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[Research Article]

Analysis of Climate Parameters in the Coastal and Mountainous Regions of Papua According to ENSO and IOD Phenomena

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Abstract

Climate change is a global issue that affects many aspects of life, including rainfall and temperature patterns, which are often influenced by the El Niño-Southern Oscillation (ENSO) phenomenon. Papua, with its varied geographical and topographic characteristics, makes it an appropriate region for studying climate variability between coastal and mountainous areas. This study aims to understand climate variability in Papua by analysing differences in rainfall, temperature, humidity, and wind patterns between the two regions in the period 2007 to 2020. The method used in this study is comparative descriptive analysis, using data from the Wamena Meteorological Station and the Dok II Jayapura Meteorological Station. The data includes daily weather observations processed into monthly data, including rainfall parameters, temperature, humidity, direction, and wind speed. Mountainous areas have relatively more stable wind patterns than coastal areas, while ENSO and Indian Ocean Dipole (IOD) variability affect changes in wind circulation and water vapor distribution. These conditions are associated with decreased rainfall during El Niño and IOD+ phases and increased rainfall during La Niña and IOD- phases.

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Abstrak

Perubahan iklim merupakan isu global yang memengaruhi pola curah hujan dan suhu udara, yang salah satunya dipengaruhi oleh fenomena El Niño–Southern Oscillation (ENSO). Papua dengan variasi karakteristik geografis dan topografi menjadikannya wilayah yang tepat untuk mengkaji variabilitas iklim antara daerah pesisir dan pegunungan. Penelitian ini bertujuan menganalisis perbedaan curah hujan, suhu udara, kelembapan, dan angin di kedua wilayah tersebut selama periode 2007–2020. Metode yang digunakan adalah analisis deskriptif komparatif dengan data pengamatan cuaca dari Stasiun Meteorologi Wamena dan Stasiun Meteorologi Dok II Jayapura yang diolah menjadi data bulanan. Wilayah pegunungan memiliki pola arah angin yang relatif lebih stabil dibandingkan dengan wilayah pesisir, sementara variabilitas ENSO dan Dipol Samudra Hindia (IOD) berpengaruh terhadap perubahan sirkulasi angin dan distribusi uap air. Kondisi tersebut berkaitan dengan penurunan curah hujan pada fase El Niño dan IOD+ serta peningkatan curah hujan pada fase La Niña dan IOD-.

INTRODUCTION

Climate variability affects aspects of human life and the environment. Climate variability can be seen from differences in rainfall patterns (Suhadi et al., 2023; Susilokarti et al., 2015; Puspitasari & Surendra, 2016), average temperatures (Samidjo & Suharso, 2017; Ainurrohmah & Sudarti, 2022), and differences in extreme weather events (Nugroho et al., 2019; Andarini & Sudarti, 2023). In regions with complex geographical and topographical conditions, climate variability does not manifest uniformly but instead varies spatially according to elevation and atmospheric circulation. This highlights the importance of regional- and topography-based climate analysis, particularly in tropical regions where large-scale climate phenomena strongly interact with local environmental characteristics.

Papua is one of the regions in Indonesia with unique climate characteristics due to its equatorial location and pronounced topographic contrasts, ranging from coastal lowlands to high mountainous areas (Prentice & Hope, 2007). These conditions result in a clear climatic dichotomy between coastal and mountainous regions, leading to distinct spatial patterns of climate variability. Geographical and topographic differences between these two regions strongly influence key meteorological parameters such as rainfall, air temperature, humidity, and wind circulation (Alfiandy et al., 2020; Aldrian et al., 2011). In addition, the Pacific Ocean surrounding Papua plays an important role in modulating regional atmospheric circulation, particularly in coastal areas. Therefore, climate characteristics in Papua vary markedly with elevation, with distinct differences observed between areas below and above 2,500 m above sea level in terms of temperature, humidity, and rainfall patterns (Ibel et al., 2025).

Climatic characteristics in Papua vary significantly across regions because of elevation differences between coastal and mountainous areas (Gunawan, 2006). Coastal regions generally experience relatively stable air temperatures, high humidity, and more uniform rainfall patterns throughout the year (Abbasnia & Toros, 2020; Edwards, 1987). In contrast, mountainous regions are characterized by lower mean temperatures, greater thermal variability, and rainfall patterns that strongly depend on altitude and orographic processes (Prentice & Hope, 2007; Beniston, 2003). These contrasts are reflected in key climate parameters analyzed in this study, namely rainfall, air temperature, humidity, and wind circulation, which vary with elevation and regional atmospheric circulation. Such differences increase the sensitivity of both coastal and mountainous climates in Papua to large-scale climate variability, particularly El Niño–Southern Oscillation (ENSO), which significantly influences rainfall and temperature variability across the region (Ibel et al., 2025; Permana et al., 2016; Suwandi et al., 2014).

El Niño–Southern Oscillation is a major driver of climate variability, particularly in tropical regions such as Indonesia, where it strongly influences rainfall and air temperature patterns (Aldrian et al., 2007; Kirono & Tapper, 1999; Kripalani & Kulkarni, 1997). In Papua, the influence of ENSO is further modulated by complex topographic conditions, which can amplify or weaken climate responses depending on elevation and regional atmospheric circulation (Gunawan, 2006). As a result, coastal and mountainous areas may exhibit different responses to ENSO phases, with El Niño generally associated with reduced rainfall and higher temperatures, and La Niña linked to increased rainfall and lower temperatures (Kasihairani et al., 2014; Fitria & Pratama, 2013; Mulsandi et al., 2023).

In addition to ENSO, the Indian Ocean Dipole (IOD) also plays an important role in climate variability over Indonesia through sea surface temperature anomalies between the western and eastern Indian Ocean (Ashok & Saji, 2007). Positive IOD (IOD+) phases are generally associated with reduced rainfall over Indonesia, while negative IOD (IOD-) phases tend to enhance rainfall (Hermawan & Komalaningsih, 2008; Putra et al., 2017). Although the IOD exerts a stronger influence over western Indonesia, its interaction with ENSO has been shown to affect climate variability in eastern Indonesia, including Papua. In regions with complex topography, such as Papua, this interaction may lead to spatially different climate responses between coastal and mountainous areas, particularly in terms of rainfall variability and extreme weather events (Yamagata et al., 2004; Santoso et al., 2012).

Despite the well-documented influence of ENSO and the IOD on climate variability in Indonesia, studies that explicitly compare climate responses between coastal and mountainous regions in eastern Indonesia, particularly Papua, remain limited. Most previous research has focused on broader regional scales without adequately accounting for the combined effects of complex topography and large-scale climate drivers. Therefore, this study aims to analyze climate variability in Papua through a comparative descriptive approach between coastal and mountainous areas, focusing on key climate parameters including rainfall, air temperature, humidity, and wind circulation. The analysis is conducted for the overall study period (2007–2020) and during specific phases of ENSO (El Niño and La Niña) and IOD (positive and negative). By integrating topographic differentiation with large-scale climate phenomena, this research is expected to contribute to a more detailed understanding of spatial climate responses in Papua, providing scientific insight that can support regional climate assessment and climate-related planning in topographically complex regions.

METHOD

This research analyzes climate variability in Papua using nine meteorological stations at different elevations (Table 1). Stations are grouped into three physiographic zones based on elevation and coastal influence: coastal (0–25 masl), lowland (25–200 masl), and mountainous (>600 masl). This classification was applied to avoid elevation overlap and to distinguish climatic conditions associated with marine influence, inland lowland environments, and orographic processes. The study area is presented in Figure 1.

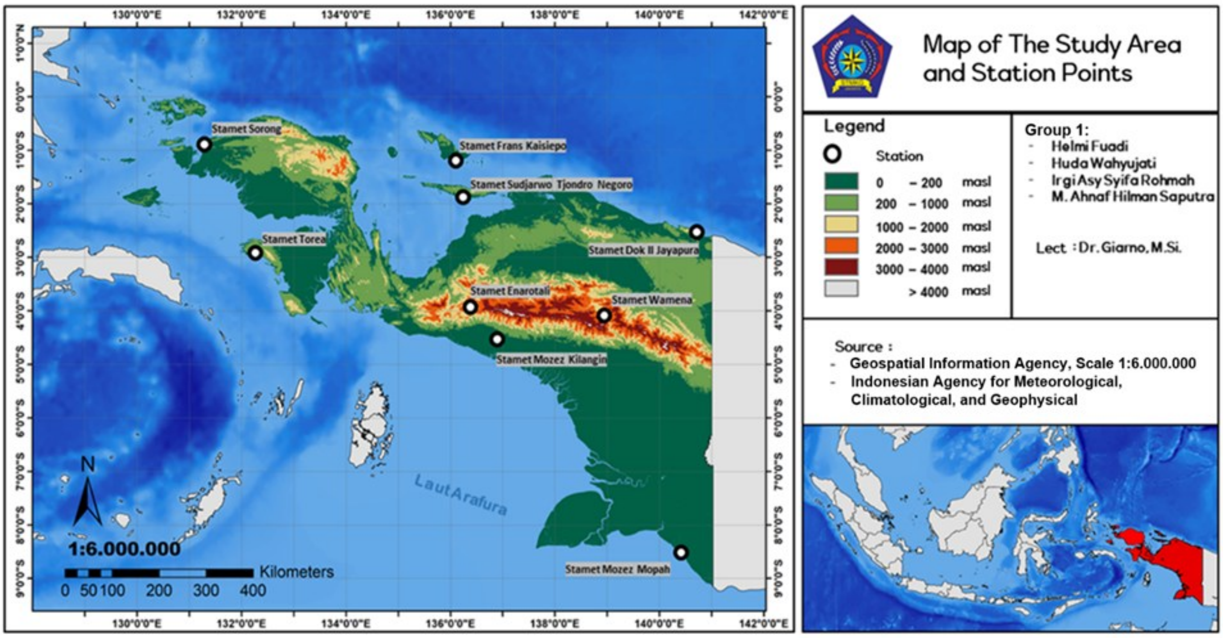

Figure 1. Study Area and Station Points in Papua

The data used in this study consist of surface weather observation data, including rainfall, air temperature, wind speed, and wind direction, recorded at BMKG meteorological stations during the period 2007–2020. These data were obtained from the global meteorological data archive OGIMET (https://www.ogimet.com/synopsc.phtml.en), which provides synoptic observation data transmitted through the World Meteorological Organization (WMO) network.

The research method applied in the comparative analysis of rainfall, temperature, humidity, direction, and wind speed uses a descriptive analysis approach supplemented by anomaly analysis and comparison with long-term normal climatological conditions, to provide a comprehensive picture and identify deviations in climate parameters during ENSO and IOD events at the research location (Susanto et al., 2024). Data collected over a certain period will be analysed using several statistical techniques, including the calculation of mean and standard deviation. Standard deviation is an algorithm used to find the average deviation in data (Sugiyono, 2009; Nafi'iyah, 2016).

Table 1. Sample Station Data

No.	Station Name	Latitude	Longitude	Elevation (masl)
1	Stamet Maritim Dok II Jayapura	-2,5302	140,7144	3
2	Stamet Domine Eduard Osok (Sorong)	-0,8912	131,2858	3
3	Stamet Sudjarwo Tjondro Negoro	-1,8754	136,2399	3
4	Stamet Mopah	-8,5202	140,4157	3
5	Stamet Frans Kaisiepo	-1,1907	136,1036	11
6	Stamet Mozez Kilangin	-4,5301	136,8935	41
7	Stamet Torea	-2,9194	132,265	130
8	Stamet Wamena	-4,0887	138,9465	1660
9	Stamet Enarotali	-3,9269	136,38	1770

Furthermore, this study compares climate parameters during El Niño and La Niña as well as IOD+ and IOD- years in the period 2007 to 2020, which were selected due to the availability of complete and consistent climate data for that period. The analysis was conducted by comparing it to neutral years, namely 2012, 2013, 2014, and 2020 (Table 2). Identification of strong El Niño and La Niña years was determined based on the El Niño index value of 3.4 issued by NOAA, with the threshold for strong El Niño at sea surface temperature anomalies of 1.5–1.9 °C (very strong ≥ 2.0 °C) and strong La Niña in the range of −1.5 to −1.9 °C (Huang et al., 2017). Data on the value of El Niño 3.4 can be accessed through https://origin.cpc.ncep.noaa.gov, while Data on the IOD index can be accessed through https://ds.data.jma.go.jp.

After determining the years with El Niño and La Niña phenomena, as well as IOD+ and IOD-, the climate element data from each station were grouped by year. Further analysis was carried out by comparing the climate parameter data obtained with normal climate conditions for the same period (2007-2020) to understand the dynamics of climate elements in coastal and mountainous areas during El Niño and La Niña events, as well as IOD+ and IOD-. The overall methodology flow can be seen in Figure 2.

Table 2. Years of ENSO and IOD Events

	La Niña	Neutral Condition	El Niño
Year	2007, 2008, 2010, 2011	2012, 2013, 2014, 2016, 2017, 2018, 2020	2009, 2015, 2019
	IOD-	**Neutral Condition**	**IOD+**
Year	2016	2007, 2008, 2009, 2010, 2011, 2012, 2013, 2014, 2015, 2020	2017, 2019

RESULT AND DISCUSSION

Rainfall

Papua has spatially and temporally variable rainfall patterns, influenced by the geographical characteristics of each region (Figure 3). Comparative analysis of rainfall at several meteorological stations shows striking differences between coastal, lowland, and mountain areas, as well as distinctive seasonal patterns in some locations. The coastal region, which includes Mopah, Sorong, Frans Kaisiepo, Sudjarwo Tjondro, and Dok II Jayapura Meteorological Stations, tends to have high rainfall throughout the year. Sorong station recorded the highest rainfall compared to other stations, especially in July (up to 800 mm), which is the peak of the main rainy season (Figure 4). The coastal region of Papua itself appears to have three rainfall patterns: monsoonal (Stamet Mopah and Dok II Jayapura), equatorial (Stamet Franskaisiepo, Sudjarwo, and Tjondro Negoro), and local (Stamet Sorong). Based on the research by Permana et al. (2016), the high rainfall in the coastal areas is attributed to local convective activity and the transport of moisture from the surrounding seas, such as the Banda Sea and the Arafura Sea. These processes are driven by seasonal wind patterns and the influence of the Intertropical Convergence Zone (ITCZ).

The lowland region, represented by Mozez Kilangin and Torea stations, shows different rainfall patterns. Torea Station, like Enarotali in the mountainous region, has a local pattern, with peak rainfall in April to August. Meanwhile, Mozez Kilangin Station shows

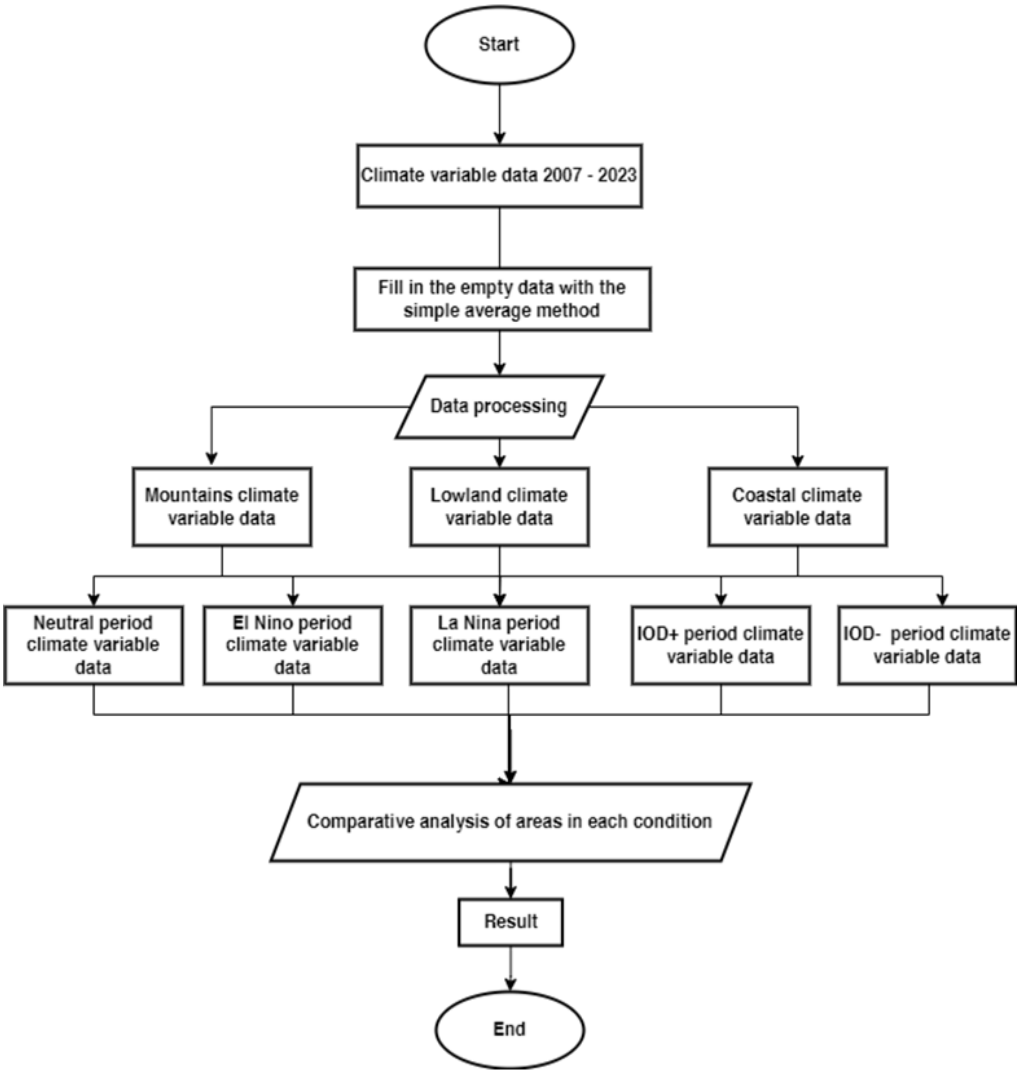

Figure 2. Flowchart of Methodology

higher rainfall than in Torea, which could be due to local microclimate conditions or topographic influences. These lowland stations act as transitional zones between coastal and mountainous climates, showing mixed characteristics influenced by both topography and local circulation.

The mountainous region, which includes Enarotali and Wamena stations, shows lower rainfall characteristics than the coastal and lowland areas. The rainfall pattern in Enarotali also follows an equatorial pattern. In contrast, Wamena records lower rainfall with a monsoonal pattern. This reduction in rainfall within mountainous areas may be attributed to orographic effects and localized rain-shadow processes that effectively limit moisture availability.

Research by Rouw et al. (2014) revealed that Papua has three main patterns of rainfall: monsoonal, equatorial, and local, which are divided based on topography and geographical location. Coastal areas tend to be wet throughout the year due to the transport of water vapor from the ocean, ITCZ activity, and seasonal winds. Lowlands, such as Mozez Kilangin, receive more rainfall than Torea due to microclimatic and topographic influences. In the mountains, rainfall is lower, with Wamena following a monsoonal pattern and Enarotali following an equatorial pattern. These variations reflect the complex interactions between topography, global atmospheric dynamics and local wind circulation.

El Niño generally causes a decrease in rainfall throughout Papua. The impact is most significant in coastal areas, such as Mopah and Sorong Stations, especially in the peak months of the rainy season, such as November to December (± 50 mm). This decrease reflects the

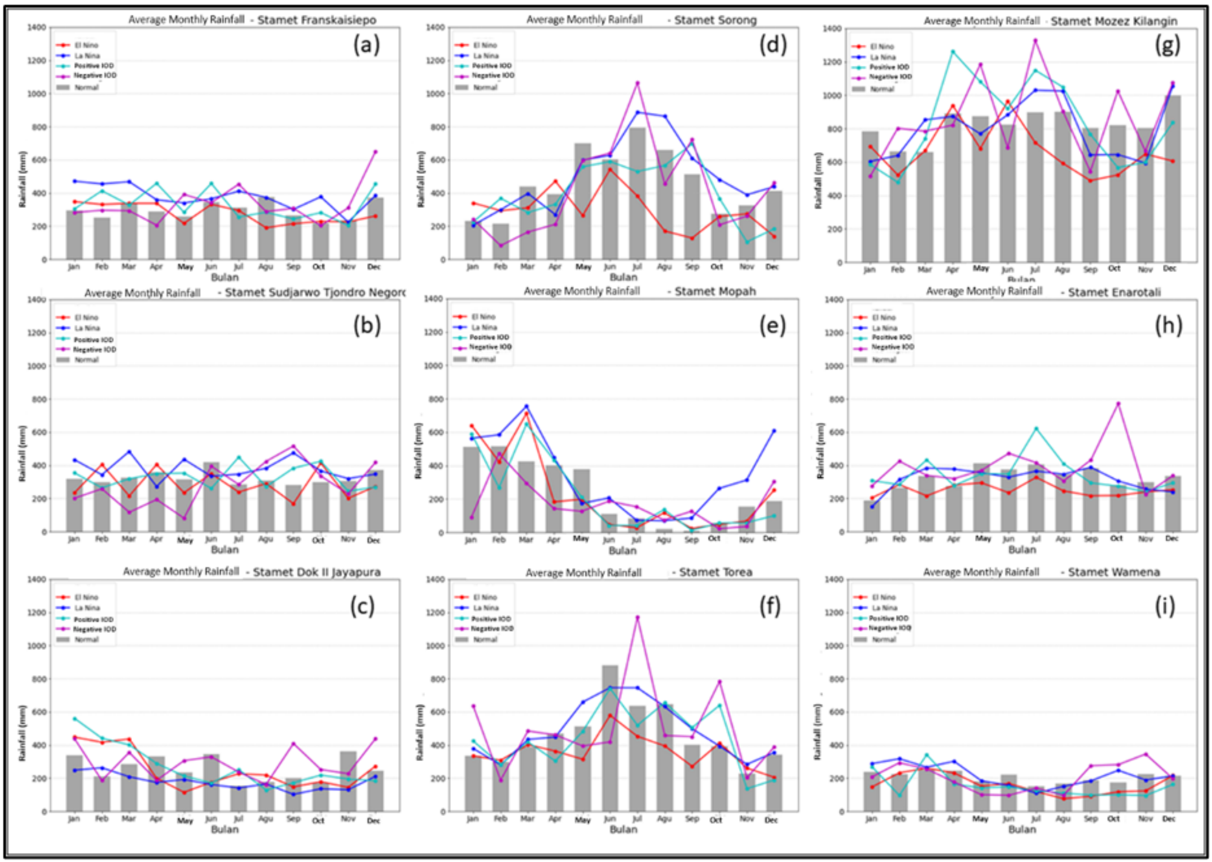

Figure 3. Rainfall of Coastal (a, b, c, d, and e), Lowland (f and g), and Mountainous (h and i) Areas each Year under El Niño, La Niña, IOD+, IOD-, and Normal Phenomena

influence of El Niño in reducing humidity in the tropics due to the weakening of water vapour flow from the Pacific Ocean. In lowland areas, such as Torea and Mozez Kilangin, El Niño also resulted in a marked reduction in rainfall, especially during the dry season, such as September. Mozez Kilangin station recorded a rainfall decrease of up to 300 mm, while Torea station showed a reduction of 100 mm. Meanwhile, mountainous areas, such as Enarotali and Wamena, experienced a more moderate impact compared to the coast and lowlands, but still showed a reduction in rainfall (20 to 80 mm).

La Niña, in contrast, significantly increased rainfall across Papua. This increase is most striking in the coastal areas, especially at Mopah (up to 400 mm) and Sorong stations (up to 200 mm), during the wet season. Lowland areas also experience higher rainfall during La

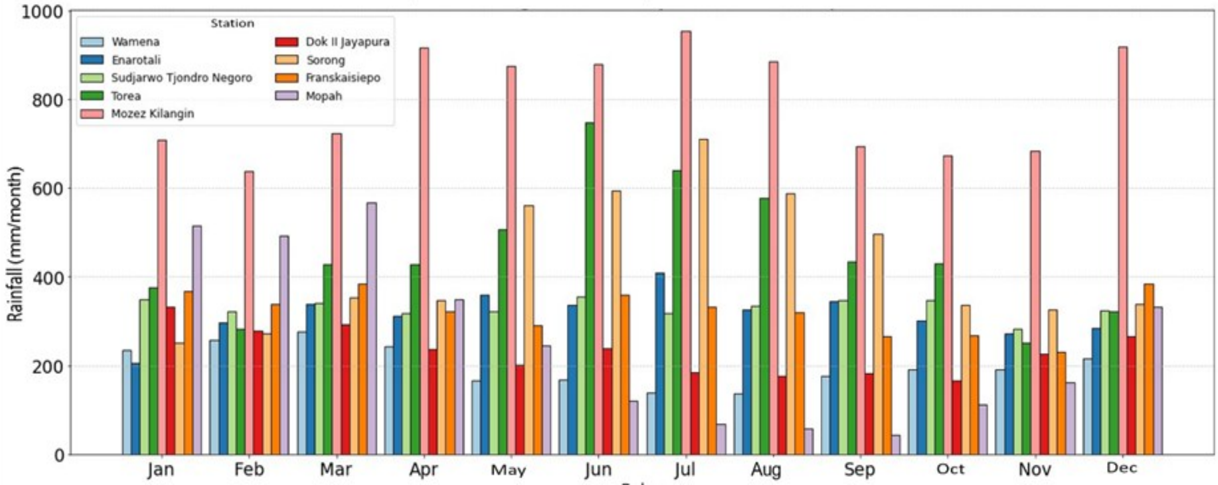

Figure 4. Comparison of Rainfall at the Papua Observation Station

Nina, with increased intensity seen at Mozez Kilangin and Torea Stations (±100 mm). Meanwhile, in mountainous areas such as Enarotali and Wamena, La Niña resulted in a more moderate increase in rainfall compared to other areas (only up to 50 mm). This suggests that La Niña's influence reinforces tropical rainfall patterns, with the greatest impact in lower elevations. Overall, the impact of La Niña on rainfall is strongest in coastal areas and gradually weakens with increasing elevation.

IOD+ has a similar impact to El Niño, but with a less extreme reduction in rainfall. In coastal areas, such as Frans Kaisiepo and Sudjarwo Tjondro, rainfall during IOD+ tends to be lower than normal, especially in the wet season. Lowland areas also show the same pattern, with moderate decreases in Torea and Mozez Kilangin. In mountainous areas, such as Enarotali and Wamena, the impact of IOD+ tends to be weaker compared to El Niño, suggesting that the influence of this phenomenon is more significant at lower elevations. Overall, IOD+ reduces rainfall in Papua, but not as strongly as El Niño.

On the other hand in IOD-, strengthened rainfall across Papua. The increase in rainfall was most striking in coastal areas, such as Mopah and Sorong, which even recorded higher rainfall than La Niña conditions in the wet months. Lowland areas, such as Mozez Kilangin and Torea, also recorded increased rainfall during IOD-, especially in the wet season. In mountainous areas, such as Enarotali, the influence of IOD- was also evident with a significant increase in rainfall, although in Wamena the impact was more moderate. This suggests that IOD- tends to strengthen rainfall patterns in Papua, with the greatest effects in coastal and lowland areas. Compared to IOD, ENSO exerts a stronger and more consistent influence on rainfall variability across Papua, particularly in coastal regions.

Wind

The results show that ENSO and IOD events significantly affect wind characteristics in Papua, primarily by increasing wind speed across all regions. Wind direction variability is most pronounced in coastal areas, where directions become more diverse than under normal conditions. In contrast, mountainous areas exhibit relatively stable wind directions, with only minor directional shifts observed, despite a clear increase in wind speed during El Niño, La Niña, IOD+, and IOD- events. The spatial distribution of wind speed under normal conditions (all years), IOD+, IOD-, La Niña, and El Niño is shown in Figure 5 below.

During active El Niño conditions, wind speeds increase markedly across coastal and island regions of Papua, accompanied by strong variability in wind direction compared to normal conditions. This pattern is evident at Stamet

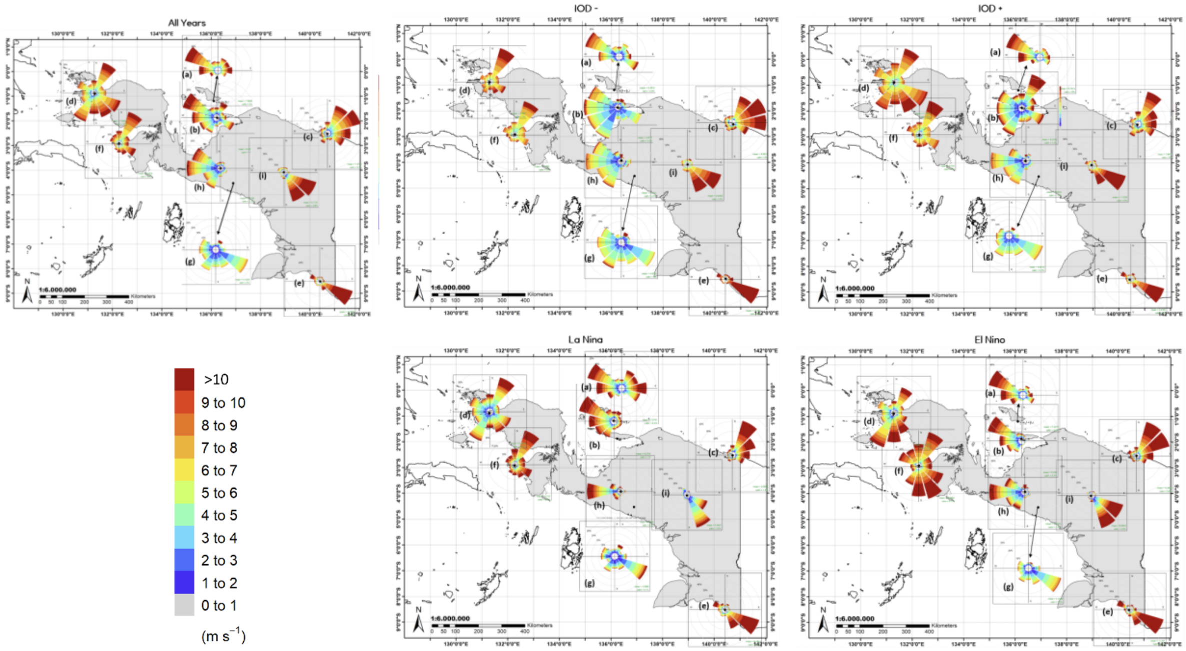

Figure 5. Spatial distribution of wind speed under normal conditions (all years), IOD+, IOD-, La Niña, and El Niño

Mopah (Figure 3e), Stamet Mozez Kilangin (Figure 3g), Stamet Torea (Figure 3f), and Stamet Sorong (Figure 3d), where winds that are typically dominated by southeasterly flow become highly variable, with strong flows originating from multiple directions. This variability is associated with weakened easterly trade winds and Walker circulation due to low-pressure anomalies in the western Pacific during El Niño events (Bjerknes, 1969; Surmaini & Faqih, 2016), leading to reduced moisture transport and decreased rainfall (Aldrian & Dwi Susanto, 2003). Similar directional variability is also observed at Stamet Frans Kaisiepo on Biak Island (Figure 3a) and Stamet Sudjarwo Tjondro Negoro on Yapen Island (Figure 3b), where local circulations such as sea–land breezes further modulate wind patterns due to the stations' island and coastal settings (Simpson, 1994).

In contrast, highland regions exhibit a more stable wind direction during El Niño conditions, despite experiencing increased wind speeds. Observations at Enarotali Station (Figure 3h) show only a minor shift in dominant wind direction from northwest to west, indicating limited directional variability compared to coastal areas. A similar response is observed at Wamena Station (Figure 3i), where wind direction remains relatively stable. Nevertheless, El Niño conditions are associated with reduced rainfall in the highlands, particularly in Wamena, where monthly rainfall drops below 150 mm in August, despite the region normally experiencing equatorial rainfall throughout the year with monthly totals exceeding 150 mm (Prentice & Hope, 2007).

During La Niña conditions, wind speeds increase and wind direction becomes more variable in coastal areas. The strengthened wind flow during La Niña enhances moisture transport from the Pacific Ocean, directly contributing to increased rainfall in most regions of Papua. When La Niña is active, low pressure occurs in the Western Pacific which makes trade winds and walker circulation stronger, bringing moisture from the Pacific Ocean (Philander, 1990; McPhaden et al., 2006) which has an impact on increasing rainfall in Papua. On the map, it can be seen that the dominant wind direction is from the Western Pacific Ocean and there are variations from local factors, especially on the coast of Biak Island (Figure 3a) according to the observations of Stamet Frans Kaisiepo, the coast of Jayapura (Figure 3c), Sorong (Figure 3d), and the coast of Fakfak according to the observations of Torea Station (Figure 3f). The impact of increased rainfall due to the flow of air masses from the Pacific Ocean can be seen from Figure 3 in almost all areas of Papua, except the Jayapura area (Figure 3c).

Although La Niña generally increases rainfall, Jayapura can experience decreased rainfall due to complex interactions between local and global factors (Permana, 2011; Permana et al., 2016). The mountainous region also experienced the same thing, namely an increase in wind speed with a lower variation in wind direction than the coast. A shift in wind direction occurred in Enarotali (Figure 3h), like the conditions when El Niño is active which may be related to local factors such as sea breezes because although it is a mountainous area, it is located close to the coast. The effect of increased rainfall in the mountains due to La Niña is insignificant when compared to the coastal areas.

During the active IOD+, divergence occurs in the Indonesian region resulting in eastward wind flow due to warming sea surface temperatures in the western Indian Ocean (Saji et al., 1999). The wind flow weakens the walker circulation and trade winds and has an impact like El Niño conditions, namely a reduction in rainfall due to reduced moisture supply from the Indian Ocean. However, increased rainfall occurs during IOD+ in Central Papua recorded from Stamet Mozez Kilangin (Figure 3g) and Stamet Enarotali (Figure 3h) due to the complexity of regional climate factors such as increased tropical convection (Yustiana et al., 2023) and local factors of Indo-Australian monsoon activity (Nuryanto, 2012) as well as land-sea winds affecting atmospheric dynamics in the region (Syaifullah, 2015). Overall, the impact of the IOD+ in Papua is an increase in wind speed and variation in wind direction which results in a decrease in rainfall in some areas.

When the IOD- is active, sea surface temperatures in Indonesian waters are warmer so that winds from the Indian Ocean tend to be stronger and create wind patterns from west to east. Convergence occurs in Indonesian waters which has an impact on variations in wind direction. The walker circulation and easterly trade winds are strengthened resulting in increased moisture supply and higher than normal rainfall in certain months (Figure 3). However, a reduction in rainfall can occur in certain months when the IOD is negative as shown in the observations of Stamet Frans Kaisiepo on Biak Island (Figure 3a), Stamet Sudjarwo Tjondro Negoro on Yapen Island (Figure 3b), Stamet Sorong (Figure 3d), and Stamet Mopah (Figure 3e). The reduction in rainfall when the IOD- is active may occur due to fluctuations in the local wind system. Overall, wind and rainfall responses associated with the IOD in Papua exhibit greater spatial heterogeneity than those related to ENSO, reflecting stronger modulation by local and regional atmospheric processes. In contrast, ENSO-driven wind variability tends to be more coherent and spatially extensive, particularly in coastal and lowland areas.

Overall, the results demonstrate that climate variability in Papua is strongly modulated by elevation and proximity to the coast, consistent with the main objective of this study to compare coastal and mountainous climate responses to ENSO and IOD. Rainfall and wind characteristics show the most pronounced variability in coastal regions, where changes in large-scale atmospheric circulation during El Niño, La Niña, and IOD phases directly affect moisture transport and wind patterns. Coastal areas experience significant rainfall reduction and increased wind variability during El Niño and IOD+, while enhanced rainfall and stronger winds occur during La Niña and IOD-events.

Mountainous regions exhibit more moderate rainfall anomalies and relatively stable wind directions, indicating the dominant role of topographic control in regulating local climate responses. Although both ENSO and IOD influence rainfall and wind variability in Papua, ENSO exerts a more dominant and spatially coherent impact, particularly in coastal and lowland areas. These findings confirm that topography-based (coastal–mountainous) analyses provide a more representative framework for assessing climate variability in Papua than generalized regional approaches.

The findings indicate that the climate response to ENSO and IOD in Papua is not spatially uniform but is strongly influenced by elevation and proximity to the sea. ENSO plays a more dominant role than IOD in modulating rainfall and wind variability, particularly in coastal areas where large-scale atmospheric circulation changes strongly affect moisturizing transport. This study highlights that climate assessments based on topographic differentiation between coastal and mountainous regions are more effective for understanding climate variability in Papua than broad regional classifications.

From a practical perspective, the results suggest that coastal regions of Papua are more vulnerable to drought during El Niño events and to extreme rainfall during La Niña and IOD-phases. The identified spatial differences in rainfall and wind responses can support the development of early climate warning systems, improve adaptation planning, and enhance area-based climate risk management, particularly for coastal and lowland communities.

This study has several limitations. First, the analysis relies on data from only nine meteorological stations, which may not fully represent the spatial complexity of Papua's climate, especially in remote mountainous regions. Second, the descriptive analytical approach does not quantify the statistical strength of relationships between climate parameters and ENSO or IOD indices. Third, the study focuses solely on ENSO and IOD, without considering other influential climate drivers such as the Madden–Julian Oscillation, regional monsoon systems, and local mesoscale processes. Finally, station-based wind and rainfall observations may be affected by local microclimatic conditions that are not fully captured in broader regional analyses.

CONCLUSION

The difference between the two regions is in the variation of wind direction, where the mountainous region, in this case, shows higher stability compared to the coastal region. Climate variability from ENSO and IOD phenomena affects wind circulation, especially in lowland and coastal areas. Changes in air circulation that carry moisture masses result in the effect of reducing rainfall during positive El Niño and IOD events. Meanwhile, the effects of La Niña and IOD- events result in increased rainfall than normal.

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