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Analysis of Rainfall and Temperature in Upper Ganga Plain of India-A Comprehensive Study

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ABSTRACT

The Upper Ganga Plain has witnessed significant climatic variations over the past seven decades, necessitating a comprehensive assessment of rainfall and temperature trends and anomalies. The historical rainfall and temperature data from 1951 to 2021 were utilized to detect warming patterns and spatial variability. Descriptive statistical methods, trend analysis, and anomaly detection techniques were employed to identify deviations from historical averages. The results indicate a general warming trend, with notable fluctuations across different decades. The highest recorded maximum temperature was observed in 1987with 31.75° C, while the lowest was in 1997 (29.17°C). Anomaly analysis revealed that extreme warm years such as 1987 (+1.18°C), 2016 (+0.79°C), and 2021 (+0.84°C), while significant cooling anomalies were recorded in 1997 (-1.40°C), 2003 (-0.89°C), and 1983 (-1.06°C). Spatial trend analysis at the district level shifted heterogeneous warming patterns, with regions like Farrukhabad and Etah consistently showing high temperatures. A decadal breakdown shows periods of relative stability (1951–1970), intermittent cooling (1971–1990), and a resurgence of warming post-2000. The recent decade (2011–2021) presents a mixed trend, with some districts experiencing minor cooling, while others continue to warm. The findings underscore the dynamic nature of temperature variations, driven by both regional climatic influences and broader global warming trends. This study contributes to understanding long-term climatic shifts in the Upper Ganga Plain and offers insights for future climate adaptation strategies.

Keywords: Mean Maximum Temperature, Climate Variability, Anomaly Analysis, Upper Ganga Plain, Spatial Trends, Long-Term Temperature Change

INTRODUCTION

The analysis of temperature and rainfall trend over a period of time is very important in understanding study climatic variability and change (Lal, 2003; Srivastava *et al.*, 2010). These climatic variables play a crucial role in determining physical and biological characteristics of a region affecting plant growth, soil moisture levels, and ultimately the hydrological cycle (Houghton *et al.,* 2001; Pant and Kumar, 1997). The past four decades have seen record-breaking global temperatures, with continuously 2016 and 2024 recorded as the hottest years (NASA, 2024). The global surface temperatures have increased by approximately 1.5°C since pre-industrial times due to various anthropogenic activities such as burning of fossil fuels and land-use changes (Jain *et al.*, 2013; Kumar *et al.*, 2019; IPCC, 2021). The increased trends of temperature has led to widespread alterations in precipitation patterns, resulting in more frequent and intense extreme weather events, including heat waves, droughts, heavy rainfall, and cloud bursts (Pant and Kumar, 1997; Krishnan *et al.,* 2019).Studies have shown a significant increase in both maximum and minimum temperatures over the past century, with pronounced warming observed in the Indo-Gangetic Plains (Murari *et al.,* 2015; Reddy and Krishna, 2019). The frequency and intensity of heatwaves have increased, particularly during summer months. Minimum temperatures have

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shown an upward trend, leading to warmer winters and reduced frost days (Rathore *et al.,* 2017; Reddy and Krishna, 2019).

A significant reduction in winter precipitation has been observed, particularly in northern India (Pal and Al-Tabbaa, 2011; Singh *et al.,* 2014). The frequency of sudden heavy rainfall in short spells (≥100 mm/day) has increased, leading to urban flooding and river overflows. Periods without rainfall have become more prolonged, affecting agriculture and water availability (Lal, 2003; Srivastava *et al.*, 2010). Such changes in temperature and precipitation have serious implications for food security, hydrological systems, and disaster management in the region.

The changing temperature and precipitation pattern are being created several challenges for agriculture, water resources and human health. The erratic rainfall also affects sowing and harvesting cycles and disrupt crop calendars, leading to lower agricultural productivity.

The Human-induced factors must be minimized particularly greenhouse gas emissions, industrialization, deforestation, and urbanization.

Study Area:

The present study area, the Upper Ganga Plain, stretches between 77°49'16º E to 82°06'66º E longitude and 29°79'61º N to 25°42'61º N latitude encompassing parts of Uttarakhand and Uttar Pradeshstates of India covering (Fig. 1). This region is delineated by the Shivalik Hills to the north, the Yamuna River to the west, and merges seamlessly with the Middle Ganga Plain towards the east 1,49,000 sq.km.The area is characterized by flat topography formed with rich alluvial deposits ofthe river Ganga and its tributaries over millions of years. This fertile landscape is being supported extensive agricultural activities for millions of populations, making it one of India's most productive agrarian zones.

The region experiences subtropical monsoon climate, with temperatures often exceeding 40°C in summer and cool winters dropping below 5°C. The averages annual rainfall is about 1,000 to 1,200mm. However, there are spatial variations in precipitation, influenced by different factors including proximity to the Himalayas and prevailing wind patterns.

Demographically, the Upper Ganga Plain is densely populated, hosting several major urban centers including Meerut and Kanpur. The region's fertile soils and abundant water resources have historically supported high population densities. Rapid urbanization and industrialization in recent decades have transformed the socio-economic landscape, leading to significant land use and land cover changes. These developments have implications for water resources and environmental sustainability.

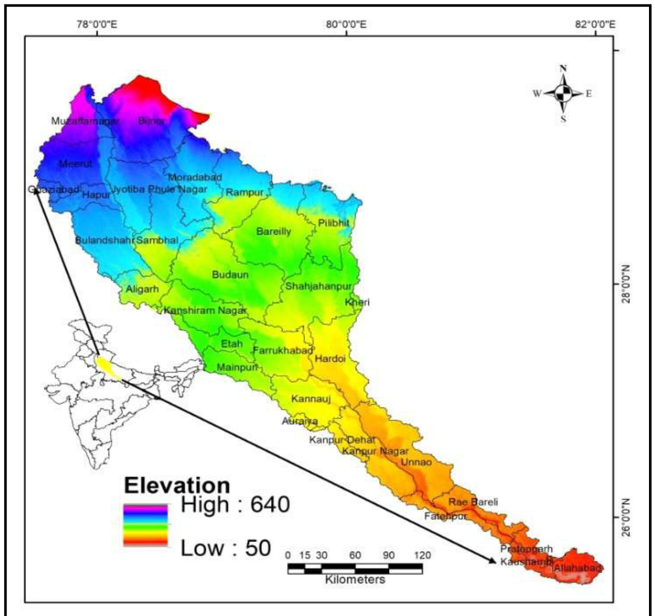

Fig. 1 : Location map of the Upper Ganga Plain

METHODOLOGY

The different statistical and spatial analysis techniques were employed to evaluate rainfall and temperature variability over the Upper Ganga Plain (UGP) during 1951 to 2021 period. The methodology is designed to assess trends, anomalies, and extreme events using historical climate datasets.

Data Collection:

The daily rainfall, mean minimum temperature, and mean maximum temperature data were collected from the Climate Research Unit (CRU), https://crudata.uea.ac.uk/cru/data/hrg. Missing values of dataset were addressed using the linear interpolation method (Pal and Al-Tabbaa, 2011).

Mean Annual Rainfall and Temperature Variability:

The mean annual climate variability analysis helps in understanding long-term changes in climate variables such as rainfall and temperature variability, which is critical for water resource planning (Singh *et al.*, 2014).

Mean annual rainfall and temperature variability was calculated using daily rainfall and temperature data as:

$$\frac{T}{R_{mean}} = \frac{1}{N}\sum_{i=1}^{N}\frac{T}{R_i}$$

Where, T/R_{mean} = mean annual rainfall/temperature
T/R_i = annual rainfall/temperature for year i
N = total number of year

Mean Decadal Variability:

The decadal variability method is commonly used in climate studies to detect decadal fluctuations in rainfall and temperature patterns (Pant and Kumar, 1997). Decadal variability analysis was conducted by averaging the mean annual variable over 10-year intervals:

$$\frac{T}{R_{decadal}} = \frac{1}{10}\sum_{j=1}^{10}\frac{T}{R_j}$$

where: $T/R_{decadal}$= Mean annual rainfall/temperature
T/R_j = Annual rainfall/temperature for year i

Extreme Events Analysis:

To analyse extreme rainfall events, the top 10 highest and lowest annual rainfall years were identified using percentile-based classification. The extreme rainfall events were extracted using:

$$\left(\frac{T}{R}\right)_{\text{extreme}} = \left\{\left(\frac{T}{R}\right)_i \middle| \left(\frac{T}{R}\right)_i \geq P_{90} \text{ or } \left(\frac{T}{R}\right)_i \leq P_{10}\right\}$$

where, P_{90} and P_{10} represent the 90th and 10th percentiles of the rainfall/temperature variable dataset.

Past and Present Period Comparison (1951-2000 vs 2001-2021):

To assess climate change impacts, rainfall and temperature data were split into two periods as Past (1951–2000) and Present (2001–2021). The mean and standard deviation for each period were computed:

$$\mu = \frac{1}{N}\sum_{i=1}^{N}X_i, \qquad \sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(X_i - \mu)^2}$$

where, μ = mean value
σ = standard deviation
X_i = rainfall/temperature variable

Anomaly Assessment:

Rainfall anomaly was determined as the deviation of annual rainfall from the long-term mean as:

$A_i = R_i - R_{mean}$
A_i = rainfall/temperature anomaly for year i

RESULTS AND DISCUSSION

Annual Rainfall Variability:

The long-term mean (LTM) annual rainfall was recorded as 77.8 mm, with a median value of around 75.6 mm during the study period. The highest recorded annual rainfall was 118.2 mm in 1961, while the lowest was 37.7 mm in 1997. A long-term trend analysis indicates a gradual decline in mean annual rainfall over the decades, although with considerable fluctuations (Fig. 2A). The 1951–1980 period experienced higher overall rainfall, with several years recording values exceeding 100 mm. However, post-1980, a clear pattern of increasing variability emerges, with a higher frequency of years recording below-average rainfall. The 1990s and early 2000s, in particular, saw multiple instances of rainfall below 70 mm, reflecting a potential dry period. While the 2010s did not exhibit a consistent increase or decrease, the erratic nature of rainfall highlights on-going climatic uncertainty.

Decadal Analysis:

The 1950s and 1960s recorded the highest average annual rainfall, with 85.4 mm and 86.8 mm, respectively. A noticeable decline began in the 1970s, with the mean value of 79.3 mm. The 1980s saw a slight recovery to 83.3 mm, but the 1990s marked a sharp decrease to 73.5 mm. The trend line indicates the downward trend continued till the 2000s, with an average of 68.3 mm, indicating a prolonged period of below-average rainfall. Although 2011–2021 period showed a slight increase to 70.2 mm, this was still significantly lower than the values observed in the earlier decades (Fig. 2B). This pattern suggests that the region may be experiencing a long-term drying trend, possibly linked to climate change, regional land-use alterations, and monsoonal behaviour.

Extreme Events:

The wettest year in the dataset was 1961, with 118.2 mm, followed by 1960 and 1978, both exceeding 112 mm (Fig. 2C & D). These years primarily fall in the pre-1980 period, reinforcing the notion that higher rainfall years were more frequent in earlier decades. In contrast, the driest year was 1997, with only 37.7 mm, followed by 1987 and 2014, which recorded 43.9 mm and 48.4 mm, respectively. Notably, extreme dry years appear more frequently in the post-1990 period.

Past and Present:

The entire analysis was divided into past and present period. The period from 1951 to 2000 was considered past while 2001 to 2021 period was considered present. Mean rainfall was found to be 81.5 mm while the mean

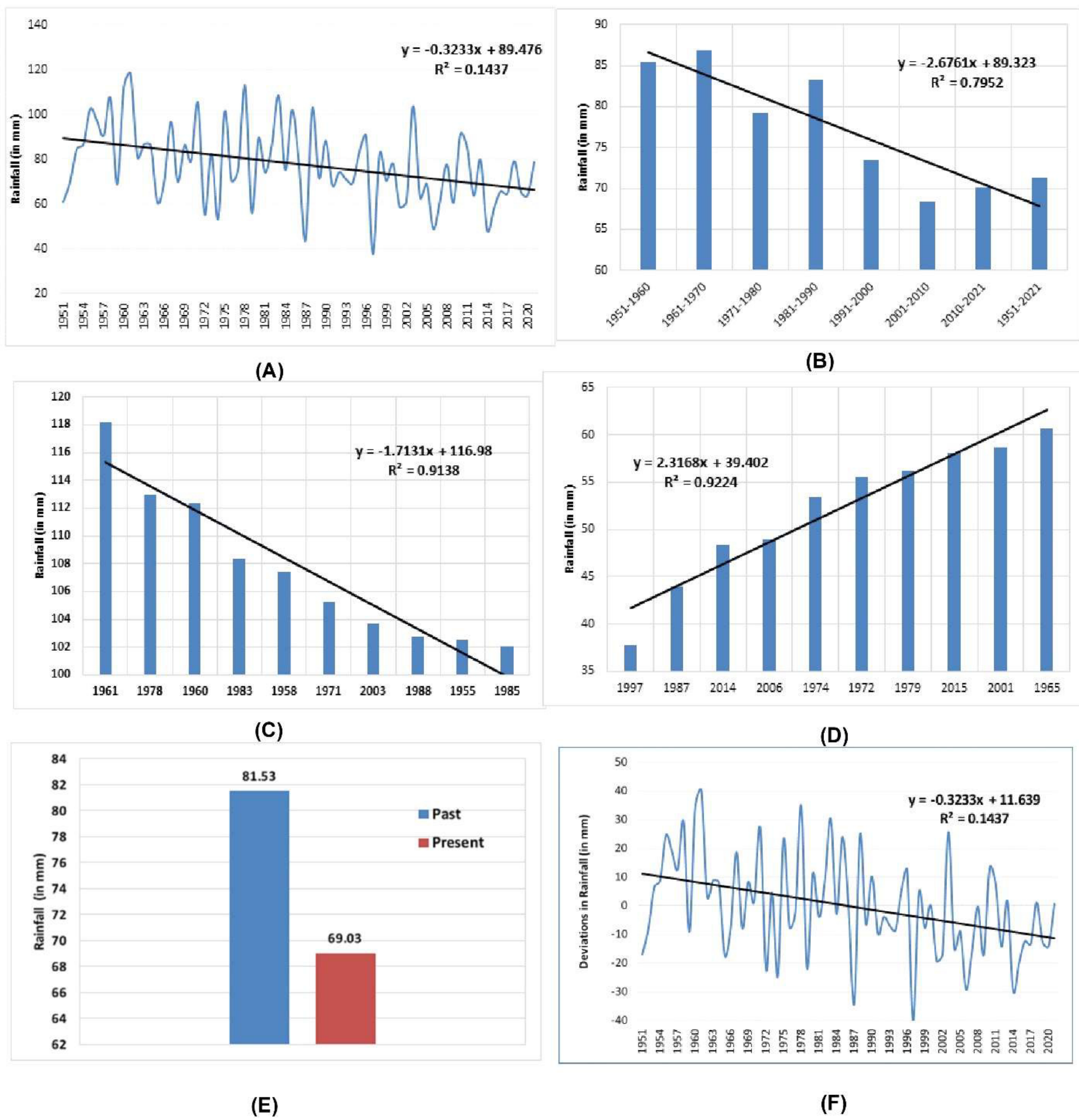

Fig. 2 : (A) Mean annual rainfall variability (B) Mean decadal rainfall (C) The highest rainfall years (D) The 10 lowestrainfall years (E) The Mean annual rainfall of the Past and present and (F) Rainfall anomaly during the period 1951-2021 in Upper Ganga Plain

rainfall for the present period was 69 mm (Fig. 2E) which clearly indicates that the present condition of rainfall scenarios is very dire and urgent attention is required.

Rainfall Anomaly:

Examining rainfall anomalies deviations from the long-term mean of 77.8 mm further strengthens this assessment. Positive anomalies was observed in 35 years, indicating above-average rainfall, were mostly observed before 1980, while negative anomalies, representing below-average rainfall was 36, dominated after 1990. (Fig. 2F) The persistence of negative anomalies suggests a potential long-term drying effect

For better understanding of the variability the rainfall data was divided in five classes. To classify the rainfall data into meaningful categories, the dataset was divided into five classes: very low (< 60 mm), low (60–70 mm), moderate (70–85 mm), high (85–100 mm), and very high (> 100 mm). The classification revealed that out of 70 years, 24 years fell into the very low and low categories, with most of these occurred after 1990 (Table 1). Conversely, very high rainfall years were observed predominantly before 1980. Moderate rainfall years, ranging from 70 to 85 mm, were the most frequent, comprising approximately 40% of the dataset. This distribution suggests a transition from frequent high-rainfall years in the early decades to a more erratic pattern with a greater prevalence of below-average rainfall in recent times.

Table 1 : Classification of annual rainfall variability in the study area

Category	Rainfall range (mm)	Number of years	Percentage of total years
Very low	< 60	9	12.6
Low	60-70	15	21.4
Moderate	70-85	22	31.4
High	85-100	13	18.6
Very high	> 100	11	15.7

Spatial Distribution of Rainfall:

The long-term mean (LTM) rainfall distribution across the Upper Ganga Plain reveals significant spatial variability influenced by topography, climate, and monsoonal patterns. The highest rainfall was recorded in Moradabad (165.63 mm) and Rampur (161.75 mm), may be due to orographic effects (Fig. 3). The central and southern districts such as Bulandshahar (27.44 mm), Bareilly (40.61 mm), and Kanpur Nagar (48.82 mm) were reported were the lowest values. Moderate rainfall was observed in districts like Prayagraj (111.46 mm) and Bijnor (112.47 mm), highlighting localized climatic influences. This variability underscores challenges for water resource management and agricultural sustainability.

The decadal analysis from 1951 to 2021 revealed

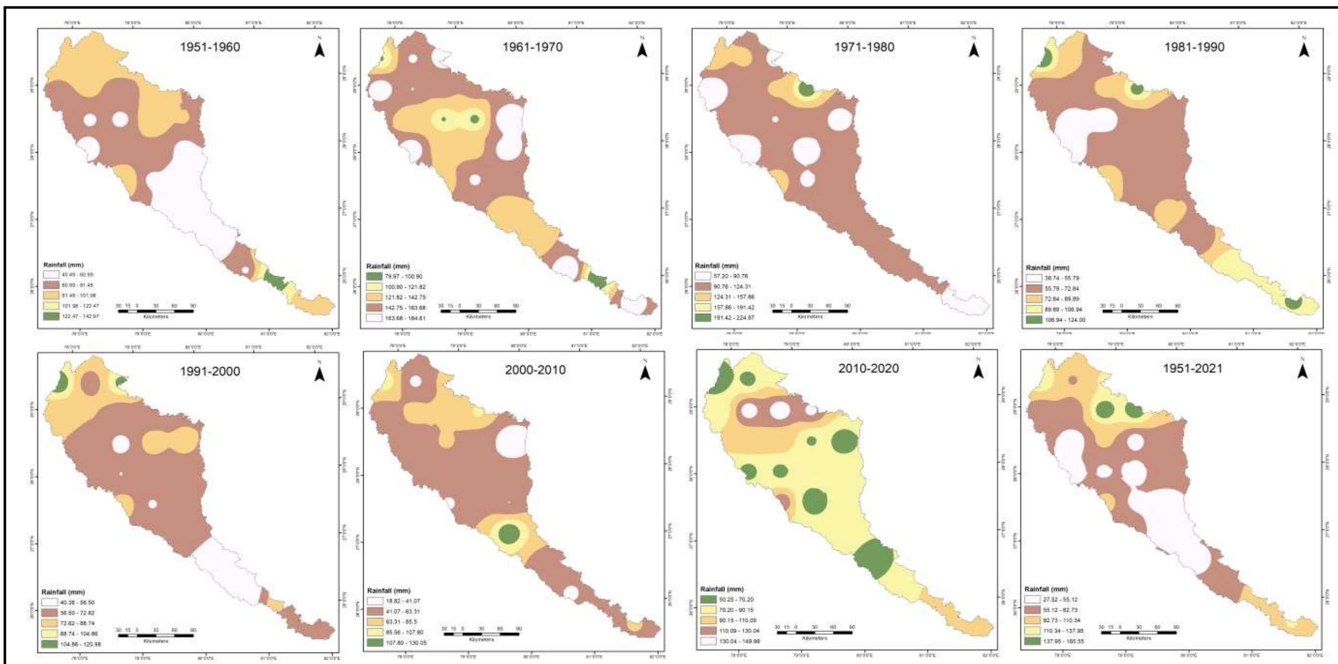

Fig. 3 : Spatial variation of annual rainfall in Upper Ganga Plain

notable fluctuations. During 1950s, rainfall was moderately distributed, with the highest in Rai Bareilly (143 mm) and in Kanpur Nagar (44 mm) and Hardoi (40.4 mm). The 1960s marked a significant increase, with Muzaffarnagar (165.2 mm) and Bareilly (169.7 mm) receiving peak precipitation. The 1970s exhibited mixed trends, with Rampur recording an anomaly (225mm) while Prayagraj (58.3 mm) and Aligarh (57.1 mm) saw declining trends.

The 1981-1990 decade saw decling rainfall trend particularly in Bareilly (66.9 mm) and Bulandshahar (45.3 mm). The 1990s continued this decline, with Kanpur

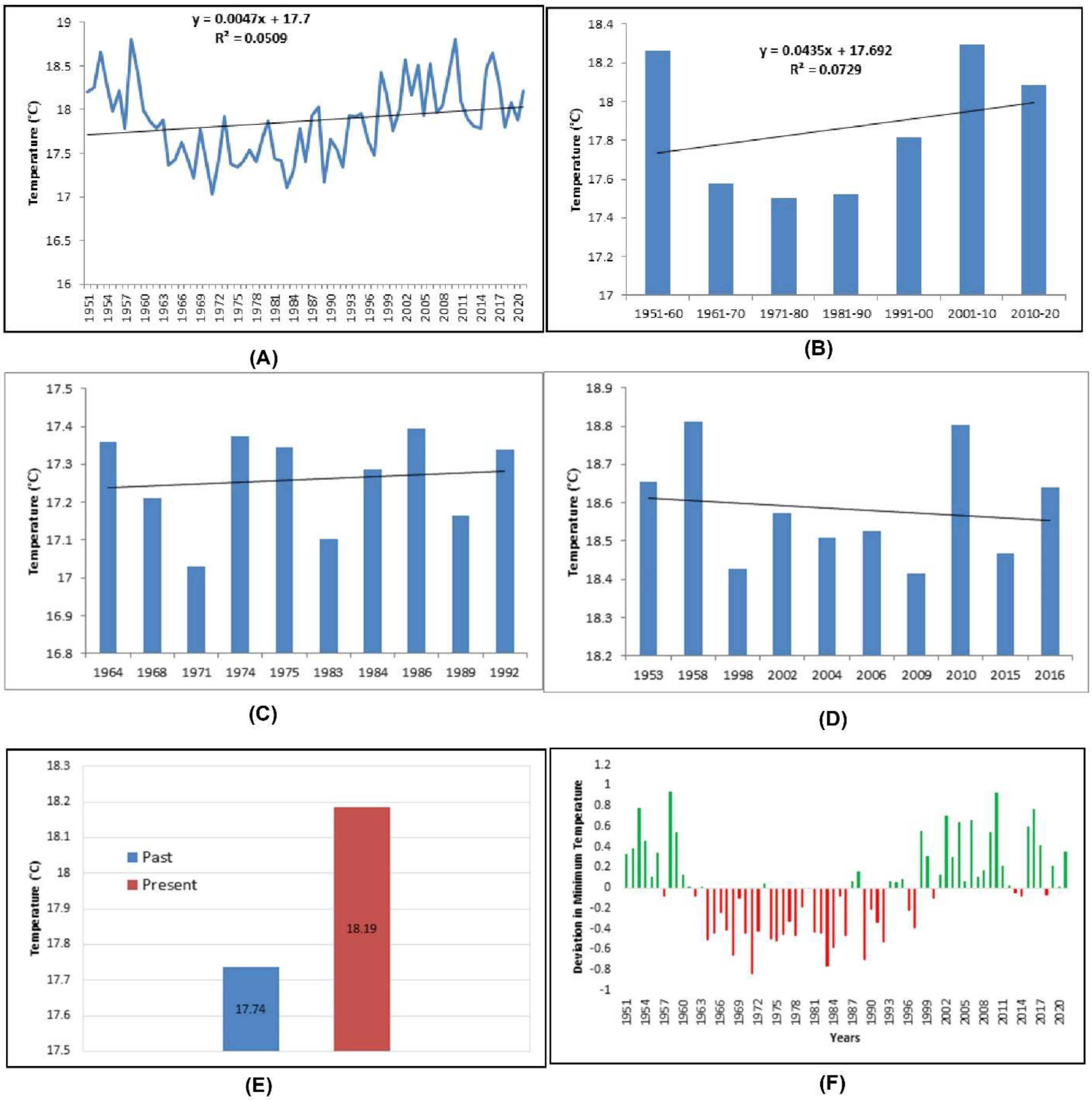

Fig. 4 : (A) Annual fluctuations of minimum temperature, (B) Decadal trend of mean minimum temperature, (C) The lowestyears of minimum temperature, (D) The 10 highest years of minimum temperature, (E) The mean minimum temperature of past and present and (F) Deviations from LTM over the years in Upper Ganga Plain

Nagar (42.8 mm) and Hardoi (56.5 mm) receiving reduced precipitation. In 2001-2010, most districts were experienced further declines, with Pilibhit (18.80 mm) witnessing an alarming drop. The 2011-2021 period had showed mixed trends, while Moradabad (150mm) and Rampur (135mm) saw recoveries, Muzaffarnagar declined sharply to 50.2 mm, indicating a shift in rainfall patterns.

Mean Minimum Temperature Analysis :

The analysis of annual minimum temperatures was shown an increasing trend in both mean temperature and anomalies. Over 70 years, 37 years recorded positive anomalies, and 34 had negative anomalies, reflecting a gradual warming trend. The long-term mean temperature (17.86°C) has also risen, confirming regional warming consistent with global climate patterns (Fig. 4). The lowest minimum temperatures were recorded in the 1960s and 1970s, with the coldest in 1968 (17.21°C). In contrast, recent decades show higher minimum temperatures, reducing the frequency of extreme cold events while increasing warm nights, may that affect agriculture, water resources, and human health.

Spatial Distribution of mean minimum temperature:

The analysis of the decadal mean minimum temperature (1951–2021) exhibited an overall warming trend with fluctuations (Fig. 5). The 1951–1960 decade was recorded the highest average minimum temperature (18.26°C), followed by a cooling phase, with the lowest mean (17.5°C) observed in 1971–1980. A reversal occurred after the 1980s, with temperatures rising steadily, reaching 18.18°C in recent decades. The 1950s recorded the highest minimum temperatures, with Prayagraj (19.5°C) and Kanpur Nagar (19.43°C) among the warmest districts. Cooling occurred in 1961–1980, with Muzaffarnagar and Bijnor consistently recording the lowest temperatures (14.7°C). The 1980s saw temperature stabilization (17.4°C), while the 1990s marked a turning point, with minimum temperatures rising to 17.78°C. The warming trend accelerated in 2001–2010 (18.15°C), making it the warmest decade. Although the 2011–2021 period saw a slight decline (18.04°C), the overall trend indicates long-term warming.

Mean Maximum Temperature Analysis:

Annual trends highlight a clear shift from predominantly negative anomalies in earlier decades to more frequent positive anomalies in recent years. Out of 71 years, 37 had positive anomalies, signaling increasing temperatures. The long-term mean (17.86°C) also exhibits an upward trajectory, with past minimum temperatures averaging 17.74°C compared to 18.18°C in the present period (Fig. 6). The mean maximum

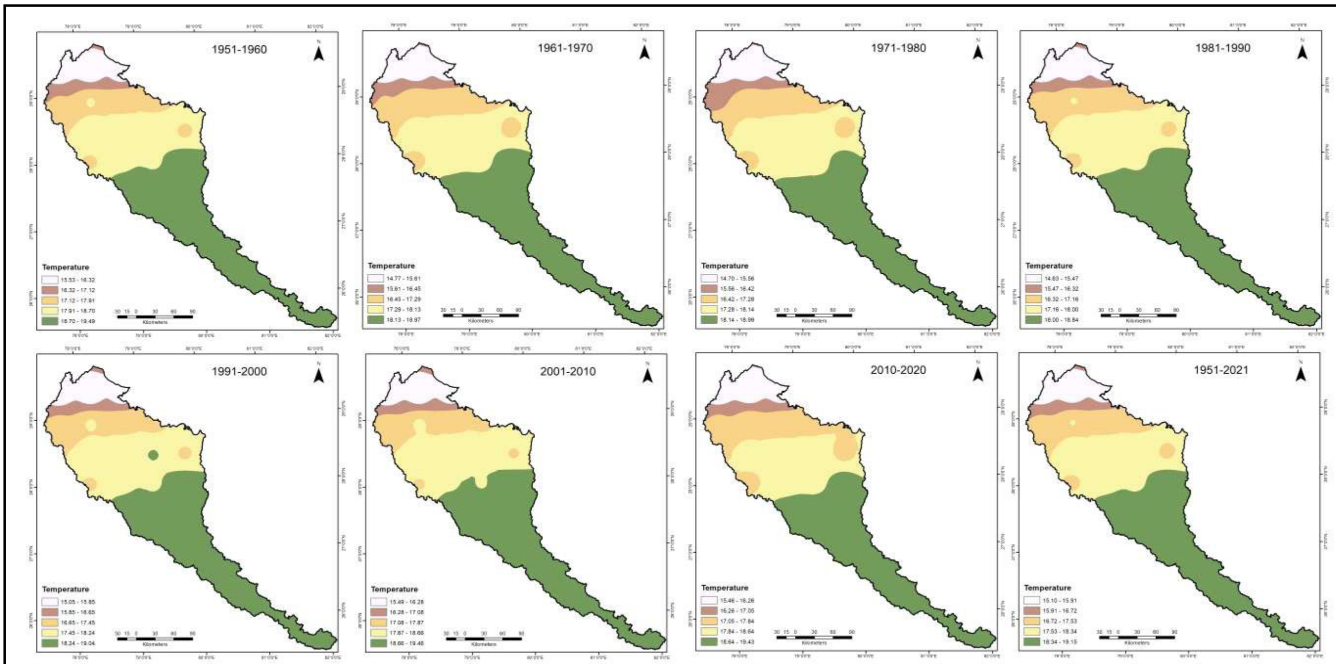

Fig. 5 : Spatial variation of mean minimum temperature in Upper Ganga Plain

temperature (30.57°C) exhibits moderate variation (SD ±0.61°C). The highest recorded maximum temperature (31.75°C) occurred in 1987, while the lowest (29.17°C) was in 1997. Anomalies indicate a shift toward warmer years, with 1987, 2016, and 2021 showing the strongest positive anomalies, while 1997 and 2003 recorded the most significant cooling anomalies.

The decadal trend of minimum temperature in the

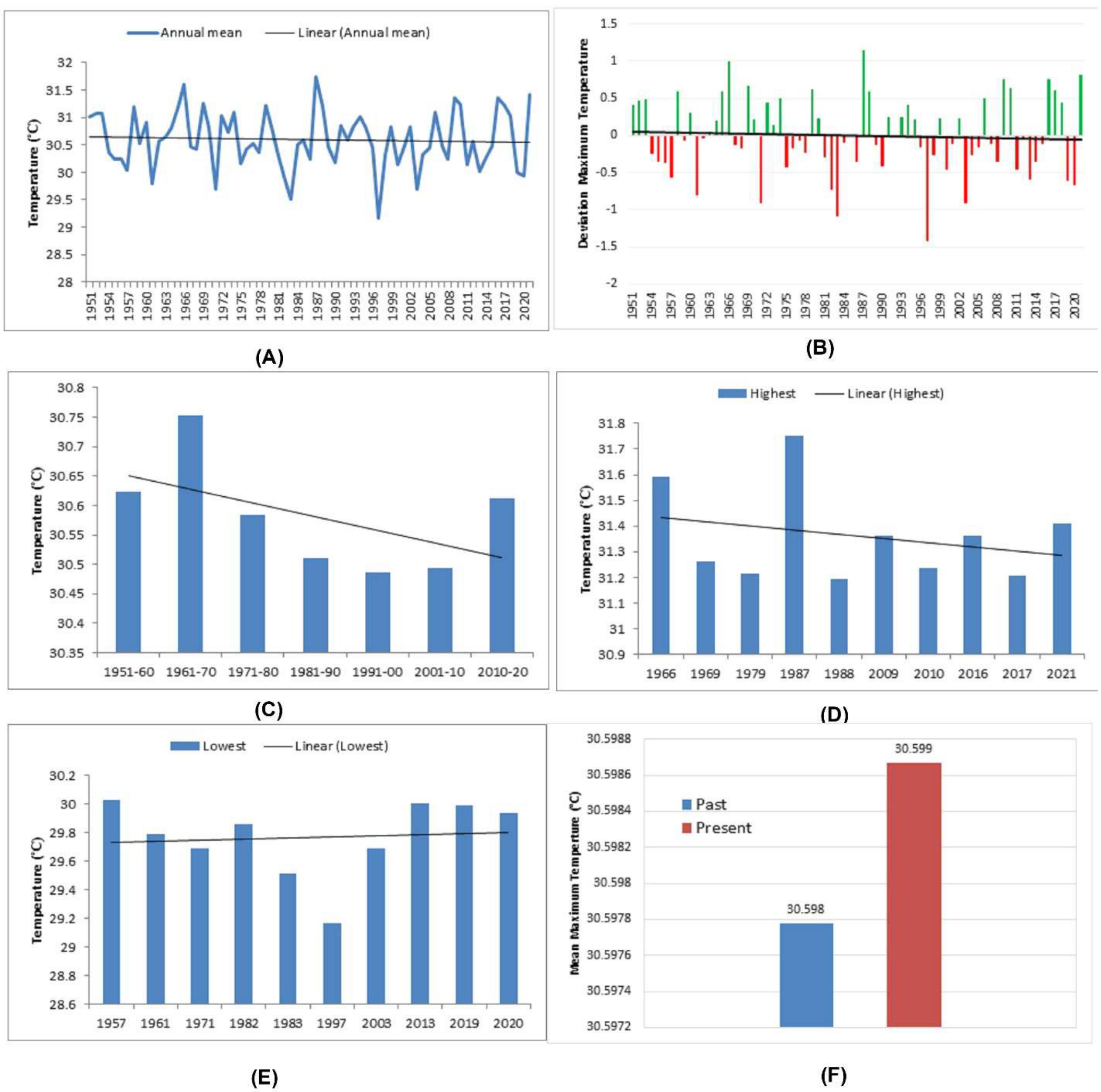

Fig. 6 : (A) Annual fluctuations of maximum temperature, (B) Deviations from the LTM of mean maximum temperature, (C)Decadal variability of mean maximum temperature, (D) Extreme events (highest) in the mean maximum temperature, (E) Extreme events (lowest) in the mean maximum temperature and (F) The annual mean maximum temperature inUpper Ganga Plain

Note: In sub-part (F), the variation is very small, therefore at least four decimals are needed to show the variation in the y axis. If you keep two decimals then all numbers on y axis will be displayed as 30.60 with no variation from bottom to top.

Upper Ganga Plain reveals an initial cooling phase (1951–1980), followed by a gradual warming trend from the 1990s onward. The lowest decadal mean (17.50°C) was recorded in 1971–1980, while temperatures increased steadily thereafter. The most recent period (2011–2021) shows minimum temperatures comparable to earlier warmer decades, indicating a sustained warming phase.

Extreme temperature events further support this trend. The coldest recorded years, mainly in the 1960s and 1970s, align with the earlier cooling phase, while the highest minimum temperatures have been recorded in recent decades. This shift suggests a decline in extreme cold events and a rise in warm nights, impacting agriculture, water resources, and human health. The analysis showed that ten warmest years occurred mostly after 1980, with 1987, 2016, and 2021 as standout hot years. Conversely, cooler years were scattered, with 1997 and 1983 exhibiting the most pronounced cold extremes.

Spatial Distribution of Mean Maximum Temperature:

From 1951–1980, The mean maximum temperatures were fluctuated, with warmer districts (e.g., Prayagraj, Farrukhabad) exceeding 32°C, while Muzaffarnagar and Bijnor remained below 27°C (Fig. 7). A cooling phase was observed in 1981–1990, but temperatures began rising in the 1990s, stabilizing slightly in the early 2000s. The warmest decade was 2001–2010, with an increasing trend in most districts. The latest decade (2011–2021) shows mixed trends, with slight declines in some areas while others continue to warm.

The spatial analysis of mean maximum temperature revealed that the shows cooling pattern across all districts from 1961 to 1980, followed by temperature stabilization in the 1980s. A reversal occurred in the 1990s, with rising temperatures in majority of the districts. The warming trend peaked in 2001–2010 (18.15°C), with a minor drop in 2011–2021 (18.04°C), suggesting possible short-term stabilization. Overall, the region has experienced significant warming, particularly in urban centers like Prayagraj and Kanpur.

Statistical Analysis of Temperature and Rainfall Data:

***Scatter plot*:**

The scatter plot visually represents the relationship between Mean Annual Temperature (°C) and Rainfall (mm) in the Upper Ganga Plain (Fig. 8 b&b). The analysis revealed that there is no strong linear correlation between the two variables, as the points appear scattered without forming a clear upward or downward trend. Some clusters indicate that higher temperatures do not necessarily correspond to higher or lower rainfall,

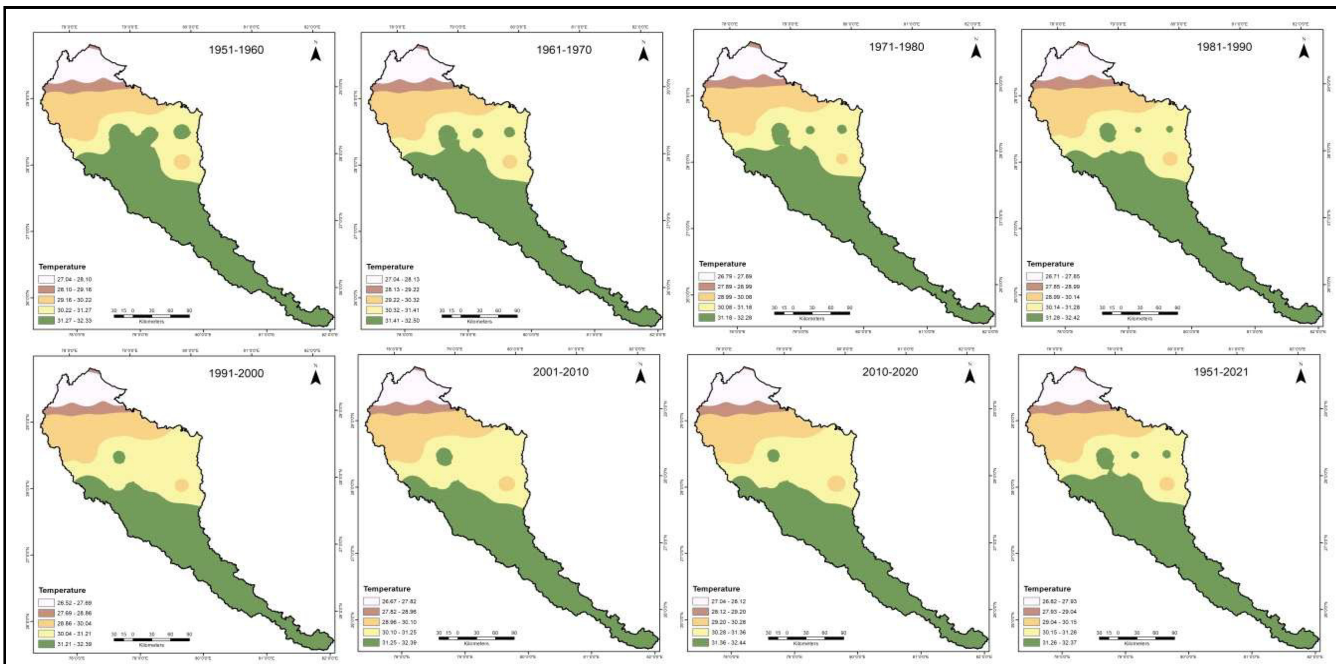

Fig. 7 : Spatial variation of mean maximum temperature in Upper Ganga Plain

suggesting a weak correlation.

Histogram analysis:

The histogram of rainfall suggests a right-skewed (positively skewed) distribution, indicating that most years had moderate rainfall, but some years experienced exceptionally high rainfall (Fig. 8a & b). The temperature histogram follows a roughly normal distribution, centered around a mean value. The peak (mode) suggests the most frequently occurring temperature range, with fewer years experiencing extreme high or low temperatures. The histograms confirm that both variables exhibit distinct distributions, with rainfall showing skewness and temperature displaying a more normal pattern.

The pearson's correlation coefficient is approximately -0.229, indicating a weak negative correlation between rainfall and temperature (Table 2). This suggests that temperature alone may not be a primary driver of rainfall variation, and other factors may also

Table 2 : Correlation analysis of rainfall and temperature

Variables	Rainfall	Mean Temperature
Rainfall	1	-0.229
Mean Temperature	-0.229	1

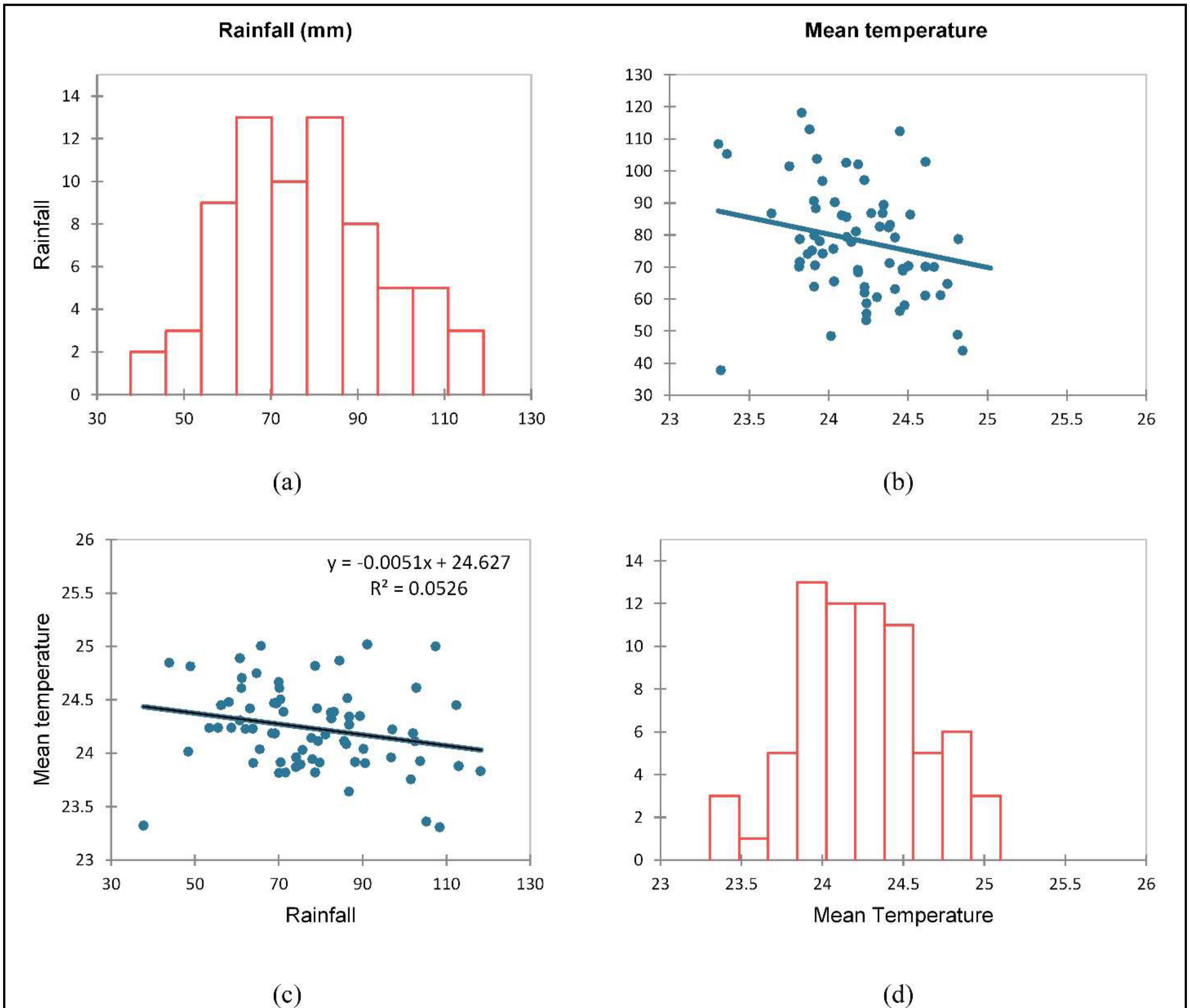

Fig. 8 : (a)Histogram of rainfall distribution (b) Scatter plot of temperature and rainfall (c) Scatter plot of Rainfall and meantemperature (d) Histogram of mean annual temperature

play a significant role.

Conclusion:

The analysis of rainfall and mean annual temperature trends in the Upper Ganga Plain provides crucial insights into the region's climatic variability over the past 70 years (1951–2021). The correlation analysis between rainfall and temperature yielded a weak correlation coefficient ($r \approx -0.229$), indicating that fluctuations in one variable do not strongly influence the other. This suggests that the interaction between rainfall and temperature in this region is complex and influenced by multiple factors such as monsoon variability, atmospheric circulation patterns, and land-use changes.

The rainfall data exhibited significant inter-annual variability, with annual precipitation ranging from a minimum of 37.74 mm (1997) to a maximum of 118.2 mm (1961). The temperature data ranged from 23.30°C (1983) to 25.02°C (2010 and 2016), with a noticeable upward trend in recent decades. The histogram analysis revealed that rainfall values are more widely dispersed, while temperature variations remain within a relatively narrow range, reinforcing the presence of a long-term warming trend in the region.

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