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Detecting Warming Trends and Climate Regime Transitions Using Satellite-Derived Temperature Data in Northeast India

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Abstract. There are growing indications that Northeast India is feeling the effects of climate change, but in-depth studies on temperature changes throughout the region are still limited. In this work, we looked at how both annual and seasonal mean temperatures have changed in 14 different locations between 1990 and 2024. To obtain a well-rounded understanding, we applied several statistical methods to capture long-term warming as well as sudden changes in temperature patterns. The Mann-Kendall and modified Mann-Kendall tests pointed to a noticeable warming in a number of locations, and Sen's slope helped us measure how these changes are taking place. We also used the innovative trend analysis to catch more complex, nonlinear trends, and the percent bias method showed that recent decades have been generally warmer than the earlier ones. Among the 14 locations, Guwahati, Dibrugarh, and Cherrapunji experienced clear warming trends, especially during the monsoon and winter. Change point detection tools such as the Pettitt and Buishand tests highlighted major changes around 2012-2013 in several stations. At the same time, stations such as Agartala and Aizawl showed gradual warming, but the upward trend is still evident. These results make it clear that warming is unfolding in different ways in the region. Understanding these local patterns is essential for developing effective responses to climate-related risks in this ecologically and climatically sensitive part of India.

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1. Introduction

Temperature is one of the clearest signs that our climate is changing. If we want to understand how these shifts play out in different parts of the world, we need reliable long-term records. The big picture is that global temperatures keep climbing, and the last few decades have seen some of the fastest warming yet [1]. But when you zoom in on India, the story becomes more complicated. Some regions heat up faster than others, and Northeast India seems especially at risk. Its unique geography full of mountains, forests, and river valleys makes it incredibly sensitive to even small changes in climate [2, 3]. Add to that its heavy dependence on monsoon rains, and you have a region where changes in temperature and rainfall can ripple through ecosystems and livelihoods. Sure, we've had studies looking at India's overall warming trends [4, 5], but they often miss the finer details the local stories that matter most to the people living there. As a result, localized temperature changes, especially abrupt shifts often go unnoticed. To fill this gap, the current study emphasizes the importance of detailed, station-level investigations that can capture both gradual changes and sudden transitions. To achieve this, we utilized a blend of statistical tools.

The Mann-Kendall (MK) and modified Mann-Kendall (MMK) tests were applied to identify consistent trends in temperature data, while Sen's slope was used to estimate the magnitude of change over time. For detecting non-linear and non-normal patterns, we adopted the innovative trend analysis (ITA) method developed by [6], which adds depth to traditional trend analysis. Additionally, the percent bias (PBIAS) metric was used to compare the mean temperatures between the two halves of the study period. A positive PBIAS value indicates warming in the later years, whereas a negative value suggests cooling, offering insight into internal shifts not always captured by linear methods [7]. Equally important is identifying when significant changes occurred. To this end, change point detection tools such as Pettitt's (PT), Buishand's range (BR) test, and Buishand's U (BU) tests were employed. These well-established techniques are particularly useful in detecting abrupt changes in climatic time series [8, 9], and their application here allowed us to pinpoint key transition periods in both seasonal and annual temperature records.

This research takes a deep dive into how temperatures have shifted across 14 weather stations in Northeast India from 1990 to 2024. Instead of just looking at yearly averages, it breaks things down season by season examining pre-monsoon, monsoon, post-monsoon, and winter periods separately. What makes this study stand out is how it blends multiple analytical methods to get a clearer picture of what's really happening. For spotting long-term trends, it uses well-established tools like the MK test (and its modified version, MMK) along with Sen's slope estimator techniques that help determine whether temperatures are consistently rising, falling, or staying the same. But it doesn't stop there. The study also applies ITA and PBIAS to cross-check findings and ensure accuracy. One of the most interesting parts is how it pinpoints when major temperature shifts occurred. Using change-point detection methods like PT, BR, and BU, the research identifies exact years where trends took a sudden turn, revealing whether changes happened gradually or in sharp jumps. By combining all these approaches, the study doesn't just confirm whether

Northeast India is warming it uncovers how and when these changes unfolded, giving a much richer understanding of the region's climate story.

2. Region of Study and Data Sources

This study focuses on the Northeastern region of India, a climatically and ecologically sensitive zone that plays important role in the country's environmental dynamics. Geographically, the area lies roughly between 21°N to 30°N latitude and 90°E to 97°E longitude, encompassing the states: Arunachal Pradesh, Assam, Mizoram, Meghalaya, Nagaland, Manipur and Tripura. The listed analysis concentrates on 14 selected grid points across seven states chosen to represent the region's climatic, physiographic, and ecological diversity [2, 3]. Northeast India is characterized by a diverse topography of hills, valleys, floodplains, and forested highlands, contributing to its complex climate system and high biodiversity. The region is predominantly influenced by the Southwest Monsoon, receiving over 70% of its annual rainfall between June and September, and is known for its vulnerability to climate extremes like floods and landslides [10]. Its unique location and physiography have led to growing recognition of the region as a climate change hotspot, yet detailed and localized climate studies remain limited [11]. The study area map with the location of the grid points is shown in Fig.1.

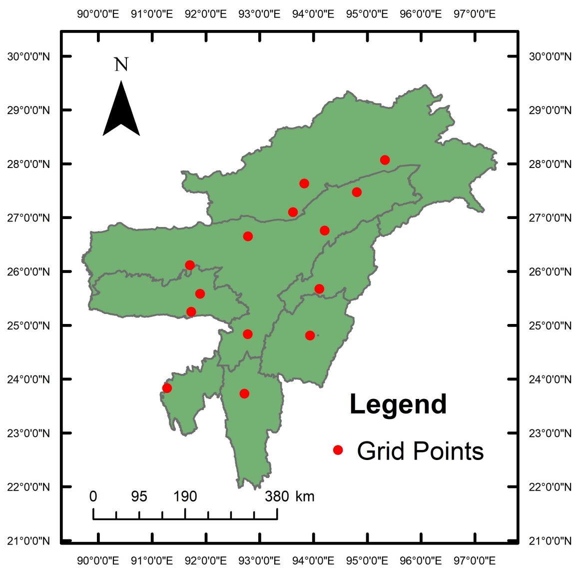

Figure 1: : Map of the study area showing 14 selected grid points across Northeast India used for temperature trend and change point analysis.

To ensure spatial and climatic representativeness, the grid points were carefully chosen from both plains and high-altitude locations. These points reflect the varied elevation, land use, and climate conditions across the region. The coordinates were used to extract consistent and quality-checked monthly mean 2-meter air temperature data from the NASA POWER website (https://power.larc.nasa.gov/).While the NASA POWER dataset is widely used and considered highly reliable for climate research due to its comprehensive spatial and temporal coverage, its robustness has been further substantiated through various validation studies that compare its outputs against ground-based observations globally and regionally [12–14]. Together, these grid points offer a robust foundation for analyzing temperature trends and regime shifts across Northeast India's diverse climate zones, providing insights that can support localized climate risk assessment and adaptation planning.

3. Methodology

This research uses a reliable mix of non-parametric and semi-parametric methods to track changes and identify possible turning points in annual and seasonal surface air temperature trends from 1991 to 2024 across 14 meteorological stations in Northeast India. The statistical tools applied include the MK and MMK tests to detect trends, along with Sen's slope to estimate their rate. ITA helps capture non-linear changes, while PBIAS is applied to compare temperature shifts between the earlier and later parts of the time-period. To detect any sudden changes in the data, change point tests such as PT, BR, and BU tests are employed. For seasonal breakdowns, the data is grouped into four periods: Winter (January–February), pre-monsoon (March–May), monsoon (June–October), and post-monsoon (November–December), based on previous studies [2, 15].

3.1. Mann-Kendall Test

The MK test, reported by Kendall [16] and later expanded by Mann [17], is a non-parametric, rank-based method used to identify monotonic trends in time series data. The test statistic, denoted by S, can be calculated utilizing the following formula

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}(x_j - x_i),$$

$$\text{where} \quad \operatorname{sgn}(x) = \begin{cases} 1, & \text{if } x > 0 \\ 0, & \text{if } x = 0 \\ -1, & \text{if } x < 0. \end{cases} \tag{1}$$

The variance under the null hypothesis can be formulated as

$$\operatorname{Var}(S) = \frac{n(n-1)(2n+5)}{18}. \tag{2}$$

The standardized Z score is calculated as

$$Z = \begin{cases} \dfrac{S-1}{\sqrt{\mathrm{Var}(S)}}, & \text{if } S > 0 \\ 0, & \text{if } S = 0 \\ \dfrac{S+1}{\sqrt{\mathrm{Var}(S)}}, & \text{if } S < 0. \end{cases} \tag{3}$$

3.2. Modified Mann-Kendall Test

To address the issue of autocorrelation in time series data, the MMK test, presented by Hamed and Rao [18], is applied. In this approach, the effective sample size is calculated as:

$$n_{\text{eff}} = \frac{n}{1 + 2\sum_{k=1}^{n-1} \rho_k \left(1 - \frac{k}{n}\right)}, \tag{4}$$

where ρ_k is the autocorrelation at lag k. The adjusted sample size is used to compute the variance and Z statistic.

3.3. Sen's Slope

Sen's method [19] is uutilized to estimate the magnitude of the trend. For each pair (x_j,x_k) where $j > k$,

$$Q_i = \frac{x_j - x_k}{j - k}. \tag{5}$$

Median of all Q_i values give the Sen's slope, $\hat{\beta} = \mathrm{median}(Q_i)$.

3.4. Innovative Trend Analysis

The ITA [6] is a non-parametric graphical method that identifies trends by comparing two halves of a time series. The two halves are sorted according to ascending or descending order and the second half is plotted against the first half. The 1:1 line (45° diagonal) represents a no-trend scenario. Deviations from this line indicate the presence and direction of a trend: Points above the 1:1 line indicate an increasing trend, points below indicate a decreasing trend, and a symmetrical spread around the line suggests no significant trend.

3.5. Percent Bias Method

The PBIAS method was used to estimate the relative change in temperature between the first and second half of the time series. This method provides a simple way to understand whether the values in the second half of the period have increased or decreased in comparison to the first half [7]. The formula used is:

$$P_{\text{BIAS}} = 100 - \left(\frac{\sum_{i=1}^{n} \frac{y_i}{x_i} \times 100}{n}\right), \tag{6}$$

where P_{BIAS} is the percent bias, x_i is the values in the first half, y_i is the corresponding values in the second half and n is the number of data points in each half. A positive P_{BIAS} value indicates an increase in temperature during the second half of the period, while a negative value indicates a decrease. This approach complements other trend analysis methods and gives a clear percentage-based measure of change over time.

3.6. Pettit Test

Pettitt's test, listed by Pettitt [9], is a rank-based approach utilized to detect a single point in a time series where a significant change occurs:

$$K = \max_{1 \le t < n} \left| U_{t,n} = \sum_{i=1}^{t} \sum_{j=t+1}^{n} \operatorname{sgn}(x_i - x_j) \right|. \tag{7}$$

The point t where $U_{\mathrm{t,n}}$ is maximized corresponds to the possible change point.

3.7. Buishand Range Test

The BR technique [8] checks for mean homogeneity in a time series by examining the cumulative deviations of data points from the overall average, where

$$\begin{aligned} S_k &= \sum_{i=1}^{k} (x_i - \bar{x}), \\ R &= \max(S_k) - \min(S_k). \end{aligned} \tag{8}$$

A large range R implies a changepoint in the mean.

3.8. Buishand U Test

The BU test, which is a standardized version of the range test, is calculated utilizing the following formula:

$$U = \frac{R}{\mathrm{sd}\sqrt{n}}, \tag{9}$$

where U represents the Buishand test statistic, R is the range of cumulative deviations from the mean, sd is the standard deviation of the original time series, and n is the total number of data points. The value of U is then compared to critical values to decide if there is a statistically significant change in the mean [20].

4. Results and Discussion

This part of the study details the outcomes and provides an interpretation of their meaning with respect to the research goals.

4.1. Descriptive Statistics of Annual Temperature

The annual mean temperature patterns from 1990 to 2024 across 14 stations in Northeast India show clear differences shaped by elevation and climate (Table 1). The IDW-interpolated maps (Fig. 2) highlight a distinct gradient: plains and valleys are warmer, while hilly and high-altitude regions remain cooler. Agartala recorded the highest annual mean temperature at 25.37°C, whereas Ziro, located in the eastern Himalayas, was the coldest at 17.49°C, followed closely by Cherrapunji at 17.86°C. This difference reflects the strong impact of terrain and altitude on local temperatures. Temperature fluctuations between years also varied. Ziro and Tezpur showed relatively higher standard deviations (0.47°C and 0.48°C), indicating noticeable year-to-year changes. When normalized, Ziro had the highest coefficient of variation (2.69%), suggesting that although it is the coolest station, it is also one of the most variable. Cherrapunji and Dibrugarh also showed moderate variability.

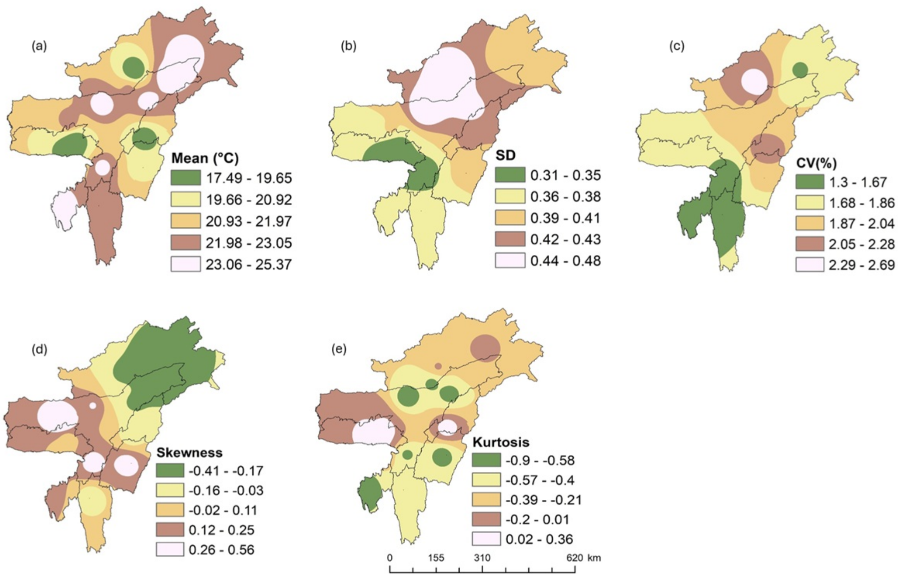

Figure 2: : Spatial patterns of annual mean air temperature and associated descriptive statistics across Northeast India (1990–2024), derived using the inverse distance weighting (IDW) interpolation method in ArcGIS. Panels show (a) mean temperature, (b) standard deviation, (c) coefficient of variation, (d) skewness, and (e) kurtosis.

Skewness values revealed differences in temperature distribution. Stations like Ziro (−0.23) and Dibrugarh (−0.41) were skewed left, meaning cooler-than-average years were more common. In contrast, Guwahati (0.56) and Agartala (0.21) showed positive skewness, pointing toward more frequent warmer years likely influenced by urbanization and land use changes. Most stations had negative kurtosis values, indicating flatter distributions and fewer extremes. Cherrapunji was an exception with a slightly positive kurtosis (0.36), hinting at occasional extreme years, possibly due to its unique local climate and terrain. Overall, the results highlight a complex temperature pattern in Northeast India. While lowland cities are steadily warming, higher-altitude areas like Ziro remain cooler but are experiencing more variability. These findings stress the importance of region-specific climate monitoring and planning, especially in ecologically sensitive hill areas. Similar patterns have been observed in other studies focusing on elevation and urban influence on temperature trends [3, 5].

4.2. Annual Trend Analysis

The analysis of annual mean temperature trends from 1990 to 2024 across 14 stations in Northeast India shows a clear warming pattern. This is confirmed by using multiple trend detection methods. The MMK test, which adjusts for serial correlation [21], find significant warming trends at 11 out of 14 stations. Stations like Ziro, Jorhat, Itanagar, and Dibrugarh show the strongest warming (p-value < 0.05). Interestingly, Aizawl and Agartala display significant cooling trends, while no notable change is detected in Manipur, Kohima, and Silchar (Fig. 3) and (Table 2). These findings reflect broader warming patterns reported across South Asia in recent decades [1]. Sen's Slope estimator supports these results, highlighting a gradual temperature rise. Ziro and Tezpur recorded the highest rates of increase, both at 0.03°C per year, followed by Itanagar and Dibrugarh at 0.02°C per year (Fig. 3). The only stations with decreasing trends are Aizawl (-0.02°C/year) and Agartala (-0.01°C/year), which may be influenced by local factors like vegetation recovery or cloud cover variability [22].

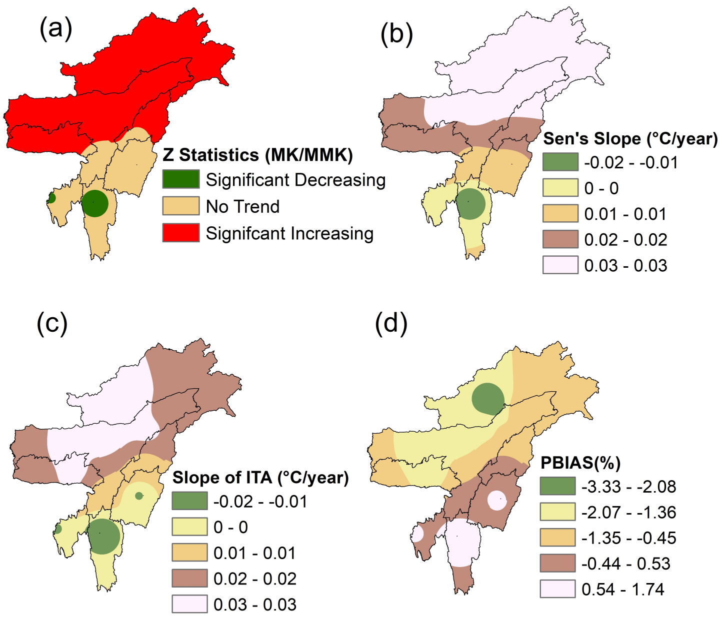

Figure 3: : Annual mean temperature trends in Northeast India (1990–2024): (a) Z-statistics, (b) Sen's slope estimator, (c) ITA slope and (d) Percent bias.

The ITA method, which is known for detecting non-linear trends, also confirmed significant warming, especially in Ziro (0.03°C/year, D = 0.33) and Tezpur (0.03°C/year, D = 0.20). Moderate warming was also noted in Cherrapunji and Guwahati (0.02°C/year). Meanwhile, stations like Manipur and Agartala had nearly zero or slightly negative ITA trends, indicating stability or slight cooling (Fig. 3). To assess how temperatures shift over time, the Percent Bias (PBIAS) method is applied. A positive PBIAS means the latter half of the period was warmer.

Stations like Aizwal (1.74%), Agartala (0.69%), and Manipur (0.80%) showed warming in recent years. In contrast, Ziro (−3.33%), Tezpur (−1.98%), and Guwahati (−1.80%) had negative values, pointing to warmer conditions in earlier decades and recent stabilization (Figure 3d). This shift could be linked to factors like monsoon changes, cloud effects, or vegetation feedback [4]. In summary, all four methods, MMK, Sen's slope, ITA, and PBIAS present a consistent picture of regional warming. Stations in the Brahmaputra Valley and Himalayan foothills, such as Ziro, Tezpur, Dibrugarh, and Jorhat, stand out as warming hotspots. On the other hand, parts of southern Mizoram and Tripura show signs of cooling or neutral trends. These contrasts highlight the region's climatic complexity and the need for localized climate strategies. The study also underlines the importance of using multiple methods to separate long-term climate trends from short-term variability, especially in diverse and topographically complex regions [23].

4.3. Seasonal Trend Analysis

4.3.1. Pre-Monson Season

The analysis of pre-monsoon temperatures (March–May) from 1990 to 2024 across Northeast India reveals a varied pattern (Table 3). While some regions show signs of cooling, others appear stable or show only slight warming. According to the MK test (Fig.4), significant decreasing trends were observed only at Aizawl and Agartala. Most other stations showed no statistically significant trend, suggesting relatively stable pre-monsoon temperatures in much of the region.

Sen's slope estimates (Fig.4) reinforce these findings. Southern stations like those in Mizoram, Tripura, and parts of southern Assam displayed slight cooling, with temperature decreases ranging from −0.01 to −0.03°C per year. In contrast, regions like Arunachal Pradesh and central Assam showed minor increases, though these were not statistically meaningful. This supports earlier studies indicating that climate responses during pre-monsoon months can differ across regions, driven by local factors [24, 25]. The ITA method, which is particularly useful for capturing non-linear or partial trends, further confirmed the cooling signal in southern parts of the region (Fig. 4). Aizawl and Agartala again stood out, showing clear negative slopes. In comparison, cities like Guwahati and parts of eastern Arunachal Pradesh exhibited stable or slightly positive trends, suggesting small and localized warming. To explore temporal shifts more clearly, the PBIAS method was applied (Fig. 4).

Interestingly, Aizawl and Agartala, despite showing cooling in other methods, have positive PBIAS values. This could imply mid-period cooling followed by recent warming. On the

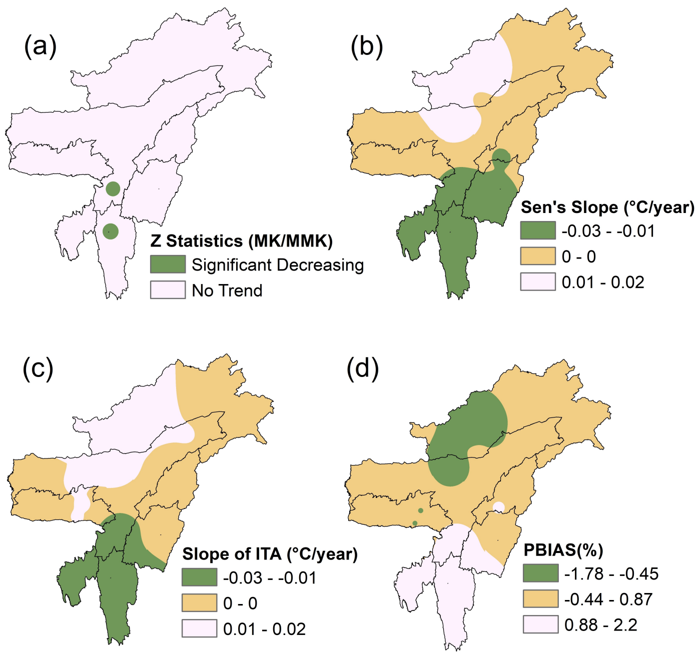

Figure 4: : Pre-Monsoon mean temperature trends in Northeast India (1990–2024): (a) Z-statistics, (b) Sen's slope estimator, (c) ITA slope and (d) Percent bias.

other hand, places like Dibrugarh and parts of Assam had negative PBIAS values, pointing to recent cooling. Taken together, these results show that pre-monsoon temperature trends in Northeast India are not uniform. Southern areas are cooling, some central and eastern regions are slightly warming, and many locations remain stable. The differences across methods such as MK, ITA, and PBIAS also suggest that temperature change here isn't always linear, it can fluctuate across decades. This reflects findings from other regional studies which show that seasonal climate patterns in Northeast India are influenced by a complex mix of topography, vegetation cover, and shifting rainfall systems [3, 22, 26].

4.3.2. Monsoon Season

The analysis of monsoon season temperatures (June–October) from 1990 to 2024 across Northeast India shows a noticeable warming trend in several areas. However, the extent and direction of change are not uniform. Local factors such as elevation, land use patterns, and urban growth have influenced temperature behavior across the region. The MK and MMK in (Fig. 5) highlight a significant warming trend in many areas of Assam, Meghalaya, and Arunachal Pradesh (Table 4). These regions show strong positive Z-values ($Z > 1.96$), indicating that monsoon temperatures have been rising steadily in recent decades. This warming is in line with broader trends seen in the eastern Himalayan region [27]. Sen's slope estimates (Fig. 5) reinforce this observation. Warming rates of 0.02°C to 0.03°C per year were found in upper Assam, Nagaland, and parts of Manipur.

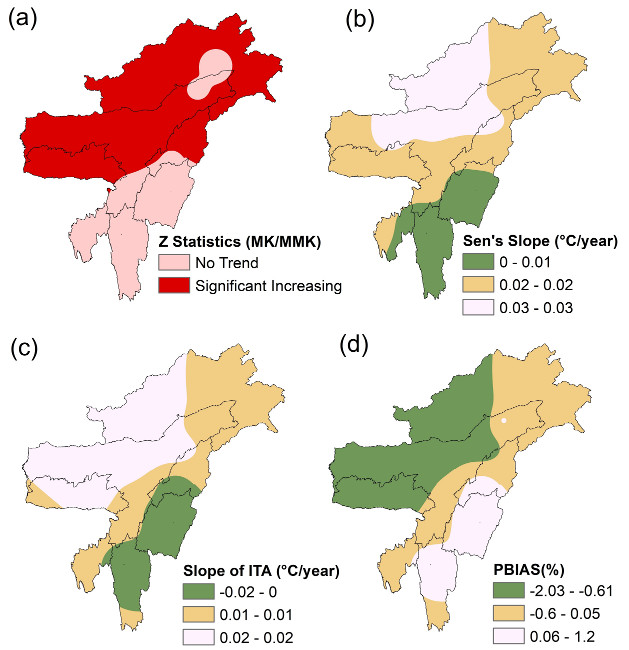

Figure 5: : Monsoon mean temperature trends in Northeast India (1990–2024): (a) Z-statistics, (b) Sen's slope estimator, (c) ITA slope and (d) Percent bias.

In contrast, regions like Tripura and Mizoram displayed smaller slope values less than 0.01°C/year, suggesting either slower warming or more stable conditions. The presence of dense vegetation in these southern states may be acting as a buffer, helping moderate the increase in surface temperatures [28]. The ITA, shown in Fig. 5(c), adds further depth to this understanding. Stations in Tripura, Mizoram, and southern Meghalaya show flat or even slightly negative ITA slopes, meaning there's little to no consistent warming trend. Meanwhile, northern Assam and Nagaland reflect positive slopes (0.01–0.02°C/year), aligning with the MK and Sen results. Interestingly, the Percent Bias (PBIAS) results (Fig. 5(d)) tell a somewhat different story. This method compares the two halves of the time series and suggests that Mizoram, Tripura, and southern Assam were generally warmer in the later years. PBIAS values here ranged from 0.06% to 1.2%. On the other hand, areas in central and northern Assam and parts of Arunachal Pradesh showed negative PBIAS values, indicating that these regions were warmer in the earlier part of the period. These differences suggest that warming during the monsoon has not been steady it may have occurred earlier and then stabilized or varied more in recent years. Overall, the clearest and most consistent warming trends during the monsoon season are found in central and upper Assam and parts of Nagaland. Here, all methods: MMK, Sen's slope, and ITA point to a rising temperature trend. In contrast, southern regions like Tripura and Mizoram show weaker or even conflicting trends. These variations highlight the importance of using multiple methods to assess climate change, especially in a region like Northeast

India where terrain and land cover can change dramatically over short distances [29]. Understanding how monsoon temperatures are changing is vital. Even small increases can affect agriculture, health, and disaster preparedness. Higher temperatures during the rainy season can disrupt crop cycles, speed up water loss through evapotranspiration, and increase heat-related stress in both humans and animals [30].

4.3.3. Post-Monsoon Season

The post-monsoon season (Nov-Dec) in Northeast India has shown a clear and widespread warming pattern in recent decades. According to the MK and MMK tests (Fig. 6), a majority of the region, particularly Assam, Nagaland, and parts of Arunachal Pradesh hhas experienced significant increasing trends in mean temperature during this season. These areas, marked in red, reflect statistically strong positive trends ($Z > 1.96$), which are consistent with broader warming signals observed in eastern and northeastern India in recent climate studies [3, 26]. The warming is also evident in the Sen's Slope estimates (Fig. 6), where large areas, especially in central and upper Assam, show slopes between 0.03°C/year and 0.05°C/year (Table 5). This suggests a steady and measurable rise in the post-monsoon temperature. Meanwhile, some zones in Tripura, Mizoram, and lower Assam display slower or even slightly negative slopes (down to −0.02°C/year), indicating relatively stable or locally moderated trends. These spatial differences could be influenced by elevation, vegetation cover, and urban land use changes [24].

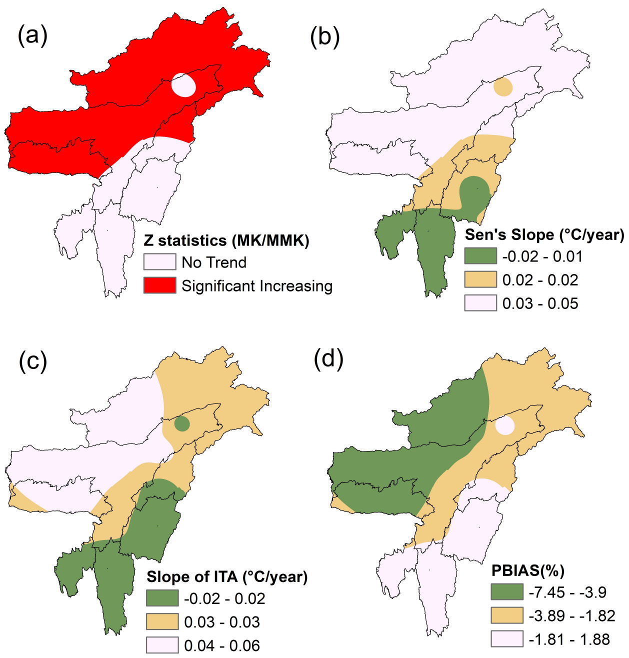

Figure 6: : Post-Monsoon mean temperature trends in Northeast India (1990–2024): (a) Z-statistics, (b) Sen's slope estimator, (c) ITA slope and (d) Percent bias.

Insights from the ITA (Fig. 6) further confirm these regional contrasts. Most warming trends cluster around central Assam and the Meghalaya Plateau, where ITA slopes range between 0.03°C/year and 0.06°C/year, suggesting persistent temperature rise. However, areas such as Aizawl, Tripura, and parts of Manipur show flat or mildly negative ITA slopes, reflecting low or reversing trends, potentially due to forest density or topographic buffering [3]. The PBIAS method (Fig. 6) offers another perspective. Here, negative PBIAS values (as low as −7.45%) dominate the map, especially in Assam and Arunachal Pradesh, indicating that temperatures in the second half of the period were lower than the first. This might appear contradictory to the MK and Sen's results, but it could point to non-linear climate behaviors such as a strong warming phase in the 1990s to 2000s, followed by a recent stabilization. In contrast, Mizoram and Tripura show positive PBIAS values (up to +1.88%), meaning those regions experienced greater warming in more recent decades, even though long-term trends appear flat in other methods. Bringing together the evidence from all four methods: MMK, Sen's slope, ITA, and PBIAS, it becomes clear that Assam and Nagaland are emerging as post-monsoon warming hotspots, with strong statistical and spatial agreement across methods. On the other hand, southern parts of Northeast India, such as Tripura, Mizoram, and Aizawl, show more variable behavior, with some warming in recent years but lacking long-term consistency. These results highlight the importance of regional-scale temperature monitoring, especially as post-monsoon warming can alter crop cycles, affect fog and dew formation, and increase the risk of vector-borne diseases [23, 25]. The use of multiple statistical methods offers a more complete and reliable understanding of climate trends in this ecologically sensitive and topographically complex region.

4.3.4. Winter Session

The Winter season in Northeast India is undergoing notable shifts in temperature patterns, as revealed through the combination of statistical trend analysis and spatial visualization (Fig. 7). The MMK test shows that most of Assam and Arunachal Pradesh are experiencing a significant increase in winter temperatures, as indicated by the widespread red shading. In contrast, Tripura stands out with a significant decreasing trend, marking it as a localized cooling spot (Table 6). These statistical trends are reinforced by the Sen's slope analysis (Fig. 7), which measures the rate of change. Regions in central and upper Assam show warming rates of 0.04–0.05°C/year, suggesting steady and substantial winter warming. Meanwhile, Tripura and parts of Mizoram have slopes in the negative range (−0.04 to 0°C/year), pointing to cooling or very slow warming. Such patterns may be linked to elevation, vegetation density, and local land use characteristics [28]. ITA further confirms these contrasting trends. Assam and the surrounding hill states mostly reflect positive ITA slopes, indicating upward temperature shifts, while southern areas like Tripura, Mizoram, and western Manipur display negative slopes of up to −0.05°C/year, supporting evidence of regional cooling. ITA is especially effective in capturing such nuanced variations, including non-monotonic trends often missed by traditional linear models. Looking at PBIAS results, most of Assam and Nagaland exhibit strong negative values (as low as

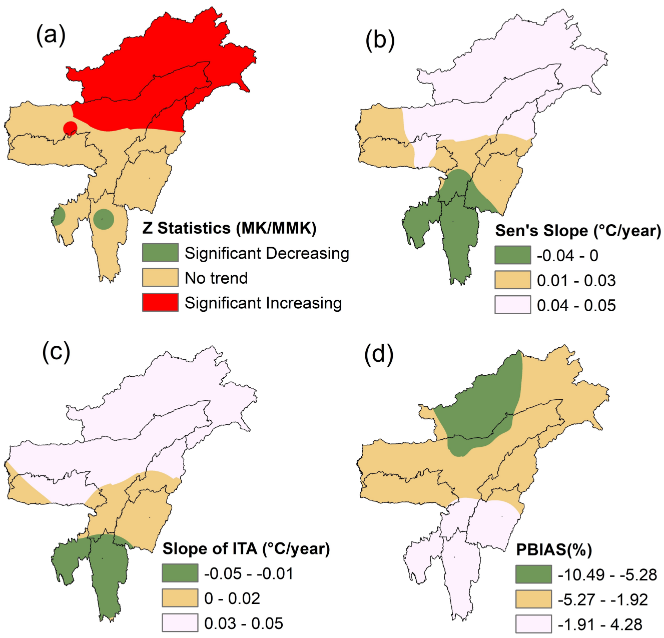

Figure 7: : Winter mean temperature trends in Northeast India (1990–2024): (a) Z-statistics, (b) Sen's slope estimator, (c) ITA slope and (d) Percent bias.

−10.49%), implying that the second half of the study period was cooler than the first. This is intriguing because these areas also show statistically increasing trends in other methods, suggesting either early-period warming followed by stabilization or short-term variability in recent years [23].On the other hand, southern zones like Mizoram and Tripura show positive PBIAS values (up to 4.28%), indicating that the second half of the series was warmer, aligning with localized recent warming despite long-term cooling trends. Together, the spatial patterns and statistical methods paint a complex picture of winter climate change across Northeast India. Assam, Arunachal Pradesh, and Nagaland are warming significantly, with robust support from MK, Sen's slope, and ITA. Meanwhile, Tripura and parts of Mizoram present an opposite trend, cooling gradually during winters. These contrasting regional behaviors underline the importance of using multiple trend detection techniques and spatial assessment to fully understand how different areas respond to climate change. Seasonal warming can influence rabi crop cycles, winter fog, and energy demands, making these insights crucial for local adaptation planning [3, 25].

4.4. Change Point Detection of Annual and Seasonal Temperature

The change point analysis of annual and seasonal mean temperatures across Northeast India reveals distinct temporal shifts, with several stations experiencing significant changes in their thermal regimes (Table 7). These shifts were primarily detected using PT, BR, and BU tests, and most occurred between 1998 and 2018, a period marked by regional-scale warming, urban expansion, and changes in monsoonal behavior [1, 3]. At the annual scale, strong and consistent change points were observed in various statistical literature. These shifts, detected across all three methods with low p-values, reflect robust warming signals particularly evident in central and southern parts of the region. The onset of significant warming in the early 2000s aligns with increased anthropogenic activity and a phase of intensified climate variability [25]. During the pre-monsoon season, some statistical researchers [24-27] emerged as key sites with statistically supported change points, indicating recent alterations in temperature regimes likely driven by forest clearance and infrastructural changes. Other stations, like Cherrapunji and Dibrugarh, displayed weaker evidence for abrupt shifts, suggesting more stable pre-monsoon conditions in those areas. In the monsoon season, the year 2012 appeared repeatedly across multiple locations. Both Cherrapunji and Guwahati showed highly significant change points during this year, supported unanimously by all three tests. These shifts coincide with a period of noticeable rainfall variability and land surface transformation in the Brahmaputra valley and Meghalaya Plateau. Stations like Agartala and Aizawl also indicated notable regime changes, though with varying levels of statistical support. For the post-monsoon season, a consistent pattern of warming onset was found between 1999 and 2013. Researchers again emerged as hotspots of change, suggesting a regional climate shift affecting the shoulder months of the monsoon cycle. Meanwhile, Agartala and Aizawl showed possible earlier change points around 1999, indicating that southern parts of the region may have begun warming earlier than the north. Winter temperature regimes revealed notable shifts around 2013 in both Dibrugarh and Guwahati, with all three methods confirming structural breaks in the series. These findings suggest that winters have become significantly warmer since the early 2010s in central Assam. In contrast, Aizawl and Agartala exhibited later or earlier shifts respectively, reflecting region-specific responses to winter warming possibly linked to elevation, land cover, and urbanization effects [29] as well as [29, 30]. Overall, the results demonstrate that change points are neither uniform across seasons nor synchronized across the region. While certain years like 2012 and 2013 emerge as common transition points in multiple seasons and locations, others are more localized. This emphasizes the nonlinear and spatially heterogeneous nature of climate change in Northeast India, reinforcing the need to analyze each season separately and apply multiple methods for reliable detection.

5. Conclusions

This study closely examined how temperatures have changed across Northeast India between 1990 and 2024. To get a complete picture, we used a combination of different methods. Technique like Sen's slope estimator as well as MK, MMK, ITA, and PBIAS tests helped us understand not just whether temperatures were increasing or decreasing but also how fast the changes were happening and whether recent decades were warmer than earlier ones. Beyond gradual trends, we also explored sudden changes in temperature patterns using change point detection methods. Tools like PT, BR, and BU tests allowed us to pinpoint the years when these shifts occurred also known as "regime shifts." For example, stations such as Guwahati, Cherrapunji, and Dibrugarh showed strong and consistent warming, particularly during the monsoon and winter seasons. In many cases, these changes became noticeable around 2012–2013, hinting at possible shifts in climate dynamics or land use around that time. However, not all locations followed the same pattern. Places like Aizwal and Agartala showed more mixed results. Although their long-term trends weren't always clearly increasing, their PBIAS values indicated that warming may have accelerated in recent years. This shows how even when a long-term trend seems flat, shorter-term warming can still be happening. By combining gradual trend analysis with sudden change detection, our research offers a deeper and more accurate understanding of how the region's climate is evolving. It also underscores the need to examine each season and location individually, rather than assuming a single pattern applies to the entire region. Future studies can look at more climate factors like rainfall, land use changes, and vegetation cover to understand how they affect temperature. Using machine learning can also help find hidden patterns and make better predictions about how temperatures might change in the future. Adding global climate projections, such as those from CMIP6 models, can show how the region could warm under different climate scenarios. Most importantly, it's essential to connect this research with real-world planning by working with policymakers, farmers, and disaster response teams. Since Northeast India is both climate-sensitive and ecologically fragile, using these insights to support local planning and action is very important.

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Appendix

Table 1: Descriptive Statistics of Annual Mean Temperature (1990–2024) at 14 Stations in Northeast India.

Station	**Mean (°C)**	**SD**	**CV (%)**	**Kurtosis**	**Skewness**
Agartala	25.37	0.36	1.43	-0.90	0.21
Aizawl	23.01	0.37	1.59	-0.56	-0.17
Cherrapunji	17.86	0.31	1.73	0.36	0.03
Dibrugarh	24.43	0.42	1.71	-0.35	-0.41
Guwahati	22.89	0.39	1.70	-0.03	0.56
Itanagar	22.16	0.45	2.02	-0.64	-0.11
Jorhat	24.01	0.45	1.87	-0.71	-0.22
Kohima	18.29	0.41	2.26	0.21	-0.14
Manipur	20.46	0.39	1.92	-0.70	0.36
Pasighat	23.74	0.38	1.62	-0.12	-0.29
Shillong	17.86	0.31	1.73	0.36	0.03
Silchar	23.71	0.31	1.30	-0.63	0.36
Tezpur	24.27	0.48	1.99	-0.77	0.26
Ziro	17.49	0.47	2.69	-0.19	-0.23

Table 2: Annual Mean Temperature Trend Summary at 14 Stations in Northeast India (1990–2024). Note: * denotes significance at the 5% level.

Station	Lag-1 AC	Z Statistics (MK/MMK)	Sen's Slope (°C/year)	ITA Trend Indicator (D)	PBIAS (%)	ITA Slope (°C/year)
Agartala	0.31	-2.16*	-0.01	-0.07	0.69	-0.01
Aizawl	0.23	-3.38*	-0.02	-0.18	1.74	-0.02
Cherrapunji	0.36	3.33*	0.01	0.18	-1.77	0.02
Dibrugarh	0.30	7.63*	0.02	0.05	-0.49	0.01
Guwahati	0.57	3.34*	0.02	0.18	-1.80	0.02
Itanagar	0.46	7.93*	0.02	0.18	-1.78	0.02
Jorhat	0.41	8.02*	0.02	0.12	-1.17	0.02
Kohima	0.37	0.81	0.01	-0.04	0.37	0.00
Manipur	0.03	0.11	0.00	-0.08	0.80	-0.01
Pasighat	0.31	3.34*	0.02	0.08	-0.84	0.01
Shillong	0.36	3.33*	0.01	0.18	-1.77	0.02
Silchar	0.23	-0.92	0.00	-0.01	0.09	0.00
Tezpur	0.46	3.55*	0.03	0.20	-1.98	0.03
Ziro	0.60	9.70*	0.03	0.33	-3.33	0.03

Table 3: Pre-Monsoon Mean Temperature Trend Summary at 14 Stations in Northeast India (1990–2024). Note: * denotes significance at the 5% level.

Station	Lag-1 AC	Z Statistics (MK/MMK)	Sen's Slope (°C/year)	ITA Trend Indicator (D)	PBIAS (%)	ITA Slope (°C/year)
Agartala	0.05	-1.93	-0.02	-0.14	1.37	-0.02
Aizawl	0.05	-2.09*	-0.03	-0.23	2.20	-0.03
Cherrapunji	-0.11	0.28	0.00	0.04	-0.47	0.00
Dibrugarh	-0.05	0.17	0.00	-0.02	0.07	0.00
Guwahati	0.20	0.00	0.00	0.02	-0.25	0.00
Itanagar	-0.07	0.27	0.00	0.02	-0.29	0.00
Jorhat	-0.06	-0.37	0.00	-0.06	0.53	-0.01
Kohima	0.11	-0.71	-0.01	-0.11	0.94	-0.01
Manipur	-0.05	-0.57	-0.01	-0.10	0.84	-0.01
Pasighat	0.12	-0.26	0.00	-0.04	0.33	-0.01
Shillong	-0.11	0.28	0.00	0.04	-0.47	0.00
Silchar	0.20	-2.26*	-0.02	-0.18	1.68	-0.03
Tezpur	0.11	1.14	0.02	0.10	-1.08	0.01
Ziro	-0.02	1.31	0.01	0.17	-1.78	0.02

Table 4: Monsoon Mean Temperature Trend Summary at 14 Stations in Northeast India (1990–2024). Note: * denotes significance at the 5% level.

Station	Lag-1 AC	Z Statistics (MK/MMK)	Sen's Slope (°C/year)	ITA Trend Indicator (D)	PBIAS (%)	ITA Slope (°C/year)
Agartala	0.01	1.02	0.01	0.02	-0.20	0.00
Aizawl	-0.08	-0.82	0.00	-0.05	0.54	-0.01
Cherrapunji	0.11	3.76*	0.01	0.10	-1.04	0.01
Dibrugarh	0.16	1.42	0.01	-0.01	0.07	0.00
Guwahati	0.16	3.11*	0.02	0.10	-0.96	0.01
Itanagar	0.31	3.82*	0.02	0.11	-1.13	0.02
Jorhat	0.27	3.70*	0.02	0.08	-0.79	0.01
Kohima	0.22	1.77	0.01	-0.05	0.51	-0.01
Manipur	0.00	-0.17	0.00	-0.12	1.20	-0.02
Pasighat	0.14	1.53	0.01	0.00	-0.02	0.00
Shillong	0.11	3.76*	0.01	0.10	-1.04	0.01
Silchar	-0.11	1.22	0.01	0.03	-0.28	0.00
Tezpur	0.20	3.66*	0.02	0.10	-1.03	0.02
Ziro	0.49	5.50*	0.03	0.20	-2.03	0.02

Table 5: Post-Monsoon Mean Temperature Trend Summary at 14 Stations in Northeast India (1990–2024). Note: * denotes significance at the 5% level.

Station	Lag-1 AC	Z Statistics (MK/MMK)	Sen's Slope (°C/year)	ITA Trend Indicator (D)	PBIAS (%)	ITA Slope (°C/year)
Agartala	0.04	-2.39*	-0.04	-0.30	2.84	-0.03
Aizawl	0.02	-2.47*	-0.04	-0.45	4.28	-0.05
Cherrapunji	0.06	1.46	0.03	0.42	-4.84	0.03
Dibrugarh	0.18	2.36*	0.04	0.36	-3.87	0.04
Guwahati	0.36	2.09*	0.03	0.45	-4.72	0.04
Itanagar	0.27	2.37*	0.04	0.53	-5.62	0.05
Jorhat	0.27	3.63*	0.04	0.41	-4.36	0.04
Kohima	0.06	0.92	0.02	0.11	-2.09	0.01
Manipur	-0.19	0.07	0.00	0.05	-1.00	0.00
Pasighat	0.14	2.50*	0.04	0.44	-4.70	0.04
Shillong	0.06	1.46	0.03	0.42	-4.84	0.03
Silchar	-0.01	-0.70	-0.01	-0.03	0.16	0.00
Tezpur	0.29	2.91*	0.05	0.53	-5.52	0.05
Ziro	0.30	2.81*	0.05	0.95	-10.49	0.05

Table 6: Winter Mean Temperature Trend Summary at 14 Stations in Northeast India (1990–2024). Note: * denotes significance at the 5% level.

Station	Lag-1 AC	Z Statistics (MK/MMK)	Sen's Slope (°C/year)	ITA Trend Indicator (D)	PBIAS (%)	ITA Slope (°C/year)
Agartala	0.04	-2.39*	-0.04	-0.30	2.84	-0.03
Aizawl	0.02	-2.47*	-0.04	-0.45	4.28	-0.05
Cherrapunji	0.06	1.46	0.03	0.42	-4.84	0.03
Dibrugarh	0.18	2.36*	0.04	0.36	-3.87	0.04
Guwahati	0.36	2.09*	0.03	0.45	-4.72	0.04
Itanagar	0.27	2.37*	0.04	0.53	-5.62	0.05
Jorhat	0.27	3.63*	0.04	0.41	-4.36	0.04
Kohima	0.06	0.92	0.02	0.11	-2.09	0.01
Manipur	-0.19	0.07	0.00	0.05	-1.00	0.00
Pasighat	0.14	2.50*	0.04	0.44	-4.70	0.04
Shillong	0.06	1.46	0.03	0.42	-4.84	0.03
Silchar	-0.01	-0.70	-0.01	-0.03	0.16	0.00
Tezpur	0.29	2.91*	0.05	0.53	-5.52	0.05
Ziro	0.30	2.81*	0.05	0.95	-10.49	0.05

Table 7: Change Point Detection of Mean Temperature at 14 Stations in Northeast India (1990–2024). Note: * denotes significance at the 5% level.

Station	Annual	Pre-Monsoon	Monsoon	Post-Monsoon	Winter
Agartala (PT)	2000*	2015	2016	1999*	2000
Agartala (BR)	2000*	2015	2016*	1999	2000
Agartala (BU)	2000*	2015*	2016	1999	2000*
Aizwal (PT)	2007*	2011	2006	1999	2017
Aizwal (BR)	2007*	2011	1997	1999	2018
Aizwal (BU)	2007*	2011*	1997	1999*	2018*
Cherrapunji (PT)	2013*	2017	2012*	2012*	2013
Cherrapunji (BR)	2013*	2017	2012*	2013*	2005
Cherrapunji (BU)	2013*	2017	2012*	2013*	2005*
Dibrugarh (PT)	1998*	1998	1998	2014	2013*
Dibrugarh (BR)	1998	1998	1998	2014	2013*
Dibrugarh (BU)	1998*	1998	1998	2014	2013
Guwahati (PT)	2013*	2000	2012*	2008*	2013*
Guwahati (BR)	2013*	2000	2012*	2012*	2013*
Guwahati (BU)	2013*	2000	2012*	2012*	2013*
Itanagar (PT)	2013*	1995	2012*	2012*	2013*
Itanagar (BR)	2013*	1995	2012*	2012*	2013*
Itanagar (BU)	2013*	1995	2012*	2012*	2013*
Jorhat (PT)	2013*	1995	2013*	2012*	2013*
Jorhat (BR)	2013*	2005	2013	2012*	2013*
Jorhat (BU)	2013*	2005	2013*	2012*	2013*
Kohima (PT)	1998	2010	1998	1998	1999
Kohima (BR)	1998*	2011	1998	1998	1999*
Kohima (BU)	1998	2011	1998	1998	1999
Manipur (PT)	2007	2010	2007	2021	1999
Manipur (BR)	2007	2010	2007	1993	1999
Manipur (BU)	2007	2010	2007	1993	1999
Pasighat (PT)	1999*	1998	1999	2014*	2013*
Pasighat (BR)	1999	1998	1999	2014*	2013*
Pasighat (BU)	1999*	1998	1999	2014*	2013*
Shillong (PT)	2013*	2017	2012*	2012*	2013
Shillong (BR)	2013*	2017	2012*	2013*	2005
Shillong (BU)	2013*	2017	2012*	2013*	2005*
Silchar (PT)	2000	2017	2016	2013	2018
Silchar (BR)	2000	2000*	2016	2013*	2018
Silchar (BU)	2000	2000*	2016	2013	2018
Tezpur (PT)	2013*	2009	2014*	2014*	2013*
Tezpur (BR)	2013*	2013	2014*	2014*	2013*
Tezpur (BU)	2013*	2013	2014*	2014*	2013*
Ziro (PT)	2013*	1998	2012*	2012*	2013*
Ziro (BR)	2013*	1998	2012*	2012*	2013*
Ziro (BU)	2013*	1998	2012*	2012*	2013*

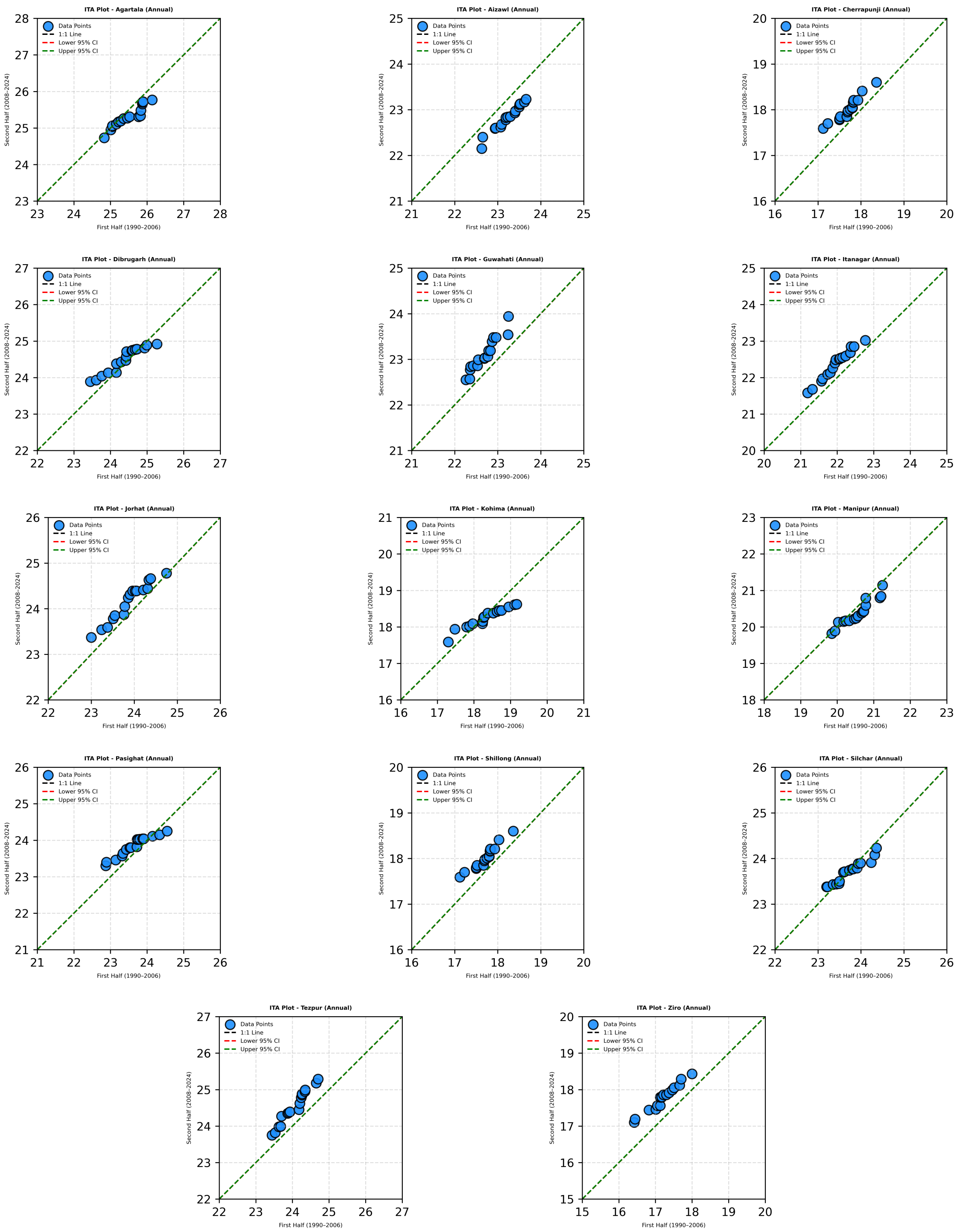

Figure 8: ITA plot of Annual Mean Temperature of the 14 stations

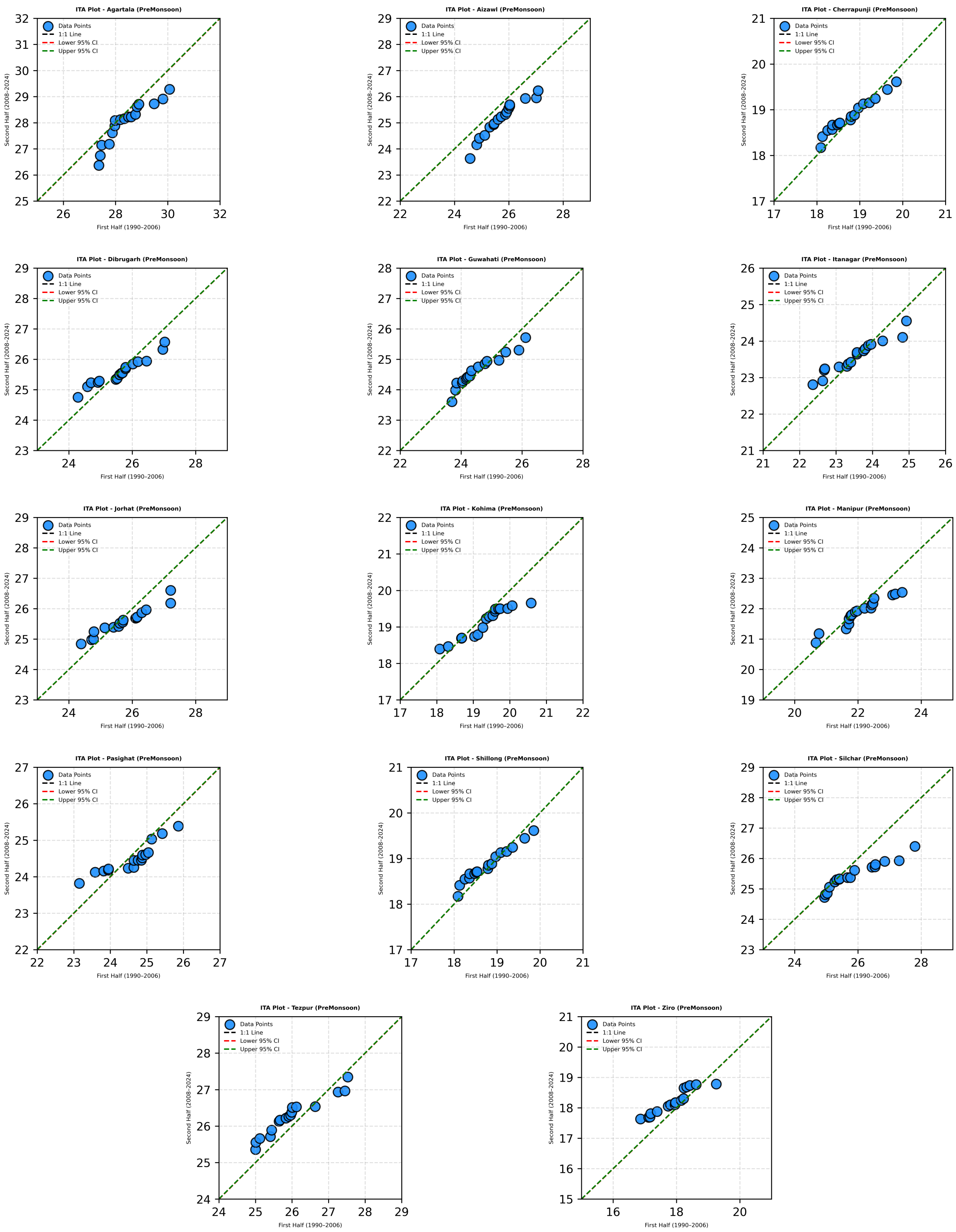

Figure 9: ITA plot of Pre-Monsoon Mean Temperature of the 14 stations

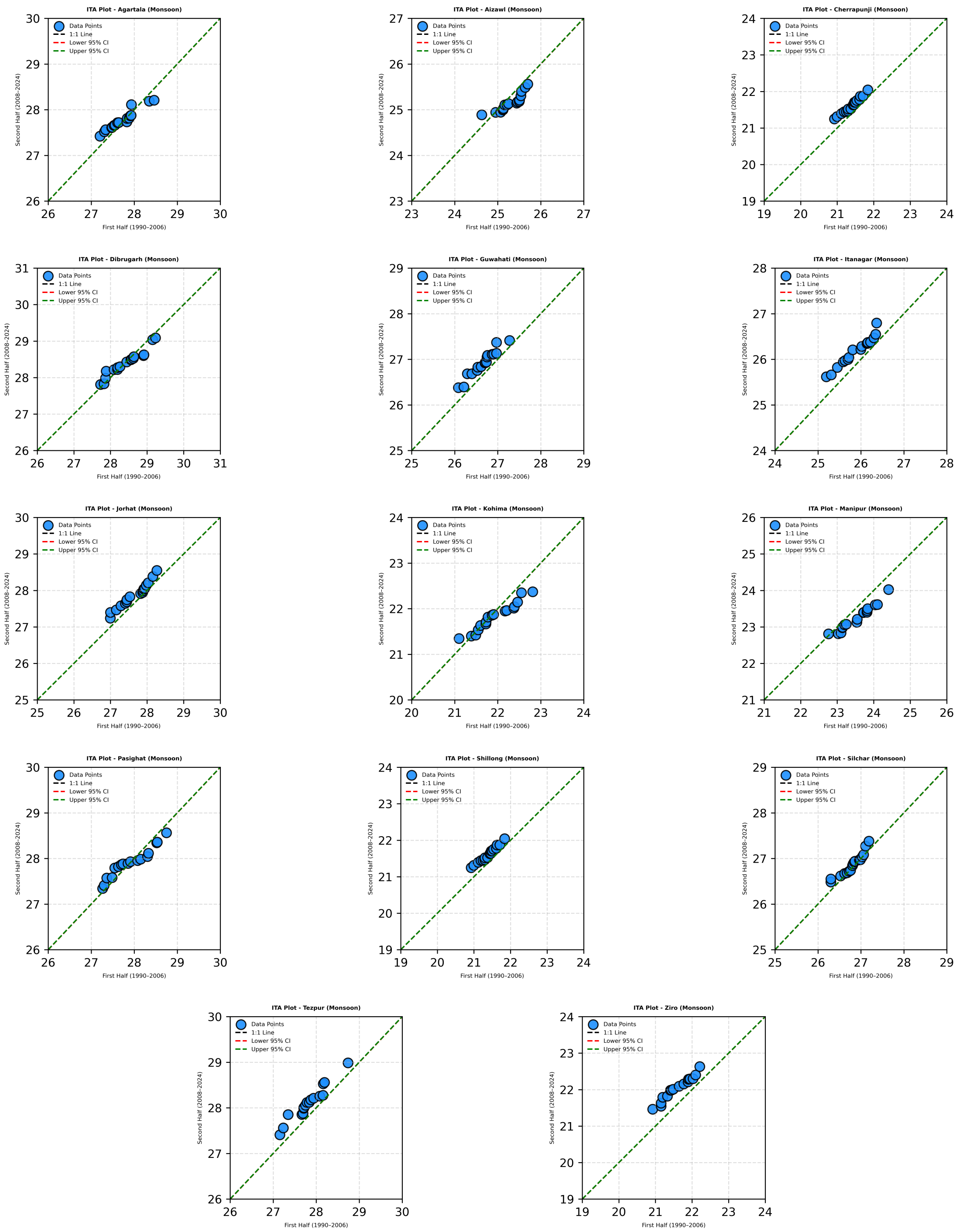

Figure 10: ITA Plot of Monsoon Mean Temperature of the 14 stations

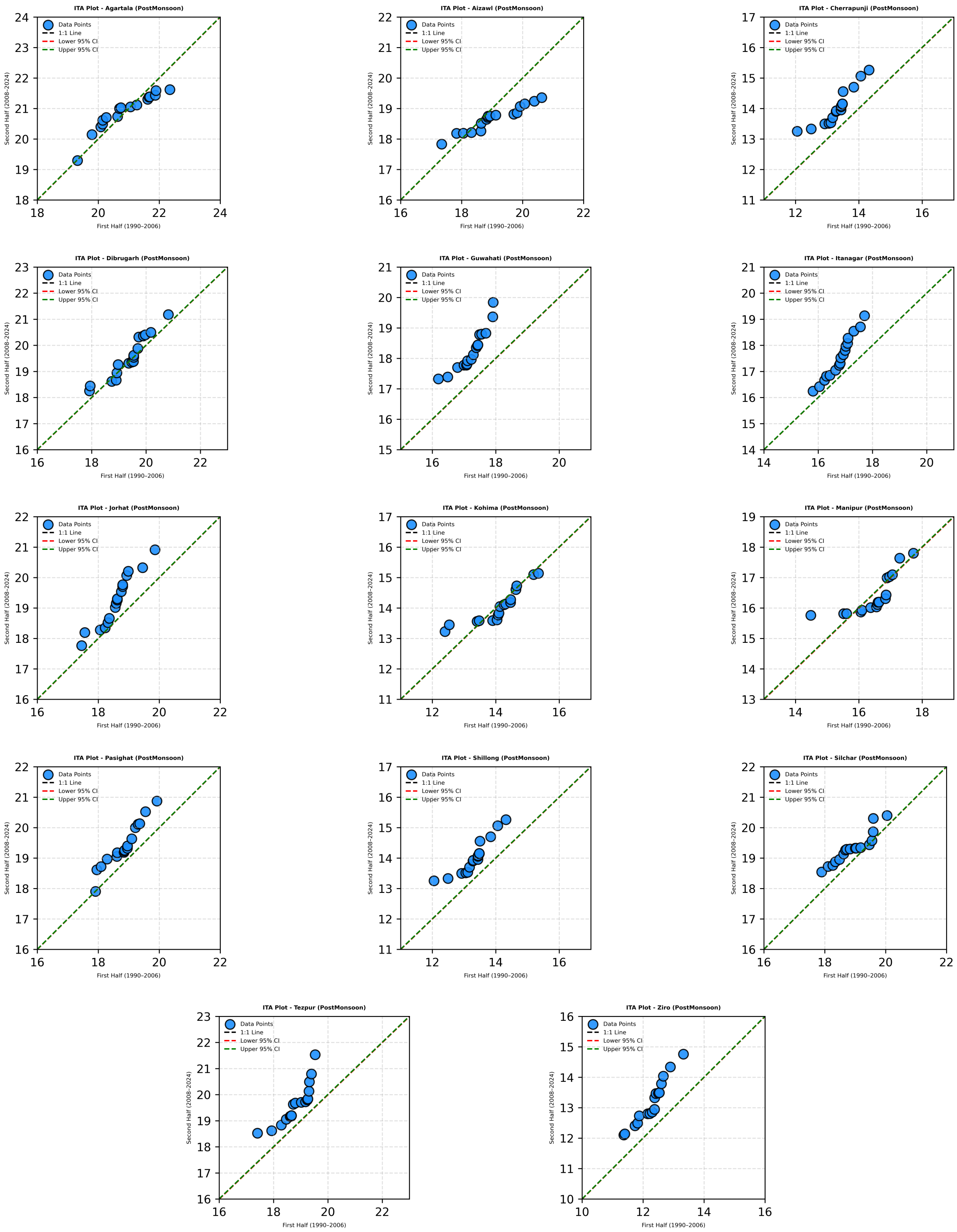

Figure 11: ITA plot of Post-Monsoon Mean Temperature of the 14 stations

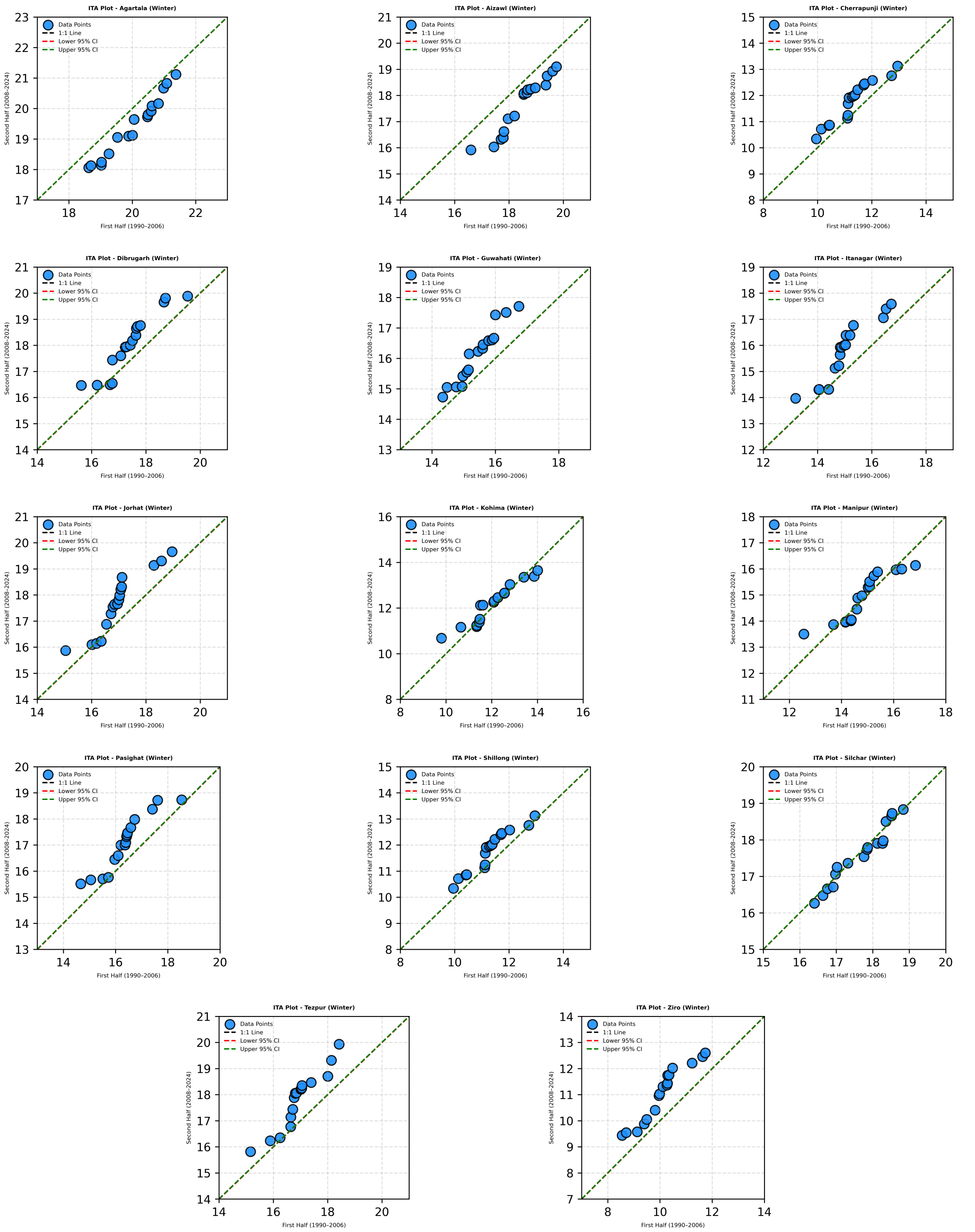

Figure 12: ITA plot of Winter Mean Temperature of the 14 stations

Figure 13: Change Point Detection of Annual Mean Temperature Using Pettit Test

Figure 14: Change Point Detection of Pre-Monsoon Mean Temperature Using Pettit Test

Figure 15: Change Point Detection of Monsoon Mean Temperature Using Pettit Test

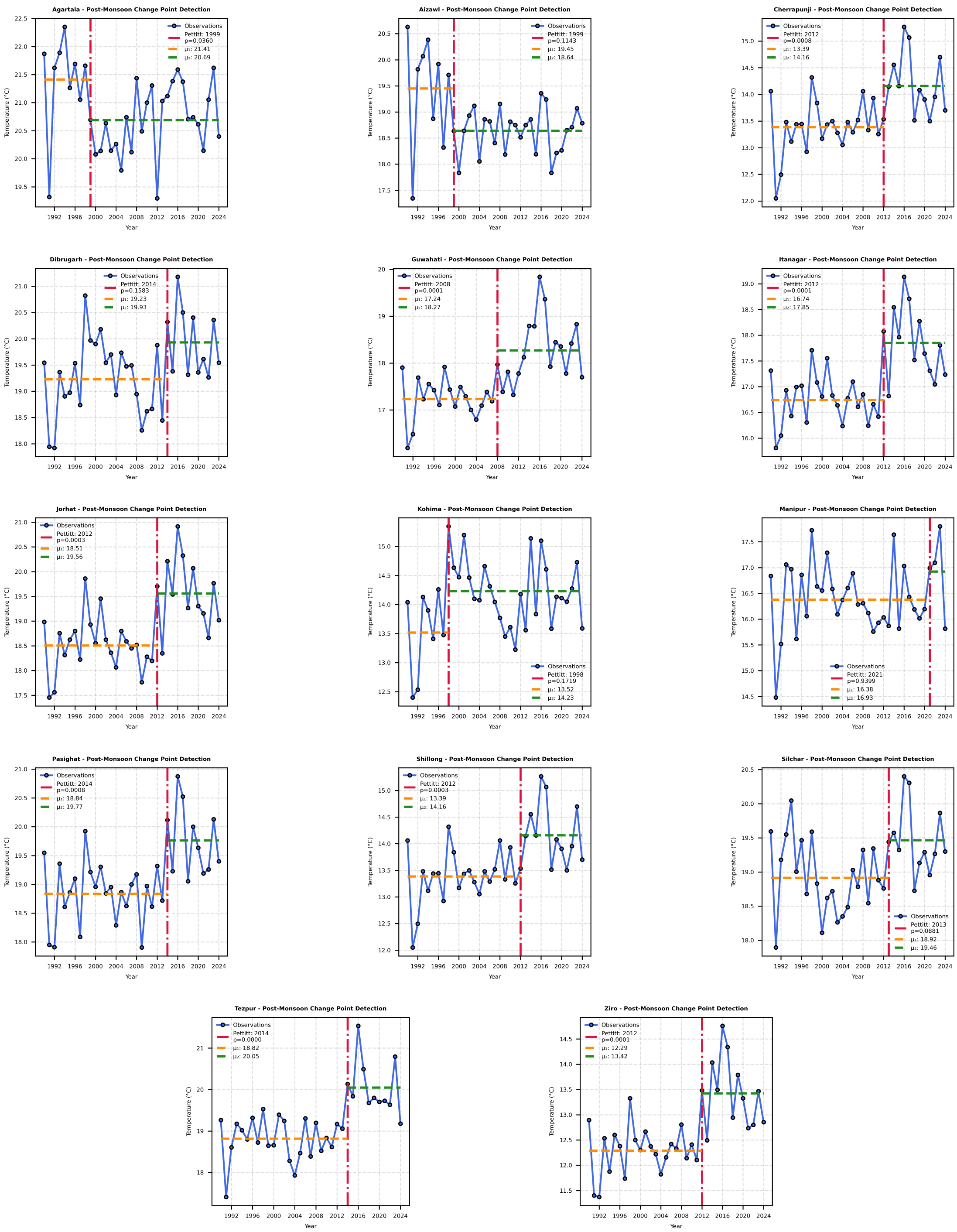

Figure 16: Change Point Detection of Post-Monsoon Mean Temperature Using Pettit Test

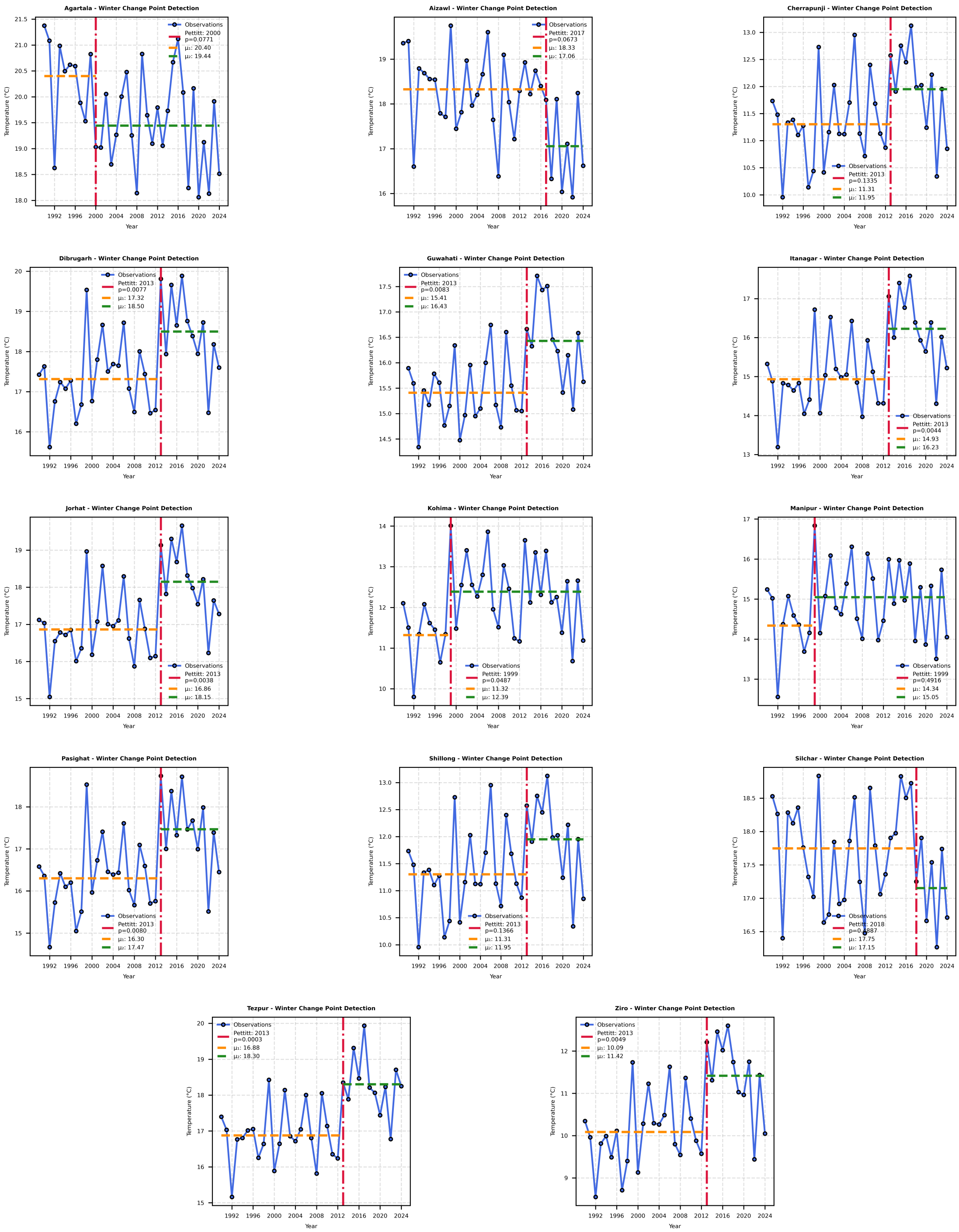

Figure 17: Change Point Detection of Winter Mean Temperature Using Pettit Test