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A Comprehensive Analysis of Long-term Trends in Temperature and Rainfall Patterns in Sikkim, India

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Abstract: One of the main global concerns of the twenty-first century is climate change, which is causing patterns of precipitation and temperature to shift, as well as a rise in the frequency of extreme occurrences. In order to evaluate the effects of climate change on the Himalayan State, the study examines the long-term changes in temperature and precipitation in Sikkim, India, over a period of 121 years (1901–2021). The study uses the "Mann-Kendall Trend Test" and "Sen's Slope Estimator" to analyse the monthly temperature and precipitation data across Sikkim's districts: East, West, North, and South. The paper shows that the state has a significant increase in average temperatures across all districts, with an upward trend and p-values <0.01. The study also shows that the precipitation trends are less uniform, with South Sikkim being the only district exhibiting a significantly decreasing rainfall trend. The rising temperatures and variable precipitation patterns highlight the region's vulnerability to climate change, with potential implications for water resources, agriculture, and ecological balance. This research points towards the need for urgency in incorporating climate understandings into the policy frameworks to mitigate the adverse effects of climate change and promote sustainability in Sikkim.

Keywords: Climate change; Trend analysis; Mann-Kendall test.

Introduction

Climate change is a major global threat affecting ecology, ecosystems, and economies. The effects of increasing temperatures, shifting precipitation patterns, and a rise in extreme weather occurrences are highlighted in the sixth IPCC report (2023). Climate change is devastating for mountainous regions, leading to floods and landslides from intense, prolonged rainfall (Hoogendoorn et al., 2020). Global warming alters the Indian Summer Monsoon, increasing extreme rainfall (Guhathakurta & Rajeevan, 2008; Rajeevan et al., 2008). The IPCC Report (2023) predicts reduced freshwater availability and a 10–30% decrease in annual runoff by the mid-21st century.

Changes in temperature and rainfall can affect stream flows, agricultural production, soil moisture, and groundwater reserves (Das et al., 2017; Disasa et al., 2024; Pettigrew, 2008; Rajeevan et al., 2008; Roy et al., 2018; Sharma et al., 2021). Higher temperatures are linked to altered rainfall patterns (Disasa et al., 2024; Guhathakurta et al., 2015; Rajeevan et al., 2008). Detailed precipitation data is essential for freshwater assessment and disaster management (Hoogendoorn et al., 2020). Anthropogenic climate changes impact monsoon patterns, affecting food security and economic development (Asseng et al., 2011; Ii et al., n.d.; Ramirez et al., 2011; Turner et al., 2000).

Studies on India's rainfall trends often lack recent data (Guhathakurta et al., 2011, 2015; Guhathakurta &

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Rajeevan, 2008). There is also a lack of regional focus, especially in the Northeastern states. Sikkim's rainfall and temperature trend analysis requires examination, both as a northeastern as well as Himalayan state. As higher elevations experience climate change differently than lowlands, it is important that it is explored separately (Flores-Palacios et al., 2023; Ingty, 2017; Kaliyeva et al., 2021; Lei et al., 2014; Oinam et al., 2005). Sen's Slope and Mann-Kendall tests are useful tools for analysing trends in rainfall and temperature (Deoli & Rana, 2019; Duhan & Pandey, 2013; Guhathakurta & Rajeevan, 2008; Mann, 1945; Rajeevan et al., 2008; S. K. Sharma et al., 2021; Yacoub & Tayfur, 2019).

This study uses the Mann-Kendall and Sen's Slope methodologies to analyse rainfall and temperature patterns from 1901 to 2021 in order to assess significant climatic changes. The study looks at the consequences of climate change in Sikkim over a 121-year period. (Bawa & Ingty, 2012). Sikkim, in northeastern India, covers approximately 7,000 square kilometres or 0.5% of India's total land area. However, the state, with its varied elevation and rugged topography, also houses a large portion of India's flora and fauna diversity. Its districts - "Gangtok" ("East Sikkim"), "Mangan" ("North Sikkim"), "Namchi" ("South Sikkim"), "Gyalshing" ("West Sikkim"), "Pakyong" and "Soreng"— experience distinct seasonal weather, with an annual average of 3,500 mm of rainfall, mostly during the southwest monsoon. Despite the small size, the state exhibits a wide range of climatic conditions, from bitterly cold temperatures at higher elevations to tropical heat in the lower valleys. The state is classified into several climatic zones: subtropical humid, semi-temperate, temperate, alpine snow forest, alpine meadow, and arctic (ENVIS Centre Sikkim, 2007). The highest zones remain permanently snow-covered, with snow reaching down to 2500m in winter. The state is especially vulnerable to landslides in the heavy rains and glacial lake outbursts, which have been made worse by deforestation due to increasing population and crop demand.

Understanding the fluctuations in temperatures and rainfall is crucial for identifying the negative consequences of climate change and enhancing management procedures to achieve environmental sustainability in development planning. The initial stage in achieving climate sustainability involves observing and identifying areas and sectors that are at risk. Research findings and recommendations should be incorporated into state and national policies.

Study Area

Sikkim is the second-smallest state in the Indian Union, covering an area of 7096 square kilometers. The state is located in the eastern Himalayas, between 27°46' to 28°7'48" N latitude and 88°0'5" to 88°55'25" E longitude (Figure 1) and the altitude varies from 220 meters in the valley regions to 8598 meters over the mountains. It shares borders with Bhutan, China, and Nepal. Sikkim is bounded by important mountain ranges and has mountains like Mt. Khangchendzonga (8,598 m), Mt. Siniolchu, Mt. Pandim, Mt. Kabru, and Mt. Jonseng and interspersed with numerous passes Jelep La, Nathu La, Cho La, ChuwaBhangyang. The state is rich in glaciers, with currently 84 glaciers in the state, including Zemu Glacier (the largest glacier in Sikkim), Rathong Glacier, Zum-thulPhuk Glacier and Lhonak Glacier, etc. The state's rivers, including the Tista and Rangit, which are regarded as Sikkim's lifelines, originate from the glaciers.

Sikkim state is a part of the Himalayan range and exhibits many commonalities with the Eastern and Central Himalayas. The state, however, also exhibits a lot of unique features. The state exhibits contiguity of habitats from the sub-tropical forests to cold deserts within a distance of less than 100 km. The Sikkim plateau is one of the smallest biogeographic provinces in India (Rodgers & Panwar, 1988). The state also has the Krummholz (stunned zone) zone in the subalpine-alpine ecotone, transboundary biological corridors - Khangchendzonga Biosphere Reserve (KBR), and the highest number of species named after any state in India. Each eco-climatic zone comes with its own distinct flora and fauna, especially a few migratory species occupying more than one zone. Sikkim has exceptionally diverse orchids (Rawat & Tambe, 2011).

Due to Sikkim's close proximity to the Bay of Bengal and exposure to the southwest monsoon makes it one of the most humid places in the Indian Himalayas, with significant rainfall from mid-April to early December. Temperature in Sikkim varies significantly with altitude, ranging from 6°C to 35°C at lower altitudes (220-1500 m). As part of the Indo-Burmese biodiversity hotspot, Sikkim's varied altitude and high precipitation make it rich in diversity of flora and fauna. Approximately 46% of the state's area is forest-covered, home to around 5000 species of plants (Forest and Environment, 2024). With 72% of India's rhododendron species found there, the state is especially well-known for its orchid and rhododendron collections.

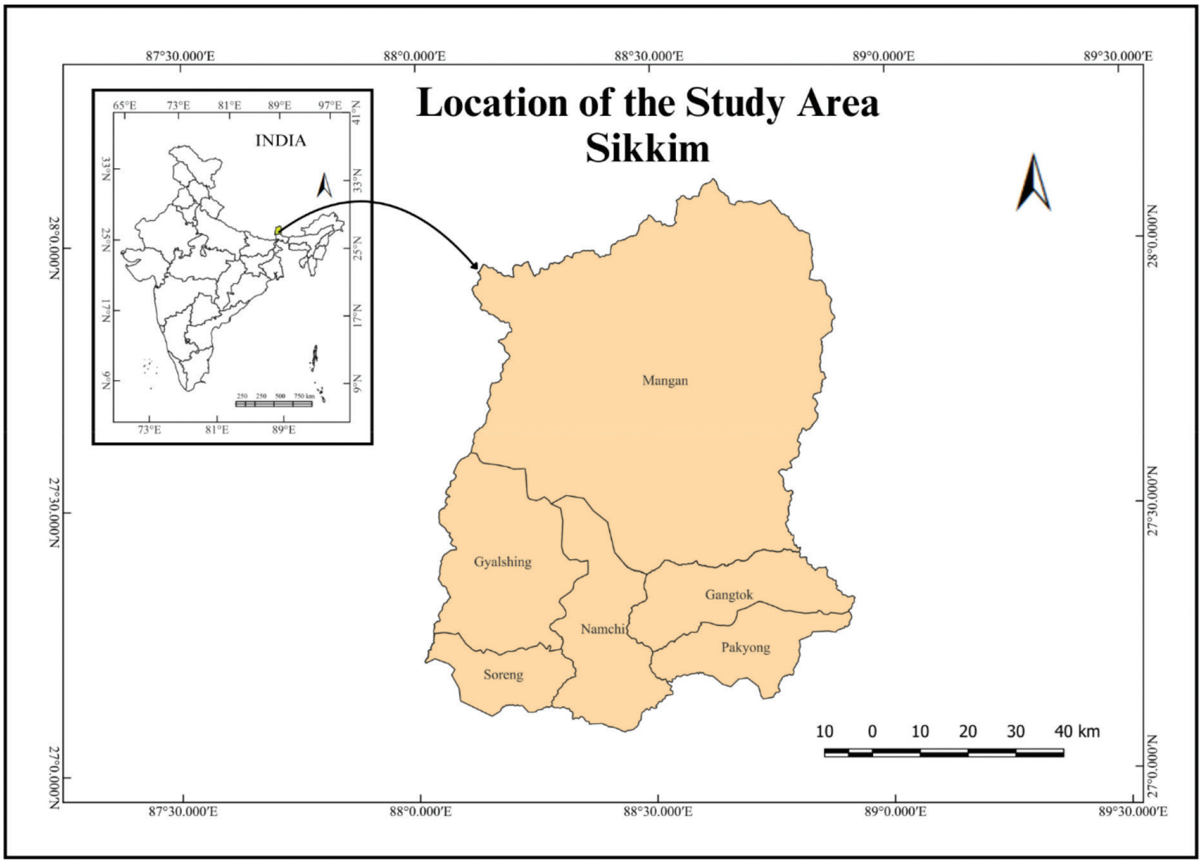

Figure 1: Location of the study area.

The backbone of Sikkim's economy is agriculture, with mixed farming practices prevalent (Sharma & Dhakal, 2011). Major cash crops include cardamom and ginger, with Sikkim being India's largest producer of large cardamom. Potatoes, mandarin, guava, kiwi, passion fruit, finger millet, mustard, barley, wheat, and a variety of vegetables are among the other agricultural goods. Sikkim also has tea plantations that produce high-quality tea for the international market (Gogoi et al., 2019; Guha, 2018).

Agriculture in Sikkim primarily depends on rainfall, and even small changes in climate and local weather influence agricultural productivity. The existing studies have concluded that the Sikkim state is experiencing climate change impact on local agriculture and the associated ecosystem. There have been studies that found about the perception of farmers on agriculture and it was found that more than 80% of the surveyed people perceived climate change and its subsequent impact on the local environment. The region has been experiencing increased velocity and discharge of rainstorms, resulting in flood-like situations and drier spells in the winter. Major crops like maize and paddy have been severely impacted. Species like deer, monkeys, and leopards have shifted their zones. Diseases and pest infestation on crops have also increased in the state as well and the fruiting and ripening times have altered (Upadhyay & Rai, 2023). The study on temperature and rainfall trends will help in understanding the changes better and preparing them to adapt and cope better with the changes.

Datasets

In order to conduct this study, three types of data, mainly rainfall, average temperature, and diurnal temperature range for four districts of Sikkim, as the study is done by taking the district boundaries before the Sikkim Legislative Assembly's Reorganization of Districts Act 2021 (East, West, North and South Sikkim) were gathered for the last 121 years ranging between 1901 and 2021 for each month. Climatic Research Unit Time Series, or CRUTS, is any input record that have been standardised to guarantee precision and coherence within the dataset.

Methodology

The data extracted from the aforementioned sources was tabulated and various approaches were used to study and analyse it. First, the summary statistics were computed, including the mean, standard deviation (SD), and coefficient of variation (CV). In order to study the average change in parameters, the average for each year over all twelve months for the three types of data was also calculated.

Second, linear regression modelling was performed to study the annual trend analysis.Time-series graphs were plotted to detect the trends. The coefficient of determination (R^2) was computed to check the statistical significance of the trend detected.

Lastly, we applied Mann–Kendall's (MK) test on the time series data to ascertain the presence of a trend in data. Several libraries and functions have been utilised in a Python script that applies the MK test to detect trends in the dataset created. The MK test is an effective method for analyzing climate data. The MK Test is a non-parametric test, and it does not make any underlying assumptions about the normality of the data, making it applicable to a wide range of environmental and climatic information. The test essentially evaluates the rank correlation between data points at different times. If the data shows a consistent upward or downward trend, the test reflects that.

The data not having any discernable trend is assumed to be the null hypothesis. The data is tested against the Alternative hypothesis (HA), which assumes that the data shows a trend that may be either increasing or decreasing. If the test's p-value is below a predetermined significance threshold, such as 0.05, then a trend in the data is statistically significant. The test can process data with seasonal trends. Sen's slope is frequently used to compute the slope of the trend and can also account for data seasonality.

Results and Discussion

Monthly data on temperature and precipitation were used to compute the average statistics like "mean," "standard," and "deviation" ("SD"), rainfall, average, and diurnal temperature. The essential statistical features of precipitation and temperature are presented month-wise in Table 1 and Table 2, respectively, for each of the four stations.

It is evident from the summary of mean monthly precipitation presented in Table 1 that the state received the highest precipitation during the monsoon months of "June", "July", and "August". East Sikkim, along with South Sikkim, which falls towards the east and south of Sikkim, has received the highest amount of precipitation, while West Sikkim (West Sikkim) has the least amount of precipitation. Further, the data shows that the maximum mean rainfall of 1067.6 millimetres was received during July in the East Sikkim district in 2004. While the highest average precipitation for the state was 647.21 mm in South Sikkim, the lowest

Table 1: Summary of statistics on mean precipitation (in millimetres) from 1901–2021 for Sikkim's districts

Month	*Gangtok*			*Mangan*			*Namchi*			*Gyalshing*		
	Mean	*Standard Deviation*	*CV*	*Mean*	*Standard Deviation*	*CV*	*Mean*	*Standard Deviation*	*CV*	*Mean*	*Standard Deviation*	**CV**
January	13.49	10.73	1.26	5.90	4.75	1.24	14.40	11.64	1.24	6.16	5.30	1.16
February	15.23	9.97	1.53	7.42	4.79	1.55	18.25	12.34	1.48	9.39	6.50	1.44
March	38.23	18.64	2.05	19.24	8.57	2.24	37.11	21.68	1.71	18.05	9.63	1.87
April	92.13	38.65	2.38	34.42	14.90	2.31	85.95	42.24	2.03	28.94	14.09	2.05
May	198.57	68.31	2.91	52.79	20.90	2.53	166.82	63.58	2.62	41.14	17.65	2.33
June	472.26	111.33	4.24	116.85	31.03	3.77	435.29	121.00	3.60	87.15	25.88	3.37
July	663.30	124.47	5.33	188.66	32.73	5.76	647.22	135.30	4.78	129.29	24.66	5.24
August	519.08	115.49	4.49	167.61	34.14	4.91	524.84	134.92	3.89	130.49	31.37	4.16
September	354.07	94.20	3.76	94.38	26.84	3.52	364.70	102.14	3.57	64.20	19.27	3.33
October	95.31	54.78	1.74	32.75	21.00	1.56	90.34	58.92	1.53	25.59	17.47	1.46
November	11.05	9.77	1.13	5.13	4.58	1.12	10.74	10.98	0.98	7.25	7.49	0.97
December	5.08	6.16	0.83	2.63	3.04	0.87	5.82	8.22	0.71	3.77	4.89	0.77

Table 2: Summary of statistics on average temperature (°C) from 1901–2021 in Sikkim's districts

Month	*Gangtok*			*Mangan*			*Namchi*			*Gyalshing*		
	Mean	*Standard Deviation*	*CV*	*Mean*	*Standard Deviation*	*CV*	*Mean*	*Standard Deviation*	*CV*	*Mean*	*Standard Deviation*	*CV*
January	5.20	0.81	6.45	-7.10	0.85	-8.32	6.21	0.84	7.38	-11.28	0.90	-12.57
February	6.57	0.92	7.16	-5.83	0.91	-6.39	7.58	0.92	8.24	-10.23	0.93	-10.98
March	10.68	1.01	10.60	-2.21	1.02	-2.17	11.69	1.02	11.49	-6.81	1.05	-6.52
April	13.50	0.88	15.32	1.61	0.87	1.84	14.50	0.89	16.35	-2.91	0.87	-3.34
May	15.49	0.75	20.62	5.10	0.74	6.87	16.41	0.77	21.41	0.91	0.76	1.20
June	17.41	0.66	26.57	8.51	0.67	12.76	18.22	0.67	27.10	4.61	0.68	6.81
July	17.75	0.43	41.13	9.25	0.44	20.95	18.46	0.44	41.76	5.65	0.44	12.80
August	17.71	0.42	41.71	8.81	0.43	20.53	18.43	0.42	43.66	5.12	0.43	11.83
September	16.65	0.43	39.13	7.25	0.45	16.16	17.44	0.43	40.73	3.44	0.44	7.83
October	14.28	0.80	17.75	2.46	0.84	2.95	15.38	0.81	18.90	-1.84	0.86	-2.15
November	10.22	0.85	11.96	-2.36	0.87	-2.71	11.43	0.88	13.01	-6.78	0.91	-7.43
December	6.96	0.81	8.65	-5.34	0.83	-6.45	8.08	0.84	9.61	-9.52	0.87	-10.92

monsoon rainfall is in West Sikkim, which only receives 129.2 mm of rainfall on average. All the districts record low precipitation during the winter months from December to February. All the districts record the lowest values for precipitation during the month of January.

It is evident from Table 2 that the average temperature varied widely depending on the region's geographical location. The lowest temperatures are recorded in the West Sikkim district, located in the western part of the state. West Sikkim showed a variation in average temperatures from -13.1ºC in January to 6.9ºC in July. The highest temperatures are recorded in South Sikkim (Namchi) at 19.5ºC.

In order to study the variation of annual temperature and precipitation for each of the four districts we used linear regression modelling and the resultant graphs are shown in Figure 2. Coefficient of determination R^2 was also computed to check the statistical significance of our results and is also shown in Figure 2. As is clearly evident from Figure 2, the annual temperature and precipitation have been changing, with the average temperature increasing in all of the four districts. The dotted straight line shows the trend for the last 121 years. As is shown in the graph there is an increasing trend (evident from the positive value of the slope in the figure) in temperature in all four districts of Sikkim with large values of R^2. However, the precipitation does not show any significant trend in the last 121 years.

The MK test was used to assess trends in average temperature and precipitation. Table 3 shows the results obtained, including p-values, using the MK test. It clearly shows the existence of an increasing trend for average temperature with a p-value <0.01 in all four districts. This indicates a consistent rise in average temperatures across these regions, highlighting a notable climatic shift. The results obtained from the MK test also match with those obtained by linear modelling, thus proving the efficacy of our analysis.

The analysis of rainfall trends revealed different patterns. While the average temperature showed a significant upward trend, precipitation trends were less uniform across the districts. Specifically, only South Sikkim (Namchi) demonstrated a significant trend in precipitation. South Sikkim, known for its considerable rainfall, is exhibiting a decreasing trend in the amount of precipitation received, as indicated by the MK test results. This decreasing trend in South Sikkim's precipitation is significant, suggesting potential changes in local hydrological cycles and possible implications for the region's water resources and agricultural practices. The absence of significant trends in rainfall for the other three districts suggests that while these areas may experience variability in rainfall patterns, there is no clear indication of an increasing or decreasing trend. This variability could be attributed to Sikkim's complex topography and climatic influences.

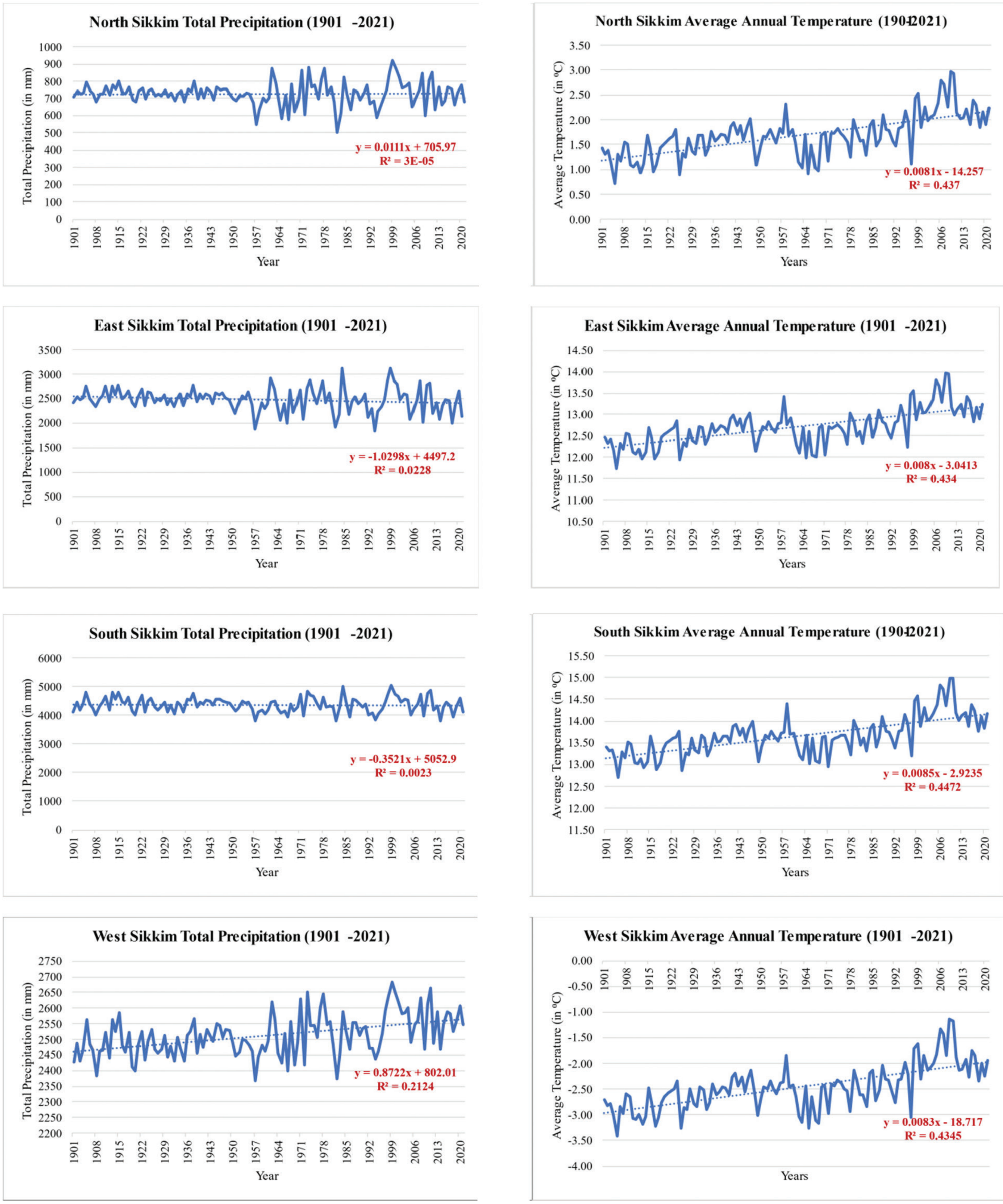

Figure 2: Annual trends of precipitation and average temperature from 1901-2021 in the districts of Sikkim.

Table 3: Results obtained by using MK test (.05) on temperature and rainfall data

District	*Average Temperature*	*P Value*	*Average Precipitation*	*P Value*	*Average Diurnal Temperature*
East Sikkim (Gangtok)	Increasing	1.9984014443252818e-15	No trend	0.079	No trend
North Sikkim (Mangan)	Increasing	4.440892098500626e-16,	No trend	0.812	No trend
South Sikkim (Namchi)	Increasing	1.3322676295501878e-15	Decreasing	0.042	No trend
West Sikkim (Gyalshing)	Increasing	6.661338147750939e-16	No trend	0.338	No trend

Conclusion

The paper has examined the impact of climate change in Sikkim by analysing “temperature” and “precipitation” trends for the past 121 years. Using statistical methods like the Mann-Kendall Trend Test, this study has identified significant variations in climate patterns across all districts of Sikkim. The findings reveal a concerning trend of rising average temperatures and shifting precipitation patterns, which aligns with the global climate change patterns. This will have profound implications for the region’s water resources, agricultural productivity, and overall ecological balance. Notably, it is important to the state as it heightens the vulnerability of Sikkim’s environment and economy—particularly its agriculture sector, which is pivotal as Sikkim is the world’s first organic state—to the adverse effects of climate change.

The results of the study call for effective coping mechanisms for the altered precipitation and temperature patterns and adaptation measures for small farmers that are tailored to the local situation. The communities in these regions have lived in the regions for ages, responding and adapting to the changes and maintaining the harmony of the area using their local knowledge. Community-based coping and adaptation mechanisms based on an indigenous knowledge base are essential to tackle the changing patterns of temperature and weather as well as the larger issue of climate change.

There is an urgent need for integrating these research findings into both state and national policy frameworks, as it is essential for devising effective strategies aimed at mitigating the negative impacts of climate change and promoting environmental sustainability within Sikkim. By doing so, it is possible to safeguard the region’s ecological and economic well-being and set a precedent for sustainable development and climate resilience that can be emulated nationally and globally.

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