ON THE INTERANNUAL VARIABILITY of INDONESIAN MONSOON RAINFALL (IMR): A LITERATURE REVIEW OF THE ROLE OF ITS EXTERNAL FORCING

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ABSTRACT

The IMR variability is notorious for its hydrometeorological disasters. This paper examines recent studies on IMR and the main factors controlling its variability. The focus of this study is to investigate the impact of the atmosphere-ocean interaction that acts as the external forcing of IMR in the tropical Indian and Pacific Oceans. Specifically, the study will examine the influence of two climate phenomena, namely the El Nino Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) and their interdecadal changes associated Pacific Decadal Oscillation (PDO), on the IMR. The review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) approach. Furthermore, data sets (such as rainfall, wind field, and SST) spanning 1990-2020 were used to verify the key findings. In general, this study concludes that the majority of the authors coincided with the following conclusion: ENSO and IOD events impact IMR by changing its amplitude, duration, intensity, and frequency of mean and extreme rainfall. Additionally, it has been shown that their impacts on IMR are most substantial during the dry seasons, specifically in June, July, and August (JJA), and not as strong as during the wet seasons, specifically in December, January, and February (DJF). Spatially, the effects of ENSO and IOD on IMR variability are clearly found more eastward and westward of the region, respectively. The expansions towards the east and west directions were facilitated by the displacement of the ascending and descending of Walker circulation patterns in the Indonesian region, respectively. Given the interannual fluctuations in IMR, caused mainly by ocean-atmosphere interactions, the knowledge gap of atmospheric factors like the Quasi-Biennial Oscillation (QBO) must be investigated in the future, as suggested by previous research and our preliminary study.

Keywords: ENSO, IOD, PDO, Indonesian Monsoon Rainfall, rainfall anomaly.

1. Introduction

The geographical area of Indonesia is located in the equatorial region and surrounded by two oceans zonally and two continents meridionally. This situation places Indonesia in the convergence zone of the Hadley cell circulation and the Walker circulation, exerting significant influence on the spatio-temporal variability of Indonesian Monsoon Rainfall (IMR) patterns in space and time. Extreme events are consistently linked to this IMR variability in the area and are widely recognized for their significant impact on hydrometeorological disasters [1], [2]. Heavy rainfall events are typical during the wet season of a La Nina year, resulting in flooding , while droughts are also common, particularly during the dry season of an El Nino year [3]–[8]. The Indian Ocean Dipole (IOD) is also widely contributed to exert a significant influence on IMR variability [3], [9]–[14]. Droughts in Indonesia are thought to be caused by the high activity of positive IOD [13].

The sea surface temperature (SST) of tropical oceans is the primary external forcing of rainfall variability in tropical climates through the teleconnection mechanism of air-sea interaction [15]. Thus, understanding how tropical ocean–atmosphere dynamics affect IMR variability is crucial. Indonesian rainfall is coherent and correlated significantly with ENSO variations [5], [6], [16]–[18] and IOD events [3], [4], [9], [10], [19]. ENSO is an irregular fluctuation in SST [referred to as El Nino (La Nina) for warming (cooling) periods] and atmospheric pressure (Southern Oscillation) in the equatorial Pacific Ocean [20]. While, an IOD event refers to intense zonal SST gradients in the equatorial Indian Ocean basin, phase-locked to the boreal summer and autumn [13], [14].

High temporal and spatial fluctuations characterize the IMR. Rainfall has diurnal to multidecadal temporal fluctuation, while IMR's spatial variability is related to regional precipitation differences. ENSO, IOD, and PDO are the main external climatic factors of tropical regions [15], [21]. Previous studies have investigated the relationship between these climate factors and IMR and discovered that ENSO, IOD and PDO are the most significant drivers of IMR variability [17], [22]–[24]. Additionally, they illustrated the impact of circulation and Indo-Pacific SST on IMR variability in order to elucidate the mechanism.

Thus, this review is focused on the impact of ENSO and IOD and their long-term variations associated with PDO on the interannual variability in the IMR. It also investigates the mechanisms that drive these fluctuations. This study is the earliest attempt to review both the individual and combined impacts of ENSO, IOD, and PDO on the variability of IMR. The conclusions derived from this analysis will benefit local authorities, policymakers, scholars, and other relevant stakeholders. Moreover, this evaluation allows researchers to select novel area study areas by highlighting the least studied research directions.

2. Methods

This study employed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol [25] (see Figure 1). This protocol has three steps: identifying, screening, and synthesizing results pertinent to the research objective, as explained in detail below:

Article Identification. The initial phase of the study involved the identification of peer-reviewed journals articles that were pertinent to achieving the research objective. Scopus-retrieved papers over the past decades were included. The articles were selected based on title in order to provide relevant and desirable outcomes. The search string was defined as: rainfall OR drought OR flood AND ENSO OR IOD OR PDO OR "El Nino" OR "La Nina" OR QBO OR "Indian Ocean Dipole" AND Indonesia OR "maritime continent" OR Java. The search string was only applied to the titles of articles. Once the search string was implemented, 47 documents published in the periods of 1981-2023 were obtained.

Article Screening. To reduce the number of unwanted articles displayed by Scopus databases, we imposed certain restrictions such as document type, year, sources, language, and publication stage (see Table1 for inclusion and exclusion criteria). Furthermore, the title of the study has been screened; articles solely focused on Indonesia, the subregion of Indonesia, and Indonesian maritime continent were retrieved. After the titles were screened, 137 documents remained for full-text reading, in this phase, 56 full-text articles were excluded because neither the effects of ENSO, IOD, or PDO over precipitation in Indonesia were addressed.

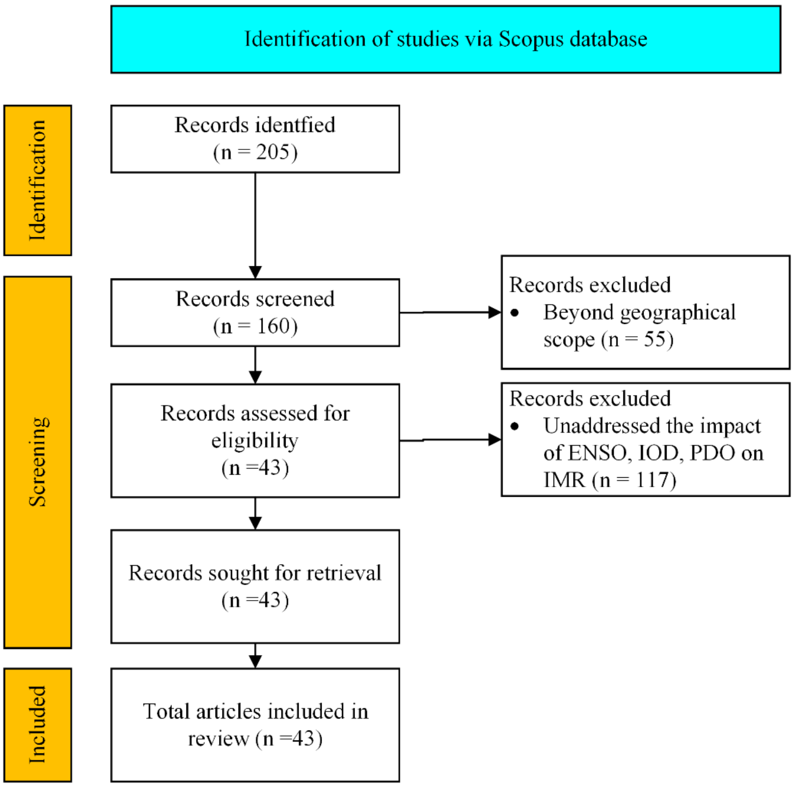

Figure 1. PRISMA 2020 flowchart of this systematic literature review. Adapted from [25].

Inclusion and Data Synthesis. Data were extracted from the selected studies to answer the research questions: they focused on the physical mechanisms involved in teleconnections and mention their specific effects on IMR.

Data supports including rainfall and wind data were employed to verify the principal findings established in this review. The monthly Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) and wind fields reanalysis data from the National Centers for Environmental Information (NOAA)'s Climate Data Record (CDR) for 30-year periods (1991-2020) were used in the study. Access the data set at https://data.chc.ucsb.edu/products/CHIRPS-2.0/ (accessed on 1 January 2023). Anomalies induced by climatic factors that cause variations in rainfall are examined using composite analysis and the statistical test of the mean difference. Also, the Singular Value Decomposition (SVD) analysis was performed to evaluate the covariability between IMR and a range of climate indices that represent QBO, ENSO, IOD, and PDO occurrences. The climate indices used in this study are obtained from the websites https://www.geo.fu-berlin.de/(accessed on 1 January 2023), https://www.ncei.noaa.gov/, https://psl.noaa.gov/ (accessed on 1 January 2023), https://www.ncei.noaa.gov/ (accessed on 1 January 2023) for the indices of QBO, ENSO, IOD, and PDO, respectively.

3. Result and Discussion

Role of Tropical Ocean on IMR variability. Tropical oceans are of significant importance in the maintenance of global climate variability. Various coupled ocean-atmosphere phenomena originating in tropical oceans have a direct impact on changes in global circulation, thereby influencing regional climate variability [26]. The impact of tropical Pacific (Indian) Ocean SST conditions on the IMR variability can be studied through the relationship between ENSO (IOD) and IMR, since both ENSO and IOD are known as the primary driver of the IMR variability.

Impact of Pacific Ocean on IMR Variability. The ENSO is widely recognized as the primary coupled ocean-atmosphere phenomenon in the tropical Pacific region, exerting a significant influence on the interannual fluctuations of IMR pattern [17]. It does not imply that ENSO is the only driver of IMR variability, but the existence of ENSO as a major coupled ocean–atmosphere phenomenon in the tropical Pacific and its strong influence on IMR variability are widely acknowledged.

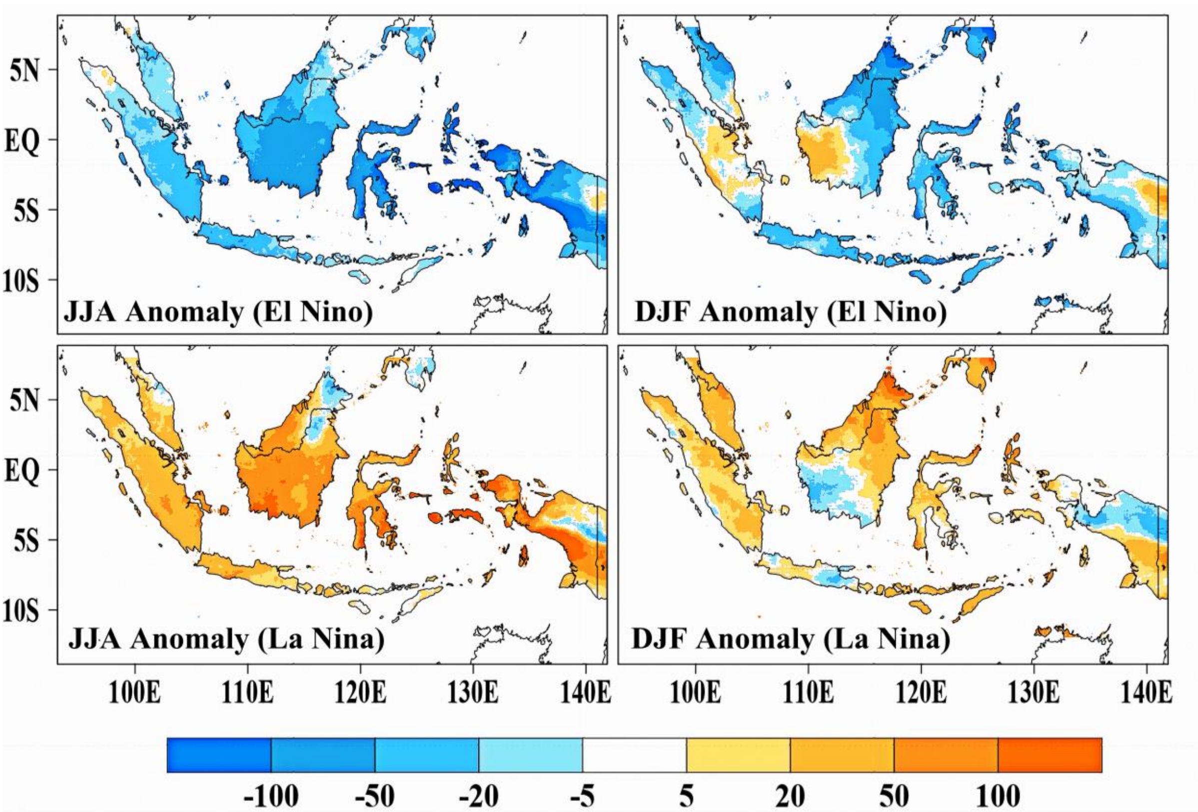

Figure 2 Composite of rainfall anomaly (mm/month) associated El Niño and La Nina years. CHIRPS Data from 1991 to 2020.

Numerous research endeavours have been conducted in recent decades to comprehend the ENSO phenomenon and its effects on the variability of the IMR [1], [3], [21], [27]–[35], [5], [36]–[45], [6], [46]–[52], [7], [9], [12], [16], [17], [19]. According to the findings of previous studies, it has been observed that El Niño events, which represent the positive phase of the ENSO, are generally linked to a decrease in IMR. However, this impact was not observed in western Kalimantan and central Papua [6], where the IMR remains unaffected and indicates only a slight rainfall response to SST throughout the year. Aldrian and Susanto [46] argued that the equatorial region, characterized by a high amount of rainfall throughout the year, lessened the effects of El Nino during June, July, and August (JJA) and December, January, February (DJF). The impact of the El Nino phenomenon is linked to a descending circulation anomaly resulting from an eastward shift in the zonal Walker circulation. On the other hand, La Niña events, representing the negative phase of ENSO, are associated with excessive rainfall patterns in the Indonesian region. However, this pattern was not observed in western Kalimantan, East Java, and central Papua [6]. These conclusions are supported by the data presented in Figure 2.

It is common knowledge that ENSO is related to shifts in the Walker circulations [53]. Figure 3 depicts the fluctuations in equatorial Walker circulation within the Indo-Pacific sector, specifically over the Indonesia domain, throughout the El Niño and La Niña occurrences spanning from 1991 to 2020. The Walker circulations were analysed by examining the zonal, meridional, and vertical wind components at various vertical levels. The IMR is governed by the tropical Pacific SST via the Walker circulation, an equatorial zonal circulation. The Walker circulation refers to a horizontal circulation pattern in the troposphere, characterized by the movement of air in an east-west direction. This circulation features regions of air ascending over the western Pacific Ocean and descending over the eastern Pacific Ocean. The IMR is influenced by the ENSO phenomenon, which occurs due to the interaction between the equatorial Walker circulation and the atmospheric zonal circulations. These circulations are widely recognized as significant and influential on a global scale.

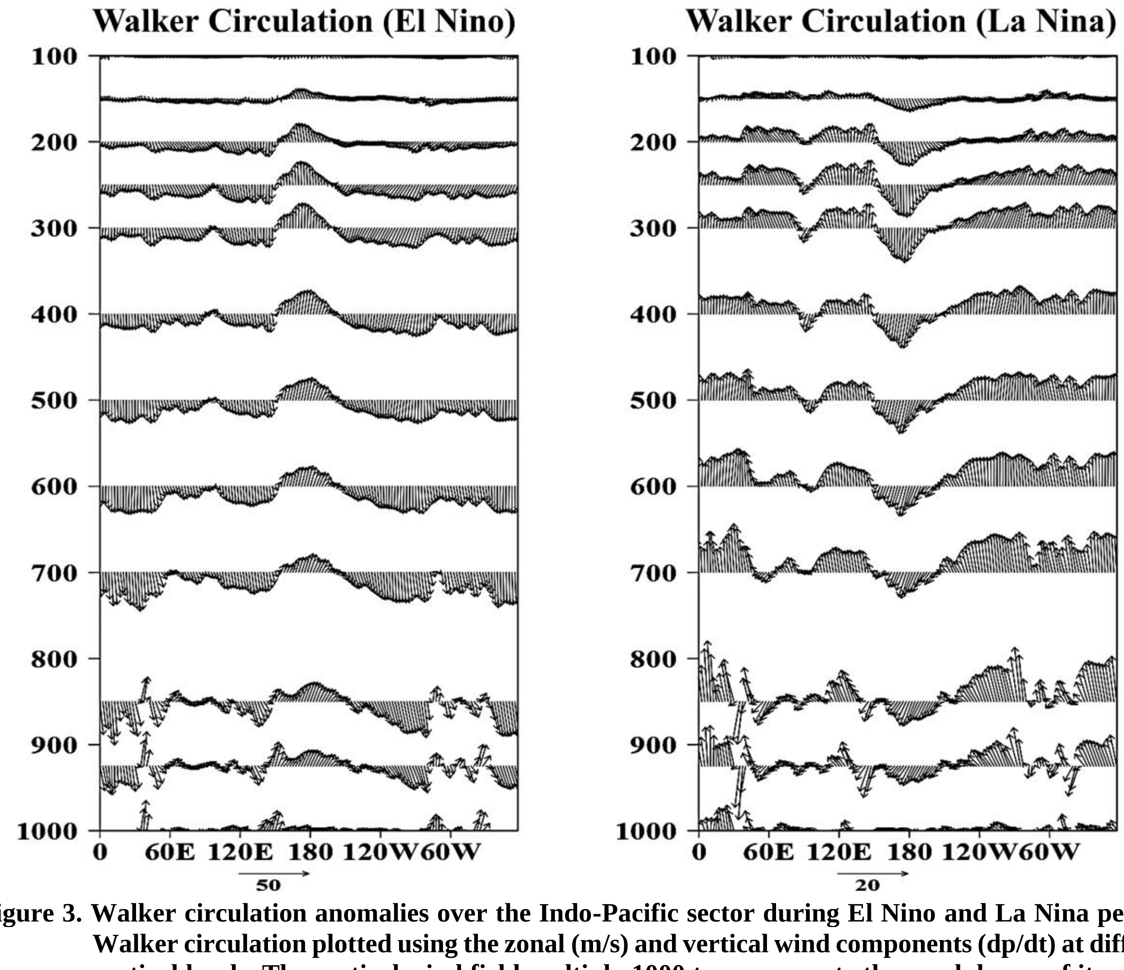

Figure 3. Walker circulation anomalies over the Indo-Pacific sector during El Nino and La Nina periods. Walker circulation plotted using the zonal (m/s) and vertical wind components (dp/dt) at different vertical levels. The vertical wind field multiply 1000 to compensate the much lower of its values. NOAA reanalysis data from 19981 to 2020.

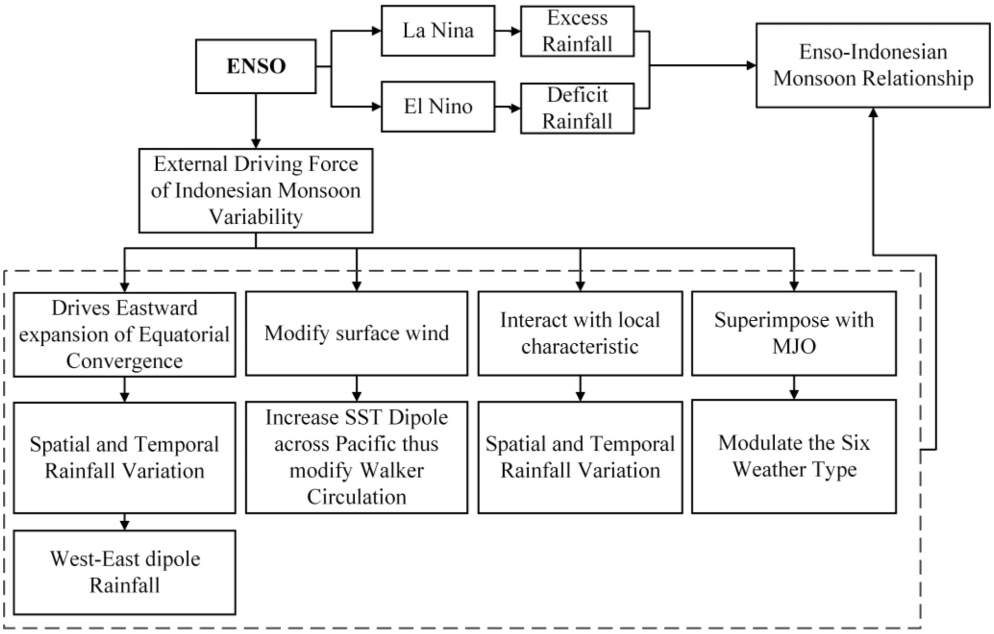

Figure 4 The ENSO-IMR relationship is depicted schematically in this diagram.

Author in [1] reported that anomalies generated by the ENSO phenomenon result in significant downward motion over the Indonesian monsoon region as indicated in Figure 3, thereby influencing the modulation of the IMR. The majority of studies have examined the relationship between the ENSO and monsoon patterns by establishing a connection between regional deviations in monsoon rainfall and anomalies in SST across the tropical Pacific [38], [54], This is due to the role of SST anomalies as intermediaries in the coupling between the ocean and atmosphere [55]. In general, the monsoon circulation over the Indonesian domain is influenced by large-scale circulation changes resulting from a spatial shift in the zonal direction of the ascending and descending limbs of the Walker circulation. The impact becomes more intricate when the interaction is coupled with equatorial wave activity, such as the Madden-Julian Oscillation, which produces six distinct weather patterns with varying features in the Indonesian region, as suggested by authors in[39]. Figure 4 depicts a schematic diagram that illustrates the relationship between the ENSO and the monsoon. It succinctly presents the key findings of this section.

Impact of Indian Ocean on IMR Variability. In addition to Pacific Ocean SSTs, Indian Ocean SSTs significantly influence IMR variability. The moisture availability within the Indian region is intricately linked to the interactions occurring between the ocean and the atmosphere over the Indian Ocean. Thus, analyzing the convective systems and the ocean–atmosphere variability in the Indian Ocean is as crucial as in the Pacific to determine the variability of IMR. The ENSO phenomenon was the main driver of ISMR variability, and scientists focused on its mechanisms until the IOD was discovered [13]. Following the identification of the IOD, it became evident that the interconnected ocean-atmosphere phenomena occurring in the Indian Ocean have the potential to induce substantial climatic variations.

According to the findings of Author in [13], there exists a correlation between the intensity of the IOD and the gradients of SST in the east-west direction, as well as the anomalies in zonal wind patterns within the equatorial region of the Indian Ocean. They showed this mode is seasonally phase locked, Indian Ocean-specific, and ENSO-independent. A positive Indian Ocean IOD event is characterized by warm (cold) SST anomalies in the west (southeast) equatorial Indian Ocean, while a negative event is the opposite. Several studies were conducted following the discovery of IOD to investigate its characteristics, relationship with IMR, ENSO, and the climate of other tropical regions.

The impact of the IOD on IMR typically results in a reduction in seasonal rainfall during positive phases of the IOD, while an increase in precipitation is observed during negative phases except in western Kalimantan, central Sumatera and Java. Figure 5 presents the response patterns in seasonal rainfall.

The Authors in references [3], [12], [40] have indicated that an excess of rainfall in the Indonesian monsoon regime is correlated with positive IOD events, while negative IOD events are associated with a reduction in rainfall. It can also change the number of extreme rainfall in India by transferring moisture from the equatorial Indian Ocean to the Indonesian monsoon regime [3]. Thus, the IOD plays a significant role in both seasonal and interannual climate variations. Figure 6 depicts a schematic diagram that illustrates the relationship between the IOD and the IMR.

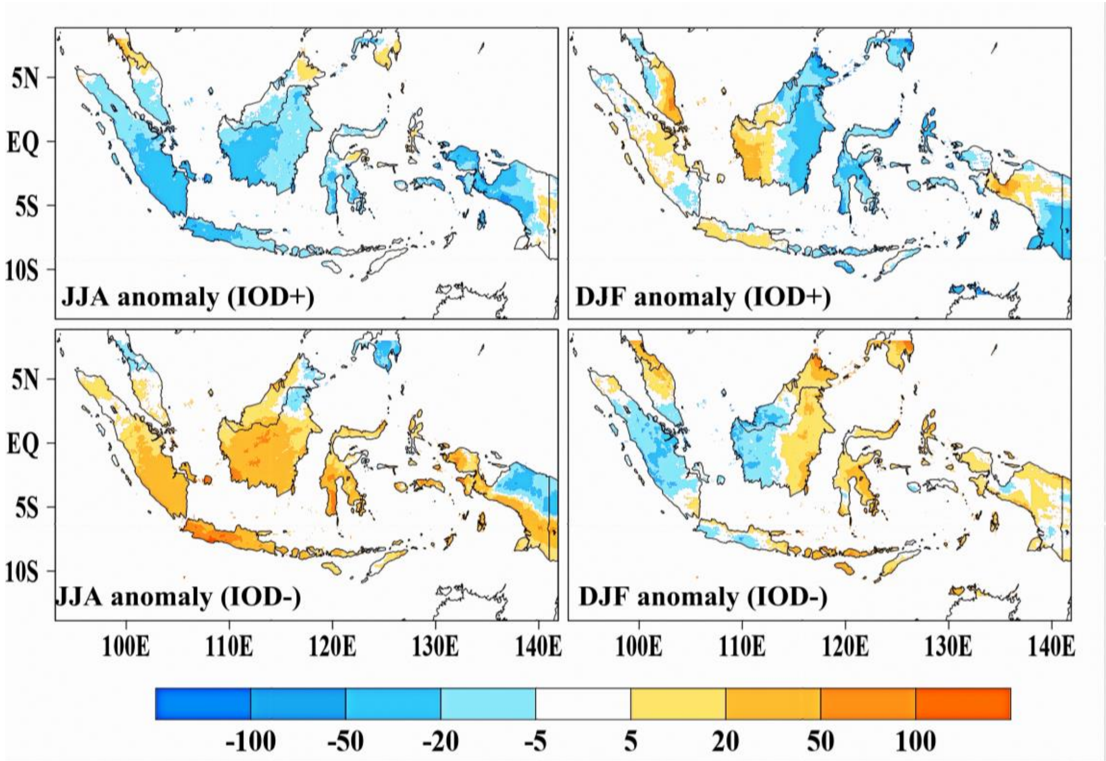

Figure 5 Composite of rainfall anomaly (mm/month) associated IOD (+) and IOD (-). CHIRPS Data from 1991 to 2020.

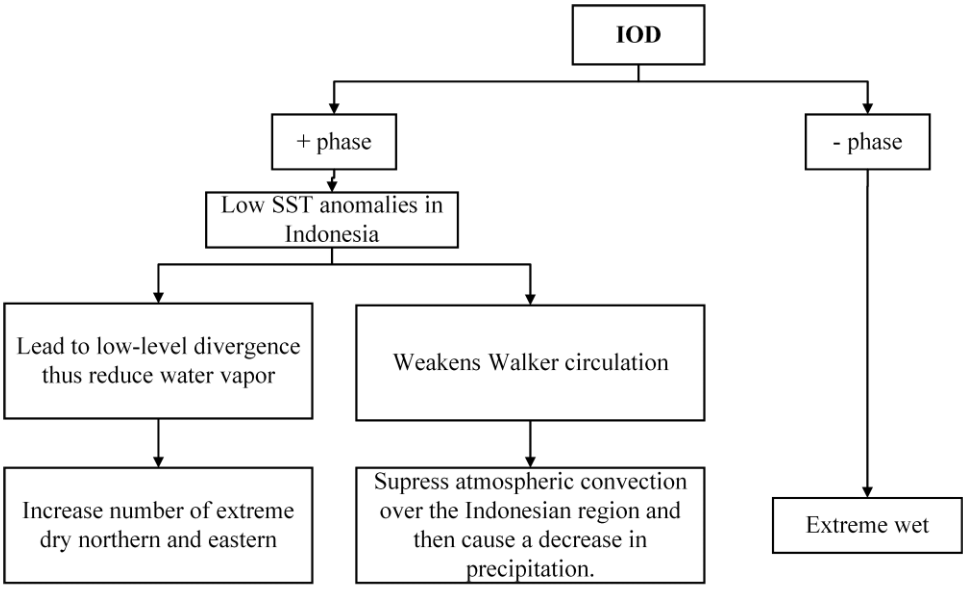

Figure 6 The IOD-IMR relationship is depicted schematically in this diagram.

Impact of PDO on IMR Variability. PDO brought on long-term variability, resulting in changes to the physical and biological environments in the surrounding area [56]. Transitions in long-term variables from one phase to another, or changes in a phase progression trend, are called climatic regime alterations [57]. Numerous studies have examined the effects of the PDO on precipitation in addition to variations in the frequency and magnitude of the canonical ENSO [53], [58], [59].

Investigating the relationship between the Pacific Decadal Oscillation (PDO) and rainfall patterns in Indonesia entails examining how the PDO influences variations in Indonesian precipitation. Authors in [17] reported that the warm (cold) phase of the PDO is associated with deficit (excess) of IMR. In this case, the warm (cold) PDO triggers a warming (cooling) trend over the tropical Pacific Ocean and a higher magnitude and frequency of El Nino (La Nina) events.

During the cold phases observed between 2007 and 2020, there is a notable presence of positive rainfall anomalies across most Indonesian regions (Figure 6). This positive anomalous rainfall is linked to anomalous easterly winds originating from the Pacific Ocean towards the Indonesian area, as well as anomalous westerly winds over the Indian Ocean that traverse Indonesia. These anomalous easterly and westerly winds are caused by negative Sea Surface Temperature Anomalies (SSTAs) in the eastern Pacific and western Indian Ocean [17].

During the warm phase PDO in 1982 – 2007, negative rainfall anomalies occur over the whole Indonesian region (Figure 7), in conjunction with anomalous westerly winds extending from eastern Indonesia to the Pacific Ocean and anomalous easterly winds spanning from western Indonesia to the Indian Ocean. These anomalous westerly and easterly winds can be attributed to positive Sea Surface Temperature Anomalies (SSTAs) in the eastern Pacific and western Indian Ocean. The described phenomenon resembles El Niño, wherein periods of drought in Indonesia during the dry season coincide with surface south-easterlies extending across and westward of Indonesia, ultimately reaching the west Indian Ocean [60].

The authors in [61] examine the fluctuations in Indonesian rainfall over a decade. The studies discovered that the primary component (PC1) of IMR indicates that the canonical ENSO, ENSO Modoki, and IOD are the main climate modes that impact the interannual changes in rainfall in Indonesia. Additionally, the PDO is a significant decadal phenomenon that influences the decade-long variations in rainfall. In addition, the IPO regulates the impact of IOD on rainfall in Indonesia. The influence is less pronounced during the positive IPO phase from 1979 to 1997, but more significant during the negative IPO periods from 1939 to 1978 and 1998 to 2016. The relationship between Indonesian rainfall and the conventional ENSO and ENSO Modoki, in relation to IPO phases, is not substantial. However, the impact of the ENSO Modoki (canonical ENSO) on the negative IPO phase during 1998-2016 is more pronounced (less pronounced) compared to earlier times. Figure 8 depicts a schematic diagram that illustrates the relationship between the PDO and the IMR.

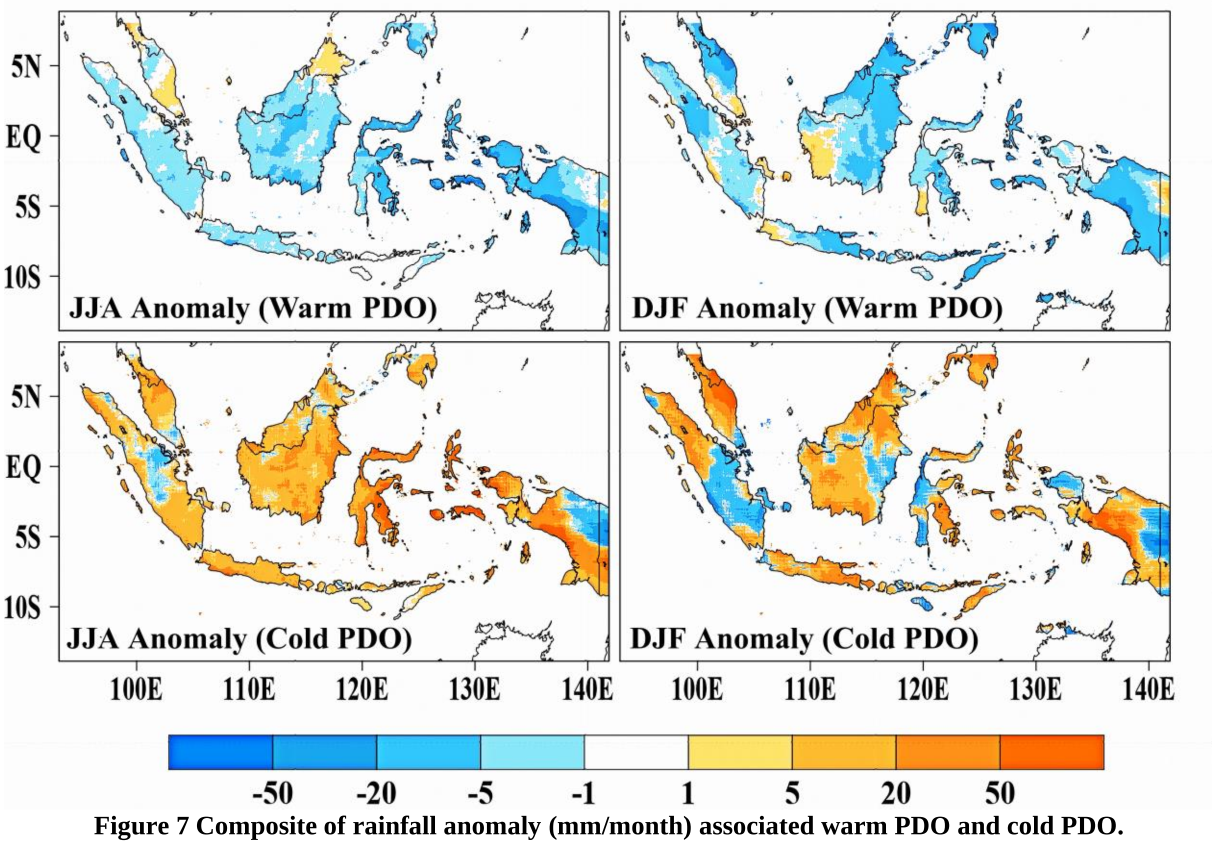

Figure 7 Composite of rainfall anomaly (mm/month) associated warm PDO and cold PDO.

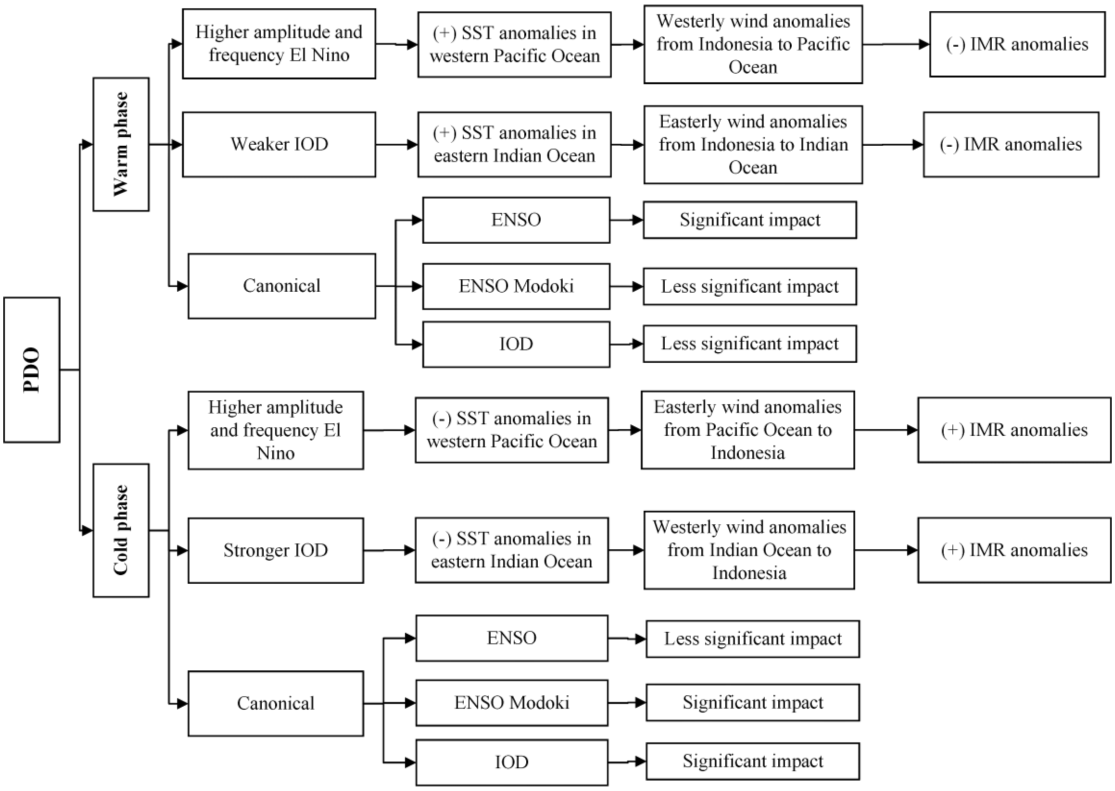

Figure 8 The IOD-IMR relationship is depicted schematically in this diagram.

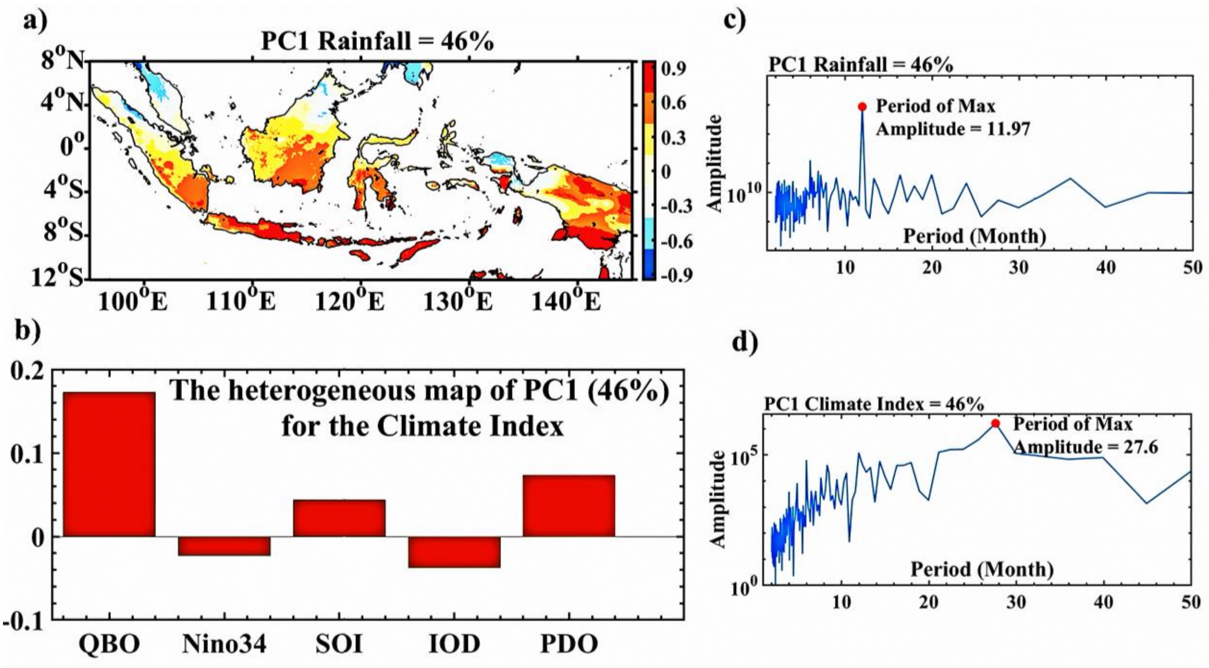

Figure 9. Spatial patterns of the first SVD mode, presented as homogenous and heterogenous correlation maps, respectively for: a) left field (Indonesian rainfall), b) right field (climate indices). The first PC explains 46% of the total covariance, whereas the PC time series exhibit a correlation of 0.86 (Correlations are significant at the 99% confidence level).

Covariability test of IMR and Climate Indices. In our preliminary study, we used singular value decomposition (SVD) to examine the co-variability between the IMR and the climate indices that serve as indicators of the climate driver in the tropical Indo-Pacific Ocean. The analysis indicates that the ENSO and the IOD do not emerge as the primary drivers of interannual variability of IMR. Figure 8a depicts the homogeneous and heterogenous correlation map of the first dominant mode associated with IMR variability (which accounts for 46% of the square covariance fractions).

The observed pattern exhibits comparatively higher loadings in the southern region of Indonesia, with loading values approximately equal to >0.6 for Indonesian rainfall (left fields). The observed spatial pattern bears resemblance to the Asian winter monsoon (Figure 9a). The PC time series anomalies show a prominent spectral peak for a one-year periodicity of FFT power spectrum, indicating a monsoon pattern (Figure 9c). The QBO index exhibits the primary mode within the homogeneous map of the first mode of the co-variability among the climate indices with loading values approximately equal to 0.2 (Figure 9b). The PC time series anomalies (Figure 9d) shows a prominent spectral peak for a two-year periodicity of the FFT power spectrum. Hence, forthcoming studies, for example, it is crucial to investigate the co-occurrence of the Quasi-Biennial Oscillation (QBO) and the Indonesian Monsoon Rainfall (IMR).

4. Conclusion and Future Directions

The interannual variability of Indonesian monsoon rainfall (IMR) in relation to climate modes over the Indo-Pacific Ocean has been thoroughly examined in our study. The analysis of various interannual climate modes reveals a consistent inverse relationship with precipitation patterns in Indonesia. The impact of the El Niño-Southern Oscillation (ENSO) on precipitation is dominant across the majority of Indonesia, encompassing a larger geographical extent compared to the region affected by the Indian Ocean Dipole (IOD). The impact of the ENSO exhibits varying degrees of regional variation, particularly in the western and southern regions of Indonesia. The precipitation patterns in response to the IOD phenomenon are primarily observed in the southwestern region of Indonesia. The impact of the transition from a positive to negative phase of the Pacific Decadal Oscillation (PDO) on Indonesian rainfall is a topic of interest in the study of interdecadal climate variability. The positive phase of the PDO in Indonesia is associated with a discernible reduction in rainfall, while the negative phase exhibits an observable augmentation in precipitation.

Extensive scholarly investigations have been conducted to examine the interannual variability in the Indonesian Monsoon Rainfall (IMR) and the significance of an exogenous factor in the tropical Indo-Pacific Ocean. Nevertheless, further investigation is required to ascertain the extent of its impact. There exists an additional biennial oscillation [e.g., quasi biennial oscillation (QBO)] in tropical regions that exerts a notable influence on the interannual variability of rainfall in Indonesia as indicated by Author in [51]. Moreover, Author in [62] revealed that Niño-3.4 and DMI forecasts are not needed as extra predictors to improve monthly precipitation due to no added value in ensemble model output statistics (EMOS) of ECMWF Seasonal Forecast System 5 (SEAS5).

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