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SPATIO-TEMPORAL ANALYSIS OF CLIMATIC PATTERNS AND SEASONAL VARIATIONS IN HARYANA: IMPLICATIONS FOR AGRICULTURAL PLANNING AND WATER RESOURCE MANAGEMENT

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Abstract

This research investigates the climatic patterns and seasonal variations across Haryana state in India, focusing on their spatio-temporal characteristics and implications for regional planning. The study analyzes historical meteorological data spanning 30 years (1991-2021) to identify trends in temperature, precipitation, humidity, and extreme weather events. Results indicate significant spatial heterogeneity in climatic parameters across different districts, with a marked warming trend of 0.26°C per decade and increasing rainfall variability. The monsoon onset has shown a delay of approximately 5-7 days over the study period, while winter precipitation has decreased by 12%. Distinct regional microclimates were identified, correlating with topographical features and urbanization levels. The research reveals concerning trends including increased frequency of heatwaves, unpredictable rainfall distribution, and extended dry spells affecting agricultural productivity. These findings provide critical insights for developing climate-adaptive agricultural practices, water resource management strategies, and regional climate action plans for Haryana.

Keywords*:* Climatic patterns, Seasonal variations, Spatio-temporal analysis, Climate change adaptation

1. Introduction

The state of Haryana, located in northern India, represents a region of significant agricultural importance yet faces increasing challenges due to climatic variability and change. Situated between 27°39' to 30°35' N latitude and 74°28' to 77°36' E longitude, Haryana exhibits diverse physiographic features ranging from the Shivalik Hills in the north to semi-arid plains in the southwest, creating a complex climatic landscape (Kumar et al., 2018). Understanding the patterns of climate and their seasonal fluctuations in this region is paramount for agricultural planning, water resource management, and overall sustainable development.

Climate change has intensified the unpredictability of weather patterns globally, with particularly pronounced effects in regions dependent on monsoon rainfall (IPCC, 2022). In Haryana, where agriculture constitutes approximately 30% of the state's GDP and employs over 45% of its workforce, climatic variations directly impact economic stability and food security (Directorate of Economics and Statistics, Haryana, 2021). The state's strategic location in the Indo-Gangetic plain and its role as a major contributor to India's food grain production further underscores the importance of understanding regional climatic dynamics.

Despite the importance of climate information for regional planning, several significant research gaps exist in the understanding of Haryana's climatic patterns:

First, there is limited research focusing on the spatial heterogeneity of climatic patterns within Haryana. Most studies have either analyzed Haryana as part of larger regional analyses of North India or focused on specific districts without establishing comprehensive spatial relationships (Singh et al., 2019). This has resulted in insufficient understanding of microclimatic zones within the state that could inform targeted adaptation strategies.

Second, seasonal transitions and their shifting patterns have received inadequate attention in research literature. While monsoon patterns have been studied extensively, the characteristics of pre-monsoon, post-monsoon, and winter seasons including their onset, duration, and intensity remain under-researched, despite their significant impact on agricultural planning and water resource management (Dhiman et al., 2020).

Third, the interaction between anthropogenic factors (such as urbanization, land-use changes, and irrigation practices) and climatic variations has not been adequately explored in the context of Haryana. Understanding these interactions is crucial for developing integrated approaches to climate resilience (Gautam & van der Hoek, 2019).

Finally, there is a notable absence of long-term comprehensive analyses that integrate multiple climatic parameters to provide holistic insights for policy formulation. Most existing studies focus on individual parameters like rainfall or temperature without examining their interrelationships or cumulative impacts on ecological and agricultural systems (Sharma & Kumar, 2021).

To address the identified research gaps, this study aims to comprehensively analyze the spatial and temporal patterns of key climatic parameters including temperature, precipitation, humidity, and wind patterns across the diverse physiographic zones of Haryana over a 30-year period (1991–2021). It seeks to identify and characterize seasonal variations by examining shifts in the onset, duration, and intensity of different seasons, with a particular focus on their implications for agriculture. Additionally, the study will investigate trends and distribution patterns of extreme weather events such as heatwaves, cold waves, heavy precipitation, and droughts across the state. A critical component involves assessing the relationship between climatic variations and anthropogenic factors like urbanization, agricultural practices, and water resource utilization. Ultimately, the research aims to develop a comprehensive climatological zonation of Haryana by integrating multiple climatic parameters to support the formulation of region-specific adaptation strategies.

2. Methodology

2.1 Study Area

This research focuses on the state of Haryana, which covers an area of approximately 44,212 km² in northern India. For analytical purposes, the state was divided into four physiographic zones: (1) Northern Zone (Shivalik foothills), (2) Central Zone (Yamuna-Ghaggar plain), (3) Southern Zone (Aravalli outcrops and plains), and (4) Western Zone (semi-arid region bordering Rajasthan). The study encompassed all 22 districts of Haryana, ensuring comprehensive spatial coverage.

2.2 Data Sources

Meteorological Data

Daily records of temperature (maximum and minimum), precipitation, relative humidity, wind speed, and wind direction for the period 1991–2021 were obtained from three primary sources: 15 weather stations operated by the India Meteorological Department (IMD), 22 Automatic Weather Stations managed by the Haryana Space Applications Centre (HARSAC), and 8 stations under the Agricultural Meteorology Division of CCS Haryana Agricultural University.

Satellite-derived Data

Satellite data included MODIS Land Surface Temperature (LST) products (MOD11A1 and MYD11A1) at 1-km spatial resolution for 2000–2021, CHIRPS rainfall estimates at 0.05° resolution, and ERA5 reanalysis datasets from the European Centre for Medium-Range Weather Forecasts (ECMWF), offering consistent climatic coverage over large spatial scales.

Agricultural and Land Use Data

Land use/land cover maps were sourced from the National Remote Sensing Centre (NRSC) for the years 1991, 2001, 2011, and 2021. Cropping pattern data were obtained from the Department of Agriculture, Haryana, while groundwater level records were collected from the Central Ground Water Board.

Socioeconomic Data

Socioeconomic datasets included district-level population density and urbanization from Census 1991, 2001, and 2011, with projected estimates for 2021. Industrial development indices were compiled from the Department of Industries and Commerce, Haryana, to assess anthropogenic pressures.

2.3 Data Processing and Quality Control

All weather station datasets underwent rigorous preprocessing, including outlier detection using the modified Z-score method and homogeneity testing with the Standard Normal Homogeneity Test (SNHT) and Pettitt test. Missing data were imputed using spatially-informed multiple imputation techniques, and cross-validation was performed using satellite-derived datasets to ensure consistency. Satellite data were processed via Google Earth Engine to standardize spatial and temporal resolutions. Where station data were sparse, reanalysis products were blended to construct a continuous daily climatic dataset.

2.4 Analytical Methods

Trend Analysis

To assess long-term trends, the Mann-Kendall test and Sen's slope estimator were applied. Seasonal trend decomposition using LOESS (STL) helped isolate seasonal, trend, and residual components. Additionally, the Innovative Trend Analysis (ITA) method was used to detect non-monotonic variations in extreme events.

Spatial Analysis

Spatial continuity was achieved through Kriging and Inverse Distance Weighted (IDW) interpolation. Empirical Orthogonal Function (EOF) analysis identified dominant spatial modes, while Geographically Weighted Regression (GWR) examined spatial non-stationarity in climate-land use relationships.

Seasonal Variation Analysis

Seasonal onset and withdrawal were determined using the cumulative anomaly approach. Spectral and wavelet analyses identified periodicities and evolving seasonal patterns, complemented by moving window analysis to detect temporal shifts.

Extreme Events Analysis

Extreme temperature and precipitation events were quantified using percentile-based thresholds (90th, 95th, and 99th). Return periods were estimated through Generalized Extreme Value (GEV) distributions, while drought conditions were assessed using SPI and SPEI indices.

Integration and Classification

Principal Component Analysis (PCA) was used to reduce variable dimensionality. Climatological zonation was performed using hierarchical clustering and Self-Organizing Maps (SOM). Classification And Regression Trees (CART) identified the most influential climatic and anthropogenic drivers of spatial variability.

2.5 Statistical Software and Validation

All statistical analyses were conducted using R (version 4.1.2), utilizing packages such as *climatol*, *trend*, *extremes*, and *spatstat*. Geospatial analyses were performed using ArcGIS Pro 2.9 and QGIS 3.22. Model reliability was ensured through 10-fold cross-validation, with performance evaluated using RMSE, MAE, and R^2. Classification accuracy was assessed using confusion matrices and kappa statistics.

3. Results

3.1 Temperature Patterns and Trends

3.1.1 Spatial Distribution of Temperature

The spatial analysis of temperature across Haryana revealed distinct regional variations influenced by topography, urbanization, and agricultural practices. Table 1 presents the district-wise annual mean maximum and minimum temperatures, revealing significant spatial heterogeneity across the state.

Table 1: District-wise Annual Mean Maximum and Minimum Temperatures (1991-2021)

District	Mean Maximum Temperature (°C)	Mean Minimum Temperature (°C)	Diurnal Temperature Range (°C)

Panchkula	31.2 ± 0.4	15.7 ± 0.3	15.5 ± 0.5
Ambala	31.8 ± 0.5	16.4 ± 0.4	15.4 ± 0.6
Yamunanagar	32.5 ± 0.4	17.1 ± 0.3	15.4 ± 0.5
Kurukshetra	32.9 ± 0.5	17.3 ± 0.4	15.6 ± 0.6
Kaithal	33.8 ± 0.5	17.8 ± 0.4	16.0 ± 0.6
Karnal	33.1 ± 0.5	17.5 ± 0.4	15.6 ± 0.6
Panipat	33.5 ± 0.5	18.1 ± 0.4	15.4 ± 0.6
Sonipat	34.2 ± 0.6	18.5 ± 0.5	15.7 ± 0.7
Jind	34.9 ± 0.6	18.6 ± 0.5	16.3 ± 0.7
Fatehabad	35.8 ± 0.6	19.1 ± 0.5	16.7 ± 0.7
Sirsa	36.4 ± 0.7	19.5 ± 0.6	16.9 ± 0.8
Hisar	35.9 ± 0.7	19.3 ± 0.6	16.6 ± 0.8
Bhiwani	35.7 ± 0.7	19.2 ± 0.6	16.5 ± 0.8
Rohtak	34.7 ± 0.6	19.0 ± 0.5	15.7 ± 0.7
Jhajjar	34.8 ± 0.6	19.2 ± 0.5	15.6 ± 0.7
Gurugram	35.2 ± 0.7	19.8 ± 0.6	15.4 ± 0.8
Faridabad	35.3 ± 0.7	19.9 ± 0.6	15.4 ± 0.8
Palwal	35.1 ± 0.7	19.6 ± 0.6	15.5 ± 0.8
Nuh	34.8 ± 0.7	19.4 ± 0.6	15.4 ± 0.8
Rewari	35.4 ± 0.7	19.5 ± 0.6	15.9 ± 0.8
Mahendragarh	35.6 ± 0.7	19.6 ± 0.6	16.0 ± 0.8
Charkhi Dadri	35.5 ± 0.7	19.3 ± 0.6	16.2 ± 0.8

3.1.2 Temporal Trends in Temperature

The Mann-Kendall trend analysis revealed significant warming trends across Haryana during the study period. The average annual mean temperature increased at a rate of 0.26°C per decade ($p < 0.01$). However, the warming was not uniform across seasons or regions.

The most pronounced warming was observed during summer (March-June), with an increase of 0.34°C per decade, followed by post-monsoon (October-November) at 0.29°C per decade. Winter temperatures (December-February) showed a more moderate increase of 0.21°C per decade, while monsoon season (July-September) exhibited the lowest warming rate at 0.18°C per decade.

Spatially, urban districts (Gurugram, Faridabad) showed significantly higher warming rates (0.32-0.38°C per decade) compared to predominantly rural districts (0.18-0.24°C per decade), indicating the influence of urban heat island effects on regional temperature patterns.

3.2 Precipitation Patterns and Trends

3.2.1 Spatial Distribution of Precipitation

Precipitation exhibited greater spatial variability than temperature across Haryana. The analysis revealed a general northeast-southwest declining gradient, with highest annual precipitation in the Shivalik foothill districts (800-1000 mm) and lowest in the semi-arid western districts (300-400 mm).

The coefficient of variation (CV) of annual precipitation ranged from 25% in the northeastern districts to over 40% in the western districts, indicating higher rainfall variability in the drier regions of the state. Table 2 summarizes the district-wise precipitation characteristics.

Table 2: District-wise Annual Precipitation Characteristics (1991-2021)

District	Annual Mean Precipitation (mm)	Coefficient of Variation (%)	Monsoon Contribution (%)	Number of Rainy Days (>2.5 mm)
Panchkula	986 ± 162	25.3	78.5	52.3 ± 8.1
Ambala	923 ± 158	26.4	79.1	49.7 ± 7.8
Yamunanagar	897 ± 154	26.9	79.8	48.5 ± 7.6
Kurukshetra	752 ± 138	28.2	80.2	43.2 ± 7.3
Kaithal	621 ± 126	31.3	81.5	37.6 ± 6.9
Karnal	679 ± 132	29.8	80.9	39.8 ± 7.1
Panipat	598 ± 125	32.1	81.7	36.4 ± 6.8
Sonipat	564 ± 122	33.5	82.3	34.2 ± 6.7
Jind	493 ± 118	36.7	83.2	30.5 ± 6.5
Fatehabad	387 ± 109	41.2	84.7	25.3 ± 6.3
Sirsa	352 ± 106	43.1	85.3	23.1 ± 6.2
Hisar	412 ± 112	40.4	84.2	26.8 ± 6.3
Bhiwani	427 ± 114	39.8	83.9	27.5 ± 6.4
Rohtak	546 ± 121	34.2	82.5	33.2 ± 6.6
Jhajjar	532 ± 120	34.7	82.8	32.4 ± 6.6
Gurugram	578 ± 123	32.8	82.1	35.3 ± 6.7
Faridabad	592 ± 124	32.4	81.9	36.1 ± 6.8
Palwal	568 ± 122	33.2	82.3	34.5 ± 6.7
Nuh	542 ± 121	34.3	82.6	33.1 ± 6.6
Rewari	498 ± 118	36.5	83.1	30.8 ± 6.5
Mahendragarh	475 ± 116	37.2	83.5	29.4 ± 6.5
Charkhi Dadri	448 ± 115	38.6	83.8	28.2 ± 6.4

3.2.2 Temporal Trends in Precipitation

The trend analysis revealed no significant change in annual total precipitation across Haryana as a whole during the 30-year period. However, significant changes were observed in precipitation patterns, including:

1. Increased rainfall intensity: The proportion of heavy rainfall events (>30 mm/day) increased by 14% over the study period, while the number of light rainfall events (2.5-10 mm/day) decreased by 8%.
2. Extended dry spells: The average length of dry spells during monsoon season increased from 6.3 days in the 1991-2000 decade to 8.7 days in the 2011-2021 decade.

Spatially, the western districts exhibited higher variability in annual precipitation and more pronounced shifts in rainfall patterns compared to the eastern districts. The Sen's slope estimator indicated a significant decreasing trend in winter precipitation (December-February) of approximately 12% over the study period.

3.3 Seasonal Characteristics and Variations

3.3.1 Seasonal Temperature Profiles

The analysis of seasonal temperature profiles revealed distinct seasonal patterns and their variations over the study period.

3.3.2 Seasonal Precipitation Profiles

The seasonal precipitation analysis revealed significant changes in rainfall distribution patterns. Table 3 presents the seasonal distribution of precipitation and its changes over the study period.

Table 3: Seasonal Distribution of Precipitation and Decadal Changes (1991-2021)

Season	Mean Precipitation (mm)	Contribution to Annual (%)	Change 1991-2021 (%)	CV (%)
Winter (Dec-Feb)	45.2 ± 18.7	7.8	-12.3*	41.4
Pre-monsoon (Mar-Jun)	54.7 ± 22.3	9.4	+5.7	40.8
Monsoon (Jul-Sep)	475.3 ± 84.6	81.5	+2.1	17.8
Post-monsoon (Oct-Nov)	8.1 ± 4.6	1.3	-8.2	56.7
Annual	583.3 ± 94.8	100	-0.5	16.3

*Statistically significant at $p < 0.05$

The analysis revealed an increasing concentration of rainfall within the monsoon season, with pre-monsoon rainfall showing a slight increasing trend and winter and post-monsoon rainfall exhibiting decreasing trends. The coefficient of variation (CV) was highest for post-monsoon rainfall, indicating high inter-annual variability during this period.

3.4 Extreme Weather Events

3.4.1 Temperature Extremes

The analysis of temperature extremes revealed an increasing trend in both frequency and intensity of heatwaves across Haryana.

The key findings regarding temperature extremes include:

1. The frequency of heatwave days increased by 68% in the western region, 57% in the central region, 53% in the southern region, and 42% in the northern region over the study period.

2. The intensity of heatwaves (average maximum temperature during heatwave episodes) increased by 1.2°C over the study period.
3. Cold wave occurrences decreased by 38% across the state, with the most significant reduction observed in the northern region (52%).
4. The frequency of tropical nights (minimum temperature > 25°C) increased by 45% in urban areas compared to 23% in rural areas.

3.4.2 Precipitation Extremes

The analysis of precipitation extremes revealed significant changes in rainfall patterns across Haryana. Table 4 presents the trends in various precipitation extreme indices over the study period.

Table 4: Trends in Precipitation Extreme Indices for Haryana (1991-2021)

Index	Definition	Northern Region	Central Region	Southern Region	Western Region
R10mm	Annual count of days with precipitation ≥ 10mm	-0.4 days/decade	-0.5 days/decade	-0.6 days/decade	-0.7 days/decade
R20mm	Annual count of days with precipitation ≥ 20mm	+0.3 days/decade	+0.2 days/decade	+0.1 days/decade	+0.1 days/decade
R95p	Annual total precipitation when daily precipitation > 95th percentile	+12.3 mm/decade	+10.8 mm/decade	+9.5 mm/decade	+8.2 mm/decade
CDD	Maximum number of consecutive dry days	+1.3 days/decade*	+1.8 days/decade*	+2.1 days/decade*	+2.6 days/decade*
SDII	Simple daily intensity index (annual total precipitation divided by the number of wet days)	+0.7 mm/day/decade*	+0.8 mm/day/decade*	+0.9 mm/day/decade*	+1.0 mm/day/decade*

*Statistically significant at $p < 0.05$

The results indicate a clear shift toward more intense precipitation events with longer dry spells in between, particularly in the western and southern regions of Haryana. The frequency of light rainfall events decreased across all regions, while extreme precipitation events (R95p) increased, indicating a more erratic rainfall pattern.

3.5 Climatic Zonation of Haryana

Based on the integrated analysis of temperature, precipitation, and seasonal characteristics, a climatic zonation of Haryana was developed using hierarchical cluster analysis.

1. **Humid Sub-montane Zone**: Covering the northeastern districts (Panchkula, Ambala, Yamunanagar), characterized by relatively high precipitation (>800 mm annually), moderate temperatures, and significant seasonal variations.
2. **Sub-humid Continental Zone**: Encompassing the central-eastern districts (Kurukshetra, Karnal, Panipat, Sonipat), with moderate precipitation (550-800 mm) and continental temperature regime.
3. **Semi-arid Transitional Zone**: Including the central districts (Jind, Rohtak, Jhajjar, Gurugram), with moderate to low precipitation (450-550 mm) and higher temperature fluctuations.
4. **Arid Plains Zone**: Covering the western districts (Sirsa, Fatehabad, Hisar, Bhiwani), characterized by low precipitation (<400 mm), high temperatures, and pronounced aridity.
5. **Semi-arid Southern Zone**: Encompassing the southern districts (Mahendragarh, Rewari, Nuh), characterized by low to moderate precipitation (400-500 mm), high temperatures, and influence of Aravalli topography.

The climatic zones showed distinct trends in climate variables over the study period, with the Arid Plains Zone exhibiting the most pronounced changes in terms of temperature increase and precipitation variability.

4. Discussion

4.1 Spatial Patterns and Their Drivers

The spatial analysis of climatic parameters across Haryana revealed significant heterogeneity influenced by multiple factors. The northeast-southwest temperature gradient aligns with the general pattern observed across the Indo-Gangetic plain and is primarily driven by topographical variations and distance from the Himalayan influence (Kumar et al., 2020). However, this study identified important local deviations from the regional pattern, particularly around urban centers and intensively irrigated agricultural zones.

The urban heat island effect was quantified for major cities in Haryana, with Gurugram and Faridabad showing temperature differentials of 2.7°C and 2.4°C, respectively, compared to surrounding rural areas during summer nights. This finding is consistent with studies by Mohan et al. (2021) who reported similar urban-rural temperature gradients in the National Capital Region. The intensity of urban heat islands showed a significant correlation with population density ($r = 0.78$, $p < 0.01$) and built-up area expansion ($r = 0.82$, $p < 0.01$), highlighting the anthropogenic influence on local climate patterns.

The precipitation gradient across Haryana reflects the interaction between monsoon circulation patterns and topography. The higher rainfall in the northeastern districts can be attributed to their proximity to the Shivalik Hills, which facilitates orographic lifting of moisture-laden monsoon winds. Conversely, the southwestern districts fall in the rain shadow of the Aravalli range and are further from the primary monsoon circulation, resulting in lower and more variable precipitation (Singh et al., 2019). The present study advances our understanding by quantifying the local modulations in this gradient due to land use changes and water management practices.

Areas with extensive irrigation networks, particularly in the central districts, showed reduced diurnal temperature range and slightly enhanced pre-monsoon rainfall compared to non-irrigated areas with similar geographical characteristics. This irrigation-climate feedback mechanism, observed in this study, aligns with findings by Prasad et al. (2022) in Punjab, indicating that intensive agricultural practices can modify local climate patterns through changes in surface energy balance and moisture availability.

The climatic zonation developed in this study provides a more nuanced understanding of Haryana's climate compared to previous classifications that treated the state as part of broader regional zones. The identification of five distinct climatic zones with different vulnerability profiles offers a valuable framework for developing targeted adaptation strategies. Particularly, the Semi-arid Transitional Zone, which covers densely populated districts with intensive agriculture, emerges as a critical region requiring focused interventions due to its rapidly changing climatic characteristics.

4.2 Temporal Trends and Climate Change Signals

The observed warming trend of 0.26°C per decade across Haryana exceeds the global average warming rate of 0.18°C per decade reported by the IPCC (2022), indicating that the region is experiencing accelerated warming. This finding aligns with other studies from the Indo-Gangetic plain that have reported above-average warming trends (Dasgupta et al., 2020). The seasonal asymmetry in warming rates, with summer experiencing the most rapid temperature increase, has significant implications for agricultural planning and human health management.

The differential warming between urban and rural areas (0.32-0.38°C vs. 0.18-0.24°C per decade) highlights the compounding effect of urbanization on climate change impacts. This urban-rural gradient has widened over the study period, suggesting that urban areas in Haryana are experiencing climate change at an amplified rate. Similar patterns have been reported by Kothawale et al. (2019) for other rapidly urbanizing regions in northern India.

While annual precipitation totals showed no significant trend, the changing characteristics of rainfall represent a more subtle but potentially more impactful aspect of climate change in the region. The shift toward more intense precipitation events with longer dry spells between them indicates a fundamental alteration in the hydrological cycle. This finding corroborates global climate model projections that suggest an intensification of the hydrological cycle with climate warming (Meehl et al., 2020).

The observed delay in monsoon onset by 5-7 days over the study period represents a significant shift in seasonal timing that has direct implications for agricultural planning. This shift aligns with findings by Mondal et al. (2021) who reported similar delays in monsoon onset across northern India and attributed them to changes in large-scale atmospheric circulation patterns influenced by warming in the Indian Ocean. The decreasing trend in winter precipitation (-12%) is particularly concerning for rabi (winter) crops that depend on winter rainfall for optimal growth. This trend, combined with the observed warming, suggests an intensification of water stress during the winter growing season, which could affect the sustainability of wheat production in the region.

4.3 Extreme Weather Events and Agricultural Implications

The substantial increase in heatwave frequency (42-68% across different regions) represents one of the most significant climate change signals detected in this study. The spatial pattern of this increase, with western districts experiencing the most pronounced change, indicates that already hot and dry regions are becoming more vulnerable to extreme heat. This finding is consistent with the "dry gets drier" paradigm proposed in climate change literature (Feng & Zhang, 2022).

The agricultural implications of these trends are profound. The increasing frequency of heatwaves coinciding with critical crop growth stages can significantly reduce yields, particularly for wheat and mustard which are sensitive to terminal heat stress. Based on the relationship between temperature extremes and crop yields established in previous studies (Kumar et al., 2021), the observed increase in heatwave days could translate to a potential yield reduction of 8-12% for wheat and 15-20% for mustard if current varieties and management practices are maintained.

The changing precipitation patterns, particularly the increase in rainfall intensity (SDII index increased by 0.7-1.0 mm/day/decade) and consecutive dry days (increased by 1.3-2.6 days/decade), present both challenges and opportunities for agricultural water management. While more intense rainfall events can increase soil erosion and waterlogging risks, they also offer opportunities for enhanced water harvesting and storage. The longer dry spells necessitate improvements in soil moisture conservation techniques and possibly adjustments in cropping calendars.

The combined effect of temperature and precipitation changes on agricultural water demand was estimated using the Penman-Monteith equation. The analysis revealed an increase in reference evapotranspiration of approximately 7% over the study period, with the highest increase observed during the summer months. This increase in atmospheric water demand, coupled with more erratic rainfall distribution, suggests a growing gap between water supply and demand that could exacerbate groundwater depletion in the region, which is already a critical concern (Central Ground Water Board, 2022).

4.4 Microclimatic Variations and Local Adaptations

The identification of significant microclimatic variations within the broader climatic zones provides insights into potential adaptation strategies. Areas with similar macro-climatic conditions but different land use characteristics showed distinct microclimatic patterns. For instance, agricultural areas with agroforestry components exhibited reduced temperature extremes (2.3°C lower maximum temperatures during heat waves) compared to areas with monoculture cultivation.

Urban areas with higher green cover (>15% of total area) showed significantly reduced urban heat island effects (mean temperature difference of 1.2°C) compared to those with minimal green cover (<5%). This finding highlights the importance of urban greening as an adaptation strategy for managing urban microclimates in the context of climate change and rapid urbanization.

The analysis of canal-irrigated versus groundwater-irrigated areas revealed distinct microclimatic signatures, with canal-irrigated regions showing higher relative humidity (difference of 8-12%) and lower daytime temperatures (difference of 1.5-2.0°C) during summer months. This irrigation-induced microclimate modification suggests that water management strategies have significant implications beyond agricultural productivity, affecting local climate conditions that can influence human comfort and health.

Topographical variations, particularly in the northeastern and southern parts of Haryana where the terrain is more undulating, created distinct microclimatic niches. Valley locations showed greater diurnal temperature ranges and frost susceptibility compared to adjacent slopes and ridges. This microclimate diversity, often occurring within short distances, offers opportunities for diversified agricultural activities but also necessitates location-specific adaptation strategies.

4.5 Implications for Water Resource Management

The changing climatic patterns identified in this study have profound implications for water resource management in Haryana. The shift toward more erratic rainfall with longer dry spells and more intense wet spells necessitates a reevaluation of water storage and distribution infrastructure. Conventional water management systems designed based on historical rainfall patterns may become increasingly inadequate under changing climate conditions.

The increased rainfall intensity (R95p index increased by 8.2-12.3 mm/decade across different regions) suggests a growing potential for surface runoff and reduced soil moisture recharge if appropriate water harvesting measures are not implemented. This trend, combined with the observed increase in consecutive dry days, indicates a growing disconnect between water availability and agricultural water demand patterns.

Groundwater, which supplies approximately 60% of irrigation water in Haryana (Directorate of Agriculture, Haryana, 2021), faces growing pressure from climate change impacts compounded by increasing agricultural intensification. The climate-induced increase in reference evapotranspiration (7% over the study period) translates to higher crop water requirements, potentially accelerating groundwater depletion in areas already experiencing declining water tables.

Surface water resources, particularly the canal network derived from the Yamuna and Sutlej rivers, are also vulnerable to climate change impacts. The observed changes in seasonal precipitation patterns, particularly the decreasing winter precipitation and more erratic monsoon rainfall, can affect river flows and consequently the reliability of canal irrigation systems. This vulnerability is further exacerbated by increasing water demands from urban and industrial sectors.

The analysis of historical groundwater level data in relation to climatic variables revealed that areas with the highest rates of groundwater depletion also experienced the most significant increases in temperature and rainfall variability. This suggests a compounding effect where climate change exacerbates water scarcity issues through increased demand and potentially reduced recharge.

5. Conclusion

This comprehensive analysis of climatic patterns and seasonal variations in Haryana over a 30-year period (1991-2021) provides critical insights into the changing climate dynamics of this agriculturally important region. The study has successfully addressed the research gaps identified in the introduction, offering a spatially comprehensive analysis of multiple climatic parameters and their interrelationships.

The key conclusions from this research are:

1. Haryana has experienced significant warming (0.26°C per decade) over the study period, with the rate exceeding global averages. This warming has been spatially heterogeneous, with urban areas and the western districts experiencing more rapid temperature increases. Seasonally, summer has shown the highest warming rate, with important implications for heat stress management in both agricultural and human health contexts.
2. While annual precipitation totals have remained relatively stable, significant changes have occurred in rainfall characteristics, including delayed monsoon onset (5-7 days over the study period), increased rainfall intensity, more extended dry spells, and decreased winter precipitation. These changes represent a fundamental shift in the hydrological regime with far-reaching implications for agricultural planning and water resource management.
3. Extreme weather events have shown alarming trends, with heatwave frequency increasing by 42-68% across different regions and cold wave occurrences decreasing by 38%. Precipitation extremes have also intensified, with more concentrated rainfall events separated by longer dry periods. These trends in extremes are likely to present the most immediate climate change challenges for Haryana.
4. The study has identified five distinct climatic zones within Haryana based on integrated analysis of multiple parameters, revealing significant spatial heterogeneity in climate characteristics and trends. This zonation provides a valuable framework for developing region-specific adaptation strategies that account for the differential vulnerability and adaptive capacity across the state.
5. Anthropogenic factors, particularly urbanization and agricultural practices, have significantly influenced local climate patterns, creating distinct microclimatic conditions that can either amplify or moderate regional climate change impacts. These human-induced microclimate modifications offer potential pathways for climate adaptation through strategic land use planning and resource management.

The findings of this study have significant implications for agricultural planning, water resource management, and climate adaptation policies in Haryana. The changing seasonal characteristics necessitate adjustments in cropping calendars and potentially crop choices to align with the shifting climatic patterns.

The increasing frequency and intensity of extreme events call for enhanced early warning systems and climate-resilient infrastructure development.

Water resource management strategies need to be reevaluated in light of the changing precipitation patterns and increasing atmospheric water demand. The growing disconnect between water availability and demand patterns highlights the importance of water conservation, efficient irrigation technologies, and possibly crop diversification toward less water-intensive options in vulnerable regions.

The spatially differentiated climate trends identified in this study emphasize the need for location-specific adaptation strategies rather than one-size-fits-all approaches. The climatic zonation developed here provides a scientific basis for tailoring adaptation measures to the specific challenges and opportunities in different parts of Haryana.

Future research should focus on developing more detailed projections of climate change impacts at local scales, particularly for extreme events that have the most significant societal impacts. There is also a need for integrated assessment of climate-water-agriculture nexus to develop holistic adaptation strategies that consider the complex interactions between these systems.

As Haryana navigates the challenges of climate change while aiming to maintain agricultural productivity and ensure water security, the insights from this comprehensive climatic analysis can inform evidence-based policies and practices that enhance resilience while promoting sustainable development.

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