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RESEARCH REPORT

Weather and Climate of Bangladesh

Vivekananda Hazra, Raghavendra Ashrit, and Mohan S. Thota

March 2024

National Centre for Medium Range Weather Forecasting
Ministry of Earth Sciences, Government of India
A-50, Sector-62, NOIDA-201309, INDIA

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10	Abstract	Bangladesh has a vibrant culture, diverse landscapes, and resilient people. Bangladesh's climate is diverse and dynamic due to its topography and proximity to the Bay of Bengal. This report uses Climatic Research Unit (CRU) datasets to analyze Bangladesh's rainfall and temperature pattern for seven decades (1951 – 2020). Studying the rainfall trends with a 95% confidence interval, it is observed that January rainfall decreases by 2 mm per decade. June is the most statistically significant negative month in the Eastern region of Bangladesh. Chittagong's October precipitation is decreasing by 0 - 6 mm per decade, which is also statistically significant. The seasonal rainfall trend reveals that pre-monsoon rainfall is increasing across Bangladesh, with central Bangladesh and Rangpur experiencing a maximum increase of 11 mm per decade. The monsoon season generally has a negative trend across the country. Post-monsoon rainfall is lower in the central and western regions. The Rangpur has the country's highest annual near-surface maximum temperature warming trend, at 0.04^0 C per decade. April has the highest cooling trend from 1951 to 2020 in the central to northern regions, with temperatures dropping by more than 0.15^0 C per decade. Area-averaged data show that the monsoon and post-monsoon show warming trends, while the winter and pre-monsoon show cooling trends. The central region experiences the highest monsoon season temperature decline, at 0.15^0 C per decade. Northern Chittagong has the highest monsoon season warming rate, at more than 0.05^0 C per decade. After the monsoon season, the country warms the most, by more than 0.1^0 Celsius per decade. The minimum temperature shows a statistically significant nationwide increasing trend. The northern region, particularly Rangpur, warms the most, exceeding 0.12^0 C per decade. The seasonal minimum temperature cycle indicates that all seasons are warming, where the increase in minimum temperature in winter is most statistically significant.
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List of abbreviations

ASCII	American Standard Code for Information Interchange
BBC	British Broadcasting Corporation
BOB	Bay of Bengal
C	Celsius
CF	Climate and forecast
CIA	Central Intelligence Agency
CRU	Climatic Research Unit
DJF	December January February
IMDAA	Indian Monsoon Data Assimilation and Analysis
JJA	June July August
MAM	March April May
MSD	Meteorological sub-division
NCMRWF	National Centre for Medium Range Weather Forecasting
NETCDF	Network Common Data Format
SD	Standard deviation
SON	September October November
SPEI	Standardized precipitation evaporation index
$\mathbf{T_{max}}$	Near-surface maximum temperature
$\mathbf{T_{min}}$	Near-surface minimum temperature
UKMO	United Kingdom Met Office

List of Figures

Table of Contents

सारांश

बांग्लादेश की जीवंत संस्कृति, विविध परिदृश्य, और दृढ़ लोग। बांग्लादेश की जलवायु उसके भूगोल और बंगाल की खाड़ी के निकटता के कारण विविध और गतिशील है। यह रिपोर्ट Climatic Research Unit (CRU) डेटासेट का उपयोग करके बांग्लादेश की बारिश और तापमान पैटर्न का सात दशकों (1951 - 2020) का विश्लेषण करती है। बारिश के निर्देशों का अध्ययन करते हुए, 95% के विश्वास के संवेदनशीलता के साथ, यह देखा गया है कि जनवरी में वर्षापात प्रति दशक 2 मिमी कम हो रहा है। जून पूर्व में सबसे वैज्ञानिक रूप से महत्वपूर्ण नकारात्मक महीना है। चित्तगांग का अक्टूबर का वर्षापात हर दशक में 0-6 मिमी कम हो रहा है, जो कि भींगने योग्य है। मौसमी वर्षा रुझान दिखाता है कि पूर्व-मानसून की वर्षा बांग्लादेश के विभिन्न हिस्सों में बढ़ रही है, मध्य बांग्लादेश और रंगपुर में अधिकतम वृद्धि हो रही है, प्रति दशक 11 मिमी। मानसून सीजन सामान्यतः देश भर में एक नकारात्मक रुझान है। पोस्ट-मानसून वर्षा मध्य और पश्चिमी क्षेत्रों में कम है। रंगपुर में देश का सबसे अधिक वार्षिक निकट-सतह मानक तापमान तापमान रुझान, प्रति दशक 0.04 डिग्री सेल्सियस है। अप्रैल का सबसे बड़ा शीतल होने का प्रवृत्ति 1951 से 2020 तक मध्य से उत्तरी क्षेत्रों में, तापमान प्रति दशक 0.15 डिग्री सेल्सियस से अधिक घट रहा है। क्षेत्र-संदर्भित डेटा दिखाता है कि मानसून और पोस्ट-मानसून में गर्म हो रहे हैं, जबकि सर्दी और पूर्व-मानसून में ठंडे प्रवृत्तियां दिखाई जा रही हैं। मध्य इलाका सबसे अधिक मानसून सीजन तापमान गिरावट का अनुभव करता है, प्रति दशक 0.15 डिग्री सेल्सियस। उत्तरी चित्तगांग में सबसे अधिक मानसून सीजन तापमान वृद्धि दर, प्रति दशक 0.05 डिग्री सेल्सियस से अधिक है। मानसून सीजन के बाद, देश सबसे अधिक गरम होता है, प्रति दशक 0.1 डिग्री सेल्सियस से अधिक।

Abstract

Bangladesh has a vibrant culture, diverse landscapes, and resilient people. Bangladesh's climate is diverse and dynamic due to its topography and proximity to the Bay of Bengal. This report uses Climatic Research Unit (CRU) datasets to analyze Bangladesh's rainfall and temperature pattern for seven decades (1951 – 2020). Studying the rainfall trends with a 95% confidence interval, it is observed that January rainfall decreases by 2 mm per decade. June is the most statistically significant negative month in the East. Chittagong's October precipitation is decreasing by 0-6 mm per decade, which is also statistically significant. The seasonal rainfall trend reveals that pre-monsoon rainfall is increasing across Bangladesh, with central Bangladesh and Rangpur experiencing a maximum increase of 11 mm per decade. The monsoon season is generally having a negative trend across the country. Post-monsoon rainfall is lower in the central and western regions.

The Rangpur has the country's highest annual near-surface maximum temperature warming trend, at 0.04^0 C per decade. April has the largest cooling trend from 1951 to 2020 in the central to northern regions, with temperatures dropping by more than 0.15^0 C per decade. Area-averaged data show that the monsoon and post-monsoon are showing warming trends, while the winter and pre-monsoon are showing cooling trends. The central region experiences the highest monsoon season temperature decline, at 0.15^0 C per decade. Northern Chittagong has the highest monsoon season warming rate, at more than 0.05^0 C per decade. After the monsoon season, the country warms the most, by more than 0.1^0 C per decade. The minimum temperature shows a statistically significant nationwide increasing trend. The northern region, particularly Rangpur, warms the most, exceeding 0.12^0 C per decade. The seasonal minimum temperature cycle indicates that all seasons are warming, where the increase in minimum temperature in winter is most statistically significant.

1 Introduction

Bangladesh, located in South Asia (nestled between India and Myanmar), is a country characterized by its rich cultural heritage, vibrant landscapes, and resilient population. With a history dating back to ancient times, the region has witnessed the rise and fall of various empires, contributing to its diverse cultural mosaic. The region is dominated by the Ganges Delta, offering fertile plains and a network of rivers that sustain a predominantly agrarian economy. Dhaka, the capital, serves as the political and economic heart of the nation, while other cities like Chittagong and Khulna contribute to its industrial and maritime sectors. Despite facing challenges such as periodic floods and cyclones, Bangladesh has made significant strides in economic development and social progress. The people, known for their warmth and hospitality, celebrate a rich tapestry of festivals, with Bengali culture deeply rooted in literature, music, and art. As the country continues to navigate the complexities of a rapidly changing world, Bangladesh stands as a testament to the strength of its people and their enduring spirit. Bangladesh boasts a diverse and dynamic climate influenced by its geographical location, topography, and proximity to the Bay of Bengal (BoB). The country experiences a tropical monsoon climate with distinct wet and dry seasons, making it susceptible to various weather extremes.

The monsoon season, typically from June to October, plays a pivotal role in Bangladesh's climate. During this period, the country receives a substantial amount of rainfall, with the south-western monsoon winds bringing moisture-laden air from the BoB. This intense rainfall often leads to flooding, affecting both urban and rural areas. The extensive river network, including the Ganges and Brahmaputra, contributes to the vulnerability of Bangladesh to riverine flooding. The monsoon rains, coupled with melting snow in the Himalayas, result in swollen rivers that overflow, inundating vast areas and causing significant damage to crops, infrastructure, and livelihoods. Historical records of floods in Bangladesh indicate a significant frequency of floods that exceeded the occurrence of flood events between 1890 and 2007 (World Bank Group, 2022; World Bank, 2014). Analysis of the time-series data for these flood events reveals a lack of any consistent historical pattern. From 1892 to 1922, the area encountered frequent occurrences of flooding, which were then followed by a subsequent 50-year period marked by a lack of floods that exceeded the normal frequency of flooding threshold. Since 1950, there has been a significant rise in the occurrence of flood events that exceed the normal frequency of flooding threshold (Hofer & Messerli, 2008). Bangladesh is also highly vulnerable to tropical cyclones that originate in the BoB. These cyclones can bring torrential rains, strong winds, and storm surges, leading to devastating coastal flooding. The low-lying coastal regions are particularly susceptible, and efforts to mitigate the impact of cyclones involve early warning systems, cyclone shelters, and coastal embankments. Apart from the wet season challenges, Bangladesh also faces heatwaves, especially during the dry season. Rising temperatures, exacerbated by climate change, can have severe implications for public health, agriculture, and water resources. Bangladesh consistently has some of Asia's highest maximum temperatures, with an average monthly maximum of around 30°C and an average of 33°C in April. Currently, the likelihood of a heatwave, defined as a three-day period in which the daily temperature exceeds the long-term 95th percentile of daily mean temperature, is between 2% and 3% (World Bank Group, 2022; Nissan et al., 2017). Despite this, the median number of days per year with a Heat Index above 35°C is unusually high, at around 70. The frequent occurrence of elevated Heat Index values, which are a combination of temperature and humidity, highlights the widespread heat stress experienced by humans, plants, and animals in Bangladesh (https://climateknowledgeportal.worldbank.org/).

Bangladesh also experiences two types of droughts: meteorological, which are typically associated with precipitation deficits, and hydrological, which are frequently associated with shortages in surface and subsurface water flow from the region's larger river basins. Agricultural droughts may result from these events, but they are also influenced by factors such as crop and land management choices. Currently, the country faces a 4% annual probability of severe meteorological drought, defined as a Standardized Precipitation Evaporation Index (SPEI) of less than 2 over a daily interval (Rahman & Lateh, 2016). Less severe droughts are more frequent. Challenges include the health of groundwater resources, many of which have been salinized, as well as inadequate management practices. According to Amarnath et al. (2017), approximately 1% of Bangladesh's population was exposed to drought between 2001 and 2013, as defined by a Normalized Difference Drought Index greater than 0.6.

As a member country of the Bay of Bengal Initiative for Multi-Sectoral Technical and Economic Cooperation (BIMSTEC), Bangladesh plays a crucial role in the collaborative efforts towards regional development. The BIMSTEC Centre for Weather and Climate (BCWC) has been instrumental in exploring and understanding the climatic conditions within the member countries, with a specific focus on Bangladesh. The BCWC has the mandate to study and analyze the climatic conditions in the BIMSTEC countries. This involves monitoring and understanding meteorological patterns, extreme weather events, and their potential impact on various sectors such as agriculture, water resources, and disaster management. Creating a research report on the climatic features of Bangladesh serves multiple purposes. Firstly, it contributes valuable data to the collective knowledge base of the BIMSTEC community, fostering a deeper understanding of regional climate dynamics. Secondly, it provides insights into the challenges and opportunities arising from the climatic conditions in Bangladesh, offering a basis for informed decision-making and policy formulation within the country and the broader BIMSTEC region.

This document delves into the intricate details of Bangladesh's weather and climate, focusing on rainfall, maximum temperature, and minimum temperature. The investigation into the climatic features of the previously mentioned parameters of Bangladesh under the purview of the BCWC is a critical initiative. It aligns with the collaborative spirit of BIMSTEC, aiming to enhance regional resilience, sustainable development, and effective climate adaptation strategies.

2 Data and methodology

2.1 Data

The University of East Anglia's Climatic Research Unit (CRU) has produced time-series datasets that document monthly climate fluctuations over the last century (Jones and Harris, 2008). The datasets are generated using high-resolution grids ($0.5^0 \times 0.5^0$) and incorporate data from a collection of monthly average data obtained from more than 4000 weather stations worldwide.

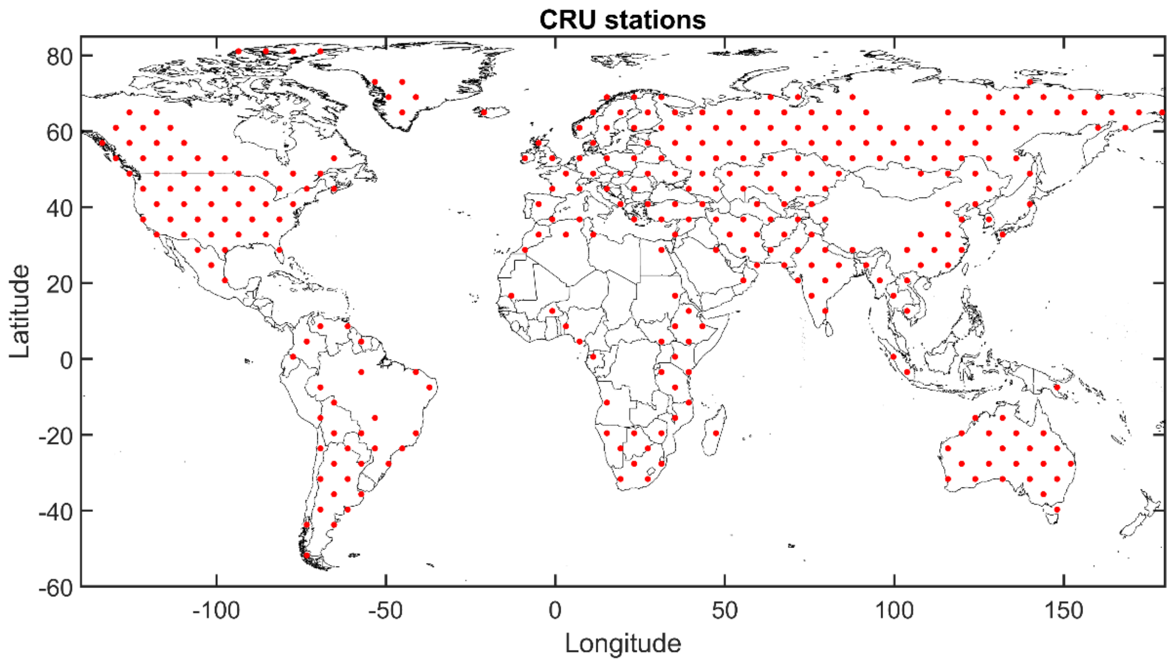

Figure 1*. CRU data stations (in red dots) for one random time stamp.*

They enable the examination of climate fluctuations and encompass a wide range of variables, such as cloud cover, diurnal temperature range, frequency of frost days, precipitation, daily mean temperature, monthly average daily maximum temperature, vapour pressure, Potential Evapotranspiration, and frequency of wet days. The output files of CRU data, formatted in

NetCDF, adhere to the CF-1.4 standards, ensuring compatibility with various types of NetCDF utilities. Except for PET, every file consists of two data variables: a named variable (e.g., 'tmp') and a station count variable ('stn'), which has the same dimensions. The ASCII text-formatted output files, along with the 'stn' data files, enable automated reading (Harris et al., 2020). The 'stn' data is crucial for measuring uncertainty, particularly by disregarding cells with a count of 0, as these are probably default climatology values. One 'stn' data for a random timestamp is shown in Figure 1 where it shows the number of stations contributing to the rainfall data for that particular time stamp. Nevertheless, it is crucial to acknowledge that specific uncertainties, especially those associated with the observational data, cannot be accurately measured. This challenge is made more difficult by the variability in representativeness across different variables and the emphasis on monthly means or totals, rather than daily or sub-daily measurements. In this present report, 70 years (1951 - 2020) of CRU monthly data has been used to investigate the pattern of precipitation, maximum temperature and minimum temperature over Bangladesh.

2.2 Methodology

In this study, various statistical indices, including Sen's Slope, Mann-Kendall Trend Test, mean, standard deviation, and linear trend slope, were computed from CRU datasets for Bangladesh. The mathematical formulas for these indices are detailed in the Appendix section of this report. Notably, when results indicate domain-averaged values, it signifies that the data has been specifically extracted for the Bangladesh region. This extraction process involved the use of a high-resolution shapefile (taken from Stanford University Library), followed by area averaging to derive representative values for the designated region.

3 Geographic and Climatic Features

3.1 Location and Topography

Bangladesh is characterized by low-lying plains, river deltas, and a network of numerous rivers, including the Ganges and Brahmaputra. Its geographic location, positioned on the northeastern edge of the Indian Ocean, exposes the country to the BoB, influencing its climate patterns. It has vast alluvial plains nourished by the network of the Ganges, Brahmaputra, and Meghna rivers. Notable features include the Sundarbans, the world's largest mangrove forest, and the Chittagong Hill Tracts, which comprise low hills and plateaus. Bangladesh's extensive coastline along the BoB is susceptible to natural disasters such as cyclones. The dynamic interplay of rivers, floodplains, and diverse ecosystems shapes both the challenges and opportunities faced by the nation. The geo-political boundary is shown in Figure 1 (the shapefile is taken from Stanford University library archive, https://library.stanford.edu/s).

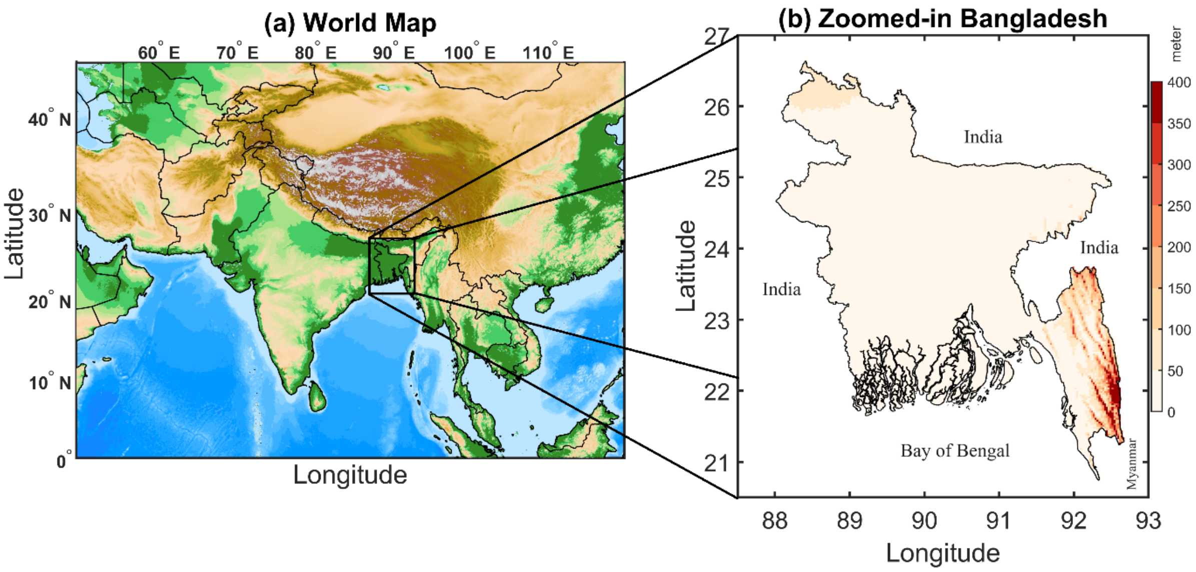

Figure 2. *Geographical map of Bangladesh. (a) location of Bangladesh along with the surrounding countries; (b) Zoomed in map of Bangladesh with Orography.*

3.2 Tropical Climate

The climate of Bangladesh is categorized as tropical monsoon, featuring distinct wet and dry seasons. The monsoon, driven by the seasonal reversal of winds, brings heavy rainfall during the wet season, while the dry season experiences comparatively lower precipitation. Bangladesh has a warm and humid climate that is affected by pre-monsoon, monsoon, and post-monsoon circulations. It often experiences heavy rainfall and tropical cyclones. According to the historical climate data (Climatic Research Unit, https://www.uea.ac.uk/groups-and-centres/climatic-research-unit) from the World Bank report (Figure 3), the average temperatures range from 15°C to 34°C throughout the year, however, with an experienced average temperature of 25.71°C (CCKP, 2021). The months with the highest temperatures align with the period of rainfall (April-September), whereas colder and less humid conditions distinguish the winter season (December-February) (https://climateknowledgeportal.worldbank.org/sites/default/files/country-profiles/15502-WB_Bangladesh%20Country%20Profile-WEB.pdf). The nation experiences a significant volume of precipitation, with an average annual amount of approximately 2,200 millimetres (mm). In this report, the entire year has been sub-divided into four seasons for simplicity, i.e., pre-monsoon (March-April-May), monsoon (June-July-August), post-monsoon (September-October-November) and winter (December-January-February).

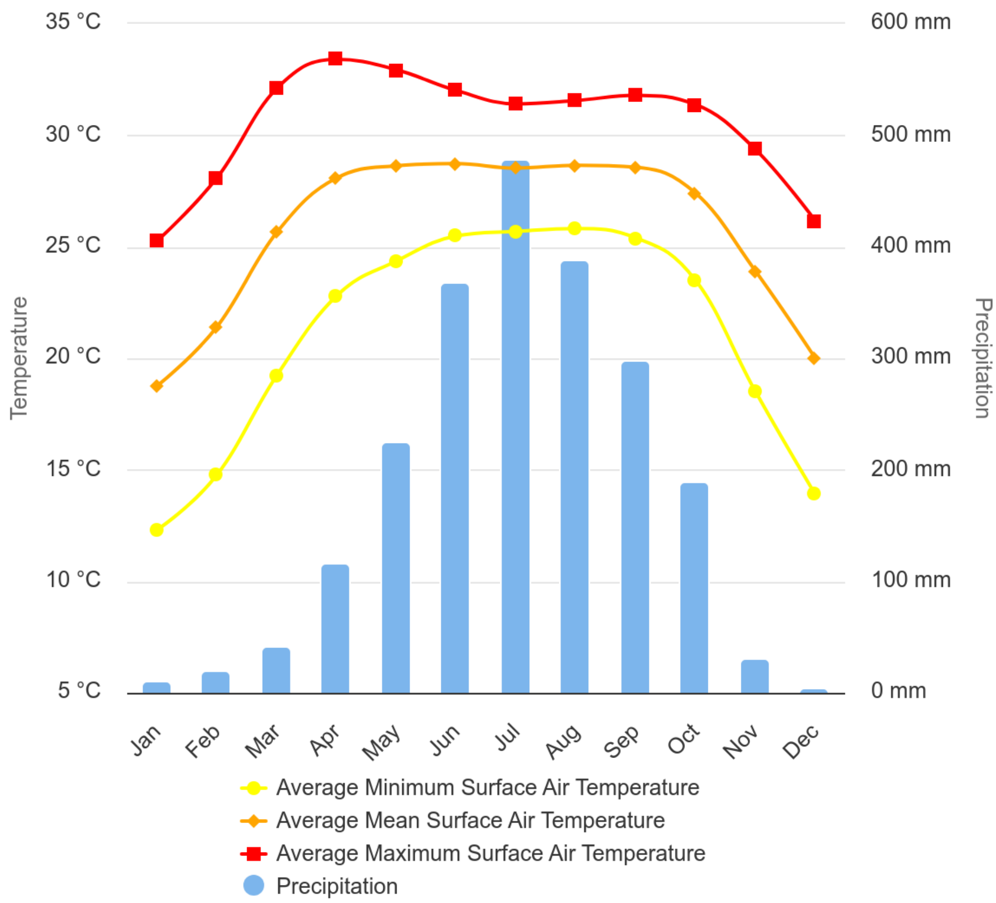

Figure 3*. Average Monthly Mean, Maximum, and Minimum Temperatures and Rainfall in Bangladesh for the period of 1991–2020. (Source: World Bank Group, 2022)*

The majority of regions experience a minimum of 1,500 mm of rainfall annually, with certain areas, particularly in the northeastern border regions, receiving as much as 5,000 mm per year (World Bank Group, 2022). The humidity remains consistently high throughout the year, with its highest levels occurring during the monsoon season from June to October. The Southwest monsoon, which originates from the Indian Ocean, induces precipitation by transporting warm, and moist air. Typically, a tropical cyclone of Tropical Storm strength (where the maximum sustained wind speed crosses 62 kilometres per hour) or greater hits Bangladesh approximately every two to three years, resulting in heavy rainfall, strong winds, and storm surges.

Bangladesh has been divided into seven meteorological sub-divisions (MSD), i.e., Dhaka, Chittagong, Sylhet, Barisal, Khulna, Rajshahi, and Rangpur (Ahmed et al., 2017). For better and improved understanding, all discussions will focus exclusively on these seven MSD categories (https://www.bangladesh.gov.bd/index.php?lang=en). These MSD-wise discussions facilitate focused analysis of geographical locations and their corresponding results, rather than the whole country.

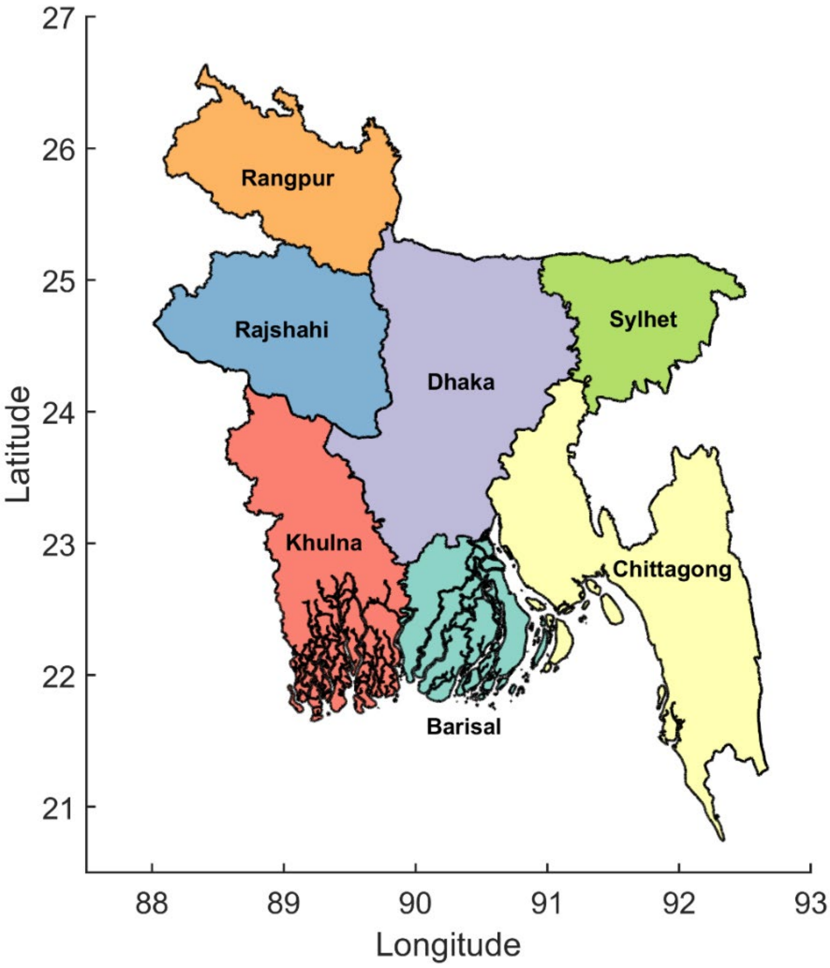

***Figure 4**. Seven meteorological sub-divisions (MSD) of Bangladesh*

4 Analysis based on CRU data

4.1 Rainfall

Recent years have witnessed shifts in rainfall patterns, with some areas experiencing more intense and prolonged rainfall, while others face reduced precipitation. This variability poses challenges for water resource management, agriculture, and urban planning. Bangladesh is highly vulnerable to the impacts of climate change, including rising sea levels, increased temperatures, and altered precipitation patterns. The melting glaciers in the Himalayas contribute to the rising sea levels, posing a long-term threat to the low-lying coastal areas. From the CRU data, the yearly mean and standard deviation (SD) have been shown in Figure 5 in the left and right panels, respectively. It has been observed that over the years from 1951 to 2020 when looking at the annual mean rainfall in Bangladesh, it's noticeable that the Sylhet MSD consistently experiences the highest amount of rainfall (~ 4500 mm per year) compared to other regions. So, on average, Sylhet MSD receives more rain throughout the year than other areas in Bangladesh.

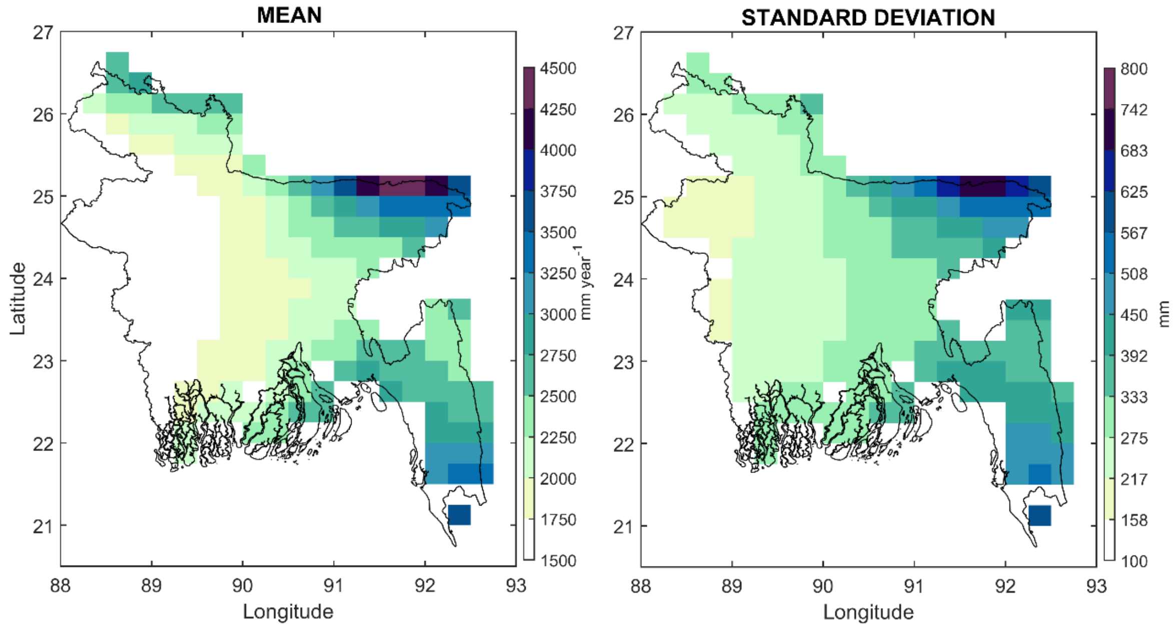

Figure 5. *Annual mean rainfall (left) and standard deviation (right) of Bangladesh.*

Following closely, the South Chittagong region emerges as the second-highest in terms of average rainfall. This pattern is further supported by the SD plot, indicating that not only does Sylhet experience consistently high rainfall, but also the South Chittagong region exhibits notable variability in precipitation. However, the annual rainfall trend reveals surprising findings, which have been shown in Figure 6, where the shaded region shows trend values and stipple points represent statistical significance with more than a 95% confidence interval.

The aforementioned regions have a statistically significant decreasing trend in rainfall, as supported by greater than 95% confidence intervals. Notably, Sylhet MSD has the most signified negative trend (> 11 mm per year), followed by the southern part of Chittagong MSD (9 – 10 mm per year). The only exception is Khulna MSD, which demonstrates a positive trend, although lacking statistical significance. Analyzing the monthly cycle plot (Figure 7) for Bangladesh's rainfall, the months from June to August stand out as the period with the highest precipitation, indicating that these months are the wettest throughout the year (~ 600 mm per month). Following closely are May, September, and April, suggesting significant rainfall during the pre-monsoon and post-monsoon seasons. On the other hand, December, January, and February exhibit the lowest rainfall spread, with values consistently below 50 mm per month. This pattern aligns with the typical monsoon climate, where the summer months experience the heaviest rains, while the winter months are relatively drier.

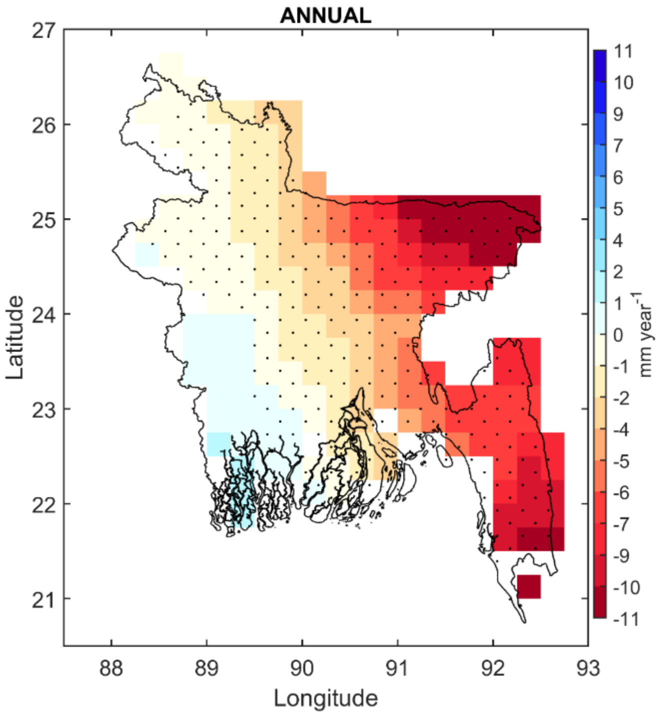

Figure 6. *Annual rainfall trend. Stipple region represents significance with > 95% confidence interval.*

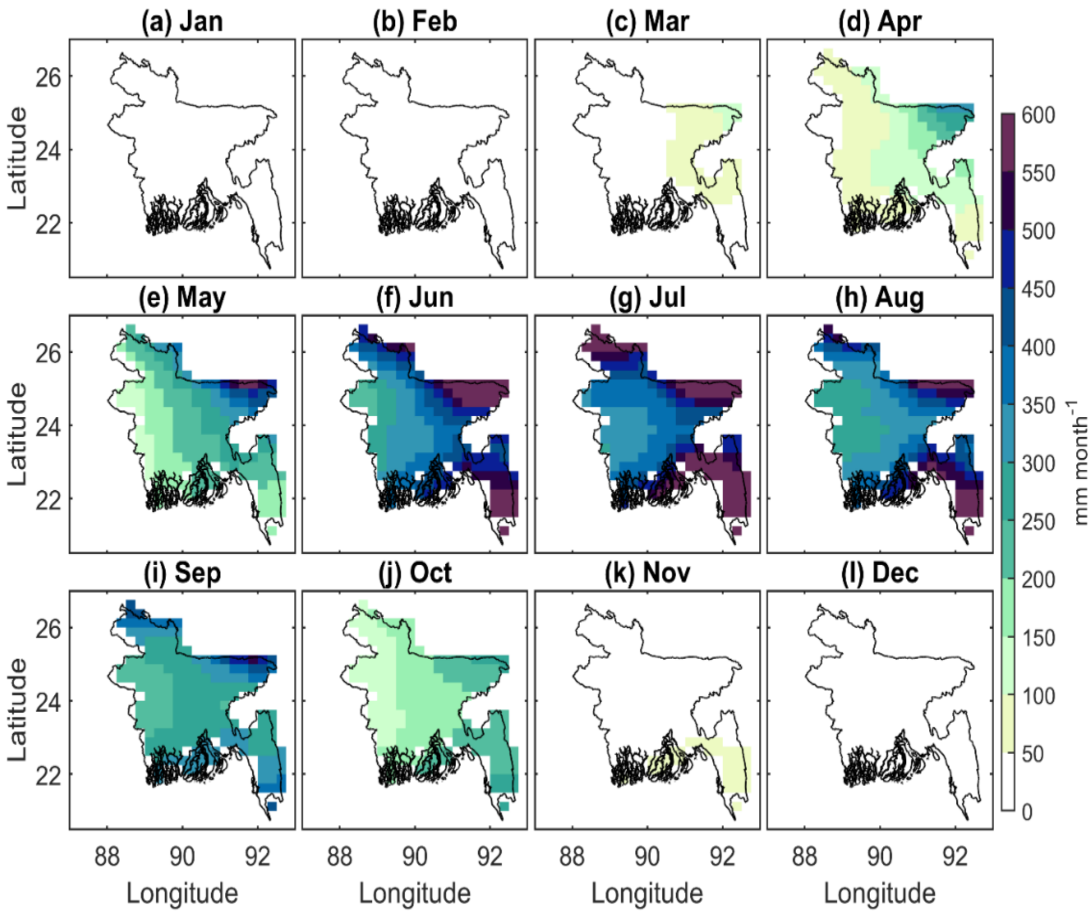

Figure 7. *Monthly cycle of rainfall patterns over Bangladesh. Units are in mm per month.*

The monthly rainfall data for Bangladesh reveals distinct trends across different regions, which is shown in Figure 8 (same as Figure 6, but for monthly). In January, a statistically significant negative trend of 2 mm per decade is observed with a 95% confidence interval. February exhibits a positive trend of 0 - 2 mm per decade, although it lacks statistical significance. March shows a statistically significant negative trend in Sylhet, Chittagong, and some parts of Dhaka. April displays a positive trend of 2 - 6 mm per decade, statistically significant in Rangpur, Rajshahi, and certain areas of Dhaka. May indicates a statistically significant negative trend of 18 mm per decade in Sylhet, Chittagong, and the eastern part of Dhaka. June registers the highest negative trend among all months, particularly pronounced in the eastern part of the country, all with statistical significance.

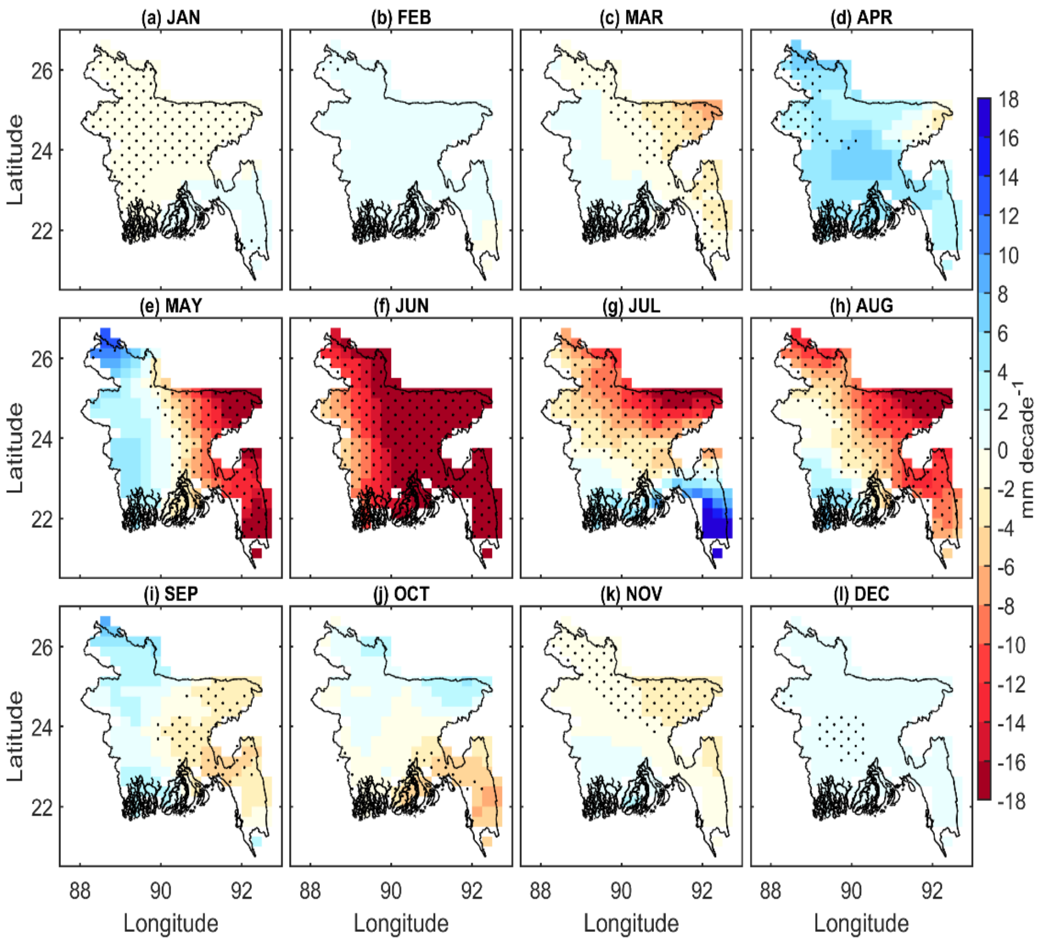

Figure 8*. Monthly trend of rainfall for Bangladesh (shaded) with significance with > 95% confidence interval (stipple).*

July and August reveal negative trends in the middle to northern regions, with the most statistically significant impact in Sylhet at 18 mm per decade. September shows a positive trend in the western part, lacking significance, while the eastern part exhibits a statistically significant negative trend of 0 – 4 mm per decade. October exhibits a negative trend in the Chittagong region, ranging from 0 to 6 mm per decade with statistical significance. November exhibits a statistically significant negative trend in the north and north-western parts, while the southern part shows a positive trend without statistical significance. December shows a positive trend of 0 - 2 mm per decade across the entire country, statistically significant only in some parts of Khulna, the southern part of Dhaka, and the northern part of the Barisal region.

Figure 9 represents the monthly domain-averaged line plot where the green (red) line represents a positive (negative) trend, which reflects a consistent and similar pattern. In January, March, May, June, July, August, and November, a negative trend is evident (Figure 9 a, c, e, f, g, h, k). The most pronounced slope occurs in June (Figure 9f), with a decline of 2.95 mm per year, followed by August (Figure 9h) at 0.77 mm per year. January exhibits the least negative trend with a slope of 0.04 mm per year (Figure 9a). Conversely, the remaining months indicate a positive trend, with April (Figure 9d) displaying the highest slope at 0.4 mm per year.

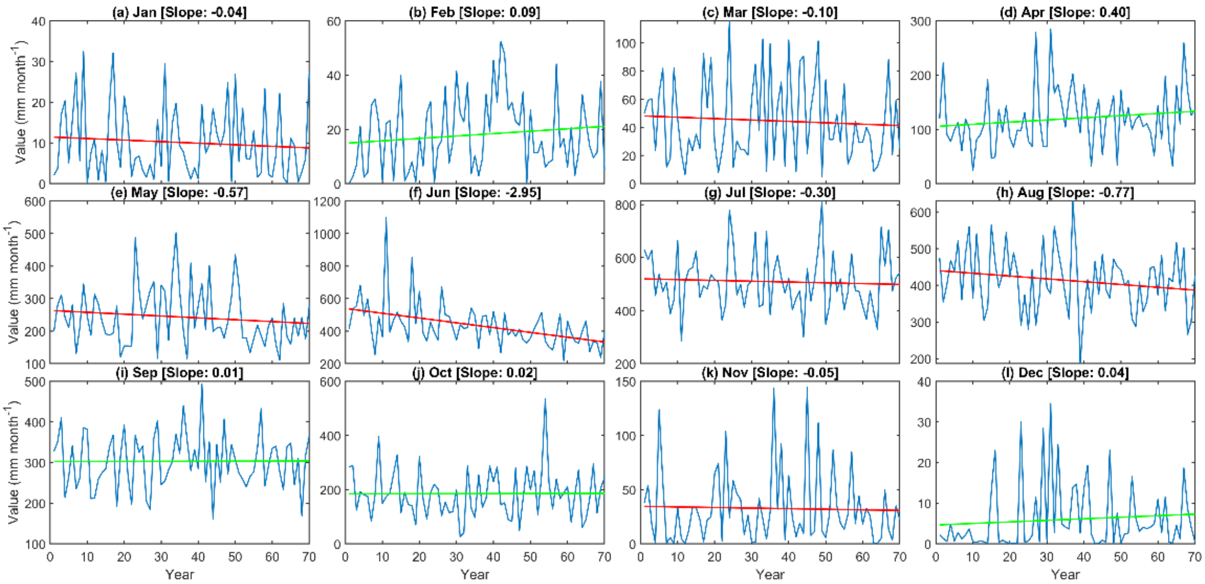

Figure 9. *Domain averaged time series plot with trend line. The green (red) line shows a positive (negative) slope.*

The seasonal rainfall patterns are depicted in Figure 10 through averaged rainfall plots of the corresponding seasonal months. During the pre-monsoon season (March-April-May), rainfall is observed over the central to western parts of the country, reaching its peak in the Sylhet region at up to 200 mm per month. The monsoon season (June-July-August) gets the highest rainfall nationwide, particularly in Sylhet and the southern part of the Chittagong region, with rainfall exceeding 600 mm per month. This pattern persists in the post-monsoon months (September-October-November), showcasing similar high-rainfall geographical locations. The winter season experiences the lowest rainfall across the entire country, with precipitation levels below 50 mm per month.

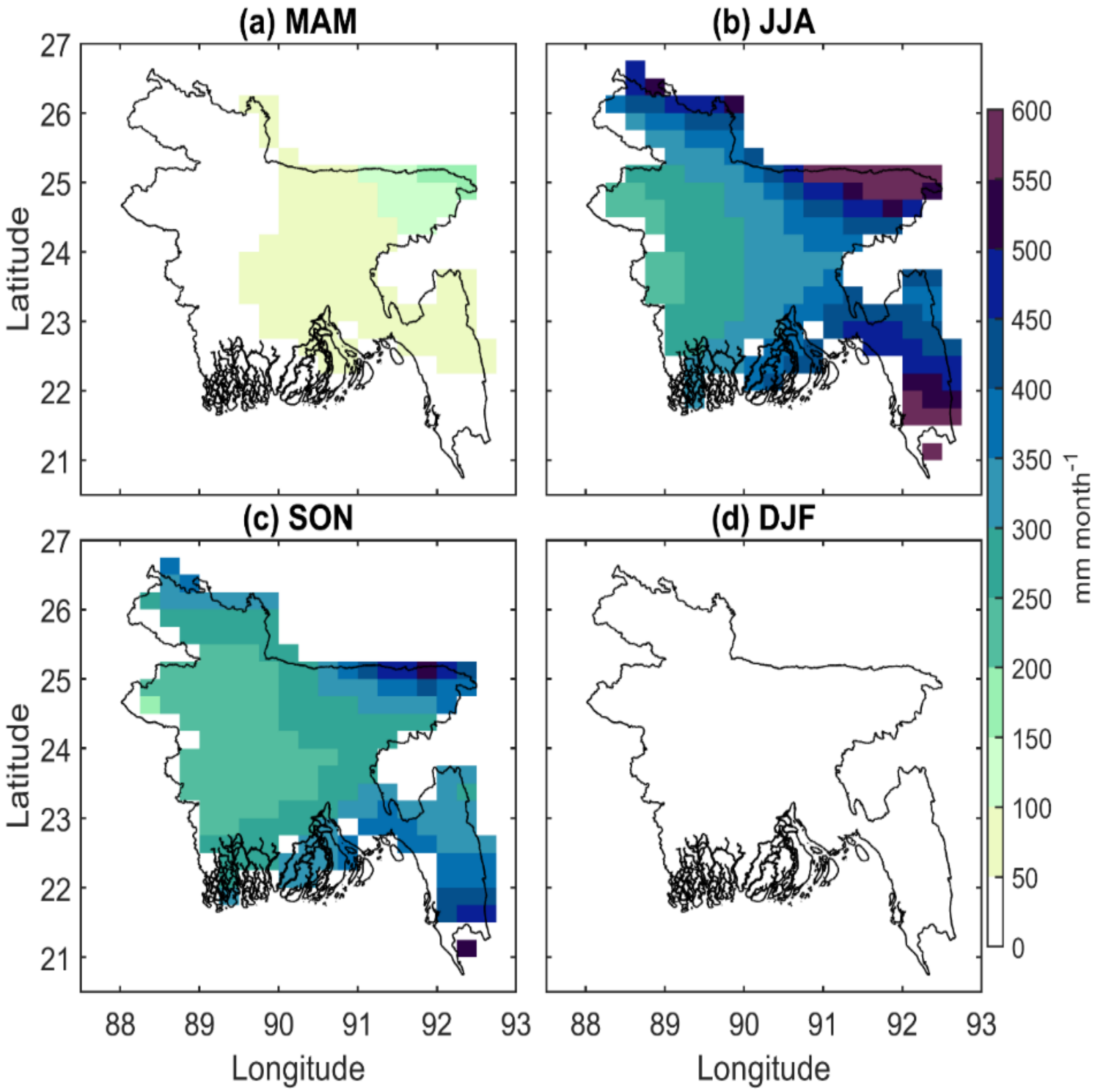

***Figure 10**. Seasonal rainfall pattern over Bangladesh.*

The trend analysis with a 95% confidence interval plot for the seasonal rainfall, as presented in Figure 11, reveals distinct patterns. During the pre-monsoon season, a positive trend is observed across the country, reaching its peak in central Bangladesh and the Rangpur region at 11 mm per decade. However, statistical significance is only established in Rangpur and the northern part of the Rajshahi region. Conversely, the Sylhet region displays a statistically significant negative trend of 11 mm per decade. In the monsoon season, a robust negative trend with statistical significance is observed throughout the country. The most substantial negative trend is noted in the western part of Dhaka, Sylhet, and the Chittagong MSD, with a decline of

50 mm per decade. The post-monsoon season exhibits a statistically significant negative trend in the central to western part of the country, with the lowest trend recorded in the Sylhet and Chittagong MSDs at 28 mm per decade.

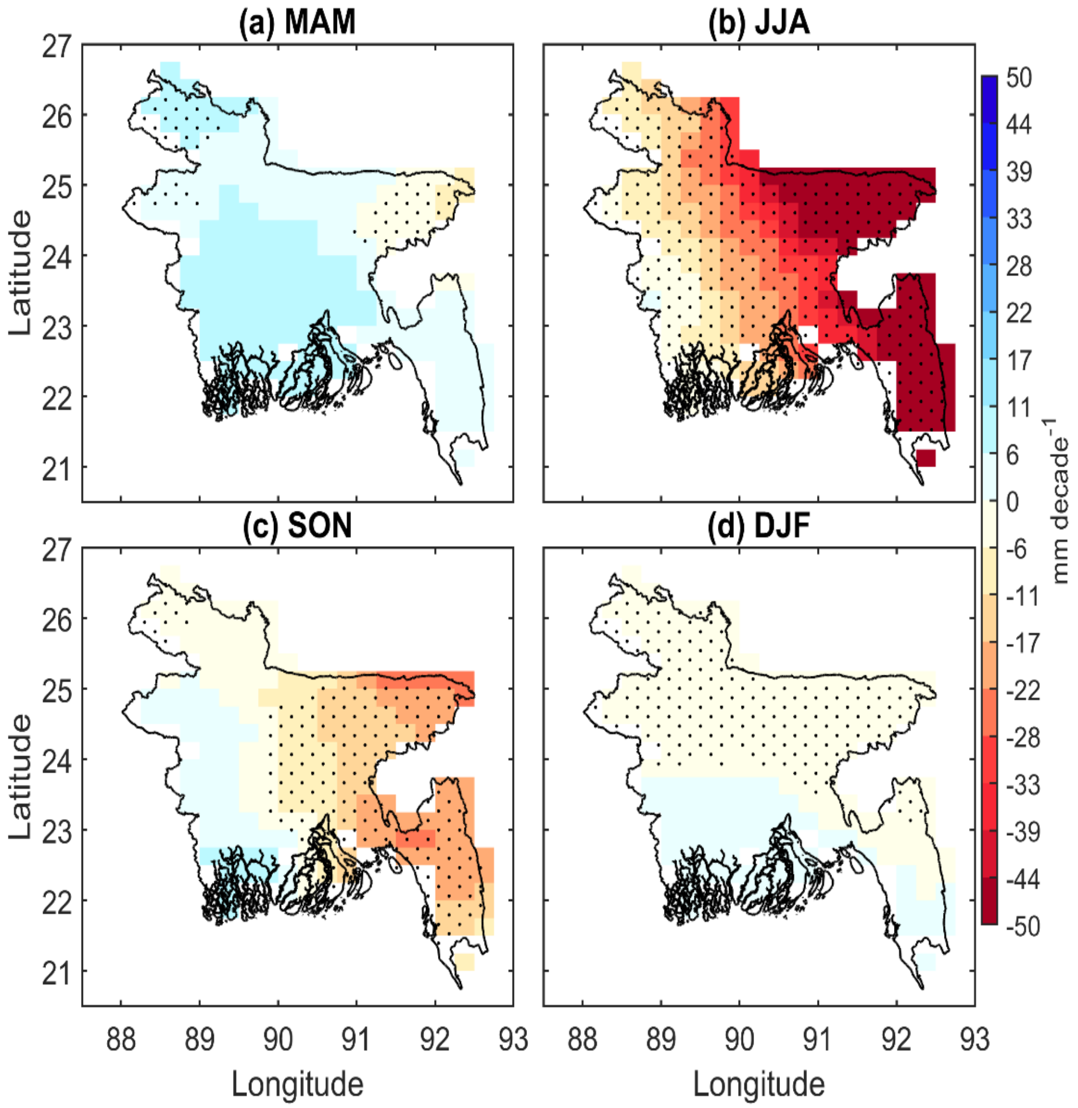

Figure 11. *Seasonal trend of rainfall for Bangladesh (shaded) with significance with > 95% confidence interval (stipple).*

4.2 Near Surface Maximum Temperature

Studying maximum temperature variations over a country yields valuable insights into climate dynamics and associated impacts. Analyzing seasonal patterns helps identify the onset and intensity of different seasons, while examination of extremely high temperatures reveals trends related to heatwaves, crucial for understanding potential impacts on ecosystems, agriculture, and human health. Long-term trend analysis provides information on whether the country is experiencing warming trends or shifts in temperature patterns. Assessing regional disparities in maximum temperatures (T_{max}) highlights differences that impact local ecosystems, water resources, and agriculture. Understanding the implications of temperature variations on agriculture is crucial for implementing sustainable farming practices. Additionally, monitoring the urban heat island effect in urban areas and considering broader climate change implications contribute to informed decision-making for climate adaptation and mitigation. T_{max} variations also influence water resources management, ecological dynamics, and health risks, making comprehensive analysis essential for addressing diverse challenges in various sectors.

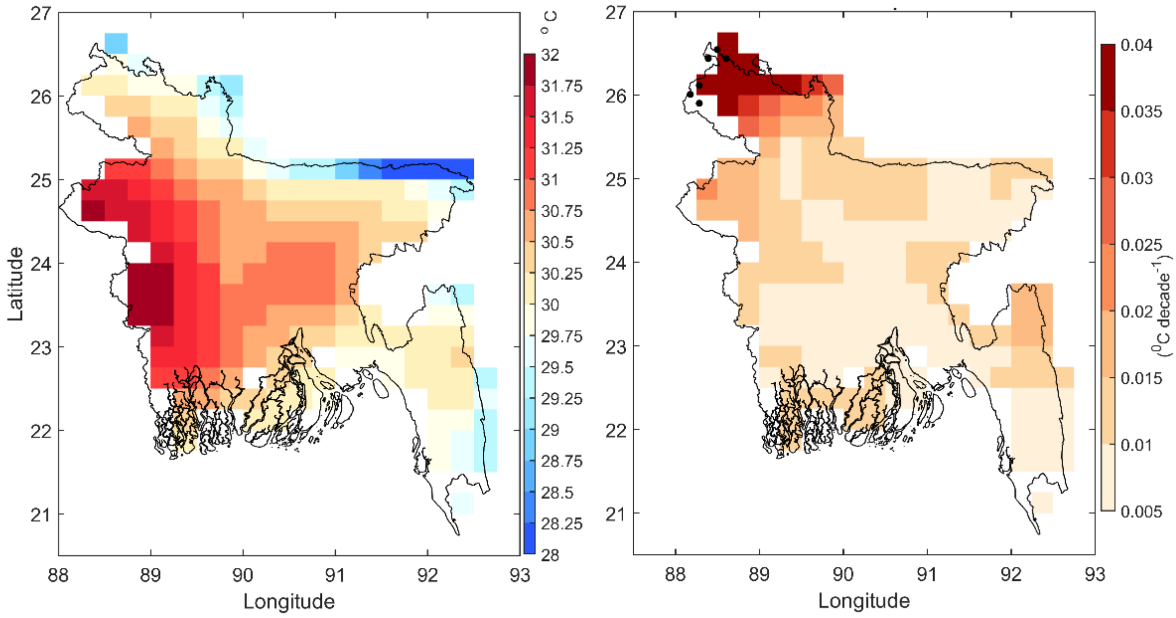

Figure 12. *Annual mean (left) and trend with 95% confidence interval (right) of T_{max} of Bangladesh.*

The mean and trend with a 95% confidence interval for T_{max} are shown in Figure 12 in the left and right panels, respectively. The examination of 70 years of CRU data on annual T_{max} indicates a consistent pattern wherein the western part of the country experiences higher temperatures compared to the eastern side. Khulna and certain areas of Rajshahi MSD consistently record the highest T_{max}, exceeding 32^0 C, while the Sylhet MSD consistently exhibits the lowest T_{max}, hovering around 28^0 Cs. In terms of the yearly trend with a 95% significance interval, the overall country displays a positive trend, with statistical significance observed exclusively in specific areas of the Rangpur MSD. Remarkably, the Rangpur MSD stands out with the highest positive trend, measuring at 0.04^0 C per decade.

Examining the monthly cycle of the T_{max} (Figure 13) plot reveals that the extreme west of the country consistently exhibits a higher temperature gradient compared to other regions. April consistently records the highest temperatures, while December consistently sees the lowest temperatures. Notably, the T_{max} spread is most extensive in August.

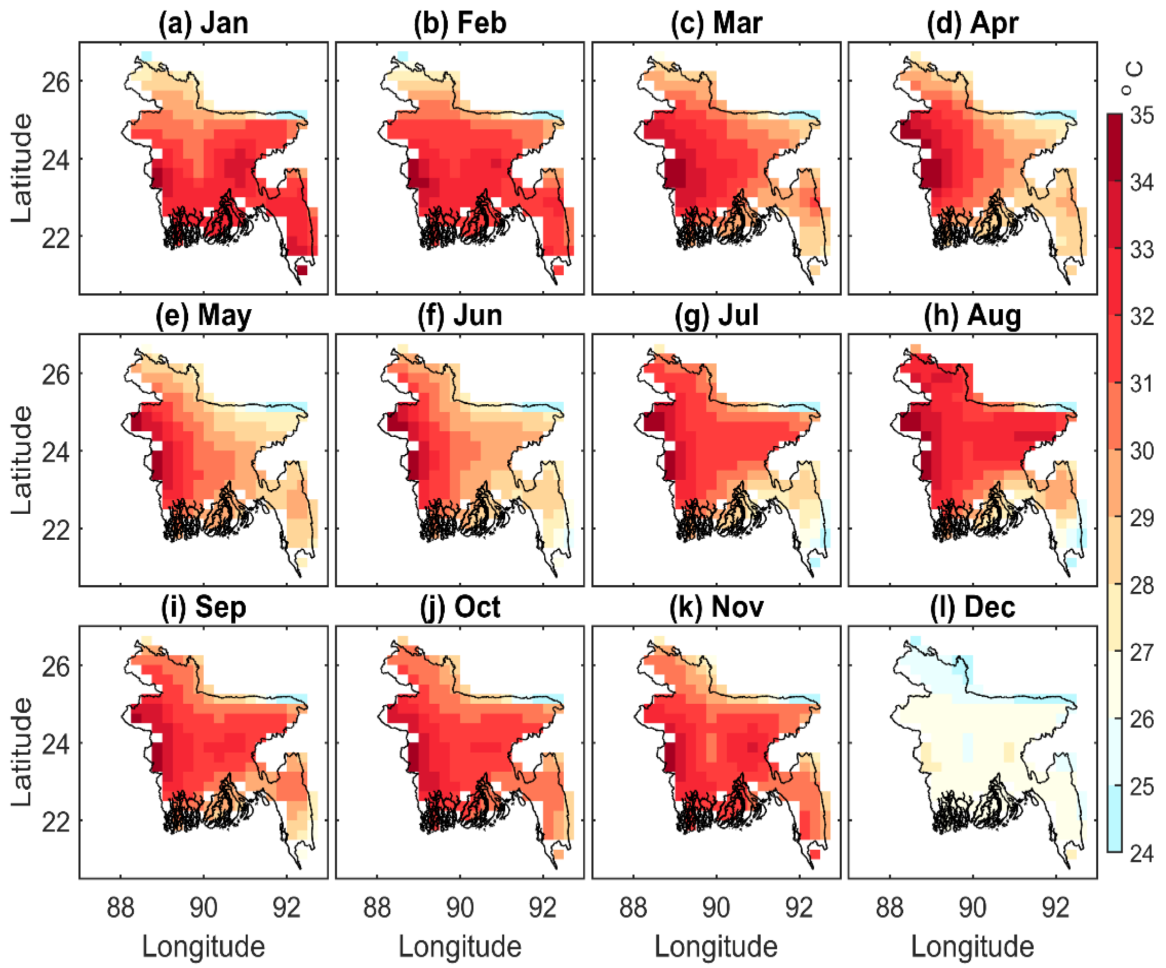

***Figure 13**. Monthly cycle of T_{max} over Bangladesh.*

Analyzing trends with statistical significance at a 95% confidence interval for T_{max} (Figure 14), it is evident that the winter months (DJF) and pre-monsoon months (MAM) consistently exhibit a negative trend in T_{max}, with significance observed in all these months except December (Figure 14l). The most substantial negative trend occurs in April (Figure 14d), particularly in the central to northern part of the country, with a value exceeding 0.15^0 Celsius (C) per decade. In contrast, the monsoon and post-monsoon months show a positive trend, with significance observed nationwide in June and August, followed by November. Notably, November (Figure 14k) stands out with the highest positive trend, exceeding 0.15^0 C per decade, predominantly in the north-northwestern part of the country. The area-averaged plot (Figure 15) conveys a consistent message; depicting a positive trend during the monsoon and post-monsoon months, while the winter and pre-monsoon months exhibit a negative trend. November (Figure 15k) stands out with the highest positive trend slope at 0.013^0 C per month, whereas April (Figure 15d) records the highest negative trend slope at 0.012^0 C per month.

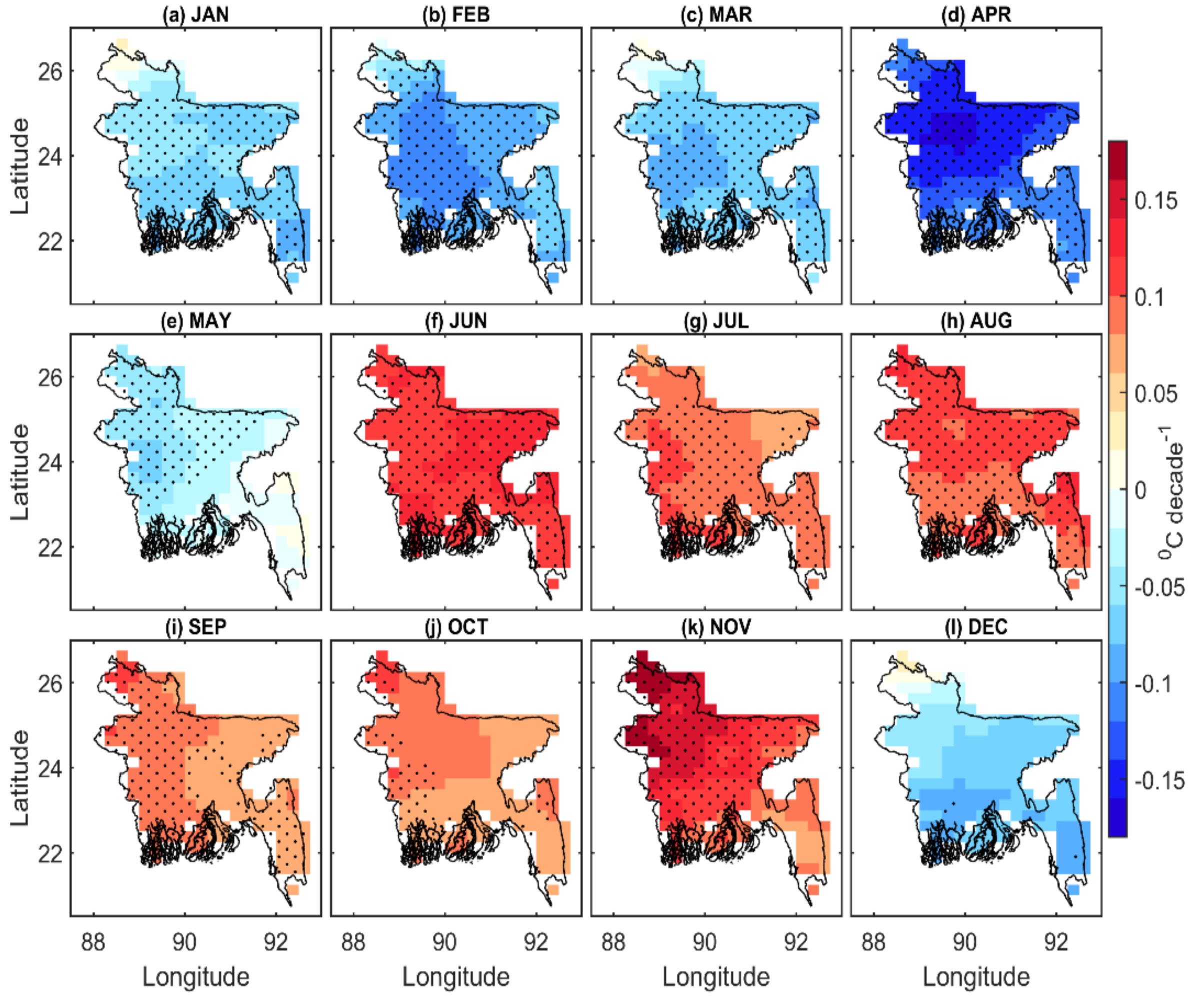

Figure 14. *Monthly trend of T_{max} for Bangladesh (shaded) with significance with > 95% confidence interval (stipple).*

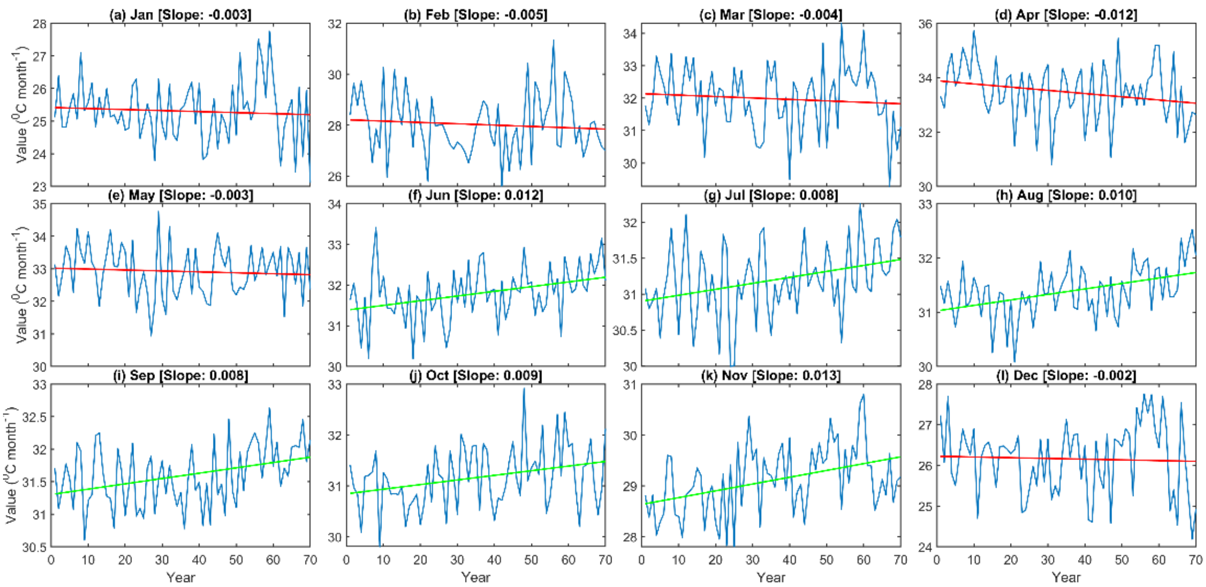

Figure 15. *Same as Figure 9, but for T_{max}. The units of line plot and slope are ^{0}C and ^{0}C per month, respectively.*

Examining the seasonal T_{max} scenario depicted in Figure 16, it is evident that during the pre-monsoon, monsoon, and post-monsoon seasons, the highest T_{max} are consistently observed in the western part of the country, particularly in Rajshahi and Khulna MSD. The peak occurs during the monsoon (June – July – August) season, exceeding 34^0 C, followed by the pre-monsoon season, especially over the northern Khulna MSD.

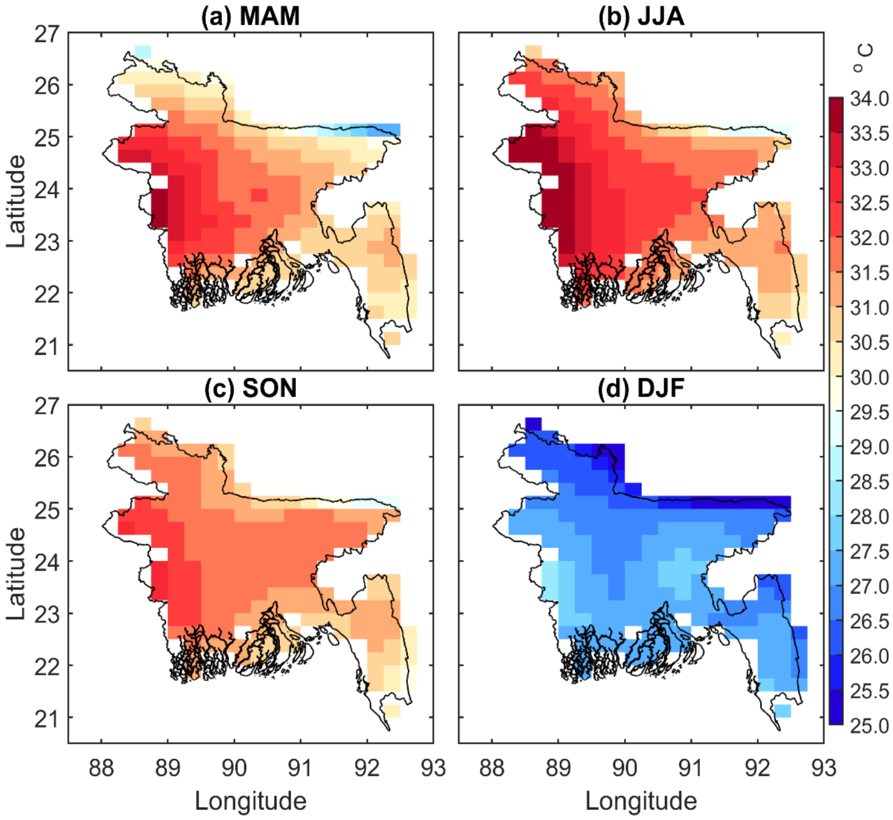

***Figure 16**. Seasonal T_{max} variations over Bangladesh.*

As anticipated, the lowest T_{max} is recorded during the winter months, with the variation mostly confined to the northern part of the country, hovering around 25^0 C. Examining trends with statistical significance at a 95% confidence interval reveals distinct patterns across seasons. In the pre-monsoon season, the entire country exhibits a statistically significant negative trend, with the central part experiencing the maximum trend at 0.15^0 C per decade. During the monsoon season, there is a warming trend observed nationwide, with the northern Chittagong region showing the highest increase at more than 0.05^0 C per decade, and this trend is statistically significant. In the post-monsoon season, the entire country experiences the highest warming trend compared to other seasons, surpassing 0.1^0 C per decade, and this trend is statistically significant. The winter season displays a warming trend in the northern part, notably in the Rangpur region, and a cooling trend in the southern part, particularly in the southern Chittagong region; however, statistical significance is not observed for the winter season.

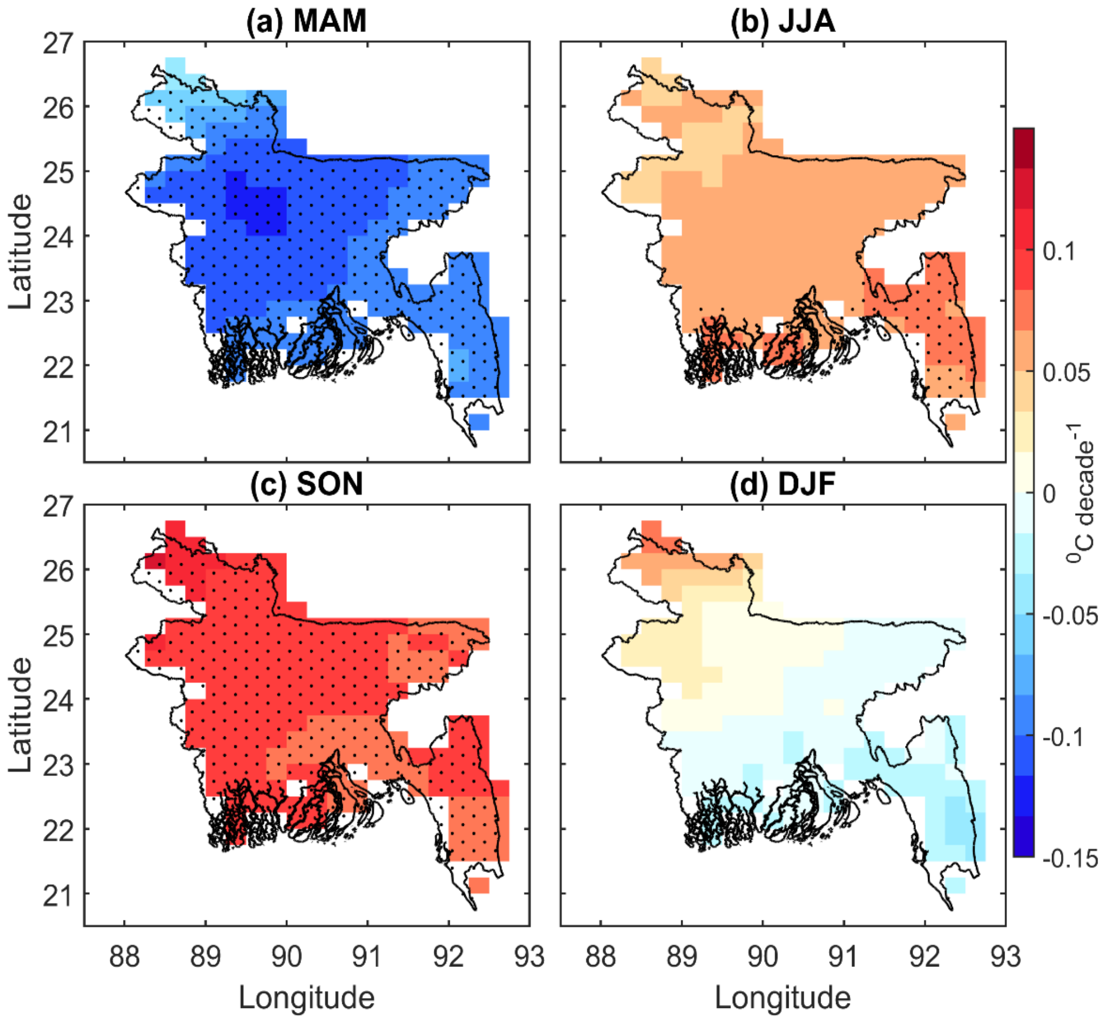

Figure 17. *Seasonal trend of T_{max} for Bangladesh (shaded) with significance with > 95% confidence interval (stipple).*

4.3 Near Surface Minimum temperature

The mean and trend with a 95% confidence interval for minimum temperature near the surface (T_{min}) are shown in Figure 18 in the left and right panels, respectively. Analyzing the 70-year annual mean of CRU data on T_{min} reveals a consistent pattern of higher T_{min} over the western part of the country compared to the eastern part. The Khulna region consistently records the maximum T_{min}, exceeding 32^0 C, while the Sylhet region exhibits the lowest T_{min}, hovering around 28^0 C. Regarding trends with significance, the entire country displays a positive or warming trend in T_{min} data, supported by a 95% confidence interval. The most substantial warming trend is observed in the northern part of the country, particularly over the Rangpur region, exceeding 0.12^0 C per decade.

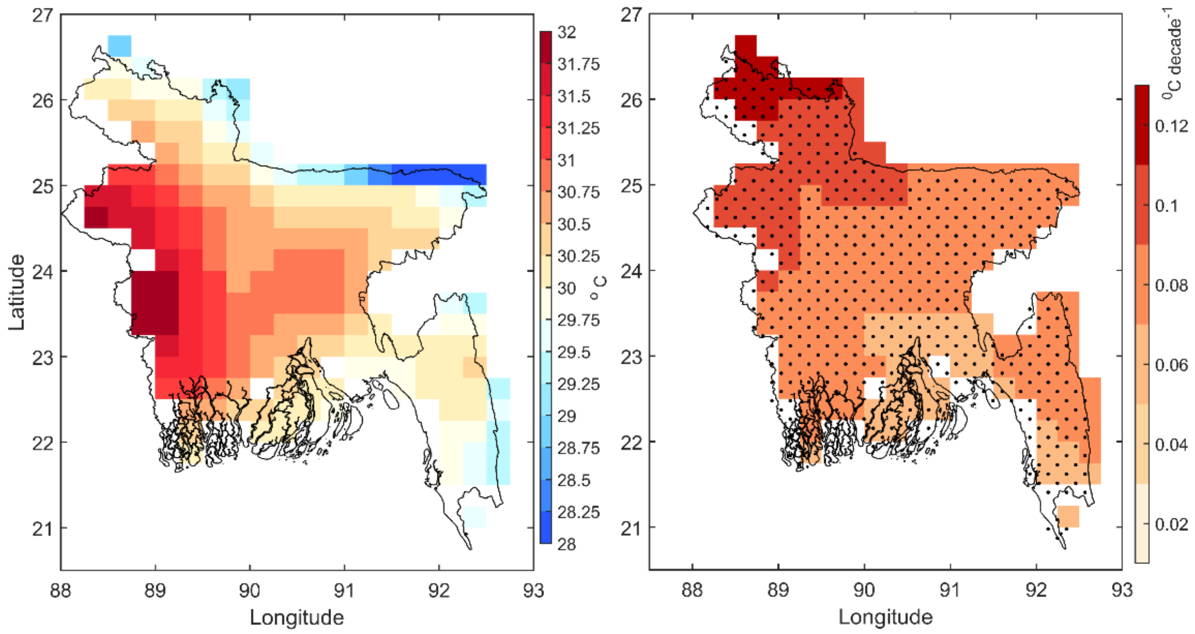

Figure 18. *Same as Figure 12, but for T_{min}.*

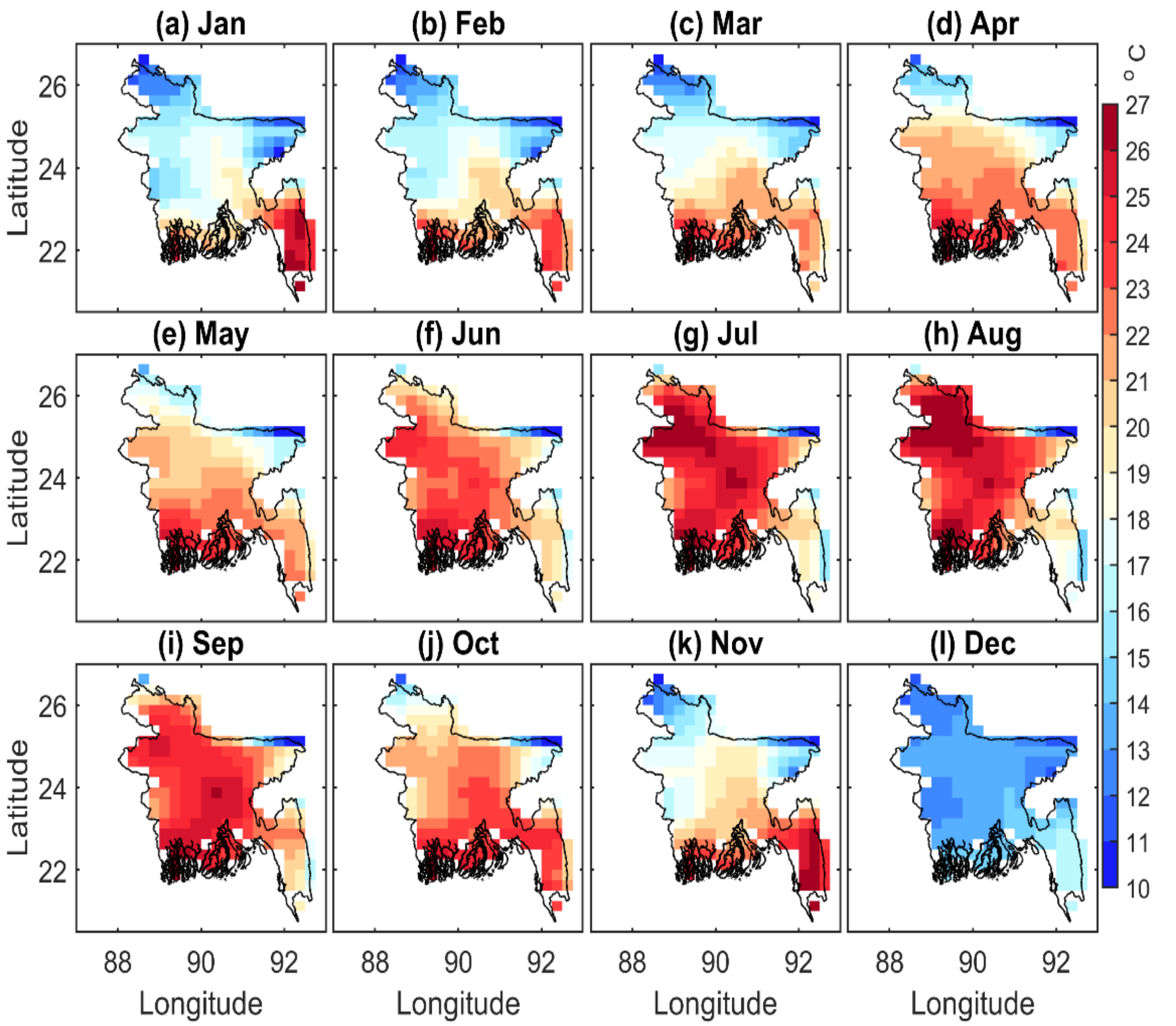

Figure 19. *Same as Figure 13, but for T_{min}.*

Examining the monthly T_{min} plot (Figure 19) reveals a distinct temperature pattern in the northern parts of the country. In January, February, March, April, May, and November, these regions experience lower temperatures. Conversely, July and August depict an opposite scenario, with the northern part exhibiting warmer conditions, particularly in Rajshahi and Rangpur regions, where temperatures exceed 27^0 C (Figure 19g, h). December (Figure 19l) emerges as the coolest month of the year. Notably, the northern Sylhet region consistently maintains cooler temperatures throughout the year.

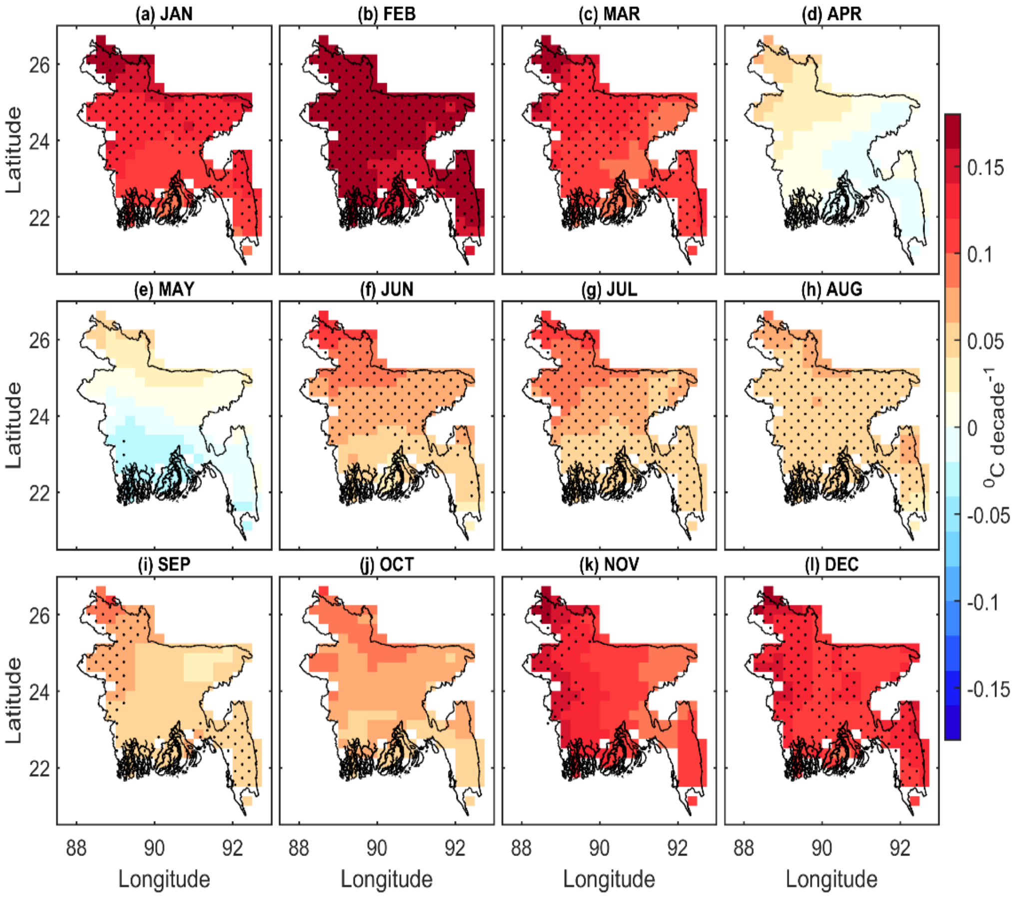

***Figure 20**. Same as Figure 14, but for T_{min}.*

Examining trends with statistical significance at a 95% confidence interval (Figure 20), it is observed that all months exhibit a warming trend, with significance in all months except April, May, and October. Notably, February stands out with the highest statistically significant warming trend, exceeding 0.15^0 C per decade across the entire country. The sole exception to the overall warming trend is identified in May, where a cooling trend is observed, particularly with slight significance in the southern part of the country, notably over the Khulna region (Figure 20e). The domain-averaged time series plot (Figure 21) reinforces the consistent warming trend, with all months exhibiting a positive trend. February (Figure 21b) stands out with the highest warming trend, featuring a slope of 0.019^0 C per month.

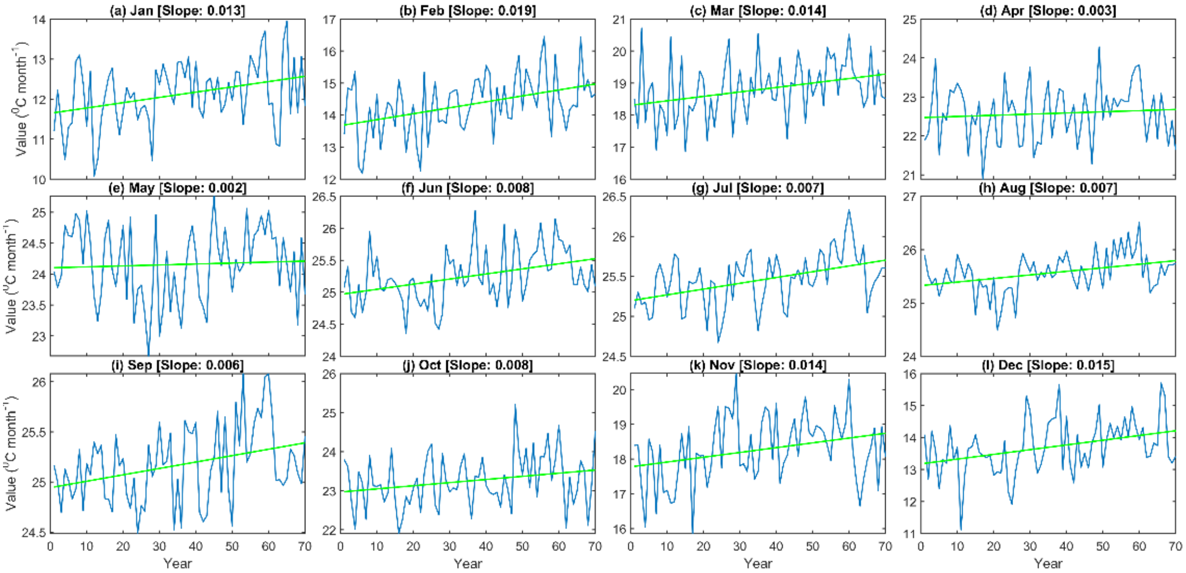

***Figure 21**. Same as Figure 15, but for T_{min}.*

Regarding the seasonal minimum temperature scenario (shown in Figure 22), it is observed that the monsoon season exhibits higher temperatures compared to other seasons, ranging between 25^0 – 26^0 C. The southernmost regions of Bangladesh, particularly the Barisal region, show the highest spread, exceeding 26^0 C.

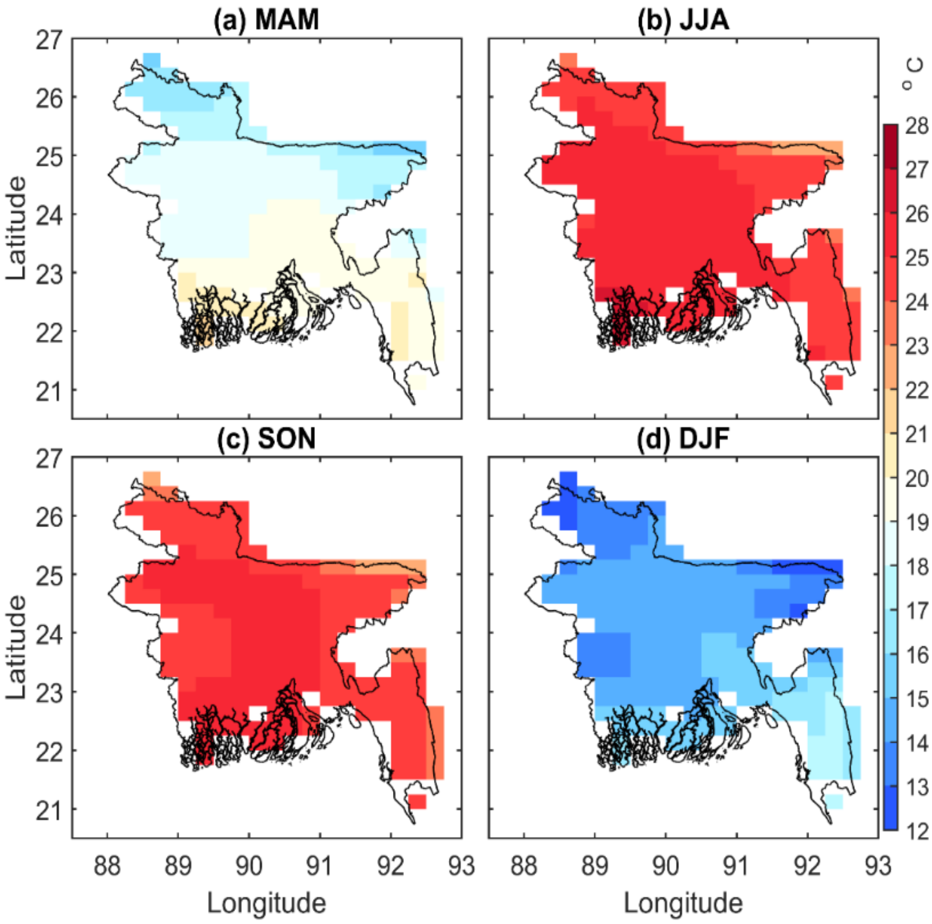

***Figure 22**. Same as Figure 16, but for T_{min}.*

Conversely, the winter season records the lowest temperatures compared to other seasons, with the northern parts of Rangpur and Sylhet experiencing the lowest minimum temperatures, approximately around 12^0 C. Analyzing trends with statistical significance at a 95% confidence interval in the seasonal cycle of minimum temperature (shown in Figure 23) reveals a consistent warming trend across all seasons throughout the country. The most substantial warming trend is identified in the winter season, and this trend is statistically significant. The northern part of the country, particularly the Rangpur region, experiences the highest warming, surpassing 0.2^0 C per decade.

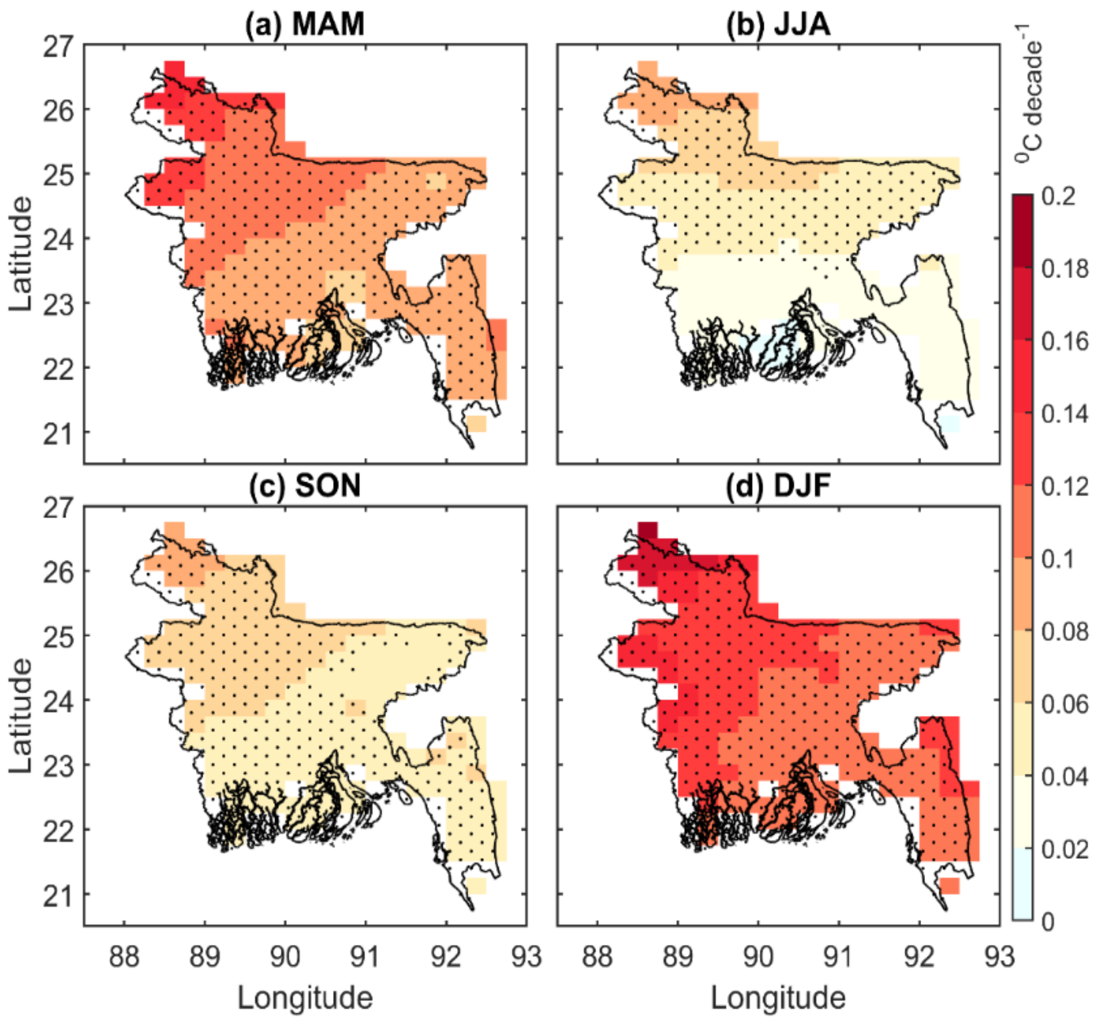

Figure 23. *Same as Figure 17, but for T_{min}.*

4.4 Conclusions

Bangladesh is a South Asian country with a rich culture, vibrant landscapes, and a resilient population. Bangladesh has a diverse and dynamic climate due to its topography, location, and proximity to the BoB. The tropical monsoon climate with distinct wet and dry seasons makes the country vulnerable to weather extremes. This report focuses on the weather and climate of

Bangladesh, covering aspects such as rainfall, as well as maximum and minimum temperatures. This study calculated various statistical indices for Bangladesh using CRU datasets. The following are the important findings from this study.

- The monsoon climate brings heavy rains in summer and dry weather in winter. Khulna MSD is the only exception, showing a positive trend though it may not be statistically significant.
- The monthly cycle for Bangladesh's rainfall shows that June to August has the most precipitation. January shows a 2 mm per decade decline with a 95% confidence interval. June has the highest statistically significant negative trend in the east. In July and August, middle to northern regions experience concerning patterns, especially in Sylhet MSD where the impact is 18 mm per decade. In September, the western part has a slight positive trend, but the eastern part has a more statistically significant negative trend of 0 – 4 mm per decade. October precipitation in Chittagong MSD is decreasing by 0 to 6 mm per decade, which is statistically significant.
- Central to western parts of the country receive rainfall during the pre-monsoon season (March-April-May), with Sylhet MSD receiving the most, up to 200 mm per month. During the monsoon season, Sylhet MSD and the southern part of Chittagong MSD receive the most rainfall, sometimes over 600 mm monthly.
- Winter precipitation is lowest nationwide, below 50 mm per month. The seasonal rainfall trend analysis with a 95% confidence interval shows clear patterns where rainfall rises across Bangladesh during the pre-monsoon season, with central Bangladesh and Rangpur MSD seeing the biggest increase of 11 mm per decade. Rangpur and northern Rajshahi MSDs are the only statistically significant areas where increase in rainfall is observed. A nationwide negative trend are observed during monsoon season. The post-monsoon season is declining in the central to western regions.
- The west consistently has higher temperatures than the east, according to 70 years of CRU annual T_{max} data. Khulna and some areas of Rajshahi MSD consistently record the highest T_{max}, over 32^0 C, while Sylhet MSD records the lowest, around 28^0 C. The country has a positive annual trend with a 95% confidence interval, but only certain Rangpur MSD areas are statistically significant. Interestingly, the Rangpur MSD has the highest warming trend at 0.04^0 C per decade.

- The extreme west has a higher temperature gradient than other regions. April has the highest and December has the lowest temps. August has the largest T_{max} spread. The DJF and MAM have a negative T_{max} trend in all months except December. At above 0.15^0 C per decade, April has the largest negative trend, especially in the central to northern regions.
- After the monsoon, June and August are meaningful nationwide, followed by November. November has the highest positive trend, exceeding 0.15^0 C per decade, mostly in the north-northwest. The area-averaged data shows a positive trend during monsoon and post-monsoon but a negative trend in winter and pre-monsoon. The monsoon (June-July-August) peaks at over 34^0 C, followed by the pre-monsoon season, especially over northern Khulna MSD. As expected, winter T_{max} is lowest in the north at 25^0 C. Monsoon season temperatures are falling nationwide, with the central region having the highest trend at 0.15^0 C per decade. Monsoon season warming is statistically significant nationwide, with northern Chittagong showing the highest increase at over 0.05^0 C per decade. After monsoon season, the country warms the most, exceeding 0.1^0 C per decade, and it is statistically significant.
- The 70-year CRU annual mean shows that T_{min} is higher in the West than in the East. Nation-wide T_{min} data shows a positive or warming trend with a 95% confidence interval. The northern region, especially Rangpur MSD, warms the most, exceeding 0.12^0 C per decade.
- Monthly T_{min} plots show that February, March, April, May, and November are cooler. Northern MSDs like Rajshahi and Rangpur reach 27^0 C in July and August. Except for April, May, and October, all months show a statistically significant warming trend at a 95% confidence interval.
- The nation warms the most in February in terms of T_{min}, exceeding 0.15^0 C per decade. The domain-averaged time series plot of T_{min} shows positive warming for all months. Minimum monsoon temperatures are 25^0 – 26^0 C, higher than others. Southern Bangladesh, particularly Barisal MSD, has the highest temperature spread, exceeding 26^0 C. All seasons in the country are warming, according to statistical significance at a 95% confidence interval in the seasonal minimum temperature cycle. Most statistically significant warming occurs in winter.

5 Future work

The Indian Monsoon Data Assimilation and Analysis (IMDAA) reanalysis dataset, a highly regarded resource for analyzing atmospheric conditions in the Indian monsoon region, including BIMSTEC region. This comprehensive dataset, utilizing a 4D-Var data assimilation technique and U.K. Met Office Unified model output data, covers the period from 1979 to 2023 with a resolution of 12 km (Indira Rani et al., 2021). The IMDAA reanalysis stands out as the most comprehensive atmospheric reanalysis currently available, incorporating a diverse range of data sources. This includes surface and upper air measurements, as well as traditional and satellite observations, providing a holistic perspective on climatic and weather patterns. Given its extensive coverage and high resolution, we will consider utilizing the IMDAA reanalysis dataset for future analyses of climatic and weather patterns over Bangladesh. The inclusion of multiple data sources and the incorporation of advanced techniques make it a valuable resource for gaining insights into the dynamics of the region. Leveraging this dataset will significantly enhance the accuracy and depth of our analyses, contributing to a better understanding of the climatic and weather variations in Bangladesh.

6 Acknowledgments

The work presented in this study utilized the computational capabilities of the MIHIR supercomputers at the NCMRWF. We extend our sincere gratitude to our colleagues and fellow scientists at NCMRWF for their invaluable assistance. Additionally, we express our thanks to the Head, NCMRWF for his encouragement and support, which greatly motivated us during this work. Authors are also thankfully expressing gratitude to the anonymous reviewer who evaluated the report.

7 Useful links

- BBC country profile: https://www.bbc.co.uk/news/world-south-asia-12650940
- CIA World Factbook: https://www.cia.gov/the-world-factbook/countries/bangladesh/
- Bangladesh national portal: https://www.bangladesh.gov.bd/index.php?lang=en
- Bangladesh Bureau of Statistics: http://www.bbs.gov.bd/site/page/29855dc1-f2b4-4dc09073-f692361112da/-

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9 Appendix

9.1 Sen's Slope

Sen's Slope, also known as the Sen's Estimator, is a non-parametric method used to estimate the slope of a trend in time series data. It is particularly useful for detecting trends in data where the assumption of linearity may not be appropriate. The formula for Sen's Slope is given by:

$$S = \frac{X_i - X_j}{i-j}$$

where X_i and X_j are the data values at time points i and j, respectively.

9.2 Mann-Kendall Trend Test

The Mann-Kendall Trend Testis a non-parametric test used to identify trends in time series data. It is based on the Kendall rank correlation coefficient and assesses the presence of monotonic trends. The Mann-Kendall statistic S is calculated as:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(X_j - X_i)$$

9.3 Mean and Standard Deviation

The mean (μ) and standard deviation (σ) are measures of central tendency and dispersion, respectively. For a set of data points $x_1, x_2, \ldots, x_n$, the formulas are:

$$\mu = \frac{1}{n} \sum_{i=1}^{n} X_i$$

$$\sigma = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (X_i - \mu)^2}$$

9.4 Linear Trend Calculation for Slope

The linear trend calculation for slope is a simple method to estimate the slope of a linear trend in time series data. The formula for the slope *m* is given by the covariance between time *t* and the data *x*, divided by the variance of time:

$$m = \frac{cov(t,x)}{var(t)}$$