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MODULATION OF ETCCDI-BASED EXTREME RAINFALL INDICES BY ENSO AND THE INDIAN OCEAN DIPOLE OVER TOPOGRAPHICALLY COMPLEX NORTH SUMATRA, INDONESIA

 Muchamad NUR¹, KHOMSIN²✉, Danar Guruh PRATOMO², Muhamad SAWAL¹
¹Meteorology, Climatology and Geophysics Agency (BMKG), Jakarta, Indonesia

²Geomatics Engineering Department, Institut Teknologi Sepuluh Nopember (ITS), Surabaya, Indonesia

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Abstract. This study examines the characteristics of extreme rainfall in North Sumatra Province, Indonesia, and its teleconnections with the El Niño–Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD). The analysis uses a blended daily rainfall dataset from 1990 to 2024, combining station observations from the Indonesian Agency for Meteorology, Climatology, and Geophysics (BMKG) with the Climate Hazards Group InfraRed Precipitation with Station (CHIRPS) satellite data. Validation of CHIRPS against 61 station records shows strong reliability, with an average Pearson correlation (r) of 0.83 and a Root Mean Square Error (RMSE) of 53.1 mm over 20 years. Analysis of extreme rainfall indices from the Expert Team on Climate Change Detection and Indices (ETCCDI) reveals a significant influence from global climate phenomena. The La Niña phase of ENSO and the negative phase of the IOD are consistently associated with wetter conditions, characterized by higher annual rainfall totals (PRCPTOT), increased maximum 1-day (RX1day) and 5-day (RX5day) precipitation, and longer Consecutive Wet Days (CWD). Conversely, the El Niño and positive IOD phases lead to drier conditions and an increased risk of meteorological drought, as evidenced by significantly higher counts of Consecutive Dry Days (CDD). Notably, a sharp decline in extreme-frequency events observed since 2020 contradicts typical La Niña patterns, suggesting a shift in teleconnections. Spatially, the highest rainfall intensity and duration are concentrated in the western and southern coastal and mountainous regions, while the northeastern lowlands are comparatively drier. These findings underscore the strong modulation of regional hydro-climatic extremes by large-scale climate drivers and provide a quantitative basis for enhancing climate change adaptation and disaster mitigation strategies in one of Indonesia's most vulnerable provinces.

Keywords: extreme rainfall, CHIRPS, hazard, El Niño, climate, weather.

✉Corresponding author. E-mail: khomsin@its.ac.id

1. Introduction

Extreme rainfall events pose significant challenges to water resource management, agriculture, infrastructure planning, and disaster risk reduction in tropical regions, particularly in archipelagic nations such as Indonesia (Alexander, 2016). In Southeast Asia, rainfall variability is strongly modulated by large-scale climate drivers, most notably the El Niño Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) (Aldrian & Susanto, 2003; Hendon, 2003). ENSO events are associated with warming or cooling in the central and eastern Pacific Ocean, which significantly influence atmospheric circulation, moisture transport, and rainfall patterns across the Indonesian archipelago. El Niño phases typically lead to drier-than-normal conditions across much of Indonesia due

to suppressed convection. In contrast, La Niña phases are often associated with enhanced rainfall and increased flood risk. Similarly, the IOD, driven by anomalous sea surface temperature gradients between the western and eastern Indian Ocean, plays a complementary role in shaping the regional climate. A positive IOD phase often coincides with rainfall deficits over parts of Indonesia, whereas the negative phase tends to enhance rainfall (Supari et al., 2017).

These two climate modes not only exert independent influences but can also interact nonlinearly, producing compound effects that may amplify or mitigate each other's impact on extreme rainfall (Kurniadi et al., 2021). North Sumatra Province, situated in western Indonesia, is a region of climatological complexity where multiple forcing mechanisms converge. Geographically bounded by

the Indian Ocean to the west and the Strait of Malacca to the east, this province is strongly influenced by maritime air masses, monsoonal transitions, and local sea-breeze dynamics (Yamanaka, 2016). The Bukit Barisan mountain range, a prominent orographic feature that runs parallel to the western coastline, significantly modulates local rainfall by inducing orographic lifting and enhancing convective activity over the highlands (Aldrian et al., 2005).

Numerous studies have examined the broader effects of the El Niño–Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) on Indonesian rainfall at national and regional scales. However, detailed investigations at the sub-provincial level, particularly in areas with complex topography, such as North Sumatra, remain limited (D'Arrigo & Wilson, 2008; Kurniadi et al., 2021). Past research shows that the strength and sign of ENSO and IOD impacts can vary over short spatial distances. This underscores the need for high-resolution climate diagnostics that integrate observational and satellite data. The Expert Team on Climate Change Detection and Indices (ETCCDI) developed a suite of indices to standardize the monitoring of climate extremes. CWD (Consecutive Wet Days) measures the longest streak of days with rainfall, while CDD (Consecutive Dry Days) captures the longest period without rainfall. SDII (Simple Daily Intensity Index) calculates the average precipitation on wet days. High-percentile indices, such as R95p and R50, count the number of days when precipitation exceeds the 95th or 50th percentile, respectively. PRCPOT represents the total annual precipitation from wet days. Using universally accepted thresholds ensures consistency in spatial and temporal analyses (Donat et al., 2013), enabling comparisons across regions and periods.

This study aims to fill critical gaps by providing a comprehensive analysis of extreme rainfall in North Sumatra. The research has three main objectives. First, it will validate CHIRPS satellite-based rainfall estimates against ground-based station observations across the province. This will help ensure data reliability in data-sparse locations.

Second, the study will evaluate the temporal trends and spatial distribution of eight key ETCCDI extreme rainfall indices using both observational and satellite-derived sources. Third, it will quantify the influence of ENSO and IOD phases on these indices, focusing on years with well-documented strong climate anomalies. By combining robust statistical analysis with spatial diagnostics, the study seeks to improve understanding of how large-scale climate change leads to local extreme rainfall events. Ultimately, these findings will support more targeted adaptation and disaster risk management strategies as climate variability and extremes increase.

2. Materials and methods

The study area covers North Sumatra Province, Indonesia, in the northern part of the island of Sumatra (Figure 1a). The province is characterized by complex geographical and topographical conditions, including western coastal areas facing the Indian Ocean, eastern lowlands adjacent to the Strait of Malacca, offshore islands such as Nias, and the Bukit Barisan mountain range extending across the central part of the province. This strong contrast between coastal, lowland, and mountainous environments produces substantial spatial variability in rainfall.

Figure 1b illustrates the research methodology flowchart, which integrates multiple datasets to analyze rainfall variability in Indonesia. Daily observational rainfall data from 61 BMKG stations served as the primary reference and ground truth, while satellite rainfall data from CHIRPS v2.0 (0.05° resolution) provided by UCSB supplemented observations and filled gaps (Funk et al., 2015). Large-scale climate drivers were incorporated through the ENSO index (ONI/Niño 3.4) from NOAA (Trenberth, 1997) and the IOD index (DMI) from the Australian Bureau of Meteorology (Saji et al., 1999). A blended dataset was created using the Pandas DataFrame combine_first method, prioritizing observational data and filling gaps with CHIRPS values (Dinku et al., 2018). Validation of CHIRPS against observations was

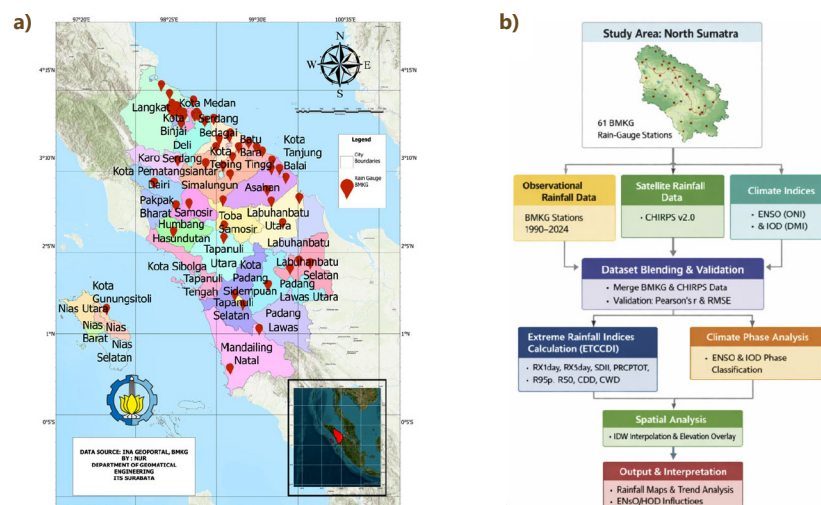


Figure 1. Study area and research methodology: a) map of the research area; b) flowchart of research methodology

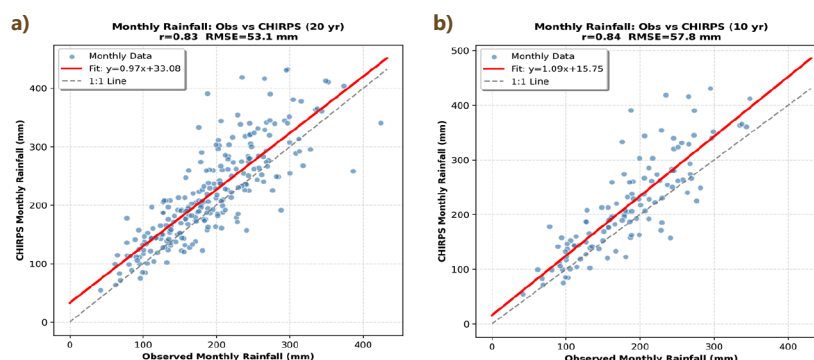


Figure 2. Scatter plot of observed vs CHIRPS rainfall: a) (20-year period); b) (10-year period)

conducted using Pearson correlation (r) and RMSE for 10- and 20-year periods (Ayehu et al., 2018).

Eight ETCCDI indices were then computed to represent rainfall extremes: RX1day (maximum 1-day rainfall), RX-5day (maximum 5-day rainfall), SDII (average rainfall intensity on wet days ≥ 1 mm), PRCPTOT (annual total rainfall on wet days), R95p (rainfall from very wet days above the 95th percentile), R50 (number of heavy rainfall days ≥ 50 mm), CDD (longest consecutive dry spell < 1 mm), and CWD (longest consecutive wet spell ≥ 1 mm). These indices collectively provide a comprehensive assessment of rainfall intensity, frequency, and persistence. ENSO phases were classified using ONI thresholds – El Niño ($\text{ONI} \geq 0.5$), Neutral ($-0.5 < \text{ONI} < 0.5$), and La Niña ($\text{ONI} \leq -0.5$) – following NOAA definitions (Saji et al., 1999). IOD phases were classified using DMI thresholds – Positive IOD ($\text{DMI} \geq 0.4$), Neutral ($-0.4 < \text{DMI} < 0.4$), and Negative IOD ($\text{DMI} \leq -0.4$) – based on BOM criteria (McKinney, 2010).

Annual ETCCDI values were grouped by climate phase and visualized with box plots to compare medians, inter-quartile ranges, and outliers across ENSO and IOD conditions (McGill et al., 1978). Spatial distribution maps of climatological mean values for each index were generated using Inverse Distance Weighted (IDW) interpolation in GIS, selected for its simplicity and effectiveness in regions with moderate station density (Li & Heap, 2014). This interpolation used station coordinates and index values to produce continuous surfaces across North Sumatra Province, enabling robust spatial diagnostics of rainfall extremes under varying climate phases.

3. Results and discussion

3.1. Validation of CHIRPS rainfall data

Validating the CHIRPS satellite precipitation dataset was central to this research, establishing its reliability for bridging rainfall data gaps. This provided a solid scientific foundation for subsequent CHIRPS-based analyses (Dinku et al., 2018; Ayehu et al., 2018). CHIRPS and ground observations were compared at annual and seasonal scales. Over 20 years in Figure 2a, CHIRPS yielded a Pearson correlation of 0.83 and an RMSE of 53.10 mm; over 10 years in Figure 2b, the correlation was 0.84, and the RMSE was 57.8 mm.

3.2. Temporal trends of extreme rainfall events

The R50 index counts the number of days each year with rainfall exceeding 50 mm. This metric reflects hydrometeorological trends, including floods and landslides (Siswanto et al., 2022). For more detailed dynamics over the last decade, Figure 3 shows data for the 10-year period (2014–2023), confirming a secondary peak in 2020 with more than 8 days. A notable feature of the temporal analysis is the decline in the frequency of heavy rainfall after 2020. This decline is important because it occurs during a period when La Niña conditions are generally associated with enhanced rainfall over many parts of Indonesia (Hamada et al., 2002; Supari et al., 2018). However, the response of rainfall extremes to ENSO is not spatially uniform and may vary depending on regional circulation, seasonal timing,

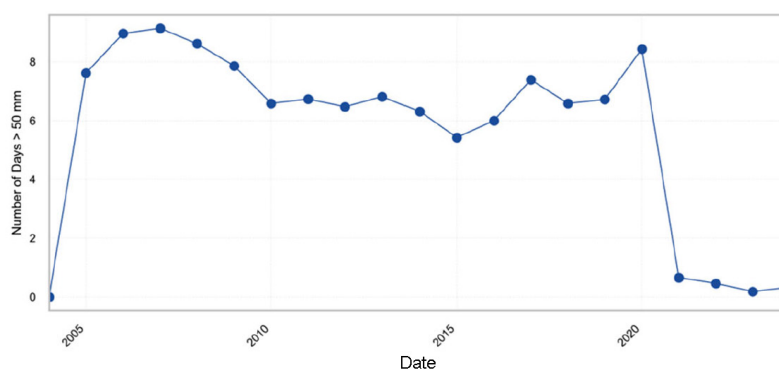


Figure 3. Annual count of daily rainfall > 50 mm

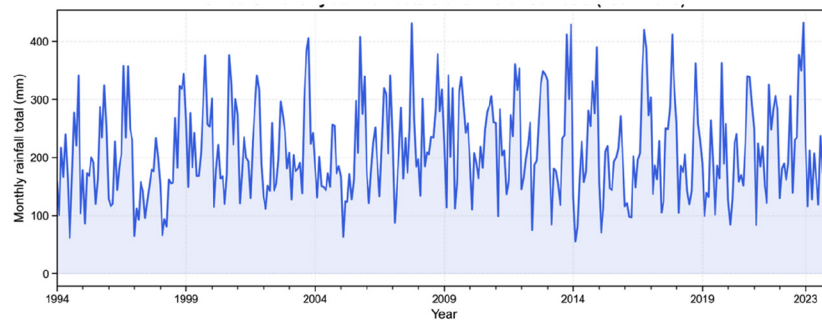


Figure 4. CHIRPS rainfall anomaly

topographic setting, and concurrent Indian Ocean variability (Yamanaka, 2016; Aldrian et al., 2005; Kurniadi et al., 2021). Therefore, the post-2020 decrease should not be interpreted as a direct contradiction of ENSO influence, but rather as an indication that the relationship between large-scale climate drivers and local threshold-based rainfall extremes in North Sumatra is complex.

3.3. Monthly rainfall characteristics and patterns

Figure 4 shows the long-term rainfall for the past 30 years. The main finding from this graph is a consistent bimodal rainfall pattern each year. There are two rainy-season peaks: one from March to May and a second, often stronger, from October to December. A drier period usually occurs between June and August. This bimodal pattern aligns with previous studies of Indonesian rainfall characteristics (Hamada et al., 2002) and is typical of equatorial regions influenced by the Intertropical Convergence Zone (ITCZ) and regional monsoon dynamics (Waliser & Gautier, 1993; Chang et al., 2005). Understanding this basic seasonal pattern is crucial for analyzing extreme events within and outside the rainy season, as such events commonly cluster around these transitional periods (Hamada et al., 2002).

3.4. Global climate dynamics (ENSO and IOD)

It is important to consider the large-scale climate dynamics that influence the region. Two main phenomena shape Indonesia's rainfall: the El Niño-Southern Oscillation (ENSO) in the Pacific Ocean and the Indian Ocean Dipole (IOD) in the Indian Ocean (Aldrian & Susanto, 2003; Hendon, 2003). ENSO dynamics during the study period were visualized using the Niño 3.4 index (Figure 5a). Seasonal fluctuations are

evident, with values above zero (Niño 3.4 > 0) indicating El Niño – marked by warmer sea surface temperatures in the central and eastern tropical Pacific – and values below zero (Niño 3.4 < 0) indicating La Niña – cooler conditions. Strong El Niño episodes occurred in 1997–1998 and 2015–2016, with index values exceeding +2.0; these events caused severe droughts across Indonesia (D'Arrigo & Wilson, 2008; Santoso et al., 2017). Strong La Niña episodes also occurred in 1999–2000 and 2010–2011, with indices at –1.5 or lower.

Meanwhile, the dynamics in the Indian Ocean are captured by the Dipole Mode Index (IOD) (Figure 5b). This graph shows the daily variability of the IOD index. Several very strong Positive IOD events are evident, marked by high-index peaks, including those in 1994, 1997, and 2019. The 2019 Positive IOD was among the strongest on record, resulting in widespread drought and fires across Indonesia (Lu & Ren, 2020). Significant Negative IOD events were also observed in 1996 and 2010, marked by very low index values. The occurrence of strong ENSO and IOD episodes during the study period indicates that the North Sumatra region is actively influenced by both global climate phenomena. The simultaneous occurrence of several events, such as the strong El Niño and positive IOD in 1997, may lead to more extreme impacts on regional rainfall patterns, as previous studies have shown amplified effects during co-occurring events (Cai et al., 2011).

3.5. Climate phase impacts on extreme rainfall

3.5.1. ENSO phase influence on extreme rainfall

ENSO phases have a clear and significant influence on the most extreme rainfall indices in North Sumatra, consistent with findings in other regions of Indonesia. Rainfall

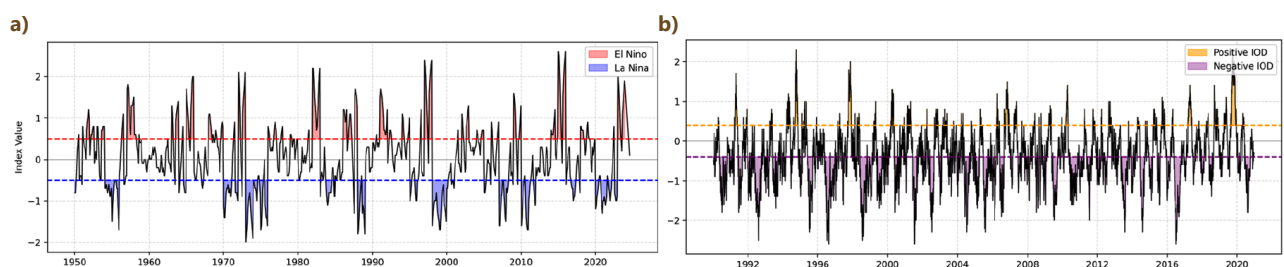


Figure 5. Time series of ENSO and Indian Ocean Dipole indices: a) Niño 3.4 index (ENSO variability); b) Dipole Mode Index (IOD variability)

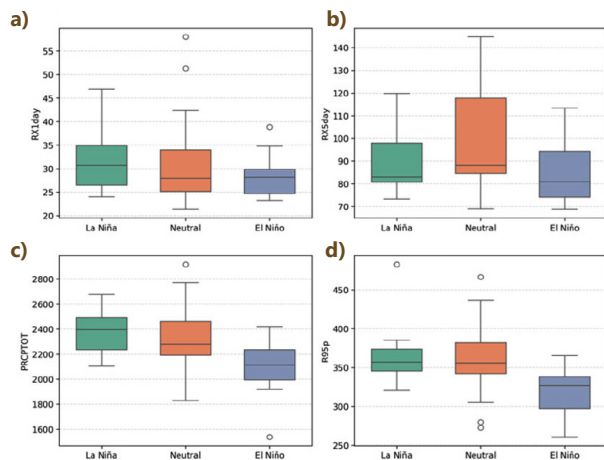


Figure 6. Boxplot of rainfall intensity and volume indices under ENSO phases: a) RX1 day; b) RX5 day; c) PRCPTOT; d) R95p

intensity and volume: The most pronounced effects are evident in indices of rainfall intensity and volume. During La Niña, conditions tend to be wetter, as shown by higher median values and broader ranges for precipitation indices such as maximum daily rainfall (RX1day, Figure 6a), maximum 5-day rainfall (RX5day, Figure 6b), Annual Total Rainfall (PRCPTOT, Figure 6c), and Total Rainfall from Very Wet Days (R95p, Figure 6d). Specifically, annual rainfall (PRCPTOT) during La Niña averages approximately 2,400 mm, which is distinctly higher than during El Niño years (~2,100 mm). Extreme intensity (R95p) also shows higher medians during La Niña (~360 mm) than during El Niño (~325 mm), indicating more frequent high-intensity storm events.

3.5.2. IOD phase influence on extreme rainfall

In terms of intensity, the maximum daily rainfall during negative IOD has a median of approximately 27–28 mm, with outliers exceeding 50 mm. The contribution of extreme wet days remains robust during negative phases (median ~345 mm), confirming that cooling in the western Indian Ocean supports active convection over North Sumatra. Like ENSO, the Indian Ocean Dipole (IOD) modulates regional rainfall, although the signal is distinct when

analyzed on an annual timescale (Saji et al., 1999, 2003). The influence of the IOD is evident in the consistency of wet conditions. The negative IOD phase is characterized by substantial rainfall accumulation. As shown in the grid panels, the median annual total rainfall during negative IOD years is approximately 2,200 mm, indicating a consistently wet regime. While the neutral phase shows a higher median (~2,400 mm) and wider variability, this is likely because the “Neutral” category in this dataset encompasses years influenced by strong La Niña events (which are typically IOD-Neutral), thereby elevating the rainfall baseline.

3.6. Spatial distribution analysis of extreme rainfall indices

3.6.1. Rainfall magnitude and intensity

The spatial distribution of rainfall magnitude indices (RX1day, RX5day, PRCPTOT) and intensity (SDII) is shown in Figure 7. A striking west-to-east gradient is evident. Annual Total Rainfall (PRCPTOT, Figure 7c) peaks in the western region, particularly in the Nias Islands, Mandailing Natal, and Tapanuli Tengah, with exceptional totals exceeding 3,000 mm/year (dark blue contours >3200 mm). Moderate values characterize the central highlands, including Dairi, Pakpak Bharat, and Tapanuli Utara (approximately 2,000–2,600 mm). In stark contrast, the eastern lowlands – spanning Langkat, Deli Serdang, Asahan, and Labuhanbatu – record significantly lower values, generally below 1,800–2,000 mm/year (light green/yellow zones).

Extreme short-duration events follow this pattern. Maximum 1-day rainfall (RX1day, Figure 7a) reaches its highest intensity (>110 mm) in the southwestern coastal areas of Nias Selatan and Mandailing Natal. Similarly, Maximum 5-day rainfall (RX5day, Figure 7b) shows cumulative extremes exceeding 220 mm in the same western zones. Interestingly, daily Intensity (SDII, Figure 7d) shows an inverse pattern; the highest daily intensities (>18–20 mm/day, indicated by dark red zones) occur in the drier eastern regions, such as Labuhanbatu, Padang Lawas, and Asahan. This suggests that although rainfall is less frequent in the east, when it does occur, it is highly intense convective bursts.

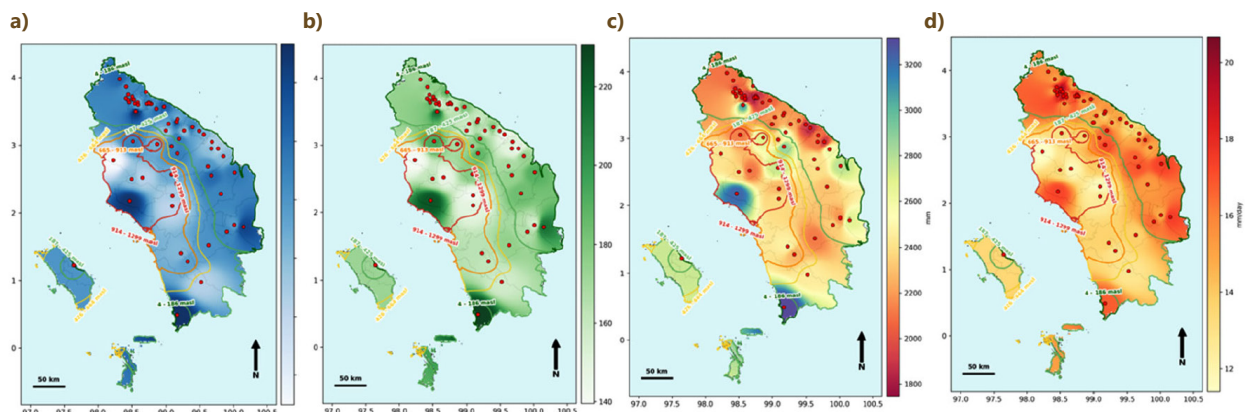


Figure 7. Spatial distribution of rainfall magnitude and intensity indices in North Sumatra: a) Max 1-day rainfall; b) Max 5-day rainfall; c) Annual total rainfall; d) Daily intensity

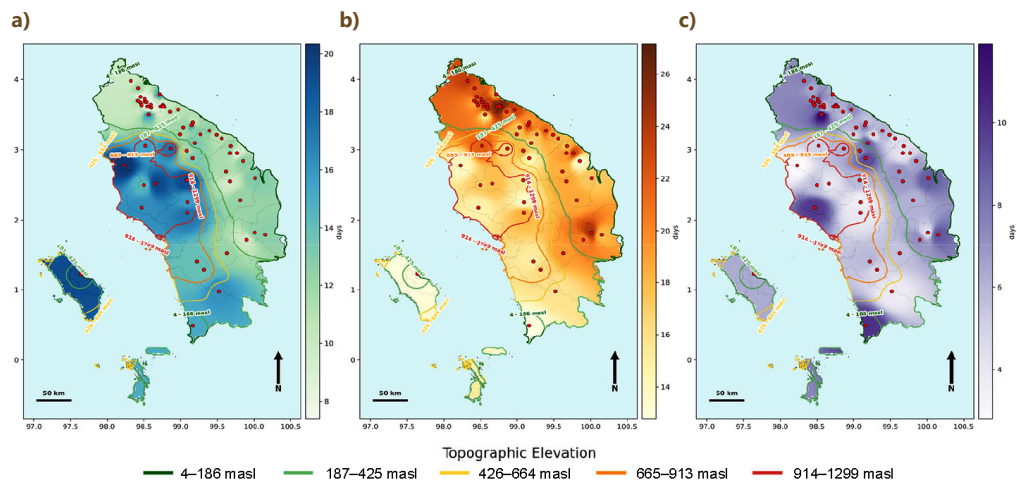


Figure 8. Spatial distribution of rainfall frequency and duration indices in North Sumatra: a) Consecutive Wet Days (CWD); b) Consecutive Dry Days (CDD); c) Heavy Rainfall Days (R50)

3.6.2. Frequency and duration of extremes

The frequency and duration indices (CWD, CDD, R50) are shown in Figure 8. Wet spell persistence (CWD, Figure 8a) is notably high in the central-western highlands, particularly in Pakpak Bharat and Tapanuli Tengah, where consecutive wet days can exceed 100 days (dark green zones). Conversely, drought vulnerability, represented by Consecutive Dry Days (CDD, Figure 8b), is highest in the eastern and southeastern lowlands. The districts of Langkat, Deli Serdang, and parts of Labuhanbatu exhibit the longest dry spells, exceeding 24 days (dark red zones), indicating a dual challenge of low rainfall and prolonged dry periods. Meanwhile, the frequency of heavy rainfall (R50; Figure 8c) is highly concentrated in the orographic capture zones along the west coast, specifically Sibolga, Tapanuli Tengah, and Nias, with frequencies exceeding 10 days/year (dark blue zones), reflecting the direct lifting of moisture-laden westerly winds.

4. Conclusions

This study examines the characteristics and modulation of rainfall in North Sumatra in the context of global climate change. Currently, CHIRPS data are reliable enough to interpolate observation gaps, with a correlation >0.83 and an error of 53 mm. Thus, CHIRPS data can be used for hydroclimatological analysis. La Niña and negative IODs indicate wet extreme events, while El Niño and positive IODs suppress the event. The topography drives a distinct west-east gradient: rainfall is >3000 – 4000 mm per year in the western region, whereas the eastern region remains dry, with <2500 mm per year and longer dry periods. Adaptation and mitigation strategies for floods in the west and droughts in the east must be integrated with ENSO-based seasonal forecasting for early warning.

Several limitations were encountered during this study. The distribution of rainfall observations (61 BMKG rain gauge stations) remains uneven across complex topographic areas,

potentially affecting interpolation results. In addition, CHIRPS-based gap-filling may still contain uncertainties, particularly in mountainous and coastal regions. The datasets used are not fully capable of capturing long-term climate variability beyond the influence of ENSO and IOD. The ETCCDI index has not captured daily extreme rainfall, which is important for assessing flash flood risk. Future studies should include additional atmospheric variables and higher-resolution topographic information to better explain the mechanisms of rainfall extremes in North Sumatra.

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