

# Spatio-Temporal Variability of Temperature and Rainfall in a Rapidly Urbanising City: Evidence from Hyderabad (2000–2024)

<sup>1</sup>Ginka Prathusha, <sup>2</sup>Sr. Prof. B. Srinagesh, <sup>3</sup>Ar. Chenna Vivek

<sup>1</sup>Research Scholar, Department of Geography, Osmania University, Hyderabad

<sup>2</sup>Senior Professor, Department of Geography, Osmania University, Hyderabad

<sup>3</sup>Faculty, NIT- Calicut, Kerala

Corresponding Author: [prathusha.star@gmail.com](mailto:prathusha.star@gmail.com)

## Abstract

Temperature and the rainfall data are the most sensitive indicators of climate variability. In the regions mainly of rapid urbanization where land atmosphere interactions are increasingly modified by anthropogenic processes. This study examines a long term variability and trends in annual maximum temperature, minimum temperature, diurnal temperature range and rainfall in Hyderabad for the period 2000-2024. Annual temperature and rainfall data are being analysed by using the time series analysis, linear trend and anomaly analysis, Mann Kendall test, Sen's slope estimator and moving average techniques. Results indicate that there is a consistent increase in the minimum temperatures accompanied by a marginal decline in the maximum temperatures. It also led to the pronounce reduction in diurnal temperature range in the region. Rainfall analysis reveals a weak long term trend but strong interannual variability and increasing frequency of extreme wet and dry years particularly after 2010. The findings are highlighting a transition towards an urban climate regime which is dominated by a nocturnal warming and episodic rainfall extremes. This analysis is highlighting implications for the thermal comfort, water resource management and urban climate resilience.

**Keywords:** urban climate, temperature variability, diurnal temperature range, rainfall extremes, urban heat island.

## 1. Introduction

The climate variability refers to the fluctuations that occur in the climatic parameter around long term mean conditions over inter annual to decadal time scales. In recent decades there is increasing evidence suggesting that climatic variability has intensified globally. There are particularly observed in urban regions where natural surface atmosphere interactions are significantly altered by different activities like land use change, built up expansion and anthropogenic heat emissions. Among various climatic parameters temperature is considered as one of the most reliable indicators of the climatic variability relates continuous thermal behaviour and rapid response to the atmospheric and surface processes.

Unlike precipitation, which is episodic and spatially heterogeneous, temperature can exhibit smooth temporal continuity which is making it more suitable for detecting both short term variability and long-term climatic trends. Analysing temperature of a single mean value however often mask the importance of the interday and intraday process. Separate examination of maximum temperatures, minimum temperatures and diurnal temperature range is providing a deeper insight to Asymmetric warming temperatures and urban heat island effect.

The rainfall variability is also another crucial dimension of the climate change and variability. This is mainly observed in monsoon dependent countries and regions. There is an increasing evidence indicating that the

rainfall changes are often expressed not just through the monotonic trends but also through enhanced variability which is intensified by extreme events. Such changes have a profound implications for the urban flooding, drought occurrence and water resource sustainability.

Hyderabad which is considered as one of the growing metropolitan cities in India is providing ideal setting to examine the urban climatic variability. Hyderabad has experienced rapid urbanisation, increase in built up density and significantly changes in land cover transformation over the last 2 decades. These changes have expected to influence both thermal regimes and the rainfall behaviour in the city. Despite its climatic sensitivity long term integrated analysis of temperature and rainfall variability in Hyderabad remain limited. This study addresses this gap by analysing temperature trends, diurnal temperature behaviour, rainfall variability and extreme events over the last 25 years.

## 2. Literature review

### 2.1 Climate variability and temperature indicators

Global urban studies have also shown asymmetric warming patterns characterised by faster increase in minimum temperatures compared to the maximum temperature this is leading to the reduction in diurnal temperature range (Vose et al. 2005; Donat et al.2013). Declining Diurnal temperature range has been identified as a key signal of climate change which is reflecting the changes in the cloud cover, atmospheric moisture and the land use interactions (Trenberth et al. 2014). These findings are underscoring the importance of the analysing maximum temperatures, minimum temperatures, and diurnal temperature range separately rather than relying solely on the mean temperature. Urbanisation has significantly altered the local climatic conditions of a region. It has modified the land cover, surface roughness, albedo and energy balance. One of the most prominent manifestations of the urban climate modification is that the heat island effect whereby urban areas are exhibiting higher temperatures rather than surrounding rural areas particularly during the night time (Oke 1982). The energetic basis of urban heat island lies in the increased heat storages in the build-up material, reduced evapotranspiration and enhanced anthropogenic heat emissions. Extensive research across the cities in North America, Europe and Asia has documented that urban heat island are primarily expressed to elevated minimum temperatures and suppressed in nocturnal cooling which is resulting in decline in the diurnal temperature range ( Arnfield 2003; Zhao et al. 2014). Kalnay and cai (2003) demonstrated that the land use change and the urbanization contribute significantly to the warming trends and often amplifying the regional climate change signals. Recent studies are also highlighting that urban heat island intensity is closely linked to the region where the building density and the land use composition is mainly observed (Santamouris 2015). The persistence of elevated night time temperatures have an important implication for the thermal comfort public health and energy demand particularly during the heat waves (Hajat and Kosatky 2010).

Several studies have documented the rising temperature trends in the urban heat island effect is majorly observed in the Indian metropolitan areas. Roy (2009) reported significant urban heat island intensity in Delhi while Kotharkar and Surawar (2016) observed a strong relationship between the land change and the declining diurnal temperature range in Nagpur. The studies also indicate that multiple Indian cities have consistently showing that minimum temperature is increasing at faster rate than the maximum temperature which is indicating the enhanced nocturnal warming (kotharkar et al. 2018; Murrari et al. 2019). These trends are particularly pronounced in the semiarid and tropical cities. Where the reduction of vegetation and increase in the high built up density are exaggerating the heat retention. Despite these advances long term integrated analysis of Tmax, Tmin, DTR and rainfall variability for several rapid growing cities including Hyderabad remain limited.

Variability in rainfall is a critical dimension of the climate change is observed mainly in the monsoon dominated regions are such as India. While long term trends in the rainfall are often weak or statistically

insignificant there is an increasing evidence suggesting that climate change is intensifying rainfall variability and extreme precipitation event (Allan and Soden 2008). Goswami et al (2006) Reported significant increase in extreme rainfall events was observed in India even in the absence of the strong trend in the mean monsoon rainfall.

Subsequent studies have been reinforced with these findings which is indicating a shift towards fewer but more intense rainfall events interspersed with the prolonged dry spells (Dash et al 2007, Roxy et al 2017). This pattern reflects an intensifying hydrological cycle driven by increased atmospheric moisture in the warming climate. Such changes have profound implications for flood risk, drought occurrence and also the water resource management.

### 3. Research gap and rationale for the present study

The review of literature highlights three key gaps. First, many of the studies are focusing either on the temperature or on rainfall but their integrated analysis of the temperature behaviour and rainfall variability still remained limited. Secondly, most urban climate studies emphasise on mean temperature trends often overlooking the value of the Tmin, Tmax, DTR. Thirdly, rainfall extremes have been widely studied at regional and national level, the city level assessment linking the rainfall variability with urbanization are relatively scarce. The present study bridges this gap by providing an integrated analysis of maximum temperatures, minimum temperatures, diurnal temperature range and rainfall variability for Hyderabad over a 25-year period. By combining the temperature asymmetry, rainfall extremes and statistical trend analysis the study contributes to a more comprehensive understanding of the urban climatic variability in a rapidly urbanising semi-arid city of Hyderabad.

### 4. Study area

Hyderabad is located in the semi-arid regions of the South-Central India which is experiencing a tropical semi-arid climate. Hyderabad characterised by hot summers, moderate monsoon rainfall, and mild winters. The city lies on the deccan plateau at an average elevation of approximately 540 metres above mean sea level. Climatically, Hyderabad is being influenced primarily by southwest monsoon. Southwest monsoons contribute most of the annual rainfall which is followed by the northeast monsoons during the post monsoon.

Over the past two decades Hyderabad has undergone rapid urbanisation making it extensive expansion of the built-up areas and reducing the vegetative cover. This land use changes have altered the local energy balance, surface roughness, and heat storage characteristics. Due to these changes the city particularly vulnerable to urban heat island effect and rainfall extremes. The combination of the semi-arid background climate and the rapid urban growth makes Hyderabad highly sensitive to the climate variability and extreme events.

### 5. Data Sources

The temperature and rainfall data were obtained from the Indian metrological department and from the Telangana state developmental planning society. These sources are officially recognised and widely used in climatological and the urban climate studies in India which is ensuring reliability and consistency of the data set.

### 6. Statistical Methods

#### 6.1 Linear Trend Analysis

To determine the direction and rate of climatic change:

$$Y = a + bX$$

Where:

- $b$  = slope (rate of change per year)
- Decadal change =  $b \times 10$

Used for Annual Tmax, Annual Tmin, DTR, Annual rainfall

### 6.2 Mann–Kendall (MK) Trend Test

A non-parametric test used to detect monotonic trends in climatic time series.

- Null hypothesis ( $H_0$ ): No trend
- Alternative hypothesis ( $H_1$ ): Significant trend exists

Significance tested at:

- 95% confidence ( $p < 0.05$ )
- 99% confidence ( $p < 0.01$ )

This method is suitable for climatic data because it:

- Does not assume normal distribution
- Is resistant to outliers
- Works effectively with hydrometeorological datasets

### 6.3 Sen’s Slope Estimator

Used to estimate magnitude of trend.

$$Q = \text{Median} \left( \frac{X_j - X_i}{j - i} \right)$$

Where:

- $Q$  = rate of change per year

Provides robust estimation of climatic change rate ( $^{\circ}\text{C}/\text{year}$  or  $\text{mm}/\text{year}$ ).

### 6.4 Diurnal Temperature Range (DTR) Analysis

$$\text{DTR} = T_{\max} - T_{\min}$$

Used to assess the Nocturnal warming, Urban Heat Island intensity, Thermal homogenisation

Trend significance tested using MK and Sen’s slope.

### 6.5 Coefficient of Variation (CV)

$$\text{CV} = \left( \frac{\sigma}{\mu} \right) \times 100$$

Where:

- $\sigma$  = standard deviation
- $\mu$  = mean rainfall

Used to assess rainfall instability.

## 7. Result

### 7.1 Trends Annual average Maximum and Minimum Temperatures

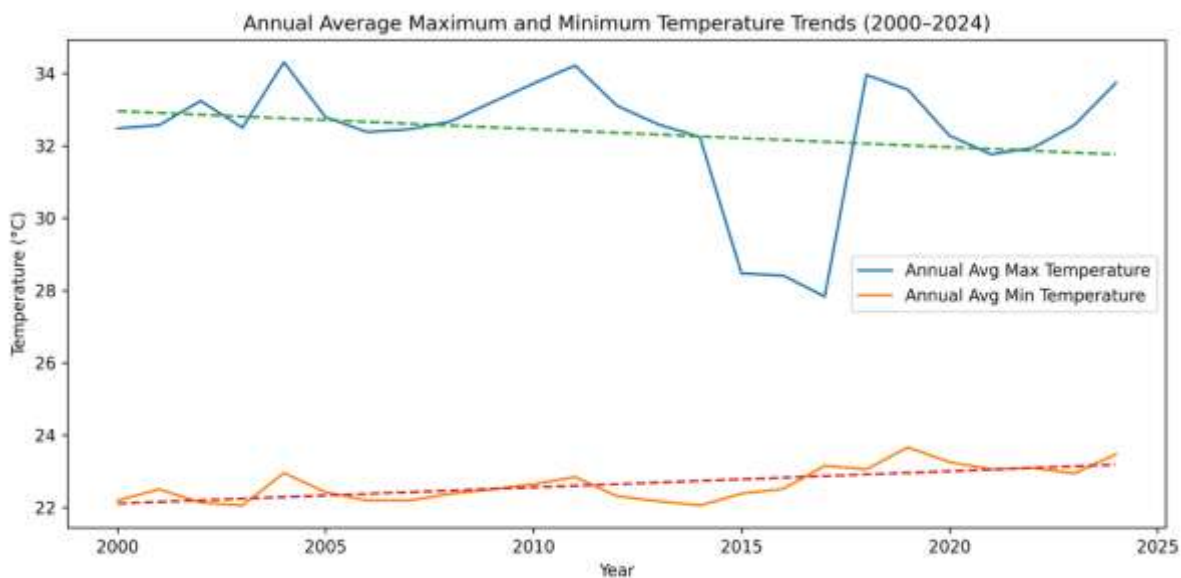
To examine the long term behaviour of the temperature annual average maximum and minimum temperatures were plotted as a time series with linear trend lines for the period 2000- 2024. Linear regression analysis was applied to quantify in the direction and the rate of change in the temperature overtime. The linear trend approach provides a numerical measure of climatic change and facilitates comparison with other regional and global studies.

Year	Annual Avg Max Temp ( $^{\circ}\text{C}$ )	Annual Avg Min Temp ( $^{\circ}\text{C}$ )
2000	32.48	22.19
2001	32.57	22.50
2002	33.24	22.13
2003	32.50	22.05
2004	34.31	22.95

2005	32.79	22.42
2006	32.38	22.19
2007	32.45	22.19
2008	32.67	22.37
2009	33.20	22.50
2010	33.72	22.64
2011	34.22	22.84
2012	33.11	22.31
2013	32.59	22.17
2014	32.24	22.05
2015	28.47	22.38
2016	28.41	22.51
2017	27.83	23.15
2018	33.96	23.05
2019	33.55	23.66
2020	32.28	23.25
2021	31.76	23.05
2022	31.94	23.09
2023	32.57	22.94
2024	33.74	23.47

Table 7.1: Annual Average Maximum and Minimum Temperature

Source: Telangana Development planning society



Graph 7.1: Annual Average Maximum and Minimum Temperature Trends (2000-2024)

The graph shows that the annual average maximum temperatures are exhibiting considerable interannual variability with notable peaks in 2004, 2011, 2018 and 2024. It is observed that the minimum temperature demonstrates a more consistent increased trend over the study. The linear trend analysis indicates a marginal decline in maximum temperatures that is  $-0.50$  degree Celsius per decade and a significant rise in minimum temperature that is  $+0.45$  degree Celsius per decade. The contrasting behaviour is suggesting there is an

enhanced nocturnal warming and increased heat retention which is characteristic feature of urban heat island effect.

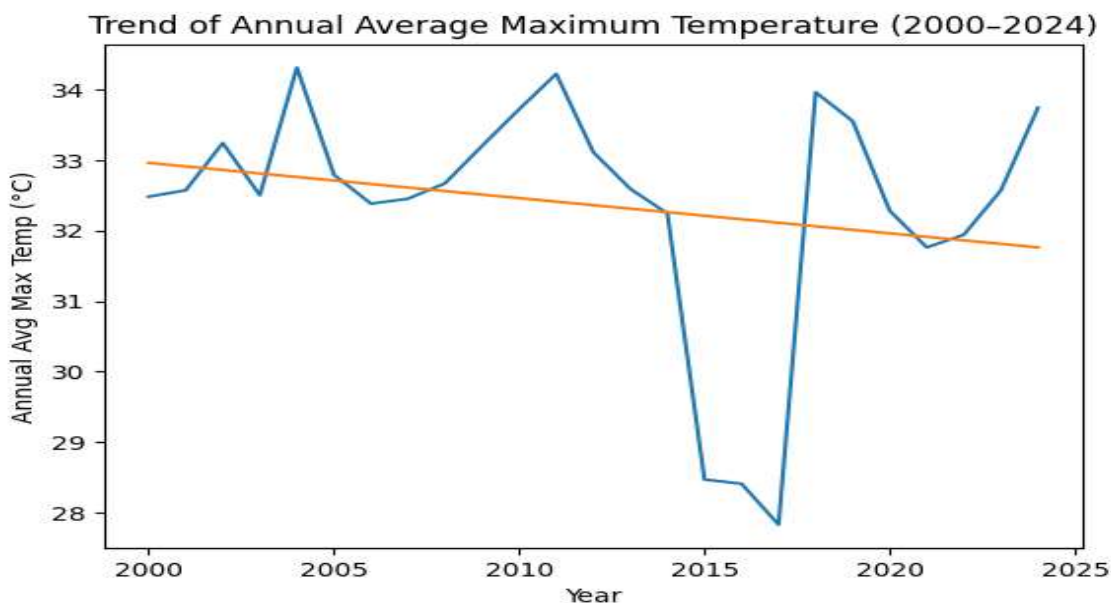
### 7.2 Trend significance and analysis of annual average maximum temperatures

To examine the presence of a monotonic trend in annual average maximum temperatures, the nonparametric Mann- Kendall (MK) test was applied. The magnitude of the trend was estimated using the Sen’s slope estimator.

The results of the statistical analysis are presented below

Statistic	Value
<b>Mann Kendall’s Z value</b>	- 0.9342
<b>p-value</b>	0.338
<b>Sen’s Slope (°C per year)</b>	-0.024
<b>Sen’s Slope (°C per decade)</b>	-0.24

Table 7.2: Statistical analysis of annual average maximum temperature



Graph 7.2: Trends of Annual average Maximum temperature (2000-2024)

It 95% confidence level (0.05), the computed p-value (0.338) is greater than 0.05. Therefore, the null hypothesis of no trend cannot be rejected. The trend is statistically insignificant. Although Sen’s slope is indicating their marginal decline of -0.24 degree Celsius per decade, this change is statistically insignificant. The observed variability in the maximum temperature is largely influenced by short term inter annual fluctuations particularly the anomalous cooling phase during 2015- 2017.

Absence of these statistically significant trends suggest that the daytime heating over Hyderabad has not undergone a consistent long term increase during the study Period. Instead, the variability in the maximum temperature appears to be governed by episodic climatic fluctuations rather than systematic nocturnal warming.

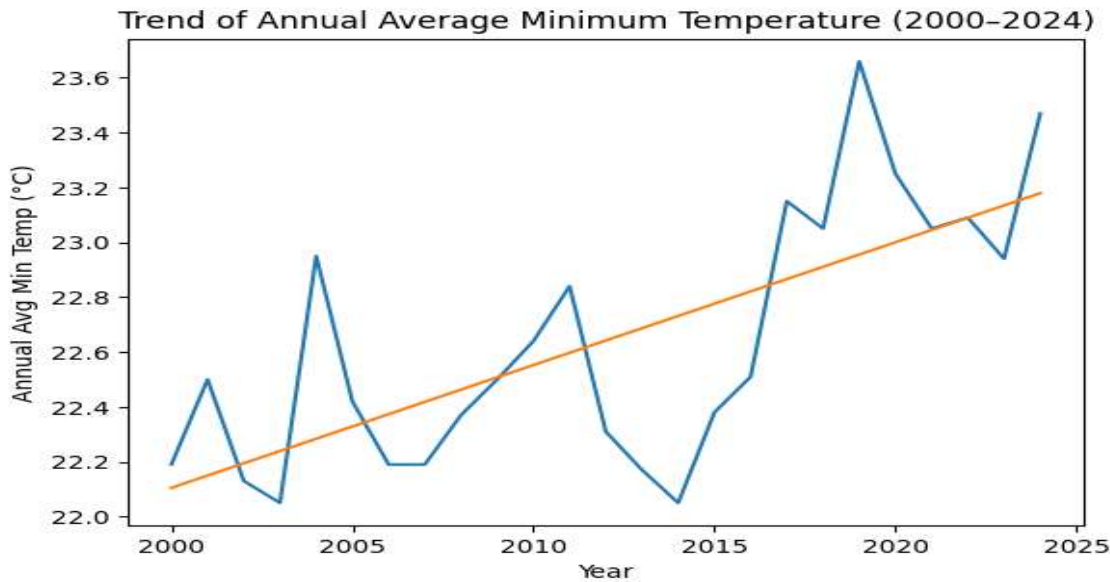
### 7.3 Trend significance and analysis of Annual average minimum temperature

The Mann-Kendall test was similarly applied to the annual average minimum temperatures. This is assessing long term nocturnal warming trends of the study period. Sen’s slope estimator was used to quantify the rate of change.

The statistical result are as follows

Statistic	Value
<b>Kendall's Z value</b>	3.34
<b>p-value</b>	0.000754
<b>Sen's Slope (°C per year)</b>	0.045
<b>Sen's Slope (°C per decade)</b>	0.45

Table 7.3: Statistical analysis of average annual minimum temperature



Graph 7.3: Trend of annual average minimum temperature (2000-2024)

The Mann Kendall trend analysis of the annual average minimum temperature for the period yields a z value of +3.34. The positive z value indicates an increasing trend and since the  $z > 2.58$ , the trend is statistically 99% confidence level.

Sen's slope estimate indicates that a minimum temperature has increased at a rate of approximately +0.45 Degree Celsius per decade over the study period. The statistically robust increase in the Minimum temperature is demonstrating an enhanced nocturnal warming in the Hyderabad. The magnitude and significance of the trend indicates intensified heat retention during the night time hours.

The contrasting behaviour between the maximum and minimum temperatures is revealing an asymmetric warming pattern. The maximum temperature does not exhibit a statistically significant trend, the minimum temperature is showing a highly significant upward trend.

This pattern is characteristics of

- Enhanced nocturnal heat retention
- Reduced night time cooling efficiency
- Progressive thermal homogenization
- Intensification of urban heat island effect

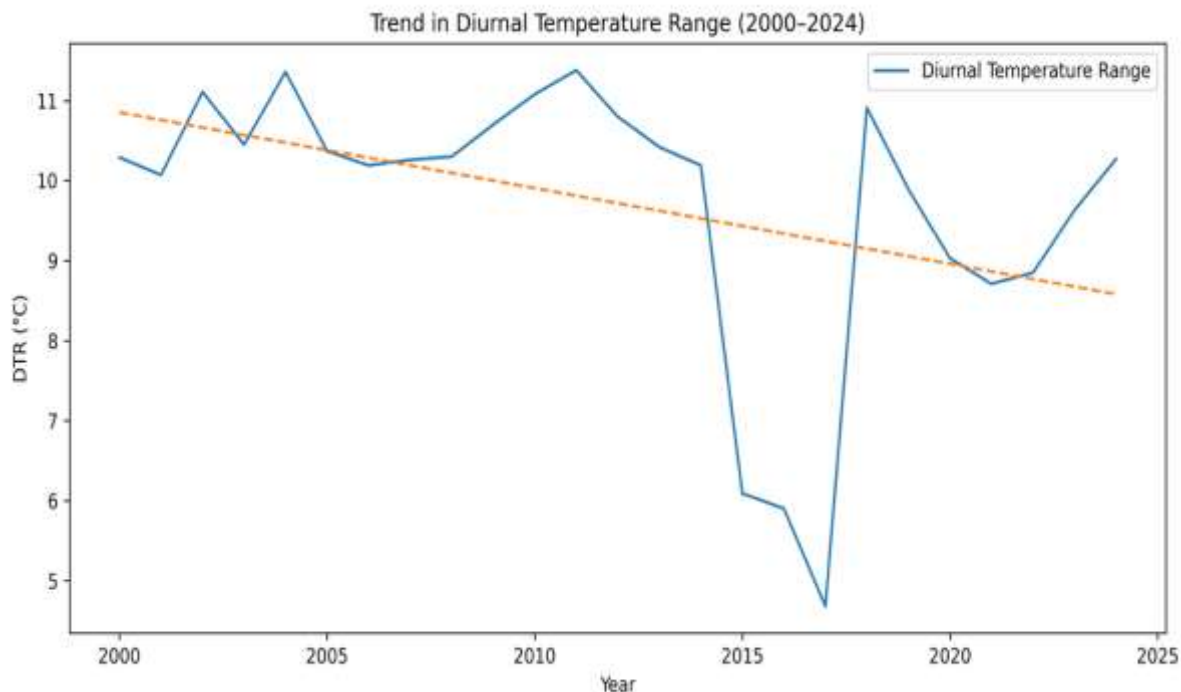
The findings suggests that the urbanization process in the Hyderabad during 2000-2024 have predominantly influenced the night time thermal regimes rather than daytime heating intensity

The statistical analysis confirms that Hyderabad is experiencing its significant nocturnal warming at a rate of +0.45, Degree Celsius per decade while observed the daytime maximum temperatures remains statistically

stable. This asymmetric thermal response is providing empirical evidence of the urban induced climatic modification in the study area.

### 7.4 Diurnal Temperature Range Variability

The diurnal temperature range was calculated as a difference between the annual average maximum and the minimum temperatures. This analysis is particularly useful for assessing the changes in day and night thermal contrast and also for the diagnosing urban heat island effect. Declining DTR is indicating enhanced nocturnal warming and reduced to surface cooling.



Graph 7.4: Trend in Diurnal Temperature range (2000-2024)

The graph is showing declining trend in the diurnal temperature range at a rate of approximately 0.95 degrees per decade. The reduction in the DTR is majorly due to rapid increase in minimum temperatures rather than rise in the maximum temperatures. A high coefficient of variation 17.76% is indicating that there is a significant inter annual instability in DTR. This declining thermal contrast is reflecting reduced to nocturnal cooling and confirms the growing influence of urbanization on local climatic conditions.

#### 7.4.1 Trend significance of diurnal temperature range

The Mann- Kendall (MK) test was applied to detect the presence of a monotonic trend and Sen’s Slope estimator was used to quantify the magnitude of change in that diurnal temperature range.

The statistical results are as follows

Statistic	Value
Mann–Kendall Z-value	-2.176
p-value	0.0298
Sen’s Slope (°C/year)	-0.0593
Sen’s Slope (°C/decade)	-0.5929

Table 7.4.1: Statistical analysis of the Diurnal Temperature Range

At the 95% confidence level the p value (0.0298) < 0.05. Therefore, the null hypothesis of no trend is rejected. This confirms a statistically significant declining trend in diurnal temperature range during 2000-2024. Sen’s

slope indicates that DTR has decreased by approximately -0.059 Degree Celsius per year and -0.59 Degree Celsius per decade.

The statistically significant decline in the diurnal temperature range is primarily driven by a strong increase in minimum temperatures rather than changes in the maximum temperatures. The decline of nearly 0.6 degrees Celsius per decade represents substantial modification of local thermal regimes.

The Mann-Kendall analysis conforms a statistically significant decline in DTR ( $Z = -2.176$ ,  $p < 0.05$ ) at a rate of -0.59 Degrees per decade. The reduction in DTR Combined with significant nocturnal warming is providing strong empirical evidence of intensifying urban heat island effect in Hyderabad during 2000-2024.

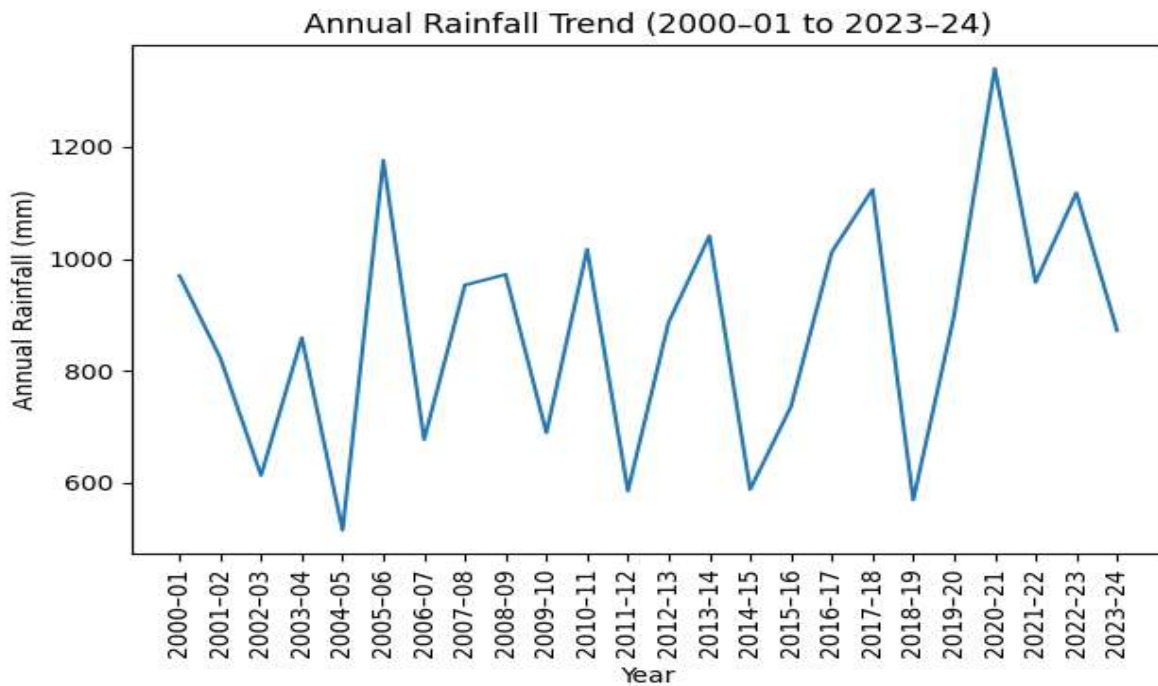
### 7.5 Annual rainfall trend analysis

The analysis of the annual rainfall trend was carried out mainly to understand the long term temporal changes and how there is an emerging rainfall behaviour observed in the study area. annual actual rainfall values were compared with the long term normal rainfall of 779 millimetres to assess deviation and overall trend characteristics.

Year	Annual Actual Rainfall (mm)	Annual Normal Rainfall (mm)	Normal Deviation (%)
2000-01	970	779	25
2001-02	823	779	6
2002-03	613	779	-21
2003-04	859	779	10
2004-05	515	779	-33.9
2005-06	1176	779	51
2006-07	677	779	-13.2
2007-08	953	779	22.3
2008-09	972	779	24.8
2009-10	689	779	-11.6
2010-11	1017	779	30.5
2011-12	585	779	-25
2012-13	887	779	13.8
2013-14	1041	779	33.6
2014-15	588	779	-24.5
2015-16	736	779	-5.5
2016-17	1012	779	29.9
2017-18	1124	779	44.3
2018-19	569	779	-27
2019-20	898	779	15.2
2020-21	1340	779	72
2021-22	958	779	23
2022-23	1118	779	43
2023-24	871.8	779	11.91

Table 7.5: Annual Actual, Normal, Deviation percentage of rainfall

Source : Telangana Development planning society



Graph 7.5: Annual Rainfall Trends (2000-01 to 2023-24)

The annual rainfall series exhibit a pronounced interannual fluctuations rather than a smooth monotonic trend. A minimum of 569 mm (2018–19) to a maximum of 1340 mm (2020–21). This wide amplitude clearly demonstrates the high degree of variability in annual precipitation within the study area. Several years record rainfall is significantly above the normal and particularly can be observed after 2010. The post 2010 phase reveals a noticeable clustering of excess rainfall years, which is suggesting an increasing frequency of extreme wet conditions in the recent decade. In contrast, early phase of the study i.e 2000-2001 to 2009-10 is mainly characterised by alternating sequence of above normal and below normal rainfall years. In this phase, it is reflecting a relatively moderate variability of precipitation. In 2010 is demonstrating a greater concentration of excess rainfall years inter spread with a few severe deficit years. This pattern is indicating a shift in the rainfall behaviour towards greater climatic instability and intensification of extreme climatic events.

Notable extreme wet years such as 2017-18 and 2020-21 highlights the growing intensity of the rainfall events. There is also sharp decline such as those observed in 2018-2019 indicate episodic drought conditions. The span of the extreme wet and dry years within a short temporal is underscoring the increasing climatic instability and heightened the precipitation variability.

Overall the annual rainfall trends are suggesting that while there is no consistent linear increase or decrease in the rainfall amounts but there is a clear tendency towards enhanced variability and extreme rainfall events. This changing rainfall regime has an important implication for the water resource management, urban flooding and drought preparedness in a study area. The emerging pattern suggests a transition from relatively stable precipitation behaviour to a more erratic and extreme rainfall regime, likely influenced by broader climatic variability and regional urbanisation processes.

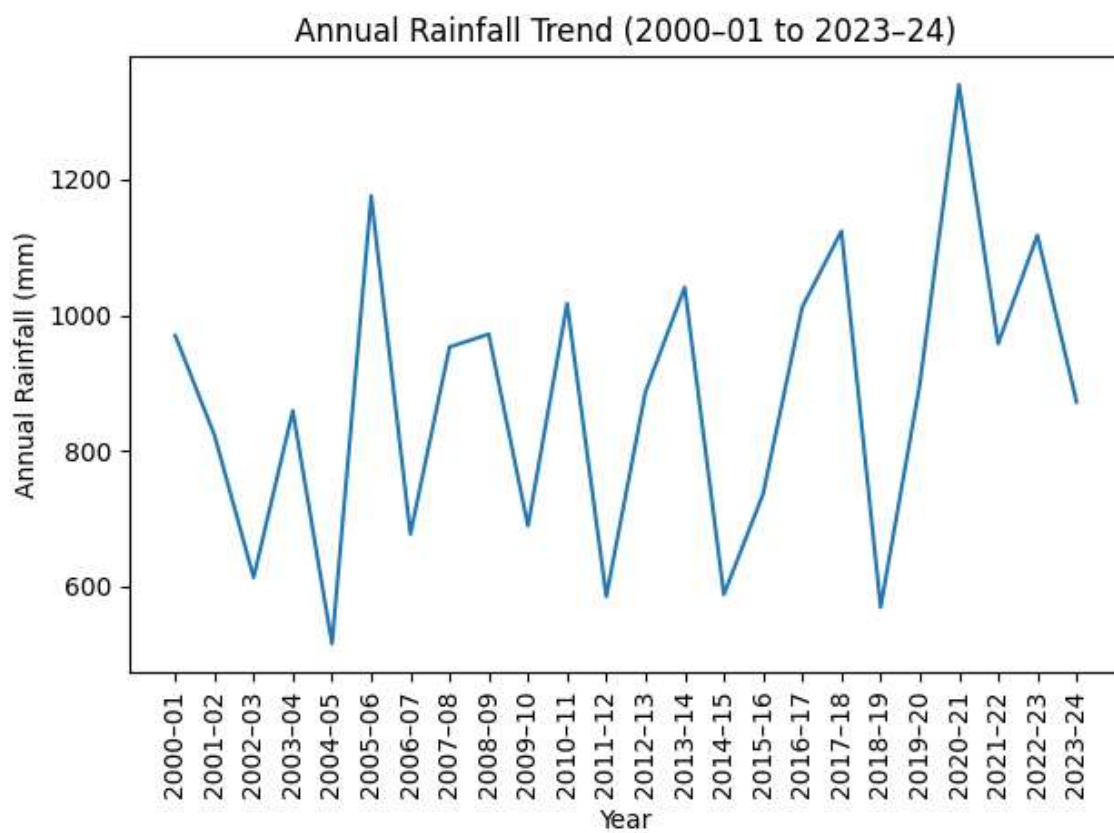
### 7.5.1 Trend significance analysis of Annual rainfall (2000-01 to 2023-23)

To examine long term rainfall behaviour in Hyderabad, the non-parametric Mann- Kendall (MK) Test was applied to detect the presence of the monotonic trend in the annual rainfall series. The magnitude of change was estimated using Sen’s Slope estimator and the rainfall variability was assessed using the Coefficient of Variation (CV).

The statistical analysis of the annual rainfall follows:

Statistic	Value
<b>Mann–Kendall Z-value</b>	1.2650
<b>p-value</b>	0.2059
<b>Sen’s Slope (mm/year)</b>	8.49 mm
<b>Sen’s Slope (mm/decade)</b>	84.86 mm
<b>Mean Annual Rainfall</b>	874.66 mm
<b>Standard Deviation</b>	216.78 mm
<b>Coefficient of Variation (CV)</b>	24.78 %

Table 7.5.1: Statistical analysis of the annual rainfall



Graph 7.5.1: Annual Rainfall and Sen’s slope trend (2000-2024)

At the 95% confidence level (0.05), p-value (0.2059) > 0.05. Therefore, the null hypothesis of no monotonic trend cannot be rejected. Although the Sen’s slope indicates a positive increase of approximately 85 mm per decade, the MK test confirms that the upward trend is not statistically significant. This implies that while the rainfall shows an increasing inclination, the trend lacks statistical robustness and cannot be considered a definitive long term climatic shift.

The time series graph demonstrates pronounced inter annual variability with alternating wet and dry years throughout the study period. The Coefficient of Variation (24.78%) is indicating about moderate rainfall variability. This is reflecting noticeable fluctuations around the mean annual rainfall of 874.66 mm.

The positive Sen’s slope suggests a gradual upward tendency. However, the statistical insignificance of the MK test indicates that this apparent increase is largely influenced by extreme rainfall years particularly high precipitation event such as 2020-21 rather than a sustained monotonic rise.

The clustering of the extreme wet years in the later phase of the study period, combined with the episodic deficit years is suggesting a transition towards greater rainfall volatility. The absence of the statistical significance is indicating that the observed increase is not yet indicative of the systematic climate intensification.

Thus, the MK analysis conforms that the annual rainfall in Hyderabad does not exhibit a statistically long-term trend during 2000-2024. Nevertheless, the moderate coefficient variation and positive Sen slope point towards increasing hydro-climate variability driven by extreme rainfall events rather than a gradual linear change.

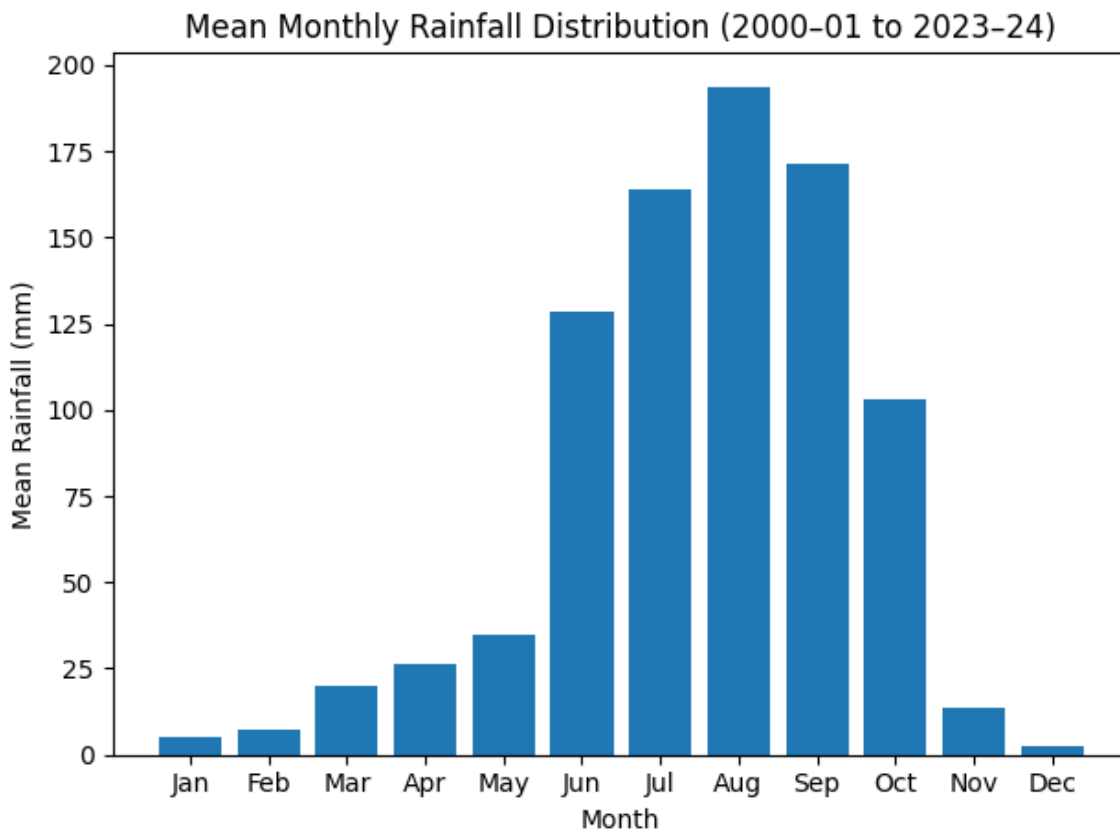
### 7.6 Monthly Rainfall Distribution

Year	Jan Act	Feb Act	Mar Act	Apr Act	May Act	June Act	July Act	Aug Act	Sep Act	Oct Act	Nov Act	Dec Act
2000-01	11	0	57	14	0	216	127	469	51	22	2	1
2001-02	11	0	16	2	64	224	43	230	91	140	2	0
2002-03	0	7	12	27	0	165	65	197	44	96	0	0
2003-04	29	1	32	59	39	66	265	144	55	169	0	0
2004-05	0	0	0	0	0	29.5	221.3	77.5	114	72.5	0	0
2005-06	0	0	30.8	53.1	75.7	88.9	370.1	115.4	220.6	221.7	0	0
2006-07	0	0	0	0	0	78.2	169.6	199.4	180.2	20.1	29	0
2007-08	0	56.7	134.7	15.3	9.5	8	165.74.6	217.9	236.4	17.1	24.9	0
2008-09	0	0	0.3	15.1	13.9	69.4	91.2	487.3	215.9	34.9	44.3	0
2009-10	7	4	6	0.7	18.8	57.3	49.2	278.7	158.5	82	22.7	4
2010-11	0	26.3	1.7	4.8	1.8	134	319.4	259.2	168.3	53.1	32.5	15.6
2011-12	0.1	0	0	19.4	0.3	26.2	185.8	231.2	56.9	58	6.6	0
2012-13	1.8	19.2	0	55.7	14.9	7	152.7	262.9	110.9	130.1	85.3	53.6
2013-14	0	0.1	60.8	3.8	47	7	146.5	222.4	132.4	170.4	241.5	16
2014-15	0	0	28.2	105.6	5.9	54.1	130.9	127.6	69.4	33.1	32.9	0.5
2015-16	0.8	0	0	7.3	149.2	144.8	40.8	95.3	218.3	78.3	1.2	0
2016-17	0	0	1	11	60.2	6	108.2	187.104	485.8	47	4.6	2.8

2017-18	0	0	1.4	39	59.6	201.1	171.7	243.3	158	250.1	0	0
2018-19	31.2	1	0	52.1	12.6	84.3	81.5	132.1	103.8	46.4	0.2	24
2019-20	14.3	4	12.6	13	22.9	91.2	91.4	162.1	337.3	141.7	1.6	5.6
2020-21	2.1	11.5	0	16.6	52.1	180.9	157.6	252.7	238.5	419.6	8.5	0
2021-22	14.6	0	1.9	5	52	106.2	292.6	118	224	129	14.4	0.3
2022-23	0	44.9	88.6	95.1	78.9	369.3	94.5	198	135.8	0.4	12.3	0.1
2023-24	0	0.5	0	22.4	54.1	129.5	225.4	68.3	248.6	10.2	12.8	0

**Table 7.6: monthly rainfall distribution of Hyderabad (2000-01 to 2022-23)**

Source: Telangana Development Planning society



**Graph 7.6: Mean Monthly Rainfall distribution (2000-01 to 2023-24)**

Monthly rainfall distribution analysis was carried out to examine the inter annual pattern of the rainfall and to identify the months contributing most significantly to the annual precipitation during the study period of 2000-01 to 2023-24. Understanding the monthly rainfall distribution is essential for analysing the spatial behaviour, seasonal dependence and the timing of the hydrological extremes.

The mean monthly rainfall pattern of the study area is revealing a highly uneven distribution of rainfall across the year. There is a strong concentration during the southwest monsoon months, rainfall during the June to September dominate the annual total confirming the monsoon driven nature of the precipitation in the study area.

All month of August records the highest mean rainfall followed by the September and July. It is indicating that peak rainfall occurs during the mature phase of the southwest monsoon. June marks the onset of the monsoon and shows a substantial increase in the rainfall compared to the pre monsoon months while rainfall begins to decline after September.

The pre monsoon months that is March to May receive comparatively low rainfall. Although occasional convective rainfall events are observed to particularly during the April and May. These rains are irregular and highly variable which is contributing only marginally it to the annual rainfall total.

The post monsoonal months of October shows moderate mean rainfall reflecting the influence of the retreating monsoon system and occasional cyclonic disturbances. In contrast the November to February months are predominantly dry months where there is a minimum range for contribution which is indicating a prolonged dry season.

Overall the monthly rainfall distribution demonstrate a strong seasonal concentration where the majority of the rainfall is confined up to the few months of monsoon. This uneven temporal distribution is increasing the vulnerability to the both floods during the peak monsoon months and the water stress during the extended dry periods.

### 7.7 Seasonal Rainfall Characteristics

Seasonal rainfall characteristics are analysed to understand the contribution and variability of different seasons and the role in shaping the annual rainfall regime of the study area. Based on the climatological classification relevant to the Indian monsoon system, the rainfall was grouped into 4 seasons winter, summer or pre monsoon, southwest monsoon and North East monsoon or post monsoons

Year	Winter	Summer	SWM	NEM
2000-01	11	71	863	25
2001-02	11	82	588	142
2002-03	7	39	471	96
2003-04	30	130	530	169
2004-05	0	0	442.3	72.5
2005-06	0	159.6	795	221.7
2006-07	0	0	627.4	49.1
2007-08	56.7	159.4	694.8	42
2008-09	0	29.2	863.9	79.2
2009-10	11	25.4	543.6	108.7
2010-11	26.3	8.3	880.9	101.3
2011-12	0.1	19.7	500.2	64.6
2012-13	21	70.6	656.5	138.9
2013-14	0.1	111.5	671.9	257.4
2014-15	0	139.6	381.8	66.5
2015-16	0.8	156.5	499.2	79.6
2016-17	0	72.2	885.5	54.4
2017-18	0	100	774.1	250.1

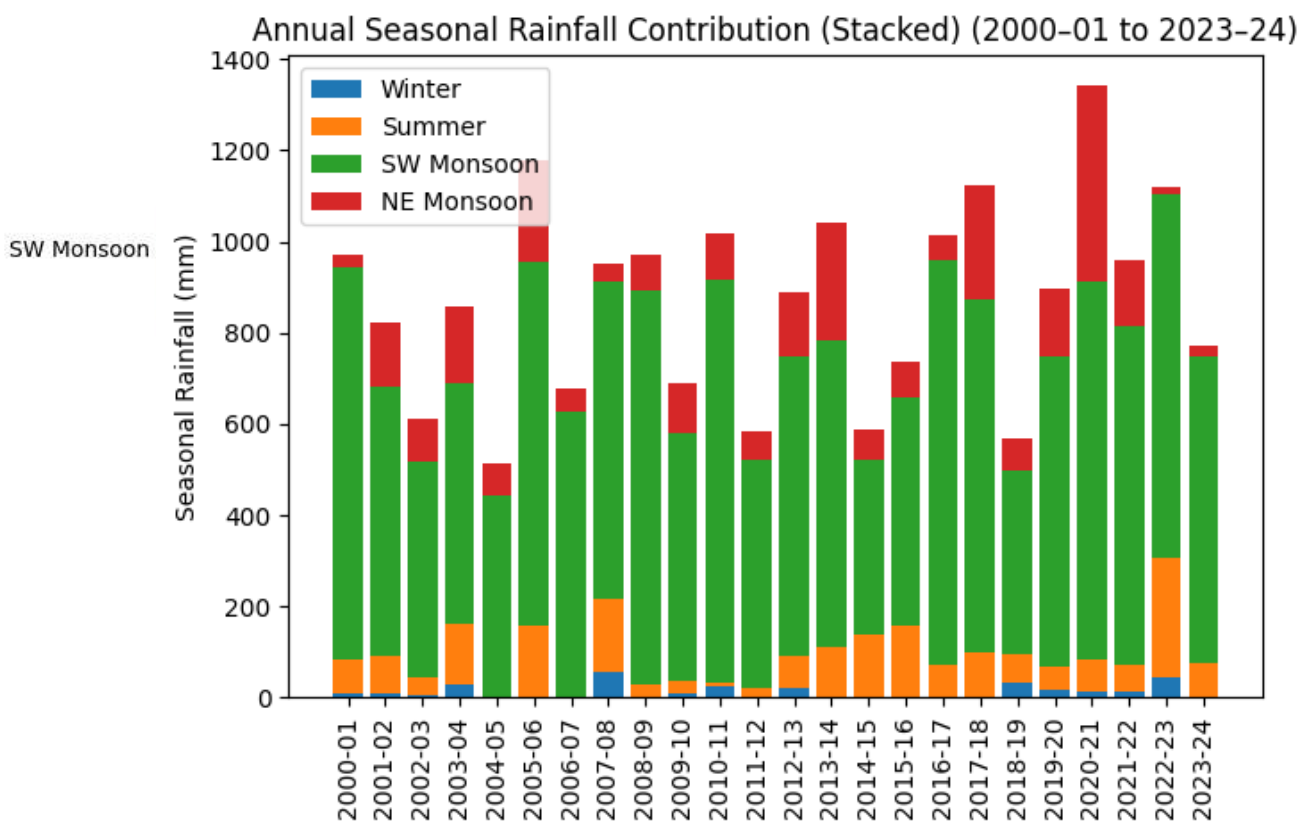
2018-19	32.2	64.7	401.7	70.6
2019-20	18.3	48.5	682	148.8
2020-21	13.6	68.7	829.7	428.1
2021-22	14.6	58.9	740.8	143.7
2022-23	44.9	262.6	797.6	12.8
2023-24	0.5	17.6	830.7	23.0

Table 7.7: Annual seasonal Rainfall of Hyderabad

Source: Telangana Development Planning Society

**Graph 7.7: Pie chart on the Average Seasonal Contribution to Annual Rainfall**

Average Seasonal Contribution to Annual Rainfall (2000–2024)



Graph 7.7a: Bar graph on seasonal rainfall contribution (2000-01 to 2022-24)

The seasonal rainfall data is clearly demonstrating the dominant influence of the southwest monsoon on the annual rainfall regime. Across most of the year's southwest monsoon accounts for large share of the total annual rainfall which is conforming the monsoon dependency nature of the precipitation in the study area. In several years, the southwest monsoon rainfall is exceeding normal level, excess rainfall years identified in the earlier analysis during 2000-01, 2008-09, 2010-2011, 2016-17 and 2020-21.

The summer or pre monsoon season is contributing to a comparatively smaller but non negligible portion of annual rainfall. Summer rainfall shows higher interannual variability which is ranging from negligible values in some years Eg., 2004-05, 2006-07) to substantial contributions exceeding 150-250mm as observed in 2015-16 and 2022-23. This is reflecting the irregular and convective nature of the pre monsoon rainfall in the study area.

The North East monsoon season is contributing a moderate share of rainfall with marked year to year fluctuations. Certain years such as 2013-14, 2017-18 and 2020-21 record exceptionally high North East monsoon rainfall which is highlighting the role of retreating monsoon systems, cyclonic disturbances on the study area. In contrast very low northeast monsoon rainfall in the year such as 2022-23 is indicating a weak post monsoon activity.

The winter season is contributing the least to the annual rainfall winter rainfall which remains minimal and sporadic throughout study. Where it is often below 20 to 30 millimetres. This is reinforcing the presence of the long dry season and limited influence of the western disturbances in the study area.

The season wise analysis is revealing a considerable interannual variability particularly observed in the Southwest monsoon and North East monsoon seasons. The years with above normal rainfall are closely associated with enhanced southwest monsoon rainfall whereas the deficit years are coinciding with the weak monsoon performance. This confirms that the annual rainfall anomalies are primarily controlled by southwest monsoon variability.

The North East monsoon season is exhibiting a greater relative variability compared to its mean rainfall. In some years strong North East monsoon rainfall partially compensates for the weak southwest monsoon rainfall as observed in 2003-04 and 2013-14. It is also observed that in the other years it contributed minimally. Such inconsistency increases uncertainty in the water availability especially during the post monsoonal period.

Summer rainfall is also showing a high variability acting as supplementary rainfall source in certain years. However its contribution is insufficient to offset the major monsoon deficits which is underlining the dominant role of southwest monsoon rainfall.

There is a notable feature emerging from the seasonal rainfall analysis is the increasing concentration of rainfall within the southwest monsoon and North East monsoon seasons particularly during the recent years. Enhanced North East monsoon rainfall in the years such as 2020-21 is suggesting a tendency towards late season rainfall intensification which may be linked to increased cyclonic activities and changing monsoon withdrawal patterns.

At the same time the occurrence of seasons with relatively lower southwest monsoon rainfall but higher North East monsoon or summer rainfall is indicating an inter annual redistribution of rainfall. Rainfall redistribution has important hydrological implications as intense rainfall concentrated in few months is increasing flood risk, will reduce effective groundwater recharge.

The strong dominance of southwest monsoon rainfall combined with inter annual, inter season and variability is highlighting the vulnerability of the study area to both monsoon failures and extreme rainfall events. The excessive rainfall during the southwest monsoon and North East monsoon season can trigger the urban flooding while the prolonged dry condition outside these seasons is intensifying the water stress.

Overall the seasonal rainfall characteristics are indicating a transition towards the more erratic and uneven seasonal rainfall regime, which in turn raising concerns related to climate variability. These findings underscore the need for seasonal specific water management strategies and climate resilient urban planning.

## 8. Discussion

The analysis of temperature and rainfall variability in Hyderabad from 2000 to 2024 reveals a clear pattern of asymmetric thermal change accompanied by increasing hydro-climatic instability. The findings suggest that the city is undergoing a gradual transition toward an urban-modified climatic regime, driven by both rapid urbanisation and broader monsoon variability.

### 8.1 Emerging Pattern of Nocturnal Warming

One of the most striking outcomes of the study is the statistically significant rise in annual average minimum temperature (+0.45 °C per decade), while maximum temperature exhibits no statistically significant long-term increase. This contrast reflects asymmetric warming, where night-time temperatures increase more rapidly than daytime temperatures. Such behaviour is consistent with intensified urban heat island processes. Hyderabad has experienced rapid expansion of built-up surfaces, reduction of vegetative cover, densification of infrastructure, and increased anthropogenic heat release over the past two decades. These transformations enhance heat storage during the day and slow radiative cooling at night, leading to elevated minimum temperatures. The statistically significant decline in diurnal temperature range (−0.59 °C per decade) reinforces this interpretation. A shrinking DTR suggests progressive thermal homogenisation, reduced nocturnal cooling efficiency, and growing dominance of urban surface energy balance processes. Importantly, the absence of significant daytime warming indicates that urbanisation is influencing nocturnal thermal regimes more strongly than daytime heating intensity. From a human perspective, nocturnal warming is particularly concerning. Elevated night-time temperatures reduce physiological recovery from daytime heat stress, increase cooling energy demand, and heighten vulnerability during heat waves. Thus, even without strong daytime warming, the city faces increasing thermal stress.

### 8.2 Rainfall Behaviour: Variability over Monotonic Change

In contrast to temperature, annual rainfall does not show a statistically significant long-term monotonic trend, despite a positive Sen's slope. The Mann–Kendall results confirm that the apparent increase is largely driven by a few extreme wet years rather than systematic intensification. However, the absence of a significant linear trend does not imply climatic stability. The rainfall series is characterised by pronounced interannual variability, a moderate coefficient of variation, and a high frequency of extreme wet and dry years. Nearly half of the study years fall under the extreme wet category, while over one-fifth represent extreme dry conditions. This alternating pattern of floods and droughts within short intervals indicates rainfall volatility rather than gradual change. The exceptional wet year of 2020–21 followed by sharp deficits illustrates the growing unpredictability of the hydro-climatic system. Seasonal analysis further highlights the dominant control of the Southwest Monsoon on total annual rainfall. At the same time, Northeast Monsoon contributions show considerable year-to-year fluctuations, and late-season rainfall intensification appears more frequent in recent years. Such redistribution of rainfall across seasons may increase both flood risk (through short-duration high-intensity rainfall) and dry-season water stress.

### 8.3 Urbanisation and Climatic Modification

The combined thermal and rainfall evidence suggests that Hyderabad is experiencing a dual climatic process:

1. Statistically robust urban-induced nocturnal warming.
2. Episodic but intensifying rainfall variability.

Urban expansion modifies land-atmosphere interactions by reducing evapotranspiration, increasing impervious surfaces, altering albedo, and enhancing heat storage capacity. These changes primarily affect thermal behaviour, particularly night-time conditions. Rainfall, in contrast, remains largely controlled by regional monsoon dynamics. However, urban surfaces amplify the impacts of rainfall extremes by accelerating runoff, reducing infiltration, and increasing flood vulnerability. Therefore, while rainfall trends may not be statistically significant, their socio-environmental impacts are becoming more severe. The coexistence of nocturnal warming and rainfall volatility suggests increasing compound climate risk, where heat stress and hydrological extremes interact within a densely urbanised environment.

## 9. Conclusion

This study provides an integrated assessment of temperature asymmetry and rainfall variability in Hyderabad over a 25-year period (2000–2024), contributing to a more comprehensive understanding of urban climate dynamics.

The major conclusions are as follows:

- a. Annual minimum temperature shows a statistically significant increase of +0.45 °C per decade, indicating intensified nocturnal warming.
- b. Maximum temperature does not exhibit a statistically significant long-term increase.
- c. Diurnal Temperature Range has declined significantly (−0.59 °C per decade), confirming progressive thermal homogenisation.
- d. Annual rainfall does not display a statistically significant monotonic trend.
- e. Rainfall variability is increasing, with frequent extreme wet and dry years.
- f. Southwest Monsoon remains the dominant rainfall contributor, but interannual and seasonal redistribution is becoming more pronounced.

Overall, Hyderabad is transitioning toward an urban-modified climate characterised by enhanced night-time heat retention and episodic hydro-climatic extremes. The findings indicate that climatic change in the city is expressed more strongly through asymmetry and variability than through uniform linear trends.

From a planning perspective, the results emphasise the urgent need for: Urban heat mitigation strategies (green cover restoration, cool roofs, reflective materials), Flood-resilient infrastructure and stormwater management, Integrated drought-flood water management systems, Climate-sensitive urban planning frameworks. Future research should incorporate high-resolution spatial datasets, land use change analysis, and urban climate modelling to disentangle local urbanisation effects from broader regional climate variability.

## References

1. Allan, R. P., & Soden, B. J. (2008). Atmospheric warming and the amplification of precipitation extremes. *Science*, 321(5895), 1481–1484. <https://doi.org/10.1126/science.1160787>
2. Arnfield, A. J. (2003). Two decades of urban climate research: A review of turbulence, exchanges of energy and water, and the urban heat island. *International Journal of Climatology*, 23(1), 1–26. <https://doi.org/10.1002/joc.859>
3. Dash, S. K., Kulkarni, M. A., Mohanty, U. C., & Prasad, K. (2007). Changes in the characteristics of rain events in India. *Journal of Geophysical Research: Atmospheres*, 112(D10), D10109. <https://doi.org/10.1029/2006JD007417>
4. Donat, M. G., Alexander, L. V., Yang, H., Durre, I., Vose, R., & Caesar, J. (2013). Updated analyses of temperature and precipitation extreme indices since the beginning of the twentieth century: The HadEX2 dataset. *Journal of Geophysical Research: Atmospheres*, 118(5), 2098–2118. <https://doi.org/10.1002/jgrd.50150>
5. Easterling, D. R., Horton, B., Jones, P. D., Peterson, T. C., Karl, T. R., Parker, D. E., ... Folland, C. K. (1997). Maximum and minimum temperature trends for the globe. *Science*, 277(5324), 364–367. <https://doi.org/10.1126/science.277.5324.364>
6. Goswami, B. N., Venugopal, V., Sengupta, D., Madhusoodanan, M. S., & Xavier, P. K. (2006). Increasing trend of extreme rain events over India in a warming environment. *Science*, 314(5804), 1442–1445. <https://doi.org/10.1126/science.1132027>
7. Hajat, S., & Kosatky, T. (2010). Heat-related mortality: A review and exploration of heterogeneity. *Epidemiology*, 21(6), 753–760. <https://doi.org/10.1097/EDE.0b013e3181f1d9c5>
8. Intergovernmental Panel on Climate Change (IPCC). (2021). *Climate change 2021: The physical science basis*. Cambridge University Press.
9. Kalnay, E., & Cai, M. (2003). Impact of urbanization and land-use change on climate. *Nature*, 423(6939), 528–531. <https://doi.org/10.1038/nature01675>
10. Kotharkar, R., & Surawar, M. (2016). Land use–land cover changes and urban heat island in Nagpur city, India. *Urban Climate*, 17, 189–206. <https://doi.org/10.1016/j.uclim.2016.04.005>

11. Kotharkar, R., Bagade, A., & Ramesh, A. (2018). Urban climate studies in India: A review. *Urban Climate*, 24, 317–333. <https://doi.org/10.1016/j.uclim.2017.12.003>
12. Murari, K. K., Ghosh, S., Patwardhan, A., Daly, E., & Salvi, K. (2019). Intensification of future severe heat waves in India and their effect on heat stress and mortality. *International Journal of Climatology*, 39(9), 3753–3764. <https://doi.org/10.1002/joc.6042>
13. Oke, T. R. (1982). The energetic basis of the urban heat island. *Quarterly Journal of the Royal Meteorological Society*, 108(455), 1–24. <https://doi.org/10.1002/qj.49710845502>
14. Roy, M. (2009). Planning for sustainable urbanisation in India: Challenges and prospects. *Habitat International*, 33(1), 76–85. <https://doi.org/10.1016/j.habitatint.2008.07.004>
15. Roxy, M. K., Ghosh, S., Pathak, A., Athulya, R., Mujumdar, M., Murtugudde, R., ... Rajeevan, M. (2017). A threefold rise in widespread extreme rain events over central India. *Nature Communications*, 8, Article 708. <https://doi.org/10.1038/s41467-017-00744-9>
16. Santamouris, M. (2015). Regulating the damaged thermostat of the cities—Status, impacts and mitigation challenges. *Energy and Buildings*, 91, 43–56. <https://doi.org/10.1016/j.enbuild.2015.01.027>
17. Shepherd, J. M. (2005). A review of current investigations of urban-induced rainfall and recommendations for the future. *Atmospheric Research*, 74(1–4), 145–162. <https://doi.org/10.1016/j.atmosres.2004.12.012>
18. Trenberth, K. E., Dai, A., Rasmussen, R. M., & Parsons, D. B. (2014). The changing character of precipitation. *Climate Research*, 47(1–2), 123–138. <https://doi.org/10.3354/cr00953>
19. Vose, R. S., Easterling, D. R., & Gleason, B. (2005). Maximum and minimum temperature trends for the globe: An update through 2004. *Geophysical Research Letters*, 32(23)\*, L23822. <https://doi.org/10.1029/2005GL024379>
20. Zhao, L., Lee, X., Smith, R. B., & Oleson, K. (2014). Strong contributions of local background climate to urban heat islands. *Environmental Research Letters*, 9(11)\*, 114002. <https://doi.org/10.1088/1748-9326/9/11/114002>
21. Zhou, D., Zhao, S., Liu, S., Zhang, L., & Zhu, C. (2019). Surface urban heat island in China's 32 major cities: Spatial patterns and drivers. *Remote Sensing of Environment*, 232, 111286. <https://doi.org/10.1016/j.rse.2019.111286>

**Copyright & License:**

© Authors retain the copyright of this article. This work is published under the Creative Commons Attribution 4.0 International License (CC BY 4.0), permitting unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.