

Assessing Climate Variability and Long-Term Trends in Agroecological Zones of Rajasthan: A Non-Parametric Trend Analysis

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Abstract

Climate variability and long-term changes in temperature and rainfall have significant implications for agricultural sustainability and water resource management in arid and semi-arid regions. Rajasthan, being one of the most climate-sensitive states of India, frequently experiences extreme temperature conditions and irregular rainfall patterns. Understanding long-term climatic trends is therefore essential for effective planning and adaptation strategies. The present study examines the trends and variability in maximum temperature (T_{max}), minimum temperature (T_{min}), and rainfall across selected districts of Rajasthan over a long-term period from 1951 to 2021. Ten districts representing different agro-climatic conditions of the state—Ajmer, Banswara, Bharatpur, Bikaner, Jaisalmer, Jalore, Nagaur, Sri Ganganagar, Tonk, and Udaipur—were selected for the analysis. The study employed descriptive statistics and the non-parametric Mann-Kendall test to detect trends in climatic variables. The results reveal noticeable changes in temperature patterns across the study region. The Mann-Kendall test indicates a significant increasing trend in minimum temperature in several districts, particularly in Tonk, Bikaner, Sri Ganganagar, and Nagaur, suggesting a gradual warming of night-time temperatures over the past seven decades. Maximum temperature also shows a moderate increasing trend in many districts, reflecting rising heat conditions during summer months. In contrast, rainfall trends show high variability with no consistent increasing pattern across districts, indicating irregular and uncertain rainfall distribution in the region. Descriptive statistics further highlight that the highest temperatures are generally recorded during May and June, while rainfall is largely concentrated during the monsoon months of July and August. Rising trends in minimum temperature may influence crop growth patterns, water demand, and pest dynamics, highlighting the need for climate-resilient crop management practices in the region. Additionally, the high variability and uncertainty in rainfall patterns emphasize the importance of improved water management strategies, such as rainwater harvesting, efficient irrigation systems, and drought preparedness measures. The analysis of long-term climatic trends provides useful insights for agricultural planning and resource management in Rajasthan and underscores the need for region-specific adaptation strategies to strengthen agricultural resilience under changing climatic conditions.

Key Words: Climate, Variability, Temperature, Rainfall

1. Introduction

Climate variability and long-term changes in temperature and rainfall have emerged as significant global concerns due to their far-reaching impacts on ecosystems, food security, and socio-economic stability. The Intergovernmental Panel on Climate Change (IPCC, 2021) reports that the last four decades have each been successively warmer than any decade since 1850, driven primarily by anthropogenic greenhouse gas emissions. Changes in precipitation patterns, increases in heat extremes, and intensified hydrological cycles have also been observed, affecting agriculture-dependent regions worldwide. According to the World Meteorological Organization (WMO, 2020), global mean temperature has already increased by approximately 1.1 °C above pre-industrial levels, contributing to heightened climate risks in arid and semi-arid environments.

India is identified as one of the world's most climate-sensitive regions, with the Ministry of Environment, Forest and Climate Change (MoEFCC, 2018) noting increased frequency of extreme temperatures, erratic monsoon behaviour, and rising incidence of droughts and floods. The India Meteorological Department (IMD, 2020) highlights a significant warming trend across most parts of the country, with notable increases in both maximum and minimum temperatures over recent decades. Rainfall variability, including delayed onset and uneven spatial distribution of monsoon rainfall, has been flagged as a major concern affecting agricultural productivity in rainfed regions. Reports by FAO (2019) and the World Bank (2013) further emphasise that climate-induced stresses pose severe risks to India's food security, water resources, and rural livelihoods.

Rajasthan, located in northwestern India between approximately 23°30'N to 30°11'N latitude and 69°29'E to 78°17'E longitude, lies predominantly in the arid and semi-arid climatic zones and is highly vulnerable to climate variability. The Rajasthan State Action Plan on Climate Change (Government of Rajasthan, 2012) identifies persistent warming, declining and erratic rainfall, high evapotranspiration, and frequent droughts as major climatic challenges. Nearly two-thirds of the state is drought-prone, and its agriculture depends heavily on monsoon rainfall, making it extremely sensitive to changes in temperature and precipitation. UNESCO (2018) further notes that water scarcity in western India, including Rajasthan, is expected to intensify due to increasing climatic stress and overexploitation of groundwater resources.

Given this context, analysing long-term trends in agro-meteorological parameters, such as temperature ($T_{\max}$ and $T_{\min}$) and rainfall, is essential to support climate-resilient agricultural planning, irrigation management, and drought mitigation strategies in Rajasthan.

The objective of the present study is to assess long-term trends in maximum and minimum temperatures and rainfall across selected regions of Rajasthan, using nonparametric statistical techniques to evaluate spatial and temporal variations in these key agro-meteorological parameters.

1.1 Review of Literature

Climate variability and long-term changes in rainfall and temperature have been widely examined at global, national, and regional scales using non-parametric trend detection techniques. At the global level, the interaction between climate change and anthropogenic land-use modification has been identified as a major driver of regional warming. A comparative assessment of station observations and reanalysis datasets demonstrated that urbanisation and land-use changes significantly enhance surface warming and reduce diurnal temperature range, indicating strong human influence on near-surface climate systems (Kalnay and Cai, 2003). These global findings provide an important context for understanding observed warming trends across India's rapidly urbanising and climate-sensitive regions.

At the national scale, long-term climatic analyses consistently indicate warming accompanied by increasing rainfall variability. A 141-year assessment (1871- 2011) across India reported declining annual and monsoon rainfall in several subdivisions alongside significant increases in maximum, minimum, and mean temperatures, with pronounced warming during winter and post-monsoon seasons (Mondal et al., 2015). Similarly, an India-wide study covering 1901-2014 identified significantly negative trends in annual and summer rainfall during recent decades, coupled with rapid warming across all seasons, suggesting that arid and semi-arid regions are experiencing stronger warming signals compared to humid regions (Radhakrishnan et al., 2017). Increasing rainfall irregularity has also been documented across northwest India, where fewer rainy days contribute to higher precipitation intensity, thereby elevating risks of both droughts and flash floods (Guhathakurta and Rajeevan, 2008).

Within this broader national context, Rajasthan- India's largest arid state exhibits strong spatial heterogeneity in climatic trends. State-level analysis using long historical records (rainfall: 1871-2016; temperature: 1901-2002) revealed increasing pre-monsoon, monsoon, and annual rainfall in western Rajasthan, while eastern Rajasthan experienced rising pre- and post-

monsoon rainfall, accompanied by significant annual temperature increases across both regions (Mehta et al., 2020). Complementing these findings, an urban-focused assessment across 33 Rajasthan cities using gridded datasets and MK-Sen's slope methods identified mixed rainfall trends but widespread significant warming in minimum, average, and maximum temperatures, highlighting rapid urban climate intensification (Pingale et al., 2014).

Future climate projections further reinforce the persistence of warming signals in the region. Downscaled General Circulation Model (GCM) projections using the LARS-WG weather generator projected consistent increases in both maximum and minimum temperatures across Rajasthan, along with rising extreme indices such as tropical nights and warm spells, indicating escalating heat stress conditions (Sharma et al., 2018). Supporting this, CMIP5-based simulations across Indian climate zones showed that warming levels between 1°C and 3°C would substantially increase hot days, warm nights, and warm spell duration, with arid regions emerging as climate-change hotspots after northern cold regions (Yaduvanshi et al., 2020).

Evidence from other arid and semi-arid regions of India demonstrates patterns comparable to Rajasthan, strengthening the regional consistency of observed climatic shifts. In Ananthapuramu district of arid Andhra Pradesh, modified MK and Sen's slope analyses (1981-2016) indicated localized increases in summer rainfall but declining trends in certain monsoon seasons, emphasizing the importance of accounting for serial correlation in trend detection (Patakamuri et al., 2020). Likewise, semi-arid Bundelkhand showed no statistically significant annual rainfall trend despite uniformly negative Sen's slope values, while ARIMA projections suggested a future rainfall decline of approximately -7.6 mm per year, indicating increasing aridity risks (Som et al., 2022). Long-term agro-climatic analysis in semi-arid Karnataka also confirmed persistent drought proneness, with most zones classified under dry climatic regimes despite localized cooling tendencies in some hilly areas (Rani et al., 2021).

Local-scale studies further highlight spatial climatic complexity within arid environments. For example, trend analysis in Junagadh (1980-2011) identified cooling in annual and winter temperatures but monsoon warming driven by rising minimum temperatures, underscoring the importance of localized climatic assessments rather than broad regional generalizations (Ram et al., 2015). Similarly, long-term analysis in Kolkata district revealed significant increases in temperature and monsoon rainfall concentration, reflecting heightened climatic variability in urbanized regions (Paira et al., 2023).

Collectively, these studies demonstrate a coherent pattern: while rainfall trends across arid and semi-arid India remain spatially inconsistent, temperature increases, particularly minimum temperature and heat extremes, are widespread and statistically significant. The convergence of observational analyses, regional assessments, and climate projections indicates intensifying heat stress, increasing rainfall irregularity, and growing hydro-climatic vulnerability in Rajasthan and similar dryland ecosystems. These findings underscore the need for region-specific climate adaptation strategies and localised climatic assessments to support sustainable agriculture and resource management in arid regions.

2. Methodology

2.1. *Locale of the study*

Rajasthan, the largest state of India in terms of geographical area, is located in the northwestern part of the Indian subcontinent and exhibits wide climatic diversity ranging from extremely arid desert conditions in the west to sub-humid climates in the southeast. For the present study, one representative district was selected from each of the ten Agro-Ecological Zones (AEZs) of Rajasthan, as classified by (National Bureau of Soil Survey and Land Use Planning, 2012) . These selected districts-Jaisalmer, Sri Ganganagar, Bikaner, Nagaur, Ajmer, Bharatpur, Udaipur, Banswara, Tonk, and Jalore-collectively provide complete spatial coverage of the state's climatic variability. Each district represents the dominant climate, soil type, and farming system of its respective agro-ecological zone, making the dataset geographically comprehensive and scientifically robust for climate trend analysis. The geographical location of the selected districts is illustrated in Figure 1, while the agro-ecological details of the study area are summarised in Table 1.

Table 1: Geographical details of the selected Agroecological zones

S.No	Agro-ecological Zones	Selected district	Latitude	Longitude	Area (sq. kms)
1	AEZ 1: Arid Western Plains	Jaisalmer	26.91° N	70.922928° E	38,401
2	AEZ 2: Irrigated North-Western Plains	Sri Ganganagar	29.90° N	73.877190° E	11,154.66
3	AEZ 3: Hyper-Arid Partial Irrigated Zone	Bikaner	28.02° N	73.302155° E	30,247
4	AEZ 4: Transitional Plain of Inland Drainage	Nagaur	26. 24° N	73.04° E	17,718
5	AEZ 5: Semi-Arid Eastern Plain	Ajmer	25.38°N	73.53° E	8,481

6	AEZ 6: Flood-Prone Eastern Plains	Bharatpur	26.41°N	76.52° E	5066
7	AEZ 7: Sub-Humid Southern Plains	Udaipur	24.58° N	73.68° E	13,430
8	AEZ 8: Humid Southern Plains	Banswara	23.54° N	74.43° E	5,037
9	AEZ 9: Central Plateau Zone	Tonk	26.24° N	76.16° E	7,194
10	AEZ 10: Arid South-Eastern Plains	Jalore	25.22° N	72.58° E	10,640

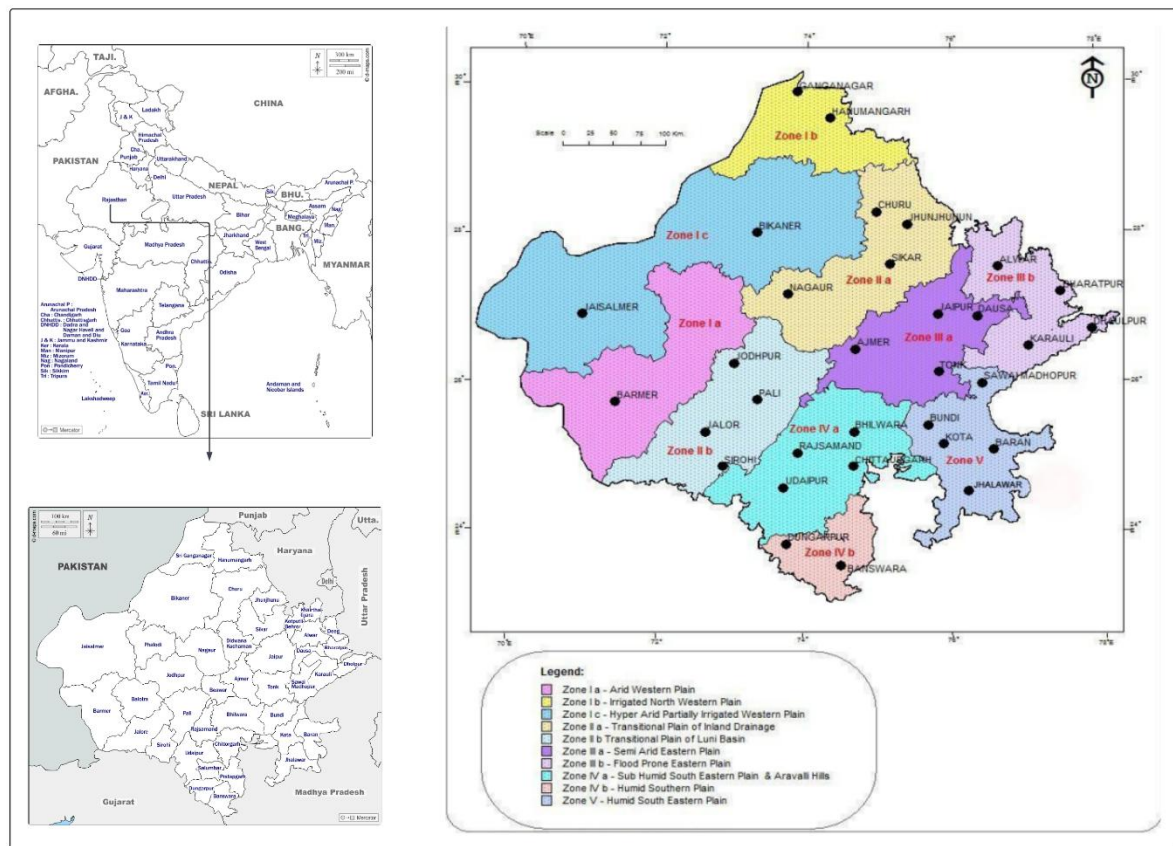


Fig.1: Map of the selected agroecological zones of Rajasthan

2.2 Data Set

For the present study, historical climatic data for rainfall, Tmin, and Tmax for the period 1950 to 2021 were accessed from the India Meteorological Department (IMD) gridded dataset through the Climate Research and Services portal. Daily rainfall ($0.25^\circ \times 0.25^\circ$) and temperature ($1^\circ \times 1^\circ$) grids corresponding to the selected districts within the ten agro-ecological zones of Rajasthan were extracted and processed in Python, enabling efficient handling of long-term datasets and ensuring reproducibility (Pai et al., 2014 ; Srivastava et al., 2009). The annual total

rainfall and mean seasonal Tmax and Tmin were prepared for trend analysis, providing a reliable and consistent climatic dataset for evaluating long-term changes across Rajasthan.

2.3 Analytical Approach

2.3.1. Mann–Kendall's Trend Test

The Mann-Kendall (MK) trend test was applied to determine the presence of a monotonic trend in the selected climatic variables. The MK test is a widely used non-parametric statistical approach for evaluating trends in climatic and hydro-meteorological data (Mezdour and Probst, 2016; Zhao et al., 2015), as well as in general time-series analysis (Pingale et al., 2014). This non-parametric method was preferred because it is particularly effective for datasets typically encountered in hydro-meteorological studies (Altin and Barak, 2014; Araghi et al., 2016). Non-parametric tests are considered more suitable than parametric tests when the data do not follow a normal distribution or when the series contains outliers or filtered values, which are common characteristics of climate datasets (Yue and Pilon, 2004; Yue et al., 2002). The Mann-Kendall test offers two major advantages: it does not require the data to be normally distributed (Karmeshu, 2012), and it is less affected by discontinuities or non-homogeneities within the time series (Tabari et al., 2011).

In the Mann-Kendall trend test, the null hypothesis (H_0) states that no trend exists in the data, implying that the observations are independent and randomly distributed. This is evaluated against the alternative hypothesis (H_1), which suggests that a trend is present in the time series (Bihrat and Mehmet, 2003). The decision on the hypothesis is based on the probability value (p-value). When the p-value is greater than the significance level $\alpha = 0.05$, the null hypothesis cannot be rejected, indicating the absence of a statistically significant trend. Conversely, if the p-value is less than $\alpha = 0.05$, the null hypothesis is rejected, confirming the presence of a significant trend in the dataset (Tian, 2016). The Mann-Kendall statistics are computed according to the procedures outlined by Kendall (1975) and Mann (1945).

$$T_{MK} = \frac{S - \text{sgn}(S)}{\sqrt{V(S)}}$$

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

where n is the number of data points; x_j and x_i are the data values in the time series; i and j ($j > i$) are the total dataset; and $\text{sgn}(x_j - x_i)$ is the sign function, whereby they are calculated as follows:

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

The variance is calculated as:

$$E(S) = 0$$

$$V(S) = \frac{n(n-1)(2n+5) - \sum_{k=1}^m t_k(t_k-1)(2t_k+5)}{18}$$

Where t_k is the total bonding point k . Standard statistical test z is calculated as

$$Z_S = \begin{cases} \frac{S-1}{\sqrt{V(S)}}, & \text{if } S > 0 \\ 0, & \text{if } S = 0 \\ \frac{S+1}{\sqrt{V(S)}}, & \text{if } S < 0 \end{cases}$$

The standardized statistical Mann- Kendall Z value follows a standard normal distribution with a mean of zero and a variance of one. A positive Z value indicates an increasing trend, whereas a negative Z value indicates a decreasing trend (Mozejko, 2012). The null hypothesis (H_0) is rejected when the absolute value of Z_s exceeds the critical value $z_{\alpha/2}$, where α denotes the chosen significance level. In such cases, the null hypothesis is considered invalid, implying that a significant trend exists in the data (Motiee and McBean 2009).

2.3.2. Sen's Slope Estimator Test

When a time series exhibits a linear trend, the actual rate of change over time can be quantified using a non-parametric slope-estimation method. Sen (1968) proposed a distribution-free approach for computing the trend slope from N pairs of observations. The present research employed Sen's slope estimator to determine the magnitude of variation in each climate parameter. This technique is widely used because it offers a reliable non-parametric estimate of the trend slope based solely on the sample of paired data. Where

$$Q_i = \frac{x_j - x_k}{j - k} \text{ for } i=1, \dots, N,$$

x_j and x_k are the data values at times j and k ($j > k$), respectively. If it only has one observation in each time period, then

$$N = \frac{n(n-1)}{2}$$

where n is the number of time periods, and if there are multiple observations in one or more time periods, then

$$N < \frac{n(n-1)}{2}$$

where n is the total number of observations. The median of slope or Sen's slope estimator is computed as,

$$Q_{med} = \begin{cases} Q_{[\frac{N+1}{2}]} & \text{if } N \text{ is odd} \\ \frac{Q_{[\frac{N}{2}]} + Q_{[\frac{N+2}{2}]}}{2} & \text{if } N \text{ is even} \end{cases}$$

If the Q_{med} gives a positive value, it indicates an upward or increasing trend, while a negative value indicates a downward or decreasing trend.

3. Results

The Mann-Kendall trend test was carried out to assess the direction and extent of change in minimum temperature, maximum temperature and rainfall in the ten agro climatic zones present in Rajasthan by selecting one district each from the Agro Ecological zone. The results are presented as per the different parameters given below.

3.1 Trend in maximum temperature (T_{max})

Table 2 presents the trend analysis of maximum temperature (T_{max}) for the period 1951-2021 across the selected districts of Rajasthan using the Mann-Kendall test. Maximum temperature is another pertinent indicator of a changing climate, and also for the sustainability of the agricultural sector. Any anomalies in the temperature can severely impact the crop production as well as physiology. The analysis highlights a consistent and pervasive warming signal across agroecological regions. Yet, the rate and statistical significance vary spatially.

Table.2. Trend analysis of T_{max} (1951-2021) using the MK test (at 5% level of significance)

District	S statistic	Sen's slope	Trend	value (Z)	tau	Significance of tau values
Jaisalmer	1081.00	0.017*	Increasing	18.740	0.435	Moderately Significant
Sri Ganganagar	127.00	0.001	Increasing	0.625	0.051	Not Significant
Bikaner	421.00	0.007*	Increasing	6.202	0.169	Not Significant
Nagaur	725.00	0.011*	Increasing	9.382	0.291	Weakly Significant
Ajmer	581.00	0.009*	Increasing	8.057	0.233	Weakly Significant
Bharatpur	41.00	0.0004	Increasing	0.768	0.016	Not Significant
Udaipur	591.00	0.0078*	Increasing	7.463	0.237	Weakly Significant
Banswara	373.00	0.0052*	Increasing	4.710	0.150	Not Significant
Tonk	371.00	0.0064*	Increasing	5.466	0.149	Not Significant
Jalore	839.00	0.0126*	Increasing	11.553	0.337	Weakly Significant

Within the hot arid ecosystem of desert and saline soils, the trend was found to be pronounced. Evidently, in Rajasthan, all the districts except Sri Ganganagar and Bharatpur exhibited statistical significance of the trend in maximum temperature. The positive values for Kendall's Tau suggested that all the districts, in general, showed a rising trend in maximum temperature. Jaisalmer showed the highest rate of change among all the districts, with an expected change of 0.017°C per year, which was followed by Jalore (0.012), Nagaur (0.011) and Ajmer (0.009). The lowest rate of change, on the other hand, was observed in Bharatpur (0.0004) and Banswara (0.005).

Thus, the highest rate of change was observed in general in Western arid plains, transitional plains of inland drainage, arid south-eastern plains and semi-arid eastern plains. The lowest rate was found, on the other hand, in flood-prone eastern plains and humid southern plains. Further, the winters showed in general a greater variability of maximum temperature, as can be seen in general from Table. The highest variability in temperature was found to be highest for Bikaner, Bharatpur and Sri Ganganagar. The strongest trends were observed to be concentrated in arid and hyper-arid regions, whereas semi-arid and sub-humid zones exhibited a slower but consistent increase. This uniform rise, when coupled with the heterogeneous rainfall trends, suggests an escalating likelihood of increasing heat stress conditions across diverse agroecosystems. Thus, the highest rate of change was observed in general in Western arid plains, transitional plains of inland drainage, arid south-eastern plains and semi-arid eastern plains. The lowest rate was found, on the other hand, in flood-prone eastern plains and humid southern.

Table 3. Summary statistics for Tmax (1951-2021) in the districts of Rajasthan

	Ajmer			Banaswara			Bharathpur			Bikaner			Jaisalmer		
Month	Mean	SD	CV	Mean	SD	CV	Mean	SD	CV	Mean	SD	CV	Mean	SD	CV
January	23.5	1.1	4.7	26.0	1.0	4.0	21.2	1.2	6.0	22.4	1.1	5.1	24.7	1.1	4.5
February	26.9	1.7	6.3	29.1	1.4	5.0	25.1	1.6	6.6	25.9	1.8	7.0	27.9	1.7	6.0
March	32.6	1.7	5.2	34.0	1.4	4.0	31.2	1.7	5.5	31.7	1.9	6.0	33.2	1.6	4.8
April	38.0	1.4	3.7	38.2	1.0	2.8	37.8	1.4	3.7	37.6	1.6	4.2	37.9	1.3	3.5
May	41.0	1.2	2.9	39.8	0.9	2.2	41.0	1.3	3.3	41.1	1.4	3.4	40.3	1.0	2.4
June	39.7	1.1	2.8	36.6	1.3	3.5	40.1	1.5	3.7	40.8	1.1	2.8	38.9	1.0	2.6
July	34.7	1.3	3.7	31.1	1.1	3.7	35.2	1.4	4.1	36.9	1.3	3.6	35.0	1.2	3.5
August	32.6	1.0	3.2	29.4	0.8	2.9	33.6	0.9	2.9	35.2	1.1	3.2	33.2	1.1	3.3
September	34.0	1.4	4.2	31.4	1.3	4.3	34.2	1.2	3.5	35.6	1.3	3.8	34.4	1.4	4.0
October	34.4	1.4	4.1	33.5	1.4	4.3	33.7	1.3	3.8	35.1	1.3	3.8	35.3	1.3	3.8
November	30.1	1.0	3.5	30.7	0.9	3.2	29.0	0.8	3.0	30.0	1.0	3.5	31.1	1.0	3.3
December	25.4	1.2	4.9	27.3	1.0	3.8	23.3	1.3	5.5	24.6	1.4	5.6	26.6	1.1	4.3

Table 4. Summary Statistics for Tmax (1951–2021) in the Districts of Rajasthan (Continued)

	Jalore			Nagaur			Sri ganganagar			Tonk			Udaipur		
Month	Mean	SD	CV	Mean	SD	CV	Mean	SD	CV	Mean	SD	CV	Mean	SD	CV
January	24.9	1.1	4.5	23.1	1.1	4.9	20.8	1.2	5.8	22.9	1.1	4.9	25.1	1.0	4.3
February	28.05	1.6	5.9	26.6	1.8	6.8	24.1	1.8	7.4	26.4	1.7	6.6	28.1	1.5	5.4
March	33.31	1.5	4.8	32.4	1.8	5.7	29.8	2.0	6.6	32.2	1.7	5.3	33.2	1.4	4.3
April	37.6	1.3	3.6	37.8	1.5	4.0	36.4	1.6	4.5	37.7	1.4	3.7	37.4	1.2	3.2
May	39.7	1.0	2.6	40.9	1.3	3.2	40.4	1.5	3.7	40.8	1.3	3.1	39.4	0.9	2.4
June	37.9	1.0	2.9	40.4	1.1	2.7	40.5	1.2	3.0	39.8	1.2	3.0	37.0	1.1	3.0
July	33.4	1.2	3.7	36.3	1.3	3.6	36.6	1.3	3.5	34.6	1.4	4.1	31.9	1.2	3.7
August	31.6	1.0	3.4	34.3	1.1	3.3	35.1	1.0	3.0	32.5	1.0	3.1	30.1	0.9	3.1
September	33.2	1.4	4.4	35.2	1.4	4.1	35.2	1.2	3.3	33.8	1.4	4.1	32.0	1.4	4.3
October	34.6	1.3	3.9	35.2	1.4	3.9	34.1	1.2	3.7	34.0	1.4	4.2	33.8	1.3	4.1
November	30.7	1.0	3.4	30.3	1.1	3.6	28.8	1.0	3.3	29.6	1.1	3.6	30.4	1.0	3.3
December	26.7	1.1	4.2	25.3	1.3	5.2	23.1	1.4	6.1	24.9	1.3	5.2	26.7	1.0	3.9

The summary statistics (Table 3 and 4) of Tmax (1951–2021) across ten districts of Rajasthan indicate clear seasonal variation in maximum temperatures. In all districts, Tmax gradually increases from January and reaches its peak during May–June, followed by a decline during the monsoon and winter months. The highest mean Tmax values are observed during May, with temperatures exceeding 40°C in several districts such as Ajmer, Bikaner, Bharatpur, Nagaur, and Sri Ganganagar, reflecting intense summer heat in the region. In contrast, the lowest mean Tmax values occur during January and December, generally ranging between about 20°C and

26°C across districts. The standard deviation values are relatively low throughout the year, indicating moderate variability in maximum temperature. Similarly, the coefficient of variation (CV) remains mostly below 7% in all districts and months, suggesting stable temperature patterns over the study period. Overall, the results highlight a consistent seasonal Tmax pattern across Rajasthan districts, with extreme heat conditions during late summer months and comparatively mild temperatures during winter.

The graphical trend analysis (Fig.2) of Tmax (1951–2021) indicated further supports the presence of a general increasing pattern in maximum temperature across the selected districts of Rajasthan. Most districts exhibit a positive trend line, indicating a gradual rise in temperature over time, although the strength of the trend varies. Districts such as Banswara, Tonk, and Jaisalmer show relatively steeper upward trends, suggesting a more pronounced increase in Tmax, whereas districts like Bharatpur, Jalore, and Sri Ganganagar display weaker or nearly stable trends. The low R^2 values in most cases indicate that, despite the upward tendency, there is considerable year-to-year variability in temperature. Overall, the figure highlights a consistent but uneven warming trend across districts, reflecting spatial differences in the rate of temperature increase in Rajasthan.



Fig.2: Variability in annual average maximum temperature in selected districts of Rajasthan(1951-2022)

3.2 Trend in Rainfall

Table 5 presents the trend analysis of annual rainfall for the period 1951-2021 across the selected districts of Rajasthan using the Mann-Kendall test. The long-term analysis of the trend for annual rainfall is calculated taking into account the importance of rainfall intensity and distribution in determining the crop yield and thereby production. The man, Kendall and Sen's slope analysis suggested that arid and hyper arid zones are likely to exhibit gradual intensification of the rainfall. On the other hand, a few semi-arid regions are exhibiting a statistically significant decline in rainfall.

In the hot arid ecosystem of desert and saline soils, a significant increasing trend was observed in the majority of the districts. Specifically, Jaisalmer exhibited a strong and statistically significant rise in rainfall with a lower p-value (<0.01), and the sen slope suggested a 1.13 mm per year rise in rainfall. Also, Bikaner exhibited a statistically significant rise of 1.16 mm per year. Despite Sri Ganganagar and Nagaur displaying increasing trends, those were statistically insignificant. This suggests a greater interannual variability rather than a strong directional shift. With a weak trend shown in Jalore, relative rainfall stability was expected for the arid and semi-arid interface.

Table 5: Trend analysis of rainfall (1951-2021) using the MK test (at 5% level of significance).

District	S statistic	Sen's slope	Trend	value (Z)	tau	Significance of tau values
Jaisalmer	303.00	1.1325*	Increasing	3.202	0.121	Not Significant
Sri Ganganagar	147.00	0.4128	Increasing	0.724	0.059	Not Significant
Bikaner	403.00	1.1579*	Increasing	1.995	0.162	Not Significant
Nagaur	79.00	0.3514	Increasing	0.953	0.031	Not Significant
Ajmer	-311.00	-1.6271*	Decreasing	-2.786	-0.125	Not Significant
Bharatpur	47.00	0.2629	Increasing	0.228	0.018	Not Significant
Udaipur	193.00	1.2956	Increasing	0.953	0.077	Not Significant
Banswara	175.00	1.7622	Increasing	0.863	0.070	Not Significant
Tonk	-275.00	-1.7427*	Decreasing	-2.115	-0.110	Not Significant
Jalore	-15.00	-0.0767	Decreasing	-0.269	-0.006	Not Significant

An altogether varying trend was observed for the hot semi-arid ecosystem of alluvial and red soils. Ajmer and Tonk showed a statistically significant decline in rainfall with Sen's slope values of -1.63 mm per year and -1.74 mm per year, respectively. These districts are located in the transitional and eastern portions of Rajasthan. It appeared to be undergoing gradual drying despite its higher baseline rainfall. Flood prone eastern plains of Bharatpur, on the other hand,

showed a marginal increasing trend but with no statistical significance. Overall rainfall trend analysis highlights a strong and statistically significant contrast between arid and semi-arid regions. Herein, core arid zones experienced rising rainfall while semi-arid western and central regions faced a decline. This divergence highlights the evolving nature of hydroclimatic stress in Rajasthan.

Figure 3 illustrates the long-term trend of annual rainfall (1951-2021) across the selected districts of Rajasthan. The graphical analysis reveals considerable interannual variability in rainfall across all districts, with no uniform pattern of change. While districts such as Jaisalmer, Bikaner, and Udaipur exhibit a slight increasing trend, districts like Ajmer and Tonk show a declining tendency over time. In most cases, the trend lines are weak, indicating that changes in rainfall are not consistent and are largely influenced by year-to-year fluctuations. The low coefficient of determination (R^2) values further confirms the high variability and unpredictability of rainfall across the region. Overall, the figure highlights that rainfall trends in Rajasthan are highly erratic and spatially diverse, unlike the relatively consistent increasing trend observed in temperature.

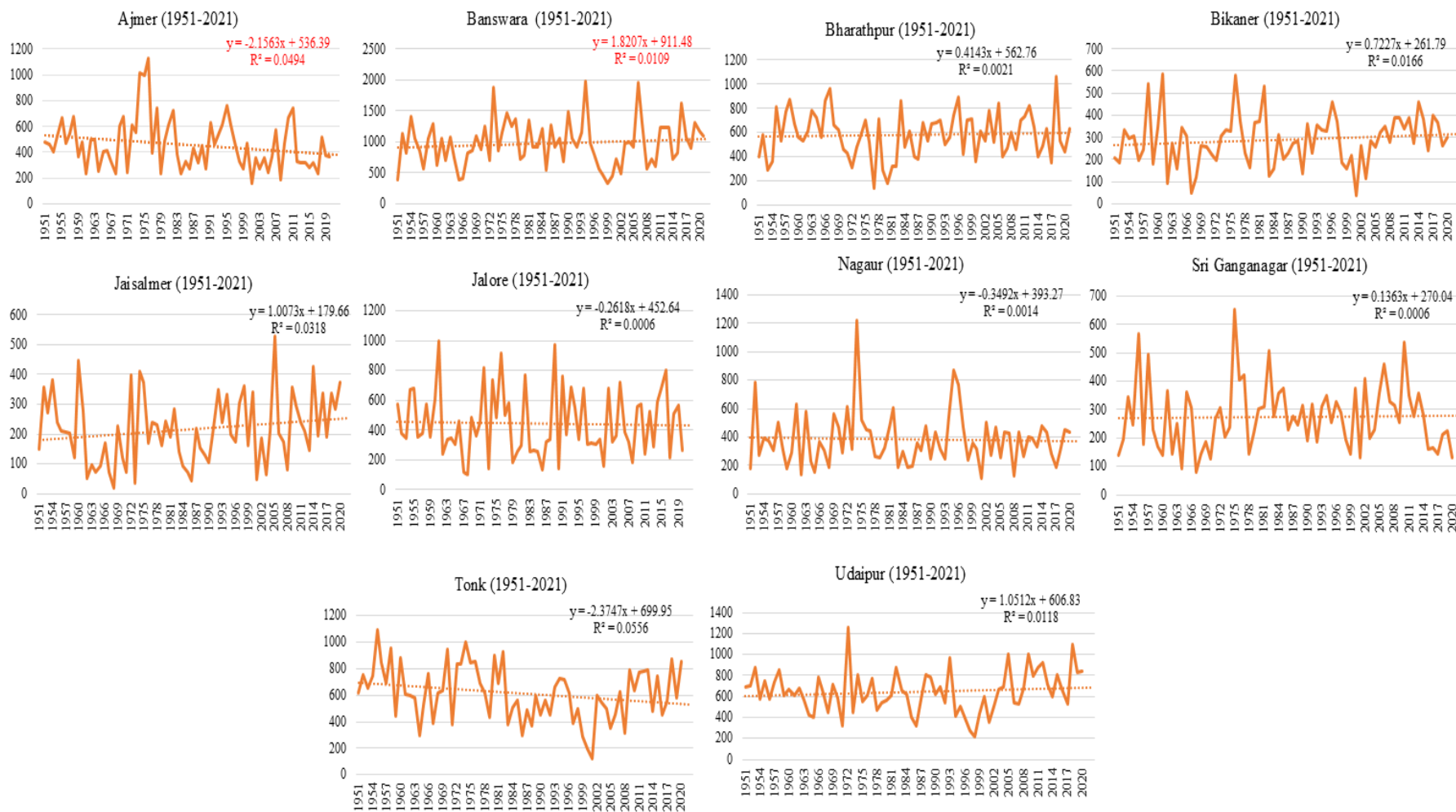


Fig.3: Variability in annual average rainfall in selected districts of Rajasthan(1951-2022)

Table 6: Summary statistics for annual rainfall in mm (1951–2021) in the districts of Rajasthan

	Ajmer			Banaswara			Bharathpur			Bikaner			Jaisalmer		
Month	Mea n	SD	CV	Mea n	SD	CV	Mea n	SD	CV	Mea n	SD	CV	Mea n	SD	CV
January	3.3	7.1	213.5	2.4	8.8	368.9	10.2	20.5	199.9	4.3	6.0	139.5	3.3	7.1	213.5
Februar y	4.6	11.1	241.6	0.7	2.9	374.6	7.2	12.5	173.8	8.3	18.1	217.8	4.6	11.1	241.6
March	2.9	7.3	246.6	1.0	4.4	412.3	6.2	10.9	176.2	7.4	13.5	182.2	2.9	7.3	246.6
April	3.4	8.8	258.6	1.5	6.3	397.9	3.8	8.1	212.7	6.8	13.9	203.0	3.4	8.8	258.6
May	13.8	29.4	212.9	3.9	9.3	236.3	10.2	13.6	133.0	18.6	22.5	120.5	13.8	29.4	212.9
June	44.4	54.9	123.8	96.1	81.4	84.7	45.8	49.1	107.0	36.2	35.4	97.7	44.4	54.9	123.8
July	158.5	107.6	67.9	311.4	170.4	54.7	191.6	113.9	59.4	83.1	71.0	85.4	158.5	107.6	67.9
August	147.2	94.7	64.3	349.6	211.6	60.5	191.5	107.1	55.9	68.2	51.7	75.7	147.2	94.7	64.3
Septem ber	62.7	59.2	94.4	172.5	166.9	96.7	89.8	81.5	90.7	40.0	52.0	129.8	62.7	59.2	94.4
October	10.5	28.1	267.5	26.8	47.7	177.8	15.9	25.6	161.1	8.4	23.7	279.5	10.5	28.1	267.5
Novem ber	3.2	9.3	287.9	8.0	23.2	288.5	2.0	5.1	246.1	2.6	8.0	301.8	3.2	9.3	287.9
Decemb er	31.5	4.8	316	2.4	12.8	525	2.9	7.7	259.2	1.9	5.4	287.1	1.5	4.8	316

Table 7: Summary Statistics for annual rainfall in mm (1951–2021) in the Districts of Rajasthan (Continued)

	Jalore			Nagaur			Sri ganganagar			Tonk			Udaipur		
Month	Mea n	SD	CV	Mea n	SD	CV	Mea n	SD	CV	Mea n	SD	CV	Mea n	SD	CV
January	2.3	4.8	205.5	4.0	7.9	195.7	5.9	8.7	147.9	5.3	11.6	217.4	3.7	9.4	253.2
Februar y	3.0	9.0	300.9	4.6	10.5	225.7	11.0	16.5	149.4	5.6	10.4	183.9	2.2	5.5	250.8
March	2.8	14.7	511.4	3.4	7.3	215.4	9.4	14.8	157.1	4.3	9.8	225.6	4.3	19.3	447.5
April	1.9	4.5	231.2	5.6	11.3	201.5	5.7	8.7	152.5	3.7	10.4	281.6	4.0	6.7	166.0
May	9.5	16.8	176.0	16.6	19.7	118.4	10.5	14.1	133.3	10.1	16.2	160.4	12.0	20.4	170.5
June	38.6	32.6	84.2	43.6	74.4	170.4	33.8	39.4	116.4	52.4	51.0	97.4	74.7	44.8	60.0
July	162.4	140.2	86.3	131.9	101.8	77.2	81.2	62.2	76.5	212.3	123.5	58.1	200.9	90.1	44.8
August	139.4	118.5	85.0	114.4	102.7	89.7	60.9	57.1	93.7	220.8	119.2	53.9	204.0	117.7	57.7

September	64.0	82.0	128.0	42.8	49.5	115.8	46.9	68.3	145.3	78.0	65.3	83.7	105.1	90.7	86.2
October	10.1	22.8	224.5	6.7	18.3	271.8	3.3	7.1	215.1	11.5	25.2	218.6	15.5	28.7	185.1
November	5.2	15.5	298.2	1.8	5.7	317.4	1.6	4.6	278.8	4.0	11.3	282.3	11.5	32.2	280.1
December	0.9	3.5	368.6	1.7	4.7	263.7	3.2	7.5	233.4	2.6	6.2	238.1	2.3	6.8	295.1

The summary statistics (Table 6 and Table7) of annual rainfall (1951–2021) across the ten districts of Rajasthan show a strong seasonal pattern, with the majority of rainfall occurring during the monsoon months of June to September. Among these months, July and August receive the highest mean rainfall in most districts. Banswara records the highest rainfall, with mean values of about 311.4 mm in July and 349.6 mm in August, followed by Udaipur and Tonk, indicating comparatively wetter conditions in the southern districts. In contrast, districts such as Jaisalmer, Bikaner, and Jalore receive relatively lower rainfall, reflecting the arid and semi-arid climate of western Rajasthan. During the winter and pre-monsoon months (January to May) and post-monsoon months (October to December), rainfall remains very low across all districts. The coefficient of variation CV is very high in most months, particularly during the non-monsoon period, indicating large variability and irregular rainfall distribution. Overall, the results highlight the strong dependence of rainfall on the monsoon season and significant spatial variability across districts.

3.3 Trend in Minimum Temperature

Table 8 presents the trend analysis of minimum temperature (Tmin) for the period 1951-2021 across the selected districts of Rajasthan using the Mann-Kendall test. It was found that all ten districts under study showed a highly statistically significant trend in temperature. In fact, a rising trend of minimum temperature across all the agro Ecological zone of Rajasthan was observed. Evidently, the tau value for all the districts was found to be positive. Sri Ganganagar, Bikaner, Bharatpur and Tonk exhibited a value of tau above 0.4, suggesting a moderate level of significance of the trend. Additionally, the values were positive for all districts. Further the Sen's slope values depicted that Bikaner and Tonk exhibited the highest rate of change in minimum temperature, which was 0.0241 and 0.0221 °C per year. The least rate of change was observed for Udaipur (0.005) and Bharatpur (0.008).

Thus, the indiscriminate effects of climate change in the form of rising temperatures are observed in Rajasthan. The agroclimatic zone-wise elaboration suggests that the hot arid ecosystem of desert and saline soils show pronounced rising trend in minimum temperature. In addition to this, the hot semi-arid ecosystem of alluvial and red soils was also found to exhibit a higher trend in rising minimum temperature. With significant warming pertaining to minimum temperature, Jaisalmer and Nagaur exhibited emergence of warmer nights across the western arid landscape.

Table 8: Trend analysis of Tmin (1951-2021) using the MK test (at 5% level of significance).

District	S statistic	Sen's slope	Trend	value (Z)	tau	Significance of tau values
Jaisalmer	629.00	0.012*	Increasing	2.95	0.253	Weakly Significant
Sri Ganganagar	1057.00	0.019*	Increasing	5.45	0.425	Moderately Significant
Bikaner	1205.00	0.022*	Increasing	6.19	0.484	Moderately Significant
Nagaur	923.00	0.018*	Increasing	4.22	0.371	Weakly Significant
Ajmer	1005.00	0.018*	Increasing	4.75	0.404	Moderately Significant
Bharatpur	623.00	0.008*	Increasing	2.83	0.250	Weakly Significant
Udaipur	363.00	0.005*	Increasing	2.54	0.146	Not Significant
Banswara	427.00	0.004*	Increasing	3.21	0.171	Not Significant
Tonk	1265.00	0.024*	Increasing	8.31	0.509	Moderately Significant
Jalore	637.00	0.010*	Increasing	3.28	0.256	Weakly Significant

Hot semi-arid ecosystem of alluvial and red soils showed a sharp and statistically significant rise in minimum temperature, where Tonk showed the highest Sen's slope (0.024°C per year). Further, the coefficient of variation for minimum temperature was highest during the months

of winter season viz. January, February, November and December (Table 9 and 10). The variation was highest for Sri Ganganagar, Tonk and Bikaner. These factors can altogether affect the sustainability of agriculture as well as natural system-based livelihoods in India.

Thus, the climate trends in Rajasthan exhibited a divergent and escalated pattern of hydro-thermal change. Rainfall trends in general revealed a strong spatial heterogeneity with escalating trends in arid western districts and significant declines in semi-arid eastern and central plateau regions. On the other hand, maximum and minimum temperatures in general showed a universal warming across all the agro-ecological regions studied. Herein, the minimum temperature showed a more consistent and rapid rise than the maximum temperature. It might altogether lead to heat accumulation in the region. This asymmetrical trend, present in the form of warming nights, intensified daytime temperature, and uneven rainfall distribution, represents a compound heat-moisture stress regime, especially in semi-arid transition zones. Declining rainfall and rising temperatures in Ajmer and Tonk. Hence, there is a greater likelihood of these regions emerging as climate stress hotspots. On the other hand, in arid districts, the increasing rainfall is present alongside a strong thermal rise. Such patterns are likely to have disproportionate consequences for climate-sensitive livelihood systems like agriculture and dairying.

Figure 4 illustrates the long-term trend of minimum temperature (1951–2021) across the selected districts of Rajasthan. The graphical analysis clearly shows a consistent upward trend in minimum temperature in all districts, indicating a steady rise in night-time temperatures over the years. Districts such as Tonk, Bikaner, Sri Ganganagar, and Ajmer exhibit relatively stronger increasing trends, while districts like Udaipur and Banswara show a slower rate of increase. Despite some year-to-year fluctuations, the overall direction remains positive across all locations. The moderate to low R^2 values suggest that, although the warming trend is evident, there is noticeable interannual variability in T_{min} . Overall, the figure highlights a uniform and widespread increase in minimum temperature across Rajasthan, reinforcing the pattern of warming nights in the region.

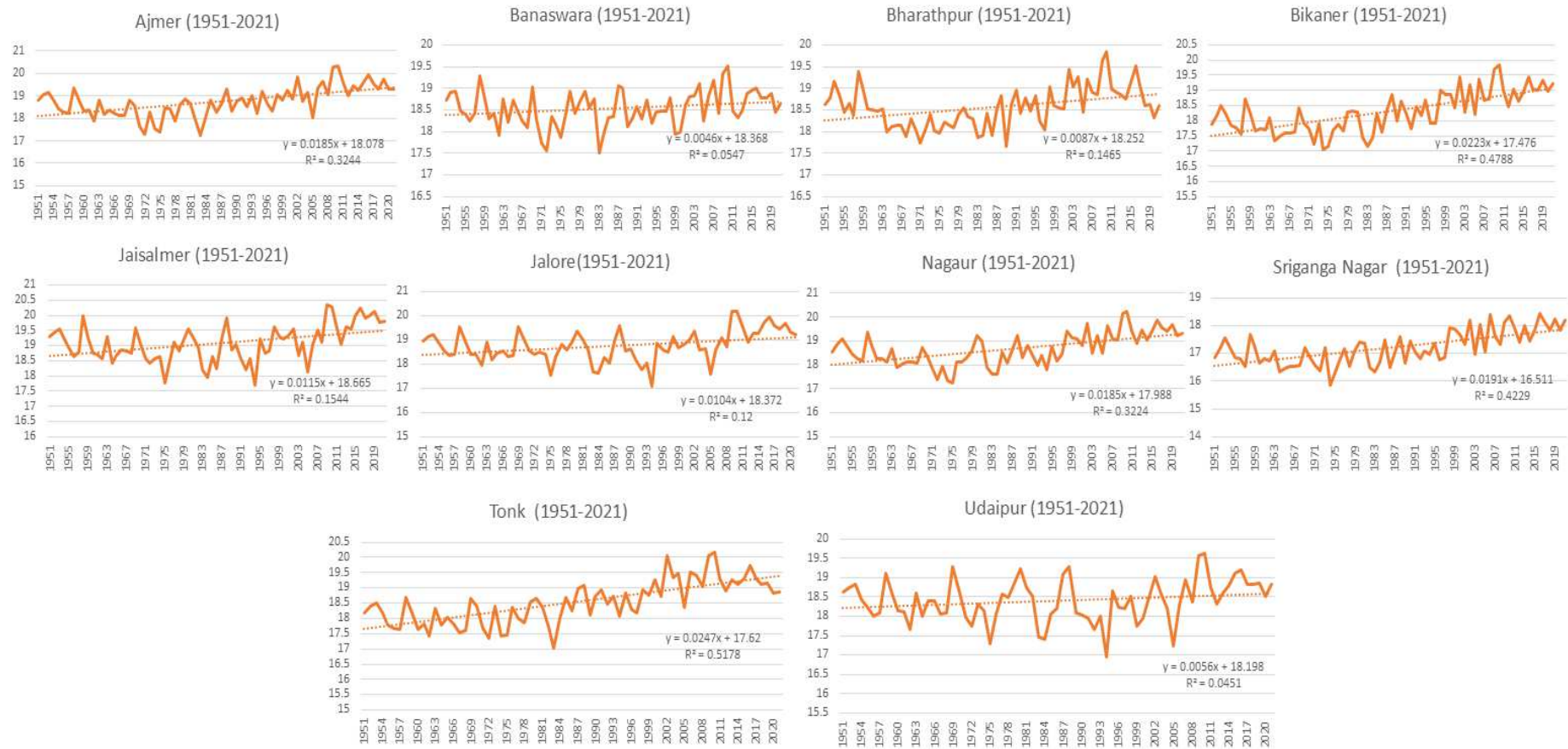


Fig.4: Variability in annual average minimum temperature in selected districts of Rajasthan(1951-2022)

Table 9. Summary statistics for Tmin (1951–2021) in the districts of Rajasthan

	Ajmer			Banaswara			Bharathpur			Bikaner			Jaisalmer		
Month	Mea n	S D	CV	Mea n	S D	CV	Mea n	S D	CV	Mea n	S D	CV	Mea n	S D	CV
January	7.7	1.1	14.4	9.6	1.0	11.1	7.0	0.9	13.5	6.3	1.1	18.1	8.3	1.0	12.7
February	10.5	1.4	13.8	11.9	1.2	10.1	9.9	1.2	12.8	9.4	1.5	16.0	11.3	1.4	12.5
March	16.1	1.2	7.7	16.7	0.9	5.9	14.9	1.0	7.2	15.0	1.2	8.3	16.8	1.1	6.9
April	21.9	1.2	5.8	21.9	0.8	4.0	20.9	1.1	5.3	20.8	1.3	6.2	22.2	1.1	5.0
May	26.2	1.2	4.7	25.2	0.7	2.9	25.6	1.1	4.5	25.3	1.2	4.9	25.6	0.8	3.4
June	27.3	0.8	3.1	25.1	0.6	2.3	27.8	0.9	3.4	27.5	0.8	2.9	26.7	0.7	2.6
July	25.6	0.6	2.6	23.5	0.4	1.8	26.7	0.7	2.8	26.7	0.7	2.6	25.6	0.6	2.4
August	24.5	0.5	2.2	22.6	0.3	1.7	25.8	0.4	1.7	25.6	0.5	2.0	24.5	0.6	2.4
September	23.4	0.7	3.3	21.8	0.6	2.7	24.2	0.6	2.8	23.8	0.7	3.3	23.5	0.8	3.4
October	19.1	1.1	6.1	18.7	1.0	5.1	18.8	1.0	5.3	18.5	1.1	6.3	19.9	1.1	5.8
November	13.1	1.5	12.1	14.1	1.6	11.3	12.3	1.2	9.9	12.0	1.4	11.8	14.1	1.4	9.9
December	8.7	1.1	13.4	10.6	1.1	10.6	7.9	1.1	14.0	7.3	1.1	16.3	9.6	1.0	11.3

Table 10. Summary statistics for Tmin (1951–2021) in the districts of Rajasthan (Continued)

	Jalore			Nagaur			Sri ganganagar			Tonk			Udaipur		
Month	Mea n	S D	CV	Mea n	S D	CV	Mea n	S D	CV	Mea n	S D	CV	Mea n	S D	CV
January	8.7	1.0	11.8	7.0	1.1	15.8	5.1	1.1	22.0	7.5	1.1	15.0	8.9	1.0	11.6
February	11.3	1.3	12.1	10.1	1.5	15.1	8.0	1.4	17.8	10.3	1.4	14.3	11.4	1.3	11.5
March	16.8	1.2	7.1	15.7	1.2	8.1	13.3	1.1	8.6	15.7	1.2	7.9	16.5	1.1	6.7
April	21.9	1.2	5.5	21.5	1.2	5.9	19.1	1.2	6.4	21.4	1.3	6.3	21.6	1.0	4.9
May	25.2	1.0	3.8	25.6	1.2	4.7	23.8	1.2	5.3	25.7	1.2	5.0	24.9	0.8	3.3
June	26.0	0.7	2.8	27.4	0.7	2.8	26.8	0.8	3.0	27.0	0.8	3.2	25.3	0.6	2.7
July	24.6	0.6	2.6	26.3	0.6	2.6	26.6	0.6	2.5	25.4	0.7	2.7	23.8	0.5	2.5
August	23.6	0.6	2.6	25.2	0.5	2.0	25.6	0.5	2.0	24.4	0.5	2.1	22.9	0.5	2.4
September	22.7	0.8	3.6	23.8	0.7	3.2	23.2	0.8	3.5	23.3	0.7	3.2	22.0	0.7	3.3
October	19.4	1.1	6.1	19.2	1.2	6.2	17.3	1.2	6.9	18.9	1.2	6.4	18.8	1.1	5.9
November	14.0	1.4	10.5	12.9	1.4	11.3	10.5	1.3	12.6	12.9	1.6	12.8	13.8	1.5	11.3
December	9.9	1.0	10.9	8.1	1.1	14.3	6.0	1.1	19.3	8.6	1.2	14.1	10.0	1.1	11.1

The summary statistics (Table 9 and 10) of Tmin (1951-2021) across the ten districts of Rajasthan show a clear seasonal pattern in minimum temperature. Tmin values are lowest during the winter months of January and December and gradually increase towards the summer season. Across districts, the lowest mean Tmin is observed in Sri Ganganagar during January (around 5.1°C), indicating colder winter conditions in the northern region. Minimum temperature steadily rises from March and reaches its peak during June, with mean values ranging from about 25°C to 27°C in most districts. After June, Tmin slightly declines during the monsoon months (July-September) and continues to decrease towards the winter months.

The standard deviation values remain relatively low throughout the year, indicating limited variability in minimum temperature. Similarly, the coefficient of variation (CV) is generally low during summer and monsoon months but comparatively higher during winter months. Overall, the results indicate consistent seasonal variation in T_{min} across Rajasthan, with cooler winters and warm nights during the summer period.

4. Discussion

The discussion interprets the observed long-term climatic trends across Rajasthan, focusing on spatial variability in rainfall patterns and the consistent rise in temperature across agro-climatic zones, and explores the underlying processes shaping these changing climate dynamics.

Arid-Semi-arid divergence in rainfall trends

The observed divergence in rainfall trends between arid and semi-arid regions of Rajasthan reflects a shifting climatic regime rather than a uniform change in precipitation patterns. Districts such as Jaisalmer and Bikaner, located in the core arid zones, show a tendency towards increasing rainfall, while semi-arid regions like Ajmer and Tonk exhibit declining trends. These results are in agreement with previous studies (Pant and Hingane 1988; Singh et al. 2001; Saini et al., 2022), where they reported increasing rainfall trends across several regions of Rajasthan. This contrast can be attributed to evolving monsoon dynamics, including changes in the trajectory of low-pressure systems and the westward extension of monsoonal activity. However, the increase in rainfall in arid regions should not be interpreted as a sign of reduced climatic vulnerability. In these regions, rainfall is often episodic, occurring in short, intense bursts that contribute more to surface runoff than to effective soil moisture recharge. As a result, despite an apparent increase in total rainfall, the actual availability of water for crops remains limited. Moreover, such intense rainfall events can lead to soil erosion and reduced infiltration, further constraining agricultural productivity. In contrast, semi-arid regions, which are more dependent on relatively stable and well-distributed rainfall, are increasingly experiencing moisture deficits. This drying trend, even if gradual, can have significant implications for cropping systems and water availability, highlighting that both increasing and decreasing rainfall patterns can contribute to heightened climate risk in different ways.

Escalation of Thermal Stress Across Agro-ecosystems

Alongside changes in rainfall, the study clearly indicates a widespread and consistent rise in both maximum and minimum temperatures across all agro-ecological zones of Rajasthan.

These results have been found consistent with that reported by Roy (2015), Sharma et al. (2018), and Mehta and Yadav (2019). Pingale et al. (2014) and Roy (2015) have attributed these warming trends to increasing anthropogenic activities, namely, land use/cover changes, industrialization, and urbanization. Notably, the increase in minimum temperature appears more pronounced than that of maximum temperature, suggesting a gradual shift towards warmer nights. This pattern is particularly important because it reflects not just episodic heat events but a sustained accumulation of thermal stress over time. Warmer nights reduce the diurnal temperature range and limit the natural cooling period that crops and livestock rely on for recovery (Cox et al., 2020). From an agricultural perspective, higher night-time temperatures can accelerate crop respiration rates, thereby reduce net biomass accumulation and ultimately affect yields (Yang et al., 2023). For livestock, especially in dairy systems, reduced night-time cooling can impair recovery from daytime heat stress, leading to declines in productivity and reproductive efficiency (Gaughan et al., 2023 ; Spires et al., 2018). Additionally, elevated minimum temperatures can increase evapotranspiration rates, contributing to faster depletion of soil moisture. This continuous thermal pressure, as opposed to isolated heat waves, creates a chronic stress environment that is more difficult for farmers to manage. The consistency of this warming trend across regions underscores the pervasive nature of climate change and its implications for long-term agricultural sustainability.

Compound Heat-Moisture Stress in Semi-arid Transition Zones

The interaction between rising temperatures and changing rainfall patterns becomes particularly critical in semi-arid transition zones such as Ajmer and Tonk. These regions represent a convergence point where declining rainfall coincides with increasing thermal stress, creating what can be described as compound heat-moisture stress conditions. Unlike core arid zones, where farming systems are traditionally adapted to water scarcity, semi-arid regions often rely on a balance between moderate rainfall and manageable temperature conditions. When this balance is disrupted, the resulting stress is not merely additive but synergistic, amplifying the overall impact on agricultural systems. Reduced rainfall limits soil moisture availability, while rising temperatures increase evapotranspiration demand, further exacerbating water deficits. This dual pressure can lead to reduced crop yields, increased crop failure risks, and greater uncertainty in farming outcomes (Masia et al., 2021 ; Ahmad et al., 2021). Moreover, these transition zones are often densely cultivated and support a large number of smallholder farmers, making them particularly vulnerable to climate variability. The emergence of such regions as climate stress hotspots highlights the need for targeted adaptation

strategies that account for both thermal and hydrological dimensions of climate change. Without such interventions, these areas may face increasing challenges in sustaining agricultural productivity and livelihoods.

Seasonal and Variability Dimensions of Climate Change

In addition to long-term trends, the study also brings attention to the importance of seasonal variability and its implications for agricultural systems. Both maximum and minimum temperatures exhibit higher variability during the winter months, which can significantly affect rabi cropping systems that depend on relatively stable temperature conditions. Similar result reported by Deoli and Rana, 2019 and Madhukar et al., 2021 indicating winter temperature variability risks yields. Increased variability, even in the absence of large changes in mean values, can disrupt critical growth stages of crops such as wheat and mustard. Similarly, fluctuations in temperature can influence fodder availability and quality, with cascading effects on livestock productivity. Rainfall variability further compounds these challenges, as irregular distribution during the monsoon season affects sowing decisions, crop establishment, and water management practices. For smallholder farmers, who often rely on traditional knowledge and seasonal predictability, such variability introduces a high degree of uncertainty. This unpredictability can lead to suboptimal decision-making, increased risk exposure, and reduced resilience to climatic shocks. Therefore, it is not only the direction of change but also the variability and reliability of climatic parameters that determine their impact on agriculture. Understanding these dynamics is crucial for designing climate-resilient farming systems that can cope with both gradual changes and increasing fluctuations in climate patterns.

5. Limitations of study

Despite providing important insights, the present study has certain limitations. The analysis is based on selected districts representing agro-climatic zones, which may not fully capture micro-level spatial variability across Rajasthan. The study relies on secondary data, which may include inherent inconsistencies or gaps. Additionally, the Mann–Kendall test identifies trends but does not explain the underlying causative mechanisms of climate variability. The high interannual variability observed in rainfall also limits the statistical significance of trends in some regions. Therefore, the findings should be interpreted with caution, and future studies incorporating high-resolution data and advanced modelling approaches are recommended for more comprehensive analysis.

6. Conclusion and implications

The present study reveals a clear and consistent warming trend across all agro-climatic zones of Rajasthan, with both maximum and minimum temperatures showing a steady increase over the period 1951–2021. Notably, the rise in minimum temperature is more pronounced, indicating warming nights and potential heat accumulation effects. In contrast, rainfall trends exhibit strong spatial variability, with increasing tendencies in western arid districts and declining patterns in parts of the semi-arid eastern regions such as Ajmer and Tonk. This divergence highlights the uneven nature of climate change across the state. The combined effect of rising temperatures and erratic rainfall suggests increasing hydro-climatic stress, particularly in transitional agro-ecological zones. Furthermore, the findings of this study are important for water management as the water is key to human survival and all kinds of vegetative growth over the dryland ecosystem. Since the state holds only 1% of the total water resources of the country, the increasing trends of rainfall can hold good for recharging of groundwater resources. The increasing availability of rainwater may help reduce the typical water deficit conditions in arid and semi-arid regions, as indicated by the positive rainfall trends. At the same time, the simultaneous rise in both rainfall and temperature across many regions clearly points toward an ongoing shift in the dryland climate. If these changes persist in the future, they could adversely affect soil and water resources, potentially leading to desertification and a decline in agricultural productivity. Additionally, changing climate conditions may create challenges related to drinking water availability as well as irrigation needs. Overall, the findings of this study can serve as a valuable reference for policymakers, hydrologists, and water resource managers in planning sustainable strategies for climate adaptation and water resource management in Rajasthan.

The findings of this study have important implications for climate adaptation and resource management in Rajasthan. The observed spatial variability in rainfall and consistent rise in both maximum and minimum temperatures highlight the need for region-specific adaptation strategies rather than uniform approaches. Increasing rainfall in arid regions, coupled with high variability, suggests a shift from water scarcity to water management challenges, necessitating improved rainwater harvesting and storage systems. At the same time, rising temperatures, particularly minimum temperature, indicate intensifying thermal stress, requiring the promotion of heat-resilient crop varieties and climate-smart agricultural practices. The identification of semi-arid regions such as Ajmer and Tonk as emerging climate stress hotspots underscores the urgency of targeted interventions in these areas. Additionally, increasing

climatic variability reduces predictability, emphasizing the need for strengthened climate advisory services and risk management strategies. Overall, the study provides a scientific basis for informed policy planning and sustainable agricultural development under changing climatic conditions.

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Data availability

The datasets analyzed during the current study are available from publicly accessible sources and can also be provided by the corresponding author upon reasonable request. The processed data, statistical methods, and analytical procedures are described in the manuscript to ensure transparency and reproducibility of results.

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Author contribution

S.K.B.: Conceptualization, methodology, formal analysis, and writing of the manuscript; S.S.A.: framing of the study objectives, supervision, and editing; S.Z.: methodology and validation; K.K.: formal analysis; N.P.: visualization; A.R.: editing and manuscript finalization; A.V.: supervision, review, and editing of the manuscript. All authors have read and approved the final manuscript.

Competing interests

The authors declare no competing interest

Ethical Approval

This article does not contain any studies with human participants performed by any of the authors.

Informed Consent

Not applicable.

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