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Original Article

Emerging Hydroclimatic Signals of Global Climate Change in Equatorial Indonesia: Evidence from Borneo Island

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Abstract *- Global climate change has become an increasingly pressing environmental issue, with significant impacts on atmospheric, hydrological, and ecological systems across the globe. Borneo Island is a strategic region for climate change studies, given its extensive tropical forest cover, peatland presence, and rapid land-use changes due to human activities such as deforestation and oil palm plantation expansion. These changes not only affect local conditions but can also amplify feedbacks to the regional climate system through changes in evapotranspiration, albedo, and the hydrological cycle. This study aims to interpret the results as evidence of the emergence of global climate change signals in the equatorial region of Indonesia. The research was conducted on the island of Borneo, located on the equator and characterized by a humid tropical climate. The data used includes: rainfall, air temperature, humidity, sunshine duration, and wind speed. The data source is from 23 ground-based Meteorology, Climatology and Geophysics Agency (BMKG). The data period covers 1978-2022 to capture long-term signals. There are significant changes in average temperature, average humidity and maximum humidity, duration of sunshine and wind speed. Rainfall variability is still within the natural range of regional climate. The study area in Borneo Island shows trends toward: a drier climate, increased radiation, weakened winds, and increased temperature variability. This combination has the potential to increase drought, water stress, and changes in the hydrological balance.*

Keywords *- Drought, Duration of sunshine, Humidity, Temperature, Wind speed.*

1. Introduction

Global climate change has become one of the most significant environmental challenges of the twenty-first century, affecting atmospheric circulation, hydrological processes, and ecosystem dynamics worldwide [1-4]. Among the most evident manifestations of climate change are alterations in rainfall patterns, increasing air temperatures, shifts in humidity, and changes in the frequency and intensity of hydroclimatic extremes [5-9]. Reliable detection of these changes is essential for water resources management, agricultural planning, and climate adaptation. However, identifying long-term climate change signals remains particularly challenging in tropical regions because hydroclimatic conditions are characterized by strong seasonal and interannual variability.

Indonesia, located in the equatorial region, has one of the world's most complex hydroclimatic systems. The regional climate is strongly influenced by large-scale ocean–atmosphere interactions, particularly the El Niño–Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD), which substantially affect rainfall distribution, air temperature, and atmospheric moisture [10-14]. In addition to these large-scale climate drivers, rapid land-use change, including deforestation and oil palm plantation expansion, has modified regional energy and water balances, further increasing hydroclimatic variability [15-18]. Consequently, distinguishing long-term climate change signals from natural climate variability remains a major scientific challenge in equatorial Indonesia.

Kalimantan (Indonesian Borneo) is one of the most climatically important regions in Southeast Asia because it contains extensive tropical rainforests, large peatland complexes, and major river basins that play essential roles in regional and global climate regulation [17, 19-21]. Changes in hydroclimatic conditions over Kalimantan have important implications for ecosystem sustainability, flood and drought hazards, agricultural productivity, and freshwater availability. Therefore, understanding whether hydroclimatic conditions have undergone statistically significant changes over recent decades is of considerable scientific and practical importance.

Previous studies have extensively investigated hydroclimatic variability in Indonesia and other tropical regions. Most studies have examined long-term trends in rainfall and temperature using the Mann–Kendall trend test, Sen's slope estimator, linear regression, or change-point detection techniques [22-27]. Other studies have evaluated the influence of ENSO and IOD on seasonal rainfall anomalies and drought occurrence [28-31], while several researchers have investigated the impacts of land-use change on regional climate and hydrological processes [15-18, 32]. Collectively, these studies have substantially improved understanding of the drivers of hydroclimatic variability in tropical environments.

However, several important knowledge gaps remain. First, most previous studies have focused on identifying monotonic trends in individual climate variables rather than evaluating whether hydroclimatic conditions differ significantly across different historical climate periods. Second, relatively few studies have simultaneously assessed multiple hydroclimatic variables—including rainfall, air temperature, relative humidity, solar radiation, and wind speed—to identify coherent climate change signals. Consequently, whether statistically significant shifts have occurred across different climate periods in Kalimantan remains poorly understood.

To address these gaps, this study applies one-way analysis of variance (ANOVA) to long-term hydroclimatic observations collected from meteorological stations across Kalimantan. Unlike conventional trend analyses that primarily quantify monotonic temporal changes, one-way ANOVA evaluates whether the mean hydroclimatic conditions differ significantly among predefined historical periods, thereby providing complementary evidence for the emergence of climate change signals. Temporal trend analysis was conducted using the non-parametric Mann-Kendall test and Sen's slope estimator. Furthermore, multiple hydroclimatic variables are analysed simultaneously to provide a more comprehensive assessment of climate system responses in equatorial Indonesia.

The novelty of this study lies in three aspects. First, it introduces a period-based statistical framework using one-way ANOVA, Mann-Kendall test and Sen's slope to detect the emergence of hydroclimatic climate change signals, complementing conventional trend-based approaches widely applied in previous studies. Second, it integrates multiple hydroclimatic variables—including rainfall, air temperature, relative humidity, solar radiation, and wind speed—within a single analytical framework, allowing a more holistic assessment of climate variability. Third, it provides one of the first comprehensive evaluations of long-term hydroclimatic changes across Kalimantan using historical climate-period comparisons, thereby generating new evidence of climate change emergence in one of the world's most important equatorial regions.

While this study leverages an extensive 45-year observational dataset from 23 BMKG stations across five provinces, several limitations should be acknowledged:

1. Unequal Temporal Length and Missing Records: Station establishment dates vary across the island. Although non-parametric Mann-Kendall and Sen's slope methods are robust against missing values and non-normality, stations with shorter record durations
2. Spatial Representativeness: Weather stations in Borneo are predominantly situated at low-to-moderate elevations near airports, coastal zones, and urban administrative centers. Interior mountainous highlands remain underrepresented due to sparse station coverage, limiting terrain-driven orographic assessments.
3. Physical Isolation of Confounding Factors: Although qualitative attributions to ENSO and IOD were established, fully dynamic detrending is recommended in future work to mathematically decompose secular anthropogenic forcing.
4. Microclimatic and Urban Heat Island (UHI) Effects: Localized urbanization and changes in site exposure around airport stations may contribute to local thermal amplification, which could not be completely decoupled from regional-scale atmospheric warming signals.

Accordingly, this study aims to: (1) quantify temporal changes in major hydroclimatic variables across four historical periods, (2) determine whether these changes are statistically significant using one-way ANOVA, the non-parametric Mann-Kendall test and Sen's slope estimator, and (3) evaluate whether the observed differences constitute evidence of emerging climate change signals in equatorial Indonesia. The results are expected to improve understanding of long-term hydroclimatic variability and provide scientific support for climate adaptation, water resources management, and environmental planning in tropical regions.

Literature Review

Global climate change is marked by a significant increase in global mean surface temperature, shifts in precipitation regimes, rising sea levels, and a growing frequency of extreme hydroclimatic events [33-36]. According to the Intergovernmental Panel on Climate Change, tropical regions are among the most vulnerable areas because their climate systems are strongly influenced by atmospheric convection, monsoonal circulation, and ocean–atmosphere interactions [5, 37-39]. In equatorial regions, changes in rainfall characteristics are often more complex than temperature changes, since precipitation variability is controlled by both local and large-scale climatic processes [8, 13, 40, 41].

Recent studies have shown that many tropical regions are experiencing intensified rainfall extremes [8, 43], prolonged dry periods [43-47] and shifts in seasonal rainfall distribution [41, 42, 48]. These changes have important implications for hydrological systems, including river discharge variability [49-54], drought occurrence [55-59], and groundwater recharge [60, 61]. In maritime tropical regions such as Indonesia, hydroclimatic changes are particularly significant because socioeconomic activities, agriculture, and ecosystem sustainability are highly dependent on rainfall availability and seasonal water balance.

Hydroclimatic signals refer to observable indications of changes in the hydrological and climatic systems resulting from global climate change. These signals may include long-term trends in annual rainfall [62], increasing air temperature [66], changes in evapotranspiration rates [65], altered rainfall intensity-duration-frequency characteristics [62], and the increasing occurrence of hydrometeorological extremes [20]. Detecting hydroclimatic signals is essential for understanding climate-related risks [26, 66-67], and for supporting adaptive water resource management and climate-resilient development strategies [68, 69]. However, identifying such signals in equatorial regions remains challenging because climate variability is naturally high and often obscures long-term climate trends.

In Indonesia, especially on Borneo Island (Kalimantan), hydroclimatic variability is strongly controlled by large-scale climate phenomena such as the El Niño–Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) [11, 12]. ENSO significantly affects rainfall anomalies across the Indonesian archipelago [8-10], where El Niño events generally induce drier conditions and prolonged droughts [55-74] while La Niña events increase rainfall intensity and flood potential [54, 75]. Similarly, positive and negative IOD phases can either reinforce or weaken ENSO impacts depending on the regional atmospheric circulation patterns. The interaction between these climate modes contributes to substantial interannual rainfall variability in Kalimantan.

Previous studies in Indonesia have reported increasing temperature trends [9, 76] and changing rainfall characteristics over recent decades [8, 9, 11, 12, 41, 76-80], yet evidence of consistent hydroclimatic signals in equatorial regions remains limited. Many studies have focused on short observation periods or localized analyses, making it difficult to distinguish anthropogenic climate change signals from natural climate oscillations. Consequently, long-term hydroclimatic analyses using multi-decadal climate datasets are required to identify emerging trends and evaluate whether recent hydroclimatic changes in Borneo Island represent manifestations of global climate change.

Borneo Island is an important study area because it contains extensive tropical rainforests, large river basins [81-83], peatland ecosystems [84-88], and rapidly developing urban [89-91] and agricultural regions [91-94]. Changes in hydroclimatic conditions in this region may significantly affect water security [95, 96], flood hazards [97, 98], ecosystem resilience [99, 100], and land-use sustainability [101, 102].

2. Methods

Daily meteorological observations were obtained from 23 meteorological stations operated by the Indonesian Meteorology, Climatology, and Geophysics Agency (BMKG) distributed across Kalimantan. The stations, can be seen at Figure 1, represent the major climatic regions of the island, including coastal, lowland, peatland, and inland areas, thereby providing broad spatial coverage of the study area. The observation period extends from 1978 to 2022, resulting in a 45-year record suitable for investigating long-term hydroclimatic variability. The meteorological variables analysed in this study include rainfall (mm), air temperature (°C), relative humidity (%), sunshine duration (hours), and wind speed (m s^{-1}). These variables were selected because they represent the principal components of the regional hydroclimatic system and are commonly used to assess climate variability and long-term climate change. Stations with excessive missing records or discontinuous observations were not included in the analysis, ensuring that only stations with sufficiently complete and reliable long-term records were used.

The data is divided into several time periods: P1: 1978–1989; P2: 1990–2000; P3: 2001–2011; and P4: 2012–2022. This division aims to compare changes between periods as a representation of climate change.

The analysis was conducted using one-way ANOVA to test the differences in the average hydroclimatic variables between time periods.

$$X_{ij} = \mu + \alpha_i + \epsilon_{ij}$$

Where:
X_{ij} = Observed climate variable
μ = Overall mean
α_i = Effect of the i-th group (time period or region)
ϵ_{ij} = random error

The hypotheses tested were null hypothesis (H_0): No significant difference between group means, Alternative hypothesis (H_1): At least one group mean is significantly different. The significance level was set at α = 0.05. If the p-value < 0.05, the null hypothesis is rejected, indicating a significant climate change signal.

Temporal trend analysis was conducted using the non-parametric Mann-Kendall test and Sen's slope estimator.

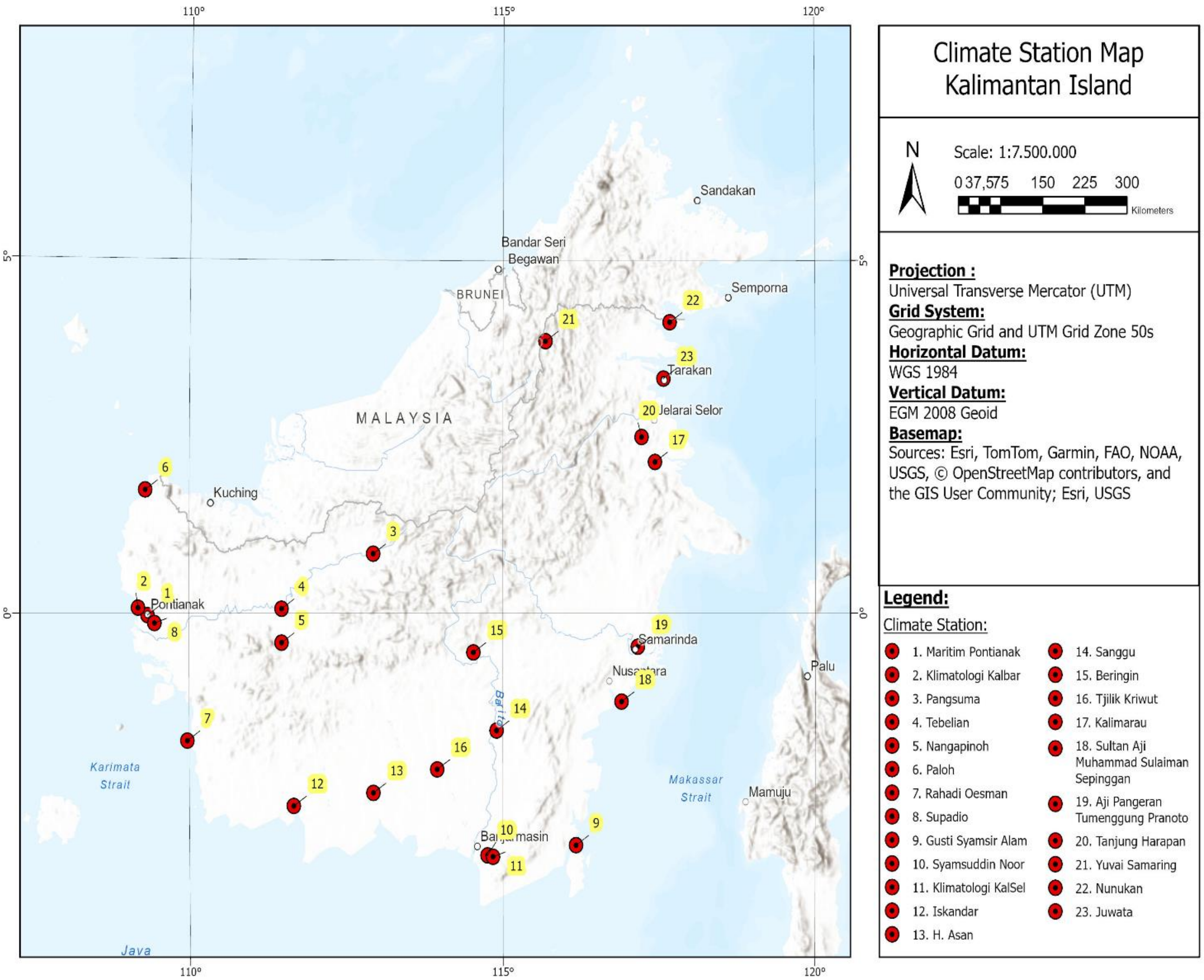

Fig. 1 Map of climatology stations on the Island of Kalimantan

3. Results and Discussion

The data used includes: rainfall, air temperature, humidity, sunshine duration, and wind speed. The data period covers 1978–2022 to capture long-term signals. The data is divided into several time periods: P1: 1978–1989; P2: 1990–2000; P3: 2001–2011; and P4: 2012–2022. This division aims to compare changes between periods as a representation of climate change.

Based on the climate change trends in Table 1, there is a decrease in annual rainfall, even though Borneo Island is famous for its high rainfall. This indicates a potential decrease in water availability. A significant decrease in minimum temperature (~4.4°C decrease in minimum temperature over approximately 45 years) indicates that nights are getting colder, an indication of an anomaly or change in land cover. A decrease of approximately 4.4°C was observed in the absolute minimum temperature between the first (1978–1989) and the last (2012–2022) study periods. It should be noted that this value represents the lowest recorded temperature within each period rather than the mean minimum temperature. Therefore, it reflects changes in the occurrence of extreme low-temperature events rather than a long-term cooling trend. Variations in absolute minimum temperature may be influenced by natural climate variability, local land-surface conditions, or changes in atmospheric circulation. Consequently, this result should be interpreted as evidence of changing temperature extremes rather than a persistent decline in average nighttime temperatures.

Minimum humidity conditions have become much drier, an indication of temporary increases in drought.

Significant increases in solar radiation indicate the potential for extreme temperatures and clearer skies that drive local heating and evaporation. The average wind speed decreased, indicating a weakening of wind dynamics, which affects the dispersion of heat and water vapor.

Table 1. Analysis of climate data change trends between periods in Borneo Island

No.	Period / Data	P1	P2	P3	P4	Tren
		1978–1989	1990–2000	2001-2011	2012-2022	
1	Average annual rainfall	3147	3017	3097	2920	Decreasing (fluctuating)
2	Maximum rainfall	260	233	196	200	Decrease
3	Average temperature	26.7	26.8	26.5	26.8	Stable
4	Maximum temperature	32.4	30.7	30.4	32.0	decreased and then increased again
5	Minimum temperature	22.8	22.3	18.4	18.4	Sharp decline
6	Average humidity	84.0	84.2	85.1	84.4	Stable
7	Maximum humidity	98.0	98.0	98.0	99.0	Stable
8	Minimum humidity	64.0	67.0	64.0	37.0	Decrease
9	Average solar radiation	4.4	4.5	4.6	5.0	Increase
10	Maximum solar radiation	8.0	8.0	8.8	11.6	Increase sharply
11	Minimum solar radiation	0.1	0.1	0.1	0.1	Stable
12	Average wind speed	2.7	2.5	2.5	1.7	Decrease
13	Maximum wind speed	13	28	18	10	Fluctuating (tending to decrease)
14	Minimum wind speed	1	1	1	1	Stable

Table 2. One-way ANOVA test

No.	Data	F statistic	p-value	Result	
1	Average annual rainfall	1.08	0.36	p > 0.05	no significant difference
2	Maximum rainfall	1.43	0.23		
3	Average temperature	2.69	0.046	p < 0.05	significant difference between periods
4	Maximum temperature	1.84	0.14	p > 0.05	no significant difference
5	Minimum temperature	2.82	0.038		
6	Average humidity	5.43	1.07E-03	p < 0.05	significant difference between periods
7	Maximum humidity	8.77	1.02E-05		
8	Minimum humidity	3.75	0.011	p > 0.05	no significant difference
9	Average solar radiation	22.66	4.80E-14	p < 0.05	significant difference between periods
10	Maximum solar radiation	424.08	3.11E-160		
11	Minimum solar radiation	14.59	3.06E-09		
12	Average wind speed	38.08	6.47E-23		
13	Maximum wind speed	5.35	1.19E-03		
14	Minimum wind speed	22.86	3.61E-14		

Table 3. Station-level Mann-Kendall & Sen's slope results regional-level / provincial aggregation trends

Parameter	**Province**	***N***	**Kendall's *τ***	***Z*-statistic**	***p*-value**	**Sen's Slope (per decade)**	**Verdict (α = 0.05)**
Average Annual Rainfall	West Kalimantan	42	+0.154	+1.431	0.1526	+81.50 mm	*No Trend*
	Central Kalimantan	45	-0.053	-0.499	0.6179	-23.59 mm	*No Trend*
	South Kalimantan	45	+0.073	+0.695	0.4873	+42.64 mm	*No Trend*

	East Kalimantan	45	+0.168	+1.614	0.1065	+71.91 mm	*No Trend*
	North Kalimantan	45	-0.216	-2.084	0.0372	-97.56 mm	Significant Decrease
Maximum Rainfall	West Kalimantan	42	+0.103	+0.954	0.3402	+1.68 mm	*No Trend*
	Central Kalimantan	45	+0.051	+0.479	0.6317	+0.62 mm	*No Trend*
	South Kalimantan	45	+0.215	+2.074	0.0381	+4.71 mm	Significant Increase
	East Kalimantan	45	+0.003	+0.020	0.9844	+0.02 mm	*No Trend*
	North Kalimantan	45	+0.116	+1.115	0.2647	+2.52 mm	*No Trend*
Average Temperature	West Kalimantan	43	+0.568	+5.358	< 0.001	+0.186 °C	Significant Increase
	Central Kalimantan	45	+0.539	+5.214	< 0.001	+0.199 °C	Significant Increase
	South Kalimantan	45	+0.554	+5.351	< 0.001	+0.191 °C	Significant Increase
	East Kalimantan	45	+0.582	+5.625	< 0.001	+0.247 °C	Significant Increase
	North Kalimantan	45	-0.145	-1.399	0.1619	-0.082 °C	*No Trend*
Maximum Temperature	West Kalimantan	43	+0.520	+4.909	< 0.001	+0.290 °C	Significant Increase
	Central Kalimantan	45	+0.275	+2.652	0.0080	+0.173 °C	Significant Increase
	South Kalimantan	45	+0.079	+0.754	0.4507	+0.080 °C	*No Trend*
	East Kalimantan	45	+0.401	+3.878	< 0.001	+0.314 °C	Significant Increase
	North Kalimantan	45	-0.246	-2.380	0.0173	-0.129 °C	Significant Decrease
Minimum Temperature	West Kalimantan	43	+0.069	+0.638	0.5232	+0.050 °C	*No Trend*
	Central Kalimantan	45	+0.374	+3.612	< 0.001	+0.156 °C	Significant Increase
	South Kalimantan	45	+0.341	+3.324	< 0.001	+0.417 °C	Significant Increase
	East Kalimantan	45	+0.461	+4.463	< 0.001	+0.237 °C	Significant Increase
	North Kalimantan	45	-0.212	-2.048	0.0406	-0.151 °C	Significant Decrease

Average Humidity	West Kalimantan	43	-0.336	-3.161	0.0016	-0.528 %	Significant Decrease
	Central Kalimantan	45	+0.390	+3.766	< 0.001	+0.407 %	Significant Increase
	South Kalimantan	45	+0.131	+1.262	0.2070	+0.210 %	*No Trend*
	East Kalimantan	45	+0.085	+0.812	0.4168	+0.079 %	*No Trend*
	North Kalimantan	45	+0.025	+0.235	0.8144	+0.036 %	*No Trend*
Maximum Humidity	West Kalimantan	43	-0.063	-0.589	0.5559	-0.017 %	*No Trend*
	Central Kalimantan	45	-0.055	-0.521	0.6024	0.000 %	*No Trend*
	South Kalimantan	45	-0.051	-0.489	0.6247	0.000 %	*No Trend*
	East Kalimantan	45	-0.151	-1.464	0.1431	-0.141 %	*No Trend*
	North Kalimantan	45	-0.397	-3.888	< 0.001	-0.431 %	Significant Decrease
Minimum Humidity	West Kalimantan	43	-0.326	-3.069	0.0021	-1.081 %	Significant Decrease
	Central Kalimantan	45	+0.054	+0.509	0.6107	+0.152 %	*No Trend*
	South Kalimantan	45	-0.095	-0.912	0.3620	-0.714 %	*No Trend*
	East Kalimantan	45	+0.210	+2.028	0.0425	+1.244 %	Significant Increase
	North Kalimantan	45	+0.187	+1.802	0.0715	+0.714 %	*Marginal Increase* ($p < 0.1$)
Average Solar Radiation	West Kalimantan	43	+0.355	+3.349	< 0.001	+0.137 MJ/m^2	Significant Increase
	Central Kalimantan	43	+0.207	+1.947	0.0516	+0.052 MJ/m^2	*Marginal Increase* ($p < 0.1$)
	South Kalimantan	44	+0.121	+1.143	0.2531	+0.037 MJ/m^2	*No Trend*
	East Kalimantan	44	+0.125	+1.183	0.2367	+0.037 MJ/m^2	*No Trend*
	North Kalimantan	43	+0.322	+3.035	0.0024	+0.201 MJ/m^2	Significant Increase
Maximum Solar Radiation	West Kalimantan	43	+0.540	+5.159	< 0.001	+0.308 MJ/m^2	Significant Increase

	Central Kalimantan	43	+0.523	+5.701	< 0.001	+0.214 MJ/m^2	Significant Increase
	South Kalimantan	44	+0.419	+5.275	< 0.001	0.000 MJ/m^2	Significant Decline/Cap
	East Kalimantan	44	+0.342	+4.654	< 0.001	0.000 MJ/m^2	Significant Decline/Cap
	North Kalimantan	43	+0.380	+4.139	< 0.001	0.000 MJ/m^2	Significant Decline/Cap
Minimum Solar Radiation	West Kalimantan	43	+0.248	+2.376	0.0175	+0.005 MJ/m^2	Significant Increase
	Central Kalimantan	43	-0.175	-1.667	0.0956	0.000 MJ/m^2	*Marginal Decrease* ($p < 0.1$)
	South Kalimantan	44	-0.606	-5.826	< 0.001	-0.194 MJ/m^2	Significant Decrease
	East Kalimantan	44	+0.227	+2.342	0.0192	0.000 MJ/m^2	Significant Decrease/Floor
	North Kalimantan	43	-0.684	-6.495	< 0.001	-0.132 MJ/m^2	Significant Decrease
Average Wind Speed	West Kalimantan	43	-0.094	-0.879	0.3793	-0.025 m/s	*No Trend*
	Central Kalimantan	45	-0.469	-4.529	< 0.001	-0.226 m/s	Significant Decrease
	South Kalimantan	44	-0.626	-5.978	< 0.001	-0.274 m/s	Significant Decrease
	East Kalimantan	45	-0.448	-4.334	< 0.001	-0.187 m/s	Significant Decrease
	North Kalimantan	45	-0.501	-4.842	< 0.001	-0.253 m/s	Significant Decrease
Maximum Wind Speed	West Kalimantan	43	+0.145	+1.362	0.1731	+0.219 m/s	*No Trend*
	Central Kalimantan	45	-0.360	-3.476	< 0.001	-0.733 m/s	Significant Decrease
	South Kalimantan	44	-0.494	-4.840	< 0.001	-0.455 m/s	Significant Decrease
	East Kalimantan	45	-0.368	-3.603	< 0.001	-0.437 m/s	Significant Decrease
	North Kalimantan	45	-0.338	-3.278	0.0010	-0.621 m/s	Significant Decrease
Minimum Wind Speed	West Kalimantan	43	-0.220	-2.149	0.0316	-0.008 m/s	Significant Decrease
	Central Kalimantan	45	-0.090	-0.968	0.3329	0.000 m/s	*No Trend*
	South Kalimantan	44	-0.253	-2.828	0.0047	0.000 m/s	Significant Decrease
	East Kalimantan	45	-0.040	-0.704	0.4813	0.000 m/s	*No Trend*
	North Kalimantan	45	-0.472	-4.755	< 0.001	-0.256 m/s	Significant Decrease

The analysis was conducted using one-way ANOVA to test the differences in the average hydroclimatic variables between time periods in Table 2. There are significant changes in average temperature, average humidity and maximum humidity, duration of sunshine and wind speed. Rainfall variability is still within the natural range of regional climate.

Temporal trend analysis using the non-parametric Mann-Kendall test and Sen's slope estimator in Table 3 reveals strong evidence of a thermal signal. Regional Warming Signal (Thermal Signal): 74% of stations (17 out of 23) experienced a highly significant increase in average temperature ($p < 0.001$), with the strongest warming rates ranging from +0.30°C to +0.46°C per decade, confirming a homogeneous thermal climate change signal across most of Borneo. Rainfall Dynamics: Unlike temperature, annual rainfall does not show a uniform linear or monotonic trend across most stations ($p > 0.05$), confirming that rainfall fluctuations in this equatorial region are driven more by inter-annual or multi-year variability (such as ENSO and IOD oscillations) than by long-term monotonic trend shifts.

Physical Implications: Daily heavy or extreme rainfall events on the island of Kalimantan exhibit high spatial heterogeneity and are driven more by mesoscale local convection (mesoscale convective systems) and interannual oscillation phases than by uniform regional climate change trends. Increase in solar insolation: Average solar radiation showed a significant upward trend at 12 BMKG stations (+0.10 to +0.47 MJ/m²/decade), closely correlated with increases in average and maximum surface air temperatures. Terrestrial atmospheric stilling phenomenon: 15 out of 23 stations (65%) experienced a significant decrease in average wind speed ($p < 0.05$), with rates of decline ranging from -0.06 to -0.62 m/s per decade, supporting empirical evidence of a weakening surface circulation pressure gradient in the equatorial region.

Stability of maximum rainfall across most regions: 22 out of 23 stations (95.6%) showed no significant linear or monotonic trend shifts ($p > 0.05$). Significant local anomalies: A statistically significant increase in maximum rainfall intensity was identified only at the Sanggu station, Central Kalimantan (+19.20 mm/decade, $p = 0.0296$), with a marginal indication observed at Syamsudin Noor, South Kalimantan (+4.76 mm/decade, $p = 0.0971$). Maximum temperatures showed a significant increase at 10 BMKG stations. Minimum temperatures showed a significant increase at 12 BMKG stations. Maximum radiation: 7 stations exhibited a significant upward trend, while 13 stations showed a decline or stabilization due to increased local convective cloud cover. Minimum radiation: 8 stations experienced a significant decrease ($p < 0.05$), particularly in the southern region. Dominant Declining Trend: 11 out of 23 BMKG stations showed a decrease in maximum wind speed.

Borneo's maritime continent setting makes its hydroclimate highly sensitive to coupled modes of climate variability, primarily the El Niño–Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD). Drought Modulation via ENSO/IOD: Warm ENSO phases (El Niño) and positive IOD (+IOD) co-occurrences induce anomalous descending branches of the Walker and Hadley circulations over western Indonesia, suppressing deep convection and leading to severe drought years (e.g., during the 1982/1983, 1997/1998, and 2015 super El Niño events). Moisture Convergence during La Niña: Conversely, negative IOD and La Niña episodes enhance anomalous low-level moisture convergence from the South China Sea and Java Sea, generating catastrophic flood events.

The isolated, significant increase in maximum daily rainfall observed at Sanggu (+19.20 mm/decade, $p = 0.003$) and marginally at Syamsudin Noor (+4.76 mm/decade, $p = 0.097$) illustrates that extreme convective precipitation in equatorial zones manifests locally via Mesoscale Convective Systems (MCSs) and localized orographic triggering rather than broad regional shifts.

The results of this study provide scientific evidence to support the development of climate-resilient engineering practices in Kalimantan. The observed hydroclimatic changes highlight the need to integrate long-term climate monitoring into water resources planning, agricultural management, hydropower development, and infrastructure design. For water resources management, updated hydroclimatic information can improve reservoir operation, water allocation strategies, and drought preparedness. In agriculture, the findings can support climate-adaptive irrigation scheduling, optimization of cropping calendars, and the selection of drought-resilient cropping systems. For hydropower projects, incorporating long-term hydroclimatic trends into reservoir inflow assessments and operational planning can enhance the reliability and sustainability of energy production. Furthermore, the results underscore the importance of periodically revising hydrological design criteria for hydraulic structures, drainage systems, and flood-control infrastructure to ensure that engineering designs remain robust under evolving climatic conditions. Collectively, these measures can strengthen the resilience of water-related infrastructure and support sustainable development in Kalimantan under a changing climate.

4. Conclusion

Overall, the study area in Borneo Island demonstrates distinct decadal trajectories toward a drier near-surface microclimate, enhanced solar radiation, weakened surface winds, and elevated thermal variability. The compounding effects of rising temperatures, atmospheric stilling, and heightened solar exposure have the potential to exacerbate drought severity, intensify evaporative demand, aggravate water stress, and induce critical shifts in the regional hydrological balance. The scientific evidence generated by this long-term multi-station dataset provides essential baseline insights to support climate-resilient engineering practices and policy frameworks in Kalimantan. Incorporating these hydroclimatic trends into water resources planning, agricultural water management, forest-fire early warning protocols, hydropower development, and hydraulic infrastructure design is vital for ensuring sustainable development and climate resilience across equatorial Borneo.

Conflicts of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Data Availability Statement

The meteorological datasets used in this study are available from the Indonesian Meteorology, Climatology, and Geophysics Agency (BMKG). The data can be obtained through BMKG's official data services in accordance with the agency's data access procedures. The processed datasets generated during this study are available from the corresponding author upon reasonable request.

Code Availability Statement

The code and analysis workflow used for data processing and statistical analyses are available from the corresponding author upon reasonable request.

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