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RESEARCH REPORT

Regional climate analysis over Bhutan

Bibhuti Sharan Keshav, Raghavendra Ashrit, Mohana S. Thota

July 2024

National Centre for Medium Range Weather Forecasting
Ministry of Earth Sciences, Government of India
A-50, Sector-62, NOIDA-201 309, INDIA

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9	Abstract (brief)	The Kingdom of Bhutan nestled within the Eastern Himalayan ecosystem exhibits diverse topography ranging from low-lying plains to high mountainous regions exceeding 7000 meters above mean sea level characterized by rugged mountains, extensive glaciers and lush forests. Bhutan faces various climatic hazards such as flash floods, glacial lake outburst floods (GLOFs) and forest fires. Understanding long-term trends in rainfall and temperature is crucial for mitigating these risks and adapting to the impacts of climate change. This study utilizes monthly precipitation, near surface maximum temperature (Tmax), and minimum temperature (Tmin) data from CRU TS (Climate research unit gridded time series) version 4.07 from 1951 to 2020 to analyze precipitation and temperature patterns over Bhutan. Mean annual rainfall touches around 4000 mm over south western Bhutan regions. Precipitation characteristics exhibit distinct seasonal and spatial variations with the southwest monsoon season from June to September contributing significantly to total annual rainfall while winter months experience minimal precipitation. Maximum temperatures demonstrate a consistent increasing trend with the highest rates around 0.2^{o} C per decade noted during the ON (October-November) period. In contrast, minimum temperatures display variability across seasons with the highest increasing trends more than 0.2^{o} C per decade observed during the winter months. Tmax shows significant increasing trends during JJAS (June to September) and ON seasons while Tmin shows across all the seasons. Some of the months have higher increasing rates of Tmax and Tmin in the recent decade show higher Tmax and Tmin especially over the regions where climatological mean temperatures are low.
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Abbreviations

BCWC	BIMSTECCentre for weather and climate
BSISO	Boreal summer intra-seasonal oscillations
BIMSTEC	Bay of Bengal Initiative for Multi-Sectoral Technical and Economic Cooperation
C	Celsius
CRU TS	Climate research unit gridded time series
DJF	December January February
E	East
ENSO	El-Nino and southern oscillation
GLOFs	Glacial lake outburst floods
IMDAA	Indian monsoon data assimilation and analysis
IMERG-	Integrated multi satellite retrievals for global precipitation measurement
IOD	Indian Ocean dipole
JJAS	June July August September
MAM	March April May
MJO	Madden-Julian oscillation
MK	Mann-Kendall
N	North
NCMRWF	National Centre for medium range weather forecasting
ON	October November
Tmax	Maximum Temperature
Tmin	Minimum Temperature

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सारांश

पूर्वी हिमालयी पारिस्थितिकी तंत्र के भीतर बसे भूटान साम्राज्य में निचले मैदानों से लेकर समुद्र तल से 7000 मीटर से अधिक ऊंचे पर्वतीय क्षेत्रों तक विविध स्थलाकृतियां दिखाई देती हैं, जो ऊबड़-खाबड़ पहाड़ों, व्यापक ग्लेशियरों और हरे-भरे जंगलों से युक्त हैं। भूटान को विभिन्न जलवायु संबंधी खतरों का सामना करना पड़ता है जैसे अचानक बाढ़, हिमनद झील विस्फोट बाढ़ (जीएलओएफ) और जंगल की आग। इन जोखिमों को कम करने और जलवायु परिवर्तन के प्रभावों को अपनाने के लिए वर्षा और तापमान में दीर्घकालिक रुझान को समझना महत्वपूर्ण है। यह अध्ययन भूटान में वर्षा और तापमान पैटर्न का विश्लेषण करने के लिए 1951 से 2020 तक सीआरयू टीएस (जलवायु अनुसंधान इकाई ग्रिडेड टाइम श्रृंखला) संस्करण 4.07 से मासिक वर्षा, सतह के अधिकतम तापमान (टीमैक्स), और न्यूनतम तापमान (टीमिन) डेटा का उपयोग करता है। दक्षिण पश्चिमी भूटान क्षेत्रों में औसत वार्षिक वर्षा लगभग 4000 मिमी तक पहुँच जाती है। वर्षा की विशेषताएँ अलग-अलग मौसमी और स्थानिक भिन्नताएँ प्रदर्शित करती हैं, जून से सितंबर तक दक्षिण-पश्चिम मानसून का मौसम कुल वार्षिक वर्षा में महत्वपूर्ण योगदान देता है, जबकि सर्दियों के महीनों में न्यूनतम वर्षा होती है। अधिकतम तापमान लगातार बढ़ने की प्रवृत्ति प्रदर्शित करता है और चालू (अक्टूबर-नवंबर) अवधि के दौरान प्रति दशक लगभग 0.2 डिग्री सेल्सियस की उच्चतम दर दर्ज की गई है। इसके विपरीत, न्यूनतम तापमान विभिन्न मौसमों में परिवर्तनशीलता प्रदर्शित करता है, जिसमें सर्दियों के महीनों के दौरान प्रति दशक 0.2^{o} C से अधिक की वृद्धि देखी गई है। टीमैक्स जेजेएएस (जून से सितंबर) और ओएन सीज़न के दौरान महत्वपूर्ण बढ़ती प्रवृत्ति दिखाता है जबकि टीमिन सभी सीज़न में दिखाता है। हाल के दशक में कुछ महीनों में टीमैक्स और टीमिन की दर अधिक बढ़ी है, विशेष रूप से उन क्षेत्रों में टीमैक्स और टीमिन की दर अधिक है जहां जलवायु संबंधी औसत तापमान कम है।

Abstract

The Kingdom of Bhutan nestled within the Eastern Himalayan ecosystem exhibits diverse topography ranging from low-lying plains to high mountainous regions exceeding 7000 meters above mean sea level characterized by rugged mountains, extensive glaciers and lush forests. Bhutan faces various climatic hazards such as flash floods, glacial lake outburst floods (GLOFs) and forest fires. Understanding long-term trends in rainfall and temperature is crucial for mitigating these risks and adapting to the impacts of climate change. This study utilizes monthly precipitation, near surface maximum temperature (Tmax), and minimum temperature (Tmin) data from CRU TS (Climate research unit gridded time series) version 4.07 from 1951 to 2020 to analyse precipitation and temperature patterns over Bhutan. Mean annual rainfall touches around 4000 mm over south western Bhutan regions. Precipitation characteristics exhibit distinct seasonal and spatial variations with the southwest monsoon season from June to September contributing significantly to total annual rainfall while winter months experience minimal precipitation. Maximum temperatures demonstrate a consistent increasing trend with the highest rates around 0.2^{o} C per decade noted during the ON (October-November) period. In contrast, minimum temperatures display variability across seasons with the highest increasing trends more than 0.2^{o} C per decade observed during the winter months. Tmax shows significant increasing trends during JJAS (June to September) and ON seasons while Tmin shows across all the seasons. Some of the months have higher increasing rates of Tmax and Tmin in the recent decade show higher Tmax and Tmin especially over the regions where climatological mean temperatures are low.

1. Introduction

The Kingdom of Bhutan, situated in South Asia, is a landlocked nation bordered with India to the south, encompassing mountain ranges such as the Tibet Autonomous Region, the Lesser Himalayas, and the Duars Plain along its southern periphery and China to the northern regions. Nestled within the Eastern Himalayan ecosystem, it boasts a diverse topography ranging from elevations as low as 94 meters to towering summits exceeding 7,000 meters above sea level. Bhutan's terrain is characterized by rugged mountains, abundant water bodies, and lush primeval forests. The topography of the country is shown in the figure 1. In the north, snow-capped peaks reaching heights over 7200 meters dominate the landscape, featuring extensive glaciers and alpine meadows. Major rivers predominantly flow southward are Toorsa, Wang, Sankosh and Manas, mostly joining the Brahmaputra river system. Glacial coverage constituted approximately 1.6% of Bhutan's land area in 2018, while forested regions encompassed a substantial 72.3% of the country, with agricultural land comprising 13.8%. Being situated in the Himalayan region, one of the youngest and highest mountain chains globally and Bhutan's ecosystem is inherently fragile and designated as a biodiversity hotspot. The nation experiences diverse climatic conditions attributable to its varied topography and geographic location, straddling the juncture between tropical and Asian monsoon circulations.

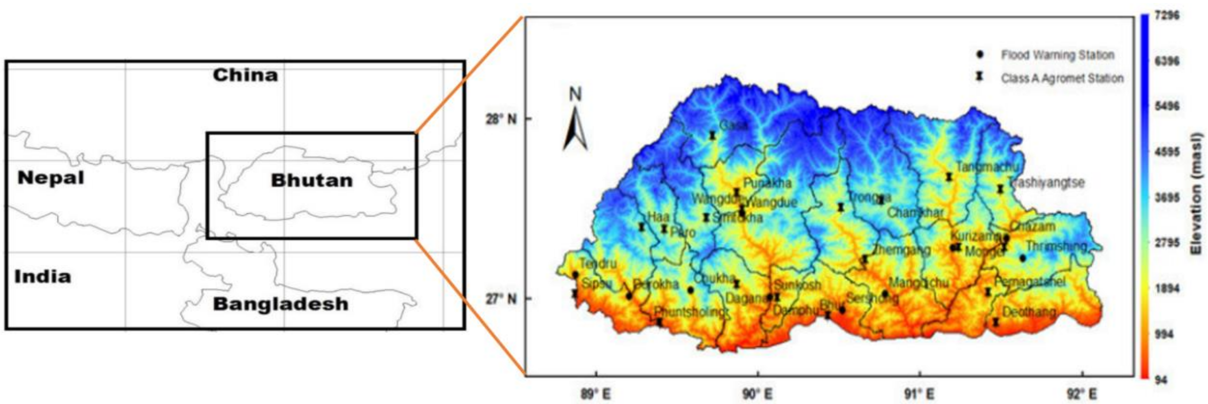

Figure 1 Bhutan’s landlocked nature and topography showing the elevation in meter above mean sea level, flood warning and class A Agromet stations

The country's economy is heavily reliant on hydropower and disruptions to hydropower production due to climate change-induced events and long-term shifts can have large economic ramifications. Bhutan faces various hazards, including flash floods, glacial lake outburst floods (GLOFs), forest fires, storms, and landslides, all of which pose significant risks. These impacts underscore the country's considerable vulnerability, therefore adaptation strategies must prioritize Bhutan's susceptibility to climate change impacts, especially given its fragile mountainous terrain and heavy reliance on agriculture and hydropower for economic growth.

Rainfall and temperature represent crucial meteorological factors that significantly influence the environmental characteristics of a specific region (Girma et al 2016). Hence, conducting long-term trend analysis of these parameters across various spatial and temporal scales holds significant importance. The Himalayan regions are widely recognized as among the most vulnerable areas globally. Bhutan, being landlocked, with a majority of its settlements situated along river basins, faces heightened susceptibility to flash floods. Moreover, irregular rainfall patterns pose a significant concern, making droughts a looming threat. These erratic weather conditions render Bhutanese citizens, particularly those residing in rural areas, highly vulnerable to the adverse impacts of extreme weather events (BICMA 2016). The changing climate in Bhutan poses significant threats to its extensive biodiversity and raises the risk of various natural disasters, including glacier lake outburst floods, flash floods, droughts, and forest fires. Enhanced comprehension of Bhutan's climate patterns and their fluctuations, along with the observed and potential climate-related impacts, is essential for effectively addressing regional socio-economic and ecological challenges, particularly within the Himalayan context. Given Bhutan's heightened vulnerability to climate change, comprehensive studies on critical variables such as temperature and rainfall remain scarce, primarily due to the limited availability of observed data. Therefore, the objective of this research is to provide a detailed analysis of long-term statistical trends in near-surface temperature and rainfall patterns. This analysis utilizes data from CRU TS (Climate Research Unit Gridded Time Series) version 4.07, offering insights into climatic trends over Bhutan.

BIMSTEC (Bay of Bengal Initiative for Multi-Sectoral Technical and Economic Cooperation) Centre for weather and climate (BCWC) is an important component of Ministry of Earth Sciences (MoES), The Government of India's BCWC actively collaborates with BIMSTEC nations, organizing annual workshops and training programs to build disaster management capacity and engages in weekly online discussions with scientists from member countries. Collaborative research focuses on developing and improving weather and climate prediction models and enhancing early warning capabilities. Under capacity building, efforts include training programs, workshops, fellowship initiatives, and international conferences to showcase advancements in weather and climate information for the BIMSTEC region.

The first section of this report is an introduction continued with data and methodology in the second section. Overview of Bhutan's climate is discussed in section 3 and results of climate analysis with CRU TS version 4.07 data are described in section 4, brief summary and future works are given in sections 5 and 6 respectively and references are given in the section 7 followed by appendix in section 8.

2. Data and methodology

For the present climate analysis, monthly precipitation, maximum temperature (Tmax), and minimum temperature (Tmin) data from CRU TS 4.07 (Climate Research Unit gridded time series version 4.07) with a horizontal resolution of 0.5°×0.5° covering the period from 1951 to 2020 were utilized. The dataset, globally available over land excluding Antarctica, was specifically extracted over the Bhutan region (26.5°N-28.5°N, 88.5°E-92°E) for this study. Detailed information regarding the preparation of the CRU dataset over an extended period can be found in the reference (Harris et al., 2020). Formulae used to get the statistical results are described in the appendix given at the end of the report.

Monthly precipitation data were aggregated to compute seasonal and annual total precipitation for the respective months, while monthly temperature data were averaged to derive seasonal and annual Tmax and Tmin profiles. These timeseries data of rainfall, Tmax, and Tmin over Bhutan were directly obtained from the CRU web portal and utilized in the analysis. Seasonal categorization of months was based on literature works available at the Meteorological Department of Bhutan, as described in further sections. Mean, standard deviation (coefficient of variation for rainfall), and trends were calculated monthly, seasonally, and annually to examine regional climate patterns over Bhutan. Slopes and trends were determined and tested using the non-parametric Mann-Kendall (MK) test, with significance assessed at a 95% confidence level.at 95% significance level.

3. Bhutan's climate overview

With a very high variability in the geography and topography of Bhutan, the country experiences a diverse climate profile over the years. Bhutan has rich in the number of glaciers with hundreds of glacier lakes with a total of 700 glaciers covering around 1.6% of the area of the country. Some Himalayan glaciers also plays an important role in water resources of the local communities and studies shows that the Himalayas are retreating more in the recent years (Basnett et al 2013; Karma and Namgay 2023) which will cause the reduction in 10% of the Bhutan's glacierized area if the climate continues with the current decreasing rate of glacier covered area (Rupper et al 2012). This may lead to the regional warming of the surrounding regions. Northern part of the country has lower temperature due to its higher elevation compared to southern regions. Bhutan receives most of its annual rainfall during the southeast monsoon season which prolongs from June to September. Study shows that approximately 73% of the total annual rainfall is received during the southwest monsoon season, with only about 1% occurring during the winter months over Bhutan (Dorji et al 2021). Bhutan is roughly categorized into four climatic regions depending on precipitation, highest rainfall (3000 to 6000 mm/year) in the southern plains, medium to high (1500 to 2500 mm/year) in the southern High Himalaya region, medium levels (600 to 800 mm/year) in central Bhutan.

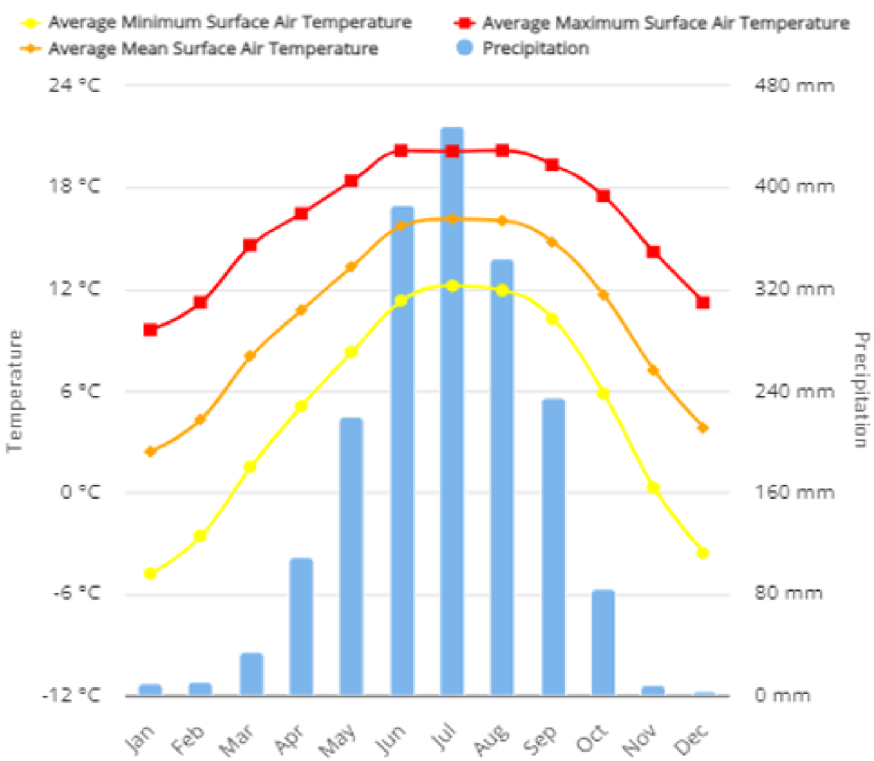

Figure 2 Monthly rainfall and temperature climatology (Climate change knowledge portal for development practitioners and policy makers, https://climateknowledgeportal.worldbank.org/country/bhutan)

Monthly climatology from 1991 to 2022 of precipitation and temperature is shown in the figure 2. The precipitation mainly occurs during summer monsoon season with maximum in July which reached more than 400 mm in a month and minimum occurs during December which had observed at most of the class A meteorological stations. Station data shows that monthly rainfall climatology from 1996 to 2021 for July is higher at some of the stations namely Sipsu, Phuentsholing and Bhur with maximum over Phuentsholing (Bhutan State of the Climate report 2022). Stations located in southern part of the country receives higher amount of rainfall compared to the central Bhutan regions. Maximum surface air temperature reached around 20° C during June to August whereas minimum surface air temperature can reach below around -6° C during December and January.

Surface temperature climatology in Bhutan is characterized by its diverse topography and varying climatic conditions across different regions. The country's rugged terrain, ranging from high mountain peaks to low-lying valleys contributes to significant temperature variations. Generally, temperatures decrease with increasing altitude resulting in cooler conditions in mountainous areas such as the Himalayas. Conversely, lower-lying valleys and plains experience relatively warmer temperatures. Bhutan experiences four distinct seasons: spring, summer, autumn, and winter, each with its own temperature patterns and characteristics. During the winter months, temperatures in Bhutan can drop considerably especially in high-altitude regions where sub-zero temperatures are common. In contrast, summer months bring warmer temperatures particularly in the southern plains where temperatures can soar due to the tropical climate. Research on surface temperature climatology in Bhutan is relatively limited but growing with studies focusing on the impacts of climate change on temperature trends. Climate change is causing shifts in temperature patterns including alterations in seasonal temperatures and increases in temperature extremes. These changes pose significant challenges for Bhutan's agricultural sector affecting crop yields, water resources and overall livelihoods. Understanding surface temperature variations is crucial for informing adaptation strategies and sustainable development initiatives in Bhutan. References to studies on climate change impacts on Bhutan's temperature patterns provide valuable insights into the country's vulnerability to climate change and the need for effective mitigation and adaptation measures.

4. Climatology using CRU TS 4.07 dataset

Analysis utilizing long-term datasets is conducted and major findings presented separately for precipitation and near surface maximum temperature (Tmax) and minimum temperature (Tmin) in two distinct subsections which are described below.

4a. Precipitation

Rainfall over Bhutan exhibits considerable spatial and temporal variability due to its diverse topography and climatic conditions. Precipitation levels vary across different regions, with higher amounts typically observed in southern and eastern Bhutan compared to the northern regions. Additionally, Bhutan experiences occasional extreme rainfall events, leading to the risk of flash floods and landslides, particularly in areas with steep slopes. Figure 3 depicts the annual climatology, coefficient of variation, trends, and timeseries of precipitation. It illustrates the variability in annual precipitation climatology, ranging from approximately 1000 mm in northern Bhutan to around 3000 mm in the southwestern region. Certain years have witnessed exceptionally high precipitation levels, exceeding 4000 mm in specific areas for a single year. The northern region of Bhutan, characterized by snow cover and sub-zero temperatures for most months, experiences reduced monsoonal precipitation. Bhutan primarily receives precipitation during the monsoon season, spanning from June to September. Despite slight fluctuations, the annual precipitation remains relatively stable. Long-term trends in precipitation exhibit both positive and negative slopes in northern and southern Bhutan, respectively, although these trends lack statistical significance countrywide. Additionally, the annual timeseries displays a negative slope, albeit without a significant decreasing trend at the 95% confidence level.

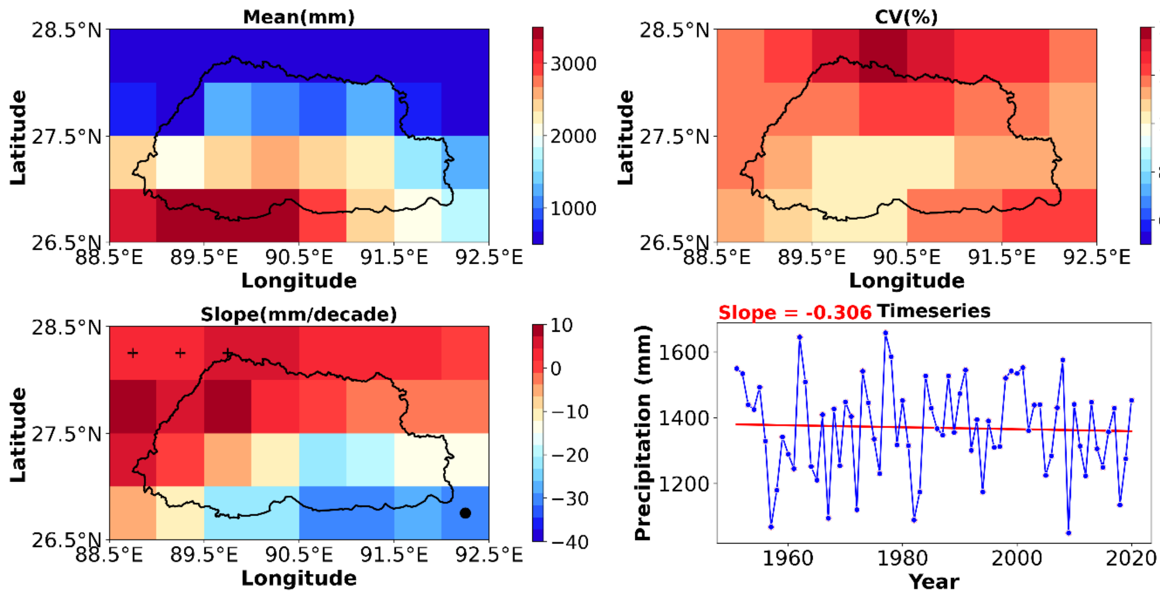

Figure 3 Annual precipitation climatology, coefficient of variation, slopes and timeseries (blue) along with trend line (red). Plus (+) sign and circle (o) show significant positive and negative trends respectively.

Figure 4 presents the seasonal precipitation patterns across four distinct seasons, revealing that the highest precipitation levels occur during the southwest monsoon season (June to September) across most of Bhutan. During the pre-monsoon season (March-April-May), precipitation reaches up to 600 mm in certain areas of southern Bhutan. Conversely, precipitation during the post-monsoon and winter seasons is considerably lower compared to other seasons, attributable to the diminished water vapor during the Northeast monsoon season, which precludes winter precipitation in Bhutan. Figure 5 displays the trend line slopes for seasonal precipitation. While significant positive trends in pre-monsoon precipitation are observed in eastern Bhutan, no significant trend is evident in monsoonal precipitation despite notably high negative slope values. It is noteworthy that pre-monsoon rainfall displays a significant positive trend of approximately 15 mm per decade across eastern Bhutan regions, indicating a notable temporal change in rainfall patterns over the years. The timeseries analysis of area-averaged rainfall over Bhutan reveals a prominent and statistically significant positive trend of 7.41 mm per decade during the MAM season over the period under consideration, as depicted in Figure 6. The country exhibits considerable heterogeneity in seasonal precipitation, prompting further classification into individual months to elucidate months associated with extreme rainfall and significant trends.

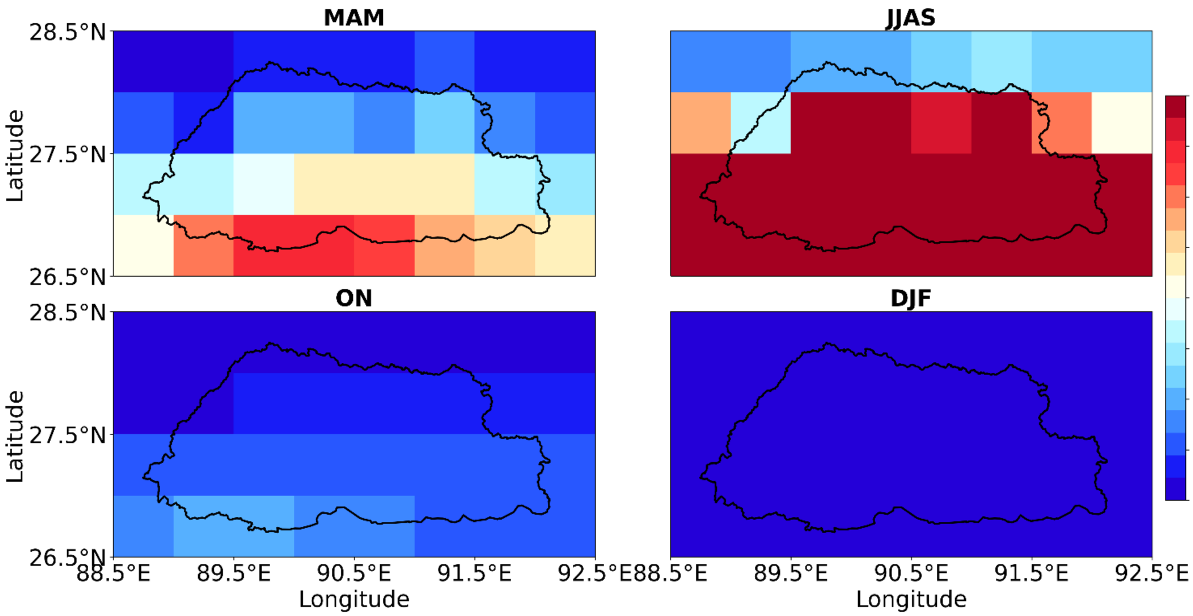

Figure 4 Seasonal precipitation climatology (Unit - mm per season)

Figure 7 presents the monthly climatology of precipitation, revealing nominal precipitation levels, typically below 50 mm, from October to April. Precipitation initiates in May and persists until September, with peak levels during June, July, and August, particularly evident in the southwestern region of Bhutan. Monthly rainfall in Bhutan's south-eastern regions can exceed 800 mm, particularly observed during the month of July, indicating significant precipitation extremes in the area. Figure 8 illustrates the trends of monthly precipitation with their significance at 95% significance level. Significant positive trends are observed in February, April, and May, particularly prevalent over the western region of Bhutan. Conversely, negative slopes are evident in June, July, and August, primarily observed in southern Bhutan. However, a significant decreasing trend is only observed in some areas of southern Bhutan during June. Consequently, the seasonal precipitation exhibits significant positive trends during the MAM season in western Bhutan regions. Notably, the significant increasing trend is more widespread during April, with higher positive slope values observed in May, particularly exceeding 10 mm/month in the southwestern region of Bhutan. Conversely, lower positive slope values are observed in February, approximately 4 mm/month, indicating a gradual increase in precipitation over time which will contribute to seasonal rainfall during the DJF season. Figure 9 shows illustrates that the time series analysis of area-averaged monthly rainfall over Bhutan reveals a noteworthy positive trend in April, attributed to widespread increasing trends across many parts of the country. In contrast, during February, the observed trends are comparatively lower and less widespread across the regions, resulting in the area averaged rainfall not showing statistical significance during this month. Additionally, the months of the southwest monsoon season do not exhibit any significant trends in rainfall, despite large negative slopes during these months. Therefore, significant negative trends are not evident during the June-July-August-September (JJAS) season.

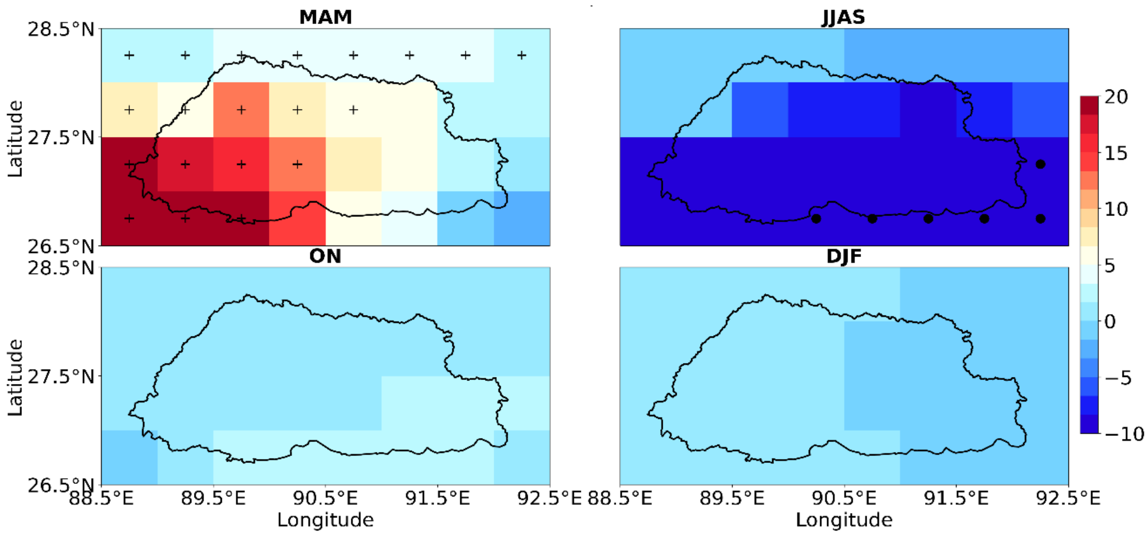

Figure 5 Seasonal precipitation trend. Significantly positive and negative trends are marked with plus sign and circle respectively (Unit of slope- mm per decade)

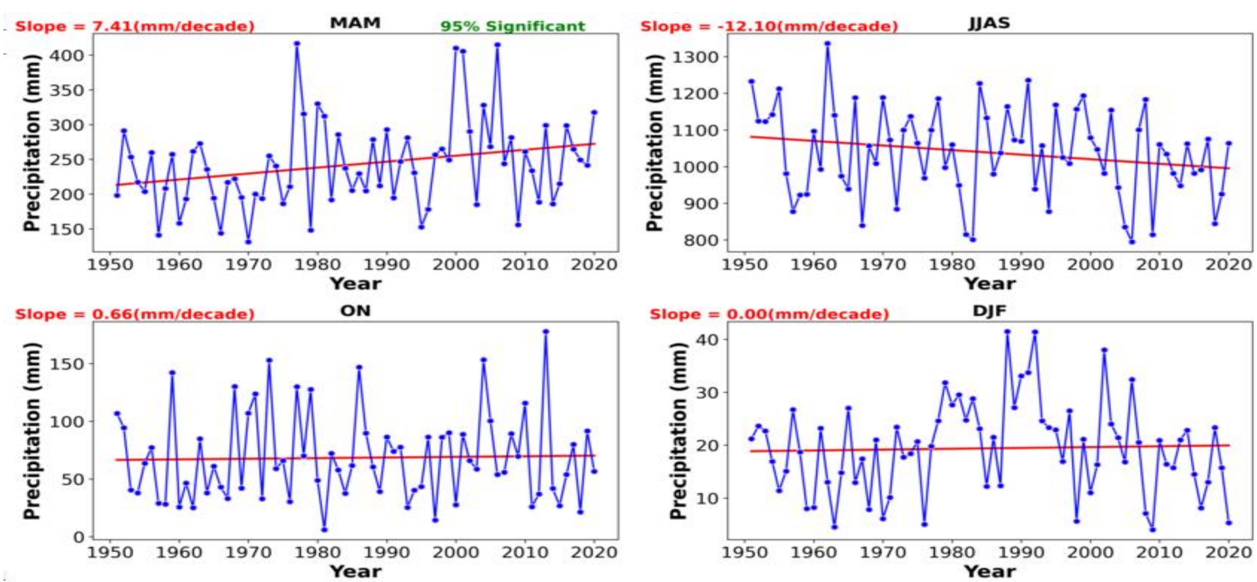

Figure 6 Timeseries (blue) along with trend lines (red). Significant trends are highlighted at 95% significance level using MK test.

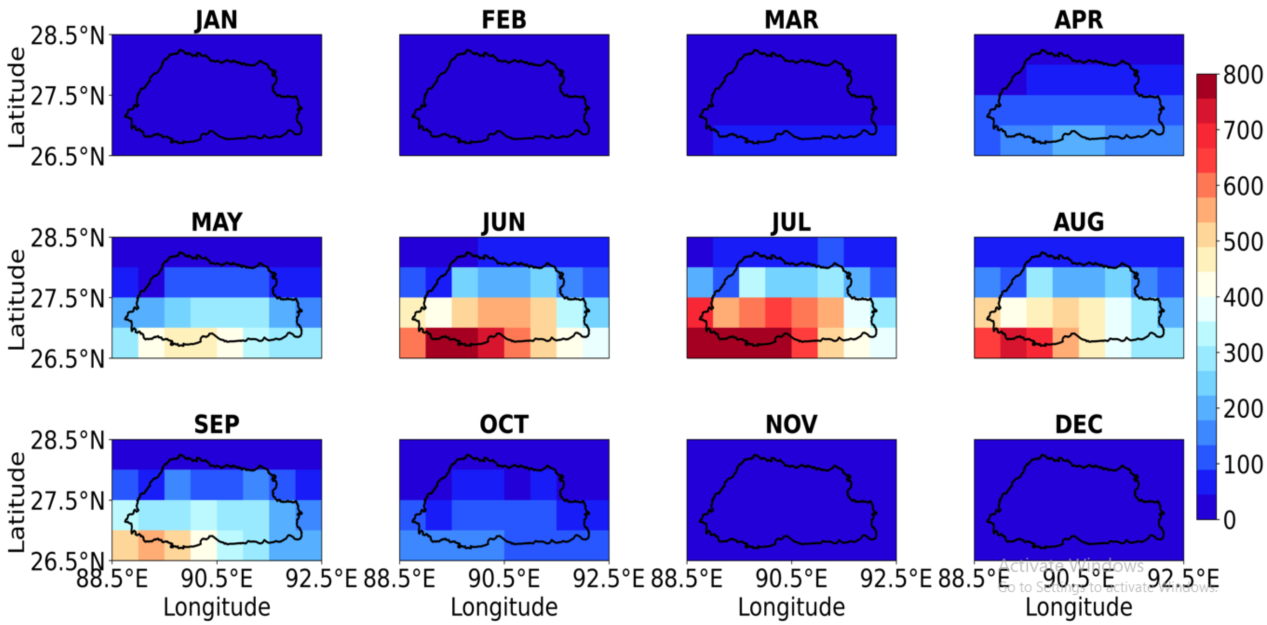

Figure 7 Monthly climatology of precipitation (Unit- mm)

The rainfall climatology of Bhutan exhibits distinct temporal and spatial patterns, evident from the analysis of area-averaged monthly rainfall trends. These findings highlight the complex dynamics of rainfall variability in Bhutan, which have significant implications for its hydrological and environmental systems. Understanding these patterns is crucial for effective water resource management and environmental conservation efforts in the region. The observed variability underscores the need for robust monitoring and adaptation strategies to address the challenges posed by changing rainfall patterns. Overall, these findings contribute to a deeper understanding of Bhutan's climatic dynamics and inform sustainable development initiatives in the country.

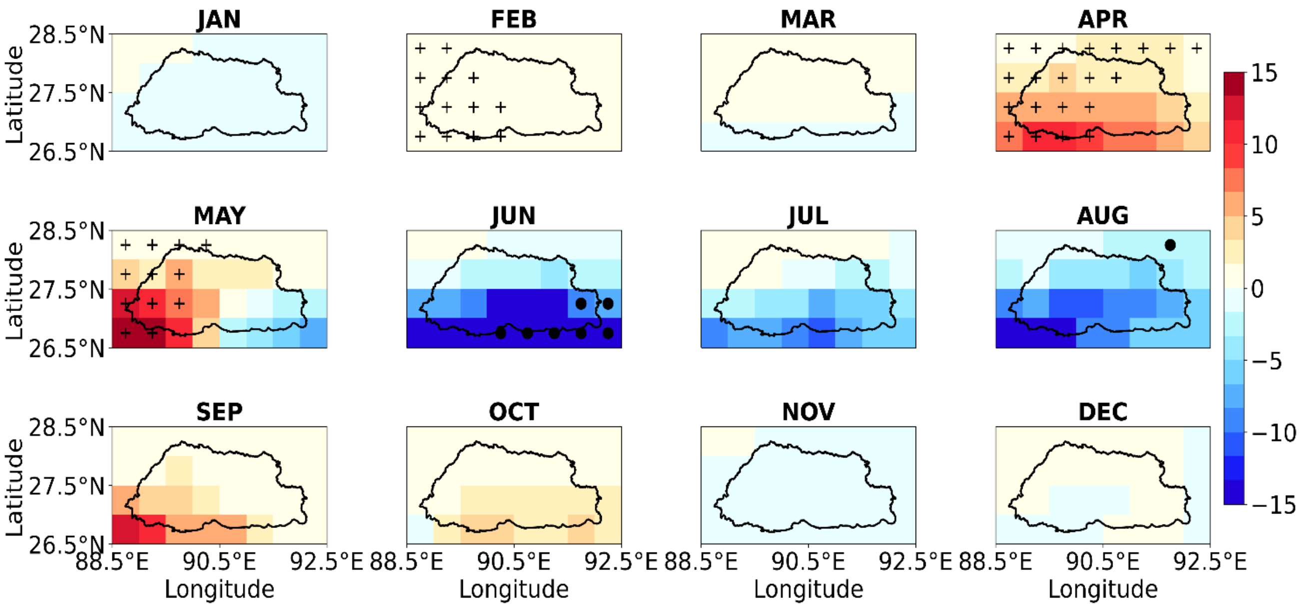

Figure 8 Monthly precipitation slopes and significant trends which are highlighted with plus sign (positive) and circle (negative) using MK test at 95% confidence level. (Unit of slope- mm per decade)

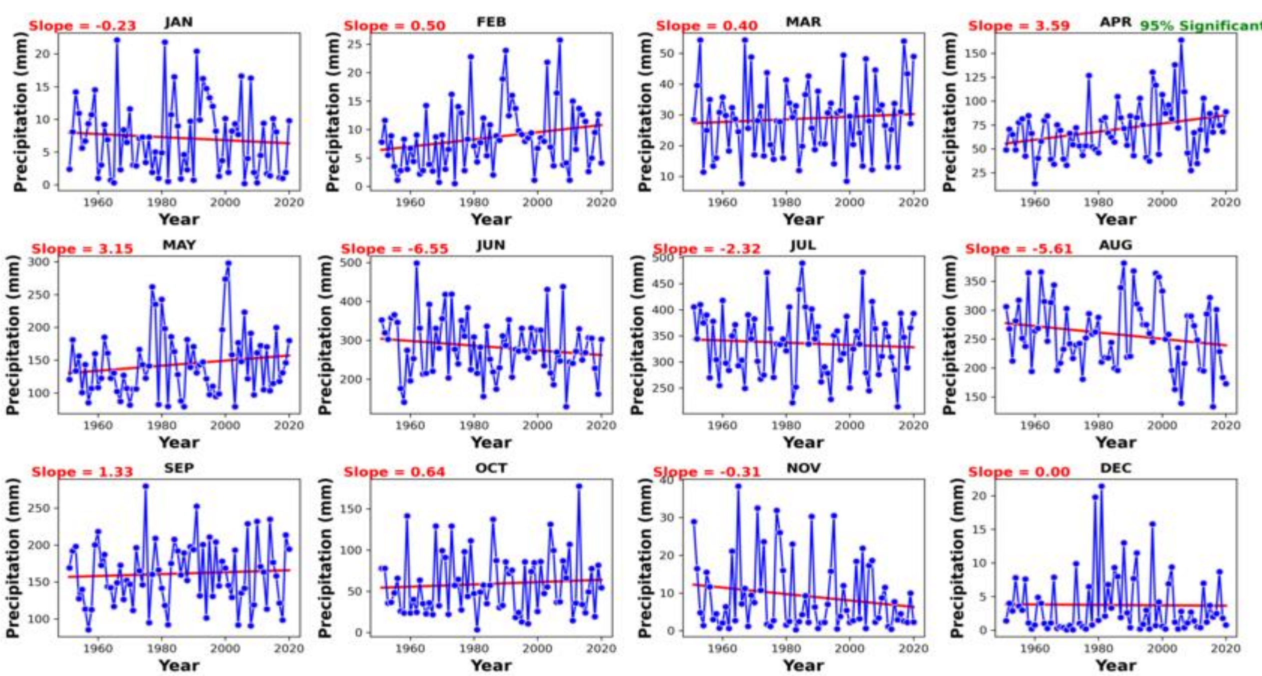

Figure 9 Monthly timeseries (blue) and trend line (red) of precipitation. Significant trends are highlighted when tested with MK test at 95% significance level.

4b. Near-surface Maximum Temperature (Tmax) and Minimum Temperature (Tmin)

In Bhutan, the climatology of maximum and minimum surface temperatures exhibits notable variability across different regions and elevations. Maximum temperatures generally peak during the summer months, particularly in the southern plains. Conversely, minimum temperatures tend to drop significantly during the winter months, especially in higher elevations, where sub-zero temperatures are common. The mountainous terrain of Bhutan contributes to diverse microclimates, with cooler temperatures prevailing at higher altitudes and warmer conditions in lower-lying areas. Climatological data indicates a gradual warming trend in both maximum and minimum temperatures over recent decades, potentially influenced by global climate change. Understanding the climatology of surface temperatures is essential for assessing the impacts of climate variability and informing adaptation strategies in Bhutan. The annual climatology, standard deviation, slope, and trends of both maximum (Tmax) and minimum (Tmin) surface temperatures using the CRU dataset are depicted in Figure 10. Tmax reaches up to 30°C over southern Bhutan regions, with comparatively lower variability. Conversely, Tmin decreases to as low as -10°C over northern Bhutan, where variability is also relatively low compared to other regions. Both Tmax and Tmin exhibit significant positive trends throughout the country, resulting in area-averaged annual Tmax and Tmin showing significant increasing trends at a 95% confidence level. Annual trends for both Tmax and Tmin exhibit a steeper gradient in the northern high-elevation areas compared to southern Bhutan. However, the rate of increment of Tmin (0.015°C per decade) surpasses that of Tmax (0.005°C per decade), leading to higher Tmin across the country in recent years. These temperature dynamics greatly contributing to the impacts of climate change on Bhutan's ecosystems, agriculture, and public health.

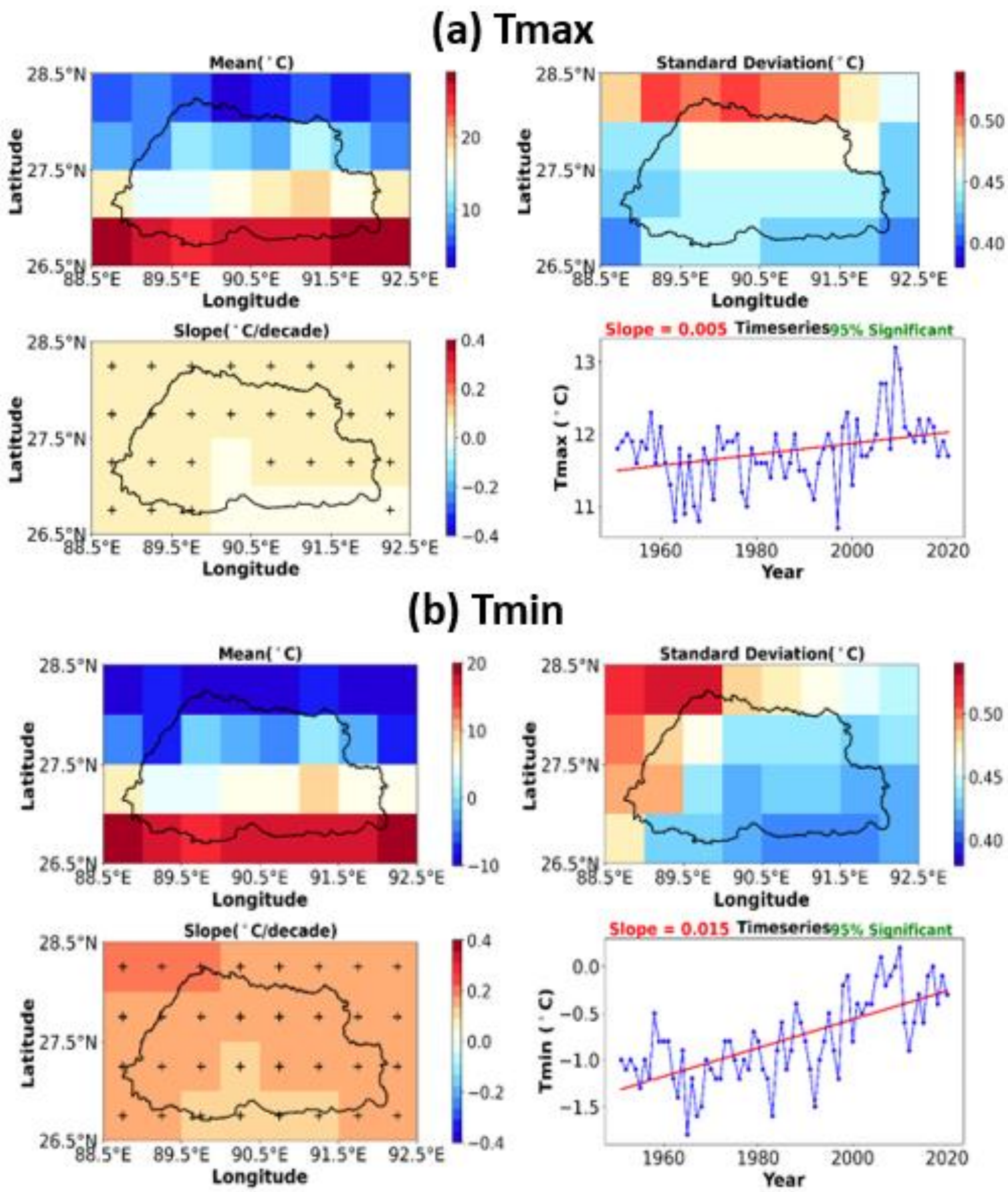

Figure 10 Mean, standard deviation, slopes and timeseries (blue) along with trend line (red) for (a) Tmax and (b) Tmin. Significant trends are highlighted with plus sign (positive) and circle (negative) at 95% confidence level.

Figure 11 illustrates the seasonal climatology of maximum (Tmax) and minimum (Tmin) surface temperatures across Bhutan. Tmax exhibits a range from slightly negative values to around 30°C, while Tmin varies from -20°C to 20°C across different seasons. Consistently, both Tmax and Tmin are higher in the southern regions and lower in the northern areas characterized by high mountainous terrain. A steep positive gradient in temperatures is observed when moving from north to south across the country, with minimal longitudinal temperature variations.

Maximum temperatures peak during the southwest monsoon season, while minimum temperatures reach their lowest levels during the DJF season throughout Bhutan. The transition from the monsoon to post-monsoon seasons is marked by a gradual decrease in temperatures, reaching their lowest points during the winter season. Understanding these seasonal temperature dynamics is essential for assessing the vulnerability of Bhutan's ecosystems and communities to climate variability and informing adaptive strategies for climate resilience. There is need for localized climate monitoring and adaptation measures to address the differential impacts of temperature variations across Bhutan's diverse landscapes.

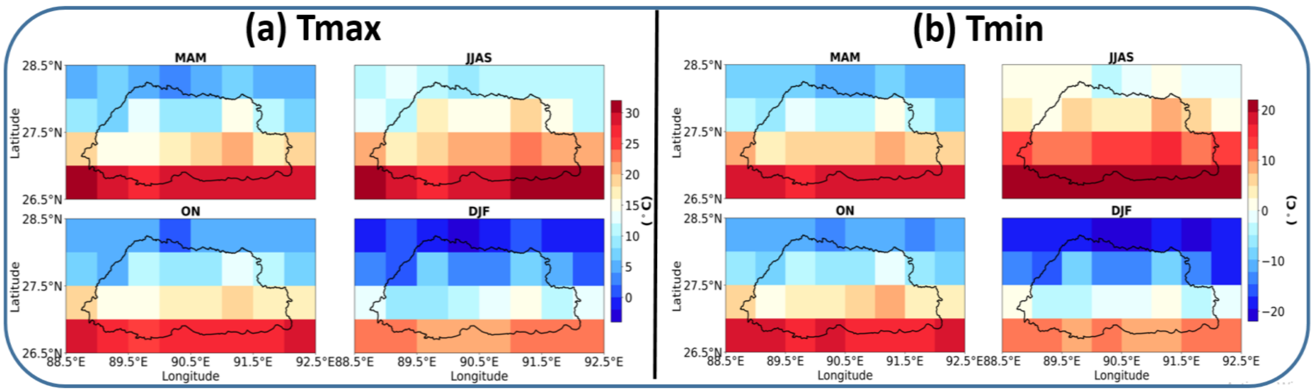

Figure 11 Seasonal climatology of (a) Tmax and (b) Tmin

In the analysis of seasonal trends depicted in Figure 12, the Tmax exhibit significant positive trends during the JJAS and ON seasons throughout Bhutan, with the highest rates observed during the ON season at a 95% significance level. However, while some northern Bhutan regions display higher slopes during the DJF seasons, these trends do not meet the significance threshold. Conversely, Tmin demonstrate significant increasing trends in all seasons across the country, with the highest rate observed during the DJF season, coinciding with the period of lowest climatological mean Tmin. This trend results in increased Tmin during the winter seasons in recent years across Bhutan. Interestingly, the increasing rate of Tmin is lowest during the JJAS season, corresponding to the period of highest mean Tmin over most parts of the country. These results underscore the complex seasonal dynamics of temperature trends in Bhutan which is responsible of warmer environment, particularly during the winter months.

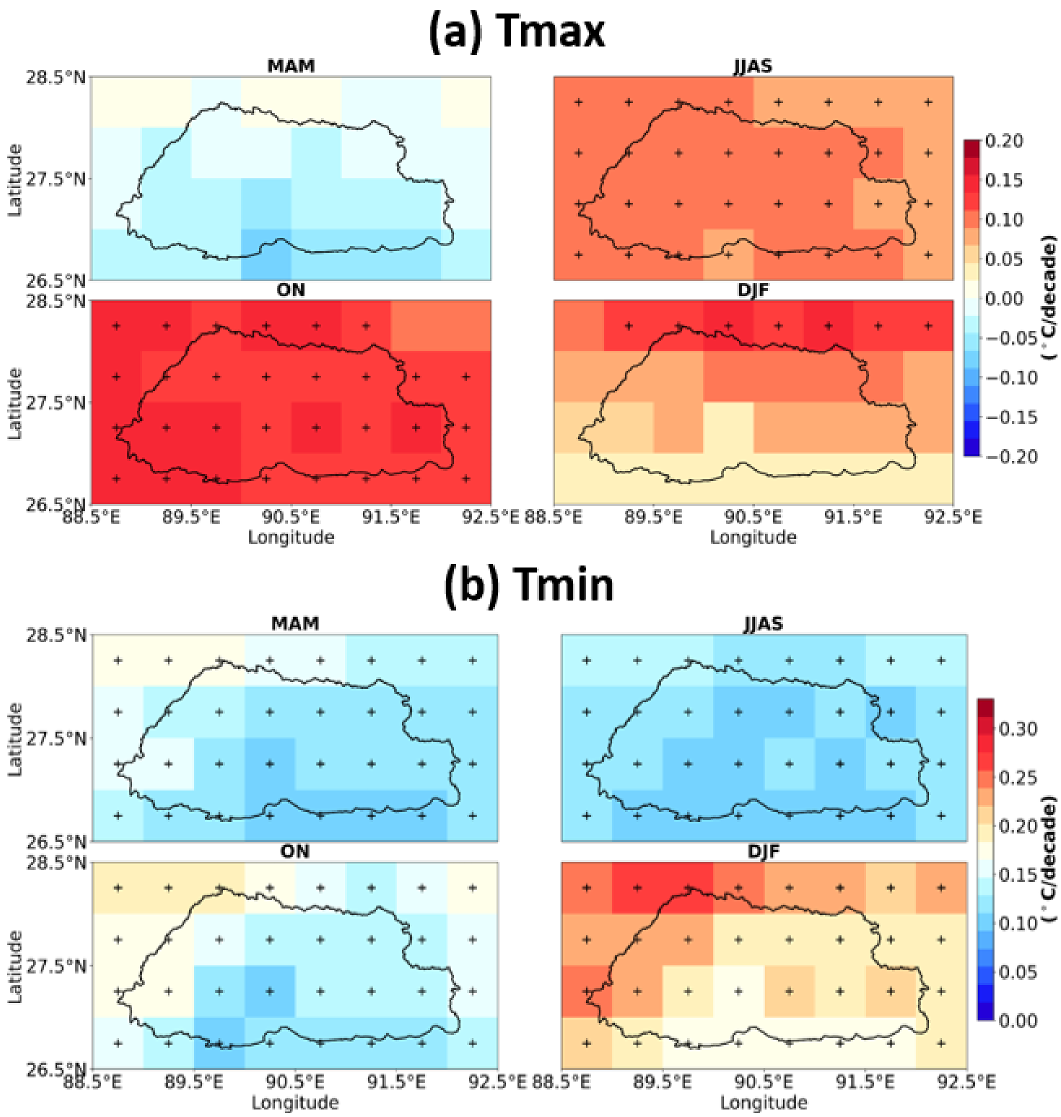

Figure 12 Seasonal trends of (a) Tmax and (b) Tmin. The regions marked with plus sign and circles show significant positive and negative trends respectively at 95% confidence level using Mann-Kendall significance test.

The analysis of area-averaged surface temperatures across Bhutan reveals consistent trends across different seasons. Tmax exhibit significant increasing trends during the JJAS and ON seasons, with the highest rate observed during the ON season at 0.13°C per decade as illustrated in Figure 13. Notably, during the JJAS season, the rate of increment of Tmax is particularly pronounced, indicating a steep gradient in recent decades. Conversely, Tmin demonstrate significant increasing trends in all seasons across the country with the highest rate observed during the DJF season at 0.21°C per decade and the lowest rate during the JJAS season at 0.13°C per decade. The observed steep gradient in the increasing rate of Tmin over recent decades contributes to the trend of warmer minimum temperatures in recent times.

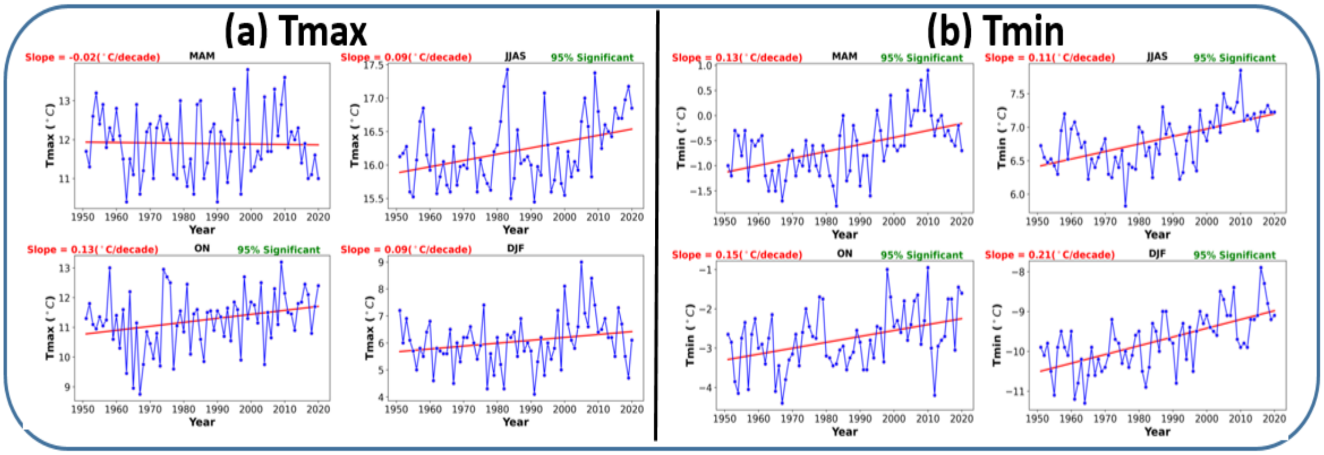

Figure 13 Timeseries (blue) and trend line (red) of seasonal (a) Tmax and (b) Tmin. MK test is used to find the significance at 95% significance level

Due to the highly variable nature of near-surface temperatures across seasons, a detailed analysis was conducted for each month to ascertain the precise monthly climatology and identify the months contributing most significantly to changing climate conditions in Bhutan over the study period. The monthly climatology of maximum surface temperatures (Tmax), as depicted in Figure 14, reveals a range from -5°C to 30°C across Bhutan. Tmax remains relatively stable during December, January, and February, gradually increasing from March onwards and peaking around 30°C in southern Bhutan regions during the summer months. A gradual decrease in Tmax is observed during the retreat of the monsoon, reaching its lowest levels in December and January. A notable temperature gradient is evident from north to south due to the presence of high mountainous regions in the northern areas. Similarly, Tmin exhibit analogous characteristics, albeit with a reduced temperature range which is shown in the figure 15. Tmin varies between -10°C in northern Bhutan during winter months to 25°C in southern Bhutan during summer months. Tmin is higher during June to August, with minimum values around 5°C in northern regions and maximum values up to 20°C in the southern part of the country. During winter months, much of the country experiences Tmin below zero resulting in very colder condition nationwide.

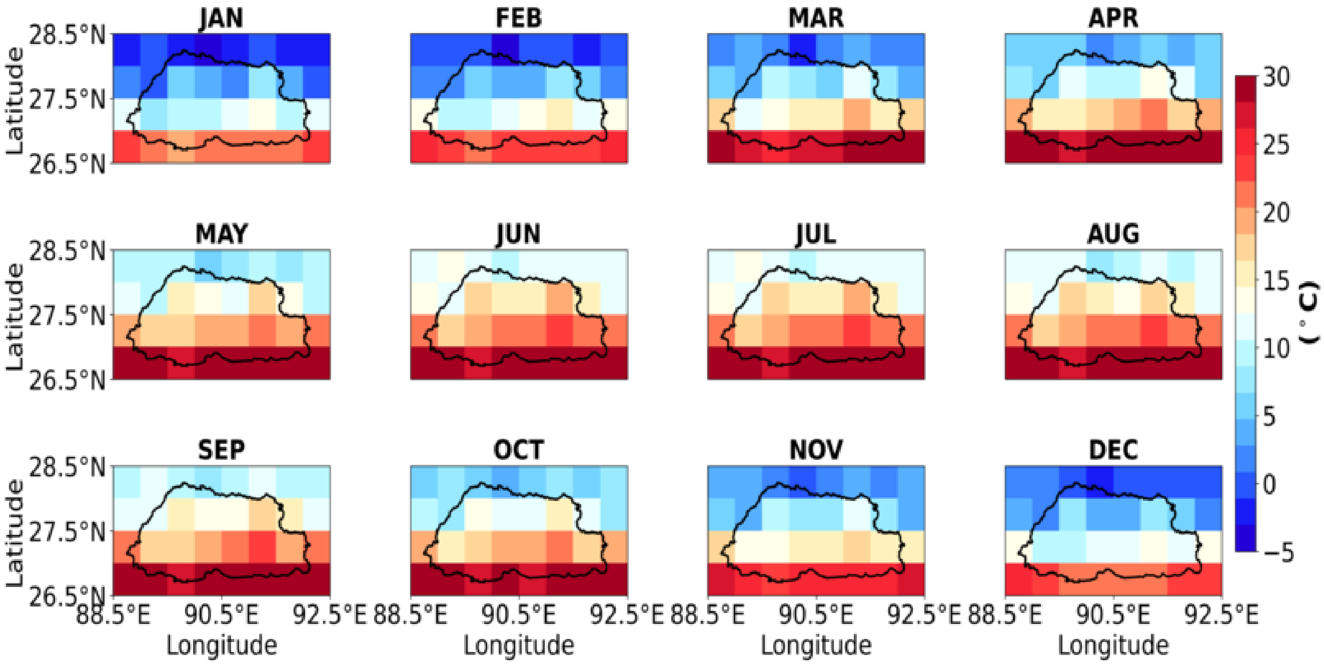

Figure 14 Monthly climatology of Tmax

Monthly trends of Tmax are depicted in Figure 16 revealing significant positive trends during June, August, September and November across all regions of Bhutan. The highest trend is observed during November reaching approximately 0.2°C per decade. Notably, Tmax is comparatively higher during August and September, while November exhibits lower climatological Tmax values, resulting in an increase in daytime temperatures during the study period. Conversely, April shows a significant decreasing trend in some southwestern regions of Bhutan with a slope of -0.15°C per decade. Positive slopes are observed in January, February, and March, albeit not meeting the significance threshold at the 95% level. These findings align with the area-averaged Tmax over Bhutan indicating the highest increasing rate (0.16°C per decade) during November as shown in Figure 17. In June and August, significant positive trends are evident with Tmax increasing at a higher rate in recent decades. While April exhibits a negative trend, it fails to achieve significance as only limited regions show significant positive trends. Overall Tmax varies from 4°C to 15°C across the months when considering area-averaged Tmax over the entire country.

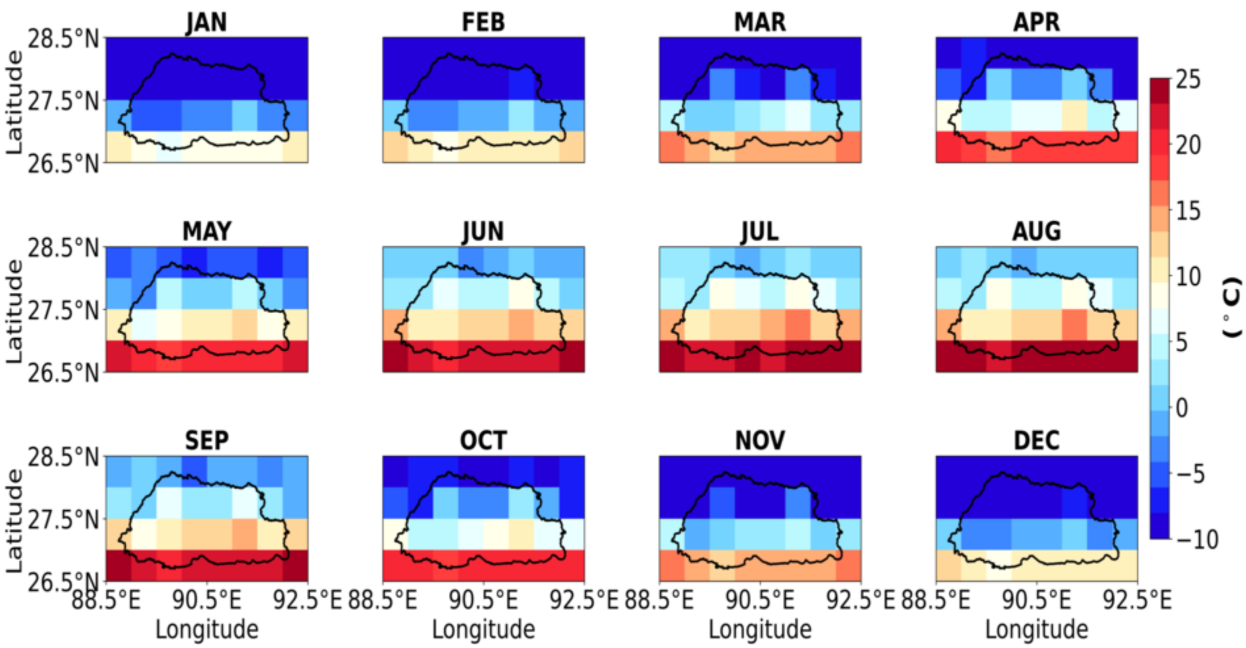

Figure 15 Monthly climatology of Tmin

Figure 18 presents monthly trends in minimum surface temperatures (Tmin) across Bhutan, revealing significant positive trends for all months. The most pronounced increases occur during January, February, and March, ranging from 0.2°C to 0.3°C per decade, coinciding with periods of relatively lower climatological Tmin. Conversely, the rates are lowest in April, May, August, and September, averaging approximately 0.1°C per decade. A discernible gradient is observed particularly over the north western region of the country.

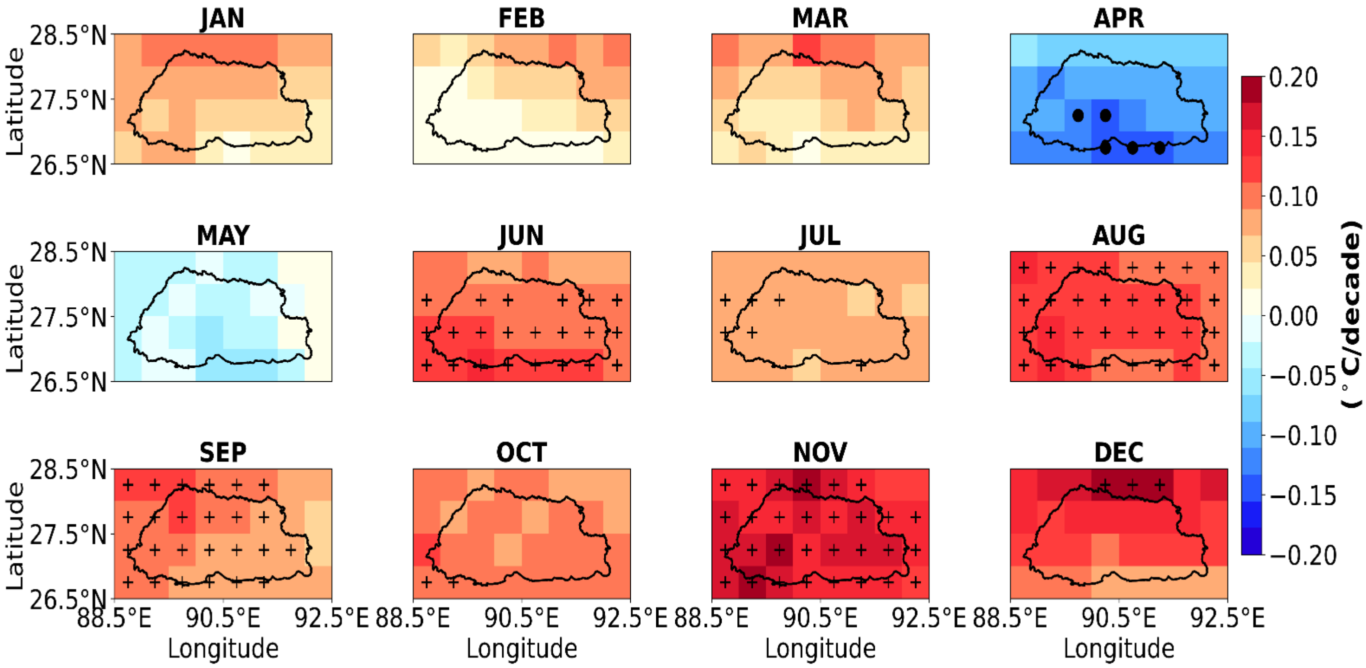

Figure 16 Monthly slopes and trends of Tmax . Significant trends are highlighted with plus sign and circles at 95% confidence level using the MK test

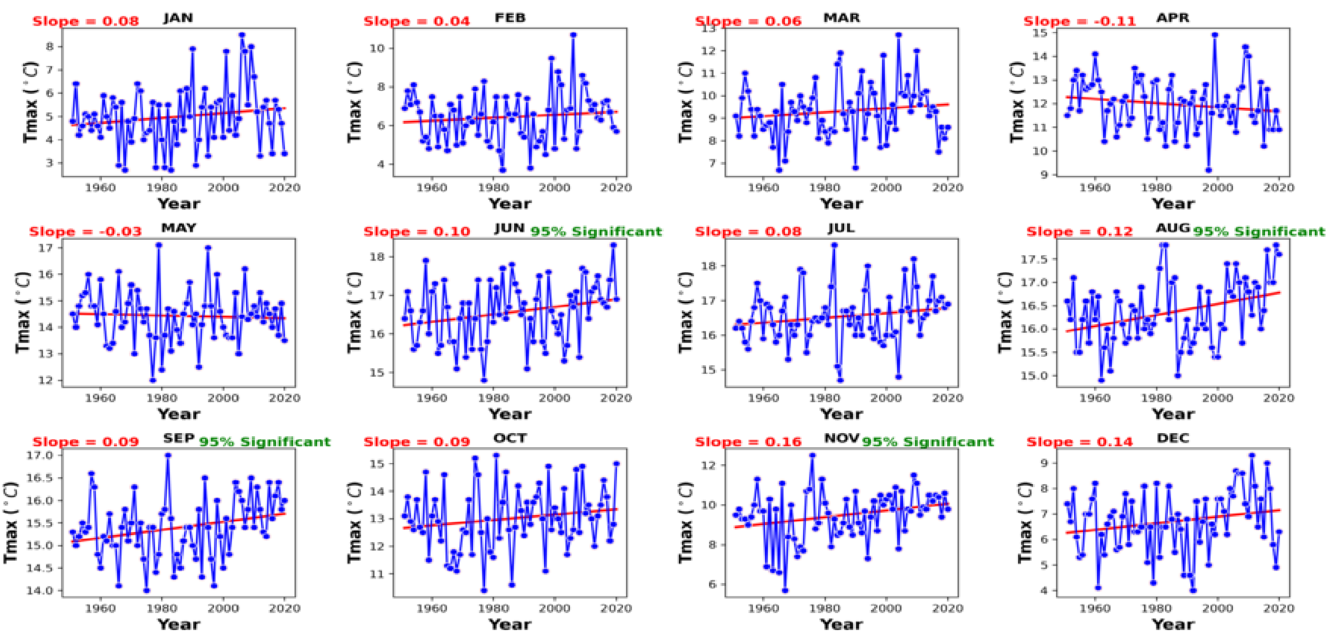

Figure 17 Timeseries (blue) and trend line (red) of monthly Tmax. Significant trends are highlighted at 95% confidence level using the MK test.

Upon averaging Tmin across Bhutan, January exhibits the most substantial increasing rate at 0.24°C per decade as depicted in Figure 19. In contrast, September records the lowest rate, corresponding to the duration of the southwest monsoon. The temperature range spans from 3°C to 5°C for each month, with January demonstrating the least variation and June, July, and August displaying the greatest. These findings elucidate the intricate the characteristics of Tmin trends in Bhutan, emphasizing the impact of temperature fluctuations on the country's ecosystems and societal well-being.

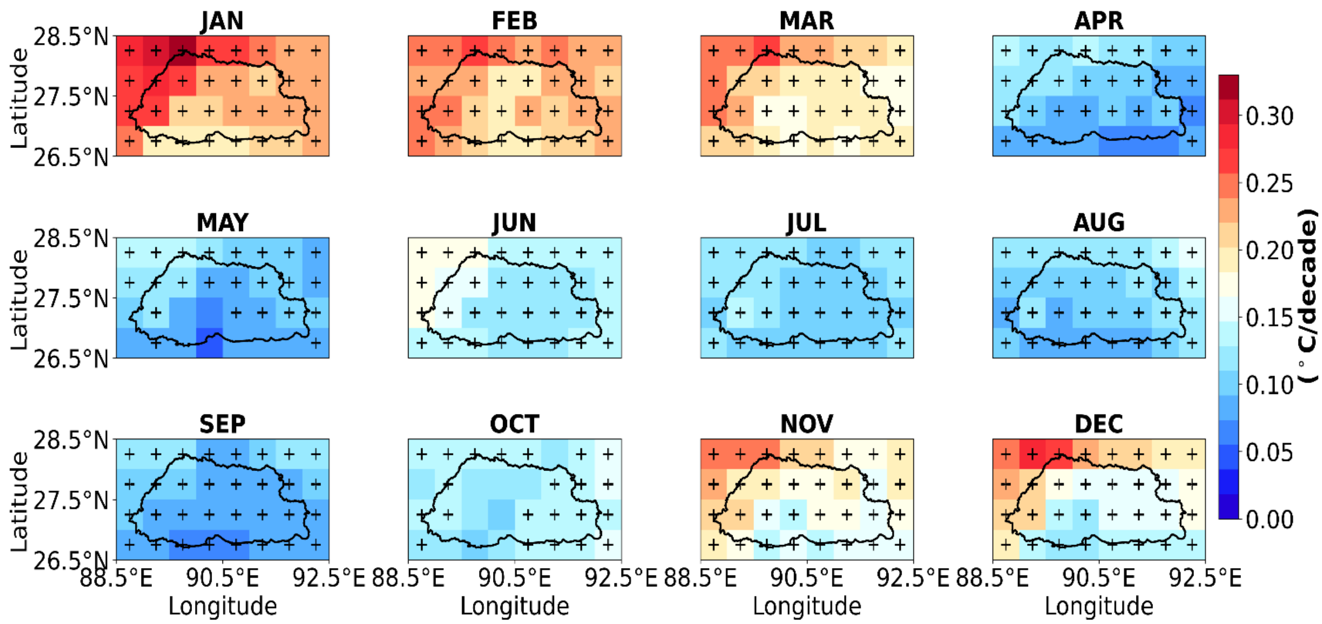

Figure 18 Same as figure 16 but for Tmin

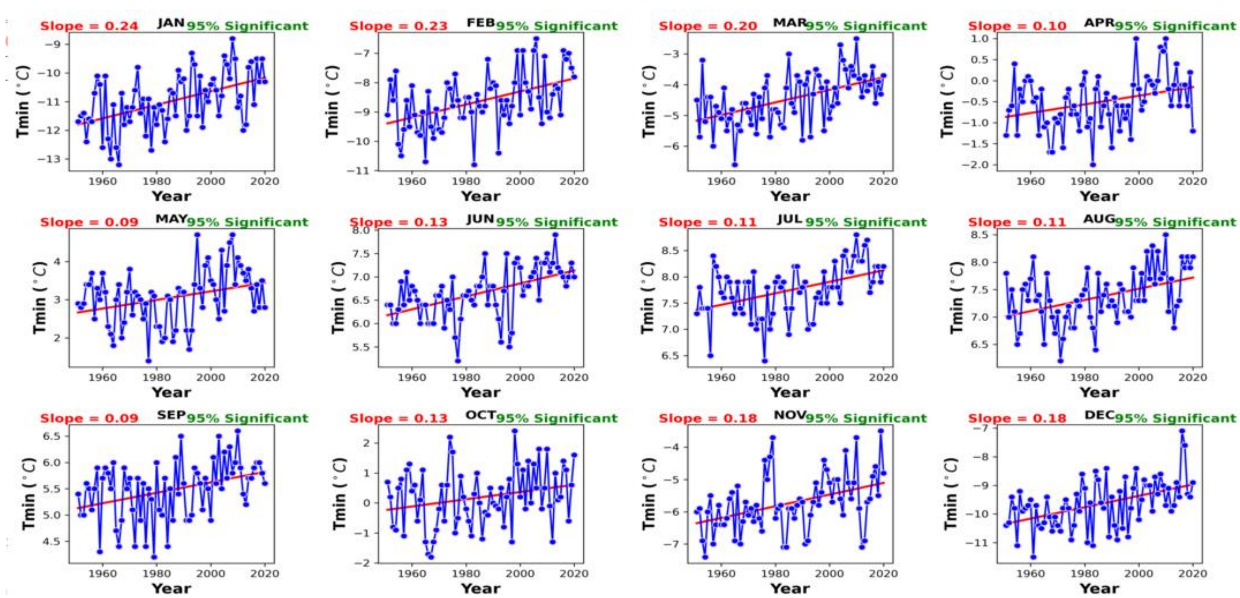

Figure 19 Same as figure 17 but for Tmin.

5. Summary

a) The aim of this report is to describe the climate information of basic atmospheric variable Precipitation, maximum temperature (Tmax) and minimum temperature (Tmin) over Bhutan using CRU 4.07 data from 1951 to 2020.

b) Precipitation patterns in Bhutan exhibit distinct seasonal and spatial variations, with the southwest monsoon season from June to September contributing significantly to total rainfall.

c) The majority of rainfall occurs during the monsoon season, particularly in July, while winter months experience minimal precipitation.

d) Both maximum and minimum surface temperatures show significant positive trends, with the most pronounced changes observed during the summer and pre-monsoon seasons.

e) Maximum temperatures demonstrate a consistent increasing trend, with the highest rates of change noted during the October-November period.

f) In contrast, minimum temperatures display variability across seasons, with the highest increasing rates observed during the winter months.

g) The complex interplay of seasonal climatic factors underscores the importance of understanding and monitoring temperature and precipitation trends.

h) There is no cooling trend observed in Tmax or Tmin in any of the month or season.

i) Monitoring temperature and precipitation trends is crucial for informing adaptive strategies and mitigating the impacts of climate change on Bhutan's ecosystems and communities.

6. Future scopes

a) Tropical regions are highly affected by the convectively coupled equatorial waves, BSISO (boreal summer intra-seasonal oscillations) and MJO (Madden-Julian oscillation), therefore impact of these waves over Bhutan will be studied.

b) Teleconnections of major oceanic phenomena like ENSO (ElNino and southern oscillation) and IOD (Indian Ocean dipole) over this region.

c) Also the studies using other data sets IMDAA (Indian monsoon data assimilation and analysis), NGFS (NCMRWF global forecast system) and IMERG (Integrated multi satellite retrievals for global precipitation measurement).

7. Acknowledgements

This report constitutes a pivotal component of an exhaustive investigation into the meteorological and climatic conditions of the BIMSTEC nations especially over Bhutan. The research undertaken in this study leveraged the computational prowess of the MIHIR supercomputers at the NCMRWF. We extend profound gratitude to our colleagues at NCMRWF for their indispensable assistance. Moreover, we sincerely thank the Head of NCMRWF for their consistent encouragement and unwavering support. Additionally, we express our gratitude to the anonymous reviewer whose valuable insights significantly enriched the refinement of this report.

8. Authors contributions

The study was collaboratively designed by all authors, who collectively contributed to refining the manuscript. Dr. Bibhuti Sharan Keshav conducted the technical work outlined in the study and generated the initial draft of the report. Dr. Mohan S. Thota and Dr. Raghavendra Ashrit provided guidance in preparing the final version of the report.

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10. Appendix

10a. Mean (μ):

The mean of a dataset is calculated by summing all the values and dividing by the total number of observations. The formula is:

$$\mu = \frac{\sum x_i}{n}$$

10b. Standard Deviation (σ):

The standard deviation measures the dispersion or spread of values in a dataset around the mean. It is calculated by taking the square root of the variance. The formula is:

$$\sigma = \frac{\sum (x_i - \mu)^2}{n}$$

10c. Coefficient of Variation (CoV):

The coefficient of variation is a dimensionless measure of relative variability, expressed as a percentage. It is calculated by dividing the standard deviation by the mean and multiplying by 100. The formula is:

$$CoV = \frac{\sigma}{\mu} \times 100$$

10d. Mann-Kendall Test:

The Mann-Kendall test is a non-parametric statistical test used to detect trends in time-series data. It assesses whether there is a monotonic upward or downward trend over time. The formula for the Mann-Kendall test statistic, S is:

$$S = \sum \sum sgn(xj - xi)$$

where, sgn(x) is the signum function.

The variance of S is given by,

$$Var\ (S) = \frac{(n(n-1)(2n+1) - \sum tp(tp-1)(2tp+1)}{18}$$

Where, tp is the number of tied groups of size p and g is the number of tied groups.

Finally, the test statistic Z is computed as:

$$Z = \frac{S}{\sqrt{Var(S)}}$$

The significance of the trend is assessed using the standard normal distribution.