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Impact of different ENSO positions and Indian Ocean Dipole events on Indonesian rainfall

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ABSTRACT

The El Niño Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) are widely recognized as the leading modes of climate variability in the tropics. This paper investigates the impact of different ENSO positions and IOD events on Indonesian rainfall during the period 1950–2021. The ENSO position is determined by the largest value of four Niño indices: Niño 1+2, Niño 3, Niño 3.4, and Niño 4. These ENSO positions are hereafter referred to as El-Niño/La-Niña 1+2, El-Niño/La-Niña 3, El-Niño/La-Niña 3.4, and El-Niño/La-Niña 4, respectively. The Dipole Mode Index (DMI) was used to observe IOD events. Different ENSO positions and IOD events result in different responses to Indonesian rainfall, obtained from the European Center for Medium-Range Weather Forecasts (ECMWF) ERA-5 data. The most significant decrease in rainfall occurs during the June-to-Septempber (JJAS) season of El-Niño 3. Conversely, during El-Niño 3.4, rainfall increases in the Sumatra and part of Kalimantan regions. The most significant increase in rainfall occurs during La-Niña 3.4, followed by La-Niña 4, La-Niña 3, and La-Niña 1+2. During a positive IOD phase, the southern part of western Indonesia experiences a decrease in precipitation of more than 30%. A more significant decrease in rainfall (>40%) occurs when a positive IOD co-occurs with El-Niño. During a negative IOD phase, Indonesia's rainfall patterns become more spatially variable. An increase in rainfall is more pronounced when a negative IOD co-occurs with La-Niña. The difference in Indonesian rainfall during different ENSO positions and IOD phases is related to differences in atmosphere-ocean interaction during each condition.

Keyword: ENSO Position, Indian Ocean Dipole, Indonesian rainfall.

1. Introduction

The El Niño Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) are atmospheric-ocean interaction phenomena that significantly affect global precipitation (Xu et al., 2016). Both phenomena occur in the Pacific and the Indian Oceans, which surround the Indonesian region. The ENSO consists of El-Niño and La-Niña phases, while the IOD consists of positive and negative IOD phases. ENSO and IOD are characterized by sea surface temperature (SST) anomalies that affect evaporation and air moisture in Indonesia. The El-Niño phase is characterized

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by increased SST in the Pacific Ocean. In contrast, La-Niña is characterized by decreased SST in this region. The ENSO phenomenon has a greater influence at mid-latitudes, such as Indonesia than at high latitudes (Minh et al., 2022). Positive IOD occurs when the SST in the western Indian Ocean is warmer than in the eastern part. At the same time, negative IOD occurs when the SST is colder in the western Indian Ocean and warmer in the eastern Indian Ocean (Vinayachandran et al., 2009).

Many studies have shown the impact of ENSO and IOD on Indonesian rainfall. Lestari et al. (2018) found that rainfall tends to decrease during El-Niño and positive IOD, while rainfall increases during La-Niña and negative IOD. The influence of ENSO and IOD on extreme rainfall is strongest during the dry season (JJA-SON) and weaker during the wet season (DJF-MAM) (As-syakur et al., 2014). Extreme rainfall throughout Indonesia is largely influenced by ENSO, with the atmosphere becomes drier (wetter) during El-Niño (La-Niña). IOD's positive (negative) phase also causes more extreme dry (wet) conditions. ENSO and IOD often occur together, with the dominant impact still influenced by one or the other. ENSO without IOD has a greater effects on extreme rainfall in northern and eastern Indonesia, while IOD without ENSO modulates extreme rainfall more in southern and western regions (Kurniadi et al., 2021). However, these effects may vary due to differences in local factors that may interact with ENSO and IOD.

The influence of ENSO and IOD on Indonesian rainfall may be affected by their position, although research on this issue is still limited. Some existing studies use one of the Niño indices (Niño 1+2, 3, 3.4, and 4) to describe ENSO conditions (Omondi et al., 2013; Trenberth & Stepaniak, 2001; Trenbeth et al., 2002). The Niño indices were developed based on the mean SST anomaly for the following regions: Niño 1+2 (0-10S, 90W-80W), Niño 3 (5N-5S, 150W-90W), Niño 3.4 (5N-5S, 170W-120W), and Niño 4 (4N-5S, 160E-150W). A detailed discussion of the Niño indices can be found in (Rasmusson & Carpenter, 1982). Because the four Niño indices represent different positions of the SST, all four indices can be used to describe the position of ENSO. Dewi & Marzuki (2020) have analyzed the influence of ENSO's position on rainfall in Indonesia. However, this study is limited to two ENSO positions (two Niño indices): the western and central Pacific Ocean. In addition, their study did not consider the influence of seasonality, even though it significantly affects the regional variability of precipitation (Marzuki et al., 2018) . Zhang et al. (2022) show a more robust influence of ENSO's position on rainfall in the Yellow River region of China. Average rainfall in the Yellow River increases by 20% during warming in the central Pacific and decreases by 30% during warming in the eastern Pacific. This study also focuses on two ENSO positions, as in Dewi & Marzuki (2020), but their discussion includes the ENSO modoki phase. Further progress is needed to improve our overall understanding of the impact of ENSO and IOD on Indonesian rainfall. This paper analyzed the influence of ENSO positions and IOD on Indonesian rainfall for 72 years (1950 to 2021). The position of ENSO is determined by the position of the maximum index value of the four Niño indices. In addition to pure ENSO and IOD events, the impact of ENSO and IOD when they co-occur is also discussed.

2. Datasets and Methods

The influence of ENSO positions and IOD on Indonesian rainfall is observed for the regions 90°E–145°E and 10°S–10°N regions (Fig. 1). There are topographic differences in several large islands, such as Sumatra, Kalimantan, and Papua, which may also cause regional variations in Indonesian rainfall. Although rainfall is concentrated in the above regions, other data cover a wider area, including the Pacific and Indian Oceans.

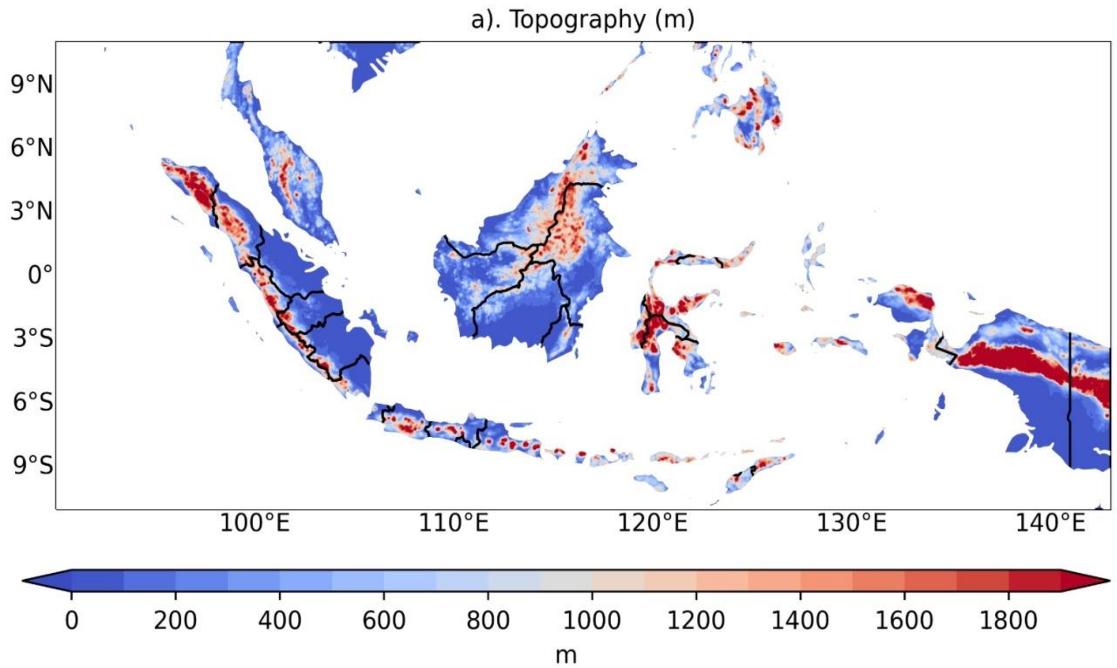

Figure 1. Topography of Indonesia

2.1. Data

ENSO was observed using the Niño Index downloaded from the link (https://psl.noaa.gov/gcos_wgsp/Timeseries/). The Dipole Mode Index (DMI) downloaded from the link (https://psl.noaa.gov/gcos_wgsp/Timeseries/DMI/) was used for the IOD observations. The DMI is determined from the gradient of SST anomalies 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 (Saji et al., 1999).

In this study, data from European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-5 were used. The data used were SST, precipitation, wind, and vertical motion in the atmosphere data for 72 years from 1950 to 2021, with a spatial resolution of 0.25°. The ERA-5 data can be downloaded from the website (https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels-monthly-means?tab=form). The CHIRPS and ERA-5 data were grouped according to the positions of the ENSO phase and the IOD.

2.2. Methods

The study began with determining the years of ENSO and IOD. The ENSO years were obtained from the website (https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ ensostuff/ONI_v5.php). Once the ENSO years were obtained, the position of ENSO was determined by comparing the values of the Niño 1+2, Niño 3, Niño 3.4, and Niño 4 indices. The index with the highest value was considered as the position of ENSO. These ENSO positions are hereafter referred to as El-Niño/La-Niña 1+2, El-Niño/La-Niña 3, El-Niño/La-Niña 3.4, and El-Niño/La-Niña 4, respectively. The IOD phase was determined by comparing the values of the DMI index in the WTIO and SETIO regions. A positive IOD occurs when the anomaly value in the WTIO region is greater than that in the SETIO region. Meanwhile, a negative IOD is indicated by a larger anomaly value in the SETIO region than in the WTIO region. Table 1 shows the years of each ENSO and IOD phase from 1981 to 2021. Once the ENSO position and IOD phase were obtained, their influence on Indonesian rainfall was analyzed. Rainfall was expressed as a percentage decrease or increase calculated from the monthly average rainfall climatology. In addition, the effect of ENSO and IOD when these two phenomena co-occur was also analyzed. To understand the SST in Indonesian water and atmosphere dynamics related to the Walker circulation, ERA-5 data were analyzed.

Table 1. Years of IOD and ENSO phase for each position

	El-Niño				Normal	La-Niña			
	Niño 1+2	Niño 3	Niño 3.4	Niño 4		Niño 1+2	Niño 3	Niño 3.4	Niño 4
Positive IOD	1997	1982, 2015	1972	1963, 2018	1961, 1967, 1982, 1994, 2006, 2007, 2012, 2017, 2019	-	-	-	-
Normal	1953, 1957, 1983, 2014, 2019	1976, 1992	1951, 1958, 1965, 1968, 1979, 1986, 2009	1969, 1977, 1991, 1994, 2002, 2004, 2006	1960, 1961, 1962, 1967, 1981, 1990, 1993, 2003, 2014	1954, 1960, 1977, 2007, 2012	1955, 1964, 1970, 2016	1983, 1988, 2000, 2005, 2010, 2011	1950, 1956, 1973, 2008
Negative IOD	-	-	-	-	1958, 1992, 1996, 2005, 2016, 2021	-	1984	1995, 1998, 2010	1974

The Asian Monsoon and Australian Moonson strongly influence Indonesia's rainfall climatology. The distribution of rainfall and wind of these two monsoons is shown in Fig. 2. Winds during the Asian Monsoon blow from December to March (DJFM), resulting in high rainfall that month, while winds during the Australian Moonson blow from June to September (JJAS), resulting in low rainfall. Meanwhile, there is a transition period between the two monsoons in other months. Since these monsoons strongly influence regional rainfall variations in Indonesia, the influence of ENSO and IOD on Indonesian rainfall is analyzed by separating DJFM and JJAS periods. Several previous studies have also performed this seasonal grouping, which classifies rainfall in the two seasons (Gu & Adler, 2019; Kumar et al., 2019).

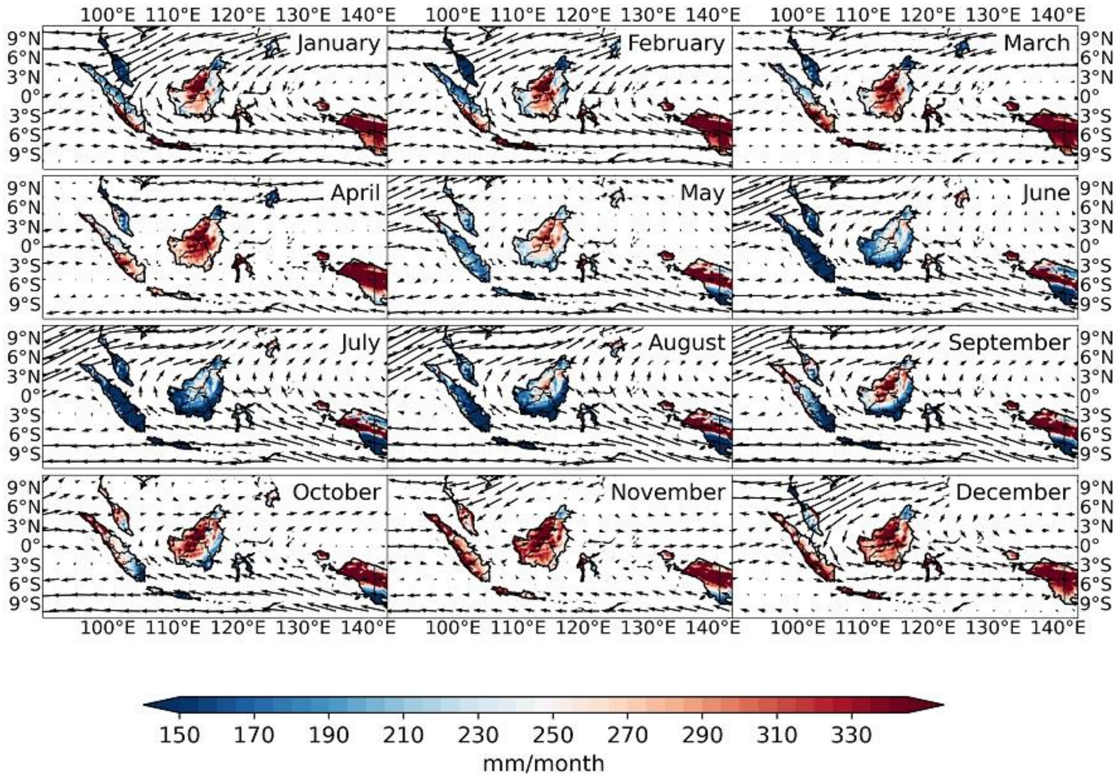

Figure 2. The wind direction and average rainfall of Indonesia each month

3. Results and Discussion

3.1. Climatology of monthly rainfall

Figure 3a shows Indonesian seasonal rainfall for 72 years (1950–2021). During the DJFM some areas have rainfall of more than 350 mm/month, while during the JJAS Indonesian rainfall is less than 150 mm/month. However, some areas, such as northern Kalimantan and Papua still have high rainfall (>350 mm/month). The complex topography of Kalimantan and Papua affects rainfall in these areas (Sobel et al., 2011). Meanwhile, low rainfall (<150 mm/month) is found in Sumatera, Java and northern Sulawesi during JJAS. Nusa Tenggara and Maluku regions also have low rainfall. The spatial distribution of rainfall in this study is consistent with several previous studies (Lestari et al., 2018; Ramadhan et al., 2022a; Ramadhan et al., 2022b). Nusa Tenggara is a semi-arid region of Indonesia. In semi-arid regions, evapotranspiration is much greater than rainfall, and rainfall intensity during the rainy season is very high (Krisnayanti et al., 2021).

Before discussing the influence of ENSO positions and the IOD event, we first examine the rainfall anomaly under normal conditions (without ENSO and IOD), as seen in Fig. 3b. Normal conditions are conditions in which ENSO and IOD do not occur. This means that if the SST does not indicate the presence of ENSO and IOD events, then the year is grouped under normal conditions. In some parts of Indonesia, increases and decreases in rainfall are observed under normal conditions, but they are less than 10%. During DJFM, all parts of Indonesia experienced an increase in rainfall, although, in some areas, the increase was less than 10%. However, during JJAS an increase in rainfall is observed in Papua, Sulawesi, and East Kalimantan. These areas are directly adjacent to the Pacific Ocean, suggesting that the increase in rainfall is due to water vapour from the Pacific Ocean. This result differs from the study by Nur'utami & Hidayat (2016) who found an increase in rainfall in western Indonesia under normal conditions. However, they only analyzed data during September, November, and December (SON). The Inter-Tropical Convergence Zone (ITCZ) and the monsoon influence rainfall in the western part of Indonesia during the SON. The ITCZ moves southward during the SON (Waliser & Gautier, 1993), and its movement across the Indian Ocean enhances convection along with the onset of the summer monsoon. Indonesia generally experiences the dry southeast monsoon from May to September and the wet northwest monsoon from November to March (Aldrian & Susanto, 2003). Therefore, Nur'utami & Hidayat (2016) found an increase in rainfall in the western part of Indonesia during the SON, even under normal conditions.

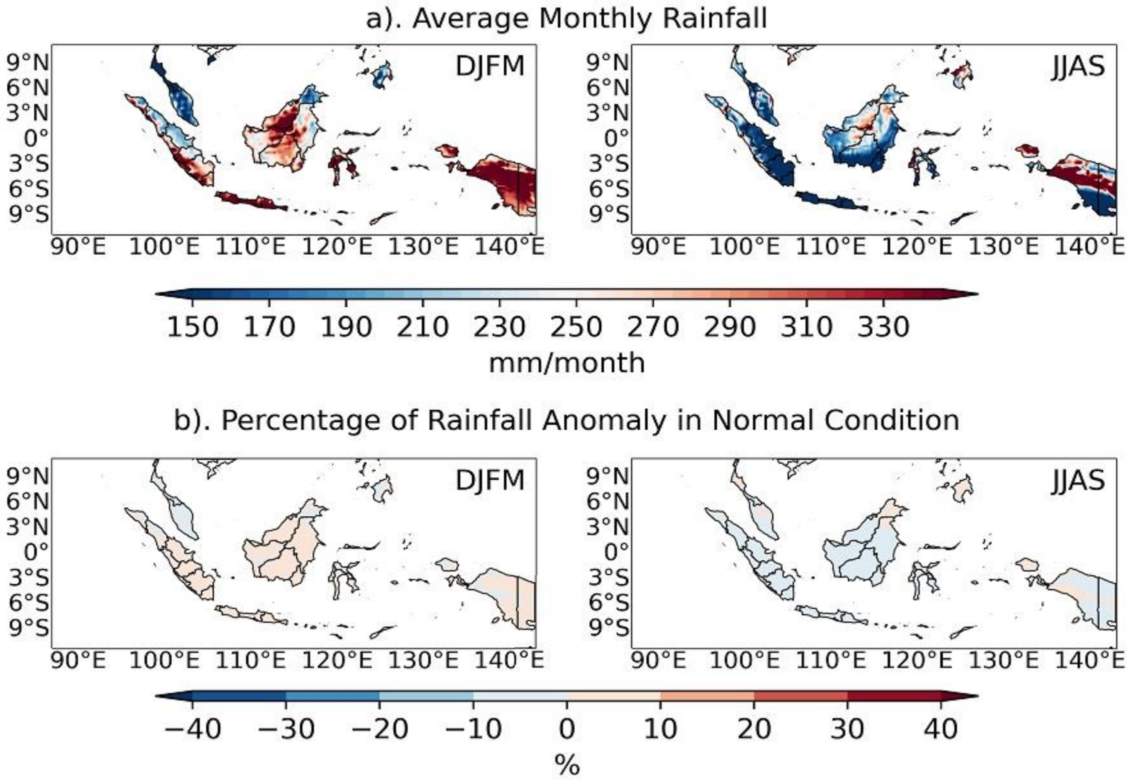

Figure 3. a) Average rainfall of Indonesia during DJFM and JJAS seasons,
b) Percentage of monthly rainfall anomaly under normal conditions during DJFM and JJAS

3.2. Effects of Different ENSO Positions on Indonesian rainfall

3.2.1. El-Niño

Figure 4 shows the spatial distribution of SST anomaly during El-Niño events at different locations. A significant increase in temperature (> 2°C) is observed in the eastern Pacific Ocean during El-Niño 1+2 and El-Niño 3. During El-Niño 3.4 and El-Niño 4, the increase of SST is smaller. These findings are consistent with Nabilah et al, (2017) and Shi & Qian (2018), who state that El-Niño has a larger anomaly in the eastern Pacific than in the central region.

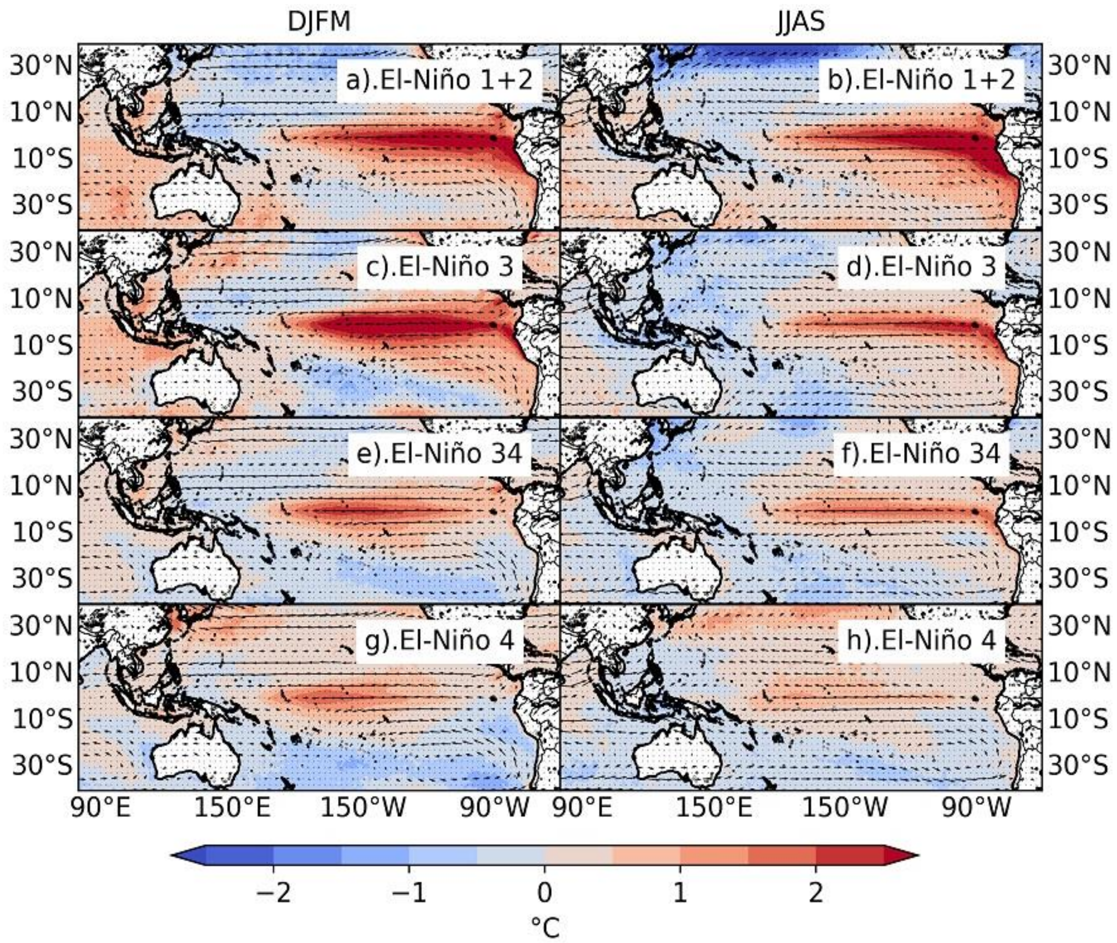

Figure 4. Distribution of SST anomaly during a) El-Niño 1+2 (DJFM), b) El-Niño 1+2 (JJAS), c) El-Niño 3 (DJFM), d) El-Niño 3 (JJAS), e) El-Niño 3.4 (DJFM), f) El-Niño 3.4 (JJAS), g) El-Niño 4 (DJFM), and h) El-Niño 4 (JJAS)

Differen El-Niño positions cause different impacts on rainfall in Indonesia (Fig. 5). During DJFM, Indonesia experiences both increases and decreases in rainfall. Significant decreases in rainfall occur in western Indonesia during El-Niño 1+2. Northern Sumatra and parts of eastern Indonesia also experienced significant decreases in rainfall (>30%) during El-Niño 3. In contrast, during El-Niño 3.4 and El-Niño 4, western Indonesia tends to increase by around 20% - 30%. The impact of El-Niño causing a decrease in rainfall is more pronounced than during JJAS. Rainfall decreases overall during El-Niño 3 and El-Niño 4 (>30%). During El-Niño 1+2, there is still a decrease in rainfall over Sumatra, Java, and Papua, but small parts of Kalimantan and Sulawesi experience an increase in rainfall. Likewise, during El-Niño 3.4, most of Indonesia experienced a decrease in rainfall while a small part of Sumatra experienced an increase in rainfall. While there are some parts of Indonesia that are not affected by El-Niño events, marked with white and black shading, these areas include parts of Sumatra and Kalimantan at all positions except for El-Niño 3 (JJAS). Certain parts of Papua also show no significant influence during the DJFM season. These findings are consistent with previous studies Nur'utami & Hidayat (2016). During El-Niño 4 (Fig. 5h), a decrease in rainfall also occurred in the eastern part of Indonesia, but less than during El-Niño 3.4 (Fig. 5f).

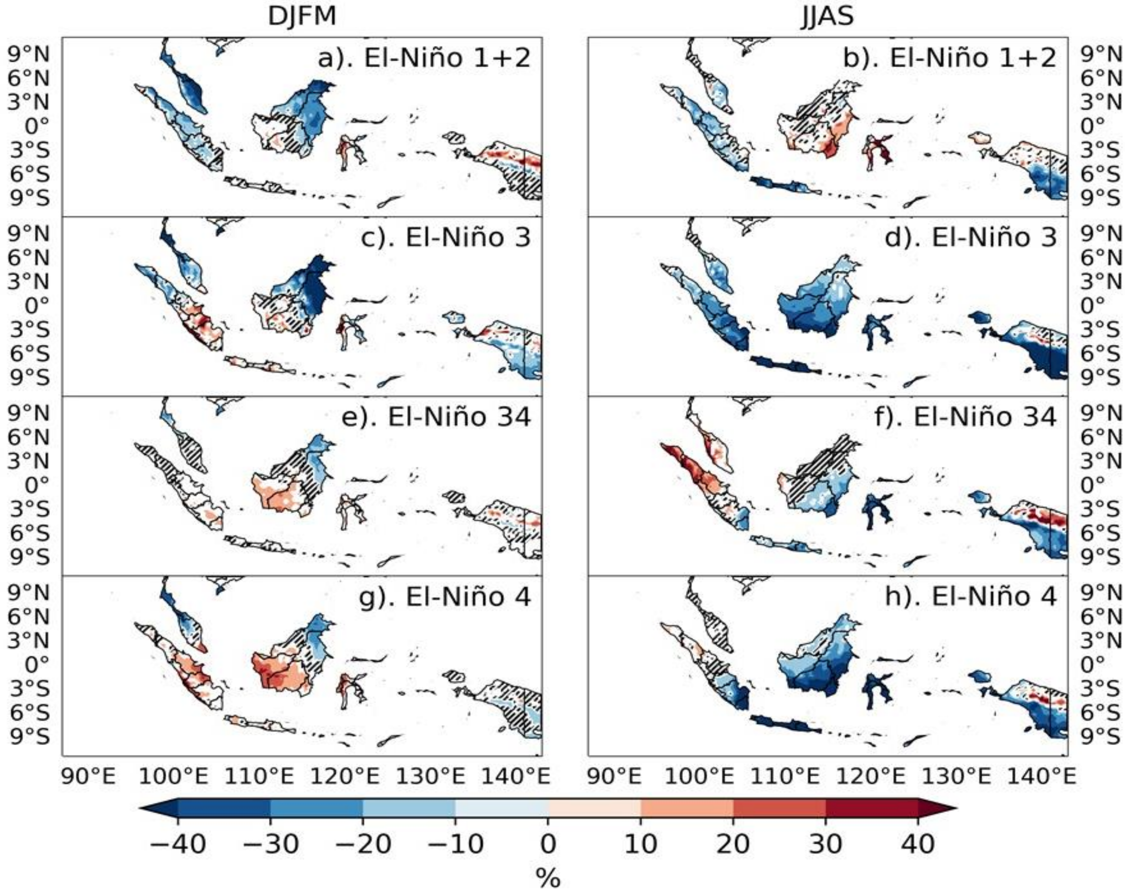

Figure 5. Distribution of the percentage of monthly rainfall anomaly during a) El-Niño 1+2 (DJFM), b) El-Niño 1+2 (JJAS), c) El-Niño 3 (DJFM), d) El-Niño 3 (JJAS), e) El-Niño 3.4 (DJFM), f) El-Niño 3.4 (JJAS), g) El-Niño 4 (DJFM), and h) El-Niño 4 (JJAS)

The difference in rainfall in each ENSO position is caused by the difference in atmosphere-ocean interaction. This pattern is depicted by the value of vertical air motion shown in Fig. 6. Negative values indicate convection or upward air movement (updraft), while positive values indicate downward air movement (downdraft). During El-Niño 1+2 over DJFM, updrafts dominate in the eastern Pacific Ocean while all of Indonesia experiences downdrafts. The downdraft is larger in western Indonesia, causing a significant decrease in rainfall in western Indonesia, as also observed by Dewi & Marzuki (2020). During El-Niño 3.4 and El-Niño 4, the updraft position shifts to the central Pacific Ocean, and the downdraft formed in Indonesia is prominent in the eastern region. These results caused a decrease in rainfall in eastern Indonesia, while western Indonesia experienced an increase. However, during El-Niño 3, a strange vertical air motion is formed. The downdraft formed over Indonesia is enormous, while the significant decrease in rainfall only occurs in a few areas (Fig. 5c).

The short duration of El-Niño 3 causes that during DJFM, which is seven months, while other El-Niño events range from (15 to 30) months. During JJAS, the downdraft formed over Indonesia is larger during El-Niño 3, which causes the most significant decrease in rainfall (Fig. 5d). During El-Niño 1+2, downdrafts formed only over western Indonesia, resulting in reduced rainfall (Fig. 5b). During El-Niño 3.4, there is an increase in rainfall in Sumatra and Kalimantan (Fig. 5f), partly due to updrafts or convection from the Indian Ocean. These findings are consistent with those of Nur'utami & Hidayat (2016) when analyzing the impact of ENSO using the Niño 3.4 index.

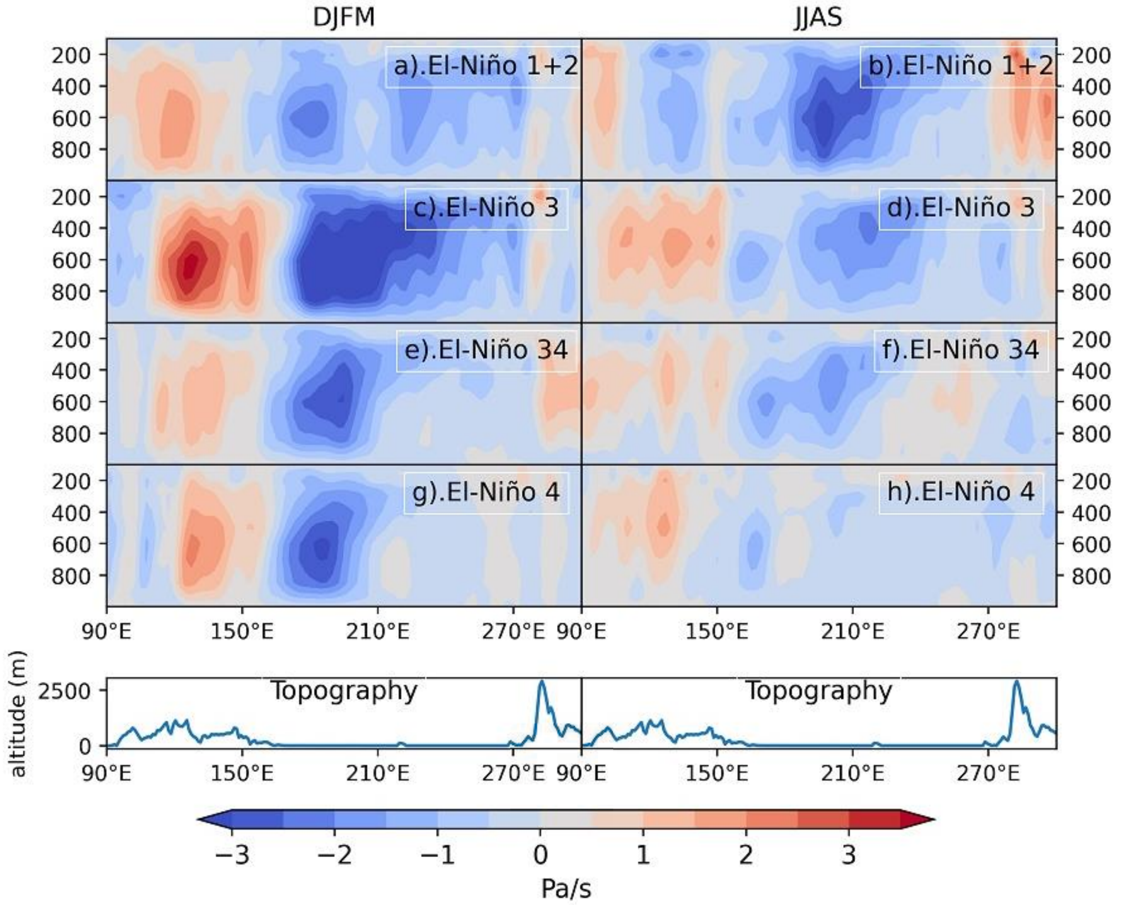

Figure 6. Mean vertical air motion from ERA-5 data during a) El-Niño 1+2 (DJFM), b) El-Niño 1+2 (JJAS), c) El-Niño 3 (DJFM), d) El-Niño 3 (JJAS), e) El-Niño 3.4 (DJFM), f) El-Niño 3.4 (JJAS), g) El-Niño 4 (DJFM), and h)El-Niño 4 (JJAS). ERA-5 data and topography is averaged over a latitude of 10°S-10°N

3.2.2. La-Niña

Figure 7 shows the distribution of SST anomalies during La Niña. The most significant temperature decrease (< -1.5°C) was observed at all positions during DJFM. While during JJAS, all positions also experienced the same decrease except during La Niña 4. The smallest Niño index in La-Niña 4 (Fig. 7h) was about -1°C to -1.5°C. This is also observed by Shi & Qian (2018), who found that the anomalies in the central Pacific Ocean were much lower than in the eastern part during La Niña events.

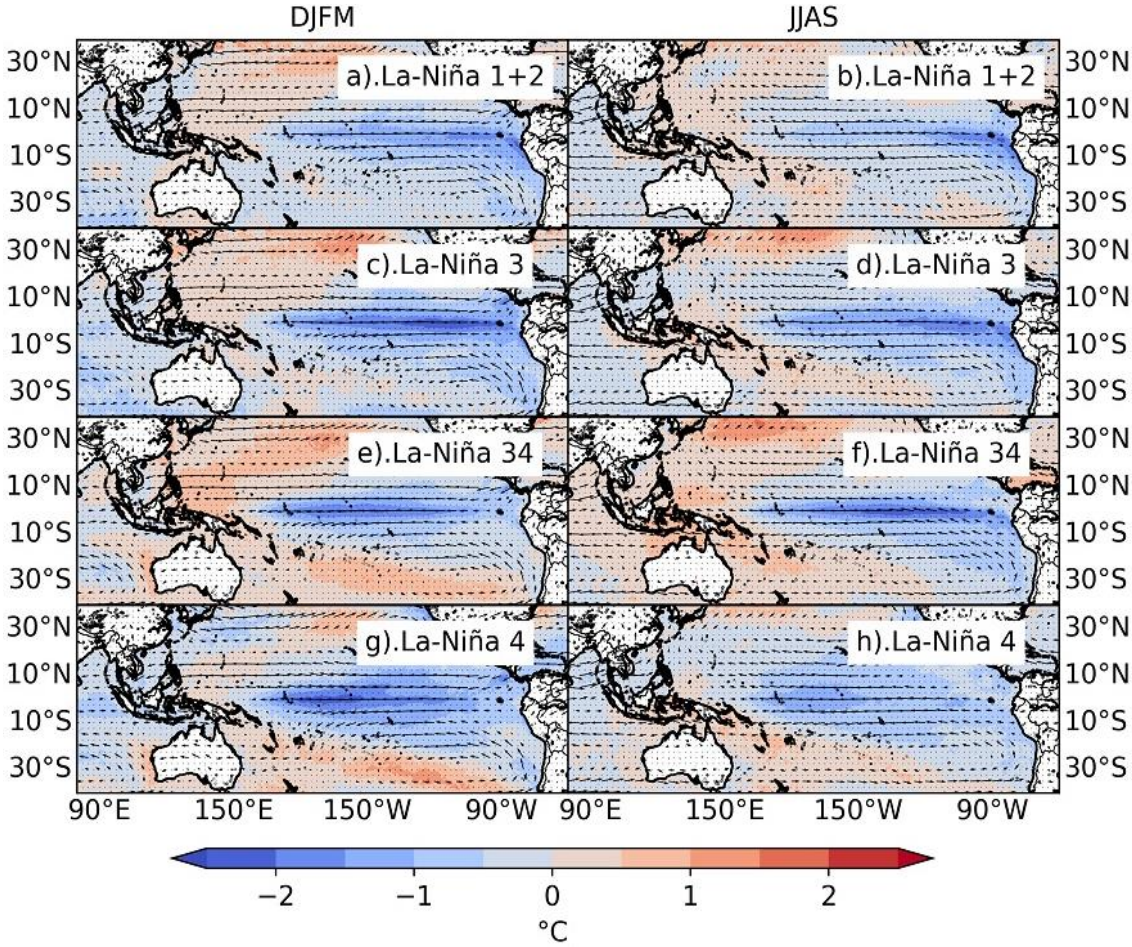

Figure 7. Distribution of SST anomaly during a) La-Niña 1+2 (DJFM), b) La-Niña 1+2 (JJAS), c) La-Niña 3 (DJFM), d) La-Niña 3 (JJAS), e) La-Niña 3.4 (DJFM), f) La-Niña 3.4 (JJAS), g) La-Niña 4 (DJFM), and h) La-Niña 4 (JJAS)

During the La-Niña phase, Indonesia is wetter than the normal and the El-Niño phase, with an increasing rate of rainfall depending on the position of La-Niña (Fig. 8). During DJFM, the increase in rainfall occurred only in a few areas, namely in northern Sumatra and eastern Kalimantan, by around 30%. This increase in rainfall occurred in all positions except for La-Niña 4, which only experienced an increase in rainfall in eastern Kalimantan. Therefore, La-Niña 3 and La-Niña 4 also decreased rainfall in parts of Sumatra, Java, and Kalimantan by 10%-20%. The impact of the La-Niña event is predominant during the JJAS season, with a significant increase in rainfall throughout Indonesia. The most significant increase in rainfall occurs during La-Niña 3.4, around 30% - 40% throughout Indonesia. A similar condition was observed during La-Niña 1+2, La-Niña 3, and La-Niña 4, where southern Sumatra, Java, most of Kalimantan, Sulawesi, and parts of Papua experienced an increase in rainfall of around 30%-40%. The Indonesian regions with insignificant influence during La-Niña are more pronounced in the DJFM season for all positions. Almost the entire Papua region does not show any influence during this event, as well as parts of Sumatra and Kalimantan. While in the JJAS season when La-Niña is present, almost all of Indonesia has a significant influence. Only small parts of Kalimantan and Papua show insignificant influence. However, at other positions during the JJAS season, parts of Sumatra, Kalimantan and also Papua show insignificant influence. This is in line with the research conducted by Dewi & Marzuki (2020), stating that the decrease in Indonesian rainfall is greater when La-Niña is close to Indonesia.

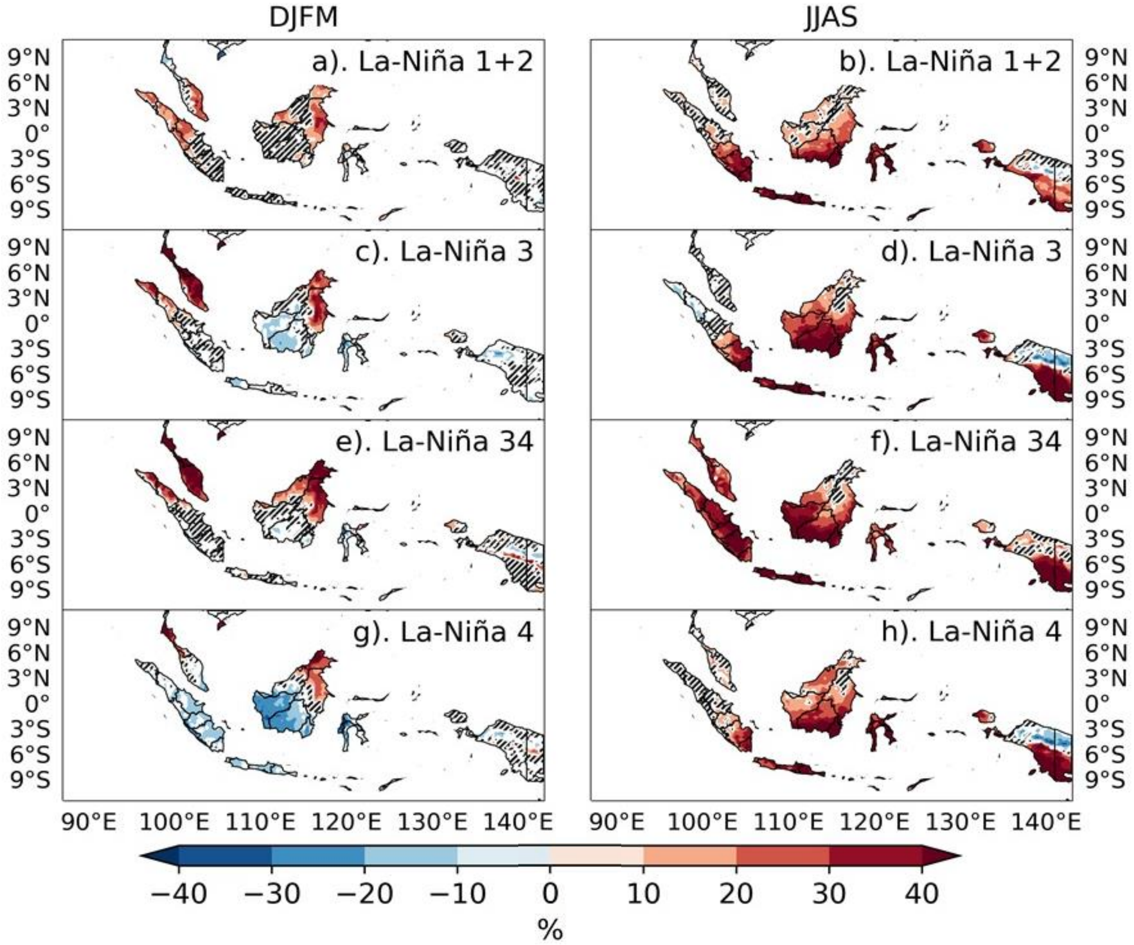

Figure 8. Distribution of the percentage of monthly rainfall anomaly during a) La-Niña 1+2 (DJFM), b) La-Niña 1+2 (JJAS), c) La-Niña 3 (DJFM), d) La-Niña 3 (JJAS), e) La-Niña 3.4 (DJFM), f) La-Niña 3.4 (JJAS), g) La-Niña 4 (DJFM), and h) La-Niña 4 (JJAS)

During La-Niña, there is an increase in rainfall consistent with convective patterns (Figure 9). During DJFM, downdrafts formed in the Pacific Ocean, while Indonesia experienced updrafts. During La-Niña 3.4, massive updrafts formed, which caused increasing rainfall significantly over parts of Indonesia. However, during La-Niña 4, a downdraft was formed in western Indonesia, which caused a decrease in rainfall in the region. In the JJAS season, the movement of air convection is relatively uniform, whereas the Pacific Ocean region forms a downdraft. In contrast, the Indonesian region experiences an updraft which peaks during La-Niña 3.4. This indicates strengthening of the Walker Circulation in the Pacific Ocean Nur'utami & Hidayat (2016).

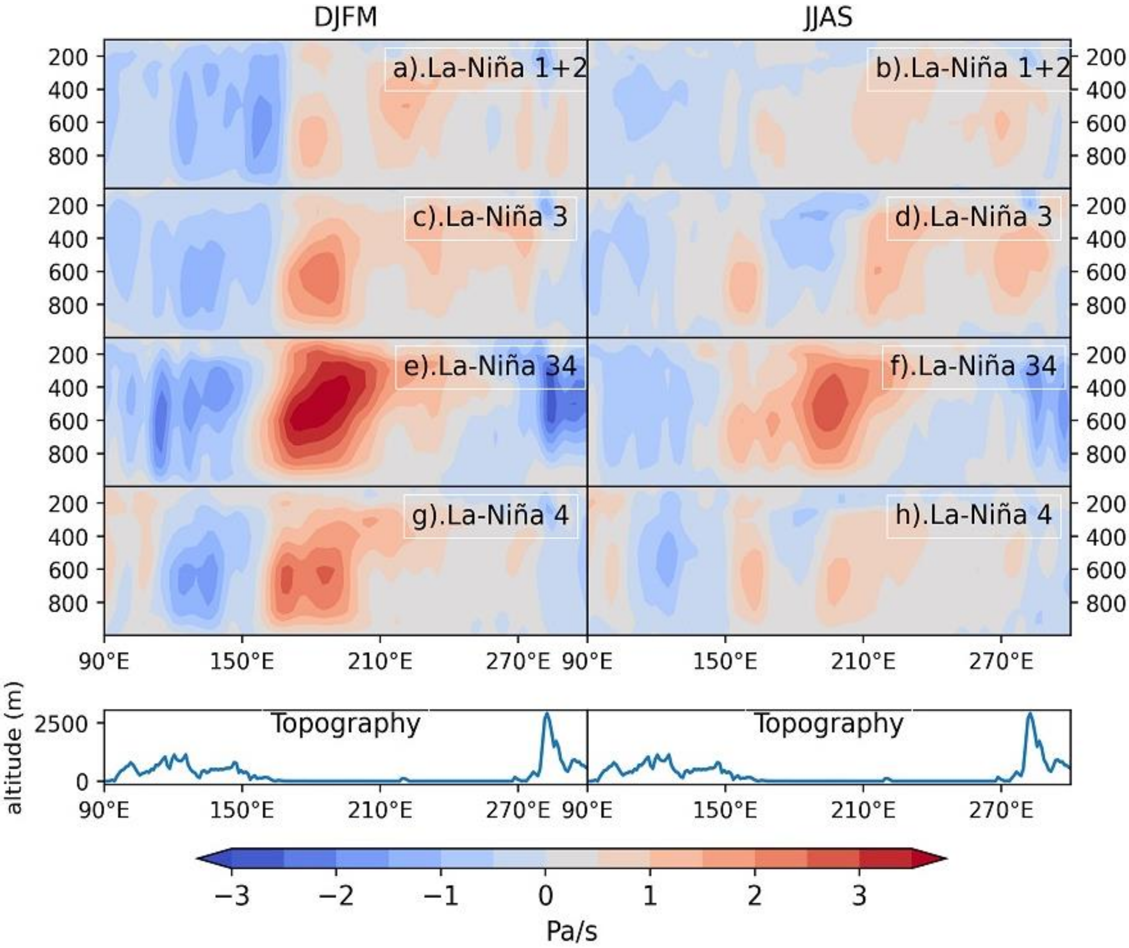

Figure 9. Mean vertical air motion from ERA-5 data during a) La-Niña 1+2 (DJFM), b) La-Niña 1+2 (JJAS), c) La-Niña 3 (DJFM), d) La-Niña 3 (JJAS), e) La-Niña 3.4 (DJFM), f) La-Niña 3.4 (JJAS), g) La-Niña 4 (DJFM), and h) La-Niña 4 (JJAS). ERA-5 data and topography is averaged over a latitude of 10°S-10°N

3.3. Effects of IOD on Indonesian rainfall

The distribution of SST anomalies during IOD is shown in Fig. 10. Unlike the ENSO phenomenon, the IOD only occurs from June to November. This is consistent with data from the Japan Meteorological Agency (JMA), which states that IOD events start in summer and end in fall. Therefore, this research only observes IOD events during the JJAS season. During a positive IOD, the WTIO region has larger anomalies than the SETIO region, and the SST around Indonesia is cooler. On the other hand, during a negative IOD, the WTIO region has smaller anomalies than the SETIO region, and the SST around Indonesia becomes warmer. These results are consistent with the findings of Saji et al. (1999).

Both phases of IOD have different responses to rainfall in Indonesia. During a positive IOD, rainfall in Sumatera and Java decreases by more than 30% (Fig. 11a). Some parts of Kalimantan and Sulawesi, especially the southern regions, also experience a decrease in rainfall of around 20% to 30%. Thus, the most significant decrease in rainfall occurs in the southern part of western

Indonesia, as also found by Kurniadi et al. (2021) and Nurdiati et al. (2022). The decrease in rainfall in Sumatra is supported by the warmer SST in the western Indian Ocean than in the waters around Sumatra. Furthermore, there are some parts of Indonesia that are not affected by this IOD event. Northern Sumatra, northern Kalimantan, and most of Papua show insignificant influence during both positive and negative IOD. As a result, the wind blows towards the warmer region and away from Sumatra (Fig. 10a). In addition, downdraft occurs throughout Indonesia during a positive IOD, while the Walker circulation in the western Indian Ocean and the central-eastern region of Indonesia experience convection (upward movement of air) (Fig. 12a). This is in line with the decrease in rainfall in Indonesia.

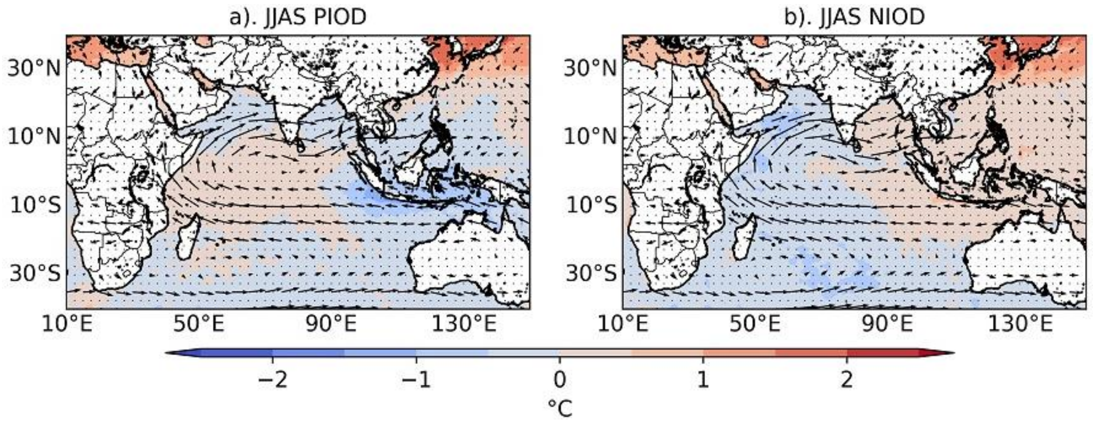

Figure 10. Distribution of SST anomaly during a) positive IOD (JJAS), b) negative IOD (JJAS)

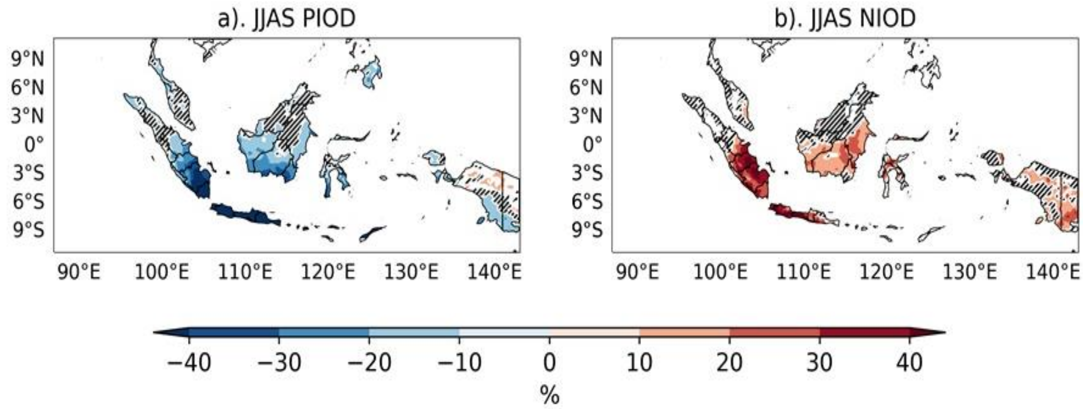

Figure 11. Distribution of monthly rainfall percentages during a) positive IOD (JJAS), b) negative IOD (JJAS)

During a negative IOD, increased rainfall is observed in Indonesia. Just like the positive IOD, the negative IOD also greatly affected the western part of Indonesia. Sumatra and Java regions experienced an increase in rainfall of more than 30%. Some areas of Kalimantan, Sulawesi, and Papua experienced an increase in rainfall around 10%-20%. This aligns with previous studies by Nur'utami & Hidayat (2016), who found that rainfall in Indonesia's western and eastern regions increased during negative IOD events but decreased up to 50 mm/month in the central region of Indonesia (Kalimantan Island). During a negative IOD, SST in Indonesian waters is higher than in the surrounding oceans, particularly in the Indian Ocean, which leads to convection in Indonesia. At the same time, downdraft is observed in the Indian and Pacific Oceans (Fig. 12b). In addition, the high SST in the Indonesian waters causes air to blow towards Indonesia from the Indian and Pacific Oceans, increasing rainfall in some parts of Indonesia (Nur'utami & Hidayat, 2016).

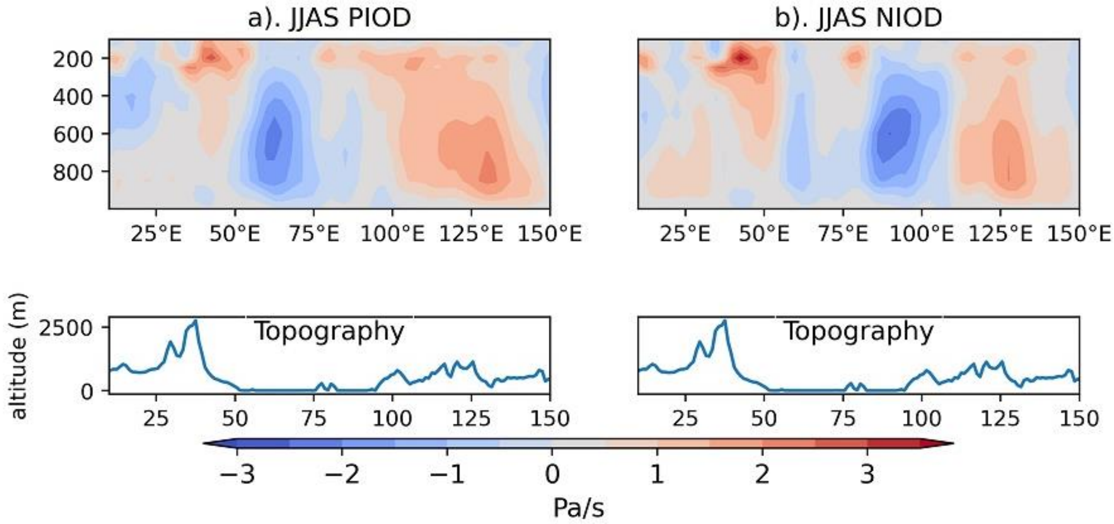

Figure 12. Mean vertical air motion from ERA-5 data during a) positive IOD (JJAS), b) negative IOD (JJAS). ERA-5 data and topography is averaged over a latitude of 10°S-10°N

3.4. Joint effects of ENSO Positions and IOD on Indonesian rainfall

Figure 13 and 16 shows the SST anomaly when ENSO and IOD co-occur. In this study, positive IOD events co-occur with El-Niño, consistent with the Annamalai et al. (2003) study, which found that El Nino can trigger a positive IOD. In contrast, negative IOD co-occurs with La-Niña. Although positive IOD can co-occur with La-Niña, the chances are very small (Song & Ren, 2022). In this study, the El-Niño that occurs with the positive IOD formed at all positions in the JJAS season. At the same time, the La-Niña that occurs with negative IOD is also formed at all positions except when La-Niña 1+2. When a positive IOD co-occurs with El-Niño, the SST anomaly in the Pacific Ocean exceeds 2℃ except for La-Niña 4, which has an anomaly of (1-1.5)℃ (Fig. 13). Thus, El Nino tends to be stronger when it co-occurs with IOD, as Behera & Yamagata (2003) found. When a negative IOD co-occurs with La-Niña, the SST anomaly in the Pacific Ocean exceeds -2℃ during La-Niña 3.4 and La-Niña 4, while during La-Niña 3 the anomaly is around (0.5-1℃) (Fig. 16).

Figure 14 shows the combined effects of ENSO and IOD on Indonesian rainfall when these two phenomena co-occur. When positive IOD co-occurs with El-Niño, rainfall in Indonesia decreases by more than 40%. This condition is observed in all positions in El Niño (Fig. 14). Such a decrease in rainfall is greater than the effect of pure El-Niño, where rainfall in Indonesia decreases by around 30%. The influence of pure IOD and El-Niño (Figs. 5 and 11a) is also not as strong as the combined effects of ENSO and IOD. Such a significant decrease in rainfall is caused by the cooling of SST in the Indonesian Ocean and warming in the eastern Pacific Ocean and western Indian Ocean (Fig. 13). During concurrent El-Niño and positive IOD events, all regions of Indonesia show significant influence, affecting eastern and western Indonesia directly. Thus, there is only a small part of Indonesia that has an insignificant influence. As a result, winds blow from Indonesia to the surrounding regions, carrying water vapor away from Indonesia (Nur'utami & Hidayat, 2016). In addition, the difference in convection is also clearly seen from the vertical movement of air masses. In the Indonesian region, the downward movement of air (downdraft) is dominant, while the upward movement of air is dominant in the Indian Ocean and Pacific Ocean (Fig. 15). Very strong convection in the Pacific Ocean is observed when IOD co-occurs with El-Niño 3 (Fig. 15b). A significant decrease in rainfall when positive IOD co-occurs with El-Niño is also observed in Australia (Meyers et al., 2007).

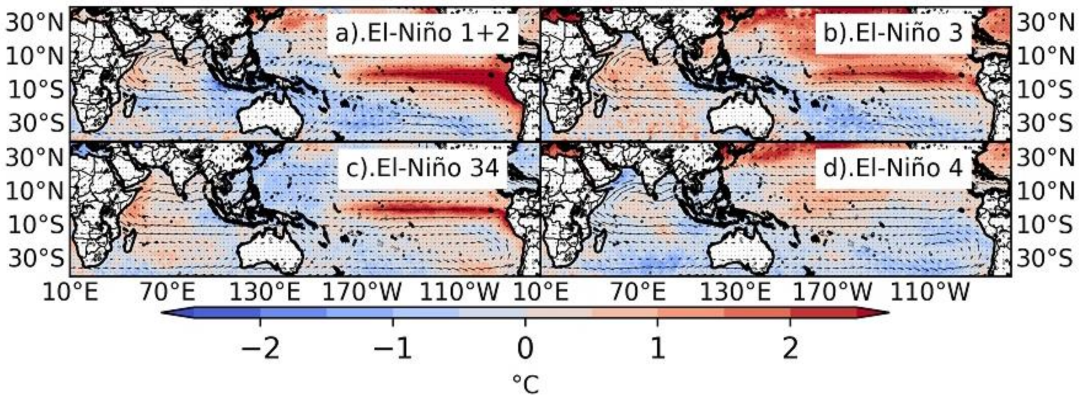

Figure 13. Distribution of SST anomaly during positive IOD occurring concurrently with El-Niño in a) El-Niño 1+2 (JJAS), b) El-Niño 3 (JJAS), c) El-Niño 3.4 (JJAS), and d) El-Niño 4 (JJAS)

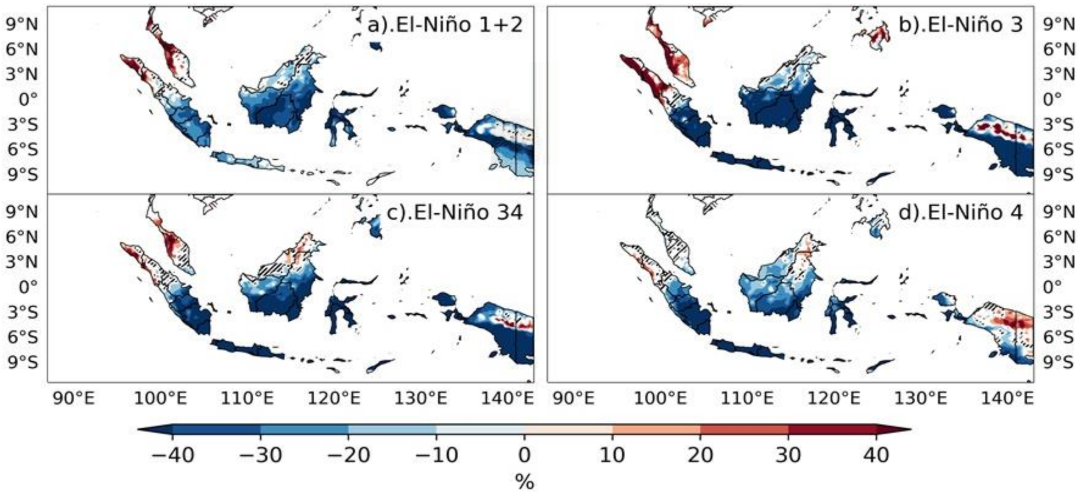

Figure 14. Distribution of monthly rainfall percentages during positive IOD occurring in conjunction with El-Niño: a) El-Niño 1+2 (JJAS), b) El-Niño 3 (JJAS), c) El-Niño 3.4 (JJAS), and d) El-Niño 4 (JJAS)

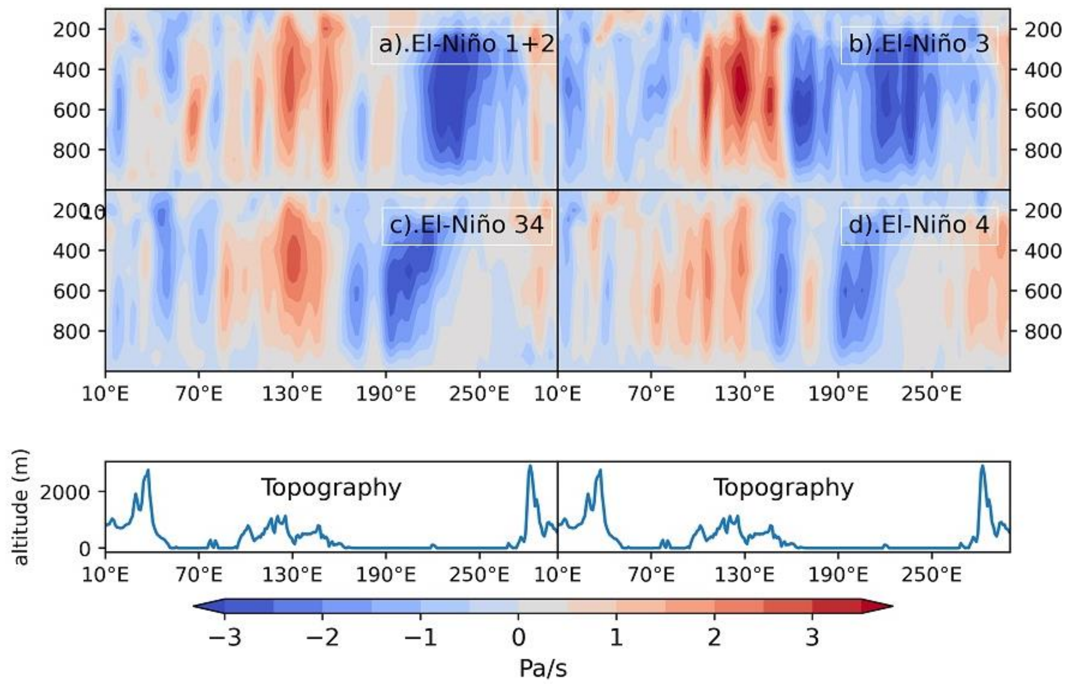

Figure 15. Mean vertical air motion from ERA-5 data during the positive IOD coinciding with El-Niño in a) El-Niño 1+2 (JJAS), b) El-Niño 3 (JJAS), c) El-Niño 3.4 (JJAS), and d) El-Niño 4 (JJAS). ERA-5 data and topography is averaged over a latitude of 10°S-10°N

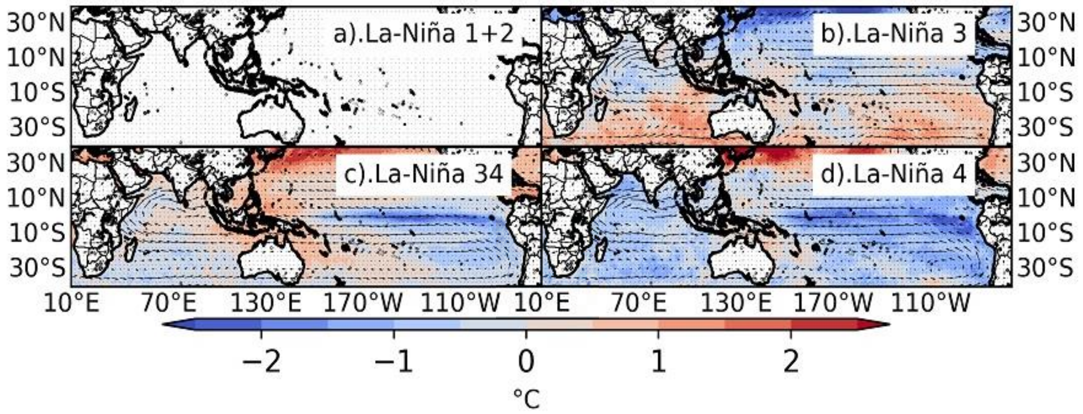

Figure 16. Distribution of SST anomaly during negative IOD coincides with La-Niña in a) La-Niña 1+2 (JJAS), b) La-Niña 3 (JJAS), c) La-Niña 3.4 (JJAS), and d) La-Niña 4 (JJAS)

When a negative IOD co-occurs with La Niña, an increase in rainfall is observed in some parts of the Indonesia region. Indonesian rainfall decreased by around 30%-40% in southern Sumatra, Java, southern Kalimantan, and parts of Sulawesi (Fig. 17b). At the same time, northern Sumatra and Kalimantan experienced more than 30% rainfall decreases. Rainfall also increases by around 30% to 40% when a negative IOD co-occurs with La Niña 3.4 (Fig. 17c). However, when a negative IOD co-occurs with La Niña 4, all parts of Indonesia experience an increase in rainfall of around 30%-40% (Fig. 17d). During these events, eastern Kalimantan, and parts of Papua show insignificant influence when negative IOD occurs along with La Niña 3. However, during La Niña 3.4 and La Niña 4, almost no insignificant influence occurs except for a small part of Papua. When a negative IOD co-occurs with La Niña, the Indonesian ocean is warmer than the surrounding ocean, causing winds to blow toward Indonesia and bring moisture from the surrounding ocean (Fig. 16). Changes in convective patterns are also observed from the Walker circulation (Fig. 18).

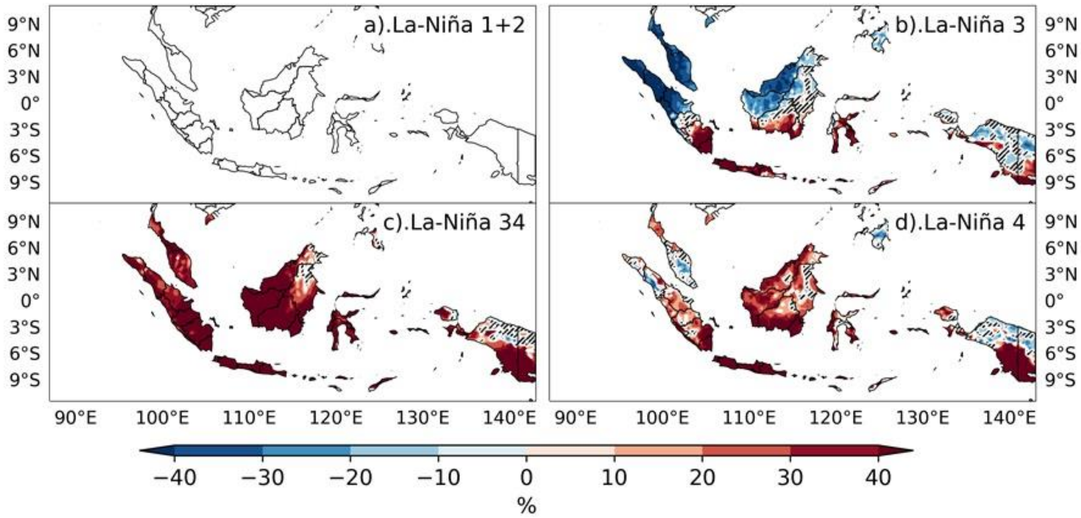

Figure 17. Distribution of monthly rainfall percentages during negative IOD occurring concurrently with La-Niña in a) La-Niña 1+2 (JJAS), b) La-Niña 3 (JJAS), c) La-Niña 3.4 (JJAS), and d) La-Niña 4 (JJAS)

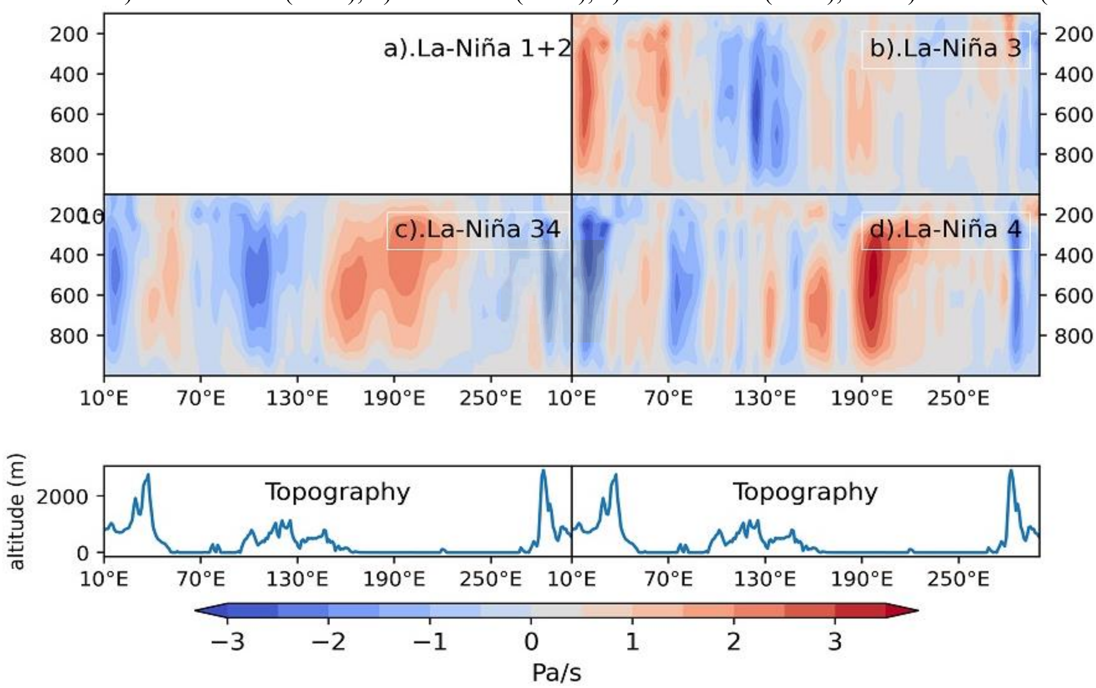

Figure 18. Mean vertical air motion from ERA-5 data during negative IOD coinciding with La-Niña in a) La-Niña 1+2 (JJAS), b) La-Niña 3 (JJAS), c) La-Niña 3.4 (JJAS), and d) La-Niña 4 (JJAS). ERA-5 data and topography is averaged over a latitude of 10°S-10°N

The Walker circulation occurs in the Indian Ocean is weaker, meaning that convection (updraft) occurs in Indonesia and subsidence of air occurs in the Indian Ocean, particularly during La Niña, as also found by Nur'utami & Hidayat (2016). During the co-occurrence of strong La Niña and negative IOD, Indonesia is surrounded by warm water in the western Pacific and the eastern Indian Ocean, also observed during La Niña 3.4 (Fig. 16c). This causes warm water to stay longer in Indonesia, especially in the Indonesian Throughflow (ITF), which increases the duration of ocean water evaporation and triggers cumulus cloud formation (Lee, 2015).

4. Conclusions

The different positions of the ENSO and IOD phases lead to different effects on Indonesian rainfall. In general, the effects of ENSO and IOD are more pronounced during the JJAS season. During the El-Niño phase, all regions of Indonesia experience a decrease in rainfall. The most significant decrease in rainfall occurs during El-Niño 1+2, followed by El-Niño 3.4 and El-Niño 4. Thus, the further away warm water is from Indonesia, the drier the Indonesian region becomes. The decrease in rainfall is even greater (>40%) when El-Niño 1+2 co-occurs with a positive IOD. The Indonesian region experiences an increase in rainfall during the La-Niña phase, with the largest increase occurring during La-Niña 3.4, followed by La-Niña 4, La-Niña 3 and La-Niña 1+2. The Indonesian water is also warmer, so convection is more common in Indonesia. In addition, winds blow towards Indonesia, bringing moisture from the western Pacific Ocean. La-Niña is not significantly modulated by negative IOD. The increase in rainfall caused by La-Niña co-occurring with negative IOD is no more significant than the increase in rainfall when La-Niña is pure without IOD. On the other hand, when negative IOD co-occurs with La-Niña 4, there is a significant increase in rainfall, as with natural La-Niña 3.4. Thus, the difference in the position of the ENSO and IOD phases leads to differences in the Walker circulation, which results in different responses to rainfall in Indonesia. Therefore, the position of ENSO should be considered in determining the status of this phenomenon, using different ENSO indices that represent many locations of SST. This study has not yet considered the influence of the Madden-Julian Oscillation (MJO), which is one of the intraseasonal oscillations that also affects rainfall in Indonesia. Therefore, the combined effects of ENSO, IOD, and MJO positions on rainfall in Indonesia are currently being investigated and will be published in a separate paper.

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