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Spatial and temporal variations of temperature and rainfall, and land use/land cover changes in the Bengaluru urban district

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सार – सतत विकास लक्ष्य (एसडीजी) 11 **'टिकाऊ शहरों और समुदायों' पर केंद्रित है। यह पत्र** 1980 **से** 2022 **तक वर्षा और तापमान में स्थानिक और लौकिक परिवर्तनों और** 1992 **से** 2022 **के बीच बेंगलुरु शहरी जिले में भूमि उपयोग और भूमि कवर (एलयूएलसी) प्रस्तुत करता है। यह अध्ययन वार्षिक, मासिक और मौसमी स्तरों पर मौसम डेटा पैटर्न के महत्व का मूल्यांकन करने के लिए रैखिक प्रतिगमन और गैर-पैरामीट्रिक संशोधित मान-केंडल तकनीकों का उपयोग करता है। निष्कर्षों से औसत अधिकतम तापमान में कमी और न्यूनतम तापमान में वृद्धि का पता चलता है, जो ठंडे दिन और गर्म रातें दर्शाता है। मौसमी वर्षा भी** 40 **वर्षों की अवलोकन अवधि में अध्ययन क्षेत्र में बढ़ती प्रवृत्ति प्रदर्शित करती है। यह विश्लेषण बेंगलुरु के परिदृश्य में एक महत्वपूर्ण परिवर्तन को इंगित करता है, जिसमें बेंगलुरु के आसपास तेजी से हो रहे शहरीकरण और उसके परिणामस्वरूप भूमि-उपयोग में बिना पर्याप्त योजना और उनके पर्यावरणीय और जलवायु प्रभावों का आकलन किए हुए परिवर्तन के कारण जल निकायों, वनस्पति और बंजर भूमि की कीमत पर निर्मित क्षेत्र बढ़ रहे हैं। हालाँकि यह अध्ययन बेंगलुरु पर आधारित है, लेकिन लेकिन इस अध्ययन में इस्तेमाल की गई विधि को एसडीजी** 11 **की उपलब्धि में योगदान देने के लिए अन्य मेगासिटीज़ तक विस्तारित किया जा सकता है।**

ABSTRACT. Sustainable Development Goal (SDG) 11 focuses on ‘Sustainable Cities and Communities.’ This paper presents the spatial and temporal changes in rainfall and temperature from 1980 to 2022 and Land Use and Land Cover (LULC) in the Bengaluru urban district between 1992 and 2022. This study employs linear regression and non-parametric Modified Mann-Kendall techniques to evaluate the importance of weather data patterns at yearly, monthly, and seasonal levels. The findings reveal a decrease in mean maximum temperature and an increase in minimum temperature, indicating cooler days and warmer nights. Seasonal rainfall also exhibits an increasing trend in the study area over the observation period of 40 years. To quantify some of the key reasons for these microclimate changes, LULC analysis was conducted over 30 years (1992-2022). This analysis indicates a substantial transformation in Bengaluru's landscape, with built-up areas growing at the expense of water bodies, vegetation, and fallow landdue to the rapid urbanization around Bengaluru and the consequent land-use alterations without adequate planning and assessing their environmental and climate impacts. While this study is based in Bengaluru, the method used in this study can be expanded to other megacities to contribute to the achievement of SDG 11.

Key words – Temperature, Rainfall, LULC, Urbanization.

1. Introduction

Urbanization is a critical step in the growth of a country. Global urbanization has increased dramatically during the last few decades.The proportion of the global population that lives in cities is expected to increase from 55% in 2018 to 68% by 2050 (Zhang *et al.*, 2022). India's urban population is expected to expand significantly by the end of 2050, accounting for 34% of the population (Gohain *et al.*, 2021). Cities are growing outside their existing boundaries to accommodate this population growth, putting pressure on the region's natural resources by replacing marshes, plant life, and agricultural lands. Therefore, it is vital to comprehend how urbanization affects the environment (*e.g.*, temperature, rainfall, air and water quality and vegetation), especially in developing nations where the rate of urbanization is rapidly increasing and generally understudied (Bai *et al.*, 2018; Malik *et al.*, 2020).

Li *et al.* (2022) found that rapid urbanization in China's Yangtze River Delta zone led to increased temperatures, decreased wind speeds in cities, and changes in air pollutant concentrations. Following the 6[th] Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC), the human-induced global surface temperature rise between the period 1850-1900 and 2010-2019 ranged from 0.8 to 1.3 degrees Celsius in the 21[st] century (2001-2020). The increase in greenhouse gases (GHGs) in the atmosphere, attributed to human activities, has raised the global temperature by just over 1℃ since the pre-industrial era.Unplanned urbanization has led to noticeable outcomes such as rising greenhouse gas, depletion of groundwater levels (~28 to ~300 meters), water pollution, higher land surface temperatures, and a surge in a proliferation of disease-carrying organisms, among various other challenges (Ramachandra *et al*., 2019).

Numerous research are being performed to understand better the connection between LULC changes and the local climate (Jiang *et al*., 2014; Pitman *et al*., 2012).Urbanization-induced changes in land use alter local hydrometeorological processes, modify the microclimate of urban areas, and can even have a notable impact on precipitation patterns (Pathirana *et al*., 2014). Urbanization has altered both natural and semi-natural landscapes into impermeable urban structures, altering the equilibrium of radiation and energy on the surface of the Earth (Yu *et al*., 2019).

Ramachandra *et al*. (2019) have focused on the implications of unplanned growthin Bengaluru city, specifically examining prime growth poles like Peenya Industrial Estate (PIE), Whitefield (WF) and Bangalore South Region (BSR). Their research reveals a decline in vegetation and open spaces due to intense urbanization in these areas. Tahir *et al*. (2015) examined the influence of urban growth on the microclimate of Abbottabad, Pakistan, spanning 50 years.They have investigated shifts in temperature and rainfall patterns to establish a correlation between urbanization and alterations in mean temperature and rainfall over various timeframes. Nelson *et al.* (2009) investigated the combined effects of urbanization and climate change on stream ecosystems, which included an analysis of temperature and precipitation patterns.Shashua-Bar *et al.* (2010) conducted microclimate modelling to assess the effects of street tree species on urban morphology and climate in the Mediterranean city of Tel Aviv. These studiescontribute to understanding how urbanization influences microclimate, temperature and rainfall patterns in various regions.

Urbanization leads to significant shifts in land use and land cover (LULC), which are crucial for understanding land surface dynamics and their impact on regional and global meteorology. Changes in LULC influence climate patterns, boundary evolution and rainfall, raising concerns about human-induced effects on global climate and the environment (Sussman *et al*., 2019; Kedia *et al*., 2021; Kilic *et al*., 2006).Changesin LULC between urban and rural surfaces can influence energy flux by boosting surface and near-surface temperatures and decreasing the amount of moisture accessible, altering the surface's albedo (Yang *et al*., 2017). Such changes can potentially alter the properties of clouds, the frequency of heat and cold waves and patterns in rainfall (Mohan and Kandya *et al*., 2015). LULC variations substantially impact weather and climate and their effects can be seen in various indices such as temperature, rainfall, wind circulations and the underlying surface fluxes (Gogoi *et al*., 2019). Yao *et al*. (2015) reported that replacing green cover and cropland with built-up areas reduces surface albedo and soil moisture, impacting regional meteorological variables such as surface air temperatures, wind patterns, and rainfall patterns.Kedia *et al*. (2021) and Prijith *et al.* (2021) document the impact of LULC variations on surface meteorology and urban heat islands in eight urban cities of northwest India.The findings reveal, among other things, a significant increase in surface temperature (3-5°C) and a drop in relative humidity (RH)in newly developed metropolitan areas. Gohain *et al*. (2021) and Kharol *et al*. (2013) have also documented the decline in the vegetation, water bodies, and fallow land components in their LULC studies conducted in Pune and Rajasthan, respectively.

Bengaluru's rapid urbanization has resulted in several urban environmental challenges, including decreasing waterbodies, higher vehicular congestion, high levels of air pollution, instances of flooding following heavy rains, and an upsurge in summer temperatures (Ramachandra & Kumar, 2010). They detected a 2-2.5°C spike in temperature accompanied by a 76% drop in foliage cover and a 79% shrink in bodies of water. Further, replacing green vegetated land surfaces with impermeable surfaces creates urban heat islands. (Sussman *et al*., 2019).

Numerous studies in Bengaluru have examined the impact of land use and land cover (LULC) changes on land surface temperature (LST).Keerthi Naidu and Chundeli (2023) employed simple linear and geographic weighted regression techniques to analyze the relationship between LULC changes in Bengaluru and their effects on LST. Their findings indicated that the city's minimum temperature rose from 16°C in 2003 to 21°C in 2021, while the average LST increased from 26°C in 2003 to 29°C in 2021. Siddiqui *et al*. (2021) conducteda study from 2006 to 2016 to compare various image indices, including vegetation, built-up index and impervious surface area (ISA) as Surface Urban Heat Island (SUHI)

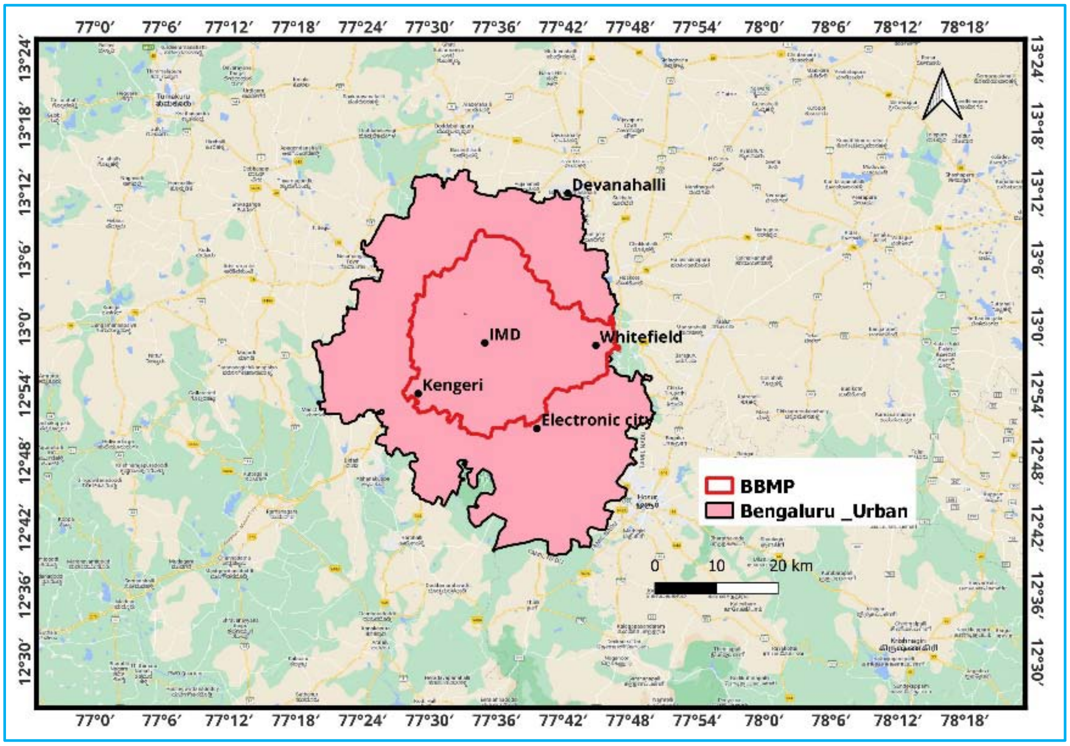


Fig. 1. Location of the study area

indicators in Bengaluru. Their results demonstrate a strong negative linear association between LST and ISA fraction, with a correlation coefficient of more than 0.8, indicating surface urban heating driven by decreased evapotranspiration, low albedo and shifts in both latent and sensible heat fluxes. Govind and Ramesh (2019) used remote sensing data to study the spatio-temporal pattern of LULC and LST and their interplay in Bengaluru, India, from 1989 to 2017. The findings of this analysis indicate that (a) the most significant LULC variations witnessed in this city are caused by an upsurge in urban areas and (b) LST trends across various land use classes show a consistent increase, with the average LST of urban areas rising by 8 degrees Celsius over 28 years. Several studies utilizing Weather Research and Forecasting Model (WRF) models have also explored the influence of LULC changes on temperature, rainfall, and humidity (Bhimala *et al.*, 2021).

However, the impact of urbanization on Bengaluru's LULC and microclimate must continue to be assessed continually since urbanization is continuing unabated. Specifically, research into the long-term effects of urbanization on LULC patterns and climatic variables such as temperature and rainfall is crucial. The present study combines meteorological data obtained from the National Centre for Medium-RangeWeather Range Forecast (NCMWRF) with LULC data derived from Landsat satellite images. This integration allows for a comprehensive analysis of the relationship between meteorological parameters and LULC dynamics. The analysis was carried out for more than 40 years (1980 to 2022).

The primary goals of this study are to explore the:

(*i*) Shifts in key weather parameters in Bengaluru Urban district between 1980 and 2022 (42 years).

(*ii*) Effect of urbanization on LULC in the Bengaluru Urban district between 1992 and 2022 (30 years).

2. Study area

The study area covers the Bengaluru urban district, which spans around 2200 km^2 (Fig. 1) and has an average elevation of 920 m above mean sea level. Five different places were chosen to explore the different microclimate influences: the IndiaMetrological Department Observatory (IMD-Bengaluru), Devanahalli, Electronic City, Kengeri and Whitefield.

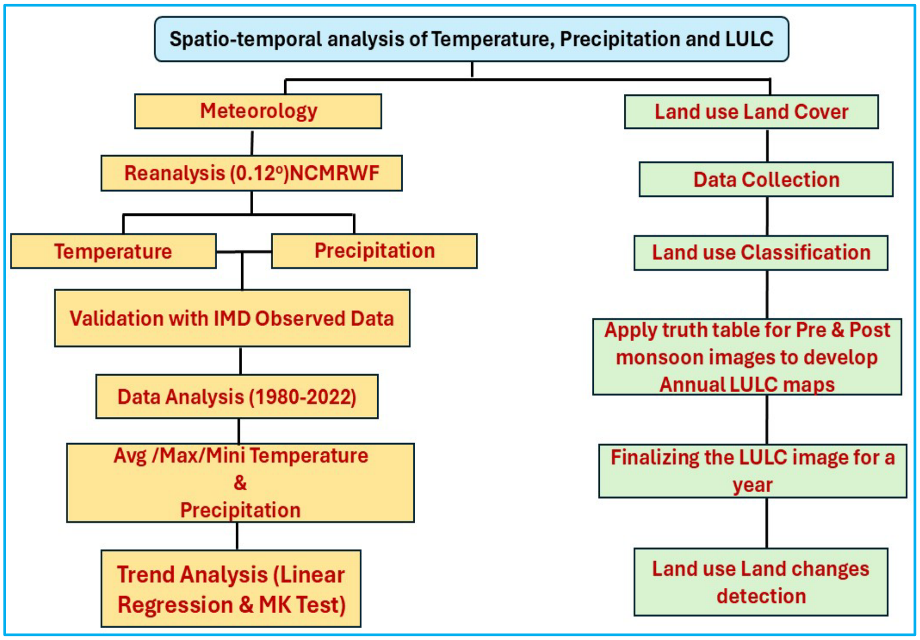


Fig. 2. Flowchart illustrating the methodology applied in the current study

3. Methodology

3.1. *Meteorological data*

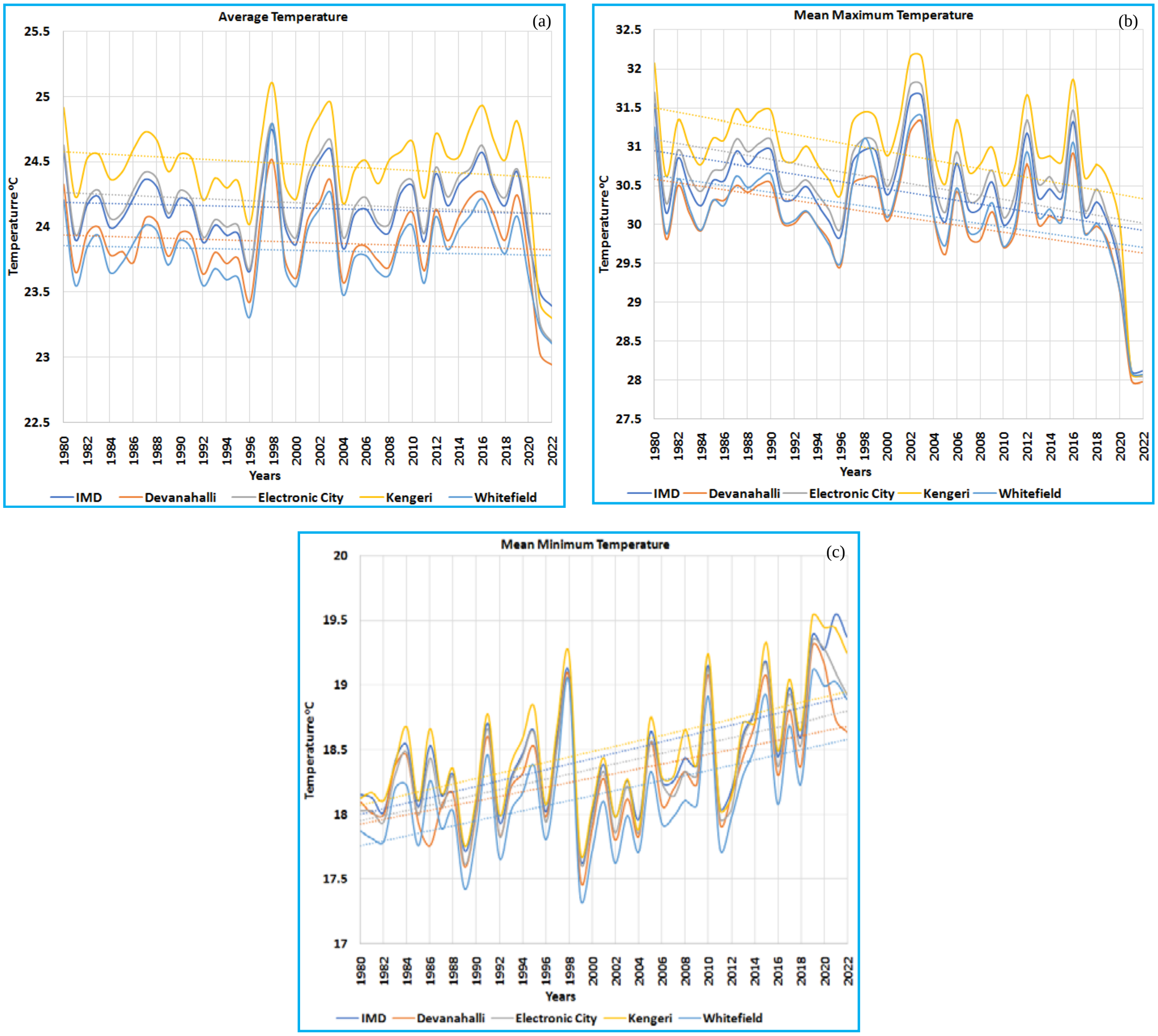
The IMDAA reanalysis is produced by the National Centre for Medium-Range Weather Forecasting (NCMRWF) and the India Meteorological Department (IMD), with funding from the National Monsoon Mission project funded by the Ministry of Earth Sciences in the Government of India (Rani *et al.*, 2021). This data website portal includes (1) IMDAA Data - high resolution (12 km, 1-hourly) and (2) NGFS Data - high resolution (25 km, 6-hourly) regional reanalysis across India (NCMRF, 2024). In this study, we used IMDAA reanalysis data to collect a dataset of meteorological characteristics such as temperature and precipitation from the IMDAA-1 hourly single-level dataset with a 12 km resolution. The data were downloaded from the NCMRWF portal for the period January 1980 to December 2022 in the form of shell script files.The shell script files are extracted using GITBASH and the data is then downloaded in nc (netCDF) format. A Python script is subsequently used to convert the nc files into csv format.

Daily temperature data is analysed using hourly temperature readings. The average temperature for each day is calculated by taking the mean of the hourly temperature values. The daily maximum temperature is the highest value recorded among these hourly data points, while the daily minimum temperature is the lowest recorded value. To determine the monthly average temperature, all daily average temperatures are averaged across the month. The mean monthly maximum temperature is computed by averaging all daily maximum temperatures for the month, and similarly, the mean monthly minimum temperature is calculated using the daily minimum values. For annual figures, the average temperature for the year is found by averaging the 12 monthly averages. Likewise, the annual mean maximum and minimum temperatures are determined by averaging the respective monthly values over the year (Fig. 2).

To check for data consistency, we conducted a correlation analysis of the temperature and rainfall recorded in the IMD observatory data with the data collected from the NCMWRF grid in which IMD-Bengaluru is located data. The correlation for average temperature, maximum temperature and minimum temperature was found to be 0.62,0.42 and 0.72, respectively. The correlations of average temp and minimum temperature extracted from the two dataset's results were significant at the 0.05 level of significance, while the correlation of maximum temperature between these two datasets was not significant. However, the correlation coefficient between the rainfall levels in these two datasets is 0.77, which is significant at the 0.05 level.

3.2. *Trend analysis*

Trend detection tests for climatological time series can be categorized into parametric and non-parametric methods. Parametric tests assume that the data are



Figs. 3(a-c). Trend analysis of Average, Mean minimum and Mean Minimum Temperature

independent and normally distributed, whereas non-parametric tests only require the data to be independent. In this study, we applied both parametric and non-parametric analyses. For the parametric approach, we used the linear regression method, while for the non-parametric approach, we employed the modified Mann-Kendall test (Gocic *et al.*, 2013).

3.3. *Linear trend analysis*

Linear regression is frequently used statistical technique to analyze trends in data across time periods. This technique is commonly employed to identify extended patterns in both seasonal and yearly rainfall data (Gadgil & Dhorde, 2005). The rate of change in each parameter is determined by the slope of the regression line. A positive slope value shows a rising trend and a negative value represents a declining trend.

3.4. *Modified Mann-Kendall Test (M-K Test)*

The long-term time series data were analysed using the non-parametric Mann-Kendall (M-K) test (Mann 1945; Kendall 1975) to find significant trends. Serial autocorrelation frequently has an impact on trend detection in time series data . The technique suggested by Shahin *et al.* (1993) and Haan (2002) was used to identify significant autocorrelations. At a confidence level of 5%, the lag-1 autocorrelation coefficient was computed and examined. For serially correlated data, having a significant

TABLE 1

Linear Trend of Monthly Temperatures (1980-2022)

Location	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average Temperaturechange (°C/month)												
IMD	***0.017***	0.003	0.007	-0.004	***-0.025***	-0.001	-0.010	***-0.016***	***-0.022***	-0.002	0.010	***0.018***
Devanahalli	0.013	-0.003	0.004	-0.006	***-0.024***	0.001	-0.008	***-0.018***	***-0.021***	-0.001	0.012	***0.019***
Electronic City	0.013	0.001	0.004	-0.007	***-0.026***	-0.002	-0.010	***-0.017***	***-0.023***	-0.003	0.008	0.014
Kengeri	0.013	0.003	0.007	-0.006	***-0.026***	-0.010	**-0.015**	***-0.020***	***-0.024***	-0.004	0.009	0.015
Whitefield	***0.017***	0.000	0.005	-0.004	***-0.023***	0.000	-0.009	***-0.016***	***-0.020***	-0.001	0.011	***0.018***
Mean Maximum Temperature change (°C/month)												
IMD	0.004	-0.007	-0.007	-0.019	***-0.053***	-0.017	***-0.044***	***-0.061***	***-0.050***	-0.017	-0.009	-0.011
Devanahalli	0.003	-0.012	-0.004	-0.014	***-0.051***	-0.014	***-0.039***	***-0.062***	***-0.046***	-0.015	-0.008	-0.008
Electronic City	0.002	-0.009	-0.007	-0.021	***-0.053***	-0.015	***-0.045***	***-0.063***	***-0.053***	-0.018	-0.013	-0.014
Kengeri	0.000	-0.010	-0.006	-0.026	***-0.055***	**-0.031**	***-0.051***	***-0.064***	***-0.054***	-0.017	-0.011	-0.012
Whitefield	0.008	-0.006	-0.003	-0.015	***-0.050***	-0.016	***-0.042***	***-0.063***	***-0.047***	-0.016	-0.008	-0.009
Mean Minimum Temperature change (°C/month)												
IMD	0.027	0.028	***0.030***	***0.021***	0.009	0.009	***0.018***	***0.018***	***0.011***	0.013	***0.034***	***0.042***
Devanahalli	0.016	0.018	0.018	0.007	0.010	0.010	***0.017***	***0.018***	***0.011***	0.013	***0.037***	***0.041***
Electronic City	0.024	0.030	0.027	***0.018***	0.008	0.008	***0.017***	***0.018***	0.010	0.011	***0.034***	***0.038***
Kengeri	0.023	0.032	0.030	***0.022***	0.009	0.005	***0.016***	***0.015***	0.011	0.010	***0.037***	***0.043***
Whitefield	0.022	0.017	0.021	***0.015***	0.011	0.010	***0.019***	***0.019***	***0.012***	0.012	***0.035***	***0.041***

Note : Bold values indicate significance at the 0.05 level.

autocorrelation coefficient, modified Mann-Kendall (MMK test) test using the Hamed and Rao, Yue and wang variance correction approach was employed. The detailed description is available in Singh *et al*., 2021. Positive and negative values of the MMK test statistics represent increasing and decreasing trends, respectively. The non-parametric Sen's slope (SS) estimator was used to quantify the trend's magnitude (true slope) (Sen 1968), where positive SS values indicate an increasing trend and negative values signify a decreasing trend.

3.5. *LULC*

Satellite remote sensing enables the creation of large-scale LULC maps, facilitating monitoring global LULC trends over extended periods (Keerthi & Chundeli, 2023). In the current study, LULC maps were prepared using Landsat (5,7 and 8) for the years 1992, 1998, 2003, 2009, 2014 and 2022 (USGS Earth Explorer). The LULC map was prepared using the unsupervised classification method, employing clustering based on ISO Data classification. Four classes were classified: water body, fallow land, vegetation and built-up. The area of each class was calculated to study land use changes. The two seasons taken into consideration for LULC categorization were pre-monsoon and post-monsoon.The data was retrieved based on the observation of the lowest atmospheric cloud cover. To establish a representative sample for a year, the two seasons were merged using a logical table facilitated through Python code. This methodology is depicted in Fig. 2.

3.6. *Accuracy Assessment*

The accuracy of a LULC map is evaluated using a confusion matrix, where rows and columns represent sample points (pixels) categorized based on actual ground data.Columns represent reference data, while rows represent classified data from satellite imagery. This matrix assesses overall map accuracy and accuracy of individual land cover classes.Accuracy is measured using the user's accuracy from classified data and the producer's accuracy from reference data. The kappa coefficient is also used to assess accuracy, determining if the confusion matrix significantly deviates from random chance (Garcia-Balboa *et al*., 2018).

TABLE 2

Linear trend analysis of seasonal temperature variations (1980-2022)

Location	Winter	Summer	Monsoon	Post monsoon
		Average Temperature		
IMD	0.011	-0.007	***-0.012***	0.004
Devanahalli	0.008	-0.008	***-0.011***	0.005
Electronic City	0.008	-0.009	***-0.013***	0.002
Kengeri	0.009	-0.009	***-0.017***	0.003
Whitefield	0.010	-0.007	***-0.011***	0.005
		Mean Maximum Temperature		
IMD	-0.006	***-0.026***	***-0.043***	-0.013
Devanahalli	-0.008	***-0.023***	***-0.040***	-0.011
Electronic City	-0.008	***-0.027***	***-0.044***	-0.015
Kengeri	-0.008	***-0.029***	***-0.050***	-0.014
Whitefield	-0.004	***-0.023***	***-0.042***	-0.012
		Mean Minimum Temperature		
IMD	***0.032***	**0.020**	***0.014***	***0.023***
Devanahalli	***0.024***	0.012	***0.014***	***0.025***
Electronic City	***0.031***	**0.018**	***0.013***	***0.023***
Kengeri	***0.032***	**0.020**	***0.012***	***0.023***
Whitefield	***0.026***	**0.016**	***0.015***	***0.024***

Note : Boldand Italic values indicate significance at the 0.05 level.

4. Results

4.1. *Trend of Average Temperature*

The average daily temperature across the five locations from 1980 to 2022 varied between 22.94°C and 24.79°C. The highest average temperature was recorded in Kengeri (24.48 °C) and the lowest average was recorded in Whitefield (23.82°C) during the last 42-year period. The mean highest and lowest temperature was observed in every location during 1998 and 2022.

According to our analysis, the average temperature decreased by 4.81%, 5.68%, 6.13%, 6.47% and 4.56% for IMD-Bengaluru, Devanahalli, Electronic City, Kengeri, and Whitefield between 1980 and 2022. The annual trend analysis of the Average temperature from 1980 to 2022 for all five locations is shown in Fig. 3(a) [Details in Supplementary Table 1(a)].

The daily average temperature recorded at the IMD-Bengaluru, Devanahalli, Electronic City, Kengeri, and Whitefield locations showed a slope of -0.002 °Cyr^{-1}, -0.002 °Cyr^{-1}, -0.004 °Cyr^{-1}, -0.004 °Cyr^{-1} and -0.002 °C yr^{-1}, respectively. This indicates a decreasing trend in temperature from 1980 to 2022. However, this trend is not statistically significant. Additionally, the non-parametric Modified Mann-Kendall (MMK) test was applied to analyze trends in average temperature (results presented in Table 4(a) of the supplementary data). The MMK test revealed that at IMD, Electronic city and Kengeri a decreasing trend and Devanahalli and Whitefield showed an increasing trend which were not statistically significant. The results of the trend analysis using both linear regression and the MMK test indicated that the average temperature trend is not statistically significant during the study period.

The study, covering a 42-year period from 1980 to 2022, recorded monthly average temperatures ranging from 19.05°C to 29.68°C. It is observed from this study that the April is the hottest month in Bengaluru in terms of average temperature, while January is the coolest. The monthly trend analysis is shown in Table 1. Monthly trend analysis of average temperature in the IMD-Bengaluru grid exhibits a declining trend (slope : -0.024 °Cyr^{-1},

TABLE 3

Correlation between Cloud Cover and Average, Maximum, Minimum Temperature

	Avg Temp	Max Temp	Min Temp
IMD	-0.15	**-0.62**	**0.82**
Devanahalli	-0.10	**-0.59**	**0.80**
Electronic City	-0.18	**-0.60**	**0.83**
Kengeri	-0.20	**-0.59**	**0.83**
Whitefield	-0.11	**-0.60**	**0.79**

Note : Bold values indicate significance at the 0.05 level.

-0.016 °C yr^{-1} and -0.020 °C yr^{-1}) during May, August and September, respectively and an increasing trend for December and January with a slope of 0.017 °C yr^{-1} and 0.016 °C yr^{-1} respectively (significant at the 0.05 level) during. Similar monthly trends are observed in others locations.

The average temperature in all locations showed a declining trend in the average temperature during the months of May, August, September and the increasing trend in the month of December are statistically significant at 95% confidence level. While there is a decreasing trend in April, July and October, these trends are not statistically significant. In the other 5 months, the average temperature increases slightly during the study period but this increase is not statistically significant. The months of May, August, and September coincide with the monsoon season which typically begins in May and continues through August and September. Another reason is the increase in cloud cover and frequent rainfall, which results in cooler temperatures. In this study, we observe a warming trend during December and January, which could be attributed to the reflection of solar radiation and the emission of terrestrial radiation scattered by aerosols and redirected back to the surface. This finding aligns with a similar trend identified by Sussman *et al*. (2021) in Bengaluru during January, December, and February, where they attributed the temperature increase to absorbing aerosols, such as black carbon, that trap and re-emit radiation, contributing to the rise in temperatures despite their reflective properties. The consistency between both studies reinforces the observed warming trend.

The India Metrological department (IMD) divides the year into four seasons for Bengaluru:Winter (December to February), Summer or Pre-monsoon (March to May), Monsoon or southwest monsoon (June to September) and Post monsoon or northeast monsoon (October to November). The summer season with an average temperature of 27.02°C at IMD-Bengalurusite was 22.60% warmer than the winter average temperature of 22.04°C. Summer had the highest average temperature at 27.02°C, followed by Monsoon (24.17°C), Post monsoon, (22.56°C) and Winter (21.47°C) for the Devanahalli. Summer exceeded winter by 22.60% during the observation period. In Electronic City,the average temperature of 26.99°C during summer, while winter had the lowest average temperature of 22.12°C. The highest average temperature recorded in Whitefield was 26.65°C during the summer, followed by 24.05°C during the monsoon, 22.54°C during the post-monsoon and 21.51°C during winter.

Table 2 shows the seasonal trend of average temperature. The trend analysis of seasonal mean temperature in various locations, including IMD-Bengaluru, Devanahalli, Electronic City, Kengeri and Whitefield reveals a significant negative trend during the monsoon season.

The analysis indicates that this trend is statistically significant only for the monsoon season, while other seasons do not exhibit significant temperature trends. So, the negative slope indicates a decreasing trend as the temperature starts to cool down with the onset of the monsoon, frequent showers and an increase in cloud cover.

4.2. *Trend of mean maximum temperature*

The mean maximum temperatures at IMD-Bengaluru, Devanahalli, Electronic City, Kengeri, and Whitefield during 1980 and 2022 are 30.43°C, 30.10°C, 30.55°C, 30.91°C and 30.17°C. The mean maximum temperature for every region was found to be highest in 2002 and lowest in 2022 in these 42 years.

The annual trend analysis of mean maximum temperature over the locations displays a declining slope of -0.024°C yr^{-1}, -0.022°C yr^{-1}, -0.025°C yr^{-1}, -0.027°C yr^{-1} and -0.022°C yr^{-1} in IMD-Bengaluru, Devanahalli, Electronic City, Kengeri and Whitefield [Fig. 3(b) [Details in Supplementary Table 2(a)]. The decline in mean maximum temperatures over the 42-year period shows a statistically significant downward trend at a rate of -0.02°C per year.We observe a sharp decline in mean maximum temperatures over the past 3-4 years, this can be explained by increased cloud cover and rainfall during this period. This reduction in maximum temperatures may be attributed to increased cloud cover and other local climatic factors.Additionally, a trend analysis using the Modified Mann-Kendall (MMK) test for mean maximum temperatures across all locations was conducted [results presented in Table 4(a) of the supplementary data]. The

TABLE 4

Accuracy assessment of LULC classified map over Bengaluru for 1992, 1998, 2003, 2009, 2014 and 2022

Year	Producer accuracy				User Accuracy				Overall accuracy	Kappa Coefficient
	WB	UB	Veg	FL	WB	UB	Veg	FL		
1992	100	100	85	65	100	72	68	96	84	0.51
1998	92	100	80	69	92	84	80	80	84	0.51
2003	96	100	91	73	96	80	80	96	88	0.54
2009	96	100	96	71	92	76	88	96	88	0.54
2014	96	100	87	71	88	92	80	88	87	0.54
2022	96	96	92	85	96	96	88	88	92	0.58
Average	96	99	88	72	94	83	81	91	87	0.54

results revealed a statistically significant decreasing trend, with a slope of -0.02°C per year.The result showing a daytime decrease in temperature confirms findings from earlier published studies on Bengaluru.Siddiqui *et al.* (2021) have published a paper entitled "Bangalore : Urban heating or Cooling", based on the study of Land surface temperature (LST), Normalized difference vegetation index (NDVI), Normalized difference built-up index (NDBI) and the fraction of impervious surface area (ISA) during the period 2006-2016.They have concluded that daytime LST in Bengaluru exhibit a negative Surface Urban Heat Island Effect (SUHI). This phenomenon may seem counterintuitive, but it suggests that factors such as increased vegetation cover, shading from buildings, and other localized cooling measures can sometimes offset the expected decrease in daytime temperatures. Similarly, a study by Govind and Ramesh *et al.* (2019) on the impact of spatiotemporal patterns of land use, land cover and land surface temperature on an urban cool island in Bengaluru also found that lower land surface temperatures (LST) were observed in the central urban area, which was cooler than the surrounding regions.

The average maximum temperature for each month indicates that April experienced the highest mean maximum temperature, while November had the lowest mean maximum temperature across all observation sites. The highest (lowest) maximum mean temperatures are 34.77(27.86) °C, 34.51(27.27) °C, 34.83(28.06), 35.22(27.46) °C and 34.48(27.42) °C for IMD-Bengaluru, Devanahalli, Electronic City, Kengeri and Whitefield respectively. The highest mean maximum temperatures were 24.84%, 26.55%, 24.14%, 23.72% and 28.46% higher than the lowest mean maximum temperature. Table 1 shows the monthly mean maximum temperature from 1980 to 2022. Monthly trend analysis of mean maximum temperature at all the locations shows a negative trend in the months of May, July, August, and September, respectively, which is statistically significant at 0.05 level. While the trends in other months are not statistically significant, they also showed a decreasing trend. The monsoon's arrival during those months, which caused the temperature to drop, may be partially responsible for the declining tendency.

The seasonal mean maximum temperature shows the maximum temperature in summer, followed by winter and the monsoon and reaching a minimum in the post-monsoon for all the locations. For the IMD-Bengalurugrid, summer experienced the highest value (34.21°C) and post-monsoon had the lowest (27.96 °C). In Devanahalli, the summertime temperature was 33.94°C, which was 22.35% higher than the post-monsoon minimum of 27.53°C. The mean maximum temperatures of Electronic City are observed to be 34.28°C, 29.96°C, 29.44°C, and 28.11°C during the summer, winter, monsoon, and post-monsoon seasons, respectively. A consistent pattern was observed in Kengeri and Whitefield, where the maximum temperature during summer was 21% and 22% higher than in the post-monsoon season.

Table 2 displays the linear trend analysis of seasonal variations in mean maximum temperature throughout the study period. We see that for the different locations, the summer and monsoon periods showed a statistically significant negative slope. The monsoon season in India brings widespread rainfall, which can have a cooling effect on the temperature. When it rains, the air is often cooler due to evaporation and the presence of cloud cover. The increase in rainfall during July, August, and September can lead to a decrease in temperature.

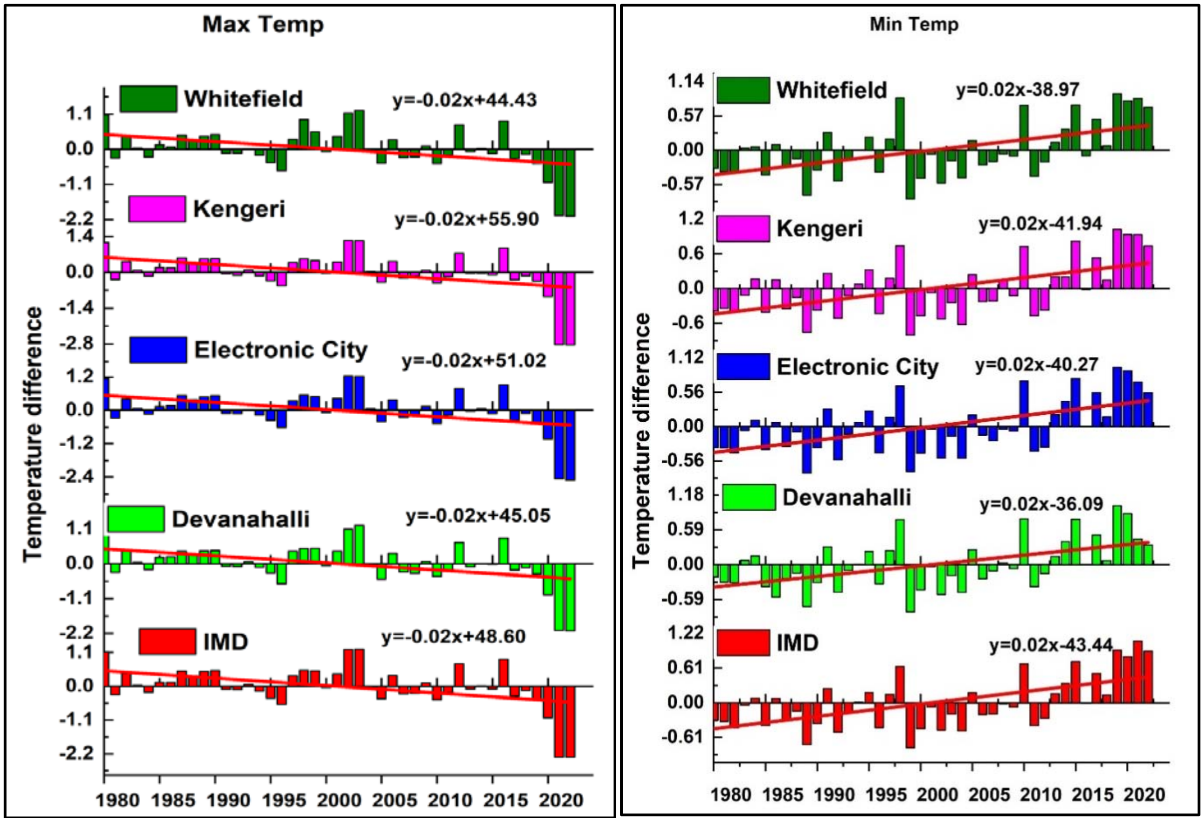


Fig. 4. Anomalies in Mean maximum and mean minimum temperature at Bengaluru from 1980 to 2022

Bengaluru's declining yearly maximum temperature results are different from the findings in other cities (Pingale *et al*., 2014).

4.3. *Trend of Mean Minimum Temperature*

The mean minimum temperature is the lowest temperature reached during a 24-hour period.Between 1980 and 2022, the mean minimum temperature varied from 17.66°C to 19.51°C in IMD-Bengaluru,17.50 to 19.30°C in Devanahalli, 17.61 to 19.33°Cin Electronic City, 17.35 to 19.10°C in Kengeri and 17.35 to 19.10°C in Whitefield. During the same period of 42 years, the mean minimum temperature decreased by 6.70%, 3.00%, 4.96%, 6.17% and 5.68% for IMD-Bengaluru, Devanahalli, Electronic City, Kengeri and Whitefield, respectively. Mean Minimum temperature shows an increase in all the locations, with Kengeri having the highest change in the mean minimum temperature percentage. Fig. 3(c) illustrates an increasing trend in the annual mean minimum temperature from 1980 to 2022 [Details in Supplementary Table 3(a)]. The slopes are 0.021°C yr^{-1}, 0.018°C yr^{-1}, 0.020°C yr^{-1}, 0.020°C yr^{-1}, 0.019°C yr^{-1} for IMD-Bengaluru, Devanahalli, Electronic City, Kengeri and Whitefield. The mean minimum annual trend suggests that nights are becoming warmer over the observation period. Cloud cover affects nighttime temperatures by trapping Earth's infrared radiation, acting like a blanket that prevents heat from escaping into space. This warming effect leads to milder nighttime temperatures. The trend analysis of cloud cover for the specified location was calculated, revealing a consistent increase during the analysis period from 1980 to 2022. The MMK test revealed that increase in mean minimum temperature for the 42-year period indicating an increase in night time temperature [Table 4(a)].

The monthly range of the mean minimum temperature for IMD-Bengaluru was 11.70 to 22.69°C; in Devanahalli, 10.94 to 22.69°C; in Electronic City, it was 11.11 to 22.71°C; in Kengeri, it was 10.73 to 22.96°C; and in Whitefield, it was 10.99 to 22.71°C. Table 1 shows the linear trend of monthly mean minimum temperature. The mean minimum temperature shows an increasing trend during the study period of 1980 - 2022 and this trend is statistically significant for the months of July, August, September and December. The month of December indicates the maximum increasing trend during

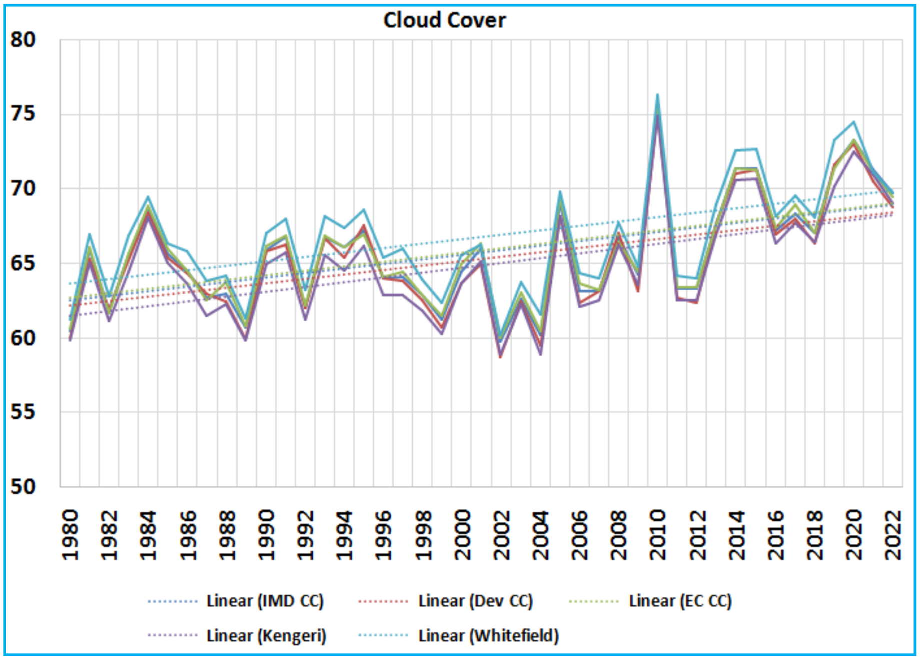


Fig. 5. Trend analysis of Cloud Cover of Bengaluru for various locations from 1980 to 2022

the study period (1980 - 2022) in all the sites studied. The increase in mean minimum temperature across all months can indeed be attributed to the Urban Heat Island (UHI) effect, where urbanization leads to infrastructure absorbing and slowly releasing heat during the night, thus raising nighttime temperatures.

As shown in Table 2, the average temperatures during the monsoon and summer seasons show a decreasing trend, and the winter and post-monsoon periods show an increasing trend during the study period of 1980 - 2022. These seasonal trends observed during a period of more than 40 years in the Bengaluru urban district are statistically significant at the 95% confidence level.Other researchers have also observed the increasing trends of annual minimum temperatures in India, with winters getting warmer in general (Gogoi *et al*., 2019; Mahato *et al*., 2021). This warming trend could be due to a variety of factors, including climate change, urbanization, changes in land use, or natural climate variability. In particular, Dhorde *et al.* (2017) conclude that an increase in night-time temperatures is a sign of urbanization.

4.4. *Analysis of temperature anomalies*

In order to have a deeper comprehension of the patterns in the average, maximum, and minimum temperatures over a 42-year period (1980 to 2022), the temperature anomalies have been calculated. The annual temperature anomalies in the average, minimum and maximum temperatures over Bengaluru are displayed in Fig. 4. Average temperature shows a decreasing trend and it is not statistically significant. The maximum temperature likewise exhibits a substantial downward trend with a slope of -0.02. Further in case of minimum temperature it shows an increasing trend with a slope of 0.02 which is statistically significant. From the above, it reveals that the night temperature is increasing and daytime temperatures are decreasing.

4.5. *Cloud cover*

Cloud cover is a key meteorological factor essential for climatology and weather forecasting, as it significantly influences weather and climate by reflecting sunlight, blocking longwave radiation, and generating precipitation. Clouds play a crucial role in recycling water vapor between the Earth's surface and the atmosphere, impacting the global energy balance. They are a major source of fluctuations in the radiation that reaches the Earth's surface, with high clouds contributing to warming and low-level clouds to cooling. Covering approximately two-thirds of the Earth's surface, clouds have a profound effect on climate change and the planet's radiation budget. Understanding variations in cloud cover is vital for comprehending the role of clouds in modern climate change (Jaswal *et al.*, 2017).

The Fig. 5 displays the annual trend analysis of the total cloud count for all locations from 1980 to 2022. The trend analysis of total cloud count over IMD, Devanahalli,

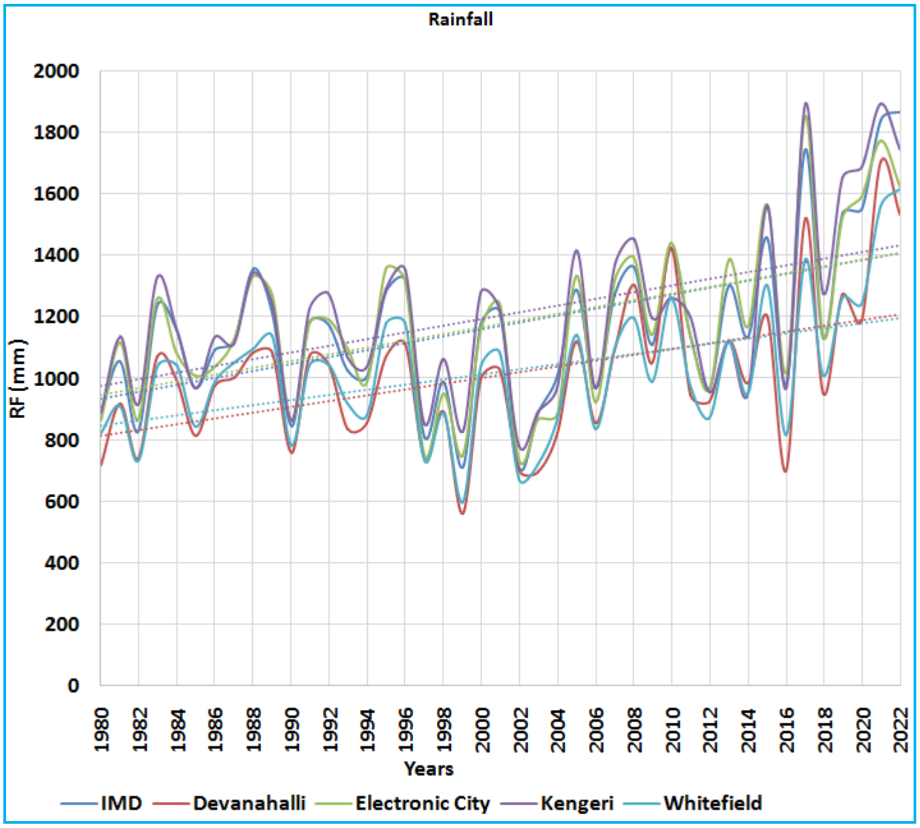


Fig. 6. Trend analysis of annual rainfall in the Bengaluru urban district (1980-2022)

Electronic city, Kengeri and white field location showed a significantly increasing with slope of 0.15, 0.14, 0.15, 0.16 and 0.15 percentage /year respectively.

Further the correlation between average temperature, maximum temperature and minimum temperature with cloud cover was performed using Pearson correlation (Table 3).

It was found that correlation between maximum temperature and cloud cover was negative and it was statistically significant at 0.05 level. The correlation of minimum temperature with total cloud count showed a positive correlation which was significant at 0.05 level. The significant negative correlation for maximum temperatures and positive correlation for minimum temperatures show that cloud cover helps cool during the day but warms at night, providing important insights into local climate behavior.

4.6. *Trend of Rainfall*

The annual average rainfall at IMD-Bengaluru, Devanahalli, Electronic City, Kengeri and Whitefield during the study period between 1980 and 2022 was 1174, 1011, 1176, 1205 and 1021 mm, respectively. During these 42 years, the annual rainfall varied from 710 to 1867mm in IMD-Bengaluru, 560 to 1706 mm in Devanahalli, 736 to 1855 mm in Electronic City, 780 to 1895 mm in Kengeri, and 598 to 1614 mm in Whitefield. The highest annual rainfall was recorded in Kengeri and the lowest was observed in the Devanahalli location. In each of these five locations, the highest annual rainfall was recorded in either 2021 or 2022 and the lowest annual rainfall was recorded in the years 1999 and 2002. The trends in annual rainfall for all five locations from 1980 to 2022 are shown in Fig. 6. The yearly rainfall levels in all five locations had a positive slope with a gradient of 11.32, 9.43, 11.05, 10.93- and 8.25-mm yr^{-1}. This trend in annual rainfall was also statistically significant at the 95% confidence level.

The highest and lowest rainfall levels were documented in September and January. In Bengaluru, the monsoon season begins in the second half of May and showers last from June through September during the southwest monsoon. However, the study area also receives showers during the northeast monsoon (October and

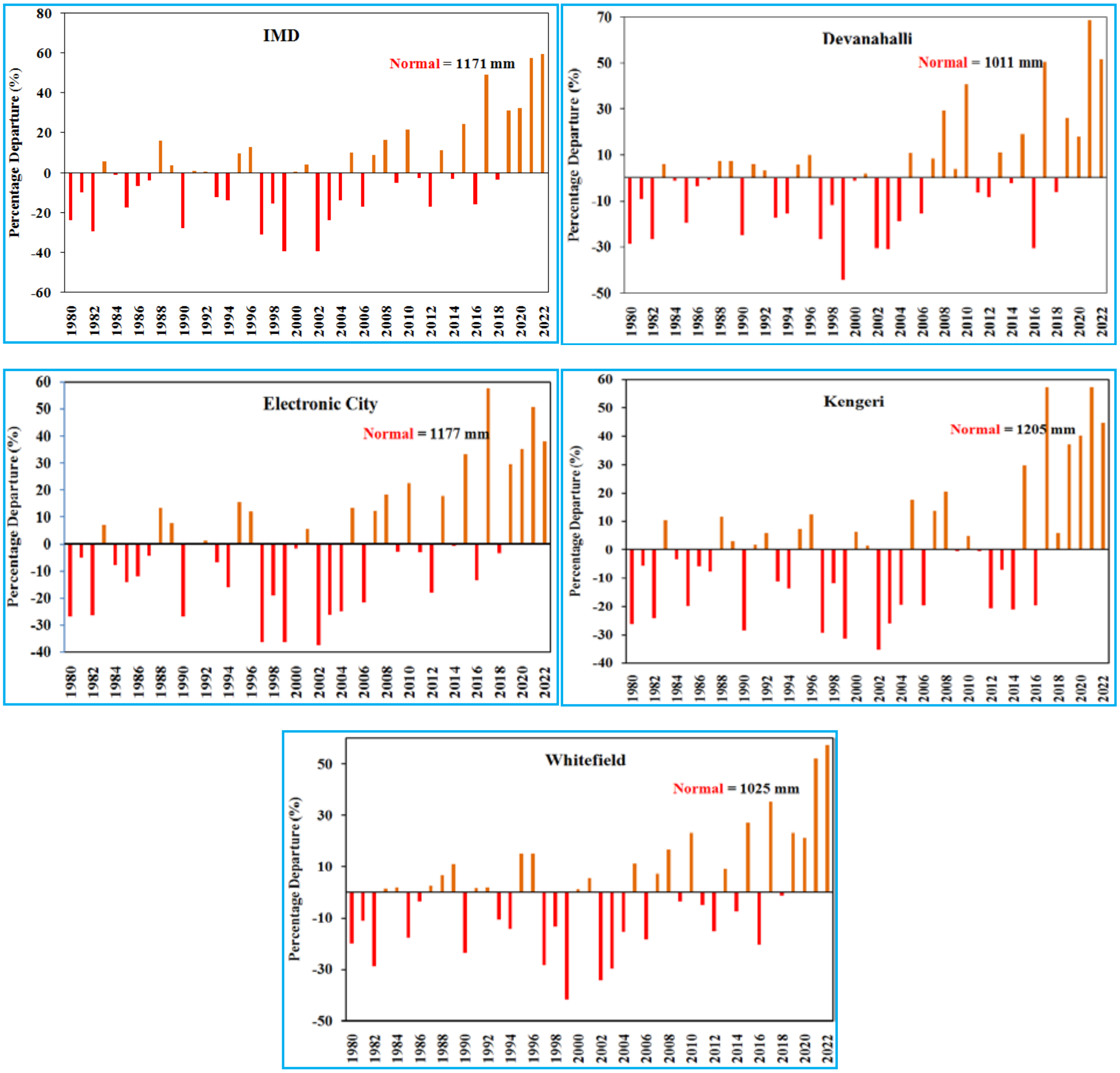


Fig. 7. Departure of annual rainfall from long term normal for five locations in the Bengaluru urban district between 1980 and 2022

December). The southwest monsoon (June - September) contributes to 50% of Bengaluru's total rainfall.

Data pertaining to the Bengaluru urban districts from 1980 to 2022 is being analyzed to investigate extreme weather events in the area. The aim is to discern surplus and deficit rainfall years based on the classification by the IMD. The percentage deviation of rainfall is worked out using the formula.

$$\text{Percentage change} = \frac{(x-y)}{y} \times 100$$

Normal rainfall is determined by averaging rainfall data over a specific region for a given period, typically 30 or 50 years. The departure of yearly rainfall from the long-term normal for different locations between 1980 and 2022 is shown in Fig. 7. The long-term annual average rainfall is as follows: 1171 mm for IMD, 1011 mm for Devanahalli, 1176 mm for Electronic City, 1205 mm for Kengeri, and 1025 mm for Whitefield.

Over the last 42 years, the area around the IMD observatory in Bengaluru experienced deficit and excess rainfall for seven years each. In the Devanahalli area, the 42-year rainfall record shows a 9-year deficiency and a 5-

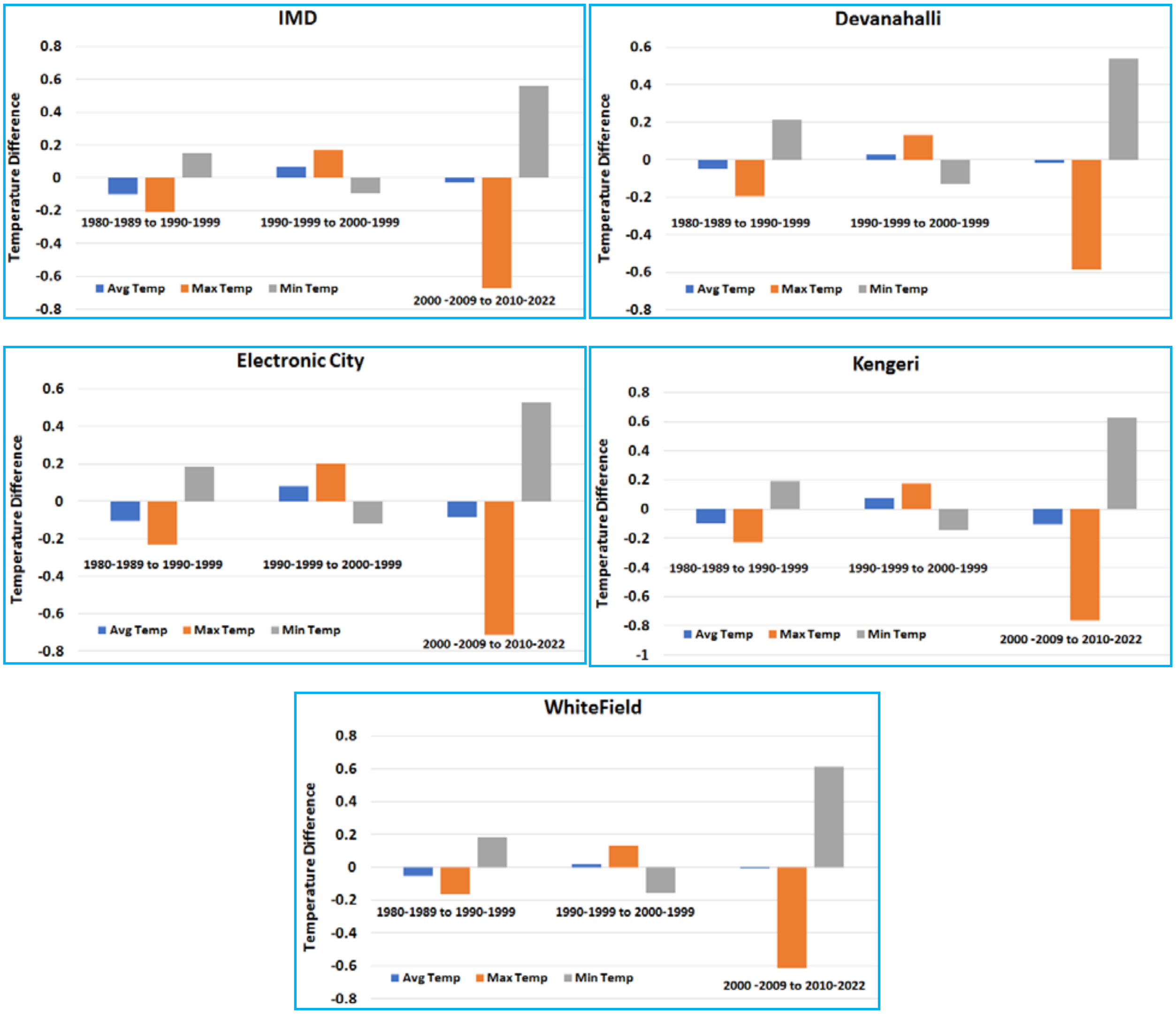


Fig. 8. Decadal changes of average, maximum and minimum Temperature for different Bengaluru urban locations

year excess, while the Electronic City area had deficit and excess rainfall for 10 and 7 years, respectively. The Kengeri and Whitefield areas on the western and eastern side of Bengaluru have experienced 13 years and 8 years of rainfall deficiency, respectively.Both these areas have experienced 7 years of excess rainfall in the last 42 years.

Therefore, there is a noticeable variability in rainfall patterns across different locations within Bengaluru urban district. Some areas experienced surplus rainfall in certain years, while others faced deficits. The distribution of surplus and deficit rainfall varies significantly among different locations. The varying patterns of rainfall deficits and excesses suggest that local geographical and meteorological factors play a crucial role in shaping the climate of each location. Factors such as elevation, proximity to water bodies, and urbanization may contribute to these differences.

4.7. *Decadal changes of temperature in the Bengaluru Urban district*

Fig. 8 shows the decadal changes of average,maximum, minimum temperatures. At the IMD Central Observatory location in Bengaluru, the average and maximum temperatures from 1980-1989 to 1990-1999declined slightly by 0.09 °C and 0.20°C, respectively, while the minimum temperature increased by 0.15°C. However, from 1990-1999 to 2000-2009, the average and maximum temperatures decreased by 0.06 °C and 0.17°C, respectively, with a notable decrease in the minimum temperature by -0.09°C. Interestingly, from

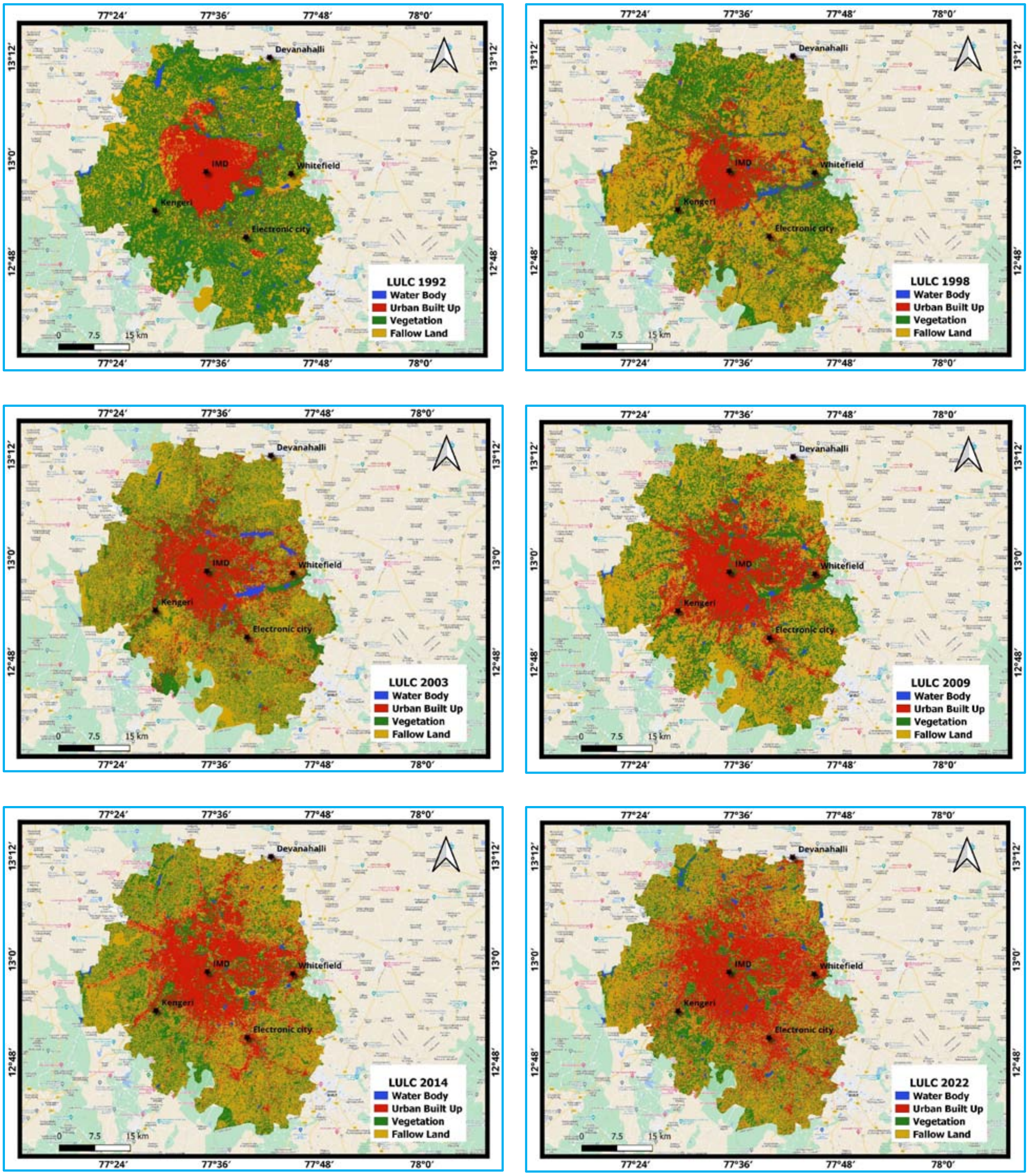


Fig. 9. Land Use Land Cover Maps of the Study area for 1992, 1998, 2003, 2009, 2014 and 2022

2000-2009 to 2010-2022, there's a reversal in trend, with average and maximum temperatures declining by 0.02 °C and 0.67°C, while the minimum temperature increased significantly by 0.56°C.

The above trends are consistent across various locations like Devanahalli, Electronic City, Kengeri and Whitefield. Each area exhibits fluctuations in temperature over different decades, showcasing a dynamic climate

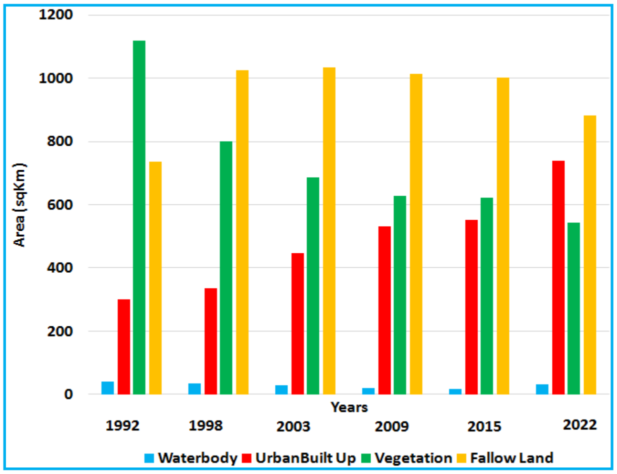


Fig. 10. Area wise of the landscape of each class

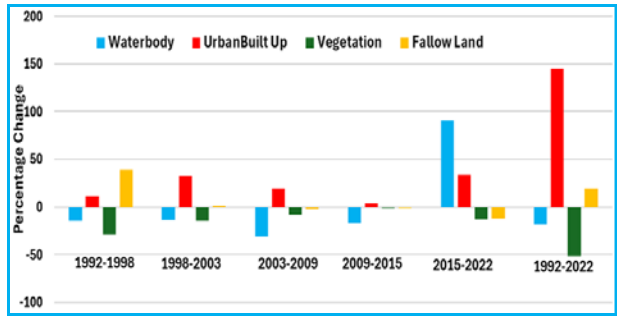


Fig. 11. LULC changes (in %) during 1992–1998, 1998–2003, 2003–2009, 2009-2015, 2015-2022 and 1992–2022

pattern. These trends indicate a dynamic pattern of temperature fluctuations over the decades, influenced by various microclimate factors such as topography, land use, and human activities. The period between 2000-2009 and 2010-2022 exhibited the most significant changes in both maximum and minimum temperatures, indicating cooler days and warmer nights. This could be attributed to factors such as urbanization, changes in land cover, and regional climate variability. The decadal changes clearly indicate rapid shifts, particularly occurring between 2000 and 2022, a period marked by substantial urbanization in the study area due to the influx of people attracted by the job opportunities provided in the Bengaluru urban district outside the limits of the city core administered by the Bruhat Bengaluru MahanagaraPalike (BBMP).

4.8. *LULC of Bengaluru Urban district*

LULC studies play a critical role in large-scale biomass and forest cover estimations, climate change, and other environmental and human factors (Kharol *et al*., 2013). Fig. 9 depicts the spatial distribution of land use land cover (LULC) changes over Bengaluru Urban Districtin 1992, 1998, 2003, 2009, 2014 and 2022.

Bengaluru's land use has altered overall, with the built-up area exhibiting a marked trend to expand, followed by an expansion in fallow land and a decline in greenery and water bodies. For the study period covering an area of 2195 km^2, the urban built-up area has increased, rising from 301 km^2 in 1992 to 738 km^2 in 2022(Fig. 10).

However, between 1992 to 2022, the area encircled by water bodies decreased from 40 km^2 to 32 km^2. In the past three decades, fallow land has increased from 736 to 881 km^2, while vegetation has decreased from 1116 to 541 km^2. In 1992, the built-up area accounted for 13% of the total landscape; by 2022, theshare of the built-up area had increased to 34%. Consequently, the area occupied by vegetation dropped from 50% in 1992 to 24% in 2022. The present study's findings align with the research conducted by Keerthi Naidu and Chundeli(2023), who examined the Land Use and Land Cover (LULC) variations in Bengaluru. Their analysis, based on Landsat images, showed a substantial growth in the built-up region, nearly doubling between 2003 and 2021, accompanied by a 50% decrease in vegetation cover. According to another study by Sultana and Satyanarayana (2018), Bengaluru's built-up area grew from 464 to 564 km^2 between 2002 and 2013, whereas its grassland and cropland decreased from 472 to 231 km^2.

Fig. 11 quantitatively displays the overall change for the whole analysis period (1992-2022) and the percentage change in land use land cover for 1992-1998, 1998-2003, 2003-2009, 2009-2014, 2014-2022 over the study region. As shown in Fig. 9, built-up area has recorded a 145% increase and fallow land has risen by 19% in the study site from 1992 to 2022. On the other hand, vegetation has shown a decrease of 51% while water bodies have reduced in area by 18% and an 18% drop in the water body.

The replacement of diverse land covers, such as green spaces, water bodies, and fallow land, by urban settlements over the study period indicates Bengaluru's increasing urbanization. Many factors, including demand, deforestation, population increase, and rapid urbanization, may contribute to transformations in land use and cover (Wang *et al*., 2018). The effects of climate change, such as altered rainfall patterns or increased temperatures, can also have an impact on urban land use patterns (Gohain *et al*., 2021).

As the city's population rises, there is a tremendous need for accommodation, infrastructure and commercial spaces, directing to changes in land use patterns seen in Bengaluru (Govind and Ramesh, 2019; Keerthi Naidu and Chundeli, 2023). Devanahalli, which is in an outlying urban area, has seen a growth in urban settlements since the airport's development in 2007. The need for new infrastructure, such as roads, highways, airports, and public utilities, often involves the conversion of agricultural or natural land into urban areas. Large-scale infrastructure projects like metro lines, flyovers, and expressways necessitated by the growing population of the Bengaluru urban district can lead to changes in land use as they require acquiring land for construction.This results in the conversion of agricultural land or open spaces into residential or commercial complexes.

Further, the areal extent of four major land use categories-waterbody, built-up, vegetation, and fallow land-were measured at a variety of locations in the study location based on the LULC images of 1992 and 2022. For the sites of IMD-Bengaluru, Devanahalli, Electronic City, Kengeri and Whitefield, the growth in built-up area from 1992 and 2022 is 110 to 112, 0.85 to 36, 12 to 86, 82 to 120 and 17 to 68 km^2. Correspondingly, the area covered by vegetation in IMD-Bengaluru, Devanahalli, Electronic City, Kengeri and Whitefield has reduced from 42 to 39, 102 to 36, 105 to 9, 48 to 6 and 110 to 40 km^2, respectively. The area occupied by water bodies also showed a decrease between 1992 and 2022, a period during which fallow land increased everywhere. The study indicates that the IMD-Bengaluruobservatory, located in an urban area previously, experienced minimal growth in urban built-up areas. In contrast, Devanahalli, situated on the outskirts where the Bengaluru airport was constructed, demonstrated a considerable growth in urban built-up. We find a major decrease in vegetation which has been converted to urban built up and fallow land. The results of this examination can be attributed to the urbanization undergone by the study site during the past 30 years.

4.9. *Accuracy assessment of LULC*

Accuracy assessment is critical to assure that the detected image is acceptable for further investigation. The classification accuracy of the LULC map is ascertained by applying high-resolution Google Earthimagesto 100 equally stratified random sample points from the classified map for the years 1992-2014. In 2022, we used Google imagery from satellites for ground truthing. The equalized stratified random makes sure that every class has the same amount of points, and that the points are dispersed at random inside each class. The estimated overall accuracy is higher than 0.80 each year and the Kappa values are greater than 0.51, which indicates a fair accuracy with classified images (Monserud& Leemans, 1992). Results indicate that the overall accuracy of the classified LULC map prepared for 1992,1997, 2003, 2009, 2014 and 2022 is 84%, 84%, 88%, 88%, 87% and 92% respectively while the Kappa coefficient is 0.51, 0.51, 0.54, 0.54, 0.54 and 0.58 for the respective years. The overall accuracy reached near perfection for urban built-up and waterbodies.

The key indicators of the LULC accuracy estimate, *viz*., the Producer's accuracy (PA), User's accuracy (UA), Overall Accuracy and the Kappa coefficient are shown in Table 4. The average values of the PA and UA for all the LULC classes exceed 80%, which demonstrates the accuracy of the classification.

5. Discussions

This study investigates temperature variation in the Bengaluru urban district over the past four decades, highlighting spatial and temporal variations in key climate variables over the study area. At the central IMD observatory, there was a decrease in both average and mean maximum temperatures (4.8% and 10.8% respectively) and an increase in mean minimum temperature (6.6%) and rainfall (109%) during the study period (1980 - 2022). The Devanahalli area experienced a 5.6% decrease in average temperature and a 10.2% drop in mean maximum temperatures, while minimum temperatures rose by 2.9% and rainfall increased by 113% over the same time. The Electronic City area underwent a decrease in the average and mean maximum temperatures (6.1% and 11.5% respectively) and an increase in minimum temperature (4.9%) as well as rainfall (88%). Kengeri saw a 6.4% decrease in average temperatures and a significant drop of 12.5% in mean maximum temperatures, while the minimum temperatures increased by 6.1% and rainfall rose by 96%. Whitefield also experienced a decrease in both average and mean maximum temperatures (6% and 10.1%, respectively), with an increase in minimum temperature (5.7%) and rainfall (96%).

The annual average temperaturearound these four locations decreased by -0.001°C yr^{-1} to -0.004°C yr^{-1} during the study period which was not statistically significant. Seasonally, the decrease in average temperature in the monsoon season was about -0.011 to -0.016° C yr^{-1} (significant at 0.05 level), while no significant trend was found in the other seasons. The mean maximum temperature in different places has decreased by -0.02 °C yr^{-1} from 1980 to 2022, while the daytime temperatures in both summer and monsoon seasons indicate a notable and statistically significant decline across all locations. The decrease in daytime temperatures during summer and monsoon seasons across various locations could be attributed to increased cloud cover. This change in cloud patterns, likely influenced by shifting weather conditions, reduces the amount of sunlight reaching the Earth's surface, leading to cooler daytime temperatures (Gadgiland Dhorde, 2005). The linear trend analysis of cloud cover across all locations clearly indicated a significant increase from 1980 to 2022, as confirmed at the 0.05 significance level for the 42 year period. The cloud cover analysis with maximum temperature shows that increased cloud cover during the day inhibit incoming solar radiation, which leads to daytime cooling. The minimum mean temperature in the different places has increased by +0.02 °C yr^{-1} from 1980 to 2022. Minimum temperatures have demonstrated notable upward trends throughout all seasons, with the winter season exhibiting the most substantial increase across all observed locations during the study period. This trend signifies a warming climate. The analysis of cloud cover in relation to minimum temperatures shows an increasing trend. At night, clouds trap outgoing longwave radiation, preventing it from escaping into space, which leads to higher nighttime minimum temperatures. The increase in minimum temperatures, especially during winter, is consistent with the broader pattern of global climate change. Warmer winters can have various impacts, including altering ecosystems, affecting agriculture, and potentially leading to changes in weather patterns (Kothawale and Rupa kumar, 2005; Mall *et al*., 2019). This also indicates that if the rising trends continue in the near future, minimum temperatures in the city of Bengaluru will be significantly higher than the temperatures experienced a few decades back.Rainfall trends for different locations show an increasing trend from 8.25 to 11.32 mm yr^{-1}. Earlier studies based on Bengaluru rainfall have shown an increase in rainfall (De and Prakash Rao, 2004., Kharol *et al*., 2013; Singh*et al*., 2015). In the present work covering a period of 40 years, it is observed that the months of May, August and October showed significant increases in rainfall. Bangalore receives precipitation during the northeast and the southwest period, and the wettest months are September, October, and August. Among the seasons, the positive trend coefficient is maximum for the monsoon season, which is significant at 0.05. The possible reason for this could be that Bengaluru is impacted more by the ample moisture from the south-westerly winds, and as an outcome, the monsoon showers are more extensive (Kharol *et al*., 2013).

This research analyses the decadal temperature pattern over Bengaluru Urban District from 1980 to 2022. It is clear from the decadal changes in temperature that rapid changes happened during 2000-2019 when rapid urbanization happened in the city. In the study region it indicates that one of the main drivers of Bengaluru's urban growth around 2000 was the establishment of noteworthy private sector companies, mostly in the information technology sector.

The results of the LULC analysis in Bengaluru Urban district tell the same tale as every other Indian metropolis.The natural environment of Bengaluru has been severely impacted by the rate of land use and land cover shifts that have occurred in the last 30 years. During the period 1992 and 2022 of LULC changes, the IMD grid has witnessed a concerning trend of losing significant water bodies and an increase in fallow land. Devanahalli grid, once covered in lush vegetation, has undergone a drastic transformation into a highlybuilt-up area, expanding by 35.96 km^2 during this period. Similarly, Electronic City, Kengeri and Whitefield grids have experienced a loss of vegetation, leading to extensive urban development. These instances underscore the rapid loss of open spaces, including vegetation cover and water bodies, in the city. While the unplanned developmental activities in these regions have generated employment and business opportunities, they have also resulted in the degradation of the biophysical environment. This environmental deterioration not only affects the health of citizens but also contributes to the scarcity of natural resources including drinking water (Ramachandra *et al*., 2019).

The results of the image classification indicate a sharp increase in built-up urban areas and a corresponding decline in other land uses like water, vegetation, and fallow land.The detrimental effects of unplanned urban sprawl in the Bengaluru urban district have resulted in a decrease in both the number and quality of essential living commodities like clean air, water, and living space in Bengaluru(Kanga *et al*., 2022).

6. Conclusion

The analysis of climatic data in Bengaluru shows decreasing mean maximum temperatures and increasing mean minimum temperatures annually, alongside a significant rise in rainfall from 1980-2022. The observed trends in temperatures and rainfall indicate the intricate interplay amongst local climate dynamics, land use changes, and urbanization. The LULC shifts, particularly the notable growth in urban built-up areas and reduction in vegetation highlight the transformative impact of urbanization on the city's microclimate. The implications of these changes incorporate warmer nights, altered precipitation patterns, and diminishing green spaces, emphasizing the urgent need for sustainable urban planning. It is crucial to manage urban growth while preserving natural habitats to mitigate the adverse effects of climate change and promote environmental sustainability in Bengaluru. Long-term monitoring and modelling studies are essential for gaining insights into future climate projections and devising effective adaptation strategies to address the challenges posed by changing microclimates. This analysis underscores the importance of continuous research and monitoring to inform the decisions of policymakers and urban planners and foster sustainable urban development in Bengaluru amidst evolving microclimate dynamics.

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Supplementary Tables

TABLE 1(a)

Average Temperature

Location	IMD	Devanahalli	Electronic City	Kengeri	Whitefield
Intercept	28.41738 ± 7.01455	29.12408 ± 7.63745	32.21693 ± 7.97679	34.03751 ± 8.36343	27.44595 ± 7.45051
Slope	-0.00214 ± 0.00351	-0.00262 ± 0.00382	-0.00402 ± 0.00399	-0.00478 ± 0.00418	-0.00181 ± 0.00372
Residual Sum of Squares	3.33627	3.95512	4.31439	4.74276	3.76387
Pearson's r	-0.09473	-0.10657	-0.15541	-0.17576	-0.07586
R-Square (COD)	0.00897	0.01136	0.02415	0.03089	0.00575
Adj. R-Square	-0.0152	-0.01276	3.51628E-4	0.00726	-0.0185
P value	0.54566	0.49638	0.31967	0.25957	0.62877

The simple linear regression (SLR) model is not statistically significant.

TABLE 2(a)

Mean Maximum Temperature

Location	IMD	Devanahalli	Electronic City	Kengeri	Whitefield
Intercept	79.03231 ± 15.75675	75.15099 ± 14.70083	81.58281 ± 16.54336	86.81832 ± 17.70507	74.60213 ± 15.29612
Slope	-0.02429 ± 0.00787	-0.02251 ± 0.00735	-0.0255 ± 0.00827	-0.02794 ± 0.00885	-0.02221 ± 0.00764
Residual Sum of Squares	16.83431	14.65365	18.55707	21.25481	15.86444
Pearson's r	-0.43402	-0.43171	-0.434	-0.44229	-0.41316
R-Square (COD)	0.18837	0.18637	0.18835	0.19562	0.1707
Adj. R-Square	0.16857	0.16653	0.16856	0.176	0.15048
P value	0.00364	0.00385	0.00364	0.00298	0.00589

The SLR model is statistically significant at the 95% level of confidence.

TABLE 3(a)

Mean Minimum Temperature

Plot	IMD	Devanahalli	Electronic City	Kengeri	Whitefield
Intercept	-24.99148 ± 9.33318	-17.78913 ± 9.08557	-21.90523 ± 9.23901	-23.43232 ± 10.06155	-20.80831 ± 9.57461
Slope	0.02171 ± 0.00466	0.01804 ± 0.00454	0.02013 ± 0.00462	0.02096 ± 0.00503	0.01948 ± 0.00478
Residual Sum of Squares	5.90638	5.59714	5.78779	6.86423	6.2159
Pearson's r	0.58806	0.52718	0.56281	0.5456	0.53652
R-Square (COD)	0.34581	0.27792	0.31675	0.29768	0.28786
Adj. R-Square	0.32986	0.26031	0.30009	0.28055	0.27049
P value	0.0000	0.0000	0.0000	0.0000	0.0000

The SLR model is statistically significant at the 95% level of confidence.

TABLE 4(a)

Modified Mann Kendall Test based for all the locations during 1980-2022

	Avg Temp (Not statistically significant)			Max Temp (statistically significant)			Min Temp (statistically significant)		
Series\Test	Kendall's tau	p-value	Sen's slope	Kendall's tau	p-value	Sen's slope	Kendall's tau	p-value	Sen's slope
IMD	-0.008	0.887	0.000	-0.262	**0.001**	-0.016	0.369	**<0.0001**	0.021
Devanahalli	0.023	0.694	0.001	-0.254	**0.001**	-0.015	0.360	**<0.0001**	0.017
Electronic City	-0.001	1	0.000	-0.269	**0.001**	-0.017	0.362	**<0.0001**	0.020
Kengeri	-0.003	0.973	0.000	-0.287	**0.001**	-0.017	0.334	**<0.0001**	0.021
Whitefield	0.010	0.839	0.000	-0.267	**0.000**	-0.016	0.340	**<0.0001**	0.019