EEET ECOLOGICAL ENGINEERING & ENVIRONMENTAL TECHNOLOGY

Ecological Engineering & Environmental Technology, 2026, 27(9), 51–69
https://doi.org/10.12912/27197050/225934
ISSN 2719–7050, License CC-BY 4.0

Received: 2026.07.07
Accepted: 2026.07.30
Published: 2026.08.15

Contrasting extreme climate trends across lowland, dry-island, and highland regions of Indonesia using ERA5-Land

Sapta Suhardono[1*], Nirina Nasywa Nurfea[1], Atha Ratna Viviani[1], Aretha Nasywa Ardhani[1], Rafda Khairunnisa[1]

[1] Department of Environmental Sciences, Faculty of Mathematics and Natural Sciences, Universitas Sebelas Maret, Surakarta, 57126 Indonesia
* Corresponding author's e-mail: sapta.suhardono@staff.uns.ac.id

ABSTRACT

This study analyzes trends and variability in climate parameters, specifically precipitation and air temperature in three regions with distinct geographic characteristics in Indonesia: Surakarta / Solo (lowlands of Java), Mataram (dry tropical island), and Wamena (highlands of Papua), during the period 1995–2025. ERA5-Land reanalysis data from the ECMWF were extracted using Google Earth Engine and analyzed using the modified Mann-Kendall trend test, Sen's Slope estimation, the precipitation concentration index (PCI). The results indicate that Wamena experienced the most significant climate change, with clear upward trends in rainfall intensity indices (SDII, R95p, PRCPTOT), rainfall frequency indices (R10 mm, R20 mm), and temperature extremes (TXx, TN90p). In contrast, Surakarta and Mataram did not show significant precipitation trends, suggesting that long-term rainfall signals in these regions may be obscured by strong interannual variability. Nevertheless, all three locations exhibited consistent and statistically significant trends toward warmer average temperatures and an increase in the frequency of warm nights (TN90p), underscoring the uniform impact of anthropogenic climate change across Indonesia's various climate zones. These findings underscore the importance of region-specific climate adaptation strategies in water resource management and agricultural planning in Indonesia.

Keywords: climate trend analysis, ERA5-Land, modified Mann-Kendall, rainfall variability, temperature extremes, Indonesia.

INTRODUCTION

Climate change has become a global issue and has received serious attention in recent decades, presenting the most significant global challenge to living organisms today (Hasbullah and Assyahri, 2024). Global climate change has become one of the greatest environmental challenges of the 21st century. The increase in greenhouse gas concentrations in the atmosphere has caused a rise in global average temperatures, changes in rainfall patterns, and an increase in the frequency and intensity of extreme weather events in various regions of the world (Kumar et al., 2024). Precipitation and air temperature are among the key aspects in detecting climate change and in determining the environmental conditions of specific regions that influence agricultural productivity (Syarifuddin et al., 2023). Climate patterns and rainfall in Indonesia exhibit spatial variations; this is due to the country's archipelagic nature and its geographical location (Natun et al., 2024). Precipitation is a fundamental component of the Earth's hydrological cycle; this cycle plays a crucial role in shaping ecosystems, agricultural productivity, and water resource management (Mustopa et al., 2025). Seasonal variability in rainfall can have a significant impact on water availability, crop yields, and the frequency of extreme weather events; therefore, it is crucial to develop robust models that can accurately capture these dynamics (Azwar et al., 2022). This study focuses on three regions with distinct geographic characteristics: Surakarta, Mataram, and Wamena. Surakarta represents a lowland region on the island of Java influenced by urban and agricultural activities. Mataram represents a dry tropical island region in West Nusa Tenggara that experiences a relatively long dry season. Meanwhile, Wamena represents a high-mountain region in the Papua Mountains, which has distinct climatic characteristics due to the influence of elevation. These differences in geographic conditions allow for varying climate responses to global climate change (Ferguglia et al., 2024).

Although global warming is a widespread phenomenon occurring throughout the world, its impacts do not manifest with the same intensity in every region, as they are influenced by local geographic conditions and climatic characteristics (Correa et al., 2025). In Indonesia, climate change has altered the patterns of the rainy and dry seasons, increased the frequency of hydrometeorological disasters, and impacted the agricultural sector and water resources (Aldyan, 2023). Changes in rainfall patterns are also linked to an increase in the occurrence of floods during the rainy season and droughts during the dry season, thereby posing challenges for environmental management and regional development (Nabinejad and Schyttrumpf, 2023). These conditions not only affect agricultural productivity but also impact ecosystem stability and the resilience of communities dependent on natural resources (Diyaolu and Folarin, 2024). Several studies indicate that Southeast Asia is experiencing consistent temperature increases accompanied by heightened rainfall variability (Fan et al., 2022). This situation underscores the importance of long-term climate analysis using data capable of simultaneously capturing both long-term trends and interannual fluctuations (Vu et al., 2023). Understanding climate responses across various regions in Indonesia is crucial for explaining the differing impacts of climate change that emerge in each distinct environmental context (Marzuki et al., 2025).

Advances in high-resolution climate reanalysis products provide better opportunities to analyze long-term climate change in regions with varying availability of observational data (Alizadeh, 2022.). ERA5-Land integrates atmospheric models with various global observational sources to produce climate data that is continuous and spatially consistent (Xu et al., 2022). Compared to meteorological station data, reanalysis datasets offer advantages in terms of spatial coverage, particularly in areas where the observation network remains limited (Mistry et al., 2022). This advantage is highly relevant for Indonesia, which has an archipelagic structure and complex topography, meaning that climatic conditions can vary significantly over relatively short distances (Vinata et al., 2023). Surakarta, Mataram, and Wamena were selected because they represent three contrasting environmental characteristics: lowland agricultural areas, dry tropical islands, and high-mountain regions. These differences in geographic conditions allow for a clearer analysis of how precipitation and temperature respond to climate change in different environments (Coelho et al., 2023). Studies in these three regions are expected to provide a more representative picture of the variation in climate responses across Indonesia.

Although station observations remain essential for local climate assessment, their spatial and temporal availability is uneven across Indonesia, particularly in remote and topographically complex regions. ERA5-Land offers a spatially complete and internally consistent alternative that allows the same analytical framework to be applied across contrasting locations. Accordingly, this study was designed to evaluate long-term climate trends using a common reanalysis dataset rather than to develop or validate a station-calibrated climate product. Nevertheless, because the accuracy of reanalysis data may vary geographically and between climate variables, the absence of location-specific station validation is explicitly considered when interpreting the findings.

METHODS

Location and time of study

This study was conducted in three regions representing different geographic and climatic characteristics in Indonesia, namely (1) Surakarta, Central Java Province, representing the lowland areas of Java Island influenced by urban activities and intensive agriculture; (2) Mataram City, West Nusa Tenggara Province, representing a dry tropical island region with a relatively long dry season; and (3) Wamena City, Papua Pegunungan Province, representing a high-altitude mountainous region with a distinctive climate due to its elevation. The geographic coordinates presented in Table 1. correspond exactly to the point locations used for ERA5-Land data extraction in Google Earth Engine. Each coordinate was treated as a fixed sampling point throughout the 1995–2025 study period.

Research tools and materials

This study employs two primary software tools for data collection and analysis:

a) Google Earth Engine data extraction

Daily climate data were obtained from the ECMWF ERA5-Land Daily Aggregated dataset (ECMWF/ERA5_LAND/DAILY_AGGR) through Google Earth Engine. Data were extracted for three fixed point locations representing Surakarta (110.8275° E, 7.5561° S), Mataram (116.1000° E, 8.5833° S), and Wamena (138.9500° E, 4.0833° S) for the period from 1 January 1995 to 31 December 2025. The variables extracted were daily maximum 2 m air temperature (temperature_2m_max), daily minimum 2 m air temperature (temperature_2m_min), and daily total precipitation (total_precipitation_sum). Temperature values were converted from Kelvin to degrees Celsius by subtracting 273.15, while precipitation values were converted from metres to millimetres by multiplying by 1.000. Values at each sampling point were extracted using the first available pixel value within the corresponding ERA5-Land grid cell through ee.Reducer.first(), with a nominal sampling scale of 11,132 m and the bestEffort option enabled. For each location, the resulting daily dataset included the date, year, month, day, geographic coordinates, daily rainfall, daily maximum temperature, and daily minimum temperature. The data were exported separately for Surakarta, Mataram, and Wamena as comma-separated value files. The complete Google Earth Engine script, including the dataset identifier, sampling coordinates, unit conversions, extraction settings, and export procedures, is available in the public repository specified in the Code Availability Statement.

b) RStudio

RStudio is used as the statistical software for data processing and climate trend analysis. The R packages utilized include the tidy verse for data manipulation and visualization, Kendall or trend for the Mann-Kendall statistical test, and ggplot2 for generating trend deviation graphs. The entire analysis process was conducted in a structured manner and documented within R scripts.

Data and data sources

The climate data used in this study are ERA5-Land reanalysis data provided by the European Centre for Medium-Range Weather Forecasts (ECMWF). ERA5-Land is a high-resolution reanalysis product with a spatial resolution of approximately 9 km that integrates atmospheric models with global historical observations. The extracted climate parameters comprise two primary variables: daily maximum air temperature (°C), representing the highest daily thermal conditions at each study location, and daily rainfall (mm), representing the accumulated daily precipitation in each area. Data were obtained for a 31-year observation period (1995–2025), yielding a time series suitable for analyzing long-term trends and climate variability. Data extraction was performed spatially based on the geographic coordinates of each city included in the study.

Climate extreme indices

The climate-extreme indices were calculated from daily precipitation and daily maximum and minimum temperature data following the definitions presented in Table 2. A wet day was defined as a day with precipitation of at least 1 mm. Percentile-based indices were calculated using the 1995–2025 reference period. The same reference thresholds were subsequently applied to all years and locations.

Data analysis techniques

Calculation of annual average values

Daily maximum temperature, daily minimum temperature and precipitation data were aggregated into annual values by calculating the annual average for maximum temperature, minimum temperature and the annual total for precipitation. This aggregation was performed for each

Table 1. Study location

Location	Geographic setting	Latitude	Longitude	Approximate elevation
Surakarta / Solo	Lowland Java	-7.5561	110.8275	95 m
Mataram	Dry tropical island	-8.5833	116.1000	16 m
Wamena	Highland Papua	-4.0833	138.9500	1654 m

Table 2. Climate extreme indices

Index	Definition	Unit
SDII	Annual precipitation total divided by the number of wet days	mm/day
RX1day	Annual maximum one-day precipitation	mm
RX5day	Annual maximum consecutive five-day precipitation	mm
R10mm	Number of days with precipitation ≥10 mm	days
R20mm	Number of days with precipitation ≥20 mm	days
CDD	Maximum number of consecutive days with precipitation <1 mm	days
CWD	Maximum number of consecutive days with precipitation ≥1 mm	days
R95p	Annual precipitation from days exceeding the 95th-percentile threshold	mm
R99p	Annual precipitation from days exceeding the 99th-percentile threshold	mm
PRCPTOT	Annual precipitation total on wet days	mm
TX90p	Percentage of days when Tmax exceeds the 90th percentile	%
TN90p	Percentage of days when Tmin exceeds the 90th percentile	%
TX10p	Percentage of days when Tmax is below the 10th percentile	%
TN10p	Percentage of days when Tmin is below the 10th percentile	%
TXx	Annual maximum of daily maximum temperature	°C
TNx	Annual maximum of daily minimum temperature	°C

study location, resulting in a 31-year annual time series (1995–2025).

Deviation analysis

Annual deviation was calculated as the difference between the annual value of each parameter and the average value across the entire observation period (baseline mean). This deviation illustrates fluctuations in climate parameter values relative to their average conditions throughout the 1995-2025 period, enabling the identification of years with conditions above or below normal levels.

Modified Mann–Kendall trend test and Sen's slope estimation

Long-term trends in the annual climate indices were evaluated using the modified Mann–Kendall test implemented through the mmkh() function in the modifiedmk package. This procedure provides a corrected Mann–Kendall Z statistic and an adjusted p-value to account for the potential influence of serial autocorrelation in the annual time series. Before analysis, missing values were removed, and the test was performed only for variables containing more than one unique value. The null hypothesis stated that no monotonic trend was present, whereas the alternative hypothesis indicated a monotonic increasing or decreasing trend. Statistical significance was assessed at $\alpha = 0.05$. The magnitude and direction of each trend were estimated using Sen's slope through the sens.slope() function in the trend package. Because the analysis was based on annual values, Sen's slope was expressed as the change in the original unit of each climate index per year. All analyses were conducted in R version 2025.09.1 using the tidyverse, lubridate, modifiedmk, trend, openxlsx, and zoo packages.

Data visualization

Analysis results were visualized as annual deviation trend graphs using the ggplot2 package in RStudio. The graph displays annual deviation values relative to the average baseline for the 1995–2025 period, featuring a zero-reference line (dashed) to facilitate the interpretation of year-to-year fluctuations. Separate visualizations have been created for each parameter (maximum temperature and precipitation) at each study location (Surakarta, Mataram, and Wamena).

RESULTS AND DISCUSSIONS

Rainfall intensity indices

As shown in Table 3, trend analysis for rainfall intensity indices (SDII, RX5day, RX1day, R99p, R95p, and PRCPTOT) was conducted at the three study sites over the period 1995–2025.

Among the three locations, Wamena showed the most significant changes, with a clear upward trend detected in SDII (Zc = 3.82, p < 0.001), R95p (Zc = 2.26, p = 0.024), and PRCPTOT (Zc = 4.65, p < 0.001). These findings indicate a clear intensification of rainfall events in the highland region of Papua over the 31-year study period (Marzuki et al., 2025).

The significant increase in SDII in Wamena suggests that rainfall on wet days has become more intense over time (Nugroho et al., 2023)). This pattern is consistent with the thermodynamic response to rising temperatures, whereby a warmer atmosphere holds more water vapor and releases it in more concentrated precipitation events. Sen's slope value of 0.060 mm/day/year for the SDII in Wamena further confirms a gradual yet consistent upward trajectory in daily rainfall intensity (Aminoto et al 2026).

The significant upward trend in R95p in Wamena (SS = 7.108 mm/year) indicates that the contribution of extreme precipitation events to total annual rainfall has been steadily increasing over time (Bakhtar et al., 2022). This is particularly important from a flood risk perspective, as higher R95p values are associated with a greater potential for flash floods and landslides, especially in mountainous terrain such as the Wamena highlands (Msimanga et al., 2026). Similarly, the highly significant trend in PRCPTOT (SS = 22.574 mm/year) indicates that annual total rainfall in Wamena has increased at a rate of approximately 22.6 mm per year, which translates to an estimated increase of more than 700 mm over the 31-year period (Tesfaye et al., 2025).

In contrast, Surakarta and Mataram did not show any statistically significant trends in any of the rainfall intensity indices studied (Maharjan et al 2022). Although some indices, such as R95p in Surakarta (Zc = 0.918) and RX1day in Mataram (Zc = 1.402), showed positive Zc values, the corresponding p-values were well above the 0.05 significance threshold. The absence of significant trends at these locations may indicate that interannual rainfall variability remains stronger than the detected long-term trend signal. It should also be noted that RX1day shows a decreasing trend in Surakarta (Zc = -1.179), although not significant, which may indicate a redistribution of rainfall rather than an intensification in Surakarta (Zc = -1.179), although this trend is not statistically significant, which may indicate a redistribution of rainfall rather than an overall intensification (Figures 1–6).

Table 3. Modified Mann–Kendall trend test results

Indices	Trend Test	Surakarta	Mataram	Wamena
SDII	Zc	0.8838	0.4759	3.8192
	p-value	0.3768	0.6341	0.0001
	SS	0.0181	0.1127	0.0599
RX5day	Zc	-0.0574	0.0000	-0.7138
	p-value	0.9543	1.0000	0.4753
	SS	-0.1043	-0.0102	-0.4015
RX1day	Zc	-1.1785	1.4019	-0.4156
	p-value	0.2386	0.1610	0.6777
	SS	-0.7159	0.2402	-0.0673
R99p	Zc	-0.3744	0.7496	0.3399
	p-value	0.7081	0.4535	0.7330
	SS	-0.6303	1.2743	0.7306
R95p	Zc	0.9178	0.4686	2.2634
	p-value	0.3587	0.6395	0.0236
	SS	3.5511	2.1537	7.1082
PRCPTOT	Zc	0.2719	0.3739	4.6484
	p-value	0.7857	0.7085	0.0000
	SS	2.7268	3.2359	22.5743

Note: Zc – standardized test statistic; SS – Sen's Slope.

Rainfall frequency indices

Table 4 summarizes the results of the trend analysis for rainfall frequency indices, including CDD, CWD, R20 mm, and R10 mm, at the three study sites. The results show significant trends at two sites, with Wamena exhibiting an increase in the frequency of heavy rainfall and Surakarta showing a decrease in the number of consecutive rainy days.

Wamena showed a significant upward trend for both R20 mm (Zc = 2.20, p = 0.028, SS = 0.667 days/year) and R10 mm (Zc = 2.40, p = 0.017, SS = 1000 days/year). The increasing trend in R10 mm indicates that the number of days with rainfall exceeding 10 mm per day has increased at a rate of approximately one additional day per year during the study period. Similarly, the increasing trend in R20 mm indicates a rising frequency of heavy rainfall events. These findings are consistent with the intensification pattern observed in the rainfall intensity index, further supporting the conclusion that Wamena

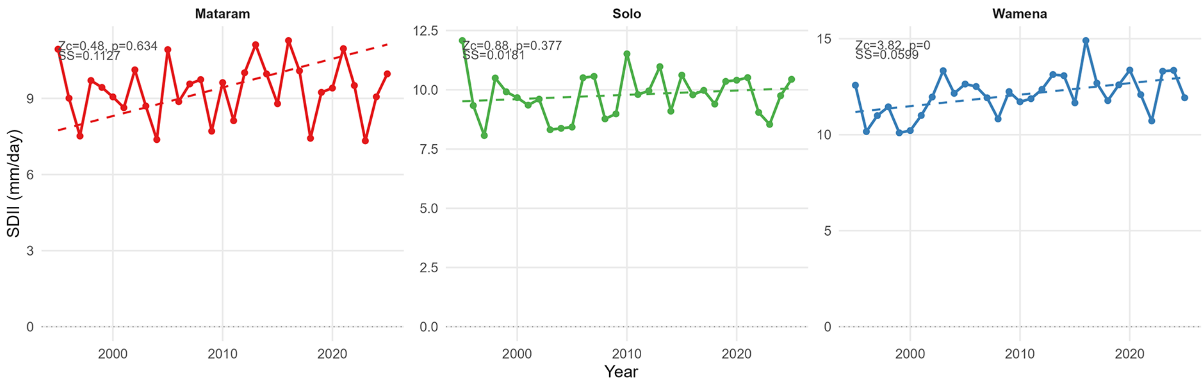

Figure 1. Trend of SDII

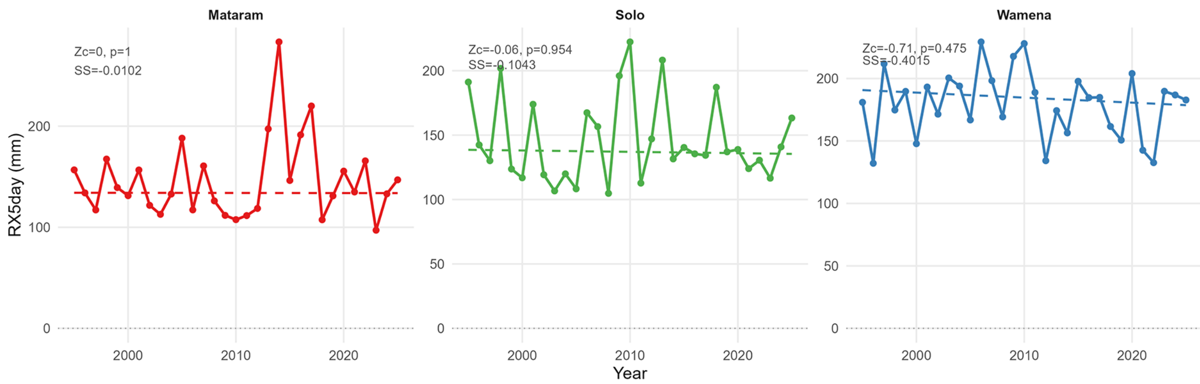

Figure 2. Trend of RX5day

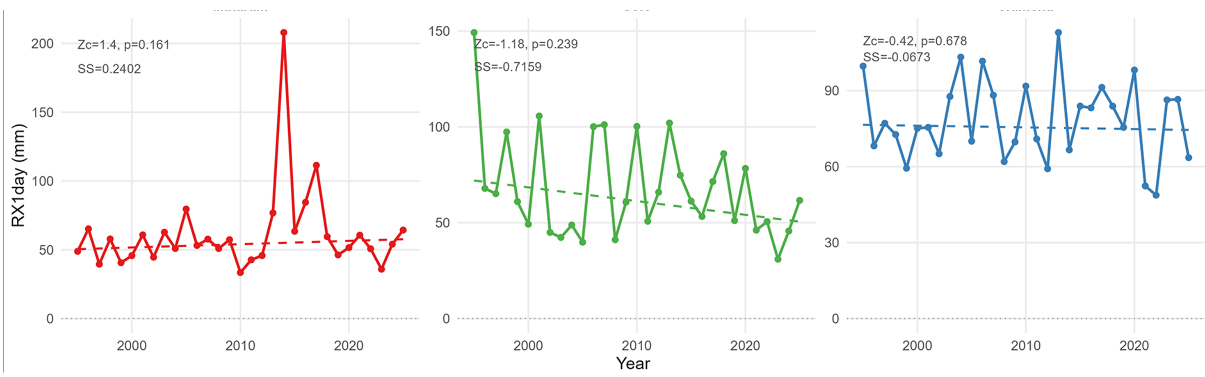

Figure 3. Trend of RX1day

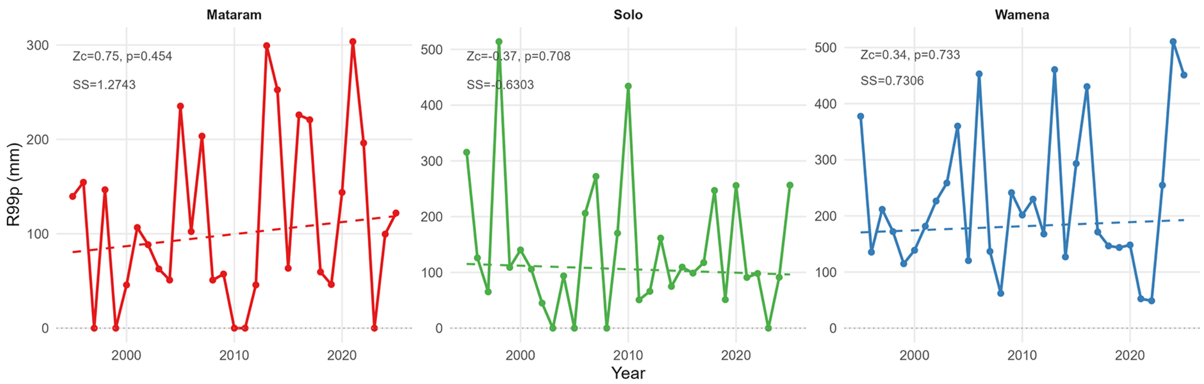

Figure 4. Trend of R99p

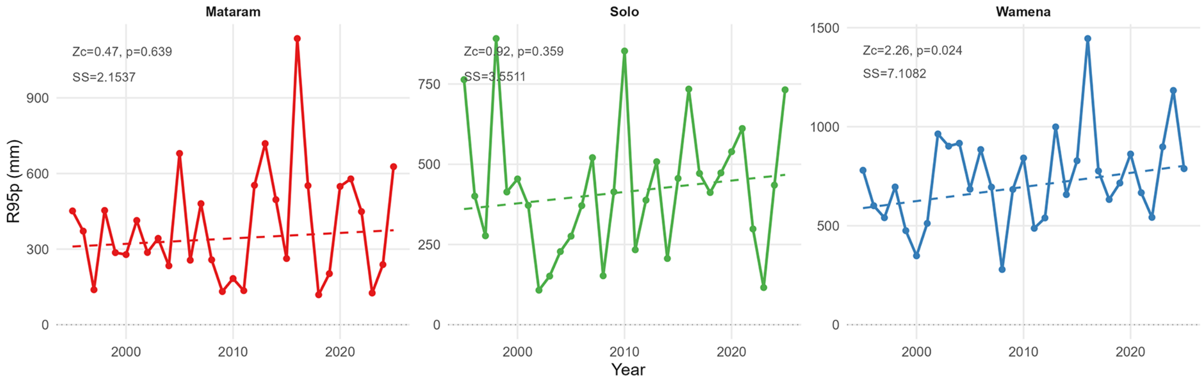

Figure 5. Trend of R95p

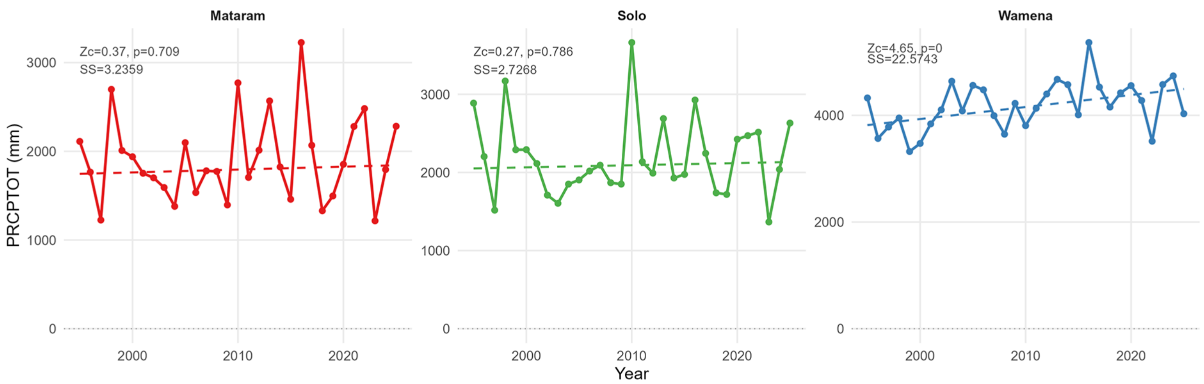

Figure 6. Trend of PRCPTOT

is undergoing a significant shift toward heavier and more frequent precipitation events.

Surakarta showed a significant downward trend in CWD (Zc = -2.46, p = 0.014, SS = -0.652 days/year), indicating a reduction in the duration of consecutive wet periods over time. These findings suggest that although total rainfall in Surakarta has not changed significantly, the temporal distribution of rainfall may be shifting, with wet periods becoming shorter but potentially more intense (Sarvina et al., 2023). Such changes in the temporal structure of rainfall can have important implications for agriculture, particularly for crops that depend on sustained soil moisture during the growing season.

No significant trends were detected for any of the frequency indices in Mataram, although the CWD showed a negative Sen's slope (-0.500 days/year), suggesting a weak downward trend similar to that observed in Surakarta. The absence of a significant trend in Mataram may reflect the influence of greater interannual climate variability at this location, which is situated in a region heavily affected by ENSO-driven drought events during El Niño years (Palmer et al., 2023).

The CDD index, which measures the maximum number of consecutive dry days, showed no significant trend at any of the three locations. However, the positive Sen's slope in Surakarta (0.167 days/year) and Mataram (0.471 days/year) suggests a weak trend toward longer dry periods, which, if it continues, could have significant implications for water resource management and agricultural planning in those regions (Figures 7–10).

Temperature index

A statistical analysis of temperature indices at the three locations is presented in Table 5. The results show a consistent warming signal at all three study sites, particularly in indices related to the frequency of warm nights and minimum temperature extremes, reflecting the broader climate warming pattern observed throughout the Indo-Pacific tropics.

A significant upward trend in TN90p was detected at all three locations: Surakarta (Zc = 3.77, $p < 0.001$, SS = 0.457%/year), Mataram (Zc = 2.99, p = 0.003, SS = 0.418%/year), and Wamena (Zc = 4.75, $p < 0.001$, SS = 0.274%/year). The TN90p index measures the percentage of days when the minimum temperature exceeds the 90th percentile threshold, and its significant increase at all three locations indicates a widespread and accelerating rise in the frequency of warm nights (Amnuaylojaroen et al 2025). These findings are particularly important because nighttime warming is often considered a more sensitive indicator of greenhouse gas-driven climate change than daytime warming, given that cloud cover and land surface feedbacks tend to suppress daytime temperature increases (Akter et al., 2024).

Complementing the TN90p results, TN10p showed a significant downward trend in Mataram (Zc = -2.14, p = 0.032, SS = -0.274%/year) and Wamena (Zc = -4.24, $p < 0.001$, SS = -0.391%/year), indicating a decrease in the frequency of cold nights. The increase in TN90p, coupled with the decrease in TN10p at these locations, provides strong evidence of a systematic shift in the distribution of nighttime temperatures toward warmer conditions (Nugraheni et al., 2025). In Surakarta,

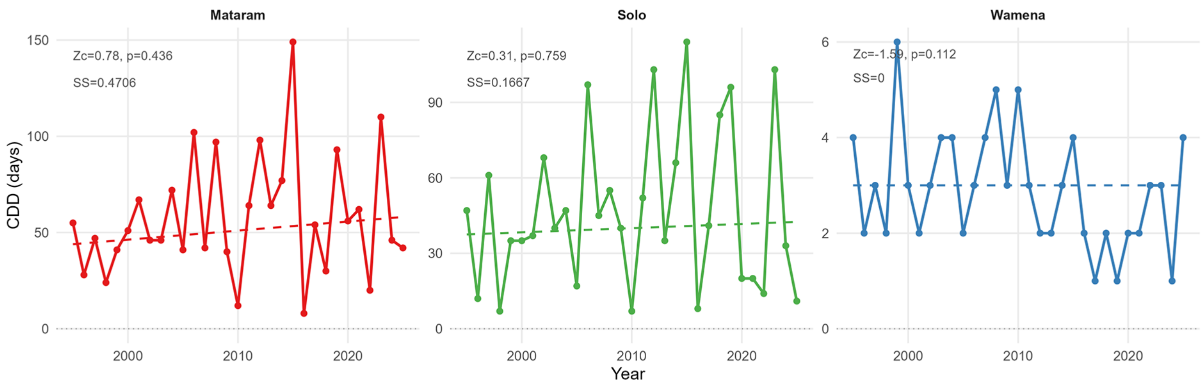

Figure 7. Trend of CDD

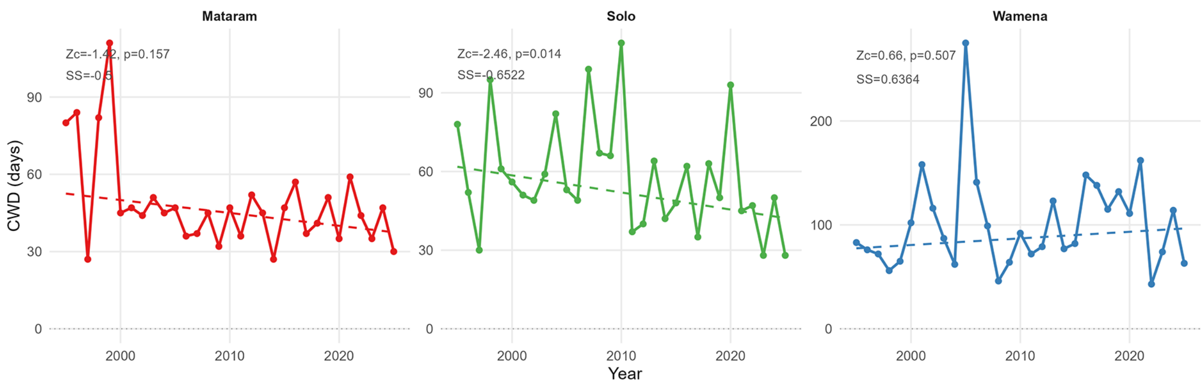

Figure 8. Trend of CWD

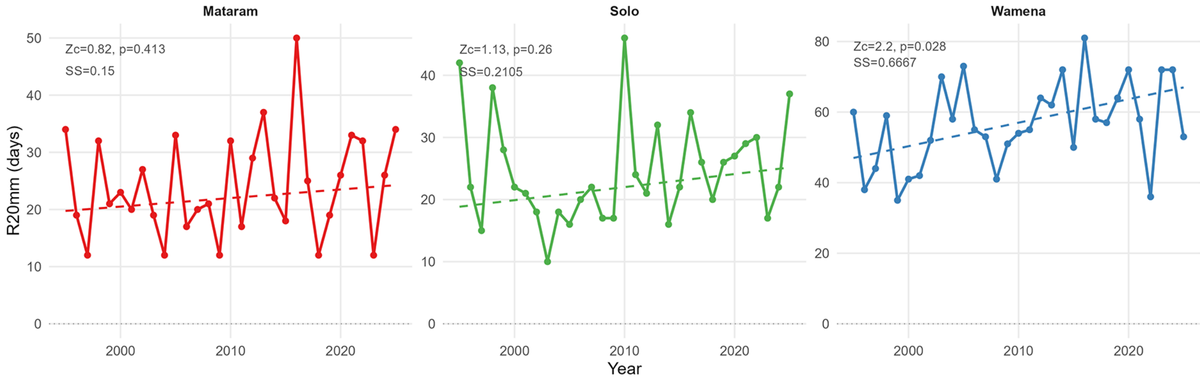

Figure 9. Trend of R20 mm

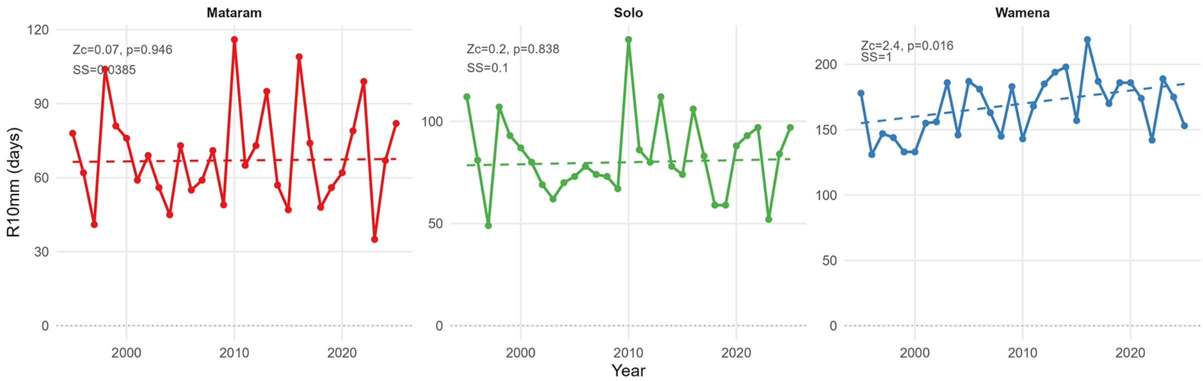

Figure 10. Trend of R10 mm

Table 4. Modified Mann–Kendall trend test results for rainfall frequency indices

Indices	Trend Test	Surakarta	Mataram	Wamena
CDD	Zc	0.3063	0.7781	-1.5881
	p-value	0.7594	0.4365	0.1123
	SS	0.1667	0.4706	0.0000
CWD	Zc	-2.4643	-1.4156	0.6630
	p-value	0.0137	0.1569	0.5074
	SS	-0.6522	-0.5000	0.6364
R20mm	Zc	1.1259	0.8194	2.1977
	p-value	0.2602	0.4126	0.0280
	SS	0.2105	0.1500	0.6667
R10mm	Zc	0.2042	0.0680	2.3985
	p-value	0.8382	0.9458	0.0165
	SS	0.1000	0.0385	1.0000

Note: Zc – corrected Z; p-value – new p-value; SS – Sen's Slope.

TN10p also showed a negative trend (Zc = -1.46), although it did not reach statistical significance at the 0.05 level.

Regarding daytime temperature extremes, TX90p showed a significantly increasing trend only in Wamena (Zc = 1.99, p = 0.046), while the trends in Surakarta and Mataram were positive but not significant. This pattern suggests that warming at the study sites is more pronounced at night than during the day, which is consistent with the asymmetric diurnal warming patterns reported in tropical regions. The TX10p index showed a decreasing trend in Surakarta (Zc = -1.96, p = 0.051) and Mataram (Zc = -1.84, p = 0.066), which, although marginally insignificant, suggests a trend toward fewer cold days at these locations.

The maximum daily temperature (TXx) showed a significant upward trend only in Wamena (Zc = 3.03, p = 0.003, SS = 0.085 °C/year), indicating that the hottest days of the year have been progressively getting hotter in the highlands of Papua. TNx, which represents the highest minimum temperature recorded each year, shows a significant increasing trend in Wamena (Zc = 2.11, p = 0.035, SS = 0.016 °C/year), while the trends in Surakarta (Zc = 1.84, p = 0.066) and Mataram (Zc = 1.90, p = 0.057) are close to but do not reach statistical significance, suggesting a developing warming trend in annual minimum temperature extremes at these locations (Figures 11–16).

Trends in total rainfall and temperature

Based on Table 6, the overall trend statistics for total annual precipitation and average temperature reveal contrasting patterns among the three locations. For precipitation, only Wamena showed a statistically significant increasing trend (Zc = 4.71, p < 0.001, SS = 22.648 mm/year), while Surakarta (Zc = −0.238, p = 0.812) and Mataram (Zc = 0.340, p = 0.734) did not show any significant trend. The magnitude of the increase in rainfall in Wamena is substantial, with Sen's slope indicating an average annual increase of approximately 22.6 mm per year, equivalent to a total increase of about 700 mm over the 31-year study period.

The absence of a significant rainfall trend in Surakarta and Mataram does not necessarily imply climate stability at these locations. Rather, the results suggest that interannual variability may obscure the underlying long-term precipitation trend in Surakarta and Mataram. Both Surakarta and Mataram are located in regions strongly influenced by the Asian-Australian monsoon system, where rainfall variability is largely controlled by sea surface temperature anomalies in the surrounding ocean basins (Panggabean et al., 2026). Future studies incorporating longer data records or climate model projections may be able to detect emerging trends at these locations.

In contrast to the varied rainfall trends, all three locations showed a statistically significant trend of increasing average temperatures. Mataram exhibited the strongest warming signal (Zc

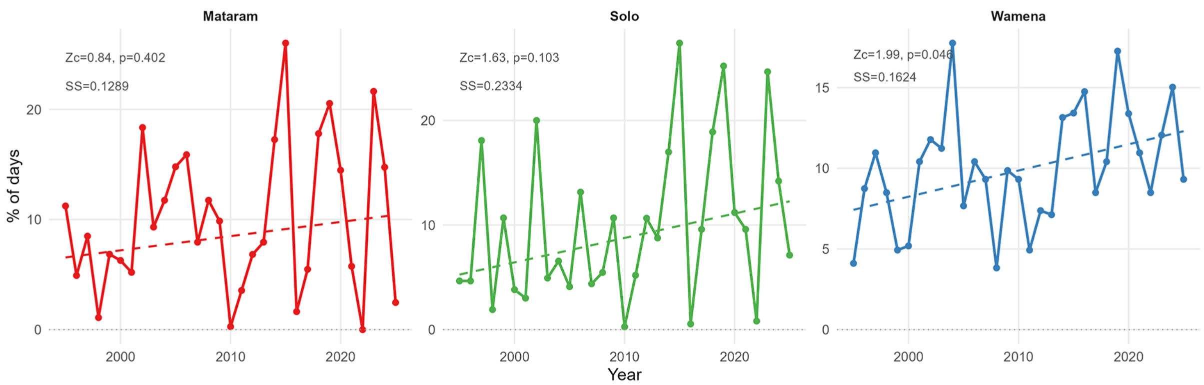

Figure 11. Trend of TX90p

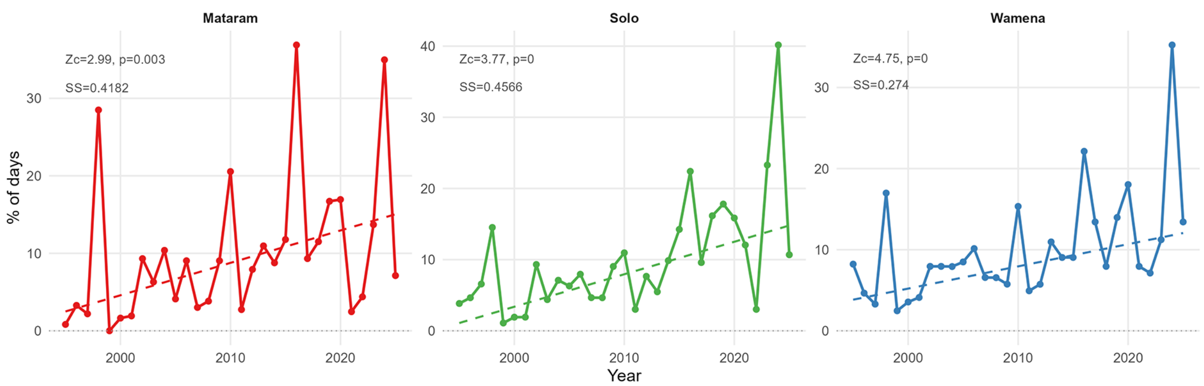

Figure 12. Trend of TN90p

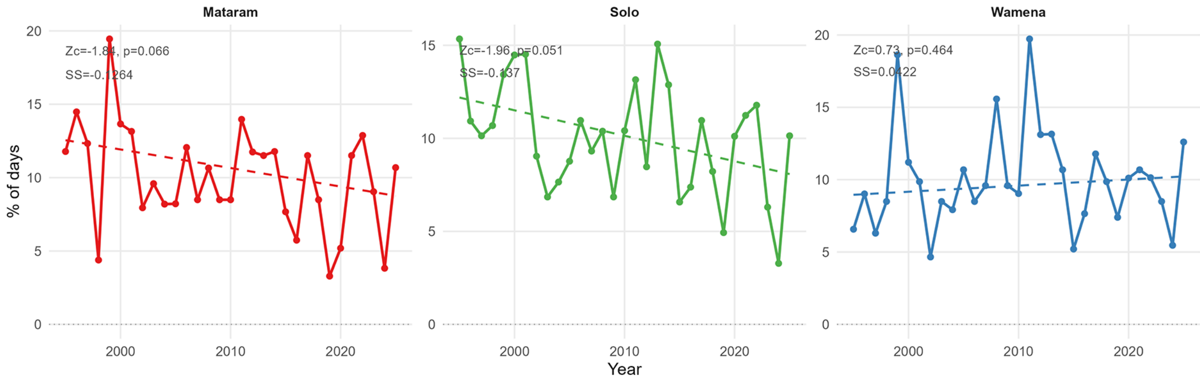

Figure 13. Trend of TX10p

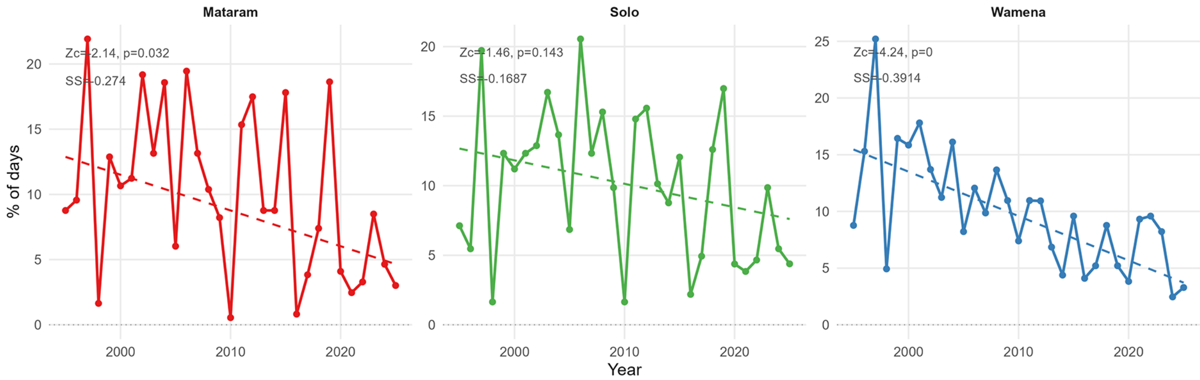

Figure 14. Trend of TN10p

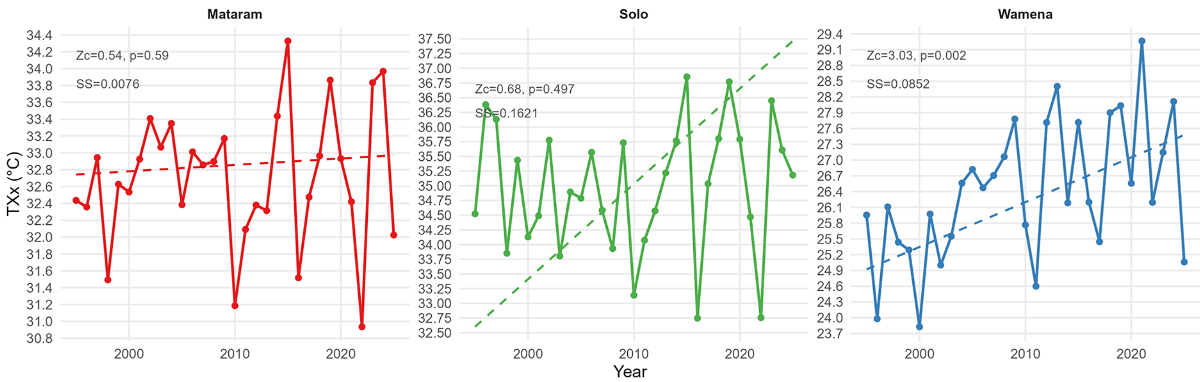

Figure 15. Trend of TXx

= 4.55, $p < 0.001$, SS = 0.016 °C/year), followed by Surakarta (Zc = 3.13, p = 0.002, SS = 0.018 °C/year) and Wamena (Zc = 3.03, p = 0.002, SS = 0.014 °C/year). The consistency of significant warming trends across all three locations, despite their differing geographic settings and climate regimes, underscores the pervasive nature of anthropogenic warming in Indonesia.

The warming rates observed in this study are generally consistent with global estimates of tropical warming, which have been reported to range from 0.1 to 0.3 °C per decade over the past several decades. The slightly higher warming rates in Surakarta and Mataram compared to Wamena may reflect additional local factors such as urbanization and land-use changes, which can amplify temperature trends through the urban heat island effect, particularly in more densely populated lowland cities (Nandi and Dede, 2022).

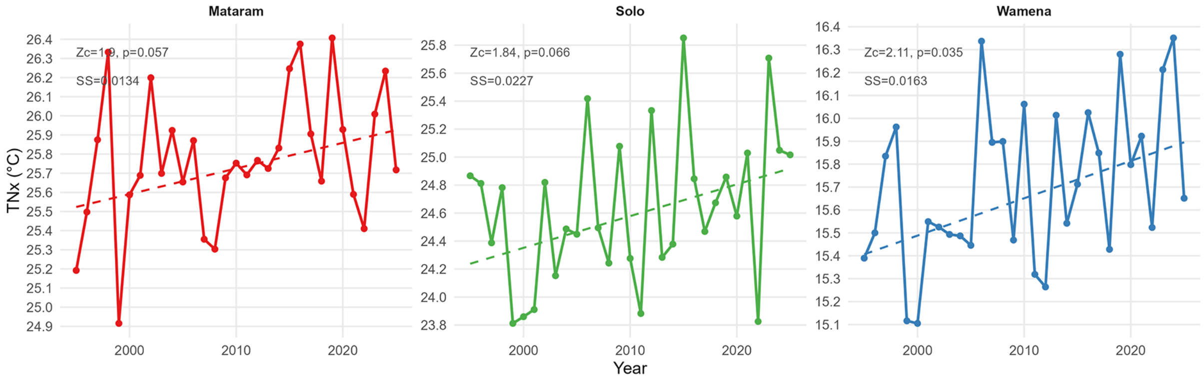

Figure 16. Trend of TNx

Table 5. Modified Mann–Kendall trend test results for temperature indices

Indices	Trend Test	Surakarta	Mataram	Wamena
TX90p	Zc	1.6321	0.8378	1.9923
	p-value	0.1027	0.4022	0.0463
	SS	0.2334	0.1289	0.1624
TN90p	Zc	3.7743	2.9922	4.7454
	p-value	0.0002	0.0028	0.0000
	SS	0.4566	0.4182	0.2740
TX10p	Zc	-1.9554	-1.8392	0.7324
	p-value	0.0505	0.0659	0.4639
	SS	-0.1370	-0.1264	0.0422
TN10p	Zc	-1.4631	-2.1430	-4.2352
	p-value	0.1434	0.0321	0.0000
	SS	-0.1687	-0.2740	-0.3914
TXx	Zc	0.6799	0.5439	3.0254
	p-value	0.4966	0.5895	0.0025
	SS	0.1621	0.0076	0.0852
TNx	Zc	1.8356	1.9036	2.1076
	p-value	0.0664	0.0570	0.0351
	SS	0.0227	0.0134	0.0163

Note: Zc – Corrected Z; p-value – new p-value; SS – Sen's slope.

Precipitation concentration index

Referring to Table 7, the PCI classification over the 31-year study period reveals distinct rainfall concentration patterns among the three locations, reflecting their different climate regimes and geographical settings. The PCI analysis provides a useful complement to the trend analysis by characterizing the degree of seasonal rainfall concentration, which has important implications for water resource management and agricultural planning (Jin et al., 2025).

Surakarta is dominated by moderate rainfall distribution, with 20 out of 31 years (64.52%) falling in the PCI range of 10–15. Nine years (29.03%) were classified as irregular distribution (PCI 16–20), and only 2 years (6.45%) showed uniform distribution (PCI < 10). The moderate PCI values at Surakarta are consistent with its monsoon-influenced climate, where rainfall is concentrated during the October–March wet season but does not reach the extreme concentration levels that would be associated with more arid climates.

Mataram exhibits a notably different pattern, with the majority of years (17 out of 31, or 54.84%) classified as irregular distribution (PCI 16–20), followed by moderate distribution (13

Table 6. Modified Mann-Kendall Trend Statistics of Rainfall and Temperature in Indonesia (1995–2025)

Region	Zc	p-value	SS
Panel A: Rainfall			
Surakarta	-0.2379	0.8119	2.0324
Mataram	0.3399	0.7339	3.8113
Wamena	4.7104*	0.0000	22.6483
Panel B: Temperature			
Surakarta	3.1273*	0.0018	0.0177
Mataram	4.5463*	0.0000	0.0159
Wamena	3.0254*	0.0025	0.0142

Note: Zc – Corrected Z; p-value – new p-value; SS – Sen's slope. *significant at $p < 0.05$.

years, 41.94%) and uniform distribution (1 year, 3.23%). The higher PCI values at Mataram reflect its more pronounced seasonal rainfall contrast compared to Surakarta, which is partly attributable to its location in the Lesser Sunda Islands, where the dry season is more severe and prolonged due to the influence of the Australian monsoon and the orographic rain shadow effect.

Wamena stands in stark contrast to both Surakarta and Mataram, with 29 out of 31 years (93.55%) classified as uniform distribution (PCI < 10), and only 2 years (6.45%) in the moderate category. This overwhelmingly uniform distribution reflects the consistently high year-round rainfall at Wamena, where convective activity is sustained throughout the year by the combination of highland topography, high humidity, and proximity to the equator. The near-absence of a pronounced dry season at Wamena results in low inter-monthly rainfall variability and consequently very low PCI values.

The contrasting PCI patterns across the three locations have important practical implications. The higher and more variable PCI values at Mataram suggest a greater risk of both drought during the dry season and flooding during the wet season, necessitating more robust water storage and flood management infrastructure (Zaman et al., 2023). In contrast, the uniform rainfall distribution at Wamena, while generally favorable for agriculture, also implies a persistent risk of rainfall-related hazards throughout the year.

Annual and seasonal rainfall variability

A comparison of mean annual and seasonal rainfall, coefficient of variation (CV), and PCI across the three study locations is provided in Table 8 The results highlight substantial differences in both the magnitude and variability of rainfall across the three locations, reflecting their contrasting climate environments.

Wamena records the highest mean annual rainfall among the three locations at 4,196.4 mm, which is approximately 1.9 times and 2.2 times greater than Surakarta (2,219.6 mm) and Mataram (1,947.7 mm), respectively. The high annual rainfall at Wamena is a characteristic feature of the Papua highlands, where orographic lifting of moisture-laden air masses from both the Pacific and Indian Oceans produces intense and persistent convective rainfall throughout the year (Ramadhani and Sudirman, 2026). The relatively low CV of 10.6% at Wamena further confirms the stability and consistency of annual rainfall at this location.

Surakarta and Mataram exhibit higher interannual rainfall variability, with CVs of 22.6% and 24.5%, respectively. This greater variability is largely driven by the influence of ENSO, which modulates monsoon rainfall in Java and

Table 7. PCI classification in Surakarta, Mataram, and Wamena

PCI	Category	Surakarta	%	Mataram	%	Wamena	%
<10	Uniform rainfall distribution	2	6.45	1	3,23	29	93,55
10–15	Moderate rainfall distribution	20	64.52	13	41,94	2	6,45
16–20	Irregular rainfall distribution	9	29.03	17	54,84	0	0,00
>20	Strong erratic rainfall distribution	0	0.00	0	0,00	0	0,00

the Lesser Sunda Islands through its effects on sea surface temperatures and atmospheric circulation patterns. During El Niño events, rainfall at these locations tends to be significantly below average, while La Niña years are typically associated with above-average rainfall (Rangga et al., 2025). This ENSO-driven inter-annual variability contributes substantially to the higher CVs observed at Surakarta and Mataram.

The seasonal analysis reveals a pronounced wet-dry contrast at Surakarta and Mataram. During the October-March wet season, Surakarta receives an average of 1,685.8 mm (76% of annual total) with a relatively low CV of 16.8%, while the April–September dry season contributes only 533.8 mm (24% of annual total) but with a much higher CV of 51.7%. A similar pattern is observed at Mataram, with the wet season contributing 1,499.8 mm (77% of annual total, CV = 20.0%) and the dry season contributing only 447.9 mm (23% of annual total, CV = 59.8%). The much higher CVs during the dry season at both locations indicate that dry season rainfall is highly variable from year to year, making it particularly sensitive to ENSO-driven variability. In contrast, Wamena shows a relatively balanced seasonal distribution, with the October–March period receiving 2,423.4 mm (CV = 12.7%) and the April-September period receiving 1,772.9 mm (CV = 12.3%). The similar CVs in both seasons confirm the absence of a pronounced dry season at Wamena and the year-round consistency of rainfall at this highland location.

Mean monthly rainfall distribution

Further analysis of monthly rainfall patterns in Table 9 reveals distinct seasonal characteristics across the three locations, which are closely linked to their respective climate regimes and geographical positions within the Indonesian archipelago (Sutapa et al., 2023). Surakarta exhibits a clear unimodal seasonal pattern, with peak rainfall occurring in January and February (318.8 mm and 340.9 mm, respectively) and a pronounced dry season during June–August, when monthly rainfall drops to as low as 20.3 mm in August. This pattern is characteristic of the Javanese monsoon climate, where the northwest monsoon brings heavy rainfall during the December–March period and the southeast monsoon results in a prolonged dry season from May to September. The transition months of October–November and April–May show intermediate rainfall values, reflecting the gradual onset and withdrawal of the monsoon systems.

Mataram shows a broadly similar seasonal pattern to Surakarta, with peak rainfall during December–January (333.2 mm and 280.4 mm) and a dry season nadir in August (14.6 mm). However, the dry season at Mataram is notably more severe than at Surakarta, with monthly rainfall dropping below 35 mm from June to September. This more pronounced dry season reflects Mataram's location on Lombok Island in the Lesser Sunda Islands, which is positioned further from the equator and more strongly influenced by the dry air masses advected from the Australian continent during the southeast monsoon season.

Wamena presents a fundamentally different monthly rainfall distribution, with no month receiving less than 246 mm and peak rainfall occurring during the November–March period (413.6–484.7 mm). The relatively modest seasonal variation in monthly rainfall at Wamena is characteristic of equatorial highland climates, where orographic processes and year-round convective activity maintain consistently high rainfall levels. The slight reduction in rainfall during June–August (246.3–262.4 mm) may reflect a weak dry season signal associated with the Australian monsoon, but this reduction is far less pronounced than that observed at Surakarta and Mataram.

The contrasting monthly rainfall distributions across the three locations underscore the importance of considering local climate contexts when designing water resource management strategies and agricultural calendars. The severe dry seasons at Surakarta and Mataram necessitate reliable irrigation infrastructure and water storage systems,

Table 8. Annual and seasonal rainfall statistics

Island	Mean Annual RF (mm)	CV (%)	Oct-Mar RF (mm)	CV (%)	Apr-Sept RF (%)	CV	PCI
Surakarta	2219.6	22.6	1685.8	16.8	533.8	51.7	13.6
Mataram	1947.7	24.5	1499.8	20.0	447.9	59.8	15.0
Wamena	4196.4	10.6	2423.4	12.7	1772.9	12.3	9.3

Table 9. Mean Monthly Rainfall

Island	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Surakarta	318.8	340.9	313.0	235.2	123.8	69.6	40.5	20.3	44.4	136.6	264.6	311.9
Mataram	280.4	241.6	271.1	219.2	87.3	53.1	34.7	14.6	39.0	101.1	272.3	333.2
Wamena	456.0	473.8	484.7	409.9	293.1	246.3	261.2	262.4	300.1	291.4	304.0	413.6

while Wamena's year-round rainfall presents both opportunities for continuous agricultural production and challenges related to persistent waterlogging and flood risk (Matchaya et al., 2022).

Annual and seasonal temperature variability

In terms of temperature variability, Table 10 highlights notable differences in annual and seasonal patterns among the three locations, primarily driven by their different elevations and latitudinal positions within the Indonesian archipelago. Wamena records the lowest annual average temperature at 16.89 °C, which is approximately 9–10 °C cooler than Surakarta (26.27 °C) and Mataram (26.66 °C). This marked temperature difference is primarily attributable to Wamena's highland elevation, as the location sits at approximately 1.550 meters above sea level in the Baliem Valley. The environmental lapse rate in tropical regions typically results in a temperature decrease of approximately 6–7 °C per 1.000 meters of elevation gain, which is broadly consistent with the observed temperature difference between Wamena and the two lowland sites.

Despite their similar annual average temperatures, Surakarta and Mataram show subtle differences in their temperature profiles. Mataram has a slightly higher annual average (26.66 °C vs. 26.27 °C at Surakarta), which may reflect differences in local land cover, urban heat island intensity, and proximity to warm ocean waters. Both locations show relatively low inter-annual temperature variability, with CVs of 1.13% and 0.95% for Surakarta and Mataram, respectively. Wamena shows a slightly higher CV of 1.37%, which may reflect greater sensitivity to large-scale atmospheric circulation changes at higher elevations.

The seasonal analysis reveals minimal temperature differences between the October–March and April–September periods at all three locations. At Surakarta, the October–March average (26.22 °C) and April–September average (26.32 °C) differ by only 0.10 °C, with corresponding CVs of 1.53% and 1.21%. Similarly small seasonal differences are observed at Mataram (26.72 °C vs. 26.60 °C) and Wamena (17.22 °C vs. 16.56 °C). The slightly cooler temperatures during the April–September period at Wamena (16.56 °C compared to 17.22 °C during October–March) may reflect the influence of cooler and drier air masses associated with the southeast monsoon during this period.

The consistently low CVs of annual and seasonal temperature across all three locations confirm that inter-annual temperature variability is relatively modest compared to rainfall variability. However, when viewed in the context of the significant warming trends detected in this study, even small but consistent year on year increases in temperature can accumulate to produce substantial changes over decadal timescales, with potentially significant consequences for agricultural systems, water availability, and human health.

Mean monthly temperature distribution

Regarding monthly temperature patterns, Table 11 shows the distribution across the three locations throughout the year. The monthly temperature data reveal relatively subtle seasonal temperature cycles at all three locations, consistent with their tropical settings where the annual temperature range is much smaller than in temperate regions. At Surakarta, monthly average temperatures range from a minimum of 25.66 °C in January to a maximum of 27.38 °C in October, representing an annual temperature range of only 1.72 °C. The warmest months at Surakarta occur during September–October, coinciding with the transition from the dry season to the wet season, when clear skies and high solar radiation during the late dry season result in maximum surface heating. Temperatures decline gradually during the November–March wet season, when increased cloudiness and rainfall reduce incoming solar radiation and evaporative cooling maintains relatively lower temperatures.

Mataram exhibits a similar monthly temperature pattern to Surakarta, with a minimum of

Table 10. Annual and seasonal temperature statistics

Island	Annual Average (°C)	CV (%)	Oct–Mar (°C)	CV (%)	Apr–Sept (°C)	CV (%)
Surakarta	26.27	1.13	26.22	1.53	26.32	1.21
Mataram	26.66	0.95	26.72	1.13	26.60	1.05
Wamena	16.89	1.37	17.22	1.26	16.56	1.60

Table 11. Monthly mean temperature (°C) for Surakarta, Mataram, and Wamena

Island	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Surakarta	25.66	25.73	25.98	26.20	26.26	26.13	25.91	26.27	27.14	27.38	26.68	25.91
Mataram	26.20	26.27	26.59	26.90	26.96	26.53	26.09	26.25	26.89	27.48	27.25	26.51
Wamena	17.31	17.34	17.36	17.11	16.95	16.42	16.14	16.25	16.48	16.89	17.16	17.27

26.09 °C in July and a maximum of 27.48 °C in October. The annual temperature range at Mataram (1.39 °C) is slightly smaller than at Surakarta, and the monthly minimum occurs in July rather than January, reflecting the stronger dry season cooling effect associated with the southeast monsoon at this location. The relatively cool temperatures during June–August at Mataram may also be influenced by the advection of cooler continental air masses from Australia during the peak of the southeast monsoon season.

Wamena shows a somewhat larger annual temperature range compared to the two lowland sites, with monthly averages spanning from 16.14 °C in July to 17.36 °C in March, representing a range of 1.22 °C. The coolest months at Wamena occur during June–August, corresponding to the austral winter period when lower solar angles and reduced convective activity result in cooler temperatures in the highlands. This pattern is broadly consistent with the temperature seasonality observed at other highland stations in tropical Papua New Guinea and the eastern Indonesian archipelago.

The monthly temperature distributions across the three locations provide important context for interpreting the warming trends identified in this study. The significant increases in TN90p and average temperature detected at all three locations, combined with the relatively small natural seasonal temperature variation, suggest that even modest long-term warming trends can substantially alter the frequency of temperature extremes. This has important implications for heat stress in agriculture, changes in disease vector distributions, and the thermal comfort of urban populations across the diverse climate zones represented by the three study locations.

Study limitations

This study has several limitations. First, the analysis was based exclusively on ERA5-Land and was not independently validated using homogenised weather-station observations. This decision allowed a consistent comparison among locations with uneven observational coverage, but it means that the results represent climate variability and trends as depicted by the reanalysis product. Second, each study area was represented by a fixed sampling point; therefore, the findings should not be interpreted as capturing the full spatial heterogeneity of the corresponding city or wider region. Third, ERA5-Land may not fully resolve local convective rainfall and fine-scale elevation effects, particularly in the mountainous environment of Wamena. Fourth, the relatively short 31-year period and the influence of interannual climate variability may affect the detectability of precipitation trends. Future research should validate these results using quality-controlled station observations, where available, and compare ERA5-Land with independent products such as CHIRPS, IMERG, or other regional gridded datasets.

CONCLUSIONS

Based on the analysis of climate trends and variability across three geographically contrasting locations in Indonesia during 1995–2025, the results indicate clear differences in regional climate responses. Wamena exhibited the most pronounced changes, with significant increases in several rainfall intensity and frequency indices, including SDII, R95p, PRCPTOT, R10mm, and

R20mm. In contrast, Surakarta and Mataram did not show statistically significant trends in annual precipitation, suggesting that long-term rainfall signals in these locations may be obscured by strong interannual variability. Despite these differences in precipitation, all three locations showed consistent warming signals, particularly through significant increases in the frequency of warm nights, while Wamena also experienced significant increases in daytime temperature extremes. These consistent warming signals across the three contrasting locations are broadly consistent with the expected regional manifestation of ongoing global climate warming. The Precipitation Concentration Index further highlighted distinct regional patterns, with moderate rainfall concentration in Surakarta, more irregular rainfall distribution in Mataram, and relatively uniform rainfall throughout the year in Wamena. These findings support the need for location-specific climate adaptation strategies, particularly in water-resource management, agricultural planning, and risk reduction. As the analysis relies exclusively on ERA5-Land point-based data, the findings should be interpreted as reanalysis-derived evidence rather than as a substitute for station-based observations. Further validation using homogenised meteorological records and independent gridded datasets is required to confirm the local magnitude of the detected trends. The ERA5-Land data used in this study are publicly available from the Copernicus Climate Data and were accessed through Google Earth Engine. The point coordinates, extracted daily data, processed annual climate indices, and summary datasets underlying the tables and figures are publicly available at https://github.com/SaptaSuhardono/Contrasting-Extreme-Climate-Trends-Using-ERA5-Land. The repository contains sufficient metadata to identify the variables, units, study locations, temporal coverage, and processing stages. The Google Earth Engine JavaScript used to extract the ERA5-Land data and the R scripts used for data preparation, climate-index calculation, Modified Mann–Kendall testing, Sen's slope estimation, descriptive analysis, and figure generation are publicly available at https://github.com/SaptaSuhardono/Contrasting-Extreme-Climate-Trends-Using-ERA5-Land. Software versions, package dependencies, and instructions for reproducing the analysis are provided in the repository README file.

Supplementary materials

Supplementary materials include the geographic coordinates of the sampling points, variable definitions, and climate-index calculation.

REFERENCES

1. Akter, M.Y., Islam, A.R.M.T., Mallick, J., Alam, M.M., Alam, E., Shahid, S., Biswas, J.C., Alam, G.M., dan Oliver, M.M.H. 2024. Temperature extremes projections over Bangladesh from CMIP6 multi-model ensemble. *Theoretical and Applied Climatology*. *155*(1), 8843–8869.
2. Aldyan, R. A. 2023. The Impact of Climate Change on Water Resources and Food Security in Indonesia. *Journal of Law Environmental and Justic*e. *1*(1), 50–63.
3. Alizadeh, O. 2022. Advances and Challenges in Climate Modeling. *Climate Change. 170*(18), 1–26.
4. Aminoto, T., Susant, N., Dani, R., dan Faqihi, A. 2026. Extreme rainfall indices trends in Indonesia during 1971–2020. *Jurnal Penelitian Pendidikan IPA. 12*(3), 456–467.
5. Amnuaylojaroen, T. 2025. Intensification of heat extremes in Southeast Asia: Spatial-temporal analysis of temperature trends and heat events (1940–2023). *International Journal of Climatology*. *45*(10).
6. Azwar, A.E., Meiliand, dan Masimin. 2022. Kajian pola curah hujan durasi panjang terkait dengan waktu kejadian banjir di Kabupaten Aceh Utara. *Jurnal Arsip Rekayasa Sipil dan Perencanaan*. *4*(1), 39–48.
7. Bakhtar, A., Rahmati, A., Shayoghi, A., Teymoori, J., Ghajarnia, N., and Saemian, P. 2022. Spatio-temporal evaluation of GPM-IMERG V6.0 Final Run precipitation product in capturing extreme precipitation events across Iran. *Water. 14*(10), 1–24.
8. Coelho M.T., E. Barreto., T. F. Rangel., and C.H. Graham. 2023. The geopgraphy of climate and the global patterns of species diversity. *Nature*, *622*(1), 537–544.
9. Correa, J., A. Lopez-Diez., P. Dorta and J. Diaz-Pacheco. 2025. Evolution of warm nights in the Canary Islands (1950–2023): evidence for climate change in the Southeastern North Atlantic. *Theoretical and Applied Climatology*. *156*(87), 1–23.
10. Diyaolu, C. O and I. O. Folarin. 2024. The role of biodiversity in agricultural resilience: Protecting ecosystem services for sustainable food production. *International Journal of Research Publication and Review*. *5*(10), 1560–1573.

11. Fan, Y., J. Li., S. Zhu., H. Li and B. Zhou. 2022. Trends and variabilities of precipitation and temperature extremes over Southeast Asia During 1981–2017. *Meteorology and Atmospheric Phsysics. 134*(78), 1–15.
12. Ferguglia, O., Palazzi, E., dan Arnone, E. 2024. Elevation dependent change in ERA5 precipitation and its extremes. *Climate Dynamics.*
13. Hasbullah, R., dan Assyahri, W. 2024. Tinjauan implementasi Program Kampung Iklim di Indonesia. *Journal of Public Administration and Management Studies*. *3*(1), 1–11.
14. Jin, T., Zhou, Y., Zhou, P., Zheng, Z., Zhou, R., Wei, Y., Zhang, Y., dan Jin, J. 2025. Spatiotemporal evolution of precipitation concentration in the Yangtze River Basin (1960–2019): Associations with extreme heavy precipitation and validation using GPM IMERG. *Remote Sensing*. *17*(2732), 1–28.
15. Kumar, S., Chatterjee, U., David Raj, A., Sooryamol, K. R. 2024. Global warming and climate crisis/extreme events. In *Climate crisis: Adaptive approaches and sustainability*. *1*(2), 1–20.
16. Maharjan, M., Yoneda, M., Talchabhadel, R., Thapa, B.R., dan Aryal, A. 2022. Use of indices on daily timescales to study changes in extreme precipitation across Nepal over 40 years (1976–2015). *Earth and Space Science*. *10*(1), 1–18.
17. Marzuki, M., Ramadhan, R., Yusnaini, H., Vonnisa, M., Muharsyah, R., Nugraha, Y., Sari, A.Y., dan Krajalita, A. 2025. Long-term spatial-temporal variability, trends and extreme rainfall events over Indonesia based on 43 years of CHIRPS data. *International Journal of Climatology*. *45*(14), 1–20.
18. Matchaya, G. C., Tadesse, G., and Kuteya, A. N. 2022. Rainfall shocks and crop productivity in Zambia: Implication for agricultural water risk management. *Agricultural Water Management*. *269.*
19. Mistry, M. N., R. Schneider. P. Masselot., D. Royce. B. Armstrong., J. Kysely. H. Orru and A. Gasparrini. 2022. Comparison of Weather Station and Climate Reanalysis Data For Modelling Temperature-related Mortality. *Scientific Reports. 12*(5178), 1–14.
20. Mustopa, A., Santoso, J.D., Nauvaldhi, M.S.F., dan Wulandari, D. 2025. Pemodelan variabilitas musiman dalam curah hujan: Pendekatan deret waktu. *Journal of Information System Management (JOISM)*. *6*(2), 148–155.
21. Nabinejad, S. and H. Schuttrumpf. 2023. flood risk management in arid and semi-arid areas : a comprehensive review challenges, needs and oppurtunities. *Water. 15*(17), 1–22.
22. Nandi, N., dan Dede, M. 2022. Urban heat island assessment using remote sensing data in West Java, Indonesia: From literature review to experiments and analyses. *Indonesian Journal of Science and Technology*. *7*(1), 105–116.
23. Natun, R., Messakh, J.J., dan Tamelan, P.G. 2024. Kajian parameter iklim di wilayah Kabupaten Timor Tengah Selatan untuk mendukung pengembangan sumber daya air berkelanjutan. *Jurnal Batakarang*. *5*(2), 75–80.
24. Nugraheni, I.R., Virgianto, R.H., Kristianto, A., Septiadi, D., Nugroho, H.A., Sugiarto, I., dan Radjah, F. 2025. Evaluating surface temperature variabilities and climate extremes in the Dieng Plateau over three decades. *Indonesian Physical Review*. *8*(2), 597–615.
25. Nugroho, S., Febriamansyah, R., Nurhamidah, N., dan Gunawan, D. 2023. Assessment of extreme precipitation for developing agricultural adaptation strategy in the Selo Watershed Area. *International Journal on Information Technology*. *13*(5), 1889–1897.
26. Palmer, P.P., Wainwright, C.M., Dong, B., Maidment, R.I., Wheeler, K.G., Gedney, N., Hickman, J.E., Madani, N., Folwell, S.S., dan Turner, A.G. 2023. Drivers and impacts of Eastern African rainfall variability. *Nature Reviews Earth and Environment*. *4*(1), 254–270.
27. Panggabean, J.R.N., Syamsudin, F., Suaydhi, S., Purba, N., dan Feng, X. 2026. Interannual climate variability impacts on rainfall extremes and flooding. *Jurnal Presipitasi: Media Komunikasi dan Pengembangan Teknik Lingkungan*. *23*(1), 244–257.
28. Ramadhani, R.P., dan Sudirman, S. 2026. Evaluasi pola dan tren curah hujan harian dalam hubungannya dengan fenomena ENSO (El Niño Southern Oscillation) di wilayah Papua Indonesia. *Titian Ilmu: Jurnal Ilmiah Multi Sciences*. *18*(1), 30–39.
29. Rangga, I.A., Zuhrita, A., dan Zalsabilah, P. 2025. Pengaruh ENSO terhadap curah hujan di Sulawesi Tengah. *Buletin GAW Bariri*. *6*(2), 61–75.
30. Sarvina, Y. 2022. ENSO and climate variability in Papua. *IOP Conference Series: Earth and Environmental Science*. *1192*(1), 1–6.
31. Sutapa, I.W., Arafat, Y., Lipu, S., dan Rustiati, N.B. 2023. A comparative study of SPI, PCI, PCD, and RAI methods for estimating drought in the Palu River Basin, Indonesia. *IOP Conference Series: Earth and Environmental Science*. *1311*.
32. Syarifuddin, A., Dharmansyah, F., dan Pattipeilohy, W.J. 2023. Analisis perubahan tren linier curah hujan di Kota Sorong, Papua Barat. *Buletin Meteorologi, Klimatologi, dan Geofisika*. *4*(1), 22–28.
33. Tesfaye, Y., Dechassa, N., Alemayehu, Y., dan Birhan, D.A. 2025. Spatiotemporal variability and trends in extreme rainfall and temperature indices

in Southeastern Oromia, Ethiopia. *Scientific Reports*. *15*(29782), 1–30.

34. Vinata, R. T. M. T. Kumala and C. Y. Serfiyani. 2023. Climate change and reconstruction of indonesia's geographic basepoints: Reconfiguration of Baselines and Indonesian Archipelagic Sea Lanes. *Marine Policy. 148*(105443), 1–6.
35. Vu, M. T., A. Jardani., N. Massei., J. Deloffre., M. Fournier and B. Laignel. 2023. Long-run forecasting surface and groundwater dynamics from intermittent observation data: An evaluation for 50 years. *Science of The Total Environment. 880*(1), 1–16.
36. Xu J. Z. Ma., S. Yan and J. Peng. 2022. Do ERA5 and ERA5-land precipitation estimates outperform satellite-based precipitation products? A comprehensive comparison between state-of-the-art model-based and satellite-based precipitation products over mainland China. *Journal of Hydrology. 605* (127353), 1–16.
37. Zaman, M., Shahid, M.A., Ahmad, I., Shen, Y.J., Usman, M., Khan, M.I., dan Saifullah, M. 2023. Spatiotemporal variability of precipitation concentration in Pakistan. *International Journal of Climatology*. *43*, 7646–7666.