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CLIMATE INSIGHTS: UNVEILING PRECIPITATION TRENDS AND SPATIAL DISTRIBUTION OVER INDIA (1980–2023) USING ERA5 DATA

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ABSTRACT

This study examines precipitation patterns across India using ERA5 data from 1980 to 2023, revealing significant geographical and temporal variations in rainfall patterns. The findings indicate that Western and Central India, encompassing states such as Rajasthan, Gujarat, Maharashtra, and Madhya Pradesh, experience markedly low levels of precipitation, identifying these areas as relatively arid. In contrast, Southern India, especially Kerala and the Western Ghats, receives moderate rainfall, while the Northeastern states - Assam, Arunachal Pradesh, and Meghalaya—are identified as the wettest regions in the country. Analysis of long-term precipitation data shows an overall mean of 115.10 mm, with fluctuations ranging from a minimum of 9.62 mm in 1987 to a maximum of 600.39 mm in 2010, highlighting substantial year-to-year variability. Notable anomaly patterns indicate a positive deviation of 21.52 mm in 1990 and a negative deviation of -21.35 mm in 1987. Seasonal variation illustrates four distinct seasons: a predominantly dry winter, a slightly wetter pre-monsoon, a monsoon characterized by heavy rainfall, and a post-monsoon period with diminished precipitation. The analysis of precipitation trends in India reveals a nuanced picture of changing rainfall patterns. The slight increase in precipitation over time, with slopes of approximately 0.31 mm per year from the Ordinary Least Squares method and 0.29 mm per year from Sen's Slope method, indicates a gradual upward trend. This consistency between the two methods suggests that the observed increase in rainfall is likely robust and not significantly distorted by outliers. These findings underscore the critical need for climate adaptation strategies to address the implications of climate variability, particularly concerning agriculture, water resources, and ecosystem stability in the context of ongoing global warming.

Keywords: *Precipitation trend, spatial distribution, ERA5, India*

1. INTRODUCTION

The impact of climate change on heavy precipitation events has been extensively researched, largely due to their potential effects on human communities and ecosystems (Handmer et al., 2012). Various modeling studies indicate that as the climate warms, extreme precipitation events are becoming more intense, though the extent of this change differs across regions. These findings are also supported by historical data concerning land precipitation (O'Gorman, 2015). The Ganga basin has transitioned from cultivating high-moisture crops like sugarcane and peas to less moisture-demanding varieties such as wheat and mustard, primarily due to diminishing precipitation (Kothyari et al., 1996). Precipitation fluctuations also play a crucial role in hydrological processes, including the effects of precipitation (Jain et al., 2012b). Many existing hydro-infrastructure systems have been designed under the assumption of stable climate conditions, but shifting precipitation patterns driven by global warming require a reevaluation of these designs. Future climate scenarios are expected to alter runoff distribution, which can be examined through trend analyses of precipitation and precipitation patterns, facilitating more effective water resource planning. Water resources are vital to the Indian economy, and elevated precipitation could significantly impact both water availability and agricultural productivity. The Himalayan region, the source of the Indus, Ganga, and Brahmaputra rivers, provides substantial meltwater; for example, glacial melt contributes approximately 49% of the flow in the Chenab River (Singh et al., 1994). Research indicates that glacier retreat (Tayal, 2019) is likely to lead to increased peak flows and sediment transport, while average flows may decline. Such changes could adversely affect hydropower generation and urban water supplies (Arora et al., 2004). Furthermore, loss of soil moisture could result in severe water stress in arid regions, while extensive coastal areas in India risk submergence due to rising sea levels. The variations in precipitation may also influence aquaculture productivity. Understanding the spatial distribution of precipitation trends is essential for formulating climate change scenarios. Rapid economic growth and population increases, particularly in areas like India, raise significant concerns regarding the availability and quality of natural resources, especially water. Since the start of the 20th century, there has been a roughly 2% increase in global land precipitation (Hulme et al., 1998; Jones et al., 1996). This rise is statistically significant but varies in both space and time (Doherty et al., 1999). It was identified that a long-term global increase in precipitation that is independent of the influences of El Niño-Southern Oscillation (ENSO) and other climate variability patterns (Dai el al., 1997; Dore, 2005). Moreover, the increase in precipitation is not uniform across different regions, displaying asymmetrical changes in precipitation rates (Mall, et al., 2006).

To adapt effectively to these challenges, it is imperative to gather comprehensive data on the frequency and intensity of extreme weather events such as floods and droughts. This study underscores the need for research into the impact of climate change on precipitation that influences Indian River basins as a foundation for developing sustainable water management strategies. A thorough assessment of precipitation change, a major factor impacted by climate change, must consider human activities and shifts in meteorological indices across various spatial and temporal scales in India. So, addressing the precipitation variations over the region and the changing rate in India is crucial for developing effective adaptation strategies and sustainable water management policies.

2. DATABASE AND METHODOLOGY

2.1 Database

2.1.1 ERA5 data

We have used ERA5 5single level precipitation data for the study (Hans, H. et al. 2016). The ERA5 is the fifth generation of the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis, encompassing global climate and weather data from the past eighty years. It provides data starting from 1940 and serves as a successor to the ERA-Interim reanalysis, known as ECMWF Reanalysis v5 (ERA5). ERA5 delivers hourly estimates for various atmospheric, land-surface, and ocean wave parameters. An underlying ensemble of ten members generates uncertainty estimates every three hours. To simplify usage, the ensemble mean and spread have been computed. The estimation of uncertainty is closely linked to the evolving data content of the observing system, highlighting sensitive areas influenced by flow patterns. While monthly means for the ensemble are not available, pre-calculated monthly mean averages for the ensemble mean and spread are provided for different climate applications. The latest climate reanalysis from ECMWF is identified as ERA5, offering hourly data on a wide range of atmospheric, land-surface, and sea-state features. ERA5 data, including atmospheric parameters across 37 pressure levels, can be accessed through the Climate Data Store on standard 0.25° x 0.25° latitude-longitude grids.

2.2 Methodology

2.2.1 Spatial distribution of precipitation

The methodology consists of two key sections: data collection and data analysis. The data processing primarily utilizes the R programming language. To generate monthly, seasonal, and annual average maps, we calculated these averages from daily precipitation datasets by overlaying and stacking raster datasets with uniform pixel sizes. For the statistical analysis, we converted the resulting raster datasets into Excel format to obtain detailed results.

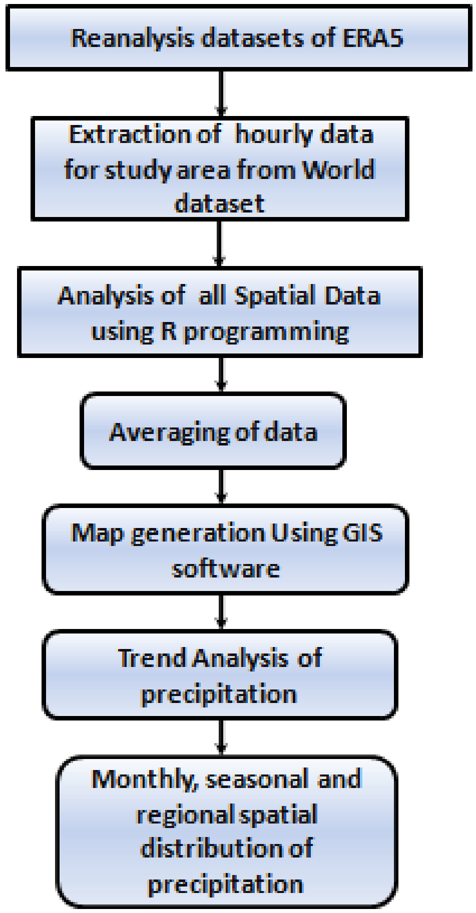


Fig.1. methodology

2.2.2 Trend Detection Approaches

We employed the Ordinary Least Squares (OLS) method for a linear regression analysis to identify trends in the data series from 1980 to 2023. To enhance our understanding of the OLS approach, we utilized the non-parametric Theil-Sen (TS) slope estimator. This method effectively detects linear trends and is robust against (Gilbert, 1987; Sen, 1968a; Theil, 1950). Additionally, it can provide slope estimates even when fewer than 20% of observations are available and can accommodate missing data (Helsel and Hirsch, 1995).

To identify significant change points in the time series, we applied the non-parametric Pettitt's test (Pettitt, 1979)' which is based on the Mann-Whitney two-sample test (Mann &Whitney, 1947). This test identifies a random shift, denoted by the letter "t." The alternative hypothesis states that the distribution function F1(X) of random variables from X1 to Xt differs from the distribution function F2(X) of random variables from Xt+1 to XT. In contrast, the null hypothesis (H0) posits that the distribution of the sequence of random variables remains unchanged.

$$U_{t,\gamma} = \sum_{i=2}^{n} \sum_{i=1}^{n} sgn(X_i - X_j)$$

$$sign(x_i - x_j) = \{+1\ if(x_i - x_j) > 0\ 0\ if(x_i - x_j) = 0\ -1\ if(x_i - x_j) =< 0\}$$

The position with the highest U-value in the series indicates where the most significant change occurs. If t represents the T-value in the series, it marks an important change point. The time series would be divided into two sub-series at these significant change points, t and T.

$$K_t = Ma\left|U_{t,T}\right|, 1 \leq t$$

The p-value provides an approximate indication of the significance level.

$$P_{OA} = 2exp\left\{\frac{-6(K^{+})^2}{(T^3 + T^2)}\right\} \; for \; T = \infty$$

When the p-value falls below the predetermined significance level (α), we have sufficient evidence to dismiss the null hypothesis and support the alternative hypothesis.

3. RESULTS

The regions of Western and Central India, encompassing Rajasthan, Gujarat, Maharashtra, and Madhya Pradesh, are characterized by predominantly low levels of precipitation (Figure 2). In contrast, Southern India, particularly Kerala and the Western Ghats, experiences moderate precipitation. The North-Eastern states of India, including Assam, Arunachal Pradesh, and Meghalaya, are noteworthy for their high levels of precipitation, making them the areas with the highest precipitation in the country.

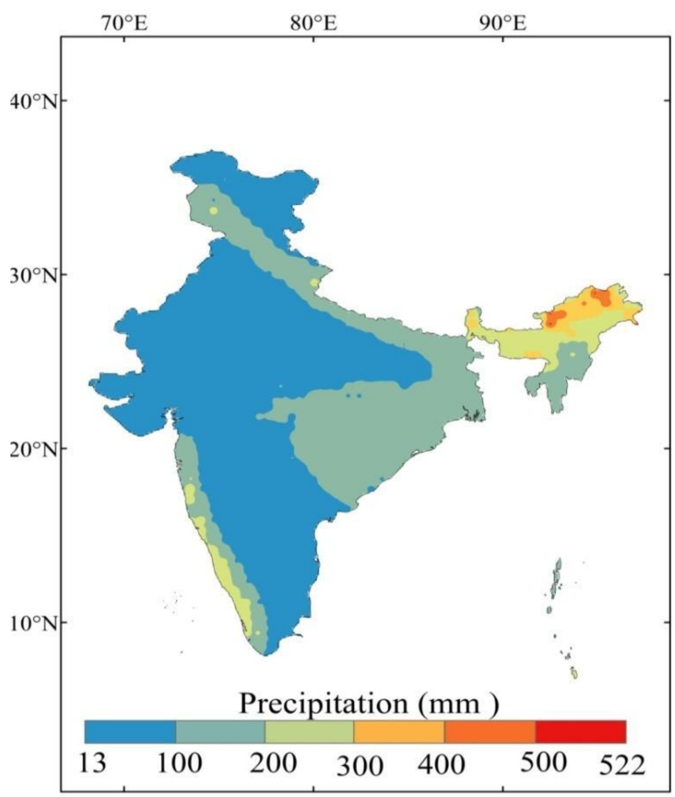


Fig.2: Spatial distribution of mean precipitation over India during 1980- 2023

The Northern Himalayan regions, comprising Uttarakhand, Himachal Pradesh, and Jammu & Kashmir, also register moderate precipitation. Overall, the data indicates that the North-Eastern states receive the most significant amounts of precipitation, while Western and Central India remain relatively arid. Additionally, the Western Ghats region is marked by moderate precipitation levels. This regional variation in precipitation patterns plays a crucial role in influencing the climate and agricultural practices across these diverse areas.

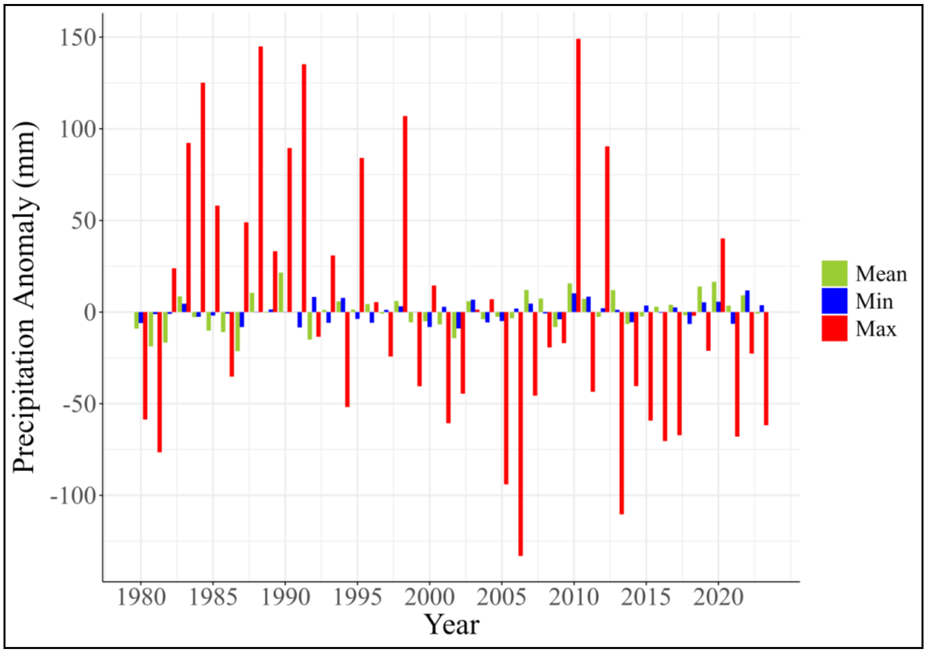


Fig.3 Precipitation anomaly over India during 1980- 2023

Analysis of annual precipitation data from 1980 to 2023 involved calculating key statistical measures, including the mean, minimum, and maximum precipitation, to understand long-term trends and variations. The overall mean precipitation during this period was 115.10 mm, with a minimum average of 9.62 mm and a maximum average of 600.39 mm. The lowest recorded mean precipitation occurred in 1987, of 93.75 mm, while the highest was in 1990, of 136.63 mm over the whole region. The minimum precipitation ranged from a low of 0.66 mm in 2002 to a peak of 21.41 mm in 2022, indicating significant year-to-year variability. For maximum precipitation, values varied from 467.31 mm in 2006 to a peak of 749.47 mm in 2010.

Anomaly analysis further revealed that the most significant positive anomaly in mean precipitation occurred in 1990, with a deviation of 21.52 mm, while the most significant negative anomaly was observed in 1987, with a deviation of -21.35 mm. For minimum values, 2022 recorded the highest deviation at 11.79 mm, whereas 2002 had the lowest at -8.96 mm. The maximum precipitation deviations displayed a similar trend, with 2010 showing the highest positive deviation of 149.08 mm and 2006 the lowest at -133.08 mm. These findings indicate periods of extreme precipitation fluctuations changed over this decade. The precipitation anomalies exhibit significant fluctuations over time, with a noticeable increase in positive anomalies in recent years, particularly for maximum precipitation. Notably, minimum precipitation anomalies also show more extreme deviations in precipitation. While mean precipitation anomalies remain relatively stable compared to maximum and minimum anomalies, the data reveal substantial positive anomalies in several years, especially during the 1980s and early 2000s, with significant spikes occurring around the late 1980s and early 2010s, likely linked to climate variability and global warming trends. Conversely, negative minimum precipitation anomalies observed post-2000 suggest considerable variations in precipitation, potentially due to shifts in atmospheric circulation, cloud cover, or urbanization effects, highlighting increased climate extremes. The contrast between extreme positive anomalies for maximum precipitations and extreme negative anomalies for minimum precipitations further suggests an expanding precipitation range, which may contribute to climate instability and indicate broader climate shifts that impact diurnal precipitation variations. Overall, the evidence presented indicates a clear trend of climate variability, with pronounced fluctuations in minimum precipitation anomalies signaling substantial shifts that could affect agriculture, water resources, and ecosystem stability, reinforcing the need for urgent climate mitigation and adaptation strategies in response to the ongoing global warming trends.

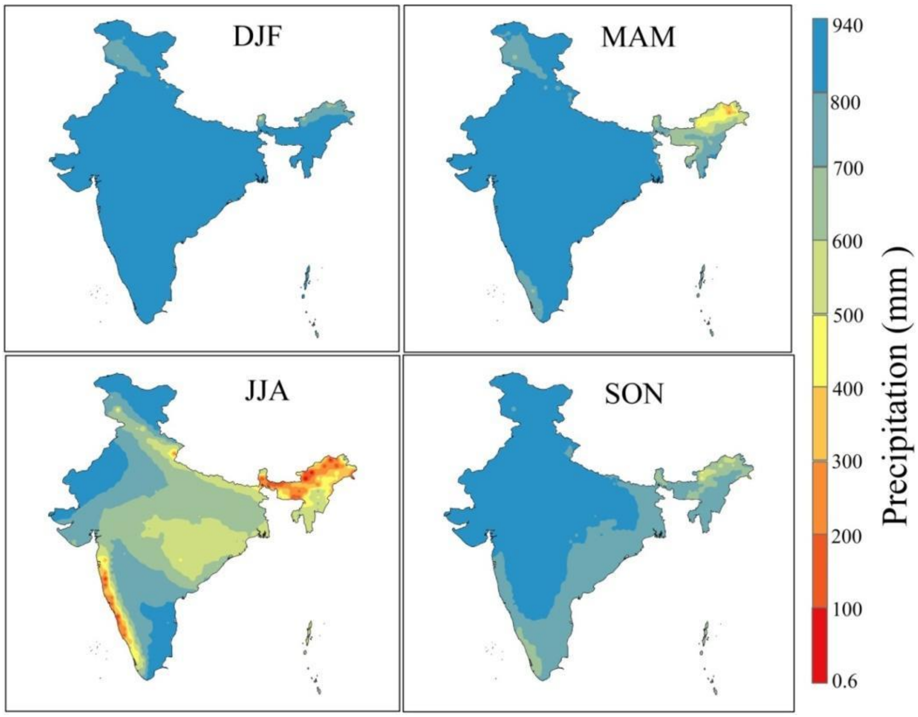


Fig.4: Seasonal variation in precipitation pattern over India during 1980-2023.

The Indian subcontinent experiences distinct seasonal variations in precipitation, categorised into four primary seasons: Winter (December-January-February), Pre-Monsoon (March-April-May), Monsoon (June-July-August), and Post-Monsoon (September-October-November). During the winter season, the country primarily remains dry, with some precipitation in the northernmost regions and northeastern states. The Pre-Monsoon season sees a slight increase in precipitation, particularly in northeastern states and parts of the western coast, while central and northern India largely remains arid. The Monsoon season is marked as the wettest, characterized by heavy precipitation concentrated in the Western Ghats and northeastern states, with central and eastern India receiving moderate precipitation. Following this, the Post-Monsoon season witnesses a significant decrease in precipitation, although northeastern India and the Western Ghats continue to receive moderate precipitation, while most of northern and central India experiences dry conditions (Fig. 4). The southern states begin to receive precipitation from the retreating monsoon. Understanding these seasonal precipitation patterns is crucial for effective agriculture, water resource management, disaster preparedness, and climate impact assessments.

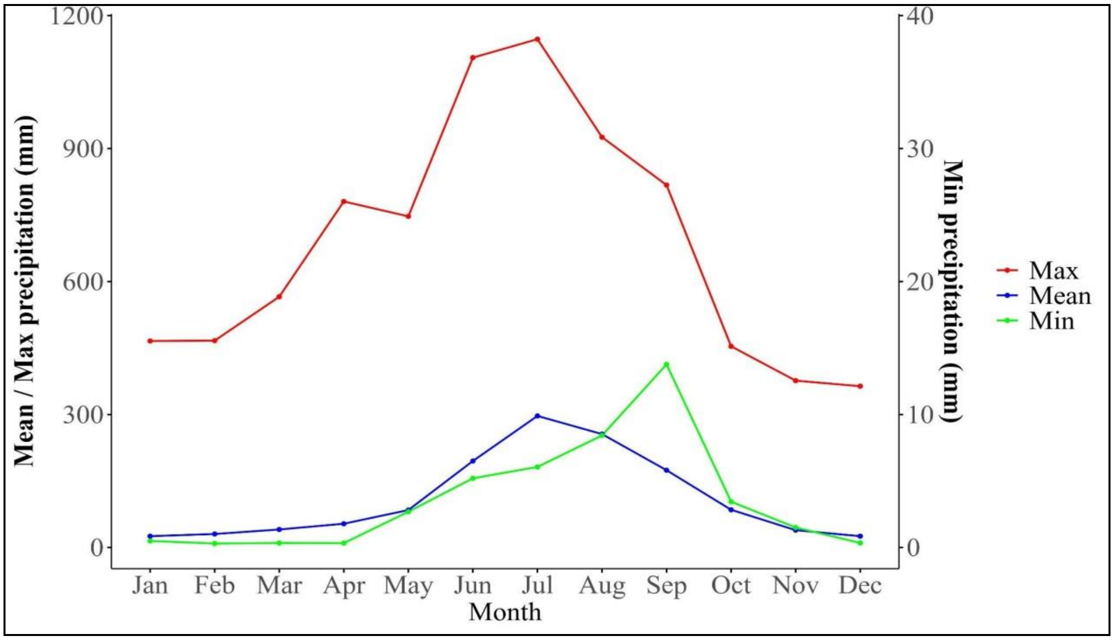


Fig.5 Spatial Variations of monthly precipitation over India during 1980-2023.

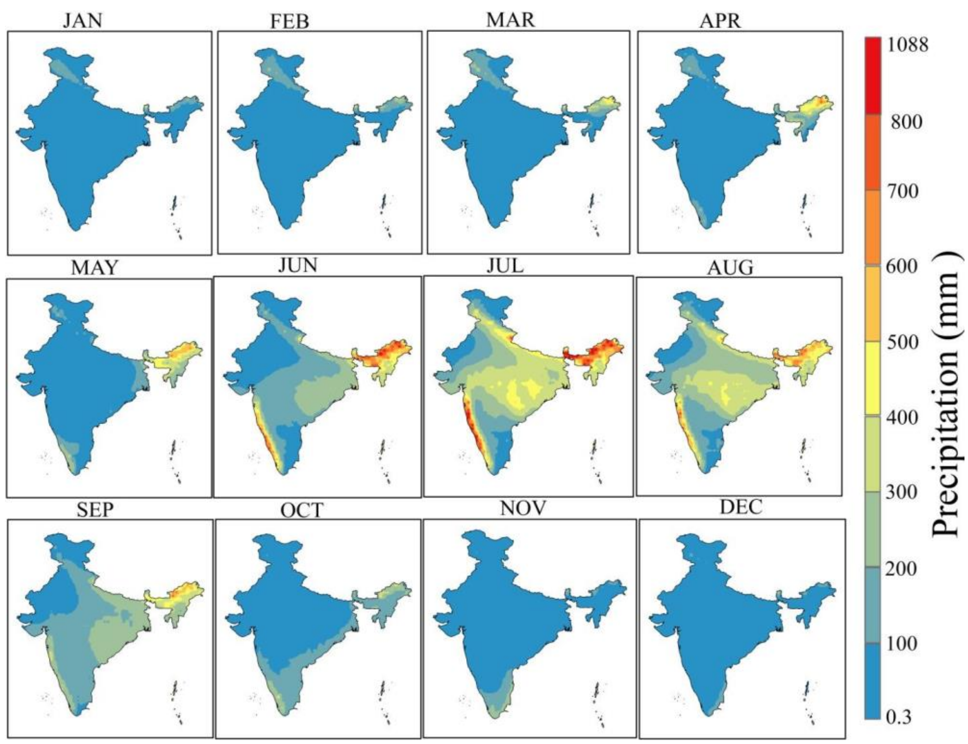


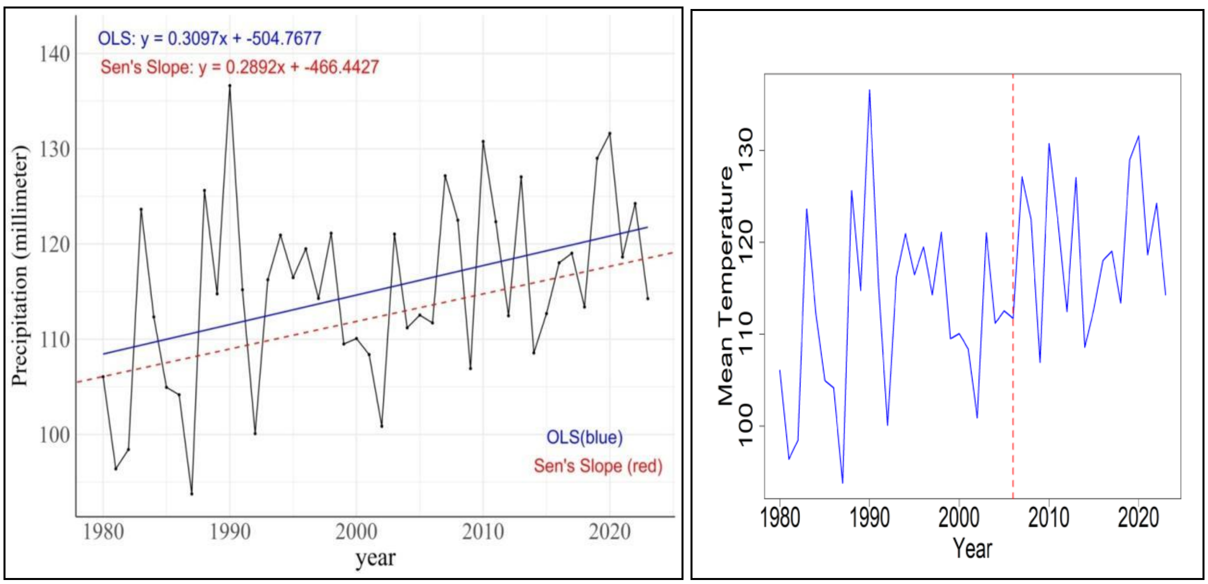
Fig.6 Monthly spatial distribution of mean precipitation over India during 1980- 2023

India's climate is characterized by a dry season from January to May and a monsoon season from June to September. During January to March, most regions experience low precipitation below 300 mm, with northeastern areas seeing modest rainfall starting in April and May (Fig.6). The post-monsoon period from October to December is also relatively dry, except for some northeastern and coastal regions. The monsoon, which begins in June, leads to significant precipitation increases, peaking in July and August, especially in central, western, and northeastern India, where areas like the Western Ghats and Himalayan foothills exceed 500 mm. By September, total precipitation declines in most areas, though some northeastern regions continue to receive significant rainfall.

Analysis shows higher precipitation levels from June to September due to the monsoon, with July and August averaging over 1100 mm. Post-September, precipitation drops sharply, hitting lows in December, January, and February during the dry winter months. While mean precipitation levels peak mid-year, minimum values remain low, indicating months of negligible precipitation. Maximum precipitation trends low throughout the year, suggesting that extreme events are not affecting monthly averages significantly. The notable increase in precipitation from May to June marks the start of the Southwest Monsoon (Guhathakurta et al., 2014b), while the dry season spans January to April and October to December, with mean values below 600 mm. This seasonal variability is crucial for water resource management, agricultural planning, and climate research in monsoon-dependent areas.

Z statistics	Sen's slope	95%confidence level		Sen's P value	Pettitt's change point (year)	Pettitt'sp-value
2.66	0.32	0.12	0.54	0.008	2006	0.074

Table1. Sen's Slope and Pettit's test value



(a) (b)

Fig.7. (a) Precipitation trend over India during 1980-2023 (b) Change point detection using Pettit's test

The analysis of precipitation trends in India reveals a slight but consistent increase over time, with slopes of approximately 0.31 mm per year from the Ordinary Least Squares (OLS) method and 0.29 mm per year from Sen's Slope method. Both approaches indicate a positive trend in precipitation, suggesting that rainfall is gradually increasing. The close alignment of the slopes from OLS and Sen's Slope indicates that outliers did not substantially affect the results, reinforcing the robustness of the observed trend. Overall, this slight increase in precipitation might reflect changing rainfall patterns, potentially driven by climate change or regional variability, and both methods confirm this emerging trend effectively. The results of the trend analysis, as illustrated in Table 1, indicate a moderate to strong positive trend in the dataset, as evidenced by a Z-statistic of 2.66 and a Sen's Slope of 0.32(Figure 7), suggesting a consistent increase over time. However, despite this trend, the Sen's P-value of 0.54 signifies that the trend is not statistically significant at conventional levels, implying that the observed changes may result from random variation rather than a true underlying effect. Additionally, Pettit's test identified a change point in the year 2006, highlighting a significant shift in the dataset around this time; although Pettit's P-value of 0.074 suggests this change is marginally significant, it does not meet the standard threshold of 0.05. These findings collectively provide important insights into the dynamics of the time series data while underscoring the need for cautious interpretation of trend significance.

4. CONCLUSION

The examination of precipitation data across India from 1980 to 2023 reveals several critical insights into geographical and temporal variations. Regions such as Western and Central India, including Rajasthan, Gujarat, Maharashtra, and Madhya Pradesh, show predominantly low levels of precipitation, remaining relatively arid, while Southern India, particularly Kerala and the Western Ghats, experiences moderate rainfall. In contrast, the Northeastern states—specifically Assam, Arunachal Pradesh, and Meghalaya—stand out as the wettest areas of the country. The Northern Himalayan regions also receive moderate precipitation. Over the analyzed period, the overall mean precipitation was recorded at 115.10 mm, with significant year-to-year fluctuations. The least average precipitation occurred in 1987 at 9.62 mm, while the highest peak was in 2010 at 600.39 mm. Notable anomalies include a positive anomaly of 21.52 mm in 1990 and a negative anomaly of -21.35 mm in 1987. The highest positive anomaly for minimum precipitation occurred in 2022 with 11.79 mm, while the largest negative anomaly was recorded in 2002 at -8.96 mm. In terms of maximum precipitation, a large positive deviation of 149.08 mm was noted in 2010, contrasting with a negative deviation of -133.08 mm in 2006. Seasonal variations highlight that the Indian subcontinent experiences four distinct seasons: Winter, which is primarily dry; Pre-Monsoon, with slight increases in rainfall; Monsoon, characterized by heavy rainfall especially in the Western Ghats and northeastern states; and Post-Monsoon, where precipitation decreases significantly but northeastern India and the Western Ghats still receive moderate rainfall. The slight increase in precipitation over time, with slopes of approximately 0.31 mm per year from the Ordinary Least Squares method and 0.29 mm per year from Sen's Slope method, indicates a gradual upward trend. Overall, the data underscores considerable spatial and temporal variations in precipitation patterns across India, indicating trends of climate variability and extreme in annual temperature pattern fluctuations that could have significant impacts on agriculture, water resources, and ecosystem stability, thereby emphasizing the need for effective climate adaptation strategies to mitigate risks associated with ongoing global warming.

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