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A Spatiotemporal Study of Climatic and Vegetation Changes (1984–2024) in Karnataka State, India

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ABSTRACT

The impacts of climate change and global warming have become increasingly evident over the past four decades, especially in climate-sensitive regions like Karnataka State, India. This study presents a spatio-temporal analysis of climatic trends and vegetation changes across Karnataka from 1984 to 2024 using meteorological data and satellite observations. Key climatic parameters including temperature, precipitation, specific humidity, and wind speed were analyzed using data from 66 ground stations and NASA POWER datasets. Additionally, MODIS-derived NDVI data were used to assess vegetation dynamics. The findings reveal significant warming trends, seasonal variations in rainfall, and spatial shifts in humidity and wind patterns. Notably, there is a strong correlation between declining vegetation cover and climatic fluctuations in certain regions. This research provides critical insights into regional climate behavior and ecosystem response, supporting evidence-based planning for agriculture, water resources, and forest management. The study emphasizes the importance of long-term monitoring and adaptive strategies in mitigating climate-related risks.

Keywords GIS, Climate change, Temperature, NDVI, Remote sensing.

INTRODUCTION

Understanding climatic trends is essential to address the impacts of climate change on agriculture, water resources, and public health. Trend analysis helps identify long-term changes in key variables such as temperature, rainfall, and humidity, which influence ecosystem dynamics and socio-economic systems (Hannachi 2007, Pal *et al.* 2017).

Karnataka is particularly important for climate studies due to its varied topography and agro-ecological zones. Regional disparities in rainfall and temperature have been observed, with increasing rainfall in the South Interior and Malnad regions, and reductions in the North Interior and Coastal areas (Reddy *et al.* 2024, Singh *et al.* 2014). The complex landscape, including coastal belts, the Western Ghats, and inte-

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rior plateaus, makes localized climate assessments more relevant than broader models (Nautiyal 2011).

Recent studies highlight rising minimum temperatures, mixed rainfall trends, and frequent droughts, especially in interior regions (Chowhan *et al.* 2024, Simpson *et al*. 2024). These variations have significant implications for agriculture and water management, necessitating adaptive strategies.

This study integrates meteorological and remote sensing data to assess long-term climatic and vegetation trends in Karnataka. By examining temperature, precipitation, humidity, wind speed, and NDVI, the research aims to inform sustainable land-use planning and climate resilience efforts.

MATERIALS AND METHODS

Study area

Karnataka, in Southern India, is the eighth-largest state, covering 191,976 km² (~6% of India's area) and bordered by multiple states and the Arabian Sea (Parthasarathy 2021).

The state features three distinct regions: The coastal belt, the Western Ghats, and the Deccan Plateau. It is divided into ten agro-climatic zones — Coastal, Hill, North Transition, North East Transition, Northern Dry, Central Dry, Eastern Dry, Southern Dry, Southern Transition, and High Rainfall Zones — as shown in Fig. 1, with two-thirds classified as arid or semi-arid (Gurulingappa *et al*. 2018). The Western Ghats significantly influence regional climate by obstructing southwest monsoons, leading to varied rainfall patterns shaped by elevation and orography (Gunnell 1997, Gadgil & Sikka 1978, Tawde & Singh 2015). These climatic variations impact agriculture, necessitating region-specific cropping strategies (Suryanarayana *et al*. 1984, Rani *et al*. 2024).

Data collection and preprocessing

This study utilizes meteorological data (1984–2022) from NASA, covering temperature (°C), precipitation (mm), specific humidity (g/kg), and wind speed (m/s) across 66 sites in Karnataka, ensuring broad geographic representation. Additionally, MODIS NDVI data (MOD13Q1, 250 m, 16-day composite) was used to analyze vegetation cover changes for se-

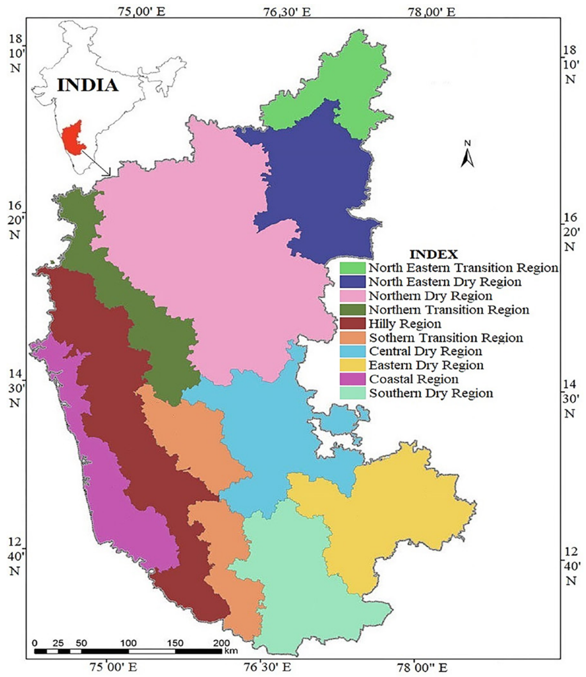

Fig. 1. Location and agro-climatic regions of Karnataka (modified after Das *et al.* 2018).

lected years (2000, 2008, 2016 and 2024), providing insights into the relationship between climate variability and vegetation dynamics. Data preprocessing involved removing missing or incorrect values to ensure accuracy.

Data processing and analysis

To examine long-term trends, meteorological data were categorized into four decadal periods (1984–1993, 1994–2003, 2004–2013 and 2014–2022), and monthly and annual averages were calculated across all 66 sites. This segmentation enabled a comparative analysis of climatic variations over time. NDVI and vegetation coverage maps were derived from MODIS imagery to assess vegetation extent in March (dry season) and October (post-monsoon) across different years.

Statistical and spatial analysis

To evaluate long-term climate variations and vegetation dynamics, spatiotemporal mapping was conducted using GIS software, visualizing temperature, precipitation, humidity, wind speed, NDVI, and vegetation cover. Trend analysis was performed using linear regression, applying the equation:

$$Y = mX + b + \varepsilon$$

Where, *Y* is the climatic variable, *X* is time, *m* is the rate of change, *b* is the intercept, and ε is the error term.

The strength of trends was evaluated using the coefficient of Determination (R^2) :

$$R^2 = 1 - \frac{\sum (Yi - \hat{Y}i)^2}{\sum (Yi - \bar{Y})^2}$$

Where, Y_i represents actual values, ($\hat{Y}_i$) represents predicted alues, and $\bar{Y}$ is the mean. The statistical significance of trends was tested using the T-statistic (t):

$$t = \frac{m}{SE\ (m)}$$

Where, *m* is slope of the regression line, *SE* (*m*) is the standard error of the slope.

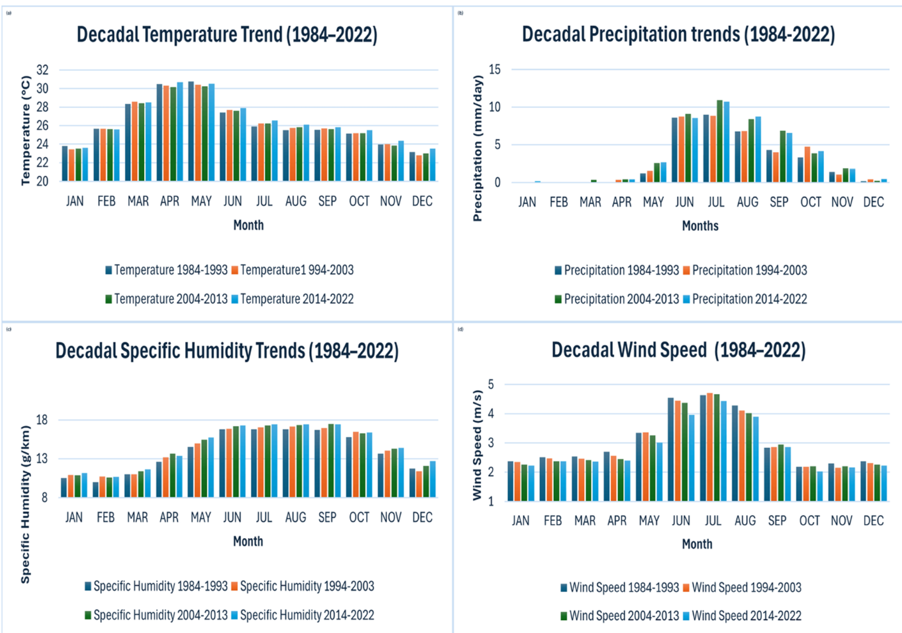

Fig. 2. Decadal trends in monthly climate variables for Karnataka (1984-2022).

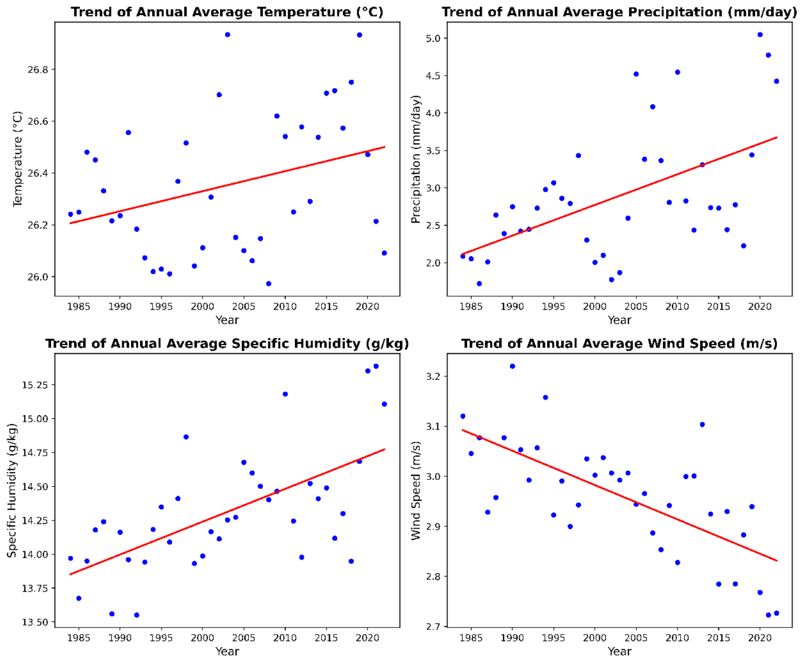

Fig. 3. Annual temperature trends in Karnataka (1984-2022).

Visualization and tools

The processed data were presented using bar charts, dot plots, summary tables, and spatial maps, ensuring clear interpretation of climatic and environmental changes. Instead of line graphs, bar charts were used for seasonal vegetation coverage trends, and dot plots were applied to meteorological parameters, enhancing the representation of variability and distribution.

Data analysis was conducted using Python, MS Excel, and GIS software, facilitating both statistical and spatial assessments of Karnataka's climate and vegetation patterns over time.

By integrating meteorological trends with MODIS NDVI-derived vegetation indices, this study provides a comprehensive understanding of climate variability and its impact on Karnataka's environment, supporting future climate adaptation strategies.

RESULTS

Decadal climate trends in Karnataka (1984–2022)

Figure 2 presents seasonal trends in temperature, precipitation, specific humidity, and wind speed across four decades. The data show a consistent seasonal cycle, with warming during March–May and cooling from November–January. A gradual increase in summer temperatures is evident in recent decades (2004–2022).

Precipitation patterns remain monsoon-driven (June–September), but recent decades exhibit slightly higher rainfall during this season, indicating an intensification of monsoon activity. Similarly, specific humidity peaks during monsoon months and has increased slightly in recent decades, reflecting higher atmospheric moisture. Wind speeds also peak during

Table 1. Statistical summary of climate trends.

Parameter	Coefficient (Change per year)	R^2 value	p-value	Significance
Temperature	0.0077 (°C)	0.110	0.040	Significant
Precipitation	0.0496 mm/day	0.296	0.000	Significant
Specific humidity	0.0242 g/kg	0.401	0.000	Significant
Wind speed	-0.0086 m/s	0.4758	0.000	Significant

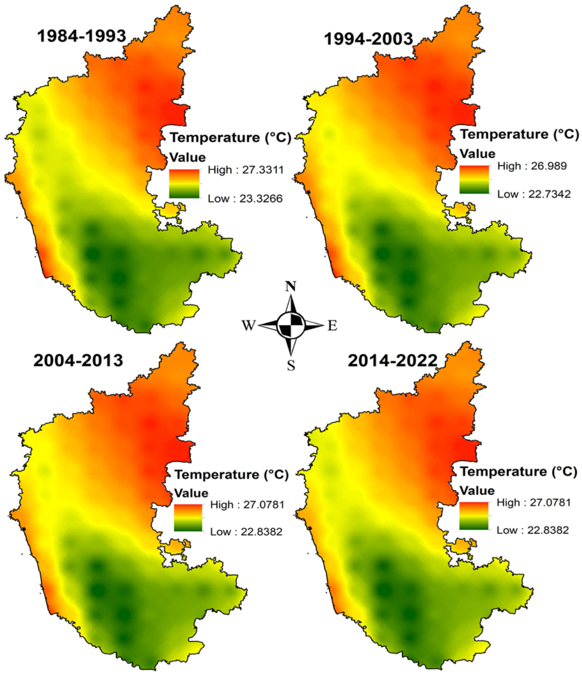

Fig. 4. Temperature distribution in Karnataka (1984-2022).

the monsoon but show a modest decline over time, suggesting reduced wind intensity in recent years.

Annual climate trends and statistical analysis

Figure 3 shows annual trends in temperature, pre-

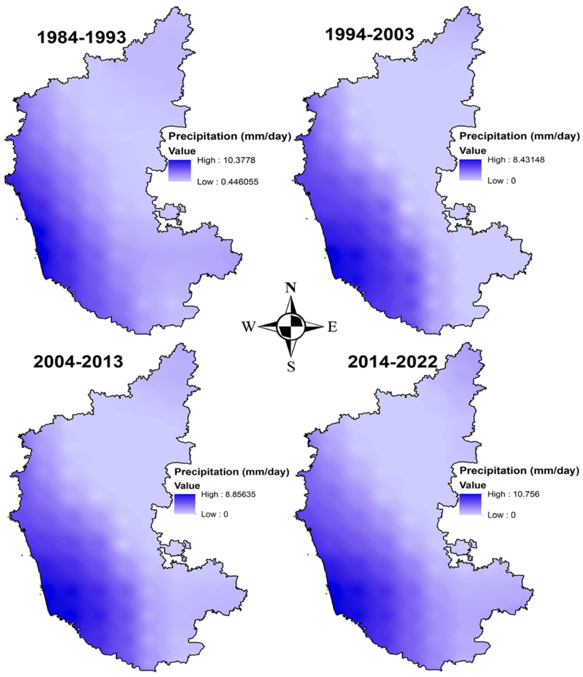

Fig. 5. Comparative decadal precipitation distribution across Karnataka (1984-2022).

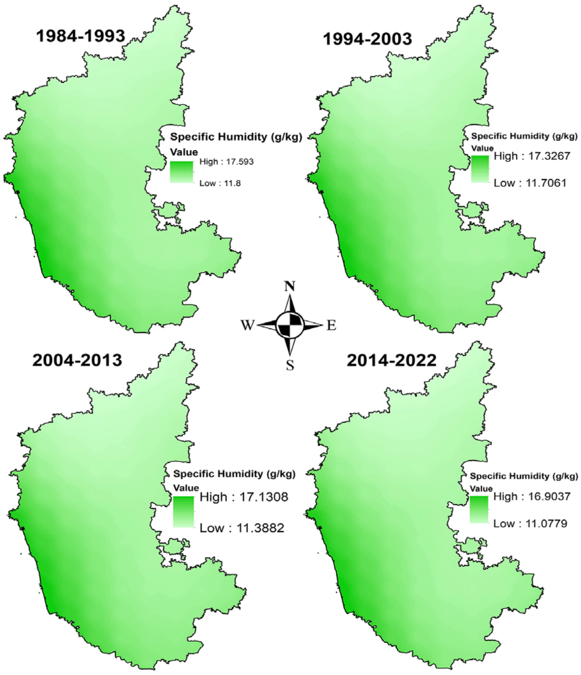

Fig. 6. Decadal specific humidity distribution across Karnataka (1984-2022).

cipitation, specific humidity, and wind speed from 1984 to 2022. The dots represent observed values, while the lines indicate linear regression trends. Table 1 summarizes the regression coefficients, R^2

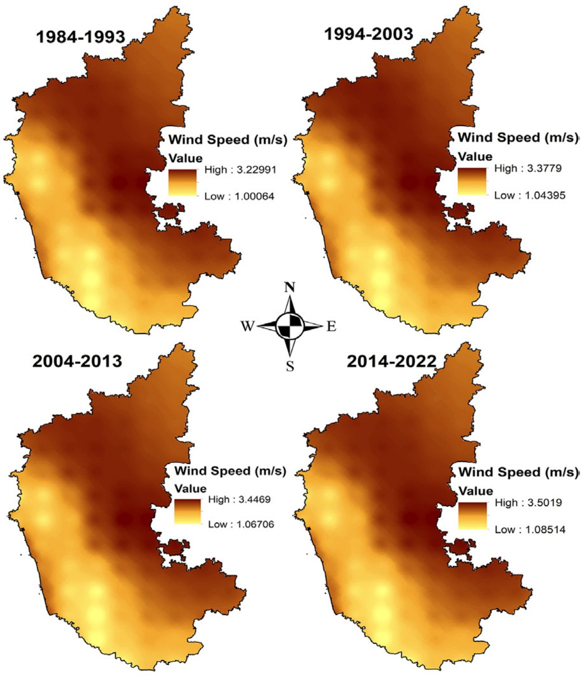

Fig. 7. Decadal wind speed distribution across Karnataka (1984-2022).

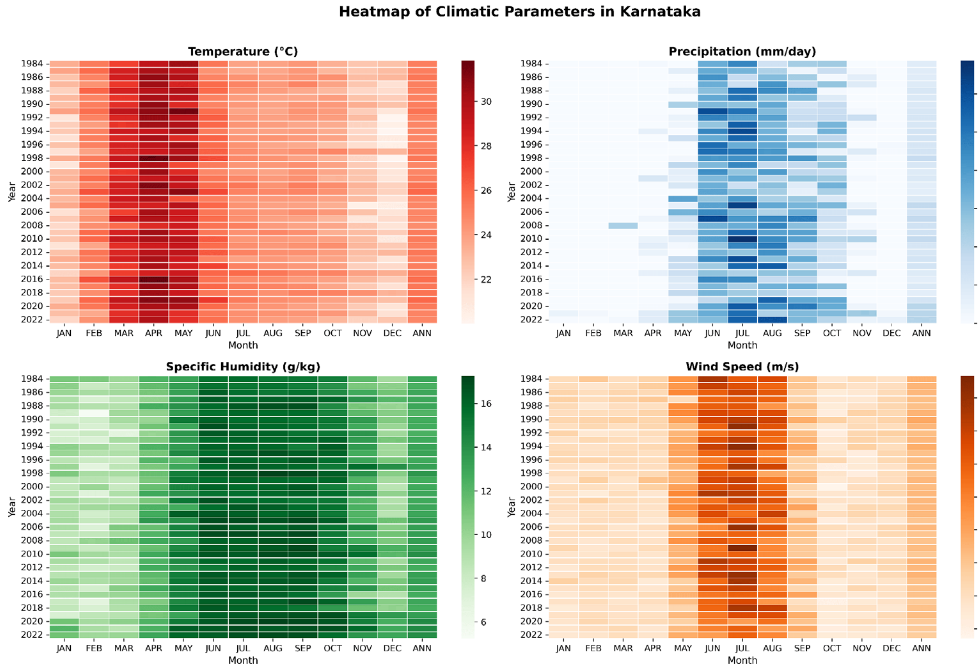

Fig. 8. Monthly variations in climate parameters (Heatmaps for 1984–2022).

values, and p-values. Temperature shows an upward trend (0.0077°C/year), with a modest R^2 (0.11) and statistically significant p-value (0.0396). Precipitation also increases (0.0496 mm/day/year), with higher

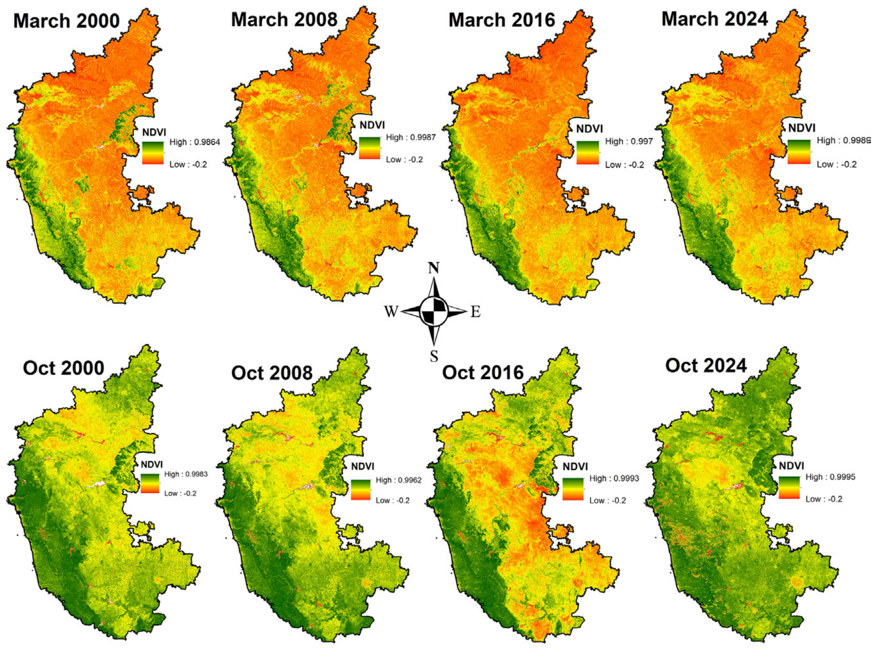

Fig. 9. NDVI variations in Karnataka (2000–2024).

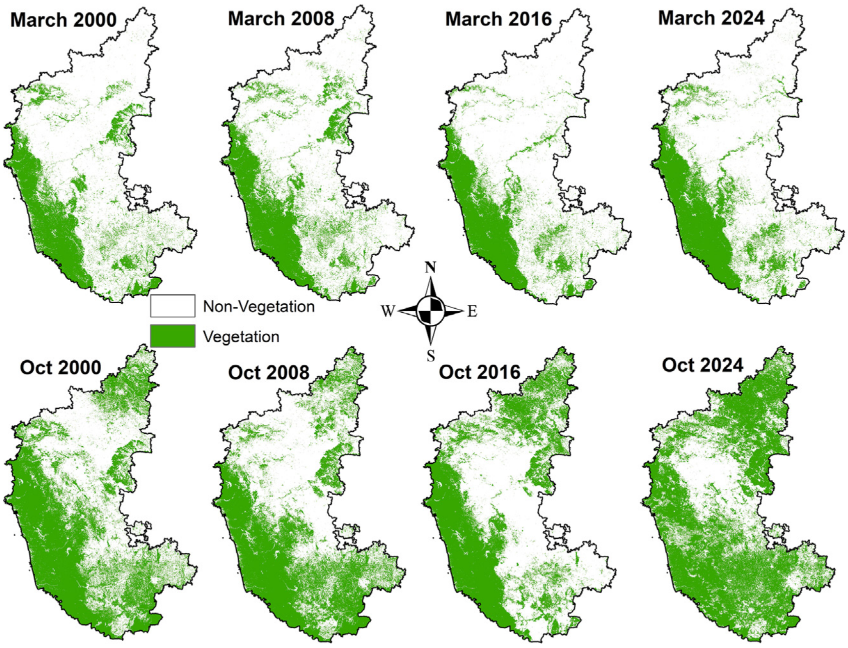

Fig. 10. Vegetation changes during the dry and post-monsoon seasons (2000–2024).

variability ($R^2 = 0.2962$, $p = 0.00034$).

Specific humidity has the strongest upward trend (0.024 g/kg/year), with an R^2 of 0.401 and high significance ($p = 0.000015$), indicating a clear rise in atmospheric moisture. Wind speed shows a decreasing trend (-0.0086 m/s/year), with the highest R^2 (0.4758) and strong significance ($p = 1.19E-06$), confirming declining wind intensity.

Overall, these results highlight significant climatic changes in Karnataka—warming, more moisture, increased rainfall, and weaker winds.

Table 2. Vegetation coverage (km²) for March and October from 2000 to 2024.

Year	Month	Area (sq^2)
2000	March	54511.63
2000	October	111536.9
2008	March	61064.69
2008	October	103750.4
2016	March	52896.44
2016	October	93241.88
2024	March	58845
2024	October	136654.4

Spatial distribution of climate variables

Temperature

Figure 4 illustrates the decadal spatial distribution of temperature across Karnataka. In the 1984–1993 map, northern and central regions show the highest temperatures (22.78°C–27.25°C). Subsequent decades reveal a gradual warming, especially in the north. By 2013–2022, temperatures exceed 27.33°C in northern and eastern areas, highlighting a clear spatial and temporal warming trend, with the most pronounced changes in the recent decade.

Precipitation

Figure 5 shows decadal precipitation distribution in Karnataka. From 1984 to 2022, rainfall remains highest along the western coast due to the Western Ghats. Over time, average precipitation gradually increases—from 8.43 mm/day in 1984–1993 to peaks of 10.75 mm/day in 2004–2013—indicating a strengthening monsoon. By 2014–2022, rainfall

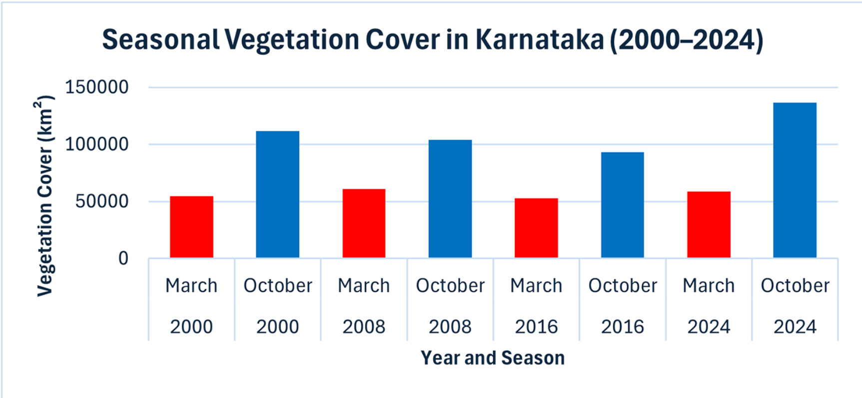

Fig. 11. Seasonal vegetation coverage trends (2000–2024).

remains high and extends further inland, suggesting intensified and spatially expanding rainfall patterns. These changes may impact agriculture, water resources, and flood management.

Specific humidity

Figure 6 displays decadal changes in specific humidity across Karnataka from 1984 to 2022. Early maps (1984–1993) show moderate humidity levels (11.1–16.9 g/kg), mostly in localized areas. Over time, higher humidity values expand spatially, reaching up to 17.6 g/kg in 2014–2022, especially in coastal and monsoon-affected regions. This increase aligns with rising temperature and precipitation trends, reflecting a broader shift in regional climate. Elevated humidity may have significant implications for agriculture, water management, and climate adaptation strategies.

Wind speed

The wind speed distribution map brings together data from four decades (1984-1993, 1994-2003, 2004-2013, and 2014-2022) into a unified view (Fig. 7). The earlier period (1984-1993) depicts higher wind speeds, notably in the southern and coastal regions, with values of up to 3.50 m/s. These values have declined slightly in subsequent decades. From 2014 to 2022, maximum wind speeds have decreased to roughly 3.23 m/s, consistent with the graphs.

Monthly variations in climate patterns

Figure 8 presents monthly climate trends in Karnataka. Temperatures peak in April–May (27–28°C) and drop in December–January (21–22°C), showing a mild winter and a slight warming trend. Rainfall and specific humidity are highest from June to October, driven by the monsoon. Wind speeds also peak in May–June (~5.0 m/s) and are lowest in the dry months. These seasonal patterns remain consistent, reflecting a stable annual cycle with gradual warming.

Spatiotemporal variations in NDVI

Figure 9 shows NDVI-based vegetation patterns in Karnataka using MODIS 250 m 16-day composites. NDVI values (–0.2 to ~1) indicate vegetation density, with maps from March (dry season) and October (post-monsoon) highlighting seasonal variation.

Over time, NDVI trends reveal regional vegetation changes. Central and northern Karnataka show gradual declines, likely due to urbanization and land degradation—while other areas display stable or improving vegetation. These patterns reflect the influence of climate, land use, and human activity, offering insights into climate monitoring and land-use planning.

Vegetation coverage changes (2000–2024)

Figure 10 shows seasonal vegetation changes in Karnataka, with lower NDVI in March (dry season) and higher values in October (post-monsoon). Over time, central and northern regions show declining vegetation, likely due to land-use change and water stress.

Table 2 quantifies these trends, while Fig. 11 highlights a growing gap between dry-season losses and post-monsoon recovery. A notable increase in October 2024 suggests improved vegetation, possibly due to higher rainfall or afforestation. However, further analysis is needed to confirm whether this is sustainable or climate driven.

DISCUSSION

Over the past 39 years, Karnataka has experienced significant climatic changes, rising temperatures, increased rainfall and humidity, and declining wind speeds. These shifts mirror broader global patterns and have important implications for agriculture, water resources, energy, and urban development.

The gradual rise in temperature, especially in summer, signals the need for adaptive measures in farming and city planning. Rainfall has intensified during the monsoon, improving water availability but also increasing flood risk. Specific humidity has risen in tandem, contributing to heavier rainfall and greater heat stress, particularly in urban areas.

Wind speeds have declined, which may affect wind energy, air circulation, and pollution dispersion. NDVI analysis shows consistent seasonal vegetation cycles, though some regions reflect long-term decline. A notable vegetation increase in 2024 may be linked to higher rainfall or conservation efforts, but its sustainability is uncertain.

Together, these trends highlight the urgency of integrated cross-sector strategies to build climate resilience.

CONCLUSION

This 39-year analysis reveals clear climatic shifts in Karnataka, including rising temperatures, increased monsoon rainfall, higher humidity and declining wind speeds. These trends reflect broader climate change patterns and suggest evolving monsoon dynamics and growing atmospheric moisture. The decline in wind speed may influence energy production, air circulation, and weather systems. NDVI and vegetation coverage analyses show largely seasonal patterns, though 2024 saw a marked increase in post-monsoon vegetation—possibly due to higher rainfall or conservation efforts. Whether this trend is sustainable remains uncertain.

Overall, the findings highlight the complex and interlinked nature of climate change in the region. Addressing these challenges will require coordinated adaptation strategies, particularly in agriculture, water management, and infrastructure planning. As Karnataka's climate continues to evolve, proactive measures will be essential to reduce risks and build long-term resilience.

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