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Analysis of Trends in Extreme Rainfall Indices (R20mm, RX1day, PRCPTOT, and CDD) Using the Mann-Kendall and Sen's Slope Estimators in the Province of Bali

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Abstract

Background: Climate change has affected rainfall patterns, particularly extreme rainfall events. As a region with high levels of tourism and socio-economic activity, the province of Bali is vulnerable to these changes. However, studies on trends in extreme rainfall in the Bali region remain limited.
Aims: This study aims to determine the trends and magnitude of changes in extreme rainfall indices (R20mm, RX1day, PRCPTOT, and CDD) in the Province of Bali during the period 1994–2023.
Methods: The data used consists of daily rainfall records from 17 BMKG stations, with a data completeness rate exceeding 90%. Extreme rainfall indices were calculated using the ETCCDI method. Trend analysis was conducted using the Mann-Kendall test and Sen's Slope estimator. Additionally, monthly trend analysis was performed as a follow-up.
Result: The results indicate an increase in intensity-based extreme rainfall indices (RX1day, R20mm, and PRCPTOT), whilst the CDD index shows a decreasing trend. Several stations showed a significant upward trend, particularly in the PRCPTOT and RX1day indices. Monthly analysis also indicated increased rainfall in certain months, including the period from May to September.
Conclusion: These results highlight the importance of climate adaptation strategies and the mitigation of hydrometeorological disasters, particularly in the Bali region.

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INTRODUCTION

Climate change is a global phenomenon that has had a significant impact on the agricultural, health, socio-economic and tourism sectors (Jit et al., 2026; Maráková et al., 2025) . This phenomenon is evidenced by an increase in rainfall and average atmospheric water vapour (Trenberth, 2011). The effects of climate change include changes in rainfall patterns, rising air temperatures and rising sea surface temperatures (Malino et al., 2021). Human activities such as deforestation, industrial activities and the use of fossil-fuel-powered vehicles cause global warming (an increase in greenhouse gas emissions) and are the main drivers of climate change (Friedlingstein et al., 2023).

Th e province of Bali is one of the regions particularly vulnerable to the impacts of climate change, especially as a world-renowned tourist destination (F. Amalia et al., 2025; Arpan, 2025) . According to data from the Central Statistics Agency (BPS), between January and August 2024, the number of tourists visiting Bali increased by 21.55% compared to 2023. This rise in tourist activity has led to an increase in greenhouse gas emissions, leaving Bali at risk of experiencing the effects of climate change. According to a report by the National Disaster Management Agency (BNPB, 2022), the Province of Bali faces a high risk of extreme weather events (Sadriani et al., 2026; Yesaya et al., 2025). This will undoubtedly affect the tourism sector and the comfort of holidaymakers. Furthermore, the activities of local communities and other sectors such as agriculture, health, and the wider socio-economic sphere will also be impacted (Guo et al., 2026).

One approach for identifying climate change involves the technique created by the World Meteorological Organization (WMO), specifically the extreme climate indices sourced from the Expert Team on Climate Change Detection and Indices (ETCCDI). Numerous research findings suggest that extreme precipitation indices based on ETCCDI, including Precipitation exceeding 20 mm (R20mm), Maximum daily precipitation (Rx1day), Annual total from wet days (PRCPTOT), and Consecutive dry days (CDD), have experienced considerable shifts in recent decades. In addition, non-parametric methods like the Mann-Kendall test and Sen's Slope estimator can also be applied for analyzing hydrometeorological trends. (Chaiwino et al., 2025; Lin & Yu, 2026).

A study conducted by Aditya et al (2021) in West Kalimantan shows that rainfall trends are not spatially homogeneous. Some areas have experienced an increasing trend in rainfall, whilst others show a decreasing trend (M. Marzuki et al., 2025) . The study also indicates that analyses of rainfall trends must account for local variability. Furthermore, there are regional-scale studies, such as the research by An et al. (2023) in the Asia-Pacific region. This study shows that most extreme rainfall indices, such as PRCPTOT and R20mm, have decreased. Meanwhile, indices indicating drought, such as CDD, have increased significantly. Based on this research, there are indications of a change in rainfall distribution, namely that dry periods are becoming longer, although extreme rainfall events continue to occur (Faya, 2025; Moreira et al., 2025).

A different investigation indicates that metrics for intense rainfall, including RX1day and R20mm, are showing an increasing pattern in multiple areas. Oddly enough, the CDD index is also demonstrating a rise in certain places, hinting that regional influences and atmospheric processes could be involved. These results are additionally backed by studies carried out. by Lestari et al. (2016) in the Maluku Islands, which discovered that the fluctuations in severe rainfall in Eastern Indonesia are significantly affected by the El Niño Southern Oscillation (ENSO). Additionally, studies by Supari et al. (2017) In Kalimantan, it is evident that the climate dynamics of the region affect the intricate spatial and temporal features of extreme climate indicators related to temperature and precipitation. (Maulida et al., 2026).

A majority of earlier research has concentrated on particular areas like Sumatra, Kalimantan, and Maluku. (Aditya et al., 2021; Lestari et al., 2016; Supari et al., 2017), whilst studies specifically examining the Province of Bali remain few in number. Many studies use the ETCCDI index; however, not all studies comprehensively combine statistical trend analysis with quantitative approaches to rates of change, such as Sen's Slope (I. Marzuki et al., 2025; Pyarali et al., 2025) . This results in limitations in understanding the magnitude of the trends occurring. There are inconsistencies in results across regions regarding rainfall index trends, particularly the PRCPTOT, which may indicate increasing or decreasing trends depending on the location (An et al., 2023). This highlights the need for region-specific studies to achieve a more accurate understanding.

The selection of Bali Province was based on its geographical characteristics, namely its coastal and mountainous regions. Bali is also an area with high socio-economic activity, making it vulnerable to the impacts of climate change. Furthermore, the limited scope of previous research in this region makes Bali an important location for further study (Loise et al., 2026; Wijaya et al., 2025) . This study utilised the ETCCDI extreme rainfall indices, including R20mm, RX1day, PRCPTOT, and CDD. These indices are considered to represent several aspects of extreme rainfall, such as frequency, intensity, and the duration of dry periods. The Mann-Kendall test was used to detect trends in the extreme rainfall indices as it is capable of identifying the significance of trends. Furthermore, Sen's Slope estimator was also used to measure the magnitude of trend changes (Y. Li et al., 2026; Mliyeh et al., 2025).

This study aims to analyse trends in changes and the magnitude of the rates of extreme rainfall indices (R20mm, Rx1day, PRCPTOT, and CDD) in the Province of Bali using daily data from 17 observation stations for the period 1994–2023. The outcomes of this research are anticipated to bolster the theory that there is a rise in the severity of extreme rain events (RX1day) and yearly cumulative rainfall (PRCPTOT), which aligns with the observed pattern of heightened precipitation in specific months. It is also expected that the results will offer a scientific foundation for developing strategies for hydrometeorological disaster prevention and climate adaptation at the community level. (Chaiwino et al., 2025).

METHOD

Research Location:
This study focuses on the province of Bali, which is astronomically situated between 08°03'40" – 08°50'48" S and 114°25'53" – 115°42'40" E. As one of Indonesia's leading tourist destinations, renowned both nationally and internationally, Bali attracts many tourists every year. Tourists' comfort on the island is greatly influenced by local weather and climate conditions. According to a 2022 report by the National Disaster Management Agency (BNPB), Bali is categorised as an area at high risk of extreme weather events (I. Amalia et al., 2026; I. Marzuki et al., 2025)

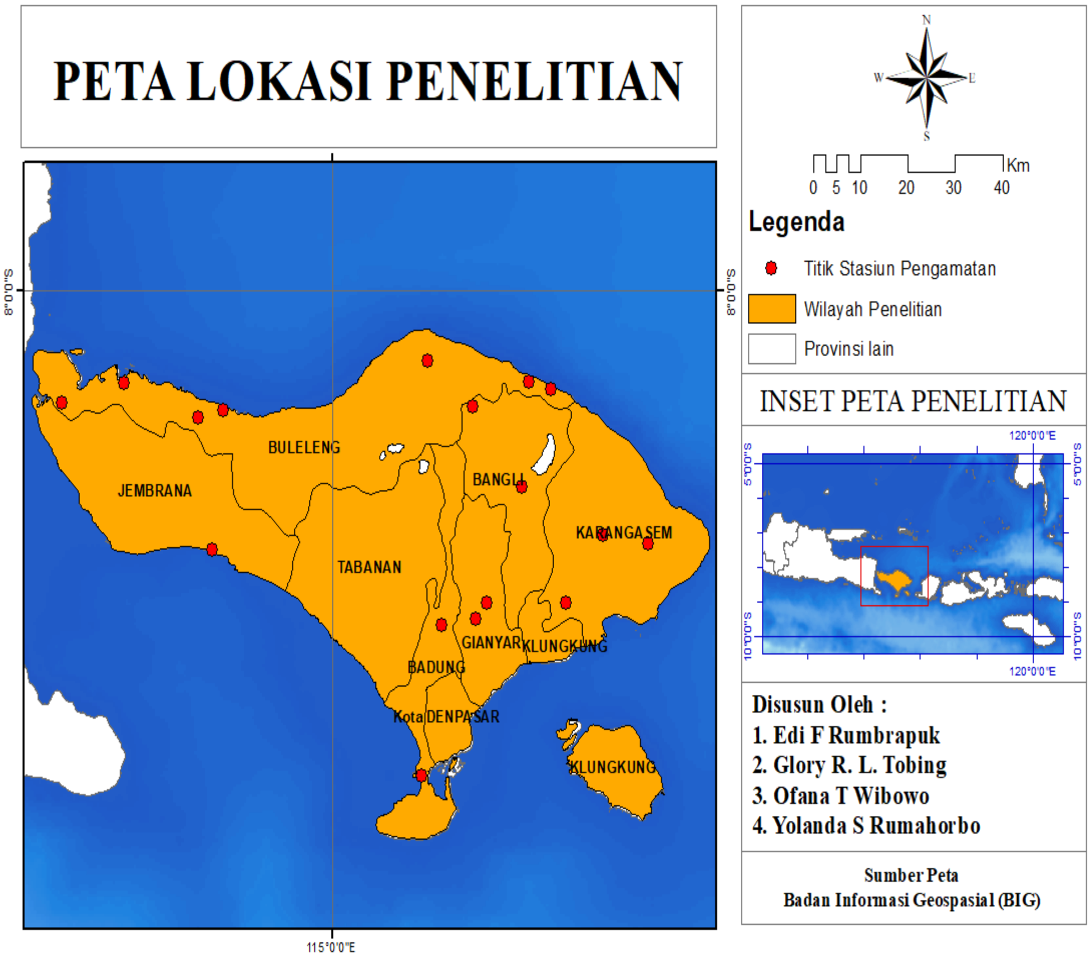

Figure 1. The province of Bali and its BMKG observation stations (Source : Badan Informasi Geospasial

Dataset :
The information utilized in this research consists of daily precipitation records spanning three decades (1994–2023) collected from 17 BMKG monitoring sites located across the Bali province.The rainfall data from these 17 observation stations were selected as they had a daily rainfall data completeness rate of over 90%. The rainfall data was downloaded from the BMKG's official website at https://bmkgsoft.bmkg.go.id. This research uses quantitative descriptive analysis with the time series method. This study seeks to determine climate change with an extreme rainfall factor approach in the area of Bali. (I. Marzuki et al., 2025).

Research Methodology:
1. Professional Group on Climate Change (PGCC) with a Working Group on Metrics

The present study uses some extreme weather indices created by the Expert Team for Climate Change Detection and Indices (ETCCDI) to evaluate climate change in Bali Province. A total of 27 severe cold weather indicators were developed using daily temperature and precipitation measurements, The basic statistics being used in this study include the number of days with rainfall equal to or greater than 20 mm (R20mm), yearly maximum daily rainfall (extreme precipitation) Rx1day, annual total wet-day precipitations (PRCPTOT), and CDD which show Max Sequence Dry days. These indicators were, in turn, subjected to the Mann-Kendall test and estimated Sen's Slope for all observation sites. Additionally, Mann–Kendall trend test and Sen's Slope estimator were performed on 30-year rainfall record (1994–2023) on a monthly basis to identify during which months the observation sites recorded an uptick in rainfall. The outcomes were then contrasted with the trend findings from the ETCCDI. (Dey & Bhardwaj, 2025; Utami et al., 2024).

Table 1. Description of ETCCDI extreme rainfall indices used in this study, including definitions and measurement units

No	Rainfall Index		Description	Unit
1	R20mm	Precipitation above 20mm	Number of days with rainfall of ≥ 20 mm per year	Day
2	RX1day	Max 1-day precipitation	Maximum annual rainfall in a single day	mm
3	PRCPTOT		Annual rainfall	mm
4	CDD	Consecutive dry day	The longest annual run of consecutive days without rain, with daily rainfall of less than 1.0 mm	Day

1. Mann-Kendall test

The Mann-Kendall test serves to evaluate the importance of trends within chosen climate indices; it is a statistical analysis method that does not rely on parameters and aims to identify trends in data by analyzing relative ranks over a determined timeframe. This test does not depend on the assumption that the data follows a normal distribution (Sa'adi et al., 2019). The World Meteorological Organization (WMO) endorses this technique as a valuable resource for examining trends in hydrological information (World Meteorological Organization, 2018). The application of the Mann-Kendall test employs the following equation:

$$S = \sum_{i=1}^{n=1} \sum_{j=i+1}^{n} sign(x_j - x_i) \ , sign(x_j - x_i) = \begin{Bmatrix} +1 \ (x_j - x_i) > 0 \\ 0 \quad (x_j - x_i) = 0 \\ -1 \ (x_j - x_i) < 0 \end{Bmatrix} \tag{1}$$

A positive S value signifies an increasing trend, whereas a negative S value signifies a decreasing trend. To determine the Z value, the variability of rainfall is assessed, with the S variance computed using this formula:

$$Var(S) = \frac{n(n-1)(2n+5)-\sum_{i=1}^{m} t_i(t_i-1)(2t_i+5)}{18} \quad (2)$$

In data analysis involving more than 10 observations, the Z-statistic, which follows a standard normal distribution, is used. The Z-value is calculated using the following equation:

$$Z = \frac{S \pm 1}{Var(S)^{1/2}} \quad (3)$$

This formula gives S – 1 when S is greater than 0, S + 1 when S is less than 0, and Z equals 0 when S is equal to 0. A Z value above zero signifies a positive trend, whereas a Z value below zero signifies a negative trend.

2. Sen's Slope Estimator

The World Meteorological Organization advises utilizing this assessment as a component of identifying patterns in hydrometeorological information (World Meteorological Organization, 2018). This assessment presumes that the trend follows a linear path and serves to measure alterations throughout time. An advantage of the Sen's slope method compared to linear regression is its immunity to the influence of outliers and inaccuracies in the data. The formula for calculating Sen's slope for a collection of N pairs of data points is expressed in the following manner:

$$Q_i = \frac{(x_j - x_i)}{j-i}, i = 1,2,3, \dots, N \quad (4)$$

xj and xi represent data points at times j and i, where j is greater than i. When there are n xj values within the time series, the total number of slope estimates will be N = n(n-1)/2. The values of Qi are arranged in ascending order, and Sen's Slope method employs the median of these Qi values (Qmed). A two-tailed test calculates the Qmed value at significance thresholds of 90% and 95%, determined by:

$$Q_{med} = \begin{cases} Q_{\left[\frac{N+1}{2}\right]} & if\ N = odd \\ \frac{Q_{\left[\frac{N}{2}\right]} + Q_{\left[\frac{N+1}{2}\right]}}{2} & if\ N = even \end{cases} \quad (5)$$

The study focused solely on the ETCCDI index using rainfall as the variable, without incorporating temperature or humidity data. The quality of the results is highly dependent on the accuracy of daily Information regarding precipitation obtained from monitoring sites, along with the chance of absent data in specific intervals, could impact the accuracy of the evaluation.

RESULTS AND DISCUSSION

Results

This part showcases the findings from the Mann-Kendall test along with the estimates of Sen's Slope for every station, utilizing the rainfall occurrence index for precipitation over 20 mm (R20mm), the maximum daily rainfall or peak intensity (Rx1day), the overall yearly rainfall derived from wet days (PRCPTOT), and the longest unbroken sequence of days without precipitation (CDD). Furthermore, a 30-year rainfall trend analysis (1994–2023) was conducted for each month across the Bali region to identify the monthly periods in which upward and downward trends occurred (Agarwal et al., 2025; Tesfaye et al., 2025).

1. Extreme Rainfall Index

The results of the analysis of extreme rainfall indices in the Bali region are shown in Table 2. The slope values of the extreme rainfall indices for the intensity categories (RX1day, R20mm, and PRCPTOT) generally show a positive (increasing) trend. The slope value of the RX1day index showed a significant increase at three observation stations, namely Pelitan, Telaga Tawang, and Abang.

Meanwhile, there was one station that experienced a significant decrease in RX1day, namely Sambirenteng 1.

Table 2. Sen's slope values of extreme rainfall indices (Rx1day, R20mm, PRCPTOT, and CDD) across 17 BMKG observation stations in Bali Province

No	Stasiun Pengamatan	ID Stasiun	RX1day	R20mm	PRCPTOT	CDD
1	Yehembang Kangin	4684	1.550	-0.044	3.250	-0.108
2	Blahkiuh	4713	1.462	0.450	25.226	-0.050
3	Pejeng Kaja	4722	1.567	0.077	20.000	-0.019
4	Peliatan	4723	1.200	-0.333	-1.000	-0.039
5	Pengotan	4735	1.000	0.211	15.500	-0.031
6	Satra	4739	-0.273	0.214	15.577	-0.291
7	Telaga Tawang	4745	2.143	0.333	28.763	-0.022
8	Ulakan	4747	0.792	0.167	20.830	-0.089
9	Abang	4754	4.800	0.056	26.375	-0.019
10	Gerokgak	4762	0.200	0.154	11.300	-0.217
11	Patas 1	4764	-0.500	-0.200	-8.944	-0.250
12	Sumberkima	4765	-0.455	0.000	6.200	-0.309
13	Sumber Klampok	4766	1.318	0.429	14.133	0.039
14	Bengkala	4777	-0.105	0.000	4.800	-0.050
15	Sambirenteng 1	4778	-1.889	0.167	4.700	-0.225
16	Les	4780	1.160	0.177	16.659	-0.232
17	Stamet Ngurah Rai	11571	-1.300	0.067	4.657	-0.042

Regarding the slope values of the R20mm index, two observation stations experienced a significant increase, namely Blahkiuh and Sumber Klampok. The slope values of the PRCPTOT index showed a significant increase at five observation stations, namely Blahkiuh, Telaga Tawang, Ulakan, Abang, and Les. The slope of the Cumulative Duration of Dryness (CDD) index shows an inverse relationship. In general, the slope of the CDD index exhibits a negative trend, except at the Sumber Klampok observation station, where a positive trend is observed, albeit not significant. This trend in the CDD index slope value indicates a decreasing trend in the number of consecutive dry days (C. Li et al., 2024). The decline in CDD along with the rise in RX1day, R20mm, and PRCPTOT points to an escalating risk for floods and landslides. Figure 2 illustrates the varying slope trend values of the

ETCCDI index at various monitoring stations throughout the Bali area.

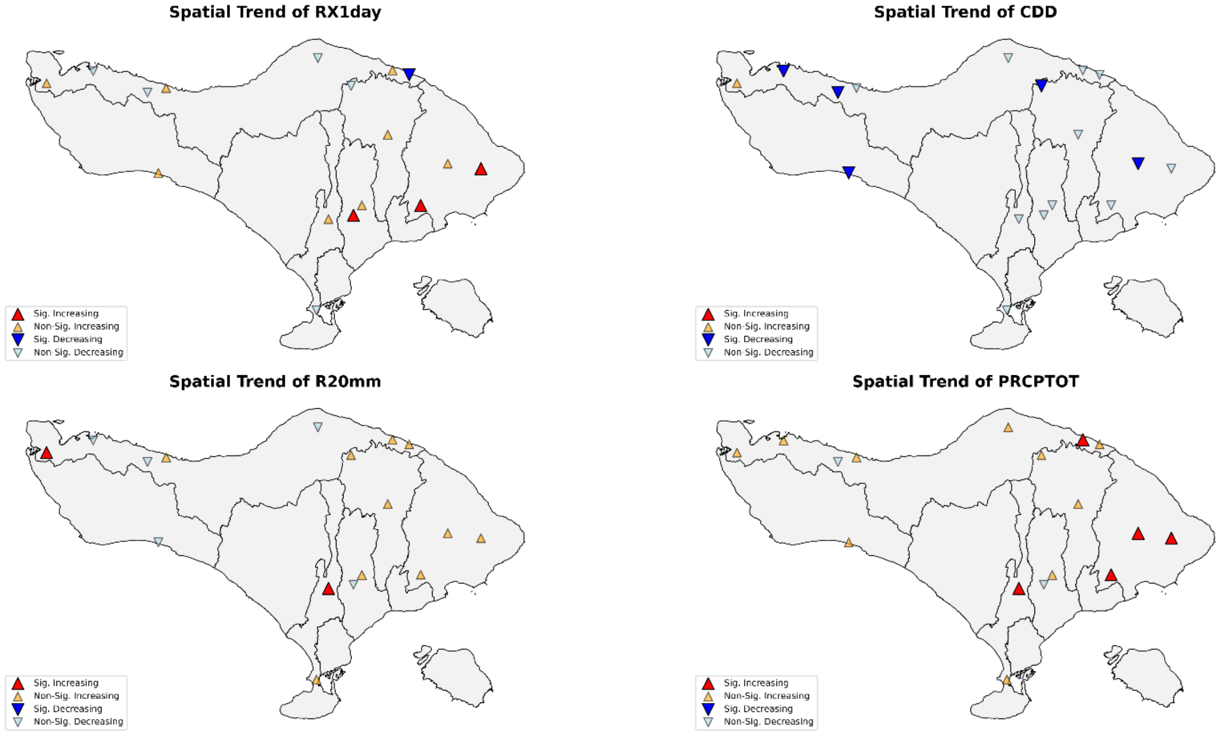

Figure 2. Spatial distribution of Sen's slope values for extreme rainfall indices (RX1day, R20mm, PRCPTOT, and CDD) across observation stations in Bali Province

2. Monthly Rainfall Trends

In general, the trend analysis of the extreme rainfall index, categorised by intensity and duration, indicates that the Bali region is experiencing increased rainfall and more frequent rainfall events. However, there are still some observation stations showing opposite results. Therefore, a 30-year rainfall trend analysis (1994–2023) was conducted for each month across the Bali region. The results are shown in Figure 3. For the CDD index, only the Sumber Klampok observation station showed an increasing trend, though this was not significant. Furthermore, when examining the monthly trends, no month exhibited an increasing trend in rainfall (Akhsan et al., 2023; Yuliana et al., 2023)

The RX1day index shows that the Sambirenteng 1 observation station is experiencing a downward trend. This decline is also supported by a downward trend in rainfall in September (Figure 3). The R20mm index generally shows an increasing trend in rainfall events exceeding 20 mm, except at Yehembang Kangin, Peliatan, and Patas 1. In terms of monthly trend analysis, all these observation stations show a decreasing trend in monthly rainfall. For instance, Yehembang Kangin experienced a decrease in June, Peliatan in August, and Patas 1 in May, September, and December (Aditya et al., 2021) . Meanwhile, the observation stations at Sumberkima and Bengkala have a slope value of zero. The PRCPTOT index generally shows an increasing trend in annual rainfall. The observation stations with significant increases are Blahkiuh, Telaga Tawang, Ulakan, Abang, and Les. This also correlates with the monthly rainfall trends in Figure 3, namely Blahkiuh, Telaga Tawang, and Ulakan. Meanwhile, the stations showing a decreasing trend in PRCPTOT are Peliatan and Patas 1. As can also be seen in Figure 3, the Peliatan station experienced a decrease in monthly rainfall in August. The Patas 1 station showed a decreasing trend in PRCPTOT in May, September, and December.

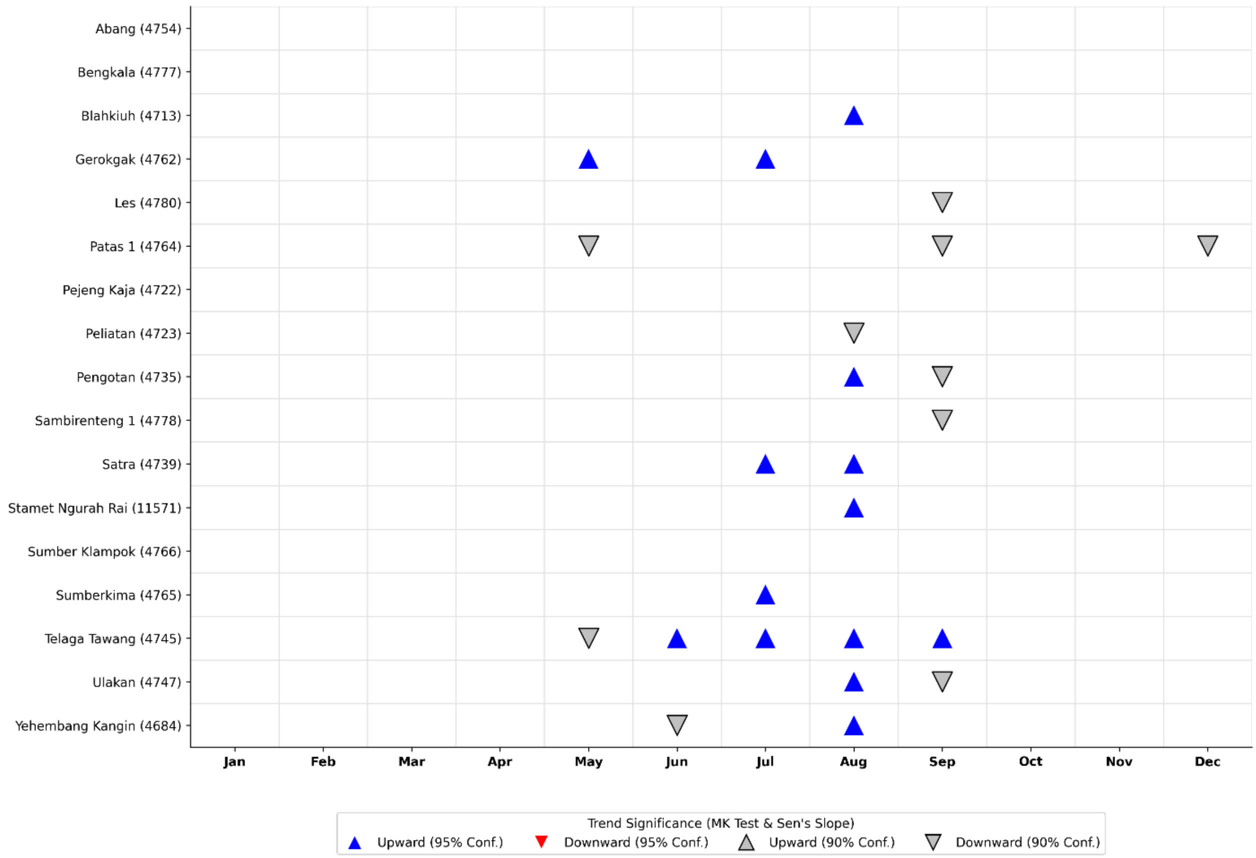

Figure 3. Monthly precipitation patterns analyzed with the MK test and Sen's slope. Grey (upward/downward) reflects a positive/negative trend at a 90% confidence interval. Blue/red (upward/downward) signifies a positive/negative trend at a 95% confidence interval.

Discussion:

The research findings indicate a relationship between monthly rainfall trends and trends in the ETCCDI extreme climate index in Bali Province during the period 1994–2023. For the RX1day and PRCPTOT indices at stations such as Abang, Telaga Tawang, and Peliatan, there is a direct correlation with a positive trend in the monthly analysis (Mann-Kendall Test), specifically from May to September (Salsabila et al., 2026).

Implications:

Generally, negative CDD index slope values indicate that the duration of consecutive dry days is becoming shorter in the Bali region. This is supported by the results of the monthly Mann-Kendall test, which show that several stations exhibit an increasing rainfall trend, even during months that are typically dry, such as July and August (Loise et al., 2025) . This condition indicates a shift in climate patterns, with the dry season becoming wetter in the Bali region.

Research contribution:

This increasing rainfall trend should also be a concern for the Bali Provincial Government. Local authorities could begin improving drainage systems and flood early warning systems in their areas. The tourism sector will also be affected by this increase in rainfall. More frequent episodes of extreme rainfall will impact visitor comfort, particularly at outdoor tourist attractions. Consequently, local authorities must begin to consider climate adaptation policies as a measure to mitigate hydrometeorological disasters such as floods and landslides (Dube & Nhamo, 2025; León-Cruz et al., 2025).

Limitations:
Although this study has demonstrated an increasing trend in extreme weather events (ETCCDI) and rising rainfall levels from May to August, rainfall alone is not sufficient to indicate climate change in the Bali region (Tulistiawan et al., 2023). In addition to rainfall, temperature and humidity also influence the dynamics of climate change. This analysis also depends on the quality of the data and the number of BMKG observation stations. This study utilised 17 BMKG observation stations with data completeness exceeding 90%, meaning there were still gaps in the data that affected the results of the Mann-Kendall and Sens-Slope tests.

Suggestions:
The analysis conducted in this study has not yet taken into account the influence of other atmospheric dynamics, such as the ENSO (El Nino Southern Oscillation), IOD (Indian Ocean Dipole), MJO (Madden-Julian Oscillation), and other atmospheric wave phenomena. In addition, future research could also include an analysis of sea surface temperatures (SST) in the waters around Bali to further investigate the causes of the increased intensity of extreme rainfall during the transition months between the rainy and dry seasons (Agarwal et al., 2025).

CONCLUSION

This study aimed to analyze indications of extreme climate change in Bali Province, specifically regarding extreme rainfall, using the ETCCDI indices. Based on the analysis, this objective has been achieved with the following findings. The results indicate that Bali Province is experiencing indications of extreme climate change, as reflected in an increase in the extreme rainfall index. The RX1day and PRCPTOT indices show a direct correlation with monthly rainfall, which tends to increase, particularly from May to September. Conversely, the CDD index shows a negative trend, indicating a shortening of the duration of consecutive dry days. Overall, these findings indicate a shift in climate patterns in Bali Province, with the dry season becoming wetter compared to the 30-year average (1994–2023). These results hold significant importance for the Bali Provincial Government as it develops strategies for adapting to climate change and mitigating hydrometeorological disasters. This includes enhancing drainage infrastructure and reinforcing early warning systems for floods. It is suggested that further investigations be conducted to broaden the analysis by incorporating more climate factors like air temperature and humidity, while also taking into account atmospheric dynamic events such as ENSO, IOD, and MJO. This approach would allow for a deeper insight into the variability of extreme rainfall in Bali.

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AUTHOR CONTRIBUTION STATEMENT

The Author Contributions Statement may consist of a few sentences and must concisely outline the roles of each author. Only include 2 initials for every author, without periods, but separate them with commas (for instance, JC, JS). If there are two authors sharing the same initials, please add their middle initial to tell them apart (for example, REW, RSW). This statement should be positioned at the conclusion of the manuscript, just prior to the References.

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