Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Assessment of Temperature and Rainfall Trends in Indian Megacities Using Mann-Kendall and Sen's Slope Methods

Jayshree Nandi
AIAS, Amity University
Dharma Raj
discoverability.drp@gmail.com

ICMR - National Institute for Research in Environmental Health
Niraj Singh
AIAS, Amity University

Research Article

Keywords: Climate change, Mann Kendall test, Precipitation, Sen's slope, Temperature

Posted Date: May 21st, 2026

DOI: https://doi.org/10.21203/rs.3.rs-9435924/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

Assessment of Temperature and Rainfall Trends in Indian Megacities Using Mann-Kendall and Sen's Slope Methods

Jayshree Nandi[1], Dharma Raj[2], Niraj Singh[3]

[1]PhD Scholar, AIAS, Amity University Noida, Uttar Pradesh

[2]Scientist-C, ICMR National Institute for Research in Environmental Health, Bhopal, Madhya Pradesh

[3]Associate Professor, AIAS, Amity University Noida, Uttar Pradesh

***Corresponding author (email address):** Dharma Raj (discoverability.drp@gmail.com)*

ABSTRACT

This study examines long-term trends in temperature and precipitation across six major Indian megacities- Delhi, Mumbai, Kolkata, Bengaluru, Chennai, and Hyderabad-over the period 1981-2024. The analysis applies the Mann-Kendall (MK) test to identify trends and Sen's slope estimator to quantify their magnitude at monthly, seasonal, and annual scales. The results indicate a consistent warming trend across all cities, with stronger and more significant increases observed in southern cities such as Bengaluru, Hyderabad, and Chennai. Notably, minimum temperatures are rising more rapidly than maximum temperatures, suggesting enhanced nocturnal warming and intensification of the urban heat island effect. Seasonal patterns show relatively uniform warming during summer, monsoon, and post-monsoon periods, while winter exhibits greater spatial variability, including cooling tendencies in northern cities like Delhi and Kolkata.

Precipitation analysis reveals increasing variability and a growing concentration of rainfall during the monsoon season. Cities such as Mumbai and Kolkata show intensified high rainfall events, whereas winter and pre-monsoon rainfall generally display declining or insignificant trends. Overall, the findings highlight pronounced and uneven climatic shifts in Indian megacities, characterized by rising temperatures and increasingly concentrated rainfall patterns. These trends underscore the need for city-specific climate adaptation strategies, resilient urban infrastructure, and improved water resource and disaster management planning.

KEYWORDS: Climate change, Mann Kendall test, Precipitation, Sen's slope, Temperature.

1. INTRODUCTION

Climate change represents one of the most profound environmental challenges confronting humanity in the twenty-first century. Multiple lines of observational, instrumental, and proxy-based evidence now confirm that the Earth's climate system is undergoing rapid and sustained change, characterized primarily by a significant rise in global surface temperatures, altered precipitation regimes, and an increase in the frequency and intensity of extreme weather events. While natural climate variability has always existed, the current magnitude and rate of change are unprecedented in the context of the last several millennia and are strongly linked to anthropogenic activities (Smith, 2024; Thompson, 2010). Global temperature records derived from meteorological stations, ocean measurements, and satellite observations demonstrate a clear warming trend since the late nineteenth century. Studies indicate that the past decade has been the warmest on record, with no evidence of a slowdown in the rate of warming (Hansen et al., 2010; IPCC, 2023). Beyond changes in mean temperature, climate change is increasingly manifested through shifts in climate extremes.

Global analyses of daily temperature and precipitation data reveal a widespread decrease in cold extremes and a significant increase in warm nights, heatwaves, and heavy rainfall events across much of the world (Alexander et al., 2006). From a human health perspective, climate change and environmental degradation are increasingly recognized as a single, indivisible global health emergency. Rising temperatures, air pollution, extreme weather events, and the spread of climate-sensitive infectious diseases pose growing risks to population health, particularly in low and middle-income countries (Abbasi et al., 2023; NIEHS, 2022; WHO, 2019; WHO, 2023) .These interconnected risks underscore the need for integrated, interdisciplinary approaches that link climate science, ecology, public health, and policy.

India, as a lower-middle-income country with high population density and strong dependence on climate-sensitive sectors, is particularly vulnerable to the impacts of climate change. Although India contributes a relatively small share of historical global greenhouse gas emissions, it bears a disproportionate burden of climate-related risks due to socioeconomic constraints, regional inequalities, and limited adaptive capacity. Studies have found increased temperatures and melting of glaciers in the nearby Himalayan region, with a loss of 26 km^2 of glaciated area between 1980 and 2017 (Ross et al., 2018; Haldar et al. ,2023; Saikh et al.,2023). Major Indian cities like Delhi, Mumbai, and Kolkata have experienced comparable shifts, with rising air pollution levels and higher average temperatures in recent

years (Dash & Mamgain, 2011; Goyal & Surampalli, 2018; Kaur & Pandey, 2021). One of the most significant impacts of climate change in India is the increase in extreme heat events. Rising mean temperatures and more frequent heatwaves have led to higher heat-related morbidity and mortality, especially among outdoor workers, the urban poor, elderly populations, and those without access to cooling or healthcare. Studies show that heat stress is already reducing labour productivity in sectors such as agriculture and construction, directly affecting incomes and economic growth in a country where a large proportion of the workforce is informal (Romanello et al., 2021).

India's heavy reliance on the southwest monsoon further amplifies its climate vulnerability. Climate change has increased monsoon variability, resulting in more frequent droughts, extreme rainfall events, and floods. These changes undermine agricultural productivity and food security, particularly for small and marginal farmers who depend on rain-fed agriculture and have limited adaptive capacity. Erratic rainfall has been linked to crop failures, farmer indebtedness, and rural distress, reinforcing existing income inequalities (Guhathakurta et al., 2011; FAO, 2018).

The changes in climatic conditions have significant implications for agriculture, water resources and public health in India's urban centres. It intensifies that study of climate parameters is essential for understanding the India's changing climate, reducing risks to ecosystems and societies, safeguarding human health, and supporting evidence-based policy. As climate impacts intensify, the importance of continuous, high-quality monitoring and analysis of climate parameters. In this study, six metropolitan cities of India have selected, represents a huge population and also represents diverse climatic zones of India. Also drives much of India's economic activity, and understanding climate risks helps in designing resilient infrastructure, early warning systems, and sustainable urban policies. These cities also play a crucial role in meeting India's climate commitments such as under the Paris Agreement. Hence, the study is aimed to unfold annual and seasonal variability and trend in climate parameter such as temperature and precipitation. The objectives of this study are:

- To assess long-term trends in temperature (minimum and maximum) across selected Indian megacities using the Mann-Kendall test and Sen's slope estimator.
- To analyze precipitation trends and variability, including seasonal distribution and intensity.

2. MATERIAL AND METHODS

2.1 Study area: Cities such as Delhi, Mumbai, Kolkata, Bengaluru, Chennai, and Hyderabad form a crucial part of the study area, as each has a population exceeding 10 million. These megacities represent some of the most densely populated and rapidly urbanizing regions in India, making them significant for understanding patterns of urban growth, infrastructure development, and demographic concentration (ToI, 2024; WPR, 2026).

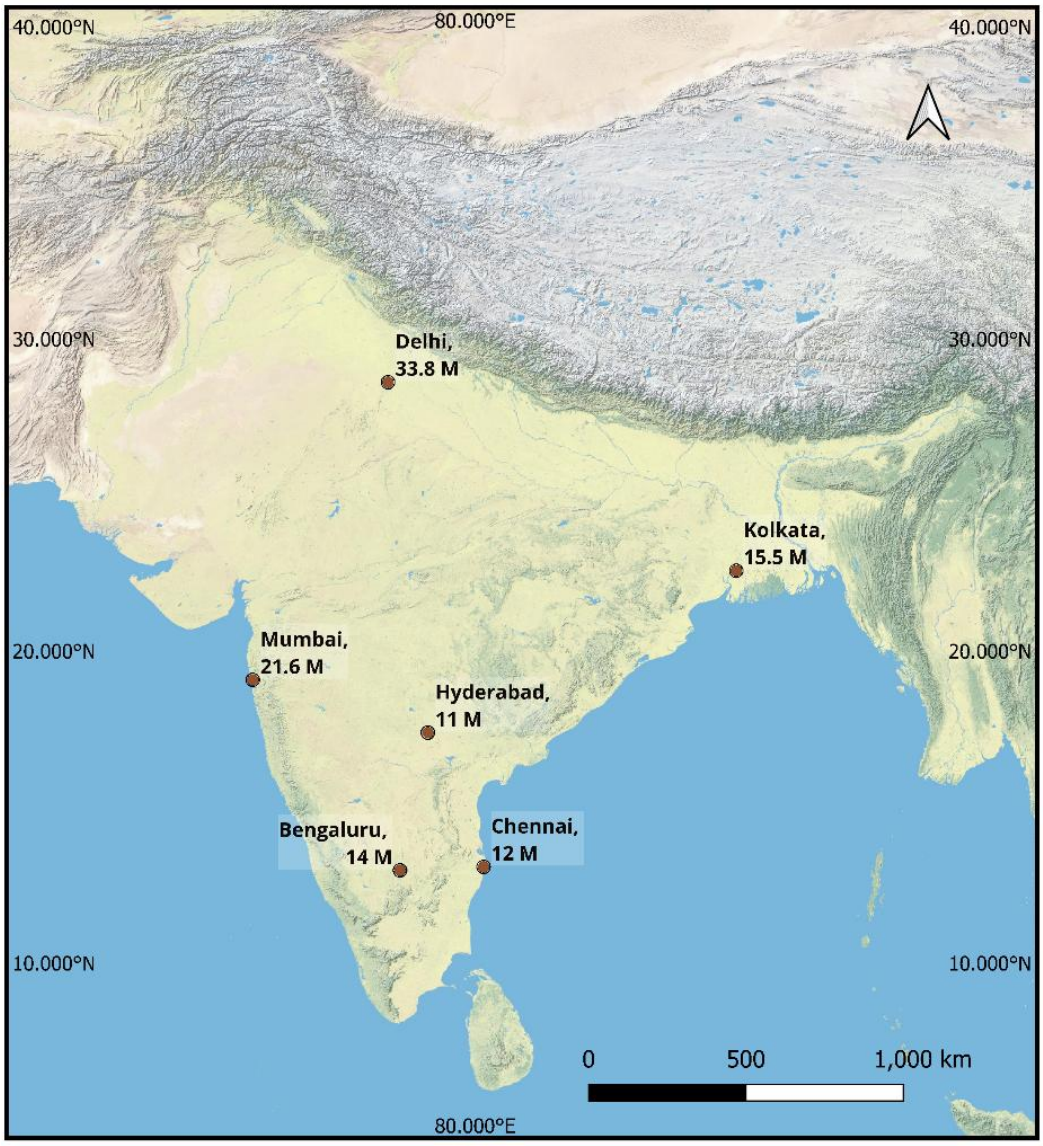


Figure 1: Geographical location of the megacities with (in millions).

2.2 Data source: Climate parameter data were obtained from The National Aeronautics and Space Administration (NASA) Langley Research Center's Prediction of Worldwide Energy Resources (POWER) open-access portal using the Data Access Viewer for cities at a single representative point. The study considered key variables, including Temperature at 2 meters (T) (i.e. the standard meteorological measurement of air temperature taken at a height of 2 meters (approximately 6.5 feet) above the Earth's surface), Maximum Temperature at 2 meters (Tmax), Minimum Temperature at 2 meters (Tmin), and corrected precipitation. A continuous dataset spanning 44 years, from 1981 to 2024, was compiled to ensure long-term consistency and reliability, enabling comprehensive analysis of temporal variations and trends in climatic conditions across the urban study areas.

Table 1: Basic Characteristics and Data Availability of Major Indian Megacities used in the Study.

City	Population (in millions)	Latitude (°N)	Longitude (°E)	Data Availability	Parameters
Delhi	33.8	28.69	77.17	1981-2024	Tmin, T, Tmax, Precipitation
Mumbai	21.6	19.15	72.87	1981-2024	Tmin, T, Tmax, Precipitation
Kolkata	15.5	22.56	88.38	1981-2024	Tmin, T, Tmax, Precipitation
Bengaluru	14	12.97	77.59	1981-2024	Tmin, T, Tmax, Precipitation
Chennai	12	13.11	80.29	1981-2024	Tmin, T, Tmax, Precipitation
Hyderabad	11	17.38	78.48	1981-2024	Tmin, T, Tmax, Precipitation

2.3 Methods: The Mann-Kendall Test (Mann, 1945; Kendall, 1975) and Sen's Slope Estimator (Sen, 1968) were employed to analyse trends in the climate parameters. Variations in temperature and precipitation were examined on annual, monthly, and seasonal scales. For seasonal analysis, each year was classified into four distinct periods: Winter (January-February), Pre-monsoon/Summer (March-May), Monsoon (June-September), and Post-monsoon (October-December).

2.3.1 Mann Kendall Test: The Mann-Kendall trend test is a non-parametric statistical test used to assess the presence of a monotonic trend in a time series data. The null hypothesis for this test is that there is no trend, and the alternative hypothesis is that there is a trend in the two-sided test or that there is an upward trend (or downward trend) in the one-sided test. For the time series x_1, .., x_n, the MK-test uses the following statistic:

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

If $S > 0$ then later observations in the time series tend to be larger than those that appear earlier in the time series, while the reverse is true if $S < 0$.

The variance of S is given by

$$var = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_t f_t(f_t-1)(2f_t+5)\right]$$

where t varies over the set of tied ranks and f_t is the number of times (i.e. frequency) that the rank t appears.

The MK Test uses the following test statistic:

$$z = \begin{cases} (S-1)/se, & S > 0 \\ 0, & S = 0 \\ (S+1)/se, & S < 0 \end{cases}$$

where se = the square root of var. The null hypothesis (no trend) is rejected if $|Z| > 1.96$ i.e. at 95% significance level (Real Statistics).

2.3.2 Sen's slope estimator: To estimate the magnitude of change or slope of trend, in a time series **(**Sen 1968**)** developed this non-parametric procedure**.**

Sen's slope is defined as**:** $$Sen's\ slope = Median\left\{\frac{x_j - x_i}{j-i} : i < j\right\}$$

A 1-α confidence interval for Sen's slope can be calculated as **(***lower, upper***)** where

$N = C(n, 2)$ $\quad k = se \cdot z_{crit}$

$lower = m_{(N-k)/2}$ $\quad$ & $\quad upper = m_{(N+k)/2+1}$

Here, N = the number of pairs of time series elements (x_i, x_j) where $i < j$ and se = the standard error for the Mann-Kendall Test**.** Also m_h = the h^{th} smallest in the set $\{(x_j\text{-}x_i)/(j\text{-}i)\text{:}\ i < j\}$ and z_{crit} = the 1-$\alpha/2$ critical value for the normal distribution (Real statistics)**.**

Trend analysis of climate parameters such as temperature and precipitation is essential for understanding how the climate is changing over time. Two widely accepted statistical tools for this purpose are the Mann-Kendall (MK) test and Sen's slope estimator, because they provide robust, objective, and non-parametric assessment of long-term trends. Temperature trends affect heatwaves, groundwater recharge, river flows, crop yields, drought/flood frequency and other such aspects. MK test along with Sen's slope together allow policymakers to determine whether these variables are increasing or decreasing and by what rate, enabling evidence-based climate adaptation (Gocic and Trajkovic,2012; Jaiswal et al. ,2015; Kodandarama et al. ,2024; Sudarsan et al. ,2023). The current study used the MK test and Sen's slope estimator to analyse temperature and precipitation trends in six important Indian cities.

RESULTS

The figure 2 illustrates long-term variations in winter minimum temperatures across six major Indian cities from 1981 to 2024, highlighting clear spatial differences. Chennai consistently records the highest winter minimum temperatures, generally ranging between ~20°C and 23°C, indicating relatively warm winters throughout the study period. Mumbai and Hyderabad also show comparatively higher minimum temperatures, typically between 16°C and 19°C, with noticeable fluctuations but a gradual warming tendency in recent years. Bengaluru and Kolkata occupy an intermediate range, with winter minimum temperatures mostly between 13°C and 17°C.

In contrast, Delhi records the lowest winter minimum temperatures among all cities, often ranging from ~6°C to 10°C, reflecting its continental climate and stronger cold-season variability. While interannual fluctuations are evident across all cities, a subtle upward shift in minimum temperatures is noticeable, particularly after the early 2000s, supporting the broader warming trends identified in the dataset. This pattern indicates that winter nights are becoming progressively warmer, especially in southern and coastal regions, whereas northern inland regions like Delhi continue to experience colder extremes despite some recent warming signals.

The figure 3 presents the variability of pre-monsoon (summer) maximum temperatures across selected Indian cities from 1981 to 2024, revealing pronounced spatial contrasts and interannual fluctuations. Hyderabad consistently records the highest temperatures, frequently exceeding 40°C, with peaks around 41°C, indicating intense heat conditions during the pre-monsoon season. Delhi and Kolkata also exhibit high variability, often reaching 39-41°C, reflecting strong continental and inland heating influences. In

comparison, Mumbai shows relatively moderated temperatures (around 37-39°C) due to maritime influence.

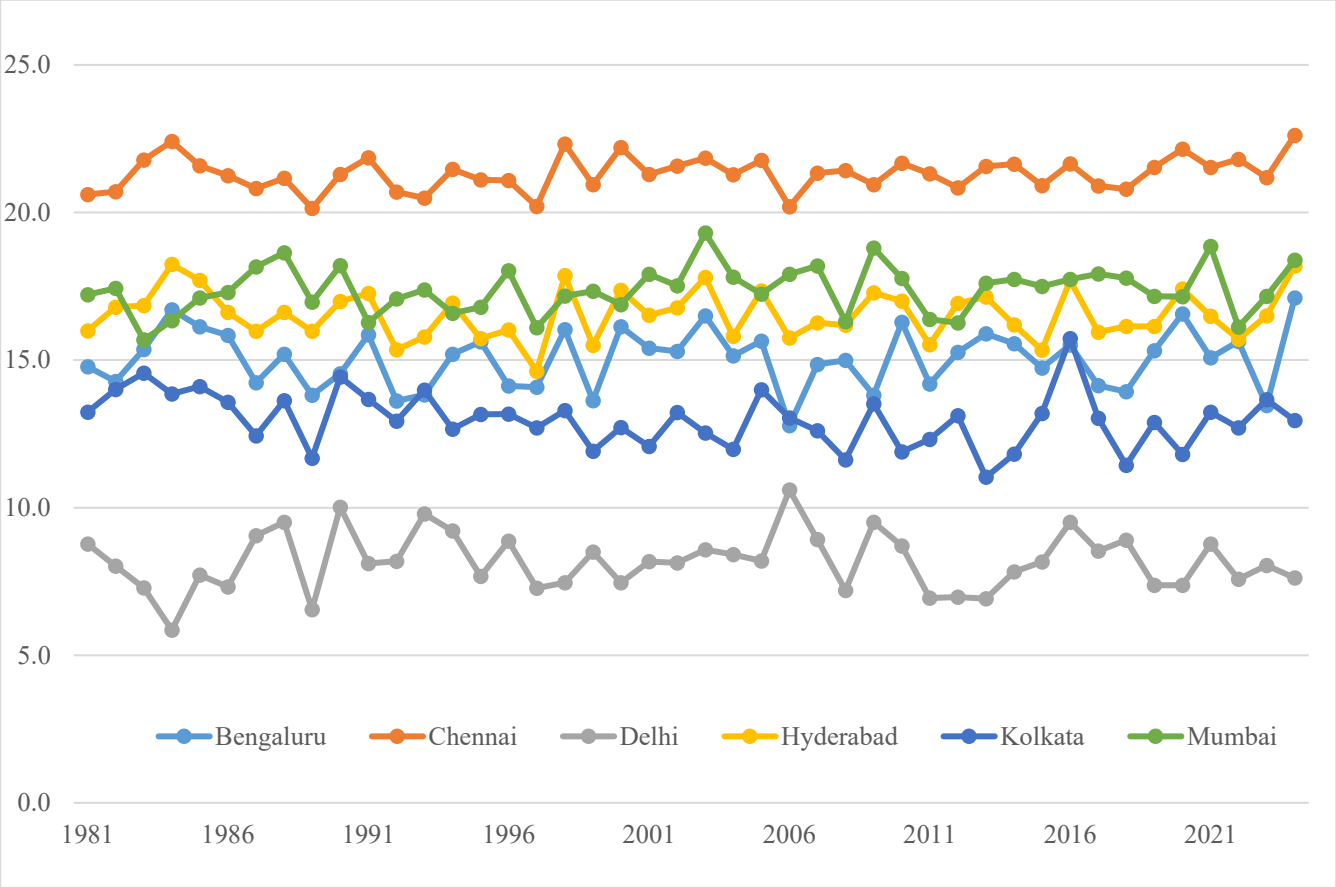


Figure 2: Pattern of annually Tmin (°C) in winter season during the year 1981-2024.

Southern cities display comparatively lower but still significant temperature ranges. Chennai generally records values between 35°C and 37°C, while Bengaluru consistently experiences the lowest maximum temperatures (approximately 33-36°C), likely due to its higher elevation and inland plateau climate. Despite year-to-year variability, there is a noticeable persistence of high-temperature extremes across all cities, with several peaks occurring after the 1990s, suggesting an intensification of pre-monsoon heat conditions in recent decades.

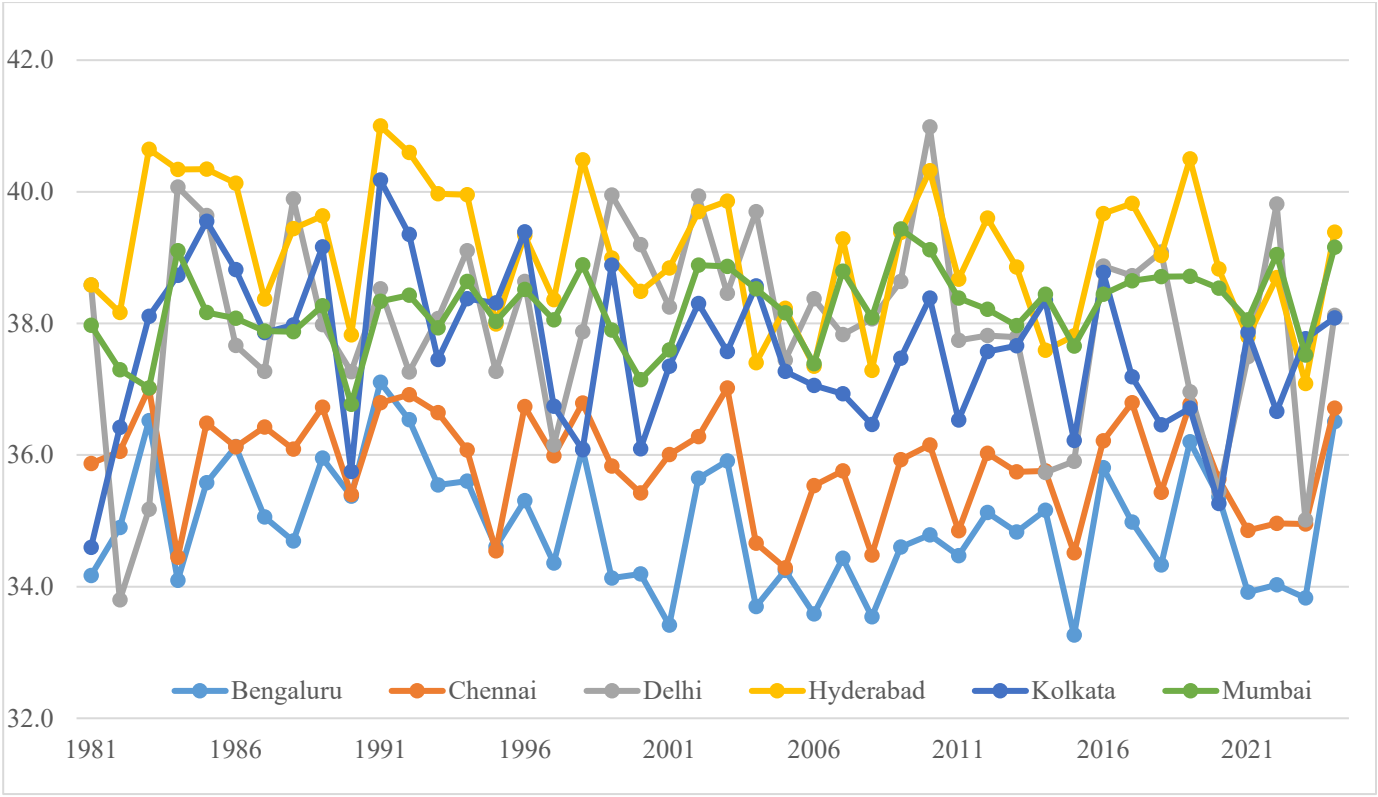


Figure 3: Pattern of annually Tmax (°C) in summer season during the year 1981-2024.

Temperature trend: The study analyzed the difference in temperature over the past 44 years. Analysis of temperature records (1981-2024) shows a consistent warming tendency across most Indian metropolitan cities, with substantial spatial and seasonal contrasts (Table 2). Hyderabad, Bengaluru, Chennai, and Kolkata exhibit the strongest warming, reflected by large positive differences in mean (T), maximum (Tmax), and minimum (Tmin) temperatures across all seasons. Hyderabad records +1.24°C (T), +1.02°C (Tmax), while Bengaluru shows annual increases of +1.57°C (T), +1.73°C (Tmax), and +1.47°C (Tmin), and +1.50°C (Tmin). Kolkata demonstrates particularly intense summer warming, with +2.60°C (T) and +3.49°C (Tmax), indicating enhanced heat stress during peak summer months. Chennai also shows notable warming, especially in minimum temperature, with an annual increase of +1.12°C (Tmin).

Seasonal analysis further highlights that the post-monsoon period is characterized by uniform and significant warming across all cities. Mumbai shows moderate warming, particularly during summer (+1.08°C in T) and post-monsoon (+1.10°C in T), along with consistent increases in Tmin across

seasons. Monsoon trends reveal rising minimum temperatures in all cities, while maximum temperatures decline in some northern regions but increase in southern cities such as Bengaluru and Hyderabad. In contrast, Delhi displays mixed behavior, with weaker warming signals compared to other cities and notable seasonal variability.

Table 2: Long-Term changes in Min, Mean, and Max Temperatures (°C) across Megacities.

Season	Parameter	Delhi	Mumbai	Kolkata	Bengaluru	Chennai	Hyderabad
Summer	Tmin	0.44	0.98*	1.42*	1.04*	0.85*	1.48*
	T	0.05	1.08*	2.60*	1.75*	0.86*	1.21*
	Tmax	-0.46	1.18*	3.49*	2.33*	0.84*	0.80*
Post Monsoon	Tmin	2.44*	1.25*	3.17*	1.92*	1.63*	1.76*
	T	1.42*	1.10*	1.53*	1.65*	1.47*	1.47*
	Tmax	0.21	0.91*	-0.33	1.55*	1.34*	1.30*
Monsoon	Tmin	0.68*	0.64*	0.95*	0.77*	0.41*	0.77*
	T	-0.43	0.59*	0.83*	1.00*	0.42*	0.76*
	Tmax	-1.80*	0.52*	0.82*	1.33*	0.54	0.86*
Winter	Tmin	-0.55	0.72	0.18	2.53*	2.02*	2.35*
	T	-0.91*	0.37	-0.75*	2.10*	1.46*	1.76*
	Tmax	-1.34*	0.03	-1.63*	1.78*	0.85*	1.27*
Annual	Tmin	0.61*	0.85*	1.24*	1.47*	1.12*	1.50*
	T	-0.12	0.748*	1.00*	1.57*	0.97*	1.24*
	Tmax	-1.02*	0.63*	0.70*	1.73*	0.83*	1.02*

*Significant at 95% confidence level

Delhi shows evidence of cooling in winter alongside warming in other seasons. The mean winter temperature (T) decreased by -0.91°C, while maximum winter temperature declined more sharply by -1.34°C, indicating cooler winters. However, minimum temperatures continue to rise annually (+0.61°C), reflecting nighttime warming. In the post-monsoon season, Delhi has become noticeably warmer, with increases of +1.42°C (T) and +2.44°C (Tmin). Despite some seasonal cooling trends, the overall pattern across cities indicates that warming is primarily driven by rising minimum temperatures, suggesting a significant shift toward warmer nights and altered urban climate conditions across India.

The analysis of extreme temperature records highlights notable inter-city variability in both summer and winter conditions across India (Table 3). Among the cities, Delhi and Hyderabad recorded the highest summer maximum temperatures at 41.0°C (in 2010 and 1991, respectively), indicating intense heatwave conditions. Kolkata and Bengaluru also experienced high summer peaks of 40.2°C (1991) and 37.1°C

(1991), while Chennai and Mumbai showed relatively moderated extremes, with highest summer maxima of 37.0°C (2003) and 39.4°C (2009), respectively. The lowest summer maximum temperatures further reflect regional differences, with Bengaluru recording the lowest at 33.3°C (2015) and Delhi at 33.8°C (1982), suggesting comparatively milder summers during those years.

Winter minimum temperatures reveal a contrasting pattern, particularly highlighting warming trends in recent years. Chennai recorded the highest winter minimum at 22.6°C in 2024, followed by Mumbai at 19.3°C (2003) and Hyderabad at 18.2°C (1984). Bengaluru and Kolkata also show recent peaks, with Bengaluru reaching 17.1°C (2024) and Kolkata 15.7°C (2016). In contrast, the lowest winter minimum temperatures were recorded in earlier decades, such as 5.9°C in Delhi (1984) and 11.0°C in Kolkata (2013), indicating colder past winters. Overall, the data suggests a shift toward warmer winter nights, especially in southern and coastal cities, alongside persistent extremes in summer temperatures.

Table 3: Recorded Extremes of Summer Maximum Temperatures (°C) and Winter Minimum Temperatures (°C) with Corresponding Years across Indian Megacities

City	Summer Tmax		Winter Tmin	
	Highest (at Year)	**Lowest (at Year)**	**Highest (at Year)**	**Lowest (at Year)**
Delhi	41.0 (2010)	33.8 (1982)	10.6 (2006)	5.9 (1984)
Mumbai	39.4 (2009)	36.8 (1990)	19.3 (2003)	15.7 (1983)
Kolkata	40.2 (1991)	34.6 (1981)	15.7 (2016)	11.0 (2013)
Bengaluru	37.1 (1991)	33.3 (2015)	17.1 (2024)	12.8 (2006)
Chennai	37.0 (2003)	34.3 (2005)	22.6 (2024)	20.1 (1989)
Hyderabad	41.0 (1991)	37.1 (2023)	18.2 (1984)	14.6 (1997)

From table 4 the Sen's slope analysis of monthly and seasonal mean temperature (T) trends from 1981 to 2024 reveals distinct spatial and temporal variations across the megacities. Delhi shows predominantly negative trends for most months, particularly during winter (e.g., January: -0.00113*, December: -0.00091*), indicating a cooling tendency in mean temperatures. In contrast, Mumbai exhibits mostly weak but positive trends, especially during the post-monsoon (0.00023*) and pre-monsoon (0.00030*) seasons. Kolkata presents mixed behaviour, with negative trends during winter months (e.g., January: -0.00177*, December: -0.00084*) and positive trends during monsoon and post-monsoon periods, suggesting seasonal variability in warming patterns.

Southern cities such as Bengaluru, Chennai, and Hyderabad largely demonstrate positive and statistically significant trends across most months, particularly during monsoon and post-monsoon seasons. Bengaluru shows consistent warming trends from June to December (e.g., July: 0.00068*, October: 0.00068*), while Chennai records steady increases, especially in the later months (November: 0.00065*, December: 0.00069*). Hyderabad also reflects increasing trends during monsoon (0.00014*) and post-monsoon (0.00025*) periods, although some negative trends are observed in pre-monsoon months. Overall, the results indicate a general warming tendency in southern and coastal cities, contrasted with weak cooling or mixed trends in northern regions, highlighting significant regional disparities in long-term temperature changes.

Table 4: Long-Term Monthly and Seasonal Mean Temperature Trends (°C) derived from Sen's Slope Estimator across Indian Megacities (1981-2024)

Months/ Season	**Delhi**	**Mumbai**	**Kolkata**	**Bengaluru**	**Chennai**	**Hyderabad**
Jan	-0.00113*	-0.00036*	-0.00177*	0.00039*	0.00046*	-0.00019
Feb	0.00042	0.00001	-0.00100*	-0.00057*	0.00003	-0.00047*
Mar	0.00084*	0.00000	-0.00050*	-0.00004	0.00022*	-0.00011
Apr	0.00077*	0.00000	0.00020	-0.00012	0.00016	-0.00011
May	0.00000	0.00000	0.00019	-0.00064*	-0.00035*	-0.00079*
June	-0.00098*	0.02630	0.00035*	0.00076*	0.00014	0.00050*
July	-0.00130*	0.00004*	0.00049*	0.00068*	0.00032*	0.00066*
Aug	-0.00078*	0.00000	0.00025*	0.00069*	0.00013	0.00077*
Sep	-0.00052*	0.00000	0.00040*	0.00045*	0.00003	0.00031*
Oct	0.00007	0.00059*	0.00062*	0.00068*	0.00042*	0.00049*
Nov	-0.00034	0.00051*	0.00008	0.00068*	0.00065*	0.00064*
Dec	-0.00091*	0.00009	-0.00084*	0.00070*	0.00069*	0.00040*
Pre-monsoon	0.00028*	0.00030*	0.00003	-0.00010*	0.00001	-0.00006
Monsoon	-0.00027*	0.00009*	0.00008*	0.00016*	0.00003*	0.00014*
Post-monsoon	-0.00012*	0.00023*	0.00016*	0.00032*	0.00024*	0.00025*
Winter	-0.00021*	0.00002	-0.00043*	0.00009*	0.00016*	-0.00002

*Significant at $p<0.05$

From table 5, Delhi shows a dominant cooling trend in Tmax across most months, with statistically significant declines in January (-0.00162*), June (-0.00183*), July (-0.00185*), and December (-0.00138*). This cooling signal is also reflected seasonally, particularly during the monsoon (-0.00047*) and post-monsoon (-0.00070*) periods. Similarly, Kolkata exhibits negative trends in several months,

especially during winter (January: -0.00268*, December: -0.00227*) and pre-monsoon months, indicating a tendency toward decreasing daytime temperatures. In contrast, Mumbai shows predominantly positive trends, with significant increases in February (0.00055*), April (0.00100*), May (0.00070*), and across all seasons except winter, suggesting gradual warming in daytime temperatures.

Southern cities display relatively consistent warming patterns in Tmax, particularly during monsoon and post-monsoon seasons. Bengaluru records significant positive trends from June to October (e.g., July: 0.00072*, October: 0.00059*), despite some cooling during pre-monsoon months (May: -0.00122*). Hyderabad also shows increasing Tmax during monsoon (0.00013*) and late summer months, though it experiences declines during pre-monsoon (-0.00023*) and early-year months. Chennai presents a mixed pattern, with decreasing Tmax in pre-monsoon months (May: -0.00091*) but increasing trends in post-monsoon and winter periods (e.g., November: 0.00040*, December: 0.00050*). Overall, the results indicate that while northern and eastern cities tend to show cooling or mixed trends in maximum temperatures, southern and coastal cities exhibit increasing Tmax, especially during the monsoon and post-monsoon seasons, highlighting strong regional variability in daytime temperature changes.

Table 5: Long-Term Monthly and Seasonal Maximum Temperature Trends (°C) Derived from Sen's Slope Estimator across Indian Megacities (1981-2024)

Months/Season	**Delhi**	**Mumbai**	**Kolkata**	**Bengaluru**	**Chennai**	**Hyderabad**
Jan	-0.00162*	-0.00088*	-0.00268*	0.00026	0.00031*	-0.00030*
Feb	0.00012	0.00055*	-0.00178*	-0.00062*	-0.00031*	-0.00088*
Mar	0.00034	0.00036	-0.00143*	-0.00033*	-0.00028*	-0.00063*
Apr	0.00008	0.00100*	-0.00025	-0.00035*	-0.00022	-0.00067*
May	-0.00075*	0.00070*	-0.00049*	-0.00122*	-0.00091*	-0.00112*
June	-0.00183*	0.00001	0.00026	0.00094*	0.00016	0.00040
July	-0.00185*	-0.00010	0.00051*	0.00072*	0.00039*	0.00083*
Aug	-0.00117*	0.00059*	0.00007	0.00055*	-0.00050*	0.00075*
Sep	-0.00167	0.00026*	0.00009	0.00042*	-0.00012	0.00014
Oct	-0.00112*	0.00027*	-0.00007	0.00059*	0.00027*	0.00023
Nov	-0.00143*	0.00015	-0.00114*	0.00030*	0.00040*	0.00029
Dec	-0.00138*	-0.00072*	-0.00227*	0.00011	0.00050*	0.00017
Pre-monsoon	0.00006	0.00023*	-0.00023*	-0.00023*	-0.00016*	-0.00023*

Monsoon	-0.00047*	0.00005*	0.00004*	0.00016*	-0.00003	0.00013*
Post-monsoon	-0.00070*	0.00010*	-0.00034*	0.00022*	0.00017*	0.00012*
Winter	-0.00036*	-0.00018*	-0.00080*	-0.00001	0.00012*	-0.00010*

*Significant at $p<0.05$

Table 6 indicates a pronounced and widespread warming trend across most cities, particularly in southern and coastal regions. Mumbai exhibits a strong and consistent increase in Tmin across nearly all months, with significant rises in February (0.00102*), March (0.00104*), April (0.00119*), and October (0.00078*), as well as across all seasons, highlighting persistent night-time warming. Kolkata also shows predominantly positive trends, especially during post-monsoon (0.00048*) and late-year months such as October (0.00118*) and November (0.00091*), although slight cooling is observed in January (-0.00081*) and February (-0.00057*). These patterns indicate an overall increase in minimum temperatures, particularly during transitional and post-monsoon periods.

In contrast, Delhi demonstrates a mixed behaviour, with significant warming during pre-monsoon (0.00047*), post-monsoon (0.00045*), and months such as March (0.00128*) and April (0.00139*), but noticeable cooling trends during monsoon (-0.00011*) and winter (-0.00005*), as well as in months like January (-0.00069*) and December (-0.00041*). Southern cities-Bengaluru, Chennai, and Hyderabad-show consistent and statistically significant warming across most months and seasons. Bengaluru records steady increases, particularly in late monsoon and winter (e.g., December: 0.00102*), while Chennai and Hyderabad display strong warming signals throughout the year, especially during monsoon and post-monsoon periods. Overall, the results clearly demonstrate that minimum temperatures are rising across most regions, emphasizing enhanced night-time warming as a key characteristic of recent climatic changes in Indian megacities.

Table 6: Long-Term Monthly and Seasonal Minimum Temperature Trends (°C) Derived from Sen's Slope Estimator across Indian Megacities (1981-2024)

Months/Season	**Delhi**	**Mumbai**	**Kolkata**	**Bengaluru**	**Chennai**	**Hyderabad**
Jan	-0.00069*	-0.000001	-0.00081*	0.00051*	0.00048*	0.00006
Feb	0.00080*	0.00102*	-0.00057*	-0.00016	0.00015	-0.00002
Mar	0.00128*	0.00104*	0.00002	0.00037*	0.00054*	0.00038*
Apr	0.00139*	0.00119*	0.00042*	0.00009	0.00028*	0.00032*
May	0.00070*	0.000678*	0.00058*	0.00012	-0.00005	-0.00026

June	-0.00006*	0.000362*	0.00053*	0.00049*	0.00024*	0.00041*
July	-0.00072*	0.000323*	0.00044*	0.00057*	0.00028*	0.00051*
Aug	-0.00052*	0.000409*	0.00033*	0.00074*	0.00056*	0.00073*
Sep	0.00042*	0.000852*	0.00050*	0.00044*	0.00016*	0.00047*
Oct	0.00103*	0.000778*	0.00118*	0.00060*	0.00048*	0.00060*
Nov	0.00081*	0.000899*	0.00091*	0.00084*	0.00078*	0.00087*
Dec	-0.00041*	0.000635*	0.00049*	0.00102*	0.00077*	0.00061*
Pre-monsoon	0.00047*	0.000358*	0.00019*	0.00015*	0.00009*	0.00010*
Monsoon	-0.00011*	0.000102*	0.00010*	0.00031*	0.00008*	0.00014*
Post-monsoon	0.00045*	0.000355*	0.00048*	0.00005	0.00027*	0.00029*
Winter	-0.00005*	0.000176*	-0.00009	0.00017*	0.00017*	0.00008*

*Significant at $p<0.05$

Precipitation trend: The analysis of monsoon rainfall extremes across major Indian megacities reveals pronounced spatial variability in rainfall intensity. From table 7, Mumbai records the highest rainfall intensity among all cities, with a peak of 25.681 mm/day (2019) and a comparatively high minimum of 10.617 mm/day (2002), reflecting the strong influence of coastal location and orographic effects. Kolkata also experiences substantial rainfall, with a maximum of 14.286 mm/day (2021) and a minimum of 4.722 mm/day (1983), indicating its humid climatic setting. In contrast, inland cities such as Delhi and Hyderabad show relatively moderate rainfall extremes, with Delhi ranging from 1.520 mm/day (1987) to 6.980 mm/day (2021), and Hyderabad from 2.678 mm/day (2015) to 6.865 mm/day (2020).

Southern cities display comparatively lower but still notable variability in monsoon rainfall. Bengaluru records a maximum of 7.638 mm/day (2022) and a minimum of 1.899 mm/day (2012), while Chennai shows a narrower range between 2.172 mm/day (1986) and 5.749 mm/day (1996). A noticeable pattern is that many of the highest rainfall events occur in recent years, particularly after 2019, suggesting a possible intensification of monsoon rainfall extremes. Overall, the findings highlight that coastal and eastern cities tend to experience higher rainfall intensities, whereas inland and southern plateau regions show comparatively lower but variable monsoon rainfall, reflecting regional climatic controls and evolving monsoon dynamics.

Table 7: Observed Extremes in Monsoon Rainfall Intensity (mm/day) with Corresponding Years across Megacities

City	Highest Monsoon Rainfall (mm/day)	Lowest Monsoon Rainfall (mm/day)
Delhi	6.980 (2021)	1.520 (1987)
Mumbai	25.681 (2019)	10.617 (2002)
Kolkata	14.286 (2021)	4.722 (1983)
Bengaluru	7.638 (2022)	1.899 (2012)
Chennai	5.749 (1996)	2.172 (1986)
Hyderabad	6.865 (2020)	2.678 (2015)

Mumbai consistently records the highest monsoon peaks among all cities (Figure 4). Its rainfall shows significant variability, with several years exceeding 20 units and notable spikes in the mid-2000s and late 2010s, indicating the city's strong exposure to intense monsoon systems along the western coast. In contrast, the other cities experience comparatively moderate rainfall levels. Kolkata and Bengaluru generally occupy the middle range, with occasional spikes suggesting periodic heavy monsoon activity. Kolkata, in particular, shows some sharp increases, reflecting its location in the eastern region influenced by the Bay of Bengal. Bengaluru's pattern is more stable, though it still experiences intermittent peaks.

Hyderabad and Chennai display relatively lower and steadier rainfall trends. While both cities see occasional increases, their values mostly remain within a narrower band, suggesting less extreme variability compared to coastal counterparts. Delhi records the lowest rainfall overall, with minimal fluctuation, consistent with its inland, semi-arid climate. In summary, the data highlights strong regional contrasts in India's monsoon behavior. Coastal cities-especially Mumbai-experience higher and more volatile rainfall, while inland cities like Delhi show lower and more stable patterns. The variation across years also suggests the influence of broader climatic factors affecting monsoon intensity over time.

Analysis of month-wise and season-wise rainfall distribution (Table 8) shows striking spatial contrasts driven by regional climatology and monsoon dynamics. Mumbai exhibits an extremely high monsoon dependency, receiving over 90% of their annual rainfall between June and September, with July alone contributing one-third of the yearly total in both cities. In contrast, Delhi's rainfall regime is less concentrated, with the southwest monsoon contributing 80% of annual rainfall, while winter Western Disturbances account for nearly 7%, making it the most winter-influenced city in this comparison. Bengaluru and Hyderabad display a distinctly bimodal rainfall pattern, with only 55% of rainfall

occurring during the southwest monsoon and a substantial 22% arriving during the post-monsoon season, supplemented by significant pre-monsoon convective activity (≈18%) in April-May. Kolkata receives nearly three-quarters (73%) of its rainfall during the southwest monsoon but also benefits from notable pre-monsoon Nor'westers (14%), characteristic of the eastern Indo-Gangetic region. Chennai stands out sharply from all other cities: only 36% of its rainfall occurs during the southwest monsoon, while an exceptional 43% is contributed by the northeast monsoon (October-November), underscoring its unique vulnerability to cyclones and Bay of Bengal depressions. These patterns highlight the profound inter-city variability in rainfall seasonality across India, driven by differing influences of the southwest monsoon, northeast monsoon, Western Disturbances, and local convective systems-each shaping the hydrological risks and climate-adaptation priorities of their respective regions.

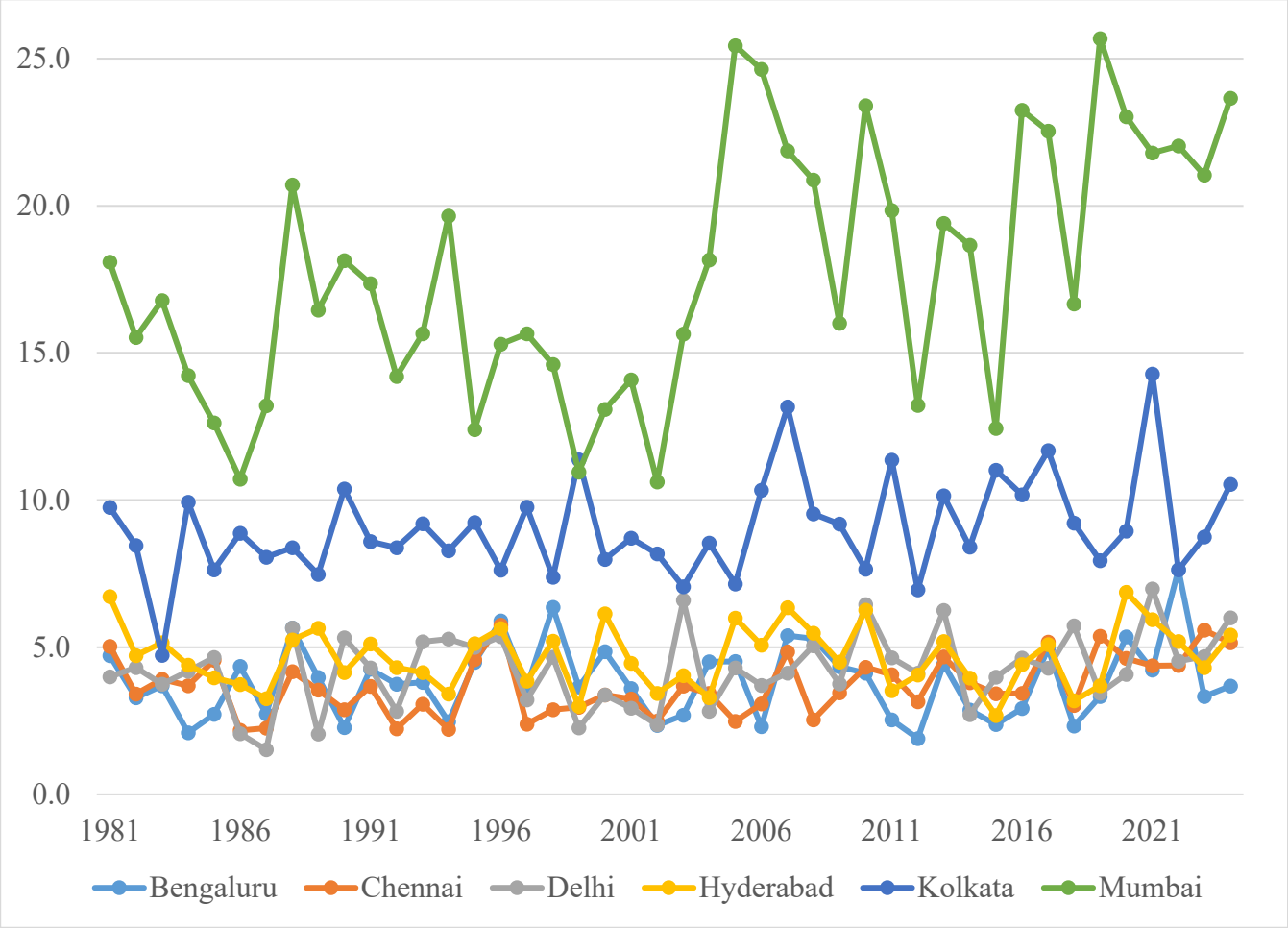


Figure 4: Annually highest rainfall per day (in mm) in Monsoon season during the year 1981-2024.

Table 8: Relative Contribution (%) of Monthly and Seasonal Rainfall to Annual Precipitation across Indian Megacities

Months/Season	Mumbai	Delhi	Bengaluru	Hyderabad	Chennai	Kolkata
Jan	0.05	2.94	0.50	0.50	1.95	0.78
Feb	0.08	2.99	0.66	0.66	0.99	1.42
Mar	0.13	2.47	1.70	1.70	0.88	2.11
Apr	0.13	2.64	5.29	5.29	1.51	3.14
May	1.43	4.71	11.69	11.69	4.04	9.19
June	20.62	10.95	10.04	10.04	6.13	15.58
July	34.40	26.53	11.64	11.64	8.59	20.32
Aug	22.25	26.63	14.79	14.79	10.62	19.72
Sep	15.41	16.07	18.54	18.54	10.91	16.99
Oct	4.58	2.32	16.01	16.01	18.59	8.39
Nov	0.66	0.70	6.46	6.46	24.38	1.59
Dec	0.27	1.05	2.67	2.67	11.40	0.78
Pre-monsoon	1.68	9.82	18.68	18.68	6.43	14.44
Monsoon	92.68	80.18	55.01	55.01	36.25	72.61
Post-monsoon	5.24	3.02	22.47	22.47	42.97	9.98
Winter	0.40	6.98	3.83	3.83	14.35	2.98
Annual	100.00	100.00	100.00	100.00	100.00	100.00

The Mann-Kendall (MK) trend analysis and Sen's slope estimator applied to long-term monthly and seasonal precipitation data across selected cities and reveals substantial spatial and temporal variability in rainfall behaviour. The results highlight a complex pattern of increasing monsoon rainfall in several cities, contrasted with stable or declining trends during winter and pre-monsoon months. The analysis indicates that Mumbai, Bengaluru, Chennai, and Kolkata exhibit statistically significant increasing trends during the core monsoon months (July-September), as reflected by positive MK statistics and small yet consistently positive Sen's slopes. Mumbai, in particular, shows strong signals of intensification in July and August, reinforcing earlier evidence of rising extreme monsoonal precipitation along the west coast. Similarly, Bengaluru and Chennai show significant increases in monsoon rainfall, indicating enhanced moisture influx and stronger convective activity over southern India. In contrast, Hyderabad displays decreasing or non-significant trends in several pre-monsoon and winter months (January-April and December). Delhi also demonstrates largely stable or non-significant rainfall trends across most months, highlighting the city's comparatively muted response to changing precipitation patterns, likely linked to its inland location and limited monsoon influence. Kolkata presents a

combination of increasing trends during monsoon months and decreasing trends in winter, reflecting the strong influence of the Bay of Bengal monsoon branch. Overall, the monthly distribution reveals a common pattern where monsoon rainfall is intensifying, whereas dry-season rainfall remains static or declining, indicating a redistribution of precipitation within the annual cycle.

Seasonal analysis further supports the monthly findings. Increasing rainfall trends are most pronounced during the Southwest Monsoon season across Mumbai, Bengaluru, Chennai, and Kolkata, signifying heightened monsoonal activity. These increases, although represented by small Sen's slopes, are statistically significant and consistent across multiple timeframes, suggesting a persistent shift toward more intense monsoon rainfall. Conversely, the winter and pre-monsoon seasons show either declining or no significant trends for most cities. Hyderabad and Delhi demonstrate clear reductions in rainfall during these seasons, which may be associated with weakening Western Disturbances and altered atmospheric circulation patterns. Such declines may exacerbate heat stress, reduce soil moisture availability, and intensify early-summer drought-like conditions.

The increasing monsoon rainfall detected in major cities such as Mumbai, Chennai, Bengaluru, and Kolkata is consistent with broader climatological assessments showing a rising frequency of short-duration, high-intensity rainfall events across India. Warming sea surface temperatures over the Arabian Sea and Bay of Bengal, coupled with enhanced moisture transport, likely contribute to these trends. The concentration of rainfall into shorter periods increases the probability of urban flooding, especially in cities with constrained drainage systems and rapid urbanization. Declining or stable trends during the winter and pre-monsoon months, observed notably in Delhi and Hyderabad, may indicate reduced Western Disturbance activity and prolonged dry spells, factors that can exacerbate urban heat island effects, increase water demand, and strain municipal water supplies. Bengaluru and Hyderabad show clear intra-seasonal redistribution of rainfall, with decreases in early months balanced by increases during monsoon peaks. This shift presents challenges for water resource planning, as shifting rainfall timing can lead to mismatches between water availability and demand. Urban expansion, loss of natural water bodies, and reduced infiltration capacity across Indian cities further amplify the hydrological impacts of even modest increases in rainfall. Thus, the statistical trends identified here likely translate into disproportionately large impacts on flooding, waterlogging, stormwater load, and infrastructure stress.

From table 9, a consistent and statistically significant increasing trend during the monsoon season is observed across all selected cities. This indicates a strengthening of monsoon rainfall over the study period (1981-2024). In contrast, the pre-monsoon season shows a dominant decreasing trend across most cities, suggesting reduced rainfall during the early part of the year. Monthly analysis further highlights widespread declines in rainfall during winter and early summer months (January-April), especially in Mumbai, Bengaluru, and Hyderabad.

Post-monsoon trends display mixed behaviour, with Chennai showing a clear increasing trend, reflecting its dependence on northeast monsoon rainfall, while other cities such as Mumbai, Hyderabad, and Kolkata exhibit decreasing tendencies. Delhi generally shows no significant trend across many months, indicating relatively stable rainfall patterns outside the monsoon season. Overall, the results suggest a shift toward more concentrated rainfall during the monsoon period, accompanied by declining or stable precipitation in other seasons, highlighting increasing seasonality and potential implications for water resource management and urban flooding risks.

Table 9: Monthly and Seasonal Precipitation Trends Based on Mann-Kendall (MK) Test and Sen's Slope Analysis across Indian Megacities (1981-2024)

Months/Season	**Delhi**	**Mumbai**	**Kolkata**	**Bengaluru**	**Chennai**	**Hyderabad**
Jan	↔	↓	↔	↓	↔	↓
Feb	↔	↓	↓	↓	↔	↓
Mar	↔	↓	↔	↔	↔	↔
Apr	↔	↓	↔	↓	↔	↓
May	↓	↓	↑	↑	↑	↓
June	↓	↑	↔	↔	↑	↔
July	↑	↑	↑	↑	↔	↑
Aug	↑	↑	↑	↔	↑	↔
Sep	↓	↑	↑	↔	↑	↑
Oct	↔	↓	↓	↔	↔	↓
Nov	↔	↓	↓	↔	↑	↓
Dec	↔	↓	↓	↓	↔	↔
Pre-monsoon	↓	↓	↓	↓	↔	↓

Monsoon	↑	↑	↑	↑	↑	↑
Post-monsoon	↔	↓	↓	↔	↑	↓
Winter	↔	↓	↔	↓	↔	↓

Note: ↑ = increasing, ↓ = decreasing, ↔ = no trend

CONCLUSION

The overall analysis of temperature trends across major Indian megacities indicates a clear and sustained warming signal with strong regional and seasonal contrasts. Cities such as Bengaluru, Hyderabad, Chennai, and Kolkata exhibit consistent warming, while Delhi shows more variable behaviour, including cooling trends in winter and maximum temperatures. Across all cities, minimum temperatures are increasing more rapidly than maximum temperatures, indicating enhanced nocturnal warming-an important signature of urban heat island intensification. Seasonal patterns further reveal that summer, monsoon, and post-monsoon periods are warming more uniformly, whereas winter displays the greatest inter-city variability, with northern cities such as Delhi and Kolkata even showing cooling tendencies. Overall, the findings confirm a multi-decadal warming trend dominated by rising minimum temperatures and amplified warming in southern cities, emphasizing the growing risks of heat stress and the need for city-specific climate adaptation and heat management strategies.

Precipitation patterns highlight increasing variability and a growing concentration of rainfall during the monsoon season. Mumbai, Delhi, and Kolkata remain highly dependent on monsoon rainfall, underscoring the importance of integrated monsoon planning, including flood forecasting systems linked with meteorological and municipal data, improved urban drainage design, and climate-resilient infrastructure such as flood-proof metro and transport systems. Cities with highly concentrated rainfall like Mumbai require annual storage buffers, whereas cities with more distributed rainfall such as Bengaluru, Hyderabad, and Chennai need multi-season water harvesting strategies. The increasing intensity of monsoon rainfall, combined with declining winter precipitation and greater temporal concentration, calls for real-time rainfall monitoring systems and enhanced disaster response mechanisms. In conclusion, Indian megacities are experiencing uneven but increasingly pronounced shifts in precipitation regimes, reinforcing the urgent need for forward-looking, city-specific climate resilience measures to manage risks, ensure water security, and safeguard urban populations.

Acknowledgement

The authors acknowledge the National Aeronautics and Space Administration (NASA) Langley Research Center's Prediction of Worldwide Energy Resources (POWER) Project for providing freely accessible data through the Data Access Viewer portal.

Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this manuscript.

References

1. Abbasi, K., Ali, P., Barbour, V., Benfield, T., Bibbins-Domingo, K., Hancocks, S., Horton, R., Laybourn-Langton, L., Mash, R., Sahni, P., Sharief, W. M., Yonga, P., & Zielinski, C. (2023). Time to treat the climate and nature crisis as one indivisible global health emergency. *BMJ, 383*, 2355. https://doi.org/10.1136/bmj.p2355
2. Alexander, L. V., Zhang, X., Peterson, T. C., et al. (2006). Global observed changes in daily climate extremes of temperature and precipitation. *Journal of Geophysical Research: Atmospheres, 111*(D5). https://doi.org/10.1029/2005JD006290
3. Dash, S. K., & Mamgain, A. (2011). Changes in the frequency of different categories of temperature extremes in India. *Journal of Applied Meteorology and Climatology, 50*(9), 1842–1858. https://doi.org/10.1175/2011JAMC2687.1
4. Food and Agriculture Organization. (2018). *Climate change and food security: Risks and responses*. FAO. https://www.fao.org/3/i5188e/i5188e.pdf
5. Gocic, M., & Trajkovic, S. (2012). Analysis of changes in meteorological variables using Mann-Kendall and Sen's slope estimator statistical tests in Serbia. *Global and Planetary Change, 100*, 172–182. https://doi.org/10.1016/j.gloplacha.2012.10.014
6. Goyal, M. K., & Surampalli, R. Y. (2018). Impact of climate change on water resources in India. *Journal of Environmental Engineering, 144*(7). https://doi.org/10.1061/(ASCE)EE.1943-7870.0001394
7. Guhathakurta, P., Sreejith, O. P., & Menon, P. A. (2011). Impact of climate change on extreme rainfall events in India. *Journal of Earth System Science, 120*(3), 359–373. https://doi.org/10.1007/s12040-011-0082-1
8. Haldar, S., Choudhury, M., Choudhury, S., & Samanta, P. (2023). Trend analysis of long-term meteorological data of a growing metropolitan city. *Total Environment Research Themes, 7*, 100056. https://doi.org/10.1016/j.totert.2023.100056
9. Hansen, J., Ruedy, R., Sato, M., & Lo, K. (2010). Global surface temperature change. *Reviews of Geophysics, 48*(4). https://doi.org/10.1029/2010RG000345
10. National Institute of Environmental Health Sciences. (2022). *Climate change and human health*. https://www.niehs.nih.gov/
11. IPCC. (2023). *AR6 Synthesis Report: Climate Change 2023*. Intergovernmental Panel on Climate Change. https://www.ipcc.ch/report/ar6/syr/

12. Jaiswal, R. K., Lohani, A. K., & Tiwari, H. L. (2015). Statistical analysis for trend detection in climatological parameters. *Environmental Processes, 2*(4), 729–749. https://doi.org/10.1007/s40710-015-0105-3
13. Kaur, R., & Pandey, P. (2021). Air pollution, climate change, and human health in Indian cities. *Frontiers in Sustainable Cities, 3*, 705131. https://doi.org/10.3389/frsc.2021.705131
14. Kendall, M. G. (1975). *Rank Correlation Methods* (4th ed.). Griffin, London.
15. Kodandarama, N., et al. (2024). Rainfall trend analysis using non-parametric methods. *Asian Research Journal of Agriculture, 17*(2), 60–69. https://doi.org/10.9734/arja/2024/v17i2422
16. Mann, H. B. (1945). Nonparametric tests against trend. *Econometrica, 13*(3), 245–259. https://www.jstor.org/stable/1907187
17. Real Statistics. (2026). Mann-Kendall test. https://real-statistics.com/time-series-analysis/time-series-miscellaneous/mann-kendall-test/
18. Real Statistics. (2026). Sen's slope. https://real-statistics.com/time-series-analysis/time-series-miscellaneous/sens-slope/
19. Romanello, M., et al. (2021). The 2021 report of the Lancet Countdown. *The Lancet, 398*(10311), 1619–1662. https://doi.org/10.1016/S0140-6736(21)01787-6
20. Ross, R. S., et al. (2018). Decadal surface temperature trends in India. *Scientific Reports, 8*. https://doi.org/10.1038/s41598-018-25347-2
21. Saikh, N. I., Saha, S., Sarkar, D., & Mondal, P. (2023). Rainfall trend and variability analysis of Kolkata. *MAUSAM, 74*(4), 1093–1112. https://doi.org/10.54302/mausam.v74i4.5909
22. Sen, P. K. (1968). Estimates of the regression coefficient based on Kendall's tau. *Journal of the American Statistical Association, 63*(324), 1379–1389. https://doi.org/10.1080/01621459.1968.10480934
23. Smith, J. A. (2024). Temperature trends and biodiversity impacts. *Journal of Earth Science & Climatic Change, 15*. DOI: 10.4172/2157-7617.1000871
24. Sudarsan, G., et al. (2023). Rainfall trend analysis using MK and Sen's slope. *E3S Web of Conferences*. https://doi.org/10.1051/e3sconf/202340504013
25. The Times of India. (2024). Top 10 largest cities in India by population. https://timesofindia.indiatimes.com/etimes/trending/top-10-largest-cities-in-india-by-population/articleshow/113791114.cms
26. Thompson, L. G. (2010). Climate change: The evidence and our options. https://doi.org/10.1007/BF03392211
27. World Health Organization. (2019). *Health and climate change survey report*. https://iris.who.int/server/api/core/bitstreams/1d54484e-83ae-4d7a-9446-9e430b376a79/content
28. World Health Organization. (2023). Climate change and health. https://www.who.int/news-room/fact-sheets/detail/climate-change-and-health
29. World Population Review. (2026). India cities by population. https://worldpopulationreview.com/cities/india
30. NASA Langley Research Center. (2025). POWER Data Access Viewer. https://power.larc.nasa.gov