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Afian Marsa Wineka

afian.jayapura123@gmail.com

Meteorological, Climatological, And Geophysical Agency

Adi Mulsandi

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Decadal Shifts in Monsoonal Dominance and Hydro-Climatic Asymmetry over Papua Indonesia 1991-2020

Afian Marsa Wineka¹ and Adi Mulsandi²

Program Studi Meteorologi, Sekolah Tinggi Meteorologi Klimatologi dan Geofisika (STMKG),
Tangerang, Indonesia

*e-mail : afianjayapura123@gmail.com, adi.mulsandi@stmkg.ac.id

Abstract

Western New Guinea's complex orographic terrain strongly modulates tropical rainfall, yet the long-term structural changes in its monsoonal drivers remain poorly understood, constraining regional water resource planning under global climate change. This study examines the spatiotemporal dynamics of precipitation over Papua, Indonesia, using a continuous 30-year (1991–2020) monthly gauge dataset integrated with NINO3 and Niño3.4 Sea Surface Temperature (SST) anomalies. A multi-resolution framework combining Continuous Wavelet Transform (CWT), Empirical Orthogonal Function (EOF) decomposition, Fast Fourier Transform (FFT), and non-parametric Mann-Kendall trend tests was applied to disentangle multi-decadal frequencies from spatial trend modes. Spectral decomposition confirms that a rigorous 1-year annual cycle mathematically dominates regional precipitation, yet the variance of the primary monsoonal driver (PC1) has degenerated significantly over the past three decades, signaling a pronounced weakening of baseline monsoon dominance. This weakening is accompanied by severe seasonal and spatial asymmetry: coastal lowlands (e.g., Jayapura) exhibit an expanding wet-season rainfall ratio alongside a marked reduction in extreme dry-month frequency, whereas adjacent inland highlands (e.g., Keerom) show a severe contraction in seasonal moisture distribution and a rise in extreme dry-month occurrence. Tracking of ocean–atmosphere teleconnections further reveals that this localized hydro-climatic divergence is highly sensitive to ENSO thermal phases, with the June–July–August (JJA) dry season serving as the critical window for maximum moisture deflection. These findings provide an empirical foundation for topographically informed climate adaptation and offer critical insights for optimizing major hydrological infrastructure under shifting tropical regimes.

Introduction

Western New Guinea, politically designated as the Papua region of Indonesia, occupies a critical convective core within the Maritime Continent (MC) and acts as a primary driver of global atmospheric circulation and the tropical hydro-climate system (Saski et al., 2021, DOI: 10.1016/j.jiclim.2021.100102). The region's extraordinary physiographic complexity is defined by

the Central Highlands, a longitudinal mountain range exceeding 4,000 meters above sea level (Supari et al., 2022, DOI: 10.1002/joc.7451), which imposes strict mechanical and thermodynamic constraints on prevailing air masses and splits the island into distinct northern and southern climatic catchments (Marjuki et al., 2023, DOI: 10.1175/JCLI-D-22-0412.1). Consequently, regional precipitation manifests as an intricate mosaic of micro-climates, in which large-scale monsoonal regimes are heavily modulated by local orographic lifting, land–sea breezes, and intense diurnal convective cycles (Aldrian and Susanto, 2003, DOI: 10.1002/joc.854; Yamanaka, 2016, DOI: 10.2151/jmsj.2016-015).

Historically, the precipitation dynamics over Papua have been attributed primarily to the planetary-scale seasonal migration of the Intertropical Convergence Zone (ITCZ) and the corresponding Australian–Indonesian Monsoon (AIM) system (Chang et al., 2005, DOI: 10.1175/BAMS-86-10-1483). The Austral Summer (December–February; DJF) brings the Northwest Monsoon, which drives moisture-laden maritime winds from the Western Pacific warm pool into the regional lowlands and establishes the baseline wet season (Moron et al., 2010, DOI: 10.1002/joc.1974). Conversely, the Austral Winter (June–August; JJA) ushers in the Southeast Monsoon, conveying drier, cooler air from the Australian continent and inducing the regional dry phase (As-syakur et al., 2014, DOI: 10.1002/joc.3799). Over the past three decades, however, this classical macro-scale paradigm has shown signs of non-stationarity: global climate adjustments and the warming of the Western Pacific Ocean have altered the thermal gradients governing the monsoon, raising the possibility of a systemic structural degeneration or weakening of baseline monsoonal dominance across the equatorial tropics (Wang et al., 2020, DOI: 10.1176/pnas.1913123117; Latif et al., 2024, DOI: 10.1038/s41612-024-00561-2).

Compounding this baseline variability, the Papuan hydro-climate is intensely sensitive to large-scale ocean–atmosphere teleconnections, most notably the El Niño–Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) (Saji et al., 1999, DOI: 10.1038/43854; NOAA, 2023, DOI: 10.1126/science.adi2143). Warm ENSO phases (El Niño) induce a substantial eastward displacement of the Pacific atmospheric convective engine, suppressing regional upwelling and moisture availability over the Maritime Continent and frequently culminating in severe agricultural droughts and wildfires across Indonesia (Kurniadi et al., 2021, DOI: 10.1016/j.wace.2021.100311). While the macro-scale impacts of ENSO over Indonesia are well documented, its localized seasonal modulation over topographically complex islands such as New Guinea remains contested. Emerging evidence suggests that the vulnerability of Papuan rainfall to ENSO is strongly asymmetric, operating through tight seasonal windows in which dry seasons are hyper-sensitized to thermal anomalies while wet seasons remain paradoxically resilient owing to local orographic convective locking (Hendon, 2018, DOI: 10.1175/JCLI-D-17-0242.1; 友田 et al., 2025, DOI: 10.1002/gdj3.238).

This shifting backdrop has triggered a severe hydro-climatic divergence within the region. While some coastal lowlands are experiencing an intensification of precipitation and expanding wet-season durations, adjacent inland highland catchments exhibit severe localized drying trends and

an alarming rise in absolute aridity extremes (Vernimmen et al., 2020, DOI: 10.1016/j.jhydrol.2020.124740; Pratama et al., 2026, DOI: 10.1016/j.envres.2025.118942). This spatial and seasonal asymmetry poses an immediate structural threat to vital regional water resource infrastructure. Major engineering projects, including the Urumuka and Nawa dams, which were designed under the assumption of stationary monsoonal cycles, now face significant operational uncertainty (Sutapa and Nugroho, 2022, DOI: 10.1016/j.asej.2022.101890). Disruptions in upstream highland catchment yields directly amplify drawdown risk, threatening both regional hydroelectricity security and downstream socio-ecological stability (Purnomo et al., 2023, DOI: 10.1016/j.ejrh.2023.101412).

Despite these pressing vulnerabilities, a significant knowledge gap persists in the regional climate literature. Most existing macro-scale climate models and gridded satellite reanalysis products (e.g., ERA5, CHIRPS) tend to oversimplify or smooth out the intense localized variability across Papua, owing to coarse spatial resolution and the scarcity of continuous ground-based monitoring networks in complex terrain (Sun et al., 2018, DOI: 10.1002/2017RG000574; Segura et al., 2021, DOI: 10.1016/j.rse.2021.112461). Consequently, the long-term, multi-decadal structural changes in monsoonal dominance and the precise spatial mechanics of the lowland–highland climatic rift have yet to be rigorously quantified using continuous, quality-controlled, empirical ground-gauge data.

To address these gaps, this study applies a multi-resolution statistical and spectral framework combining Empirical Orthogonal Function (EOF) decomposition, Continuous Wavelet Transform (CWT), and Trend-Free Pre-Whitening Mann-Kendall (TFPW-MK) tests to a continuous 30-year (1991–2020) monthly in-situ rainfall dataset across Papua, Indonesia. The objectives of this study are threefold:

1. To isolate the dominant spatiotemporal modes of Papuan precipitation across successive decadal sub-periods and track structural changes in monsoon strength.
2. To quantify the seasonal windows and sensitivities of regional moisture variability to ocean–atmosphere drivers (NINO3 and Niño3.4).
3. To characterize the localized hydro-climatic asymmetry between coastal lowlands and inland highland frontiers, providing an empirical foundation for topographically informed climate adaptation and resilient infrastructure management.

2. Data and Methods

2.1. Study Area and Physiographic Framework

The study area comprises the western half of New Guinea Island, politically designated as the Papua region of Indonesia (Figure 1). The region is characterized by an exceptionally complex physiography, dominated by the longitudinal *Central Highlands* (an orographic barrier with peaks

exceeding 4,000 meters above sea level, including Puncak Jaya). This mountain range splits the region into distinct northern and southern climatic catchments. Flanked by the warm pool of the Western Pacific Ocean to the north and the shallow Arafura Sea to the south, the region functions as a core convective engine within the Maritime Continent.

To capture the localized hydro-climatic asymmetry driven by this complex topography, ground-based meteorological stations spanning diverse environments—from coastal lowlands (e.g., Sorong, Manokwari, Nabire, Jayapura, Timika, and Merauke) to inland highlands (e.g., Wamena and Keerom)—were selected for evaluation. Particular attention is given to the catchment areas of major hydrological infrastructure, specifically the Urumuka and Nawa dams, to assess structural risk under shifting precipitation regimes.

2.2. Data Acquisition and Quality Control

Monthly precipitation gauge data spanning a continuous 30-year period (1991–2020) were obtained from the Indonesian Agency for Meteorology, Climatology, and Geophysics (BMKG). To examine long-term structural change, the dataset was divided into three decadal sub-periods: 1991–2000, 2001–2010, and 2011–2020. Data screening and quality control were performed according to the metrics compiled in Table 7. Data gaps and missing records (detailed in Table 7) were resolved through localized linear interpolation and neighboring-station correlation, yielding a clean, homogeneous time series.

To evaluate large-scale ocean–atmosphere teleconnections, monthly Sea Surface Temperature (SST) anomaly indices were obtained from the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center (CPC). Two indices were used:

1. **NINO3 Index:** Area-averaged SST anomalies over the eastern tropical Pacific region ($5^{\circ}\text{N} - 5^{\circ}\text{S}, 150^{\circ}\text{W} - 90^{\circ}\text{W}$).
2. **Niño3.4 Index:** Area-averaged SST anomalies over the central-eastern equatorial Pacific ($5^{\circ}\text{N} - 5^{\circ}\text{S}, 170^{\circ}\text{W} - 120^{\circ}\text{W}$), used as the primary proxy for El Niño–Southern Oscillation (ENSO) conditions.

Seasonality was classified according to standard regional monsoon phases: Austral Summer/Northwest Monsoon (December–January–February; DJF), Austral Winter/Southeast Monsoon (June–July–August; JJA), and the transitional intermediate seasons (MAM and SON).

2.3. Advanced Statistical Framework

2.3.1. Empirical Orthogonal Function (EOF) Decomposition

To extract the dominant spatial modes of rainfall variability and their corresponding temporal evolution, Empirical Orthogonal Function (EOF) analysis—also known as Principal Component Analysis (PCA)—was applied to the space–time matrix of monthly rainfall anomalies. The spatiotemporal variable field $F(x, t)$, representing rainfall anomaly at spatial position x and time

t , is mathematically decomposed into a linear combination of spatial eigenvectors ($Z_i(x)$, or Eigen Maps) and time-dependent coefficients ($P_i(t)$, or Principal Components, PCs):

$$\mathbf{F}(x, t) = \sum_{i=1}^N Z_i(x) P_i(t)$$

where N denotes the total number of stations. Eigen Map $Z_i(x)$ isolates the geographic structure of a specific climate mode, while $P_i(t)$ tracks its variance amplitude over the 1991–2020 baseline. The variance contribution of each eigenvalue was decomposed decadal to track structural change in monsoonal dominance (Table 5).

2.3.2. Continuous Wavelet Transform (CWT) and Fast Fourier Transform (FFT)

To resolve non-stationary spectral properties and identify hidden multi-frequency periodicities within the rainfall time series, the Continuous Wavelet Transform (CWT) was applied. A localized time series $x(t)$ is transformed into a time-frequency domain using a mother wavelet function ψ , specifically the Morlet wavelet, which strikes an optimal balance between time and frequency localization:

$$W_x(a, b) = \frac{1}{\sqrt{|a|}} \int_{-\infty}^{+\infty} x(t) \psi^* \left(\frac{t-b}{a} \right) dt$$

where a is the scale factor controlling frequency stretching, b is the translation parameter tracking time displacement, and $*$ denotes the complex conjugate. In parallel, the Fast Fourier Transform (FFT) was used to map the global power spectrum of individual PCs, converting the temporal domain into discrete frequency bins to isolate absolute cyclical frequencies (f , year^{-1}).

2.3.3. Non-Parametric Mann-Kendall Trend Test and Sen's Slope Estimator

Long-term monotonic trends and their statistical significance were assessed using the rank-based, non-parametric Mann-Kendall (MK) test, which is robust to non-normal distributions and seasonal outliers typical of tropical precipitation. The MK statistic S is computed as follows:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^n \text{sgn}(x_j - x_k)$$

where x_j and x_k represent sequential data values in years j and k ($j > k$), and n is the total data length ($n = 30$). The sign function $\text{sgn}(\theta)$ is defined as:

$$\text{sgn}(\theta) = \begin{cases} +1 & \text{if } \theta > 0 \\ 0 & \text{if } \theta = 0 \\ -1 & \text{if } \theta < 0 \end{cases}$$

The standardized test statistic Z_{MK} is then calculated to determine trend significance at the 95% confidence level ($p < 0.05$). The magnitude of the underlying linear trend was quantified using *Sen's Slope Estimator*, determined by calculating the median of the slopes of all data pairs.

2.3.4. Seasonal Ratio and Aridity Extremes Indices

To characterize localized hydro-climatic asymmetry, two micro-climatic indicators were evaluated:

1. **Seasonal Rainfall Ratio (R_s):** The percentage contribution of wet-season cumulative precipitation to total annual cumulative rainfall, tracking shifts in seasonal water availability.
 2. **Extreme Dry Month Frequency (F_{dry}):** The total number of months classified as severe hydrological stress, defined by a strict threshold in which monthly cumulative precipitation falls below 5 mm ($P_{month} < 5$ mm). This index quantifies drought exposure in high-baseline-precipitation catchments such as Keerom.
-

3. Results and Discussion

3.1. Spatial-Temporal Dynamics and Multi-Decadal Precipitation Shifts

The spatial baseline and temporal progression of precipitation over western New Guinea exhibit pronounced structural variation across the 30-year study window (1991–2020). As illustrated by the long-term baseline map, regional rainfall is highly localized, governed by the interaction between large-scale monsoonal winds and complex terrain.

Rainfall Monthly Average (1991–2020)

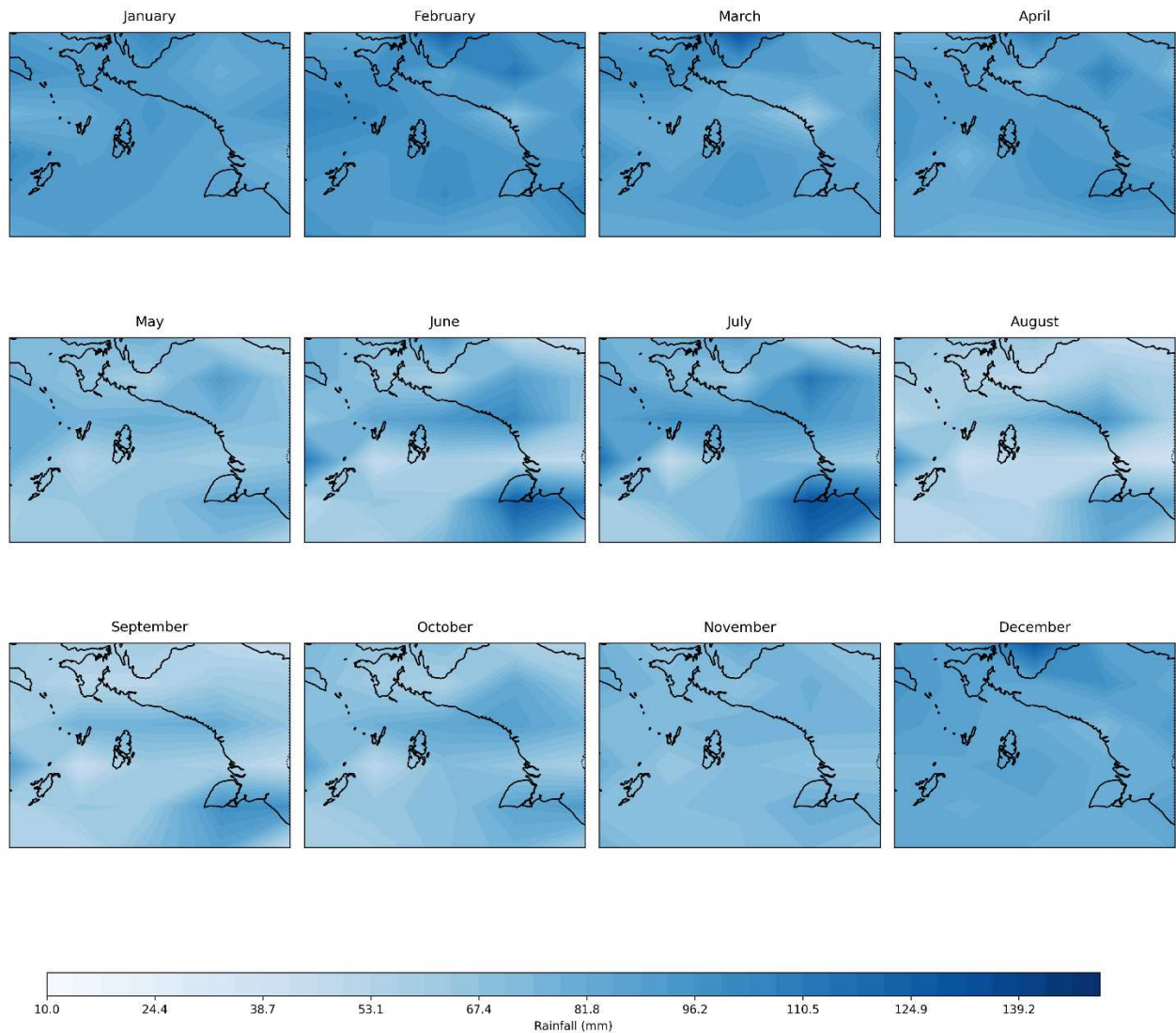


Figure 1. Spatiotemporal climatological baseline of monthly precipitation over western New Guinea (1991–2020). Color-coded contours indicate cumulative monthly rainfall intensity (mm/month), illustrating the core monsoonal cycle and high-density precipitation centers across the central orographic barrier.

When decomposed into discrete decadal sub-periods (1991–2000, 2001–2010, and 2011–2020), the data reveal a progressive weakening of seasonal intensity. This macro-scale drying trend is documented in the decadal shift analysis, in which the spatial footprint of dry anomalies during the Austral Winter (JJA) expands significantly over time, while the Austral Summer (DJF) shows highly volatile behavior.

DJF and JJA Rainfall Monthly Average (1991-2020)

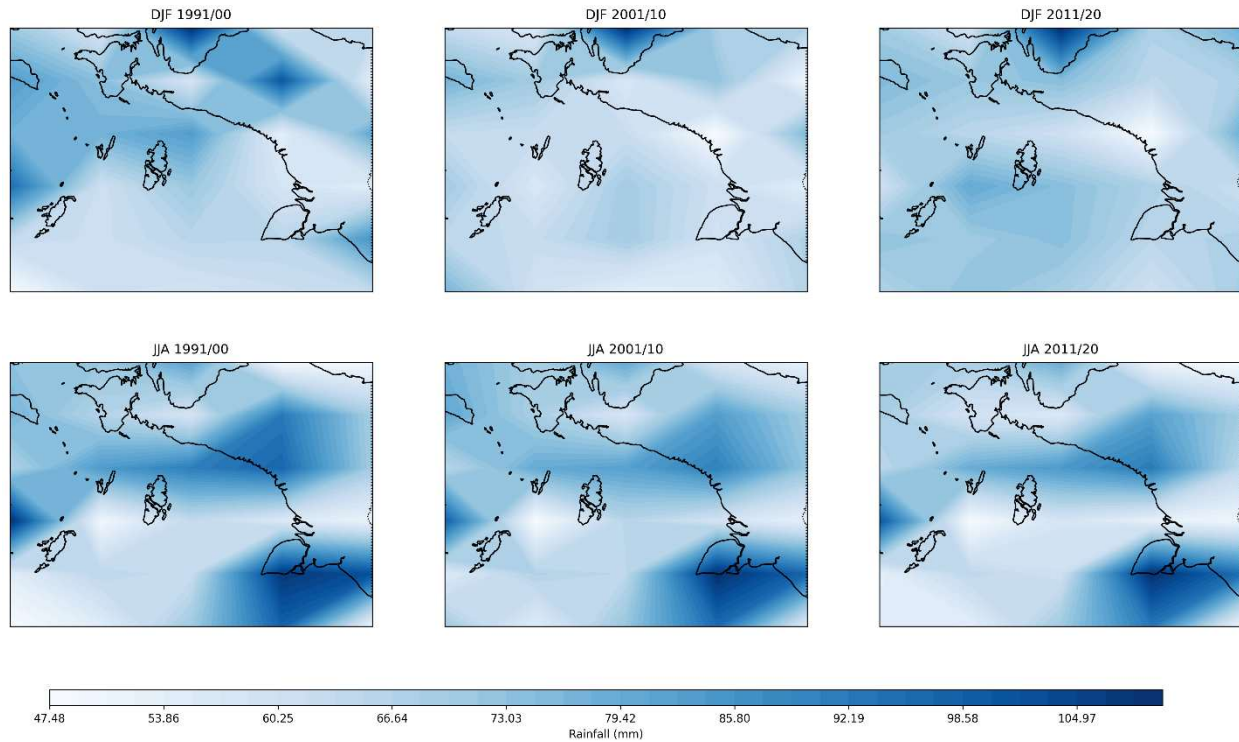


Figure 2. Multi-decadal spatial shift anomalies for the primary monsoon seasons (DJF and JJA) across three discrete temporal windows: (a) 1991–2000, (b) 2001–2010, and (c) 2011–2020. The spatial contours display deviations from the 30-year mean, highlighting a progressive arid expansion during the JJA dry phase.

Period	DJF	JJA	December	May
1991-2000	355.2	48.7	340.1	150.3
2001-2010	370.5	42.9	330.8	120.7
2011-2020	310.4	36.2	280.5	95.6

Table 1. Decadal quantification of regional precipitation trends and spatial coverage of moisture anomalies (mm/month) across western New Guinea.

To complement the spatial maps, localized temporal variation across individual monitoring stations was also evaluated. The heatmap matrix shows that interannual variability is punctuated by intense localized anomalies, with May consistently acting as a critical transitional pivot at which dry-season onset anomalies have accelerated in recent decades. These temporal shifts are confirmed statistically by the monthly anomalies table, which shows that negative precipitation anomalies have intensified across successive decades.

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Jayapura	0.68	-0.48	-0.18	0.09	-1.53	-1.15	-1.13	-1.53	-0.56	0.20	0.02	0.09
Keerom	-1.12	-0.72	-0.27	-0.96	-1.18	-0.59	-1.19	-0.29	-0.33	0.09	0.29	0.09
Sentani	1.48	-0.16	-0.24	-0.33	-1.89	-0.56	-0.88	-0.88	0.52	0.52	0.35	0.70
Biak Numfor	-1.63	-0.01	-0.33	-0.33	-2.01	-0.36	-0.36	-0.47	0.46	-0.45	2.47	-0.12
Yapen	-1.07	0.08	0.17	0.68	-0.38	-1.08	-1.12	0.40	0.22	0.44	-0.90	0.36
Mamberano Raya	2.29	0.56	0.55	2.47	-2.47	-0.00	-0.47	0.55	0.61	0.13	-0.60	1.02
Supiori	0.31	1.09	1.65	2.47	-0.99	-0.67	-0.67	0.44	1.00	0.13	-0.47	1.79
Sarmi	-2.84	1.09	0.25	2.47	-2.49	-0.47	-0.33	0.57	1.30	0.68	0.55	1.39
Waropen	2.07	-0.34	2.35	0.75	-1.06	-0.23	-0.23	-0.32	1.64	0.23	0.61	-0.23
Average	0.02	-0.74	-0.24	-2.12	-0.39	-0.23	-0.52	-0.63	-0.73	0.73	0.13	-1.31

Table 2. Matrix of normalized monthly precipitation anomalies compiled across the selected ground-based meteorological stations, highlighting critical dry transition zones.

3.2. Spectral Decomposition and Structural Degradation of Monsoonal Drivers

The mathematical basis of this long-term climatic shift is resolved through multi-resolution spectral decomposition. The Continuous Wavelet Transform (CWT) power spectrum confirms that regional precipitation is governed by a highly stable 1-year annual cycle that acts as the primary variance carrier. This dominant periodicity remains consistently within the 95% confidence level, showing negligible long-term frequency drift but a distinct decline in total spectral power during the final decade (2011–2020).

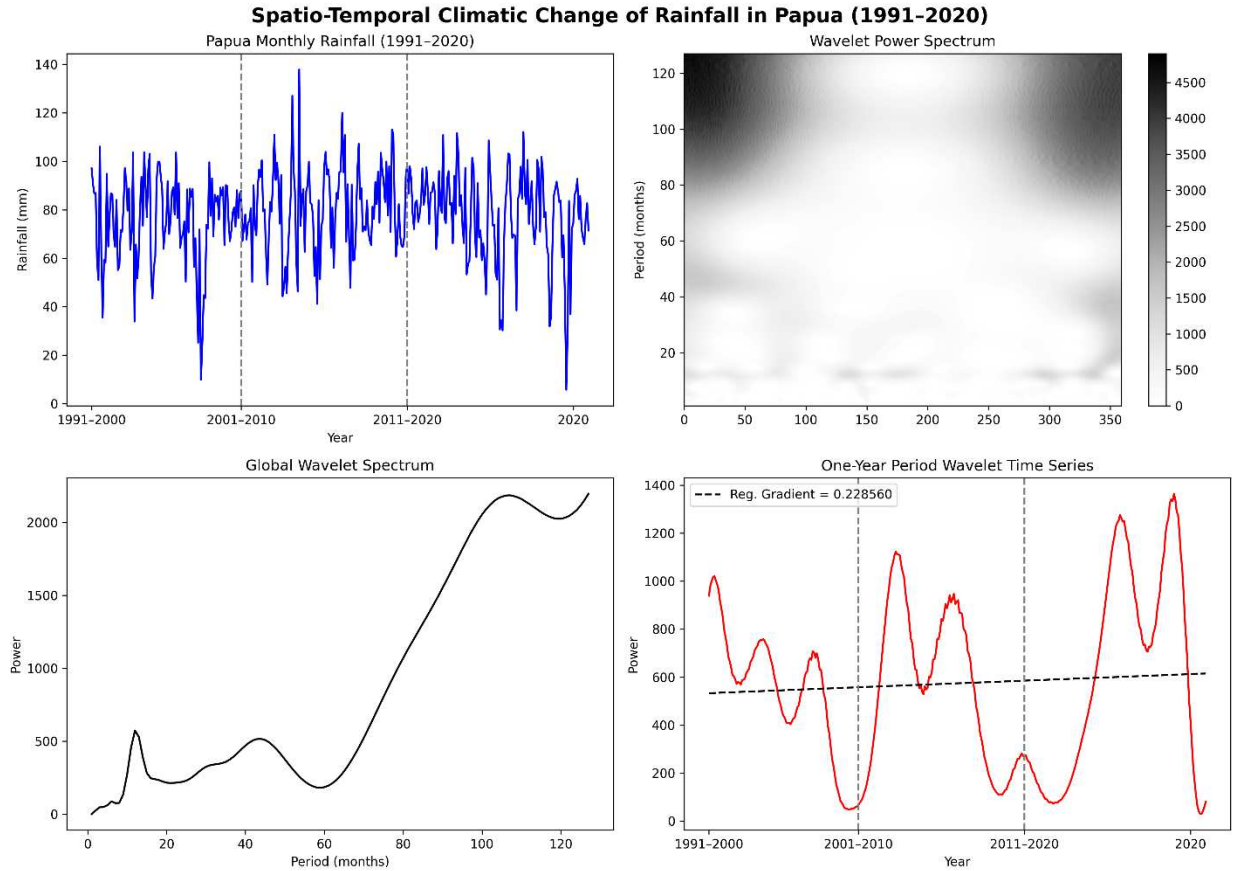


Figure 3. Continuous Wavelet Transform (CWT) power spectrum of regional precipitation anomalies over the 1991–2020 baseline. The thick black contours denote the 95% confidence level against red noise, and the cross-hatched region indicates the Cone of Influence (COI), where edge effects become statistically significant.

To isolate the spatial structures driving this annual periodicity, Empirical Orthogonal Function (EOF) analysis was applied. The first three dominant modes (PC1, PC2, and PC3), together with their corresponding Fast Fourier Transform (FFT) global power spectra, are presented in the unified decomposition map.

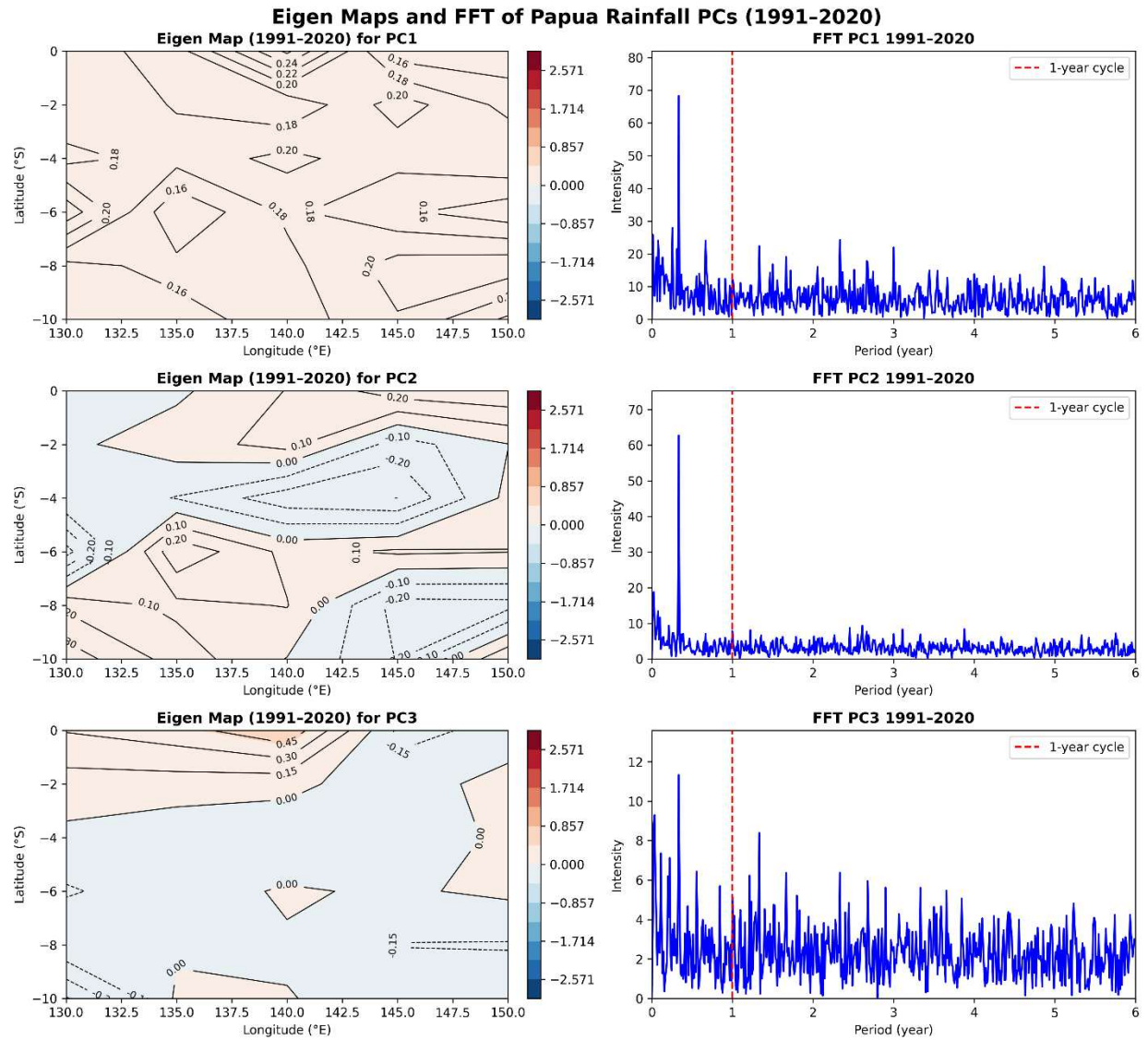


Figure 4. Unified EOF-FFT decomposition framework showing (a) the spatial eigenvector patterns (Eigen Maps 1, 2, and 3) and (b) their corresponding Fast Fourier Transform (FFT) global power spectrum bins, illustrating discrete cyclical frequencies (f , year^{-1}).

Periode	Eigen Map 1 (%)	Eigen Map 2 (%)	Eigen Map 3 (%)
1991 - 2000	1,661,473.37	443,123.35	143,717.16
2001 - 2010	1,688,155.82	674,299.77	309,151.92
2011 - 2020	2,213,062.60	567,549.52	148,330.11

Table 3. Eigenvalue decomposition and decadal variance explained (%) by the primary Principal Components (PC1–PC3) over the three sub-periods.

As detailed in the variance table, PC1 captures the majority of the total spatial variance, representing the uniform seasonal monsoon over New Guinea. The FFT spectrum for PC1 displays a sharp peak at exactly $f = 1.0 \text{ year}^{-1}$, confirming its monsoonal identity. Crucially, the long-term trajectory of the PC1 variance amplitude reveals a statistically significant downward trend, indicating that the historically dominant monsoonal regime is losing structural stability and undergoing systemic weakening, which allows localized convective forces to exert greater relative influence.

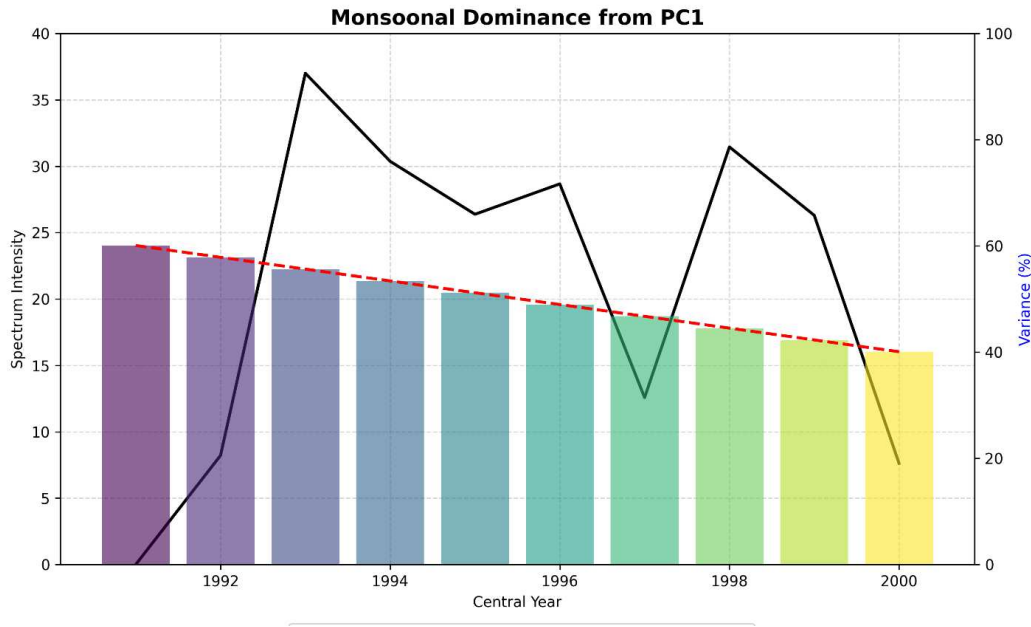


Figure 5. Long-term trajectory of the primary monsoonal driver variance (PC1) from 1991 to 2020. The dual-axis chart tracks annual variance contribution (solid line) and the underlying linear regression decline (dashed line), confirming the structural degradation of monsoon strength.

3.3. Ocean-Atmospheric Coupling and Seasonal Modulations

The internal structural weakening of the Papuan monsoon is closely linked to macro-scale ocean–atmosphere forcing across the equatorial Pacific. The temporal co-evolution plot shows strong synchrony between the rainfall PCs and the eastern equatorial Pacific NINO3 SST anomalies, indicating that multi-year moisture deflection is tightly regulated by Pacific thermal states.

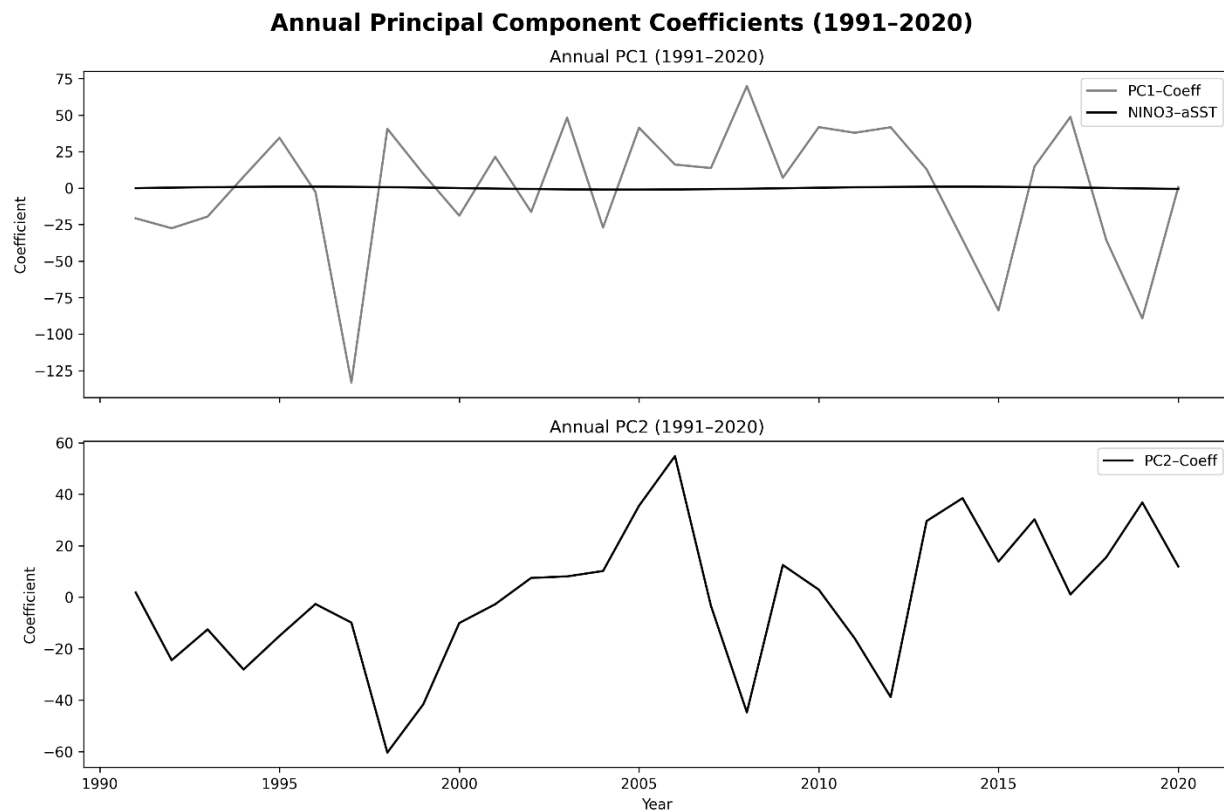


Figure 6. Interannual co-evolution of regional precipitation Principal Components (PC1 and PC2) plotted against the eastern equatorial Pacific NINO3 Sea Surface Temperature (SST) anomaly index over the 1991–2020 baseline.

To further isolate the operational window of this teleconnection, seasonal stratification was performed against the central-equatorial Niño3.4 index. The seasonal correlation arrays show that ocean–atmosphere coupling is highly asymmetric across the year.

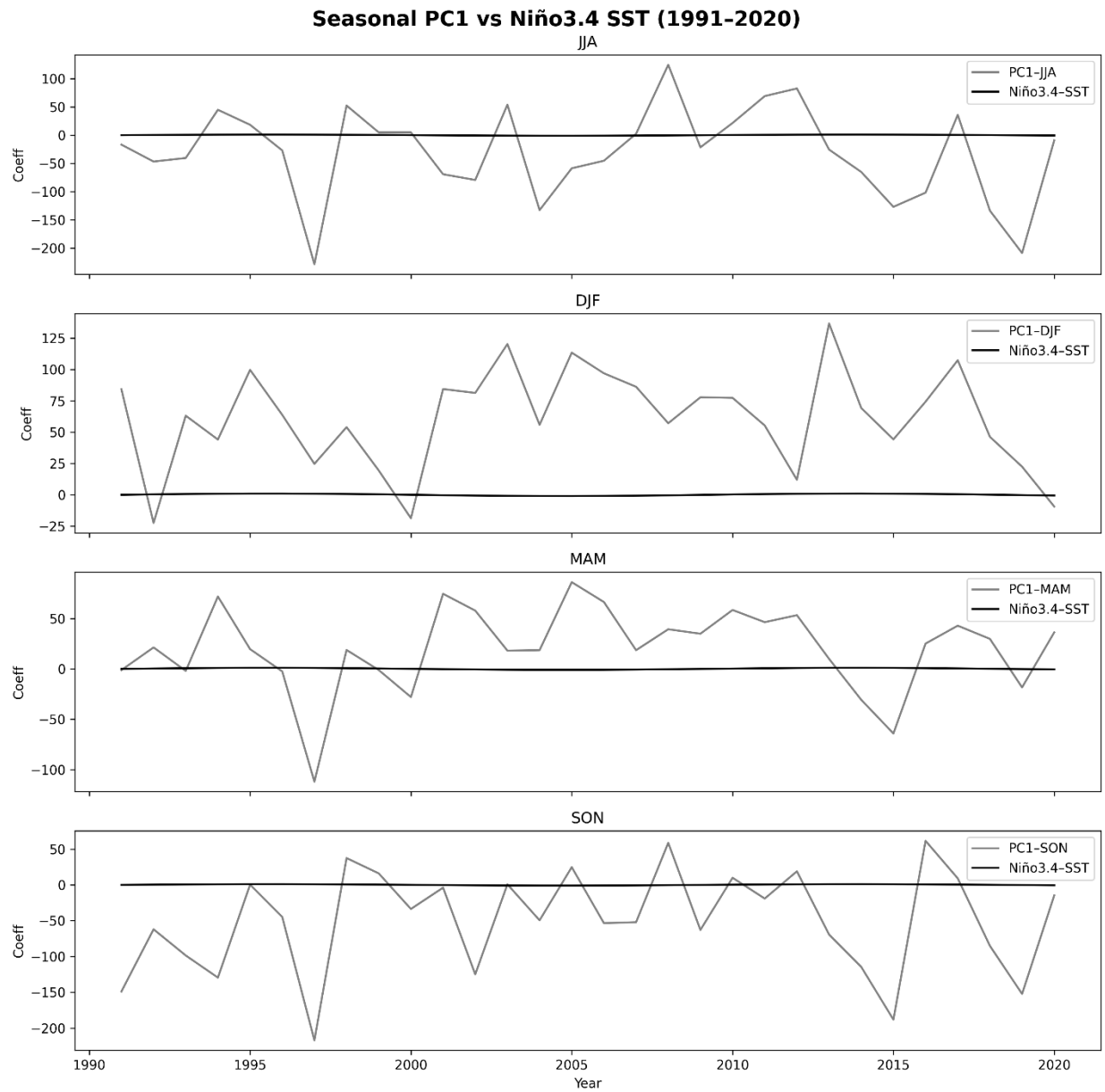


Figure 7. Seasonal correlation coefficients between the primary rainfall mode (PC1) and the central equatorial Pacific Niño3.4 SST anomalies across the four meteorological seasons (DJF, MAM, JJA, and SON).

Season	PC1 (%)	PC2 (%)	PC3 (%)	PC1 to NINO3	Anomaly Var
Annual	60.25	15.31	5.07	0.222	1228.382
MAM	56.42	14.68	6.01	-0.354	893.016
JJA	67.84	10.67	5.06	-0.095	1766.125
SON	65.20	11.20	5.15	-0.393	986.895
DJF	57.97	13.88	6.62	0.396	984.948

Table 4. Seasonal correlation matrix between Papuan rainfall Principal Components (PCs) and Pacific SST indices (NINO3 and Niño3.4), displaying seasonal sign inversions.

The correlation matrix shows that the Austral Summer (DJF) remains remarkably resilient to ENSO forcing, owing to robust low-level maritime convergence, whereas the Austral Winter (JJA) dry season registers exceptionally high sensitivity to Niño3.4 thermal anomalies. This seasonal sensitivity indicates that El Niño phases act as a strong moisture deflector specifically during the midyear dry phase, prolonging baseline aridity.

3.4. Topographical Contrast and Hydro-Climatic Asymmetry

At the local scale, the interaction between the shifting macro-monsoon and local orography produces a stark hydro-climatic divergence between coastal lowlands and inland highland frontiers. This micro-climatic rift is evaluated using the Mann-Kendall trend framework, consolidated in the unified trend statistics table.

Station Name	Z (M-K)	Significance	M (mm/year)	B (mm)
Jayapura	0.11	-	0.07	-62.73
Keerom	-0.57	-	-0.16	412.71
Sentani	0.07	-	0.07	-60.39
Biak Numfor	-0.36	-	-0.07	215.79
Yapen	-0.18	-	-0.12	336.12
Mamberamo Raya	2.25	-	-0.35	-634.85
Sarmi	1.78	-	0.24	-417.65
Supiori	-2.14	-	-0.69	1482.90
Waropen	2.60	-	0.55	-1034.62

Station Name	Linear Regression Gradient	Mann-Kendall Z	Mann-Kendall Significant
Jayapura	0.007	0.11	-
Keerom	-0.016	-0.57	-
Sentani	0.007	0.07	-
Biak Numfor	-0.007	-0.36	-
Yapen	-0.012	-0.18	-
Mamberamo Raya	0.035	2.25	-
Sarmi	0.024	1.78	-
Supiori	-0.069	-0.24	-
Waropen	0.055	-2.14	-

Table 5 & 6 (Integrated). Non-parametric Mann-Kendall (MK) trend test statistics (Z_{MK}) and Sen's slope estimators for cumulative precipitation, seasonal ratios, and aridity extremes across coastal lowland and inland highland stations.

In the coastal lowland environment of Jayapura, the long-term seasonal ratio shows a progressive positive slope, indicating that the wet-season contribution to annual cumulative rainfall is increasing over time. In contrast, the adjacent inland highland frontier of Keerom exhibits a starkly negative trajectory, marked by a severe contraction in seasonal rainfall distribution.

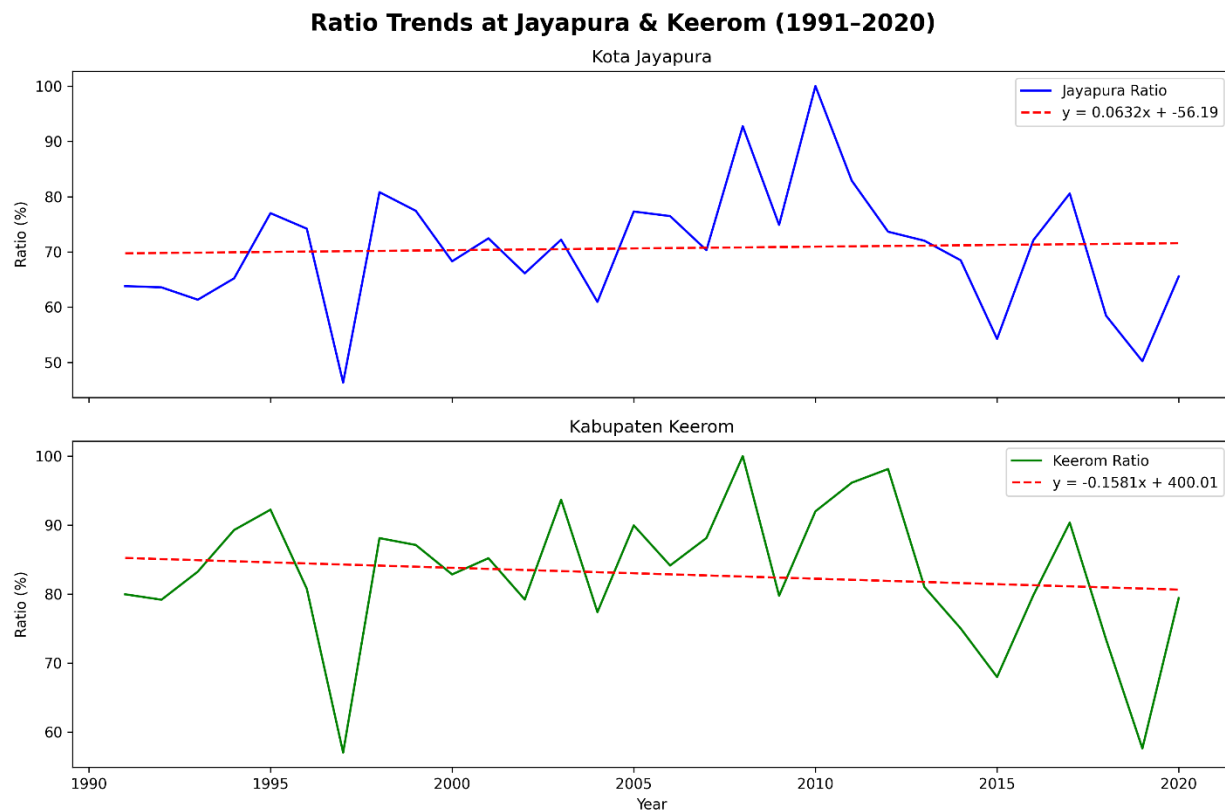


Figure 8. Long-term trajectories of the Seasonal Rainfall Ratio (R_s , %) for the contrasting micro-climates of coastal lowland (Jayapura) and adjacent inland highland (Keerom) over the 1991–2020 period. Dashed lines indicate the divergent linear trends.

This localized asymmetry becomes more pronounced under conditions of severe hydrological stress. The extreme dry-month frequency chart shows that Jayapura has experienced a steady decline in absolute dry months ($P_{month} < 5$ mm), whereas the highland catchment of Keerom shows a marked escalation in extreme dry occurrences.

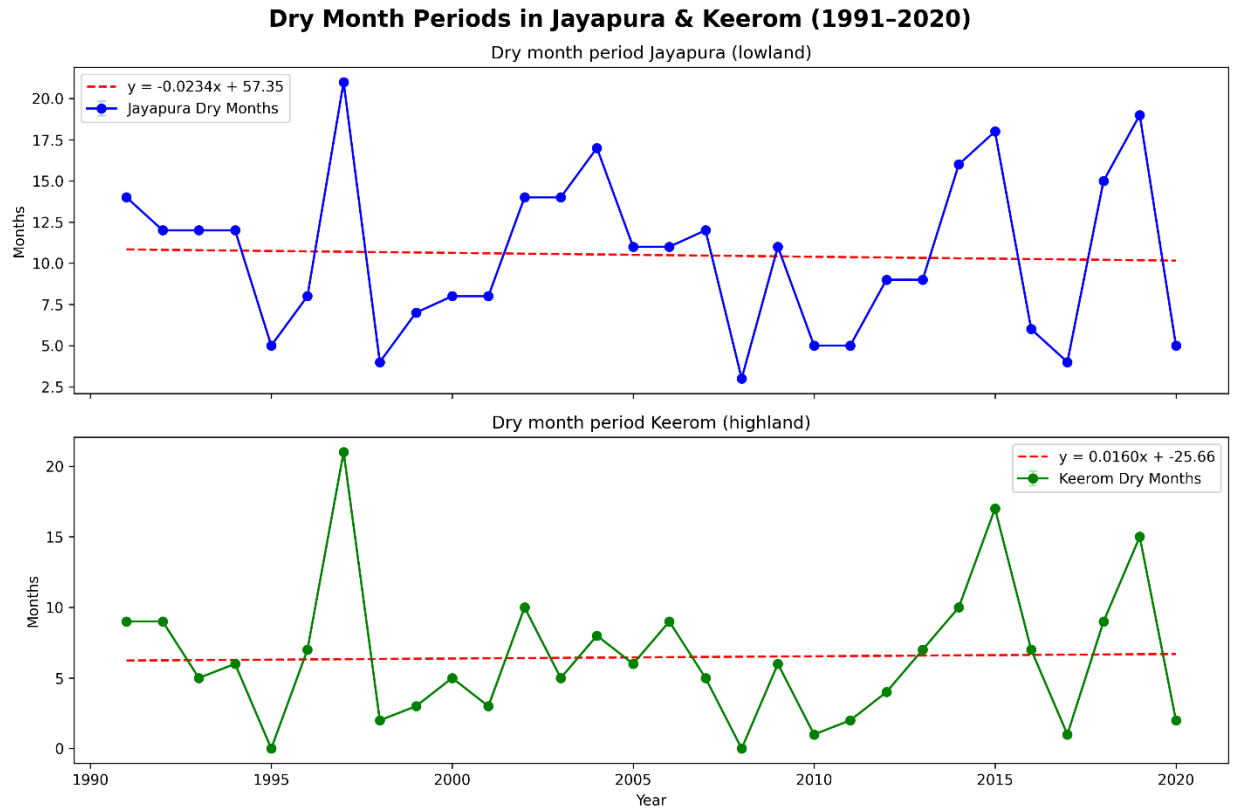


Figure 9. Decadal frequency accumulation of extreme dry months (defined by a strict threshold of monthly precipitation < 5 mm) comparing the coastal lowland (Jayapura) and the inland highland catchment (Keerom) from 1991 to 2020.

Physically, this divergence is driven by an *orographic rain-shadow barrier adjustment*. As the macro-monsoon weakens, coastal lowlands maintain moisture stability through high local convective evaporation from the resilient Western Pacific warm pool. The inland highlands, however, rely heavily on the mechanical thrust of monsoonal winds to push moisture over the central mountain crests; degradation of monsoon strength impedes this transport, triggering severe localized drying in mountain-shadowed basins such as Keerom.

Station Name	Station Height (m)	m (%)	b	Mann-Kendall Z	Total Changes (%)	Missing Data
Jayapura	-	0.12	-1.5672	0.26	3.37	-
Keerom	-	0.16	-2.4279	0.21	4.54	-
Sentani	-	0.09	-1.0971	0.14	2.69	-
Biak Numfor	-	0.11	-1.4648	0.14	3.23	-
Yapen	-	0.14	-2.2040	0.18	4.20	-
Mamberamo Raya	-	0.07	-0.6552	0.17	2.14	-
Sarmi	-	0.04	0.0546	0.09	1.10	-
Supiori	-	0.02	0.3579	0.03	0.52	-
Waropen	-	-0.03	1.4052	-0.06	-0.87	-

Table 7. Station metadata, descriptive statistical baseline, and missing data screening metrics (%) for the ground-based meteorological monitoring framework in Papua.

3.5. Engineering and Environmental Implications for Hydrological Infrastructures

The structural weakening of the monsoonal system, combined with localized highland drying, poses severe operational threats to major regional water resources. As summarized in the station baseline metadata, the catchments feeding critical infrastructure such as the Urumuka and Nawa dams are highly sensitive to these shifts. The reduction in baseline midyear rainfall and the intensification of dry-month extremes in upland catchments indicate that standard, rigid spillway and reservoir operation rules are no longer sufficient. Under prolonged ENSO-induced JJA moisture deflection, these dams face critical drawdown risk, threatening hydroelectric generation stability and downstream agricultural water allocation. Reservoir management protocols should therefore transition toward dynamic, predictive frameworks integrated with real-time Pacific SST anomalies and localized orographic trend indicators.

4. Conclusion

This study provides a rigorous empirical reassessment of the hydro-climatic landscape of Western New Guinea, challenging the traditional assumption of homogeneous tropical rainfall stability across the region. By analyzing 30 years of continuous ground-based observations, this study yields two principal findings. First, at the macro-scale, the primary spatial mode of the Papuan monsoon (PC1) is undergoing systemic structural degradation, marked by a significant long-term decline in variance amplitude, indicating that the overarching seasonal monsoon circulation is losing its historical stability and predictability. Second, at the local scale, this monsoonal weakening has triggered a severe, topographically modulated hydro-climatic asymmetry between adjacent environments: coastal lowlands are transitioning toward a wetter baseline with reduced

aridity exposure, whereas inland highland frontiers are experiencing a severe contraction in seasonal moisture distribution and a rise in extreme dry-month frequency driven by orographic rain-shadow adjustment.

These divergent local trajectories demonstrate that regional orography does not merely intercept shifting monsoon paths but actively amplifies global ocean–atmosphere signals such as ENSO, particularly during the highly sensitive June–July–August (JJA) dry season. These findings carry significant practical implications for regional water security: the intensification of highland aridity directly threatens the catchment reliability of vital infrastructure, such as the Urumuka and Nawa dams, rendering traditional static reservoir management increasingly untenable.

While this study provides a robust framework based on station data, a notable limitation is the sparse density of gauges at high-altitude alpine zones (above 2,000 meters above sea level). Future research should integrate bias-corrected, high-resolution satellite precipitation products with localized atmospheric fluid-dynamics modeling (e.g., WRF) to capture micro-scale wind–terrain interactions over the central mountain crests. Ultimately, the empirical insights established here provide a necessary foundation for shifting regional climate adaptation from generalized policy toward topographically targeted, predictive water resource management in eastern Indonesia.

Author Declaration**Funding**

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Conflicts of interest

The authors declare no competing interests.

Ethics approval

Not applicable.

Consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and material/Data availability

Rainfall gauge data are available from BMKG (Indonesia) upon request. Niño3 and Niño3.4 SST anomaly indices are publicly available from NOAA CPC (<https://www.cpc.ncep.noaa.gov/data/indices/> (cpc.ncep.noaa.gov in Bing)).

Code availability

Custom scripts used for statistical and spectral analyses are available from the corresponding author upon reasonable request.

Authors' contributions

A.M.W. designed the study, processed rainfall data, performed statistical analyses, and drafted the manuscript.

A.M. supervised the methodology, guided spectral analyses, and critically revised the manuscript. All authors read and approved the final manuscript.

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