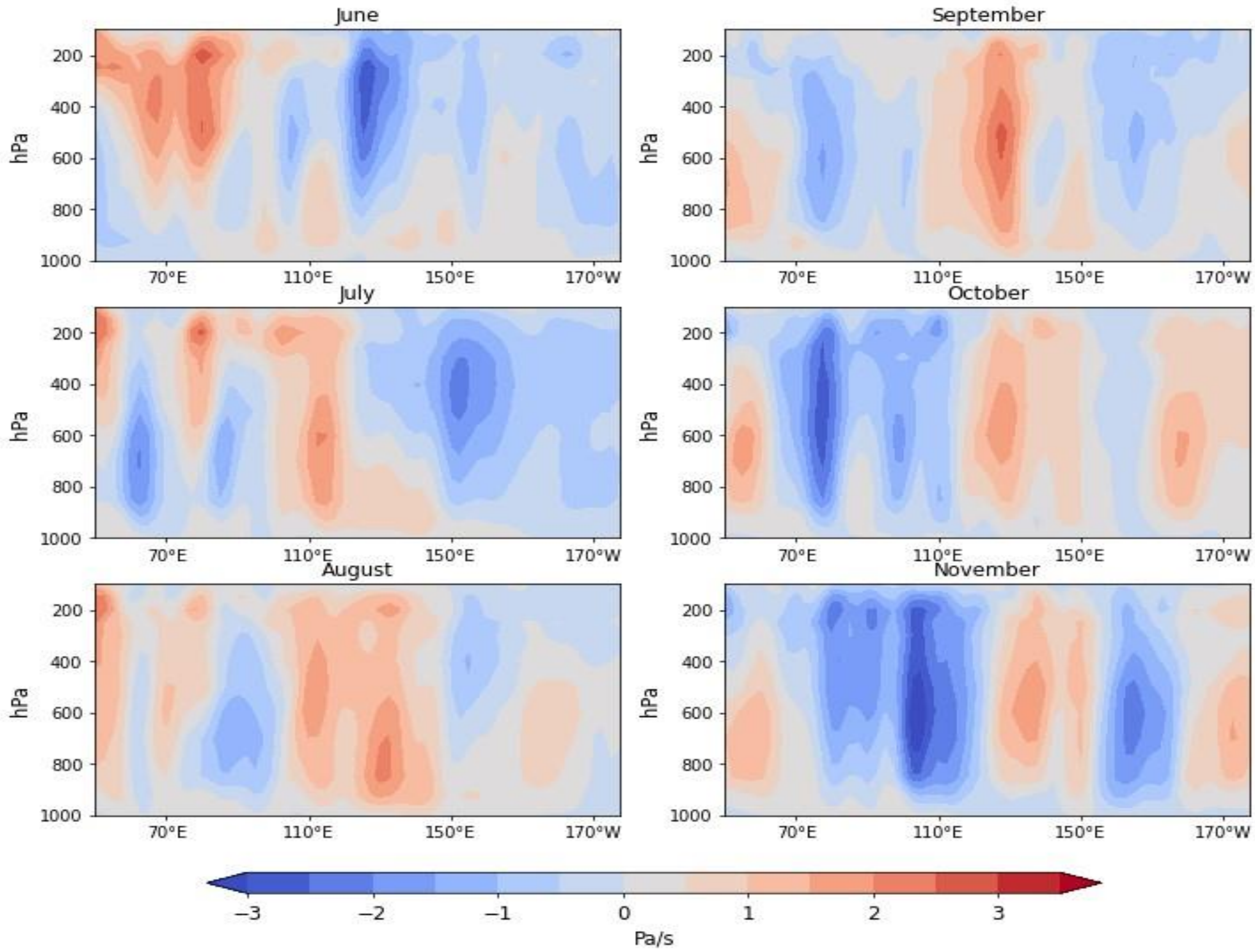

Figure 7. Same as figure 4, but for June-November

Rainfall Peak Period

Figure 8a shows the number of rainfall peaks in Indonesia. Most of the Indonesian region experiences two peaks of rainfall in a year. Regions with a single peak are observed in Java, Bali, Nusa Tenggara, and the southern part of Sumatra. The distribution of peak numbers is similar to Aldrian et al. (2003), who divided Indonesia into three distinct regions: Region A, Region B, and Region C. Region A, characterized by a single rainfall peak, includes Java, southern Sumatra, Timor Island, parts of Kalimantan, parts of Sulawesi, and parts of Papua. Region B, with two rainfall peaks, encompasses eastern Sumatra and eastern Kalimantan. Region C, with a single rainfall peak, covers the Maluku Islands and parts of Sulawesi. Although Region A and Region C have a single peak, they occur at different times.

Figure 8b displays the peak rainfall timing for regions with a single peak throughout the year. The dominant peak occurs during DJF (December-January-February). Some regions exhibit different peak timings, such as Sulawesi and Maluku, which have peaks during MAM (March-April-May), and parts of Papua, which have a peak during JJA (June-July-August). The first and second peak timings for regions with two peaks can be seen in Figures 8c and 8d. The dominant first peak is observed during SON (September-October-November), and some areas have peaks during MAM. The dominant second peak is observed during MAM, and some regions have peaks in November and December.

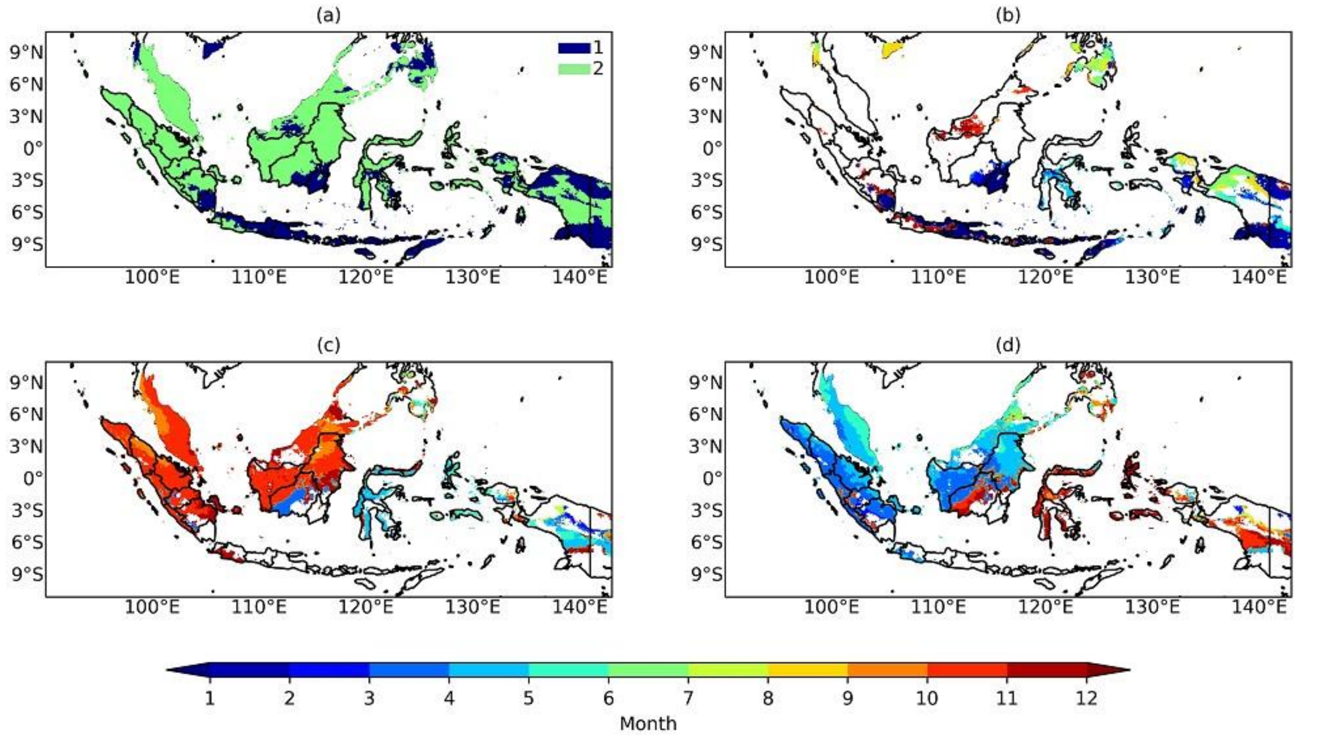

Figure 8. (a). The number of rainfall peaks throughout the year in Indonesia, (b). The timing of the peak when there is a single rainfall peak, (c). The timing of the first peak when there are two rainfall peaks, (d). The timing of the second peak when there are two rainfall peaks

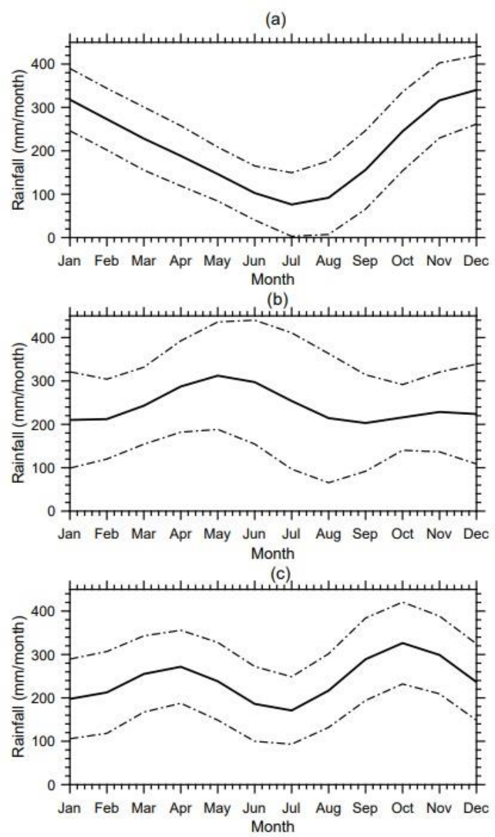

Figure 9. The annual cycles showing one (a, b) and two peaks (c) of rainfall in Indonesia. Dashed lines indicate one standard deviation (σ) above and below the average.

To better understand peak rainfall timing, monthly data is averaged for each grid with the same number of peaks (Figure 9). Regions with a single peak throughout the year exhibit two dominant peak timings: DJF (Figure 9a) and May-June (MJ) (Figure 9b). The regions with a single peak during DJF include Java, southern Sumatra, Timor Island, parts of Kalimantan, parts of Sulawesi, and parts of Papua (Figure 8b). These regions correspond to Zone A in the classification of Aldrian et al. (2003). Regarding the MJ peak, this study differs slightly from Aldrian et al. (2003), who identified a peak during June-July (JJ) in Region C, which includes the Maluku Islands and parts of Sulawesi. For regions with two peaks, the first peak (more dominant) is observed during SON, while the second peak, with a smaller amplitude, is observed during MAM. This finding aligns with Aldrian et al. (2003) and Yuda et al. (2021), categorizing regions with two peaks as Region B, which includes eastern Sumatra and eastern Kalimantan. However, the regions with two peaks in this study (Figures 8c and 8d) are broader than Region B in Aldrian et al. (2003).

Conclusion

Our findings underscore that the seasonal rainfall patterns in Indonesia, absent the influences of ENSO and IOD, align with previous comprehensive studies covering all *atmospheric* conditions. The normative occurrence of one or two rainfall peaks throughout the year in the Indonesian region, as established by Aldrian & Susanto (2003), remains consistent with our observations. Notably, our study highlights a subtle deviation in the timing of the May-June peak, diverging from Aldrian & Susanto (2003), encompassing the Maluku Islands and sections of Sulawesi. Our results affirm the insignificance of ENSO and IOD influences on the overall seasonal variation of rainfall, as supported by the congruence in peak rainfall during normal conditions with previous research inclusive of all data. While Hidayat et al. (2016) notes the potential impact of ENSO and IOD on the amplitude of seasonal variation in the eastern and western regions of Indonesia, our study emphasizes that these phenomena do not exert influence over the timing of rainfall peaks. Instead, the timing of these peaks emerges as a product of the combined effects of the Asian and Australian monsoons. In essence, this investigation contributes valuable insights into the nuanced intricacies of seasonal rainfall variation in Indonesia, shedding light on the intricate interplay between regional monsoons and emphasizing the limited role played by ENSO and IOD in determining the temporal dynamics of rainfall peaks.

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Author Contributions
Conceptualization, A.Z.A.Z., M.V and M.M.; methodology, A.Z.A.Z, M.V and M.M; software, A.Z.A.Z.; validation, M.M; formal analysis, A.Z.A.Z and M.M.; investigation, A.Z.A.Z; resources, A.Z.A.Z; data curation, M.V. and M.M; writing—original draft preparation, A.Z.A.Z.; writing—review and editing, A.Z.A.Z, M.V and M.M; visualization, A.Z.A.Z.; supervision, M.V. and M.M; project administration, A.Z.A.Z and M.V; funding acquisition, M.V. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest
The authors declare no conflict of interest.

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