Analysis of Historical Climate and Climate Projection for Bhutan

NATIONAL CENTER FOR HYDROLOGY AND METEOROLOGY

ROYAL GOVERNMENT OF BHUTAN

2019

REPORT ON THE ANALYSIS OF HISTORICAL CLIMATE AND CLIMATE PROJECTION FOR BHUTAN

NATIONAL CENTER FOR HYDROLOGY AND METEOROLOGY

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Foreword

Bhutan is highly vulnerable to the impacts of climate change. Bhutan is already facing the impacts of climate change such as extreme weather and changing rainfall patterns. The Royal Government of Bhutan (RGoB) recognizes the devastating impacts climate change can cause to the country's natural resources, livelihood of the people and the economy. Bhutan is committed to addressing these challenges in the 12th Five Year Plan (2018-2023) through various commitments, mitigation and adaption plans and actions on climate change at the international, national, regional levels. Bhutan has also pledged to stay permanently carbon neutral at the Conference of Parties (COP) Summit on climate change in Copenhagen.

Accurate, reliable and timely hydro-meteorological information underpins the understanding of weather and climate change. The National Center for Hydrology and Meteorology (NCHM) is the national focal agency responsible for studying, understanding and generating information and providing services on weather, climate, water, water resources and the cryosphere. The service provision of early warning information is one of the core mandates of NCHM that helps the nation to protect lives and properties from the impacts of climate change.

The Strategic Program for Climate Resilience (SPCR) which is being implemented by Gross National Happiness Commission (GNHC) focuses on four main pillars. The pillars are:

- Enhancing information base for hydro-met services and climate resilience
- Preparedness, food and water security
- Sustainable growth and resilient infrastructure
- Strengthening governance, institutional coordination and human resource capacity

NCHM is one of the four technical agencies under the SPCR and it is responsible for undertaking a technical study under the *Pillar I- Enhancing Information Base Hydro-met Services and Climate Resilience*. The fundamental objective of the study is to improve hydro-met base information and identify future investment plans. The list of studies carried out under the Pillar I of SPCR are as follows:

- Analysis of historical climate and climate change projection for Bhutan
- Re-assessment of potentially dangerous lakes of Bhutan
- Bhutan glacier inventory 2018

The study on Historical Climate Data Analysis and Climate Change Projection for Bhutan discusses data and methods used to study the past and future climate change projections for Bhutan. The findings of the study indicate possible future increases in temperature and rainfall for Bhutan under future climate scenarios based on Representative Concentration Pathways (RCP 4.5 and RCP 8.5).

This report is submitted by NCHM to GNHC and to the World Bank under the SPCR Project. The findings from this study provide initial assessments of possible future changes of climate over Bhutan. In this regard, I would like to thank all the Divisions, the SPCR Management of NCHM who have worked hard to bring out this report.

(Karma Dupchu)
Director

Acknowledgement

The NCHM would like to thank the Gross National Happiness Commission, Royal Government of Bhutan and the World Bank for selecting NCHM as one of the lead technical agencies to implement the activities of the Pillar I of SPCR Project. The Center thanks the GNHC, the World Bank and all stakeholders for the support during the course of the studies under the SPCR Project.

The Center thanks Dr. Srivatsan V Raghavan and his colleagues at the Tropical Marine Science Institute, National University of Singapore for the technical guidance. Thanks to the Regional Integrated Multi-Hazard Early Warning System (RIMES) for Africa and Asia for the technical guidance and giving the Center access to the Climate Data Access and Analysis System (CDAAS).

The Center would also like to thank the Divisions and in particular, the Project Manager, SPCR and his technical team members of the Center for their contribution to this report.

Executive Summary

Bhutan's economy is highly dependent on climate-sensitive sectors such as agriculture, hydropower, and forestry. The most significant impact of climate change in Bhutan is the formation of supra-glacial lakes due to the accelerated retreat of glaciers with increasing temperatures. Other impacts include extreme weather, changing rainfall, drying of streams, and flash floods. The Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) projects an increase of about 4.8 °C in global mean surface temperature by the end of the century. IPCC indicated that much more studies on climate change are required especially at the regional and national levels. There is a requirement for climate change information at high temporal and spatial scales for impact studies over Bhutan such as flooding, drought, agriculture, health, energy and socio-economic changes. Unlike most of the developed countries, climate sciences and climate research remains a challenge for Bhutan. It is limited by lack of available historical climate data, dense and robust observational network, resources, model and computational facilities, technology and capacity to undertake climate research.

Scope and objectives

This study is a contribution to the Strategic Program for Climate Resilience (SPCR) that describes possible future climate changes over Bhutan. The results and findings from this study offer a glimpse of expected changes in the future for long term adaptation planning, which could be useful to the Government, policymakers, stakeholders and other interested end-users.

The objectives of the study are:

i. To assess and analyse the observed or historical climate trends over Bhutan
ii. To assess how the climate has been varying: temperature and precipitation-annual and seasonal trends
iii. To project future climate changes over Bhutan using downscaled regional climate model data
iv. To identify future investment plans

Approach and Findings

The Fifth Phase of the Coupled Model Inter-comparison Project (CMIP5) comprises state-of-the-art coupled global models developed by different climate modelling groups around the world. In this study, ensemble of five global climate models of CMIP5 were chosen to analyse future temperature and rainfall changes over Bhutan. Multi-model ensemble (MME) is believed to be superior to individual global climate models as it provides a bandwidth of climate responses to be considered for climate adaptation. The GCMs selected in this study comprise the empirically downscaled NASA (National Aeronautics and Space Administration) Earth Exchange Global Daily Downscaled Projections (NEX-GDDP) dataset (https://cds.nccs.nasa.gov/nex-gddp/). The datasets contain downscaled climate scenarios for the globe that are derived from the General Circulation Model (GCM) runs conducted under the CMIP5 and across two of the four greenhouse gas emissions scenarios known as Representative Concentration Pathways (RCPs). The NEX-GDDP datasets include downscaled projections for RCP 4.5 and RCP 8.5 from the 21 models and scenarios for which daily scenarios were produced and distributed under CMIP5. Each of the climate projections include daily maximum temperature, minimum temperature, and precipitation for the periods from 1950 through to 2100. The spatial resolution of the dataset is 0.25 degrees (~25 km x 25 km). The NEX-GDDP dataset is provided freely to help the science community in conducting studies of climate change impacts at local to regional scales, and to improve public understanding of possible future global climate patterns at the spatial scale of individual towns, cities, and watersheds.

It is to be noted that the models in this study were selected based on the list of NEX-GDDP datasets given in the Climate Data Access and Analysis System (CDAAS) of Regional Integrated for Multi-Hazard Early Warning System (RIMES), Bangkok for South Asia. No specific ranking of GCMs or detail evaluation of these models were performed over the study region. The exhaustive assessment of each of the 5 models is out of the scope of this study and such assessment might differ from the findings of this study. Therefore, it is recommended for interested parties to use the results of the study considering a wider range of climate uncertainties.

The climate projections for Bhutan has been assessed over the two future climate periods, 2021-2050 and 2070-2100, under the climate change scenarios, the RCP 4.5 and RCP 8.5.

The findings from the analysis of historical climate indicated an increasing trend in temperature both at mean seasonal and mean annual scales and a decreasing trend in rainfall at mean annual scales. The rainfall indicated a larger variability.

Under the RCP 4.5 scenario, the climate projection for surface temperature indicates an increase of about of 0.8ºC – 1.6ºC during 2021-2050 (representing the 2030s mid-term climate change scenario) and about 1.6º C – 2.8ºC towards the end of the century (2070-2099). Overall the climate projection of surface temperature under the RCP4.5 scenario indicated an increase in about of 0.8ºC – 2.8ºC during 2021-2100. Higher values are projected under the RCP 8.5 scenario with climate projection for surface temperature indicated increase of about 0.8ºC to more than 3.2º C towards the end of the century.

The mean annual rainfall over Bhutan is likely to increase in the future. Under the RCP 4.5 scenario, the mean annual rainfall over Bhutan indicates an increase of about 10%-30% on the mean annual scale, with summer (JJAS) rainfalls between 5% - 15 %. Under the RCP 8.5 scenario, the mean annual rainfall indicates an increase of about 10% - 20% during 2021-2050 and with more than 30% increase all over Bhutan towards the end of the century (2070-2100). Under both scenarios, there is an indication of a marginal increase in rainfall trend.

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Glossary of Acronyms

ACCESS	Australian Community Climate and Earth System Simulator
AWOS	Automatic Weather Observing System
BCSD	Bias-Corrected Statically Downscaled
BOM	Bureau of Meteorology
CDAAS	Climate Data Access and Analysis System
CDMS	Climate Database Management System
CMIP5	Coupled Model Inter-comparison Project Phase 5
CNRM	Centre National de Recherches Meteorologique
CO2	Carbon dioxide
CRU	Climatic Research Unit
CSIRO	Commonwealth Scientific and Industrial Research Organization
CV	Coefficient of Variation
DHMS	Department of Hydro-Met Services
DJF	December, January and February
DMS	Database Management System
DoAT	Department of Air Transport
GCM	General Circulation Model
GDP	Gross Domestic Product
GFS	Global Forecasting System
GHG	Green House Gases
GLOF	Glacial Lake Outburst Floods
GNHC	Gross National Happiness Commission
GPS	Global Positioning System
ICAO	International Civil Aviaition Organisation
IPCC	Intergovernmental Panel for Climate Change
IPSL	Institut Pierre-Simon Laplace
JJSA	June, July, August and September
km	Kilometre
LZ	Lhyengye Zhungtshog
MAM	March, April and May
METAR	Meteorological Terminal Aviation Routine
MIROC	Model for Interdisciplinary Research on Climate
mm	Millimetre
MPI-ESM	Max Planck Institute for Meteorology

MRI	Meteorological Research Institute
NASA	National Aeronautics and Space Administration
NASA GEX-GDDP	NASA Global Earth Exchange Global Daily Downscaled Projections
NCHM	National Center for Hydrology and Meteorology
NEX-GDDP	NASA Earth Exchange Global Daily Downscaled Projections
NSB	National Statistical Bureau
NUS	National University of Singapore
ODE	Organisation Development Exercise
ON	October and November
PPCR	Pilot Program for Climate Resilience
RCM	Regional Climate Model
RCP	Representative Concentration Pathways
RCSC	Royal Civil Services Commission
RIMES	Regional Integrated Multi-hazard Early Warning System
RMSE	root mean square errors
SD	Standard Deviation
SMRC	SAARC Meteorological Research Center
SPCR	Strategic Program for Climate Resilience
Tavg	Average Temperature
Tmax	Maximum Temperature
Tmin	Minimum Temperature
UK	United Kingdom
UNDP	United Nation Development Program
VFR	Visual Flight Rule
WMO	World Meteorological Organisation
WRF	Weather Research for Forecasting
° C	Degree Celsius
%	Percentage

1. INTRODUCTION

1.2 Region Overview: Bhutan

Bhutan is a landlocked and a mountainous country situated in the southern slopes of the eastern Himalayan range in between China and India. It has an area of 38,394 square kilometres. It has a complex and rugged topography that varies from less than 100 meters in the south to over 7500 meters in the north. It has a population of 727,145 as of 30 May 2017 (National Statistical Bureau, 2017) and it is one of the lowest in the South Asia region. About 70 per cent of the country's land area (38,394 square kilometres) is under forest cover. The country has three distinct climatic zones: subtropical, alpine and temperate, which encompass numerous micro-climates due to dramatic variations in elevation and topography.

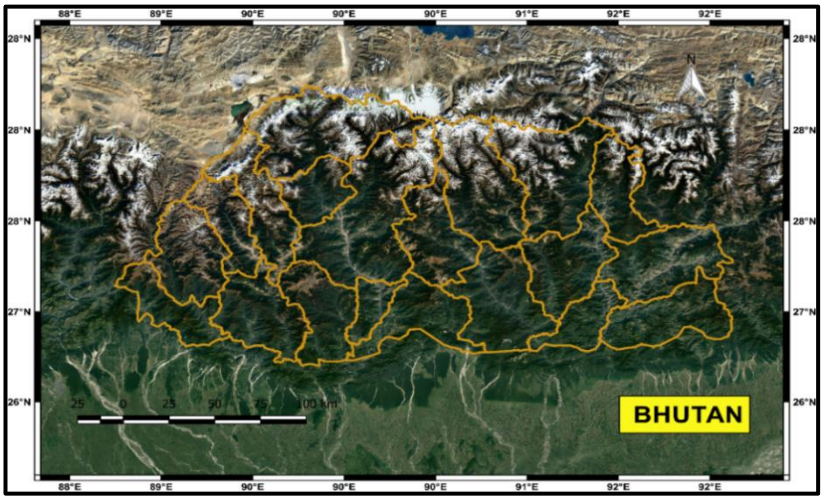


Figure 1.1 Physiographical features of Bhutan and surrounding areas

1.3 Climate Controls

The climate in Bhutan is mainly controlled by the following factors:

- Topography that varies from low elevation rolling plains of the south to high mountains to the northwest and north of the country.
- Relative distance from the coast, which controls the extent of the moist monsoon current penetration into the country. The eastern regions being closer to the Bay of Bengal are influenced more by the bay current of the Southwest monsoon, much in a similar way as most of Bangladesh and the Northeast India.
- The rainfall regime of Bhutan is controlled by Southwest monsoon circulation that prevails over the Indian sub-continent during summer months. This produces a seasonal cycle with rainy summer seasons over most of the country lasting from June to September. During this part of the year, most of the country has an almost sub-tropical climate, particularly the southern Dzongkhags. Therefore, these areas are prone to dry-spells and drought induced by the variability of monsoon rainfall.
- The control exerted by the dry winter-time air mass from the northern high latitudes during the winter seasons are primarily modulated by what is popularly known as the "western disturbances" bringing a temperate nature to Bhutan's climate. This also results in temperature variations and the little rainfall/snowfall received during the otherwise dry winters.

- Periodic impact by remnants of cyclonic systems that sometimes cross through India from the Bay of Bengal also result in high rainfall events, particularly in the eastern areas. Southernmost areas of the country are prone to severe thunderstorms during the months of April to June due to strong summertime heating and development of strong convective systems. Further north, during the transition months of autumn or spring, such systems can cause damaging hailstorms.

1.3.1 Seasons

Bhutan has four seasons - the winter season from December to February; spring season from March to May; summer season from June to September; and the autumn season of October and November. The Southwest or Summer Monsoon (June-September, JJAS) contributes about 72% to the total annual rainfall of Bhutan with the highest amount received in the month of July followed by August. The spring (March-May, MAM) and autumn (October-November) period contribute about 22 % to the total annual rainfall.

1.4 Impacts of Climate Variability and Change

About 70 per cent of the country's land area (38,394 square kilometres) is under forest cover. Even though Bhutan is a net sequester of greenhouse gases (GHG), the effects of climate change and variability are becoming increasingly visible. Precarious geographical location and effects of climate variability and change have highly exposed Bhutan to a diversity of hazards, including cyclone induced storms, flash/floods, landslides, earthquakes, glacial lake outburst floods (GLOF) and droughts. Heavy seasonal monsoon rains and glacial melt are the most common cause of flooding and landslides in Bhutan. Over 70 per cent of settlements (MoWHS, 2017) including infrastructures and fertile agricultural lands are located along the main drainage basins (Figure 1.2), hence posing threats from flooding.

GLOF events were experienced in the country in 1957, 1960, 1968 and 1994 (RGOB-WB, 2015). The 1994 GLOF event from Luggye Tsho killed 21 people, damaged 91 houses and 1,781 acres of land. The heavy rainfall brought about by Cyclone Aila in 2009 caused Bhutan to incur an estimated loss of US$ 17 million. The country is also increasingly experiencing prolonged and extreme droughts in some parts of the country, which in turn increases the risk of loss of biodiversity, forest fires, reduction of crop yield and agricultural productivity. Unseasonal and intense rainfall and hailstorms can destroy crops thereby affecting farmers who are caught unprepared. Heavy rainfall triggering floods and flash floods are a recurring phenomenon in Bhutan, especially during the summer monsoon. In July 2016, the southern part of the country experienced a flash flood triggered by intense monsoon rainfall displacing more than 100 families and damaging infrastructures. Landslides are a major problem for the roads sector, the only transport and a lifeline for Bhutan, during the summer monsoon. With most of the rivers confined in narrow gorges, blockage of rivers by landslides risks the formation of artificial dams that pose a great danger to downstream settlements and assets such as hydropower due to landslide dam outburst flood (LDOF). Extreme weather events have significant socio-economic consequences and adversely affect people's livelihoods and well-being, particularly marginal and poorer communities.

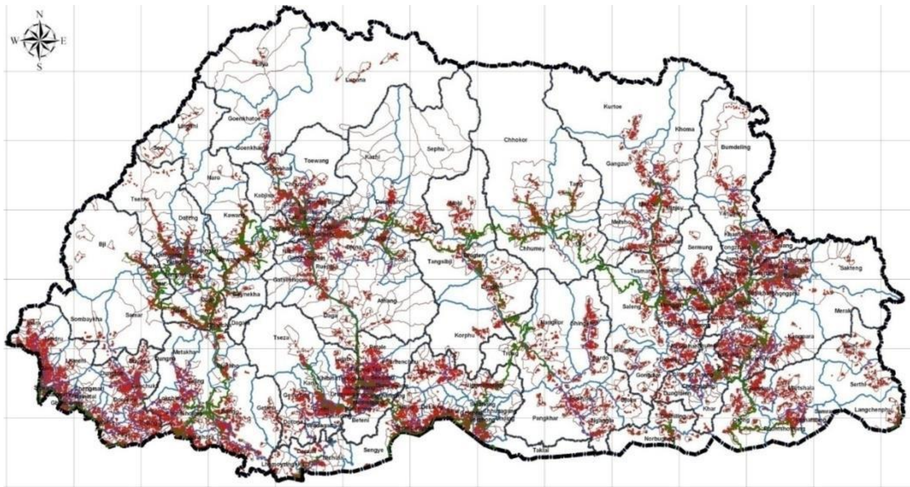


Figure 1.2 Location of settlements along the river basins (source: National Statistical Bureau, 2005)

Climate variability and change risks reduction of productivity and performance of key socio-economic sectors such as agriculture, hydropower, tourism, transport, infrastructure and water. As per the statistical yearbook of the National Statistical Bureau, agriculture accounts to 16.52 percent of Bhutan's GDP; electricity and water supply account for 13.38 percent of GDP and construction accounts for 16.28 percent of GDP. Erratic rainfall patterns are already impacting agricultural productivity. Farmers increasingly report instability in crop yields, loss in production, declining crop quality, and decreased water availability for farming and irrigation. Changes in precipitation pattern are impacting the availability of water for drinking and energy production in the short, medium and long-term, with cycles of flooding during monsoons and very low flows and drying streams during other seasons. Extreme weather events expose infrastructure assets (such as hydropower and road network) to increased risk of floods and landslides.

1.5 The rationale of the study

Bhutan is in the process of implementing the phase I of the Strategic Program for Climate Resilience (SPCR) under the Pilot Program for Climate Resilience (PPCR). The SPCR program implementation is led by the GNHC and the NCHM is one of the lead technical agencies responsible to carry out the study under the **Pillar I: Enhancing Information Base for Hydro-met Services and Climate Resilience.**

Under the Pillar I of SPCR, NCHM's technical studies were focused on**:**

- **Analysis of historical climate and climate change projection for Bhutan.**
- Re-assessment of potentially dangerous lakes of Bhutan
- Bhutan glacier inventory 2018

This study is one of the three technical studies implemented by NCHM under the Pillar I of SPCR. To prepare and adapt to the impacts of climate variability and change, information on historical and future climate is vital. Himalayan region is understudied when it comes to climate change. Unlike most of the developed countries across the globe and even in the south Asian region, climate research and studies are limited for Bhutan due to lack of available historical climate data, dense and robust observational network, resources, model and computational facilities, and scientific technology/capacity building.

Bhutan's development and the economy are highly dependent on climate-sensitive sectors such as agriculture, hydropower, and forestry. The most significant impact of climate change in Bhutan is the formation of supra-glacial lakes due to the accelerated retreat of glaciers with increasing temperatures (UNDP). The Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) projects an increase of about 4.8 °C in global mean surface temperature by the end of the century. IPCC indicated that much more studies on climate change are required especially at the regional and national levels. There is a requirement for climate change information at high temporal and spatial scales to conduct several impacts studies over Bhutan such as flooding, drought, agriculture, health, energy and socio-economic changes.

This study is a contribution to the Strategic Program for Climate Resilience (SPCR) that describes possible future climate changes over Bhutan. The results and findings from this study offer some basic assessments of expected changes in the future for long term adaptation planning which could be useful to the Government, policymakers, stakeholders and other end-users.

The objectives of the study are:

i. To assess and analyse the observed or historical climate trends over Bhutan
ii. To assess how the climate has been varying: temperature and precipitation-annual and seasonal trends
iii. To project future climate changes over Bhutan using downscaled regional climate model data

2. DATA AND METHODS

This chapter describes the climate data (Observed and Global Climate Model data) used in this study.

2.2 Observed data: Surface data of Bhutan 1996-2017

Bhutan has observational data available from 1996 to till date. For this study, the data period of 1996-2017 was used from the stations (Table 2.1) that were used in comparing with the global observed data and also to provide basic insights of the climate of the past few decades. The data is available in the data repository of the NCHM. The purpose of comparing the station data against other global data is to check if the other global data can be used as proxies for Bhutan if and where data scarcity exists.

Table 2.1 List of climate stations used in this study

Sl. No	Station Name	Lat (N)	Lon (E)	Elevation (m)	Year of Record
1	Bhur	26.907	90.4309	390	1996 - 2017
2	Chamkhar	27.5454	90.75373	2470	1996 - 2017
3	Damphu	27.0081	90.1216	1520	1996 - 2017
4	Deothang	26.8597	91.4632	890	1996 - 2017
5	Haa	27.3864	89.2785	2751	1996 - 2017
6	Kanglung	27.282	91.5185	1980	1996 - 2017
7	Mongar	27.2792	91.2355	1580	1996 - 2017
8	Paro	27.3871	89.4195	2406	1996 - 2017
9	Pemagatshel	27.0304	91.4379	1780	1996 - 2017
10	Punakha	27.5803	89.8649	1236	1996 - 2017
11	Sibsoo	27.0087	88.8821	413	1996 - 2017
12	Simtokha	27.4414	89.6627	2310	1996 - 2017
13	Trashiyangtse	27.6127	91.4946	1810	1996 - 2017
14	Wangdue	27.489	89.898	1180	1996 - 2017
15	Zhemgang	27.215	90.6588	1820	1996 - 2017

2.3 Observed data: CRU TS 3.2.3

For this study CRU data was chosen as an alternative to the Bhutan station data because of the relatively short data records available in Bhutan. CRU TS 3.2.3 data, developed at the Climatic Research Unit at the University of East Anglia, UK, is one of the most widely used data products by the climate research community. This dataset comprises monthly grids of observed climate, for the period 1901-2014 and covering the global land surface at a 0.5° horizontal resolution. The dataset is widely recognized across the scientific community in the world and mostly used in the study of natural and anthropogenic climate change (Karmacharya et al., 2007). The CRU data was used for climate change study in the Central Himalayan region (Karmacharya et al., 2007) and to predict future scenarios of precipitation in the Hindu-Kush Karakoram Himalaya by Palazzi and others (2013). Studies indicated that the use of CRU data has resulted in obtaining a consistent picture of climate at seasonal and annual times scales.

There are nine climate variables available: mean, minimum and maximum temperature, diurnal temperature range, precipitation, wet day frequency, frost day frequency, vapour pressure and cloud cover (Harris et al. 2014). In this study, temperature and rainfall variables have been used.

2.4 Model dataset: NASA data BCSD

The NASA (National Aeronautics and Space Administration) Earth Exchange Global Daily Downscaled Projections (NEX-GDDP) dataset is comprised of downscaled climate scenarios for the globe that are derived from the General Circulation Model (GCM) runs conducted under the Coupled Model Inter-comparison Project Phase 5 (CMIP5) and across two of the four greenhouse gas emissions scenarios known as Representative Concentration Pathways (RCPs). The CMIP5 GCM runs were developed in support of the IPCC's Fifth Assessment Report (AR5). The NEX-GDDP dataset includes downscaled projections for RCP 4.5 and RCP 8.5 from the 21 models and scenarios for which daily scenarios were produced and distributed under CMIP5. Each of the climate projection includes daily maximum temperature, minimum temperature, and precipitation for the periods from 1950 through 2100. The spatial resolution of the dataset is 0.25 degrees (~25 km x 25 km). The NEX-GDDP dataset is provided to assist the science community in conducting studies of climate change impacts at local to regional scales, and to enhance understanding of possible future global climate patterns at the spatial scale of individual towns, cities, and watersheds.

Each of the climate projections includes monthly averaged maximum temperature, minimum temperature, and precipitation for the periods from 1950 through 2005 (Retrospective Run) and from 2006 to 2099 (Prospective Run). A comprehensive documentation is available at https://cds.nccs.nasa.gov.

Out of the 21 models, a subset of 6 models was chosen based on the selection done by Regional Integrated Multi-Hazard Early Warning System (RIMES) for Asia and Africa at http://cdaas.rimes.int/nexnasa/daily. Table 2.2 shows the raw CMIP5 GCMs. The downscaled data of the listed GCMs are available at NASA data portal for download at https://www.nccs.nasa.gov/services/data_portal.

Table 2.2 List of GCMs used in this study

Sl No.	Model	Investment	Resolution
1	ACCESS1-0	CSIRO (Commonwealth Scientific and Industrial Research Organization) & BOM (Bureau of Meteorology), Australia	1.25° × 1.85°
2	CNRM-CM5	Centre National de Recherches Meteorologiques / Centre European de Recherche et Formation Avancees en Calcul Scientifique	1.4° × 1.4°
3	IPSL-CM5A-LR	Institut Pierre-Simon Laplace	1.8° × 3.75°
4	MIROC5	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	1.4° × 1.4°

5	MPI-ESM-MR	Max Planck Institute for Meteorology (MPI-M)	1.8° × 1.8°
6	MRI-CGCM3	Meteorological Research Institute	1.12° × 1.12°

2.5 Climate variables and parameters

The observed climate variables and the time periods over which they are analysed in this study are tabulated below. The focus is on observed rainfall and surface temperatures (Table 2.3) that were analysed on monthly, seasonal and annual time scales along with their ranges, standard deviation (SD), trends, the coefficient of variation (CV) and incremental changes.

Table 2.3 Climate variable and metrics analysed in this study

Rainfall	Mean	Annual, Seasonal, Range, SD, CV, Trend, Incremental Change
Temperature	Mean	Annual, Seasonal, Range, SD, Trend, Incremental Change
	Minimum	Annual, Seasonal, Range, SD, Trend, Incremental Change
	Maximum	Annual, Seasonal, Range, SD, Trend, Incremental Change

3. ANALYSIS OF HISTORICAL DATA

3.1 Overview of the climatology of Bhutan

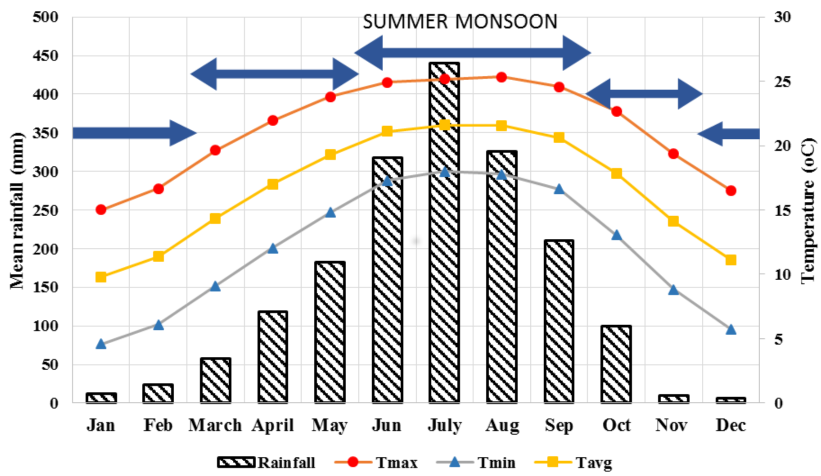


Figure 3.1 Seasonal variation of temperature- maximum (Tmax), minimum (Tmin) and mean (Tavg.) and rainfall (mm) over Bhutan as a whole (based on the stations observation for the period from 1996-2013 for 44 number of stations) (Source: Climatology of Rainfall and Temperature in Bhutan, 2017)

Figure 3.1 shows the seasonal variation of temperature and rainfall over Bhutan. It shows that Bhutan's rainfall regime is dominated by summer rainfall. The rainfall during the southwest monsoon season accounts to more than 72 % of the total annual rainfall. Winter season receives the least rainfall with low temperatures recorded.

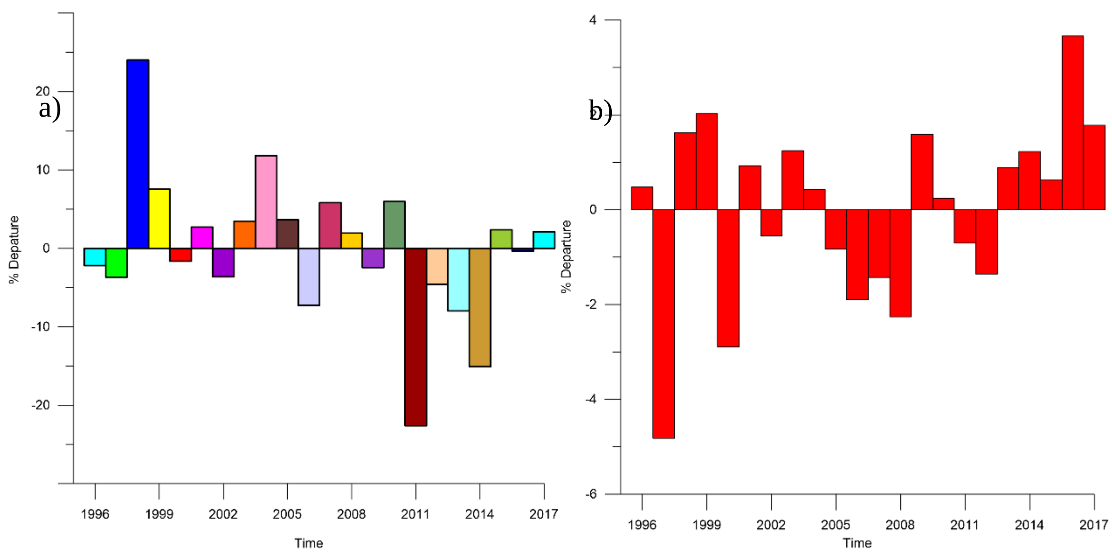


Figure 3.2 The figures shows the yearly percentage of departure for rainfall (a) and yearly percentage departure for temperature (b) from the normal.

Analysis of number of hot days and rainy days from selected weather stations are shown in the appendices.

3.2 Selection of CRU data for analysis

For this study CRU dataset was chosen as an alternative to the Bhutan station data because of the relatively short data records of Bhutan station data.

A time series comparison was made against the observed station data of Bhutan. The two data sets were mainly compared based on their signals (peaks and troughs) and no comparison in terms of values and biases were made. This is because the observed data do not represent the country completely and the period is also short.

Readers should note that matching of one to one values of the data is not possible due to the difference in resolution in data and other methods used while generating the CRU data. While biases are obvious, the time series graphs (Figure 3.3 and Figure 3.4) of both annual total rainfall and annual mean temperature indicate a clear and consistent peaks and troughs. In other words, CRU data is able to capture the annual variation of temperature and rainfall of Bhutan. However, clear bias is seen especially for temperature because the observed data used here is mainly the long term mean of the data from the stations which are mostly located in the south and central parts of the country that is not well reflected in CRU. Therefore, this bias is not unusual but bias correction of the data is beyond the scope of this study. These analyses reveal that at local scale, the station data are much different and that Bhutan needs a concerted effort in building more station observations as climate studies are furthered in the years to come.

The signal of CRU dataset tends to match with the time series of the ensemble average of model historical simulation (Figure 3.5 and Figure 3.6). Hereafter, for brevity, the ensemble average of the models is referred as 'NEX'.

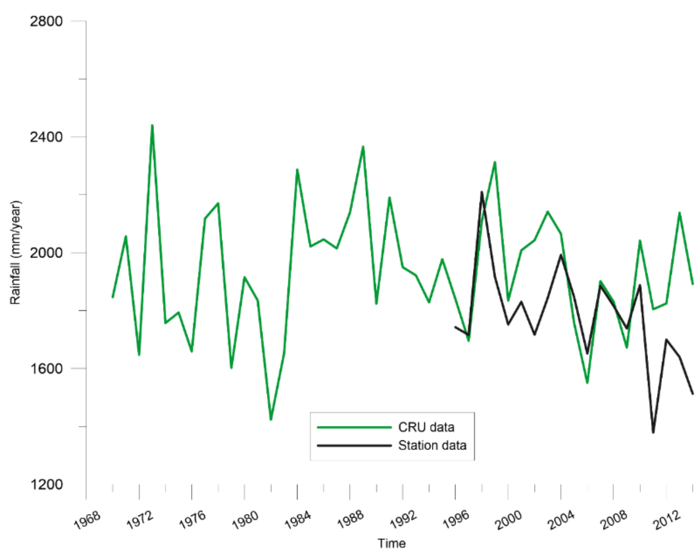


Figure 3.3 Time series - annual total rainfall of CRU data against station data of Bhutan

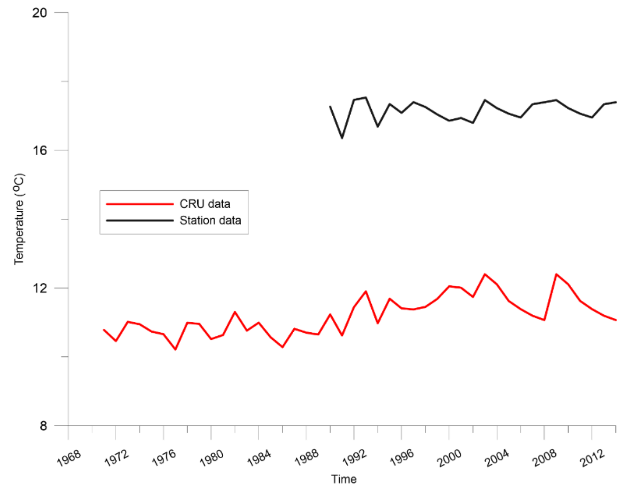


Figure 3.4 Time series- annual mean temperature CRU data against station data of Bhutan

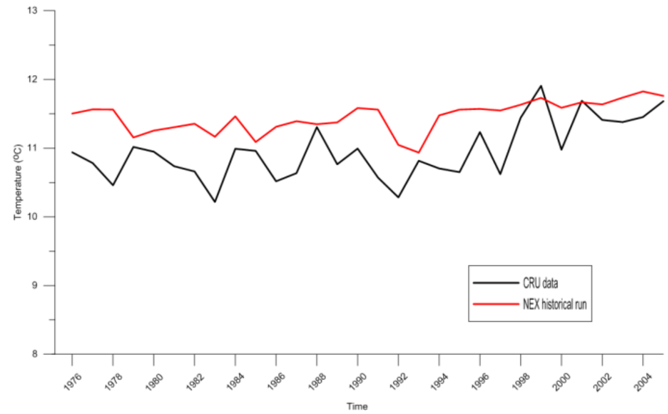


Figure 3.5 Time series of annual mean temperature CRU dataset and NEX history

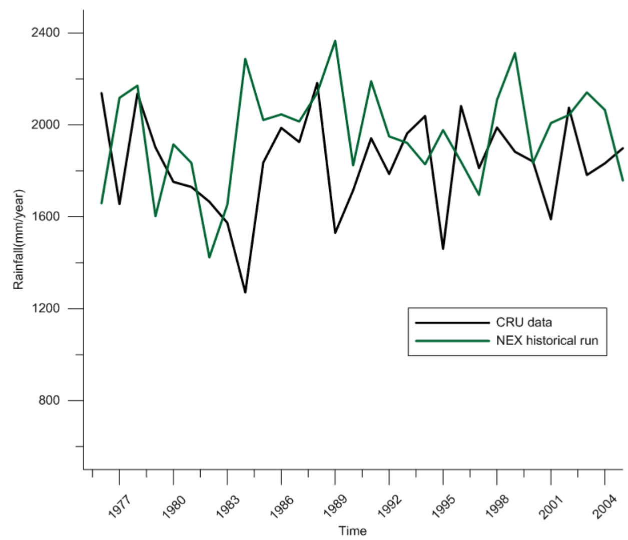


Figure 3.6 Time series of annual mean rainfall CRU dataset and NEX history

Seasonal time series analysis of the CRU data (1975-2005) is included in the appendices for more information.

3.3 Spatial distribution of annual mean temperature

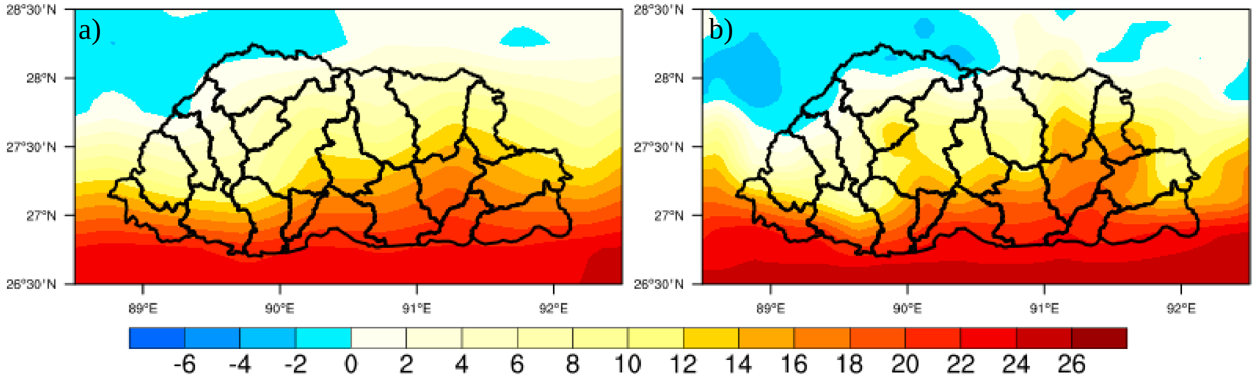


Figure 3.7 Spatial pattern of annual mean temperature (a) CRU and (b) NEX over Bhutan for the period 1975-2005

Figure 3.7 shows the spatial distribution of annual mean temperature over Bhutan. The observed data (CRU dataset) and NEX_GDDP historical data almost indicate a similar spatial distribution with area averaged annual mean temperature of 11^{o} C and 11.5^{o} C (Table 3.1), respectively.

Table 3.1 Mean, range and standard deviation of annual mean temperature

	Mean Temperature		
	Mean	**Range**	**SD**
NEX	11.5	0.9	0.2
CRU	11.0	1.7	0.4

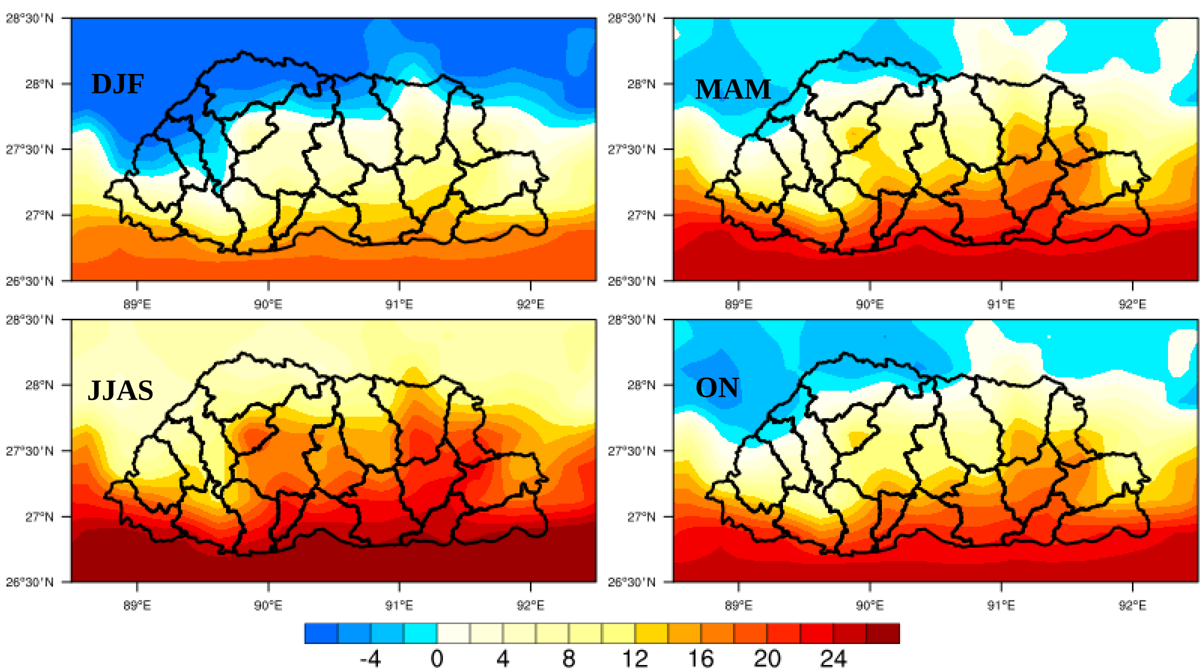


Figure 3.8 Spatial distribution of seasonal mean temperature (ºC) over Bhutan for the period 1975-2005

Table 3.2 Incremental change in seasonal and annual mean temperature during the period of 1976-2005 over Bhutan for CRU dataset.

CRU	Change in mean temperature (°C)
DJF	1.3
MAM	0.6
JJAS	0.8
ON	0.7
Mean	0.8

The spatial distribution of seasonal mean temperature over Bhutan for the period 1975-2005 using CRU datasets is shown in Figure 3.8. It can be seen that the JJAS and MAM seasons are warmer than the rest of the seasons. The northern regions are relatively cooler than the rest of the regions. Overall, the seasonal temperature ranges between -1°C and 28°C.

The seasonal mean, range and standard deviation of temperature for CRU dataset and model historical data are shown in Table 3.2.

Table 3.3 Average, range and standard deviation of the seasonal mean temperature of NEX and CRU data

Seasons	NEX History			CRU Data		
	Mean	Range	SD	Mean	Range	SD
DJF	4.9	1.9	0.4	4.2	2.7	0.8
MAM	11.5	1.7	0.4	11.1	2.6	0.6
JJAS	16.6	0.5	0.1	16.3	1.6	0.4
ON	10.9	1.2	0.3	10.2	2.7	0.8

3.4 Spatial distribution of annual mean rainfall

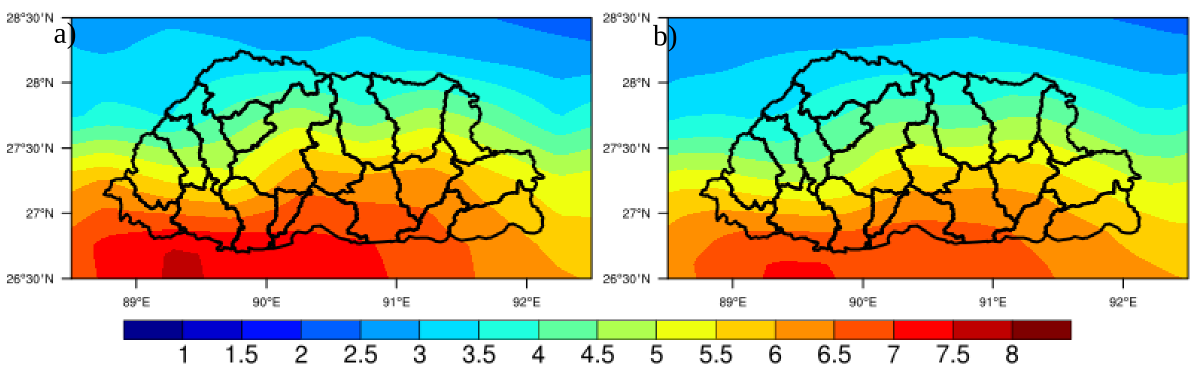


Figure 3.9 Spatial distribution of annual mean rainfall (a) CRU data and (b) NEX history for the period 1975-2005

The spatial distribution of annual mean rainfall (Figure 3.9), both the CRU data and NEX_GDDP historical simulation data depicts a similar distribution of rainfall. Bhutan is influenced largely by the South Asian Monsoons. Figure 3.10 shows the spatial distribution of mean rainfall during the period 1975-2005 over the different seasons. During the two monsoon seasons (summer and winter), strong gradients can be distinctly seen. Bhutan is wettest during the summer monsoon (JJAS) and generally dry during the winter (DJF) season.

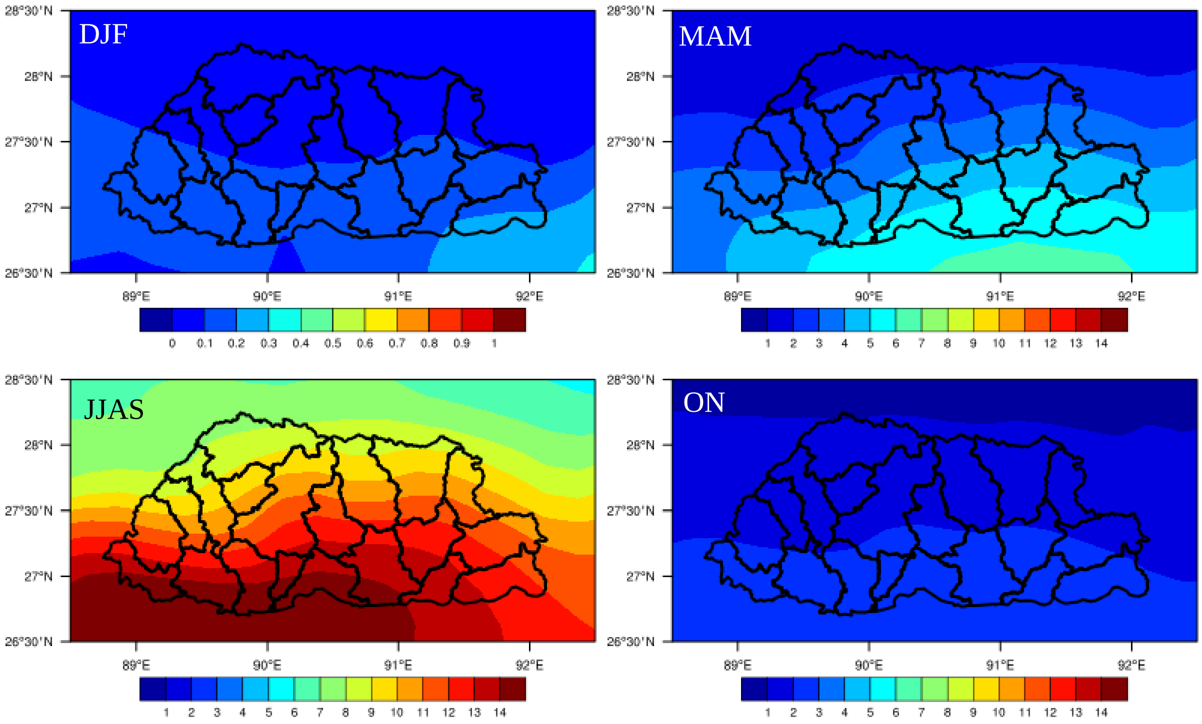


Figure 3.10 Spatial distribution of seasonal mean rainfall, DJF(Winter), MAM (Spring), JJAS (summer) and ON (Autumn)

The average, range, standard deviation and coefficient of variation at annual and seasonal scales of mean annual and seasonal mean rainfall is shown in Table 3.3.

Table 3.4 Average, range, standard deviation and coefficient of variation of annual and seasonal mean rainfall over Bhutan

	NEX History				**CRU dataset**			
	Mean	**Range**	**SD**	**CV**	**Mean**	**Range**	**SD**	**CV**
Annual	152.7	75.9	17.9	0.1	163.2	78.6	18.5	0.1
DJF	2.9	5.9	1.36	0.4	10.2	27.5	6.0	0.6
MAM	107.9	94.5	26.2	0.2	119.5	108.3	23.8	0.2
JJAS	347.1	214.4	48.5	0.1	367.3	195.5	48.8	0.1
ON	55.7	105.4	24.2	0.4	50.1	98.0	29.3	0.6

4. CLIMATE CHANGE PROJECTION

4.1 Model Selection

Out of the six models that were investigated, five global climate models (CMIP5) were chosen to analyse temperature and rainfall changes over the future in this study. The GCMs listed in Table 4.1 comprise the NASA (National Aeronautics and Space Administration) Earth Exchange Global Daily Downscaled Projections (NEX-GDDP) dataset. The datasets contain downscaled climate scenarios for the globe that are derived from the GCM runs conducted under the CMIP5 and across two scenarios. The NEX-GDDP dataset includes downscaled projections for RCP 4.5 and RCP 8.5 from the 21 models and scenarios for which daily scenarios were produced and distributed under CMIP5. Each of the climate projections includes daily maximum temperature, minimum temperature, and precipitation for the periods from 1950 through 2100. The spatial resolution of the dataset is 0.25 degrees (~25 km x 25 km).

Table 4.1 List of downscaled GCMs, resolutions and period of future climate analysed in this study

Downscaled GCMs (NASA GEX-NDDP data)	Resolution	Period for projection
CNRM-CM5	25 km x 25 km (daily)	2021 to 2050 2070 to 2099
IPSL-CM5A-LR	25 km x 25 km (daily)	2021 to 2050 2070 to 2099
MIROC5	25 km x 25 km (daily)	2021 to 2050 2070 to 2099
MPI-ESM-MR	25 km x 25 km (daily)	2021 to 2050 2070 to 2099
MRI-CGCM3	25 km x 25 km (daily)	2021 to 2050 2070 to 2099

4.2 RCP Scenario Selection

The Intergovernmental Panel for Climate Change (IPCC) used four Representative Concentration Pathways (RCP) (2.6, 4.5, 6.0, and 8.5) to represent a broad range of climate scenarios of possible future outcomes replacing the earlier scenarios of the Special Report on Emissions (SRES) of the Fourth Assessment Report (AR4). These RCPs are defined by their total radiative forcings (a cumulative measure of human emissions of GHGs from all sources expressed in watts per square meter) pathway and level by 2100. The scenarios were used for climate change projection and simulation of global climate models. Amongst the four scenarios, namely the 4.5 and 8.5 scenarios were chosen for all analyses in this study. RCP 4.5 is the mitigation/stabilization scenario and the RCP 8.5 is the high emissions scenario. The fundamental purpose of RCPs cited as ‘Pathways’, is to provide time-dependent projections of atmospheric greenhouse gas (GHG) concentrations. Van Vuuren et al. (2011) and the fifth assessment report of the IPCC may be referred to for further information.

4.3 Climate variables/parameters selected for Analysis

Table 4.2 Climate variables and metrics analysed for projection study

Temperature	Mean	Annual, Monthly Mean, Range, SD, Trend, Incremental Change
	Minimum	Annual, Monthly Mean, Range, SD, Trend, Incremental Change
	Maximum	Annual, Monthly Mean, Range, SD, Trend, Incremental Change
Rainfall	Precipitation	Annual, Seasonal, Monthly Mean, Range, SD, CV, Trend, Incremental Change

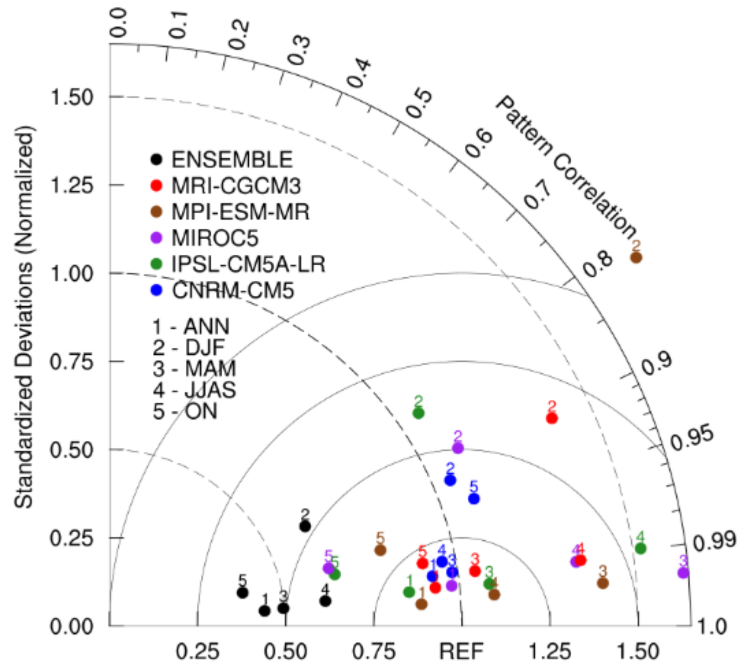
4.4 Validation of the models (precipitation & temperature)

The global climate models have to be evaluated for confidence in these models in simulating the possible future outcomes with certain credibility. A commonly used method in this regard is to evaluate global climate models against observations to examine how reasonable the present day (historical) climate are.

In this study, only limited evaluations on the state of climate simulated by global climate models were chosen, focusing on the annual and seasonal mean precipitation and temperature. Taylor diagrams provide a concise graphical summary of patterns matching observations based on correlation, root means square differences and ratio of variances (Taylor, 2001). The comparisons of CRU vs NEX-GDDP spatial distributions of temperature and rainfall mentioned earlier also stand as support in this validation exercise.

The Taylor diagrams for temperature and rainfall for Bhutan is depicted in Figure 4.1 (a and b). Bilinear interpolation was used to derive these diagrams in reference to Bhutan grid point based on the resolution of the downscaled global models. Therefore, the results are only representative and do not portray the observed state of the climate in its entirety. For rainfall, the correlations for individual models are between 0.9 to 0.99, root means square errors (RMSE) between 1.50 to 0.25 with high variability both on the seasonal and annual means. The ensemble shows higher variability with correlation from 0.87 to 0.99. In the case of temperature, there is low variability with lesser RMSE and good correlation. This as mentioned earlier, can be attributed to the relatively coarser resolution of the global models.

a)



b)

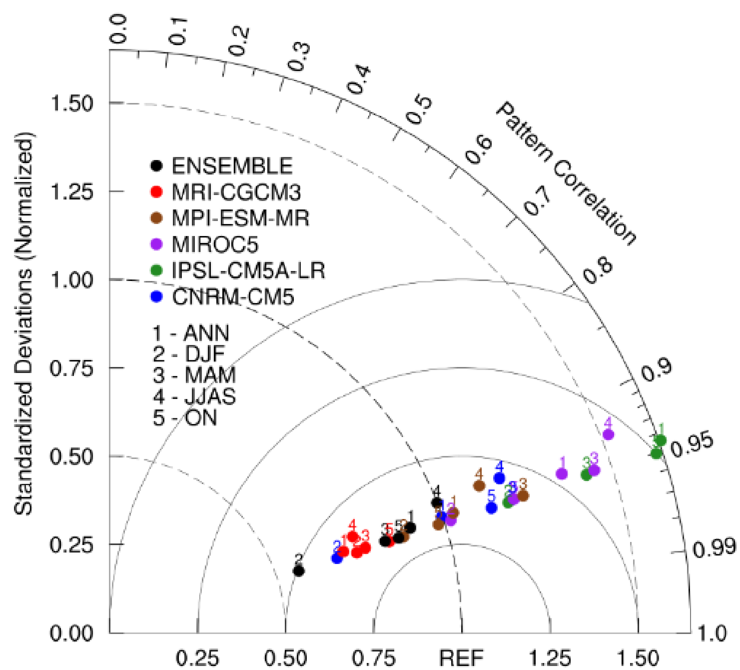


Figure 4.1 Taylor diagrams of precipitation and temperature for historical simulations for the period 1975-2005

4.5 Historical Climate and Future Climate Projections

Figure 4.2 shows the future climate projection for temperature (ensemble of 5 GCMs chosen in this study), for Bhutan. The historical values are shown to compare GCM simulations with the observation and to suggest future projected trends.

As depicted in Figure 4.2, the rise in temperature over Bhutan is evident under the future scenarios of RCP 4.5 and 8.5. There is a clear divergence of the signal after the mid-century. The RCP4.5 and RCP8.5 follow closely during the immediate future and differently by the end of the century. As to rainfall, an overlap is seen with higher values projected by RCP 8.5.

The rainfall projection shows no significant increase on an average (Figure 4.3), however, the variability within the model is large and increasing towards the end of the century.

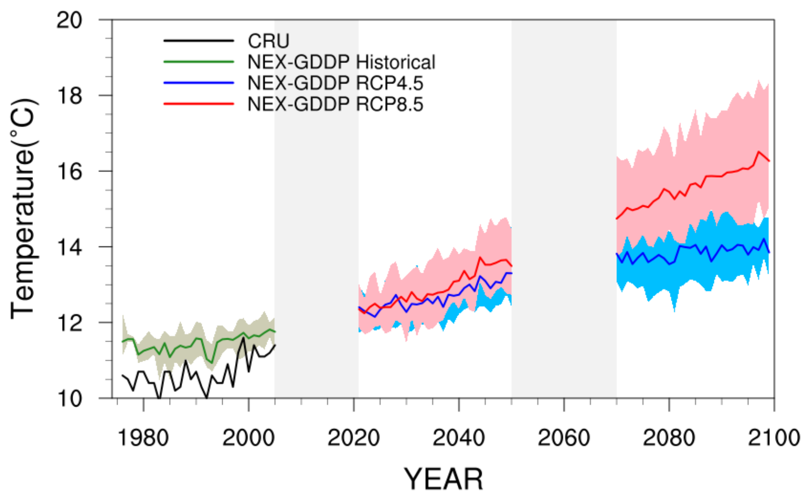


Figure 4.2 Historical climate and climate projections for temperature

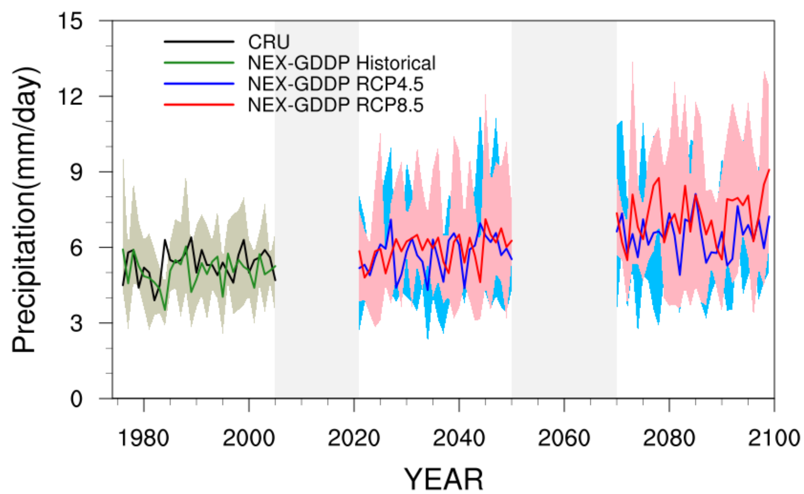


Figure 4.3 Historical climate and climate projection for Rainfall

4.5.1 Temperature Projections

Projected Annual Mean Temperature: RCP4.5 Scenario

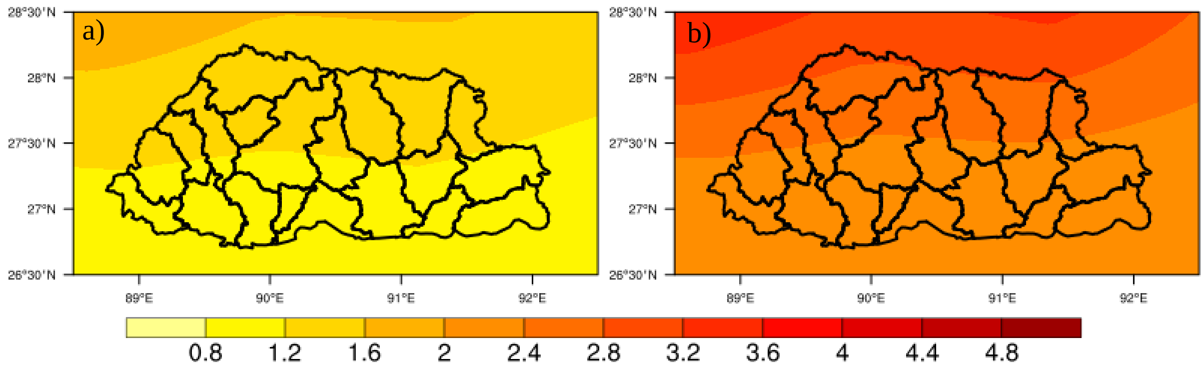


Figure 4.4 RCP 4.5: Difference in annual mean temperature (ºC) between future and present-day climate (a) 2021-2050 (b) 2070-2099

Projected Seasonal Mean Temperature: RCP4.5 Scenario

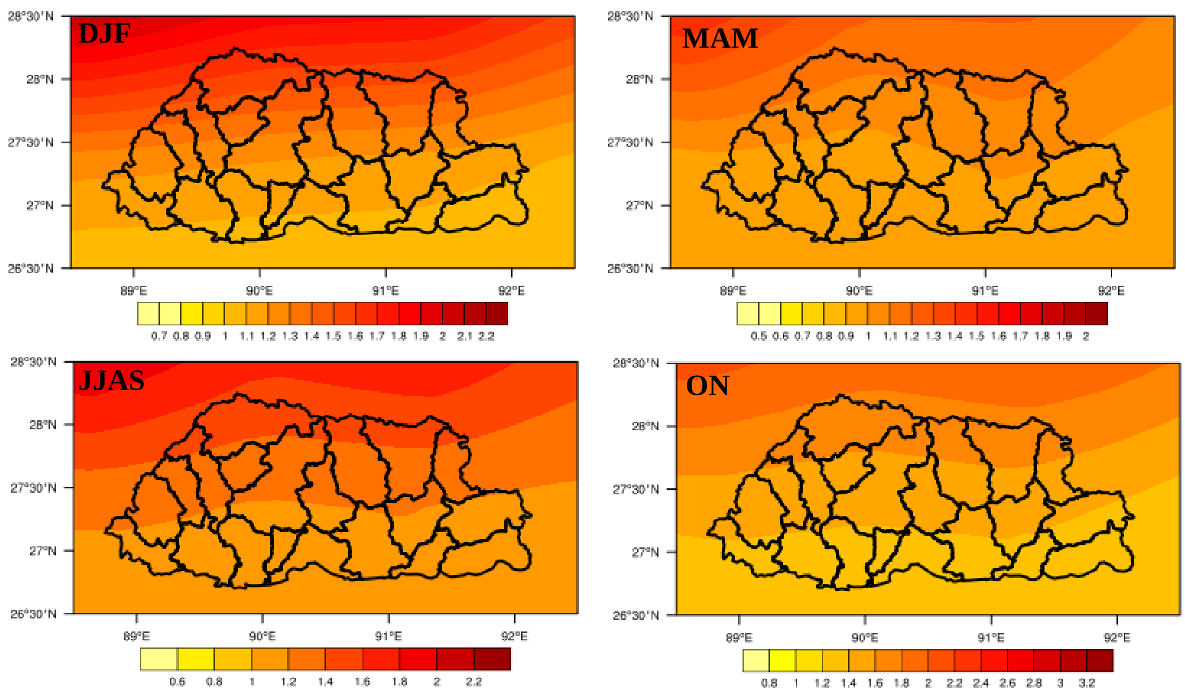


Figure 4.5 RCP4.5: Difference in seasonal mean temperature (ºC) between future and present-day climate: 2021-2050

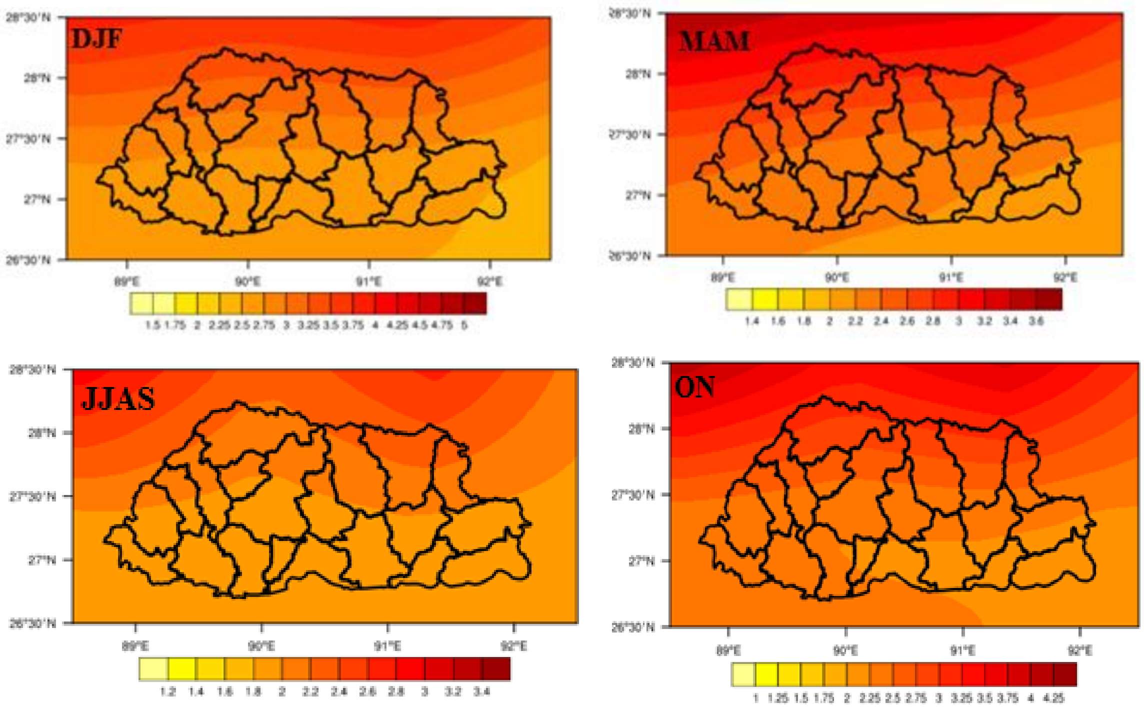


Figure 4.6 RCP 4.5: Difference in seasonal temperature (ºC) between future and present-day climates: 2070-2099

The above figures depict the change in mean surface temperature over Bhutan under the RCP 4.5 scenario.

Figure 4.4 shows changes in annual mean temperature. By 2021-2050, an increase in the range of 0.8ºC – 1.6ºC is expected all over Bhutan. These changes are likely to be higher towards the end of the century (2070-2099) with expected increase in the range of 1.6º C – 2.8ºC. Accordingly, the seasonal changes during 2021-2050 (Figure 4.5) show increase in the range of 0.9ºC – 1.8ºC over Bhutan and about 1.8ºC – 2.8ºC by the end of the century (Figure 4.6). Larger warming is indicated during MAM and DJF seasons. The country as a whole is expected to experience an increase in temperature with a larger increase projected in the high lands.

Projected Annual Mean Temperature: RCP8.5 Scenario

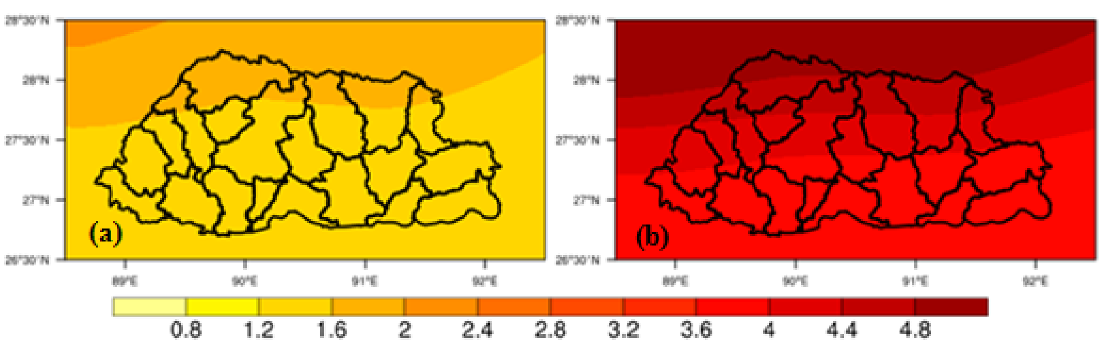


Figure 4.7 RCP 8.5: Difference in annual mean temperature (ºC) between future and present-day climates (a) 2021-2050 (b) 2070-2099

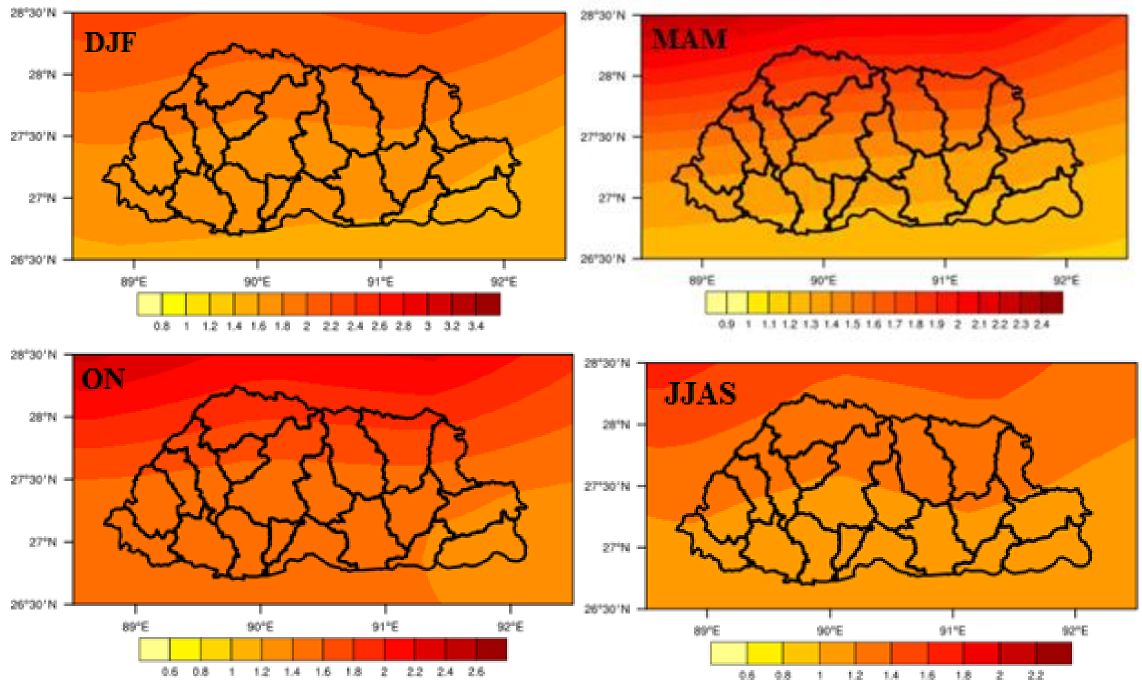


Figure 4.8 RCP 8.5: Difference in seasonal mean temperature (ºC) between future and present-day climates: 2021-2050

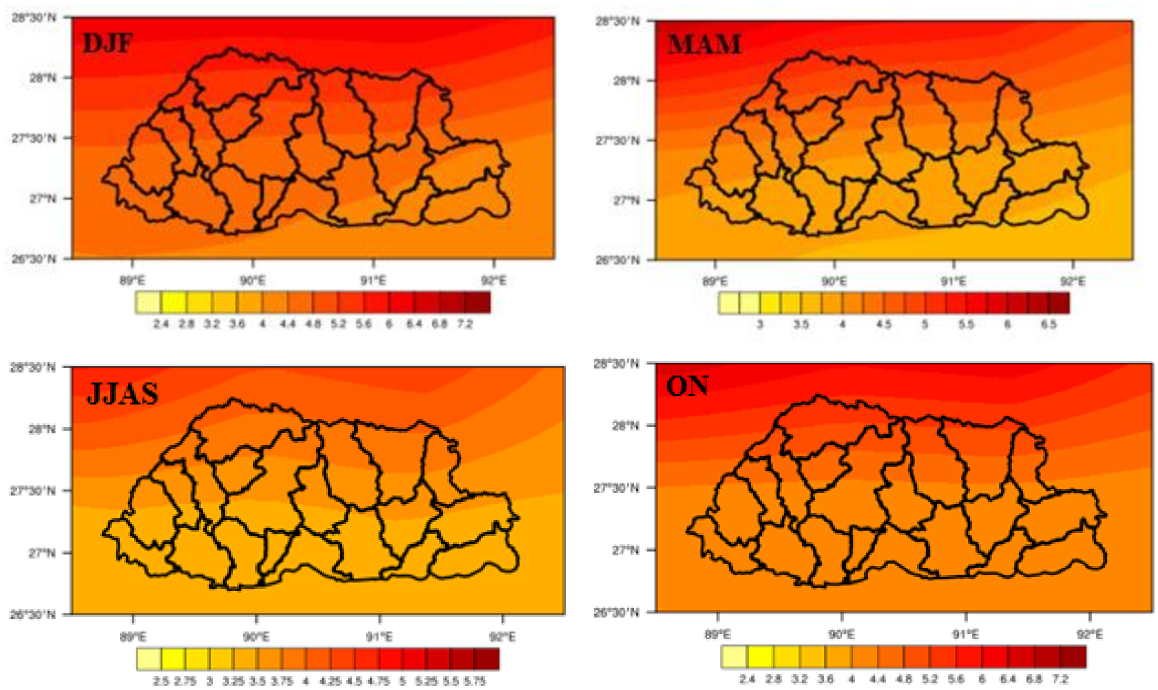


Figure 4.9 RCP8.5: Difference in seasonal mean temperature (ºC) between future and present-day climates: 2070-2099

The above figures depict the change in annual mean surface temperature over Bhutan under RCP 8.5 scenario.

Figure 4.7 show changes in annual mean temperature. During 2021-2050, an increase in the range of 0.8ºC – 2.0ºC is expected all over Bhutan. These changes are likely to be higher towards the end of the century (2070-2099) with the expected increase in the range of more than 2.8º C. During 2021-2050, similar seasonal changes are expected to that of RCP 4.5 over Bhutan (Figure 4.8). However, more pronounced changes can be noted towards the end of the century (Figure 4.9) in the range of 3.2ºC – 5.6ºC.

A detailed table of all these temperature changes, during 2021-2050 and 2070-2099, under both the scenarios of RCP 4.5 and RCP 8.5 are provided in following Tables on annual and seasonal timescales.

Table 4.3 Annual and seasonal mean temperature projected during 2021-2050 under RCP 4.5

RCP4.5	**Mean Temperature 2021-2050**			**Minimum Temperature 2021-2050**			**Maximum Temperature 2021-2050**		
	NHist (°C)	**NEX (°C)**	**Change (%)**	**NHist (°C)**	**NEX (°C)**	**Change (%)**	**NHist (°C)**	**NEX (°C)**	**Change (%)**
ANN	11.46	12.69	10.74	5.78	7.10	22.76	17.13	18.28	6.69
JJAS	16.58	17.59	6.06	12.33	13.38	8.57	20.84	21.79	4.57
DJF	4.94	6.42	30.13	-2.08	-0.46	-77.65	11.95	13.31	11.37
MAM	11.55	12.81	10.88	5.70	7.03	23.28	17.40	18.59	6.82
ON	10.85	12.11	11.62	4.60	5.97	29.82	17.10	18.25	6.72

NHist – NEX_GDDP Historical run

Table 4.4 Annual and seasonal mean temperature projected during 2021-2050 under RCP 8.5

RCP8.5	**Mean Temperature 2021-2050**			**Minimum Temperature 2021-2050**			**Maximum Temperature 2021-2050**		
	NHist (°C)	**NEX (°C)**	**Change (%)**	**NHist (°C)**	**NEX (°C)**	**Change (%)**	**NHist (°C)**	**NEX (°C)**	**Change (%)**
ANN	11.46	12.92	12.8	5.78	7.34	27	17.13	18.5	8
JJAS	16.58	17.79	7.3	12.33	13.58	10.2	20.84	22	5.6
DJF	4.94	6.68	35.4	-2.08	-0.17	-91.9	11.95	13.54	13.3
MAM	11.55	13.02	12.8	5.7	7.25	27.3	17.4	18.8	8
ON	10.85	12.39	14.2	4.6	6.28	36.5	17.1	18.5	8.2

Table 4.5 Annual and seasonal mean temperature projected during 2070-2099 under RCP 4.5

RCP4.5	**Mean Temperature 2070-2099**			**Minimum Temperature 2070-2099**			**Maximum Temperature 2070-2099**		
	NHist (°C)	**NEX (°C)**	**Change (%)**	**NHist (°C)**	**NEX (°C)**	**Change (%)**	**NHist (°C)**	**NEX (°C)**	**Change (%)**
ANN	11.46	13.85	20.9	5.78	8.27	43.0	17.13	19.43	13.4
JJAS	16.58	18.59	12.1	12.33	14.37	16.6	20.84	22.81	9.5

DJF	4.94	7.75	57.0	-2.08	0.98	-147.3	11.95	14.52	21.5
MAM	11.55	13.98	21.0	5.70	8.16	43.2	17.40	19.80	13.8
ON	10.85	13.31	22.7	4.60	7.16	55.6	17.10	19.47	13.8

Table 4.6 Annual and seasonal mean temperature projected under RCP 8.5

RCP8.5	**Mean Temperature 2070-2099**			**Minimum Temperature 2070-2099**			**Maximum Temperature 2070-2099**		
	NHist (°C)	**NEX (°C)**	**Change (%)**	**NHist (°C)**	**NEX (°C)**	**Change (%)**	**NHist (°C)**	**NEX (°C)**	**Change (%)**
ANN	11.46	15.61	36.2	5.78	10.09	74.6	17.13	21.12	23.3
JJAS	16.58	20.16	21.6	12.33	15.98	29.7	20.84	24.34	16.8
DJF	4.94	9.70	96.5	-2.08	3.01	-245.0	11.95	16.38	37.1
MAM	11.55	15.70	35.9	5.70	9.96	74.9	17.40	21.44	23.2
ON	10.85	15.22	40.3	4.60	9.13	98.4	17.10	21.32	24.7

4.5.2 Rainfall Projections

This section discusses the future projections of rainfall under RCP 4.5 and RCP 8.5 scenarios.

Projected Annual Mean Rainfall: RCP4.5 Scenario

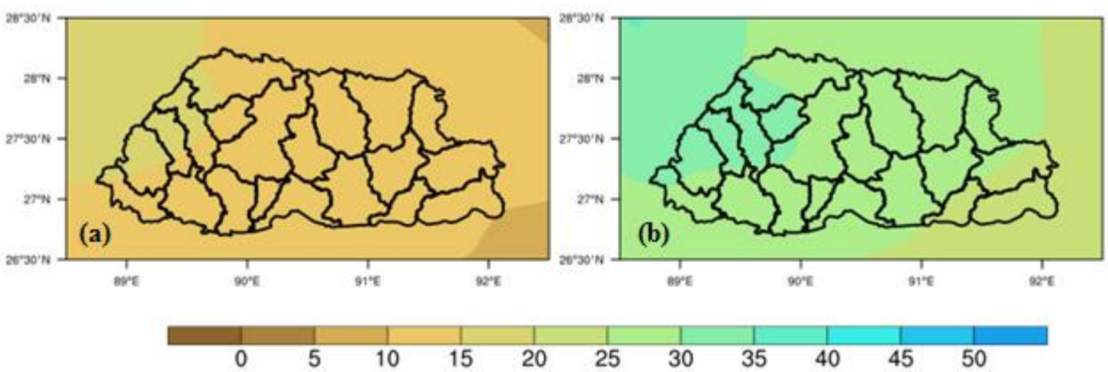


Figure 4.10 RCP4.5 Change (%) in annual mean precipitation between future and present-day climates: (a) 2021-2050 (b) 2070-2099

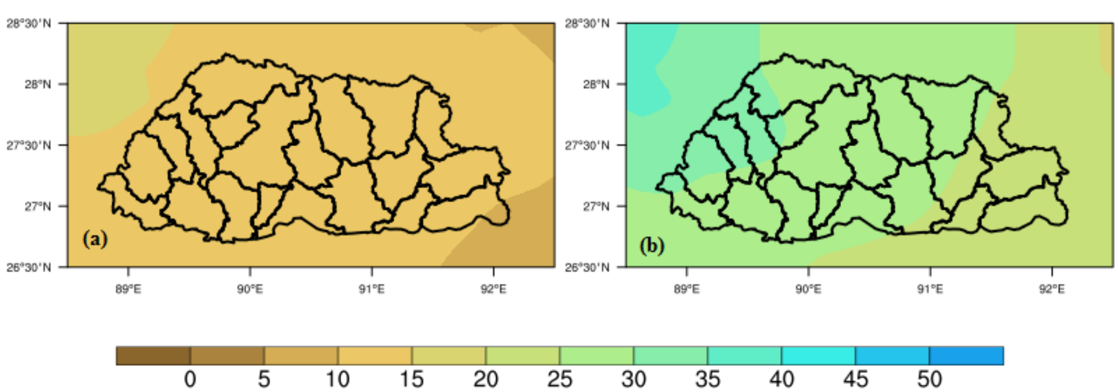


Figure 4.11 RCP4.5 Change (%) in JJAS precipitation between future and present-day climates: (a) 2021-2050 (b) 2070-2099

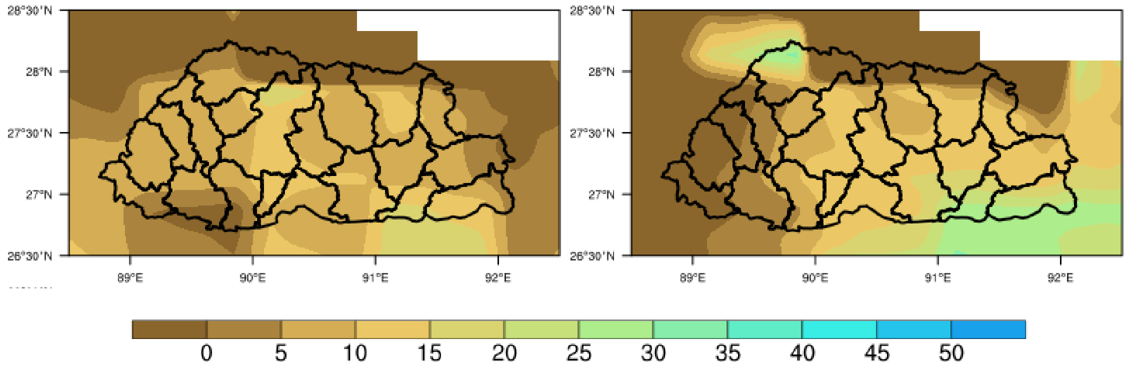


Figure 4.12 RCP 4.5 Change (%) in DJF precipitation between future and present-day climates: (a) 2021-2050 (b) 2070-2099

The figures show the percentage change in the projected rainfall in the future under the RCP 4.5 scenario. Figure 19 depicts the projected annual mean rainfall in the future (2021-2050 and 2070-2099) with respect to the baseline of 1975-2005. Bhutan is likely to experience increases in annual rainfall (10-30%) in summer (JJAS) rainfall between 5% -15 %. While the increase in rainfall is likely in DJF in Bhutan, some parts of the northern and northern west are likely to experience a decrease in rainfall. During 2021-2050, Bhutan is likely to experience increasing trends in rainfall (Figure 4.13) with a marginal decrease towards the end of the century (2070-2099).

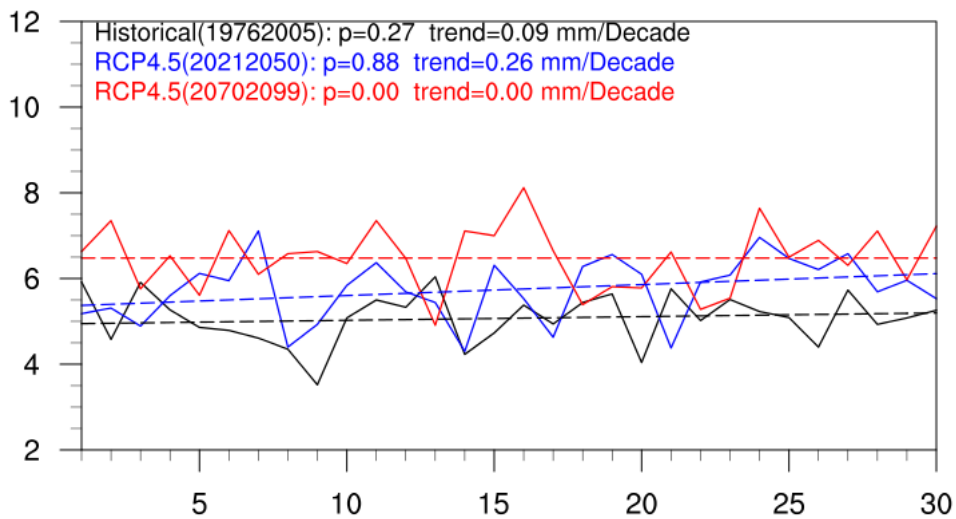


Figure 4.13 RCP 4.5 Time series and trends (mm/decade) of annual mean precipitation over Bhutan

Projected Annual Mean Rainfall: RCP 8.5 Scenario

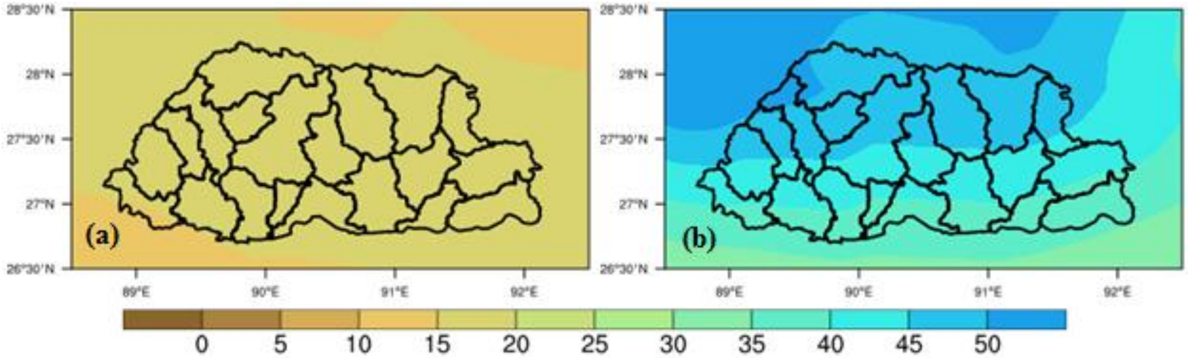


Figure 4.14 RCP 8.5 Change (%) in annual mean precipitation between future and present-day climates: (a) 2021-2050 (b) 2070-2099

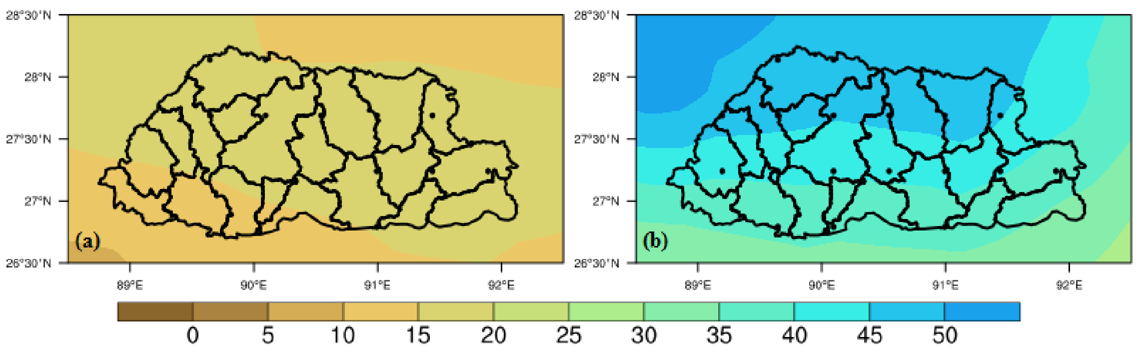


Figure 4.15 RCP 8.5 Change (%) in JJAS seasonal mean precipitation between future and present-day climates: (a) 2021-2055 (b) 2070-2099

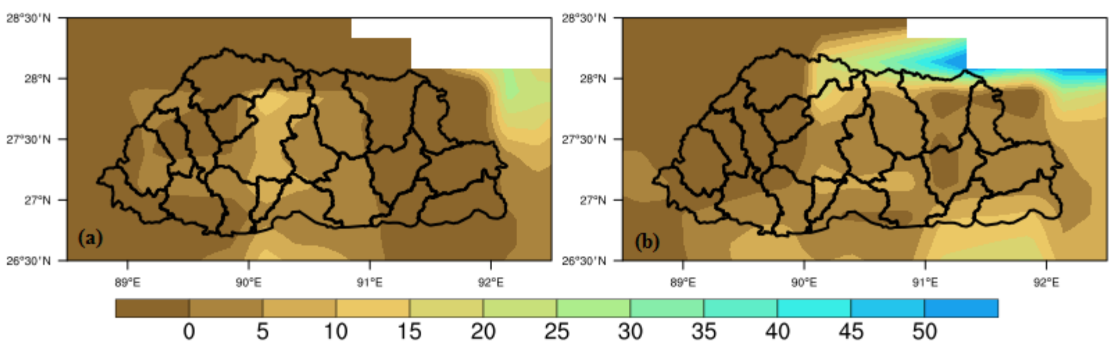


Figure 4.16 RCP 8.5 Change (%) in DJF seasonal mean precipitation between future and present-day climates: (a) 2021-2050 (b) 2070-2099

Figure 4.14 shows the projected annual mean rainfall change in the future for RCP 8.5 (2021-2050 and 2070-2099) with respect to the baseline of 1975-2005. The increase in the rainfall during 2021-2050 is in the ranges of 10-20% and with more than 30% increase all over Bhutan towards the end of the century. While the projections suggest increasing rainfall during the JJAS, the winter (DJF) seasons are likely to receive a decrease in rainfall in some parts of the country, in particular in the northwestern region of Bhutan. A marginal increase in rainfall trend is expected.

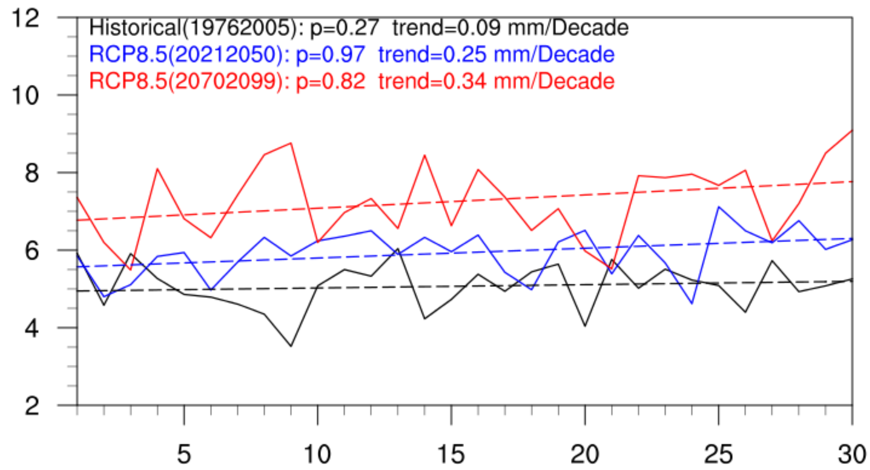


Figure 4.17 RCP 8.5 Time series and trends (mm/decade) of annual mean precipitation over Bhutan

The following tables show the projected increases of rainfall during 2021-2050 and 2070-2099 over Bhutan, on annual and seasonal time scales.

Table 4.7 Annual and seasonal mean rainfall projected under the RCP 4.5 scenario

RCP 4.5	**Rainfall projections 2021-2050 (mm/month)**			**Rainfall projections 2070-2099 (mm/month)**		
	Historical mean	**Projected mean**	**% change in rainfall**	**Historical mean**	**Projected mean**	**% change in rainfall**
Ann	152.71	173.08	13.3	152.71	195.17	27.8
DJF	2.94	3.21	9.1	2.94	3.25	10.4
JJAS	347.11	389.35	12.2	347.11	441.17	27.1

Table 4.8 Annual and seasonal mean rainfall projected under RCP 8.5 scenario

RCP 8.5	**Rainfall projections 2021-2050 (mm/month)**			**Rainfall projections 2070-2099 (mm/month)**		
	Historical mean	**Projected mean**	**% change in rainfall**	**Historical mean**	**Projected mean**	**% change in rainfall**
Ann	152.71	178.74	17.0	152.71	218.95	43.4
DJF	2.94	2.91	-0.9	2.94	2.98	1.4
JJAS	347.11	402.74	16.0	347.11	491.92	41.7

The annual number of rainy days for both RCP 4.5 and 8.5 are included in the appendix for further information.

5. CONCLUSIONS AND RECOMMENDATIONS

This study was implemented as one of the technical studies to enhance hydro-met base information under the Strategic Program for Climate Resilience Project. The findings from this study provide some initial assessments of possible future climate change over Bhutan. In this study, the analyses of historical climate and future climate changes were done. For the future climate change, the downscaled data of the NASA GEX-GDDP project was used. The NASA-GEX-GDDP is a downscaled data of CMIP5 models of the IPCC's AR5. These datasets were selected by RIMES's in their CDAAS system for South Asia. Findings have been made over Bhutan by a bi-linear interpolation to Bhutan coordinates.

The key findings from this study:

5.1 Historical climate analysis (Temperature and Rainfall)

- Bhutan has a data period from 1996-2017 during the time of the study. A simple data analysis was done on the data period from 1996-2017 over Bhutan from 15 weather stations. The analysis of the 21-year data period revealed that there was an increasing temperature trend over Bhutan.
- Analysis of data on individual stations showed a decrease in the trend of the average temperature.
- For the analysis of the historical climate, CRU dataset was used. The CRU dataset indicated similar climate signal to the observed data of Bhutan 1996-2017 with bias in values.
- The difference in the values of the CRU dataset and observed dataset of Bhutan may have resulted due to the difference in spatial resolution and data length.
- From the analysis of CRU dataset, during 1975-2005, the MAM and JJAS seasons have been warmer than ON and DJF seasons.
- For that period (1976-2005), the DJF season has been relatively cooler than the rest of the months/seasons.
- The analysis of 1996-2017 rainfall data of Bhutan revealed that the there is a marginal decrease in the trend of rainfall over Bhutan. A similar signal was shown when data from individual stations were analysed. Overall, the rainfall over Bhutan during 1996-2017 has been largely variable.
- The analysis of CRU dataset revealed that rainfall over JJAS season has been the wettest and DJF has been the driest seasons.
- The overall trends in rainfall indicated a decrease over Bhutan.

5.2 Climate projections - Temperature

- Under the RCP 4.5 scenario, the climate projection for surface temperature indicates an increase of about of 0.8^{o}C – 1.6^{o}C during 2021-2050 and about 1.6^{o} C – 2.8^{o}C towards the end of the century (2070-2099). Overall the climate projection of surface temperature under the RCP4.5 scenario indicated an increase in about of 0.8^{o}C – 2.8^{o}C during 2021-2100.
- Larger warming is indicated during MAM and DJF seasons. The country as a whole is expected to experience an increase in temperature with a larger increase projected in the high lands.

- Under the RCP 8.5 scenario, the climate projection for surface temperature indicated an increase of about 0.8ºC – 2.0ºC during 2021-2050 and increase of about 3.2ºC towards the end of the century (2070-2099).

5.3 Climate projection- Rainfall

- The mean annual rainfall over Bhutan is likely to increase in the future. Under the RCP4.5 scenarios, the annual rainfall over Bhutan indicates an increase of about 10%-30 in summer (JJAS) rainfall between 5% -15 %. While the increase in rainfall is likely in DJF in Bhutan, some parts of the northern and northern west are likely to experience a decrease in rainfall. During 2021-2050, Bhutan is likely to experience increasing trends in rainfall with a marginal decrease towards the end of the century (2070-2099).
- Under the RCP 8.5 scenario, the mean annual rainfall indicates an increase of about 10-20% during 2021-2050 and with more than 30% increase all over Bhutan towards the end of the century. While the projections suggest increasing rainfall during the JJAS, the winter (DJF) seasons are likely to receive a decrease in rainfall in some parts of the country, in particular in the northwestern region of Bhutan. A marginal increase in rainfall trend is indicated under theRCP8.5 scenarios.

5.4 Recommendations - Limitations and future scope

The climate responses of the surface temperature show good agreement amongst all the GCM simulations while the rainfall ensemble also shows strong increase. In general, the simulations of surface temperature are robust, given the temperature variable is largely homogeneous, more so given the size of the country. Rainfall at different locations are strikingly different and the models might not be able to capture this variability, primarily due to the relatively coarse resolution of the NASA dataset and the inability of this dataset to resolve terrain features well enough, which in local scale and reality are rather different Further work is required not only in thoroughly investigating the observed data but also in sourcing for better global projections that can be downscaled as suitable for Bhutan.

While the results from this study are indications of possible changes, further detailed studies are required for Bhutan. There is an urgent need to use a high resolution climate model that is able to reproduce the observed climate characteristics. To this end, future work should focus on country-specific downscaling experiments, both in the light of improving climate science and for the national capacity building. Whilst improving observations should be performed in parallel, downscaling at high spatial resolutions, as required for Bhutan's size, is crucial. This is necessitated given the country's size, deep terrain and physical features. A model that can reflect the national/local climate characteristics is strongly desired as climate projections from such a model can be deemed more credible. The results of such an exercise would also be useful for other national agencies who could use them for their own studies and operations.

It is equally important to establish a wide network of observations over the country. Globally available gridded datasets (such as CRU) might not be able to adequately reflect the climate history of the past, especially rainfall. This limitation could pose challenges when attempting to understand recent past-present changes, especially in the rainfall extremes. Due to the deep terrain and local influences, station data can give a different picture than the other datasets which cannot reflect such gradients in reality. Given that station data are more credible, efforts on scrutinizing existing data and to augment collection of new data should be set in war front at the earliest so that there is no chance for losing data records down the road. Such high resolution (spatial and temporal) shall also provide a strong basis for climate model validations whenever they are used for national studies. As aforementioned, such an exclusive high-resolution study needs to be performed to keep abreast of the evolving climate science.

Also, within the global modelling community, despite much improvements in modelling it is essential to remember that climate model projections are possible outcomes based on scenarios. Technical advancements and model improvement in the coming years could augment the use of high-resolution climate simulations to yield better and more realistic simulations of climate. Using more GCM's and higher number of ensembles are likely to provide robust multiple ensembles of probabilistic scenarios of climate change in the future. It stays with the modelling community to constrain uncertainties in models such as model physics and dynamics, incorporation of complex processes, the inclusion of land use changes, atmospheric chemistry and simulations of extreme events, to make climate projections more reliable and useful for impact studies.

The study used only a small subset of multiple climate projections available from the IPCC GCMs, and the downscaled data which have been derived by a bias-corrected statistical downscaling method are the most noticeable limitation of this study. This might underestimate the full range of uncertainties. A future study could take an ensemble approach of using multiple methods of downscaling and use a greater number of GCMs to give a wider range of possible outcomes. Such an approach will place higher confidence in the findings within a large range of climate uncertainties.

Despite these limitations, this study contributes towards providing some useful information on future climate change over Bhutan which could be useful to the Government, policymakers, stakeholders and other users for strategic planning towards climate resilience.

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APPENDICES

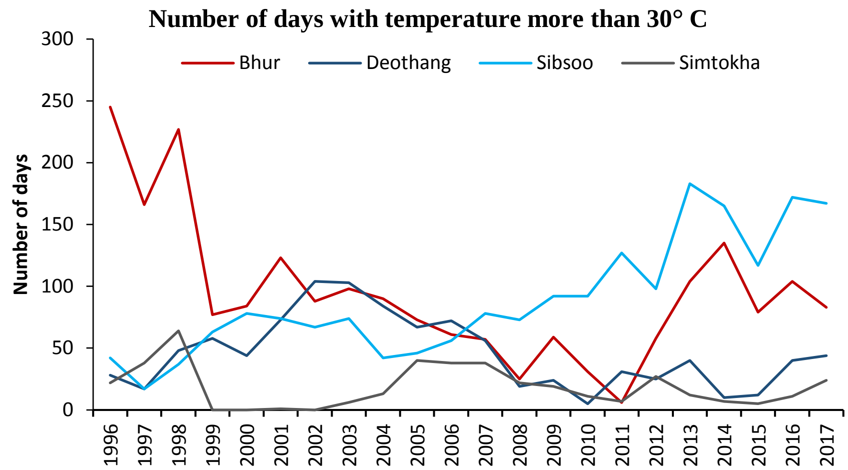

Figure 1 Number of days with a temperature greater than 30° C from observed station data

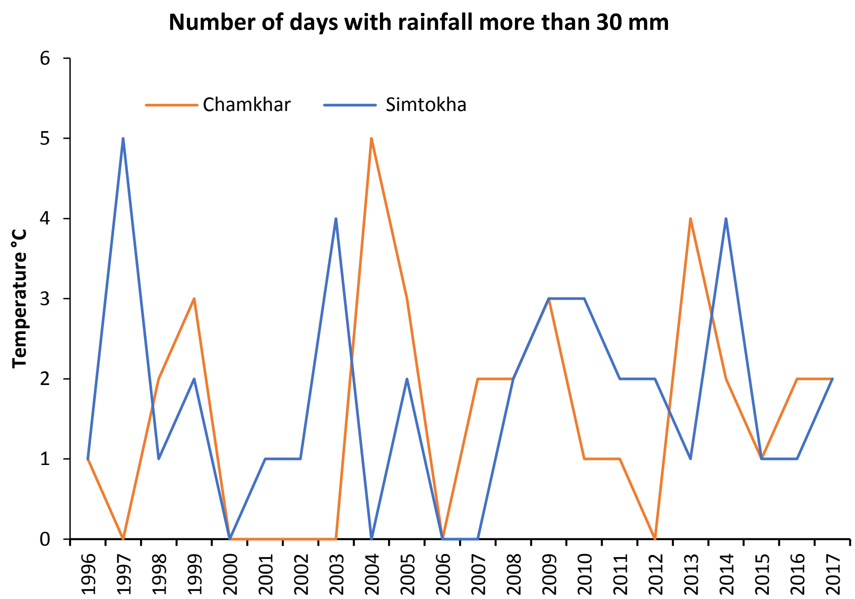

Figure 2 Number of rainy days with more than 30 mm rainfall from observed station data

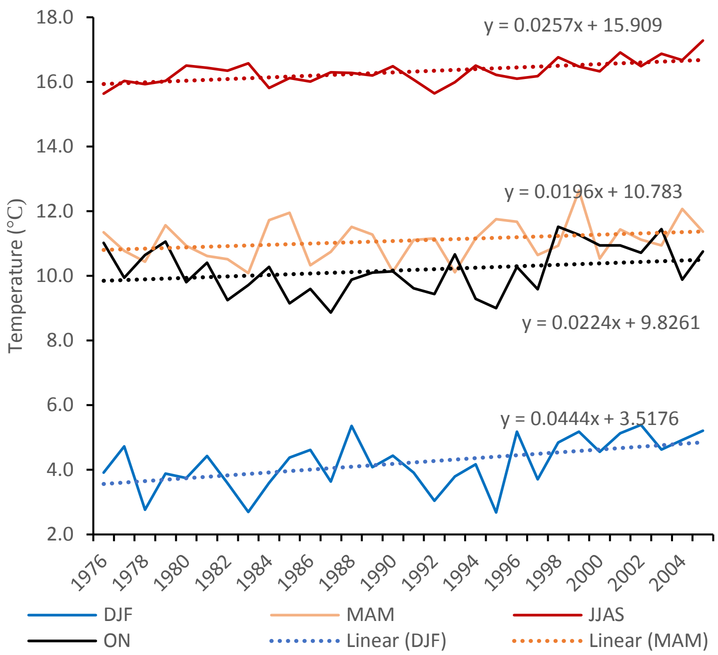

Figure 3 Time series of seasonal temperature from 1976-2005 using CRU dataset.

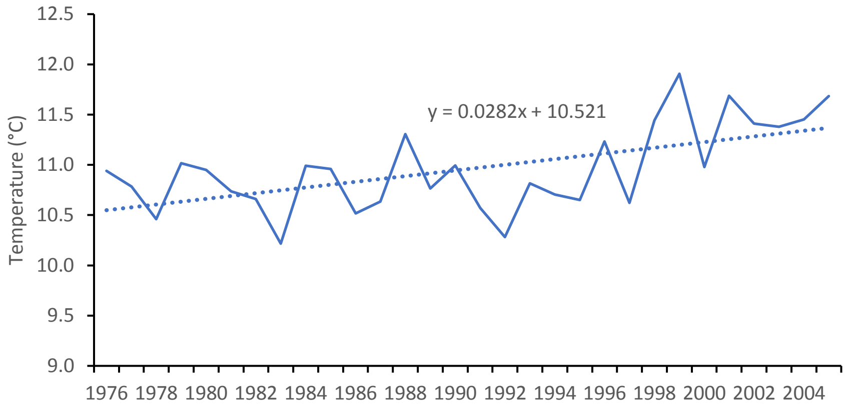

Figure 4 Time series of annual mean temperature from 1976-2005 using CRU dataset

Table 1 Number of days for rainfall greater than 10mm and 20mm during the period of 2021-2050 and 2070-2099 respectively under RCP 4.5

RCP45	Rain (10mm)	Rain (20mm)
2021	68	25
2022	65	22
2023	65	19
2024	78	26
2025	80	33
2026	72	34
2027	90	35
2028	50	19
2029	62	20
2030	69	32
2031	77	35
2032	67	26
2033	72	21
2034	53	16
2035	83	30
2036	72	24
2037	59	16
2038	78	36
2039	88	43
2040	78	30
2041	50	20
2042	73	33
2043	72	30
2044	86	42
2045	79	41
2046	79	34
2047	82	32
2048	71	32
2049	78	26
2050	69	26

RCP45	Rain (10mm)	Rain (20mm)
2070	78	36
2071	97	46
2072	72	29
2073	76	38
2074	73	23
2075	87	44
2076	74	30
2077	90	37
2078	86	35
2079	85	31
2080	95	38
2081	88	32
2082	61	22
2083	81	43
2084	86	43
2085	81	44
2086	89	36
2087	73	28
2088	77	21
2089	74	29
2090	79	39
2091	65	26
2092	68	31
2093	88	47
2094	87	30
2095	88	42
2096	80	34
2097	98	38
2098	63	28
2099	85	37

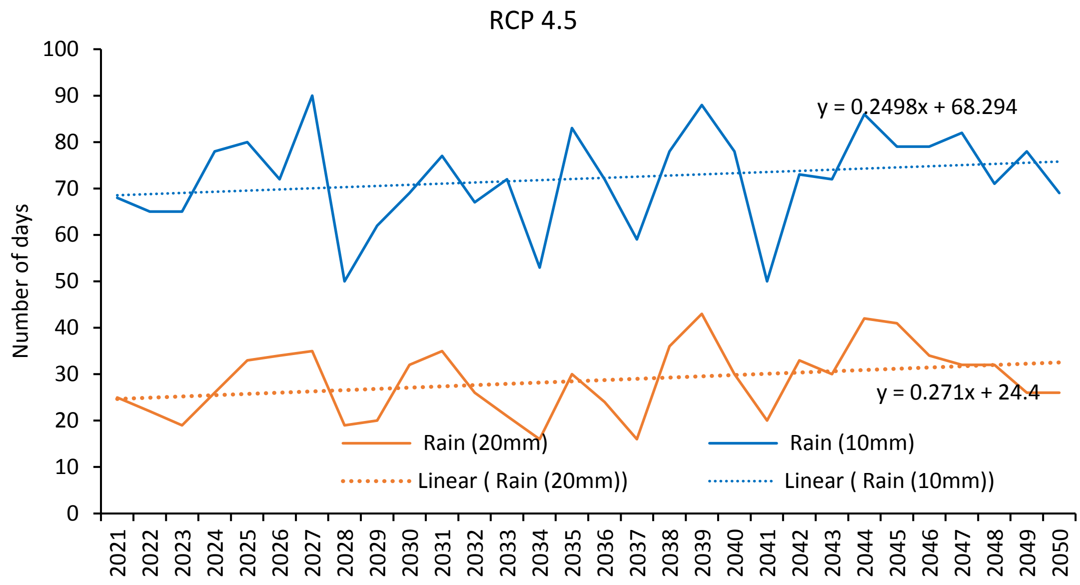

Figure 5 Shows the time series plot of the number of days with rainfall greater than 10mm (blue) and 20mm (red) for the period 2021-2050 under RCP 4.5

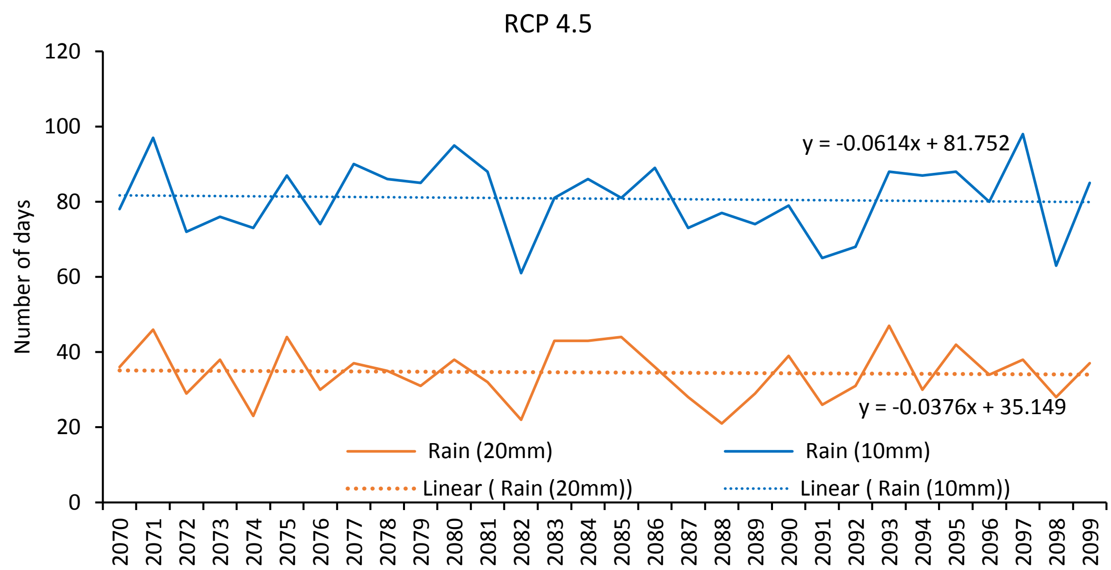

Figure 6 Shows the time series plot of the number of days with rainfall greater than 10mm (blue) and 20mm (red) for the period 2070-2099 under RCP 4.5

Table 2 The table shows the number of days for rainfall greater than 10mm and 20mm during the period of 2021-2050 and 2070-2099 respectively under RCP 8.5

RCP85	Rain (10mm)	Rain (20mm)
2021	77	30
2022	57	15
2023	57	21
2024	83	28
2025	0	0
2026	68	20
2027	69	25
2028	79	34
2029	74	32
2030	81	31
2031	85	30
2032	88	36
2033	63	29
2034	82	38
2035	72	33
2036	79	33
2037	75	28
2038	60	24
2039	80	33
2040	88	35
2041	72	21
2042	87	30
2043	75	31
2044	57	14
2045	69	34
2046	87	37
2047	72	34
2048	87	42
2049	66	31
2050	83	33

RCP85	Rain (10mm)	Rain (20mm)
2070	90	44
2071	75	36
2072	72	24
2073	98	42
2074	90	36
2075	78	34
2076	104	45
2077	92	54
2078	93	54
2079	77	33
2080	86	37
2081	92	43
2082	90	38
2083	79	45
2084	91	31
2085	107	49
2086	96	43
2087	85	36
2088	84	41
2089	65	25
2090	64	26
2091	94	44
2092	114	48
2093	97	51
2094	83	44
2095	111	49
2096	79	30
2097	84	39
2098	108	56
2099	105	58

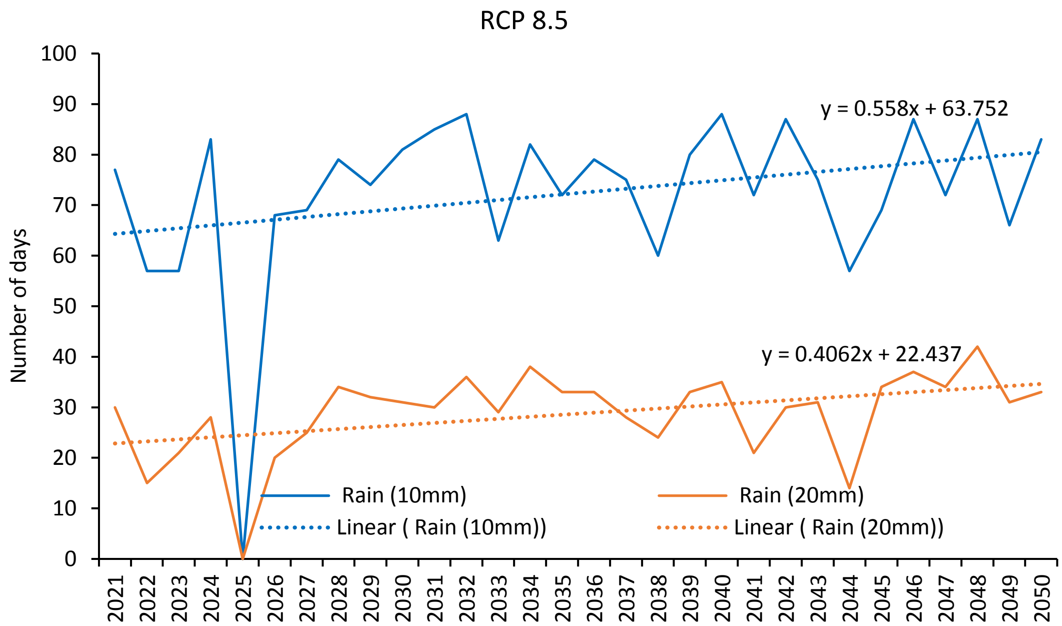

Figure 7 Shows the time series plot of the number of days with rainfall greater than 10mm (blue) and 20mm (red) for the period 2021-2050 under RCP 8.5

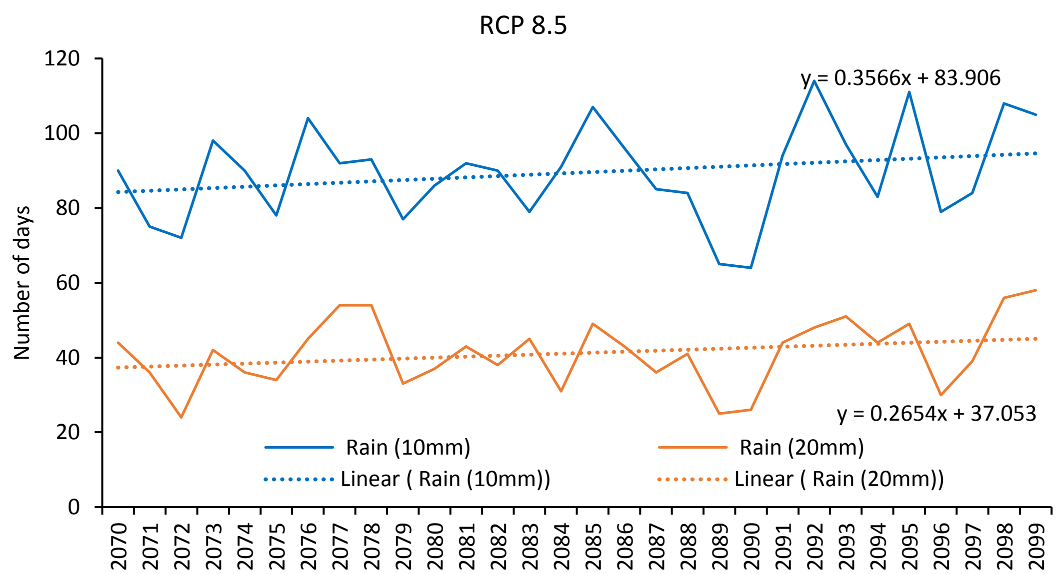

Figure 8 Shows the time series plot of the number of days with rainfall greater than 10mm (blue) and 20mm (red) for the period 2070-2099 under RCP 8.5

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