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Article

Analysis of Temperature Trends and Variability in Eastern Himalaya: Evidence from Sikkim

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Abstract: The study examines temperature patterns in Sikkim for an extended period, using 72 years (1951-2023) of IMD gridded data. Several statistical methods, including Coefficient of Variation, Analysis of Variance, Moving Average, Standardized Anomaly Index, and Regression analysis, were applied to explore the trends and variability across mean, minimum, and maximum seasonal temperatures. Results reveal a significant warming tendency in monsoon and post monsoon seasons, with minimum temperatures showing the highest variability. Extreme hot anomalies are rising in recent years which are more pronounced in the cases of monsoon and post monsoon seasons. Maximum winter temperature shows a declining trend, where mean and minimum temperatures are rising but not statistically significant. On the other hand, summer temperatures have been relatively stable over the decades. These temperatures shifts are critical for the livelihoods of rural population who heavily depend on natural resources. These outcomes emphasize the urgent need of climate adaptation strategies and enhanced monitoring and early warning systems to support sustainable development in this vulnerable mountain region.

Keywords: climate variability; seasonal temperature; temperature trends; sikkim himalaya

1. Introduction

Several global challenges are being experienced in the 21st century; among these, one pressing challenge is climate change. It is widely accepted by scientists that the Earth's temperature is increasing at an unprecedented rate in the last few decades (Beniston, 2003; O'Brien & Leichenko, 2000). Temperature is a fundamental climatic element that directly affects evapotranspiration, soil moisture content, crop health and productivity, and human comfort. Accelerating global temperature is mainly attributed to anthropogenic greenhouse gas emissions. It has already led to concerning shifts in climatic patterns across various regions of the world. These changes not only influence the growing seasons and yield potential of crops but also intensify heat waves, contributing to multiple health issues and even mortality rates of humans and livestock (Lobell & Field, 2007; IPCC, 2021). The shifting pattern and variability of temperature are crucial. These can reduce the tolerance power of many crops, problems regarding early maturing and heat stress upon crops, etc., challenging food security. Further, most of the agricultural workforce is exposed to direct thermal stress, affecting labor productivity. Moreover, the rising temperature can increase the severity of drought by accelerating soil moisture depletion. It can reduces surface water availability, posing a challenge for sustainable water resource management (Mall et al., 2006).

Mountain regions are susceptible to climatic variability. In recent decades, a rapid warming trend can be observed in the Hindu Kush Himalayan (HKH) region. Temperature change has been very significant since the beginning of the 21st century. The annual surface temperature rises at a rate of 0.1ºC per decade from 1901 to 2014 and faster between 1951 and 2014 at 0.2 ºC per decade. Due to this alarming rate of increasing warming, several places of the Hindu Kush Himalayan regions are exhibiting declining snowfall and retreating glaciers (Vellore et al. 2022). Snow melting and retreating of glaciers have become more pronounced in the last five decades (Kulkarni et al., 2014). The eastern and western Himalayan river basins show a progressive warming trend where minimum temperature is rising more pronouncedly than the maximum temperature (Rajbhandari et al., 2016). As per Ren et al. (2016), the HKH is experiencing an increasing mean temperature of 0.3 ºC per decade. A study by Sreshtha, Gautam, and Bawa (2012) illustrates that the Himalayan temperature increased by 1.5 ºC between 1982 and 2006, which is about three times the global average. The temperature in mountains is rising faster than low-lying areas. The Himalayas are not an exception to that, which is also warming faster than the adjacent Indian landmass (Pepin et al., 2015).

As situated in the Himalayas, Sikkim is also experiencing significant warming and related adversities. Altered climatic conditions affect livestock and agricultural yield. Food security is at risk because of declining agricultural output brought on by changing precipitation patterns and rising temperatures (Chaudhary & Bawa, 2011). Increased insect and disease outbreaks are being reported by farmers in Sikkim, which further lowers agricultural production (Ingty, 2016). Heat stress, a lack of feed, and increased disease prevalence are problems for livestock farmers. These lower output and cause financial losses (Tambe et al., 2012). These effects increase rural populations' susceptibility, underscoring the pressing need for adaptable responses. Due to rising temperatures in high altitudes, many glaciers are melting rapidly. As a result, the lake areas of Sikkim's higher altitudes have increased over the last 50 years. Also, the addition of water volume is exacerbating the glacier lake outburst flood risks (Kumar & Prabhu, 2012). Evidences show that the floral and faunal groups, including birds, reptiles, amphibians, butterflies, etc., are affected by changing climatic conditions. Shifts in ranges, shrinkage in habitats, altered mechanisms of breeding, skewed sex ratios, and also some species are on the verge of extinction due to increasing warming in Sikkim (Chettri et al., 2012; Kumar et al., 2012). These shifts have manifold impacts on the livelihood of Sikkim's people. Reducing pasture lands is affecting cattle health and in turn the livelihood of pastoralists (Sharma & Rai, 2012). The quality of milk is also deteriorating. The sourness of milk is increasing due to rising temperatures. Several crops show a decrease in productivity (Kumar, 2012; Bawa & Ingty, 2012).

2. Methodology

To ensure a comprehensive coverage of temperature pattern in Sikkim, each method has been selected to fulfill particular criterion. For example, descriptive statistics (CV) is applied to detect seasonal temperature variability, inferential statistics (ANOVA) is used to identify between and within group variability, standardized anomaly index allowed to explore the temperature extremes within the study period and simple moving average is used to explore long-term trends in seasonal temperature dataset.

2.1. Study Area

Sikkim is a northeastern state located in the Eastern Himalayas. It borders with Tibet, Nepal, and Bhutan. The state is the second smallest in India, covering an area of about 7096 sq. km. The state possesses a population of 610,577 as of the 2011 Census, and 86 persons per square kilometer (Sikkim Statistics, 2013). Approximately 80% of people in Sikkim rely on farming and allied activities (Kumar et al., 2018). Lepchas, Bhutias, and Nepalis are among the largest ethnic groups in the state, and they all contribute to its rich cultural fabric. With an impressive 81.4% literacy rate, Sikkim's economy is primarily driven by agriculture, tourism, and hydropower, bolstered by the region's distinctive geography and biodiversity (Tambe et al., 2012). 74.84% of Sikkim's population is rural, making up most of the population. More than 70% live in rural areas and 80% are employed in agriculture. Rice, maize, cardamom, and other fruits like oranges and pears are cultivated in different altitudes in this state. Rural residents also make a substantial living from animal husbandry in addition to agriculture. According to the Government of Sikkim (Sikkim Statistics, 2013), more than 80% of rural households own livestock and rely on producing milk, meat, eggs, skins, manure, and wool for their income. As a major portion of the population in this state relies on nature for agriculture and animal husbandry, therefore, changes in the climate are seriously endangering their way of life (Jain et al., 2013). The study area map of Sikkim is given in Figure 1.

2.2. Data Source

Sikkim's gridded temperature data was collected from the India Meteorological Department (IMD) with a grid cell size of 1.0 × 1.0 from 1951 to 2023. As per the World Meteorological Organization (WMO) and the National Oceanic and Atmospheric Administration (NOAA), a 30-year average of atmospheric conditions is considered to define it as climate (Getahun et al., 2016). IMD provides temperature data from 1951. Hence, to find a broader pattern of changes and variability of temperature, a total period of 72 years of temperature was taken. IMD gridded temperature dataset used in this study is provided in preprocessed and quality controlled form by the source agency. Therefore, no additional preprocessing and outlier detection was performed by the authors. The data structure has been prepared by using Python coding from the raw data and all statistical analyses are done using MS Excel. The daily temperature data consists of three variables – TMAX (daily maximum), TMIN (daily minimum), and TMEAN (daily mean). To prepare monthly averages, the date column was first used to extract year and month. The data was then grouped month-wise for each year. Missing daily values were treated using interpolation, and large gaps were excluded. Monthly averages of TMAX, TMIN, and TMEAN were then computed using the valid daily records only. Within each month, the arithmetic mean of all daily values was calculated:

- Monthly TMAX= mean of all daily maximum temperatures of that month
- Monthly TMIN= mean of all daily minimum temperatures of that month
- Monthly TMEAN= mean of daily mean temperatures, or (TMAX + TMIN)/2 if not directly available

Finally, these monthly averages were arranged in a table where rows represent years and columns represent the 12 months (Jan–Dec).

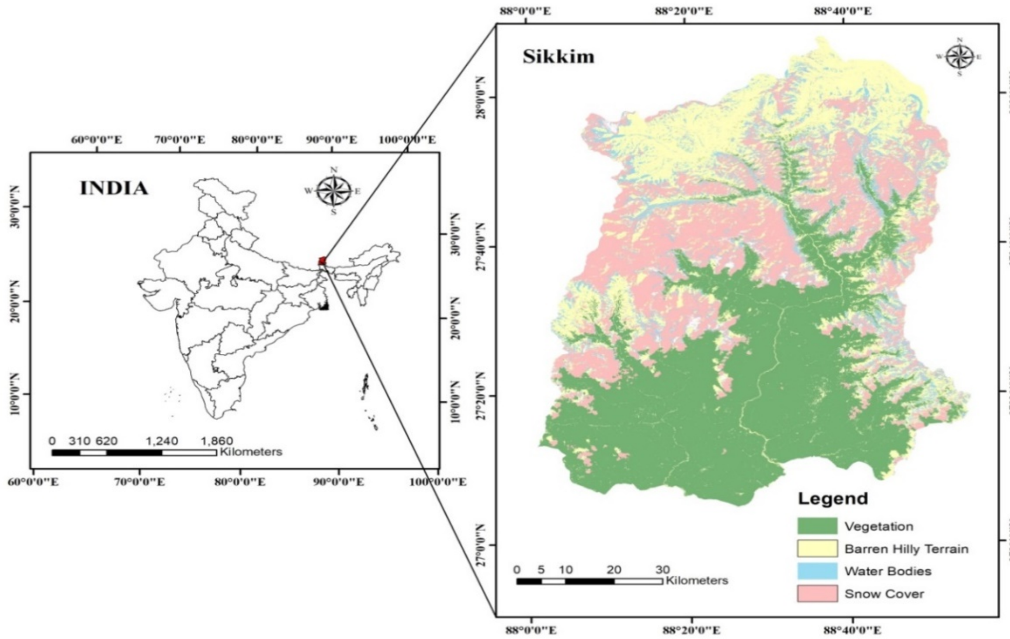


Figure 1. Study Area Map (Source: Compiled by Authors).

2.3. Coefficient of Variation (CV)

CV is a prevalent method to identify variability in a dataset. It portrays how much the values vary relative to their mean. This method removes units by dividing the standard deviation by the mean, which makes the dataset comparable with different units or scales (Abdi & Williams, 2010). CV has been applied here because it standardizes the variability, making it easy to compare across different seasons and time periods. A higher CV indicates higher temperature variability and vice versa. Some limitations prevail in the method, such as CV is highly sensitive to mean values. A low mean value, even a slight standard deviation, can produce a very high variation (Livers, J.J., 1942). The coefficient of variation is calculated using the following equation:

$$\mathrm{CV} = \frac{\sigma}{\mu} \times 100$$

Here, CV represents the Coefficient of Variation
σ means Standard Deviation, and μ signifies the mean of rainfall.

2.4. One Way Analysis of Variance (ANOVA)

ANOVA is a parametric statistical technique used to find variation between two or more groups of observations by comparing their mean values (Umar et al., 2019; Larson, 2008). This statistical tool has been applied to test whether the seasonal temperature varies significantly between groups. ANOVA is based on mathematical linear regression and general linear models that quantify the association between response and explanatory variables (Sawyer, 2009). The sources of variation are recognized by comparing the between-group and within-group variability. The F value is measured and compared with the F critical ratio to establish the acceptance or rejection of the hypothesis (Agada et al., 2018). ANOVA, though powerful for variability testing, has some limitations. It assumes that the data in all groups are normally distributed and have equal variance. Further, it only tells that differences exist in mean values but cannot identify which groups differ from others (Buckless & Ravenscroft, 1990). In this study, only one independent variable, temperature, is analyzed.

2.5. Standardized Anomaly Index (SAI)

The Standardized Anomaly Index is a simple and effective method used to detect and quantify deviations in climate variables, e.g., temperature and rainfall from long-term averages. This method helps to identify abnormal conditions, such as unusually hot or cold, and wet or dry periods. In this present study, the SAI has been applied to determine the deviations in temperature variables from the long-term mean of 72 years. Though it is a widely used technique, some limitations prevail in this method. SAI heavily relies on the quality and length of the dataset. Hence, data from a short time period and incomplete temperature records can misrepresent the result. Further, as it standardized, the equal values at different locations may not indicate the identical level of severity which can mislead the interpretation (Raziei, T., 2021). The formula is given below (Babatolu & Akinnubi, 2013; Koudahe et al., 2017):

$$\text{SAI} = \frac{r - r_i}{\sigma}$$

Here, SAI represents Standardized Anomaly Index
r is the mean temperature of a particular season of a particular year
r_i is the long-term mean and
σ indicates the standard deviation of the long-term mean temperature

2.6. Moving Average

Moving average is a statistical method to explore trends in a dataset in a time series analysis. There are three types of moving average methods. The first is the Simple Moving Average (SMA), where each time series data point is given equal weight. The next one is the Weighted Moving Average (WMA), which provides weightage to each time series data point. The third one is the Exponential Moving Average (EMA), which is a type of WMA that assigns weights based on exponential numbers (Hansun, 2013). In our present study, the simple moving average method has been applied. SMA is excellent for smoothing the short-term fluctuations in the data and visualizing temperature pattern changes. But the simple moving average method assigns equal weights to all the values, which can underrepresent the recent fluctuations (Johnstone et al., 1999). This method is applied by using the following equation:

$$\text{SMAt} = \frac{1}{N}\sum_{i=0}^{N-1} X_{t-i}$$

Here, SMAt means Simple Moving Average
N is the number of period in the moving average window
X_{t-i} is the observed value at time t-i
i is the index of summation, starting from 0 up to N-1

2.7. Linear Regression

Regression analysis helps to find answers to the influence of single or multiple predictor variables on the response variable. It also includes prediction of future values of a dependent variable, exploring which predictors are essential, and estimating the impact of changing a predictor on the value of the response (Beckman & Weisberg, 1987). Linear regression is the simplest form of regression function as a linear combination of predictors (Su et al., 2012). It is a valuable tool for predicting a quantitative response. Simple linear regression is a very straightforward approach for predicting a quantitative response on a dependent variable based on an independent variable (James, 2023). Simple linear regression has been applied here to determine the direction, magnitude, and significance of long-term trend in temperature data. It is a straightforward technique that is suitable for identifying the rate of change in climatic variables and whether the trend is statistically significant. Though this method is simple and very useful, it has several limitations. It assumes the linear association between two variables but if the relationship is not linear, this model cannot accurately represent the association. Linear regression analysis is sensitive to outliers, which can significantly influence the regression line, leading to inaccurate predictions. Also linear regression cannot handle missing values efficiently. Hence, methods like removing rows with missing values are required in this analysis (Anandhi & Nathiya, 2023). The formula is given below:

$$Y = \alpha + \beta X + \varepsilon \quad \text{(Step-1)}$$

Here, Y is the dependent variable,
X is the independent variable,
α indicates the intercept, which means the value of Y when X is zero,
β represents the slope, which represents the change in Y for a one unit change in X, and
ε is the error term which indicates the differences between observed and predicted values.

To estimate the slope (β) of the linear regression, Least Square Method is applied to minimize the sum of the squared residuals by using the following equation:

$$\beta = \frac{\sum(x_i - \bar{x})(Y_i - \bar{Y})}{\sum(x_i - \bar{x})^2} \quad \text{(Step-2)}$$

Here, β represents the slope
x_i is the observed value of the independent variable for the i^{th} observation
Y_i is the observed value of the dependent variable for the i^{th} observation
$\bar{x}$ denotes the mean of the independent variable
$\bar{Y}$ denotes the mean of the dependent variable
To calculate the intercept (α), the following equation is used:

$$\alpha = \bar{Y} - \beta\bar{x} \quad \text{(Step-3)}$$

Here, α represents the intercept
β represents the slope
$\bar{Y}$ denotes the mean of the dependent variable
$\bar{x}$ denotes the mean of the independent variable

After finding the intercept and slope parameters, the predicted values can be identified using the following formula:

$$\hat{Y}_i = \alpha + \beta X \quad \text{(Step-4)}$$

where $\hat{Y}_i$ is the predicted value
The following equation is performed to find out the residuals (ε):

$$\varepsilon = Y_i - \hat{Y}_i \quad \text{(Step-5)}$$

where ε is the residual
Y_i is the observed value and
$\hat{Y}_i$ is the predicted value

2.8. Mann-Kendall Test and Sen's Slope

The non-parametric statistical technique, MK test was originally propounded by Mann in 1945 and further modified by Kendall in 1975. This method detects monotonic trends in climate variables. Sen's Slope is another method assesses the slope or direction of the trend. These methods are statistically robust compared to parametric statistics as they do not need any normality or linear assumption in the dataset and are less sensitive to outliers (Zhu et al., 2022; Kumar et al., 2020). This method is incorporated to detect the upward and downward trends in the temperature indices. The following equations show the step-by-step calculation of the two methods:

$$S = \sum_{i=1}^{n-1}\sum_{j=i+1}^{n} sgn\left(x_j - x_i\right) \quad \text{(Step-1)}$$

Here, S denotes Mann-Kendall statistic, n shows total data points, xi and xj represents data values in time series I and j, respectively (j > i), and sgn (x_j-x_i) is shown below:

$$sgn\left(x_j - x_i\right) = \begin{cases} +1, xj - xi > 0 \\ 0, xj - xi = 0 \\ -1, xj - xi < 0 \end{cases} \qquad \text{(Step-2)}$$

The variance of S value is given below:
If there is no equal values (no ties)-

$$Var\ (S) = \frac{n(n-1)(2n+5)}{18} \qquad (\text{Step} - 3)$$

If ties exist, the correction is:

$$Var\ (S) = \frac{(n-1)(2n+5) - \sum_{i=1}^{n} ti(ti-1)(2ti+5)}{18} \qquad (\text{Step} - 4)$$

Here, t means size of each group of tied ranks

Z value is calculated to evaluate the significance of the trends. The test examines the trend at a significant level of 0.05 where the cut-off point of Z value is 1.96. The equation is written below:

$$Z = \begin{cases} \frac{S-1}{\sqrt{Var(S)}}\ if\ S > 0 \\ 0\ if\ S = 0 \\ \frac{S+1}{\sqrt{Var(S)}}\ if\ S < 0 \end{cases} \qquad (\text{Step} - 5)$$

where, if |Z| > 1.96, then the trend is significant
if |Z| < 1.96, then the trend is insignificant
The following equation is applied to estimate Sen's Slope:

$$Qij = \frac{\left(x_j - x_i\right)}{j - i} \qquad (\text{Step} - 6)$$

For all pairs j > i

Here, Qij denotes the slope between point I and point j, xi and xj represents data point at time I and j, respectively, and j-i is the time difference between two observations. After calculating Qij for every possible pair of points, the median of all Qij values will the Sen's Slope.

3. Result

3.1. Coefficient of Variation

The above figures show the variability in seasonal temperature from 1954 to 2023. Figure 2 represents the mean temperature variability of four seasons, where the highest variability can be noticed in winter average temperature, with the highest value of 5.39% between 1999 and 2003 and the lowest value of 1.69% between 1974 and 1978. It is followed by summer temperature with the highest variability of 3.61% in 1969-73 and the lowest variability of 0.74% in 1954-58. The average temperature of the post monsoon season shows a moderate variability level, with the highest value up to 2.65% between 1984 and 1988. The lowest value is 0.31% in 1959-63, where monsoon average temperature exhibits the lowest variability throughout the year, with the highest value of 1.37% in 2019-23 and the lowest value of 0.56% in 1989-93.

On the other hand, Figure 3 represents the seasonal minimum temperature variability, whereas, winter minimum temperature exhibits higher variability, with the highest value of 6.92% in 2019-23 and the lowest value of 3.24% between 1974 and 1978. Here, a moderate level of variability can be observed in the cases of the summer and post monsoon minimum temperature, where the highest value for both goes up to 4.44% and 4.2% in 1984-88, and the lowest value of 1.15% in 2004-08 and 0.89% in 2019-23, respectively. Similarly, the lowest variability could be seen in monsoon minimum temperature, where the highest value is 2.53% in 1984-88 and the lowest is 0.56% in 1959-1963.

In the case of seasonal maximum temperature (Figure 4), all four seasons exhibit no extreme fluctuations except winter in 2014-18; the highest peak goes at 32.67%. The above discussion illustrates that the monsoon average, minimum, and maximum temperatures remain more or less consistent over the period, where winter temperatures show a more erratic pattern. Besides, summer and post monsoon temperatures represent a moderate level of fluctuations.

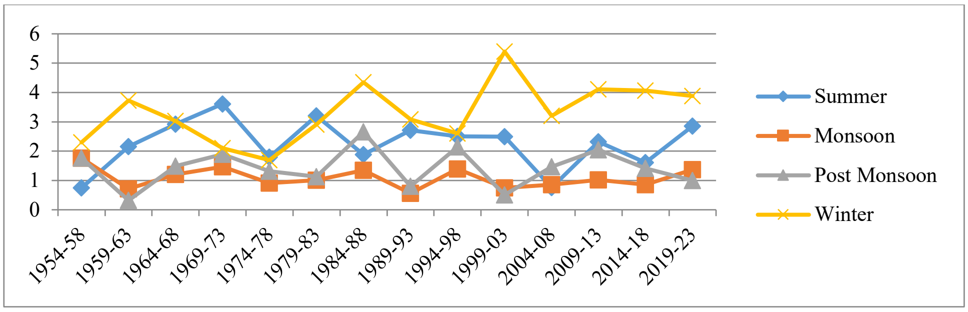
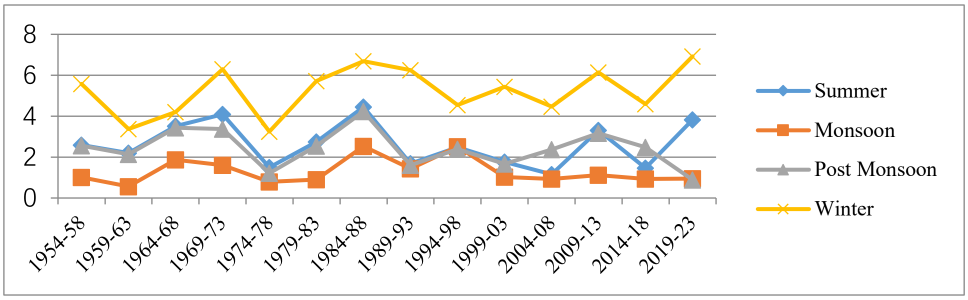


Figure 2. Seasonal Mean Temperature Variability of 14 clusters from 1954 to 2023. Winter shows highest rainfall variability. Summer and post monsoon exhibits moderate fluctuations while monsoon illustrates lowest variable rainfall *(Source: Compiled by Authors).*



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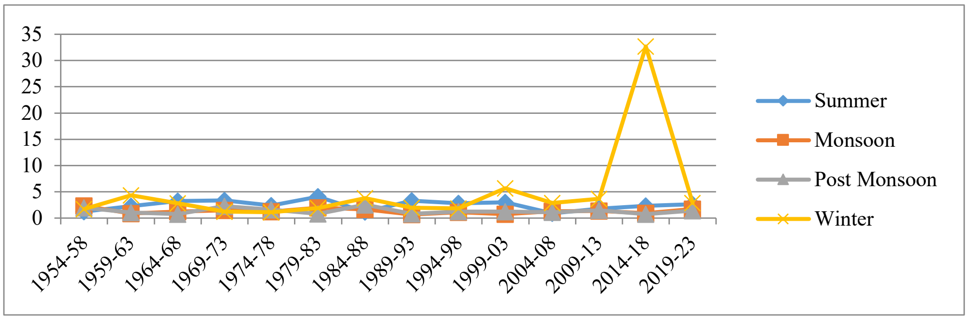


Figure 4. Seasonal Maximum Temperature Variability of 14 clusters from 1954 to 2023. All the seasonal rainfall remains stable over time except winter rainfall between 2014-2018 where it shows highest variability from mean *(Source: Compiled by Authors).*

3.2. Analysis of Variance

The mean, minimum, and maximum temperatures are divided into fourteen clusters with five years each to explore the seasonal temperature variability from 1954 to 2023. The tables consist of seven columns where the first column represents four seasons; between-group variability indicates the variations between the clusters; within-group variability represents the variations within an individual cluster; F depicts the ratio between the between group variability and within group variability, where higher F value indicates more possibility that at least one group mean is different; besides F crit shows the F critical value in the F distribution table which is a measure of significance. The F value should be higher than the F critical value to reject the null hypothesis. P value represents the probability of getting the current F by chance, which measures the significance at 0.05 significance level. The last column shows the significance of the variability analysis.

Table 1 depicts the average temperature variability of the four seasons, where only monsoon and post monsoon seasons shows significant between-groups variability with values of 16.08 and 11.73, respectively, which means the clusters of temperature significantly vary after five years. Conversely, the summer and winter seasons exhibit a higher within-group variability but are statistically insignificant. Besides, the minimum temperature throughout the years and seasons shows the most variation among the three categories.

It is evident from the Table 2 that all the seasons, viz. summer, monsoon, post monsoon, and winter, illustrate significant variation between the five-year clusters with a value of 27.21, 29.40, 23.26, and 25.04, respectively.

Table 3 represents the variability in the case of maximum temperature. Here, all the seasons significantly vary except summer. The monsoon and post monsoon seasons depict more fluctuations between the five-year groups, with a value of 15.96 and 15.76, respectively. However, in the case of maximum winter temperature, the within-group variability is higher, with a value of 177.72, which indicates more year-to-year fluctuations for winter maximum temperature.

From the above observations, it is noticed that the minimum temperature varies the most compared to the maximum and average temperature in Sikkim. In the seasonal variation context, the monsoon and post monsoon temperatures show the most variability in average, minimum, and maximum categories, followed by winter. In contrast, the summer season exhibits the least variability, where the variation can only be observed in the minimum temperature.

Table 1. Between-group and Within-group variability analysis of Mean Seasonal Temperature.

Seasons	**Between Group Variability**	**Within Group Variability**	***F***	***P-value***	***F crit***	***Significance***
Summer	8.799101125	20.70191821	1.830933	0.06042	1.899265	No
Monsoon	16.08709937	5.884606824	11.77619	0.000	1.899265	Yes
Post Monsoon	11.73391499	8.689812564	5.816707	0.000	1.899265	Yes
Winter	7.117936451	20.26804854	1.512819	0.141676	1.899265	No

(Source: Compiled by Authors)

Table 2. Between-group and Within-group variability analysis of minimum seasonal temperature.

Seasons	**Between Group Variability**	**Within Group Variability**	***F***	***P-value***	***F crit***	***Significance***
Summer	27.21664848	16.31160316	7.18758	0.000	1.899265	Yes
Monsoon	29.40543733	6.728155877	18.82679	0.000	1.899265	Yes
Post Monsoon	23.26172146	15.9212686	6.293741	0.000	1.899265	Yes
Winter	25.04566338	17.4023085	6.199695	0.000	1.899265	Yes

(Source: Compiled by Authors)

Table 3. Between-group and Within-group variability analysis of maximum seasonal temperature.

Seasons	**Between Group Variability**	**Within Group Variability**	***F***	***P-value***	***F crit***	***Significance***
Summer	4.812083035	38.72154358	0.535334	0.892392	1.899265	No
Monsoon	15.96416158	12.02864549	5.717077	0.000	1.899265	Yes
Post Monsoon	15.76974777	10.42542857	6.515916	0.000	1.899265	Yes
Winter	126.0445337	177.729097	3.054993	0.001842	1.899265	Yes

(Source: Compiled by Authors)

3.3. Standardized Anomaly Index

3.3.1. Temperature anomaly of seasonal mean temperature

Figure 5 shows the mean standardized anomaly index for seasonal temperatures, which assesses deviations in seasonal temperature patterns from the long-term average. The above bar graph shows a very hot mean summer temperature occurred in 1958 and 2022, and an extremely hot mean temperature could be noticed in 2010 at a value of 2.07. In contrast, very cold mean summer temperature anomalies can be observed in 1981 and 1990, and a severely cold mean temperature anomaly occurred in 1971, where the SAI value was -2.95.

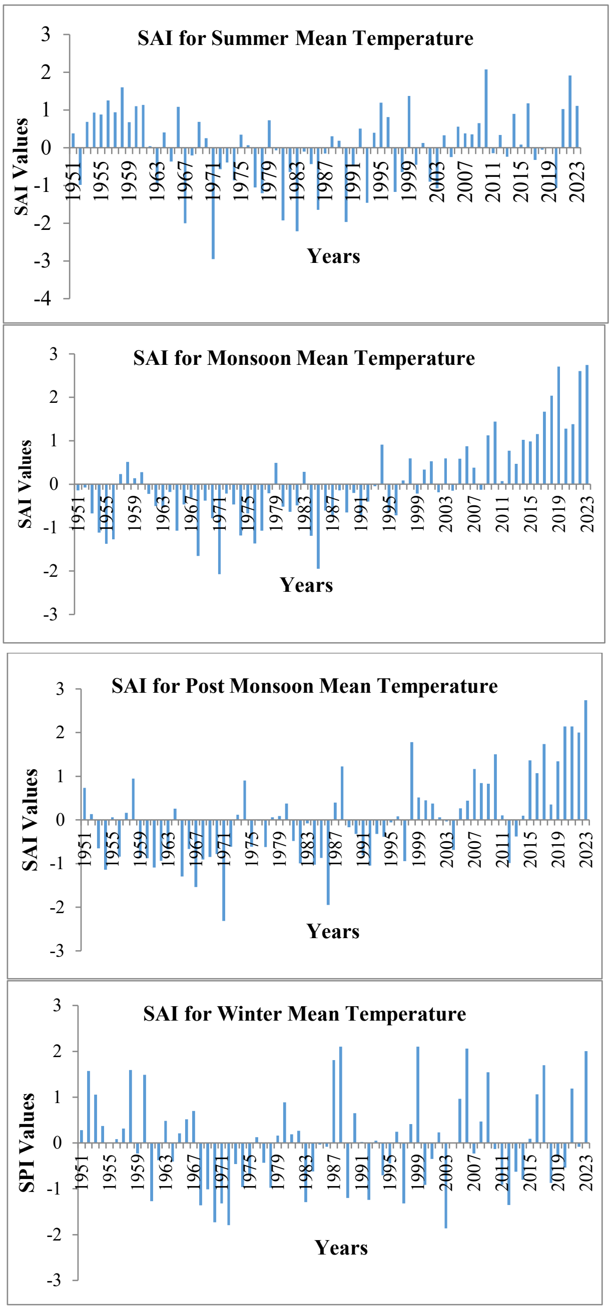


Figure 5. Standardized Anomaly Index for Seasonal Mean Temperatures from 1951 to 2023. All the seasons show variability in hot extremes over the year though Summer and Winter hot extremes are not showing any clear positive or negative tendencies in recent years. While monsoon and post monsoon SAI illustrates an increasing positive warming extremes in recent years. *(Source: Compiled by Authors).*

For the monsoon season, the very cold mean temperature anomaly can be seen 1968 and 1985, respectively, whereas a severe cold temperature anomaly could be seen in the year 1971. Conversely, a very hot mean temperature anomaly occurred in 2017, and severely hot mean temperature anomalies occurred in the years 2018, 2019, 2022, and 2023.

In the post monsoon season, a very cold mean temperature anomaly could be noticed in 1998, where the SAI value was -1.95, and an extremely cold mean temperature anomaly could be observed in 1971 with a value of -2.31. On the other hand, very hot temperature anomalies have occurred in 1998, 2010, 2017, 2020, 2021, 2022, and 2023.

Besides, for winter season, very hot mean temperature anomalies has been seen in the years 1952, 1958, 1987, 2009, and 2017 and extremely hot temperature anomalies can be seen in the years of 1988, 2006, and 2023 with values of 2.10, 2.05, and 2.00, respectively.

It is evident from the above analysis that the extreme anomalies are relatively low in summer temperature, indicating that they have been more consistent throughout the years. But in the cases of monsoon and post monsoon temperatures, the extreme anomalies have increased in recent years, which signify a greater variability of temperature in the recent decades. On the other hand, higher anomalies in winter mean temperatures can be observed throughout the years.

3.3.2. Temperature anomaly of seasonal minimum temperature

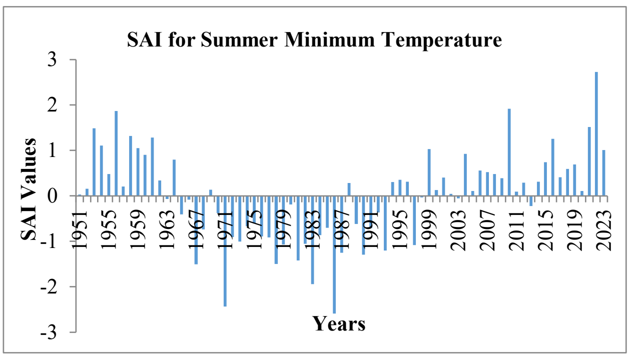
Figure 6 depicts the standardized anomaly for minimum temperatures for summer, monsoon, post monsoon and winter in Sikkim. In summer, very cold minimum temperature anomalies can be seen in the years 1967 and 1983, and a severe cold anomaly occurred in 1971 with a value of -2.43. Very hot minimum temperature anomalies could be found in 1956, 2010, and 2021. Besides, an extremely hot minimum temperature anomaly occurred with a value of 2.72 in the year 2022.

In the case of the monsoon season, very cold minimum temperature anomalies have occurred in the years 1971, 1986, and 1987, and extremely cold temperature anomalies are noticed in 1985 with a SAI value of -2.19. On the other hand, very hot minimum temperature anomalies can be seen in the years of 2018, 2020, and 2021, where extremely hot minimum temperature anomalies have occurred in 2019, 2022, and 2023 with values of 2.26, 2.40, and 2.41, respectively.

For the post monsoon season, very cold temperature anomalies have been observed in 1967, 1970, 1971, 1986, and 1992. Here, the occurrence of extremely cold temperature anomalies is absent. The very hot minimum temperature anomaly could be seen in 1998, 2019, 2020, 2021, and 2022. Besides, the extremely hot temperature anomaly occurred in 2023 with a value of 2.35.

On the other hand, in the winter, the very cold minimum temperature anomaly can be seen in 1969 and 1983. The severely cold temperature anomalies could be observed in 1970, 1971, and 1972 with SAI values of -2.32, -2.18, and -2.06, respectively. Besides, very hot temperature anomalies can be found in 1957 and 2021. On the other hand, extremely hot minimum temperature anomaly occurred in the years of 1958 and 2023, where the SAI values were 2.06 and 2.39, respectively.

This analysis revealed that, unlike the mean temperature anomaly, the summer minimum temperature anomaly shows comparatively higher variability than the previous one and shows rising positive warming tendency in recent years. Conversely, a clustered pattern can be found in the monsoon and post monsoon seasons, where the cold extremes majorly occurred in the 1960s and 1990s, and hot extremes majorly occurred in recent decades. But in the case of the winter season, the hot and cold anomalies occurred repetitively throughout the years.



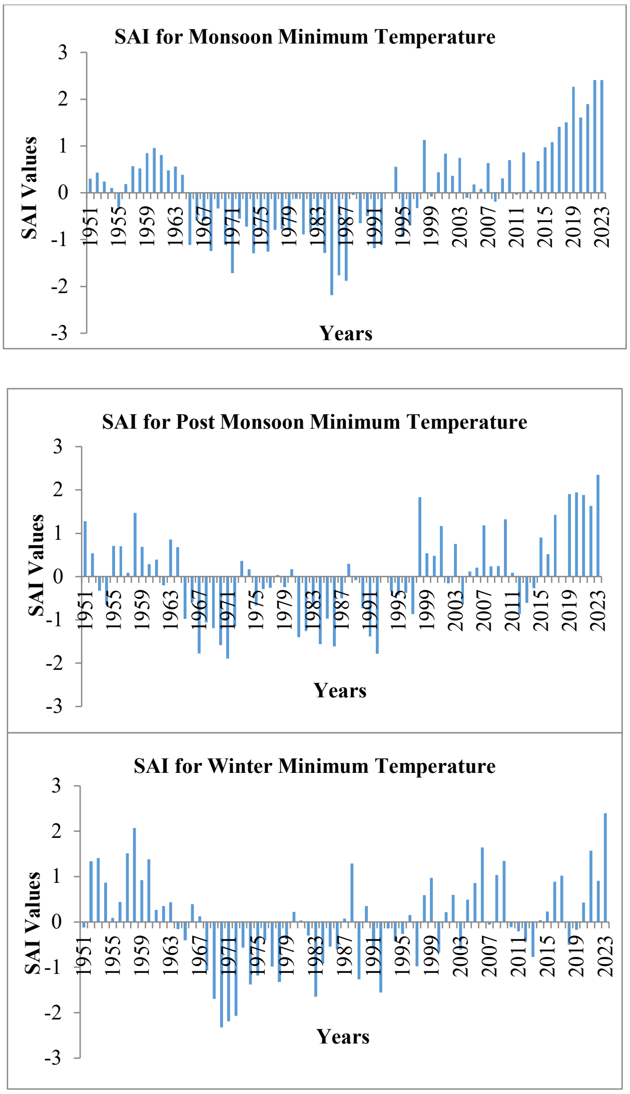


Figure 6. Standardized Anomaly Index for Seasonal Minimum Temperatures from 1951 to 2023. Summer, monsoon and winter SAI shows a shift in positive warming extremes in recent years. While winter temperature extremes do not exhibit any such clear tendency though variability exists over the time period *(Source: Compiled by Authors)*.

3.3.3. Temperature anomaly of seasonal maximum temperature

Figure 7 represents the temperature anomaly for seasonal maximum temperature. The very cold maximum temperature anomaly for the summer season can be seen in 1952, 1967, 1990, 2002, 2003, and 2020. Besides, a severely cold temperature anomaly occurred in 1971 with a value of -2.37. Very hot temperature anomalies in this season happened in the years of 1966 and 1995, where a severely hot temperature anomaly can be seen in 1979 with a value of 2.24.

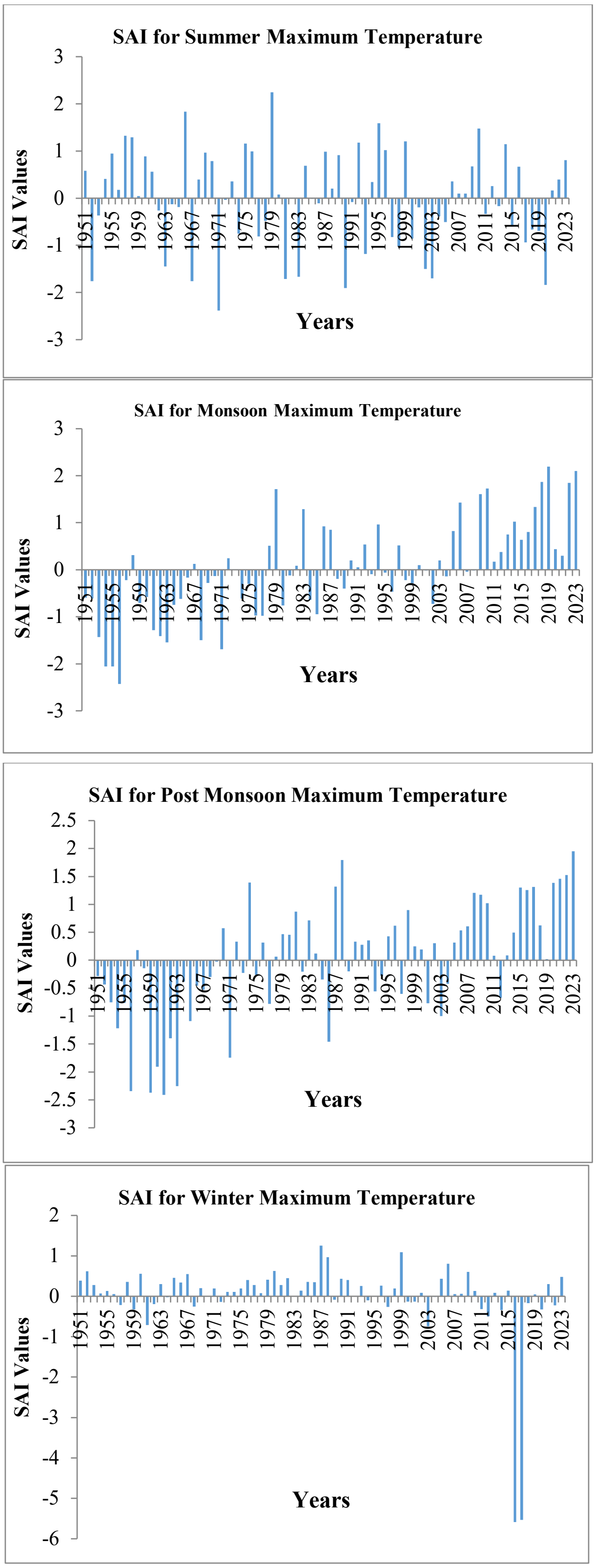


Figure 7 Standardized Anomaly Index for Seasonal Maximum Temperatures from 1951 to 2023. Summer and winter temperature extremes exhibit variability over the years but do not show any positive or negative tendency in recent times. Where, monsoon and post monsoon positive temperature extremes are increasing in recent years *(Source: Compiled by Authors)*

In the monsoon season, a very cold temperature anomaly occurred in 1963. On the other hand, extremely cold temperature anomalies with values of -2.05, -2.05, and -2.42 happened in the years of 1954, 1955, and 1956, respectively. Conversely, very hot temperature anomalies occurred in 1979, 2009, 2010, 2018, and 2022, where extremely hot maximum temperature anomalies can be seen in 2019 and 2023 with values of 2.19 and 2.09, respectively.

For the winter season, cold temperature anomalies are not present. Still, extremely hot maximum temperature anomalies can be seen in 2016 and 2017 with very high SAI values of -5.58 and -5.53, respectively.

In the context of post monsoon maximum temperature, very cold temperature anomalies occurred in 1960 and 1971. In contrast, severely cold anomalies can be seen in 1956, 1959, 1961, and 1963. Besides, very hot maximum temperature anomalies occurred in 1988, 2022, and 2023. Here, an extremely hot maximum temperature anomaly did not occur throughout the period.

This analysis reveals that summer maximum temperature has more negative than positive temperature anomalies. The monsoon maximum temperature shows a similar pattern to minimum temperatures, where negative anomalies were clustered in the 1950s and 1960s, but positive temperature anomalies mainly occurred in recent decades. Identical to the monsoon, post monsoon maximum cold temperature anomalies happened between the 1950s and 1970s, where most of the hot temperature anomalies occurred in recent years, except 1988. Here, negative maximum temperature anomalies occurred more than positive anomalies like the summer season. The winter shows minimum temperature anomalies in this case, but it shows two very high hot temperature anomalies in the previous decade.

3.4. Trend Analysis

To capture long term behavior of temperature parameter, trend detection method has been employed by applying 5-year Moving Average technique. The trend analysis is performed on mean, minimum and maximum temperatures revealing distinctive characteristics in long term seasonal and temporal behavior. From the following figures (Figures 8, 9 & 10) it is observed that all mean, minimum and maximum temperatures are showing increasing trend except maximum summer and maximum winter. Their significance test is necessary which is calculated by linear regression analysis (Tables 4, 5 & 6).

3.4.1. Trend for seasonal mean temperature

Trend analysis for seasonal mean temperature is shown in figure 8 from 1951 to 2023. The trend line of summer average temperature shows less gradual increase between 22.5 to 23ºC. A similar scenario can be observed in winter average temperature. The trend line shows steady increase between 15 to 16ºC. On the other hand, the mean monsoon and post monsoon temperature exhibits a higher gradual increase from 25 to 26ºC and around 22 to 23ºC. These indicate the warming intensification in monsoon and post monsoon seasons.

3.4.2. Trend for seasonal minimum temperature

The seasonal minimum temperature reveals a similar pattern to seasonal mean temperature (Figure 9). Summer minimum temperature displays steady increase in its trend line around 15.2ºC. The winter minimum temperature shows a less gradual positive shift around 9ºC. In contrast, the monsoon and post monsoon minimum temperature trends reveal higher gradual shift compared to summer and winter. The monsoon and post monsoon minimum temperature trends are shifting from 21.5 to 22ºC and 17.5 to 18ºC, respectively showing increase in temperature especially in these two seasons.

3.4.3. Trend for seasonal maximum temperature

The scenarios of summer and winter maximum temperature is different from mean and minimum temperature characteristics (Figure 10). Instead of steady increase, they showed steady decline in their trends from 28.3-28.4ºC to 28ºC and from 22 to 20ºC, respectively. But the monsoon and post monsoon maximum temperature trends exhibit higher positive shift compared to mean and minimum temperatures. These temperatures are increasing from 28.1-28.2ºC to 29.5-30ºC and from 26.4ºC to 28ºC, respectively. This phenomenon is again indicating warming intensification in monsoon and post monsoon seasons but decreasing maximum temperature in summer and winter seasons.

3.5. Regression Analysis

The simple moving average method is applied to visualize trends in seasonal temperature (Figures 8, 9 & 10). Further, regression analysis is performed to check the significance of the trend at 10%, 5%, and 1% significance intervals (Tables 4, 5 & 6). The seasonal mean temperature for summer, monsoon, post monsoon, and winter shows an upward trend throughout the years, but it is not statistically significant for summer and winter temperatures. On average, the monsoon and post monsoon mean temperature increases at 0.0178ºC and 0.0143ºC per year at significance level of 0.01. A similar scenario can be seen in the minimum temperature. Here, the summer and winter minimum temperatures show no significant increase. Besides, monsoon and post monsoon minimum temperature illustrates a rising trend at 0.014367ºC and 0.011068ºC per year on average at significance level of 0.01. For maximum temperature, the summer season again shows a non-significant increasing trend. Similar to the previous analyses, the monsoon and post monsoon maximum temperatures are increasing at a rate of 0.021279ºC and 0.017708ºC per year on average at $p < 0.01$. Unlike the mean and minimum temperatures, the winter maximum temperature shows a decreasing trend on average at a rate of -0.025ºC per year at significance level of 0.05. These findings underscore a consistent warming tendency particularly for monsoon and post monsoon seasons across all the temperature parameters, while summer and winter temperatures exhibit relatively weaker or statistically insignificant trends.

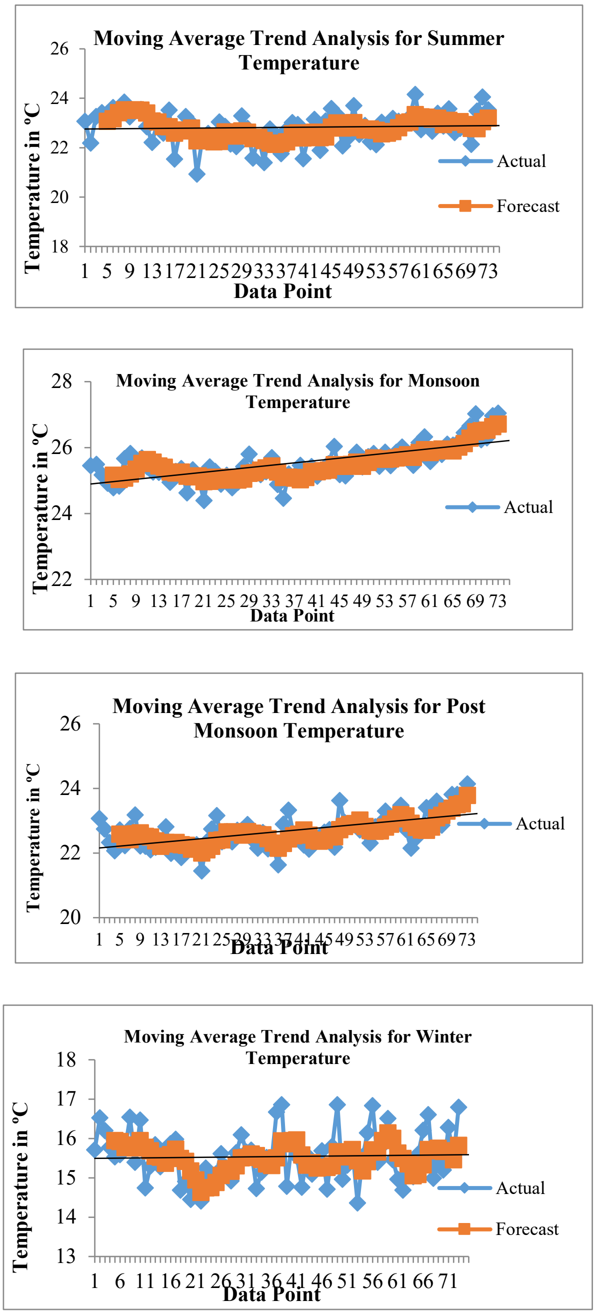


Figure 8. Trend Analyses for Seasonal Mean Temperature from 1951 to 2023. All the seasonal mean temperatures display an increasing trend. Though summer and winter temperature shows slight increase, these are not statistically significant. While monsoon and post monsoon temperature illustrates significant upward trend throughout the years *(Source: Compiled by Authors).*

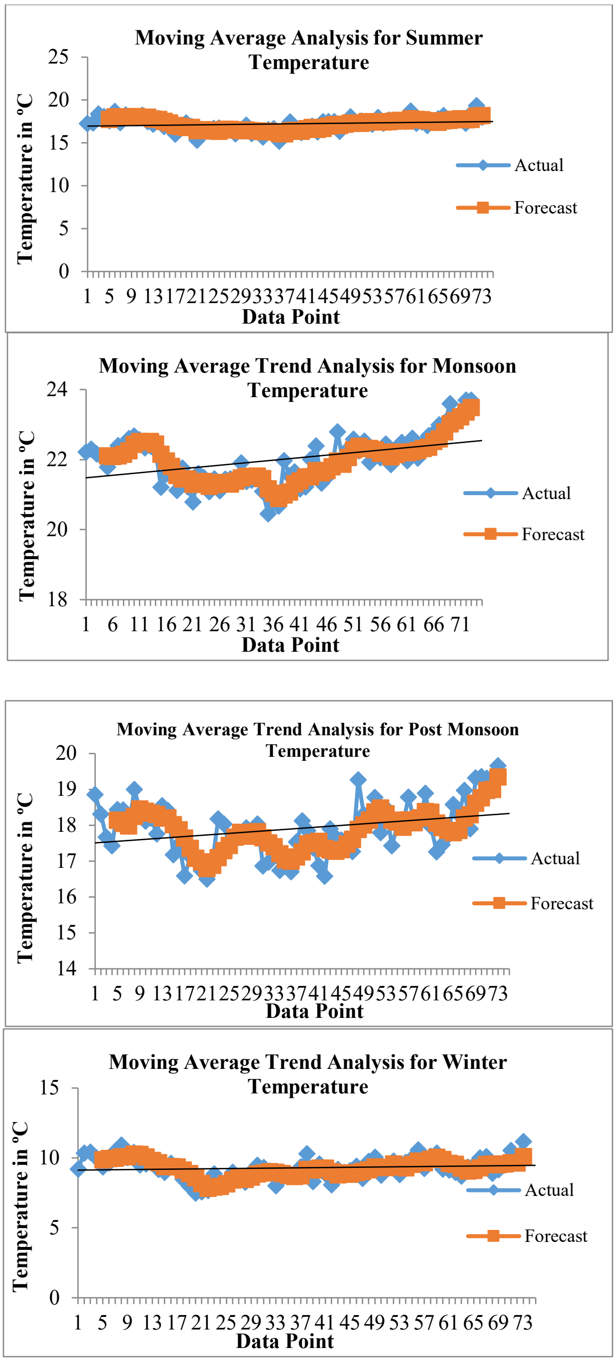


Figure 9 Trend Analyses for Seasonal Minimum Temperature from 1951 to 2023. All the seasonal minimum temperatures exhibit increasing trend. Summer and winter temperatures show slight increase but statistically insignificant. While monsoon and post monsoon temperatures illustrates statistically significant rising tendency in temperature throughout the study period *(Source: Compiled by Authors)*.

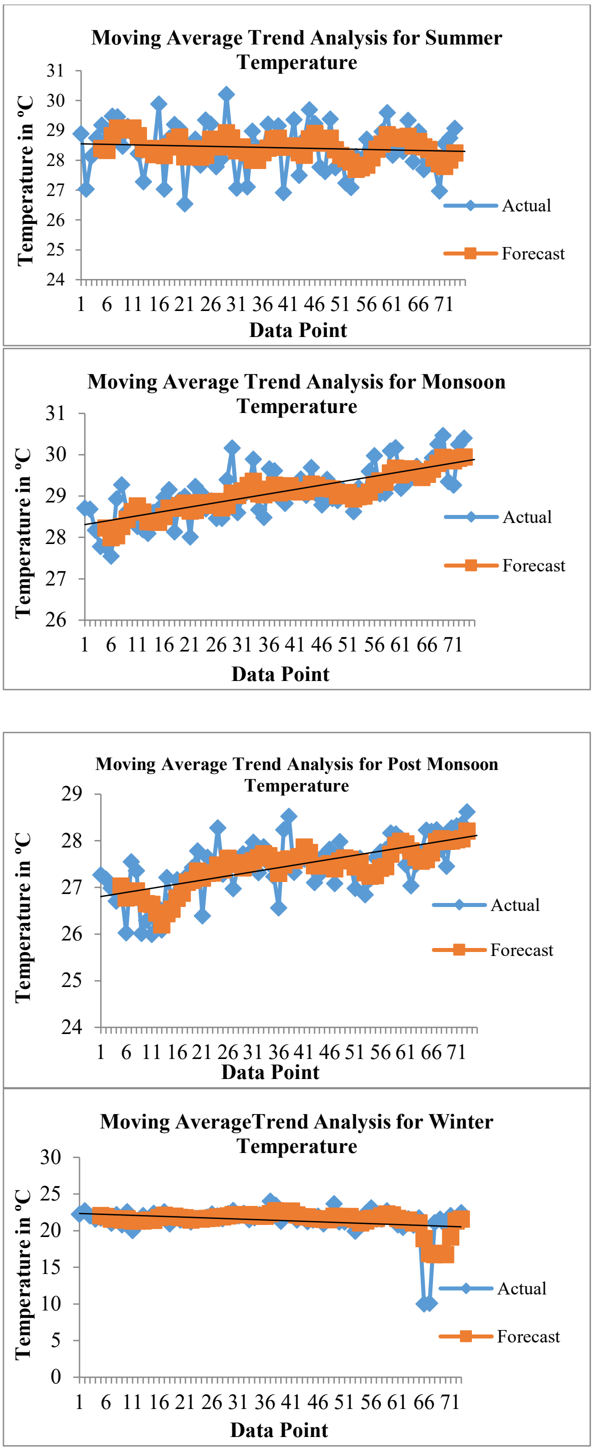


Figure 10 Trend Analyses for Seasonal Maximum Temperature from 1951 to 2023. Summer and winter temperatures illustrate a decreasing trend in maximum temperature where only winter temperature is statistically significant. While monsoon and post monsoon maximum temperatures depict an significant increasing trend throughout the time period *(Source: Compiled by Authors).*

Table 4. Linear Regression results of seasonal mean temperature (1951-2023).

Seasons	Coefficient	R^2	P-Value	SE	Significance
Summer	0.001	0.003802	0.604	0.003613	No
Monsoon	0.0178	0.465502	0.00***	0.002267	Yes
Post Monsoon	0.0143	0.324153	0.00***	0.002466	Yes
Winter	0.00126	0.001787	0.722	0.003539	No

Significance Level *=0.1, **= 0.05, ***= 0.01 *(Source: Compiled by Authors)*

Table 5. Linear Regression results of seasonal minimum temperature (1951-2023).

Seasons	Coefficient	R^2	P-Value	SE	Significance
Summer	0.007185	0.037245	0.101869	0.004336	No
Monsoon	0.014367	0.184274	0.000***	0.003587	Yes
Post Monsoon	0.011068	0.098473	0.0068***	0.003974	Yes
Winter	0.004599	0.015287	0.29734	0.004381	No

Significance Level *=0.1, **= 0.05, ***= 0.01 *(Source: Compiled by Authors)*

Table 6. Linear Regression results of seasonal maximum temperature (1951-2023).

Seasons	Coefficient	R^2	P-Value	SE	Significance
Summer	-0.003424	0.0083	0.44334	0.004442	No
Monsoon	0.021279	0.503658	0.00***	0.002507	Yes
Post Monsoon	0.017708	0.383428	0.00***	0.002665	Yes
Winter	-0.025253	0.067452	0.0264**	0.011144	Yes

Significance Level *=0.1, **= 0.05, ***= 0.01 *(Source: Compiled by Authors)*

3.6. Non-Parametric Trend Analysis

Linear regression assumes normality in residuals but climatic data generally illustrates skewed pattern, which may violate these assumptions. Hence, a non-parametric statistical analysis has been applied to validate the results from regression analysis (Tables 7, 8 & 9). Here, MK test and Sen's slope produced similar outcomes as linear regression. The monsoon and post monsoon mean temperature (Table 7) are increasing at a rate of 0.17 ºC and 0.14 ºC per year which are significant at $p<0.01$ and Z>1.96 and identical to previous regression findings. On the other hand, summer and winter temperatures are not visualizing any significant trend. In the case of minimum temperature (Table 8), again the monsoon (slope= 0.016) and post monsoon (slope= 0.011) shows rising trend at a significance level of 0.01 and 0.05 and Z>1.96, respectively. Summer and winter minimum temperature is not significant in this case. Maximum seasonal temperatures (Table 9) also represent similar characteristics. Monsoon and post monsoon maximum temperatures are increasing at a rate of 0.02 ºC and 0.017 ºC per year and significant at $p<0.01$ and Z>1.96. Though winter maximum temperature trend is significant at $p<0.1$ but the Z value is less than 1.96, therefore the increasing winter maximum temperature cannot be considered as statistically significant like the linear regression results. Hence it can be concluded that only monsoon and post monsoon mean, minimum and maximum temperatures are significantly increasing in Sikkim.

The above findings underscored a distinctive pattern of long-term temperature shifts and variability in mean, minimum and maximum temperatures across different seasons in Sikkim. While these outcomes establish quantitative results, a deeper understanding is required by comparing earlier studies to establish their practical implications on ecosystem and society. These aspects are discussed in the following section.

Table 7. Mann-Kendall test and Sen's slope of seasonal mean temperature (1951-2023).

Seasons	Z-Stat	Sen's Slope	P-Value (<0.05)	Trend	Significance
Summer	0.157157	0.00076664	0.875	Positive	No
Monsoon	6.062***	0.01762935	0.000***	Positive	Yes
Post Monsoon	4.843***	0.01428831	0.000***	Positive	Yes
Winter	-0.00476	-0.0001138	0.996	Negative	No

Significance Level *=0.1, **= 0.05, ***= 0.01 *(Source: Compiled by Authors)*

Table 8. Mann-Kendall test and Sen's slope of seasonal minimum temperature (1951-2023).

Seasons	Z-Stat	Sen's Slope	P-Value (<0.05)	Trend	Significance
Summer	1.8430	0.00885655	0.06	Positive	Yes
Monsoon	3.538***	0.01652541	0.0004***	Positive	Yes
Post Monsoon	2.233**	0.01153632	0.02**	Positive	Yes
Winter	1.042952	0.0053619	0.29	Positive	No

Significance Level *=0.1, **= 0.05, ***= 0.01 *(Source: Compiled by Authors)*

Table 9. Mann-Kendall test and Sen's slope of seasonal maximum temperature (1951-2023).

Seasons	Z-Stat	Sen's Slope	P-Value (<0.05)	Trend	Significance
Summer	-0.90008	-0.00407746	0.36	Negative	No
Monsoon	6.491***	0.021285642	0.000***	Positive	Yes
Post Monsoon	5.557***	0.017191231	0.000***	Positive	Yes
Winter	-1.843	-0.00818982	0.06	Negative	Yes

Significance Level *=0.1, **= 0.05, ***= 0.01 *(Source: Compiled by Authors)*

4. Discussion

Based on the findings stated above, this section interprets the results aligning with earlier studies and highlighting their relevance in adaptation strategies. Though the studies on seasonal temperature variation of Sikkim are limited, some research is significant in exploring the long-term climatic variability in this state. A study by Rahman et al. (2012) show a drastic departure in minimum temperature, which is increased by 1.95ºC from 1981 to 2010. Still, in case of maximum temperature, it is more or less consistent over time at Tadong station. Another study by Seetharam (2008) shows both minimum and maximum temperature increases in the Gangtok station. It is evident from the research done by Upadhyay & Rai (2023) that seasonal temperature is changing in the Rangit basin of Sikkim. They analyzed the temperature trends from 1985 to 2017, which exhibit a significant rising trend in summer, monsoon, and winter temperature but no changes in post monsoon season. Another study by Kumar et al. (2020) suggested that the minimum temperature of Gangtok station is rising at 0.036 ºC per year from 1961 to 2017, and the coefficient of variation is 10.9% in the observed period. Unlike the minimum temperature, the maximum temperature shows a declining trend at a rate of -0.027 ºC per year, and the coefficient of variation is 3.92% for the same period. On the other hand, Gupta et al. (2024) illustrate an upward trend in average temperature for all four districts of Sikkim. According to the research by Patle et al. (2020), the mean, minimum, and maximum temperatures increased by 0.038 ºC, 0.075 ºC, and 0.001 ºC per year, respectively, in this state from 1985 to 2013. Yadav et al. (2016) calculated monthly temperature trends for East Sikkim. They exhibited a significant warming trend for January and March; conversely, a significant declining trend for the months of November and December from 1985 to 2009. Chakma and Biswas (2022) also showed that mean, minimum, and maximum temperatures remarkably rose for all the months. The mean annual temperature of West Sikkim has increased at 0.027 ºC per year from 1901 to 2014. The seasonal mean temperature is highest in monsoon but shows the lowest variability of 3.27%. Besides, the mean temperature is lowest in winter months but shows the highest variability of 9.96% for the same period. The increasing mean warming trend can be observed for all the seasons, but it is more pronounced during the pre monsoon and monsoon seasons but relatively lower for the post monsoon and winter seasons.

The findings of temperature variability and rising tendencies in monsoon and post monsoon seasons have significant practical implications. Rising temperature severely affect the ecological stability especially in mountainous region. Species extinction due to inability to heat tolerance; changes in distributional range of species which means species tend to move higher altitude and poleward due to increasing temperature; shifts in phonological events in plant and animal species such as flowering, fruiting, timing of egg laying, nest building etc. can be observable under altering temperature regime. To mitigate the ecological risks associated with mountain ecosystem, adaptation strategies should include establishing protected corridors for habitat conservation, ecosystem restoration by afforestation and reforestation, promoting seed banks, establishing national parks to protect plant and animal species, phonological monitoring, implementing policies and planning oriented towards biodiversity conservation etc. For local livelihoods, especially those depend on agriculture and livestock farming; greater exposure to thermal stress underscores the varied climate adaptation strategies. The elevated temperature can increase heat tress among crops which can reduce yield and also extreme heat can cause crops to die. Rising warming level can shorten growing season which can accelerate the early maturing of plants and in turn decrease productivity. Increased temperature also brings frequent pest attacks and disease outbreaks as hot and humid condition is favorable for different types of insects or pests. Along with crops, the livestock are also exposed to extreme heats which can cause reduced feed intake, impair digestion and decreased productivity in milk, meat, and eggs. Prolonged heat stress and cause heat strokes among animals. Hot and humid condition creates vector borne diseases in livestock. Hence, adaptation should be taken to strengthen the livelihoods of people. For agricultural sector, the government should promote heat resistant crop varieties especially for monsoon and post monsoon seasons; integrated pest management technique to sustainably manage pest without toxictaing crops such as using organic pesticides, trap cropping, installing traps or barriers, using natural predators etc.; climate innovative agricultural practices for example, contour farming, mulching, integrated nutrient management, crop diversification; regular research in Krishi Vigyan Kendras and training and awareness program for farmers to adopt modern technology in agricultural practices. For the livestock sector, fodder storage to store during surplus, climate resilient shelters for animals, regular animal health check-ups through mobile veterinary services, increasing the number and coverage of local cooling centers to protect livestock products from spoilage, etc., can be very helpful to the marginal farmers. Moreover, disaster preparedness, an early warning system of climate- related hazards, and the dissemination of information to the locals would be great strategies for climate resilience.

The above analyses comprehend a drastically varying and changing climatic condition in Sikkim. Although the studies on temperature variation are limited in the context of this state, the available research collectively indicates consistent warming across regions and time periods. The observed discrepancies in the findings can be attributed to the differences in data sources, geographical focus, and temporal coverage. These findings underscore the importance of climate monitoring and the need for more comprehensive, long-term studies to better understand the climate dynamics of Sikkim and support effective adaptation strategies.

The above discussion highlights that Sikkim is undergoing a significant shifts in climatic conditions with ecological and socioeconomic consequences. To provide a concise synthesis of these insights and broader meaning, the concluding section summarizes the major findings and key recommendations.

5. Conclusion

A comprehensive analysis of temperature patterns in Sikkim over 72 years reveals significant variability and shifts. A continuous warming trend exists, particularly for monsoon and post monsoon seasons. The findings from the coefficient of variation, analysis of variance, standardized anomaly index, and regression analysis collectively indicate that mean and minimum temperature exhibits greater variability than maximum temperature. Seasonal variability is most prominent in summer and winter temperatures, but the shifts in temperature trends are more concerning for the monsoon and post monsoon season. As Sikkim is a mountainous region, its climatic sensitivity is more pronounced and can significantly impact agriculture, livestock, biodiversity, and livelihoods. This is further substantiated by the increasing occurrence of temperature anomalies, especially in recent decades, and supported by multiple studies highlighting similar warming trends in different parts of the state. Based on these findings, monitoring of seasonal extremes should be prioritized. The evidences point towards the urgent need for strengthening climate monitoring, enhancing resilience through adaptive practices, and integrating climate data into regional planning and policy frameworks. Policymakers should integrate these outcomes into the State Action Plan on Climate Change promoting crop diversification, heat resistant varieties, integrated pest management, climate resilient shelters for domestic animals, regular health check-up of livestock etc. Improved data-sharing frameworks and investment in high-resolution climate monitoring would also support more localized adaptation strategies. A multidisciplinary approach involving climate science, social sciences, and community engagement is imperative to address Sikkim's evolving climate realities and to ensure sustainable development in this ecologically fragile region.

Limitations: One major limitation of this study is that IMD provides one single gridded temperature data rather than stationwise records as Sikkim belongs to one single temperature grid. Though the dataset ensured temporal continuity and consistency, it may smooth out local climatic variations especially in a mountainous region like Sikkim where microclimates differs within short distances. Large scale climatic drivers, local factors may also influence the temperature pattern in the state. Altitudinal differences in Sikkim can create microclimatic variations; anthropogenic activities such as, land use land cover changes including agricultural expansion, deforestation, urbanization can contribute to localize warming or cooling tendencies. Hence, the results are interpreted as a regional scale trends and variability rather than precise local temperature shifting patterns. Additionally, the statistical methods applied in this study assumed data normality and linearity which can oversimplify the extreme effects. The study is useful for long-term perspective on temperature variability and trend in Sikkim but acknowledging these limitations in future studies can provide a comprehensive view on localized climatic shifts in the state.

Author's contribution

The authors take complete responsibility for the following: Amrita Dwivedi and Jyotirmayee Sarkar have planned this work; Jyotirmayee Sarkar and Yash Nayan have performed the data extraction of database, analyzing and interpreting the results; Jyotirmayee wrote the manuscript draft; Amrita Dwivedi reviewed and edited the manuscript.

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Conflict of Interest Statement
The authors declared no potential conflicts of interest.

Data Availability Statement
The link of the processed dataset is given below
https://docs.google.com/spreadsheets/d/1WY60clTxzPeNYbSkZzoHK0hKKDOjoPsB/edit?usp=sharing&ouid=11 8375851847902707828&rtpof=true&sd=true

Ethical approval
The research uses publicly available climate data without involving human or animal participants or any experiments. Hence ethical approval is not applicable.

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