CHAPTER 5
ASSESSING SPATIO-TEMPORAL TRENDS OF RAINFALL AND TEMPERATURE IN GUJARAT'S PHYSIOGRAPHIC REGIONS

5.1 Introduction

The complexities of climate variability are evident across diverse temporal and spatial scales, indicated by observable variations resulting in distinct trends and magnitudes, including irregular rainfall patterns, prolonged dry spells, and temperature extremes (Ghil & Lucarini, 2020). The IPCC AR6 stated that the global temperature during the initial two decades of the 21st century exceeded the 1850-1900 level by 0.9°C (IPCC, 2023). In 2023, global temperature surpassed the 20th century average for the 47th consecutive year since 1977 (Bardan, 2024). The observable trend exhibits a substantial increase in the global annual temperature, with an average increase of 0.08°C per decade since the late 19th century (1880) (NOAA, 2023). The warming trend has recently increased, exceeding the average rate, reaching 0.18°C per decade since 1981 (Malakouti, 2023). A continuous temperature analysis conducted by NASA's Goddard Institute for Space Studies (GISS) reveals that the Earth's average global temperature has increased by at least 1.1°C compared to pre-industrial levels (L. Wang et al., 2023). Regarding variations in rainfall, there has been a substantial increase in occurrences of extreme rainfall events globally in the past few decades (Zhang et al., 2013). These findings stress the urgent need for a comprehensive understanding of the complex nature of climate variables.

Climate variables have been quantified or assessed globally at numerous sites for years, initially with basic and eventually more complex instruments (Adler et al., 2017). Numerous dedicated researchers have focused on the comprehensive study of rainfall and temperature trends, aiming to discern the broader implications of climate change on a global (Daramola & Xu, 2022; Gu & Adler, 2023; Malakouti, 2023) and regional (Ahsan et al., 2022; dos Santos et al., 2022; Todaro et al., 2022) scales. Variability in climate encompasses short-term fluctuations, such as daily or seasonal changes in temperature and rainfall, and long-term alterations that span decades or even centuries, including historical climate trends and global climate change. The western region of India, characterized by substantial climate variability, particularly in Gujarat (Ray et al., 2008), faces several threats. Large portions of Gujarat fall under arid and semi-arid climate zones, characterized by relatively low and irregular rainfall (Machiwal et al., 2016). Most of the state experiences frequent water scarcity, with drought occurring approximately every four years (Bandyopadhyay et al., 2020). The Gujarat State

Action Plan on Climate Change (SAPCC) reveals a significant increase in the state's average temperature, reaching 2.9°C between 1986 and 2019 (Nair, 2021). Projections from the SAPCC suggest that by the end of the 21st century, temperatures may escalate by 5°C, which accentuates the urgency to understand and address these dynamics (Nair, 2021). Additionally, rainfall patterns exhibit substantial changes, reflecting the region's vulnerability to climate variability. There has been an apparent shift in rainfall trends, with irregular and unpredictable rainfall patterns for a few decades (Guhathakurta et al., 2020). Over the last decade, the state has encountered an increase in the frequency and intensity of extreme events (Bandyopadhyay et al., 2016). The GSDMA report reveals a significant increase in the frequency of heatwaves compared to the previous decade, and the number of deaths reported throughout Gujarat has increased from 58 in 2015 to 775 in 2018 (Gujarat State Disaster Management Authority, 2020). Simultaneously, incidents of severe rainfall have increased, contributing to flooding and waterlogging (Ray et al., 2019) in various parts of the state, which poses huge challenges to Gujarat's overall development, exhibiting the tangible impact of variations in climate variables, highlighting the critical need for adaptive measures and trend analysis to comprehend the evolving patterns and inform strategic planning for communities and essential infrastructure.

Undoubtedly, the increasing temperature and rainfall trends, along with increasing variability, highlight the need for rigorous trend analysis methodologies. Recent shifts in climate variables reveal significant trends in hydrometeorological records across various regions. Progressively gaining acclaim among nonparametric techniques, the Mann-Kendall (MK) test, introduced by Mann, 1945 and modified by Kendall, 1975, has garnered recognition and earned the endorsement of the World Meteorological Organization (WMO, 2012) for scrutinizing trends in hydrometeorological time series (Ali et al., 2019). The Mann-Kendall (MK) test is recognized for its several advantages, setting it apart from other analysis techniques. To assess the magnitude of the trend, Sen's Slope Estimator (Sen, 1968; Theil, 1950) has been employed widely on a global (Zhong et al., 2023) and regional (Frimpong et al., 2022; Li et al., 2022; Stefanidis et al., 2022) scale. Although preventing potential errors in identifying substantial concealed short-term trends and overcoming the disadvantages in classical tests, Şen, 2012 introduced the Innovative Trend Analysis (ITA) method, designed for graphical trend assessment across various data value ranges. It effectively addresses the challenges associated with trend detection, which has led to its widespread application in discerning trends within meteorological variables (Caloiero et al., 2018). ITA combines the advantages of conventional tests by discerning the trend's nature based on the slope's sign and evaluating the significance of the detected trend (Swain et al., 2022). This approach enables a thorough analysis of trends in data, providing valuable insights into the behaviour and significance of observed changes over time. An additional benefit of this method is its robustness in the face of a small number of missing data points within a time series, making it suitable for shorter data sequences. It categorized data values in high, medium, and low regimes (Dabanlı et al., 2016).

This chapter focuses on assessing the trends of climate variables across distinct physiographic regions in Gujarat from 1961 to 2020, and its significance lies in comparing outcomes between the MK test and Sen's ITA test. The ITA method identifies trends even when they are non-monotonic, a capability that distinguishes it from the MK test, which detects monotonic trends. This study aims to assess and analyze the results on annual and seasonal scales from different contemporary and traditional tests, contributing to a more comprehensive understanding of the climate variables (Rainfall, T_{min}, and T_{max}) using the high spatial resolution IMD4 dataset of 0.25° x 0.25 ° (Pai et al., 2014) for rainfall and 1° x 1° (Srivastava et al., 2009) for Temperature.

5.2 Methodology

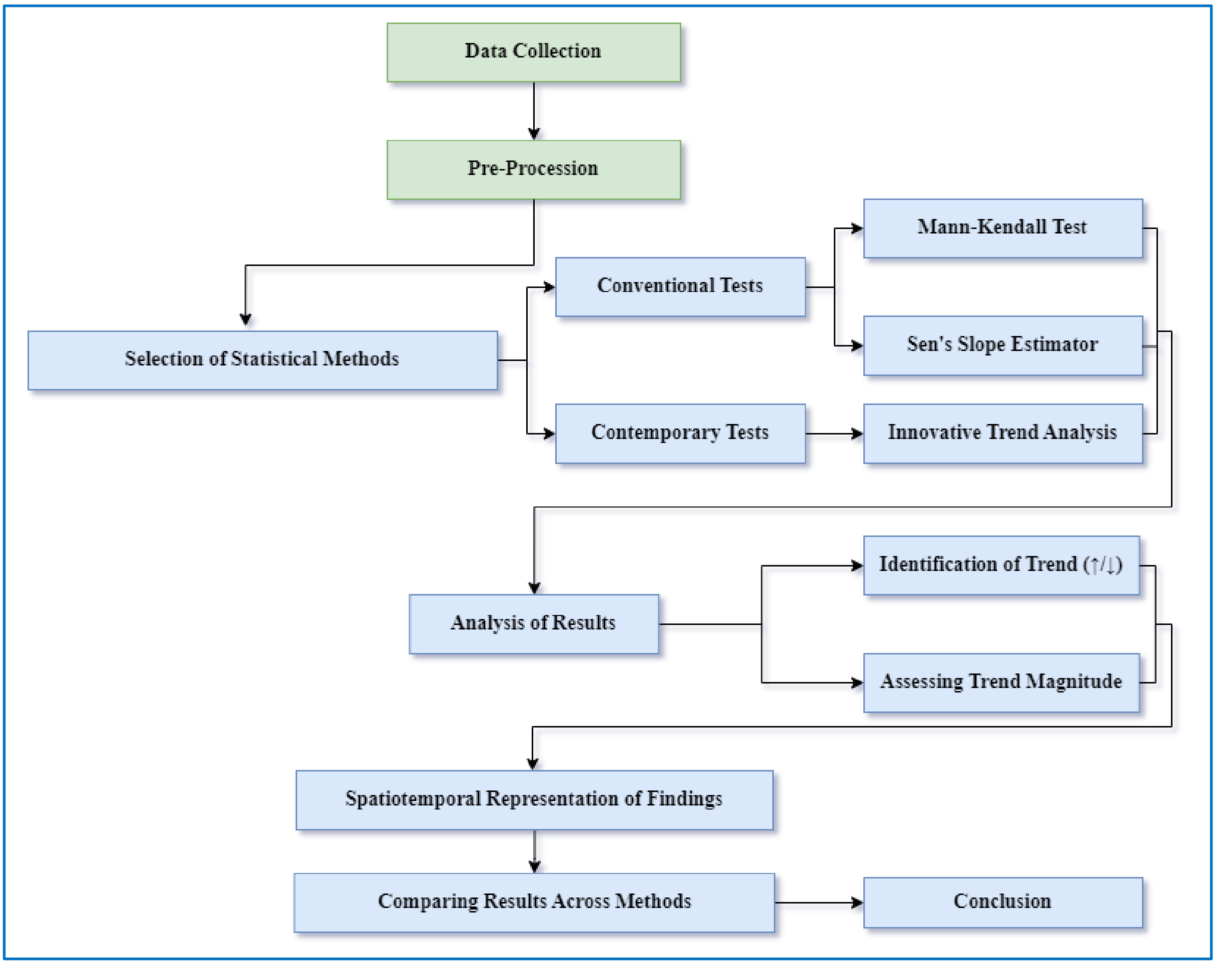


Figure 5.1 Flowchart of the methodology adopted.

Figure 5.1 shows the methodology flowchart used in this study. The preceding chapters covered the study's significance, data sources, study area, literature, and decadal changes in Climate variables. This chapter assesses trends and magnitudes of change in climate variables at 90%, 95%, and 99% CI. The trends have been thoroughly analyzed across multiple time scales, including monthly, seasonal, and annual variations, ensuring a comprehensive understanding of the climate dynamics. The results obtained from different statistical techniques, MK, SSE, and ITA, have been compared across various levels of statistical significance. Additionally, the trends within the series have been assessed across three distinct regimes using ITA, providing a more detailed view of how trends differ across data ranges. The findings presented in this chapter will serve as a foundation for the subsequent chapters, aiding in forecasting variables and enhancing understanding of the region's vulnerability and the nature of extreme events.

5.2.1 Mann-Kendall Test

The Mann-Kendall (Mann, 1945; Kendall, 1975) (MK) test is categorized as a non-parametric statistical method for trend detection and is considered a widely standard technique for assessing monotonic trends in natural language processing (Curiac & Micea, 2023). Numerous scholars have applied the MK test to climatological, meteorological, and hydrological time series (Agbo et al., 2023). The purpose for employing non-parametric statistical tests is the suitability for non-normally distributed and censored data (Monir et al., 2023), which are prevalent in hydro-meteorological time series, in contrast to parametric methods (Monir et al., 2023). The test is widely used when a dataset aligns with a linear relationship (Agbo et al., 2023). The MK test exhibits efficacy in handling skewed variables (Deni et al., 2010), accommodating missing values (Mishra et al., 2009), and exhibiting resilience against the influence of extreme values (Jain & Bhatt, 2022). The MK statistic (S) is used when the time series contains less than 10 values and its calculation is based on the following equation.

$$S = \sum_{i=1}^{n-1} \sum_{j=i=1}^{n} \operatorname{sgn}\left(X_j - X_i\right) \quad (1)$$

Where n refers to the frequency of data points in a series; X_i and X_j are the values in the time series i and j (j > i) (da Silva et al., 2015), and the expression "sgn (X_j - X_i)" corresponds to the sign function.

$$\operatorname{sgn}(X_j - X_i) = \begin{cases} +1 \text{ if } (X_j - X_i) > 0 \\ 0 \text{ if } (X_j - X_i) = 0 \\ -1 \text{ if } (X_j - X_i) < 0 \end{cases} \quad (2)$$

A positive S value denotes an upward trend, while a negative value signifies a downward trend (Agbo et al., 2023). When the dataset has values (n > 10), the standard practice is to employ the normal approximation, specifically the Z_{mk} statistic. The Z_{mk} statistic's value is determined by computing the variance of S, denoted as Var(S).

$$\mathrm{Var(S)} = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{i=1}^{p} T_i i(i-1)(2i+5)\right] \quad (3)$$

Where, T_i is the quantity of data in a tied group, and p is the number of tied rank groups (F. Wang et al., 2020). The standardized test statistic Z_{mk} is calculated using the formula below:

$$\mathrm{Zmk} = \begin{cases} \frac{s-1}{\sqrt{V(s)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{s+1}{\sqrt{V(s)}} & \text{if } S < 0 \end{cases} \quad (4)$$

Analyzing outcomes involves interpreting the Z_{mk} value, where a negative Z_{mk} value indicates a declining trend, while a positive Z_{mk} value signifies an ascending trend. When the p-value is below the pre-established significance level, it shows a significant trend. Conversely, if the p-value is above the significance threshold, the trend is considered insignificant (Agbo et al., 2023). At a significance level of 0.1, a Z_{mk} value exceeding ±1.645 indicates significance. For levels of 0.05 and 0.01, the Z_{mk} value should exceed ±1.960 and ±2.576, respectively.

5.2.2 Sen's Slope

The SSE (Sen, 1968) has found widespread application in meteorological time series and is suitable for situations with data gaps. The SSE, a nonparametric method, can be employed to evaluate the magnitude of a trend in a time series (Panda & Sahu, 2019). The slope for each pair of data points is computed using Sen's method (Atta-ur-Rahman & Dawood, 2017).

$$f(t) = Qt + \beta \quad (5)$$

Where, Q represents the slope, and β is constant. To obtain the slope estimation (Q), the slopes for the entire time series dataset were first calculated.

$$Q_i = \frac{x_j - x_k}{j-k} \quad (6)$$

Where x_j and x_k represent the data values at times j and k (where j > k) (da Silva et al., 2015), When there is one datum point in each period, N equals n (n - 1)/2. However, if there are multiple observations in one or more periods (da Silva et al., 2015), N will be less than n (n - 1)/2. The n values of Q_{med} are arranged in ascending order, and the median, or Sen's slope estimator, is calculated as follows:

$$Q_{med} = \begin{cases} Q_{\left[\frac{N+1}{2}\right]} & \text{if n is odd} \\ \frac{1}{2} Q_{\left[\frac{N}{2}\right]} + Q_{\left[\frac{N+2}{2}\right]} & \text{if n is even} \end{cases} \quad (7)$$

The Q_{med} indicates the data trend. To identify whether the slope significantly differs from zero (da Silva et al., 2015), it's necessary to set a significance level. A positive Q_{med} indicates an increasing trend. However, a negative Q_{med} signifies a decreasing trend (Gajbhiye et al., 2016).

5.2.3 Innovative Trend Analysis (ITA)

The Innovative Trend Analysis introduced by Şen, 2012 provides a modern approach to trend detection using a Cartesian coordinate system (Paramaguru et al., 2023). Unlike other methods, ITA doesn't require assumptions about normality, serial correlation, or sample size, making it more versatile (Seenu & Jayakumar, 2021) and its competent graphical approach to detect the hidden trends in time series (Arab Amiri & Gocić, 2021). The graphical representation reveals hidden sub-trends within the time series. Figure 5.2 shows the schematic representation of the ITA test. Primarily, the time series has split into two equal segments, each sorted independently in ascending order. Subsequently, the first and second halves of the time series are positioned on the X-axis and Y-axis, respectively (Caloiero, 2020). When the data points closely align with the 1:1 (45°) line, it indicates the absence of a significant trend (Figure 5.2c). Data points above this line (in the upper triangle) suggest an upward trend (Figure 5.2b), while data points below the line (in the lower triangle) indicate a downward trend. This graphical representation enables a clear visual assessment of trends based on the positioning of data points relative to the 1:1 line (Paramaguru et al., 2023). Additionally, the ITA provides a distinct advantage by categorizing trends into three regimes: low, medium, and high, allowing for a more detailed analysis across various datasets. This multi-tiered approach enhances the detection of slight variations within different intensity levels (Serinaldi et al., 2020).

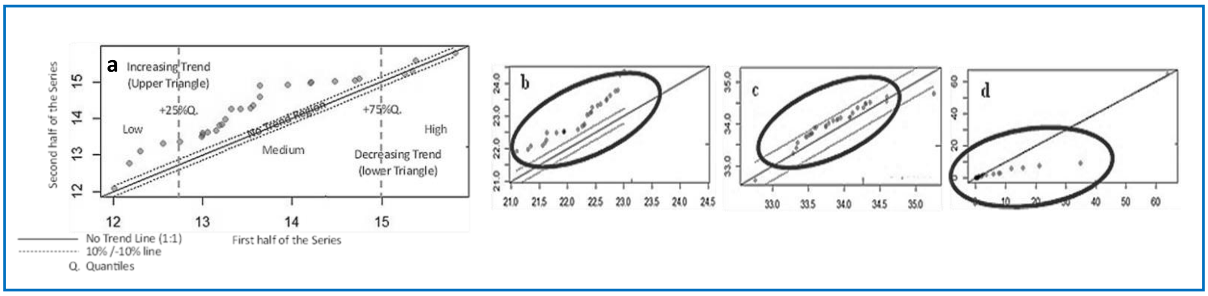


Figure 5.2 (a) Şen's ITA Graph with Percentile Ranges, (b) Data Concentration in Upper Triangle Indicating Upward Trend, (c) Proximity to 1:1 Line Indicating No Trend, (d) Data Concentration in Lower Triangle Indicating Downward Trend.

Source- (Şen, 2012)

5.3 Results and Discussion

5.3.1 Comparative Assessment of Seasonal Trends

Figures 5.3 and 5.4 show the seasonal trends in Rainfall, T_{min}, and T_{max} across physiographic regions using the MK and ITA tests, respectively. Both methods identified trends in seasonal rainfall across distinct regions, with ITA proving more effective in handling the complexities of rainfall data. The ITA method showed a higher sensitivity to minute changes and could detect more intricate trends in rainfall patterns, making it particularly useful for regions with variable and non-linear rainfall data. Although the MK test identified significant trends in a few instances, particularly for Saurashtra during the post-monsoon season, it often failed to produce statistically significant results for rainfall trends at the 90% CI. This suggests that while there may be emerging patterns in rainfall, such as insignificant increases or decreases in certain regions, these changes are not strong enough to be deemed statistically significant based on the MK test. This limitation suggests that the MK test may not fully capture the complexity of seasonal rainfall variability. In contrast, ITA provides a more comprehensive and reliable assessment of seasonal trends, particularly for regions with inconsistent rainfall patterns.

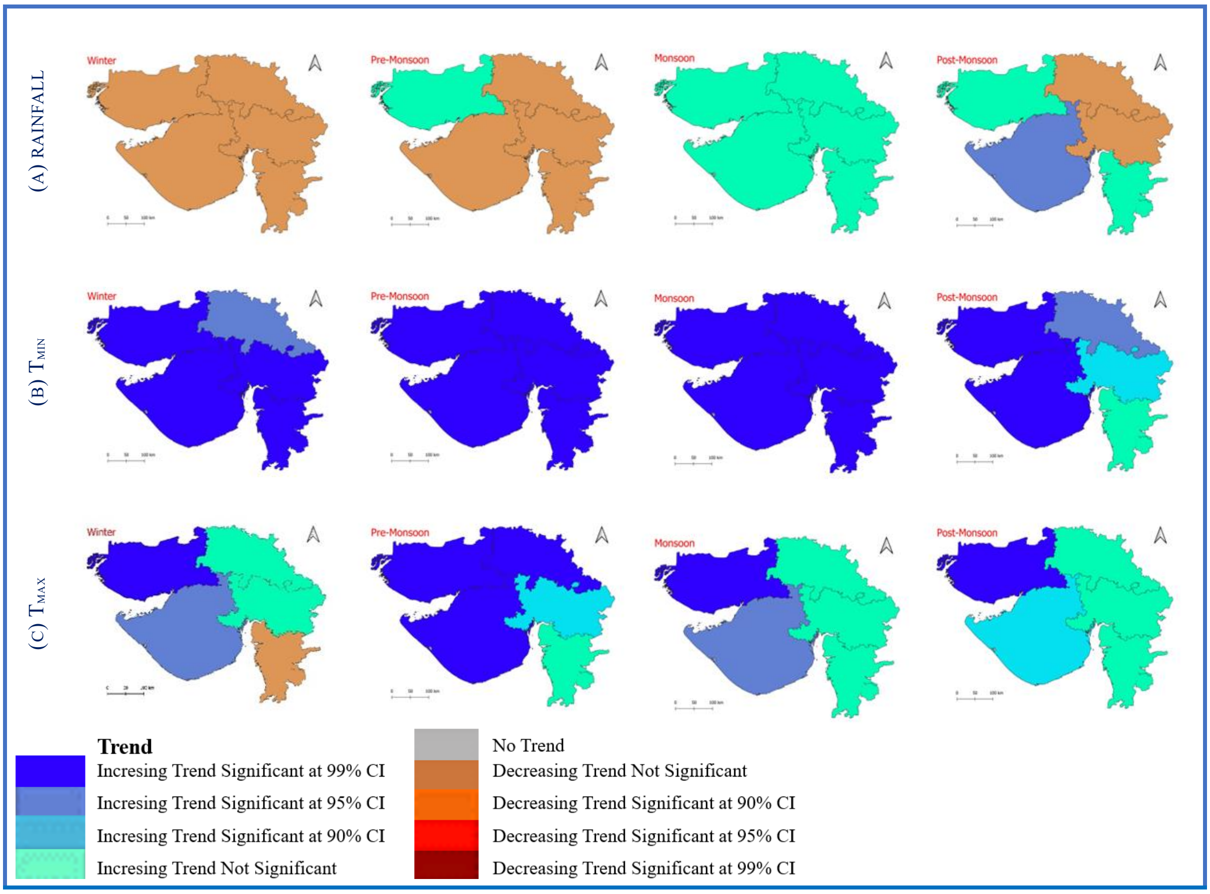


Figure 5.3 Spatio-Temporal Analysis of Seasonal (a) Rainfall, (b) T_{min}, and (c) T_{max} Trends Using the MK Test Across Physiographic Regions of Gujarat.

Although the MK test did not identify significant trends in seasonal rainfall data, it revealed an overall pattern of insignificant increases in rainfall during the SWM season across regions. Specifically, the findings indicate slight, yet statistically insignificant, increases in rainfall in Kutch during both the pre-monsoon and post-monsoon seasons and in South Gujarat during the post-monsoon period. In contrast, the MK test identified an insignificant decrease in rainfall during the winter and pre-monsoon seasons across most regions, except for Kutch, which showed an insignificant increase during the pre-monsoon season. These results suggest variability in rainfall patterns but not strong enough trends to reach statistical significance, highlighting the complexity of seasonal rainfall behaviour across regions. However, the MK test effectively identified significant T_{min} and T_{max} trends across regions. It revealed a robust increase in T_{min} during the pre-monsoon and SWM seasons at 99% CI across regions. Additionally, except for South Gujarat during the post-monsoon season, all regions exhibited statistically significant increasing trends in T_{min} at 90% CI during the winter and post-monsoon seasons. While, T_{max} shows a consistent increasing trend in Kutch and Saurashtra across seasons at 99% and 90% CI, respectively. In contrast, an insignificant increase is observed in Central, North, and South Gujarat during the winter, SWM, and post-monsoon seasons, except for South Gujarat during winter, showing an insignificant downtrend. The findings indicate a consistent warming trend across regions, suggesting shifts in seasonal temperature patterns.

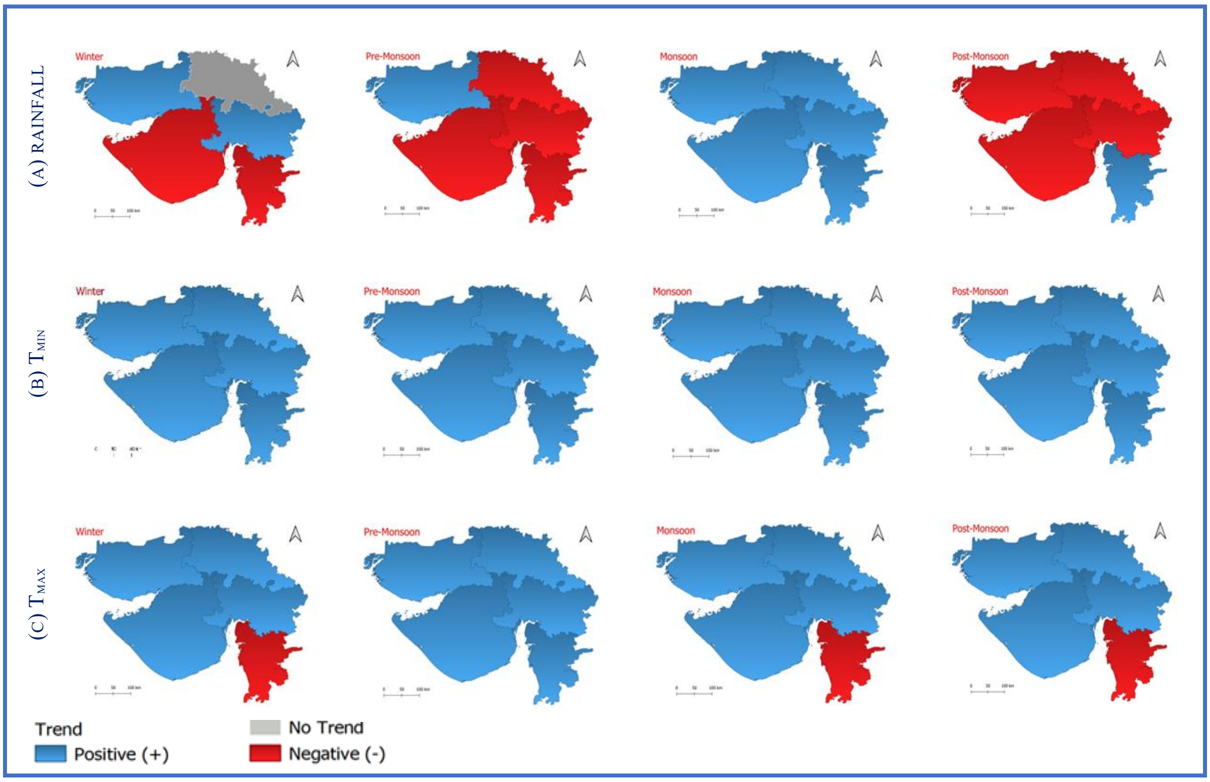


Figure 5.4 Spatio-Temporal Analysis of Seasonal (a) Rainfall, (b) T_{min}, and (c) T_{max} Trends Using the ITA Test Across Physiographic Regions of Gujarat.

However, ITA consistently reveals upward trends in T_{min} and T_{max} across regions, except for T_{max} in South Gujarat (Figure 5.4b, c). This consistent performance highlights the method's reliability in detecting temperature trends across various seasonal intervals. Additionally, no data points were concentrated within the no-trend zone across any season, strengthening the ITA in capturing subtle variations in temperature trends. Table 5.1 presents the categorization of trends identified by the ITA into three distinct regimes: 'Low' values below the 10th percentile, 'Medium' values ranging between the 10th and 90th percentiles, and 'High' values exceeding the 90th percentile (Şen, 2012). This classification enhances the understanding of the varying intensities of trends in Rainfall, T_{min}, and T_{max} across different regions.

Table 5.1 ITA Trends for Rainfall, T_{min}, and T_{max} Across Gujarat's Physiographic Regions.

Region	Rainfall			T_{min}			T_{max}		
	Low	Medium	High	Low	Medium	High	Low	Medium	High
Central Gujarat									
Winter	O↑	↑↑	↑↑	O↑	↑	↑O	↑O	O	O
Pre-Monsoon	O↓	↓↓	↓O	↑	↑O	↑↑	O↑	↑O	O↑
Post-Monsoon	O↓	↓↓	↓↓	↑	↑O	O↑	O↓	O	O↑
SWM	↑O	O	O↓	O↑	↑	↑O	↓O	↑O	O↓
Kutch									
Winter	↓↑	↑↑	↑↑	↑	↑↑	↑	↑O	O↑	↑O
Pre-Monsoon	O↓	↓	↑	↑↑	↑↑	↑↑	↑	↑	↑↑
Post-Monsoon	O↓	↑↓	↑↑	↑↑	↑↑	↑O	O↑	↑	↑
SWM	↑O	O↑	↑↑	↑	↑ O	O	O↑	↑O	O↓
North Gujarat									
Winter	O↑	↓O	↑↑	↑	↑	O ↑	↑O	O ↑	O↑
Pre-Monsoon	O↓	↓↓	↓↓	↑O	O↑	↑↑	O↑	↑O	↑
Post-Monsoon	O↓	↓↓	↑↓	↓O	↑	↓O	↓↑	↑O	O↑
SWM	↑	↑ O	↓↑	↓O	O ↑	↓O	↓↑	↑O	O↓
Saurashtra									
Winter	O	↓↓	↓↓	↑	O↑	O	↑	O↑	↑O
Pre-Monsoon	O↓	↑↓	↑	↑	↑↑	↑↑	↑O	O↑	↑
Post-Monsoon	O↓	↑↓	↓↓	↑↑	↑	O↑	↑O	↑O	↑
SWM	↑↑	O↑	↑↑	↑O	O↑	O	O↑	↑O	O↓
South Gujarat									
Winter	O↓	↓↓	↓↓	↑	↑	O↑	O	O	O↑
Pre-Monsoon	O	O↓	↓	↑	↑	↑↑	O↑	O	O

Post-Monsoon	↑O	O↑	↑↑	↑	↑O	↓O	↓O	O	O
SWM	↑	O↑	↓	O	O↑	↓	↓O	O	O↓

↑ DENOTES AN UPWARD TREND CLOSE TO THE 1:1 LINE IN THE UPPER SECTION OF THE PLOT, WHILE ↑↑ SIGNIFIES A PROLONGED INCREASE AWAY FROM THE 1:1 LINE. CONVERSELY, IN THE LOWER SECTION OF THE PLOT, ↓ INDICATES A CONTINUAL DECLINE NEAR THE 1:1 LINE, ↓↓ INDICATING A MORE PRONOUNCED DECREASE AWAY FROM THE 1:1 LINE. THE SYMBOL ↓↑ IMPLIES AN INITIAL DECREASE FOLLOWED BY A SUBSEQUENT INCREASE. WHEREAS O↑ SHOWS AN INITIAL LACK OF TREND SUCCEEDED BY AN UPWARD TREND, AND ↑O SIGNIFIES AN INITIAL INCREASE TRANSITIONING INTO A LACK OF TREND.

However, the overall trend identified by the ITA indicates an increase in Rainfall, T_{min}, and T_{max} across most regions, except for a few regions during different seasons. The categorization into three distinct categories facilitates a more detailed assessment of trends at a finer scale. This approach not only highlights outliers but also provides insights into their behaviour and impacts. This analysis provides a deeper understanding of regional climate dynamics and helps identify specific regions that may require targeted interventions or further investigation. While quantifying the magnitude of seasonal trends, Figure 5.5 shows the trend slopes across time series using SSE. This approach effectively captures the rate of change in Rainfall, T_{min}, and T_{max}, providing a robust measure even in the presence of outliers or non-normal distributions.

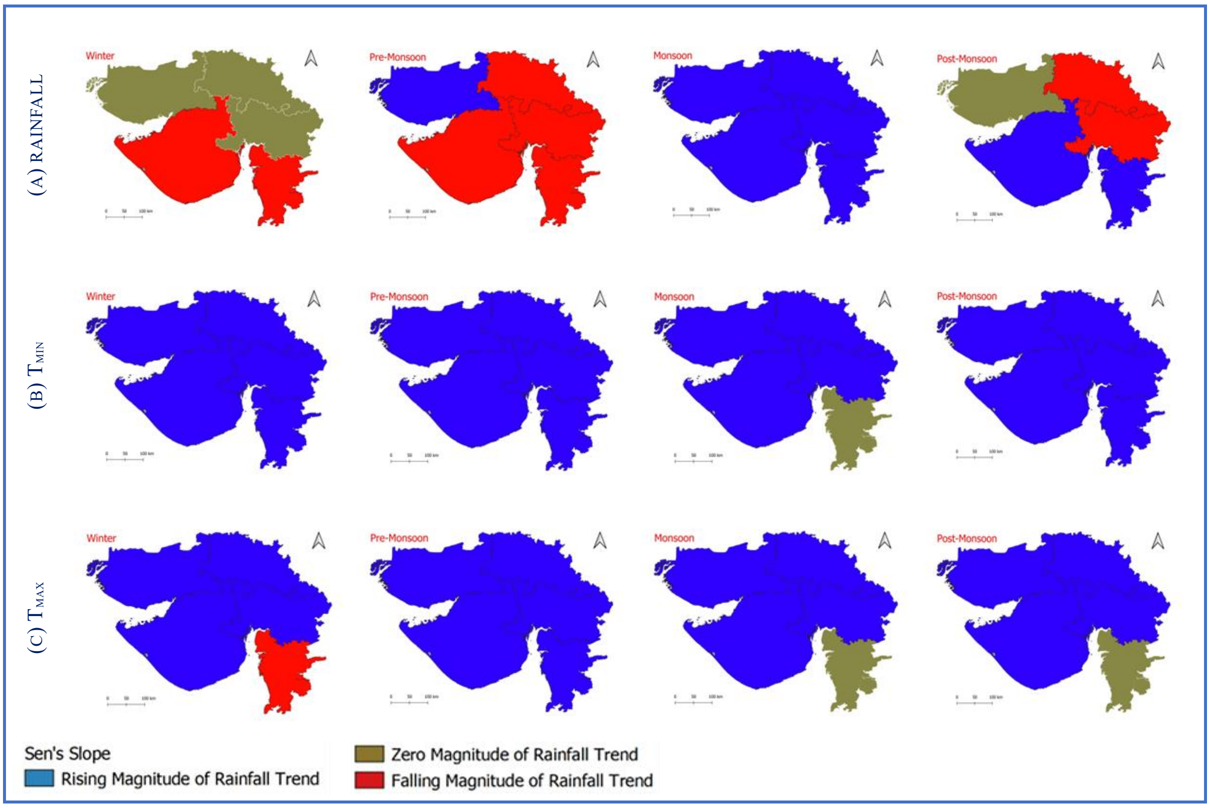


Figure 5.5 Spatio-Temporal Analysis of Seasonal Trend Magnitudes for (a) Rainfall, (b) T_{min}, and (c) T_{max} Using SSE Across Physiographic Regions of Gujarat.

Figure 5.5 shows the magnitude of seasonal trends assessed using the SSE, revealing distinct patterns across rainfall, T_{min}, and T_{max}. The rainfall data indicates a positive slope during the SWM, showing an overall increase in rainfall during this period. While, pre-monsoon and winter seasons exhibit negative slopes for rainfall, except for Kutch. In the post-monsoon period, North and Central Gujarat experienced negative trend slopes, while South Gujarat and Saurashtra showed positive slopes, highlighting regional variability during post-monsoon. Instances of 'No trend' are observed in Kutch during winter and post-monsoon rainfall, showing periods of stability in these areas. However, the T_{min} shows a consistent positive trend slope across all regions except South Gujarat during the SWM, indicating 'No trend.' Similarly, T_{max} shows a positive trend slope across most regions, except South Gujarat in winter, where a negative slope is observed. Additionally, T_{max} shows 'No trend' during the SWM and post-monsoon seasons, emphasizing periods of temperature stability.

Figure 5.6 Comparative Analysis of SSE and ITA Slope Statistics Across Regions.

Figure 5.6 shows a comparative analysis of slope statistics calculated using the SSE and ITA across regions. Although the magnitude of the trends varies substantially, their directions are largely consistent. Due to high variations observed within the rainfall series, especially during non-SWM seasons, the conventional test failed to detect significant trends at a 90% CI across regions. This led to considerable disparities in both direction and magnitude between ITA and SSE statistics, particularly evident in non-SWM rainfall data. However, a contrasting nature of tests has been observed in detecting rainfall trends: the slope value of ITA is higher during the monsoon than SSE, while an opposite trend occurs at an annual scale. Additionally, the findings show that while SSE indicates a significant increasing trend in pre-monsoon rainfall in Saurashtra, ITA reveals a decreasing trend. Meanwhile, temperature data consistently shows the same trend direction across both methods, though the magnitude varies, particularly at the annual scale for T_{min} and T_{max} across Gujarat's regions. Except for South Gujarat, neither the traditional SSE nor ITA tests detected any downtrends in temperature trends for T_{min} and T_{max}.

5.3.2 Assessment of Monthly Rainfall Trends

Although the assessment reveals significant variations in seasonal trends through the MK and ITA tests, a detailed analysis at the monthly scale has also been conducted. Figures 5.7 and 5.8 show the monthly rainfall trends identified by the MK and ITA tests, respectively. The MK test indicates an insignificant increasing trend in SWM (JJAS) months across regions, except for Central and South Gujarat in June and Kutch in July. In the post-monsoon (OND) months, significant trends are observed in South Gujarat and Kutch during October and November, respectively, although December shows an insignificant increase, except in North Gujarat. During the pre-monsoon (MAM) months, the MK test reveals a significant decrease in rainfall trends in Saurashtra and Central Gujarat in May, while Kutch exhibits an insignificant increase. In winter (JF), a significant decrease was observed in South Gujarat during January.

In contrast, the ITA test reveals a consistent increasing trend across the SWM months, except for Saurashtra, North Gujarat, and Central Gujarat during August. The ITA test indicates an upward rainfall trend in October across regions, yet it highlights a negative trend in November and December. During the pre-monsoon months, the ITA identifies a decreasing rainfall trend in March, while Kutch experiences an increase in April and May. In the winter months (JF), Central Gujarat shows an increasing rainfall trend, whereas South Gujarat exhibits a decreasing trend. Despite the ITA test's effectiveness in identifying monthly rainfall trends, significant discrepancies arise between the two tests. For instance, during August, the MK test indicated an insignificant increase in rainfall trend across regions, while the ITA test showed a decreasing trend. Similarly, in July, the MK test observed an insignificant decrease in rainfall for Kutch, contrasting with the ITA test's sign of an increasing trend. In June, while the MK test identified an insignificant decrease in rainfall for South Gujarat, the ITA test identified an upward trend.

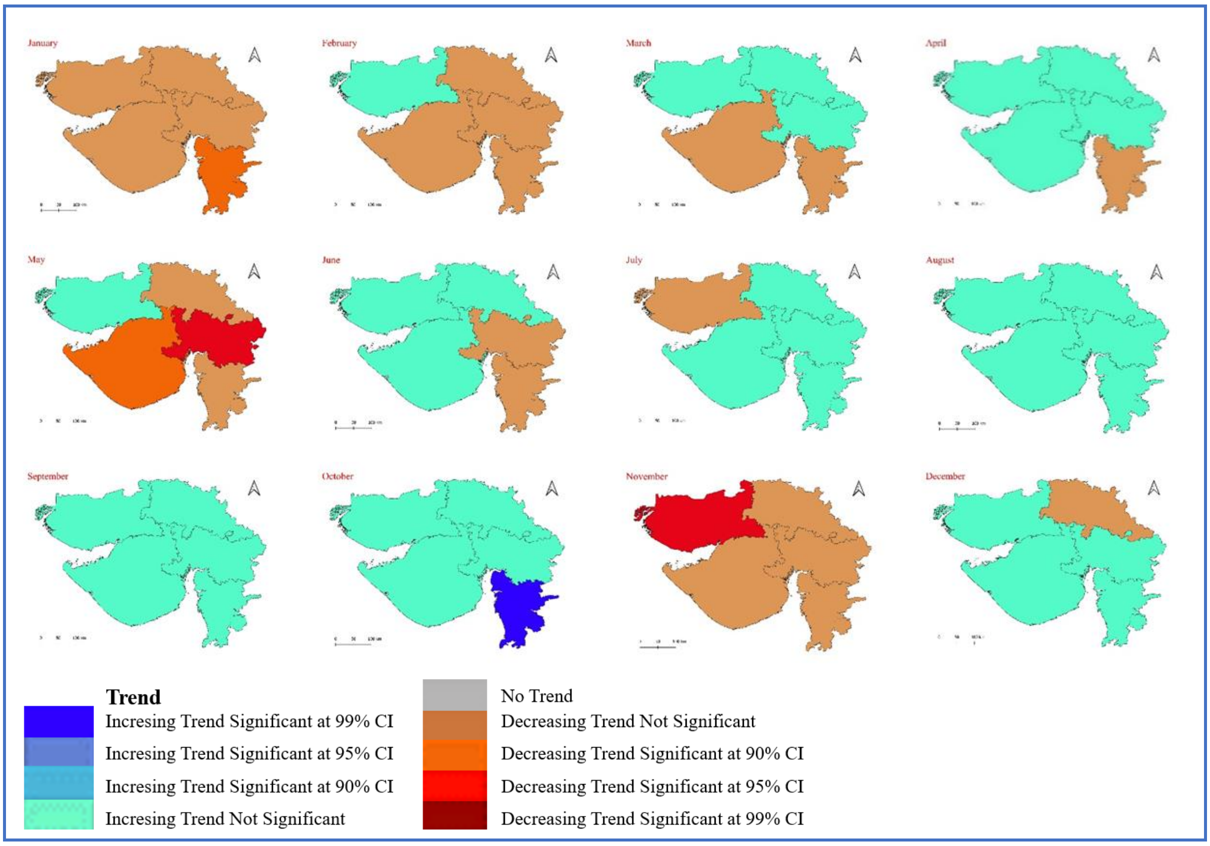


Figure 5.7 Spatio-Temporal Analysis of Monthly Rainfall Trends Identified by the MK Test**.**

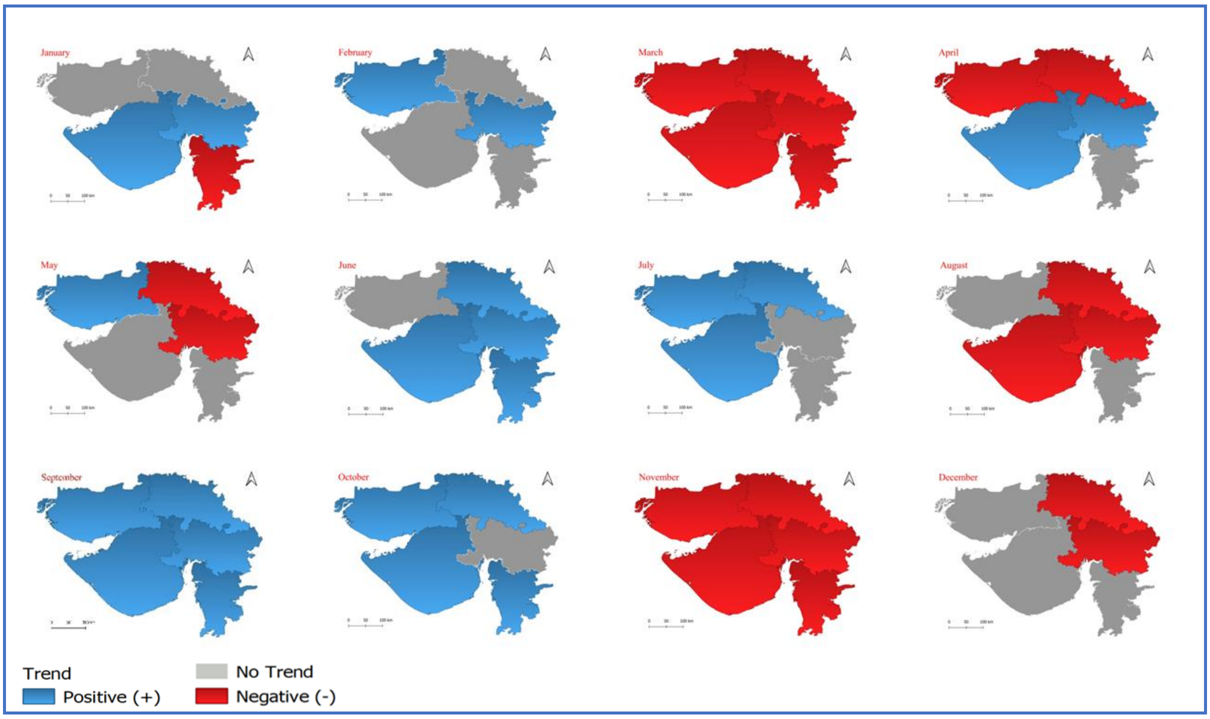
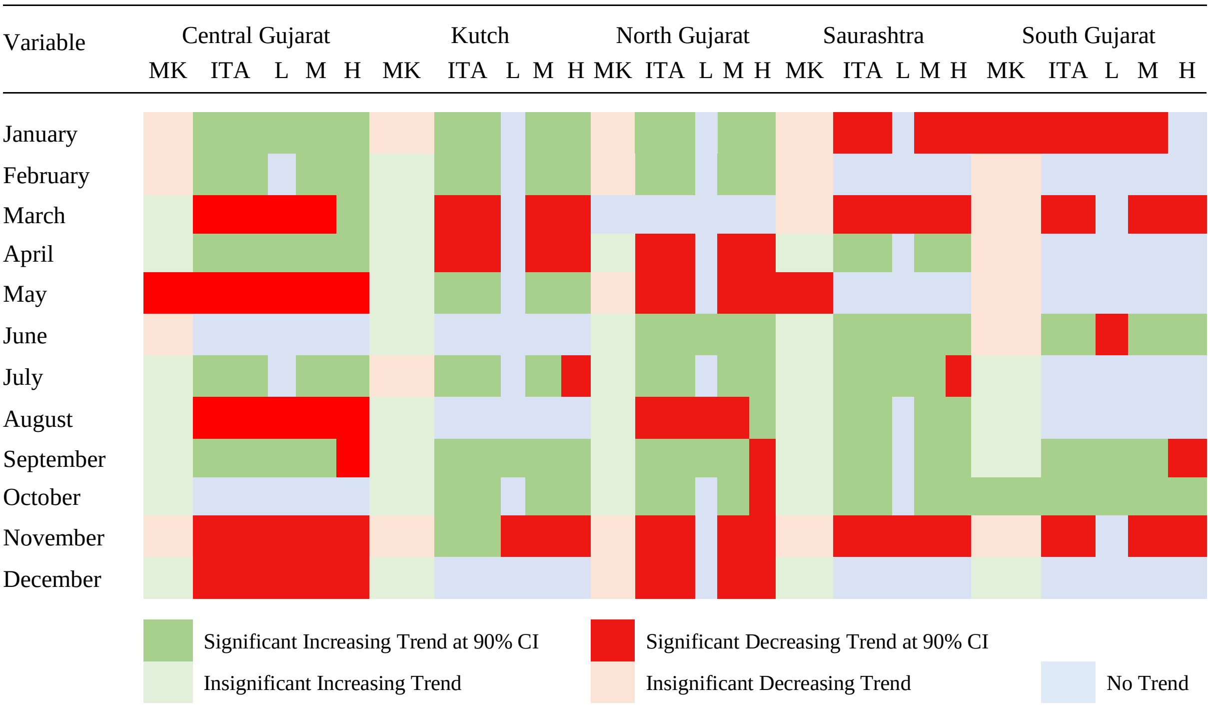


Figure 5.8 Spatio-Temporal Analysis of Monthly Rainfall Trends Identified by the ITA Test.

These discrepancies between the MK and ITA tests highlight the need for careful interpretation, as they can have substantial implications for understanding regional rainfall dynamics. The recognition of the strengths and limitations of each test will be crucial for accurately assessing and addressing the complexities of rainfall patterns across distinct regions. Table 5.2 shows a comparative assessment of monthly rainfall trends identified using the MK and ITA tests. It includes a detailed analysis of trends at a minute level across three distinct regimes, providing a comprehensive overview of the study's focus on rainfall dynamics across various regions.

Table 5.2 Monthly Rainfall Trends Analyzed by the MK and ITA Tests Across Regions.



L, M, and H represent Low, Medium, and High, respectively.

Table 5.2 indicates that at the monthly scale, South Gujarat shows a complex pattern of rainfall trends characterized by variability and inconsistency. This complexity is reflected in the observation of numerous instances of 'No Trend,' suggesting a lack of clear and consistent directional changes in rainfall over time within this region. This phenomenon implies that rainfall data in this region tends to cluster around the 1:1 (45°) line or between the lower and upper confidence limits, indicating a lack of clear directional trends. In contrast, at the seasonal scale, only an instance of 'No Trend' was observed in North Gujarat during the winter season, indicating a relatively stable rainfall pattern. The outcomes also suggest that the ITA is more effective for monitoring rainfall trends, especially with highly variable data. While the MK test yields some significant results, the ITA's capability to categorize series into different regimes enhances its analytical power, demonstrating its potential for comprehensive trend analysis.

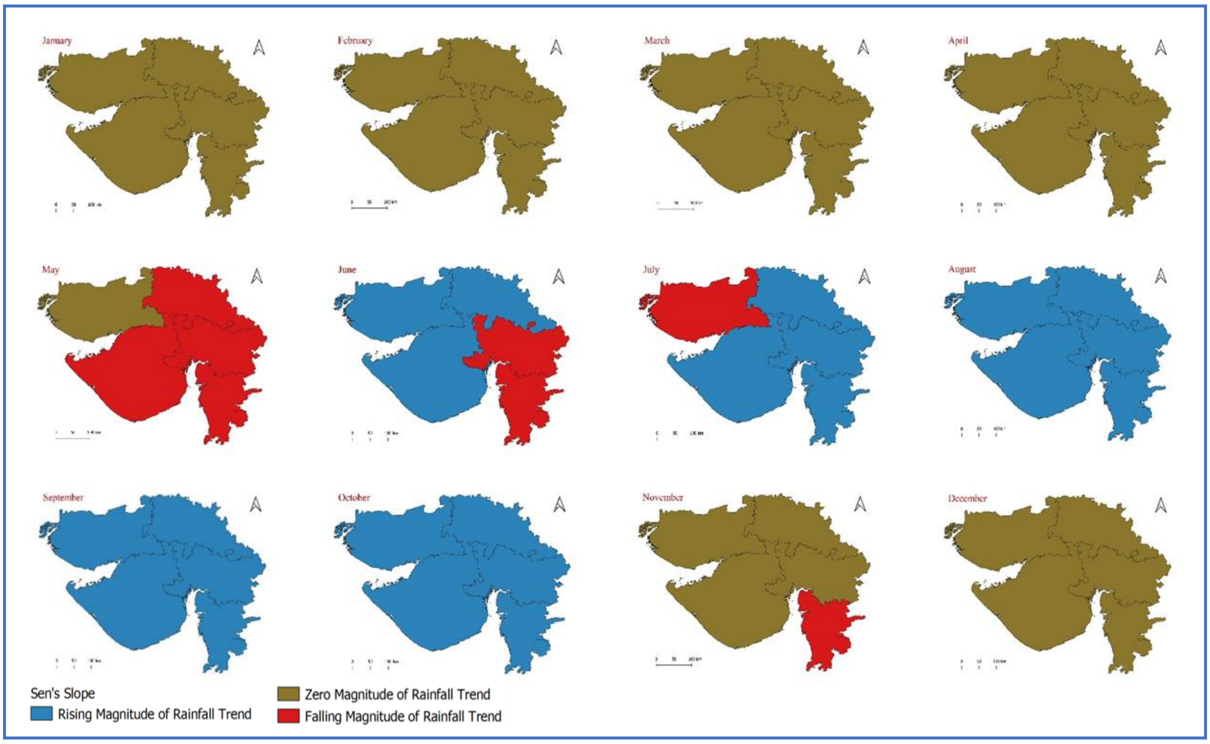


Figure 5.9 Spatio-Temporal Variations in Monthly Rainfall Trend Magnitudes Using SSE Test.

Figure 5.9 exhibits an increasing trend slope during the JJAS months across most regions, except for South and Central Gujarat in June and Kutch in July. In October, an upward slope was identified across regions, while a decreasing slope was evident in South Gujarat during November. Additionally, the analysis did not reveal significant trend magnitudes for the winter and pre-monsoon months, except May, which shows a decreasing trend slope across all regions except for Kutch. However, the decreasing trend slope in the early SWM months raises concerns, as it may signal a delayed onset of the SWM. Additionally, the increasing trend slope observed in October is concerning, as it suggests a potential shift in the SWM's retreat, potentially leading to extended rainfall beyond usual. These variations highlight the need for monitoring and adaptation strategies to address potential disruptions in the SWMR pattern.

5.3.3 Assessment of Monthly T_{min} Trends

Figures 5.10 and 5.11 show trends in T_{min} as identified by the MK and ITA tests, respectively. While the MK test did not yield significant outcomes for rainfall data, it did reveal for T_{min} across the months. The analysis using the MK test identified a significant increase in T_{min} at various CIs throughout the observed period. With the exception of the late post-monsoon months, particularly November and December, all other months show an increasing T_{min} trend across regions. Although the upward trend is consistent, the level of statistical significance varies among regions and months, highlighting the importance of further scrutiny of these spatial and temporal temperature changes, as they may indicate emerging climate challenges.

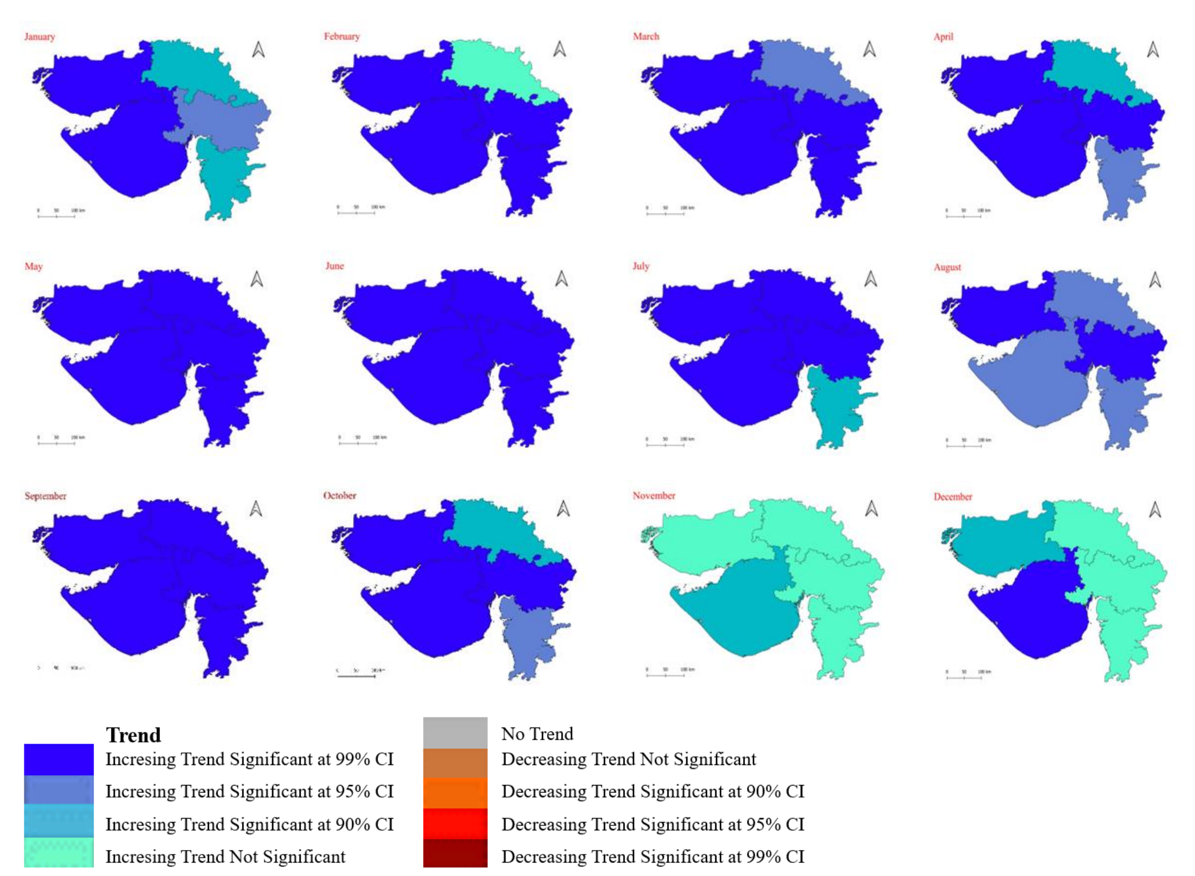


Figure 5.10 Spatio-Temporal Analysis of Monthly T_{min} Trends Identified by the MK Test.

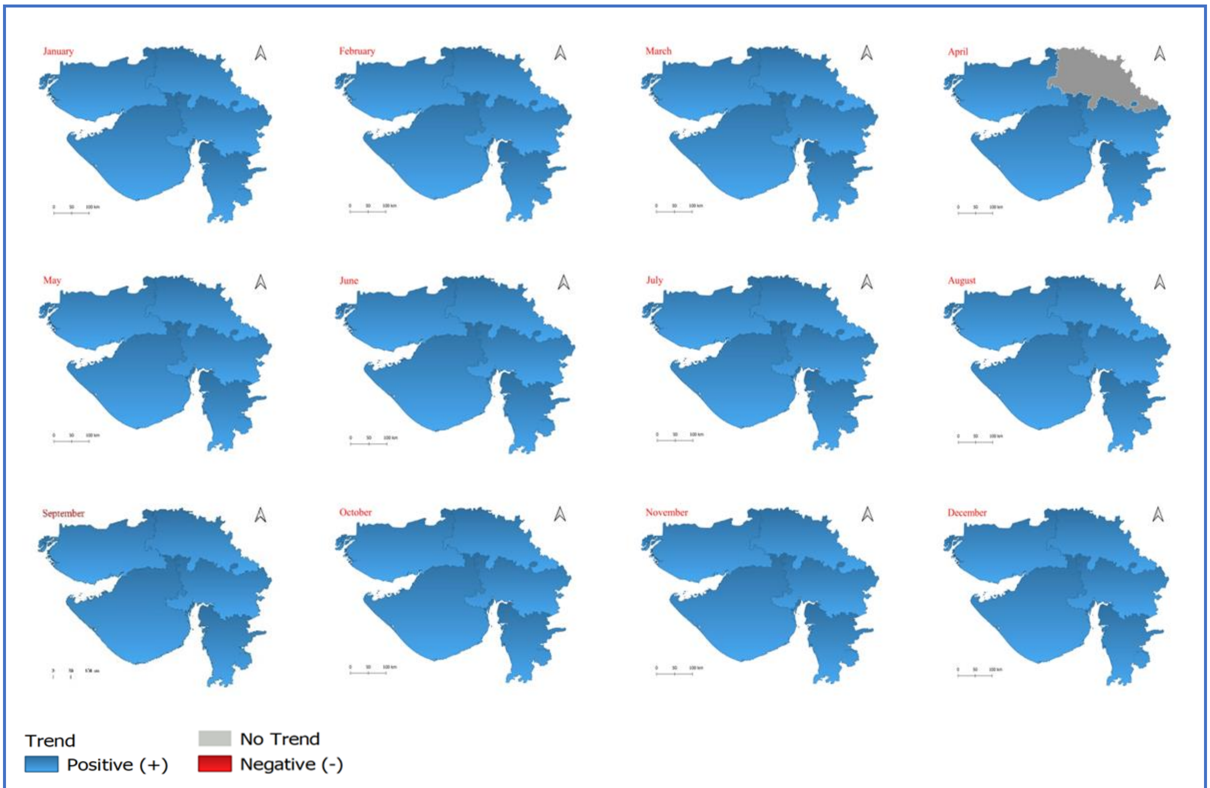
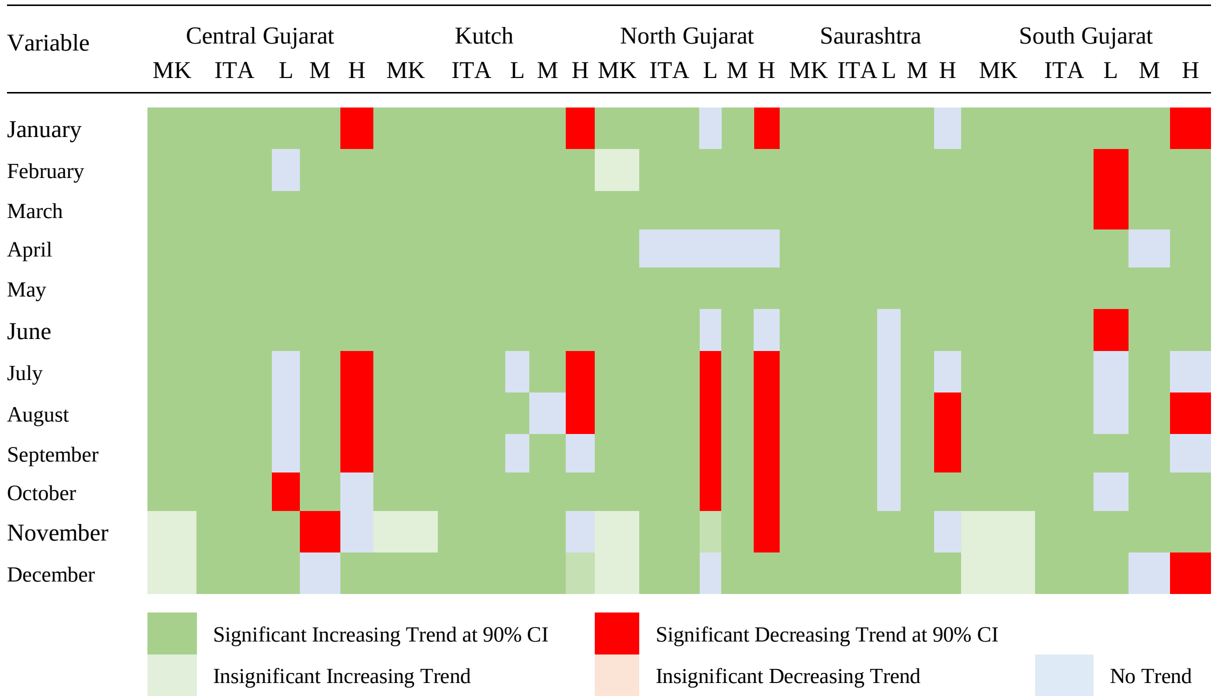


Figure 5.11 Spatio-Temporal Analysis of Monthly T_{min} Trends Identified by the ITA Test

Similarly, ITA reveals an increasing trend across months, except for North Gujarat in April, which shows no discernible trend. However, ITA effectively identified significant trends in post-monsoon T_{min} that the MK test did not detect, highlighting its sensitivity in capturing changes during this period. The consistent upward trends in T_{min} highlight a broader warming pattern, suggesting increased vulnerability to heat stress, particularly during nighttime. This trend can contribute to longer periods of increased temperatures, reduced cooling nights, and overall higher baseline temperatures. While assessing changes across different regimes, Table 5.3 shows monthly trends categorized into three distinct regimes, which allows for a more detailed analysis of outliers. The ITA test, in particular, proves valuable for detecting these outliers by highlighting deviations from usual patterns and identifying shifts in trends that the MK test may ignored. This comparative analysis of tests across months enhances the ability to discern regional variations and pinpoint unusual data points, providing a more comprehensive understanding of temperature trends across distinct physiographic regions.

Table 5.3 Monthly T_{min} Trends Analyzed by the MK and ITA Tests Across Regions.



While both the MK and ITA tests indicate a significant increasing trend in T_{min} across months on a broader scale, a detailed categorization into different regimes reveals substantial variations, particularly for high regimes, which exhibit a decreasing trend during the SWM and winter months. This decline suggests a potential shift in the concentration of T_{min} data points toward the medium regimes, possibly reflecting increasing variability in extreme temperature patterns. In contrast, the low regime shows a lack of discernible trend during these months across regions, highlighting a stabilization in the lower temperature extremes. These findings suggest that while T_{min} is generally increasing, the distribution of temperature changes across different regimes may indicate shifts in climate behaviour, with important implications for local climate resilience and planning efforts. The ITA test's capability to identify these regime-based trends and outliers is invaluable for achieving a more detailed understanding of T_{min} dynamics.

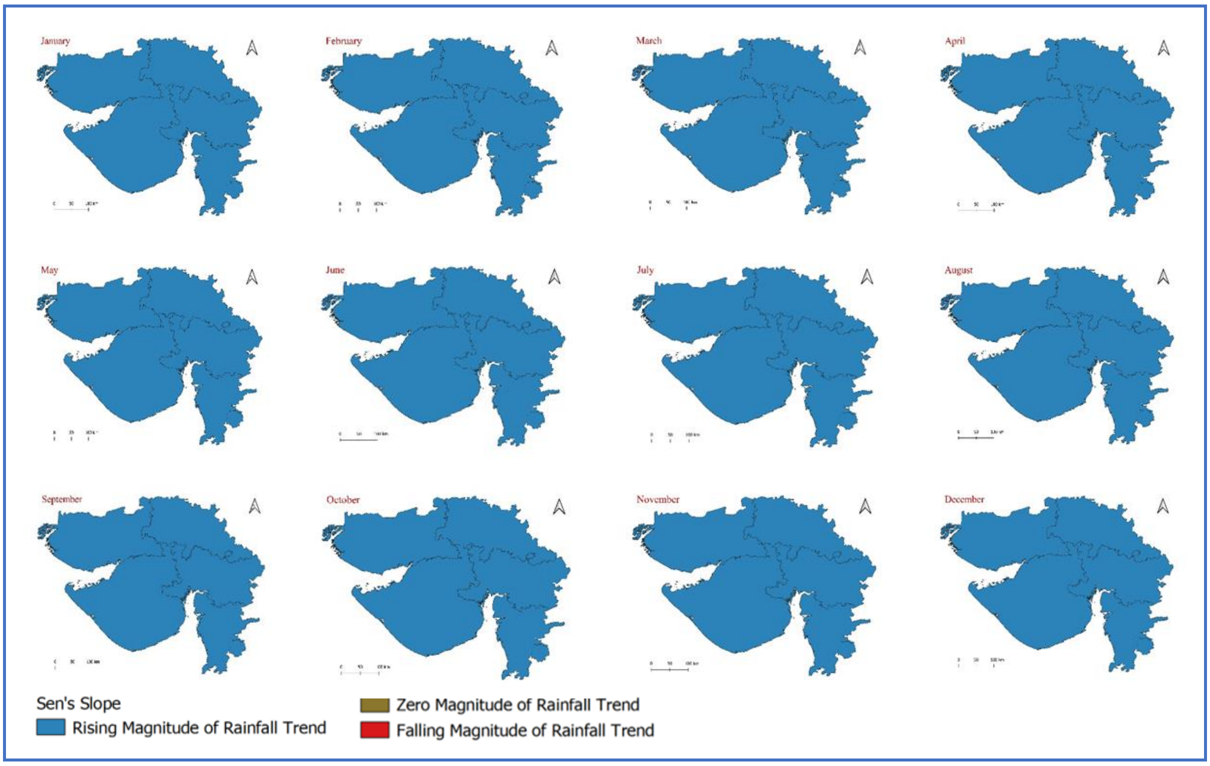


Figure 5.12 Spatio-Temporal Variations in Monthly T_{min} Trend Magnitudes Using SSE Test.

Figure 5.12 shows the trend magnitude for T_{min} across months for distinct regions, revealing a consistent increase in the trend slope for T_{min} across regions, indicating a clear warming pattern over time. No instances of negative slopes or a lack of trend were observed in any region, which strengthens the reliability of the increasing temperature trend. The absence of negative or neutral trends suggests a continuous and unidirectional increase in T_{min}, signalling a pervasive climate shift with significant implications for local ecosystems, agriculture, and public health.

5.3.4 Assessment of Monthly T_{max} Trends

Figures 5.13 and 5.14 show the monthly T_{max} trends using the MK and ITA tests. While both tests generally show an upward trend at the seasonal scale across regions, some inconsistencies are evident in South Gujarat. The MK test shows an insignificant decrease in T_{max} during the winter months, whereas the ITA reveals a decreasing trend not only in winter but also during the SWM and post-monsoon seasons, where the MK test indicates an insignificant increase. To address these variations and limitations, a detailed analysis was conducted on a monthly scale.

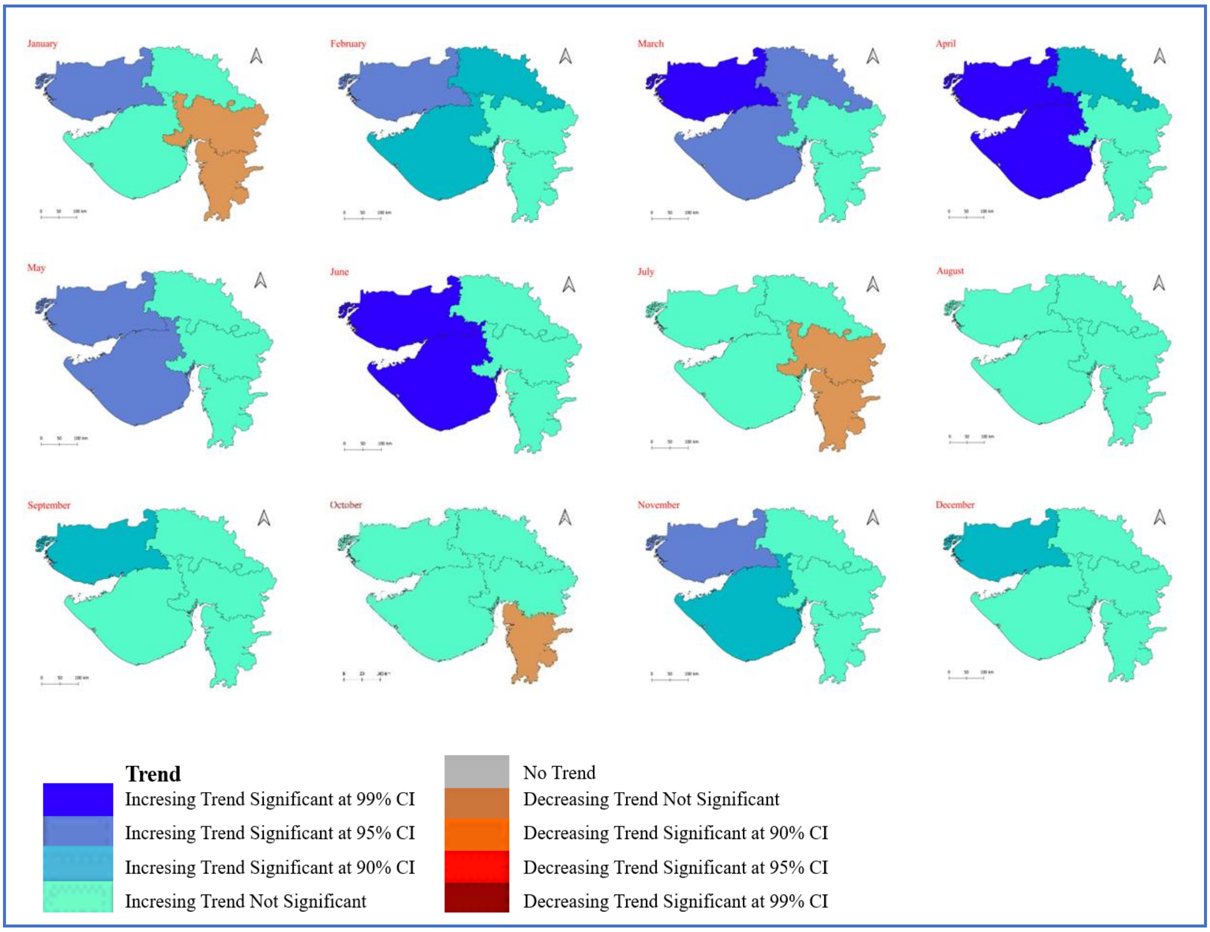


Figure 5.13 Spatio-Temporal Analysis of Monthly T_{max} Trends Identified by the MK Test.

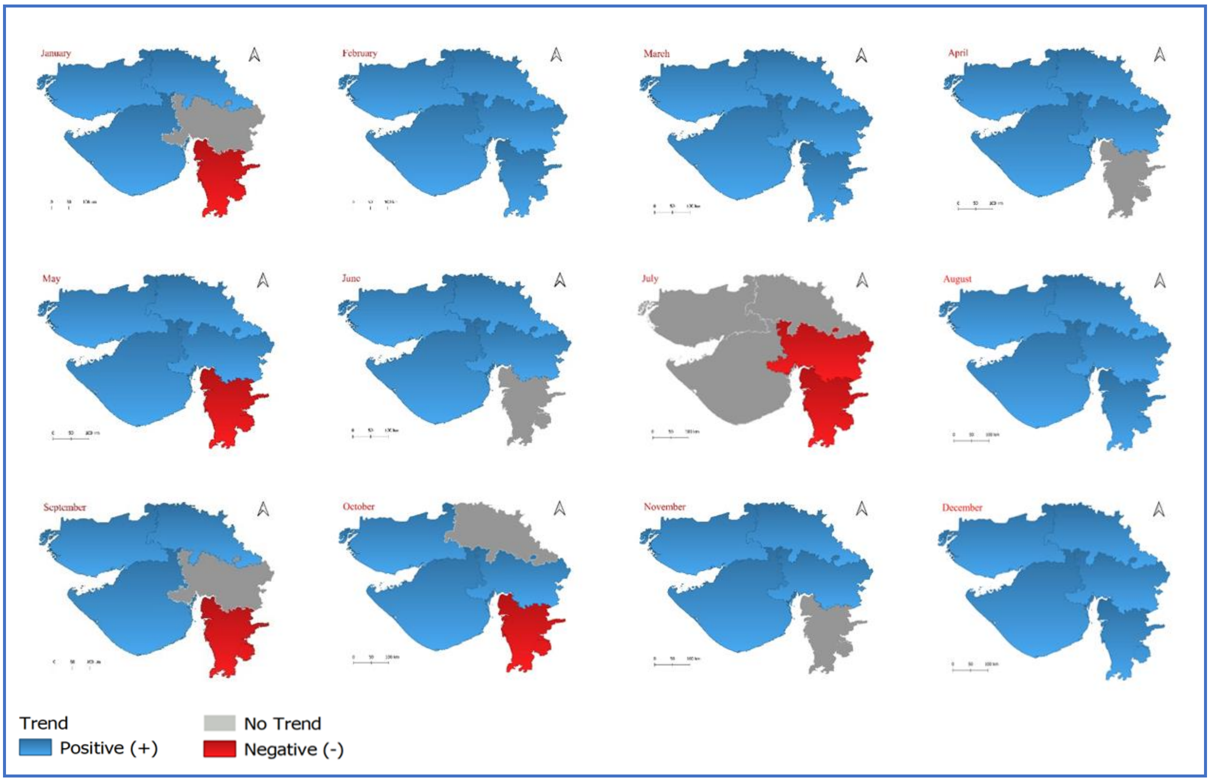
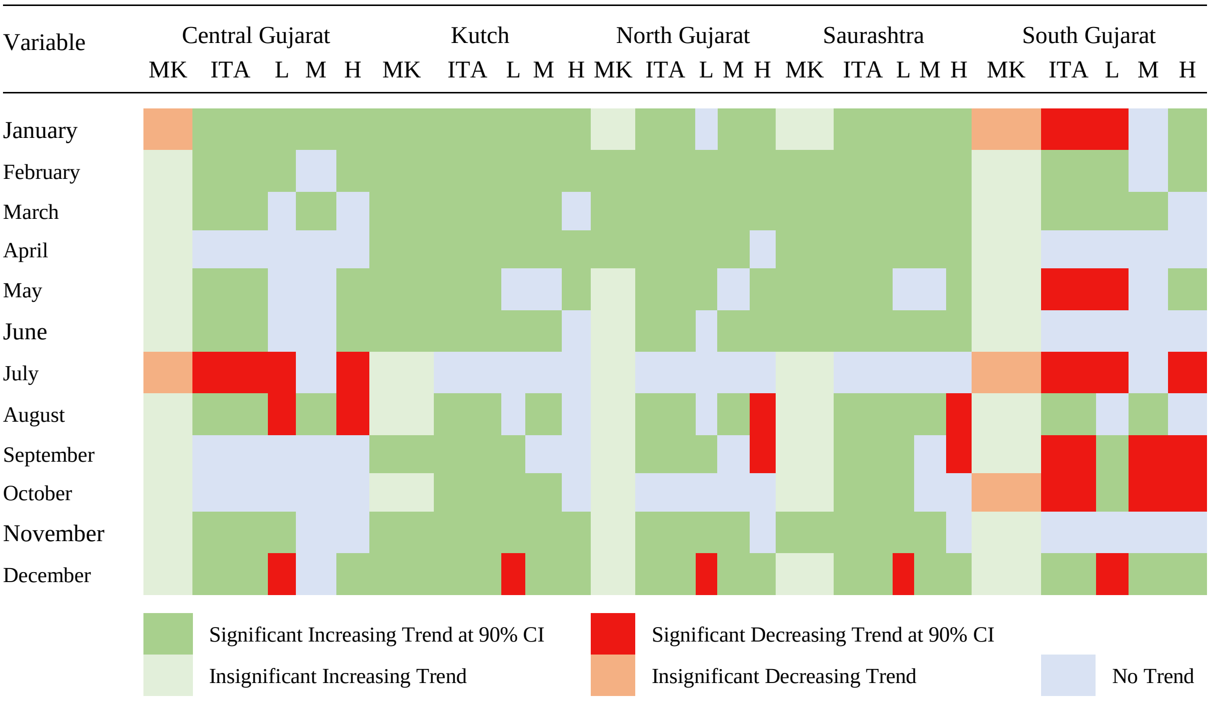


Figure 5.14 Spatio-Temporal Analysis of Monthly T_{max} Trends Identified by the ITA Test.

The MK test indicates a significant increase in T_{max} for Kutch, North Gujarat, and Saurashtra during the winter and pre-monsoon months. An insignificant increase is observed across the SWM months, except for Kutch, which shows a significant increase in T_{max} during June and September. In the post-monsoon months, November and December exhibit a significant increasing trend in T_{max} for both Kutch and Saurashtra. However, October shows an insignificant increasing trend across regions, except for South Gujarat, which shows an insignificant downtrend. However, the ITA tests show overall similar results for T_{max}, indicating an increasing trend during the winter and pre-monsoon months, except for South Gujarat in January and May. The SWM months exhibit an increasing trend across most regions, except for July. In the post-monsoon season, an increasing trend is observed in November and December. The findings reveal high variability in T_{max} for South Gujarat, highlighting a concerning trend in temperature fluctuations. In contrast, Kutch, North Gujarat, and Saurashtra show no instances of a downward trend across the months when analyzed using both tests. This highlights the need for further investigation into the underlying factors contributing to the temperature instability in South Gujarat, as it may have important implications for local climate resilience and adaptation strategies. Meanwhile, Table 5.4 shows the variations in trends across distinct regimes, alongside a comparative assessment of the MK and ITA test results.

Table 5.4 Monthly T_{max} Trends Analyzed by the MK and ITA Tests Across Regions.



The results indicate significant variability in T_{max} for South Gujarat across different regimes and months, particularly during the pre-monsoon and SWM months. This variability raises concerns about the region's climate stability. Additionally, there are no instances of an increasing T_{max} trend across the region during July; instead, the data reveal an overall downtrend for this month, especially in Central and South Gujarat. In contrast, Kutch exhibits the fewest months with a downtrend, followed by Saurashtra and North Gujarat. Additionally, the low regime in December shows a negative trend across all regions, suggesting a consistent pattern of temperature decline during this time. MK and ITA tests have proven effective in assessing T_{max} trends, with the ITA particularly highlighting these variations. This indicates the importance of using multiple analytical approaches to capture the complexity of temperature trends, thereby providing a more detailed understanding of regional climate dynamics.

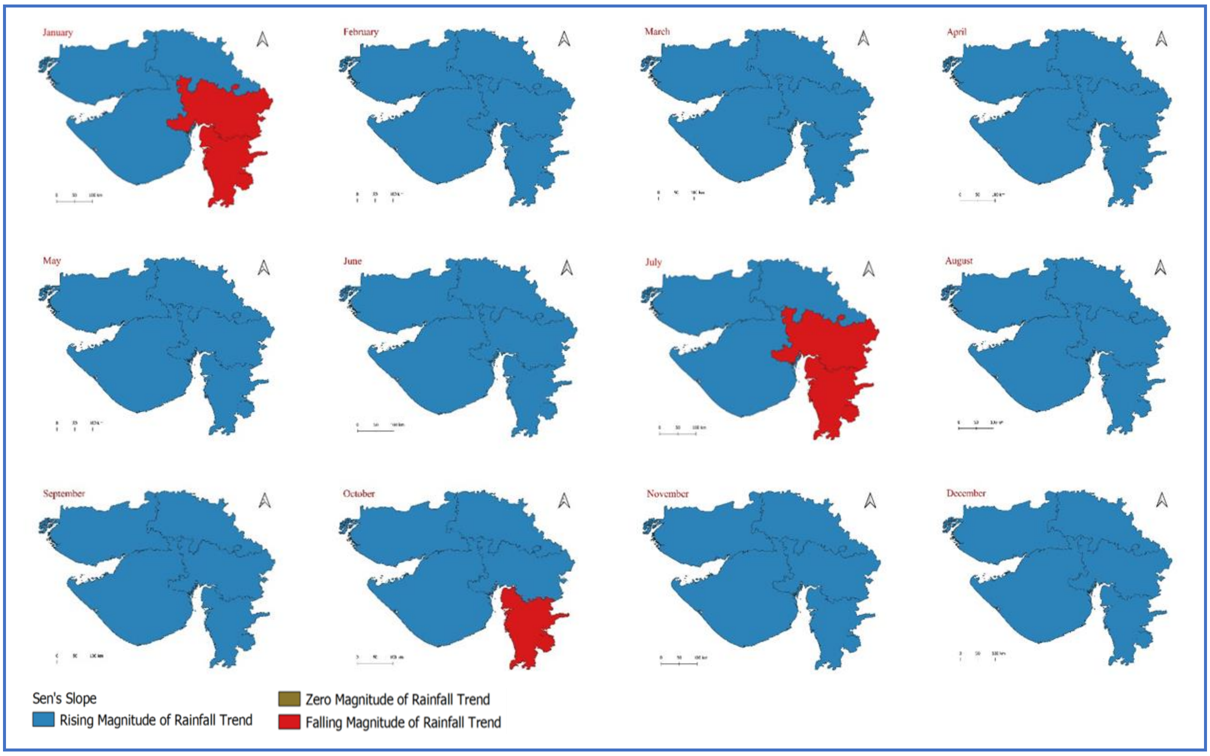


Figure 5.15 Spatio-Temporal Variations in Monthly T_{max} Trend Magnitudes Using SSE Test.

Figure 5.15 shows the trend magnitude for T_{max} across different months in distinct regions, revealing a consistent upward trend in temperature over time. This indicates a clear warming pattern. However, negative trend slopes were observed in South Gujarat and Central Gujarat during January and July, suggesting that, despite the overall warming trend, there are periods when temperatures deviate from this pattern. The analysis also highlights significant variability between monthly and seasonal trends. While T_{max} shows no downtrend during the SWM season, the monthly data reveal a decreasing trend for Central and South Gujarat in July. Additionally, although Central Gujarat exhibits an increasing trend during winter on a seasonal scale, the monthly data indicate a negative trend slope in January. These discrepancies highlight the complexities of temperature patterns and the need for targeted climate assessments.

5.3.5 Trends in Temperature and Rainfall Extremes

5.3.5.1 Extreme Heat Events

Gujarat has witnessed a concerning trend of increasing extreme heat events over the past few decades. Both the MK test (Figure 5.16) and the ITA test (Table 5.5) show a significant increasing trend in 'Above Normal Temperature days' across regions at 95% CI, except for Saurashtra, where an insignificant increase was observed using the MK test.

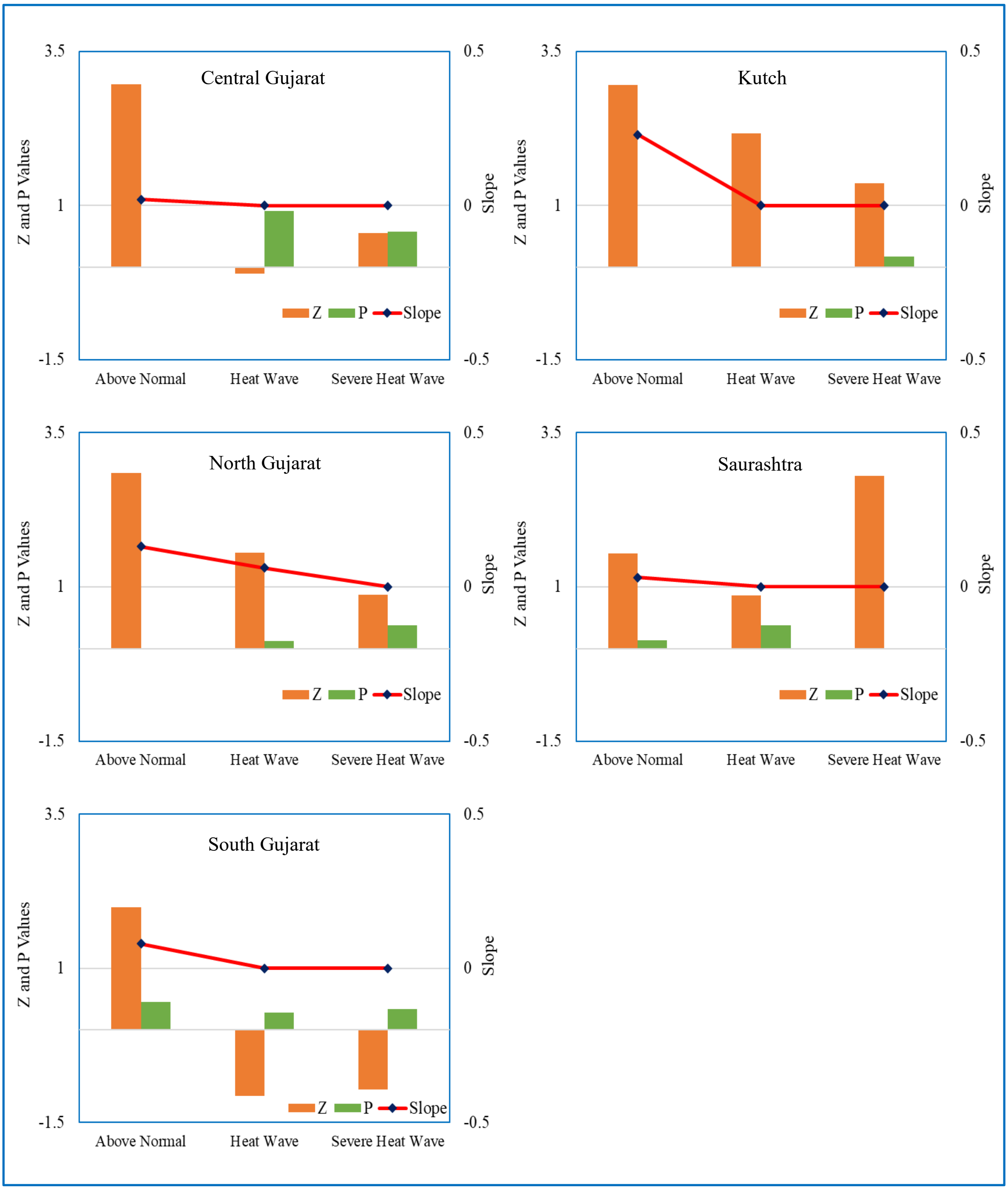


Figure 5.16 Annual Assessment of Heat Event Trends Using the MK Test.

Severe Heat Wave (SHW) events are insignificantly increasing across regions, except for South Gujarat, where both the MK and ITA tests identify an insignificant decreasing trend. In Saurashtra, contrasting results were observed for SHW events. Additionally, while the MK test failed to identify any significant trends in Heat Wave (HW), except for Kutch, the ITA method effectively detected trends in HW across distinct regions, except for Central Gujarat.

Table 5.5 Annual Assessment of Heat Event Trends Using the ITA Test.

Condition	Central Gujarat	Kutch	North Gujarat	Saurashtra	South Gujarat
Above Normal	↑	↑	↑	↑	↑
Heat Wave	NO	↑	↑	↑	↓
Severe Heat Wave	↑	↑	↑	↓	↓

The increasing occurrences of HW and SHW identified by both tests in Gujarat raise concerns. This trend poses significant risks to public health, agriculture, and ecosystems. Prolonged exposure to high temperatures can lead to heat-related illnesses, crop failures, and disruptions in natural habitats. Additionally, the increasing intensity of HW exacerbates water scarcity and energy demands, further straining resources and infrastructure.

5.3.5.2 Extreme Cold Events

The observed trend of increasing T_{min} at spatial and temporal scales across regions shows a significant shift in temperature patterns. This shift is particularly evident in the decrease in occurrences of below-normal temperature days leading to cold waves. As T_{min} increases, the instances of temperatures falling below the normal thresholds associated with cold weather events become significantly less frequent. This alteration in temperature dynamics highlights the impact of warming trends on the occurrence of extreme cold events, indicating a shift in the climate patterns that have been traditionally observed. The findings from both the MK (Figure 5.17) and ITA (Table 5.6) tests reveal a consistent pattern: a decrease in the frequency of events associated with cold extremes. These events encompass a range of conditions, including 'Below Normal,' 'Appreciably Below Normal,' 'Moderate Cold Wave (MCW),' and 'Severe Cold Wave (SCW).' Figure 5.17 shows a significant downward trend in MCW and SCW across the region, except for SCW in Kutch. The MK test did not identify any significant trend in 'Below Normal' temperature days in Central Gujarat, North Gujarat, and South Gujarat. However, neither of the statistical tests detected any upward trend, whether significant or insignificant, in the occurrences of cold events. The absence of any detected increase, regardless of its magnitude, suggests that there is no observable upward trend in the frequency of cold events based on the analyses conducted. This finding indicates a consistently decreasing occurrence of events, which has implications for local climate patterns and seasonal variability.

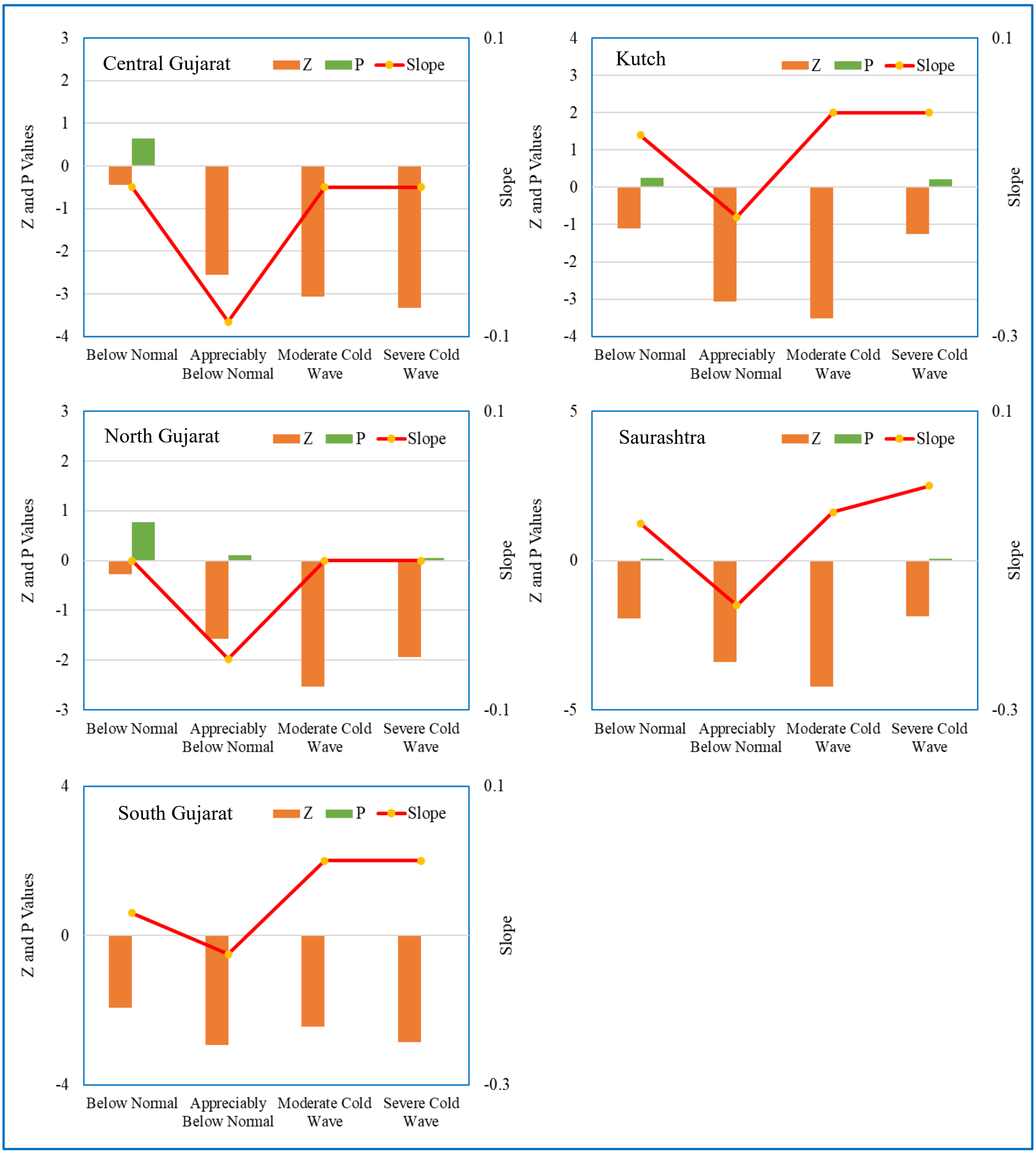


Figure 5.17 Annual Assessment of Cold Event Trends Using the MK Test.

Additionally, with the exception of SCW trends in Central Gujarat, the ITA test indicates a downtrend for all conditions across regions. Not a single event in any region shows an increase or an instance of no trend using the ITA method. The findings from these tests provide strong evidence of the diminishing occurrence of cold-related events, reflecting the broader trend of increasing temperatures and the decreasing frequency of extreme cold events in the regions.

Table 5.6 Annual Assessment of Cold Event Trends Using the ITA Test.

Condition	Central Gujarat	Kutch	North Gujarat	Saurashtra	South Gujarat
Below Normal	↓	↓	↓	↓	↓
Appreciably Below Normal	↓	↓	↓	↓	↓
Moderate Cold Wave	↓	↓	↓	↓	↓
Severe Cold Wave	NO	↓	↓	↓	↓

This observed trend signifies a significant shift in temperature dynamics over the study period. The reduction in the frequency of cold extremes indicates a departure from historically colder temperatures, moving towards milder conditions. This trend suggests a gradual transition towards warmer temperatures over time, which may significantly impact various aspects of life and ecosystems. Such changes could affect agriculture, biodiversity, and public health, highlighting the urgent need for adaptive strategies to mitigate potential consequences.

5.3.5.2 Trends in Rainy Days and Intense Rainfall Events

Upon a thorough examination of rainfall patterns at both monthly and seasonal levels across distinct regions, a concerning downward trend in the majority of regions was revealed using both the MK and ITA tests. The next crucial step entails analyzing the trend in the frequency of rainy days across regions. This analysis aims to shed light on the potential implications of diminishing rainy days, highlighting the importance of understanding and addressing the factors contributing to this worrisome trend, and aiding in comprehending the dynamics of rainfall distribution over time. In Figure 5.18, the analysis indicates no significant trend in the frequency of rainy days across regions when examined on a seasonal scale at a 90% CI. However, a downward trend, although statistically insignificant, was observed during the post-monsoon season across the regions. Except for North Gujarat, a similar insignificant downtrend in rainy days frequency was also observed during the pre-monsoon season across regions. These findings indicate that the conventional MK test did not detect a significant trend in the frequency of rainy days when analyzed at a seasonal level. Transitioning from a seasonal to an annual scale, Figure 5.19 depicts an insignificant downtrend across all regions. Despite the considerable variations observed in the number of rainy days, these variations do not show a significant trend on either seasonal or annual scales using the MK test.

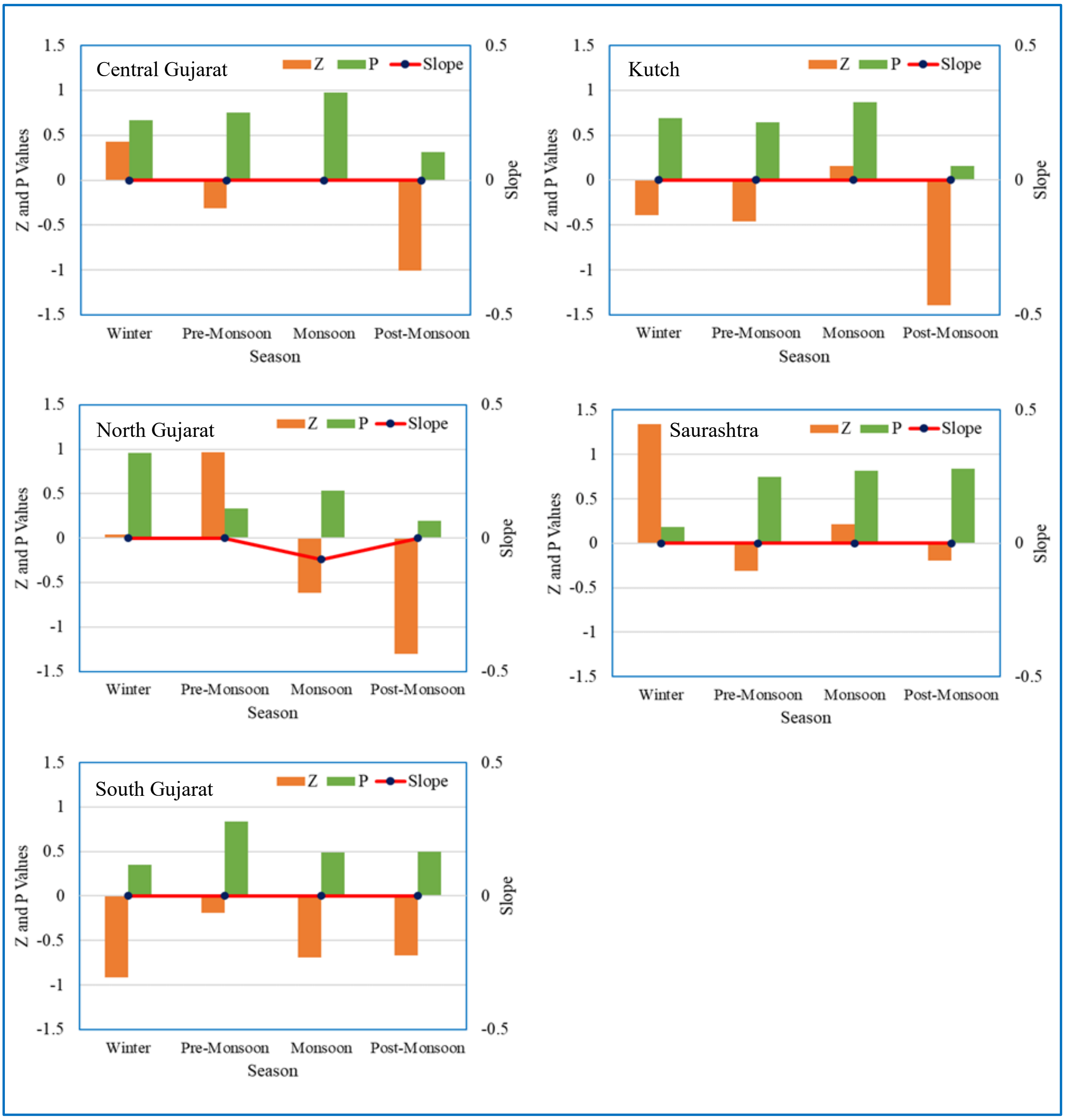


Figure 5.18 Frequency Assessment of Rainy Days on a Seasonal Scale Using the MK Test.

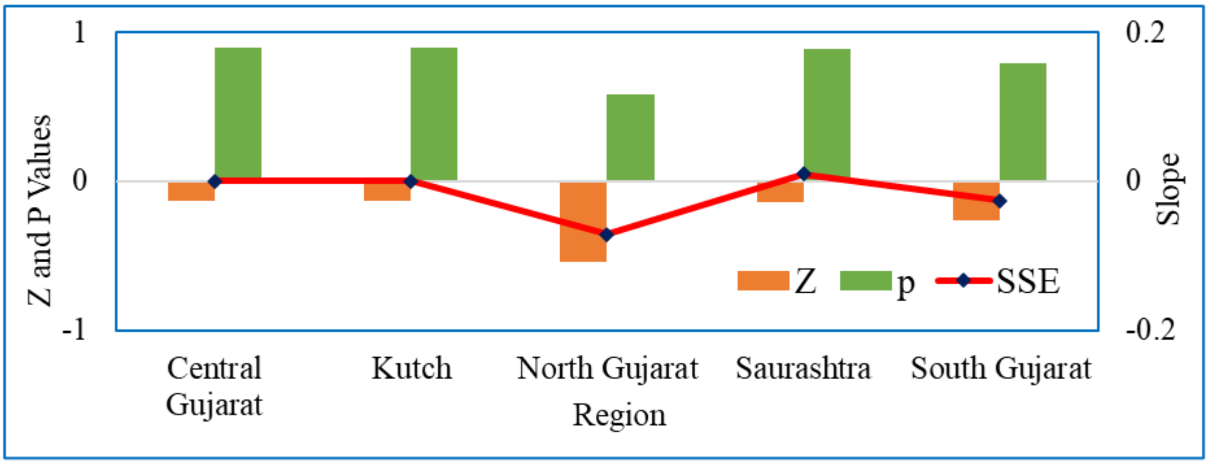


Figure 5.19 Frequency Assessment of Rainy Days on an Annual Scale Using the MK Test.

After conducting the MK test, the subsequent application of the contemporary ITA test provided further insights into the trends observed in different seasons across the regions. The results indicated a consistent decreasing trend in the number of rainy days during the pre-monsoon and SWM seasons across regions (Table 5.7). However, Central Gujarat and Kutch stood out with opposite trends, showing an increasing trend in the number of rainy days during the winter and post-monsoon seasons, respectively. Despite these findings, the ITA test failed to identify significant trends in winter, particularly in Kutch, North Gujarat, and South Gujarat.

Table 5.7 Frequency Assessment of Rainy Days on an Annual Scale Using the ITA Test.

	Central Gujarat	Kutch	North Gujarat	Saurashtra	South Gujarat
Winter	↑	NO	NO	↓	NO
Pre-Monsoon	↓	↓	↓	↓	↓
SWM	↓	↓	↓	↓	↓
Post-Monsoon	↓	↑	↓	NO	↓
Annual	↓	↓	↓	↓	↓

Although categorizing rainy days based on their rainfall level or intensity, such as 'Light Rain', 'Moderate Rain', 'Rather Heavy', 'Heavy', 'Very Heavy', and 'Extremely Heavy Rain' (IMD Met Glossary, https://www.imdpune.gov.in/Reports/glossary.pdf), can yield significant results. This classification allows a detailed analysis of how varying rainfall intensities contribute to overall rainfall patterns across regions. Additionally, "Very Light Rain" events capture even the slightest rainfall occurrences, which might be overlooked or dismissed as insignificant. By considering these events, a more comprehensive view of rainfall patterns emerges, enhancing the understanding of how different rainfall intensities affect overall rainfall dynamics. In Figure 5.20, significant trends in "Rather Heavy to Extremely Heavy" (RHTE) rainfall events are evident across various regions, except for South Gujarat, which shows an insignificant increasing trend. The observed trends, identified using the MK test at a 90% CI, suggest an increase in intense rainfall events over time in these regions. This indicates a potential shift towards more frequent and severe rainfall, which could have important implications for various sectors. In contrast, 'Very Light' and 'Light' rainfall events exhibit a decreasing trend across regions. Specifically, a significant decline in Light rain is observed in North Gujarat and South Gujarat, while 'Very Light Rain' has decreased significantly across all regions except Kutch and South Gujarat. However, these events are often considered insignificant due to their minimal rainfall contribution, but consistent decline raises several concerns. Even though the individual rainfall events may be small, their cumulative effect over time can still contribute to overall water availability and ecosystem health. A declining trend in these events could potentially lead to drier conditions, impacting soil moisture levels, and water resources. Similarly, the MK test failed to detect any significant trend for 'Moderate Rainfall' events across the regions, indicating variability in their occurrence, with an insignificant decreasing trend observed across regions except for South Gujarat. Although variations were observed in 'Moderate Rainfall' events, they do not exhibit a consistent upward or downward pattern.

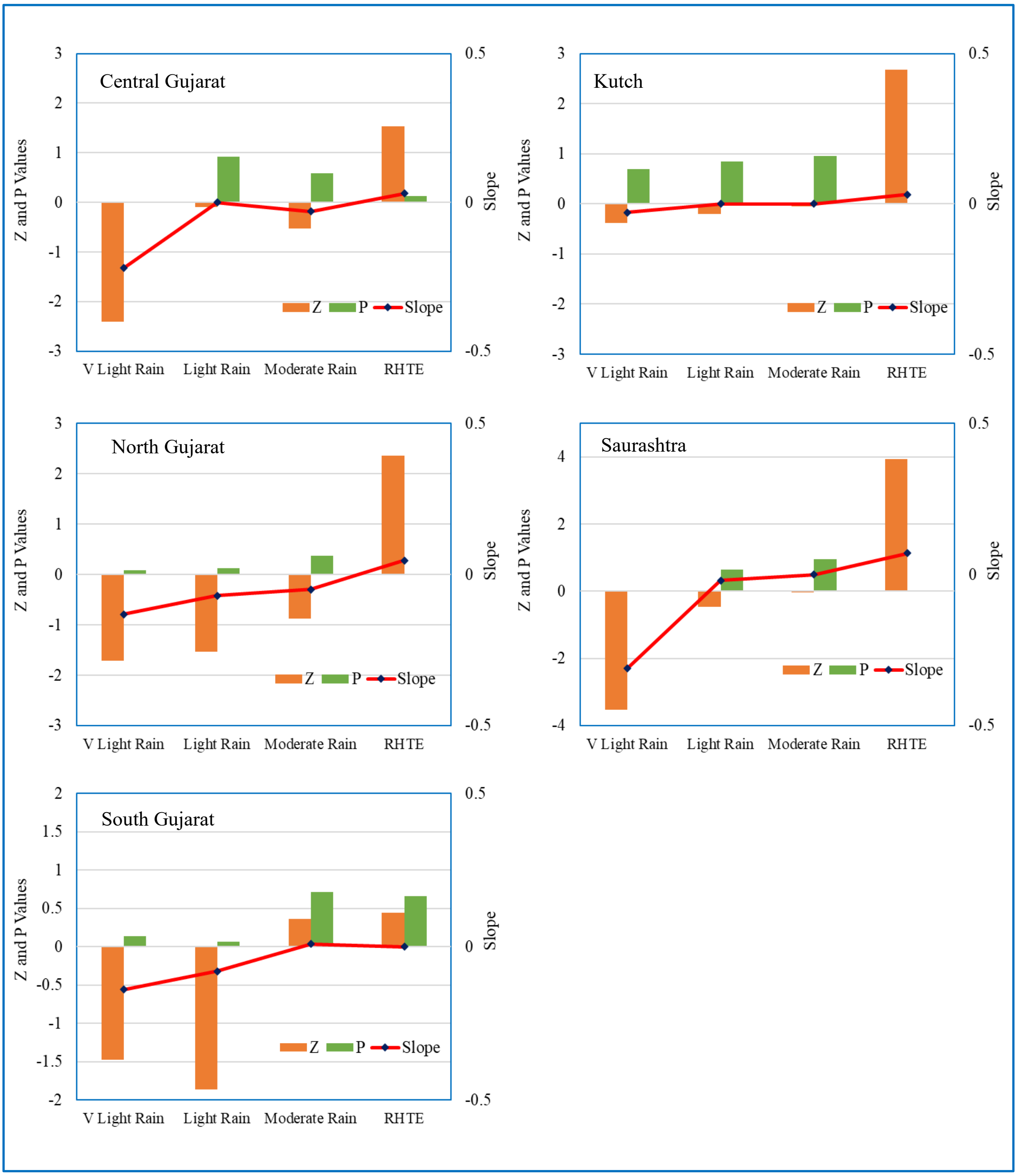


Figure 5.20 Annual Assessment of Trends in Rainfall Intensity Events Using the MK Test.

Table 5.8 Annual Assessment of Trends in Rainfall Intensity Events Using the ITA Test.

	Central Gujarat	Kutch	North Gujarat	Saurashtra	South Gujarat
Very Light Rain	↓	↓	↓	↓	↓
Light Rain	↓	NO	↓	↓	↓
Moderate Rain	↓	↑	↓	↑	↑
RHTE	↑	↑	↑	↑	↑

The ITA analysis reveals a decreasing trend in 'Very Light Rainfall' and 'Light Rainfall' events across distinct regions, as shown in Table 5.8. However, no significant trend was identified for 'Light Rain' events in Kutch. This suggests that, while 'Very Light' and 'Light' rainfall events are generally declining across regions, there may be variations, such as in Kutch, that deviate from this overall trend. For 'Moderate Rainfall' events, the ITA analysis indicates an increasing trend in Kutch, Saurashtra, and South Gujarat, while a decreasing trend is observed in Central Gujarat and North Gujarat. Although the MK test failed to detect any significant trends in 'Moderate Rainfall,' the ITA effectively identified them. Both methods, however, show an increasing trend in RHTE events across the regions. This increase in extreme rainfall events poses challenges, as it increases the risk of flooding, infrastructure damage, and disruption to agricultural productivity, highlighting the need for urgent adaptation and mitigation strategies.

5.4 Conclusion

The comprehensive analysis conducted in this study has revealed the complex dynamics of rainfall and temperature trends in Gujarat over the past six decades (1961-2020). Utilizing conventional statistical methods such as the MK test, SSE, and the contemporary Sen's ITA, significant spatial and temporal trends in rainfall and temperature have been identified across different scales and regions at varying confidence intervals. The findings suggest that ITA is more effective in monitoring rainfall trends, especially when dealing with highly variable data, as it showed a higher sensitivity to minute changes and could detect more intricate trends in rainfall patterns, making it particularly useful for regions with variable and non-linear rainfall data. While the MK test yields a limited number of significant outcomes, ITA, with its ability to categorize time series into three regimes, produces more pronounced results, highlighting its potential for comprehensive trend analysis. However, the slope identified through SSE shows comparable or even greater effectiveness than ITA, particularly at the SWM and annual scales. The assessment reveals that Kutch shows an upward trend in rainfall across seasons, except during the winter. South Gujarat and Saurashtra exhibit significant monthly and seasonal variations, with increasing rainfall during non-SWM months, raising potential concerns for water management and agricultural practices. The analysis of rainfall trends provides valuable insights into evolving patterns, highlighting the need for further micro-level studies in South Gujarat and Saurashtra to understand localized impacts and inform adaptive strategies. The findings also indicate an upward trend in T_{min} and T_{max} across all regions, identified at monthly and seasonal scales. Conventional and contemporary approaches yield proximate results, with ITA standing out for its ability to categorize trends into distinct regimes, offering a more comprehensive evaluation. However, when comparing temperature results, SSE proved more effective than ITA slope at the annual scale. The significant increase in both T_{min} and T_{max} across the regions raises concerns about the increasing frequency and intensity of heat waves, disruptions to the rainfall cycle, and potential impacts on agricultural productivity.

The study also evaluated trends in temperature and rainfall extremes using both the MK and ITA tests. It revealed a significant increase in extreme heat events across the studied regions, while an opposite trend was observed in severe cold events, indicating a significant decrease. These findings highlight a shift in the traditionally observed climate patterns, emphasizing the growing prevalence of extreme heat and the diminishing frequency of extreme cold. The comprehensive application of both the MK and ITA tests enhances the reliability of these results, providing a clearer understanding of the changing temperature dynamics and their implications for regional climate resilience. Additionally, the assessment of rainy day frequency revealed insignificant outcomes when using the MK tests; however, effective results emerged through the ITA. By categorizing rainfall events, the study has enhanced the assessment of rainfall patterns, highlighting a significant increasing trend in RHTE rainfall events across regions, as evidenced by conventional and contemporary approaches, highlighting the increased risk of flash floods and severe property damage. Such events pose substantial challenges for urban planning and water management, necessitating the implementation of resilient infrastructure solutions to mitigate these impacts. Additionally, agriculture, which relies heavily on predictable weather patterns, may face adverse effects due to increased soil erosion, waterlogging, and crop failure from excessive rainfall. In contrast, 'Very Light' and 'Light' intensity rainfall events exhibited a significant decrease over the analyzed period. The insights derived from this chapter provide a robust foundation for subsequent chapters and future research endeavors.