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Rainfall Characteristics in Kalimantan Island During ENSO and IOD Phases: Insights from Composite Analysis

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ABSTRACT

This study aims to analyze the characteristics of rainfall in Kalimantan Island during the ENSO and IOD phases using composite method. This study uses ERA5 reanalysis data for the period 1985-2023. The analysis was carried out using Python in Jupyter Notebook Software to visualize rainfall patterns across four seasons (DJF, MAM, JJA, and SON). The results indicate that El Niño events reduce rainfall during the JJA season, with the largest deficit occurring in the southern region of Kalimantan, where rainfall drops to less than 5 mm per season. Conversely, Positive IOD conditions exacerbate drought, resulting in decreased rainfall in the southern and central parts of the island. The combined effects of El Niño and Positive IOD cause an even more significant decline in rainfall, with the dry season experiencing a substantial reduction compared to normal conditions. This study provides important insights for hydrometeorological risk mitigation in Kalimantan, highlighting the need for adaptive management in response to climate variability.

1. INTRODUCTION

Borneo is one of the largest islands in Indonesia, with significant ecosystem diversity, including tropical rainforests that serve as the lungs of the world (Mantili et al., 2022; Lesmana, 2022). The island's topography is highly varied, encompassing lowlands, mountains, and a vast network of rivers, contributing to complex rainfall patterns' dynamics (Mudiawati et al., 2023). Based on the results of research conducted by Nadzirah et al. (2020), Higher rainfall occurs in mountainous and highland areas compared to lowland and coastal areas. Major rivers, such as the Kapuas River and the Mahakam River, also play a role in rainfall distribution and hydrological dynamics in Kalimantan (Firmansyah et al., 2021).

Rainfall in Indonesia is influenced by various global and local climatological factors (Madani et al., 2012). One of the weather phenomena that affects rainfall conditions is ENSO (Ariska et al., 2022). El Niño Southern Oscillation (ENSO) is a phenomenon that occurs due to surface temperature differences in the Pacific Ocean region around the equator (Butona et al., 2023). ENSO consists of two phases, namely the hot phase when El Niño occurs and the cold phase when La Niña occurs (Ariska et al., 2022). The El Niño event can create more severe droughts, thereby increasing the risk of fires, especially in the territory of Indonesia (Bana et al., 2022).

Based on research conducted by Akhsan et al. (2023) Regarding the dynamics of extreme rainfall and its impact on forest and land fires on the East Coast of Sumatra, it shows that the variability of rainfall due to ENSO and IOD can also prolong the dry season and shorten the rainy season, which contributes to dry conditions that support the occurrence of forest and land fires. In addition, global climate variability such as ENSO and IOD is also known to significantly influence rainfall patterns in Indonesia, including in Kalimantan (Kurniadi et al., 2021).

In addition, research by Zahra (2023) highlighted that El Niño events caused a prolonged period of drought in Indonesia, including Kalimantan, which led to massive forest fires in 2015. These fires result in huge economic losses, and negatively impact the region's public health and air quality. The socio-economic impact of El Niño is also a major concern. Research by Rahma & Ludwig (2024) emphasizes the need for climate adaptation to increase farmers' capacity to deal with rice production uncertainty caused by climate change. Overall, these studies show that El Niño has a vast and complex impact on the island of Borneo, affecting environmental, social, and economic aspects.

Previous studies have examined the impact of ENSO and IOD separately; however, their combined effects on Kalimantan's rainfall remain understudied. This study aims to bridge this gap by analyzing the rainfall characteristics on the island of Borneo during the period 1985-2023, focusing on the ENSO and IOD phases. This research not only aims to provide new scientific insights but also offers a practical foundation for developing adaptation and mitigation strategies against climate change, especially on the island of Kalimantan. With a better understanding of the influence of these two climate phenomena, this study is expected to contribute to efforts to mitigate the risk of hydrometeorological disasters on the island of Kalimantan.

2. METHOD

The research method used is quantitative research using secondary data. The data used in this study is satellite-based total rainfall data sourced from the Climate Data Store (https://cds.climate.copernicus.eu/) website. The data is in the form of ERA5 data on total monthly rainfall on the island of Kalimantan for 38 years (1985-2023). Meanwhile, El-Niño data can be accessed on the https://psl.noaa.gov/gcos_wgsp/Timeseries/Data/nino34.long.anom.data website and then DMI (*Dipole Mode Index*) data can be taken from https://psl.noaa.gov/gcos_wgsp/Timeseries/Data/dmi.had.long.data sites during the period 1985-2023, to be calculated on average in December-January-February (DJF), March-April-May (MAM), June-July-August (JJA), and September-October-November (SON). We classified the occurrences of the ENSO and IOD events during the study period from January 1985 to December 2023 (Table 1).

Tabel 1. Years ENSO-IOD Composited

Climate Mode	**Years**
El Nino	1986, 1987, 1991, 1994, 1997, 2002, 2004, 2006, 2009, 2015, 2019, 2023
La Nina	1988, 1995, 1998, 2000, 2005, 2007, 2008, 2010, 2011, 2012, 2016, 2017, 2018, 2020, 2021, 2022
Positive IOD	1987, 1991, 1994, 1997, 2002, 2003, 2006, 2008, 2011, 2012, 2015, 2019, 2023
Negative IOD	1989, 1992, 1996, 1998, 2010, 2014, 2016, 2022

The classification of ENSO and IOD years in table 1, we also verified based on research Suhadi et al. (2024). In addition, if a Nino index of 3.4 that passes or falls below 1 std occurs in at least 5 consecutive months, it is identified as ENSO (McGregor & Ebi, 2018). Likewise with IOD, if a DMI that passes or is less than 1 std occurs at least in 3 consecutive months, it is identified as IOD (Handoko et al., 2024).

Furthermore, the analysis was carried out using a composite method to explore the impact of ENSO on rainfall in various regions of the world. This approach is in line with Alizadeh & Mousavizadeh. (2025) which examined the influence of ENSO on extreme rainfall in Southwest Asia. The study used a composite analysis method, to investigate the impact of El Niño and La Niña on rainfall. The main advantage of the composite method is its ability to combine information from various data sources, such as satellite observations and climate models, thus providing a more accurate picture of precipitation patterns (Millenia et al., 2023). The data that has been synthesized is then calculated using the composite formula as follows:

$$\bar{X} = \frac{1}{n}\sum_{i=1}^{n} xi \tag{2.1}$$

With xi declares rainfall in the i month of the ENSO-IOD period.

3. RESULTS AND DISCUSSION

3.1 Rainfall in the Normal Phase

Most of Kalimantan in the DJF season, experienced moderate to high rainfall, which was reflected from green to light blue with rainfall values of around 9.51 to 12.42 mm/season (Figure 3.1). The highest rainfall intensity was recorded in the northern and northeastern parts of Kalimantan, which are characterized by a dark blue color, with rainfall approaching or exceeding 13.87 mm/season. This indicates that the DJF season is a period of heavy rainfall in Kalimantan, especially in the northern region. This finding aligns with research by As-syakur et al. (2014), which confirms that during the DJF period, rainfall in Indonesia, including Kalimantan, tends to increase in response to vigorous monsoon activity.

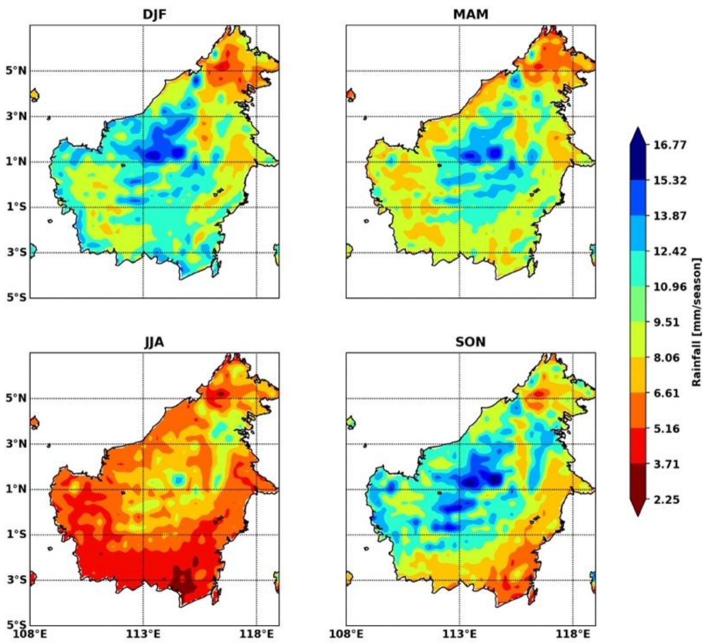

Figure 3.1 Average Rainfall When Normal. The color gradation shows the average rainfall of each season during the occurrence of Normal.

Although the rainfall pattern is still similar to the DJF in the MAM phase, there is a slight decrease in rainfall intensity, especially in the southern region of Kalimantan. The area is depicted in yellow and light green, which indicates rainfall between 8.06 and 10.96 mm/season. In the north, rainfall is still moderate, indicating that despite the decline, Kalimantan experienced rainfall during this period.

The JJA phase shows a very different pattern, with very low rainfall in most parts of Kalimantan, especially in the south and central. It is depicted in red to orange, indicating rainfall values between 2.25

and 6.61 mm/season. Although wetter, the northern region of Kalimantan, still experienced a decrease in rain intensity, making the JJA season the driest period in Kalimantan.

In the SON phase, rainfall began to increase again, especially in the central and northern parts of Kalimantan, which was reflected in blue to green colors, indicating rainfall between 8.06 to 13.87 mm/season. An increase in rainfall also occurred in the southern part, although it was still in a lower range compared to the northern region.

From this pattern, it can be concluded that Kalimantan shows a pattern of rainfall that varies in each season. The rainy season occurs in the DJF and SON periods, especially in the northern part of the island, while the most intense dry season occurs in the JJA period, especially in the southern part. This characteristic of rainfall provides important information related to Kalimantan's seasonal climate, which can be used as a basis for water resource management policies and natural disaster risk mitigation such as floods, according to the season. This analysis reveals that rainfall patterns in Kalimantan tend to follow the monsoon cycle, with more intense rains at the end and beginning of the year (DJF and SON) and drier droughts in the middle of the year (JJA).

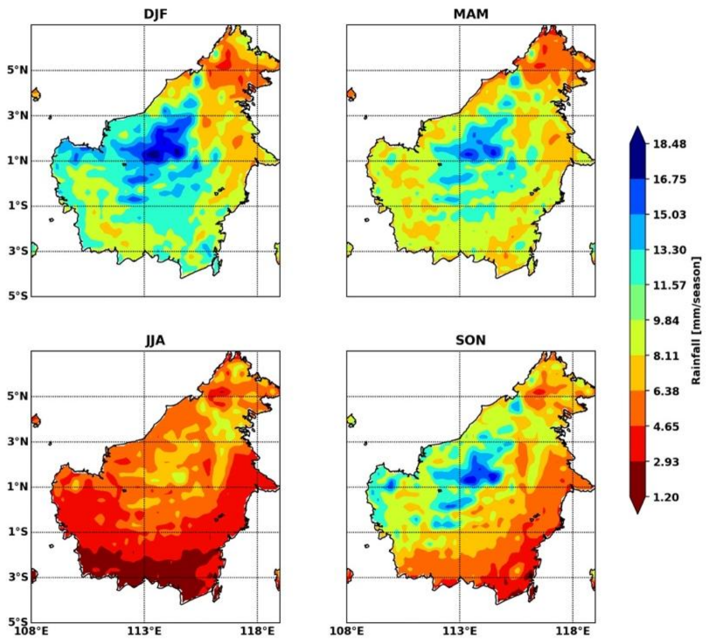

Figure 3.2 Average Rainfall During El Niño. The color gradation shows the average rainfall of each season during the occurrence of El Nino.

3.2 Rainfall in El-Niño Phase

Figure 3.2 illustrates the average rainfall distribution over Kalimantan during El Niño phases for the four seasons: DJF (December-January-February), MAM (March-April-May), JJA (June-July-August), and SON (September-October-November) in the El Niño phase. The results show that during the El Nino phase there is a significant decrease in rainfall in most parts of Kalimantan, with the worst impact in South Kalimantan. This is supported by a study by Putri et al. (2024) which showed that rainfall in West Kalimantan in 1985-2022 was higher than in the South Kalimantan regions. In the JJA season, South Kalimantan experiences an extreme rainfall deficit, with an accumulation of less than 5 mm of rainfall per season, much lower than usual. This decline is due to the weakening of Walker's circulation, which reduces the transport of water vapor from the Pacific Ocean to the territory of Indonesia. This impact is in line with previous El Niño events, such as research conducted by Ihwan et al., (2019) which confirmed that the extent and severity of drought tend to increase during El Niño events, with the impact visible in 2015, which was the year with a strong El Niño (Ihwan et al., 2019).

When entering the MAM season, a decrease in rainfall began to be seen in almost all regions of Kalimantan. However, the spatial pattern remains consistent, where the northern region still receives higher rainfall than the southern region. The decrease in intensity that is more pronounced in the southern region is an early indication of the influence of El Niño that is getting stronger this season.

The impact of El Niño reaches its peak during the JJA season, which is characterized by the most extreme decrease in rainfall throughout the Kalimantan region. Almost all areas, including North Kalimantan, which was previously wet, experienced a decrease to rainfall intensity of less than 5 mm per season. This decrease is equivalent to a decrease in rainfall of about 59% compared to the normal conditions average of 11 mm per season. This creates a very dry situation and highlights the peak of El Niño's impact during the dry season. At this stage, spatial variation is almost imperceptible as almost the entire region experiences severe drought. The impact of El-Niño and IOD in the month of JJA is not only felt on the island of Kalimantan, research conducted by Suhadi et al., (2023) obtained results that the impact of El-Niño is also felt in the northern Sumatra region and affects rainfall.

The SON season saw a slight recovery in rainfall, but the southern region still experienced drier conditions than the climatological average. This suggests that the El Niño effect may persist longer in some regions. Overall, the El Niño phase contributed to a more prolonged and more intense dry season, increasing the risk of hydrometeorological drought in Kalimantan.

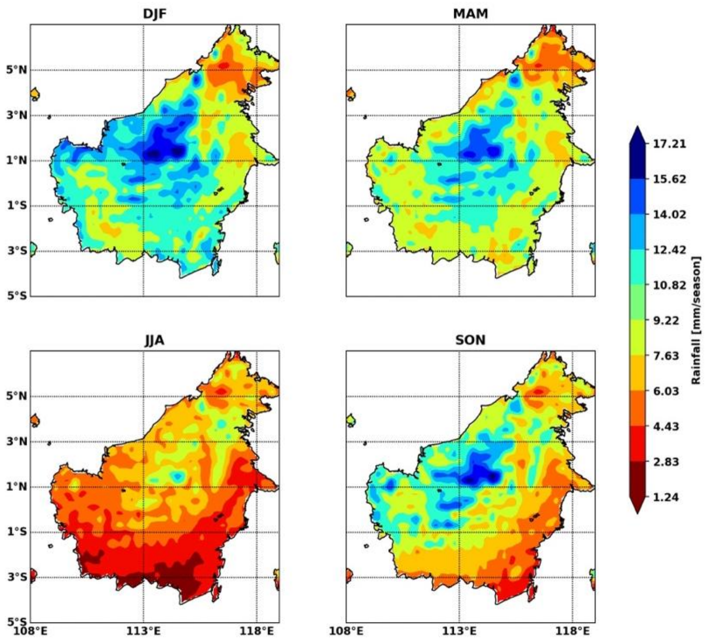

Figure 3.3 Average Rainfall When IOD is Positive. The color gradation shows the average rainfall of each season during the occurrence of Positive IOD.

3.3 Rainfall in the Positive IOD Phase

During the Positive IOD phase, rainfall in central and southern Kalimantan experienced a marked decrease compared to the northern regions (Figure 3.3). Overall, during the Positive IOD phase, the variation in rainfall in Borneo showed apparent spatial and temporal differences. The southern and central regions are more prone to drought, especially in the dry season (JJA), while the northern regions tend to be more stable. However, they continue to experience a decrease in rainfall in the same period. The positive IOD impact exacerbated drought in the southern and central regions, showing how global climate phenomena can affect rainfall patterns in Kalimantan.

When entering the MAM season, rainfall is still relatively high in the northern region and parts of central Kalimantan. However, compared to the DJF, its intensity began to decline. Nonetheless, rainfall remained relatively evenly distributed, indicating that in this first transitional season, the effect of Positive IOD has not been significant in reducing rainfall.

During the JJA season, rainfall in almost all areas of Kalimantan decreases drastically. The southern and central regions recorded very low rainfall intensity less than 5 mm per season. Meanwhile, the northern region still receives little rainfall, but the amount is much smaller than in previous seasons. This sharp decline reflects that the Positive IOD phase strengthens drought conditions, especially in the southern and central regions, which become particularly vulnerable to water deficits in the dry season.

In the SON season, rainfall in the north increase, but the central and southern regions remain drier than in normal years. The decrease in rainfall during the Positive IOD is related to sea surface temperature (SST) anomalies in the western Indian Ocean, which disrupted monsoon wind patterns and increased atmospheric subsidence over Indonesia. As a result, convective cloud formation processes are reduced, leading to rainfall deficits.

This is in line with research conducted by Sulaiman et al. (2023) which revealed that during a significant positive IOD event, there can be a decrease in rainfall and a decrease in groundwater levels, potentially increasing the risk of forest fires in Kalimantan. Another study by Nurdiati et al. (2022) revealed that positive IOD can affect atmospheric circulation patterns that support increased rainfall. However, the impact is not as strong as in the Sumatra region. This suggests that while positive IODs can increase rainfall, their impact on wildfires still requires attention, especially in the context of broader climate change. Overall, a better understanding of the interaction between the positive phase of IOD and certain seasons in Kalimantan is essential for natural resource management and forest fire risk mitigation.

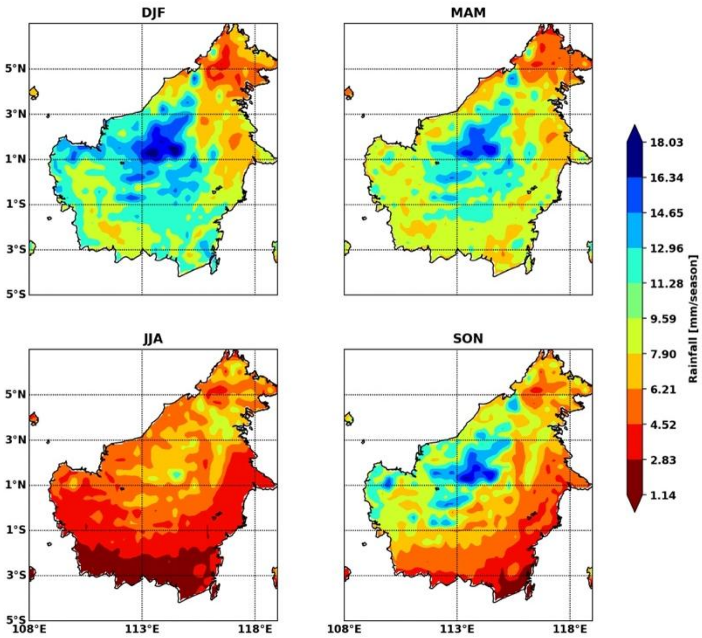

Figure 3.4 Average Rainfall During El Niño When IOD Positive. The color gradation shows the average rainfall of each season during the occurrence of El Niño When Positive IOD.

3.4 Rainfall in the El-Niño phase during the occurrence of Positive IOD

In the DJF season, the northern region of Kalimantan Island recorded higher rainfall compared to the southern region (Figure 3.4). The area around latitudes 2°N to 5°N shows the highest accumulated rainfall, as indicated by the dark blue color, which indicates that the region is relatively wetter this season. This pattern is likely influenced by the active monsoon pattern in the northern hemisphere, which brings more water vapor to the northern region of Kalimantan. In contrast, the southern part shows lower rainfall, reflected from yellow to green on the rainfall map.

Continuing to the MAM season, there was a slight decrease in rainfall intensity in most areas of Kalimantan compared to the DJF. The central area of Kalimantan, especially around latitudes of 1°S to

1°N, is starting to show lower rainfall (marked in green and yellow). This indicates that this season's transition brings significant changes, with the central region becoming drier than the climatological average, although the northern part still maintains a relatively higher rainfall intensity than the southern region.

The JJA season has the highest rainfall deficit, especially in southern Kalimantan, where there is almost no rain (<5 mm of rainfall per season). These longer, more intense droughts are due to a combination of the weakening of the Pacific Ocean due to El Nino and the increased atmospheric decline due to Positive IOD, which hamper cloud formation over Indonesia..

Entering the SON season, several areas began to show signs of increased rainfall, especially in the northern part and a small part of central Kalimantan. This is illustrated by the appearance of yellow and green colors on the map, indicating a transition to the rainy season. Although rainfall has not yet returned to the level it was in the DJF season, an increase in humidity is beginning to be seen, especially in the northern part. On the other hand, the southern part remains in dry conditions, with low rainfall as indicated by the red color on the map.

The impact of this phenomenon not only causes a significant decrease in rainfall, but also prolongs the duration of the dry season, which increases the risk of hydrometeorological disasters, such as prolonged droughts and forest fires. This was seen during the 2015/2016 El Niño phenomenon; rainfall in some parts of Indonesia, including Kalimantan, experienced a significant decrease, which was attributed to rainfall anomalies caused by the interaction between El-Niño and IOD (Avia & Sofiati, 2018). This study supports the findings of Irfan et al. (2024), who stated that the El Niño and IOD+ phenomena trigger extreme dry seasons, such as significant fires in South Sumatra in 2006, 2015, and 2019. For example, the drought caused by IOD+ in 2019, made peatlands very dry and flammable. These findings confirm that the pattern of declining rainfall due to El Niño and IOD+ has a similar impact on the Kalimantan region, especially on the increased risk of drought and forest fires.

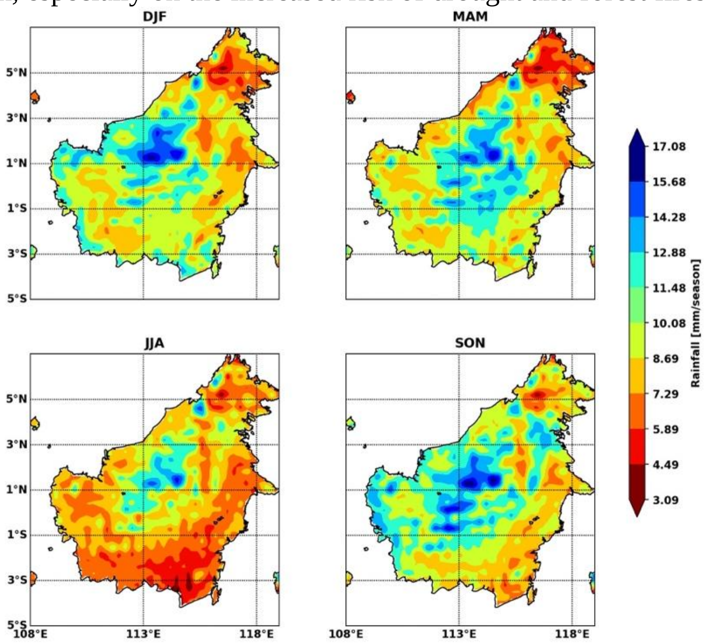

Figure 3.5 Average Rainfall During La Niña. The color gradation shows the average rainfall of each season during the occurrence of La Nina.

Overall, the variation in rainfall on the island of Borneo shows clear spatial differences between the northern and southern regions. During the El Niño and Positive IOD phases, the most reduction in rainfall occurs during the dry season (JJA), with almost the entire region of Kalimantan experiencing severe drought. In contrast, the northern region exhibits wetter characteristics in the rainy season (DJF), signaling the role of global climate dynamics in influencing seasonal rainfall patterns. The interaction between El Niño and positive IODs can result in more extreme rainfall events. Xiao et al. (2022) showed that the event of El Niño concurrently with positive IOD tended to be more substantial compared to the incidence of El Niño without IOD.

3.5 Rainfall in the La Niña Phase

Figure 3.5 shows that during the La Niña phase, most of Kalimantan experienced an increase in rainfall, especially in the DJF and MAM seasons. Kalimantan's northern and central parts show higher rainfall than normal conditions, while the southern region still experiences a more limited increase. In the DJF season, rainfall in northern Kalimantan can reach more than 16 mm per season, suggesting that La Niña contributes to increased humidity in this region.

The La Niña phenomenon occurs when sea surface temperatures (SSTs) in the central and eastern Pacific Ocean are lower than average, which strengthens the Walker circulation and increases convection over Indonesia. As a result, water vapor transport from the Pacific Ocean to the Kalimantan region increases, resulting in higher rainfall. The La Niña phenomenon occurs when sea surface temperatures (SSTs) in the central and eastern Pacific Ocean are lower than average, strengthening the Walker circulation and increasing convection over Indonesia. As a result, water vapor transportation from the Pacific Ocean to the Kalimantan region has increased, resulting in higher rainfall. Research by Pradiko et al. (2016) shows that rainfall increases significantly during the La Niña period, which can lead to extreme flooding in regions of Indonesia, including Kalimantan. Another study by Wulandari et al. also noted that atmospheric conditions triggered by La Niña can cause very high rainfall, potentially causing catastrophic flooding in certain areas (Wulandari et al., 2018)

In the JJA season, although Kalimantan still experiences the dry season, the northern region still receives higher rainfall than in normal years. This indicates that La Niña can reduce the intensity of the dry season in Kalimantan, especially in the northern region. During the SON season, rainfall increased again, marking the beginning of the rainy season.

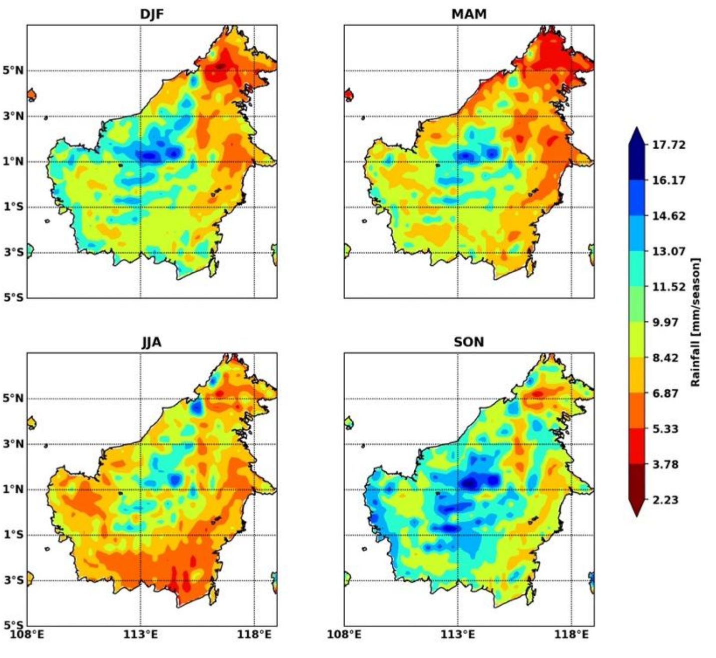

Figure 3.6 Average Rainfall When IOD is Negative. The color gradation shows the average rainfall of each season during the occurrence of Negative IOD.

Overall, the La Niña phenomenon influences rainfall patterns in Kalimantan, especially in the northern region and parts of the central region. The impact is evident in the DJF season with a increase in rainfall, as well as the extension of the rainy season to SON in the northern region. La Niña's impact must be watched as it can increase the risk of hydrometeorological disasters such as floods and landslides, especially in areas with hilly topography and large watersheds. In addition, an excessive increase in rainfall can lead to soil saturation that risks erosion and ecosystem damage.

3.6 Rainfall in the Negative IOD Phase

Figure 3.6 shows that during the Negative IOD phase, most areas of Kalimantan experienced increased rainfall, with higher intensity occurring during the DJF and SON seasons. During this phase, Kalimantan's central and northern regions showed higher rainfall than normal conditions, while the southern regions experienced a more moderate increase. Negative IOD is characterized by an increase in sea surface temperature (SST) in the eastern Indian Ocean, strengthening convection and bringing more water vapor to Indonesia. As a result, rainfall is increasing, especially in areas closer to moisture sources in the Indian Ocean. In the DJF season, the increase in rainfall reaches more than 15 mm per season in the northern region of Kalimantan, which shows the strong influence of Negative IOD on rainfall patterns in these areas.

In the JJA season, although Kalimantan is still in the dry season period, the impact of Negative IOD can reduce the intensity of drought, especially in the central and northern regions. This pattern is similar to what occurred during La Niña, where greater water vapor transport from the Indian Ocean helped maintain higher levels of rainfall than normal conditions. Negative IODs are often associated with increased rainfall in Indonesia, including Kalimantan, which can exacerbate flood risk and other negative impacts on agriculture (Yuggotomo & Ihwan, 2014; Putra et al., 2020).

Subsequently, rainfall began to increase across Kalimantan during the SON season, marking the transition to the wet season. The central and southern regions that previously experienced drier conditions began to show an increase in rainfall intensity. This can be seen from the dominance of blue to green colors, indicating that the negative impact of the IOD strengthens rainfall patterns in the central and northern regions, while replenishing groundwater reserves before the rainy season arrives.

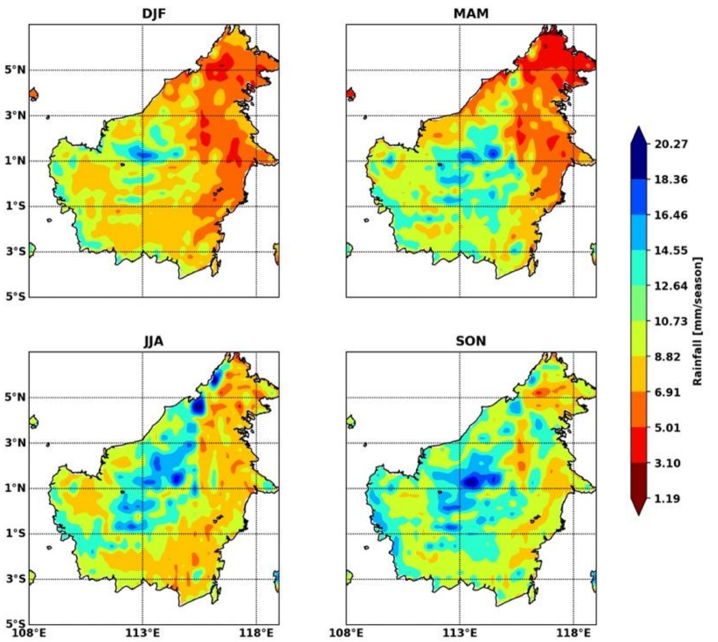

Figure 3.7 Average Rainfall During La Niña When Negative IOD Occurs. The color gradation shows the average rainfall of each season during the occurrence of La Niña When Negative IOD Occurs.

However, while this increase in rainfall reduces the risk of drought, excess rainfall can also trigger floods and landslides, especially in areas with steep slopes and limited drainage systems. Therefore, the impact of Negative IOD must be considered in the planning of hydrometeorological disaster mitigation in Kalimantan.

3.7 Rainfall in the La-Niña phase during the occurrence of Negative IOD

Figure 3.7 shows that when La Niña and Negative IOD occur simultaneously, the rainfall increase in Kalimantan becomes more extreme than when each phenomenon occurs separately.During the DJF and SON seasons, most areas of Borneo experienced much higher rainfall than normal conditions, with the northern region receiving the highest intensity.

The combination of Walker's circulation strengthening due to La Niña and the increase in convection due to Negative IOD created very wet conditions in most parts of Indonesia, including Kalimantan.. Meanwhile, the central and southern regions show lower rainfall, characterized by yellow to orange colors, although it remains wetter than normal conditions without the influence of La Niña and negative IOD. During the DJF season, rainfall in some northern regions can reach more than 18 mm per season, which is much higher than in normal years.

In the JJA season, although Kalimantan experiences a dry season, the remaining rainfall is still higher than in normal years. This suggests that the combination of La Niña and Negative IOD can reduce the intensity of the dry season, potentially benefiting the agricultural sector and the availability of water resources.

However, the negative impact of this combination must also be considered. Excessive increases in rainfall can cause major flooding, especially in areas that already have high levels of rainfall under normal conditions. Rainfall variability affected by La Niña and negative IODs is related to broader climate change. Research in West Kalimantan shows that variations in rainfall due to climate change can affect agricultural productivity, especially paddy rice, which is highly dependent on water availability (Aditya et al., 2021; Mareta et al., 2020). In addition, the impact of this phenomenon is also seen in the context of forest and land fires, where high rainfall can reduce the risk of fires, but can also cause destructive flooding (Rahayu et al., 2023).

Overall, the La Niña and IOD phenomena negatively affect rainfall patterns on the island of Borneo. In the DJF and SON phases, rainfall tends to be higher in the northern and northeastern regions, with more even intensity throughout the year. Meanwhile, the southern region experiences lower rainfall intensity. In this context, it is important to understand the interaction between these two phenomena predict and manage their impacts on society and the environment in Kalimantan.

4. CONCLUSION

This study identified the rainfall characteristics on Kalimantan Island during the 1985–2023, influenced by ENSO and IOD phenomena. The El Niño phase significantly reduced rainfall, particularly during the dry season (JJA), with the largest deficit observed in southern Kalimantan. This condition increases the drought risk, adversely impacting agriculture, water resources, and ecosystems. Conversely, the La Niña phase increased rainfall, particularly during the rainy season (DJF) in northern and central regions, although southern Kalimantan continued to receive less rainfall. Positive IOD exacerbated drought in southern and central regions, while Negative IOD increased rainfall, particularly during the rainy season, raising the risk of flooding in some areas. The interaction of El Niño and Positive IOD worsened drought conditions, with a more pronounced decline in rainfall and a prolonged dry season. In contrast, the combination of La Niña and Negative IOD led to extreme rainfall increases in northern and central regions, particularly during the rainy season, although this heightened the risk of flooding and landslides. During the normal ENSO-IOD phase, rainfall patterns remained relatively stable with moderate intensity, but southern Kalimantan continued to receive less rainfall than other regions.

These findings highlight the need for improved drought monitoring and forest fire mitigation strategies in Kalimantan, particularly during concurrent El Niño and Positive IOD events. Evidence-based adaptation policies are crucial to enhance the region's resilience to global climate variability. Governments should develop better early warning systems for ENSO and IOD detection and integrate these into disaster risk mitigation policies. An inclusive approach involving governments, the private sector, and communities is essential for sustainable water resource management, reducing drought impacts, and preventing forest fires. Strengthening adaptation policies and long-term planning considering climate variability's impacts on rainfall patterns is vital to support sustainable development in Kalimantan.

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