Plant Archives Vol. 25, Supplement 2, 2025 pp.1154-1160 e-ISSN:2581-6063 (online), ISSN:0972-5210

Plant Archives

Journal homepage: http://www.plantarchives.org
DOI Url : https://doi.org/10.51470/PLANTARCHIVES.2025.v25.supplement-2.143

SPATIOTEMPORAL ANALYSIS OF CLIMATIC VARIABILITY IN THE CENTRAL PLAINS OF UTTAR PRADESH INDIA

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(Date of Receiving : 09-04-2025; Date of Acceptance : 19-06-2025)

ABSTRACT

This study investigates the long-term climatic variability of the Central Plain Region (CPR) of Uttar Pradesh, India, using a 32-year dataset (1990–2022) of daily temperature and rainfall data from the India Meteorological Department. The analysis aimed to evaluate seasonal and annual trends in maximum and minimum temperatures and rainfall, employing statistical tools such as the Mann–Kendall test and Sen's slope estimator. Results reveal a statistically significant upward trend in minimum temperatures, particularly during the pre-monsoon (0.05°C/year, $p < 0.001$) and monsoon (0.01°C/year, $p = 0.009$) seasons, while maximum temperatures showed relative stability with a notable winter cooling trend (–0.06°C/year, $p = 0.02$). Rainfall trends were seasonally dependent, with significant increases during the monsoon (9.45 mm/year, $p = 0.05$) and annually (12.45 mm/year, $p = 0.01$), enhancing water availability for Kharif crops. Conversely, winter and pre-monsoon rainfall exhibited high variability and no significant trends. The findings underscore the agronomic risks associated with night-time warming and rainfall irregularities, emphasizing the need for climate-resilient agricultural strategies, including crop diversification, modified sowing dates, and enhanced monsoon water harvesting. This regional climate assessment contributes to the broader discourse on sustainable agriculture and climate adaptation in zone.

***Keywords*:** Climatic Variability, Central Plain Region, Uttar Pradesh, Temperature Trends, Rainfall Analysis, Mann–Kendall Test, Sen's Slope Estimator, Seasonal Climate Assessment

Introduction

Over the past century and continuing into the current one, climate change has emerged as a critical area of scientific inquiry due to its potential to significantly disrupt natural systems and socio-economic structures at local, regional, and national levels. Observational records indicate a rise in global temperatures by approximately 0.5–0.6°C, with projections suggesting an additional increase of 0.3–0.7°C by 2035 (Jaswal *et al.*, 2015). These warming trends are primarily attributed to alterations in radiative forcing mechanisms, driven by anthropogenic modifications to land cover, vegetation dynamics, and surface moisture regimes (Thomas *et al.*, 2012). Interestingly, findings by England *et al*. (2014) report a stagnation in mean global air temperature post-2001, despite a continuous rise in atmospheric greenhouse gas concentrations.

A key dimension in climate change research is the analysis of long-term trends and variability in temperature and precipitation. Numerous studies have documented statistically significant alterations in these parameters globally, with notable examples reported from the United States (Vose *et al*., 2017), India (Prasad *et al*., 2017), and Brazil (Rosso *et al*., 2015). Within the South Asian context, the Intergovernmental Panel on Climate Change (IPCC, 2007) projects a temperature rise of 0.5–1.2°C by 2020, 0.88–3.16°C by 2050, and 1.56–5.44°C by 2080. The rate of warming across India is estimated at approximately 0.57°C per century, mirroring global trends (Dash *et al.*, 2007). Regional assessments reveal a warming of about 1.0°C over the past century in India, with even greater increases observed during winter and post-monsoon months (Jain & Kumar, 2012).

Seasonal analyses across eight locations in Central Northeast India have shown a rising trend in maximum temperatures during the monsoon (0.008°C year^{-1}), post-monsoon (0.014°C year^{-1}), and annual periods (0.008°C year^{-1}) for the 1914–2003 period. Minimum temperatures also displayed an increasing trend during the post-monsoon season (0.012°C year^{-1}), but a slight declining trend (0.002°C year^{-1}) during the monsoon (Subash *et al.*, 2011). Such temporal analyses often employ non-parametric statistical approaches like the Mann–Kendall test (Mann, 1945; Kendall, 1955) to ensure robust trend detection in climate datasets.

The interplay of temperature and rainfall variability exerts profound implications on water resources and agricultural productivity in India a predominantly agrarian nation. For instance, a 1°C rise in mean temperature throughout the wheat-growing period may result in yield reductions of up to 5 million tonnes (Aggarwal, 2007). However, adaptation strategies such as modifying sowing dates and selecting heat-tolerant crop varieties have shown potential in mitigating such impacts. In the Bundelkhand region, temperature variability influences agricultural decision-making, cropping patterns, and ultimately, rural livelihoods and economic resilience (Rai *et al.*, 2017).

National-scale studies further indicate a statistically significant decrease in the frequency of cold days and a marginal increase in hot days ($p \approx 0.05$) over India (Dash & Mamgain, 2011). However, the Indian monsoon does not exhibit any substantial trend, with only a minor decline of 0.4 mm year^{-1} observed from 1871 to 2009 (Mall *et al.*, 2007; MoEF, 2010). Notably, night-time temperatures have increased at a faster rate than daytime temperatures, and future projections suggest continued intensification in both maximum and minimum extremes (Kumar *et al.*, 2006). Spatial heterogeneity is also evident in precipitation trends: while Central and Northern India have experienced a reduction in the frequency of heavy rainfall events, the peninsular east and North-Eastern regions have shown an opposite trend (Rajeevan *et al.*, 2008; Guhathakurta *et al.*, 2011; Duhan & Pandey, 2013). Projections for mid-century (2050s) anticipate a temperature rise of 2–4°C across India, a reduction of over 15 rainy days in western and central regions, and an increase of 5–10 rainy days in the Himalayan foothills and North-Eastern areas. Additionally, flood frequency is expected to rise by 10–30% relative to 1970s levels in various regions by the 2030s (MoEF, 2010). Sea-level rise trends also align with global observations, with the Indian Ocean experiencing an accelerated rise from 1.7 mm yr^{-1} (1901–2010) to 3.2 mm yr^{-1} (1993–2010) (Unnikrishnan *et al.*, 2015).

In this context, the present investigation aims to assess the long-term variability and trend of seasonal and annual temperature and rainfall patterns across the Central Plain Zone of Uttar Pradesh. Such analysis is instrumental for climate-resilient agricultural planning and for formulating localized mitigation and adaptation strategies responsive to evolving climate risks.

Materials and Methods

Study area and Data collection

The present study was undertaken for the Central Plain Zone (CPZ) of Uttar Pradesh, which geographically spans approximately between latitudes 25.0°N to 27.5°N and longitudes 80.5°E to 83.5°E. The analysis focused on the temporal period from 1990 to 2022, utilizing high-resolution gridded climatic datasets. Daily rainfall data, provided by the India Meteorological Department (IMD), were obtained at a spatial resolution of 0.25° × 0.25°, while maximum and minimum temperature data (Tmax and Tmin) were sourced at a coarser resolution of 1.0° × 1.0°.

Climatic Variability Assessment and Time Series Trend Analysis

To investigate long-term patterns and variability in regional climate, this study utilized a 32-year dataset of daily meteorological observations comprising rainfall, maximum temperature (Tmax), and minimum temperature (Tmin) sourced from the India Meteorological Department (IMD). The daily records were first aggregated into monthly values using Weather Cock software (Version 15), allowing for consistent seasonal and interannual comparisons. The monthly datasets for each climatic variable were subjected to statistical analysis to evaluate spatial-temporal variability. Descriptive statistics such as the arithmetic mean, standard deviation (SD), and coefficient of variation (CV) were computed for all three parameters. These metrics served as primary indicators of intra- and inter-annual climatic variability. The CV, in particular, offers insight into the degree of dispersion relative to the mean, facilitating comparative variability assessments across different seasons and parameters (Hundal & Kaur, 2002).

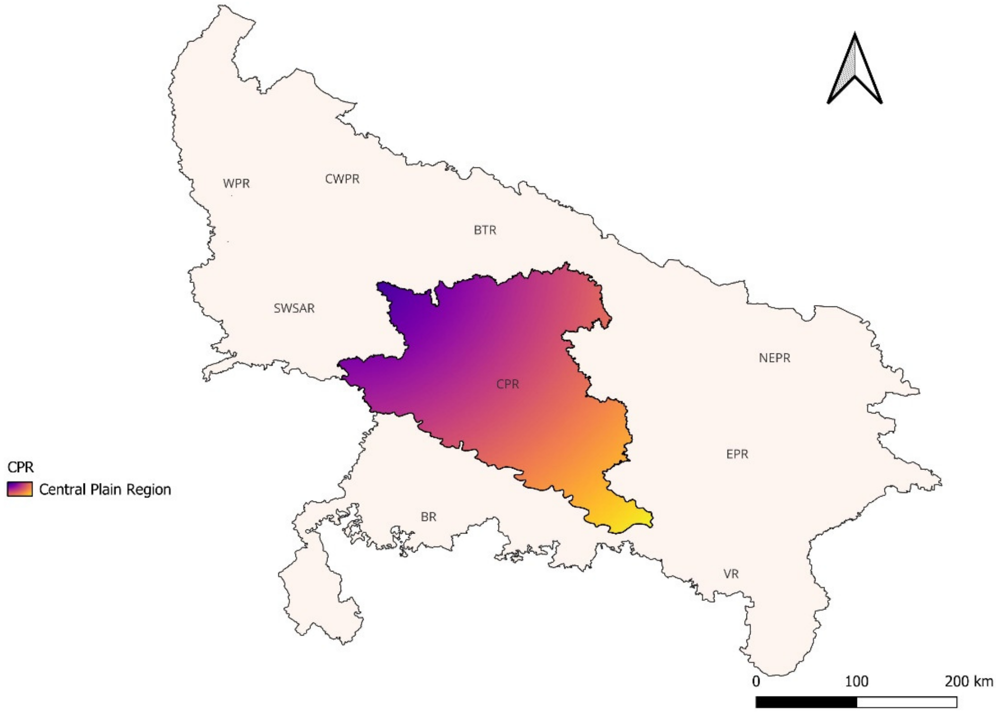

Fig. 1: Study Area Map of Central Plain Region (CWP) of Uttar Pradesh

The formulae employed for basic statistical evaluation are defined as follows:

$$Mean = \frac{(Sum\ of\ all\ values)}{(Number\ of\ values)} \quad (1)$$

$$SD = \sqrt{\frac{\Sigma_{i}^{n}=(x_i-\bar{x})^2}{n}} \quad (2)$$

Where, x_i represents each individual data point, $\bar{x}$ is the mean of the data, and n is the total number of data points

$$CV = \left(\frac{SD}{Mean}\right) \times 100 \quad (3)$$

Where, x_i denotes each observation, $\bar{x}$ represents the mean of the dataset, and n is the total number of observations.

To assess directional trends and long-term shifts in climatic variables, time series data were further examined using both parametric and non-parametric approaches. While parametric techniques typically assume a normal distribution and are sensitive to outliers, non-parametric methods provide robust alternatives when such assumptions are not met (Hamed & Rao, 1998). Among non-parametric tools, the Mann–Kendall (MK) trend test, originally developed by Mann (1945) and later refined by Kendall (1975), is widely recognized for its efficacy in detecting monotonic trends in climatological and hydrological time series. This method was applied in conjunction with Sen's slope estimator to quantify the rate and direction of change across the study period.

Trend Analysis of Weather Data

Mann Kendell Test:

The Mann-Kendall test is recognized as a non-parametric statistical method, which offers the significant advantage of not requiring any specific distributional assumptions regarding the data series. Its robustness is not compromised by the presence of breakpoints, and it demonstrates greater efficacy compared to parametric alternatives. Consequently, the World Meteorological Organization endorses its use for evaluating monotonic trends in hydro-meteorological time series. The foundation of this test lies in the null hypothesis (H0), which posits that the series under examination are independent, randomly ordered, and exhibit no discernible trend. The test statistics, Zc and β, are defined in straightforward terms. Specifically, the parameter Zc indicates the overall trend of the series for the data points (x1, x2, …, xn).

$$Zc = \begin{cases} \frac{S-1}{\sqrt{var(S)}} & S > 0 \\ 0 & 0 \\ \frac{S-1}{\sqrt{var(S)}} & S < o \end{cases} \quad ...(4)$$

In which,

$$S = \sum_{j=1}^{n-1}\sum_{j=i+1}^{n} sign(x_j - x_i) \quad ...(5)$$

$$sign(x_j - x_i) = \begin{cases} 1 & x_j - x_i > 0 \\ 0 & x_j - x_i = 0 \\ -1 & x_j - x_i < 0 \end{cases} \quad ...(6)$$

$$var[S] = \frac{n(n-1)(2n+5)}{18} \quad ...(7)$$

Zc follows the standard normal distribution. Therefore, Ho is rejected if $|Zc| \leq Z_{1-\propto/2}$, which means there is a significant change trend for the series (abbreviated as R), while accepting H_0 suggests no obvious trend for the series (abbreviated as A). Besides, $Zc > 0$ represents an upward trend of the series, while $Zc < 0$ denotes a negative trend. In which, $\propto$ is the significance level for the test; $\pm Z_{1-\propto/2}$ are the standard normal deviates. In this paper, $\propto = 95\%$ was applied, $\pm Z_{1-\propto/2} = \pm 1.96$. The parameter β represents the Kendall gradient and serves as a measure for estimating the average rate of change within the series. This estimation relies on the premise that the series exhibits a monotonic change trend, indicating that the trend can be characterized as a linear function of time.

$$\beta = Median\left(\frac{x_i - x_j}{i-j}\right) \quad (1 < j < i < n) \quad ...(8)$$

Sen's slope:

The method proceeds by calculating the slope as a change in measurement per change in time,

$$Q' = \frac{x_{t'} - x_t}{t' - t} \quad ...(9)$$

Where:

- Q' = slope between data points $x_{t'}$ and x_t
- $x_{t'}$ = data measurement at time t'
- x_t = data measurement at time t

Sen's estimator of slope is simply given by the median slope,

$$Q = Q'_{[(N+1)/2]} \quad if\ N\ is\ odd \quad ...(10)$$

$$Q = \left(Q'_{[N/2]} + Q'_{[(N+1)/2]}\right)/2 \quad if\ N\ is\ even \quad ...(11)$$

Where:

N is the number of calculated slopes.

Results and Discussion

Season-wise Analysis of Climatic Parameters in the Central Plain Region

Maximum Temperature Analysis

The analysis of maximum temperature (Tmax) across different seasons in the Central Plain Region indicates largely stable climatic conditions with isolated significant variations. Table 1. On an annual basis, Tmax averaged 31.85°C, with a low standard deviation (0.50 °C) and coefficient of variation (CV = 1.58%), signifying limited inter-annual fluctuation. The Kendall's tau value of 0.10 and p-value of 0.33 suggest a statistically non-significant trend, with a Sen's slope of –0.01 °C/year, indicating thermal stagnation in annual maximum temperatures. During the winter season, Tmax was 23.82 °C, with the highest CV (4.79%) among seasons. Notably, this season showed a statistically significant negative trend (τ = –0.30, p = 0.02), with a Sen's slope of –0.06 °C/year, signifying a cooling tendency. This decline in winter Tmax may benefit wheat, a rabi-season crop, by ensuring sufficient low-temperature exposure required for its reproductive development. The pre-monsoon season, with the highest Tmax (36.79 °C), exhibited moderate variability (CV = 2.58%) and a non-significant increasing trend (p = 0.59), with a slope of 0.01 °C/year. High pre-monsoon temperatures, while expected, could affect nursery management and early sowing decisions for rice. Monsoon Tmax remained steady at 34.61 °C (CV = 2.21%), showing no significant trend (τ = 0.03, p = 0.82), suggesting stable thermal conditions during rice vegetative and flowering phases. Similarly, post-monsoon Tmax averaged 30.93 °C, with a CV of 2.46% and no significant trend (p = 0.66), ensuring no undue thermal stress during wheat sowing or early vegetative growth. These findings are consistent with those of (Bhatt *et al.*, 2019), who similarly reported a statistically significant declining trend in winter maximum temperatures across the Central Plain Region, suggesting a localized seasonal cooling effect confined primarily to the rabi season. The absence of significant changes in other seasons reinforces the notion that this cooling is not a broader annual phenomenon but rather seasonally restricted. Furthermore, the observed range of annual maximum temperatures aligns closely with the values reported by (Anonymous, 2009), thereby corroborating the regional climatological patterns and enhancing the credibility of the present Tmax analysis.

Minimum Temperature Analysis

Minimum temperature (Tmin) displayed a more dynamic seasonal behaviour and greater statistical significance than Tmax. Table 1. The annual Tmin averaged 19.2 °C, with a low CV of 2.11%, and demonstrated a statistically significant positive trend ($\tau = 0.27$, $p = 0.03$), with a Sen's slope of 0.01 °C/year, implying gradual warming of night-time conditions. Such warming may reduce cold stress on early germinating wheat, but could also lead to higher respiration losses, affecting grain weight. The winter Tmin was 9.88 °C, with the highest seasonal CV (5.58%), indicating notable variability. It showed a weakly significant increasing trend ($\tau = 0.18$, $p = 0.09$), with a slope of 0.02 °C/year a shift that could limit chilling accumulation essential for certain wheat varieties, potentially reducing yields in late-sown conditions. The pre-monsoon Tmin, critical for rice nursery development, showed a mean of 21.0 °C and the lowest variability (CV = 1.52%), yet the strongest warming trend across all parameters ($\tau = 0.44$, $p < 0.001$), with a Sen's slope of 0.05 °C/year. This could adversely affect early-stage rice development due to higher metabolic stress. The monsoon season Tmin (mean = 25.81 °C; CV = 1.51%) also showed a significant increasing trend ($\tau = 0.29$, $p = 0.009$), with a Sen's slope of 0.01 °C/year—a critical concern as high night-time temperatures during anthesis and grain filling in rice can lower yield through spikelet sterility and reduced grain density. The post-monsoon Tmin (mean = 17.28 °C; CV = 5.12%) remained statistically stable ($p = 0.51$), posing minimal risk to wheat germination.

Table 1 : Climatic variability and trend analysis

Region	Season	Mean	SD	CV	Kendall's tau	p-value	Sen's Slope
	MAXIMUM TEMPERATURE						
Central Plains Region (CPR)	Annual	31.85	0.5	1.58	-0.12	0.33	-0.01
	Winter	23.82	1.14	4.79	-0.3	0.02**	-0.06
	Pre-Monsoon	36.79	0.95	2.58	0.07	0.59	0.01
	Monsoon	34.61	0.76	2.21	0.03	0.82	0
	Post-Monsoon	30.93	0.76	2.46	-0.06	0.66	-0.01
	MINIMUM TEMPERATURE						
	Annual	19.2	0.41	2.11	0.27	0.03**	0.01
	Winter	9.88	0.55	5.58	0.21	0.09***	0.02
	Pre-Monsoon	21	0.72	3.42	0.23	0.06***	0.03
	Monsoon	25.81	0.39	1.51	0.21	0.09***	0.01
	Post-Monsoon	17.28	0.89	5.12	0.08	0.51	0.01
	RAINFALL						
	Annual	657.01	261.51	39.8	0.3	0.01**	12.45
	Winter	33.2	35.57	107.14	0.11	0.38	0.37
	Pre-Monsoon	28.58	36.6	128.06	0.2	0.1	0.59
	Monsoon	563.71	233.71	41.46	0.25	0.05**	9.45
	Post-Monsoon	31.52	48.25	153.1	0.17	0.17	0.38

Where, * 0.01 level of significance; ** 0.05 level of significance, *** 0.1 level of significance

Rainfall Analysis

Rainfall trends show seasonal specificity, with annual and monsoonal precipitation being the most prominent. The annual rainfall averaged 657.01 mm, with a relatively high standard deviation (261.51 mm) and CV of 39.8%, indicating moderate inter-annual fluctuations. Importantly, it demonstrated a statistically significant increasing trend ($\tau = 0.30$, $p = 0.01$) with a Sen's slope of 12.45 mm/year, suggesting enhanced hydrological support to rainfed crops like rice. The winter rainfall was low (33.2 mm) but highly variable (CV = 107.14%). Despite a positive slope (0.37 mm/year), the trend was statistically insignificant ($p = 0.38$), making winter rainfall unreliable for wheat establishment or supplemental irrigation. The pre-monsoon rainfall, crucial for nursery establishment of rice, averaged 28.58 mm with the highest variability (CV = 128.06%). The trend was again statistically insignificant (p = 0.15), though the slope of 0.59 mm/year indicates a minor positive drift. The monsoon season, with rainfall of 563.71 mm and moderate variability (CV = 41.46%), showed a statistically significant increasing trend ($\tau = 0.25$, $p = 0.05$), with a slope of 9.45 mm/year. This trend is vital for upland and lowland rice cultivation, as it supports continuous field saturation and reduces reliance on irrigation, though excess rainfall may elevate flood risks and crop lodging. Post-monsoon rainfall (mean = 31.52 mm, CV = 153.1%) remained erratic and statistically non-significant (p = 0.17), offering limited utility for wheat sowing or soil moisture recharge, as illustrated in Table 1. In terms of precipitation, the current results agree with Kulariya *et al.* (2024), who identified statistically significant increasing trends in both annual and monsoonal rainfall over the CPR, further supporting the evidence of a hydrological intensification phase in this region.

Conclusion

The long-term climatic evaluation of the Central Plain Region (CPR) of Uttar Pradesh from 1990 to 2022 reveals a statistically significant rise in minimum temperatures, particularly during the pre-monsoon and monsoon seasons, alongside stable to marginally increasing rainfall trends. Minimum temperature increased annually at a rate of 0.01 °C/year ($p = 0.03$), with the pre-monsoon season exhibiting the steepest rise of 0.05 °C/year ($p < 0.001$), followed by monsoon (0.01 °C/year, $p = 0.009$) and winter (0.02 °C/year, $p = 0.09$). This night-time warming poses substantial agronomic risks: it may reduce rice yields by inducing heat stress during panicle initiation and grain filling, and compromise wheat vernalization during late sowing. In contrast, maximum temperature remained mostly stable, with a significant winter cooling trend of –0.06 °C/year ($p = 0.02$), potentially beneficial for wheat flowering. Rainfall increased significantly on an annual scale at 12.45 mm/year ($p = 0.01$), driven largely by the monsoon season (9.45 mm/year, $p = 0.05$), ensuring sufficient water availability for Kharif rice, while winter and pre-monsoon rains remained erratic and statistically non-significant (CV >100%). Overall, the region is witnessing a shift toward warmer nights and more consistent monsoon rainfall, necessitating immediate climate-adaptive strategies such as heat-resilient crop varieties, modified sowing dates, and enhanced monsoon water harvesting to safeguard future rice and wheat productivity.

Acknowledgements

We are deeply grateful for the numerous sources of support that have made this study possible. The resources and responsiveness of the Sam Higginbottom University of Agriculture, Technology, and Sciences Prayagraj, would be lauded. The support and motivation provided by colleagues and other researchers would be appreciated.

Author Statement

Both authors significantly contributed to the development of this manuscript. Nilesh Kumar Singh led the database management, analysis, and, while Shraddha Rawat helped in supervising. Additionally, both authors diligently reviewed and finalized the manuscript.

Conflict of Interest Statement

The authors declare that there is no conflict of interest regarding the publication of this paper.

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