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Historical Geospatial Analysis of Tropical Cyclone Intensity and Rainfall Variability in Alor Regency, Indonesia

Thomas Y. Blegur[1*], Khomsin[2]
Badan Meteorologi, Klimatologi, dan Geofisika, Alor, Indonesia[1]
Institut Teknologi Sepuluh Nopember, Indonesia[2]
Email: thomasblegur@bmkg.go.id*

ABSTRACT

Tropical cyclones rarely make landfall in Indonesia; however, their indirect influence can substantially affect regional rainfall variability, particularly in eastern Indonesia. This study aims to analyze the historical geospatial characteristics of tropical cyclone intensity and to quantify their contribution to rainfall variability in Alor Regency, East Nusa Tenggara, over the period 1996–2024. The analysis integrates tropical cyclone best-track data, in-situ daily rainfall observations, and satellite-based rainfall estimates. Geospatial techniques were applied to examine cyclone track density, spatial exposure, and seasonal patterns, while statistical analyses—including descriptive statistics, non-parametric correlation, and linear and non-linear regression—were employed to evaluate temporal variability in maximum wind intensity. The results indicate that tropical cyclone activity in the surrounding region is strongly seasonal, with peak occurrences during the wet season months, while cyclone intensity is dominated by low- to moderate categories and exhibits no statistically significant long-term trend. Rainfall analysis reveals that tropical cyclones contribute substantially to monthly rainfall totals, particularly during the early and late phases of the rainy season, when cyclone-related rainfall accounts for a large proportion of climatological monthly rainfall. Spatially, higher rainfall sensitivity is observed in eastern and southern Alor, reflecting the combined effects of moisture advection from nearby seas and local orographic enhancement. These findings demonstrate that tropical cyclones play a critical indirect role in shaping rainfall variability and hydrometeorological risk in Alor Regency, highlighting the importance of incorporating cyclone-related rainfall influences into regional climate assessment, disaster risk reduction, and adaptation planning.

Keywords: *Alor regency; geospatial analysis; rainfall variability; tropical cyclones*

INTRODUCTION

Tropical cyclones are synoptic-scale atmospheric systems characterized by intense low-pressure centers, closed circulation, and strong surface winds. These systems typically develop over warm tropical oceans where sea surface temperatures exceed *26.5 °C*. Their formation and intensification are governed by complex ocean–atmosphere interactions, including ocean heat content, atmospheric moisture, vertical wind shear, and the Coriolis force. Consequently, tropical cyclones rarely form near the equator, and Indonesia is not classified as a primary tropical cyclone genesis or track region. Nevertheless, increasing observational evidence indicates that tropical cyclones developing in adjacent basins can exert substantial influence on atmospheric circulation and rainfall patterns over Indonesia (Fine et al., 2016; Napitupulu, 2025; Satiadi et al., 2025; Syamsudin et al., 2025).

Southern and eastern Indonesia are particularly vulnerable to the indirect impacts of tropical cyclones originating from the southern Indian Ocean and the Australian region. These systems can enhance low-level convergence, intensify moisture transport, and promote deep convection, leading to extreme rainfall events even when cyclone centers remain far offshore. Recent studies have shown that, under a warming climate, tropical cyclones are increasingly contributing to rainfall extremes over the Maritime Continent, including Indonesia (Chang et al., 2021; Zhang et al., 2022). Such indirect impacts pose serious hydrometeorological risks, especially for small islands with limited adaptive capacity. The catastrophic impacts of *Tropical Cyclone Seroja* in April 2021 clearly demonstrated this vulnerability, as extreme rainfall triggered widespread flooding and landslides across East Nusa Tenggara, resulting in severe infrastructure damage and significant loss of life (Alves, 2022; CLIMA & Te, 2021; Hagenlocher et al., 2022; Jasmine et al., 2021).

Numerous studies have examined the contribution of tropical cyclones to rainfall variability at global and regional scales. Holland (1993) demonstrated that the spatial extent of tropical cyclone circulation allows atmospheric influences to propagate several hundred kilometers from the cyclone center. Frank and Young (2007) highlighted inter-basin variability in tropical cyclone activity across the Indo-Pacific region, emphasizing the interconnected nature of cyclone dynamics. More recent global analyses have shown that tropical cyclones contribute substantially to seasonal and interannual rainfall variability, particularly in coastal and island regions (Dare et al., 2012; Khouakhi et al., 2017). Updated climatological assessments further indicate that tropical cyclone–related rainfall accounts for a significant fraction of extreme precipitation events worldwide (Gori et al., 2022; Lavender & McBride, 2021; Mazza & Chen, 2023; Messmer & Simmonds, 2021).

In the context of the Maritime Continent, Kubota and Wang (2009) demonstrated that tropical cyclones enhance rainfall through moisture advection and convective amplification. Building on this, Feng et al. (2022) showed that tropical cyclones play a critical role in modulating extreme rainfall over the Maritime Continent, even in regions distant from cyclone tracks (Amirudin et al., 2020; Li et al., 2023; Tridaiana & Marzuki, 2023; Trismidianto et al., 2024). Additionally, recent attribution studies suggest that anthropogenic warming has intensified tropical cyclone–related rainfall, increasing flood risk in vulnerable regions (CHHIN et al., 2016; Hermawan et al., 2022; Mulyana et al., 2018; Yulianti et al., 2025).

Despite the growing body of literature, most previous studies have emphasized regional to global scales using relatively coarse spatial resolution (Benavidez et al., 2018; Bhaga et al., 2020; Huang et al., 2020; Zhou et al., 2018). As a result, the local-scale response of rainfall to variations in tropical cyclone intensity, distance, and duration remains insufficiently understood. In particular, limited attention has been given to historical geospatial characteristics of tropical cyclone intensity and their quantitative contribution to rainfall variability at sub-regional or district levels. This gap is especially evident in small island regions, where topography, exposure, and limited observational networks may strongly modulate cyclone-related rainfall impacts.

Alor Regency, located in eastern East Nusa Tenggara and south of the equator, lies in close proximity to the tropical cyclone development region of the southern Indian Ocean. The region exhibits a monsoonal rainfall regime, characterized by a single dominant wet season and a prolonged dry season. Rainfall variability in *Alor Regency* has critical implications for water resources, food security, and hydrometeorological disaster risk. However, to date, no comprehensive study has integrated a *historical geospatial analysis of tropical cyclone* *intensity* with a quantitative assessment of cyclone-related rainfall contributions at the local scale in this region.

Therefore, this study aims to analyze the historical spatiotemporal characteristics of tropical cyclone intensity around East Nusa Tenggara and to quantify their contribution to monthly and annual rainfall variability in *Alor Regency*. By integrating long-term tropical cyclone records with rainfall observations within a geospatial analytical framework, this research addresses a critical knowledge gap in cyclone–rainfall interactions at the local scale. The findings are expected to provide robust scientific evidence to support hydrometeorological risk assessment, climate-resilient regional planning, and the development of more effective early warning systems for extreme weather events in small island regions of eastern Indonesia.

METHOD

This research adopts a quantitative, observational, and retrospective design, based entirely on secondary geophysical and meteorological datasets. No surveys, interviews, or experimental interventions were conducted. The methodological framework integrates descriptive statistical analysis, geospatial analysis, and time-series statistical modeling to address the formulated research questions.

The locus of this study is Alor Regency, East Nusa Tenggara Province, Indonesia, located between 123°–125° E and 6°–8° S. The region is characterized by a monsoonal rainfall regime with a single dominant wet season and a relatively long dry season. Geographically, Alor Regency lies south of the equator and in close proximity to the tropical cyclone development region of the southern Indian Ocean, making it particularly susceptible to indirect impacts of tropical cyclones, especially enhanced rainfall and strong winds.

This study also considers a broader spatial domain (5°–20° S and 110°–135° E) to capture tropical cyclone systems that potentially influence rainfall over East Nusa Tenggara and Alor Regency.

Data Collection

1. Tropical Cyclone Data

Historical tropical cyclone data for the period 1996–2024 were obtained from the Australian Bureau of Meteorology (BoM). The dataset includes cyclone position, maximum sustained wind speed, central pressure, and cyclone duration. Only cyclones occurring within the defined spatial domain were selected to ensure relevance to the study area.

2. Rainfall Data

Rainfall data were collected from two primary sources:

a. Satellite-based rainfall data from the CHIRPS v2.0 dataset, including:
   1) Daily rainfall data (1996–2024)
   2) Monthly rainfall data (1991–2020) used to construct 30-year climatological normals with a spatial resolution of 0.05°.

b. In situ rainfall observations from three official meteorological stations operated by the Indonesian Meteorological Agency (BMKG), covering the period 1996–2024.

These datasets were used complementarily to ensure spatial completeness and temporal consistency.

3. Supporting Geospatial and Climate Data

1) Administrative boundary and elevation data were obtained from the Geospatial Information Agency of Indonesia (BIG).
2) ENSO phase classification was based on the Oceanic Niño Index (ONI) from the NOAA Climate Prediction Center, used to contextualize interannual variability.

Respondents, Informants, and Ethical Considerations

This study does not involve human respondents, informants, or participants. All analyses are based on publicly available secondary data. Therefore, ethical clearance related to human subjects is not required. The study complies with standard scientific and ethical guidelines for the use of open-access environmental data.

Data Processing and Analysis

1. Geospatial Analysis

All spatial data processing was conducted using ArcGIS 10.8. Tropical cyclone tracks were spatially clipped to the study domain and overlaid with rainfall datasets. Daily rainfall data were temporally matched with cyclone occurrence periods to distinguish between:

a. Cyclone-related rainfall (TC rainfall): rainfall recorded during active cyclone periods
b. Non-cyclone rainfall: rainfall recorded outside cyclone periods

Monthly and annual composites were generated for both rainfall components.

The percentage contribution of cyclone-related rainfall was calculated by comparing TC rainfall totals with climatological monthly rainfall.

2. Tropical Cyclone Classification

Cyclones were classified based on maximum sustained wind speed into:

a. Tropical Depression (<34 knots)
b. Tropical Storm (34–63 knots)
c. Tropical Cyclone (≥64 knots)

Cyclone intensity was further categorized using the Saffir–Simpson scale (Categories 1–5). Cyclone lifetime was classified as short (1–3 days), moderate (4–7 days), or long (>7 days). Seasonal classification was based on the month with the dominant number of cyclone days.

3. Statistical Analysis

Statistical analyses were conducted using the R programming language to evaluate temporal trends in tropical cyclone intensity. The following analytical steps were applied:

a. Shapiro–Wilk test to assess the normality of maximum sustained wind speed data
b. Spearman rank correlation to examine monotonic relationships between cyclone occurrence year and intensity
c. Ordinary Least Squares (OLS) regression to identify linear trends in cyclone intensity over time
d. LOESS regression to capture non-linear and localized temporal variability

These techniques were selected to jointly address both long-term trends and short-term fluctuations in cyclone intensity.

Analytical Workflow and Response to Research Questions

The methodological steps were explicitly designed to address the research questions as follows:

a. Characterization of spatiotemporal cyclone properties was achieved through descriptive statistics and spatial mapping of cyclone frequency, intensity, and lifetime.
b. Assessment of temporal changes in cyclone intensity was conducted using correlation analysis, OLS regression, and LOESS smoothing.
c. Quantification of cyclone-related rainfall contribution was performed through geospatial overlay and temporal compositing of rainfall data during cyclone periods.

This integrated workflow ensures a systematic and reproducible response to the formulated research problems.

RESULTS AND DISCUSSION

Spatiotemporal Characteristics of Tropical Cyclones Affecting Alor Region

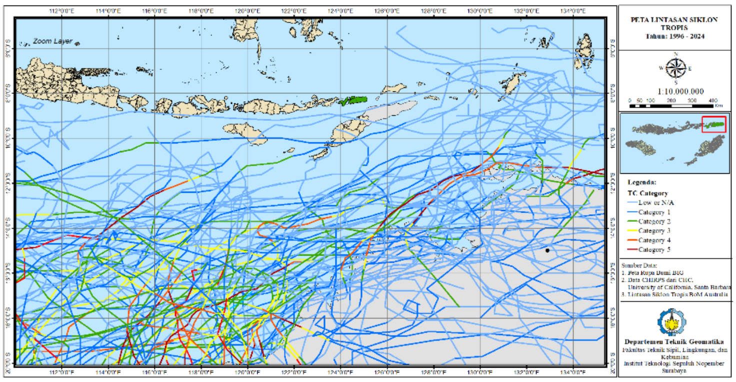

Figure 1. Spatial distribution of historical tropical cyclone tracks in the southern Indonesian region during 1996–2024. Colored lines indicate cyclone intensity based on the Saffir–Simpson scale. The location of Alor Regency is shown for reference

Source: Australian Bureau of Meteorology (BoM)

The spatial distribution of tropical cyclones during the 1996–2024 period indicates that cyclone activity in eastern Indonesia is primarily concentrated south of the equator, particularly over the Timor Sea and the southeastern Indian Ocean (Fig. 1). Although cyclone centers rarely make landfall over Alor Island, the region lies within the main zone of indirect cyclone influence, where enhanced moisture transport, strong wind convergence, and prolonged rainfall frequently occur.

A total of 161 tropical cyclones were identified within the study domain, accounting for approximately 22.36% of all tropical cyclones recorded in the Southern Hemisphere Maritime Continent during the same period. This confirms that the southern Indonesian region, particularly Nusa Tenggara Timur, represents an active cyclone-affected zone rather than a peripheral area.

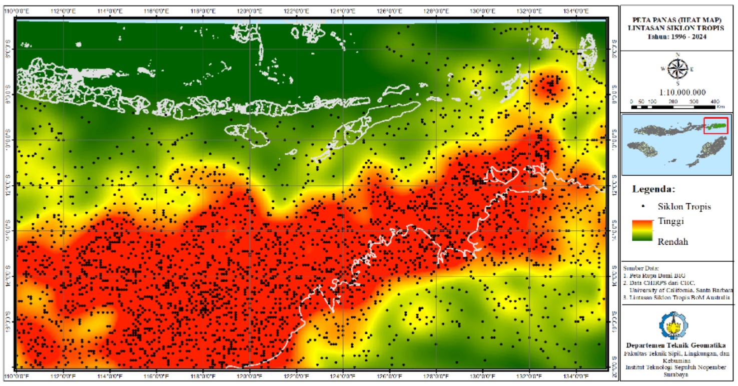

Figure 2. Heat map of tropical cyclone track density showing dominant cyclone pathways south of Nusa Tenggara Timur during the period 1996–2024.
Source: BoM data processed in ArcGIS.

The spatial density map (Fig. 2) reveals a dominant cyclone corridor extending from the southern Nusa Tenggara waters toward northwestern Australia. This pattern reflects the preferred genesis and movement pathways of tropical cyclones associated with warm sea surface temperatures, low vertical wind shear, and favorable large-scale circulation in the austral summer. Although Alor is located north of the primary cyclone tracks, its proximity allows indirect impacts through enhanced convection, moisture advection, and synoptic-scale circulation anomalies

Although Alor Regency is rarely crossed directly by tropical cyclone centers, its geographical position south of the equator and proximity to the southern Indonesian seas make it highly susceptible to indirect cyclone impacts, especially enhanced rainfall through moisture advection, wind convergence, and interactions with local topography.

Interannual Variability of Tropical Cyclone Occurrence

The annual number of tropical cyclones exhibits strong interannual variability, ranging from 1 to 9 events per year, with a long-term average of approximately six cyclones per year (Fig. 3). No statistically significant long-term increasing or decreasing trend is observed, indicating that cyclone activity in the region is primarily governed by climate variability rather than long-term climate change.

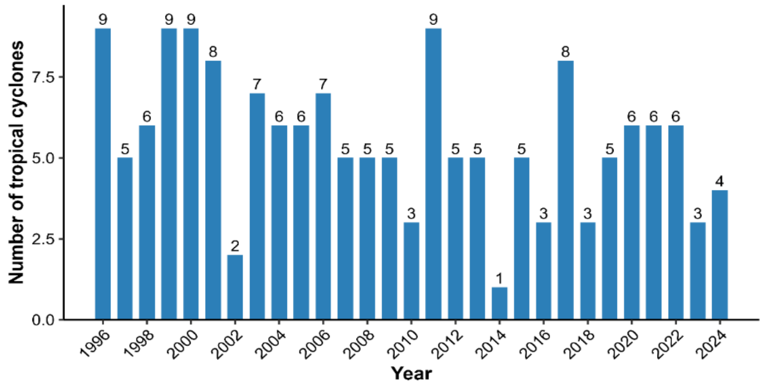

Figure 3. Annual frequency of tropical cyclones affecting the study region during the period 1996–2024. Bars indicate the total number of tropical cyclones recorded each year.
Source: BoM.

Years with elevated cyclone activity (e.g., 1996, 1999, 2000, and 2011) coincide with periods of enhanced ocean–atmosphere coupling, while years with minimal activity reflect less favorable atmospheric conditions. This variability is consistent with previous findings that tropical cyclone occurrence in the Maritime Continent is strongly modulated by large-scale climate modes rather than monotonic trends.

Influence of ENSO on Tropical Cyclone Activity

1. ENSO Control on Cyclone Frequency

The El Niño–Southern Oscillation (ENSO) exerts a strong control on cyclone occurrence. During the study period:

a. La Niña: 83 events (51.5%)
b. El Niño: 45 events (28.0%)
c. Neutral: 33 events (20.5%)

The dominance of La Niña reflects enhanced convection, increased sea surface temperatures, and stronger low-level convergence over the Maritime Continent. These conditions favor cyclone genesis and maintenance. Conversely, El Niño years are characterized by suppressed convection and stronger vertical wind shear, resulting in reduced cyclone activity.

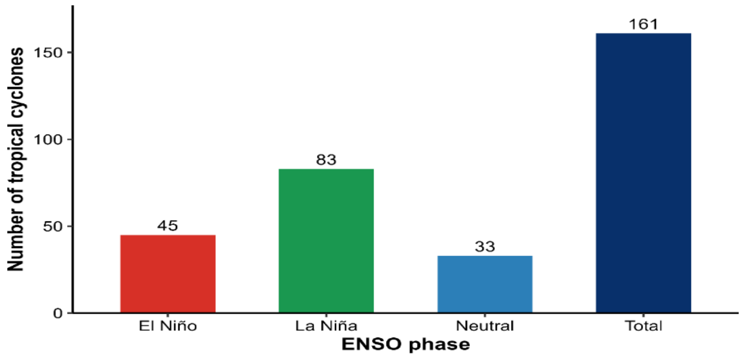

Figure 4. Distribution of tropical cyclone occurrences classified by ENSO phase (El Niño, La Niña, and Neutral) for the period 1996–2024

Source: NOAA ONI and BoM.

2. Cyclone Intensity Characteristics

Most cyclones reaching the study region developed into tropical storms or moderate tropical cyclones. Of the 161 events:

a. Tropical storms dominate (43.5%)
b. Moderate cyclones (Categories 1–3) are common
c. Intense cyclones (Categories 4–5) are rare

This distribution indicates that the region is not a primary intensification basin but rather a transition zone where cyclones either intensify before moving southward or weaken due to environmental constraints.

Table 1. Distribution of Tropical Cyclone Categories in the Study Area during 1996–2024

Tropical cyclone category	Wind speed (knots)	Number of events
Tropical Depression	< 34	9
Tropical Storm	34–63	70

Tropical cyclone category	Wind speed (knots)	Number of events
Category 1	64–82	26
Category 2	83–95	17
Category 3	96–112	15
Category 4	113–136	20
Category 5	≥ 137	4

Source: BoM

Seasonal Characteristics of Tropical Cyclones

Cyclone activity exhibits a strong seasonal cycle, confined almost entirely to November–May, with peak activity in January–March (Fig. 5). No cyclone events were recorded between June and October.

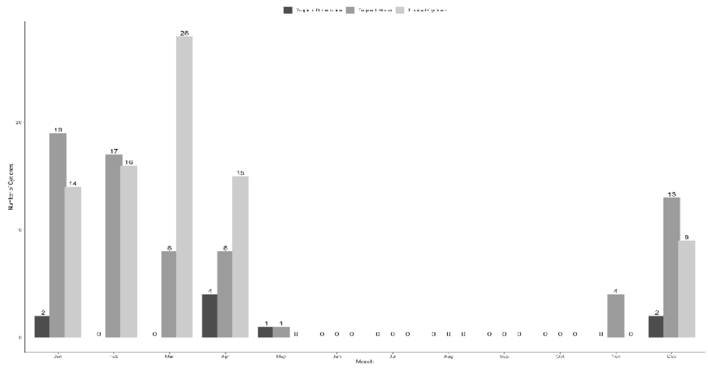

Figure 5. Monthly distribution of tropical cyclone categories in the study area during 1996–2024
Source: BoM

This seasonality reflects the influence of the Australian monsoon system, warm sea surface temperatures, and enhanced atmospheric instability during the austral summer. The absence of cyclones during the dry season corresponds to increased atmospheric stability and reduced convective activity.

Cyclone Lifetime Characteristics

Cyclone lifetime analysis shows a strong dominance of long-lived systems:

a. >7 days: 66.5%
b. 4–7 days: 33.5%
c. <3 days: 0%

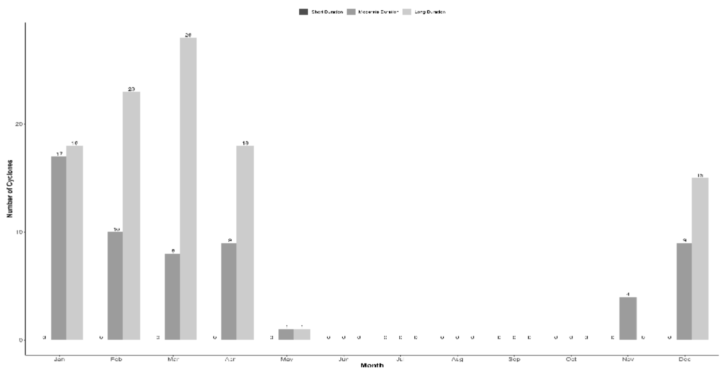

Figure 6. Monthly distribution of cyclone lifetime during the period 1996–2024
Source: BoM

The absence of short-lived cyclones indicates that once cyclogenesis occurs, environmental conditions generally support sustained development. This persistence enhances the potential for prolonged rainfall and cumulative hydrometeorological impacts in the Alor region.

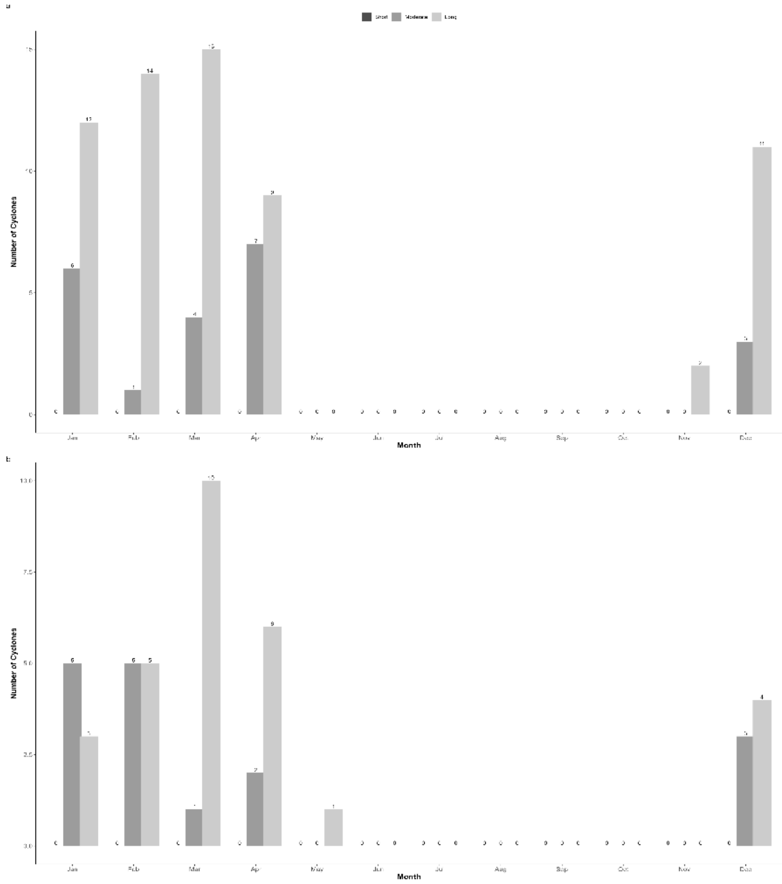

Figure 7. Monthly distribution of tropical cyclone lifetime during (a) La Niña and (b) El Niño phases for the period 1996–2024

Source: BoM and NOAA ONI

ENSO-phase analysis reveals that long-lived cyclones occur predominantly during La Niña years, while El Niño events are associated with shorter cyclone durations.

Maximum Wind Speed Characteristics

The distribution of maximum wind speed exhibits a positively skewed pattern, with dominant values between 35–55 knots, indicating prevalence of weak-to-moderate cyclones (Fig. 8). Extremely intense cyclones (>100 knots) are rare.

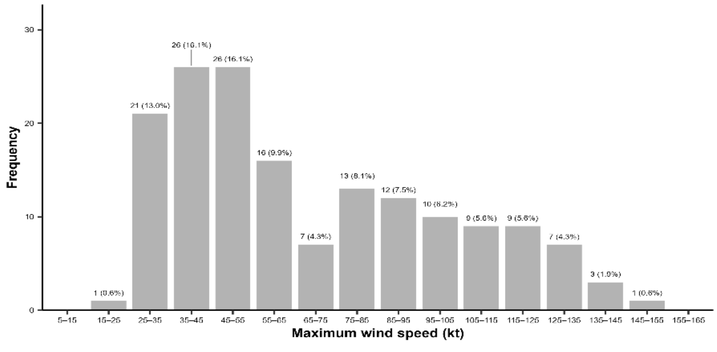

Figure 8. Distribution of maximum wind speed of tropical cyclones for the period 1996–2024

Source: BoM

Statistical testing confirms:

a. Non-normal distribution (Shapiro–Wilk, $p < 0.001$)

b. No significant temporal trend (Spearman $\rho = -0.1147$, $p > 0.05$)

c. No significant linear trend (OLS $R^2 = 0.013$)

Spearman correlation and OLS regression analyses show no statistically significant linear trend in cyclone intensity over time. LOESS regression further indicates that intensity variations are characterized by multi-decadal fluctuations rather than long-term trends, with alternating periods of relative strengthening and weakening. These results suggest that cyclone intensity variability in the region is governed primarily by short- to medium-term climate variability, rather than systematic long-term change.

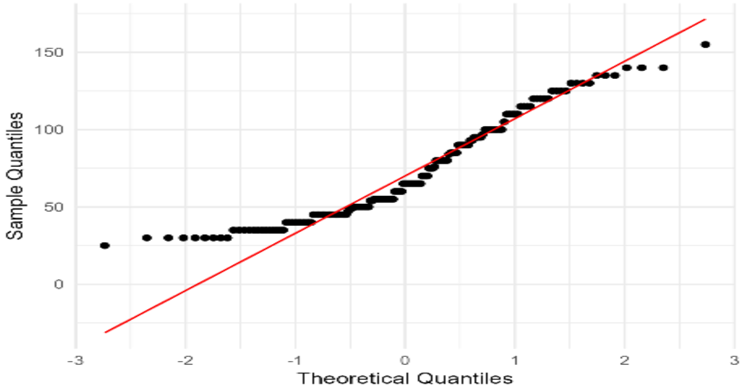

Figure 9. Histogram and Q–Q plot of maximum wind speed

Source: BoM data analysis in R

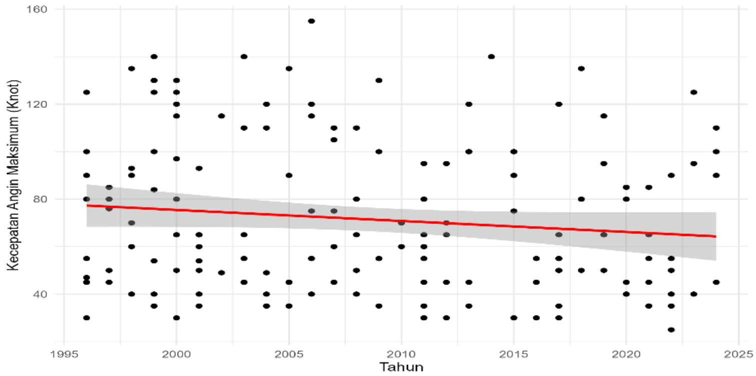

Figure 10. OLS regression between year and maximum wind speed

Source: BoM data analysis in R

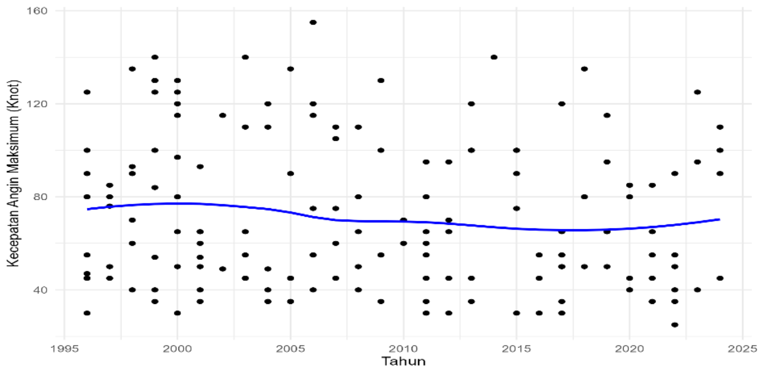

Figure 11. LOESS regression showing non-linear variability of cyclone intensity

Source: BoM data analysis in R

Monthly Rainfall Characteristics and Cyclone Influence

Tropical cyclones represent one of the most important atmospheric systems influencing rainfall variability in eastern Indonesia. To quantify their role, rainfall data from three observation stations (Alor, Larantuka, and Kupang) were analyzed using in-situ daily rainfall (1996–2024), climatological normals (1991–2020), and CHIRPS satellite rainfall data. Rainfall was separated into cyclone-related rainfall and non-cyclone rainfall to evaluate the contribution of tropical cyclones to monthly precipitation.

Overall, rainfall variability in the study area shows strong seasonal dependence, with the highest values occurring during the wet season (November–April). Cyclone influence is most evident during transitional months and decreases during the peak monsoon period, when rainfall is primarily controlled by large-scale monsoonal circulation.

1. In-situ Rainfall Characteristics During Cyclone and Non-cyclone Periods

Figure 12 presents the distribution of monthly mean rainfall during cyclone and non-cyclone conditions at Alor, Larantuka, and Kupang stations.

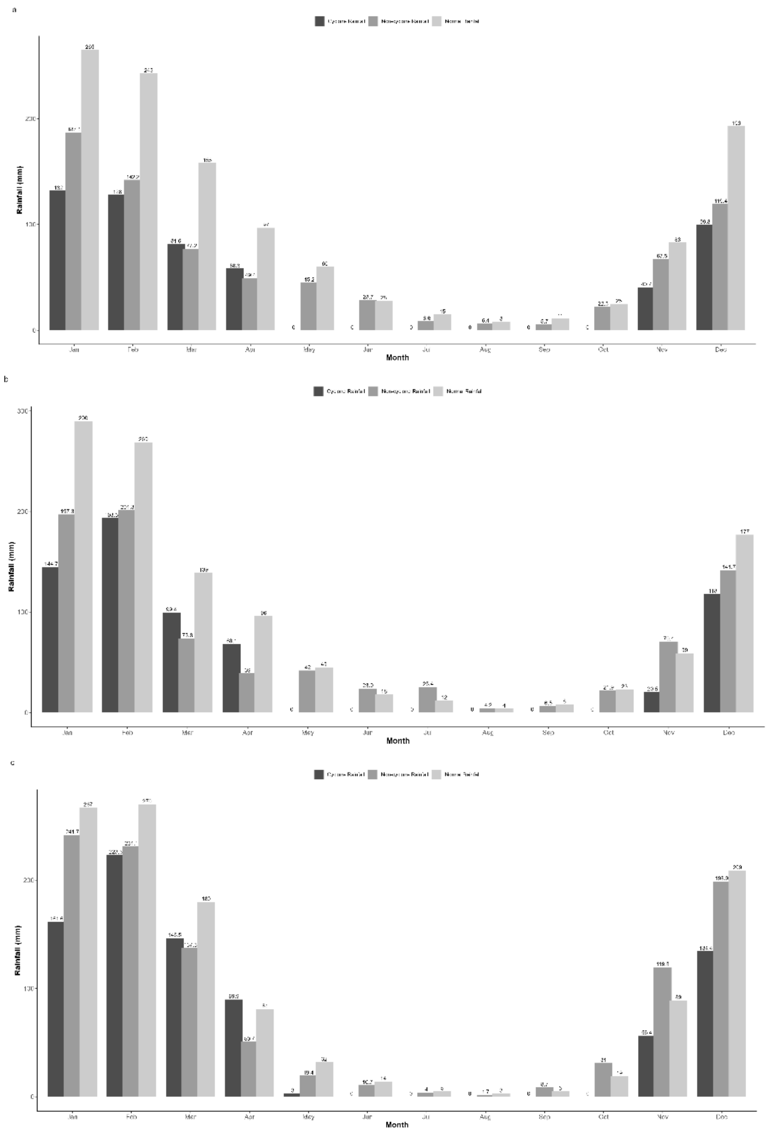

Figure 12. Monthly rainfall distribution under cyclone, non-cyclone, and normal conditions in (a) Alor, (b) Larantuka, and (c) Kupang during 1996–2024

Source: BMKG station data and CHIRPS v2.0.

The results show that, for most months, rainfall during non-cyclone periods exceeds rainfall during cyclone events. This indicates that the dominant rainfall-generating mechanism in the region is the Asian–Australian monsoon system rather than direct cyclone influence. However, several exceptions occur. In Kupang, cyclone rainfall exceeds non-cyclone rainfall in April, while in Larantuka this occurs in March and April.

These differences are associated with seasonal transitions when monsoonal forcing weakens and synoptic-scale systems such as tropical cyclones become more influential. During these periods, cyclones enhance moisture convergence and rainfall intensity despite their relatively low frequency.

Contribution of Tropical Cyclones to Monthly Rainfall

The contribution of cyclone rainfall to monthly climatological rainfall is summarized in Table 2. Cyclone contribution increases markedly from November to March, with the highest values observed during the peak cyclone season.

Table 2. Contribution of Tropical Cyclone Rainfall to Monthly Normal Rainfall

No.	Rain Observation Location	Month/Contribution (%)					
		Nov	Des	Jan	Feb	Mar	Apr
1	Alor	8.45	35.66	41.22	47.21	44.54	33.16
2	Larantuka	4.79	43.67	43.02	62.01	61.67	41.57
3	Kupang	10.93	56.34	51.61	71.71	68.03	62.92
Average		**8.06**	**45.22**	**45.29**	**60.31**	**58.08**	**45.88**
Maximum		**10.93**	**56.34**	**51.61**	**71.71**	**68.03**	**62.92**
Minimum		**4.79**	**35.66**	**41.22**	**47.21**	**44.54**	**33.16**

Source: BMKG and CHIRPS v2.0.

The average cyclone contribution reaches:

a. 45–60% during December–March,

b. with a maximum of 71.71% in February at Kupang,

c. and minimum values during November and April.

Kupang shows the highest sensitivity to cyclone activity, followed by Larantuka and Alor. This pattern reflects the geographical exposure of Kupang to moisture transport from the Timor Sea, where most tropical cyclones develop and propagate. In contrast, Alor exhibits lower contribution values due to partial shielding by complex topography and its relative distance from dominant cyclone tracks.

These findings confirm that tropical cyclones are a major driver of rainfall variability in Nusa Tenggara Timur, particularly during the core wet season.

ENSO Modulation of Cyclone–Rainfall Relationships

Rainfall response to tropical cyclones varies significantly between ENSO phases. During La Niña, enhanced convection and warmer sea surface temperatures lead to increased cyclone activity and higher rainfall totals. Cyclone rainfall contribution is highest during this phase, especially from December to April.

During El Niño, baseline rainfall decreases substantially. However, cyclones still provide important episodic rainfall, particularly during January–March. In several cases, cyclone-related rainfall exceeds non-cyclone rainfall, indicating that cyclones act as critical moisture sources during otherwise dry conditions.

This behavior highlights the strong modulation of cyclone–rainfall relationships by large-scale climate variability, consistent with previous studies on ENSO–cyclone interactions in the Maritime Continent.

Spatial Distribution of Cyclone Rainfall Based on CHIRPS Data

1. November: Onset of the Rainy Season

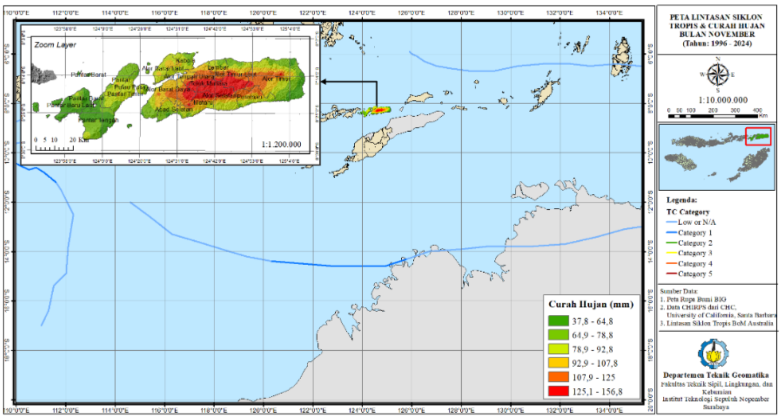

Figure 13. Spatial distribution of mean rainfall and tropical cyclone tracks in November (1996–2024)
Source: BMKG station data and CHIRPS v2.0.

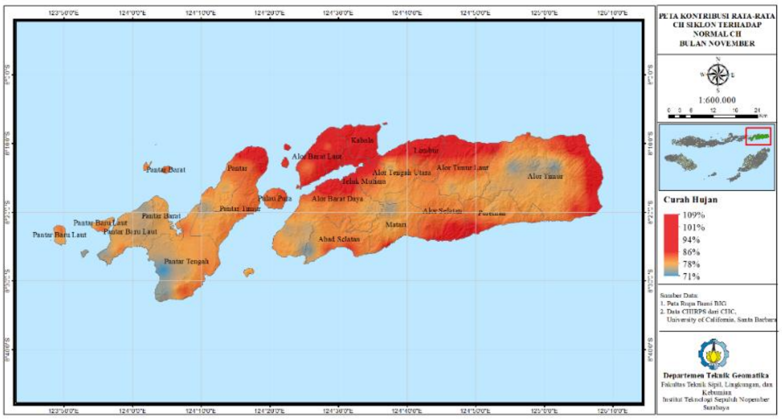

Figure 14. Contribution of cyclone rainfall to monthly climatological rainfall in November.
Source: BMKG station data and CHIRPS v2.0.

November marks the transition from dry to wet season. Cyclone tracks are concentrated south of Alor, yet their outer rainbands significantly enhance rainfall across the region. Rainfall exceeds 125 mm in central and eastern Alor, while western areas receive lower amounts.

Cyclone rainfall contribution exceeds 78% across most of Alor and exceeds 100% in some eastern areas, indicating that cyclones act as the primary rainfall trigger during the early wet season.

2. December: Strengthening of the Monsoon

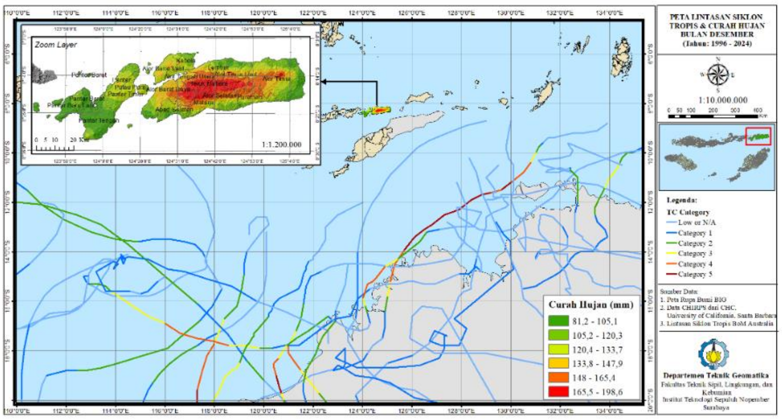

Figure 15. Spatial distribution of rainfall and cyclone tracks in December.

Source: CHIRPS v2.0 and BoM

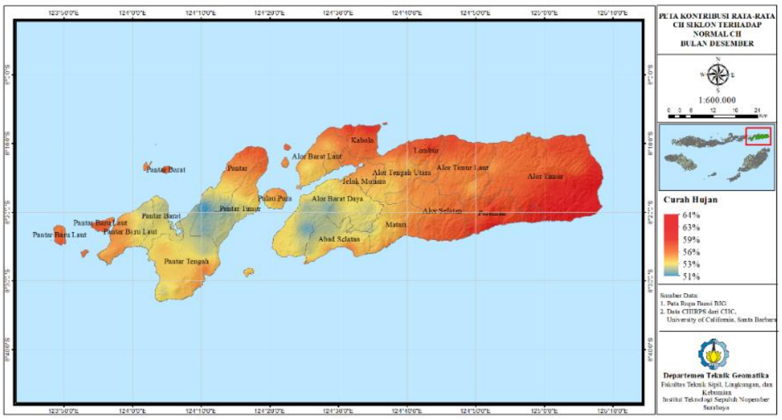

Figure 16. Contribution of cyclone rainfall to normal rainfall in December

Source: CHIRPS v2.0 and BoM

In December, rainfall intensifies as the monsoon becomes fully established. Although cyclone activity increases, its relative contribution declines (51–64%) due to the dominance of monsoonal rainfall. Cyclones mainly enhance rainfall intensity rather than initiate rainfall events.

3. January: Peak Monsoon Period

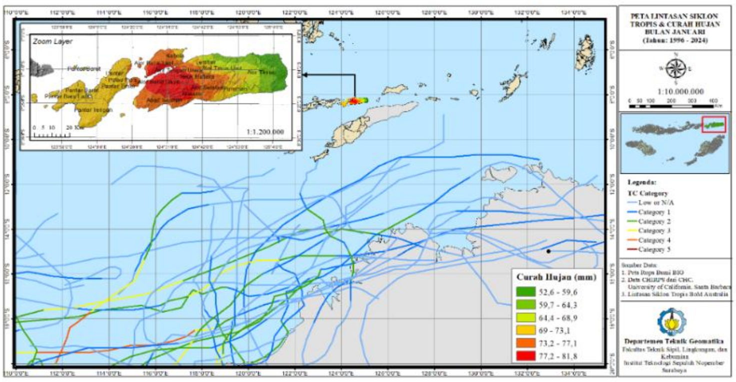

Figure 17. Rainfall distribution and cyclone tracks in January.

Source: CHIRPS v2.0 and BoM

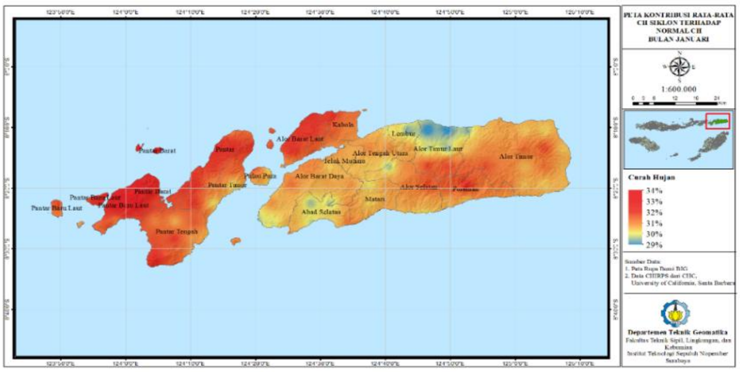

Figure 18. Cyclone contribution to rainfall in January

Source: CHIRPS v2.0 and BoM

January represents the peak of the rainy season. Despite frequent cyclone activity, their contribution to rainfall is lowest (29–34%), indicating that precipitation is primarily driven by large-scale monsoon circulation rather than cyclonic systems.

4. February: Transitional Reinforcement

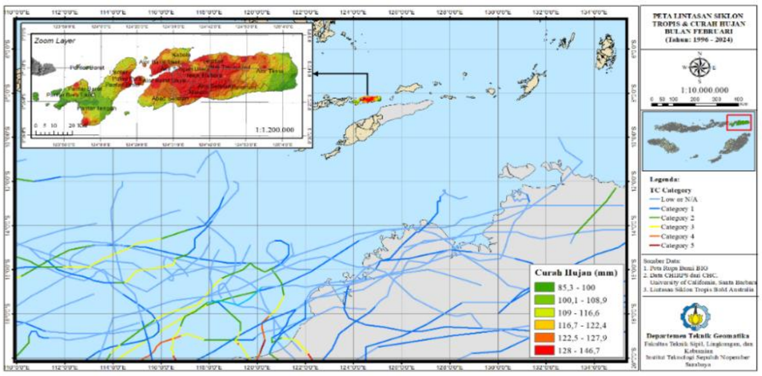

Figure 19. Rainfall and cyclone distribution in February.

Source: CHIRPS v2.0 and BoM

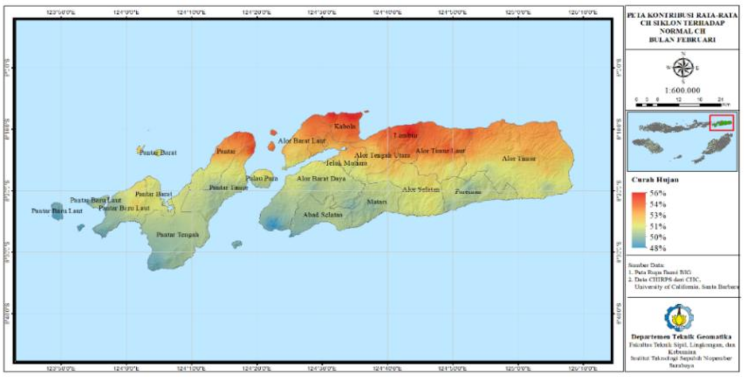

Figure 20. Cyclone contribution to rainfall in February.

Source: CHIRPS v2.0 and BoM

In February, cyclone contribution increases again to 48–56%. This reflects a transitional phase in which monsoon intensity weakens slightly, allowing cyclone-related rainfall to become more influential, particularly in eastern and central Alor.

5. March: Increasing Cyclone Dominance

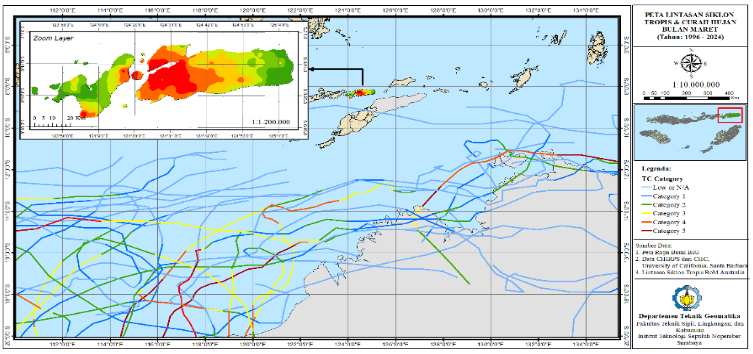

Figure 21. Rainfall distribution in March
Source: CHIRPS v2.0 and BoM

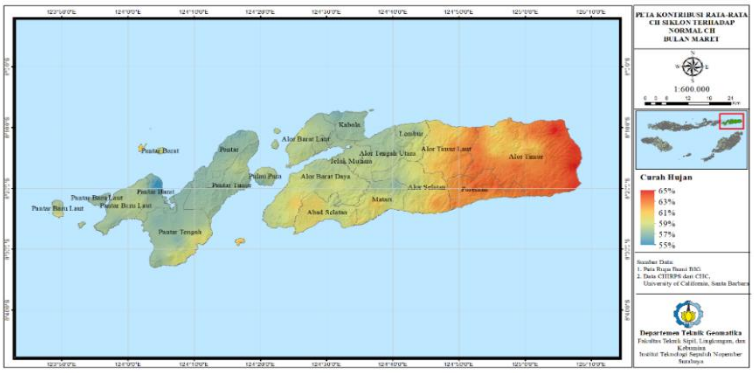

Figure 22. Cyclone rainfall contribution in March
Source: CHIRPS v2.0 and BoM

During March, cyclone contribution rises to 55–65%, particularly in eastern Alor. As monsoon influence diminishes, rainfall becomes increasingly dependent on cyclone-induced moisture transport.

6. April–May: Declining Cyclone Influence

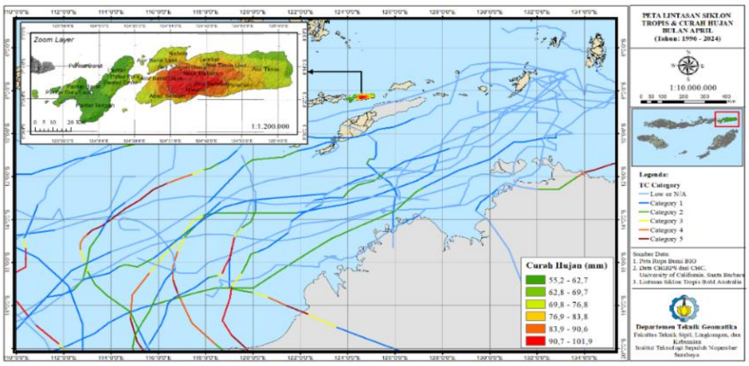

Figure 23. Rainfall distribution inApril
Source: CHIRPS v2.0 and BoM

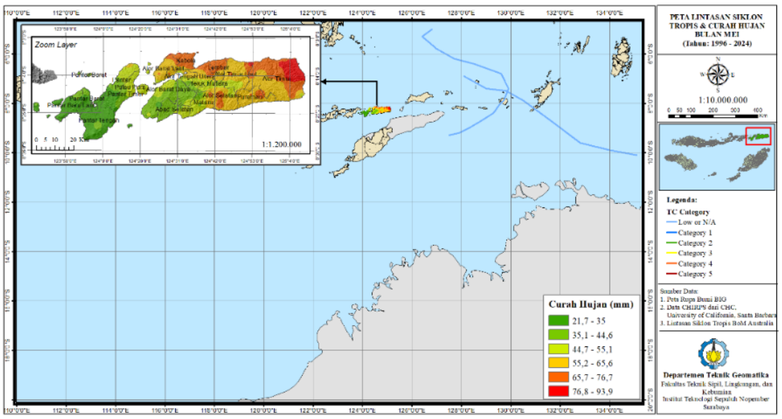

Figure 24. Rainfall distribution in May.

Source: CHIRPS v2.0 and BoM

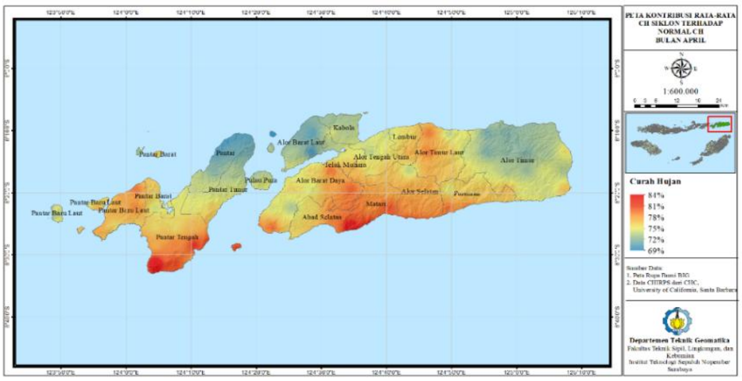

Figure 25. Cyclone rainfall contribution in April

Source: CHIRPS v2.0 and BoM

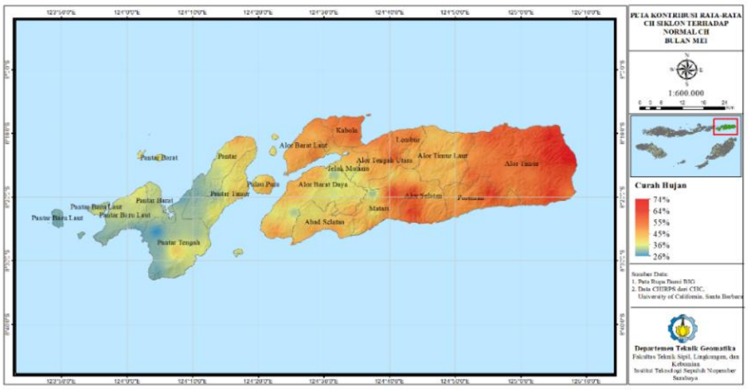

Figure 26. Cyclone rainfall contribution in May

Source: CHIRPS v2.0 and BoM

In April, cyclone contribution remains high (69–84%), particularly in southern Alor. By May, cyclone frequency declines substantially, yet residual cyclone effects remain significant due to reduced background rainfall. This period represents the final phase of cyclone influence before the onset of the dry season.

Integrated Discussion

The results demonstrate that tropical cyclones play a seasonally variable but critical role in controlling rainfall over Alor Regency. Their influence is strongest during:

a. Early wet season (November–December),
b. Transitional months (March–April),

c. Years affected by La Niña conditions.

During peak monsoon months (January–February), rainfall is dominated by large-scale monsoonal circulation, reducing the relative contribution of cyclones.

Spatially, eastern and southern Alor show the highest sensitivity to cyclone-induced rainfall due to their exposure to moisture transport and orographic lifting, while western regions are less affected.

Implications for Hydrometeorological Risk

The strong linkage between tropical cyclones and rainfall variability has significant implications for disaster risk management. Cyclone-induced rainfall contributes substantially to flooding and landslide hazards, particularly during transitional seasons when rainfall intensity increases rapidly.

The results highlight the importance of:

a. Integrating cyclone monitoring into early warning systems,
b. Considering seasonal cyclone behavior in regional planning,
c. Improving preparedness during La Niña years and seasonal transitions.

CONCLUSION

This study conducts a historical geospatial analysis of tropical cyclone intensity and rainfall contributions in Alor Regency, eastern Indonesia, from 1996 to 2024, integrating cyclone records, satellite-derived rainfall products, and in situ observations. Despite no direct cyclone track intersections, the region faces substantial indirect impacts via enhanced rainfall from cyclone rainbands and atmospheric circulation, with strong interannual variability linked to ENSO phases—La Niña favoring higher frequency, longer lifetimes, and greater rainfall, while El Niño reduces activity. Predominantly moderate-intensity cyclones (Categories 1–3) amplify effects through prolonged durations, contributing significantly to monthly precipitation, especially during wet-season transitions, with pronounced impacts in southern and eastern areas due to moisture transport and topography. These findings underscore the need to account for cyclone proximity, duration, ENSO, and seasonal timing in rainfall assessments, disaster risk reduction, and early warning systems, particularly in La Niña years. Future studies could extend this analysis by incorporating high-resolution climate model projections under various warming scenarios to evaluate how intensifying tropical cyclones and shifting ENSO patterns might alter rainfall extremes and hydrometeorological risks in Alor Regency and similar small island regions, informing adaptive infrastructure and policy development.

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