COMPARATIVE STUDY OF MONSOON AND IOD EFFECTS ON RAINFALL VARIABILITY IN NORTH AND SOUTH SUMATRA

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ABSTRACT

Sumatra Island exhibits distinct rainfall characteristics between its northern and southern regions due to its equatorial position. Generally, Northern Sumatra displays a bimodal rainfall pattern driven by the movement of the Intertropical Convergence Zone (ITCZ), whereas Southern Sumatra follows a monomodal pattern influenced by the Asian-Australian Monsoon system. This study aims to evaluate the respective roles of the monsoon and the Indian Ocean Dipole (IOD) on rainfall variability in both regions from 1991 to 2020. Monthly rainfall data were analyzed using Continuous Wavelet Transform (CWT) to identify dominant periodicities. Subsequently, a Butterworth Bandpass Filter was applied to isolate monsoon-related (0.85-1.15 years) and IOD-related (3-5 years) signals, while Cross Wavelet Transform (XWT) was utilized to examine the coherence between rainfall variability and the climate indices (DMI and AUSMI). Furthermore, multiple linear regression was employed to assess the relative contributions of these indices. The results indicate that the annual monsoon cycle is the primary driver of rainfall variability in both regions. Meanwhile, the IOD's influence is more pronounced at inter-annual scales. Regression analysis reveals that DMI and AUSMI contributions are negligible in Northern Sumatra ($R^2 = 0.012$) but significant in Southern Sumatra ($R^2 = 0.356$). These findings highlight a clear divergence in climatic response, with Northern Sumatra predominantly governed by equatorial dynamics, while Southern Sumatra is highly sensitive to the combined variability of the IOD and the Australian monsoon.

Keywords: Rainfall variability, Monsoon, Indian Ocean Dipole, Wavelet, Sumatra.

1. Introduction

Sumatra Island, located within the Indonesian Maritime Continent, exhibits complex rainfall patterns due to its diagonal orientation across the equator. The Bukit Barisan mountain range contributes to distinct climate regimes in the island's northern and southern regions [1]. North Sumatra typically experiences a bimodal rainfall pattern, characterized by two primary rainy seasons each year, associated with the Intertropical Convergence Zone (ITCZ), where winds from the northern and southern hemispheres converge, enhancing precipitation. In contrast, South Sumatra exhibits a monomodal pattern, with a single main rainy season each year, predominantly influenced by the Asian-Australian Monsoon [2, 3].

Rainfall variability in this region is shaped by local air circulation, land-sea interactions, and broader climate anomalies at both global and regional scales [4]. On a seasonal basis, the Asia-Australia Monsoon governs the annual distribution of wet and dry periods [5, 6]. Furthermore, ocean-atmosphere interactions, such as the Indian Ocean Dipole (IOD), defined by irregular differences in sea surface temperatures (SST) between the western and eastern Indian Ocean, regulate humidity in the tropical Indian Ocean on an interannual basis [7, 8]. The positive phase of the IOD, characterized by warmer SST in the western Indian Ocean and cooler SST near Sumatra and Java, is closely associated with rainfall deficits in western Indonesia, frequently resulting in droughts and extensive forest and land fires [9, 10, 11].

Recent climate research has identified additional complexity arising from ocean-anomaly sub-variants. These include the Coastal IOD, an Indian Ocean Dipole event occurring near the Sumatran coast [12], and thermal oscillations known as the Java-Sumatra Niño/Niña (JSN). The JSN describes sea surface temperature fluctuations specific to the Java-Sumatra region that influence rainfall independently of the El Niño-Southern Oscillation (ENSO) in the Pacific [13]. The equatorial zone of northern Sumatra is particularly susceptible to short-term intraseasonal phenomena, including convective activity associated with the Madden-Julian Oscillation (MJO), an eastward-propagating disturbance of clouds and precipitation, and Kelvin wave propagation. These atmospheric waves frequently suppress seasonal signals and induce prolonged rainfall events [14].

Although both the IOD and monsoon circulation are associated with rainfall variability in Indonesia, limited research has quantified their respective roles within Sumatra's distinct climate zones. Most existing studies aggregate precipitation anomalies without distinguishing key periodicities between interannual and seasonal timescales [15]. The present study analyzes and compares the impacts of the monsoon and IOD on monthly rainfall variability in North and South Sumatra from 1991 to 2020. Enhanced understanding of these climatic drivers is anticipated to inform hydrometeorological disaster mitigation strategies for each province.

2. Methods

This study examines 30 years (1991-2020) of rainfall data from North and South Sumatra. The main precipitation records come from the CHIRPS v2.0 remote sensing database, with a spatial resolution of 0.05° [16]. CHIRPS is preferred due to its proven accuracy in identifying precipitation onset along Sumatra's coast [17].

Weather forcing is indicated by the Dipole Mode Index (DMI), which measures variations in the Indian Ocean Dipole (IOD) [7]. The monsoon circulation parameter is derived from zonal wind anomalies at the 850 hPa level (about 1.5 km above sea level) using ERA5 reanalysis data to calculate the Australian Summer Monsoon Index (AUSMI) [18].

The analysis began by normalizing monthly rainfall anomalies to remove the seasonal cycle. Next, the Continuous Wavelet Transform (CWT) with the Morlet wavelet was used to map dominant energy and trace non-stationary oscillation periods in the rainfall series [19, 20]. The Morlet wavelet is reliable for analyzing quasi-periodic climate dynamics, such as IOD interactions and monsoonal cycles.

The next stage is the filtering process for climate data decomposition. The Infinite Impulse Response (IIR) type Butterworth Bandpass Filter, a digital filtering method designed to isolate signals within a specified frequency range, was applied to two band blocks: (1) the 0.85-1.15 years range to filter the annual monsoon signal, and (2) a 3-5 years wide band to accommodate the interannual frequency of the IOD signal [15, 21]. The relationship between two variables, indicating whether they reinforce or weaken each other, is assessed using the Cross Wavelet Transform (XWT), a technique that analyzes how two time series interact in the time and frequency domains [22]. Finally, multiple linear regression quantified and compared the contributions of DMI and AUSMI to rainfall fluctuations across provinces.

3. Result and Discussion

Rainfall pattern in the study area. Rainfall data from 1991 to 2020 reveal distinct patterns in North and South Sumatra. North Sumatra exhibits a bimodal pattern, with two primary peaks occurring in March-April and October-November, likely reflecting the passage of the Intertropical Convergence Zone (ITCZ) across the equatorial region. Conversely, South Sumatra shows a monomodal pattern, with a single peak in December-January, attributable to the monsoon system.

These contrasting rainfall patterns underscore the role of distinct atmospheric mechanisms as primary drivers of precipitation in North and South Sumatra. In North Sumatra, equatorial dynamics exert a greater influence, whereas in South Sumatra, monsoon variability is the dominant factor. Figure 1 shows these regional rainfall patterns.

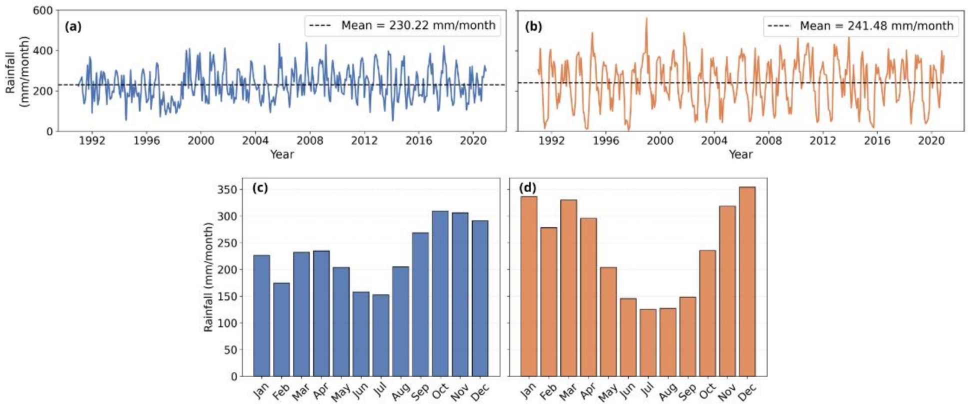

Figure 1 Monthly rainfall time series and climatological monthly rainfall in North Sumatra and South Sumatra for the period 1991-2020. Panels (a) and (b) show the monthly rainfall time series in North Sumatra and South Sumatra, respectively, while panels (c) and (d) show the average monthly rainfall, indicating a bimodal pattern in North Sumatra and a monomodal pattern in South Sumatra

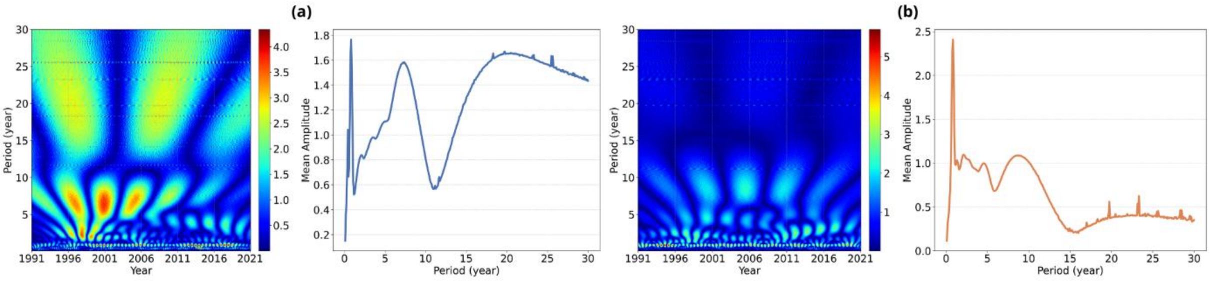

Figure 2 Continuous Wavelet Transform (CWT) spectra of rainfall in North Sumatra and South Sumatra. Panels (a) and (b) show the CWT spectra for North Sumatra and South Sumatra, respectively. The North Sumatra rainfall exhibits dominant annual, interannual, and long-term variability, whereas the South Sumatra rainfall is dominated mainly by annual variability

Multi-scale rainfall variability. Continuous Wavelet Transform (CWT) analysis indicates that annual signals, with a periodicity of approximately one year, dominate rainfall variability in both regions, reflecting the influence of the monsoon. Additionally, interannual variability in the 2-8 year range is observed and associated with global phenomena such as the Indian Ocean Dipole (IOD).

Figure 2 illustrates rainfall variation in North Sumatra, highlighting annual, interannual, and long-term (20-25 years) fluctuations. The presence of these variations suggests the influence of potential decadal phenomena. These findings demonstrate that seasonal, interannual, and long-term factors collectively affect rainfall in this region. In contrast, rainfall variability in South Sumatra is predominantly governed by the annual signal, indicating that monsoon variation is the principal influence. In comparison, interannual and long-term signals exert a substantially weaker impact, underscoring the monsoon's heightened sensitivity and control over rainfall in this region.

Monsoon and IOD signal. Application of the Butterworth bandpass filter reveals that the monsoon (0.85-1.15 years) component is dominant in both regions (Figure 3). The amplitude of the monsoon signal is higher in South Sumatra, averaging approximately 2.3, compared to North Sumatra.

The strength of the monsoon signal varies across specific years in each region, reflecting interannual differences in the intensity of the seasonal cycle in Indonesia. Contributing factors include the Asia-Australia monsoon, local sea surface temperature variations, and major climate modes such as ENSO and IOD [1].

The IOD signal (3-5 years) also influences rainfall, exhibiting distinct characteristics in each region. In North Sumatra, the IOD signal was pronounced during the early years of the study, diminished between 2005 and 2011, and subsequently intensified until 2020. This pattern indicates the variable influence of Indian Ocean dynamics on rainfall. Li [23] similarly reported fluctuations in sea surface salinity, which are likely associated with changes in the Indian Ocean.

In South Sumatra, the IOD signal was initially weak but became more pronounced after 2010. In both regions, the influence of the IOD on rainfall is inconsistent and is highly dependent on local geography and regional atmospheric interactions.

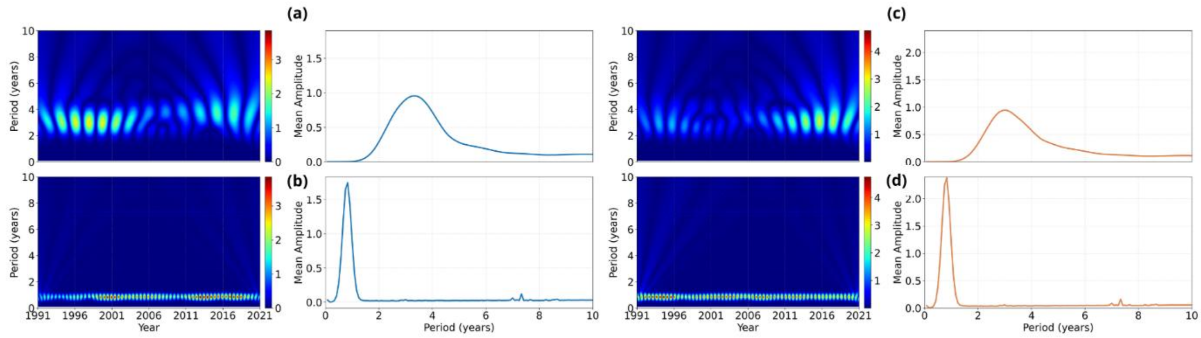

Figure 3 Rainfall variability derived from filtered rainfall spectra in North Sumatra and South Sumatra. Panels (a) and (b) illustrate the 3-5 year and 0.85-1.15 year variability in North Sumatra, respectively, while panels (c) and (d) show the corresponding variability in South Sumatra

Relationship between rainfall and climate phenomena. Cross Wavelet Transform (XWT) analysis demonstrates a relationship between rainfall and the Dipole Mode Index (DMI) at the interannual scale (3-5 years). Periods of coherence indicate that the IOD's influence on rainfall is episodic rather than constant, consistent with the IOD's inherent variability. Figure 4 illustrates this relationship, showing that coherence at the interannual scale indicates a strong association between IOD variability and rainfall in North Sumatra.

In South Sumatra, the relationship between rainfall and climate phenomena is also evident, though it exhibits distinct characteristics. The observed coherence indicates that the monsoon's influence is more consistent than the IOD's. Figure 4 demonstrates the predominance of the seasonal relationship between the monsoon and rainfall in South Sumatra

Furthermore, the relationship between DMI and AUSMI reflects interactions between global and regional climate phenomena. Figure 4 depicts this complex relationship, illustrating how both indices jointly influence rainfall variability in both regions. These findings suggest that rainfall variability is governed by multiscale interactions involving the monsoon system and global ocean-atmosphere processes, rather than by a single controlling factor.

Relative contribution of the monsoon and IOD. Multiple linear regression analysis reveals that the relative contributions of DMI and AUSMI differ between the two regions (Table 1). In North Sumatra, the regression model does not show a statistically significant relationship, suggesting that rainfall variability in this region is more likely influenced by factors other than the ITCZ or local atmospheric processes.

In contrast, the regression model for South Sumatra reveals a significant relationship, with AUSMI contributing positively and DMI contributing negatively. These results convey that increased monsoon intensity is associated with higher rainfall, whereas a positive IOD phase tends to reduce rainfall in the region. This finding reinforces the idea that South Sumatra is more strongly influenced by the combined dynamics of the monsoon and IOD than North Sumatra.

Variations in coefficient values demonstrate that the influence of the monsoon and IOD is region-specific and not uniform across Sumatra. The absence of significant effects from DMI and AUSMI in North Sumatra suggests the predominance of local factors and other equatorial phenomena, such as ITCZ movement and MJO dynamics, which are not examined in detail in this study.

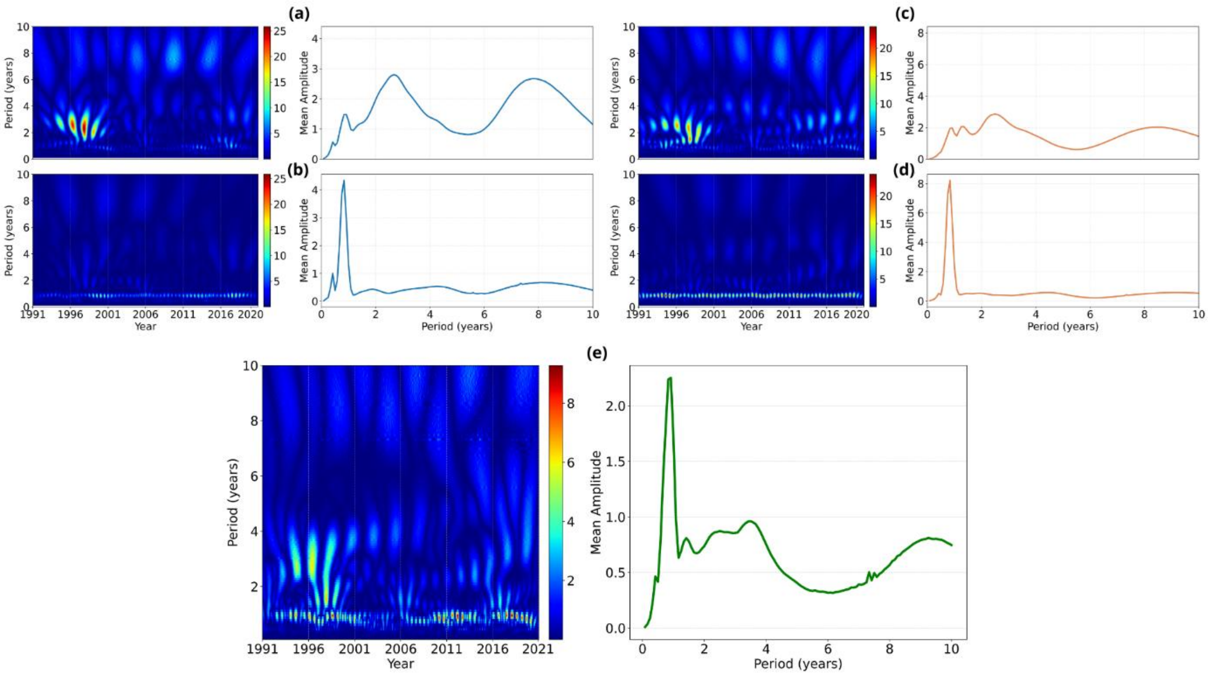

Figure 4 Cross Wavelet Transform (XWT) between rainfall, the Dipole Mode Index (DMI), and the Australian Monsoon Index (AUSMI). Panels (a) and (b) show the XWT between North Sumatra rainfall and DMI and AUSMI, respectively; panels (c) and (d) show the XWT between South Sumatra rainfall and DMI and AUSMI, respectively; and panel (e) shows the XWT between the DMI and AUSMI indices

Table 1 Linear regression results between rainfall, DMI, and AUSMI in North Sumatra and South Sumatra

Region	R^2	Variable	Koef.	p-value
Northern Sumatra	0.012	DMI	-0.2898	0.071, ns
		AUSMI	0.0434	0.411, ns
Southern Sumatra	0.356	DMI	-0.6531	0.001, sig
		AUSMI	0.5405	0.001, sig

4. Conclusion

This study investigates the roles of the monsoon and Indian Ocean Dipole (IOD) in influencing rainfall variability in North and South Sumatra from 1991 to 2020. The results demonstrate that the two regions exhibit distinct rainfall patterns where North Sumatra displays a bimodal pattern associated with equatorial dynamics, whereas South Sumatra predominantly exhibits a monomodal pattern more closely linked to the monsoon system.

Continuous Wavelet Transform (CWT) analysis indicates that the annual component is the most dominant signal in both regions, underscoring the monsoon's strong influence on rainfall patterns. Additionally, interannual variation over the 3-5 year range, associated with the IOD, was identified. In North Sumatra, the influence of the IOD was inconsistent throughout 1991-2020, whereas in South Sumatra, it became more prominent after 2010.

The results of the Cross Wavelet Transform (XWT) indicate that the relationship between rainfall and climate indices is discontinuous. The connection with DMI appears on the interannual scale, while the relationship with AUSMI is seen on the annual scale. These findings indicate that the monsoon influences seasonal patterns, while the IOD plays a larger role in interannual variation.

Regression analysis reveals differing responses between the two regions. In North Sumatra, the effects of DMI and AUSMI are not statistically significant, indicating that rainfall is more likely influenced by local factors or atmospheric processes specific to the equatorial region. Conversely, these two indices exert a stronger influence in South Sumatra.

Overall, the findings of this study indicate that rainfall variability in Sumatra cannot be attributed to a single mechanism. Each region exhibits distinct characteristics: North Sumatra is more strongly influenced by equatorial processes, whereas South Sumatra is more affected by the combined influence of the monsoon and IOD.

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