ASSESSING THE IMPACT OF CLIMATE CHANGE ON RAINFALL PATTERNS IN THAILAND

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ABSTRACT

Climate change is significantly altering rainfall patterns in Thailand, impacting water resource management and agricultural productivity, particularly through increased floods and droughts. This study investigates the impact of climate change on rainfall patterns in Thailand using long-term data (1965–2024) from 675 stations, with an average record length of 45 years. Rainfall trends are analyzed in terms of amount (annual, seasonal, monthly, and maximum daily rainfall) and occurrence (rainy days, wet spells, and dry spells) using non-parametric statistical methods, including the Mann-Kendall test and Sen’s slope estimator. Statistically significant changes in rainfall trends across Thailand are limited and vary by parameter and region. Positive trends in rainfall amount were rare, with a maximum of 3.4% for annual rainfall, while negative trends were more common, reaching up to 13.6% for maximum 1-day rainfall. For rainfall occurrence, the most frequent positive trend was in the number of rainy days (12.9%), whereas the highest negative trend was 9.8% for wet spells. The most significant rainfall changes in Thailand are found in the Eastern, Southern, and Western regions. Eastern Thailand shows the largest increases in annual and wet season rainfall (about 20.02 and 19.33 mm/year), along with declines of 11.65% and 13.47%. Southern Thailand also shows strong positive trends (~14.68 and 14.54 mm/year), but also notable decreases. It records the most extreme changes in maximum 1-day rainfall and rainy days, with both positive and negative trends. Regional averages are influenced by the number of stations with significant trends.

This study examined extreme rainfall trends across seven return periods using data from 169 stations (1963–2022), employing the Gumbel distribution and a 30-year sliding window. Nationally, the trends were mixed: about half of the stations showed increases (average +23.3%), while the other half showed decreases (average –13.4%). Regionally, the Northeast recorded the largest increase (32.1%), whereas the Central region experienced the greatest decrease. The 100-year return period was used as an example to illustrate the impact of the 30-year sliding window on the results. This focused analysis revealed increasing trends across all regions, with Northern Thailand showing the most consistent pattern and a national average annual increase of 0.25%. These findings indicate that while statistically significant changes in rainfall patterns across Thailand are generally limited, they show clear regional differences, with both increases and decreases observed depending on the metric and location. Notably, extreme rainfall events, particularly those analyzed using a 30-year sliding window, exhibit a consistent upward trend across all regions - especially in Northern Thailand - highlighting the gradual intensification of climate extremes over time.

Keywords: Rainfall pattern; Extreme rainfall trends; Climate change; Mann-Kendall Trend (MK) test; Sen's Slope (SS) test; Sliding window technique; Thailand.

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1. Introduction

Climate change is altering both the amount and the timing of rainfall, leading to longer dry spells and more intense storms in many regions (Trenberth, 2011; Allan et al., 2020). Rising temperatures also increase evaporation and intensify the water cycle, causing more extreme precipitation events (Held & Soden, 2006). These changes challenge water management, agriculture, and disaster planning. Thailand, located in the tropical zone, receives an average annual rainfall of approximately 1,450 mm, with over 85% occurring during a six-month period. This concentrated rainfall is vital for the country's agriculture and irrigation systems (Sriwongsitanon et al., 2023; Kaprom et al., 2025). However, increasing climate variability has resulted in more frequent and intense occurrences of both flooding and drought, posing serious challenges for water resource management. Consequently, accurately analyzing long-term rainfall trends has become essential for effective planning, sustainable water use, and the mitigation of climate-related risks (Sun et al., 2018a; Wang et al., 2020). This highlights the importance of identifying changes in rainfall patterns across Thailand's river basins to support better water management and climate adaptation strategies.

Over recent decades, various statistical methods have been developed to detect trends in rainfall time series, including linear regression, the Mann-Kendall (MK) test, Spearman's rho (SR) test, the Theil-Sen approach (TSA), seasonal Kendall methods, and Sen’s slope (SS) estimator (Asadi et al., 2015; Esterby, 2015; Wang et al., 2016; Sun et al., 2016). Among these, the MK test is the most widely used non-parametric method for identifying monotonic trends in hydroclimatic data due to its robustness against non-normal distributions and missing values (Yue & Wang, 2004; Wang, 2020). To complement this, Sen’s slope estimator is commonly applied to quantify the magnitude of detected trends (Gilbert, 1987). Lee et al. (2020) utilized the Mann-Kendall (MK) test and Sen’s slope estimator to analyze trends in three rainfall indices—R20 (≥20 mm), R50 (≥50 mm), and R100 (≥100 mm)—across the Mekong Delta over a 32-year period. Their findings revealed an insignificant upward trend in R20 in coastal areas and a slight downward trend in inland provinces, indicating spatial variability in extreme rainfall patterns. Similarly, Alahacoon et al. (2021) applied the MK test and Sen’s slope estimator to investigate rainfall trends in Sri Lanka from 1989 to 2019, observing significant increases in annual rainfall across all climatic zones. These studies highlight the importance of employing robust statistical techniques to assess both temporal and spatial rainfall trends, especially in regions susceptible to climate change impacts (Wang et al., 2020; Sun et al., 2018b).

This study uses the Mann-Kendall (MK) test and Sen’s slope (SS) estimator to quantitatively assess long-term rainfall trends, focusing on both rainfall amount and occurrence, using daily data from gauge stations across Thailand. Additionally, the impact of climate change on extreme rainfall events is evaluated by conducting frequency analysis of maximum daily rainfall for different return periods. To capture variations in the trends of extreme rainfall, a sliding window technique is applied, examining how maximum rainfall trends change over time for each return period.

2. Study area

Thailand, situated between latitudes 5°37′N and 20°37′N and longitudes 97°22′E and 105°37′E, covers an area of approximately 514,050 km² and is divided into 22 river basins. The country is geographically classified into six regions: North, Central, Northeast, East, West, and South (see Figure 1). Thailand has a tropical climate characterized by warm temperatures, high humidity, and significant annual rainfall. The climate is influenced by the monsoon, with the wet season from May to October driven by the southwest monsoon, and the dry season from November to April, associated with the northeast monsoon. The average annual rainfall in Thailand is about 1,400 mm, with the southern and eastern regions receiving the highest rainfall amounts. Agriculture plays a vital role in the national economy, with approximately 3.52 million hectares dedicated to irrigated agricultural land. The Chao Phraya River Basin, located in central Thailand, supports the country’s largest irrigated area and is essential for food production and water management (FAO, 2018; Thai Meteorological Department, 2020).

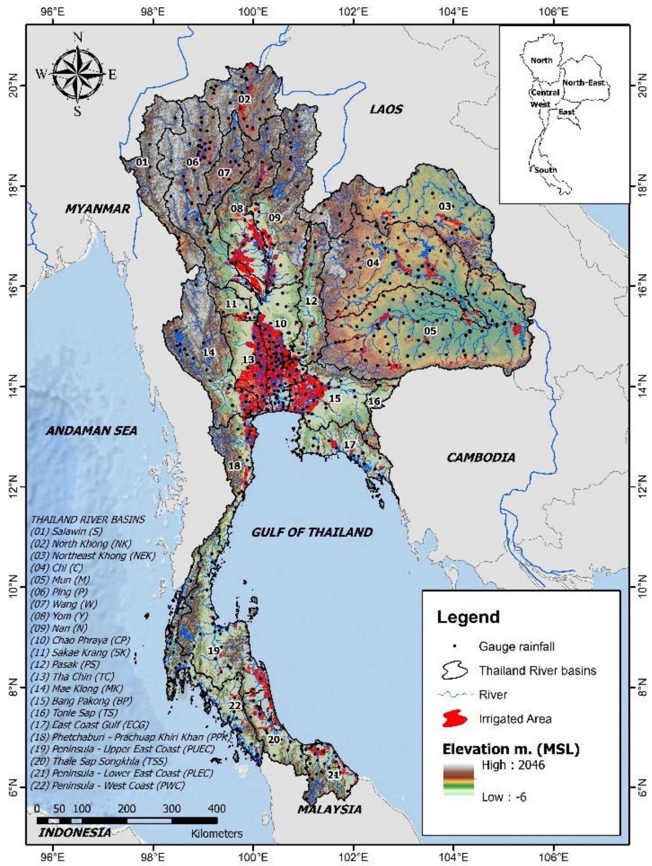


Figure 1. Study area and gauged rainfall data used in this study

3. Method

3.1 Data collection

This study utilized long-term daily rainfall data from the Thailand Meteorological Department (TMD), covering the period from 1965 to 2024 (60 years). A total of 675 rain gauge stations were included, with their locations shown in **Figure 1.** Each station provided at least 30 years of rainfall data, with an average record length of 45 years. The average annual rainfall approximately 1,228, 1,126, 1,360, 1,676, 1,365, and 2,119 mm for the northern, central, eastern, western, and southern regions, respectively, while the national average for Thailand is 1,424 mm. To ensure data reliability, a stepwise quality control process developed by the Remote Sensing Research Centre for Water Resources Management (SENSWAT) was applied. To ensure data reliability, a stepwise quality control process developed by the Remote Sensing Research Centre for Water Resources Management (SENSWAT) was applied. This process was adapted and further developed from the quality control procedure proposed by Hamada et al. (2011). The procedure comprises fourteen steps, organized into three main categories: metadata quality control, accuracy verification of individual station records, and reliability assessment across multiple stations. These categories consist of 2, 10, and 2 steps, respectively. The complete procedure is described in detail by Kaprom et al. (2025).

3.2 Assessing long-term rainfall trends

This study aimed to assess the impact of climate change on rainfall patterns in Thailand by analyzing long-term rainfall data using non-parametric statistical methods, including the Mann-Kendall (MK) test and Sen's slope (SS) estimator. The assessment of long-term rainfall trends is divided into two main categories: rainfall amount and rainfall occurrence. For rainfall amount, five parameters are considered: annual rainfall (R_a), wet season rainfall (R_{wet}), dry season rainfall (R_{dry}), monthly rainfall (R_{mi}), and maximum 1-day rainfall (R_{max}). For rainfall occurrence, three parameters are included: number of rainy days (R_{da}), wet spells (R_{ws}), and dry spells (R_{ds}). Details of these parameters are provided in **Table 1**.

Table 1. List of rainfall parameters used in this study

Index	Parameters	Definitions	Units
R_a	Annual rainfall	Total rainfall each year	mm
R_{wet}	Rainfall in wet season	Total rainfall during wet season each year	mm
R_{dry}	Rainfall in dry season	Total rainfall during dry season each year	mm
R_{day}	Rainy days	Annual count of days with rainfall ≥ 1 mm	days
R_{ws}	Wet spells	Maximum wet spells recorded for each year	days
R_{ds}	Dry spells	Maximum dry spells recorded for each year	days
R_{mi}	Monthly rainfall	Rainfall for a particular month of the year	mm
R_{max}	Maximum 1-day	Annual daily maximum rainfall	mm

The Mann-Kendall (MK) test and Sen's Slope (SS) estimator are widely used to detect both the direction and magnitude of trends in climatic data. The MK test is especially well-suited for identifying monotonic trends in time series data, as it does not require any assumptions about the underlying data distribution. Meanwhile, Sen's Slope provides a robust estimate of the trend magnitude. The theoretical background and equations used in the Mann-Kendall test and Sen's Slope estimator are described below.

3.2.1 Mann-Kendall Trend (MK) test

The Mann–Kendall test (MK) is a widely recognized non-parametric technique used to detect trends in time series data. It is commonly employed to assess long-term trends in various rainfall parameters, such as seasonal, annual, and daily maximum rainfall (Kendall, 1948; Hirsch et al., 1982). The Mann–Kendall statistics are calculated using **Equations (1) and (2)**, as outlined below.

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(x_j - x_i) \tag{1}$$

$$sgn(x_j - x_i) = \begin{Bmatrix} +1, = (x_j - x_i) \\ 0, = \ (x_j - x_i) \\ -1, = (x_j - x_i) \end{Bmatrix} \tag{2}$$

In this case, x_j and x_i represent the sequential data values, and n denotes the total number of data points in the time series. A positive value of S suggests an upward trend, while a negative value indicates a downward trend. When assessing trends in time series data, if the number of data points exceeds 10 (n > 10), the variance of S (Var(S)) is calculated using **Equation (3)**. For cases where n ≤ 10, the procedure follows the method described by Gilbert (1987).

$$Var(s) = \frac{1}{18}[n(n-1)(2n+5) - \sum_{i=1}^{m} t_i(t_i - 1)(2t_i + 5)] \tag{3}$$

where m is the number of tied groups and t_i represents the number of observations in the m^{th} group. Then, Mann– Kendall' s statistics Zc (standard average deviation) for N>10 is computed using **Equation (4)**.

$$Zc = \begin{Bmatrix} \frac{s-1}{\sqrt{Var(s)}} \ if \ S > 0 \\ 0 \qquad if \ S = 0 \\ \frac{s+1}{\sqrt{Var(s)}} \ if \ S < 0 \end{Bmatrix} \tag{4}$$

The test statistic Zc follows a standard normal distribution. A positive value of Zc suggests an upward trend, whereas a negative value indicates a downward trend over the observed period. If the absolute value of Zc exceeds the critical value $Zc \mid z \propto/2$, the null hypothesis (which assumes no trend) is rejected at the selected significance level (commonly α = 0.05). Alternatively, the p-value can be used to assess statistical significance, with a p-value less than 0.05 indicating a significant trend.

3.2.2 Sen's slope (SS) test

The magnitude of the trend detected by the Mann–Kendall (M–K) test can be quantified using Sen's slope estimator. In contrast to traditional linear regression, which assumes a constant linear relationship over time, Sen's method estimates the actual slope of a trend, allowing for variations. Introduced by Sen (1968), this non-parametric approach is widely applied to assess the rate of change in rainfall over time. To calculate Sen's slope, the median of all pairwise slopes between data points is determined, as outlined in **Equation (5)**.

$$T_i = \frac{x_j - x_k}{j-k} \; for \; i = 1,2,3, \ldots .n, j > k \quad (5)$$

where T_i is the slope and x_j and x_k are the data value at time j and k, respectively

3.3 Assessment of extreme rainfall variability using frequency analysis

To investigate the impact of climate change on extreme rainfall events, maximum daily rainfall data were analyzed using the Gumbel distribution to estimate rainfall depths for return periods of 5, 10, 25, 50, 100, 200, and 500 years. Detecting the influence of climate change requires a sufficiently long period of observation. From a total of 675 rain gauge stations, with an average record length of 45 years, only stations with at least 50 years of continuous data were selected. This criterion resulted in a subset of 169 stations. A sliding window technique was applied to examine temporal changes over time. The 50-year data period (1963–2022) was divided into overlapping 30-year windows, with each window shifting forward by one year. In the first iteration, data from 1963 to 1992 were used to estimate rainfall depths for the selected return periods using the Gumbel distribution. The second iteration used data from 1964 to 1993, the third from 1965 to 1994, and so on, until the 31st iteration, which covered the period from 1993 to 2022. This moving window approach allows for the detection of trends in extreme rainfall over time, helping to identify potential changes in both the frequency and intensity of extreme rainfall events. Such changes could significantly impact the design and performance of water resource infrastructure and pose risks to public safety.

4. Results and discussion

4.1 Change in long-term rainfall trends

An assessment of long-term rainfall trends was carried out for 675 rain gauge stations across Thailand, focusing on seven rainfall parameters. The analysis employed the Mann-Kendall (MK) test and Sen's Slope (SS) estimator. A p-value threshold of 0.05 was used to determine the statistical significance of observed trends. **Table 2** presents the number of stations—out of 675 with complete data—exhibiting positive or negative trends, along with their corresponding annual rates of change for the nine rainfall parameters, disaggregated by five regions of Thailand. It also highlights the number and percentage of stations showing statistically significant changes (p-value ≤ 0.05) relative to the full set of 675 stations. Additionally, the table provides the average annual rates for positive and negative trends, as well as the overall average across all parameters. Within the five parameters related to rainfall amount, only a limited number of the 675 stations showed statistically significant positive trends. Specifically, significant trends were observed at 23 stations for annual rainfall (R_a), 14 for wet season rainfall (R_{wet}), 19 for dry season rainfall (R_{dry}), and 15 for maximum 1-day rainfall (R_{max}). These correspond to approximately 3.4%, 2.1%, 2.8%, and 2.2% of all stations, respectively. On the negative trends within these parameters, there are around 6.1%, 7.4%, 1.3%, and 13.6% of all stations showing statistically significant trends. Similarly, for the three rainfall occurrence parameters, only a small number of stations exhibited significant positive trends. Specifically, 87 stations showed significant trends in the number of rainy days (R_{day}), 66 in wet spells (R_{ws}), and 45 in dry spells (R_{ds}), corresponding to approximately 12.9%, 9.8%, and 6.7% of all stations, respectively. On the negative trends within these parameters, there are around 9.2%, 9.8%, and 7.7% of all stations showing statistically significant trends.

Table 2 also presents the annual rate of change for seven rainfall parameters across five regions in Thailand, using a normalized colour scale to facilitate easy comparison. The table indicates that the most significant changes occur in Eastern, Southern, and Western Thailand. Eastern Thailand exhibits the most pronounced positive trends in both annual rainfall (R_a) and wet season rainfall (R_{wet}), with increases of 20.02 mm/year and 19.33 mm/year, respectively. However, it also shows notable negative trends of 11.65% and 13.47%, respectively. Similarly, Southern Thailand exhibits the second most significant positive trends in R_a and R_{wet}, increasing by 14.68 mm/year and 14.54 mm/year, respectively. At the same time, it also shows notable negative trends of 13.54 mm/year and 11.05 mm/year for these parameters. Additionally, Southern Thailand records the most extreme positive trends in maximum 1-day rainfall (R_{max}) and the number of rainy days (R_{day}), with increases of 1.3 mm/year and 0.58 day/year, respectively. It also shows the most extreme negative trends for these parameters, with decreases of 1.16 mm/year for R_{max} and 0.56 day/year for R_{day}. However, the mean annual rate of change for the seven rainfall parameters shown in **Table 2** across the five regions largely depends on the number of stations with statistically significant trends. For example, although Eastern Thailand exhibits the most pronounced positive trends in both annual rainfall (R_a) and wet season rainfall (R_{wet}), these trends are based on only one station showing statistically significant increases and one showing significant decreases. In contrast, Northeastern Thailand also shows positive trends in R_a and R_{wet}, with increases of 10.57 mm/year and 10.20 mm/year, respectively. However, these trends are supported by a larger number of stations, nine with significantly increasing trends and seven with significantly decreasing trends. Given this variability, it is more appropriate to illustrate rainfall trends at the station level, focusing only on stations with statistically significant changes. **Figure 2** presents the annual trends for the seven rainfall parameters at these stations. It also summarizes the number and percentage of stations showing significant changes, along with the average rates of change for positive, negative, and overall trends across the country.

4.2 Impact of climate change in extreme rainfall

To assess temporal changes in extreme rainfall patterns, maximum daily rainfall data from 169 stations, each with at least 50 years of records, were analyzed using the Gumbel distribution. A 30-year sliding window (1963–2022) was applied to estimate rainfall depths for multiple return periods, allowing the identification of trends in rainfall intensity and frequency potentially associated with climate change. The results are presented below at both national and regional levels. Additionally, an example illustrating the impact of the sliding window on variations in maximum rainfall for the 100-year return period across five regions is also provided.

National level

The average maximum daily rainfall depths for each return period, calculated using the Gumbel distribution, are summarized across all of Thailand in **Table 3.** The table presents values from the 1st, 11th, 21st, and 31st iterations, which correspond to the periods 1963-1992, 1973-2002, 1983-2012, and 1993-2022, respectively, for seven return periods: 5, 10, 25, 50, 100, 200, and 500 years. Among the 169 stations, approximately half show increasing trends, while the other half show decreasing trends in maximum rainfall depths over time. For stations with increasing trends, the percentage change in maximum rainfall between the first and last iterations ranges from approximately 14.2% for the 5-year return period to 30.4% for the 500-year return period, with an average change of 23.3% across all seven return periods. In contrast, stations with decreasing trends show reductions of about 11.9% and 14.6% for the 5-year and 500-year return periods, respectively, with an average change of 13.7% across all return periods. These findings demonstrate that the magnitude of increases in maximum rainfall is approximately twice as great as the magnitude of decreases, indicating a stronger overall upward trend where increases occur.

Regional level

To observe changes across different regions of Thailand, **Table 4** presents the average maximum daily rainfall for various return periods across six regions for the 1st and 31st iterations, corresponding to the periods 1963-1992 and 1993-2022, respectively. The number of rainfall stations used in the analysis for each region is as follows: 25, 21, 7, 43, 33, and 40, respectively. A normalized color scale was applied to visualize increasing and decreasing trends in maximum rainfall across seven return periods for each region. The highest maximum daily rainfall across return periods was observed in Southern Thailand, followed by Eastern, Western, Northeastern, and Central regions, with Northern Thailand showing the lowest values. For stations with increasing trends, Northeastern Thailand exhibited the most significant increase in maximum rainfall between the 1st and 31st iterations, with an average change of approximately 32.1%. This was followed by the Southern region, with a 25.9% increase. The Western region showed the smallest increase, averaging only 0.8%. Conversely, among stations showing decreasing trends, Central Thailand experienced the greatest reduction in maximum rainfall, with an average decrease of 16.1%, followed closely by the Southern region at 15.1%. The smallest decreases were observed in the Northern and Western regions, with similar values of 10.6% and 11.2%, respectively.

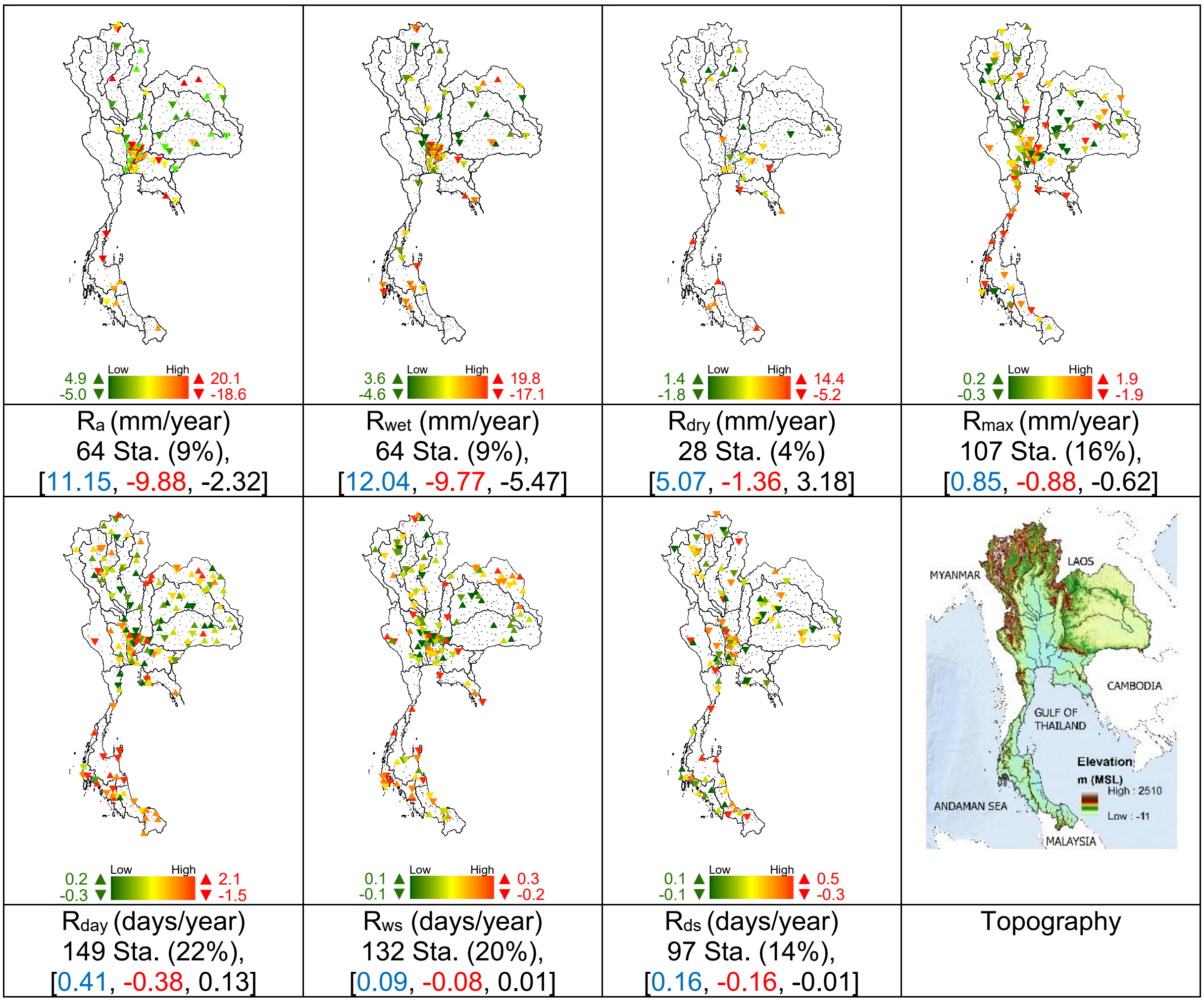
Table 2. Number of stations showing positive and negative trends among 675 total stations and their mean annual rate of change in seven rainfall parameters across five regions of Thailand

Parameter	Significant station (%)	Avg. trend	Mean annual rate of change						
			Northern	Central	North-Eastern	Eastern	Western	Southern	Thailand
R_a	23 (3.4%)	▲	11.13 (4)	9.03 (6)	10.57 (9)	20.02 (1)	-	14.68 (3)	11.15
(mm)	41 (6.1%)	▼	-10.90 (4)	-11.06 (21)	-7.44 (9)	-11.65 (3)	-	-13.54 (4)	-9.88
	64 (9.5%)	•	0.12 (8)	-6.6 (27)	1.56 (18)	-3.73 (4)	-	-1.44 (7)	-2.72
R_{wet}	14 (2.1%)	▲	10.2 (2)	7.29 (3)	10.2 (7)	19.33 (1)	-	14.54 (1)	10.42
(mm)	50 (7.4%)	▼	-9.98 (5)	-9.38 (24)	-7.29 (8)	-13.47 (2)	-6.45 (1)	-11.05 (10)	-9.31
	64 (9.5%)	•	-4.22 (7)	-7.53 (27)	0.87 (15)	-2.54 (3)	-6.45 (1)	-8.72 (11)	-5.15
R_{dry}	19 (2.8%)	▲	2.12 (7)	3.39 (3)	2.32 (1)	3.55 (3)	-	9.39 (5)	3.67
(mm)	9 (1.3%)	▼	-	-2.29 (3)	-2.43 (3)	-3.50 (3)	-	-	-1.36
	28 (4.1%)	•	2.12 (7)	0.55 (6)	-1.24 (4)	0.02 (6)	-	9.39 (5)	2.15
R_{max}	15 (2.2%)	▲	0.60 (5)	1.02 (2)	0.78 (2)	-	1.25 (1)	1.30 (5)	0.85
(mm)	92 (13.6%)	▼	-0.76 (15)	-0.89 (35)	-0.70 (22)	-1.20 (4)	-1.01 (7)	-1.16 (9)	-0.88
	107 (15.9%)	•	-0.42 (20)	-0.79 (37)	-0.57 (24)	-1.2 (4)	-0.73 (8)	-0.28 (14)	-0.62
R_{day}	87 (12.9%)	▲	0.34 (19)	0.40 (12)	0.36 (34)	0.42 (6)	0.49 (2)	0.58 (14)	0.41
(days)	62 (9.2%)	▼	-0. 36 (12)	-0.41 (18)	-0.28 (13)	-0.31 (4)	-0.35 (3)	-0.56 (12)	-0.38
	149 (22.1%)	•	0.16 (31)	-0.10 (30)	0.32 (47)	0.18 (10)	-0.30 (5)	0.08 (26)	0.13
R_{ws}	66 (9.8%)	▲	0.07 (13)	0.10 (11)	0.07 (24)	0.08 (3)	0.15 (4)	0.10 (11)	0.09
(days)	66 (9.8%)	▼	-0.06 (16)	-0.06 (23)	-0.06 (8)	-0.11 (4)	-0.23 (1)	-0.09 (14)	-0.08
	132 (19.6%)	•	-0.01	-0.01	0.04	-0.03	0.08	-0.01	0.01
R_{ds}	45 (6.7%)	▲	0. 15 (5)	0.20 (16)	0.15 (4)	0.10 (1)	0.11 (2)	0.18 (17)	0.16
(days)	52 (7.7%)	▼	-0.15 (15)	-0.15 (8)	-0.13 (18)	-0.11 (3)	-0.29 (4)	-0.20 (4)	-0.16
	97 (14.4%)	•	-0.07 (20)	0.08 (24)	-0.08 (22)	-0.06 (4)	-0.16 (6)	0.11 (21)	-0.01

Note: "Significant stations" refer to those exhibiting statistically significant changes (p-value ≤ 0.05). Percentages indicate the proportion of these stations relative to a total of 675 stations. ▲ represents the average of positive trend values, ▼ indicates the average of negative trend values, and • denotes the overall average of all values.

Sliding window impact on 100-Year maximum rainfall variations

Since a 30-year sliding window was applied to analyze maximum rainfall depths for seven return periods, **Figure 3** illustrates the percentage change in average maximum rainfall depth for the 100-year return period from the 1st to the 31st iteration across 169 stations distributed across five regions of Thailand. The figure also includes the regression equations and Sen's slope estimates for each of the five regions, as well as for Thailand as a whole. The figure shows that all regions exhibit an increasing trend in average maximum rainfall over the 31 iterations, each representing a 30-year period. Among the regions, Northern Thailand displays the least fluctuation between consecutive iterations, as indicated by a high coefficient of determination (R^2) of 0.9194. In contrast, the Eastern, Central, Northeastern, Western, and Southern regions show lower R^2 values of 0.5650, 0.6213, 0.6728, 0.7078, and 0.7501, respectively. For Thailand as a whole, the R^2 value is notably high at 0.9418, suggesting a consistent national trend. Additionally, Sen's slope estimates were calculated to assess the rate of change. The annual increase in average maximum rainfall ranges from 0.23% in the Eastern region to 0.32% in the Central region, showing relatively small differences across regions. For the entire country, the Sen's slope indicates an average annual increase of 0.25%.



Note: "64 Sta. (9%)" indicates the number and percentage of stations that show statistically significant trends. The values [11.15, -9.88, -2.32] represent the average rates of change for positive trends, negative trends, and overall trends across Thailand, respectively.

Figure 2. Annual trends of seven rainfall parameters, showing the number and percentage of stations with significant changes, along with the average rates of positive, negative, and overall trends across the country.

Table 3. Average maximum daily rainfall depths for each return period across 169 stations for the 1st, 11th, 21st, and 31st iterations

Period	Avg.	R_{tr} for each return period (mm)							
		5 yr.	10 yr.	25 yr.	50 yr.	100 yr.	200 yr.	500 yr.	Average
1963-1992	R	126.6	147.4	173.7	193.2	212.6	231.8	257.3	191.8
1973-2022	R	126.9	147.9	174.6	194.3	213.9	233.5	259.2	192.9
	▲	7.2%	8.8%	10.2%	10.3%	10.7%	11.2%	11.9%	10.0%
	sta.	(80)	(79)	(80)	(86)	(89)	(90)	(90)	(85)
	▼	-5.9%	-6.4%	-7.1%	-8.0%	-8.7%	-9.1%	-9.5%	-7.8%
	sta.	(89)	(90)	(89)	(83)	(80)	(79)	(79)	(84)
	•	0.3%	0.7%	1.1%	1.3%	1.5%	1.7%	1.9%	1.2%
1983-2012	R	129.3	151.1	178.7	199.2	219.6	239.8	266.5	197.7
	▲	11.7%	13.5%	16.5%	17.8%	18.6%	19.8%	21.2%	17.0%
	sta.	(89)	(93)	(90)	(91)	(93)	(92)	(91)	(91)
	▼	-8.0%	-9.6%	-10.5%	-11.3%	-12.2%	-12.5%	-12.9%	-11.0%
	sta.	(80)	(76)	(79)	(78)	(76)	(77)	(78)	(78)
	•	2.4%	3.1%	3.9%	4.4%	4.7%	5.1%	5.5%	4.2%
1993-2022	R	129.9	152.0	179.9	200.6	221.1	241.6	268.6	199.1
	▲	14.2%	17.7%	21.6%	24.0%	26.9%	28.3%	30.4%	23.3%
	sta.	(97)	(93)	(89)	(87)	(83)	(83)	(82)	(88)
	▼	-11.9%	-12.5%	-13.2%	-13.7%	-13.7%	-14.2%	-14.6%	-13.4%
	sta.	(72)	(76)	(80)	(82)	(86)	(86)	(87)	(81)
	•	3.1%	4.1%	5.1%	5.7%	6.2%	6.7%	7.2%	5.4%

Note: R represents the maximum rainfall depth for each return period. ▲ indicates the percentage increase in maximum rainfall for the 11th, 21st, and 31st iterations compared to the 1st iteration, while ▼ indicates the percentage decrease over the same periods. Numbers in parentheses denote the number of stations showing increasing or decreasing maximum rainfall depths.

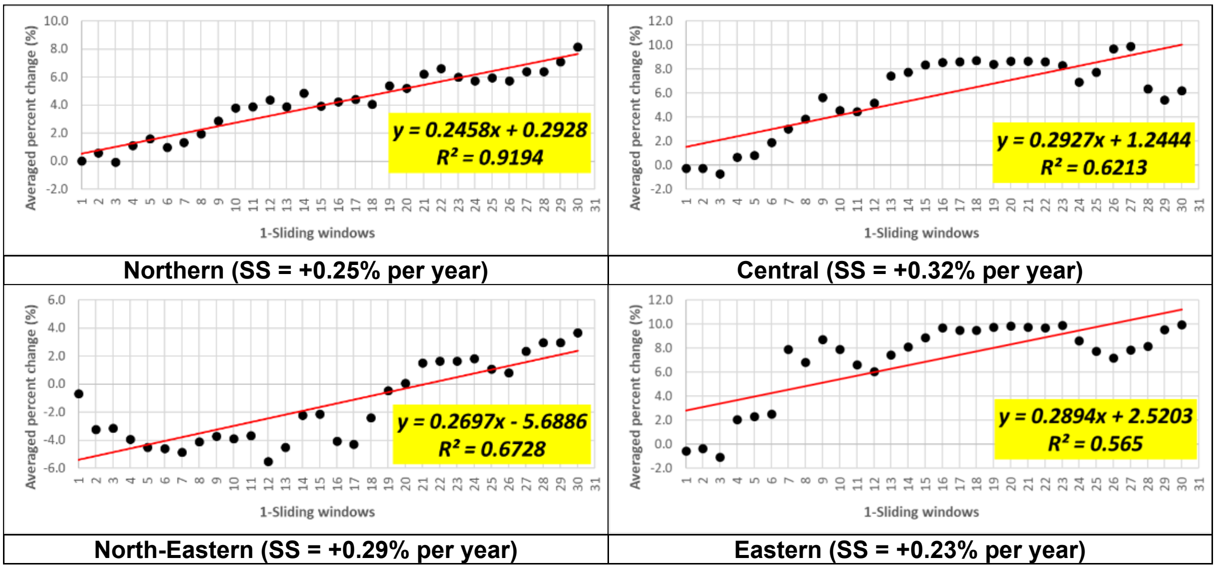
Table 4. Average maximum daily rainfall depths for each return period across six regions of Thailand during the 1st and 31st iterations

Region	Avg.	R_{tr} for each return period (mm)							
		5 yr.	10 yr.	25 yr.	50 yr.	100 yr.	200 yr.	500 yr.	Average
Northern	R_{itr1}	103.8	119.4	139.1	153.7	168.2	182.6	201.7	152.6
(40 stations)	R_{itr31}	109.2	126.2	147.6	163.6	179.4	195.1	215.9	162.4
	▲	11.5%	14.7%	16.7%	17.9%	20.6%	21.6%	22.8%	18.0%
	sta.	(29)	(26)	(26)	(26)	(24)	(24)	(24)	(26)
	▼	-9.9%	-9.0%	-10.5%	-11.3%	-10.5%	-11.1%	-11.7%	-10.6%
	sta.	(11)	(14)	(14)	(14)	(16)	(16)	(16)	(14)
	•	5.60%	6.40%	7.20%	7.70%	8.10%	8.50%	9.00%	7.50%
Central	R_{itr1}	115.2	134.6	159.1	177.3	195.4	213.4	237.1	176.0
(33 stations)	R_{itr31}	113.3	135.1	162.6	183	203.3	223.5	250.1	181.6
	▲	14.1%	18.4%	23.1%	25.9%	28.2%	30.1%	34.4%	24.9%
	sta.	(16)	(16)	(16)	(16)	(16)	(16)	(15)	(16)
	▼	-15.0%	-15.1%	-15.8%	-16.4%	-16.8%	-17.1%	-16.6%	-16.1%
	sta.	(17)	(17)	(17)	(17)	(17)	(17)	(18)	(17)
	•	-0.90%	1.10%	3.00%	4.10%	5.00%	5.80%	6.60%	3.53%
North-	R_{itr1}	124.6	144.7	170.1	189	207.8	226.4	251.1	187.7
Eastern	R_{itr31}	126.1	146.9	173.2	192.7	212.1	231.4	256.8	191.3
(43 stations)	▲	15.4%	19.8%	27.6%	36.3%	39.3%	41.8%	44.6%	32.1%
	sta.	(23)	(22)	(19)	(16)	(16)	(16)	(16)	(18)
	▼	-12.5%	-13.6%	-13.5%	-12.9%	-13.6%	-14.2%	-14.9%	-13.6%
	sta.	(20)	(21)	(24)	(27)	(27)	(27)	(27)	(25)
	•	2.40%	3.50%	4.70%	5.40%	6.10%	6.60%	7.30%	5.14%

Table 4. Average maximum daily rainfall depths for each return period across six regions of Thailand during the 1st and 31st iterations (Con.)

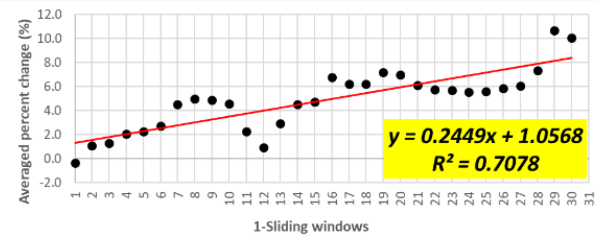
Region	Avg.	R_{tr} for each return period (mm)							
		5 yr.	10 yr.	25 yr.	50 yr.	100 yr.	200 yr.	500 yr.	Average
Eastern (21 stations)	R_{itr1}	140.3	162.3	190	210.5	230.9	251.3	278.1	209.1
	R_{itr31}	141.5	164.8	194.3	216.2	237.8	259.5	288	214.6
	▲	10.6%	13.6%	16.5%	18.2%	21.6%	23.0%	24.5%	18.3%
	sta.	(11)	(11)	(11)	(11)	(10)	(10)	(10)	(11)
	▼	-10.0%	-11.5%	-12.7%	-13.4%	-12.7%	-13.1%	-13.6%	-12.4%
	sta.	(10)	(10)	(10)	(10)	(11)	(11)	(11)	(10)
	•	0.80%	1.70%	2.60%	3.10%	3.60%	4.10%	4.50%	2.91%
Western (7 stations)	R_{itr1}	128.8	154.3	186.6	210.5	234.3	258	289.2	208.8
	R_{itr31}	117.5	139.2	166.7	187.1	207.3	227.4	254	185.6
	▲	2.0%	1.2%	1.3%	0.8%	0.4%	0.0%	0.2%	0.8%
	sta.	(2)	(2)	(1)	(1)	(1)	(1)	(1)	(1)
	▼	-11.0%	-11.8%	-10.5%	-10.9%	-11.2%	-11.4%	-11.8%	-11.2%
	sta.	(5)	(5)	(6)	(6)	(6)	(6)	(6)	(6)
	•	-7.30%	-8.10%	-8.80%	-9.20%	-9.50%	-9.80%	-10.10%	-8.97%
Southern (25 stations)	R_{itr1}	169.8	199.6	237.3	265.2	292.9	320.5	357	263.2
	R_{itr31}	185.3	217.1	257.4	287.3	317	346.5	385.5	285.2
	▲	21.9%	23.7%	25.5%	25.0%	27.5%	28.3%	29.2%	25.9%
	sta.	(16)	(16)	(16)	(17)	(16)	(16)	(16)	(16)
	▼	-9.7%	-12.1%	-14.2%	-17.3%	-16.4%	-17.4%	-18.3%	-15.1%
	sta.	(9)	(9)	(9)	(8)	(9)	(9)	(9)	(9)
	•	10.50%	10.80%	11.20%	11.50%	11.70%	11.90%	12.10%	11.39%

Note: R_{itr1} and R_{itr31} represents the maximum rainfall depth for the 1st and 31st iterations. ▲ indicates the percentage increase in maximum rainfall for the 11th, 21st, and 31st iterations compared to the 1st iteration, while ▼ indicates the percentage decrease over the same periods. Numbers in parentheses denote the number of stations showing increasing or decreasing maximum rainfall depths.

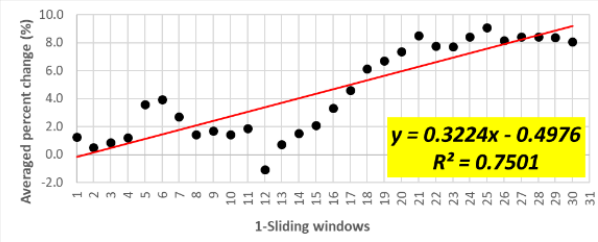


Note: SS denotes Sen's slope calculated for each region and for Thailand as a whole.

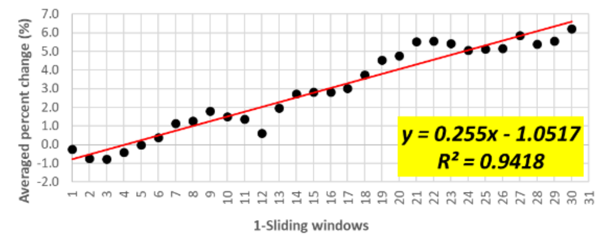
Figure 3. Variation of the percentage change of average maximum rainfall depth for the 100-year return period from the 1st to the 31st iteration across 169 stations distributed across five regions in Thailand



Western (SS = +0.24% per year)



Southern (SS = +0.32% per year)



Thailand (SS = +0.25% per year)

Note: SS denotes Sen's slope calculated for each region and for Thailand as a whole.

Figure 3. Variation of the percentage change of average maximum rainfall depth for the 100-year return period from the 1st to the 31st iteration across 169 stations distributed across five regions in Thailand (Con.)

5. Conclusions

This study presents a comprehensive analysis of how climate change has influenced rainfall patterns across Thailand, using long-term data from 675 stations covering the period 1965 to 2024. It examines both rainfall amount (annual, seasonal, monthly, and maximum daily) and rainfall occurrence (rainy days, wet spells, and dry spells) using robust non-parametric statistical methods, including the Mann-Kendall test and Sen's slope estimator.

Overall, statistically significant trends in rainfall are relatively limited but show clear regional variation. Decreasing trends in rainfall amount, particularly in extreme events such as maximum daily rainfall, are more common than increasing ones. In contrast, rainfall occurrence indicators, such as the number of rainy days, show more frequent increases, although wet spells are generally decreasing.

The most notable changes are observed in Eastern, Southern, and Western Thailand. The Eastern region shows the largest increases in both annual and wet season rainfall, while the Southern region experiences both significant increases and decreases, especially in maximum daily rainfall and the frequency of rainy days.

In addition, the study investigates trends in extreme rainfall using data from 169 stations (1963-2022), applying the Gumbel distribution and a 30-year sliding window. At the national level, the trends are mixed, with roughly half the stations showing increases and the other half showing decreases. Regionally, the Northeast exhibits the strongest increasing trend, whereas the Central region shows the most notable decline. However, a detailed analysis of the 100-year return period - used to illustrate the effect of the sliding window - reveals a consistent upward trend in extreme rainfall across all regions, with Northern Thailand showing the most stable and steady increase. This highlights the usefulness of the sliding window method in detecting long-term, gradual shifts in climate extremes.

These findings underscore the need for region-specific climate adaptation strategies and ongoing monitoring to effectively respond to the evolving risks associated with changing rainfall patterns and intensifying hydrological extremes in Thailand.

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