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M Murugan

murugankarthick796@gmail.com

Bidhan Chandra Krishi Viswavidyalaya

Banjul Bhattacharyya

Bidhan Chandra Krishi Viswavidyalaya

B Santhoshkumar

Bidhan Chandra Krishi Viswavidyalaya

S Vivek Menon

Bidhan Chandra Krishi Viswavidyalaya

Gautam Saha

Bidhan Chandra Krishi Viswavidyalaya

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Spatiotemporal Exploration of Rainfall and Extreme Rainfall Indices in Two High-Risk Agro-Climatic Zones of West Bengal

M Murugan[1*], Banjul Bhattacharyya[2], B Santhoshkumar[3], S Vivek Menon[4], Gautam Saha[5]

[1] PG Scholar, Department of Agricultural Meteorology and Physics, Bidhan Chandra Krishi Viswavidhyalaya, West Bengal, India-741252.

[2]Professor, Department of Agricultural Statistics, Bidhan Chandra Krishi Viswavidhyalaya, West Bengal, India -741252.

[3]Ph. D. Scholar, Department of Agricultural Meteorology and Physics, Bidhan Chandra Krishi Viswavidhyalaya, West Bengal, India-741252.

[4]Ph. D. Scholar, Department of Agricultural Statistics, Bidhan Chandra Krishi Viswavidhyalaya, West Bengal, India -741252.

[5]Professor and Head, Department of Agricultural Meteorology and Physics, Bidhan Chandra Krishi Viswavidhyalaya, West Bengal, India-741252.

*Corresponding author : murugankarthick796@gmail.com

Author Name	ORCID
M Murugan	https://orcid.org/0009-0001-3488-9616
Banjul Bhattacharyya	https://orcid.org/0000-0001-7473-4726
B Santhoshkumar	https://orcid.org/0009-0006-4200-1548
S Vivek Menon	https://orcid.org/0000-0001-9074-5652
Gautam Saha	-

Abstract

This study investigates the variability and trends of rainfall and extreme rainfall indices across the Red and Laterite Zone (RLZ) and Coastal Saline Zone (CSZ) of West Bengal during 1901–2024 using IMD gridded data. Descriptive statistics indicate strong seasonal dominance of monsoon (JJAS) rainfall with comparatively lower variability while other seasons exhibit higher fluctuations. Trend analysis using Mann–Kendall (MK) and Modified Mann–Kendall (MMK) tests show largely non-significant annual and winter (DJF) trends whereas pre-monsoon (MAM) and monsoon seasons reveal localized significant increases particularly in Jhargram (Sen's slope ≈ 1.435 mm/year in JJAS). Coastal districts display stronger positive trends with South 24 Parganas recording a notable annual increase (Sen's slope ≈ 2.773 mm/year) highlighting enhanced rainfall accumulation in CSZ. Change point analysis using Pettitt and Buishand tests identifies temporal shifts primarily during the late 1960s–1980s in RLZ and earlier (1930s–1950s) in CSZ. Extreme rainfall indices (ETCCDI) reveal intensification in

rainfall characteristics especially over coastal regions. Significant increases in magnitude are evident from R95p values reaching up to ~1.519 mm/year in Purba Medinipur while intensity indices (RX1day, RX5day, SDII) also show consistent positive trends. Frequency indices (R10mm, R20mm) indicate rising occurrences of heavy rainfall days particularly during JJAS. Persistence analysis suggests decreasing consecutive wet days (CWD) and increasing dry spells (CDD) in inland districts pointing to enhanced intra-seasonal variability. The findings show a shift toward more intense, irregular and spatially heterogeneous rainfall regimes with stronger signals in CSZ. These changes carry important implications for water resource management, agricultural stability and climate adaptation strategies in Eastern India.

Keywords : Rainfall variability; ETCCDI Indices; extreme events ; rainfall trend ; red and laterite zone ; coastal saline zone ; trend analysis

1. Introduction

South Asian summer monsoon is the main hydroclimatic system that regulates water availability, agricultural productivity and socio-economic stability across the Indian subcontinent (Lal, 2011). Its Long-term stability is gradually declining due to anthropogenic climate change which leads to significant changes in rainfall magnitude, variability and distribution. Recent evidence indicates that weak significant decline in total monsoon rainfall across parts of eastern India, including West Bengal and Bihar over recent decades (World Bank Group, 2021). The monsoon system is undergoing structural changes with decreasing seasonal rainfall, increased variability and more irregular rainfall patterns. The timing is becoming uneven and extreme events are becoming stronger and more frequent. (Singh et al., 2019). Decline in mean rainfall along with the increase in extremes has become a key feature of monsoon variability.

A key sign of this change is a shift toward fewer rainfall events but higher intensity precipitation (Trenberth et al., 2003). Studies show that extreme rainfall events exceeding 150 mm per day have increased by nearly 75% over central India since 1950 which are largely driven by enhanced atmospheric moisture under warming conditions (Krishnan et al., 2020). This intensification aligns with the Clausius–Clapeyron relationship which governs the increase in atmospheric moisture-holding capacity with temperature. Decline in light and moderate rainfall events has resulted in greater rainfall unpredictability and longer dry spells within the monsoon season (World Bank Group, 2021). Similar patterns have been observed where extreme precipitation contributes an increasing fraction of total rainfall and event duration declines which indicates a transition toward short-duration, high-intensity rainfall regimes at the global scale (Li et al., 2024). These changes significantly increase the risk of hydrological hazards including flash floods and droughts occurring within the same season (Gimeno et al., 2022).

India's rainfall system shows large spatial and temporal variability with the Indian Summer Monsoon contributing nearly 75–80% of annual precipitation (Kushwaha et al., 2024) . The long-term trends in mean rainfall is remaining weak at the national scale significant changes have been observed in rainfall extremes and distribution patterns (Jain et al., 2023). In many areas, including eastern India, rainfall is becoming more irregular with declining rainy days and increasing intensity of extreme events (S. K. Dash et al., 2009). Importantly, climate change signals are often more pronounced in extreme events than in mean rainfall as extremes respond more sensitively to atmospheric warming and variability (Mondal & Mujumdar, 2015). Studies further confirm that both the frequency and intensity of extreme precipitation events are increasing under anthropogenic warming with significant implications for flooding, agriculture and infrastructure (Mukherjee et al., 2018).

The spatiotemporal variability of rainfall in eastern India is governed by a complex interaction of large-scale climatic drivers and regional factors. Teleconnections associated with sea surface temperature anomalies, including the El Niño–Southern Oscillation and Pacific Warm Pool expansion, significantly influence precipitation variability and extremes across the region (Vinod & Mahesha, 2024). Localized factors such as land use changes, urbanization, physiography and elevation gradients also contribute to spatial heterogeneity in rainfall patterns (Pielke Sr. et al., 2007). These interacting drivers result in non-uniform trends where some regions experience intensified rainfall extremes while others show declining or highly variable rainfall patterns.

West Bengal represents a climatically diverse region with distinct agro-climatic zones particularly the Red and Lateritic Zone (RLZ) and the Coastal Saline Zone (CSZ). The RLZ is characterized by undulating terrain, low soil moisture retention and higher susceptibility to rainfall deficits and intra-seasonal droughts (Banerjee et al., 2012) . In contrast, the CSZ is influenced by the Bay of Bengal which experiences higher rainfall, increased humidity and greater exposure to cyclonic disturbances (Samanta, 2018) . Extreme rainfall events in coastal regions are often associated with monsoon depressions and cyclones which can produce exceptionally high rainfall amounts, sometimes exceeding 800 mm within 24 hours (Gore et al., 2006). As a result, Coastal regions are more prone to flooding and waterlogging and inland regions of RLZ are more vulnerable to rainfall variability and drought conditions.

Recent studies show that rainfall systems are changing with higher intensity, shorter duration and longer dry gaps. The reduction in consecutive wet days alongside changes in dry spell duration suggests a shift from prolonged rainfall events to short-duration high-intensity bursts. This pattern reflects a broader transition toward occasional rainfall events where extreme events contribute a larger proportion of total rainfall (Li et al., 2024). Similar trends have been observed across India where extreme rainfall is increasing even in regions with stable or declining mean rainfall (Mukherjee et al.,

2018). These changes have significant consequences on hydrological processes which increase the likelihood of both floods and droughts within the same climatic system.

Despite extensive research on rainfall variability and extremes, several gaps still remain. Most studies focus on large national or regional scales and often miss zone-specific differences within smaller areas. There is also limited work that combines total rainfall trends, extreme rainfall indices and structural changes in a single framework. Seasonal analysis of rainfall variation is still limited, especially for pre-monsoon (MAM), monsoon (JJAS), post-monsoon (ON) and winter (DJF) periods. The use of change point detection along with trend analysis is also not common, particularly for agro-climatic zones like RLZ and CSZ. Recent anomalies, including the 12% monsoon rainfall deficit observed in East and Northeast India in 2024 (India Meteorological Department, 2024) additionally highlight the need for detailed spatiotemporal investigations in this region.

The present study aims to investigate the spatiotemporal variability of rainfall and extreme rainfall indices across multiple seasons in the Red and Lateritic Zone and Coastal Saline Zone of West Bengal. The study integrates statistical analysis of rainfall characteristics, non-parametric trend detection using Mann–Kendall and Modified Mann–Kendall tests, magnitude estimation using Sen's slope and structural shift detection using Pettitt and Buishand tests. In addition, extreme rainfall indices are analyzed to understand changes in rainfall intensity, frequency and persistence. The novelty of this study lies in its zone-specific, seasonally resolved and integrated approach, combining total rainfall, extremes and structural changes within the same framework. This comprehensive analysis provides critical insights into evolving rainfall regimes and supports the development of targeted adaptation strategies for agriculture, water resource management and climate resilience in this agroclimatic zones.

2. Materials and Methods

2.1. Study area

The present study focuses on two different agro-climatic zones of West Bengal, India namely the Red and Laterite Zone (RLZ) and the Coastal Saline Zone (CSZ) which together represent distinct hydroclimatic and physiographic settings within the eastern Indian monsoon domain. The study area map and the grid points used in the study is presented below in **Fig. 1.** The Red and Laterite Zone which is located in the western part of the state includes districts such as Bankura, Birbhum, Jhargram, Paschim Bardhaman, Paschim Medinipur and Purulia. This region is characterized by undulating terrain, lateritic soils with low moisture retention and relatively lower annual rainfall, making it highly susceptible to rainfall variability and prolonged dry spells. Whereas, the Coastal Saline Zone lies along the southern fringe of West Bengal including districts such as South 24 Parganas and Purba Medinipur. This zone is influenced by the Bay of Bengal receiving comparatively higher rainfall and experiencing frequent cyclonic disturbances, tidal flooding and salinity intrusion. The hydroclimatic regimes of these two zones are governed by the Indian Summer Monsoon with major rainfall occurring during the June–

September (JJAS) period. The comparison of a drought-prone inland zone and a flood-prone coastal zone within the same monsoonal system provides a unique framework to examine spatial heterogeneity in rainfall variability and extreme precipitation characteristics in the high risk agroclimatic zone.

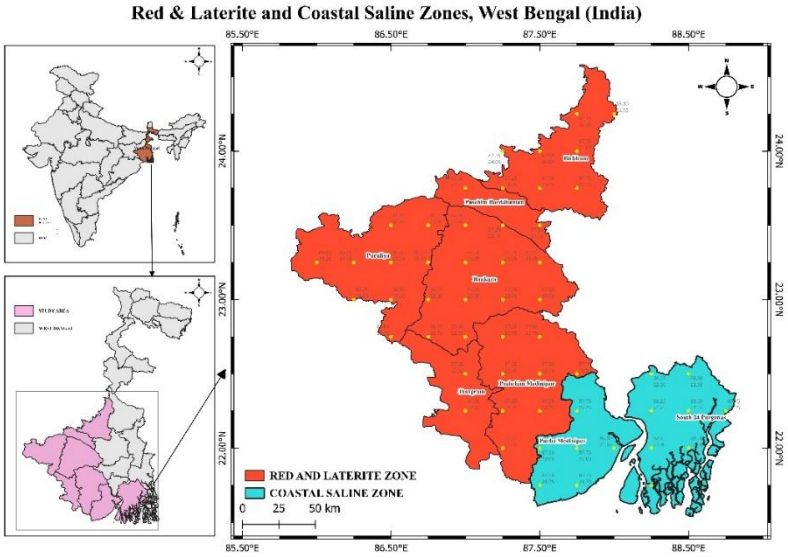


Fig. 1 Study area

2.2. Data used

The data used in the study is gridded rainfall data at a spatial resolution of 0.25° × 0.25°, spanning the period 1901–2024 were obtained from the India Meteorological Department (IMD)(Pai et al., 2014). This high-resolution dataset is widely recognized for its reliability in long-term hydroclimatic assessments over India. The daily rainfall records were extracted for the study region and converted into seasonal and annual time series to conduct further analysis. Seasonal classification was carried out following the standard climatological divisions of India , winter (December–February), pre-monsoon (March–May), monsoon (June–September) and post-monsoon (October–November). The processed dataset formed the basis for variability analysis, trend detection, change point assessment and the computation of extreme rainfall indices across both grid and district scales.

2.3. Extreme rainfall indices

Extreme rainfall characteristics were assessed using eight precipitation indices based on the Expert Team on Climate Change Detection and Indices (ETCCDI) framework derived from daily rainfall data for the period 1901–2024. The indices represent different dimensions of extremes, including intensity (Rx1day, Rx5day, SDII), frequency (R10mm, R20mm), persistence (CWD, CDD) and magnitude (R95p). All indices were computed at the grid level and aggregated to the district scale for comparative analysis and easy interpretation. The definition of all the indices used in the study is mentioned below in the **Table 1**.Temporal trends were evaluated using the Modified Mann–Kendall

(MMK) test to account for serial correlation and Sen's slope estimator was used to quantify the rate of change with statistical significance assessed at the 5% level.

Table 1. Definition of extreme rainfall indices used in the study

Index	Name	Definition and Unit
Rx1day	Max 1-day rainfall	Annual maximum 1-day precipitation (mm)
Rx5day	Max 5-day rainfall	Annual maximum consecutive 5-day precipitation (mm)
SDII	Simple Daily Intensity Index	Total rainfall divided by number of wet days (mm/day)
R10mm	Heavy rainfall days	Number of days with rainfall ≥ 10 mm (Days)
R20mm	Very heavy rainfall days	Number of days with rainfall ≥ 20 mm (Days)
R95p	Very wet days	Annual total rainfall from days > 95th percentile (mm)
CWD	Consecutive wet days	Maximum number of consecutive days with rainfall ≥ 1 mm (Days)
CDD	Consecutive dry days	Maximum number of consecutive days with rainfall < 1 mm (Days)

2.4. Descriptive statistics

Descriptive statistical measures were employed to summarize and understand the fundamental characteristics of the rainfall over the study area. These included measures are mean, standard deviation and coefficient of variation (CV). These metrics provide a comprehensive overview of the magnitude and variability properties of rainfall across temporal scales.

2.5. Trend Detection and Change Point Analysis

2.5.1. Mann–Kendall (MK) Test

The Mann–Kendall (MK) (Mann, 1945) test is a non-parametric method used to detect the presence of a monotonic trend in a time series without requiring normality. For a time series $x_1, x_2, \ldots, x_n$, the test statistic $S$is computed as:

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

where the sign function is defined as:

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

For large samples ($n > 10$), $S$is approximately normally distributed with mean:

$$E(S) = 0$$

and variance:

$$Var(S) = \frac{n(n-1)(2n+5) - \sum t_p(t_p-1)(2t_p+5)}{18}$$

where $t_p$is the number of ties.

The standardized test statistic $Z$is computed as:

$$Z = \begin{cases} \frac{S-1}{\sqrt{Var(S)}}, & S > 0 \\ 0, & S = 0 \\ \frac{S+1}{\sqrt{Var(S)}}, & S < 0 \end{cases}$$

A positive (negative) Z indicates an increasing (decreasing) trend.

2.5.2. Modified Mann–Kendall (MMK) Test

The MK test assumes independence of observations; however, hydroclimatic data often exhibit serial correlation. The Modified Mann–Kendall (MMK) test corrects the variance of $S$to account for autocorrelation.

The corrected variance is given by:

$$Var^*(S) = Var(S) \times \frac{n}{n^*}$$

where $n^*$is the effective sample size:

$$n^* = \frac{n}{1 + 2\sum_{k=1}^{n-1}\left(1 - \frac{k}{n}\right)\rho_k}$$

Here, $\rho_k$is the autocorrelation coefficient at lag k.

The standardized statistic $Z$is then recalculated using $Var^*(S)$, providing a more reliable assessment of trend significance in autocorrelated series.

2.5.3. Sen's Slope Estimator

The magnitude of the trend was estimated using Sen's slope (Sen, 1968), a non-parametric method that calculates the median of all pairwise slopes:

$$Q_i = \frac{x_j - x_i}{j - i}, \forall\, j > i$$

The Sen's slope $Q$is:

194 $$Q = \text{median}(Q_i)$$

195 This estimator is robust against outliers and provides the rate of change in rainfall (e.g., millimetres per
196 year).

197 **2.5.4. Pettitt Test**

198 The Pettitt test (Pettitt, 1979) is a rank-based non-parametric method used to detect a single change
199 point in a time series. The test statistic U_t is defined as:

201 $$U_t = \sum_{i=1}^{t} \sum_{j=t+1}^{n} \text{sgn}(x_j - x_i)$$

200

202 The change point K corresponds to:

204 $$K = \arg\max |U_t|$$

203 The significance level (p-value) is approximated by:

205 $$p \approx 2\exp\left(\frac{-6K^2}{n^3 + n^2}\right)$$

206 A significant K indicates an abrupt shift in the median of the time series.

207 **2.5.5. Buishand Range Test**

208 The Buishand test (Buishand, 1982) detects shifts in the mean of a time series using cumulative
209 deviations. The adjusted cumulative deviation is given by:

210 $$S_k = \sum_{i=1}^{k} (x_i - \bar{x}), k = 1,2,\ldots,n$$

211 where $\bar{x}$ is the mean of the series.

212 The rescaled range statistic R is:

213 $$R = \max(S_k) - \min(S_k)$$

214 The test statistic is:

215 $$Q = \frac{R}{s}$$

216 where s is the standard deviation.

A significant Q indicates a shift in the mean rainfall regime.

3. Result and Discussion

3.1. Statistical summary

The statistical summary of rainfall in various season across both the zones is listed in the **Table 2**. The annual rainfall across the study area exhibits clear spatial variability between the Red Lateritic Zone (RLZ) and Coastal Saline Zone (CSZ). Annual mean rainfall ranges from 1343.52 mm (Puruliya) to 1560.35 mm (Paschim Medinipur) which shows moderate variability between districts in RLZ. The coefficient of variation (CV) remains relatively low (17.03–20.52%) suggesting a comparatively stable annual rainfall regime in this zone. CSZ districts record higher annual rainfall totals exceeding all RLZ districts with Purba Medinipur (1689.10 mm) and South 24 Parganas (1654.82 mm) This increase in magnitude is accompanied by greater variability, particularly in South 24 Parganas (CV = 22.63%) reflects the higher interannual fluctuations due to the coastal effect. RLZ shows relatively greater consistency and CSZ receives more rainfall annually.

Winter rainfall (DJF) is minimal across both zones and shows extremely high variability. Mean rainfall ranges from 33.67 mm (Birbhum) to 45.74 mm (Jhargram) with very high CV values (85.70–93.40%) which indicates the erratic and unreliable precipitation in RLZ. Similarly, CSZ shows slightly higher mean values (47.11–48.61 mm), yet variability remains comparably high (CV ≈ 89–92%). This suggests that winter rainfall is sporadic and contributes negligibly to the annual water balance in both zones. The lack of considerable zonal contrast in variability implies that large-scale atmospheric controls dominate winter precipitation patterns rather than localized geographic influences.

The monsoon (JJAS) dominates the rainfall regime across both zones by contributing the majority of annual precipitation. Mean rainfall in monsoon season ranges from 1041.32 mm (Paschim Bardhaman) to 1157.67 mm (Paschim Medinipur) with relatively low CV values (18.67–22.65%) indicating stable and dependable rainfall in RLZ. Rainfall amounts are substantially higher in the CSZ with Purba Medinipur (1246.06 mm) and South 24 Parganas (1225.87 mm) receiving the highest totals in the entire study area. However, variability is slightly higher in CSZ (CV ≈ 24.92%), particularly in South 24 Parganas which mentions the occasional fluctuations in monsoon intensity due to cyclonic activity or coastal disturbances. The monsoon season remains the most reliable period for rainfall in both zones with lower variability compared to other seasons.

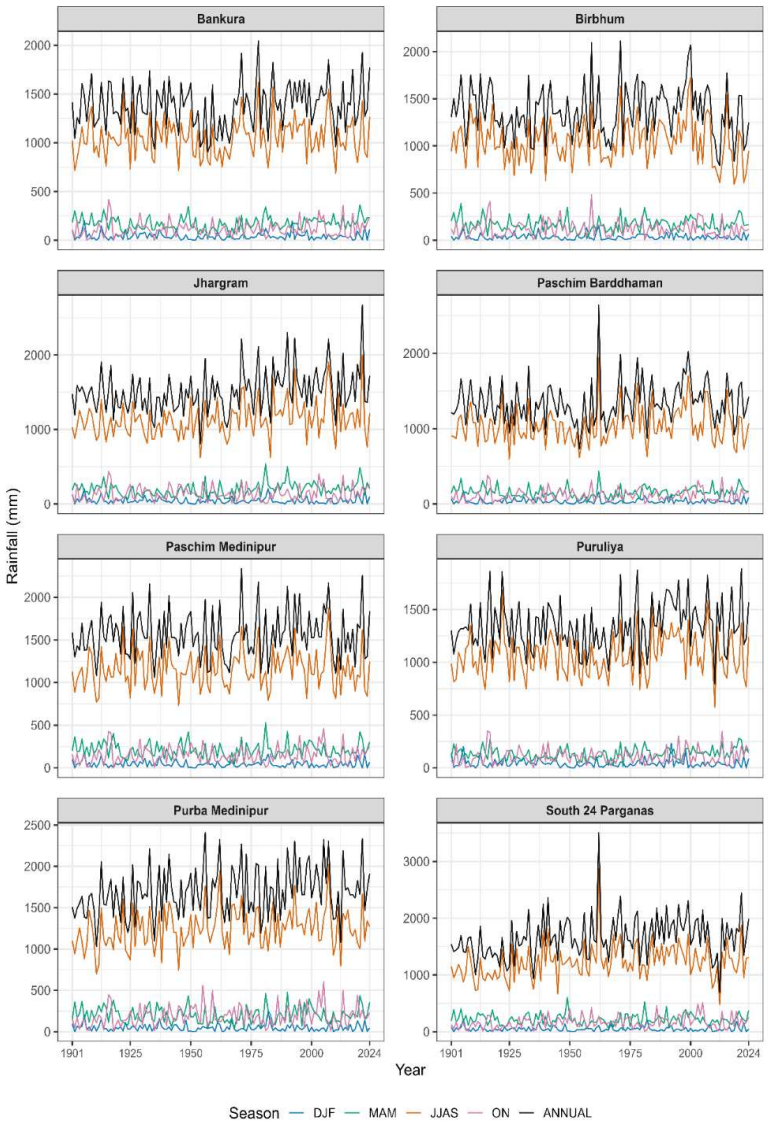
Post-monsoon rainfall (ON) shows a secondary peak particularly in CSZ. Mean rainfall ranges from 104.86 mm (Puruliya) to 148.29 mm (Paschim Medinipur) with high variability (CV: 65.70–71.20%), indicating considerable interannual fluctuations in RLZ. The districts of CSZ receives significantly higher post-monsoon rainfall than RLZ especially in Purba Medinipur (188.54 mm) and South 24 Parganas (164.76 mm). Although variability remains high (CV ≈ 65–67%) it is slightly lower

than RLZ which suggests relatively more consistent rainfall in CSZ during this season. This enhanced rainfall in CSZ can be attributed to its coastal proximity and increased influence of cyclonic systems during the retreating monsoon phase.

A summary of rainfall characteristics along with the corresponding raw time series plots is presented in **Fig. 2** and **Fig. 3** to illustrate the overall distribution and temporal behaviour of rainfall across the study area. The climatology of the study area can be clearly understood as monsoon-dominated with a stable core rainfall season embedded within highly variable and uncertain non-monsoon periods (Dutta et al., 2025). CSZ consistently records higher rainfall totals, particularly during the monsoon and post-monsoon seasons reflecting strong maritime influence whereas the red and laterite zone reflects greater variability and intermittency particularly outside the monsoon season (Dey & Bhardwaj, 2025; Dutta et al., 2025). These findings reinforce the importance of zonal climatic controls where coastal proximity enhances rainfall magnitude but also introduces variability while inland regions exhibit more stable yet lower precipitation regimes.

3.2. Seasonal Trend Analysis of Rainfall

The seasonal wise rainfall trend analysis provides deeper understanding into the temporal evolution of rainfall across the Red and Laterite Zone (RLZ) and Coastal Saline Zone (CSZ) which reveals clear differences in the strength, consistency and spatial coherence of trends which is represented in **Table 3**. The annual rainfall trend reveals a marked zonal variation when assessed using the Mann–Kendall (MK), Modified Mann–Kendall (MMK) and Sen's slope estimator. most districts exhibit positive MK and MMK tau value indicating an overall increasing tendency in RLZ. Specifically, Jhargram shows a statistically significant upward trend (MK $\tau = 0.181$; MMK $\tau = 0.181$; $p = 0.003$) confirming robustness even after accounting for serial correlation. The magnitude of this increase as quantified by Sen's slope is substantial (2.025 mm/year) making it the most prominent trend within RLZ. Other districts such as Paschim Bardhaman ($\tau \approx 0.096$–0.088) and Puruliya ($\tau = 0.112$) also indicate increasing tendencies but their MMK p-values (>0.05) suggest these trends are not statistically significant. Birbhum remains the only district with a weak negative trend ($\tau \approx -0.020$) but this is statistically insignificant and also negligible in magnitude (–0.191 mm/year). The trend signal is stronger and more coherent in the coastal zone. Both Purba Medinipur (MK $\tau = 0.169$; MMK $\tau = 0.169$; $p = 0.005$) and South 24 Parganas (MK $\tau = 0.199$; MMK $\tau = 0.199$; $p = 0.001$) exhibit statistically significant increasing trends under both MK and MMK methods confirming the persistence of the signal even after autocorrelation correction. The magnitude of increase is also notably higher compared to RLZ with Sen's slope values of 2.088 mm/year and 2.773 mm/year respectively. The concurrence of MK and MMK significance with high Sen's slope values in CSZ highlights a robust intensification of annual rainfall which is likely associated with enhanced ocean–atmosphere interactions, whereas RLZ reflects weaker and spatially inconsistent changes than the other zone.



286

287 **Fig. 2.** Raw time series plot of rainfall of various season and annual in both the zones

Table 2. Statistical summary of rainfall in different seasons and annual scale over the study area

Zone	District	Annual			DJF			MAM			JJAS			ON		
		Mean	SD	CV	Mean	SD	CV	Mean	SD	CV	Mean	SD	CV	Mean	SD	CV
RLZ	Bankura	1377.65	234.56	17.03	41.34	37.96	91.82	171.65	66.24	38.59	1051.43	196.28	18.67	113.20	78.68	69.50
	Birbhum	1368.90	269.26	19.67	33.67	30.43	90.37	168.71	71.53	42.40	1047.16	229.77	21.94	119.36	82.95	69.49
	Jhargram	1514.19	287.89	19.01	45.74	42.70	93.36	197.03	90.44	45.90	1133.82	238.81	21.06	137.53	96.92	70.47
	Paschim Barddhaman	1347.49	276.44	20.52	36.86	33.71	91.44	156.88	70.96	45.23	1041.32	235.90	22.65	112.42	80.04	71.20
	Paschim Medinipur	1560.35	276.64	17.73	45.04	38.60	85.70	209.28	89.27	42.66	1157.67	226.99	19.61	148.29	97.43	65.70
	Puruliya	1343.52	231.40	17.22	42.45	39.65	93.40	131.98	55.48	42.04	1064.19	200.02	18.80	104.86	74.01	70.58
CSZ	Purba Medinipur	1689.10	302.22	17.89	48.61	43.58	89.67	205.81	97.86	47.55	1246.06	240.66	19.31	188.54	123.82	65.67
	South 24 Parganas	1654.82	374.43	22.63	47.11	43.36	92.04	217.03	96.53	44.48	1225.87	305.47	24.92	164.76	110.74	67.21

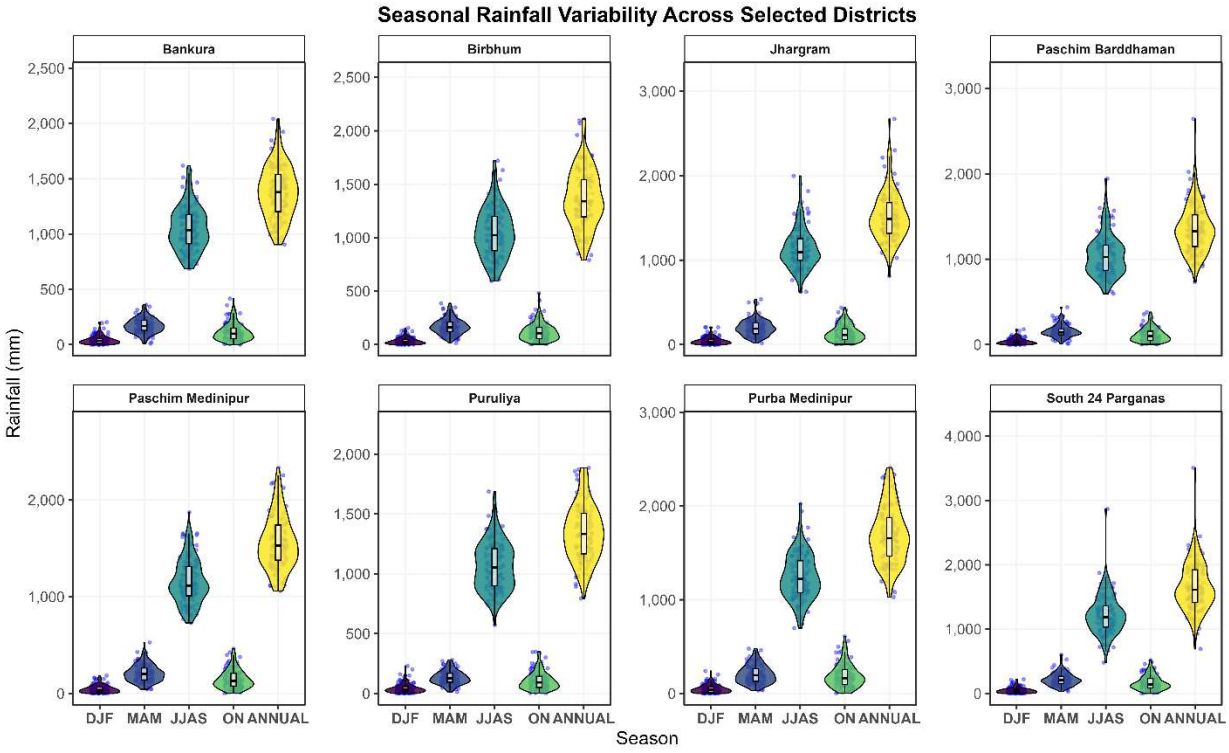


Fig. 3. Seasonal rainfall distribution across district

The DJF season is characterized by predominantly negative or near-zero trends across both zones with no statistically significant signals detected using either MK or MMK tests. All districts od RLZ exhibit negative MK and MMK tau values, such as Jhargram (τ = –0.066) and Puruliya (τ = –0.063) but corresponding p-values remain well above 0.05 which indicates the lack of statistical significance. Sen's slope values are also very small (ranging approximately from –0.100 to 0.009 mm/year) shows negligible magnitudes of change. Similarly, In CSZ, both Purba Medinipur and South 24 Parganas show weak negative trends ($\tau \approx$ –0.050 and –0.031) with MMK p-values confirming non-significance. The spatial pattern corroborates a general dominance of decreasing or neutral trends but without statistical robustness. The absence of significant MK/MMK trends combined with very low Sen's slope values indicates that winter rainfall remains highly stochastic governed more by episodic synoptic disturbances than by systematic climatic shifts. The similar results were reported by several researcher (Halder et al., 2023; Mukhopadhyay et al., 2016).

The MAM season presents a more complex and spatially heterogeneous trend structure. several districts in RLZ exhibits statistically significant increasing trends. Jhargram (MK τ = 0.152; MMK τ = 0.141; p = 0.012–0.021) and Puruliya (MK τ = 0.130; MMK τ = 0.123; p = 0.032–0.044) show consistent significance across both tests indicating robust upward trends. Sen's slope values further quantify these increases at 0.534 mm/year and 0.289 mm/year respectively which signifying moderate intensification of pre-monsoon rainfall. Bankura and Paschim Bardhaman also show positive tau values,

but lack statistical significance under MMK. Paschim Medinipur exhibits a slight negative trend (τ = –0.020) though with negligible magnitude (–0.072 mm/year). In divergence, districts of CSZ show weak and statistically insignificant negative trends. Purba Medinipur (τ = –0.019) and South 24 Parganas (τ = –0.006) both fail to achieve significance under MK and MMK tests and their Sen's slope values (–0.090 and –0.022 mm/year) indicate minimal decline. The presence of significant MK/MMK trends with moderate Sen's slope values in RLZ suggests strengthening of convective pre-monsoon systems inland while the absence of similar signals in CSZ indicates a relatively stable or slightly weakening pattern in coastal regions. Pre-monsoon trends appear more pronounced in RLZ than in CSZ. (L. Das & Bhowmick, 2018) have reported that RLZ is having more trend in future rainfall than other zone in RCP 4.5.

The JJAS season exhibits a dominant increasing trend across the study area with stronger statistical significance and magnitude in CSZ compared to RLZ. In RLZ, Jhargram again emerges as a key district with a statistically significant trend (MK τ = 0.152; MMK τ = 0.152; p = 0.012) and a relatively high Sen's slope of 1.435 mm/year which indicates substantial intensification of monsoon rainfall. Other districts such as Bankura, Paschim Bardhaman and Puruliya show positive tau values but their MMK p-values (>0.05) suggest non-significant trends. Birbhum shows a weak negative trend ($\tau \approx$ –0.022) though negligible in magnitude (–0.238 mm/year). Both districts in CSZ demonstrate strong and statistically significant increasing trends under both MK and MMK tests. Purba Medinipur (τ = 0.164; p = 0.007) and South 24 Parganas (τ = 0.199; p = 0.001) show high Sen's slope values of 1.679 mm/year and 2.224 mm/year respectively. These magnitudes are considerably higher than those observed in RLZ which indicates stronger increase of monsoon rainfall in coastal areas. The alignment of statistically significant MK/MMK results with high Sen's slope magnitudes in CSZ underscores a clear intensification of monsoon rainfall likely linked to increased moisture transport and enhanced monsoon dynamics over coastal regions.

The ON season reveals a general increasing trend across both zones though statistical significance is largely confined to CSZ. All districts in RLZ exhibit positive MK and MMK tau values showing an upward tendency. But none of these trends are statistically significant (p > 0.05) and Sen's slope values remain relatively small (generally between 0.162 and 0.210 mm/year) which suggests slow and weak increases. Both districts in CSZ exhibits statistically significant increasing trends under MK and MMK tests. Purba Medinipur (τ = 0.122; p = 0.045) and South 24 Parganas (τ = 0.132; p = 0.030) show consistent significance with Sen's slope values of 0.532 mm/year and 0.552 mm/year respectively. These values indicate a meaningful rise in post-monsoon rainfall magnitude. The significant MK/MMK trends combined with moderate Sen's slope values in CSZ suggest increasing influence of post-monsoon systems particularly cyclonic activity and RLZ remains characterized by weak and non-significant changes.

The combined application of MK, MMK and Sen's slope provides a comprehensive understanding of total rainfall trends across zones and seasons. Statistically significant trends (as confirmed by both MK and MMK tests) are predominantly observed in CSZ during annual, monsoon and post-monsoon periods with consistently higher Sen's slope values indicating stronger magnitudes of change. RLZ showing positive tendencies in several cases shows fewer significant trends and generally lower magnitudes. Winter rainfall remains largely non-significant across all districts while pre-monsoon trends show localized significance mainly in RLZ. The seasonal analysis further highlights that statistically significant increasing trends are primarily concentrated in the coastal saline zone particularly during the monsoon and post-monsoon seasons with Sen's slope values exceeding 2 mm/year in certain districts. In disparity, the red and lateritic zone displays weaker and more spatially restricted trends with significant increases mainly limited to Jhargram and isolated pre-monsoon signals. Winter rainfall remains largely unchanged across both zones as evidenced by very low Sen's slope values demonstrating minimal long-term variation which is also consistent with the spatial patterns observed in **Fig. 4**. The results indicate a clear intensification of rainfall magnitude and accumulation in coastal regions while inland areas continue to experience relatively modest and less consistent changes. This pattern aligns with recent studies suggesting enhanced hydro-climatic variability and rainfall intensification along coastal belts compared to interior regions (S. Das & Goswami, 2023; Ghosh et al., 2025).

Table 3. Trend using MK,MMK and Sen slope's estimator for seasonal and annual rainfall

Period	Zone	Place	MK tau	MK p_value	MMK tau	MMK p_value	Sen Slope (mm/year)	Sen p_value
Annual	RLZ	Bankura	0.083	0.174	0.083	0.174	0.894	0.174
		Birbhum	-0.020	0.744	-0.028	0.649	-0.191	0.744
		Jhargram	0.181	0.003	0.181	0.003	2.025	0.003
		Paschim Barddhaman	0.096	0.115	0.088	0.148	1.018	0.115
		Paschim Medinipur	0.048	0.428	0.048	0.428	0.555	0.428
		Puruliya	0.112	0.066	0.112	0.066	1.099	0.066
	CSZ	Purba Medinipur	0.169	0.005	0.169	0.005	2.088	0.005
		South 24 Parganas	0.199	0.001	0.199	0.001	2.773	0.001
DJF	RLZ	Bankura	-0.036	0.557	-0.036	0.557	-0.038	0.557
		Birbhum	0.011	0.853	0.011	0.853	0.009	0.853
		Jhargram	-0.066	0.276	-0.066	0.276	-0.100	0.276

		Paschim Barddhaman	-0.007	0.905	-0.007	0.905	-0.007	0.905
		Paschim Medinipur	-0.050	0.414	-0.050	0.414	-0.059	0.414
		Puruliya	-0.063	0.299	-0.063	0.299	-0.069	0.299
	CSZ	Purba Medinipur	-0.050	0.413	-0.050	0.413	-0.066	0.413
		South 24 Parganas	-0.031	0.610	-0.031	0.610	-0.036	0.610
MAM	RLZ	Bankura	0.075	0.216	0.077	0.210	0.200	0.216
		Birbhum	0.015	0.811	0.015	0.811	0.039	0.811
		Jhargram	0.152	0.012	0.141	0.021	0.534	0.012
		Paschim Barddhaman	0.068	0.262	0.064	0.294	0.173	0.262
		Paschim Medinipur	-0.020	0.748	-0.020	0.748	-0.072	0.748
		Puruliya	0.130	0.032	0.123	0.044	0.289	0.032
	CSZ	Purba Medinipur	-0.019	0.751	-0.019	0.751	-0.090	0.751
		South 24 Parganas	-0.006	0.923	-0.006	0.923	-0.022	0.923
JJAS	RLZ	Bankura	0.076	0.214	0.076	0.214	0.682	0.214
		Birbhum	-0.022	0.722	-0.025	0.684	-0.238	0.722
		Jhargram	0.152	0.012	0.152	0.012	1.435	0.012
		Paschim Barddhaman	0.070	0.250	0.062	0.308	0.648	0.250
		Paschim Medinipur	0.044	0.467	0.044	0.467	0.382	0.467
		Puruliya	0.095	0.119	0.095	0.119	0.745	0.119
	CSZ	Purba Medinipur	0.164	0.007	0.164	0.007	1.679	0.007
		South 24 Parganas	0.199	0.001	0.199	0.001	2.224	0.001
ON	RLZ	Bankura	0.068	0.264	0.068	0.264	0.198	0.264
		Birbhum	0.025	0.677	0.025	0.677	0.069	0.677
		Jhargram	0.040	0.510	0.040	0.510	0.162	0.510
		Paschim Barddhaman	0.076	0.214	0.074	0.228	0.204	0.214
		Paschim Medinipur	0.048	0.433	0.043	0.479	0.181	0.433
		Puruliya	0.074	0.224	0.074	0.224	0.210	0.224
	CSZ	Purba Medinipur	0.122	0.045	0.122	0.045	0.532	0.045
		South 24 Parganas	0.132	0.030	0.132	0.030	0.552	0.030

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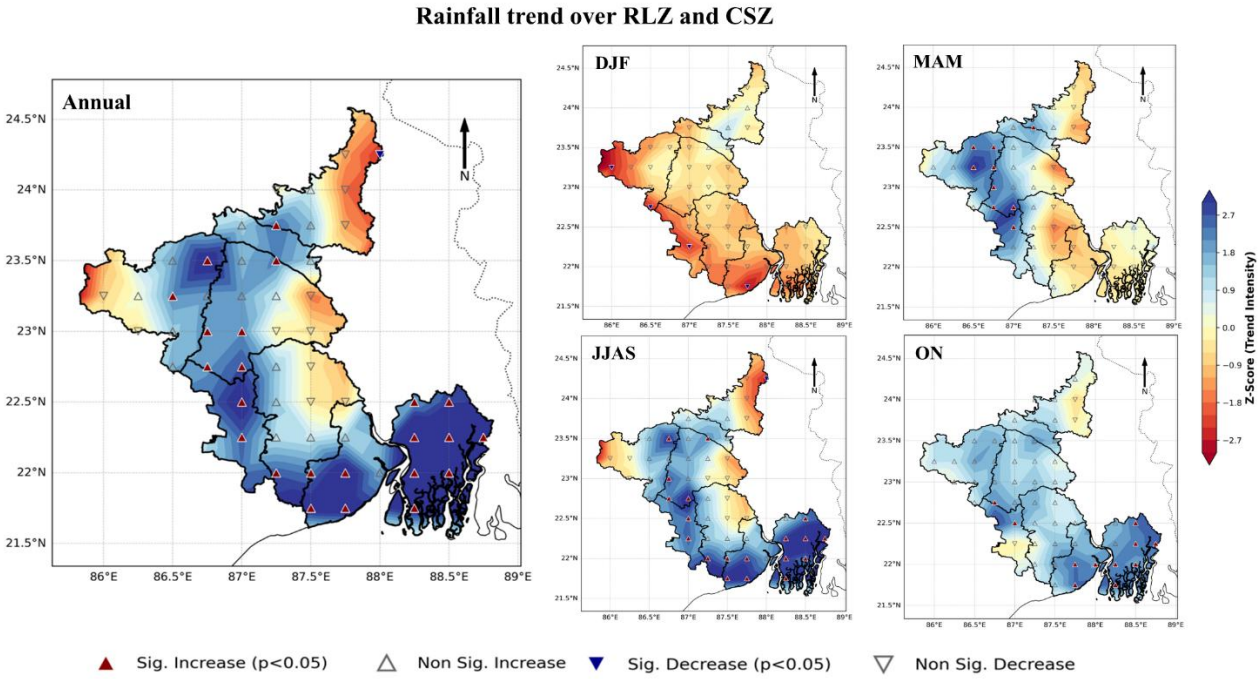


Fig. 4. Seasonal and Annual rainfall trend showing the intensity of change in study in the study periods

3.3. Change point detection

Change point detection was performed using the non-parametric Pettitt and Buishand tests to identify shifts in rainfall time series. The Pettitt test detects abrupt changes in the median, while the Buishand test identifies shifts in the mean. Statistical significance was assessed at the 5% level ($\alpha = 0.05$), where $p \leq 0.05$ indicates a significant change point and $p > 0.05$ indicates no significant structural change and the result of both tests were tabulated at **Table 4.**

The annual rainfall series reveals clear sign of structural shifts with notable changes between zones. Statistically significant change points are identified in districts of RLZ ie. Jhargram (1970; Pettitt $p = 0.001$, Buishand $p = 0.001$), Paschim Bardhaman (1969; Pettitt $p = 0.013$) and Puruliya (1983; Pettitt $p = 0.012$). These indicate that major shifts in rainfall regimes occurred mainly during the late 1960s to early 1980s. Birbhum shows a later breakpoint in 2008 significant only under the Buishand test ($p = 0.032$) signifying a comparatively recent and less consistent shift. Other districts such as Bankura and Paschim Medinipur exhibit non-significant breakpoints which demonstrates weak or gradual transitions. CSZ demonstrates earlier and more consistent structural changes than RLZ. South 24 Parganas exhibits a highly significant breakpoint in 1936 under both tests (Pettitt $p = 0.001$; Buishand $p = 0.003$) while Purba Medinipur shows a shift around 1947 though marginally significant. These earlier breakpoints indicate that rainfall regime changes in coastal regions began much earlier than in

inland areas. Annual rainfall shifts are earlier and statistically stronger in CSZ and RLZ shows delayed and more localized changes.

The DJF season does not exhibit any statistically significant change points across either zone., several break years are identified in RLZ (e.g., Bankura ~1945, Jhargram ~1944, Paschim Bardhaman ~1945) but all associated p-values exceed 0.05 under both tests. Similarly, in CSZ, breakpoints such as 1913 (Purba Medinipur) and 1983 (South 24 Parganas) are detected but remain statistically insignificant. Although both tests identify approximate timing of shifts the lack of significance indicates that these do not represent true structural changes but rather short-term variability. Winter rainfall remains highly erratic with no detectable long-term structural shift.

The MAM season shows clear and statistically significant change points particularly in RLZ. Jhargram exhibits a highly significant breakpoint around 1975–1976 (Pettitt $p = 0.000$; Buishand $p = 0.000$) signifying a strong and consistent shift. Paschim Bardhaman also shows a significant change in 1979 (Pettitt $p = 0.031$; Buishand $p = 0.006$) while Puruliya records a significant breakpoint in 1972 under both tests (Pettitt $p = 0.008$; Buishand $p = 0.002$). These results indicate a clustering of structural changes during the 1970s in RLZ. In CSZ, change points are detected around the early 20th century (~1920) but none are statistically significant. This suggests relative stability in pre-monsoon rainfall in coastal areas. Significant shifts during MAM are concentrated in RLZ which shows a reorganization of pre-monsoon rainfall patterns inland.

The JJAS season exhibits the most pronounced and spatially consistent change points. In RLZ, Jhargram shows a significant breakpoint around 1966 (Pettitt $p = 0.006$; Buishand $p = 0.004$) while Puruliya records a significant shift in 1983 (Pettitt $p = 0.044$). Paschim Bardhaman also shows significance under the Buishand test (1961; $p = 0.046$) highlighting partial agreement between methods. These findings suggest that monsoon rainfall in RLZ experienced structural changes mainly between the 1960s and 1980s. Change points are earlier and more robust in CSZ. South 24 Parganas exhibits a highly significant breakpoint around 1938 under both tests (Pettitt $p = 0.001$; Buishand $p = 0.004$) while Purba Medinipur shows a significant change around 1951 (Pettitt $p = 0.026$). The consistency between tests strengthens the reliability of these early shifts. Monsoon rainfall changes occurred earlier and more consistently in CSZ and RLZ shows later and less uniform transitions.

The ON season shows limited but distinct structural changes., several break years are identified (1920s–1940s) in RLZ but none are statistically significant under either test which highlighting the absence of a strong structural shift. South 24 Parganas shows statistically significant change points under both Pettitt (1930; $p = 0.044$) and Buishand (1938; $p = 0.049$) tests indicating a consistent shift in post-monsoon rainfall regime. Other districts exhibit early but non-significant breakpoints. Post-monsoon rainfall changes are localized but significant in coastal areas particularly South 24 Parganas.

Rainfall regime shifts are concentrated within specific periods rather than being uniformly distributed. Most significant change points occur between the late 1960s and early 1980s, indicating a phase of hydroclimatic reorganization, particularly during the monsoon and pre-monsoon seasons in the Red and Laterite Zone (RLZ). Shifts occur earlier mainly during the 1930s to 1950s which suggests earlier structural changes in coastal rainfall regimes. Across seasons, change points are more frequent during monsoon and pre-monsoon while winter and post-monsoon remain largely stable in the other zone (CSZ). Rainfall regime shifts in West Bengal's Red and Laterite Zone (RLZ) and Coastal Saline Zone (CSZ) are concentrated within specific periods rather than uniformly distributed across the record, signaling abrupt hydroclimatic reorganizations akin to those documented across Indian monsoon regions (Jain et al., 2023). The pattern indicates earlier shifts in coastal regions and relatively later adjustments in inland areas of RLZ

Table 4. Change point years identified from Pettit and Buishand test

Season	Station	Pettitt Year	Pettitt p value	Buishand Year	Buishand p value
Annual	Bankura	1967	0.053	1967	0.102
	Birbhum	2008	0.294	2008	0.032
	Jhargram	1970	0.001	1970	0.001
	Paschim Barddhaman	1969	0.013	1969	0.067
	Pashchim Medinipur	1983	0.808	1968	0.652
	Puruliya	1983	0.012	1983	0.096
	Purba Medinipur	1947	0.060	1947	0.171
	South 24 Parganas	1936	0.001	1936	0.003
DJF	Bankura	1945	0.582	1938	0.448
	Birbhum	1975	0.960	1962	0.982
	Jhargram	1944	0.472	1913	0.379
	Paschim Barddhaman	1945	0.974	1938	0.940
	Pashchim Medinipur	1945	0.697	1944	0.486
	Puruliya	1945	0.147	1944	0.432
	Purba Medinipur	1945	0.899	1913	0.988
	South 24 Parganas	1983	0.977	1983	0.924
JJAS	Bankura	1967	0.122	1967	0.167
	Birbhum	2008	0.182	2008	0.040
	Jhargram	1966	0.006	1966	0.004
	Paschim Barddhaman	1969	0.109	1961	0.046
	Pashchim Medinipur	1966	0.731	1967	0.447

	Puruliya	1983	0.044	1983	0.090
	Purba Medinipur	1951	0.026	1951	0.054
	South 24 Parganas	1938	0.001	1938	0.004
MAM	Bankura	1979	0.057	1979	0.001
	Birbhum	1970	0.317	1970	0.095
	Jhargram	1975	0.000	1976	0.000
	Paschim Barddhaman	1979	0.031	1979	0.006
	Pashchim Medinipur	1920	0.449	1920	0.292
	Puruliya	1972	0.008	1972	0.002
	Purba Medinipur	1920	0.531	1920	0.219
	South 24 Parganas	1920	0.939	1950	0.545
ON	Bankura	1927	0.507	1994	0.990
	Birbhum	2005	0.852	2005	0.459
	Jhargram	1923	1.000	2002	0.966
	Paschim Barddhaman	1940	0.365	1938	0.657
	Pashchim Medinipur	1928	0.865	1994	0.902
	Puruliya	1923	0.486	1989	0.985
	Purba Medinipur	1928	0.082	1940	0.266
	South 24 Parganas	1930	0.044	1938	0.049

3.4. Extreme rainfall

3.4.1. Seasonal distribution of extreme rainfall indices

The seasonal variability of extreme rainfall indices (**Fig. 5**) reveals clear differences in magnitude, frequency and persistence of rainfall extremes across RLZ and CSZ. The indices show strong seasonal concentration with numerical contrasts evident across all districts with no statistical outliers observed .

Extreme rainfall at the annual scale is largely governed by monsoon contributions with higher magnitudes observed in CSZ compared to RLZ. Rx1day ranges around 80–130 mm (RLZ) and 100–160 mm (CSZ) and Rx5day varies between 200–350 mm and 300–450 mm respectively. The frequency of heavy rainfall days remains high (R10mm: 30–45 days; R20mm: 12–22 days) and R95pTOT (300–700 mm) specifies a substantial contribution from extreme events. These results confirm that annual rainfall characteristics are dominated by monsoon-driven extremes with stronger intensity and accumulation in coastal regions

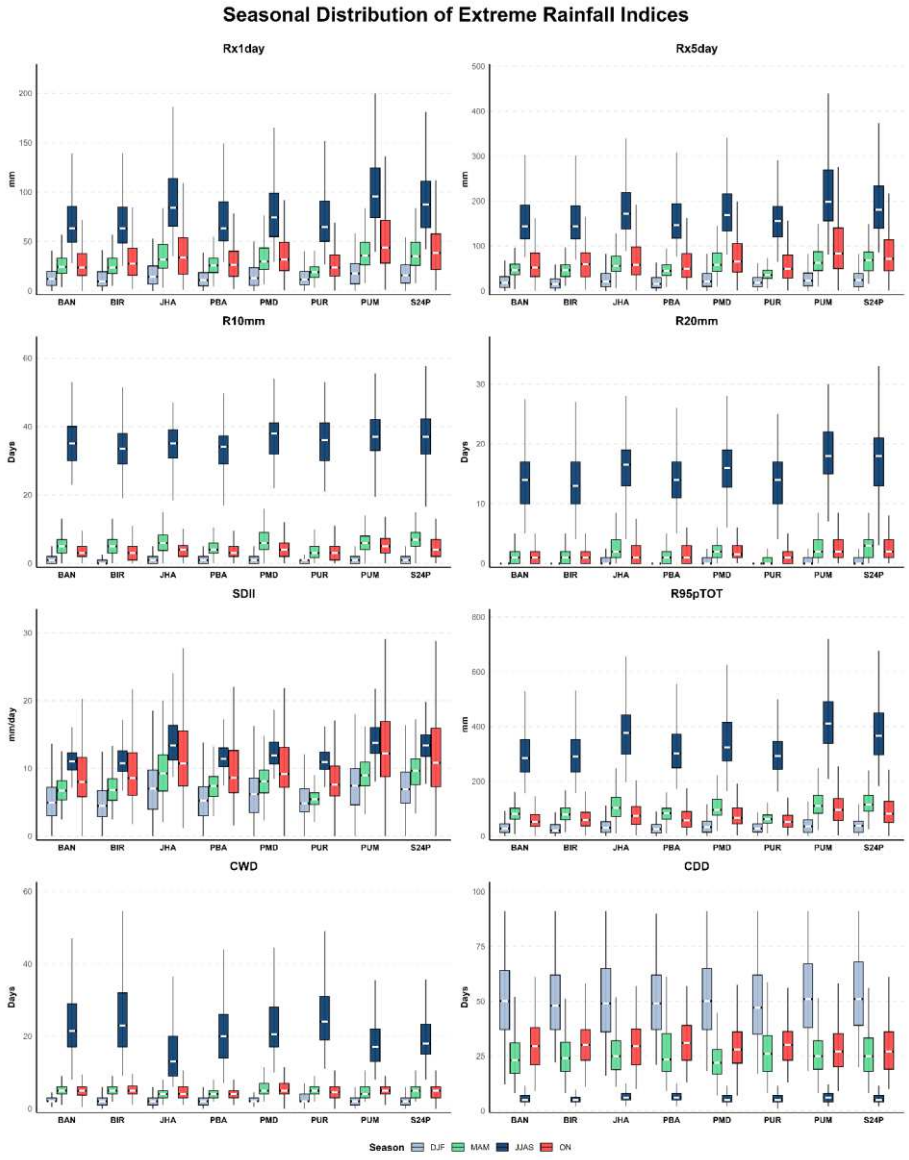


Fig. 5. Seasonal distribution of extreme rainfall indices across districts using median–IQR boxplots (whiskers = 1.5×IQR)

All indices during DJF register very low magnitudes across both zones. Rx1day values remain mostly below 20–30 mm and Rx5day rarely exceeds 40–60 mm. The frequency of heavy rainfall days is negligible with R10mm generally < 2–3 days and R20mm close to 0–1 day across all districts. Rainfall intensity (SDII) is also minimal typically around 3–6 mm/day and R95pTOT values remain below 50–80 mm highlighting almost no contribution from extreme rainfall. Dry conditions dominate this season with CDD values ranging from 40 to 70 days which is the highest among all seasons and CWD remains very low (1–3 days). Both RLZ and CSZ exhibit similar patterns with minimal spatial variation. The consistently low magnitudes confirm that DJF rainfall is negligible and does not contribute meaningfully to extreme rainfall characteristics consistent with the weak winter precipitation regime in eastern India during the winter season.

A noticeable increase in rainfall extremes is observed in the premonsoon season particularly in RLZ. Rx1day values rise to around 30–60 mm and Rx5day ranges between 80–150 mm which mentions the short-duration intense rainfall events. R10mm increases to approximately 4–8 days and R20mm to 2–5 days especially in districts such as Jhargram and Paschim Medinipur. Rainfall intensity (SDII) increases to 6–10 mm/day and R95pTOT ranges from 80–150 mm showing modest contributions from extreme rainfall. CDD values decrease compared to DJF but remain relatively high (20–35 days) and CWD increases slightly to around 3–6 days. CSZ districts show slightly lower magnitudes compared to RLZ during this season. The moderate but highly variable extremes during MAM reflect convective thunderstorm activity (Nor'westers) which produce localized but intense rainfall events over inland regions .

The JJAS season shows the maximum magnitude and frequency of extreme rainfall across all indices. Rx1day values range from 60 to 120 mm in RLZ and extend up to 120–150 mm in CSZ with maximum values occasionally exceeding 180–200 mm. Rx5day shows substantial increases which ranges from 150–250 mm in RLZ and reaching 250–450 mm in CSZ particularly in Purba Medinipur. Frequency indices peak during this season with R10mm ranging from 30–45 days and R20mm from 12–22 days highlighting frequent heavy rainfall events. Rainfall intensity (SDII) is highest typically between 10–18 mm/day and R95pTOT ranges from 250–450 mm in RLZ and exceeds 400–700 mm in CSZ highlighting the dominant contribution of extreme rainfall. Wet spell duration (CWD) also peaks with value ranging from 15–30 days and CDD drops to its lowest values (5–10 days). CSZ districts consistently exhibit higher magnitude and variability than RLZ. The dominance of extreme rainfall during JJAS reflects the core influence of the Indian Summer Monsoon with coastal amplification of extremes driven by moisture influx and large-scale circulation patterns .

A secondary peak in rainfall extremes is observed during ON particularly in CSZ. Rx1day values range from 30–80 mm in RLZ and 50–110 mm in CSZ and Rx5day varies between 80–180 mm (RLZ) and 120–250 mm (CSZ). R10mm values range from 3–8 days and R20mm from 2–6 days indicating moderate frequency of heavy rainfall events. Rainfall intensity (SDII) remains relatively high at 8–16 mm/day and R95pTOT ranges from 100–200 mm in RLZ and 150–300 mm in CSZ showing continued contribution from extreme rainfall. CWD values remain moderate (4–8 days) and CDD increases compared to JJAS (20–35 days) indicating transition toward drier conditions. The variability is higher in CSZ particularly for intensity-based indices. The elevated extremes during ON in coastal districts are associated with cyclonic systems and depressions over the Bay of Bengal which enhance rainfall intensity and variability during this season.

The seasonal distribution clearly shows that extreme rainfall is highly concentrated during the monsoon season with contribution to the largest magnitude and frequency of extremes. The post-monsoon season provides a secondary contribution specifically in coastal districts and pre-monsoon

rainfall is moderate and highly variable. Winter remains largely inactive due to low or rainfall activity. Statistically, CSZ consistently records higher values for intensity (SDII), extreme contribution (R95pTOT) and magnitude (Rx1day, Rx5day) compared to RLZ indicating stronger rainfall extremes in coastal regions. However, RLZ also shows relatively moderate but consistent behavior across seasons. These results confirm that coastal regions are more prone to high-intensity and high-magnitude rainfall extremes and inland regions exhibit lower but more stable patterns which is consistent with observed regional climate variability and increasing extreme precipitation trends over eastern India .

3.4.2. Trend of extreme rainfall indices

Annual

The annual trends in extreme rainfall magnitude indicate a steady increasing pattern with stronger magnitudes in CSZ compared to RLZ is visible on the heatmap **(Fig. 6 A)**. Rx1day shows modest increases ranging from 0.052 mm/year (Bankura) to 0.291 mm/year (Jhargram) and Rx5day varies between 0.097 mm/year and 0.521 mm/year with Jhargram exhibiting the highest magnitude. However, statistical significance (MK/MMK) is largely limited to Jhargram and isolated grid pockets as seen in the spatial maps in RLZ **(Fig. 7).** In the other zone, the scale of increase is markedly higher particularly for Rx5day with Purba Medinipur recording 0.611 mm/year and South 24 Parganas 0.392 mm/year representing stronger multi-day rainfall intensification. The grid wise MMK Z-score maps show clusters of significant positive trends over coastal belts which confirms spatial coherence in increasing extremes. The stronger increase in multi-day extremes (Rx5day) over CSZ suggests intensification of prolonged rainfall events, consistent with coastal amplification of extreme precipitation driven by enhanced moisture availability and cyclonic influences (Dey & Bhardwaj, 2025).

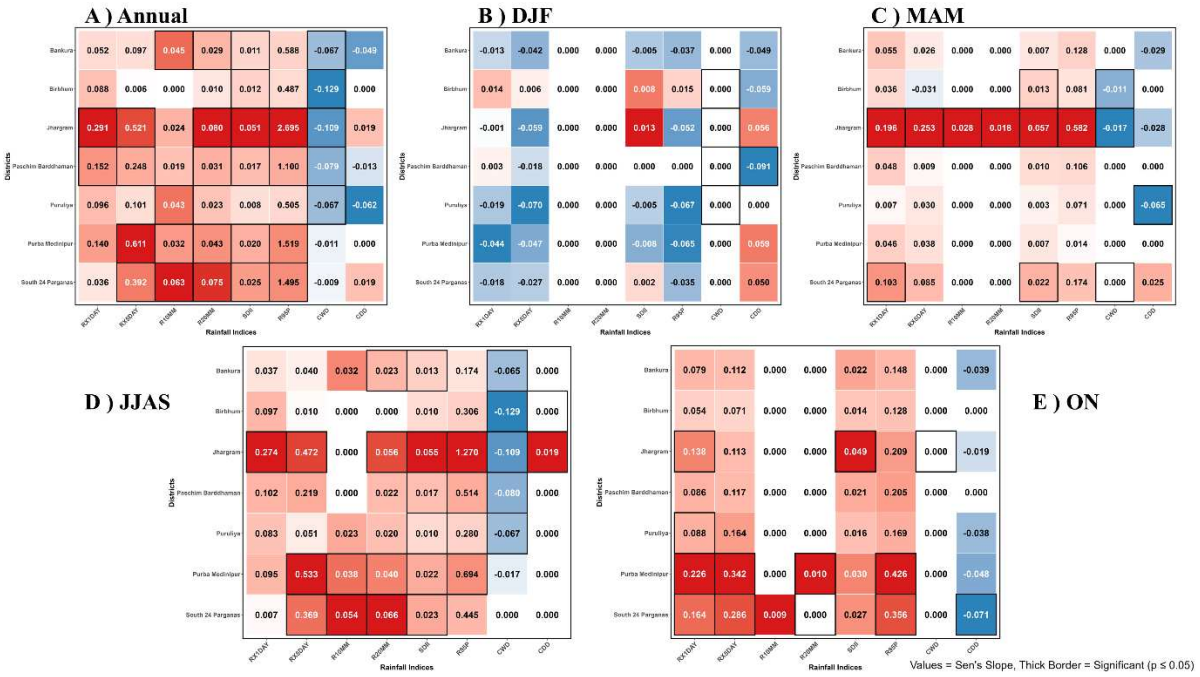
The frequency indices show modest increasing trends across most districts though with varying magnitude and significance. R10mm increases range from 0.000 to 0.045 days/year and R20mm varies from 0.010 to 0.060 days/year with higher values observed in Jhargram and Bankura in RLZ. These trends are mostly non-significant under MMK which highlights gradual changes. In CSZ, the increase is more pronounced particularly in South 24 Parganas (0.063 days/year for R10mm; 0.075 days/year for R20mm) and Purba Medinipur (0.032 and 0.043 days/year, respectively). The spatial distribution further confirms significant positive trends in coastal grids especially for R20mm indicating an increase in higher-intensity rainfall days. The increase in heavy rainfall frequency particularly in coastal regions reflects a shift toward more frequent extreme events, aligning with observations of increasing rainfall event frequency over eastern India (Li et al., 2024).

Rainfall intensity (SDII) and the contribution of extreme rainfall (R95pTOT) show indistinct and vigorous increasing trends specifically in CSZ. SDII increases are relatively modest (0.008–0.051 mm/day/year) and R95pTOT shows moderate increases with Jhargram recording the highest value

(2.695 mm/year) in RLZ. The magnitude of increase is consistently high with R95pTOT reaching 1.519 mm/year (Purba Medinipur) and 1.495 mm/year (South 24 Parganas). SDII also shows steady increases (0.020–0.025 mm/day/year) in CSZ. The spatial maps reveal widespread positive MMK Z-scores across coastal regions indicating statistically significant intensification of rainfall extremes. The increasing SDII and R95pTOT indicate that a larger fraction of annual rainfall is contributed by extreme events which supports the notion of intensified short-duration precipitation under warming conditions (Li et al., 2024; Mukherjee et al., 2018).

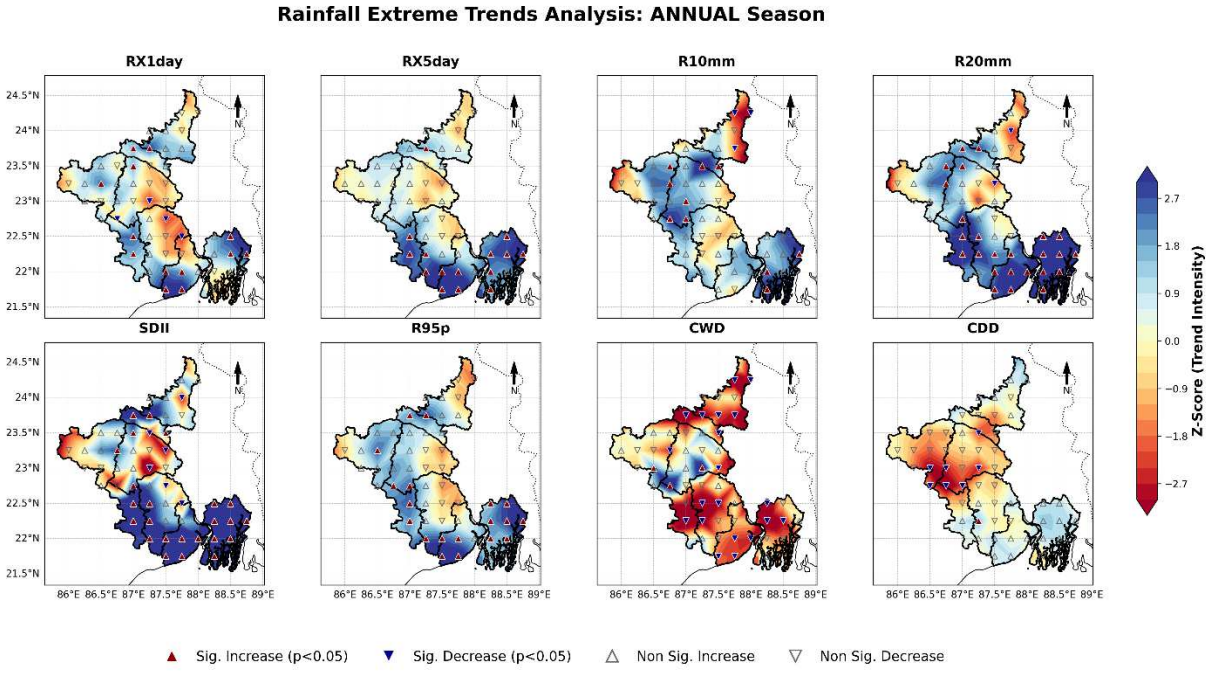
The duration based indices exhibit contrasting behavior. Consecutive wet days (CWD) show a declining trend across most districts with Sen's slope values ranging from –0.011 to –0.129 days/year with stronger declines in RLZ (e.g., Birbhum: –0.129; Jhargram: –0.109). The spatial maps show dominant negative Z-scores indicating widespread reduction in wet spell persistence. On the other hand, consecutive dry days (CDD) show slight increasing or mixed trends ranging from –0.067 to 0.019 days/year suggesting a tendency toward longer dry intervals between rainfall events. However, most trends are not statistically significant. The simultaneous decrease in CWD and increase in CDD suggests a transition toward intermittent but intense rainfall patterns a feature widely reported in changing precipitation regimes under climate variability (S. Dash et al., 2024).

The annual trend analysis clearly demonstrates that extreme rainfall is intensifying particularly more in Coastal Saline Zone than RLZ. Magnitude (Rx1day, Rx5day), intensity (SDII) and contribution (R95pTOT) indices show higher Sen's slope values and stronger MK/MMK significance in CSZ whereas RLZ exhibits weaker and more spatially variable trends. The grid-level MMK Z-score analysis further confirms that significant increasing trends are spatially concentrated in coastal regions whereas inland areas show mixed or non-significant patterns. Additionally, the reduction in wet spell duration (CWD) combined with slight increases in dry spells (CDD) indicates a shift toward short-duration, high-intensity rainfall events rather than prolonged rainfall periods. The results indicate a transition toward more intense and episodic rainfall regimes particularly in coastal regions influenced by oceanic processes and inland areas exhibit weaker and less coherent responses to changing climatic conditions.



554

555 **Fig. 6.** Trend magnitude of extreme rainfall indices in A) Annual , B) DJF, C)MAM, D) JJAS, E) ON
556 seasons. Significant trends ($p \leq 0.05$) are highlighted by thick black borders.



557

558 **Fig. 7.** Spatial distribution maps of Annual extreme rainfall trends (Z-score intensity). Significant
559 trends ($p \leq 0.05$) are indicated by filled triangles.

560 **Winter (DJF)**

561 During the winter season (DJF) extreme rainfall magnitude indices exhibit largely weak and
562 negative trends across both RLZ and CSZ which is presented in **Fig. 6 B.** Rx1day shows small

decreasing magnitudes extending from –0.044 mm/year (Purba Medinipur) to 0.014 mm/year (Birbhum) demonstrating negligible change overall. Similarly, Rx5day reflects a consistent decreasing tendency particularly in RLZ districts such as Puruliya (–0.070 mm/year) and Jhargram (–0.059 mm/year). Most of these trends are statistically non-significant under MK/MMK as also evident from the spatial maps **(Fig. 8)** showing largely neutral to weak negative Z-scores. The near-zero and non-significant trends indicate that winter extreme rainfall remains largely unchanged consistent with the weak and sporadic nature of DJF precipitation in eastern India.

The frequency indices (R10mm and R20mm) show no meaningful trends across all districts with Sen's slope values effectively ~0.000 days/year. This indicates an absence of change in the occurrence of heavy rainfall days during DJF. Both RLZ and CSZ display uniform behavior with no statistically significant trends identified. The spatial distribution also confirms a lack of coherent pattern with mostly non-significant grid-level variations. The absence of trends in heavy rainfall frequency highlights the negligible contribution of winter rainfall to extreme precipitation dynamics.

Rainfall intensity (SDII) and extreme contribution (R95pTOT) also show weak and inconsistent trends. SDII values range between –0.008 mm/day/year (Purba Medinipur) and 0.013 mm/day/year (Jhargram) demonstrating minor variability. R95pTOT generally exhibits declining tendencies with values such as –0.067 mm/year (Puruliya) and –0.065 mm/year (Purba Medinipur) though most trends are not statistically noteworthy. Spatially, the MMK Z-score maps indicate scattered and weak signal with no clear zonal dominance. The lack of significant change in intensity and extreme contribution confirms that winter rainfall extremes remain negligible and do not exhibit systematic climatic shifts.

The duration-based indices show contrasting but weak trends. Consecutive wet days (CWD) exhibit no change across all districts (0.000 days/year) signifying complete absence of trend. In disparity, consecutive dry days (CDD) show slight increasing tendencies particularly in Jhargram (0.056 days/year), Purba Medinipur (0.059 days/year) and South 24 Parganas (0.050 days/year). But these trends are mostly non-significant. The spatial maps indicate weak positive signals for CDD and neutral behavior for CWD signifying minor shifts toward longer dry spells. The slight increase in dry spells alongside stable wet spells suggests marginal intensification of dryness during winter though the overall impact remains minimal due to low rainfall magnitude.

The DJF season shows no substantial or statistically significant trends across extreme rainfall indices with most Sen's slope values close to zero. Both RLZ and CSZ exhibit similar behavior, indicating a lack of zonal differentiation during winter. All indices such as magnitude, frequency, intensity and duration demonstrate negligible changes confirming that winter rainfall remains stable, low and highly variable without long-term structural shifts which is discussed in trend and change point detection. These results reinforce that winter precipitation plays a minimal role in shaping long-term

rainfall extremes with observed variability primarily driven by episodic synoptic systems rather than sustained (Jain et al., 2023).

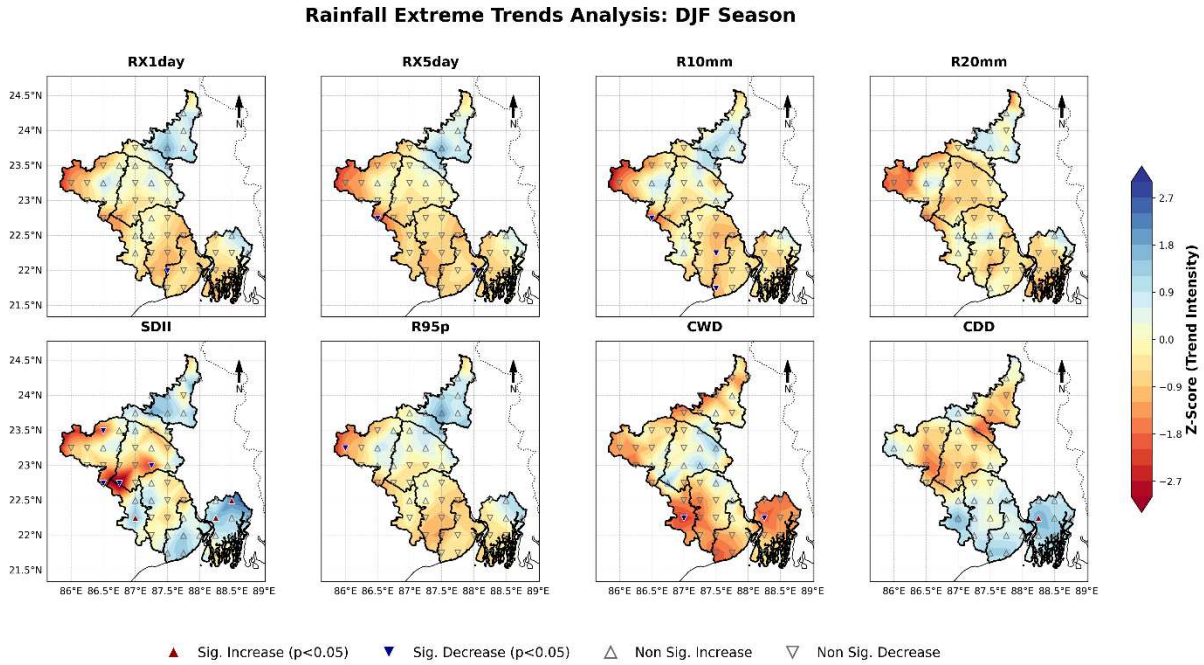


Fig. 8. Spatial distribution maps of Winter (DJF) extreme rainfall trends (Z-score intensity). Significant trends ($p \leq 0.05$) are indicated by filled triangles.

Pre-Monsoon (MAM)

During the pre-monsoon period (MAM), extreme precipitation magnitude indices show a clear increasing tendency chiefly in RLZ **(Fig. 6 C)**. Rx1day exhibits sensible upsurges extending from 0.036 mm/year (Birbhum) to 0.196 mm/year (Jhargram) with Jhargram showing a statistically significant trend. Similarly, Rx5day increases range from –0.031 mm/year (Birbhum) to 0.253 mm/year (Jhargram) again highlighting strong intensification in this district. In CSZ, the magnitude of increase is relatively lower but still positive with South 24 Parganas showing 0.103 mm/year (Rx1day) and 0.085 mm/year (Rx5day). The spatial maps **(Fig. 9)** indicate localized significant increases over western and central RLZ grids and coastal regions show weaker and more scattered signals. The stronger inland increase in Rx indices suggests intensification of convective pre-monsoon rainfall, consistent with studies indicating enhanced thunderstorm-driven extremes over eastern India (Biswas, 2023).

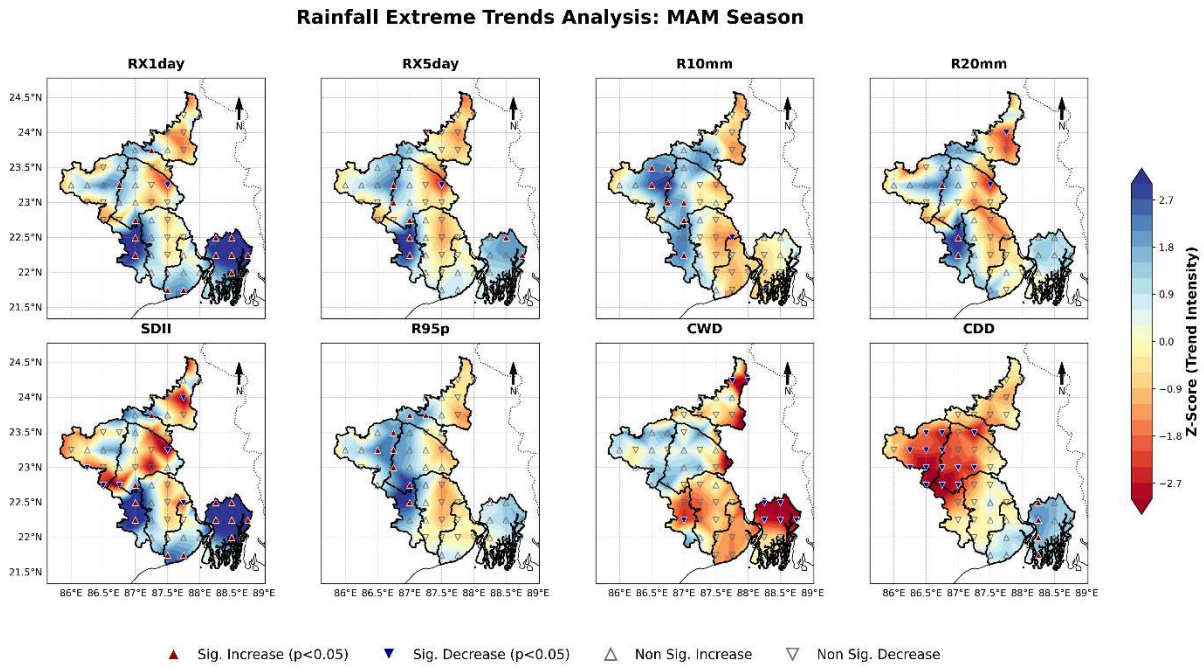
The frequency indices show very limited but localized increasing trends mainly confined to RLZ. In most districts, R10mm and R20mm exhibit negligible trends (~0.000) except in Jhargram where increases of 0.028 days/year (R10mm) and 0.018 days/year (R20mm) are observed both statistically significant. CSZ districts show no meaningful trends indicating stable frequency of heavy rainfall events during MAM. The spatial maps further confirm that significant positive trends are restricted to isolated inland grid cells with no coherent coastal pattern. The localized increase in rainfall

frequency over RLZ reflects enhanced convective activity rather than large-scale climatic forcing which typically dominates during the monsoon season.

Rainfall intensity (SDII) and extreme contribution (R95pTOT) show steady increasing drifts with stronger signals in RLZ. SDII ranges from 0.003 to 0.057 mm/day/year with Jhargram showing the highest and statistically significant increase. R95pTOT exhibits substantial increases predominantly in Jhargram (0.582 mm/year) and South 24 Parganas (0.174 mm/year) indicating increasing contribution from extreme rainfall events. Spatially, positive MMK Z-scores are observed across central and western regions and coastal areas show moderate increases. The increase in SDII and R95pTOT indicates that pre-monsoon rainfall is becoming more intense and concentrated aligning with evidence that localized extreme precipitation is strongly influenced by atmospheric instability and moisture influx (Mukherjee et al., 2018).

The duration-based indices show contrasting behavior during MAM. Consecutive wet days (CWD) exhibit weak decreasing trends predominantly in Jhargram (–0.017 days/year) and Birbhum (–0.011 days/year) yet mostly non-significant. In contrast, consecutive dry days (CDD) show mixed behavior with a notable decrease in Puruliya (–0.065 days/year) and slight increases in South 24 Parganas (0.025 days/year). The spatial maps indicate increasing dry spell dominance in several RLZ grids whereas coastal regions show relatively stable conditions. The reduction in wet spells combined with localized changes in dry spells suggests increasing intermittency of rainfall consistent with the shift toward short-duration, high-intensity precipitation events (S. Dash et al., 2024)

The MAM season reveals a distinct inland-dominated intensification of rainfall extremes with RLZ showing stronger and more statistically significant increases compared to CSZ. Indices related to magnitude (Rx1day, Rx5day), intensity (SDII) and extreme contribution (R95pTOT) indicate that pre-monsoon rainfall is becoming more intense and localized particularly in districts like Jhargram. In contrast, CSZ shows weaker and mostly non-significant trend indicating that coastal influence is less dominant during this season. The spatial MMK Z-score analysis confirms that significant trends are concentrated in inland regions with limited coastal coherence. The results submit that pre-monsoon rainfall extremes are progressively driven by localized convective processes rather than large-scale monsoonal systems with inland regions showing stronger responses to atmospheric instability and warming-induced moisture dynamics which are consistent with recent regional findings (Ghosh et al., 2025).



649

650 **Fig. 9.** Spatial distribution maps of Pre-Monsoon (MAM) extreme rainfall trends (Z-score intensity).
651 Significant trends ($p \leq 0.05$) are indicated by filled triangles.

652 **Monsoon (JJAS)**

653 During the monsoon season (JJAS), extreme rainfall magnitude indices show a marked and
654 spatially clear increasing tendency with stronger signals in CSZ compared to RLZ which is observable
655 from **Fig. 6 D**. In RLZ, Rx1day increases range from 0.037 mm/year (Bankura) to 0.274 mm/year
656 (Jhargram) and Rx5day varies between 0.040 mm/year and 0.472 mm/year with Jhargram again
657 showing statistically significant intensification. Paschim Bardhaman also exhibits notable increases
658 (0.102 and 0.219 mm/year). In CSZ, the magnitude of increase is substantially higher chiefly for multi-
659 day extremes. Purba Medinipur records 0.095 mm/year (Rx1day) and 0.533 mm/year (Rx5day) while
660 South 24 Parganas shows 0.007 and 0.369 mm/year, respectively. The spatial MMK Z-score maps (**Fig.**
661 **10**) reveal strong clusters of significant positive trends across coastal grids indicating widespread
662 intensification of monsoon rainfall extremes. The stronger increase in Rx5day compared to Rx1day
663 suggests intensification of prolonged rainfall events reliable with findings that multi-day extremes are
664 increasingly dominant in monsoon-driven precipitation regimes (Du et al., 2019).

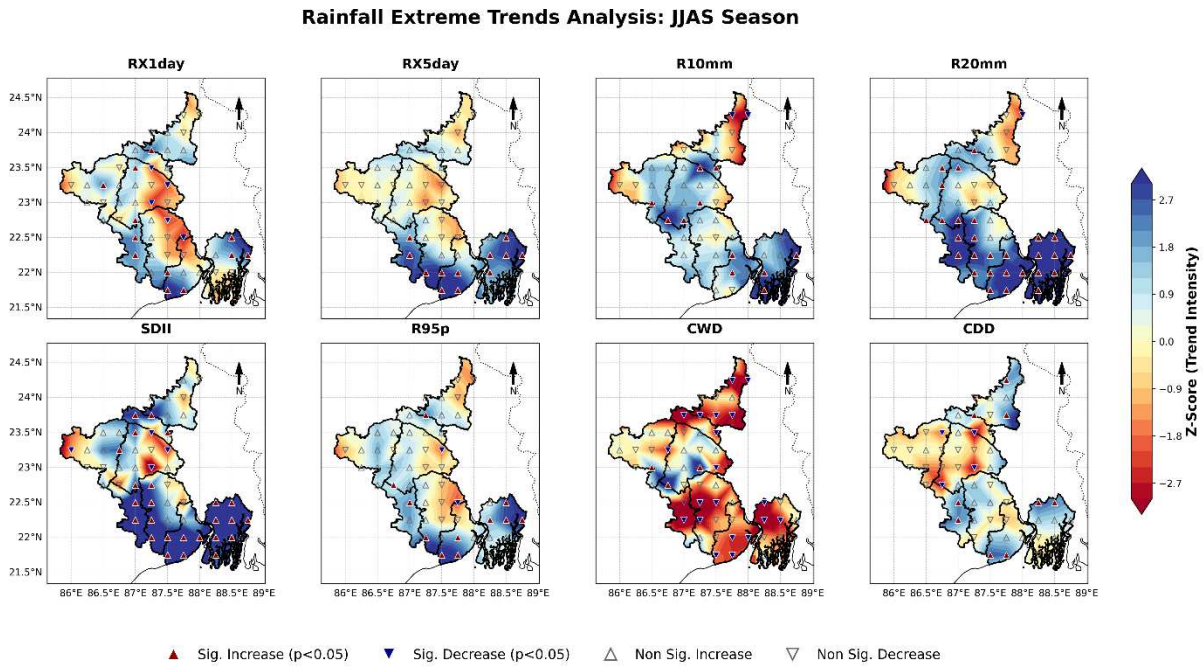
665 The frequency indices show clear rising trends mainly in CSZ indicating more frequent heavy
666 rainfall events during JJAS. In RLZ, R10mm and R20mm increases are modest (e.g., Bankura: 0.032
667 and 0.023 days/year; Puruliya: 0.023 and 0.020 days/year) with limited statistical significance.
668 However, Jhargram shows a significant increase in R20mm (0.056 days/year). In CSZ, the increase is
669 more pronounced and statistically significant exclusively in South 24 Parganas (0.054 days/year for
670 R10mm; 0.066 days/year for R20mm) and Purba Medinipur (0.038 and 0.040 days/year). Spatial maps

confirm strong positive Z-scores over coastal regions indicating coherent intensification of heavy rainfall frequency. The increasing frequency of heavy rainfall days in coastal regions reflects enhanced monsoon variability and moisture availability, consistent with studies showing rising extreme precipitation frequency in eastern India (Li et al., 2024).

Rainfall intensity (SDII) and extreme rainfall contribution (R95pTOT) show strong and statistically significant increasing trends across both zones with higher magnitudes in CSZ. In RLZ, SDII increases range from 0.010 to 0.055 mm/day/year and R95pTOT varies from 0.174 to 1.279 mm/year with Jhargram showing the highest value. In CSZ, the magnitude of increase is remarkably higher with R95pTOT reaching 0.694 mm/year (Purba Medinipur) and 0.445 mm/year (South 24 Parganas). SDII also shows consistent increases (0.022–0.023 mm/day/year). The spatial maps display widespread positive Z-scores across coastal and central regions, confirming robust intensification of rainfall intensity. The increase in SDII and R95pTOT indicates that a growing proportion of rainfall is contributed by extreme events which are confirmed with regional evidence linking intensified monsoon rainfall to warming-induced moisture amplification and ocean–atmosphere interactions (Dey & Bhardwaj, 2025).

The duration-based indices show contrasting but meaningful trends. Consecutive wet days (CWD) exhibit a consistent declining trend across all districts with values ranging from –0.017 to –0.129 days/year demonstrating reduced persistence of rainfall events. This decline is more pronounced in RLZ (e.g., Birbhum: –0.129; Jhargram: –0.109). On the other hand, consecutive dry days (CDD) show mixed but slightly increasing tendencies with Jhargram (0.019 days/year) and some coastal grids indicating longer dry intervals. Spatially, negative Z-scores dominate for CWD and CDD shows localized positive signals. The reduction in wet spell duration alongside increasing intensity supports the shift toward episodic high-intensity rainfall, a pattern widely reported in changing monsoon systems (S. Dash et al., 2024).

The JJAS season clearly reveals the strongest and most spatially coherent intensification of extreme rainfall indices across the study area. Both RLZ and CSZ show increasing trends but CSZ exhibits higher magnitudes and stronger statistical significance mainly for Rx5day, R20mm and R95pTOT. The grid-level MMK Z-score analysis confirms that significant increasing trends are concentrated in coastal regions and inland areas show moderate but consistent increases. The simultaneous decline in CWD and increase in intensity-related indices indicates a transition toward short-duration, high-intensity rainfall events rather than prolonged wet periods. Such changes significantly elevate flood risks and hydrological instability. These results strongly indicate that monsoon rainfall dynamics are shifting toward more intense and variable extremes, particularly in coastal regions influenced by Bay of Bengal processes, aligning with both regional and global evidence of increasing extreme precipitation under climate change (S. Dash et al., 2024; Li et al., 2024) .



706

707 **Fig. 10.** Spatial distribution maps of Monsoon (JJAS) extreme rainfall trends (Z-score intensity).
708 Significant trends ($p \leq 0.05$) are indicated by filled triangles.

709 **Post-Monsoon (ON)**

710 Extreme rainfall magnitude (**Fig. 6 E**) indices show a clear increasing trend across both RLZ
711 and CSZ with stronger magnitudes in coastal districts during the post-monsoon season (ON). Rx1day
712 ranges from 0.054 mm/year (Birbhum) to 0.138 mm/year (Jhargram) and Rx5day varies between 0.071
713 mm/year and 0.164 mm/year (Puruliya) which indicates the moderate intensification in RLZ. In CSZ,
714 the increase is more noticeable particularly in Purba Medinipur (0.226 mm/year for Rx1day; 0.342
715 mm/year for Rx5day) and South 24 Parganas (0.164 and 0.286 mm/year, respectively) with numerous
716 trends statistically significant. The spatial MMK Z-score maps (**Fig. 11**) reveal strong positive clusters
717 over coastal grids which confirms clear intensification of post-monsoon extremes. The stronger coastal
718 increase in extreme rainfall magnitude reflects the growing influence of post-monsoon cyclonic systems
719 over the Bay of Bengal which enhance rainfall intensity in coastal regions (Biswas, 2023).

720 The frequency indices show limited but notable increasing trends primarily restricted to CSZ.
721 In RLZ, both R10mm and R20mm show tiny trends (~0.000) indicating minimal change in heavy
722 rainfall frequency. In contrast, CSZ shows statistically significant increases particularly in South 24
723 Parganas (0.009 days/year for R10mm) and Purba Medinipur (0.010 days/year for R20mm). The spatial
724 maps support this pattern with localized significant increases in coastal grids and inland areas remain
725 largely unchanged. The increase in heavy rainfall frequency in CSZ highlights the role of post-monsoon
726 disturbances especially cyclones in enhancing rainfall occurrence over coastal belts.

Rainfall intensity (SDII) and extreme contribution (R95pTOT) express steady and statistically significant increasing trends mainly in CSZ. In RLZ, SDII increases range from 0.014 to 0.049 mm/day/year, while R95pTOT varies between 0.128 and 0.209 mm/year indicating moderate intensification. The magnitude is substantially higher with Purba Medinipur showing 0.030 mm/day/year (SDII) and 0.426 mm/year (R95pTOT) and South 24 Parganas recording 0.027 and 0.356 mm/year, respectively in CSZ. The spatial distribution confirms widespread positive MMK Z-scores over coastal regions indicates the robust intensification of extreme rainfall contribution. The increase in SDII and R95pTOT suggests that post-monsoon rainfall is becoming more intense and dominated by extreme events, consistent with studies linking coastal rainfall intensification to ocean–atmosphere interactions and warming sea surface temperatures (Dey & Bhardwaj, 2025).

The duration-based indices show contrasting but weak trends. Consecutive wet days (CWD) exhibit no significant change (0.000 days/year) across all districts indicating stable wet spell duration during ON. In disparity, consecutive dry days (CDD) show a consistent decreasing trend particularly in CSZ (e.g., South 24 Parganas: –0.071 days/year; Purba Medinipur: –0.048 days/year) and parts of RLZ (e.g., Puruliya: –0.038 days/year). This suggests a reduction in dry spell persistence during the post-monsoon season. Spatial maps also indicate dominant negative Z-scores for CDD especially in coastal and central regions. The decrease in dry spell duration alongside increasing rainfall intensity indicates more frequent rainfall interruptions likely associated with enhanced cyclonic activity and moisture influx during the retreating monsoon phase.

The ON season demonstrates a clear coastal-dominated intensification of rainfall extremes with CSZ exhibiting higher Sen's slope values and stronger statistical significance across most indices. Magnitude (Rx1day, Rx5day), intensity (SDII) and extreme contribution (R95pTOT) all show robust increasing trends and RLZ exhibits moderate but less coherent changes. The grid-level MMK Z-score analysis further confirms that significant increasing trends are concentrated in coastal regions reflecting the influence of Bay of Bengal processes suggesting weaker cyclone penetration inland. The decrease in CDD coupled with stable CWD indicates a shift toward more frequent rainfall events with reduced dry intervals. This seasonal asymmetry underscores the growing vulnerability of coastal regions to late-season extreme events. The results highlight that post-monsoon rainfall extremes are intensifying primarily in coastal regions due to increased cyclonic activity and oceanic forcing, reinforcing the growing importance of coastal climate dynamics in shaping extreme precipitation patterns.

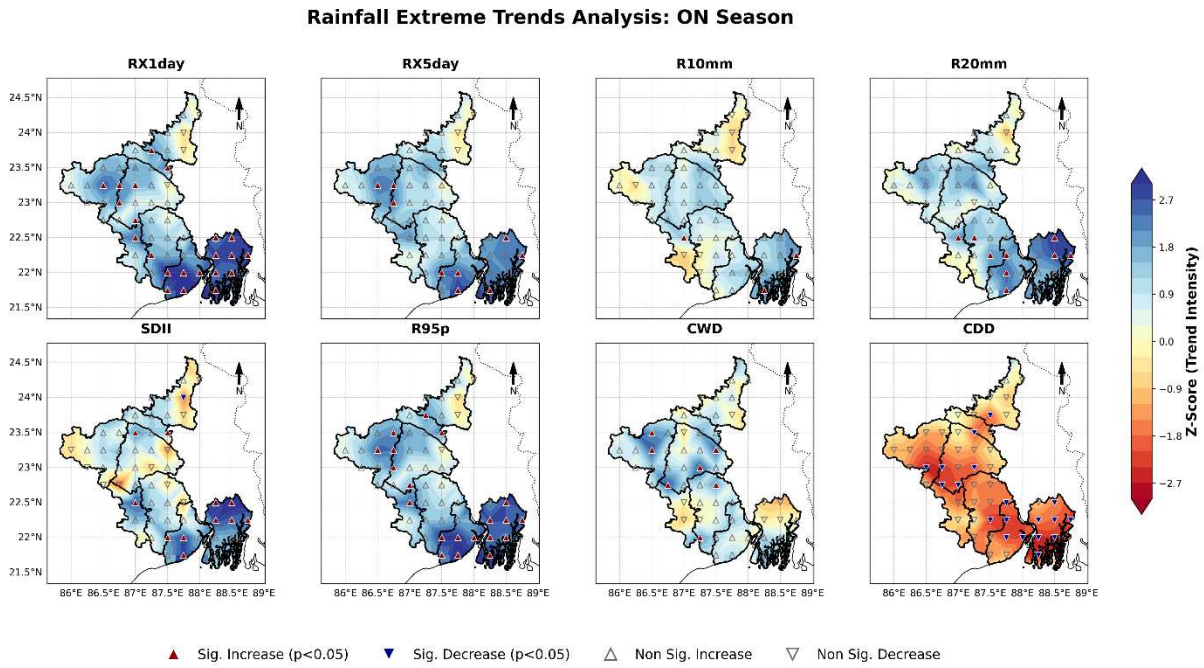


Fig. 11. Spatial distribution maps of Post-Monsoon (ON) extreme rainfall trends (Z-score intensity). Significant trends ($p \leq 0.05$) are indicated by filled triangles.

4. Summary

The present study provides a comprehensive assessment of rainfall variability, long-term trends, structural shifts and extreme precipitation behavior across the Red and Lateritic Zone (RLZ) and Coastal Saline Zone (CSZ) of the study area. By integrating statistical summaries, non-parametric trend analysis (MK, MMK, Sen's slope), change point detection (Pettitt and Buishand) and extreme rainfall indices, the analysis reveals a coherent and multi-dimensional transformation of the regional rainfall regime.

The climatological baseline confirms that rainfall is strongly monsoon-dependent with JJAS contributing the dominant share of annual total and winter rainfall remains negligible and highly erratic. The CSZ consistently records higher annual and seasonal rainfall compared to RLZ reflecting the influence of coastal proximity and moisture availability. Variability patterns further indicate that while monsoon rainfall is relatively stable, non-monsoon seasons especially DJF are highly uncertain, reinforcing the seasonal asymmetry of rainfall distribution.

Trend analysis unveils a strong spatial divergence in rainfall progression. The CSZ exhibits statistically significant and higher magnitude increasing trends mainly in annual, monsoon and post-monsoon rainfall with Sen's slope values indicating a steady intensification over time. In disparity, RLZ shows weaker, delayed and spatially inconsistent trends with significant increases largely confined to specific districts such as Jhargram. Seasonal analysis further highlights that the most robust changes are concentrated in the monsoon (JJAS) and post-monsoon (ON) periods and winter rainfall remains largely unchanged. Rainfall is not increasing equally everywhere. Instead, it changes depending on location

and season. The coastal regions show quicker and stronger increases because of the ocean-driven climate changes.

The change point analysis provides additional insight into the temporal dynamics of rainfall variability. The detection of earlier and statistically significant breakpoints in CSZ (1930s–1950s), compared to later shifts in RLZ (1960s–1980s) proposes that coastal rainfall regimes have undergone structural transformation much earlier than inland regions. Importantly, these shifts are most prominent during monsoon and pre-monsoon seasons indicating that the fundamental drivers of rainfall change are linked to large-scale atmospheric circulation and ocean–atmosphere interactions rather than local variability alone.

A key contribution of this study lies in the analysis of extreme rainfall indices which clearly demonstrate that rainfall changes are not merely quantitative but also structural in nature. Indices representing magnitude (Rx1day, Rx5day), frequency (R10mm, R20mm), intensity (SDII) and contribution (R95pTOT) show a systematic increase particularly in CSZ. The monsoon season exhibits the strongest intensification while the post-monsoon season shows a secondary peak likely influenced by cyclonic activity over the Bay of Bengal. In contrast, pre-monsoon extremes are more pronounced in RLZ driven by localized convective processes such as thunderstorms.

Equally significant is the observed shift in rainfall persistence. The decline in consecutive wet days (CWD) coupled with changes in dry spell duration (CDD) indicates a transition from prolonged rainfall events to short-duration, high-intensity bursts. This shift toward increased intermittency reflects a fundamental reorganization of the rainfall regime where precipitation is becoming more episodic, concentrated and extreme.

5. Conclusion

These changes carry deep implications from an agricultural perspective. The increasing intensity of rainfall particularly during the monsoon can lead to soil erosion, nutrient leaching and waterlogging adversely affecting crop productivity. In coastal areas, intensified rainfall combined with saline intrusion may exacerbate soil salinity and crop stress threatening traditional cropping systems. Conversely, the reduction in rainfall persistence and the emergence of longer dry intervals may increase the risk of intra-seasonal droughts particularly in RLZ where agriculture is already vulnerable due to lower rainfall and poorer soil conditions. This dual risk of both excess and deficit complicates agricultural planning and necessitates adaptive strategies such as improved drainage systems, resilient crop varieties and dynamic sowing schedules.

The socio-economic implications are equally significant. Rural livelihoods in the area are heavily dependent on rain-fed agriculture, making them highly sensitive to rainfall variability. The shift toward extreme and unpredictable rainfall patterns increases the likelihood of crop failures, income

instability and food insecurity. Coastal communities are already exposed to cyclones and flooding may face compounded risks due to intensified post-monsoon rainfall which leads to infrastructure damage, displacement and heightened vulnerability. In inland regions, increased rainfall variability may strain water resource management affecting both agriculture and domestic water availability.

The findings strongly suggest that the study area is undergoing a transition toward a high-intensity, low-persistence rainfall regime driven by a combination of monsoonal dynamics and oceanic influences. The stronger and earlier signals observed in CSZ highlight the critical role of the Bay of Bengal in modulating regional climate and the delayed and weaker responses in RLZ underscore the heterogeneity of climate change impacts across agro-climatic zones.

This study concludes that rainfall variability in the region is not only increasing but also fundamentally changing in structure and behavior. The convergence of increasing extremes, shifting temporal regimes and growing spatial disparities underscores the need for region-specific climate adaptation strategies. Policymakers and stakeholders must prioritize climate-resilient agriculture, improved water management and disaster preparedness particularly in vulnerable coastal zones. Future research should focus on integrating climate projections with crop and hydrological models to better anticipate the impacts of these changes and support sustainable development in the face of evolving climatic risks.

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Statements and Declarations

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Competing Interests

The authors declare that there are no competing interests.

Author Contribution

The study was conceptualized and designed by M.M. and G.S.. Material preparation, data collection, and analysis were performed by M.M. G.S. and B.B. provided supervision and academic guidance. B.S. and S.V.M. contributed through technical inputs and discussion of results. The first draft of the manuscript was written by M.M., and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Data availability

The data used in this study are publicly available from the India Meteorological Department (IMD) and can be accessed at: https://www.imdpune.gov.in/cmpg/Griddata/Rainfall_25_Bin.html