**Rainfall Variability in the Central Plain Zone of Uttar Pradesh, India**

 **ABSTRACT**

This study aimed to evaluate the long-term variability and trends in monsoonal rainfall across the Central Plain Zone of Uttar Pradesh, with a focus on its impact on agricultural sustainability. A retrospective analysis was conducted using 50 years of historical rainfall data (1975–2024) sourced from the India Meteorological Department (IMD) and Chandra Shekhar Azad University of Agriculture and Technology, Kanpur. This study analyzed annual rainfall records for the Kanpur and Luck now districts using a combination of statistical methods. These included calculating average rainfall, identifying years with unusually high or low rainfall, and examining long-term trends across decades. To trace significant shifts in rainfall patterns, linear regression and the Mann-Kendall trend test were applied. In Kanpur, the average annual rainfall was found to be 897.90 mm, with the highest recorded in 1980 (1982.3 mm) and the lowest in 1979 (451.8 mm). In comparison, Luck now mean annual rainfall stood at 881.21 mm, with its wettest year also in 1980 (1721.5 mm) and the driest in 1987 (490.7 mm). Both districts displayed notable year-to-year and decadal fluctuations. While there were brief periods of recovery, the overall trend pointed to a steady decline in rainfall over time. This increasing variability in monsoon behavior presents serious concerns for regions dependent on rain fed agriculture. The findings underscore the urgent need for adaptive planning and robust water resource strategies to ensure the long-term sustainability of agriculture in the Central Plain Zone.

**Keyword:** Rainfall Variability, Climate trends, Rain fed, Monsoonal behavior and Central Plain Zone

1. **Introduction**

Climate change poses a substantial challenge to ecosystems across the globe. As highlighted in the Intergovernmental Panel on Climate Change’s Sixth Assessment Report (IPCC,2018), communities that depend heavily on agriculture particularly those in arid and semi-arid zones are especially susceptible to the impacts of climate variability. In regions like Africa and Asia, where agriculture underpins rural economies, changing rainfall patterns, temperature instability, and an increase in severe weather events are placing immense strain on food production systems (Morton, 2007; Wheeler & von Braun, 2013). These climatic fluctuations are expected to become more frequent and intense over time, thereby worsening food insecurity especially for smallholder farmers who lack the capacity to adapt effectively (FAO, 2016).

The Central Plain Zone of Uttar Pradesh represents a crucial agricultural hub, heavily reliant on monsoonal rainfall, which contributes nearly 80% of its total annual precipitation (Srivastav et al., 2021). With more than 60% of the cultivated area depending on rain fed agriculture, fluctuations in rainfall timing and intensity can significantly disrupt planting calendars, affect crop productivity, and threaten rural livelihoods. In recent decades, the region has experienced an increase in climate variability—evident in delayed monsoon arrivals, uneven rainfall distribution, and more frequent extreme weather events such as floods and droughts. These disruptions have made farm-level planning more complex and uncertain (Mall et al., 2006).

Global shifts in climate, primarily driven by escalating greenhouse gas concentrations, are now altering local water cycles. Forecasts indicate a potential rise in average temperatures ranging from 0.4–2.0°C during the *kharif* season and 1.1–4.5°C during the *rabi* season by the year 2070, which would intensify the stress experienced by crops. Although some projections suggest a 10% increase in overall rainfall, the irregular timing and spatial distribution of precipitation present greater obstacles than the total rainfall amount itself (Maurya et al., 2023). Small-scale, fragmented landholdings heighten farmers’ vulnerability, as even slight deviations in rainfall during critical crop growth stages can cause major losses in yield (Baliyan K., 2022). For this reason, analyzing long-term rainfall trends and understanding their variability are vital steps toward promoting agricultural systems that are resilient to climate change (Srivastav et al., 2021).

Change in rainfall patterns due to global warming, particularly after the 1990s and the era of rapid industrialization, has significantly impacted the hydrological cycle. These shifts necessitate a re-evaluation of water demand, hydrological planning, and agricultural practices. Consequently, analyzing long-term trends in rainfall and other climatic parameters across various spatial scales becomes essential for establishing future plans for crop planning and management (Jain & Kumar, 2012).

In India, In the rainy season, the average temperature is expected to rise by 0.1°C to 0.3°C, and in the dry season, by 0.3°C to 0.7°C, by 2010. In a similar vein, mean rainfall is predicted to rise by up to 10% by 2070 but not to alter much by 2010 (IPCC, 2007). At the same time, there is a greater chance of climate extremes such altered monsoon onset timing and more frequent and severe floods and droughts. (Adhya T.K., 2010). While the debate on global warming continues, the majority of scientific research shows that the climate is becoming more unpredictable over time. Agriculture, being highly dependent on weather conditions, is more affected by extreme weather events such as flooding, drought, cold spells, heat waves, cyclones and soil degradation. Unfortunately, these occurrences are growing more frequent and widespread, threatening India's agricultural gains. (Adhya, T. K. 2010).

Climate change is a serious threat to many different ecosystems worldwide. According to the Intergovernmental Panel on Climate Change's sixth assessment report (IPCC, 2018), those that depend on agriculture for a living and those living in arid regions are disproportionately more vulnerable to climate variability. Particularly in India, where 60% of all crops are still rain-fed and a large percentage of landholdings are small and dispersed, the growing frequency of intersession variations Regarding temperature, rainfall, and various other extreme events has a substantial impact on agricultural production and livelihoods (Jain *et al*. 2015).

1. **Materials and method**

**The present study, titled “Climatic Variability Analysis of Central Plain Zone of Uttar Pradesh,” Was conducted using the primary objective of evaluating long-term trends and fluctuations in rainfall patterns over an extensive period of 50 years, spanning from 1975 to 2024.** The investigation was centered on the Central Plain Zone of Uttar Pradesh, a region where agricultural productivity is predominantly dependent Regarding the performance of the monsoon season. As such, any irregularity in Rainfall can greatly impact crop yields, water availability, and overall rural livelihoods.

For this purpose, historical rainfall data were meticulously obtained from two major and reliable sources: the India Meteorological Department (IMD), Pune, and Chandra Shekhar Azad University of Agriculture and Technology (CSAUAT), Kanpur. The compiled dataset was comprehensive, encompassing rainfall records on daily, monthly, seasonal, and annual timescales. This extensive and detailed dataset provided a strong and credible foundation for conducting a thorough analysis of temporal variations and climatic anomalies over the selected timeframe.

During the preliminary stage of the research, raw daily rainfall records were systematically aggregated to calculate totals at various temporal resolutions, including weekly, monthly, seasonal (both *kharif* and *rabi* seasons), and annual levels. These aggregations allowed for a multi-scale examination of rainfall behavior and facilitated trend identification over both short and long durations.

Basic data processing and preliminary Statistical analyses were performed using Microsoft Excel, which served as the primary platform for organizing, analyzing, and visualizing the data. To enhance the reliability and accuracy of the analysis, a cross-verification process was undertaken. This involved comparing rainfall records obtained from different datasets and sources to detect inconsistencies or anomalies, thereby ensuring that The refined dataset utilized for analysis was both authentic and scientifically sound.

Rainfall analysis included the calculation of total and mean rainfall across different time scales. Mean rainfall was computed using the formula $Rˉ =\frac{\sum\_{i=1}^{n}Ri}{n}$​​ where *Ri*​ is annual rainfall and *n* Refers to the total number of years. Rainfall occurrences were categorized into intensity categories -light, moderate, heavy, and extremely heavy based on daily thresholds.

Trend analysis was performed with the help of both linear regression and the non-parametric Mann-Kendall test. Linear regression determined the direction and rate of change in rainfall using the equation Y=mX+C. The Mann-Kendall test assessed the statistical significance of trends without assuming data normality, utilizing the standardized Z-statistic for interpretation.



 Fig.1 District map of Lucknow

Fig.2 District map of Kanpur. (Source: burningcompass.com)

**Result and Discussion**

**3.1 Annual Rainfall Variability of Kanpur District**

An examination of yearly rainfall variability in the Kanpur district over a 50-year period (1975–2024) ( Table 1 and Graph 1) revealed significant inter-annual and decadal fluctuations, with a calculated mean Yearly rainfall of 897.90 mm. The peak yearly rainfall was observed in 1980 (1982.3 mm), Where as the minimum occurred in 1979 (451.8 mm), indicating pronounced variability even within short time spans.

Decadal analysis further highlighted notable shifts in rainfall patterns. The first decade (1975–1984) recorded the highest mean annual rainfall of 1026.79 mm. This was followed by a substantial decline in the second decade (1985–1994), with the mean dropping to 783.51 mm reflecting a marked increase in rainfall irregularity. A slight improvement was observed throughout the third decade (1995–2004), where the mean rose to 925.26 mm, supported by significantly wet years such as 1997 and 1998. But this recovery could not be maintained. The fourth decade (2005–2014) witnessed a further decrease in average rainfall to 835.48 mm, underscoring climatic instability. This period included years of both high rainfall (2013 with 1234.1 mm) and deficient rainfall (2006 with 551.3 mm). The fifth and most recent decade (2015–2024) showed a modest rebound, with a mean of 918.57 mm, although variability persisted illustrated by below-average years like 2015 (623.3 mm).

These findings are supported by the observations of **Mall et al. (2006)** and **Kumar et al. (2010)**, who documented similar rainfall fluctuations in central and eastern Uttar Pradesh, attributing them to increased climate variability and anthropogenic influences post-1980s. **Rathore et al. (2013)** also found that rainfall trends in the Indo-Gangetic Plain exhibited significant inter-annual variability, with an increasing occurrence of dry spells and short-term wet extremes, a pattern reflected in Kanpur's rainfall behavior in this study.

In addition, **Sinha Ray and De (2003)** noted a weakening trend in monsoon strength post-1980s in north-central India, consistent with the declining rainfall observed in the second and fourth decades of this study. Moreover, the increased variability observed here where extreme rainfall years are followed by deficit years aligns with the findings of **Jain and Kumar (2012)**, who emphasized the erratic nature of rainfall due to shifting monsoon dynamics.

Overall, the long-term trend suggests a gradual decline in mean annual rainfall accompanied by an increased frequency of extreme rainfall events, both excess and deficit. This growing variability directly affects agricultural planning and water resource management, and crop productivity in the Central Plain Zone, particularly in rain-fed farming systems where rainfall reliability is critical.

**3.2 Annual Rainfall Variability of Luck now District**

The analysis of annual rainfall variability in the Luck now district over the 50-year period from 1975 to 2024 (Table 1 and Graph 2) revealed significant inter-annual and decadal fluctuations, with a mean yearly rainfall of 881.21 mm. The highest annual rainfall was recorded in 1980, reaching 1721.5 mm, whereas the lowest was observed in 1987 at just 490.7 mm. highlighting significant year-to-year variability in precipitation. Analyzing decadal patterns revealed alternating phases of increase and decline, indicative of rising unpredictability in monsoon behavior. The first decade (1975–1984) exhibited the highest mean decadal rainfall at 1033.98 mm, with several high-rainfall years such as 1980, 1975, and 1982. However, this period also included notably dry years like 1979 and 1976, reflecting continued fluctuations.

A marked decline followed in the second decade (1985–1994), where the average annual rainfall dropped to 721.01 mm. critically dry years including 1987, 1993, and 1989 were key contributors to this downward trend. The third decade (1995–2004) remained below the long-term average, recording a mean of 794.91 mm. While certain years such as 1997 and 1998 saw relatively higher rainfall, they were offset by drier years like 1995, 2000, and 2002.

Some recovery was evident during the fourth decade (2005–2014), as the mean annual rainfall rose to 889.32 mm. However, this improvement was partial and did not signal a full return to earlier levels, suggesting ongoing variability and instability in regional rainfall trends. This improvement was supported by wetter years such as 2008, 2011, and 2012; however, drought-prone years like 2006 and 2007 reflected continued climatic instability. The most recent decade (2015–2024) exhibited further improvement, with a mean annual rainfall of 966.85 mm second only to the first decade. Above-average rainfall in years such as 2018, 2019, and 2023 contributed to this rise, although deficits remained in years like 2015 and 2017.

These results align with regional trends identified by **Rathore and Attri (2008)**, who noted an increase in rainfall variability in Uttar Pradesh, largely due to shifting climatic regimes and industrial expansion post-1990. **Das et al. (2011)** observed similar rising and falling decadal rainfall patterns in eastern Uttar Pradesh, pointing out that while total rainfall may not always show a strong declining trend, its spatial and temporal distribution is becoming more erratic.

Furthermore, **Mondal et al. (2015)** and **Jain et al. (2015)** noted an increase in extreme rainfall events in northern India, which aligns with the higher rainfall years in Luck now (2018 and 2023) that contributed to the recent decadal rise. The alternating pattern of dry and wet years found in this study reflects larger climatic oscillations, such as ENSO events and monsoon Fluctuations that have proven to influence rainfall behavior in north India.

In summary, the long-term rainfall pattern in Luck now district is characterized by high variability, with alternating periods of drought and excessive rainfall. These fluctuations pose significant challenges to sustainable agriculture, irrigation planning, and water resource management. The findings emphasize The essential requirement for adjustable and climate-resilient strategies, particularly in rain-fed agricultural systems within the Central Plain Zone.

1. **Conclusion**

**The 50-year climatic analysis of rainfall variability in the Central Plain Zone of Uttar Pradesh**, focusing on Kanpur and Luck now districts, reveals a concerning trend of increasing irregularity in monsoonal patterns. While certain decades showed signs of partial recovery, the overarching trajectory indicates a gradual decline in average annual rainfall accompanied by a rising frequency of extreme events, including both prolonged droughts and episodes of intense precipitation.

This level of variability significantly impacts rain-fed agriculture, irrigation planning, and overall water resource management. These fluctuations threaten regional food security and disrupt rural livelihoods, making agricultural systems increasingly vulnerable to climatic uncertainties.

The observed trends underscore The essential requirement for adjustable strategies, including the promotion of climate-resilient cropping systems, enhanced weather forecasting capabilities, and the implementation of sustainable water management practices.

**Practical Recommendations**:

* **Promotion of drought-resistant and short-duration crop varieties** suitable for erratic rainfall patterns.
* **Expansion of micro-irrigation systems** (drip and sprinkler) to improve water-use efficiency.
* **Establishment of decentralized rainwater harvesting structures** to enhance groundwater recharge.
* **Development of real-time agro-advisories and early warning systems** at the village level.
* **Capacity-building programs for farmers** to adopt climate-smart agricultural techniques.

**Policy Recommendations**:

* **Inclusion of rainfall variability data in district-level agricultural planning** and crop insurance schemes.
* **Integration of climate risk mapping** into the Mahatma Gandhi National Rural Employment Guarantee Act (MGNREGA) for water conservation asset creation.
* **Enhanced funding for research and development activities** in climate-resilient agriculture and local weather modeling.
* **Incentivizing water-efficient technologies** and sustainable practices through subsidies and credit support.
* **Strengthening coordination between meteorological departments and agricultural extension services** to bridge the information gap.

This research offers significant insights into the long-term climatic dynamics of the region and serves as a foundational reference for policymakers, researchers, and agricultural communities striving to mitigate climate risks and promote sustainable farming in the Central Plain Zone.

**Table 1. Annual Rainfall variability in Kanpur and Lucknow districts**

|  |  |  |
| --- | --- | --- |
| **Year (1975-2024)** | **Annual Rainfall (mm) in Kanpur District** | **Annual Rainfall (mm) in Luck snow District** |
| 1975 |  937.80  | 1243.50 |
| 1976 | 811.30 | 664.70 |
| 1977 | 1045.00 | 828.90 |
| 1978 | 1035.00 | 1197.90 |
| 1979 | 451.80 | 540.70 |
| 1980 | 1982.30 | 1721.50 |
| 1981 | 1054.90 | 947.40 |
| 1982 | 1204.50 | 1205.80 |
| 1983 | 996.00 | 1157.90 |
| 1984 | 749.30 | 831.50 |
| 1985 | 1250.30 | 1216.70 |
| 1986 | 939.80 | 725.30 |
| 1987 | 437.40 | 490.70 |
| 1988 | 752.70 | 829.70 |
| 1989 | 666.30 | 548.10 |
| 1990 | 870.70 | 792.70 |
| 1991 | 629.80 | 810.10 |
| 1992 | 754.50 | 694.20 |
| 1993 | 661.80 | 532.70 |
| 1994 | 871.80 | 569.90 |
| 1995 | 756.90 | 657.90 |
| 1996 | 1053.20 | 943.20 |
| 1997 | 1116.30 | 1006.50 |
| 1998 | 1347.60 | 1127.50 |
| 1999 | 865.40 | 698.10 |
| 2000 | 755.00 | 604.10 |
| 2001 | 641.30 | 780.50 |
| 2002 | 845.40 | 546.00 |
| 2003 | 1105.90 | 746.90 |
| 2004 | 765.60 | 838.40 |
| 2005 | 702.90 | 703.66 |
| 2006 | 551.30 | 551.50 |
| 2007 | 590.90 | 590.33 |
| 2008 | 1175.30 | 1419.50 |
| 2009 | 809.00 | 1129.60 |
| 2010 | 998.10 | 695.29 |
| 2011 | 904.50 | 1134.80 |
| 2012 | 725.40 | 1092.40 |
| 2013 | 1234.10 | 931.97 |
| 2014 | 663.30 | 644.20 |
| 2015 | 623.30 | 669.40 |
| 2016 | 690.90 | 878.80 |
| 2017 | 669.90 | 749.10 |
| 2018 | 981.10 | 1262.70 |
| 2019 | 963.90 | 1184.90 |
| 2020 | 1228.70 | 934.00 |
| 2021 | 1025.60 | 961.40 |
| 2022 | 1083.40 | 1086.80 |
| 2023 | 934.80 | 1117.60 |
| 2024 | 984.1 | 823.80 |

**Fig. 3 Graphical representation of Annual Rainfall in Kanpur district 50 years (1975 - 2024)**

**Fig. 4 Graphical representation of Annual Rainfall in Lucknow district 50 years (1975-2024)**

**ACKNOWLEDGEMENT**
The first author gratefully acknowledges the India Meteorological Department (IMD), Pune, and Chandra Shekhar Azad University of Agriculture & Technology (CSAUAT), Kanpur, for generously providing dependable meteorological data. The authors gratefully acknowledge the Department of Agricultural Meteorology, ANDUAT, Kumarganj, for their consistent support and valuable guidance throughout the course of this study.

**AUTHOR’S CONTRIBUTION**
Author A conceptualized the study, carried out the statistical analysis, formulated the research protocol, and prepared the initial draft of the manuscript. Authors B and C supervised and coordinated the analytical work. Authors D and E contributed to the comprehensive literature review. Author F supported the editing process and ensured accuracy through data verification.

**Disclaimer (Artificial intelligence)**

The authors affirm that no artificial intelligence tools (such as ChatGPT, GitHub Copilot, or similar platforms) were utilized in the writing, analysis, or preparation of this manuscript. All the content, including analytical scripts and interpretations, is entirely original, manually developed, and grounded in scientific methodology.

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