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Decadal variation of climatic variables in south Tamil Nadu (1990-2020): A comprehensive geospatial analysis with geo ai tools

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Abstract
Climate change is profoundly altering regional climatic patterns, posing significant challenges to environmental management, agriculture, and resource planning. This study examines the decadal variation in key climatic variables viz. precipitation, maximum temperature, and minimum temperature over three decades (1990-2020) in South Tamil Nadu, a region with diverse geography and a climate crucial to its agriculture-driven economy. Using monthly weather data sourced from WorldClim.org and GeoAItool - Google Earth Engine, the study identifies a comprehensive geospatial analysis including spatial and temporal trends in climatic variables during the pre-monsoon (January-May) and monsoon (June-December) seasons across 11 districts in South Tamil Nadu. Results highlight significant variations in temperature and precipitation, underscoring the region's vulnerability to climate change impacts. By offering a detailed interpretation of decadal climate dynamics, this research contributes to strategies for climate adaptation and resilience building. The findings aim to inform regional policy formulation and support sustainable agricultural and environmental planning.

Keywords: Climate change, decadal variation, geo ai, geospatial analysis, precipitation, gis

1. Introduction
Climate change, driven by increasing greenhouse gas concentrations, remains one of the most pressing environmental challenges of the 21st century. Its effects extend beyond the global climate system, profoundly impacting regional weather patterns, biodiversity, and socio-economic activities. South Tamil Nadu, with its distinct geography and climate, is especially vulnerable to these changes. The region's heavy reliance on agriculture and allied sectors makes it highly sensitive to variations in precipitation and temperature, which directly influence water resources and crop productivity. Global studies highlight the critical role of long-term climatic data in understanding decadal trends and their implications. For instance [1] underscored the importance of decadal variability in extreme heat events across Europe, emphasizing the potential for improved predictability using advanced climate models. Similarly, [2] examined the complexities of forecasting decadal climate variability, shedding light on the challenges of regional climate systems. In the Indian context, [3] conducted a spatio-temporal analysis of climatic variables in Jharkhand, revealing significant shifts in temperature and precipitation [4]. documented substantial regional variations in rainfall and temperature across India over decades, while [5] provided insights into regional climate impacts through an analysis of long-term meteorological data in Jharkhand. The IPCC Fifth Assessment Report [6] highlighted global warming trends, particularly in tropical regions, which resonate with observations from South Tamil Nadu [7,8]. Several studies specific to India have detailed changing precipitation patterns, increasing variability, and shifts in the monsoon season [9,10,11]. Research by [12,13] identified declining annual precipitation trends and a rise in drought frequency in Tamil Nadu. Climate variability has also affected biodiversity hotspots in the Western Ghats [14,15]. Furthermore, GIS-based studies have demonstrated the value of high-resolution satellite data in analysing spatiotemporal climate variability in India [16,17,18,19]. Projections for southern India suggest further warming and increased precipitation variability by 2050 [20,21]. Understanding the spatial and temporal variations of climatic variables is essential for effective environmental management, agricultural planning, and policy formulation. Over recent decades, significant

changes in maximum temperature (T-max), minimum temperature (T-min), and precipitation have been observed globally and in India, emphasizing the importance of regional-level studies. The present study examines these parameters over three decades (1990-2020) across 11 districts of South Tamil Nadu. It provides a comprehensive geospatial analysis of climatic trends during the pre-monsoon and monsoon seasons, offering valuable insights into regional climate dynamics.

2. Study area

The study area encompasses the 11 southern districts of Tamil Nadu, namely Dindigul, Pudukottai, Sivagangai, Madurai, Theni, Virudhunagar, Ramanathapuram, Thoothukudi, Tenkasi, Tirunelveli, and Kanyakumari, each showcasing diverse geographical, climatic, and ecological characteristics.

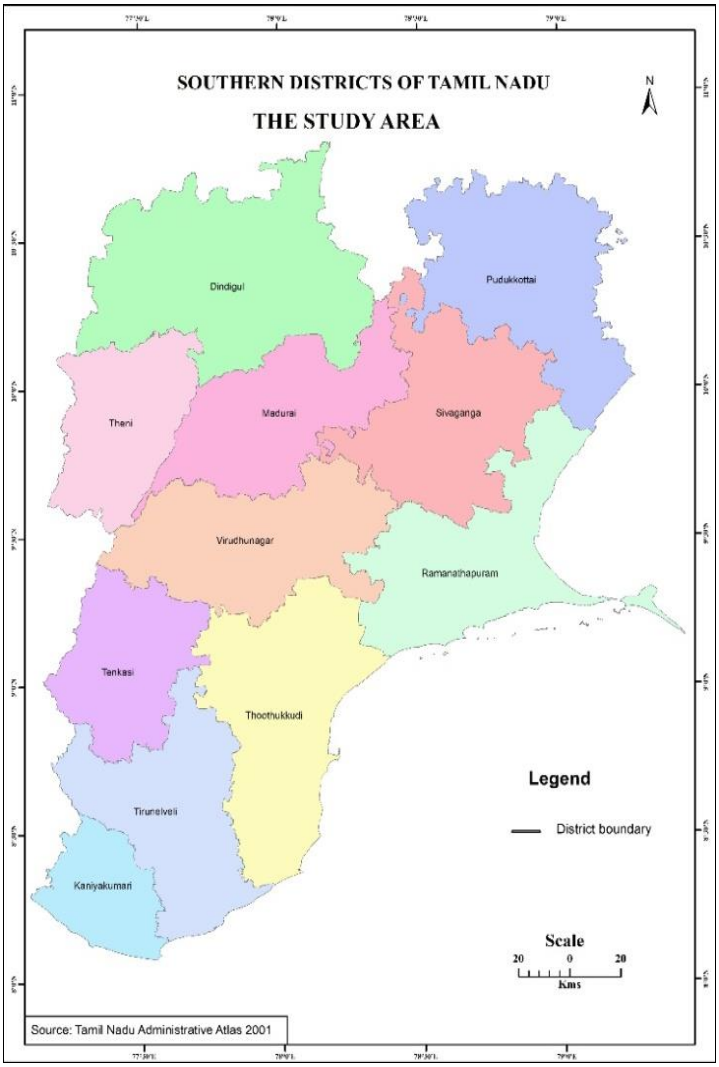

Fig 1: Study area

The coastal districts of Thoothukudi and Ramanathapuram are marked by sandy beaches, mangroves, and their proximity to the Gulf of Mannar, which influences their semi-arid climate, characterized by low rainfall and frequent dry spells. In contrast, districts like Tirunelveli, Kanyakumari, Theni, and Tenkasi, located along the Western Ghats, feature mountainous terrain, dense tropical forests, and significant rainfall, making them vital for biodiversity and hydrological balance. The inland districts, including Madurai, Virudhunagar, Dindigul, Sivagangai, and Pudukottai, are primarily plains with hot climates and sparse vegetation, dominated by scrublands and thorn forests (Fig 1).

These regions are significant for dry land agriculture but face challenges like water scarcity during summer months. Climatically, the southern districts display notable variability, influenced by monsoonal winds and the orographic effects of the Western Ghats. The northeast monsoon is the primary source of annual rainfall, with inland regions experiencing temperature extremes and coastal districts benefitting from moderating sea breezes. Ecologically, the Western Ghats regions, particularly in Kanyakumari, are recognized for their tropical evergreen forests, biodiversity, and ecological significance, while the coastal districts play a crucial role in supporting marine ecosystems and fisheries. Inland districts contribute to agricultural production and water resource management. This diversity in geography, climate, and ecology makes the southern districts of Tamil Nadu an essential area for understanding spatiotemporal variations in climatic parameters, particularly trends in temperature and precipitation over time.

3. Methodology

The methodology for analyzing the spatial and temporal variations of climatic parameters across the 11 southern

districts of Tamil Nadu (1990-2020) integrates advanced GeoAItools for geospatial analysis and comprehensive data sources to ensure accuracy and reliability in the study.

3.1 Data Collection

Monthly climatic data for minimum temperature (°C), maximum temperature (°C), and precipitation (mm) were obtained from https://worldclim.org/ for the years 1990-2020.
Spatial Resolution: 2.5 minutes (~21 km² at the equator).
Data Format: GeoTIFF (.tif).
These datasets are globally recognized for their high reliability and are specifically designed for long-term climate analyses.

3.2 Climatic Parameters

Minimum Temperature (°C): The lowest temperature recorded during night-time or early morning.

Maximum Temperature (°C): The highest air temperature observed during the daytime over 24 hours.

Precipitation (mm): Total water (in all forms) falling to the ground, measured in millimetres.

3.3 Data Pre-processing

The collected climatic data were imported into ArcGIS Pro, powerful GIS software designed for spatial analysis and mapping.
Using ArcGIS Pro, the datasets were:
Clipped: Restricted to the boundaries of the study area comprising the 11 districts of southern Tamil Nadu.
Categorized by Season: The data were divided into pre-monsoon months (January to May) and monsoon months (June to December).

3.4 Spatial Analysis

1. **Spatial Variations**
   ArcGIS Pro was used to map and analyse the spatial patterns of the climatic parameters across the study area.
   Maps highlighting minimum and maximum temperatures and precipitation for both pre-monsoon and monsoon periods were created to identify district-level variations.

2. **Temporal Trends**
   Temporal analysis of climatic parameters over the 30-year period (1990-2020) was conducted to observe long-term trends and anomalies.

3.5 Use of GeoAI - Google Earth Engine

Google Earth Engine (GEE), a cloud-based platform, was employed for additional processing and visualization of satellite imagery.

GEE Capabilities Used

Processing of large-scale climatic data.
Enhanced visualization of spatial and temporal variations.
By leveraging the combined capabilities of ArcGIS Pro and Google Earth Engine, this methodology enabled the precise spatial delineation of climatic variations across the 11 districts, identification of regions with significant climatic anomalies or trends and insights into seasonal differences in temperature and precipitation patterns, providing a comprehensive understanding of the area's climatic dynamics over three decades.

4. Results

4.1 Spatial Variations of Climatic Parameters (1990-2020)

Minimum Temperature (T-Min)

Pre-Monsoon Season

Madurai, Sivagangai, Thoothukudi, Ramanathapuram and Virudhunagar recorded the highest minimum temperatures. Dindigul, Pudukkottai, Kanyakumari, and Tenkasi experienced moderate minimum temperatures, whereas, Tirunelveli and Theni had the lowest minimum temperatures during this period (Fig2).

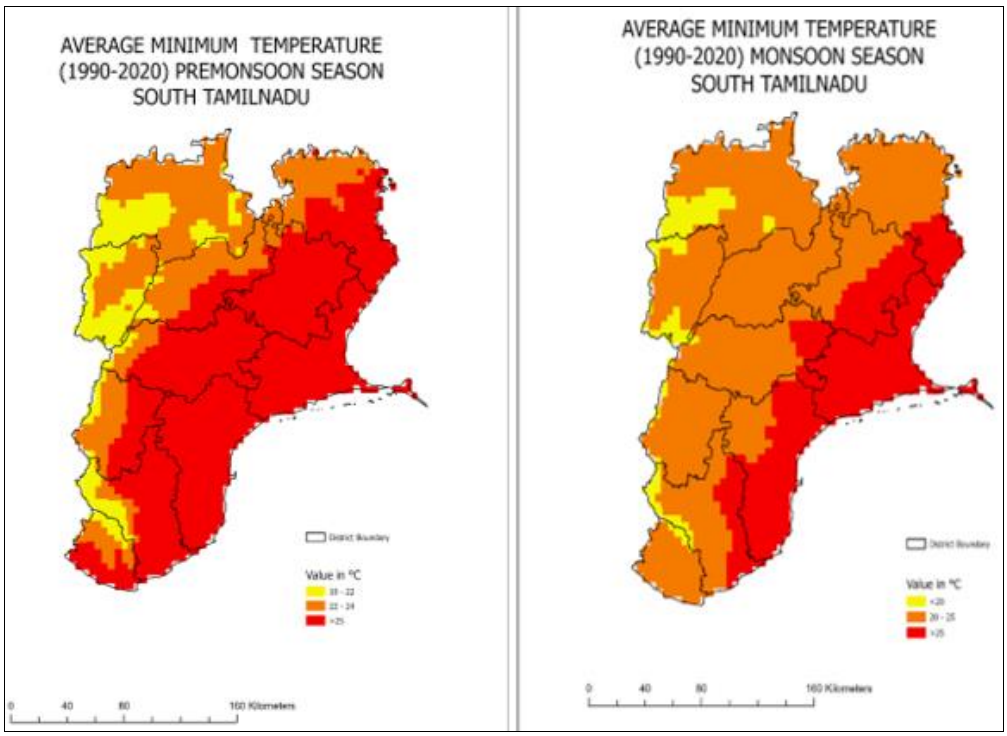

Fig 2: Average minimum temperature-premonsoon and monsoon season in Southern Tamilnadu (1990-2020)

Monsoon Season

High Minimum Temperatures are recorded in Sivagangai, Thoothukudi, and Ramanathapuram. Moderate Minimum Temperatures are seen in Madurai, Pudukkottai, Kanyakumari, and Tenkasi whereaslow Minimum Temperatures are recorded atDindigul, Theni, and Tirunelveli (Fig 2).

Maximum Temperature (T-Max)

Pre-Monsoon Season

High Maximum Temperatures are recorded atKanyakumari, Tenkasi, and Tirunelveli. Moderate Maximum Temperatures are seen atSivagangai, Theni, Thoothukudi, and Madurai, whereas,low Maximum Temperatures are recorded inDindigul, Pudukkottai, and Ramanathapuram(Fig 3).

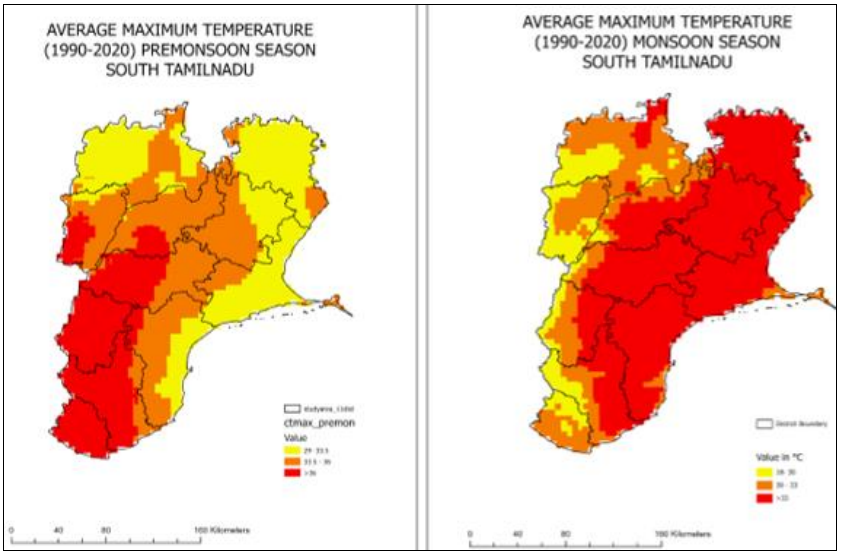

Fig 3: Average maximum temperature-premonsoon and monsoon season in Southern Tamilnadu (1990-2020)

Monsoon Season

High Maximum Temperatures: Thoothukudi, Madurai, Sivagangai, Virudhunagar, Pudukkottai, Ramanathapuram, and Tirunelveli. Moderate Maximum Temperatures: Tenkasi and Kanyakumari. Low Maximum Temperatures: Dindigul and Theni. (Fig 3).

Precipitation

Pre-Monsoon Season

High Precipitation is recorded inTheni, Tenkasi, and Kanyakumari. Moderate Precipitation is observed in Madurai and Virudhunagar. Low Precipitation is atThoothukudi, Ramanathapuram, Sivagangai, Pudukkottai, and Dindigul (Fig 4).

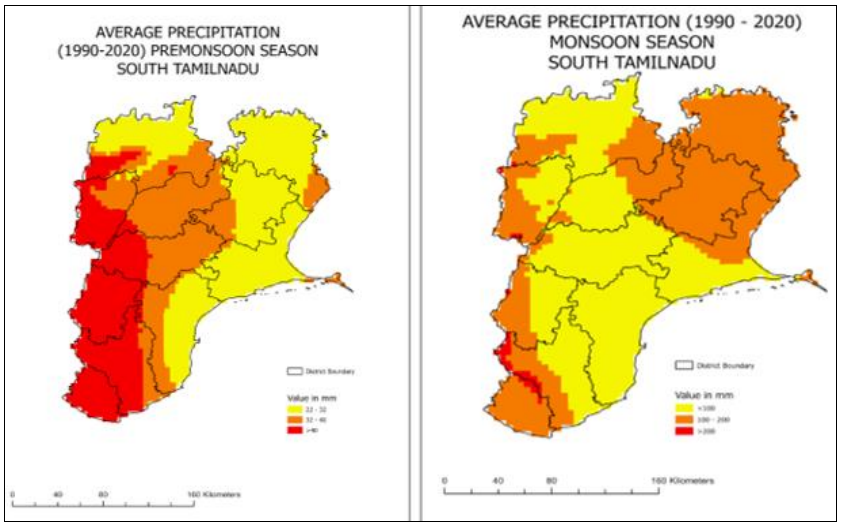

Fig 4: Average Precipitation-premonsoon and monsoon season in Southern Tamilnadu(1990-2020)

Monsoon Season

Specific parts of Tirunelvelirecords high precipitation. Moderate Precipitation is recorded atPudukkottai, Theni, Sivagangai, and Kanyakumari. Low Precipitation is seen inThoothukudi, Tirunelveli, Ramanathapuram, Dindigul, Madurai, and Virudhunagar (Fig 4).

4.2 Temporal Variations of Climatic Parameters (1990-2020)

Temperature Trends

Maximum Temperature (T-Max): Pre-Monsoon Season

Trend: Increasing trend with the highest T-max recorded in 2020 (36.4°C) and the lowest in 1990 (24.8°C).

Observation: The upward trend signifies a warmer pre-

monsoon season with more intense heat waves (Fig 5).

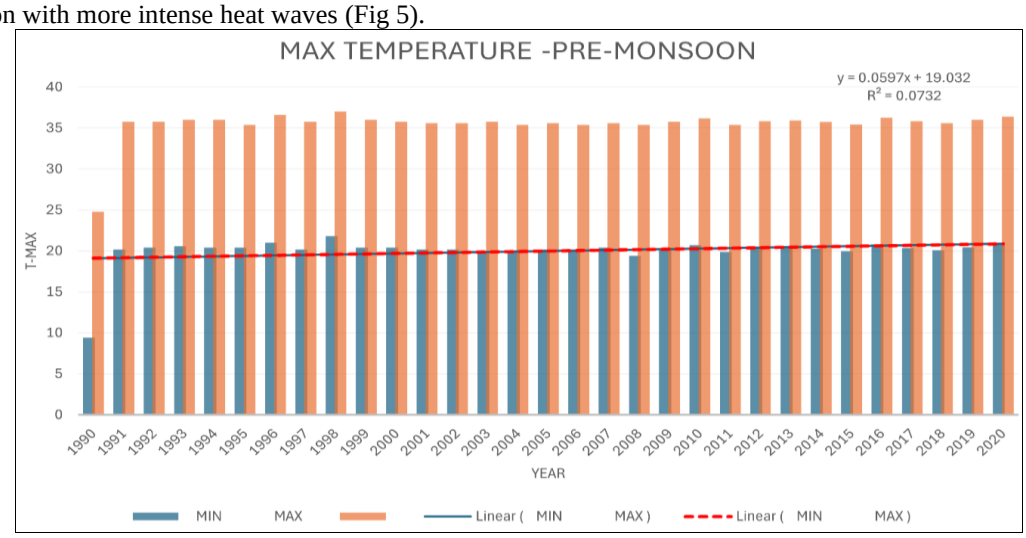

Fig 5: Maximum temperature-pre-monsoon

Minimum Temperature (T-Min): Pre-Monsoon Season
Trend: Increasing trend, with the highest T-min in 2016 (11.016°C) and the lowest in 1992, 1994, 1996, and 1999 (9.4°C).
Observation: Warmer nights indicate a narrowing diurnal temperature range, consistent with global warming (Fig 6).

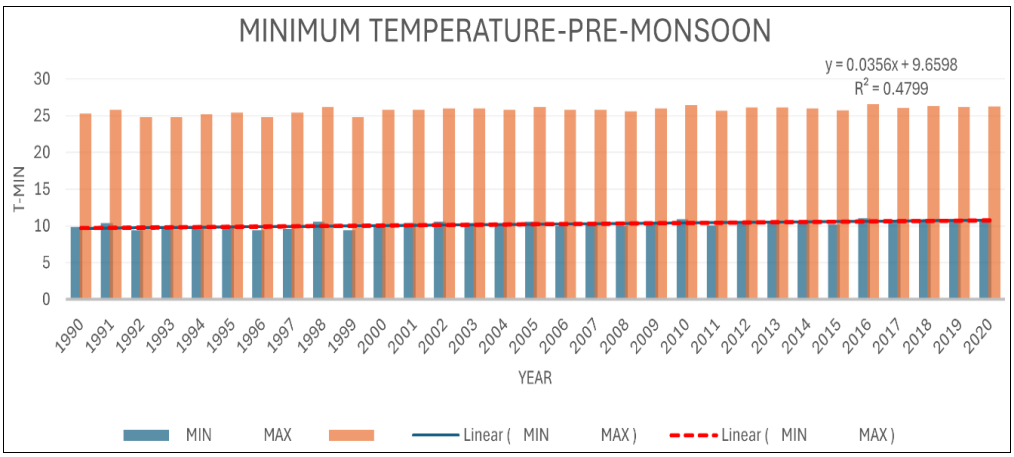

Fig 6: Minimum temperature-pre-monsoon

Maximum Temperature (T-Max): Monsoon Season
Trend: Increasing trend with a gradual rise from 34.8571°C (1991) to 35.5714°C (2020). Observation: The warmer monsoon seasons impact evaporation rates and humidity (Fig 7).

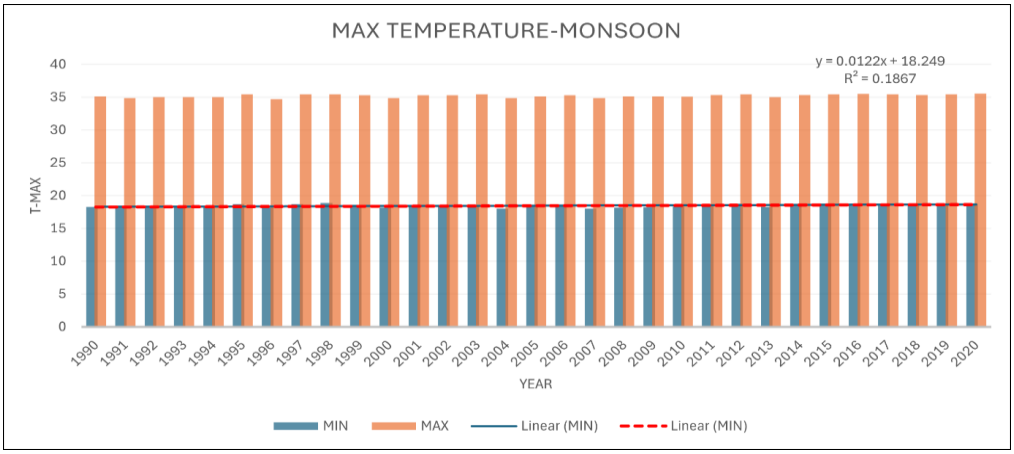

Fig 7: Maximum Temperature Monsoon Season

Minimum Temperature (T-Min): Monsoon Season
Trend: Consistent increase, with the highest minimum temperature recorded in 2016 (11.272°C) and the lowest in 1992 and 1993 (10.2857°C).

Observation: Warmer monsoon nights contribute to ecological changes and human discomfort (Fig 8).

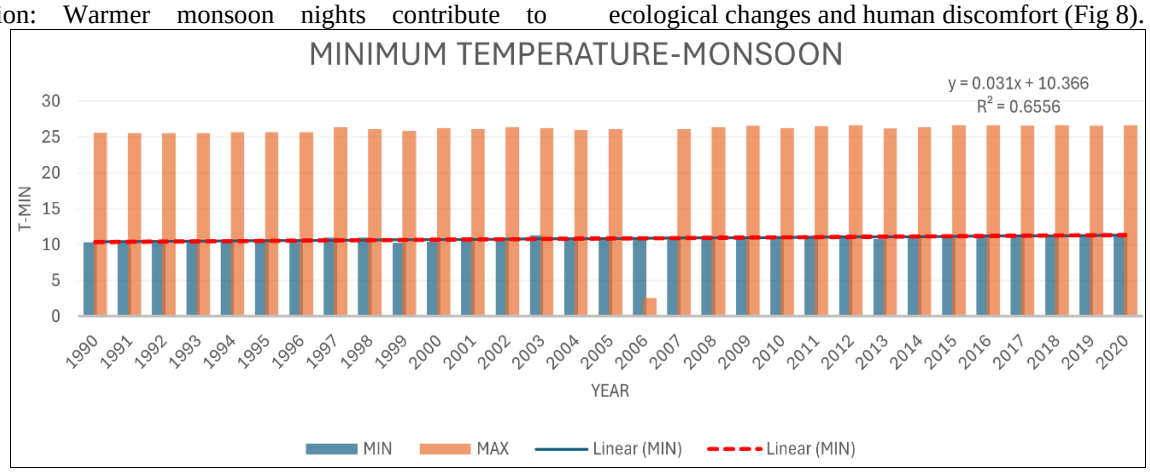

Fig 8: Minimum Temperature Monsoon Season

4.3 Precipitation Trend: Pre-Monsoon Season

Trend: High inter-annual variability, with wet years like 1995 and 2015 and dry years such as 1992 and 2012.

Observation: The fluctuations indicate an increased frequency of extreme weather events (Fig 9).

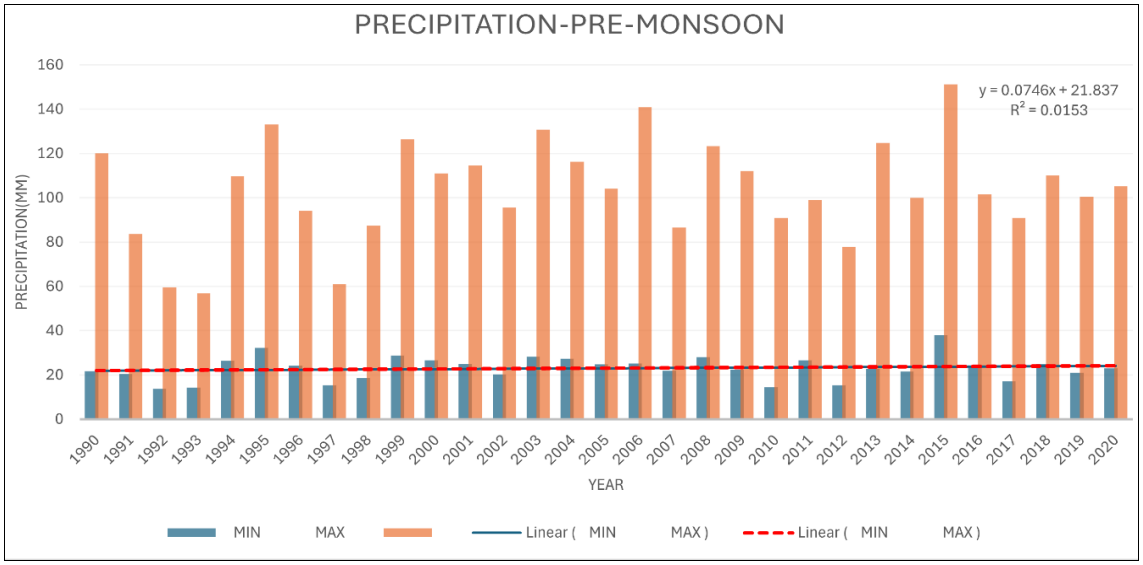

Fig 9: Precipitation- Pre-Monsoon Season

Monsoon Season

Trend: Fluctuations with high rainfall years such as 1992 and 2010 and low rainfall years like 1995 and 2016.

Observation: The variability in monsoon precipitation highlights the unpredictability of monsoon patterns (Fig 10).

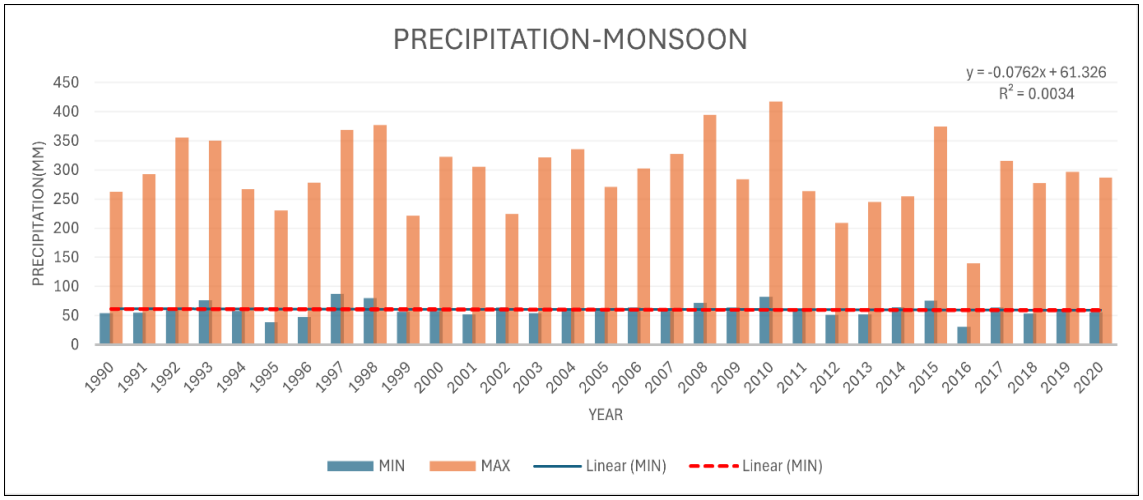

Fig 10: Precipitation-Monsoon Season

5. Discussion

This study analyzed the spatial and temporal variations in key climatic parameters maximum temperature (T-max), minimum temperature (T-min), and precipitation across the 11 districts of South Tamil Nadu from 1990 to 2020, offering critical insights into the region's climatic changes.

Spatial Variations

The spatial distribution of climatic parameters revealed significant heterogeneity across districts during both pre-monsoon and monsoon periods:

Minimum Temperature (T-min)

During the pre-monsoon season, higher minimum temperatures were observed in Madurai, Sivagangai, and Thoothukudi, potentially influenced by urban heat island effects and coastal proximity. Conversely, districts like Theni and Tirunelveli, located near the Western Ghats, recorded lower minimum temperatures, reflecting the cooling effect of elevation and dense vegetation. In the monsoon season, the highest minimum temperatures persisted in coastal districts such as Ramanathapuram, while the lowest temperatures remained in hill-adjacent districts like Theni.

Maximum Temperature (T-max)

High maximum temperatures during the pre-monsoon season in districts like Kanyakumari and Tirunelveli can be attributed to their location near the equatorial zone and prevailing dry conditions. Lower temperatures in Dindigul and Ramanathapuram may reflect differences in vegetation cover and land use. During the monsoon season, a shift towards higher maximum temperatures in most districts highlights the general warming trend across the region.

Precipitation:

Pre-monsoon precipitation showed pronounced spatial disparities, with districts like Kanyakumari and Tenkasi receiving higher rainfall due to their proximity to the Western Ghats. In contrast, drier districts like Ramanathapuram experienced consistently low precipitation. Monsoon precipitation revealed high variability, with Tirunelveli showing localized areas of heavy rainfall while other districts experienced significantly reduced precipitation.

Temporal Variations

Temperature Trends

The upward trend in maximum and minimum temperatures aligns with global warming patterns. The consistent increase in minimum temperatures during the pre-monsoon and monsoon periods reflects warmer nights, potentially impacting nocturnal cooling and crop growth cycles. Maximum temperatures during the pre-monsoon period rose significantly, with a peak of 36.4°C in 2020, indicating more frequent heat waves. The monsoon period showed similar warming trends, though less pronounced.

Precipitation Trends

Pre-monsoon and monsoon rainfall exhibited significant inter-annual variability. Notable high-rainfall years like 1995 and 2010 were interspersed with dry years such as 1992 and 2016. The lack of a consistent trend highlights the complexity of regional rainfall patterns influenced by both local and global climate drivers.

Implications of Findings

Agricultural Impact

Rising temperatures during critical agricultural periods may lead to increased evapotranspiration, soil moisture deficits, and stress on water resources. Coupled with unpredictable precipitation patterns, these changes pose a significant threat to crop yields and agricultural livelihoods.

Water Resource Management

Variability in rainfall necessitates improved water management strategies, including rainwater harvesting and sustainable groundwater use, to mitigate water scarcity during dry years.

Urban and Ecosystem Resilience:

Urban areas, especially Madurai and coastal districts, may face amplified heat stress due to the urban heat island effect. Ecosystems near the Western Ghats may experience shifts in biodiversity due to changing temperature and precipitation patterns.

Policy and Climate Adaptation

The observed trends underscore the need for localized climate adaptation strategies, including promoting climate-resilient crops, improving early warning systems for extreme weather events, and strengthening community-based adaptation initiatives.

The findings of this study are consistent with national and global trends of increasing temperatures and more variable precipitation under climate change. These patterns underscore the importance of integrating regional climate studies into broader frameworks for sustainable development and disaster risk reduction. By providing a detailed understanding of spatial and temporal variations in climatic parameters, this study contributes to evidence-based policy formulation and offers a foundation for future research into the regional impacts of climate change.

6. Conclusion

The analysis of decadal variations in climatic parameters in South Tamil Nadu from 1990 to 2020 reveals significant trends and spatial patterns in temperature and precipitation. The findings provide critical insights into the region's evolving climate and its potential implications for agriculture, water resources, and overall environmental management. Both maximum (T-max) and minimum (T-min) temperatures exhibit a consistent upward trend during the pre-monsoon and monsoon seasons. The rise in maximum temperatures indicates hotter pre-monsoon periods and more intense heatwaves, while the increase in minimum temperatures reflects warmer nights. This warming trend contributes to overall higher average temperatures, impacting human health, agriculture, and biodiversity. Precipitation patterns show increased variability, with extreme weather events such as unusually high or low rainfall becoming more frequent during both seasons. The unpredictability of rainfall presents challenges for agricultural planning, water resource management, and flood risk mitigation. Coastal districts like Thoothukudi and Ramanathapuram experience relatively lower precipitation and higher temperatures, reflecting their arid climatic conditions. Districts near the Western Ghats, such as Theni, Tenkasi, and Kanyakumari, show higher precipitation and moderate temperatures due to their unique geographical features. The warming trend and rainfall variability pose significant risks to the region’s agriculture-dependent

economy. Crop yields, water availability, and soil health may be adversely impacted. The observed trends underscore the need for adaptive strategies, including water conservation, climate-resilient crops, and efficient disaster management systems. This study emphasizes the urgency of integrating climate adaptation strategies into regional planning and policy frameworks. By leveraging the findings of this comprehensive geospatial analysis, stakeholders can develop informed strategies to enhance resilience against climate change and ensure sustainable development in South Tamil Nadu.

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Declarations
Conflict of Interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

Ethical Approval Ethical approval not required
Human or Animal rights This article does not contain any studies with human participants or animals performed by any of the authors, since only the secondary data collected at various centres are used in the study.

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