Assessing the Impact of Climate Change in Tawang River Basin, Eastern Himalayas

A Thesis

Submitted in Partial Fulfillment of the Requirements

for the Degree of

Doctor of Philosophy

by

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परिवार, प्रकृति की उत्कृष्ट कृतियों में से एक है।

–जॉर्ज संतयान (1863–1952)
दार्शनिक

परम् पूजनीय माता–पिता
एवं
आदरणीय गुरुओं
को समर्पित

भारतीय प्रौद्योगिकी संस्थान गुवाहाटी
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Statement

I hereby declare that the work embodied in this thesis entitled **Assessing the Impact of Climate Change in Tawang River Basin, Eastern Himalayas** carried out by me in the Centre for the Environment, Indian Institute of Technology Guwahati, Assam, India, under the supervision of **Prof. Chandan Mahanta** and **Prof. Anamika Barua**. Wherever I have consulted the research findings of others in the creation of this work, I have given due credit by citing them in the text of the thesis and giving their details in the references.

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Certificate

This is to certify that work described in this thesis entitled **Assessing the Impact of Climate Change in Tawang River Basin, Eastern Himalayas** by **Juna Probha Devi** (Roll No. 176152006) is an authentic record of the results obtained from the research work carried out under my supervision in the Centre for the Environment, Indian Institute of Technology Guwahati, Assam, India. I certify that she has fulfilled all the requirements according to the rules of this institute regarding the investigations embodied in her thesis and this work has not been submitted elsewhere for a degree.

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Nomenclature

Terms	Abbreviations
°C	Degree Celsius
AP	Arunachal Pradesh
AR5	Fifth Assessment Report
AR6	Sixth Assessment Report
asl	Above Sea Level
BCSD	Bias-Correction Spatial Disaggregation
CC	Climate Change
CERES	Clouds snd The Earth's Radiant Energy System
CMIP5	Coupled Model Intercomparison Project Phase 5
C_R	Runoff Coefficient for Rain
C_S	Runoff Coefficient for Snow
CSIRO-Mk3-6-0	Commonwealth Scientific and Industrial Research Organisation-Mk3-6-0
CWC	Central Water Commission
DAAC	NASA's Distributed Active Archive Center
DEM	Digital Elevation Model
DTR	Diurnal Temperature Range
Dv	Volume Difference
ECMWF	European Centre for Medium-Range Weather Forecasts
EDW	Elevation-Dependent Warming
EOS	Earth Observation System
Eq.	Equation
ERA5	Fifth Generation European Environment Agency
GCMs	General Circulation Models
GEWEX	Global Energy and Water Cycle Experiment
GFDL-CM3	Geophysical Fluid Dynamics Laboratory- Coupled Physical Model Phase 3
GIS	Geographic Information Systems
GMFD	Global Meteorological Forcing Dataset
GPM	Global Precipitation Measurement
H_0	Null Hypothesis
H_a	Alternate Hypothesis
HKH	Hindu Kush Himalayas
IHR	Indian Himalayan Rivers

IMERG	Integrated Multi-Satellite Retrievals for GPM
IPCC	Intergovernmental Panel On Climate Change
J&K	Jammu & Kashmir
Kg	Kilogram
km	Kilometre
Lat	Latitude
Long	Longitude
m	Meter
MAE	Mean Absolute Error
MCDM	Multiple Criteria Decision Making
MK	Mann-Kendall Test
mm	Millimetre
MODIS	Moderate Resolution Imaging Spectroradiometers
msl	Mean Sea Level
NASA	National Aeronautics and Space Administration
NASA LaRC	NASA Langley Research Center
NASA POWER	NASA Prediction of Worldwide Energy Resources
NASA-JAXA	NASA-Japan Aerospace Exploration Agency
NER	North East Region
Netcdf	Network Common Data Form
NEX-GDDP	NASA Earth Exchange Global Daily Downscaled Projections
NSE	Nash-Sutcliff Efficiency
NSIDC	National Snow and Ice Data Center
R	Pearson Correlation Coefficient
R^2	Coefficient of Determination
RCA	Rainfall Contributing Area
RCMS	Regional Circulation Models
RCPs	Representative Concentration Pathways
RMSE	Root Mean Square Error
RS	Remote Sensing
S	Sen's Slope Estimator
SAW	Simple Additive Weighting
SDGS	Sustainable Development Goals
SCA	Snow Cover Area
SRB	Surface Radiation Budget
SRM	Snowmelt Runoff Model
SRTM	Shuttle Radar Topography Mission
T_average	Temperature Average

T_max	Temperature Maximum
T_min	Temperature Minimum
TMPA (TRMM)	Multi-Satellite Precipitation Analysis (TRMM)
TP	Total Precipitation
TRMM	Tropical Rainfall Measuring Mission
UN	United Nations
UNCED	UN Conference on Environment and Development
UNDESA	United Nations Department of Economic and Social Affairs
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNWTO	United Nations World Tourism Organization
USGS	United States Geological Survey
V06	Version 06
W/m^2	Watts per Square Metre
WCRP	World Climate Research Program
WinSRM	Snowmelt Runoff Model for Windows
WSM	Weighted Sum Model
WSSD	World Summit on Sustainable Development
WTO	World Tourism Organization
yr	Year

Abstract

Climate change in the Himalayan region has been adversely affecting various systems- physical as well as socio-economic which the mountain people depend on. Snow plays a crucial role in the hydrological cycle, in these high-elevation regions. The Eastern Himalayas is not an exception in facing the changes. The region holds uneven topography and harsh terrain and has limited ground-based data, and thus needs a better comprehension of the hydrological cycle and water resource management. The changes in climate variables (temperature and precipitation), snow cover, and/or glacier, resulting streamflow highly influence the mountain people's lifestyle as well as livelihood. Mountain tourism is one of the socio-economic sectors that has seen the climate change impact directly. These changes are elevating in nature and are projected to be increased in the future. Taking all these facts into consideration, a framework is developed to study and assess the climate change impact on the Tawang river basin, a tributary to the Brahmaputra river in the Eastern Himalayas, in this research work. Thus, this study aims to assess the changes in snow cover area, climate change (temperature and precipitation) trends, its impact on snowmelt runoff in snow cover areas of the Mago Chu sub-basin in the Arunachal Himalayas and corresponding streamflow under different projected climatic scenarios. This thesis also study the impact of climate change on the tourism sector and livelihood that depends on the tourism sector which can be a help to the water resources management of the region and other agencies.

The precipitation and temperature trends analysis in historical and futuristic time series is done using statistical trend analysis techniques- Mann-Kendall test (MK) and Sen's slope estimator (S) and the homogeneity test using Pettitt's test. The long-term historical and future (1950-2099) trends for the NEX-GDDP data RCP4.5 and RCP8.5 on approximately 30-year timescale at annual and seasonal for precipitation and at annual, seasonal, monthly, and diurnal temperature range (DTR) for temperature maximum (T_max), temperature minimum (T_min) variations is chosen. The study is carried out in three spatial points across the Tawang Chu of Tawang district , Arunachal Pradesh. The summer means precipitation for RCP4.5 (2006-2065) shows a positive trend for point 1, point 2, and point 3, with a rise in precipitation in all the study points. The mean annual precipitation statistics for all the points show an increase for RCP4.5 in the 2006-2052 and 2053-2099 timescale. During the study, all points in both RCP4.5 and RCP8.5 display a uniform rise in mean annual T_min and T_max. Still, the inter-decadal temperature statistical analysis shows that the increase in mean annual T_min is greater than the increase in T_max, indicating a decreasing trend in DTR.

After the trend analysis, the selected dataset for the precipitation, T_max, and T_min are used for the simulation of snowmelt in the Mago Chu basin (842.294 km^2), a small

tributary to the Tawang river basin using Snowmelt Runoff Model (SRM). For the simulation of future projection of the basin discharge, the selected General Circulation Models (GCM) are used. The SRM is a degree-day-based deterministic model that uses the Snow Cover Area (SCA) and meteorological variables such as rainfall and temperature. The SCA as a critical variable for SRM is calculated using images of the SCA collected from the MODIS satellite-based product, MOD10A2. A total of 8 sub-basins are demarcated within the basin. The model performance is evaluated using the coefficient of determination (R^2), Pearson correlation coefficient (r), Nash-Sutcliff Efficiency (NSE), and Volume difference (D_v) for three different years - 2007, 2009, and 2013. The results of the SRM model in simulating daily runoff for both the calibration and validation periods were satisfactory. It is found that for the snow-dominated regions, SRM is a suitable hydrological model as it considers more snow-related parameters for modeling (such as lapse rate, recession coefficient, critical temperature, etc.). Further, runoff projections were studied using the SRM model for NEX-GDDP under two different representative concentration pathways (RCP4.5 and RCP8.5) scenarios for the years 2040, 2060, and 2090. The projections indicate an increase in the flow under RCP4.5 and RCP8.5 for the years 2040, 2060, and 2090, respectively.

The change analysis and impact assessment of the climate variables and streamflow showed that the study elements would be affected by global warming. The impact of the same may affect the mountain's livelihood, especially in the tourism sector. This part of study has been carried out in the Tawang district of Arunachal Pradesh, Eastern Himalayas, and examines the perception of climate change and its consequences in tourist industry facilities including the owners and management (hotels, restaurants, souvenir shops and transportation) in Tawang and the investigation is done using questionnaire-based survey and interviews. The purposive sampling approach is used since the study is focused on climate change perception, its influence on tourism, resilience, and adaptation to climate change. The study population is divided into four groups based on their reliance on tourism-related occupations and tourism service providers: travel/tour operators, permanent workers: hotel/restaurant/resorts, seasonal workers: hotels/restaurants/resorts, and tourism-dependent livelihoods. A total of 15 respondents have been interviewed for each of the classes with a total of 60 numbers of population samples engaged in the tourism sector. The historical meteorological data is also used to validate the perception of the respondents and the homogeneity test analysis for the period 1991-2020 - average maximum temperature (T_max), average minimum temperature (T_min), average temperature (T_average) and total precipitation (TP) from the NASA POWER. The historical meteorological data used in the study are classified into three decades from- 1991-2000, 2001-2010, and 2011-2020, for a better understanding of inter-decadal changes. The results highlight that people have a clear perception of climate change and its impact which coincides with the climate data.

It is anticipated that outcomes of this study will contribute to a better understanding of the relationship between change in climate and regional hydrological behavior. It can benefit society to develop a regional strategy for water resource management and can serve

as a resource for climate impact research scope such as assessments, adaptation, mitigation, and disaster management strategies for India's north-eastern region. The study can be used in planning a tourism-economic development nexus and in sustainable tourism initiatives.

Keywords: Climate Change Perception; Climate Change; Climate Scenarios; Eastern Himalayas; Mountain Tourism; Precipitation; Snow; Snowmelt Runoff; Sustainable Tourism; Temperature.

1

Introduction and Literature Review

1.1 IPCC- High Mountain Asia

Uneven terrain, a climate with low temperatures, steep inclines, and institutional and geographical remoteness are all characteristics of high mountain regions. Mountains frequently have cryosphere elements such as glaciers, snow cover, and permafrost, because of their higher elevation than the adjoining environment, which has a significant impact even far from the mountains on surrounding lowland areas (Huggel et al., 2015). According to gridded population estimates from 2010 (Jones and O'Neill, 2016), the proportion of the worldwide population living in the high mountainous regions is approximately 10% (671 million people).

Mountain surface air temperature data suggest 0.3°C per decade on average during the last few decades, with a plausible range of 0.2°C, exceeding the pace of global warming of 0.2±0.1°C each decade (IPCC, 2018). Seasonal variations affect local warming rates. Research comparing data from observations made at different elevations throughout the world shows that warming is typically accelerated over 500 m above sea level (asl) (Qixiang et al., 2018; Wang et al., 2016). Evidence for altitude-dependent warming, or the idea that the rate of warming varies between elevation bands, is sporadic and occasionally inconclusive both locally and regionally. Evidence from a combination of in-situ measurements, which are frequently rare at high elevations, with the remote sensing data and modeling techniques shows that warming is magnified between 4,000 m asl and 5,000 m asl at the Tibetan Plateau (Qin et al., 2009; Gao et al., 2018). Wintertime sees stronger warming in the Tibetan Plateau (Liu et al., 2009; You et al., 2010). According to studies conducted in the Nepal Himalayas (Nepal, 2016), warming is stronger at lower altitudes.

Even within mountain regions, past variations in precipitation are frequently more varied and less precisely measured than changes in temperature (Hartmann and Andresky, 2013). Decadal variability defines local patterns, which are affected by modifications to the broad-scale atmospheric circulation (Winski et al., 2017; Mankin and Diffenbaugh, 2015). Snowfall has decreased due to increased temperatures, but mountainous regions do not show a clear path of changes in yearly precipitation. According to future predictions of yearly precipitation, the Hindu Kush and the Himalayas will experience rises between 5 and 20% during the next century. Depending on the season and place, extreme precipitation event rates and severities fluctuate. For instance, it is anticipated that throughout the 21st century, extreme rainfall events would occur more frequently and with greater severity, especially during the summer monsoon season throughout the Himalayan-Tibetan Plateau mountains (Sanjay et al., 2017; Panday et al., 2015). This may signal a change towards heavier, more erratic monsoon rainfall, particularly in the easternmost Himalayan range (Palazzi et al., 2013).

An important and common element of the mountain cryosphere is snow on the ground. It has an impact on mountain ecosystems and is a significant factor in the mass movement and mountain floods. Owing to recent climate change, observations suggest a widespread drop in low-elevation snow cover area, glaciers, and permafrost. The High Mountain Asia had the least detrimental mass budgets on average (–150 ±110 kg m^{-2} yr^{-1}), despite the big regional variances. Key determinants of the commencement and growth of the snow cover, like snowfall, as well as the factors that led to the ablation, are altered by climate change elements air temperature, and radiation. In low-elevation and mid-elevation mountain regions in particular, snow cover has long been known to be highly vulnerable to climate change. Similar to its primary driving force of snowfall, the inter-annual and decadal fluctuation of the mountain snow cover is highly substantial (Mankin and Diffenbaugh, 2015; Lafaysse et al., 2014). To quantify trends, there is a need for observations covering several decades. Likewise, in several parts of the planet, High Mountain Asia also has rare long-term in situ records (Rohrer et al., 2013). For regionally based mountain snow cover monitoring, satellite remote sensing offers new capabilities. At lower elevations, the majority of the changes in snow cover area can be credited to an increase in rainfall and an increase in snowmelt, both of which are primarily caused by changes in atmospheric forcing, particularly an increase in air temperature (Martín et al., 2017; Kapnick and Hall, 2012), which is then linked to higher anthropogenic forcing. Based on climate model experiments, there are two ways to look at expected changes in mountain snow cover: downscaled and using snowpack models or directly from GCM or RCM output. An overall rise in the amount of winter snow could come from the anticipated rise in snowfall. The inter-annual variety of snow conditions is expected to persist into the 21st century at all elevations and mountain regions. Throughout the 21st century, almost all regions are expected to see a continued drop in glaciers, snow cover, and permafrost.

According to Hock et al. (2019), the amount and season of runoff have changed in river basins where snow and glaciers predominate, with local implications on water resources and farming. Due to greater precipitation occurring as rain in recent decades, winter runoff has amplified. Due to accelerated glacier melt, some glacier-fed rivers have seen increases in summer and yearly flow; yet, where glacier area has shrunk, glacier meltwater has declined. In several high mountain locations, like the Hindu Kush Himalaya, agricultural yields have decreased locally due to glacier withdrawal and changes in snow cover area.

In prior decades, a shift in timing towards early spring snowmelt discharge maxima was seen in AR5, as well as increased winter runoff. According to predictions, meltwater yields from glaciers in river basins fed by glaciers would rise for decades in many places before falling. Current research suggests that the seasonality of runoff in river basins with a dominant snow and glacier cover has undergone significant alterations. In various basins of High Mountain Asia, research has shown a rise in the average summer runoff over the previous few decades (Engelhardt et al., 2017; Reggiani and Rientjes, 2015; Duethmann et al., 2015; Mukhopadhyay and Khan, 2014).

Despite the High Mountain Asia climate scenario (Kriegel et al., 2013), projections show that numerous snow and glacier-fed rivers will continue to experience increased winter runoff due to a rise in winter snowmelt, an increase in precipitation in some basins, and more precipitation falling as rainfall. Strong evidence suggests that summer runoff will decrease throughout the 21st century in several basins of High Mountain Asia (Engelhardt et al., 2017; Prasch et al., 2013), as a result of reduced snowfall and less glacier melt after peak water (Prasch et al., 2013). Although a few percent of glacier cover numerous important river basins of High Mountain Asia during dry seasons, a global-scale assessment predicts that by 2100 (RCP8.5), a decline in glacial runoff likely lessens basin discharge by 10% or more in at least a month of the melting season (Huss and Hock, 2018).

Based on the duration of the period and schedule of the water peak, there might be increases or declines in yearly runoff in glacier-dominated basins during the twenty-first century. Peak water levels in High Mountain Asia are expected to be achieved before or around the middle of the century, according to local and regional predictions. Over 16% of the world's electricity is produced via hydropower, although certain mountainous nations use close to 100% of it (IHA, 2018; Hamududu and Killingtveit, 2012) and it is a substantial source of revenue for mountainous areas (Gaudard et al., 2016). Hydropower set-ups are anticipated to be influenced by changes in glacier runoff and snow cover area since water resources are a crucial input. In various high mountain locations, such as High Mountain Asia, both rises and declines in yearly/seasonal water intake to hydroelectric amenities have been observed (Ali et al., 2018). In some Indian basins, glacier and snow runoff to hydropower facilities is expected to decrease (Ali et al., 2018). Seasonal fluctuation in runoff has been lessened by releasing and storing water from reservoirs under sectoral demands (agricultural, drinking water,and ecosystems).

In several High Mountain Asia regions (Nüsser and Schmidt, 2017), there is evidence that decreasing streamflow caused by glacier withdrawal or lessened snow cover area has resulted in decreased water accessibility for agricultural activities. Declining cryosphere elements have a detrimental influence on leisure and tourism activities including skiing, glacier tourism, and climbing. People's quality of life has decreased in the Himalayas due to the decline, which has affected the spiritual as well as aesthetic and other mountain environments' cultural components. The effects of climate change have been attempted to be lessened through adaptation in the areas of agriculture, tourism, and supply of drinking water, though there is little information on the effectiveness of these efforts due to a lack of formal studies or institutional, technical, and financial barriers to implementation.

Irrespective of the Representative Concentration Pathway (RCPs), low elevation snow depth for 2031-2050 will probably fall by 10-40% as compared to the period 1986-2005, as would snow depth at a lower elevation for 2081-2100, presumably by 10-40% for RCP2.6 and by 50-90% for RCP8.5. Between 2015 and 2100, projected glacier mass losses from RCP2.6 to RCP8.5 ranges from 22-44% to 37-57%. In areas with predominantly smaller glaciers and little to no ice cover, by 2100, under RCP8.5, glaciers will have lost more than 80% of their existing mass, and many glaciers would melt regardless of the emission scenario. In response to anticipated alterations in snow cover loss and glacier retreat, river runoff might fluctuate in snow and/or glacier-fed river basins in quantity and with seasonal fluctuations, potentially having detrimental effects on certain areas' agriculture, hydropower, and water quality.

It is anticipated that typical snowmelt runoff from winter would increase, and spring peak periods will move earlier. There will be a peak in the average annual discharge from glaciers in all regions by the end of the twenty-first century, and will then begin to decline. Projected changes in yearly runoff vary greatly between areas and can even go the other way. In some areas, declining runoff is anticipated to lower irrigation agriculture output. As a result of snow and glacier melt, the quantity and seasonality of water supply will change, having an increasing influence on hydropower operations.

1.1.1 Why Eastern Himalayan Region: vulnerability/ sensitivity?

There is evidence that mountain communities, especially those in developing nations, are extremely susceptible to the harmful consequences of increased cryosphere-related hazards. This is due to the variety of institutional, social, and economic aspects that allow communities to appropriately prepared for, respond to, and revive from the impacts of climate change (Cutter and Morath, 2013). Few studies have carefully examined how vulnerable mountain communities are to natural disasters (Carey et al., 2017). There are a variety of factors that limit mountain communities' ability to cope with the effects of natural disasters. To aid in both long-term planning for adaptation and short-term early warning for approaching disasters, fundamental meteorological and climatic information is required (Xenarios et al., 2019; Rohrer et al., 2013). Communities might experience social and political marginalization (Marston, 2008) as incomes are often modest, and possibilities to diversify one's source of income are limited (McDowell et al., 2013). During disasters, it may be difficult for emergency personnel to reach isolated mountain valleys (Sati and Gahalaut, 2013). Land-based cultural or social connections might restrict freedom of mobility (Oliver-Smith, 1996).

Besides, due to the huge concentration of glaciers and seasonal snow, as well as the substantial population that depends on its water, the Himalayan cryosphere is studied by scientists worldwide. It is still necessary to obtain complete information, even if recent developments in remote sensing technology have made it feasible to examine glaciers in the Himalayas that had never before been studied. Moreover, research in the Himalayan region frequently concentrates on the more accessible area, leaving a sizable void in the Eastern Himalayan and Karakoram areas (Kulkarni et al., 2021).

1.1.2 Water security

Few studies offer thorough empirical studies of how cryosphere change affects the amount of water that is available for consumption. Rural regions in the Nepal Himalayas have reported decreased drinking water supplies as a result of a decreased glacier and snowmelt water (Dangi et al., 2018; McDowell et al., 2013). Populations located nearer to glaciers are more susceptible overall, particularly during dry and droughts seasons, and related challenges to water security and associated vulnerabilities vary even at small geographic scales vary even at small geographical scales (Mark et al., 2017; Buytaert et al., 2017).

The control and management of water as a resource for ecosystems and communities is affected by cryospheric changes brought on by climate change, particularly in regions where snow and glacier play a substantial role in the basin river runoff (Carey et al., 2017; Beniston and Stoffel, 2014; Hill, 2013). Except for the Karakoram, the majority of Himalayan glaciers are losing bulk, which has a detrimental impact on future water supply. To evaluate the variety of water supply in the basin, research is required (Kulkarni et al., 2021).

1.1.3 Climate change adaptation in the tourism sector

Future cryosphere change is anticipated to have a detrimental impact on cultural resources, such as peaks covered in snow and glacier in numerous UNESCO World Heritage sites, as well as the tourism industry and recreational activities in many places. Important cultural, aesthetic, and recreational amenities are provided to civilization by the mountain cryosphere (Xiao et al., 2015) and these complement tourisms by giving mountain communities and others choices for a living and financial support. Shorter snow cover seasons, greater winter precipitation that falls as rain rather than snow, diminishing glaciers, and permafrost are some of the key changes in the cryosphere that have an impact on mountain tourism and leisure. The Himalayan hiking and climbing industries are predicted to suffer as a result of current and future glacier retreats (Watson and King, 2018) and the mountains are less popular with tourists, and there is less water available, hiking in the Himalayas has also been badly impacted by the snow cover reduction (Becken et al., 2013).

In high mountain locations, the risk to infrastructure and people from cryosphere hazards has grown over the past few years, and this pattern is anticipated to stay. Landslides and floods brought on by the cryosphere may significantly impact people's lives and means of sustenance, frequently continuing for years and extending considerably beyond the region that was immediately impacted, according to empirical data from historical occurrences.

Important transportation routes being disrupted, which can influence the trading of products and services (Khanal et al., 2015; Gupta and Sah, 2008) and the decline of tourism revenue alone can have significant, sweeping, and everlasting repercussions (IHCAP, 2017; Nöthiger and Elsasser, 2004).

1.2 Climate change variables: precipitation and temperature pattern

Outside of the polar zone, the Himalayas have the highest concentration of glaciers. These glaciers provide a source of fresh water for millions of people downstream in countries. There is clear evidence that due to climate change, in recent decades, the Himalayan glaciers have melted at an unprecedented rate, causing dramatic fluctuations in freshwater flow regimes (Gurung et al., 2011). The Himalayas (Pamir Plateau) are a massive mountain range that stretches 2500 km east to west over several nations and encompasses about 67,028 glaciers with a total area of 120,162 km^2 in Bhutan, Nepal, Pakistan, Afghanistan, China, and India (IPCC, 2014). The important features that define climate change are related to climate variablesprecipitation and temperature. The elements of the two variables are increasing global temperature, cloud cover changes, abrupt changes in precipitation over land, seasonal variation in precipitation, and temperature patterns. The IPCC (2007) concluded that global temperature has seen unequivocal warming trend since 1950. Multiple hydrological phenomena, as well as the availability of water, are altering in frequency and magnitude as greenhouse gas concentrations in the atmosphere increase (Bhave et al., 2016; Sharma and Goyal, 2020; Shivam et al., 2017). According to the IPCC (2014), in the fifth assessment report (AR5), these ongoing warming trends are affecting the hydrology of the mountainous region leading to the occurrence of flash floods, drought, loss of life, and agricultural activities (Radinović and Ćurić, 2014; Sharma et al., 2011). Significant impacts of warming trends will be on the snowpack and glaciers of the mountainous systems. With the increasing trend of air temperature across the globe, the Himalayan glaciers are retreating faster than normal (Scarlett, 2011). Eventually, this will influence regional hydrology and water resources. The relationship between global warming and anthropogenic activities is closely related to each other, threatening each other. Therefore, the assessment and detection of the historical trend, changes, variability, and futuristic projections became crucial for the regions at the regional and local levels (Sharma et al., 2016; Shifteh Some'e et al., 2012). To assess the historical trend of the climatic parameters, statistical analysis proved to be very useful. Numerous statistical tests, both parametric and non-parametric, are used to analyze trends in hydro-meteorological series data at global as well as in Indian regions including observed positive and negative yearly precipitation trends (Dash et al., 2013; Duhan and Pandey, 2013; Jain et al., 2013; Kumar et al., 2010, 2022; Milentijević et al., 2020; Shivam et al., 2018; Yürekli, 2015) and rising patterns in T_max and T_min on both an annual and monthly scale (Bapuji Rao et al., 2014; Kothawale et al., 2010; Liu et al., 2019; Shivam et al., 2017). The rising number of studies on precipitation and temperature trend analysis in recent years, where the use of the non-parametric method, Mann-Kendall test, and Sen's slope estimator is extensively applied (Kousari et al., 2013; Li et al., 2018b; Mahjabin and Abdul-Aziz, 2020; Malik et al., 2020; Milentijević et al., 2020; Mir et al., 2015). Unlikely, various international and national studies on precipitation and temperature trends have been performed in mountain areas and projection using climate models; Eastern Himalayas (India) lack studies in the particular field at the spatial and temporal scales. Eastern Himalayas, covering the entire northeast part of India, are experiencing rising temperature and precipitation variables like maximum, minimum, mean, and prevailing ranges. Arunachal Pradesh, one of the major states falling in the eastern Himalayas, has glaciers and good seasonal snow cover at a higher elevation towards the northern part of the state inaccessible and has a minimal meteorological network. Due to changes in temperature and precipitation, this region is experiencing a change impact on the water resources. Only a few studies have been conducted in this large region, including temporal aspects of a few river basin boundaries, political boundaries (at the district and state levels), covering parts of the region's mountain and plain areas (Deka et al., 2016; Soraisam et al., 2018; Jhajharia et al., 2012; Gupta et al., 2021; Shivam et al., 2017; Chakraborty et al., 2017) with no reported study in the present study area. Thus, the present study is aimed at studying long-term historical and future (1950-2099) annual and seasonal precipitation trend analysis, and temperature-temperature maximum (T_max), temperature minimum (T_min) variations-annual, seasonal, monthly, and diurnal temperature range (DTR) trend analysis using statistical trend analysis techniques Mann-Kendall test (MK) and Sen's slope estimator (S). Further, the mean annual and monthly precipitation and T_min and T_max homogeneity tests are done using Pettitt's test. It is anticipated that the findings of this study will aid in a better understanding of regional hydrological behavior as well as the link between climate change and the hydrological cycle. Formulating a regional water resources management strategy will be beneficial. It might provide data for climate impact research, such as monitoring, adaptation, mitigation, and disaster management plans for the northeast Indian region.

1.3 Climate Change impact on mountain water resources

Throughout history, the human population has relied heavily on water supplies for drinking, agriculture, hydropower generation, and other purposes (Sofi et al., 2021). Mountains serve as a precursor to climate change (Kuniyal et al., 2021). A significant freshwater source for a sizable population in the nearby lowlands is found in high mountain regions around the world (Thapa et al., 2021; Viviroli et al., 2007; Barnett et al., 2005; Viviroli and Weingartner, 2004). The Himalayan Mountain System in Asia is also a contributor to large amounts of fresh water in the region. Most of the major rivers draining southern Asia originate from the Himalayas, and their catchments continue to be shielded in snow and glacier peaks (Prakash, 2020). The upstream catchments of the Indus, the Ganga, and the Brahmaputra get a substantial quantity of precipitation in the form of snow (Khan et al., 2017; Arora et al., 2010). More than 10,000 glaciers are reported in the Himalayan mountain system that supplies water to several rivers (Raina and Srivastava, 2008). The runoff in the Himalayan basins is significantly influenced by glacial meltwater, which varies annually, depending on the prevailing climate conditions (Rautela et al., 2022; Khajuria et al., 2022; Dobhal et al., 2021).

Snow cover, a crucial element of the cryosphere, plays a key role in the global climate system through its effects on the water cycle, surface energy balance, surface gas exchange, primary production, land and sea level, etc. (Stocker et al., 2013). Snow accumulation and ablation processes dominate the surface water cycle in many mountainous and interior continental regions above 40° latitudes (Hussainzada et al., 2021; Adam et al., 2009). These basins primarily store water in the form of snow, making them vulnerable to climate change and global warming (Kumar et al., 2022; Mote, 2006). Understanding the snow cover dynamics in the high mountainous regions is crucial given the significance of snow cover in mountainous areas. Due to factors like hard terrain, unfriendly climate, and others, there are typically not enough stations to monitor the dynamics of the snow in higher-elevation areas (Saloranta et al., 2019). It is challenging to measure the amount of snow cover in the mountainous basins due to the tough climate, complicated approachability, and inadequate infrastructure for communication. With the development of technologies like remote sensing (RS) methods and geographic information systems (GIS), this gap has been filled, and thus presents an amazing opportunity for prospective RS and GIS application areas in mountain climates, such as snow cover analysis (Yang et al., 2016; Khajuria et al., 2022). The datasets from remote sensing have in this instance been employed as an alternative to track the dynamics of the snow cover in such areas. The dynamics of the snow cover have been tracked using a variety of datasets, including MODIS snow cover products. These product-MODIS/Terra (MOD10A2) have an 8-day composite of snow cover which have a spatial resolution of 500 m, and the MODIS/Terra (MOD10A1) and (MOD10A2) snow cover products with similar spatial resolutions have different temporal resolutions. MOD10A1 daily snow cover product 8-day periods are utilized to construct MODIS/Terra (MOD10A2) (Thapa et al., 2021; Shrestha et al., 2015). The most widely used data from remote sensing for snow cover area (SCA) is MOD10A2, which has been utilized in numerous research simulating alpine snowmelt flow (Meng et al., 2022; Tahir et al., 2011; Tekeli et al., 2005).

Water resources in mountainous river basins are anticipated to be impacted by climate change, particularly when warming is anticipated to be greater at higher elevations, or warming based on elevation (Pepin et al., 2015; Gobiet et al., 2014; Kotlarski et al., 2012). Warmer temperatures can reduce snowfall by converting it to liquid precipitation and shortening the length of the snow cover (Bavay et al., 2013; Magnusson et al., 2010; Brown and Mote, 2009; Barnett et al., 2005; Mote, 2006). The flow rate and water resource availability in the downstream regions can be impacted by deviations in precipitation and reduced snow cover, particularly in the spring when snowmelt is more likely to predominate the river discharge (Thapa et al., 2021; Smith et al., 2017). The key sector most adversely impacted by the climate change phenomenon is water resources (Payne et al., 2004). The Intergovernmental Panel on Climate Change (IPCC) and the Assessment Report- AR5 place a strong emphasis on the water resources availability and notes that variations in temperature and precipitation will have a considerable impact on streamflow in rivers (IPCC, 2013). A rise in greenhouse gas concentrations is anticipated to increase the atmosphere's ability to hold more water, which will eventually change the hydrological cycle (Milly et al., 2002). One of the most effective ways to assess changes in water resources and the impact of climate change is through the use of General Circulation Models (GCMs) that provide future climate forecasts to simulate the hydrological basin (Xu, 1999). For the long-term projection of runoff based on future climate scenarios, the future monthly variations in precipitation and temperature projected by GCMs have been added to the base precipitation and temperature data in various studies (Khan et al., 2017). CMIP5 uses RCP-based scenarios, which incorporate adaptation policies in GCM runs. Four RCPs were defined for CMIP5 based on projections of future population growth, technological advancement, and society's response (Taylor et al., 2012). The GCMs and RCPs- 2.6, 4.5, and 8.5 scenarios have been used in numerous hydro-climatic research climate scenarios for the future (Tan et al., 2014, 2017). These RCPs were specified based on the rough estimate of radiative forcing by the year 2100 relative to the pre-industrial period (Taylor et al., 2012; van Vuuren et al., 2011). RCP2.6 is a low emission or mitigation scenario with 2.6 Wm^{-2} of a peak-and-decay value in 2100. Similarly, RCP4.5 and RCP6.0 are intermediate pathways, stabilizing radiative forcing at 4.5 Wm^{-2} and 6.0 W^{-2} after 2100. RCP8.5 is a high-emission scenario, with above 8.5 Wm^{-2} radiative forcing by 2100. The results of CMIP5 experiments were used to prepare AR5 of IPCC, where global temperature rises of 1.0°C at RCP2.6, 1.8°C at RCP4.5, 2.2°C at RCP6.0, and 3.7°C at RCP8.5 are predicted (IPCC, 2014; Taylor et al., 2012). Climate change and its impact poses a severe threat to the Himalayan mountain region (Bhutiyani et al., 2007, 2010), which is dominated by glaciers, as a result of the region's rising temperature (Singh and Kumar, 1996; Singh and Bengtsson, 2005). Alterations in precipitation and temperature patterns have an impact on the hydrology of the Himalayan region (Immerzeel et al., 2009; Chen et al., 2012; Shrestha et al., 2012). Dahal et al. (2016) showed a rise in precipitation in the investigation across an eastern Himalayan river basin, which subsequently enhances the water supply in the basin. There has been a continual rise in temperature and precipitation in the Indian Himalayan range, according to numerous recent research (Shivam et al., 2017; Singh and Goyal, 2016; Khadka et al., 2014; Bhutiyani et al., 2007). Northeast India is particularly vulnerable to global warming up and the impact of climate change, as indicated by recent studies in the region (Gupta et al., 2021; Singh and Goyal, 2016; Khadka et al., 2014; Jain et al., 2013).

The analysis of the catchment's hydrological regime is a crucial and effective strategy for managing and conserving water resources (Kushwaha et al., 2016; Jeelani et al., 2012, 2010). The mountain snowpack captures and stores a solid form of precipitation during the winter and releases it as streamflow in the spring season and summer seasons is a crucial element and component of the hydrological cycle (Jain et al., 2010; Kumar et al., 2022). In mountainous areas and basins, snowmelt runoff is essential for downstream planning, managing, and assessing water resources. To project runoff from higher elevation sites that are covered in snow and/or glaciers, snowmelt runoff modeling is an important component.

In general, two methods- the energy balance method and the temperature degree-day method are implied to compute snowmelt and following runoff. the energy balance approach can be used when there are sufficient observed data to answer the physical governing equations, however, the later approach may be more practical in the deficiency of enough observed data (Senzeba et al., 2016). The snowmelt runoff models can be categorised into lumped models, semi-distributed models, and distributed models based on the spatial distribution features of models. Lumped models suggest that the amount of snow and the rate of melting are constant throughout the watershed or the sub-basin., as shown by the Snowmelt Runoff Model (SRM). The Soil and Water Assessment Tool (SWAT), the Hydrologiska Byrns Vattenbalansavdelning (HBV), and Precipitation-Runoff Modelling System (PRMS) semi-distributed models (Leavesley et al., 1995) divides the basin into sub-basin or hydrological response units based on a particular basin attribute (elevation, vegetation cover, LULC, and physical characteristics). The basin is distributed into grids in distributed models like the Distributed Hydrology Soil Vegetation Model (DHSVM), the European Hydrological System (SHE), and Variable Infiltration Capacity (VIC), which also take into account each grid's soil freezing, wind, and snow processes. With the speedy advancement of computational power in recent years, models like the Water and Energy Budget-based Distributed Hydrological Model (WEB-DHM) (Wang et al., 2009), nested and multi-layer hybrid models are emerging. Nested calculations are utilised to understand better the snowmelt process using sub-catchments, grids, and slopes. Table 1.1 contrasts the benefits and drawbacks of popular snowmelt models.

MARTINEC (1975) designed the snowmelt runoff model (SRM), the model is conceptual, based on semi-distribution, and works on a temperature degree-day approach for modeling and forecasting daily runoff in mountainous basins from snowmelt and rainfall. The model- SRM has been widely utilized in 29 nations (Martinec et al., 2008), among others, across over 112 basins in a variety of geographic and spatial contexts (Ma et al., 2013; Boudhar et al., 2009; Sharma et al., 2012; Panday et al., 2014). These studies using the SRM demonstrated that SRM model simulations provide acceptable precision even using inadequate or fragmented ground data, including snow cover data from satellites (Senzeba et al., 2016). To provide the spatial distribution of snow cover area as input data for snowmelt runoff modeling, snow cover products from remote sensing data are thus especially helpful (Hussainzada et al., 2021; Boudhar et al., 2009). Numerous studies have used SRM with snow cover products from MODIS to account for runoff, particularly in mountainous basins with glaciers and/or snow cover (Adnan et al., 2017; Jin et al., 2019). For computing the snow cover depletion area in SRM, the regular availability of remote sensing data for geographical and temporal resolution is a valuable source. Because it has a higher spatial as well as temporal resolution, the MODIS snow cover products are commonly utilized for snow cover area (SCA) calculation as input to the SRM model (Munawar et al., 2022; Mahmood and Babel, 2013).

Table 1.1 Tabulation of different commonly used snowmelt runoff models- classified based on category, spatiotemporal resolution, snowmelt algorithm and the advantages- disadvantages of the models identified.

Model	Category	Spatio-temporal Resolution	Snow Melt Algorithm	Advantages and Disadvantages	References
SRM	Lumped and Conceptual	Daily and Elevation zone	Degree-Day	It can estimate snowmelt runoff in mountainous areas with less data because it has fewer model parameters, less input data, is adaptable and simple to use, and has high simulation accuracy. Not enough accuracy in the forecast timeframe.	Martinec and Rango (1986)
HBV	Semi-distributed and Conceptual	Daily and Elevation zone	Degree-Day	It has fewer model parameters, less input data, and is flexible and simple to use. Utilised for glacier and snow-covered field hydrological forecasting. Inadequate study of physical processes.	Bergstrom (1995)
SWAT	Semi-distributed and Physical	Daily and HRU	Degree-Day	The simulation accuracy is high, broadly used and developing, overcoming the scale of long-term large and medium watersheds. It is difficult to use when scarce monitoring data requires stringent input parameters and data requirements.	Arnold et al. (1998)
PRMS	Semi-distributed and Physical	Hourly and HRU	Energy Balance	It has the ability to model deviations in water balance, peak flood and discharge levels, water, soil, etc. along with precipitation, extreme precipitation, and snowmelt processes using various simulation functions. Additionally, the physical processes required are more extensive.	Leavesley et al. (1995)
SHE	Distributed and Physical	Hourly and Grided	Energy Balance	Both the model and its software are at a reasonably advanced stage. During the terrestrial water cycle, the simulation is significant to hydrological processes, such as sediment transport, water flow, and water quality. The model needs a lot of input data, excessive parameters, and computation.	Abbott et al. (1986)
DHSVM	Distributed and Physical	Hourly and Grided	Energy Balance	The relationships between the climate, vegetation, soil, snow cover and hydrology and feedback processes are accurately depicted in the model. It is challenging to apply when monitoring data are few and have stringent input parameters and data requirements.	Wigmosta et al. (1994)
VIC	Distributed and Physical	Hourly and Grided	Energy Balance	It is frequently used in changes in land use impact analysis, runoff projections, climate change impact analysis, and soil moisture simulations and is appropriate for applying large-scale land surface events. Contrary to mountain watersheds, the model's assumptions align with those of plain watersheds.	Liang et al. (1994)
SNOWPACK	Point-scale and physical	Hourly and point-scale	Energy Balance	The complicated snow structure may be described, and the changing properties of the internal snow structure can be simulated using only four microstructure parameters. Ideal for mountain avalanche forecasting. Gathering information on the snow water equivalent is impossible, and it is challenging to model snowmelt runoff.	Bartelt and Lehning (2002)

1.4 Climate Change impact on tourism and adaptation process

The tourism industry is considered a vulnerable and extremely climate-sensitive sector due to its strong ties to the environment and climate. According to the fifth assessment report of the IPCC (AR5), (2014), the effects of climate change are expected to increase the average world surface temperature by 2.6-4.8°C by 2100, thereby subjecting the industry to various direct and indirect effects. Many of the popular tourist destinations would lose their appeal under rising temperatures. For instance, subareas such as beach and coastal tourism, ocean and marine life tourism, forest and lake tourism, biodiversity and agricultural tourism, mountain, and snow tourism, and cities and urban center tourism face imminent danger from climate change. According to IPCC (AR6) (Pörtner et al., 2023), climate change-related economic harm has been identified in climate-exposed industries, with local impacts on forestry, agriculture, fisheries, energy, and tourism. Climate impacts numerous environmental resources that play an important role in drawing tourists to particular destinations and they would likely become less appealing due to climate change. As a consequence, revenue streams will be at significant risk. Direct effects of climate change include shifts in seasonal patterns, coastal and beach area loss, and increased coastline protection and maintenance expenses, while indirect effects include problems such as water scarcity from changing precipitation patterns. Reduced water supply, severe weather, expensive or unavailable insurance, and measures to limit emissions are just a few of the operational-level effects. Winter sports seasons are getting shorter due to rising temperatures, endangering the future of several ski resorts in turn. Finally, policy modifications and initiatives to cut emissions also impact tourism unfavorably. As per global estimates in the year 2005, tourism's share of human emissions ranged between 3.9% to 6%.

1.4.1 Sustainable tourism

Although people around the world base their vacation plans on the suitability of the weather and environment, they rarely tend to consider how their actions may affect the sustainability of the destination and the climate in the long run. During the World Summit on Sustainable Development (WSSD) in 2002, "sustainable tourism" was emphasized due to the bidirectional relationship between tourism and climate change. According to the World Tourism Organization (WTO), "sustainable tourism" is defined as tourism that takes full account of its current and future economic, social and environmental impacts, addressing the needs of visitors, the industry, the environment, and host communities (UNEP and WTO, 2005). A desirable goal of tourist strategies is now the development of sustainable tourism. It is also viewed as an adaptable paradigm (Sharpley, 2000). Though intended for a comprehensive, egalitarian, and future-focused development approach, sustainable tourism exhibits a product-focused orientation. Being one of the most climate-sensitive economic sectors, quantifying the effect of climate change on the tourist industry is a key goal of sustainable tourism (Araña et al., 2013). However, knowledge creation and capacity development are still in their infancy to educate organizations, communities, and the government on the issues and difficulties caused by climate change (Katyaini et al., 2017;

Scott, 2011; Araña et al., 2013).

1.4.2 Role of sustainable tourism in climate change adaptation and mitigation

Studies pertaining to climate change impacts on mountain tourism have reported that a decline in snow cover is expected to harm India's winter tourism (Dar et al., 2014). Water stress brought on by climate change is a significant challenge for the tourism sector in high-altitude regions (Faulon and Sacareau, 2020), and climatic unpredictability and weather extremes are already having an impact on tourism-related livelihoods and nature-based tourism (Devkota et al., 2017; Nyaupane and Chhetri, 2009; Rijal, 2013; Jasrotia and Sharma, 2020). Higher rainfall irregularity and temperature increase predicted by regional and local climate models would further affect the tourism industry (Torres et al., 2019).

Research focusing on the perspectives of tourism and climate change with respect to tourism executives (Shakeela and Becken, 2015), locals (K C et al., 2015), communities (Becken et al., 2013), lodge owners, tour guides, and visitors (Rayamajhi, 2012; Anup, 2017; Wu et al., 2017; Salpage et al., 2020) show that the stakeholders are unprepared for rapid response to adverse impacts and current adaptation efforts are also insufficient in dealing with impending climate risks (Shakeela and Becken, 2015). In South Asia, the question of how well this industry can adapt to climate change is becoming increasingly crucial. Numerous studies have concentrated on the adaptation strategies of mountainous regions (Adler et al., 2019; Nepal, 2013; Joshi et al., 2012; Bhandari, 2014).

Over the past few decades, tourism in the Indian Himalayan Region (IHR) has continued to grow and become more diverse than before, thereby making it a profitable economic sector. This development is consistent with the tourism sector estimates, which predicted a 7.9% average annual growth from 2013 through 2023. IHR has always drawn tourists and pilgrims from around the world and the subcontinent with its majestic peaks, stunning natural beauty, and abundant wildlife. People visit the IHR drawn by its mesmerizing sceneries, adventure, and sports, excellent summertime conditions, spiritual solace and calm, and the rich cultural benefits of mountain areas. These factors have made tourism a significant engine of economic expansion. According to the UN, tourism development needs to address issues like climate change, poverty alleviation, improved resource management, and inclusive economic growth. All stakeholders must engage in cooperative partnerships to achieve the Sustainable Development Goals (SDGs), now recognized as a global 17-goal action plan for people, the environment, and prosperity for all nations. Goals 8 and 12 specifically include mountain-specific tourism as an aim, in addition to many other SDGs (Gaur and Kotru, 2018).

1.4.3 Impact on Arunachal Pradesh

Comparing the North East Region (NER) to the Western Himalayas, such as Jammu & Kashmir (J&K), Uttarakhand, and Himachal Pradesh, tourism development in the NER is more recent. The states of NER aspire to overcome the isolation and economic seclusion of the past with a development strategy for the tourism industry that strongly emphasizes creating an environment that will build intrastate and interstate ties. The Government of

India's extremely laudable "Go East Policy" has recently begun attempting to remove obstacles to the economic growth of NER (Gaur and Kotru, 2018). Arunachal Pradesh continues to underutilize its tourism potential to grow its economy and increase employment. Despite the state's tremendous potential for tourism, most of it is inaccessible to visitors due to a lack of infrastructure, including transportation, communication, lodging, and other services needed to support tourism.

A significant environmental problem to tourism progress is climate change. According to data and estimates, climate change will significantly impact the industry, as would almost every other sector of the economy. However, it is first crucial to comprehend how stakeholders at the local level interpret the climate change effect and to identify the steps they have taken or are prepared to take to adapt to this new reality and mitigate potential consequences. In this respect, not many studies have thoroughly examined how the general public or certain societal groups perceive climate change and its potential implications. To guide mitigation and adaptation measures and assist stakeholders in preparing for the risks (Martín et al., 2017), especially water shortages, a deeper knowledge of public view is required. Whether the consequences of climate change are amplified or reduced in the present or the future will depend on the actions of various stakeholders (Bord et al., 1998). This study looks into the perception of climate change consequences in industry facilities among the owners and management (hotels, restaurants, and transportation) in Tawang. The objective was to ascertain what adaptation strategies have already been implemented or are intended to implement. Therefore, this objective presents the assessment and analysis of the impact of climate change on the livelihood of the mountain community in Tawang, keeping in view two different research questions- (a) how does the impact of climate change affect the livelihood of the community dependent on the tourism sector and (b) how the community adapts to these impacts? This study aims to assist the travel and tourism sector and the local population whose livelihood depends on tourism.

1.5 Problem statement

Proper management of water resources over the Himalayan catchments is essential in the present scenario. Integrated watershed management where a process of organizing and guiding land, water, and other natural resource use in a watershed to provide desired goods and services to people without affecting soil adversely and water resources can be done. In the present context, various hydrological modeling tools have been developed to assess the climate variability over the watershed in an integrated manner in the presence of physical and meteorological parameters. Apart from data input errors and uncertainties related to model structure, hydrological simulation and prediction of watershed components using advanced hydrological models in the highly variable and inaccessible topography brings several uncertainties in their outcomes. Studies say that the majority of rainfall-runoff hydrological models perform less efficiently in high-altitude regions due to precipitation gauging errors and the dominancy of snowmelt runoff. It is more complex when the watershed contains snow and glacier, and general hydrological modeling shows errors in the runoff. Thus, a comprehensive parameter-based sensitivity and uncertainty analysis under different climatic settings in the temporal scales is necessary. Eastern Himalayas, covering the entire north-east part of India, is experiencing a rising trend in both temperature and precipitation variables like maximum, minimum, and mean and prevailing ranges. Arunachal Pradesh, one of the states falling in the eastern Himalayas, is a state in northeast India that has glaciers and good seasonal snow cover at higher elevation range towards the northern part of the state which is inaccessible and has a minimal meteorological network. Due to changes in temperature and precipitation, this region is experiencing a climate change impact on the water resources. Again, this region especially the Tawang district, for its snow cover passes and mountains, waterfalls, and scenic beauty, experiences a considerable flow of tourists. The tourism sector in Tawang district is an important source of livelihood for the local community. The impact of climate change on the tourism sector can change the livelihood scenario of the area.

1.6 Research objectives

Taking all these facts into consideration, this thesis aims to evaluate the changes in snow cover area (Mago Chu basin) a sub-basin of Tawang River Basin, climate change (vairables: temperature and precipitation) trends in Tawang River Basin, its impact on snowmelt runoff in snow cover areas of the Mago Chu sub-basin in the Arunachal Himalayas and corresponding streamflow under different projected climatic scenarios. The thesis will also aim to study the impact of climate change on the tourism sector and livelihood depends on the tourism sector which can be a help to the water resources management of the region and other agencies. Based on this, the following are the research objectives of the present work:

- ⁂ To analyze the precipitation and temperature trends in historical (1981-2005) and futuristic time series (2006-2100) domains incorporating seasonal and intra-decadal variations.
- ⁂ To analyze the hydrological Snowmelt in the Tawang river (Mago Chu sub-basin) using the Snow Melt Runoff model and future projection of the streamflow for different climate change scenarios.
- ⁂ To assess and analyze the impact of climate change on the livelihood of the mountain community in the Tawang district.

Research questions

Objective 1

1. What is the trend in the precipitation and temperature in the Tawang river basin over the historical and future time series?
2. Is there any major shift in the precipitation and temperature time series in the river basin?

Objective 2

1. How the snow cover area in the upper Tawang river basin has changed between 2000-2018?
2. What is the impact of climate change- temperature and precipitation on future snowmelt runoff in the upper Tawang river catchment?

Objective 3

1. How the impact of climate change affects the livelihood of a community dependent on the tourism sector?
2. How does the community adapt/cope with these impacts?

Data and their sources

- ⁎ Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) (30 m) from the United State Geological Survey (USGS) is used for semi-automatic delineation of drainage basins and extraction of topographic elevation.
- ⁎ The Central Water Commission (CWC) discharge site- Muruga Bridge site (Lat 27°37'4.8" and Long 92°0'28.8") for air temperature-maximum and minimum; precipitation and ground station discharge data.
- ⁎ The ERA5-Land hourly precipitation, a reanalysis dataset, is used for the trend analysis taken from ECMWF (European Centre for Medium-Range Weather Forecasts). (Temperature and precipitation)
- ⁎ NASA POWER (Prediction of Worldwide Energy Resources) project data (temperature-maximum and minimum; and precipitation).
- ⁎ The Tropical Rainfall Measuring Mission (TRMM).
- ⁎ The Global Precipitation Measurement (GPM).
- ⁎ Geospatial study of Snow Cover Area in the Mago Chu sub-basin catchment by utilizing multi-spectral and multi-temporal Modis (MOD10A2) level-3 dataset (2000-2018).
- ⁎ GCM- NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP) dataset from 1950-2100, which are biased corrected and downscaled climate scenarios for two (scenarios: RCP4.5 and RCP8.5).
- ⁎ Field-based data collection using a questionnaire-based survey.

1.7 Organization of the thesis

This thesis contains five chapters. The first chapter focuses on the background, and literature review based on the three objectives, chapters second, third, and fourth cover the data source, methodology, analysis, and discussion of objectives 1, 2, and 3 findings and chapter fifth discusses the major findings from the present research and prospects on the current study.

The detail of all the chapters is mentioned below:

- Chapter 1: This chapter contains a brief background on climate change's impact on mountain ecosystems; literature review on climate variables, climate change impact on mountain water resources and climate change impact on tourism and adaptation process; problem statement; research objectives and research questions.
- Chapter 2: This chapter covers objective 1. Historical and futuristic analysis and discussion of precipitation and temperature trend in the study area coving the entire Tawang river basin.
- Chapter 3: In this chapter objective 2 is discussed. It contains the analysis of the snow cover changes and the resulting hydrological Snowmelt in the Tawang river (Mago Chu sub-basin) using the Snow Melt Runoff model and future projection of the streamflow for different climate change scenarios.
- Chapter 4: This chapter contains objective 3 discussing and assessing the climate change impact on tourism- the livelihood of the mountain community in Tawang district and the adaptation process.
- Chapter 5: The final chapter summarises the key findings from all the objectives and emphasizes a few recommendations for more research in this area.

2

Analysis of Non-Parametric Trend and Climatic Parameter Homogeneity Tests

2.1 Study area

The northern part of the Himalayan state, Arunachal Pradesh in India, is mostly covered with snow and glacier across the year. Tawang is one of the 23 districts in Arunachal Pradesh. The Tawang River (Chu) basin (shown in Fig. 2.1) with a downstream area of 2596.78 km^2 covering the entire Tawang district of Arunachal Pradesh has been selected as the study area (a large part of the upstream Tawang chu basin falls in the Tibetan region). This basin in its upstream is covered by snow cover. The Tawang chu and Nyamjang chu are the two main rivers in the basin. The Tawang chu is the confluence of the Nyukcharong chu and Mago chu flowing from the eastern and north-eastern regions of the basin. This basin is a tourist attraction place due to its snow-covered mountains and pass, scenic beauty, waterfall, and culture.

The entire basin extends between latitudes 27° 27' N and 27° 54' N and longitudes 91° 33' E and 92° 19' E, lies on the west of the state of Arunachal Pradesh. The study area is shared by national and international boundaries, surrounded by Tibet in the North, Bhutan in the West, and West Kameng district in the South-East. The entire basin ranges over 979–6443 m above mean sea level (msl). The climate is marked by elevation-related temperature variance at such varied altitudes. In winter, the temperature typically drops to the freezing point. The winter season's lowest temperature is –3°C in December, while the summer season's highest temperature is 25°C in July. The Tawang Chu basin experiences a monsoon climate, rainy or wet summers, and dry and cold winters. The monsoon season onsets at the end of May and continues till September or early October. The region experiences annual rainfall ranging from 1500 mm to 2000 mm. The winter season is dominant in October, November, December, January, and February.

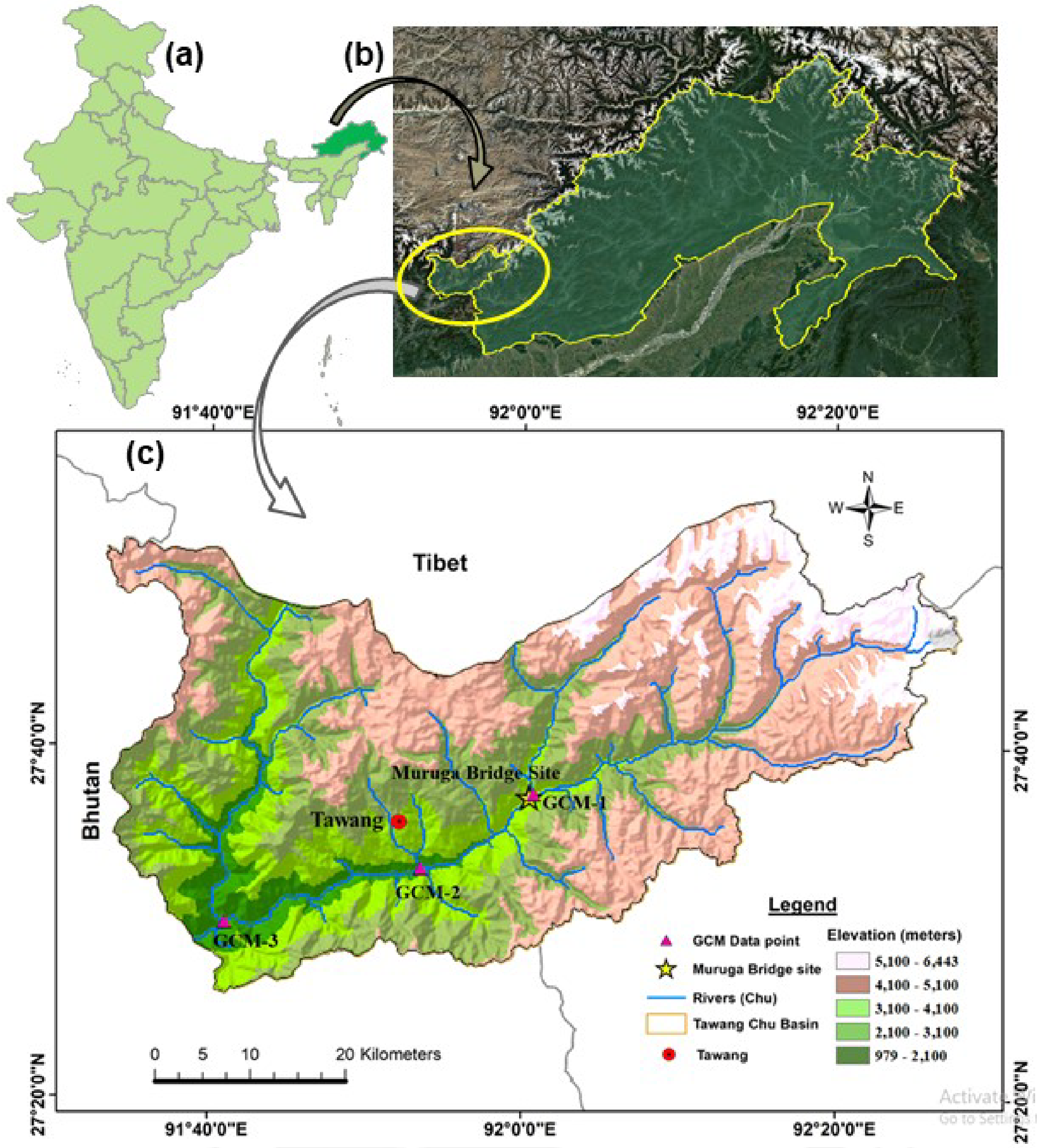

Fig. 2.1 (a) Political map of India, (b) Tawang river basin marked on the map of Arunachal Pradesh, and (c) Elevation map of Tawang river basin.

The basin is found to be mountainous and mostly bare and uninhabited. Here, three location points given in Table 2.1 are used for the study. Point 1 is used for replicating the Central Water Commission data with the suitable ERA5-Land hourly reanalysis datasets, the Tropical Rainfall Measuring Mission (TRMM), and the Global Precipitation Measurement (GPM) for precipitation; and the ERA5-Land hourly reanalysis dataset for temperature maximum (T_max) and temperature minimum (T_min).

Table 2.1 Location of study points with geographical extension and elevation.

Location point	Latitude	Longitude	Altitude (m)
Point 1	27° 37’ 04”	92° 00’ 28”	2401
Point 2	27° 33’ 03”	91° 53’ 34”	1733
Point 3	27° 29’ 59”	91° 41’ 07”	1081

2.2 Data source

2.2.1 Central Water Commission (CWC) India Datasets

In this analysis, the Central Water Commission (CWC) meteorological data- precipitation and temperature (maximum and minimum) ground station data has been utilized. The study area in its downstream has several gauge stations with varied data collection start periods, and the nearest gauge CWC station discharge site- Muruga Bridge site (Lat 27° 37' 4.8" and Long 92° 0' 28.8") is used for the study location near the basin outlet. The limited daily temperature and precipitation CWC dataset for the station are available for two consecutive years 2017 and 2018 and are used in the study to replicate with available satellite dataset or climate reanalysis datasets using statistical tests (*Appendix I (A)*).

2.2.2 Climate Datasets

The climatic data (air temperature-maximum and minimum) for the current study were collected from the NASA POWER (Prediction of Worldwide Energy Resources) project since ground data was insufficient for selecting a General Circulation Model (GCM) for trend analysis. The data for the POWER project comes from NASA's World Climate Research Program (WCRP), Global Energy and Water Cycle Experiment (GEWEX), Surface Radiation Budget Project (NASA GEWEX SRB), and Clouds and the Earth's Radiant Energy System (CERES) projects at NASA LaRC, as well as the Goddard Space Flight Center's Global Modeling and Assimilation Office (https://power.larc.nasa.gov). The ERA5-Land hourly data from the European Centre for Medium-Range Weather Forecasts (ECMWF), the Tropical Rainfall Measuring Mission (TRMM) and the IMERG data from Global Precipitation Measurement (GPM), the global successor to TRMM data has been also used to imitate the ground data for precipitation. The ERA5-Land hourly– a reanalysis dataset, comprises both temperature and precipitation datasets. The land component of the ECMWF ERA5 climate reanalysis has been replayed to create ERA5-Land. Reanalysis assimilates data from the model and observations from all across the world to create a global dataset that is both complete and consistent (Muñoz Sabater, 2019). The ERA5-Land hourly data is gridded from 1 January 1981 to 31 December 2019 with 0.1°×0.1° spatial resolution in Network Common Data Form (NetCDF) format. The TRMM is a NASA-JAXA collaborative project that was launched in 1997 to research tropical rainfall. TMPA (TRMM) data, which were used for this investigation, have a spatial resolution of 0.25°×0.25° with a coverage range of 50°N–50°N, and are accessible on a monthly basis. The latest version of the IMERG-GPM final-run product V06, released in April 2014, are also utilised. This product has a spatial resolution of 0.1°×0.1° and a coverage of 60°N–60°N (https://disc.gsfc.nasa.gov/datasets).

2.2.3 GCM- NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP) dataset

The NEX-GDDP (General Circulation Model (GCM) carried out with the Coupled Model Intercomparison Project Phase 5 (CMIP5)) dataset that consists of global downscaled climate scenarios has been used. These datasets are developed supporting the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5). It contains two scenarios: range from moderate (RCP4.5) to extreme (RCP8.5) RCP scenarios from the four Representative Concentration Pathways scenarios for greenhouse gas emissions (RCPs) with 0.25°×0.25° of spatial resolution (Melton, 2015). Daily precipitation, maximum temperature, and minimum temperature are included in each of the climatic projections for the period from 1950-2005 as a retrospective run and from 2006-2099 as a Prospective run (https://www.nccs.nasa.gov/services/data-collections/land-based-products/nex-gddp). These datasets offer a collection of global, high-resolution, bias-corrected climate change estimates that are used to assess the effects of climate change on processes that are susceptible to smaller-scale climatic gradients as well as the influence of local topography on climate conditions. The Bias-Correction Spatial Dis-aggregation (BCSD) method, which was designed expressly to overcome these existing constraints of global GCM outputs (Maurer et al., 2016; Wood et al., 2002, 2004; Thrasher et al., 2012), is used to bias-correct these datasets. The method makes adjustments to future climate estimates based on information obtained from comparing the GCM outputs with corresponding climatic observations over a common period. The programme additionally interpolates the GCM outputs to higher-resolution grids using the spatial detail offered by observationally derived datasets. The dataset used to create NEX-GDDP is known as the Global Meteorological Forcing Dataset (GMFD) for land surface modelling and is available from the Terrestrial Hydrology Research Group at Princeton University. These observed values are needed for bias correction and statistical downscaling (Sheffield et al., 2006). This dataset combines observational data with reanalysis data. The historical 0.25°×0.25° data for daily maximum temperature, daily minimum temperature, and daily precipitation from 1950 to 2005 are used to generate the NEX-GDDP dataset.

The NEX-GDDDP temperature and precipitation data have been extensively used in several hydro-climatological investigations all around the world (Jose and Dwarakish, 2022; Singh et al., 2019; Yu et al., 2018; Raghavan et al., 2018). Also, the highest resolution gridded data for climate change studies available in India is the NEX-GDDP data, which has been deemed to be the most accurate climate model data based on CMIP5 scenarios.

2.3 Methodology

2.3.1 Validation process

Data scarcity is one of the main problems in study areas with high mountain regions. Our study area has very few data stations. For analysis or any validation process, relatively large ground data is valuable. Therefore, to meet the said demand, the small temporal scale CWC data of 2017-2018 meteorological data has been validated with the ERA5-Land hourly reanalysis dataset, the Tropical Rainfall Measuring Mission (TRMM) dataset, and the Global Precipitation Measurement (GPM) dataset for precipitation (mm); and the NASA POWER along with the ERA5-Land hourly reanalysis dataset for T_max (°C) and T_min (°C). The statistical validation has been done using Pearson's Correlation coefficient (r) and Bias (%), resulting with r value- 0.91, 0.90, 0.86 and 0.88; and Bias (%) value of -14.72, -19.05, -10.34 and 34.93 for the ERA5, GPM, TRMM and NASA POWER precipitation datasets respectively. Likewise, the CWC- T_max and T_min data is also validated with the ERA5-Land hourly reanalysis and the NASA POWER dataset for T_max and T_min using the same statistical method and resulted for T_max 'r' value- 0.80 and 0.79, Bias (%) value 7.83 and 2.40; and T_min 'r' value- 0.88 and 0.87, Bias (%) value 10.23 and 4.99, respectively. From the statistical validation of CWC datasets with the ERA5 hourly, GPM, TRMM data and NASA POWER data, the NASA POWER T_max and T_min and ERA5 precipitation is justifiable and can be replicated with the CWC dataset.

The second step considered for the study is validating the NASA POWER and ERA5 data with the NEX-GDDP dataset and selecting the GCM models that are suitable to the study area. The NEX-GDDP historical data for the year 1998-2005 of 11 GCMs, as shown in Table 2.2, has been used to validate an assortment of the suitable GCM for the trend analysis. The agreement and the Bias (%) between the NASA POWER and the NEX-GDDP GCM data for T_max and T_min; and the ERA5 and the NEX-GDDP GCM data performances have been evaluated and compared using few selected statistical methods- Bias (%), Pearson's Correlation coefficient (r), Root Mean Square Error (RMSE), and Mean Absolute Error (MAE) (Kanda et al., 2020; Tang et al., 2020; Zhang et al., 2020), as shown in Table 2.3. These

Table 2.2 List of GCMs used for replicating ERA5-Land hourly reanalysis dataset.

S. No.	GCM name	Institution	Source
1	ACCESS1	Australian Community Climate and Earth-System Simulator, version 1.0	Australia
2	BNU-ESM	Beijing Normal University Earth System Model	China
3	CCSM4	National Center for Atmospheric Research	United States
4	CESM1-BGC	Community Earth System Model, version- Biogeochemistry, National Science Foundation, Department of Energy, & National Center for Atmospheric Research	United States
5	CNRM-CM5	Centre National de Recherches Meteorologiques/Centre Europeen de Recherche et Formation Avancees en Calcul Scientifique	France
6	CSIRO-Mk3-6-0	Commonwealth Scientific and Industrial Research Organization in collaboration with Queensland Climate Change Centre of Excellence	Australia
7	CanESM2	Second generation Canadian Earth System Model, Canadian Centre for Climate Modelling and Analysis (CCCma) of Environment and Climate Change Canada	Canada
8	GFDL-CM3	NASA Geophysical Fluid Dynamics Laboratory	United States
9	GFDL-ESM2G	Geophysical Fluid Dynamics Laboratory Earth System Model with Generalized Ocean Layer Dynamics (GOLD) component	United States
10	GFDL-ESM2M	Geophysical Fluid Dynamics Laboratory Earth System Model with Modular Ocean Model 4 (MOM4) component	United States
11	IPSL-CM5A-LR	L'Institut Pierre-Simon Laplace Coupled Model, version 5A	France
12	IPSL-CM5A-MR	L'Institut Pierre-Simon Laplace Coupled Model, version 5A	France

Table 2.3 List of the statistical method.

Statistical method	Equation	Optimal value
Bias (%)	$\sum_{i=1}^{n} \frac{Obs_i - Est_i}{\sum_{i=1}^{n} Obs_i} \times 100$	0
Pearsons Correlation coefficient (r)	$\frac{\sum_{i=1}^{n}(Obs_i - \overline{Obs})(Est_i - \overline{Est})}{\sqrt{\sum_{i=1}^{n}(Obs_i - (\overline{Obs})^2}\sqrt{\sum_{i=1}^{n}(Est_i - \overline{Est})^2}}$	1
Root Mean Square Error (RMSE)	$\sqrt{\frac{\sum_{i=1}^{n}\lvert Obs_i - Est_i \rvert^2}{n}}$	0
Mean Absolute Error (MAE)	$\frac{\sum_{i=1}^{n}\lvert Obs_i - Est_i \rvert}{n}$	0

[Obs_i and $\overline{Obs}$ refers to observation and mean of observation and Est_i and $\overline{Est}$ indicate to estimated value (derived from NEXGDDP data) and mean of estimated value, respectively.]

statistical methods are used for the ranking of the best GCM to be used for further steps in the study. The weighted sum model is used to rank the GCM models. The two GCMs- GFDL-CM3 and CSIRO-Mk3-6-0 are ranked 1 for temperature and precipitation, respectively, and used in the trend analysis study. The final step in the study, i.e., The Mann–Kendall (MK) test, and Sen's slope estimator are used to analyse trends in the data as shown in methodology flowchart (Fig. 2.2)

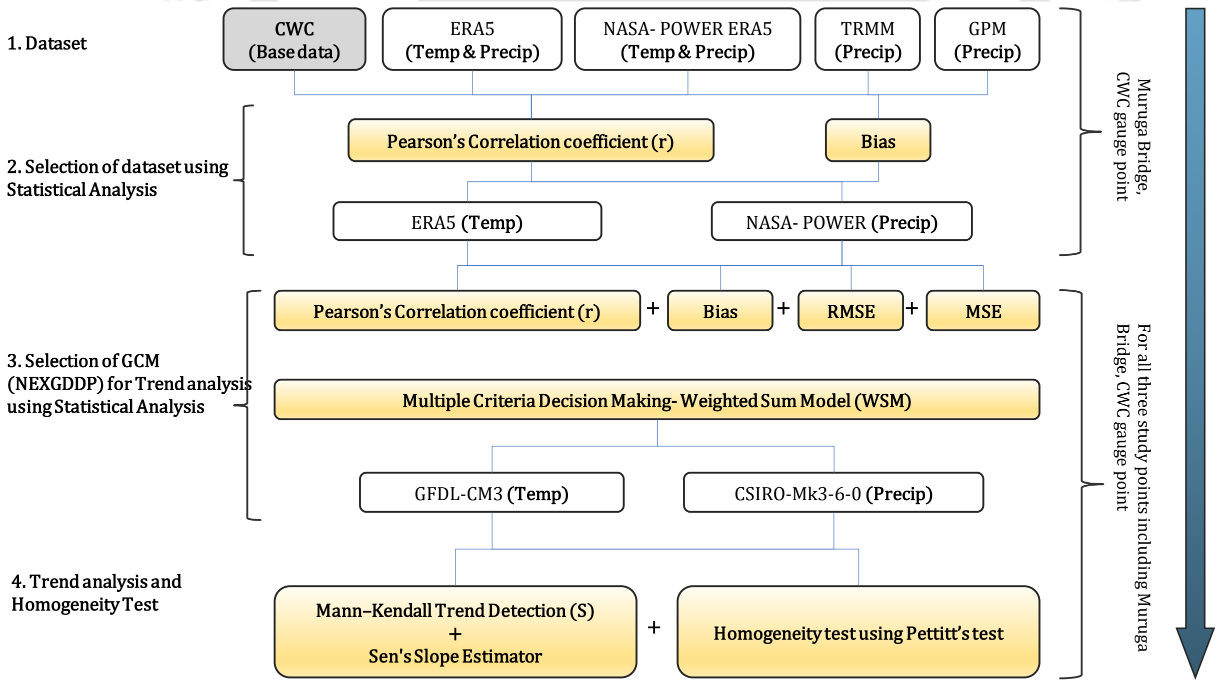

Fig. 2.2 Methodology flowchart.

The goal of this research is to investigate climate change in the study area using the appropriate bias-corrected GCM model from NEX-GDDP. Because this work only uses one GCM for one element at a time (GFDL-CM3 for temperature and CSIRO-Mk3-6-0 for precipitation), uncertainty in climate change projections induced by model uncertainty cannot be stated, as it is not recommended to perform uncertainty assessment when just one model is used (Sahany et al., 2019).

Ranking the datasets

The weighted sum model (WSM)- a multiple criteria decision making (MCDM) approach has been used for ranking the GCMs validated with ERA5. The WSM or simple additive weighting (SAW) (Eq. 2.1) is one of the simplest and most commonly used MCDM techniques (Kolios et al., 2016; Mulliner et al., 2016; Triantaphyllou, 2000) combines the criteria values for each alternative and applies the individual criteria weights.

$$A^*_{WSM} = max \sum_{i}^{m} a_{ij} w_j \tag{2.1}$$

where $i = 1, \ldots, m$, A^*_{WSM} denotes the weighted sum score, a_{ij} denotes the score of the $i-th$ option in relation to the $j-th$ criterion, and wj is the weight of the $j-th$ criterion.

2.3.2 Mann–Kendall Trend Detection

The precipitation and temperature trend tests are done using the Mann–Kendall (MK) test (Mann, 1945; Kendall, 1948), a non-parametric statistical test identifying monotonic increasing or decreasing trends. This method is extensively used in climatic variable trend analysis and to know the existence of a trend in the climatic variables (Milentijević et al., 2020; Mir et al., 2015; Sharma and Goyal, 2020; Sharma et al., 2016; Shivam et al., 2018). If the Mann–Kendall Z-value is larger than +1.96 for a significance threshold of 0.05, the test shows a significantly rising (positive) trend. If the Z-value is calculated lower than -1.96, the test shows a declining (negative) trend. The test's null hypothesis (H_0) says that there is no trend in the series. The alternate hypothesis (H_a) signifies the presence of an increasing or decreasing trend in the temporal data series. The magnitude of the trend or shift throughout the study is determined using Sen's slope estimator. Here, the MK test is used for historical and futuristic time series analysis of precipitation and temperature trends. The definition of MK statistics (S) is as follows Eq. 2.2:

$$S = \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} sgn(x_j - x_i) \tag{2.2}$$

where N is the number of data points, assuming $(x_j - x_i) = \theta$, the value of $sgn(\theta)$ (Eq. 2.3) is computed as follows:

$$sgn(\theta) = \begin{cases} 1 & \text{if} \quad \theta > 1 \\ 0 & \text{if} \quad \theta = 1 \\ -1 & \text{if} \quad \theta < 1 \end{cases} \tag{2.3}$$

For all the differences evaluated, this statistic indicates the number of positive variations minus the number of negative variations. The statistic S's (Eq. 2.4) variance is computed as follows:

$$Var(S) = \frac{N(N-1)(2N+5) - \sum_{k=1}^{n} t_k\,(t_k-1)(2t_k+5)}{18} \tag{2.4}$$

where N represents the total number of data points in the data series, n represents the number of tied groups in the set of data, and t_k represents the number of tied groups in the k^{th} tied group, respectively. The "Z-statistic" of Mann-Kendall is calculated as follows in Eq. 2.5:

$$Z = \begin{cases} \frac{s-1}{\sqrt{Var(s)}} & \text{if S} > 0 \\ 0 & \\ \frac{s+1}{\sqrt{Var(S)}} & \text{if S} < 0 \end{cases} \tag{2.5}$$

The null hypothesis of no trend is accepted or rejected at a 95 percent confidence interval depending on the Z-statistics value.

Sen's Slope Estimator

Sen's slope estimator (Eq. 2.6) is a non-parametric approach for determining the amplitude of a trend in a time series (Sen, 1968). The Sen's slope may be computed using the following formula:

$$T_i = \frac{x_j - x_k}{j-k} \quad \text{i} = 1, 2, 3, \ldots \text{N} \tag{2.6}$$

where x_j and x_k are data values at time j and k, respectively; Sen's estimate of slope (β) is the median of these N values of T_i. A positive value indicates an increasing trend in the time series, whereas a negative value suggests a downward trend.

Homogeneity test using Pettitt's test

A test for change point detection is a crucial strategy for determining when a major shift in a time series of variables occurred. In homogeneity in time series can lead to erroneous interpretations of exceptional occurrences and can be deceiving when interpreting time-series tendencies. Significant fluctuations in the mean are a common existence in time series data due to in-homogeneity. The Pettitt's test (Pettitt, 1979) is a non-parametric test that does not make any assumptions about data distribution and is commonly employed in continuous data hydrological or climatic series to detect any significant change in the data series (Ilori and Ajayi, 2020; Kocsis et al., 2020; Liu et al., 2012; Chakraborty et al., 2017). It compares the null hypothesis (H_0) where the T variables follow one or more distributions with the same location parameter is compared to the alternative hypothesis (H_a), which depicts the existence of a change point. The Pettitt's test for change point (K_T) (Eq. 2.7) statistics is described as-

$$K_T = max|U_{t,T}| \tag{2.7}$$

where,

$$U_{t,T} = \sum_{i=1}^{t} \sum_{j=t+1}^{T} sgn\ (X_i - X_j) \tag{2.8}$$

The statistic K_T is significant at probability approximated for p≤0.05.

2.4 Results and Discussion

2.4.1 Validation of GCMs

For the three study points point 1, point 2, and point 3 in the Tawang basin, the statistical method of validation and ranking of GCMs using the weighted sum model resulted in the selection of the two most suitable GCMs- GFDL-CM3 and CSIRO-Mk3-6-0 for temperature and precipitation data for further trend analysis, respectively. A boxplot is used to comprehend and evaluate the distribution and variability of datasets on a temporal scale as well as for various RCP scenarios. According to World Meteorological Organization (2017), the standard time for averaging weather variables or elements such as temperature, precipitation, and wind for defining 'climate' is 30 years. Keeping these 30 years as reference period, this study uses a time scale of 30 years based on the definition and research in precipitation and temperature trend analysis (Rivera et al., 2019; Shivam et al., 2018; Singh et al., 2015; Ruwangika et al., 2020; Dash et al., 2012; Shivam et al., 2017). Temperature and precipitation datasets are divided into three categories: historical (1950-1977 and 1978-2005), RCP4.5 scenario (2006-2035, 2036-2065, and 2066-2099), and RCP8.5 scenario (2006-2035, 2036-2065, and 2066-2099). The box-plots of points 1, 2, and 3 for precipitation on a historical and futuristic scale of approximately 30 years are shown in Fig. 2.3. In both the historic and RCP scenarios, the plot distribution reveals an overall growing trend in the mean and a broad range of variation in the lower and upper ranges of the datasets.

In contrast to scenario RCP8.5 for 2066-2099, scenario RCP4.5 for 2066-2099 shows an increasing upper and lower precipitation limit at all study locations. Fig. 2.4 shows the box-plots of points 1, 2, and 3 for T_min and T_max on a historical and futuristic scale of around 30 years, skewed in character. The plot distribution for T_min in both the historic and RCP scenarios demonstrates an overall rising trend in the mean in both the lower and upper ranges of the datasets. The RCP 8.5 scenario for 2066-2099 shows a rise in the upper and lower limits of T_min at all study locations in the box-plot. Also, T_max at points 2 and 3 shows a similar temperature distribution pattern, with the mean steadily increasing and the minimum and maximum temperature limits for the T_max increasing. At point 1, a huge difference is observed between the historic 1978-2005 and RCP 2006-2035, which later shows a dramatic increase of 11.29°C and 11.24°C in the lower and upper limits T_max, respectively.

2.4.2 Precipitation trend analysis

Fig. 2.5 shows the Mann–Kendall trend test results applied on mean annual and seasonal precipitation on a temporal scale using the GCM- CSIRO-Mk3-6-0 for the three selected study points. The three study points point 1, point 2, and point 3 are studied on an annual scale and seasonal scale (winter, summer, monsoon, and post-monsoon) for the temporal scale historical (1950-1977 and 1978-2005), RCP4.5 scenario (2006-2035, 2036-2065, and 2066

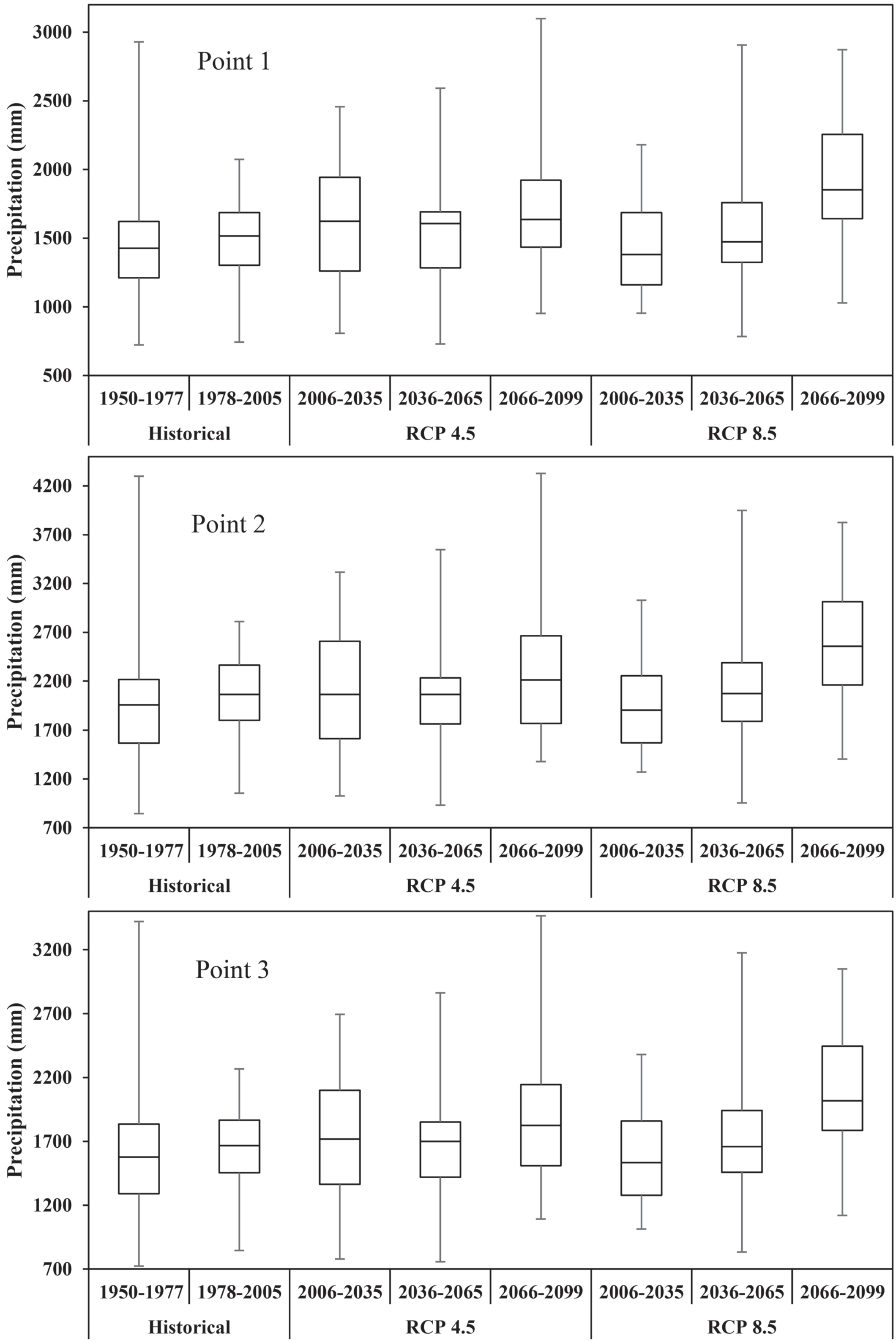

Fig. 2.3 Box-plot of historical (1950-2005) and futuristic RCP4.5 and RCP8.5 scenarios (2006-2099) precipitation for different time scale over all the study points.

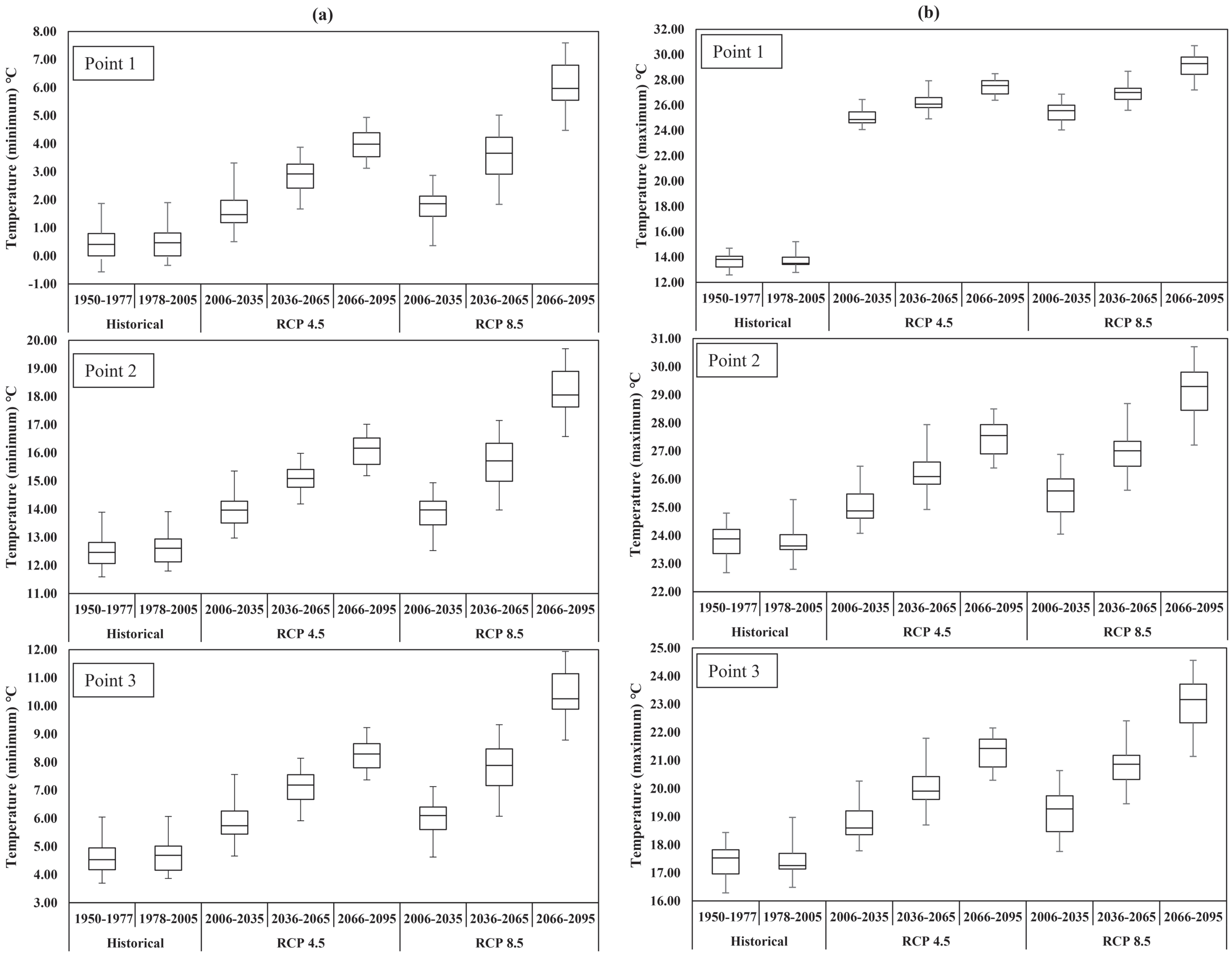

Fig. 2.4 Box-plot of historical (1950-2005) and futuristic RCP4.5 and RCP8.5 scenarios (2006-2099) temperature- (a) T_min and (b) T_max for different time scale over all the study points.

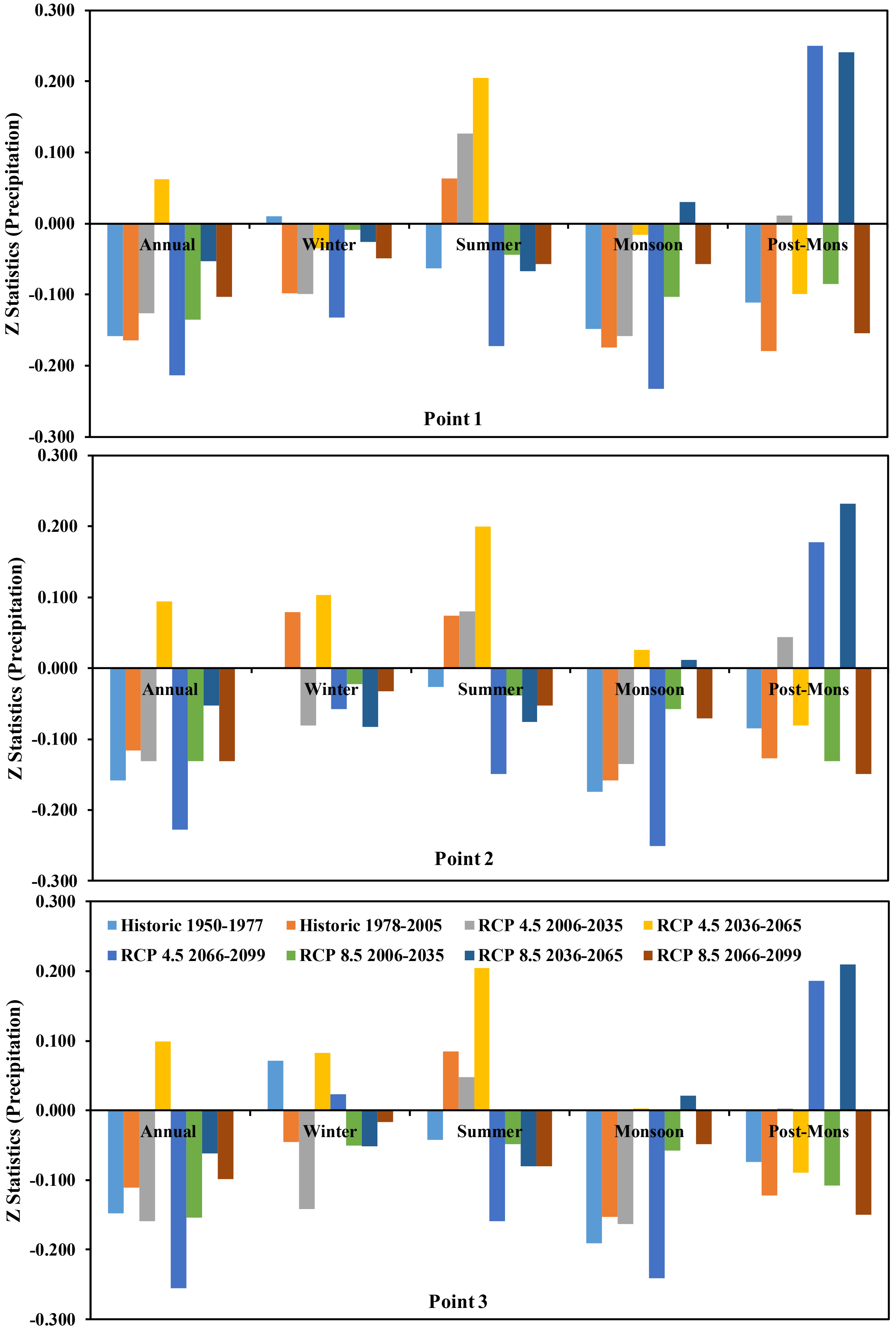

Fig. 2.5 Mann–Kendall test Z-statistics of annual and seasonal precipitation during historic period (1950-2005) and RCP4.5 and RCP8.5 scenarios (2006-2099) over all the study points.

-2099), and RCP8.5 scenario (2006-2035, 2036-2065, and 2066-2099).

At all the temporal scales and spatial scales, there is no significant trend found. Only at study point 3 with RCP4.5 for the mean annual precipitation in the intra-decadal time scale 2066-2099, a significant declining trend was observed at a 95% confidence level. Table 2.5 also shows Sen's slope magnitude of precipitation (annual) in all the basins. The maximum precipitation increase can be seen in all the study points as 9.14 mm, 0.08 mm, 9.94 mm, 2.34 mm, and 3.19 mm for the annual, winter, summer, and post-summer, respectively. The maximum precipitation decrease is as low as –22.15 mm (annual precipitation) at study point 2 for the time scale 2066-2099 at scenario RCP4.5.

Fig. 2.6 shows the trend test for the monthly precipitation at all three study points. There is a marked increasing trend observed in few months for the various time scale RCP4.5 April (2036-2065) and October (2066-2095) and a decreasing trend in August (2006-2035), June, and November (2066-2095) at point 1. A similar trend is also observed in the other 2 points for the same months. Across the months of a year, the maximum increase and maximum decrease in the magnitude of precipitation for study points 1, 2, and 3 are found in April and August -3.40 mm and -7.90 mm; 4.36 mm and -10.73 mm; 3.86 mm and -9.04 mm, respectively, as shown in Table 2.4. Although decreasing in mean annual precipitation in study point 1 is not in agreement with previous reports and studies (Government of Arunachal Pradesh, 2011; Shivam et al., 2018), but the increasing total precipitation in the later years of both RCPs in study point 2 and 3 looks in agreement with the report.

2.4.3 Temperature trend analysis

2.4.3.1 Mean maximum temperature (T_max)

Fig. 2.7(a) shows the trend in all the study points for mean T_max for all the seasons. At all the study points, the historic mean T_max has shown a negative trend, but a positive trend observed for the RCP scenarios at all the timescale. There is an overall increase in the annual, monsoon, and post-monsoon mean T_max at all the points, with the RCP8.5 scenario being the highest trend for T_max at all the seasons. The mean T_max positive trend can be seen in both the RCP8.5 at all the seasons, the highest trend in the monsoon season at the intra-decadal (2066-2099). At all the study points, for the RCP8.5, the winter season is also showing a positive trend. The magnitude of increasing or decreasing in the mean annual and seasonal T_max is shown in Table 2.6, where it can be observed that there is a maximum rise in T_max is seen in the mean monsoon and post-monsoon season at study point 1 for RCP8.5; and annual mean T_max, winter mean T_max and summer mean T_max at study point 2 for RCP8.5- 2066-2099. A maximum mean T_max is observed as 0.161°C in study point 2, and the minimum mean T_max is observed as -0.060°C at study points 1 and 2.

Similarly, the trend test for mean monthly T_max in Fig. 2.8(a) is observed to increase positively for all the months and time scale at all the study points. The historical (1950-1977) mean monthly T_max is observed to have a negative trend at all the study points for January, July, August, and September. Apart from historical (1950-1977), all other study points with

Table 2.4 Mann–Kendall test Z-statistics and Sen's slope (mm/year) for the study points (sub-basin level) of mean monthly precipitation for historical (1950-2005) and futuristic (2006-2095) with RCP4.5 and RCP8.5 scenarios.

Station	Time Scale/Months		Jan		Feb		Mar		Apr		May		Jun		Jul		Aug		Sep		Oct		Nov		Dec	
			Z	Slope	Z	Slope	Z	Slope	Z	Slope	Z	Slope	Z	Slope	Z	Slope	Z	Slope	Z	Slope	Z	Slope	Z	Slope	Z	Slope
SB 1	Historical	1950-1977	0.04	0.00	0.10	0.00	-0.12	-0.22	-0.01	-0.03	-0.05	-0.35	-0.21	-6.32	-0.10	-3.00	-0.05	-1.08	-0.14	-2.38	-0.06	-0.49	-0.04	-0.03	0.03	0.00
		1978-2005	-0.11	0.00	-0.08	0.00	0.08	0.16	0.04	0.25	0.05	0.78	-0.07	-2.42	-0.04	-0.68	-0.20	-5.38	0.03	0.68	-0.17	-1.25	0.19	0.09	-0.30	0.00
	RCP4.5	2006-2035	0.09	0.00	-0.08	0.00	-0.02	-0.06	-0.04	-0.46	0.10	1.59	-0.10	-2.29	-0.03	-0.43	-0.34	-7.90	-0.03	-0.69	-0.02	-0.22	0.19	0.11	-0.26	0.00
		2036-2065	-0.12	0.00	-0.06	0.00	0.19	0.48	0.26	3.40	0.07	1.06	-0.15	-5.15	-0.02	-0.29	-0.01	-0.10	0.06	1.16	-0.09	-0.96	0.05	0.02	-0.26	0.00
		2066-2095	-0.22	0.00	-0.08	0.00	0.13	0.32	0.03	0.52	-0.18	-2.90	-0.26	-6.91	-0.01	-0.19	0.10	2.95	-0.06	-1.15	0.29	2.17	-0.24	-0.20	-0.27	0.00
	RCP8.5	2006-2035	0.09	0.00	0.04	0.00	0.12	0.31	-0.10	-1.01	-0.01	-0.33	0.04	0.66	-0.07	-1.20	-0.22	-5.31	-0.03	-0.87	-0.09	-0.54	-0.20	-0.12	-0.05	0.00
		2036-2065	-0.04	0.00	0.02	0.00	0.04	0.14	0.18	2.97	-0.15	-2.95	-0.18	-4.49	0.02	0.16	0.16	1.99	0.12	2.65	0.23	1.92	0.05	0.02	-0.19	0.00
		2066-2095	0.13	0.00	-0.10	-0.01	-0.04	-0.21	-0.11	-2.04	0.06	1.23	-0.11	-3.29	0.13	3.27	0.11	2.97	-0.02	-0.24	-0.22	-2.29	0.05	0.02	0.11	0.00
SB 2	Historical	1950-1977	0.13	0.04	-0.07	-0.03	-0.11	-0.30	-0.06	-0.37	-0.08	-1.27	-0.17	-5.61	-0.16	-6.59	-0.09	-2.16	-0.14	-2.82	-0.03	-0.25	0.03	0.03	0.05	0.00
		1978-2005	0.02	0.01	0.10	0.03	0.04	0.14	0.02	0.48	0.05	0.89	-0.05	-2.19	-0.01	-0.14	-0.23	-7.94	0.05	1.47	-0.12	-1.28	0.13	0.08	0.19	0.00
	RCP4.5	2006-2035	0.20	0.02	-0.12	-0.02	-0.10	-0.35	-0.08	-1.15	0.14	3.44	-0.06	-5.18	0.02	0.71	-0.36	-10.73	-0.07	-2.09	-0.02	-0.45	0.18	0.14	0.11	0.00
		2036-2065	-0.17	-0.04	0.16	0.06	0.22	1.00	0.24	4.36	0.05	1.27	-0.14	-4.66	0.08	1.46	0.01	0.22	0.05	1.57	-0.04	-1.42	0.08	0.08	0.08	0.00
		2066-2095	-0.09	-0.02	-0.09	0.00	0.05	0.17	0.03	0.66	-0.20	-4.46	-0.20	-9.31	-0.03	-1.52	0.08	2.37	-0.06	-1.52	0.24	2.79	-0.32	-0.56	-0.01	0.00
	RCP8.5	2006-2035	0.13	0.05	-0.02	0.00	0.13	0.66	-0.09	-1.83	0.01	0.21	0.05	1.28	-0.04	-0.95	-0.21	-7.03	-0.04	-0.92	-0.12	-1.12	-0.24	-0.31	-0.05	0.00
		2036-2065	-0.06	0.00	-0.12	0.00	-0.03	-0.15	0.13	2.47	-0.14	-4.01	-0.16	-5.80	-0.03	-0.66	0.10	2.84	0.05	0.87	0.24	3.05	0.02	0.02	0.18	0.00
		2066-2095	-0.20	-0.05	-0.08	0.00	-0.10	-0.57	-0.16	-3.71	0.03	0.53	-0.09	-3.19	0.02	0.81	0.10	3.78	-0.10	-2.34	-0.21	-1.96	-0.02	-0.05	-0.05	0.00
SB 3	Historical	1950-1977	0.22	0.00	-0.06	0.00	-0.09	-0.17	-0.03	-0.14	-0.10	-1.04	-0.17	-6.24	-0.14	-4.97	-0.06	-1.32	-0.16	-2.65	-0.03	-0.19	-0.01	0.00	0.05	0.00
		1978-2005	-0.11	-0.02	0.11	0.01	0.04	0.07	0.04	0.20	0.06	1.80	-0.07	-1.95	0.04	0.81	-0.22	-5.82	0.06	1.43	-0.12	-0.89	0.15	0.06	-0.05	0.00
	RCP4.5	2006-2035	0.06	0.00	-0.14	-0.01	-0.10	-0.17	-0.08	-0.63	0.07	1.55	-0.09	-4.12	0.01	0.41	-0.34	-9.04	-0.04	-0.87	-0.04	-0.44	0.15	0.09	-0.10	0.00
		2036-2065	-0.06	0.00	0.08	0.00	0.22	0.51	0.25	3.86	0.07	1.55	-0.15	-4.24	0.05	1.51	0.00	0.11	0.04	0.96	-0.08	-0.96	0.09	0.06	0.11	0.00
		2066-2095	-0.13	0.00	-0.05	0.00	0.09	0.16	0.03	0.68	-0.18	-3.55	-0.24	-8.15	-0.05	-1.45	0.09	3.02	-0.03	-1.09	0.25	2.12	-0.33	-0.35	-0.02	0.00
	RCP8.5	2006-2035	0.05	0.00	0.10	0.00	0.14	0.40	-0.10	-1.28	0.00	0.07	0.00	0.05	-0.07	-1.63	-0.19	-5.94	-0.03	-0.37	-0.10	-0.64	-0.20	-0.16	-0.05	0.00
		2036-2065	-0.11	0.00	-0.04	0.00	-0.06	-0.13	0.12	2.30	-0.13	-2.39	-0.16	-4.05	-0.03	-0.59	0.11	1.91	0.06	0.95	0.23	2.31	0.00	0.00	0.28	0.00
		2066-2095	-0.19	0.00	-0.10	0.00	-0.10	-0.41	-0.17	-3.56	0.04	0.61	-0.07	-1.97	0.03	1.41	0.11	2.95	-0.07	-1.72	-0.18	-1.40	-0.02	0.00	-0.02	0.00

[Bold numbers show a significant trend at a 95% confidence level.]

Table 2.5 Mann–Kendall test Z-statistics and Sen's slope (mm/year) for the study points with mean annual and seasonal precipitation for historical (1950–2005) and futuristic (2006-2095) for RCP4.5 and RCP8.5 scenarios.

Station	Time Scale/Seasons		Annual		Winter		Summer		Monsoon		Post-Monsoon	
			Z	Slope	Z	Slope	Z	Slope	Z	Slope	Z	Slope
SB 1	Historical	1950-1977	-0.16	-12.26	0.01	0.00	-0.06	-1.37	-0.15	-6.77	-0.11	-1.00
		1978-2005	-0.16	-8.94	-0.10	-0.01	0.06	2.70	-0.17	-7.96	-0.18	-1.10
	RCP4.5	2006-2035	-0.13	-10.56	-0.10	-0.01	0.13	2.75	-0.16	-11.55	0.01	0.07
		2036-2065	0.06	3.48	-0.03	0.00	0.20	5.94	-0.02	-1.68	-0.10	-0.85
		2066-2095	-0.21	-18.58	-0.13	-0.01	-0.17	-5.79	-0.23	-12.15	0.25	1.96
	RCP8.5	2006-2035	-0.14	-7.98	-0.01	0.00	-0.04	-1.46	-0.10	-6.41	-0.09	-0.83
		2036-2065	-0.05	-2.97	-0.03	0.00	-0.07	-3.56	0.03	2.34	0.24	2.45
		2066-2099	-0.10	-11.97	-0.05	-0.01	-0.06	-2.09	-0.06	-3.43	-0.15	-1.56
SB 2	Historical	1950-1977	-0.16	-18.16	0.00	0.00	-0.03	-1.10	-0.17	-10.49	-0.08	-0.77
		1978-2005	-0.12	-9.84	0.08	0.08	0.07	4.00	-0.16	-8.21	-0.13	-1.06
	RCP4.5	2006-2035	-0.13	-14.38	-0.08	-0.06	0.08	3.51	-0.14	-12.38	0.04	0.68
		2036-2065	0.09	9.14	0.10	0.08	0.20	9.94	0.03	1.11	-0.08	-1.55
		2066-2099	-0.23	-22.15	-0.06	-0.04	-0.15	-7.82	-0.25	-20.62	0.18	2.80
	RCP8.5	2006-2035	-0.13	-10.84	-0.02	-0.02	-0.04	-0.75	-0.06	-6.40	-0.13	-1.68
		2036-2065	-0.05	-5.88	-0.08	-0.07	-0.08	-6.61	0.01	0.95	0.23	3.19
		2066-2099	-0.13	-20.45	-0.03	-0.04	-0.05	-4.70	-0.07	-9.85	-0.15	-2.54
SB 3	Historical	1950-1977	-0.15	-15.25	0.07	0.03	-0.04	-1.46	-0.19	-8.62	-0.07	-0.69
		1978-2005	-0.11	-6.16	-0.05	-0.01	0.08	3.88	-0.15	-6.69	-0.12	-0.87
	RCP4.5	2006-2035	-0.16	-13.83	-0.14	-0.05	0.05	1.56	-0.16	-13.46	0.00	0.02
		2036-2065	0.10	7.78	0.08	0.03	0.20	7.26	0.00	0.63	-0.09	-1.15
		2066-2099	**-0.26**	-21.57	0.02	0.00	-0.16	-7.24	-0.24	-17.29	0.19	1.83
	RCP8.5	2006-2035	-0.15	-8.74	-0.05	-0.01	-0.05	-1.10	-0.06	-3.63	-0.11	-1.03
		2036-2065	-0.06	-4.46	-0.05	-0.01	-0.08	-4.08	0.02	0.70	0.21	2.65
		2066-2099	-0.10	-12.47	-0.02	0.00	-0.08	-3.68	-0.05	-4.95	-0.15	-1.50

[Bold numbers show a significant trend at a 95% confidence level.]

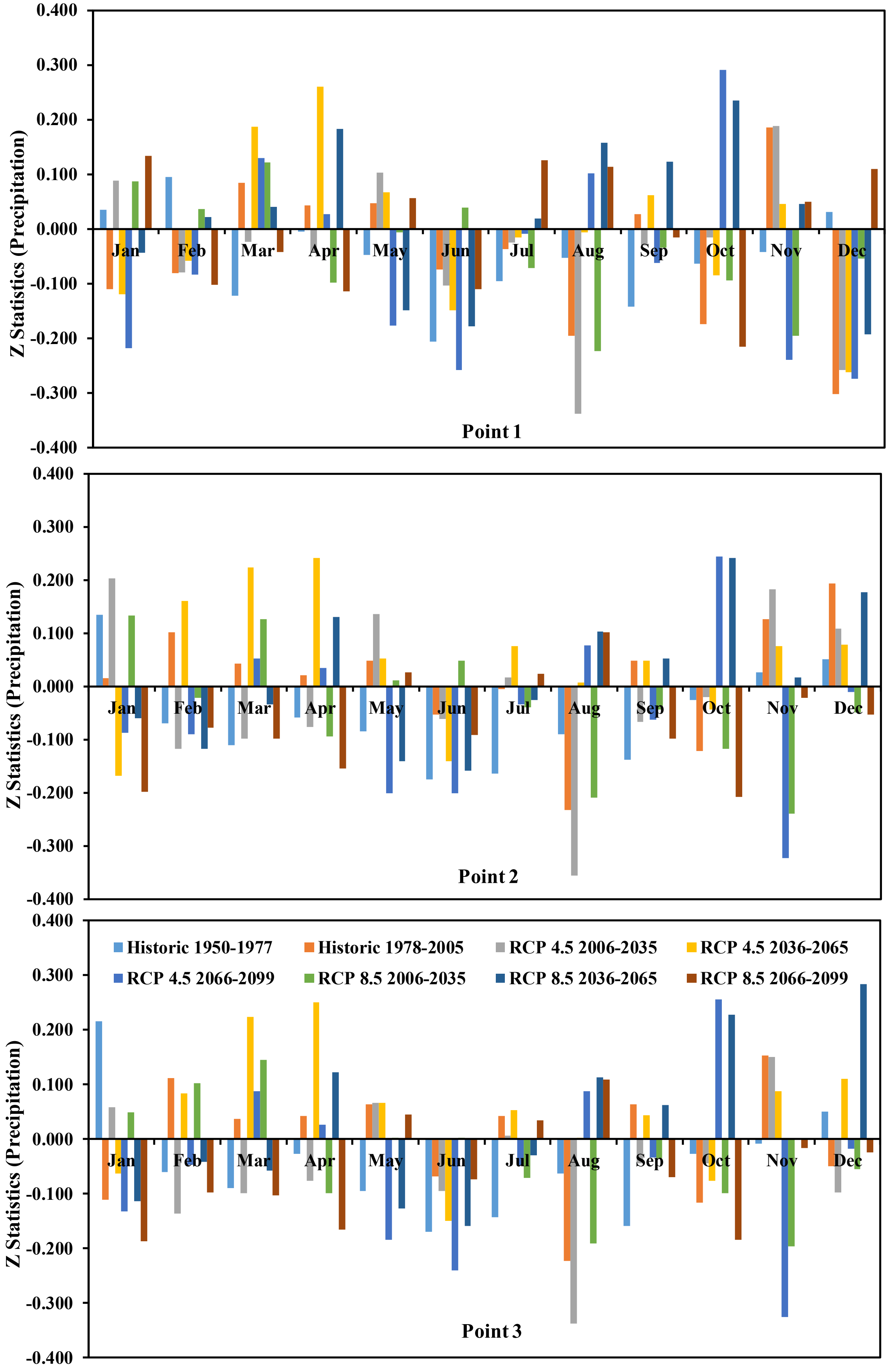

Fig. 2.6 Mann–Kendall test Z-statistics of monthly precipitation during historical period (1950-2005) and RCP4.5 and RCP8.5 scenarios (2006-2099) over all the study points.

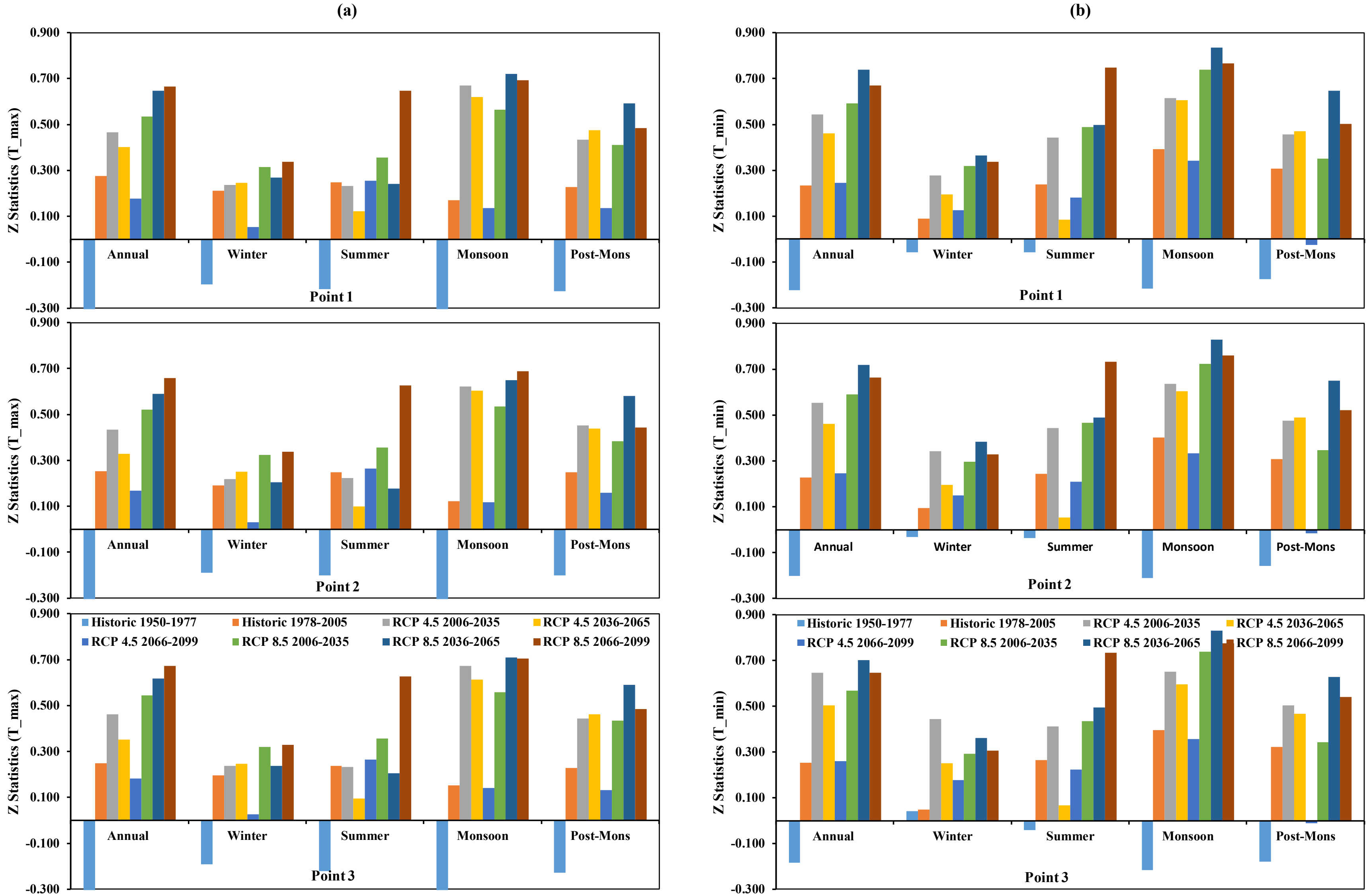

Fig. 2.7 Mann–Kendall test Z-statistics of (a) T max and (b) T min for annual and seasonal periods over the historical period (1950-2005) and RCP4.5 and 8.5 scenarios (2006-2099) over the study points.

Table 2.6 Mann–Kendall test Z-statistics and Sen's slope (°C/year) for the study points (sub-basin level) of mean annual and seasonal T_max for historical (1950–2005) and futuristic (2006-2095) with RCP4.5 and RCP8.5 scenarios.

Station	Time Scale/Seasons		Annual		Winter		Summer		Monsoon		Post-Monsoon	
			Z	Slope	Z	Slope	Z	Slope	Z	Slope	Z	Slope
SB 1	Historical	1950-1977	**-0.360**	-0.041	-0.196	-0.060	-0.217	-0.048	**-0.540**	-0.029	-0.228	-0.033
		1978-2005	**0.275**	0.029	0.212	0.060	0.249	0.059	0.169	0.013	0.228	0.038
	RCP4.5	2006-2035	**0.467**	0.053	0.237	0.050	0.232	0.055	**0.669**	0.046	**0.434**	0.054
		2036-2065	**0.402**	0.042	0.246	0.080	0.122	0.022	**0.618**	0.043	**0.476**	0.055
		2066-2095	0.177	0.015	0.053	0.004	**0.255**	0.028	0.136	0.007	0.136	0.016
	RCP8.5	2006-2035	**0.536**	0.067	**0.315**	0.099	**0.356**	0.068	**0.563**	0.049	**0.411**	0.053
		2036-2065	**0.646**	0.063	**0.269**	0.048	0.241	0.041	**0.720**	0.066	**0.591**	0.075
		2066-2099	**0.664**	0.095	**0.338**	0.084	**0.646**	0.151	**0.692**	0.060	**0.485**	0.057
SB 2	Historical	1950-1977	**-0.365**	-0.040	-0.190	-0.060	-0.201	-0.044	**-0.582**	-0.029	-0.201	-0.031
		1978-2005	0.254	0.030	0.190	0.060	0.249	0.061	0.122	0.012	0.249	0.041
	RCP4.5	2006-2035	**0.434**	0.046	0.218	0.044	0.223	0.047	**0.623**	0.040	**0.453**	0.050
		2036-2065	**0.329**	0.038	0.251	0.068	0.099	0.013	**0.605**	0.041	**0.439**	0.051
		2066-2099	0.168	0.014	0.030	0.008	**0.264**	0.025	0.117	0.006	0.159	0.016
	RCP8.5	2006-2035	**0.522**	0.067	**0.324**	0.104	**0.356**	0.069	**0.536**	0.045	**0.384**	0.046
		2036-2065	**0.591**	0.057	0.205	0.040	0.177	0.026	**0.651**	0.061	**0.582**	0.068
		2066-2099	**0.660**	0.097	**0.338**	0.085	**0.628**	0.161	**0.687**	0.059	**0.444**	0.056
SB 3	Historical	1950-1977	-0.349	-0.042	-0.190	-0.055	-0.222	-0.044	**-0.561**	-0.030	-0.228	-0.033
		1978-2005	0.249	0.027	0.196	0.059	0.238	0.062	0.153	0.015	0.228	0.041
	RCP4.5	2006-2035	**0.462**	0.053	0.237	0.050	0.232	0.058	**0.674**	0.046	**0.444**	0.056
		2036-2065	**0.352**	0.039	0.246	0.073	0.094	0.016	**0.614**	0.042	**0.462**	0.052
		2066-2099	0.182	0.015	0.025	0.006	**0.264**	0.026	0.140	0.008	0.131	0.015
	RCP8.5	2006-2035	**0.545**	0.068	**0.320**	0.101	**0.356**	0.073	**0.559**	0.048	**0.434**	0.052
		2036-2065	**0.618**	0.060	0.237	0.044	0.205	0.034	**0.710**	0.065	**0.591**	0.072
		2066-2099	**0.674**	0.095	**0.329**	0.081	**0.628**	0.159	**0.706**	0.061	**0.485**	0.056

[Bold numbers show a significant trend at a 95% confidence level.]

with change in RCPs and time scale observed a significant positive trend, a maximum trend observed in all the months except February, March, and April in the RCP4.5 scenario. The T_max magnitude in Table 2.7 also shows a maximum rise in mean monthly T_max for all the months, the maximum rise in April 0.196°C (RCP8.5 2066-2099), and maximum fall in April at -0.023 °C (RCP4.5 2036-2065) in study point 1. Likewise, in study points 2 and 3, maximum rise and fall of mean T_max is observed in April 0.184°C (RCP8.5 2066-2099), 0.168°C (RCP8.5 2066-2099), and -0.027°C (RCP4.5 2036-2065), and -0.030°C (RCP4.5 2036-2065), respectively.

2.4.3.2 Mean minimum temperature (T_min)

Similar to mean annual and seasonal T_max, the trend test for T_min also shows a significant negative trend in the historical time scale for both the RCPs at all the study points, as shown in Fig. 2.7(b). A significant positive trend is observed in both annual and seasonal scale at all the study points for the two RCPs- RCP4.5 and RCP8.5, the latter showed the maximum positive trend at three intra-decadal time scale. The annual scale has shown a maximum positive trend in T_min for both the RCPs at all the time scale. The highest Z value of 0.738 is observed at study point 1 in the annual scale at the RCP4.5 scenarios. The RCP8.5 has shown a significant positive trend among all the study points for all the seasons- summer (Z=0.747), monsoon (Z=0.834), and post-monsoon (Z=0.651), winter maximum positive T_min trend is observed at study point 2 for RCP4.5. The maximum negative trend in T_min is observed in the historic scale at all study points maximum lowest negative is as follows: -0.222 at study point 1. Table 2.8 shows the maximum magnitude ranges between 0.138°C at study point 2 and 0.073°C at study point 1 in the mean annual and seasonal T_min for the RCP8.5 summer season and RCP4.5 monsoon season, respectively. The minimum decrease in T_min is between -0.031°C and -0.010°C for the post-monsoon (historical) at study point 2 and summer season (historical) at study point 1, respectively.

For the mean monthly T_min, Fig. 2.8(b) shows a significant positive trend for all the twelve months at each study point, especially for May-December in both the RCP scenarios. The mean monthly T_min with the maximum positive trend is observed for RCP8.5 as 0.710 for September at study point 1 and 0.706 for June and September at study points 2 and 3, respectively. The maximum negative range for the minimum monthly T_min is observed as -0.238, -0.233, and -0.249 at all the study points for the historical time scale. Table 2.9 clearly shows the magnitude rise and fall of the mean monthly T_min in the study points. The maximum rise in the mean monthly T_min is observed in RCP8.5 as 0.144°C March month at the study point 1, 0.138°C December month at study point 2, and 0.135°C December month at the study point 3. Similarly, the maximum fall in mean monthly T_min is observed in historic timescale as -0.058°C January at study point 1, -0.052°C October at study point 2, and -0.051°C January at study point 3.

Table 2.7 Mann–Kendall Test Z-statistics and Sen's slope (°C/year) for the study points (sub-basin level) of mean monthly T_max for historical (1950-2005) and futuristic (2006-2095) with RCP4.5 and RCP8.5 scenarios.

Station	Time Scale/Months		Jan		Feb		Mar		Apr		May		Jun		Jul		Aug		Sep		Oct		Nov		Dec	
			Z	Slope	Z	Slope	Z	Slope	Z	Slope	Z	Slope	Z	Slope	Z	Slope	Z	Slope	Z	Slope	Z	Slope	Z	Slope	Z	Slope
SB 1	Historical	1950-1977	**-0.312**	-0.086	-0.185	-0.100	-0.222	-0.049	-0.185	-0.040	-0.243	-0.043	-0.265	-0.029	**-0.376**	-0.036	**-0.455**	-0.040	-0.365	-0.034	-0.175	-0.034	-0.090	-0.017	-0.148	-0.031
		1978-2005	**0.275**	0.089	0.000	-0.002	0.132	0.037	0.217	0.080	0.238	0.046	0.201	0.023	0.153	0.017	0.190	0.022	0.175	0.020	0.180	0.032	0.175	0.033	0.153	0.020
	RCP4.5	2006-2035	**0.324**	0.054	0.218	0.094	0.223	0.050	0.177	0.038	**0.310**	0.053	**0.457**	0.034	**0.439**	0.038	**0.503**	0.044	**0.549**	0.062	**0.393**	0.058	**0.315**	0.051	0.113	0.025
		2036-2065	-0.067	-0.009	0.246	0.092	0.145	0.046	-0.094	-0.023	0.283	0.056	**0.467**	0.054	**0.439**	0.034	**0.416**	0.041	**0.411**	0.052	**0.471**	0.052	**0.416**	0.049	**0.384**	0.080
		2066-2095	-0.126	-0.020	0.011	0.001	-0.080	-0.019	0.090	0.020	**0.480**	0.079	**0.301**	0.024	0.030	0.002	-0.007	0.000	-0.016	-0.002	0.034	0.002	0.136	0.021	0.016	0.003
	RCP8.5	2006-2035	**0.347**	0.080	**0.237**	0.116	**0.324**	0.091	**0.292**	0.064	**0.292**	0.050	**0.407**	0.048	**0.526**	0.044	**0.568**	0.066	**0.389**	0.047	0.260	0.040	**0.375**	0.066	**0.416**	0.077
		2036-2065	0.103	0.026	0.113	0.026	0.149	0.028	0.264	0.052	0.140	0.027	**0.591**	0.076	**0.669**	0.060	**0.595**	0.053	**0.577**	0.081	**0.476**	0.088	**0.425**	0.066	**0.320**	0.080
		2066-2099	**0.361**	0.096	0.186	0.105	**0.503**	0.187	**0.536**	0.196	**0.563**	0.095	**0.467**	0.047	**0.577**	0.060	**0.651**	0.061	**0.572**	0.083	**0.444**	0.057	**0.490**	0.058	**0.251**	0.062
SB 2	Historical	1950-1977	**-0.307**	-0.091	-0.169	-0.080	-0.222	-0.045	-0.169	-0.036	-0.228	-0.044	-0.228	-0.026	**-0.376**	-0.037	**-0.497**	-0.039	**-0.365**	-0.034	-0.148	-0.034	-0.101	-0.016	-0.143	-0.034
		1978-2005	**0.280**	0.090	-0.026	-0.012	0.175	0.040	0.243	0.079	0.228	0.044	0.116	0.014	0.090	0.009	0.185	0.024	0.196	0.025	0.201	0.033	0.164	0.034	0.201	0.032
	RCP4.5	2006-2035	**0.264**	0.045	0.228	0.088	0.195	0.053	0.145	0.042	**0.274**	0.048	**0.398**	0.029	**0.379**	0.034	**0.485**	0.041	**0.540**	0.059	**0.379**	0.057	**0.352**	0.046	0.090	0.019
		2036-2065	-0.108	-0.024	0.232	0.081	0.113	0.034	-0.103	-0.027	0.251	0.050	**0.430**	0.049	**0.416**	0.030	**0.425**	0.043	**0.370**	0.049	**0.448**	0.052	**0.356**	0.041	**0.389**	0.070
		2066-2099	-0.117	-0.019	0.016	0.012	-0.085	-0.018	0.108	0.021	**0.46**	0.081	**0.260**	0.023	0.030	0.002	0.002	0.000	-0.048	-0.004	0.016	0.002	0.140	0.019	-0.002	0.000
	RCP8.5	2006-2035	**0.324**	0.079	**0.255**	0.118	**0.329**	0.094	**0.297**	0.066	**0.297**	0.048	**0.343**	0.036	**0.513**	0.042	**0.554**	0.065	**0.370**	0.044	0.218	0.038	**0.352**	0.059	**0.370**	0.072
		2036-2065	0.053	0.014	0.085	0.028	0.108	0.019	0.191	0.052	0.080	0.015	**0.536**	0.070	**0.632**	0.054	**0.563**	0.052	**0.536**	0.077	**0.448**	0.087	**0.379**	0.054	**0.306**	0.077
		2066-2099	**0.430**	0.106	0.137	0.079	**0.458**	0.148	**0.544**	0.184	**0.633**	0.107	**0.462**	0.044	**0.619**	0.062	**0.668**	0.060	**0.579**	0.075	**0.430**	0.060	**0.565**	0.075	**0.312**	0.071
SB 3	Historical	1950-1977	**-0.302**	-0.086	-0.190	-0.093	-0.228	-0.047	-0.175	-0.040	-0.243	-0.046	-0.249	-0.033	**-0.381**	-0.041	**-0.476**	-0.039	**-0.370**	-0.035	-0.180	-0.037	-0.090	-0.016	-0.153	-0.030
		1978-2005	**0.270**	0.087	-0.011	-0.006	0.175	0.041	0.233	0.077	0.243	0.045	0.190	0.022	0.159	0.016	0.190	0.022	0.185	0.020	0.212	0.034	0.164	0.034	0.153	0.026
	RCP4.5	2006-2035	**0.333**	0.058	0.223	0.097	0.228	0.056	0.177	0.042	**0.329**	0.056	**0.457**	0.034	**0.421**	0.037	**0.494**	0.043	**0.549**	0.062	**0.398**	0.058	**0.343**	0.052	0.113	0.026
		2036-2065	-0.076	-0.018	0.237	0.083	0.103	0.038	-0.131	-0.030	**0.264**	0.051	**0.434**	0.054	**0.434**	0.033	**0.421**	0.040	**0.398**	0.052	**0.476**	0.053	**0.343**	0.043	**0.389**	0.078
		2066-2099	-0.131	-0.021	0.007	0.002	-0.085	-0.021	0.108	0.018	**0.471**	0.079	**0.269**	0.023	0.030	0.001	-0.007	0.000	-0.021	-0.002	0.021	0.001	0.126	0.020	0.021	0.003
	RCP8.5	2006-2035	**0.352**	0.077	0.241	0.116	**0.343**	0.094	**0.306**	0.064	**0.310**	0.053	**0.389**	0.046	**0.526**	0.045	**0.577**	0.067	**0.407**	0.046	**0.255**	0.042	**0.384**	0.066	**0.402**	0.081
		2036-2065	0.076	0.022	0.094	0.028	0.140	0.023	0.246	0.049	0.136	0.027	**0.559**	0.075	**0.655**	0.059	**0.591**	0.053	**0.563**	0.083	**0.476**	0.087	**0.416**	0.063	**0.320**	0.078
		2066-2099	**0.419**	0.104	0.141	0.076	**0.462**	0.143	**0.540**	0.168	**0.622**	0.106	**0.444**	0.042	**0.633**	0.063	**0.683**	0.062	**0.586**	0.075	**0.487**	0.063	**0.572**	0.070	**0.319**	0.072

[Bold numbers show a significant trend at a 95% confidence level.]

Table 2.8 Mann–Kendall test Z-statistics and Sen's slope (°C/year) for the study points (sub-basin level) of mean annual and seasonal T_min for historical (1950–2005) and futuristic (2006-2095) with RCP4.5 and RCP8.5 scenarios.

Station	Time Scale/Seasons		Annual		Winter		Summer		Monsoon		Post-Monsoon	
			Z	Slope	Z	Slope	Z	Slope	Z	Slope	Z	Slope
SB 1	**Historical**	1950-1977	-0.222	-0.025	-0.058	-0.020	-0.058	-0.010	-0.217	-0.013	-0.175	-0.031
		1978-2005	0.233	0.021	0.090	0.025	0.238	0.029	**0.392**	0.024	**0.307**	0.043
	RCP4.5	2006-2035	**0.545**	0.060	**0.278**	0.054	**0.444**	0.062	**0.614**	0.054	**0.457**	0.064
		2036-2065	**0.462**	0.036	0.195	0.048	0.085	0.005	**0.605**	0.042	**0.471**	0.071
		2066-2095	0.246	0.023	0.126	0.025	0.182	0.025	**0.343**	0.017	-0.025	-0.004
	RCP8.5	2006-2035	**0.591**	0.059	**0.320**	0.070	**0.490**	0.051	**0.738**	0.062	**0.352**	0.039
		2036-2065	**0.738**	0.080	**0.366**	0.084	**0.499**	0.078	**0.834**	0.073	**0.646**	0.105
		2066-2099	**0.669**	0.090	**0.338**	0.093	**0.747**	0.137	**0.766**	0.063	**0.503**	0.062
SB 2	**Historical**	1950-1977	-0.185	-0.021	0.042	0.009	-0.042	-0.005	-0.217	-0.014	-0.180	-0.031
		1978-2005	0.254	0.020	0.048	0.009	0.265	0.033	**0.397**	0.026	**0.323**	0.052
	RCP4.5	2006-2035	**0.646**	0.057	**0.444**	0.070	**0.411**	0.053	**0.651**	0.050	**0.503**	0.068
		2036-2065	**0.503**	0.032	0.251	0.035	0.067	0.007	**0.595**	0.040	**0.467**	0.066
		2066-2099	**0.260**	0.024	0.177	0.033	0.223	0.031	**0.356**	0.017	-0.011	-0.002
	RCP8.5	2006-2035	**0.568**	0.059	**0.292**	0.069	**0.434**	0.052	**0.738**	0.060	**0.343**	0.042
		2036-2065	**0.701**	0.079	**0.361**	0.091	**0.494**	0.077	**0.830**	0.068	**0.628**	0.104
		2066-2099	**0.646**	0.087	**0.306**	0.090	**0.733**	0.138	**0.775**	0.061	**0.540**	0.063
SB 3	**Historical**	1950-1977	-0.201	-0.023	-0.032	-0.009	-0.037	-0.006	-0.212	-0.013	-0.159	-0.027
		1978-2005	0.228	0.020	0.095	0.016	0.243	0.029	**0.402**	0.026	**0.307**	0.043
	RCP4.5	2006-2035	**0.554**	0.066	**0.343**	0.062	**0.444**	0.060	**0.637**	0.054	**0.476**	0.066
		2036-2065	**0.462**	0.036	0.195	0.051	0.053	0.005	**0.605**	0.041	**0.490**	0.072
		2066-2099	0.246	0.023	0.149	0.030	0.209	0.026	**0.333**	0.018	-0.016	-0.001
	RCP8.5	2006-2035	**0.591**	0.059	**0.297**	0.075	**0.467**	0.056	**0.724**	0.063	**0.347**	0.040
		2036-2065	0.720	0.081	**0.384**	0.091	**0.490**	0.078	**0.830**	0.071	**0.651**	0.108
		2066-2099	**0.664**	0.090	**0.329**	0.090	**0.733**	0.137	**0.761**	0.062	**0.522**	0.065

[Bold numbers show a significant trend at a 95% confidence level.]

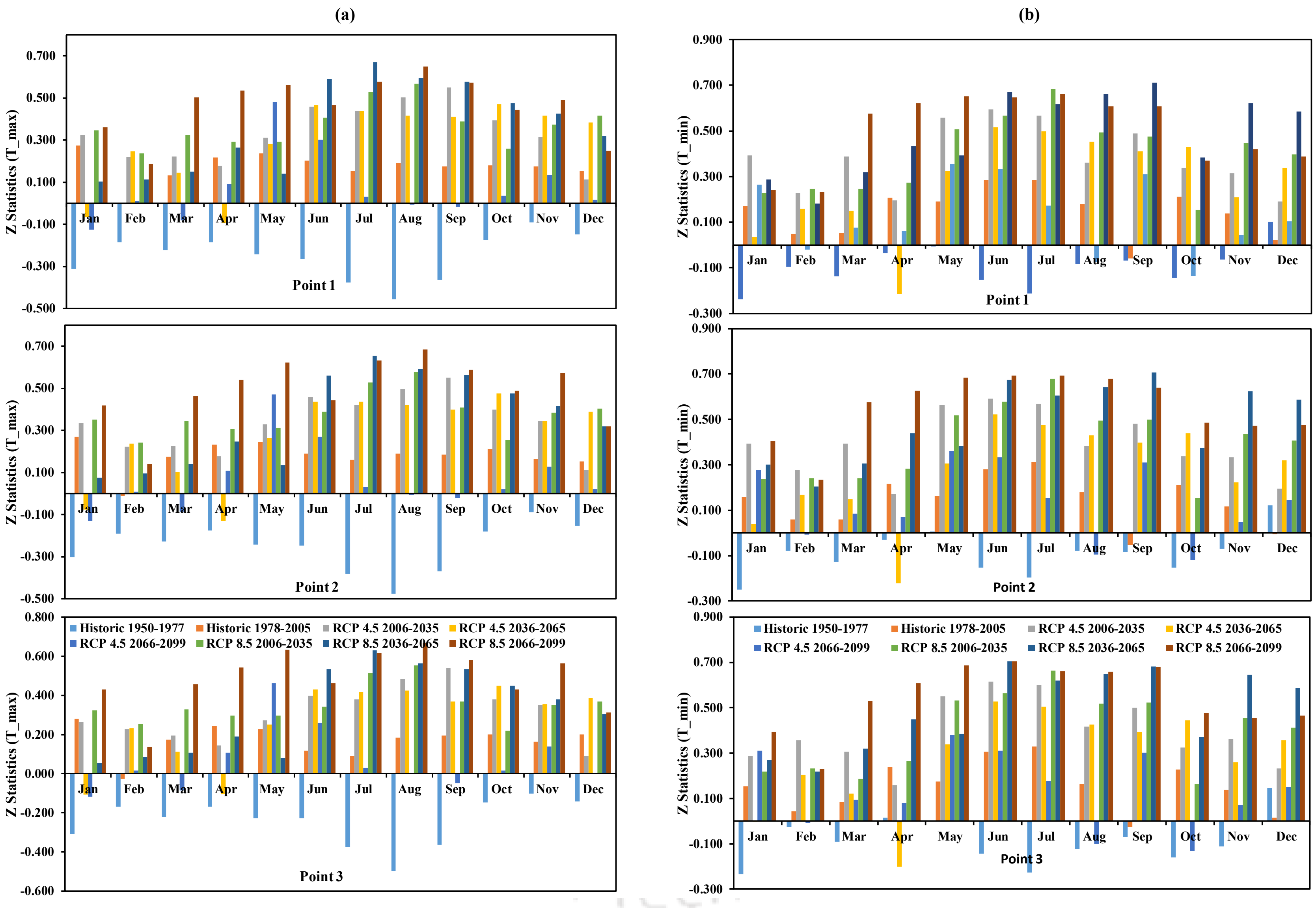

Fig. 2.8 Mann–Kendall test Z-statistics of monthly (a) T max and (b) T min during the historical era (1950-2005) and RCP4.5 and RCP8.5 scenarios (2006-2099) over all the study points.

Table 2.9 Mann–Kendall test Z-statistics and Sen's slope (°C/year) for the study points (sub-basin level) of mean annual T_min for historical (1950-2005) and futuristic (2006-2095) with RCP4.5 and RCP8.5 scenarios.

Station	Time Scale /Months		Jan		Feb		Mar		Apr		May		Jun		Jul		Aug		Sep		Oct		Nov		Dec	
			Z	Slope	Z	Slope	Z	Slope	Z	Slope	Z	Slope	Z	Slope	Z	Slope	Z	Slope	Z	Slope	Z	Slope	Z	Slope	Z	Slope
SB 1	Historical	1950-1977	-0.238	-0.058	-0.095	-0.039	-0.138	-0.031	-0.037	-0.008	-0.005	-0.001	-0.153	-0.024	-0.212	-0.017	-0.085	-0.008	-0.069	-0.010	-0.143	-0.047	-0.063	-0.020	0.101	0.045
		1978-2005	0.169	0.032	0.048	0.025	0.053	0.010	0.206	0.042	0.190	0.027	**0.286**	0.043	**0.286**	0.026	0.180	0.018	-0.058	-0.008	0.212	0.045	0.138	0.034	0.021	0.008
	RCP4.5	2006-2035	**0.393**	0.085	0.228	0.069	**0.389**	0.066	0.195	0.034	**0.559**	0.092	**0.595**	0.078	**0.568**	0.047	**0.361**	0.030	**0.490**	0.046	**0.338**	0.065	**0.315**	0.066	0.191	0.047
		2036-2065	0.034	0.011	0.159	0.067	0.149	0.034	-0.214	-0.037	**0.324**	0.037	**0.517**	0.043	**0.499**	0.032	**0.453**	0.043	**0.411**	0.044	**0.430**	0.079	0.209	0.047	**0.338**	0.084
		2066-2095	**0.264**	0.043	-0.021	-0.005	0.076	0.013	0.062	0.019	**0.356**	0.057	**0.333**	0.024	0.172	0.012	-0.076	-0.005	**0.310**	0.029	-0.136	-0.026	0.044	0.006	0.103	0.020
	RCP8.5	2006-2035	0.228	0.058	0.246	0.091	0.246	0.047	**0.274**	0.047	**0.508**	0.078	**0.568**	0.071	**0.683**	0.050	**0.494**	0.046	**0.476**	0.069	0.154	0.032	**0.448**	0.050	**0.398**	0.077
		2036-2065	**0.287**	0.067	0.182	0.067	**0.320**	0.063	**0.434**	0.080	**0.393**	0.078	**0.669**	0.085	**0.618**	0.059	**0.660**	0.067	**0.710**	0.084	**0.384**	0.083	**0.623**	0.115	**0.586**	0.130
		2066-2095	0.241	0.066	0.232	0.087	**0.577**	0.144	**0.623**	0.130	**0.651**	0.114	**0.646**	0.057	**0.660**	0.063	**0.609**	0.052	**0.609**	0.067	**0.370**	0.078	**0.421**	0.057	**0.389**	0.093
SB 2	Historical	1950-1977	-0.233	-0.048	-0.026	-0.009	-0.090	-0.018	0.016	0.003	0.000	0.000	-0.143	-0.023	-0.228	-0.017	-0.122	-0.009	-0.069	-0.008	-0.159	-0.052	-0.111	-0.021	0.148	0.061
		1978-2005	0.153	0.023	0.042	0.010	0.085	0.021	0.238	0.050	0.175	0.022	**0.307**	0.038	**0.328**	0.029	0.164	0.017	-0.026	-0.004	0.228	0.041	0.138	0.043	0.016	0.005
	RCP4.5	2006-2035	**0.287**	0.065	**0.356**	0.089	**0.306**	0.051	0.159	0.023	**0.549**	0.088	**0.614**	0.070	**0.600**	0.045	**0.416**	0.031	**0.499**	0.045	**0.324**	0.068	**0.361**	0.070	0.232	0.060
		2036-2065	-0.002	0.000	0.205	0.063	0.122	0.025	-0.200	-0.037	**0.338**	0.040	**0.526**	0.042	**0.503**	0.032	**0.425**	0.042	**0.393**	0.040	**0.444**	0.073	**0.260**	0.056	**0.356**	0.091
		2066-2095	**0.310**	0.064	-0.007	-0.005	0.094	0.015	0.080	0.013	**0.379**	0.059	**0.310**	0.022	0.177	0.011	-0.099	-0.007	**0.301**	0.029	-0.131	-0.026	0.071	0.013	0.149	0.026
	RCP8.5	2006-2035	0.218	0.048	0.232	0.088	0.186	0.044	**0.264**	0.044	**0.531**	0.075	**0.563**	0.070	**0.664**	0.050	**0.517**	0.042	**0.522**	0.071	0.163	0.033	**0.453**	0.053	**0.411**	0.081
		2036-2065	**0.269**	0.058	0.218	0.077	**0.320**	0.065	**0.448**	0.084	**0.384**	0.075	**0.706**	0.079	**0.618**	0.059	**0.651**	0.062	**0.683**	0.081	**0.370**	0.082	**0.646**	0.112	**0.586**	0.138
		2066-2095	**0.394**	0.106	0.230	0.084	**0.529**	0.114	**0.608**	0.126	**0.686**	0.116	**0.704**	0.056	**0.661**	0.058	**0.658**	0.056	**0.679**	0.067	**0.476**	0.090	**0.455**	0.055	**0.465**	0.112
SB 3	Historical	1950-1977	-0.249	-0.051	-0.079	-0.040	-0.127	-0.029	-0.032	-0.004	0.005	0.001	-0.153	-0.024	-0.196	-0.017	-0.079	-0.008	-0.085	-0.009	-0.153	-0.048	-0.069	-0.007	0.122	0.047
		1978-2005	0.159	0.029	0.058	0.026	0.058	0.011	0.217	0.042	0.164	0.021	**0.280**	0.043	**0.312**	0.028	0.180	0.018	-0.053	-0.007	0.212	0.042	0.116	0.036	-0.005	-0.001
	RCP4.5	2006-2035	**0.393**	0.084	**0.278**	0.101	**0.393**	0.067	0.172	0.030	**0.563**	0.093	**0.591**	0.077	**0.568**	0.048	**0.384**	0.031	**0.480**	0.047	**0.338**	0.068	**0.333**	0.072	0.195	0.054
		2036-2065	0.039	0.011	0.168	0.066	0.149	0.034	-0.223	-0.036	**0.306**	0.037	**0.522**	0.043	**0.476**	0.030	**0.430**	0.043	**0.398**	0.043	**0.439**	0.080	0.223	0.049	**0.320**	0.084
		2066-2095	**0.278**	0.054	-0.007	-0.002	0.085	0.011	0.071	0.017	**0.361**	0.058	**0.333**	0.023	0.154	0.012	-0.094	-0.006	**0.310**	0.028	-0.117	-0.027	0.048	0.007	0.145	0.023
	RCP8.5	2006-2035	0.237	0.052	0.241	0.091	0.241	0.045	**0.283**	0.046	**0.517**	0.080	**0.577**	0.074	**0.678**	0.051	**0.494**	0.045	**0.499**	0.070	0.154	0.033	**0.434**	0.051	**0.407**	0.082
		2036-2065	**0.301**	0.064	0.205	0.071	**0.306**	0.064	**0.439**	0.081	**0.384**	0.083	**0.674**	0.084	**0.605**	0.058	**0.641**	0.067	**0.706**	0.084	**0.375**	0.082	**0.623**	0.117	**0.586**	0.135
		2066-2095	**0.405**	0.114	0.234	0.087	**0.576**	0.120	**0.626**	0.126	**0.683**	0.116	**0.693**	0.056	**0.693**	0.061	**0.679**	0.056	**0.640**	0.070	**0.487**	0.093	**0.472**	0.059	**0.476**	0.118

[Bold numbers show a significant trend at a 95% confidence level.]

2.4.3.3 Mean monthly Diurnal Temperature Range (DTR)

Table 2.10 shows the trend test for the Diurnal temperature range for the two RCP scenarios at all the study points. The DTR is calculated by subtracting minimum daily temperature from the maximum daily temperature data for RCP4.5 and RCP8.5 scenarios at each point. From the Table 2.10, both significant positive and significant negative trend is observed. The negative maximum mean monthly DTR Z value falls to -0.499 (June) at study point 2 for RCP4.5 scenario and a significant positive trend of Z value= 0.366 (April) at study point 1 for RCP8.5 scenario. The maximum magnitude rise and maximum fall in mean monthly DTR are different in all the study points. A maximum rise in mean monthly DTR at all the study points 1, 2, and 3 are 0.057°C (April, RCP8.5=2066-2099), 0.076°C (February, RCP4.5=2036-2065) and 0.062°C (April, RCP8.5=2066-2099), respectively. Similarly, the maximum fall in mean monthly DTR at all the study points falls for both the RCP8.5 and RCP4.5 scenarios: -0.055°C (December, RCP8.5= 2036-2065), -0.079°C (December, RCP4.5= 2066-2099) and -0.066°C (December, RCP8.5= 2066-2099) at study point 1, 2, and 3, respectively. The inter-decadal temperature statistical analysis shows that increase in mean annual T_min is greater than the increase in T_max, indicating a decreasing trend in DTR (Government of Arunachal Pradesh, 2011; Shivam et al., 2017).

2.4.3.4 Homogeneity test using Pettitt's test

The homogeneity test using Pettitt's test on mean annual and monthly precipitation, T_min, and T_max is done for the three study points in the Tawang river basin. The change point of the year is made on three-time scales: historical (1950-2005), RCP4.5 (2006-2099), and RCP8.5 (2006-2099). The RCP scenarios are further divided into near-future (2006-2052) and distant future (2053-2099). The statistically significant Pettitt's test result is given in Table 2.11, which shows the change point year and shift direction in the continuous time-series datasets. A negative change in precipitation is likely to be observed in the historical time scale at study points 1 and 2 for October (1988). This decline in precipitation is observed in the (Statistics Branch Office of the Deputy Commissioner Tawang District, 1989), where a sudden decline of precipitation can be noticed in October (1988). The RCP4.5 and RCP8.5 have also indicated an increasing precipitation pattern for April, August, and October and a decline in the pattern for January (RCP8.5- 2038) and July (RCP4.5- 2020), mostly observed in study point 1. Annual precipitation increasing change point is only likely to be observed for RCP8.5 from the year 2065, from an annual mean of 1490 mm (1.6%) to 1902 mm (29.7%), 1996 mm (0.9%) to 2588 mm (30.8%), and 1622 mm (1%) to 2071 mm (29%) increase from historic precipitation for study points 1, 2 and 3, respectively.

Unlike precipitation, the change point year in the mean T_min and T_max is observed in all the months in both RCP scenarios. The historical data (from 1963) reveals a decrease in both T_min and T_max; however, validation is unattainable due to data unavailability. All of the months of the year, as well as the overall mean yearly change, demonstrate a positive change point in the future T_min and T_max. The majority of the mean T_min changes in

Table 2.10 Mann–Kendall test Z-statistics and Sen's slope (°C/year) for the study points (sub-basin level) of mean annual DTR for historical (1950–2005) and futuristic (2006-2095) with RCP4.5 and RCP8.5 scenarios.

Station	Time Scale / Months		Jan		Feb		Mar		Apr		May		Jun		Jul		Aug		Sep		Oct		Nov		Dec	
			Z	Slope	Z	Slope	Z	Slope	Z	Slope	Z	Slope	Z	Slope	Z	Slope	Z	Slope	Z	Slope	Z	Slope	Z	Slope	Z	Slope
SB 1	Historical	1950-1977	-0.159	-0.026	-0.090	-0.025	-0.095	-0.023	-0.259	-0.048	-0.196	-0.032	0.053	0.011	-0.143	-0.018	-0.365	-0.029	-0.228	-0.022	0.021	0.006	-0.079	-0.017	-0.159	-0.050
		1978-2005	0.159	0.039	-0.085	-0.020	0.159	0.034	0.217	0.049	0.132	0.012	-0.095	-0.010	-0.127	-0.013	-0.032	-0.003	0.175	0.025	-0.116	-0.012	-0.026	-0.006	0.212	0.034
	RCP4.5	2006-2035	-0.163	-0.036	-0.071	-0.016	-0.048	-0.012	0.039	0.009	-0.246	-0.039	**-0.434**	-0.039	-0.071	-0.007	0.159	0.015	0.149	0.011	-0.034	-0.005	-0.113	-0.020	-0.149	-0.034
		2036-2065	0.021	0.004	0.090	0.013	0.053	0.011	0.168	0.034	0.117	0.017	0.071	0.006	0.025	0.001	0.007	0.000	-0.039	-0.004	-0.200	-0.030	0.039	0.006	-0.016	-0.002
		2066-2095	**-0.301**	-0.048	-0.076	-0.020	-0.232	-0.044	0.039	0.011	0.103	0.022	0.034	0.005	-0.131	-0.009	0.053	0.005	-0.246	-0.028	0.113	0.023	0.002	0.001	-0.122	-0.025
	RCP8.5	2006-2035	0.117	0.021	0.186	0.030	0.168	0.033	0.145	0.036	-0.205	-0.028	-0.246	-0.031	-0.062	-0.004	0.154	0.021	-0.186	-0.022	0.186	0.030	0.030	0.006	0.025	0.004
		2036-2065	-0.085	-0.013	-0.159	-0.032	-0.246	-0.037	-0.117	-0.022	-0.209	-0.039	-0.007	-0.002	0.067	0.004	-0.131	-0.011	-0.071	-0.009	0.007	0.001	**-0.352**	-0.054	**-0.306**	-0.055
		2066-2095	0.218	0.049	0.090	0.013	0.200	0.036	**0.366**	0.057	-0.136	-0.026	-0.131	-0.017	-0.076	-0.006	0.154	0.015	0.140	0.019	-0.071	-0.013	0.030	0.003	-0.168	-0.028
SB 2	Historical	1950-1977	-0.228	-0.047	-0.201	-0.042	-0.074	-0.017	**-0.270**	-0.058	-0.212	-0.032	0.037	0.008	-0.153	-0.019	**-0.386**	-0.028	-0.228	-0.025	0.037	0.011	-0.037	-0.008	-0.190	-0.058
		1978-2005	0.143	0.048	0.058	0.013	-0.032	-0.006	0.175	0.041	0.048	0.007	-0.127	-0.021	-0.153	-0.016	-0.005	0.000	0.228	0.029	-0.005	-0.002	0.005	0.002	0.206	0.035
	RCP4.5	2006-2035	-0.099	-0.032	-0.140	-0.041	-0.076	-0.014	-0.149	-0.026	**-0.370**	-0.053	**-0.499**	-0.058	-0.016	-0.002	0.117	0.009	**0.343**	0.030	0.195	0.026	0.016	0.001	-0.071	-0.011
		2036-2065	-0.071	-0.016	0.145	0.076	-0.136	-0.045	-0.062	-0.014	-0.039	-0.008	-0.039	-0.006	0.053	0.002	-0.030	-0.002	0.126	0.022	-0.048	-0.004	-0.080	-0.011	0.191	0.038
		2066-2095	-0.177	-0.041	-0.057	-0.021	-0.085	-0.029	-0.103	-0.022	0.214	0.044	0.113	0.008	-0.154	-0.009	0.007	0.001	-0.136	-0.021	0.025	0.003	0.062	0.011	**-0.283**	-0.079
	RCP8.5	2006-2035	0.126	0.035	0.191	0.043	**0.260**	0.046	0.191	0.041	-0.149	-0.028	-0.232	-0.033	-0.080	-0.008	0.131	0.022	-0.228	-0.029	0.122	0.016	-0.021	-0.002	-0.057	-0.017
		2036-2065	-0.113	-0.027	-0.131	-0.027	**-0.315**	-0.062	-0.131	-0.031	-0.209	-0.041	-0.039	-0.006	-0.044	-0.003	-0.117	-0.009	-0.090	-0.013	-0.057	-0.009	**-0.333**	-0.055	**-0.343**	-0.072
		2066-2095	0.209	0.047	0.126	0.031	0.177	0.035	**0.352**	0.069	-0.108	-0.026	-0.099	-0.012	-0.030	-0.002	0.131	0.012	0.136	0.017	-0.044	-0.007	-0.011	-0.003	-0.067	-0.008
SB 3	Historical	1950-1977	-0.180	-0.033	-0.153	-0.033	-0.090	-0.021	**-0.270**	-0.053	-0.233	-0.032	0.053	0.008	-0.153	-0.018	**-0.392**	-0.030	-0.249	-0.023	0.000	0.000	-0.101	-0.018	-0.175	-0.063
		1978-2005	0.143	0.042	0.063	0.013	0.042	0.004	0.212	0.043	0.063	0.005	-0.159	-0.022	-0.143	-0.014	-0.011	-0.001	0.233	0.027	-0.005	-0.001	0.021	0.004	0.217	0.039
	RCP4.5	2006-2035	-0.131	-0.036	-0.145	-0.033	-0.090	-0.017	0.025	0.006	-0.241	-0.042	**-0.402**	-0.044	-0.080	-0.009	0.136	0.015	0.191	0.016	0.011	0.001	-0.090	-0.018	-0.168	-0.025
		2036-2065	-0.025	-0.007	0.205	0.049	-0.085	-0.031	0.094	0.024	0.085	0.013	0.007	0.000	-0.002	0.000	0.044	0.003	-0.011	-0.003	-0.177	-0.026	-0.007	-0.002	-0.011	-0.005
		2066-2095	**-0.343**	-0.059	-0.076	-0.021	-0.145	-0.042	0.016	0.003	0.085	0.017	0.067	0.005	-0.145	-0.012	0.048	0.005	-0.228	-0.026	0.140	0.018	-0.011	-0.002	-0.159	-0.032
	RCP8.5	2006-2035	0.126	0.029	0.186	0.038	0.237	0.042	0.182	0.039	-0.140	-0.025	-0.209	-0.031	-0.090	-0.007	0.136	0.022	-0.232	-0.028	0.136	0.019	0.039	0.004	-0.030	-0.006
		2036-2065	-0.117	-0.025	-0.094	-0.024	-0.287	-0.052	-0.117	-0.027	-0.209	-0.039	-0.044	-0.004	0.030	0.001	-0.136	-0.012	-0.094	-0.009	-0.076	-0.013	**-0.347**	-0.058	**-0.352**	-0.066
		2066-2095	0.191	0.043	0.076	0.021	0.154	0.027	**0.347**	0.062	-0.113	-0.030	-0.140	-0.016	-0.080	-0.007	0.136	0.013	0.145	0.022	-0.039	-0.002	-0.025	-0.003	-0.122	-0.016

[Bold numbers show a significant trend at a 95% confidence level.]

Table 2.11 Changepoint analysis of mean monthly and annual precipitation, T_min, and T_max over the three study points under historic, RCP4.5, and RCP8.5.

Month	Study Point 1						Study Point 2						Study Point 3					
	Precipitation		T_min		T_max		Precipitation		T_min		T_max		Precipitation		T_min		T_max	
	Change year	Shift	Change year	Shift	Change year	Shift	Change year	Shift	Change year	Shift	Change year	Shift	Change year	Shift	Change year	Shift	Change year	Shift
January	2038 (8.5)	↓	2033 (4.5) 2055 (8.5)	↑	2065 (4.5) 2055 (8.5)	↑			2033 (4.5) 2051 (8.5)	↑	2065 (4.5) 2055 (8.5)	↑			2033 (4.5) 2055 (8.5)	↑	2065 (4.5) 2055 (8.5)	↑
February			2044 (4.5) 2052 (8.5)	↑	2060 (4.5) 2064 (8.5)	↑			1976 (Hist) 2043 (4.5) 2052 (8.5)	↑	2060 (4.5) 2064 (8.5)	↑			2044 (4.5) 2052 (8.5)	↑	2060 (4.5) 2064 (8.5)	↑
March			2059 (4.5) 2050 (8.5)	↑	2060 (4.5) 2067 (8.5)	↑			2059 (4.5) 2050 (8.5)	↑	2060 (4.5) 2067 (8.5)	↑			2059 (4.5) 2050 (8.5)	↑	2060 (4.5) 2067 (8.5)	↑
April	2048 (4.5)	↑	2035 (4.5) 2051 (8.5)	↑	2037 (4.5) 2051 (8.5)	↑			2035 (4.5) 2051 (8.5)	↑	2037 (4.5) 2074 (8.5)	↑			2035 (4.5) 2051 (8.5)	↑	2037 (4.5) 2074 (8.5)	↑
May			2052 (4.5) 2051 (8.5)	↑	2052 (4.5) 2051 (8.5)	↑			2052 (4.5) 2051 (8.5)	↑	2054 (4.5) 2051 (8.5)	↑			2052 (4.5) 2051 (8.5)	↑	2052 (4.5) 2051 (8.5)	↑
June			2049 (4.5) 2051 (8.5)	↑	2052 (4.5) 2049 (8.5)	↑			2049 (4.5) 2050 (8.5)	↑	2052 (4.5) 2054 (8.5)	↑			2049 (4.5) 2051 (8.5)	↑	2052 (4.5) 2054 (8.5)	↑
July	2020 (4.5)	↓	2051 (4.5) 2052 (8.5)	↑	2053 (4.5) 2050 (8.5)	↑			2051 (4.5) 2052 (8.5)	↑	2053 (4.5) 2050 (8.5)	↑	2044 (4.5)	↑	2051 (4.5) 2052 (8.5)	↑	2053 (4.5) 2050 (8.5)	↑
August	2049 (8.5)	↑	2051 (4.5) 2055 (8.5)	↑	2048 (4.5) 2049 (8.5)	↑	2049 (8.5)	↑	2051 (4.5) 2055 (8.5)	↑	2048 (4.5) 2054 (8.5)	↑			2051 (4.5) 2055 (8.5)	↑	2048 (4.5) 2054 (8.5)	↑
September			2047 (4.5) 2048 (8.5)	↑	2053 (4.5) 2050 (8.5)	↑			2047 (4.5) 2050 (8.5)	↑	2053 (4.5) 2054 (8.5)	↑			2047 (4.5) 2048 (8.5)	↑	2053 (4.5) 2052 (8.5)	↑
October	2059 (8.5)	↑	2057 (4.5) 2057 (8.5)	↑	2051 (4.5) 2052 (8.5)	↑	1988 (Hist) 2056 (8.5)	↓ ↑	2057 (4.5) 2057 (8.5)	↑	2051 (4.5) 2052 (8.5)	↑	1988 (Hist) 2059 (8.5)	↓ ↑	2057 (4.5) 2057 (8.5)	↑	2051 (4.5) 2052 (8.5)	↑
November			2051 (4.5) 2049 (8.5)	↑	2051 (4.5) 2044 (8.5)	↑			2051 (4.5) 2052 (8.5)	↑	2049 (4.5) 2050 (8.5)	↑			2051 (4.5) 2049 (8.5)	↑	2051 (4.5) 2050 (8.5)	↑
December			2048 (4.5) 2045 (8.5)	↑	2048 (4.5) 2054 (8.5)	↑			2048 (4.5) 2054 (8.5)	↑	2048 (4.5) 2054 (8.5)	↑			2048 (4.5) 2054 (8.5)	↑	2048 (4.5) 2054 (8.5)	↑
Annual	2065 (8.5)	↑	2052 (4.5) 2052 (8.5)	↑	1963 (Hist) 2049 (4.5) 2050 (8.5)	↓ ↑	2065 (8.5)	↑	2052 (4.5) 2052 (8.5)	↑	1963 (Hist) 2049 (4.5) 2054 (8.5)	↓ ↑	2065 (8.5)	↑	2052 (4.5) 2052 (8.5)	↑	1963 (Hist) 2049 (4.5) 2054 (8.5)	↓ ↑

[Sign ↑ showing increasing change point and sign ↓ showing decreasing change point.]

both RCP scenarios are observed between 2033 and 2059 at the end of the near future and the early years of the distant future (Government of Arunachal Pradesh, 2011). A drastic change is likely to be observed for T_min at study point 1 from the year 2052 with as high as 5-10 times in the near future and from 6-15 times in the distant future than the historical in both RCP4.5 and RCP8.5, respectively. Other study points for T_min also show an increasing change from 2052 with 14.1% to 74.0% to the historic T_min in both RCPs. Similarly, mean monthly (all 12 months) and annual T_max also show an increasing change point in the scenarios between 2037 and 2074. The mean annual T_max changes for all study points range from 6.6% to 14.9% and 8.7% to 36.4% to the historic mean T_max in RCP4.5 and RCP8.5, respectively.

2.5 Conclusions

Precipitation and temperature are two important variables in the weather system that define a region's climate and varies according to the geographical features and time scale. This paper aims to investigate and quantify the trend and homogeneity in total precipitation, T_min, and T_max for the RCP4.5 and RCP8.5 from 1950–2099 using a class of approximately 30 year duration. The study carries three study points across the Tawang Chu in the district of Tawang, Arunachal Pradesh. The NEX-GDDP data is used to complete the study validated using a minimum set of meteorological acquired from the CWC. The historic precipitation trend analysis in the study reveals that there is no significant increasing trend in the annual and seasonal mean precipitation. The summer mean precipitation for RCP4.5 (2006-2065) shows a positive trend with a positive rise in precipitation between 1.56 mm to 9.94 mm in all the study points, which is not observed in the RCP8.5. The monthly mean precipitation at all study points, there is a clear increasing trend within 12 months for the various time scales- RCP4.5 April (2036-2065) and October (2066-2095) and a clear downward trend in August (2006-2035), June, and November (2066-2095). The mean annual precipitation statistics show an increase of 10.2% and 10.7% than the historic precipitation for RCP4.5 in 2006-2052 and 2053-2099 at study point 1, which declined for RCP8.5 than the historical mean annual. Study points 2 and 3 show an increase in mean annual precipitation by 7.5% to 12.2% for RCP4.5 and by 1.4% to 19.6% for RCP8.5 as compared to the historic mean annual. The mean annual T_min statistics in the study reveal a significant increase against the normal increase of T_max in RCP4.5, similar to the precipitation statistics and behavior of study point 1. Both RCP scenarios show a uniform increase in T_min and T_max for study points 2 and 3. The results also show a consistent increase in mean annual T_min and T_max for the three study points. Only a few studies have been conducted in the eastern Himalayan region, particularly in India's Arunachal Pradesh. The lack of similar studies in the Tawang region has resulted in a low comparison between study results and published data. The three study points fall in the Tawang river basin with a large area covered with snow and glacier, which plays an important role in the Tawang basin's hydrology and downstream hydrology. Any change in temperature and precipitation can influence the region's hydrology as glacier basins are more sensitive to temperature and precipitation changes. Thus, detailed temperature and precipitation studies can help understand and assess the changes in the basin hydrology and help related affairs (irrigation activities, agricultural, tourism sector, etc.) mitigate with changes.

3

Analysis of Hydrological Snowmelt and Future Projection

3.1 Study area

Arunachal Pradesh, a Himalayan state in the northern part of India, is commonly blanketed in snow and glaciers throughout the year. Tawang is one of Arunachal Pradesh's 23 districts, which is situated in the Mago River (Mago Chu) basin, as shown in Fig. 3.1. The study area is located in the upstream section of the basin, which covers an area of 842.294 km^2. The district's snow-covered mountains and passes, natural scenic beauty, several waterfalls, and rich culture make it a popular tourist destination. The geographical extension of the basin is between latitudes 27° 31' N and 27° 53' N and longitudes 92° 01' E and 92° 28' E, falls in

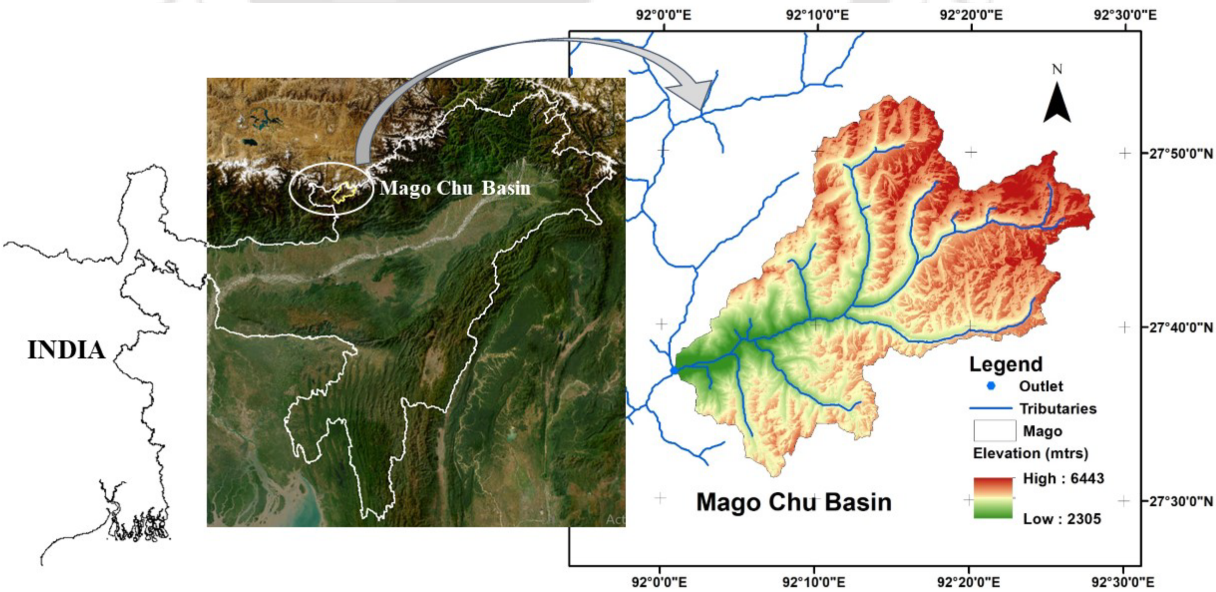

Fig. 3.1 Location and topographical (using Digital Elevation Model) map of the Mago Chu basin in Tawang district of Arunachal Pradesh (India).

the NE extreme of the Tawang district. The study area shares its borders with Tibet in the northeast, Bhutan in the southwest, and the West Kameng district in the southeast. The elevation of the basin ranges from 2305 m to 6443 m above mean sea level.

The Mago Chu basin is characterized by wet summers, dry and cold winters, and a monsoon climate. The monsoon period typically begins at the end of May and lasts until September or early October. From October to February, the basin experiences the winter season. The area is hilly, mostly barren, and uninhabited.

3.2 Materials and Methods

3.3 Spatial Data- Digital Elevation Model and Snow Cover Data

The Shuttle Radar Topography Mission (SRTM) DEM (30 m) acquired from the USGS is utilized for semi-automatic drainage basin delineation and topographic elevation extraction. Prior to the model running, the study watershed is separated into a number of sub-regions in accordance with the elevation intervals. This process is known as elevation zoning. The study region was classified into 8 elevation zones with a 500 m elevation range for the current study. Calculations were made to determine the basin's hypsometric mean elevation and the area of each elevation zone as mentioned in Table 3.1. For snow cover mapping, MOD10A2, the 8-day composites of global snow cover product from 2001-2018, are used with the <20% clouds criteria (Hussain and Bano, 2019; Tahir et al., 2011). With daily data, MODIS is the most essential and commonly used sensor in snow cover area mapping. The snow-mapping methodology is meant to create a global snow cover product using MODIS data-Earth Observation System (EOS), and the level-3 products include daily (MOD10A1) and eight-day composites of the global snow cover (MOD10A2) at a resolution of 500 m. The maximum snow extent is determined as the snow cover over eight days in 1200 km ×1200 km tiles (Abudu et al., 2016; Hall et al., 2002, 2016). Tiles are generated by compositing 500 m observations from the MODIS/Terra Snow Cover Daily L3 Global 500m Grid (MOD10A1) data set (Hall et al., 2016). Data have been accessible via the National Snow and Ice Data Center (NSIDC) of the NASA's Distributed Active Archive Center (DAAC) in an equal-area sinusoidal projection.

Table 3.1 Mean zonal points with geographical extension and elevation.

Zone	Longitude	Latitude	Zone Area (km^2)	Hypsometric Mean Elevation (m)
1	92° 3’ 32.82”	27° 38’ 8.92”	12.100	2805.48
2	92° 5’ 45.45”	27° 38’ 51.08”	34.366	3283.81
3	92° 8’ 16.28”	27° 39’ 32.18”	77.666	3779.76
4	92° 11’ 6.79”	27° 39’ 58.82”	204.912	4294.76
5	92° 14’ 45.65”	27° 42’ 19.61”	292.587	4748.75
6	92° 18’ 32.01”	27° 47’ 2.81”	181.690	5206.48
7	92° 22’ 13.67”	27° 48’ 22”	33.602	5680.78
8	92° 23’ 45.98”	27° 48’ 38.54”	5.331	6129.47

3.3.1 Snow cover area estimation

For the SCA extraction, the MOD10A2 scenes for the year 2001-2018 has been selected for the SCA estimations. Later, the MOD10A2 free cloud cover scenes for the year 2007, 2009 and 2013 with the months of April- September representing the melting period are chosen from the year 2001-2018. The temporal snow cover area from MOD10A2 data is derived using methodology flowchart shown in Fig. 3.2. The images used to study the snow cover area have a minimum of cloud cover. To avoid a maximum of cloud cover area, pixels ≤ 30 concentrated in areas of continuous snow area or non-snow area are assumed as to the respective class within which they are falling in. A pixel-to-pixel comparison of the elevation band with pixels shrouded by clouds is done in accordance with the DEM data, which separates elevation zones. When cloud pixels'elevations in a picture are more than or equal to the average elevation of the snow pixels in a certain elevation zone, in that elevation range, the cloud pixels are considered to be snow. A cloud pixel is categorised as a land pixel if its altitude is lower, on par with, or lower than the average elevation of a land pixel. It is also validated

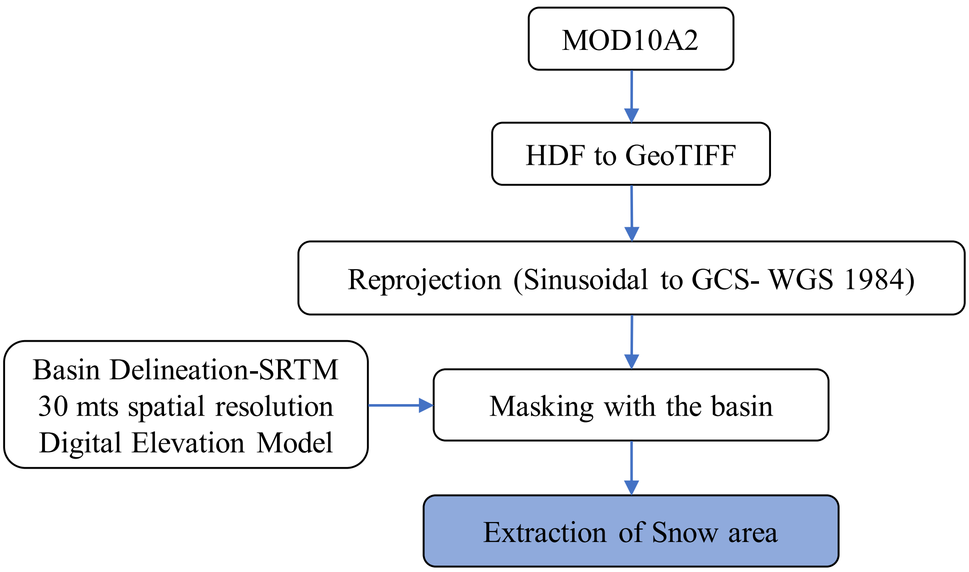

Fig. 3.2 Snow Cover Area (SCA) mapping methodology.

using the series of Landsat imageries and Google Earth Pro high-resolution imageries and cross-checked with the elevation band of 500 metres from mean sea level drawn from SRTM 30 metres Digital Elevation Model. The MOD10A2 cloud free scenes for the year 2007, 2009 and 2013 has been taken for the SCA. Based on these datasets the hydro-meteorological data has been chosen for calibrating and validating the WinSRM model (*Appendix I (B)*).

3.3.2 Historical hydro-meteorological dataset

The study utilized the Central Water Commission (CWC) ground station discharge data for the year 2003-2013. Many gauge stations having various data gathering start times are located in the study areas downstream, and the closest gauge station is at Mago Chu, near confluence with Nyukcharong Chu (Lat $27^{\circ} 37' 22''$ N and Long $92^{\circ} 0' 48''$ E). This station is used for this study for the year 2007, 2009 and 2013 as shown in Fig. 3.3. Similarly,

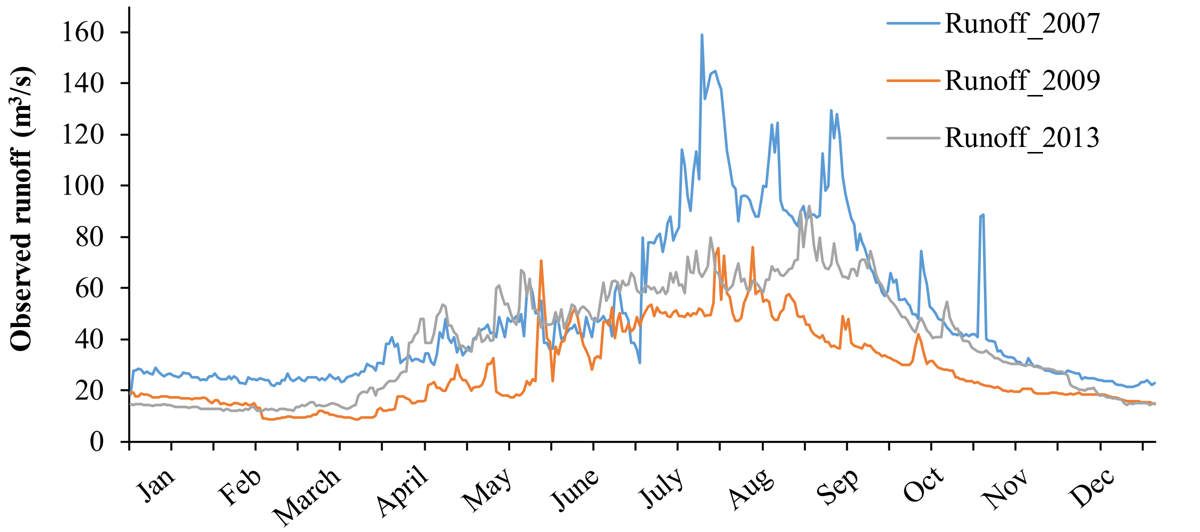

Fig. 3.3 Observed runoff at the CWC station discharge site- Mago Chu for the year 2007, 2009 and 2013.

since there wasn't enough observed data to choose suitable GCM for the analysis on climate change impact on snowmelt runoff, the climatic data for the current study-air temperature, maximum and minimum; and precipitation-were gathered from the project- NASA's POWER (Prediction of Worldwide Energy Resources) for the years 2001-2018. Fig. 3.4 shows the pattern of the variable for the year 2007, 2009 and 2013. The NASA Surface Radiation Budget Project (NASA GEWEX SRB), Clouds and the Earth's Radiant Energy System (CERES), Global Modeling and Assimilation Office at the Goddard Space Flight Center, and the World Climate Research Program (WCRP) at NASA LaRC are the sources of the data for the POWER project (https://power.larc.nasa.gov).

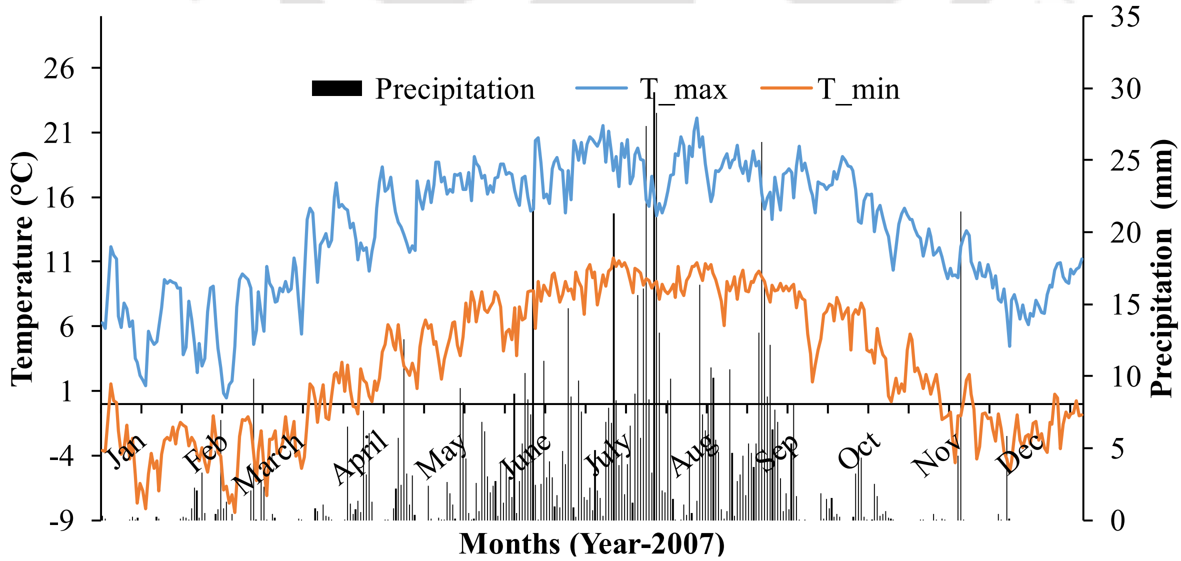

Fig. 3.4 Monthly temperature and precipitation for the year 2007 at the Mago Chu outlet acquired from the NASA POWER. The year 2007 is the year for calibrating the WinSRM model.

3.3.3 The Model Setup- Snowmelt Runoff Model (WinSRM)

Because the upstream of Mago basin is snow covered throughout year, the snowmelt runoff model (SRM) (MARTINEC, 1975) is used in this study. It based on the degree-day method and also widely used in both simulation and forecasting, which combines snow cover area data and hydro-meteorological data as input as depicted in Fig. 3.5, is utilised to simulate and predict the flow of streams on a daily basis in mountain basins where snowmelt runoff plays a significant role (Azmat et al., 2018). The SRM formula is given below:

$$Q_{n+1} = [c_{sn}a_n(T_n + T_n)S_n + c_R n P_n] \times \frac{A10000}{86400}(1 - k_{n+1}) + Q_n k_{n+1} \tag{3.1}$$

where, Q denotes the average daily discharge (m^3s^{-1}), c denotes the runoff coefficient, for c_{sn} snowmelt and c_R is rain, a denotes the degree-day factor (cm $°C^{-1}d^{-1}$), for T the number of degree-days (°C d), ΔT indicates the temperature lapse rate adjustment when extrapolating the temperature values from the basin's average hypsometric elevation from the base station or zone (°C d), the components of c_{sn} $(T + \Delta T)$ are the melt rate, S represents the proportion of snow cover area (SCA) to total area, P represents precipitation that contributes to runoff (cm), A represents the basin area or zone (km^2), k represents the recession coefficient, which represents the decline in discharge during a period without snowmelt or rainfall, and n represents the sequence of days that make up the computation period for discharge. The

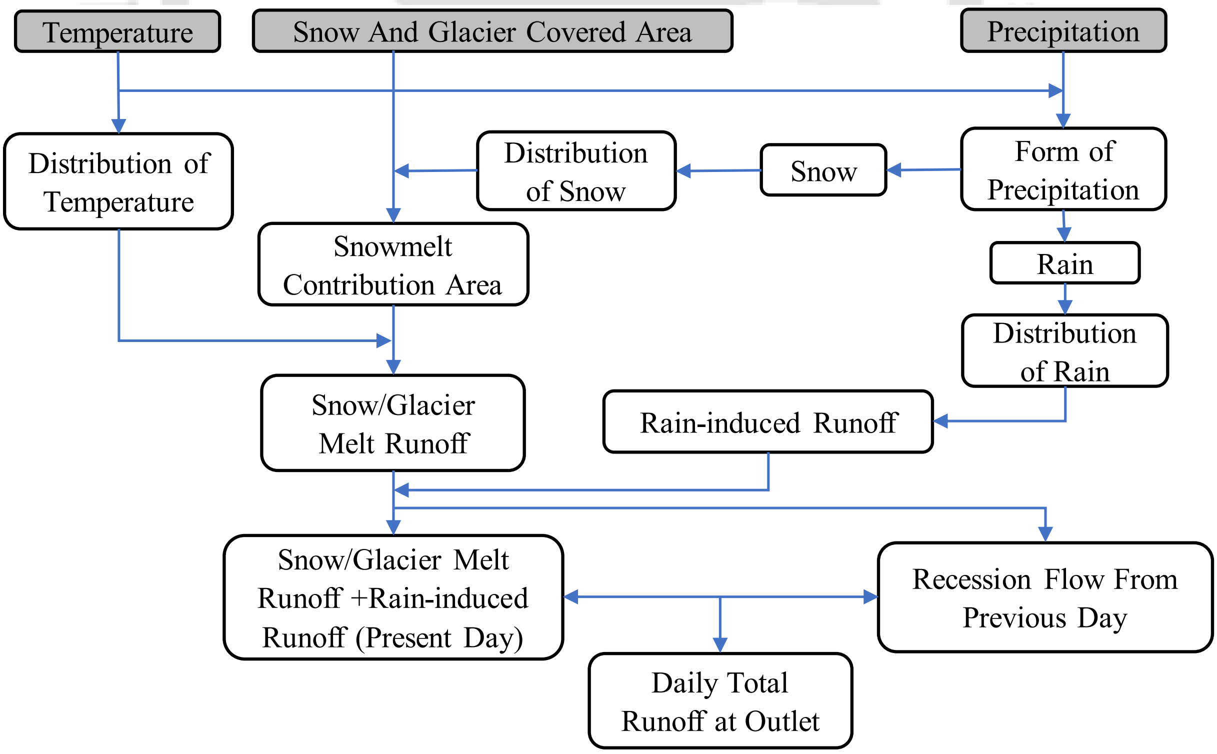

Fig. 3.5 Methodological flow chart for SRM model.

calibration parameters for SRM (Table 3.2), values set for every hypsometric zone are adjusted using the Users Manual (Martinec et al., 2008) and considering local literature (Senzeba et al., 2015, 2016) for zonal characteristics. The SRM model is calibrated for the year- 2007

Table 3.2 Ranges of parameter values used in the SRM model for calibration and validation.

Parameters	Range	
	Min	Max
Lapse rate (°C/100 m)	0.3	0.65
Tcrit (°C)	0	3
Degree-day factor (cm $°C^{-1}d^{-1}$)	0.1	0.8
Lag time (hr)	2	18
Runoff coefficient for snow (c_s)	0.1	0.9
Runoff coefficient for rain (c_R)	0.1	0.9
Rainfall contribuitng area (RCA)	0	1
X_{coeff}	0.918	0.918
Y_{coeff}	0.012	0.014

and 2009 and validation of the model is completed for the year 2013. The study area has snow cover and thus the melt season from April-September has been chosen for the model simulations. The rationale behind the choice of these years are (a) besides availability of cloud free scenes: the year 2007 has the lowest SCA since 2001, the year 2009 shows the year of declining slope for the SCA and the year 2013 is the starting year of a continuous declined SCA till 2018; and (b) for discharge data: the year 2007 has the highest observed discharge (annual total) for the year 2003-2013, the year 2009 has the lowest observed discharge and the year 2013 has the closest observed discharge from the median value (annual total) among the year 2003-2013.

3.3.4 The Model Performance Assessment

The WinSRM computer programme evaluates model accuracy using a graphical depiction of the estimated hydrograph and observed runoff. In addition to plots, the SRM employs two performance indices: the Volume Difference (D_v) and the Coefficient of determination (R^2) (Martinec et al., 2008). Besides these two measures, the study also used the Pearson correlation coefficient (r) (Pearson, 1894) and the Nash-Sutcliffe model efficiency coefficient (NSE) (Nash and Sutcliffe, 1970). The D_v, R^2, r, and NSE are calculated as follows:

$$D_v(\%) = \frac{V_{obs} - V_{cal}}{V_{obs}} \times 100 \tag{3.2}$$

$$R^2 = 1 - \frac{\sum (y_i - \widehat{y}_i)^2}{\sum (y_i - \bar{y})^2} \tag{3.3}$$

$$r = \frac{\sum_{i=1}^{n}(Obs_i - \overline{Obs})(Est_i - \overline{Est})}{\sqrt{\sum_{i=1}^{n}(Obs_i - (\overline{Obs})^2}\sqrt{\sum_{i=1}^{n}(Est_i - \overline{Est})^2}} \tag{3.4}$$

$$NSE = 1 - \frac{\sum(y_i - y_{i,\,sim})^2}{\sum(y_i - \bar{y})^2} \tag{3.5}$$

For D_v (%), V_{obs} is the annual or seasonally measured runoff volume, and V_{cal} the yearly or seasonally computed runoff volume. While R^2, y_i denotes the observed variable of interest values, $\widehat{y_i}$ represents the predicted values, and $\bar{y}$ denotes the observations mean. In the Pearson correlation coefficient, Obs_i is the observation value and Est_i is the predicted value and $\overline{Obs}$ is average of observation values and $\overline{Est}$ is average of predicted values. While for NSE, y_i represents the variable of interest observed values, $y_{(i,sim)}$ are the predictions from the simulation, and $\bar{y}$ is the mean of the observations.

3.3.5 Climate dataset - NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP)

For future projection of the streamflow for different climate change scenarios, the dataset from the NEX-GDDP- GCM under the Coupled Model Intercomparison Project Phase 5 (CMIP5) was utilized. This dataset comprises of downscaled and bias corrected climate scenarios for the globe. It includes two of the four Representative Concentration Pathways (RCPs) based on greenhouse gas emissions (RCP4.5 and RCP8.5), with spatial resolution of 0.25°× 0.25° (Melton, 2015). These data sets were created to support the Fifth Assessment Report (AR5)- the Intergovernmental Panel on Climate Change (IPCC). Daily precipitation, maximum temperature, and minimum temperature are included in the climatic projections for the time frames from 1950 to 2005 as a retrospective run and from 2006 to 2099 as a prospective run (https://www.nccs.nasa.gov/services/data-collections/land-based-products/nex-gddp). The SRM model climate change scenario runoff was done using the temperature and precipitation data for the three different future years 2040 (near future), 2060 (middle future), and 2090 (far future), using two selected GCMs namely- GFDL-CM3 and CSIRO-Mk3-6-0 respectively, for the RCP4.5 and RCP8.5 (from *section 2.2.3.1*).

3.4 Results and Discussion

3.4.1 Snow cover area estimation

Seasonal snow dominates the entire catchment. Although snow accumulation and ablation periods vary each year, it is noticed that snow accumulation begins in October and ends in March. Snowmelt occurs in the current research area from March to September, and snow build-up begins in October. In the Himalayan area, the accumulation season, which starts from October through the following March and is characterised by snowfall episodes and colder air temperatures, peaks in March. The period of increased air temperatures between April and September is frequently referred to as the ablation/melt season (Bothale et al., 2015; Ahluwalia et al., 2016; Tiwari et al., 2015; Jain et al., 2009). The temporal snow cover extraction and area estimation were observed using cloud-free MODIS MOD10A2 data. In this study, the snow accumulation period is categorized into two distinct sub-periods: snow accumulation or pre-ablation period (January, February, March and April) as maximum snow cover area and snow post- ablation (October, November and December) as minimum snow cover area time periods, as per the Himalayan snow properties (Kulkarni et al., 2010). The months April to September are the season of summer and monsoon generating snowmelt in the upstream snow cover mountain basins and thus termed as melting period or ablation period. Considering the <20% cloud threshold products and the algorithm threshold of pixels ⩽30 concentrated in areas of continuous snow or non-snow area as uncertainty for calculating the SCA, the SCA variability for the study is discussed. This study reveals an oscillation of changes. The temporal heterogeneity across the study period depicts an average of SCA (%) - 80.20% for the pre-ablation period with a maximum average of 96.52% (February) and a minimum of 29.23% (January) of SCA; the melting period shows the lowest SCA of the three periods, a total average SCA of 48.10% with a maximum of 90.35% (April) and a minimum of 18.45% (July) SCA and the post-ablation period with 58.09% of SCA (maximum 85.86% for November and minimum 26.39% for December) as shown in Fig. 3.6. Although the SCA results for all the three periods shows a uniform monthly distribution for January shows a large inter-annual variability, shrinking SCA up to a minimum of 29.23% in the year 2013, for the pre-ablation months. The SCA roughly declined in the post-ablation months- October, November and December. In this study, the Melting Period has the highest average snow cover area (April-September), followed by the Pre-ablation and Post-ablation periods. The Melting Period has the lowest variability of 3.53% for April month, May- 11.85%, June- 7.30%, July- 8.20%, August- 9.05% and September- 7.47%, indicating that the snow cover area values during this period are relatively consistent compared to the other periods. The Pre-ablation period has the highest variability of 20.10% for January, followed by 10.01% in February and 4.47% for March, suggesting more significant variation in the snow cover area during this period suggesting an experience of much higher or lower snow cover compared to the average by the region. The range of snow cover area values shows moderate variability for the Post-ablation period, indicating a wider spread of values during this period with variability of 12.86%, 19.84% and 15.86% for October- December, respectively. The annual average SCA for 2001-2018 is observed to be a maximum of 67.86% for 2005 and a minimum of 52.68% for 2013. The average SCA % for the melting period is a maximum of 55.68% for 2005 and a minimum of 40.96% for 2010. The SCA% for the year 2007 (55.60%) has the lowest SCA since 2001, the year 2009 (57.39%) shows the year of declining slope for the SCA and the year 2013 (52.68%) is the starting year of a continuous decline SCA till 2018. As SCA is among the most important variable input to the SRM model, the model has been simulated for 2007, 2009 and 2013.

Fig. 3.7(a) shows the monthly variation in the snow cover area (SCA) in the Mago Chu sub-basin for the years 2007, 2009, and 2013, indicating the maximum and minimum snow cover area values in each year. The monthly fluctuations in the SCA% for the aforementioned years follow a similar pattern. The SCA% exhibits temporal heterogeneity, with the highest value of 94.91% (799.41 km^2) observed in February and the lowest value of 26.29% (221.48

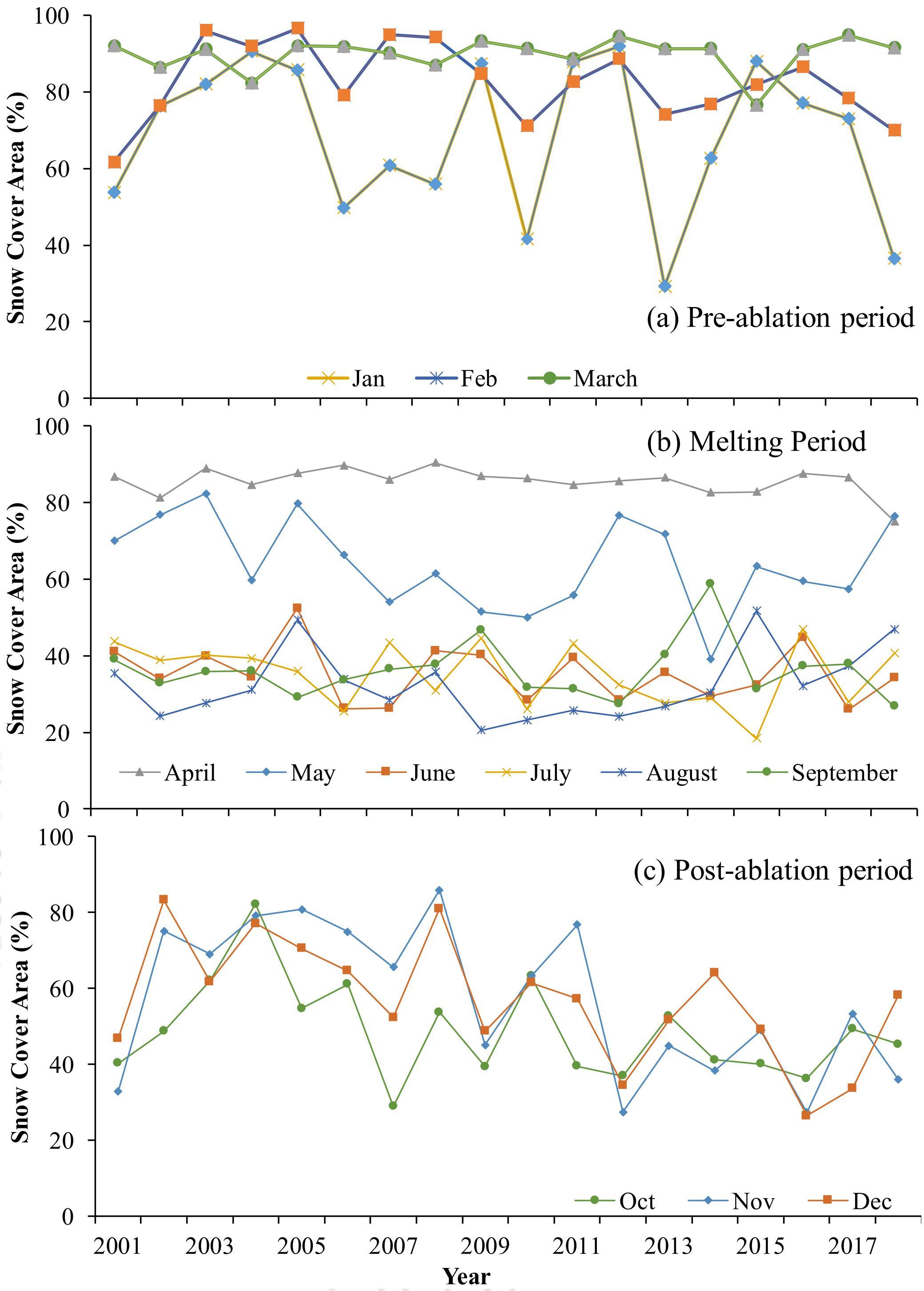

Fig. 3.6 Snow Covered Area (SCA) extracted from MOD10A2, 2001 to 2018, (a) Pre- ablation period, b) Melting period and c) Post- ablation period.

km^2) observed in June in 2007. In 2009 and 2013, the month with the maximum SCA% shifted to March, while the month with the minimum SCA% shifted to August, with values as low as 20%.

This study reveals two separate accumulation phases in the SCA in the Mago sub-basin. The first accumulation phase begins in January and peaks between mid-February and March, whereas the second phase starts in September and peaks in November/December. The snow ablation begins in mid-March and hits its minimum between late June and early September,

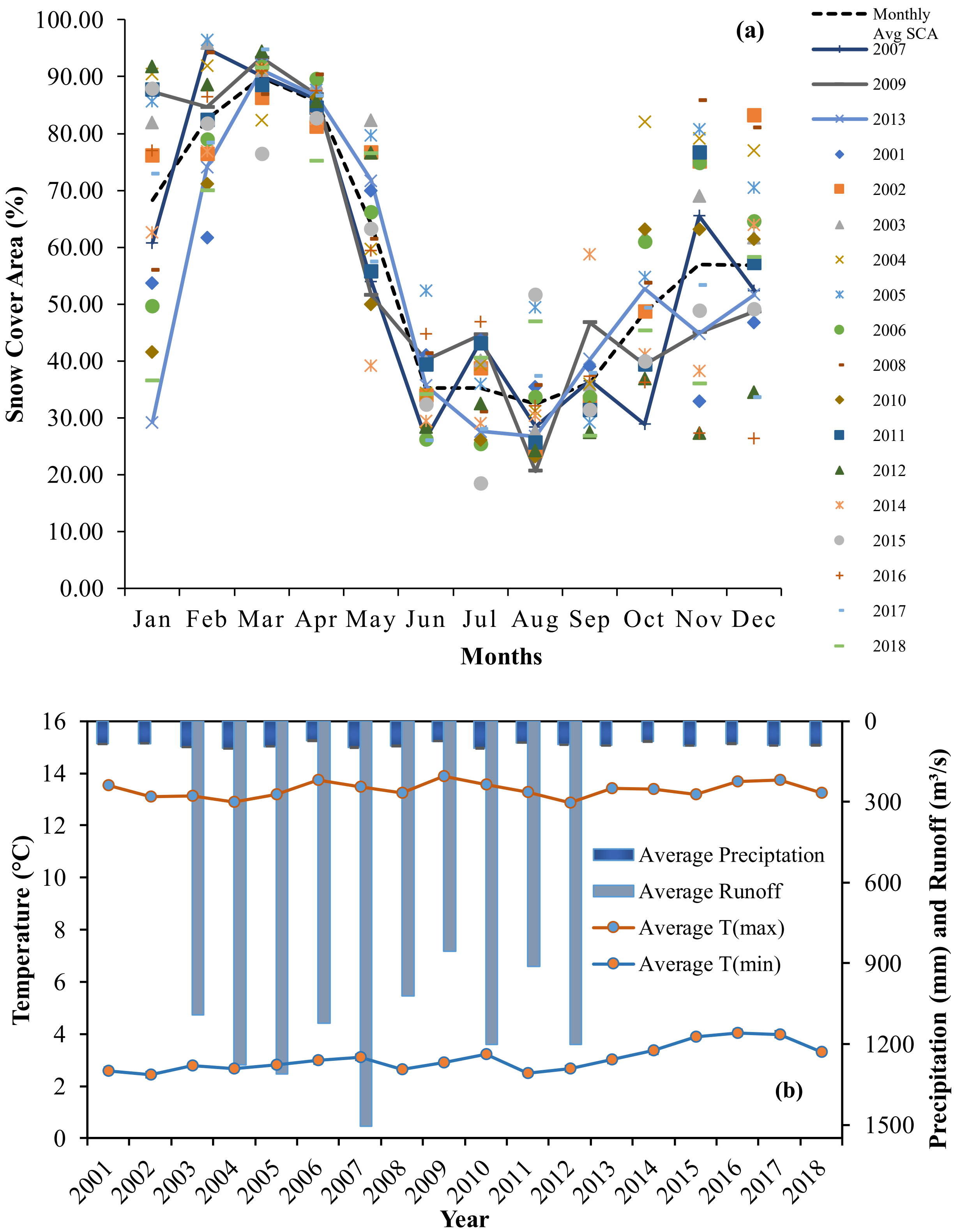

Fig. 3.7 (a) Monthly Snow Cover Area distribution (%) in the Mago Chu sub-basin from MOD10A2 and (b) Pattern of average precipitation, average runoff, average of T_max and T_min in the basin outlet.

with lowest SCA in August. When compared to the SCA peaks for both the accumulation periods, the SCA peak is higher during the first accumulation period. When compared to other earlier studies, the outcomes of both the accumulation periods and different SCA peaks occur during annual cycles in the central and western Himalayas (Bothale et al., 2015; Ahluwalia et al., 2016; Tiwari et al., 2015; Jain et al., 2009) but comparable to that of the Nuranang basin (a tributary to Tawang river basin) in the eastern Himalayas mountain region adjacent to the study area (Kiba et al., 2021; Bandyopadhyay et al., 2015; Senzeba et al., 2015). This might be brought by variations in the elevation, air temperature (maximum and minimum), and precipitation in various basins, or by the utilization of various datasets and investigation periods. The most likely explanation for the basin's small declining trend in snow cover is a decrease in winter precipitation as shown in Fig. 3.7(b). A few studies have suggested and supported elevation dependent warming (EDW) as a potential justification for the declining trends in the SCA (Pepin and Lundquist, 2008; Pepin et al., 2015; Qin et al., 2009; Liu et al., 2009). According to reports, the lesser SCA in the higher elevation river basins of the Tibetan Plateau and the nearby mountain region, specifically the Indus, the Yarkant, the Salween, and the Brahmaputra river basins, denotes high-altitude warming rates connected with the EDW (Li et al., 2018a).

3.4.2 Snowmelt runoff simulation and Model performance

The snow melt induced runoff in the Mago Chu sub basin is simulated using the SRM model based on observed runoff, snow cover area, temperature and precipitation data. The model needs snow cover area as a major input variable therefore the cloud free scenes acquired from MOD10A2 for the year 2007, 2009 and 2013 have been the selected as the simulation period- calibration period 2007 and 2009 and validation period 2013. The basin has its snow melt starting from March and ends almost in September and based on the melting period the model simulation is done. The study area sub-basin is classified into 8 nos. of elevation zones ranging between 2305-6443 m above msl. The other variables i.e., daily maximum temperature T_max, minimum temperature T_min, precipitation data and observed runoff data are feed in the model according to the 8 elevation bands. The model calibration for the year 2007 melt season was done with several iterative runs. The parameters- lapse rate, T_{crit}, AN (degree day factor), lag time, C_S, C_r, RCA, X_{coeff} and Y_{coeff} are calibrated with optimal values as shown in Table 3.2 and result in a satisfactory agreement with the observed runoff data as reported in the Table 3.3. The model performance for calibrated results of the simulated runoff against the observed runoff shows D_v 4.43%, R^2 0.833, r 0.91 and NSE 0.73 for the year 2007. The model performance results for the calibrated simulation

Table 3.3 Statistical parameters and results for model evaluation of melt season simulation in SRM, 2007, 2009 and 2013 in the Mago Chu sub-basin.

Statistical Parameter	2007	2009	2013
Volume Difference (D_v) %	4.43	2.38	1.56
Coefficient of determination (R^2)	0.833	0.769	0.774
Pearson correlation coefficient (r)	0.91	0.88	0.88
Nash-Sutcliffe model efficiency coefficient (NSE)	0.73	0.76	0.72
Measure Runoff Volume (10^6 m^3)	1080.37	610.44	895.04
Computed Runoff Volume (10^6 m^3)	1032.51	595.91	881.05

runoff for the year 2009 as D_v 2.38%, R^2 0.769, r 0.88 and NSE 0.76 with the observed or actual runoff for the melting season. The performance parameters for the calibrated years indicates that the calibrated parameters are well set for the melting season and can go with the model's validation. The model validation was done by changing the observed input data-daily temperature maximum: T_max, temperature minimum: T_min, precipitation data and observed runoff data while slight adjustment of the calibrated parameters. With the statistical parameters falling within a reasonable range, the same parameters used for calibration were also utilised to validate the model for the melting seasons of 2013, which are shown in Table 3.2. The graphical representation in Fig. 3.8 indicates that both the simulation process-model calibration and validation are in a close agreement and gives a model performs well for the two different years 2009 and 2013 melt season runoff. The statistical parameter that depicts the model performances illuminates D_v 1.56%, R^2 0.774, r 0.88 and NSE 0.72 for the year 2013, and the model is considered acceptable to use in snow cover mountain region.

Unlike the peak discharge in the Western Himalayan river basins, the discharge in the Eastern Himalayan river basins normally has a high flow from mid-June through late August. When snowmelt starts, which usually happens in April or May in the Mago sub-basin, a rise

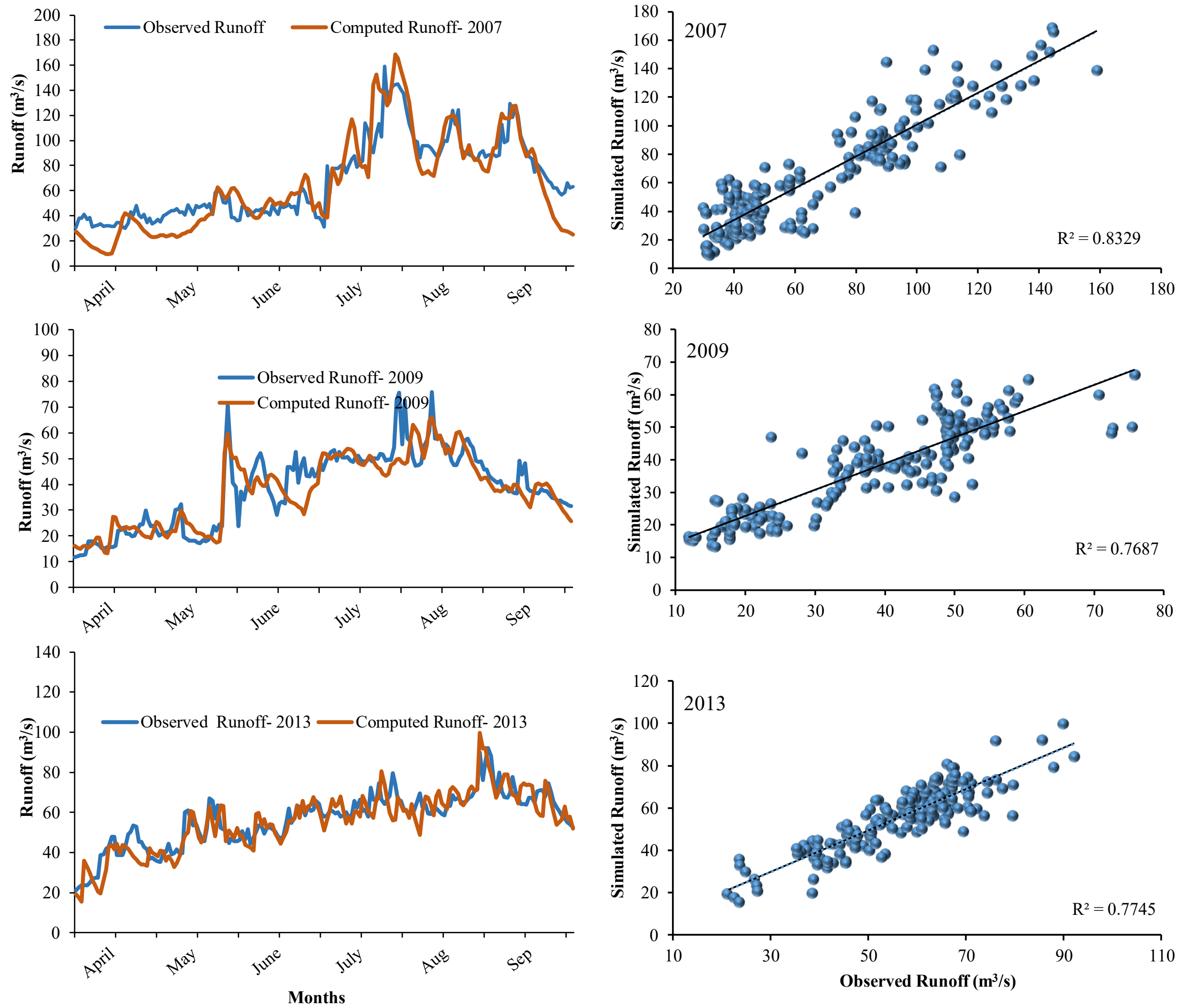

Fig. 3.8 Graphical representation of the model Calibrated runoff (2007) and validated runoff (2009 and 2013) for the Mago Chu sub-basin for the melting season.

in hydrograph is seen. Additionally, it can be concluded that the contribution of snowmelt runoff in the IHR begins in April, which seems to be in line with the findings of other studies that have been published (Kiba et al., 2021; Ahluwalia et al., 2013). It is evident from the model's results for both the calibration period and validation periods that the streamflow is both overestimated and underestimated by the model at various points during the melt season. These results suggest that the SRM precision range achieved in this study is found to be very noble and may be used in the runoff prediction in the area in the future. It can also be utilised in water resource management and planning in other similar Himalayan river basins where snow cover predominates the flow.

3.4.3 Climate Change Scenario- RCP4.5 and RCP8.5

The impact of climate change scenarios on the Mago Chu sub basin future runoff for three different future years 2040 (near future), 2060 (middle future), and 2090 (far future), using two GCMs namely- GFDL-CM3 for T_max and T_min and CSIRO-Mk3-6-0 for precipitation for the RCP4.5 and RCP8.5 can be pictured as shown in Fig. 3.9. The model was assessed using the simulation period of 2007 for all the climate change scenarios. According to the GCM models used in the study, the average monthly T_max, T_min and precipitation is projected to rise in the future, i.e., average T_max of 0.15°C, 0.18°C and 0.23°C at RCP4.5 and 0.13°C, 0.24°C and 0.37°C at RCP8.5 for the year 2040, 2060 and 2090 as compared to the base year 2007. Similarly, the rise in T_min is also observed as shown in Fig. 3.9, -0.02°C, 0.36°C and 0.53°C at RCP4.5 and 0.32°C, 0.51°C and 1.00°C at RCP8.5 for the year 2040, 2060 and 2090 as matched to the base year 2007.

The precipitation amount predicted in the GCM when compared to the base year has also shown an increase as shown in Fig. 3.9. Based on the input GCM variables to the SRM model for the future runoff prediction, the climate change effected runoff for different RCP scenarios can be seen in Fig. 3.9. The result of RCP4.5 showed a flow variability between the selected projected years which shows an increase in double fold average predicted runoff as compared to base year 2007. In the study area the sub basin runoff is found to be high in the month of July- September. A similar pattern of high flow is observed in the predicted runoff for the months in the base year, July being the month of highest runoff- 108.03 m^3/s (2040), 301.70 m^3/s (2060) and 571.46 m^3/s (2090) for RCP4.5 Scenario as compared to 101.02 m^3/s (2007), the highest flow months justified by the wet season.

This significant increase in discharge from streams from the base year to 2040, 2060, and 2090 is due to temperature increases (both maximum and minimum) and changing precipitation patterns projected for the future in the form of rain, as illustrated in Fig. 3.10.The average annual for the future year 2040, 2060 and 2090 discharge reports an increase in many folds over the years of assessment for RCP4.5 Scenario highest runoff being in the year 2090 i.e., the far future as shown in Fig. 3.10. The month of April has the lowest predicted runoff in both scenarios followed by all the simulation years except the far future year 2090 for the RCP8.5 scenarios. Unlike the RCP4.5 scenarios, the RCP8.5 predicted runoff do not

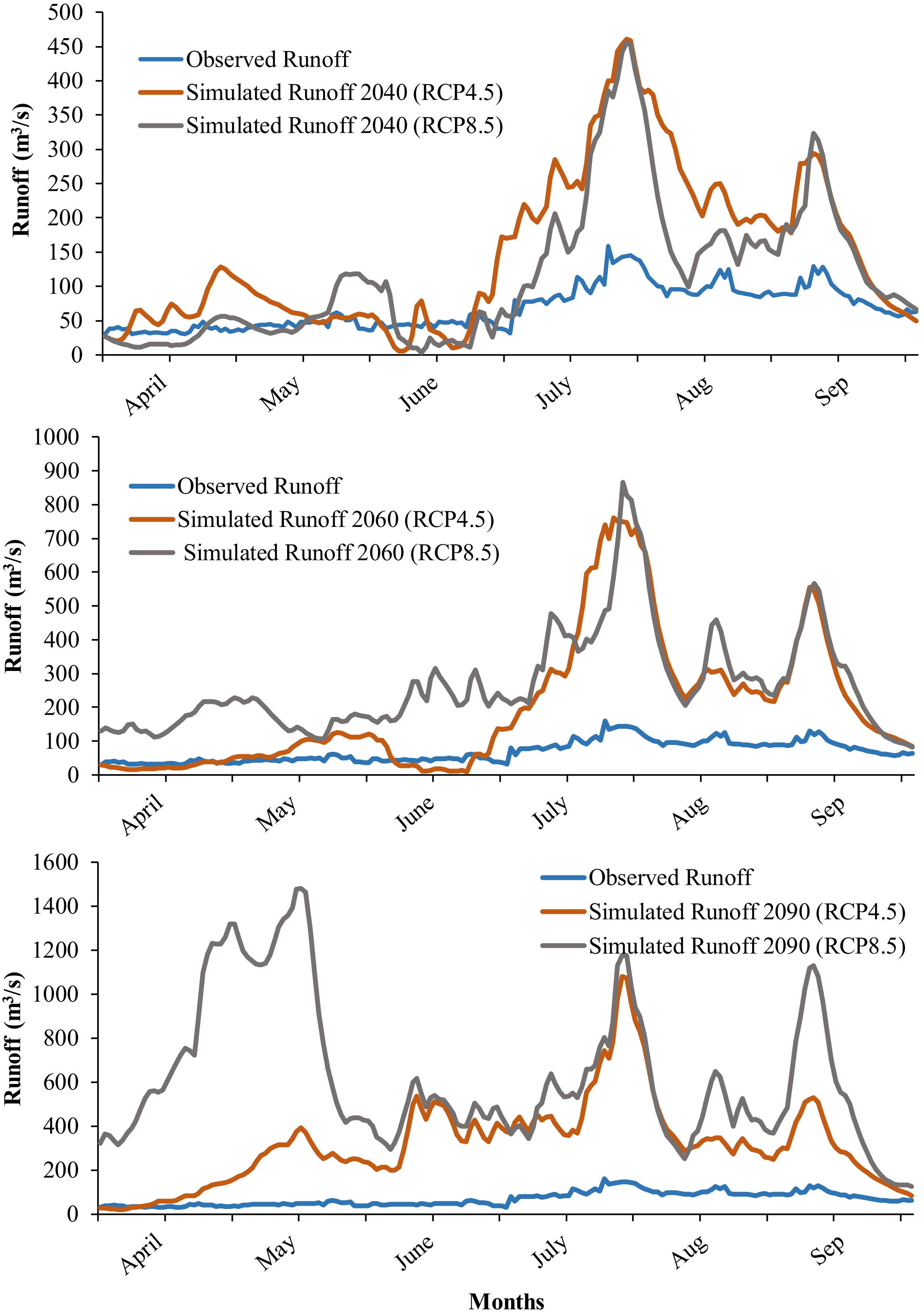

Fig. 3.9 Climate change affected runoff for RCP4.5 and RCP8.5 (year 2040, 2060 and 2090) as compared to the base year 2007.

show a similar pattern of highest flow month behaviour. The future (far) year has the highest predicted runoff in the month of May with 985.90 m^3/s runoff for RCP8.5, thus a clear Climate-affected runoff time shifting from the normal highest runoff month of July to May month as shown in Fig. 3.8. The results of predicted runoff in the far future for both the

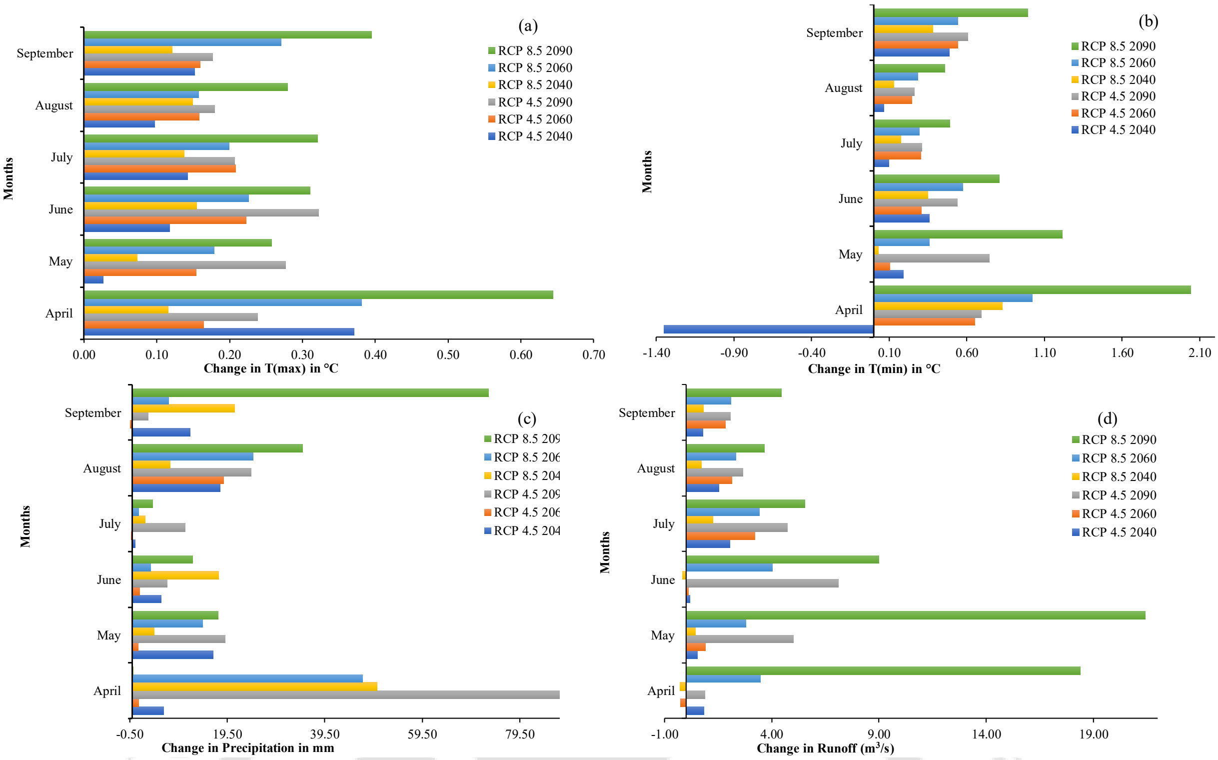

Fig. 3.10 Monthly change (a) T_max, (b) T_min, c) Precipitation and d) Runoff in climate change affected scenarios for RCP4.5 and RCP8.5 (year 2040, 2060 and 2090) as compared to the base year 2007.

scenarios RCP4.5 and RCP8.5 do not follow any shifting and the snowmelt runoff shows a longer melt period.

Climate change is clearly having an impact on hydrological regimes throughout the HKH region. If the Paris Agreement from 2015 achieves its goal of limiting global warming to pre-industrial levels by 1.5°C, the predicted regional warming ranges from 1.8 to 2.2°C in different parts of the HKH (Kraaijenbrink et al., 2017). The projected regional temperature and precipitation for the twenty-first century (Kraaijenbrink et al., 2017; Krishnan et al., 2020) would impact the snow cover and mass balance of HKH glaciers (Devi et al., 2023) resulting in volume and seasonal changes in the melting of glaciers and snow (Azam et al., 2021; Lutz et al., 2014). According to Nie et al. (2021), the glacier melt-related runoff will reach its peak in RCP8.5 in the 2060s and in RCP4.5 in the 2050s. It is anticipated that projected global warming will cause changes in snow and glacier melt runoff, primarily an earlier start to snow and glacier melt and a later start to snow cover, leading to prolonged melt periods (Azam et al., 2021). Despite the upper Indus basin's overall discharge drop, an early start to snowmelt was predicted (ul Hasson, 2016).

3.5 Conclusions

The SRM is widely used for estimation of the daily discharge from hilly and mountainous regions where snow is a dominating land cover variables. The Mago Chu sub basin has found to be covered with snow with 60% annual average of the total basin area, hence SRM is justified to estimate the present and future discharge to the outlet. As meteorological ground data was not sufficient for the study, the climatic data (air temperature-maximum and minimum; and precipitation) used in here is collected from the NASA POWER found to be reliable for input to the SRM model. To establish the model for daily runoff modelling in the study, statistical criteria - D_v, R^2, r, and NSE are used to compare the simulated output with the observed output. According to the findings of this study, the SRM performs well in both validation and calibration periods. The results show that in both the calibration and validation periods, SRM's modelled data has a stronger correlation with observed data and is efficient for simulation of daily runoff in the Mago Chu sub-basin, which is a hilly basin in the Eastern Himalayas with persistent snow cover and snow melt runoff has a significant impact on daily flow. The GCM- GFDL-CM3 for T_max and T_min and the CSIRO-Mk3-6-0 for precipitation with the RCP4.5 and RCP8.5 are used further for the assessment of runoff prediction in the three different future years 2040 (near future), 2060 (middle future), and 2090 (far future). The assessment showed a positive correlation between the possible high future predicted runoff and the high change in the GCM modelled future temperature and precipitation data and could be threat to downstream settlement from the flood generated from predicted high runoff. The general rise in runoff from snow and glacier melt and fluctuations in seasonality during the 21st century predict a multifaceted influence on agriculture, hydroelectric power supply, and fragile ecosystems in the HKH, raising the attention of policymakers working for the sustainable development of Himalayan water resources. As, the mountain people are more reliable on the basin hydrology for the irrigation, cropping pattern, hydro-electricity, domestic water consumption, etc., thus a proper water management planning keeping in view the future predicted high runoff is necessary.

4

Impact of Climate Change on Livelihood in Tawang District

4.1 Methodology

4.1.1 Study area description

With an area of around 2172 km^2, Tawang is located between 90° 45´ and 92° 15´ N latitude and 27° 22´ to 27° 45´ E longitude in the western region of Arunachal Pradesh, India (the Eastern Himalayas) (Fig. 4.1). The Sela Ranges separates the district from the West Kameng District in the east, while Tibet and Bhutan border it in the north and west. The area comprises a continuous series of hills and mountains, ranging in elevation from around 1066 to 6858 meters. According to the state's cartographic research, Tawang Valley spans the whole district. East Himalayan moist temperate type thick forest covers the area. It is a valley in the interior Himalayas of the "Dun" type. The two principal rivers in Tawang District are the Tawang Chu and the Nyamjang Chu. At 2240 meters, Tawang Chu rises at the junction of the Mago Chu and Nyukcharong Chu rivers. The district's climate may be described as rather nice in the summer and bitterly cold and snowy in the winter. The district is primarily up of high land. With such a wide range of heights, the climate is distinctive for its elevation-dependent temperature variance. In winter, the temperature typically drops to the freezing point.

Its magnificent snow-covered hills and mountains, green Tawang-Chu and Namjang-Chu river valleys, colorful flora and wildlife, bountiful Kharsaneng Valley, historic monasteries and monuments, and colorful people with a rich cultural heritage, the Tawang area provides idealistic tourism. Arunachal Pradesh's government promotes the tourist business, which boosts the economy and cultural interaction. This area is home to several historical sites, pilgrimage sites, significant natural areas, and a beautiful landscape that is gradually becoming a popular tourist destination. The region's geography and scenery provide opportunities for

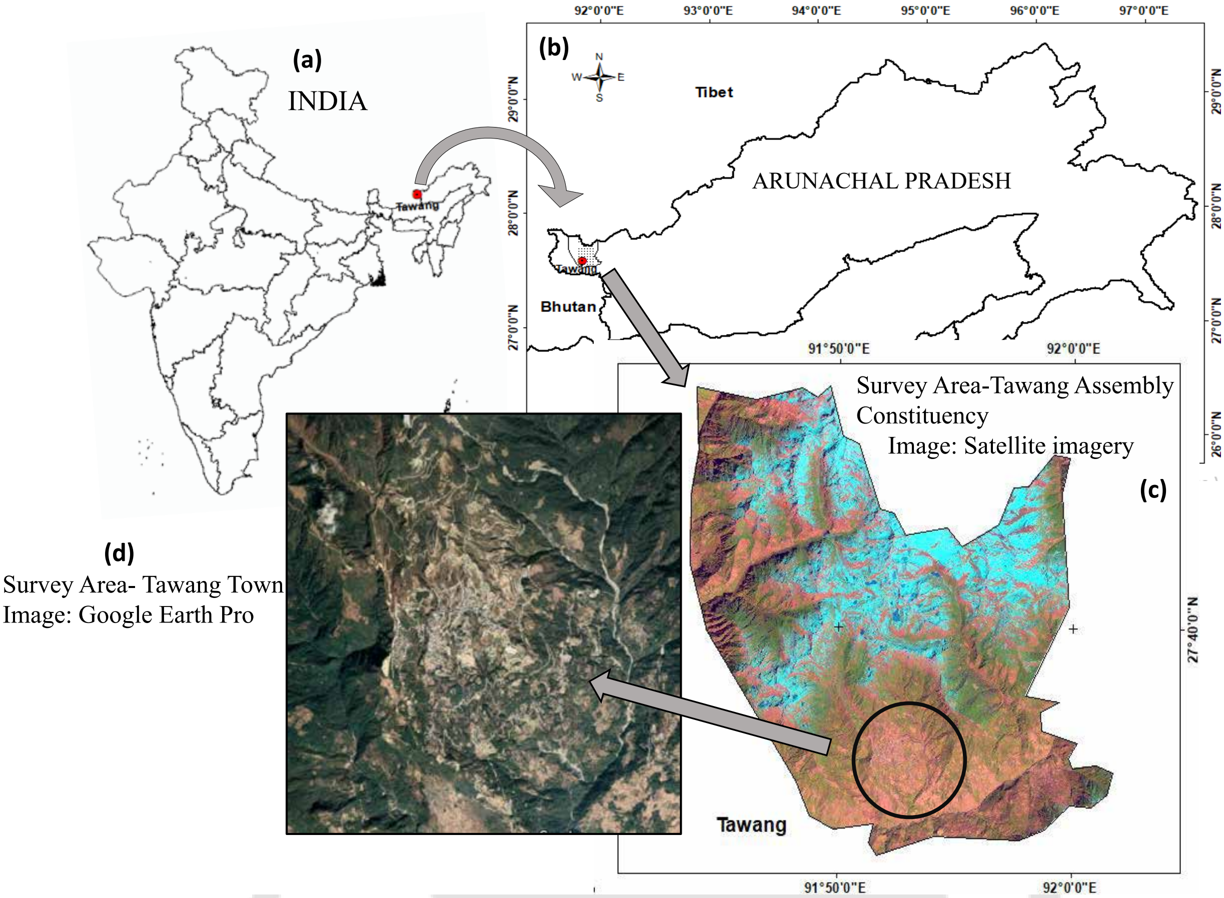

Fig. 4.1 Study area- Tawang (a town and administrative headquarter of Tawang district) in Eastern Himalayas, Arunachal Pradesh- India: (a) India, (b) Arunachal Pradesh with Tawang district, (c) Survey Area-Tawang Assembly Constituency (Image: Satellite imagery) and d) Survey Area- Tawang Town (Image: Google Earth Pro), and (d) Survey area of Tawang Town (image: Satellite imagery).

the growth of mountaineering, trekking, adventure tourism, sightseeing, hiking, and other outdoor activities. Fig. 4.2 shows a steep rise in tourist inflow since 2011 that has been dropped unanimously in year 2020 due to Covid-19 pandemic.

4.1.2 Data and Methods

4.1.2.1 Historical meteorological data

The climatic data (for the period 1991-2020) - average maximum temperature (T_max), average minimum temperature (T_min), average temperature (T_average), and total precipitation (TP) for the current study were collected from the NASA POWER (Prediction of Worldwide Energy Resources) project since ground data was insufficient for Homogeneity test analysis. The historical meteorological data used in the study is taken for three decades- 1991- 2000, 2001-2010, and 2011-2020, to better understand inter-decadal changes. The data for the POWER project comes from NASA's World Climate Research Program (WCRP), Global Energy and Water Cycle Experiment (GEWEX), Surface Radiation Budget Project (NASA GEWEX SRB), and Clouds and the Earth's Radiant Energy System (CERES) projects at NASA LaRC, as well as the Goddard Space Flight Center's Global Modeling and Assimilation Office (https://power.larc.nasa.gov) (*Appendix I (C)*).

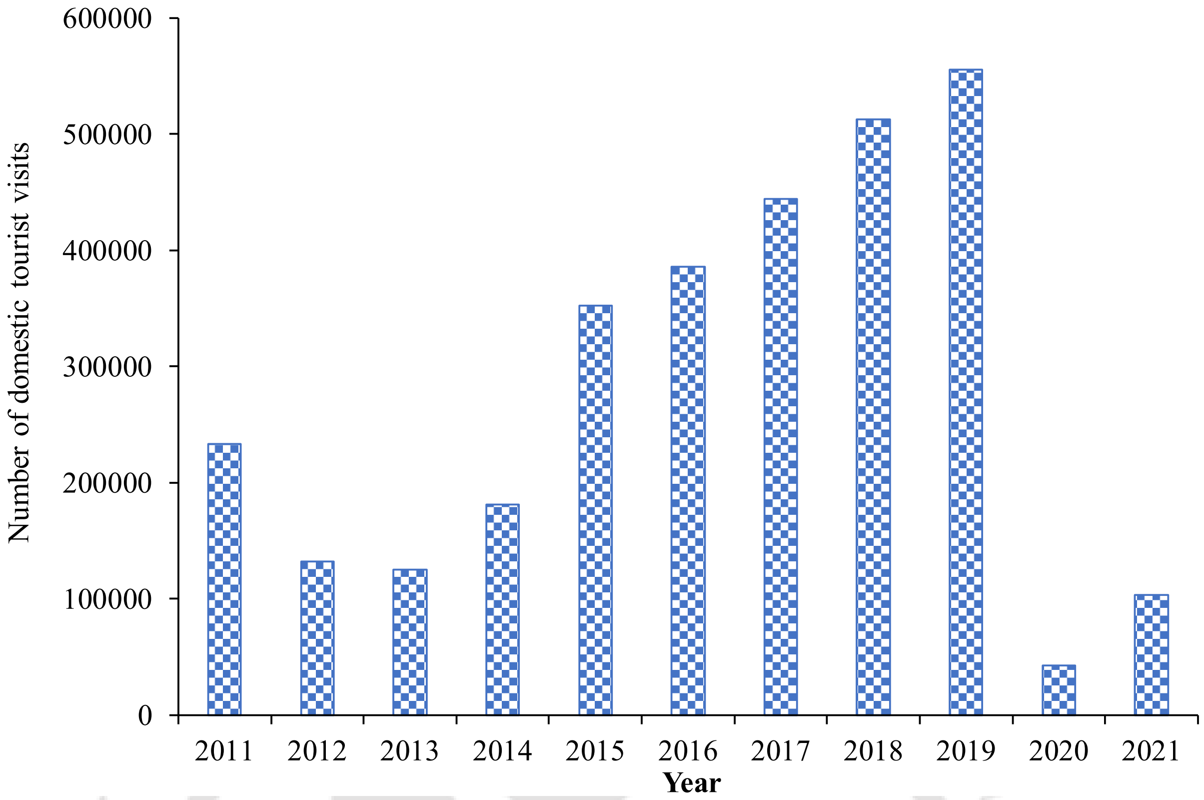

Fig. 4.2 Domestic tourist visits in Arunachal Pradesh since 2011. The lowest tourist influx is observed for 2020 and 2021, affected by the Covid-19 pandemic and travel restrictions (Ministry of Tourism, Govt. of India).

4.1.2.2 Homogeneity test using Pettitt's test on meteorological data

A test for change point detection is a crucial strategy for determining when a major shift in a time series of variables occurred. Inhomogeneity in time series can lead to erroneous interpretations of exceptional occurrences and can be deceiving when interpreting time-series tendencies. Significant fluctuations in the mean are common in time series data due to inhomogeneity. Pettitt's test (Pettitt, 1979) is a non-parametric test that does not make any assumptions about data distribution and is commonly employed in continuous data hydrological or climatic series to detect any significant change in the data series (Chakraborty et al., 2017; Ilori and Ajayi, 2020; Kocsis et al., 2020; Liu et al., 2012). It compares the null hypothesis (H_0), where the T variables follow one or more distributions with the same location parameter is compared to the alternative hypothesis (H_a), which depicts the existence of a change point. Pettitt's test for change point (K_T) statistics is described as

$$K_T = max \mid U_{t,T} \mid \tag{4.1}$$

where

$$U_{t,T} = \sum_{i=1}^{t} \sum_{j=t+1}^{T} sgn(X_i - X_j) \tag{4.2}$$

The statistic K_T is significant at probability approximated for $p \leq 0.05$.

4.1.2.3 *Survey-based data collection methods and analysis technique*

The impact of climate change on the tourism sector and local people's livelihoods and the adaption strategies employed by the locals are investigated using a paper-based survey (questionnaire-based survey) and interviews (Pandey et al., 2018). A research design for survey-based data collection methods as indicated in Fig. 4.3(a), involves carefully planning and structuring the process of gathering information from individuals or groups. A step-by-step guide for creating a research design for survey-based data collection: defining the research objectives, selecting the survey type, selecting the target population, developing survey questions, data collection procedures, data collection method, pilot testing, sampling strategy/method, data management, and analysis plan. The purposive sampling approach was used since the study is focused on climate change perception, its influence on tourism, and the adaptation of the tourist sector to climate change, as shown in Fig. 4.3(b). The study area's population is divided into four groups based on their reliance on tourism-related occupations and tourism service providers: travel/tour operators, permanent workers: Hotels/Restaurants/Resorts, seasonal workers: Hotels/Restaurants/Resorts, and tourism-dependent livelihoods as presented in *Appendix II*. In this study, a total of 15 respondents have been interviewed for each of the groups, with a total of 60 respondents who are engaged in the tourism sector; please see Fig. 4.4 below. The survey was conducted in November

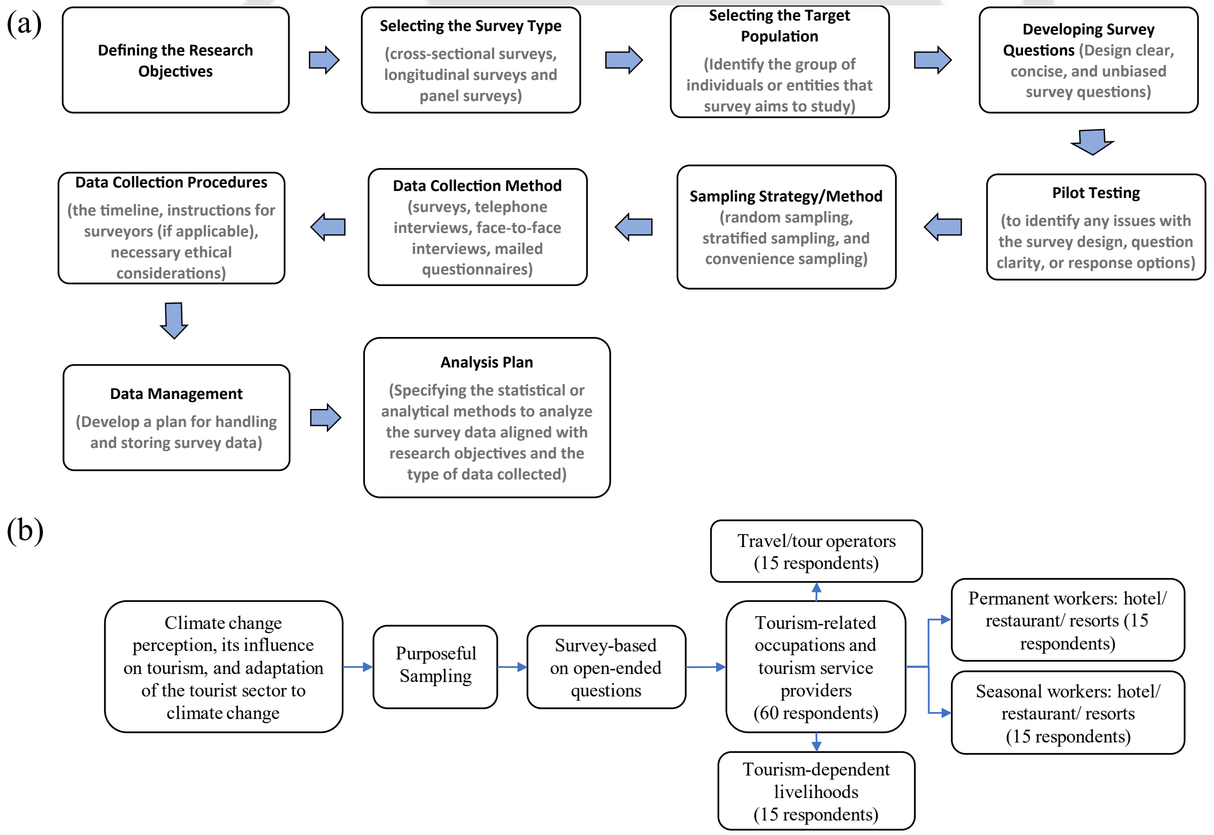

Fig. 4.3 (a) A comprehensive research design that ensures survey-based data collection method effectively addresses research objectives, and (b) flow diagram for sample selection and respondent type: 60 respondents engaged in the tourism sector in Tawang were selected for the study.

Fig. 4.4 Respondents during the field visit in Tawang- (a) tour operators, (b) taxi owners, and (c) restaurant owners with students from Tawang College.

when the tourist inflow began post Covid pandemic. The sampling was done in the Tawang township, and the people interviewed included hotel staff: seasonal and permanent workers in travel/tour agencies and shops. Seasonal workers are employed only during the busiest months for tourism and in the remaining period they are engaged in agriculture and allied activities including non-local people. Permanent workers are employed all year round.

The interview questionnaires were aimed to gather qualitative data on respondents' perceptions of climate change, the impact of climate change on tourism and challenges, adaptation, and community knowledge of policy initiatives. The questionnaires were left open-ended except for the various sets of questions. The conversations aided in identifying the key socioeconomic challenges for resilience research. The survey findings were analyzed to collect data on various elements of climate-tourism interaction. The survey questions included, in addition to the basic question about the respondents' information (tourism service providers), what are the busiest months of tourism (hotel occupancy rates denote the baseline and most important factor of tourism), observed impact of climate change (temperature and precipitation), impact on raw material supply, an alternate source of income, and water use behaviors and adaptation concept and measures. This study was carried out with the assistance of a group of Tawang College (Tawang) students and a few local people including a local tourist guide. Before beginning fieldwork, these students and locals were instructed on the research's objectives, study site, and interview schedule. Similarly, consent was obtained from respondents before the commencement of the survey.

4.2 Results and Discussion

4.2.1 Historical meteorological data analysis (1991-2020)

The inter-decadal historical meteorological data analysis reveals that the T_max, T_min, and T_average is slightly increasing since 1991 as shown in Fig. 4.5. For T_max although the minimum and maximum decadal temperature is almost constant the mean of the T_max has been in increasing gradually. For T_min the maximum temperature limit is seen to be

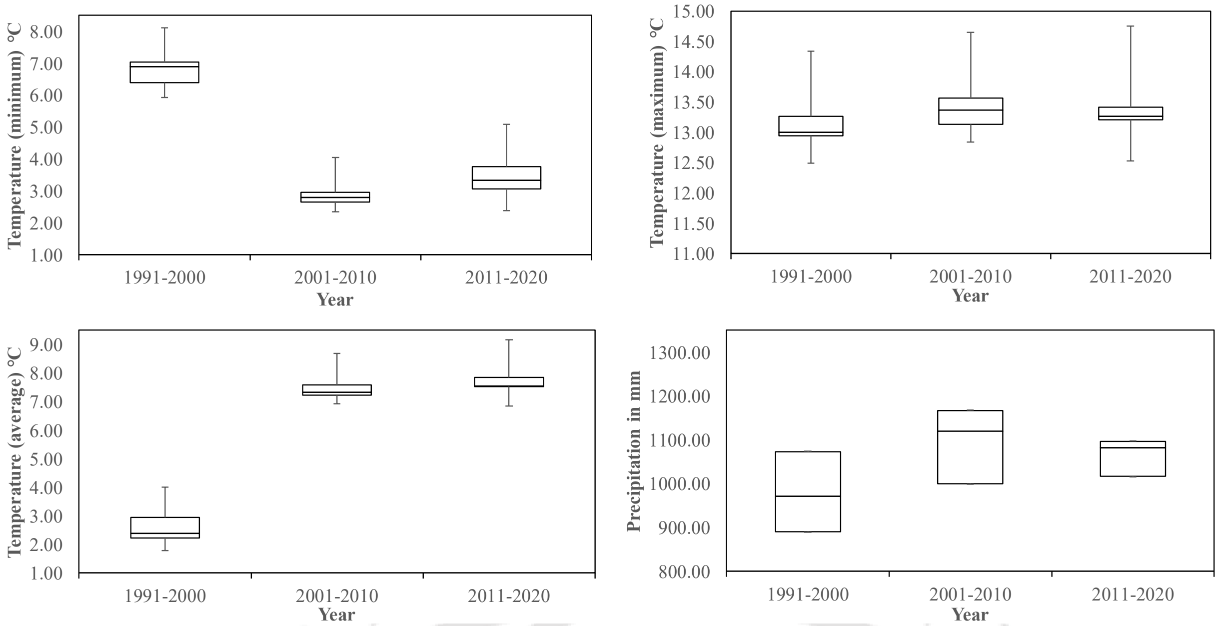

Fig. 4.5 Historical meteorological data representation on Box-plot.

constant in all three decades, on the contrary, the lower or the minimum temperature is found to be decreasing with the average T_min. The analysis of the trend of T_average shows a different scenario- the upper and lower temperature limit in T_average is seen to be increasing in all three decades with an abrupt positive rise in 2001-2010 and continues to increase. From the perspective of Total Precipitation (TP), the region is observed to get a low declining precipitation with a shrinking maximum and minimum precipitation range in the decade 2011-2020. The findings coincide with Srivastava et al. (2021) findings where it is found that the entire state of Arunachal Pradesh had a significantly increasing temperature range and the eastern and the western parts of Arunachal Pradesh showed a significantly decreasing trend in TP.

4.2.2 Homogeneity test using Pettitt's test

The homogeneity test using Pettitt's test on mean annual TP, T_min, T_max, and T_average is done for the study for the year 1991-2020. The statistically significant Pettitt's test result is given in Table 4.1, which shows the change point year and shift direction in the continuous time-series datasets for the year 1991-2020. The results show a negative change is likely to be observed in the historical time scale in annual T_min in the study area from the year 1999.

Table 4.1 Change point analysis of mean annual TP, T_min, T_max and T_average over the study area.

Variables	Change year	Shift
Annual T_min	1999	↓
Annual T_max	No change	No change
Annual T_avg	2004	↑
Annual Precipitation	No change	No change

[A sign ↑ showing an increasing change point and a sign ↓ showing decreasing change point.]

Similarly, a change point year in the mean annual T_average is observed for the year 2004 and shows an increasing change. In both the variables the computed p-value is lower than the significance level alpha=0.05. On the other side, annual T_max and annual TP show no change point in the test as the computed p-value is greater than the significance level alpha=0.05 (as shown in Fig. 4.6), and thus the dataset is homogenous.

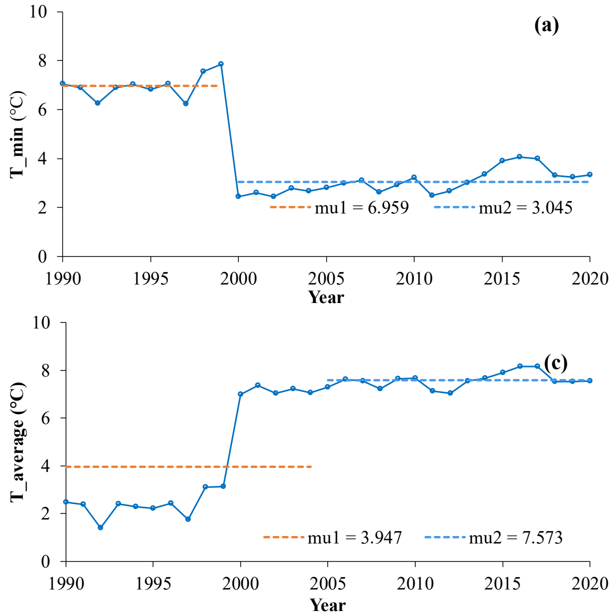

Fig. 4.6 Change point in the (a) T_min, (b) T_max, (c) T_average and (d) Total Precipitation time-series Tawang study area as depicted by Pettitt's test, where 1 and 2 are the mean values before and after change point has occurred, respectively.

4.2.3 Survey-based perception of climate change and impacts as observed by the study population

4.2.3.1 An overview

Fig. 4.7 shows the distribution of the respondents as per their age group, educational qualification, and gender. The ages varied between 22-49 years in the travel/tour operators, 18-65 years in the tourism-dependent livelihoods, 26-72 age years in the

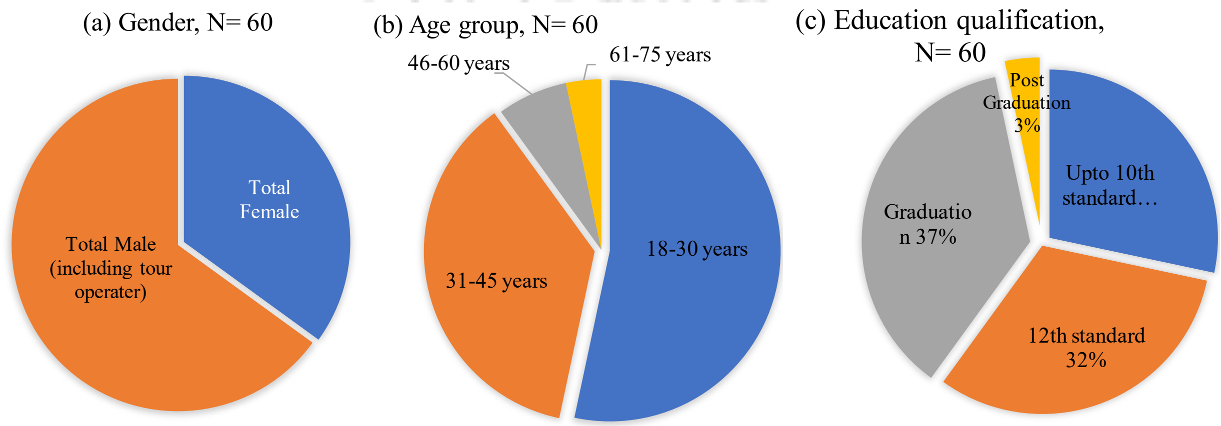

Fig. 4.7 Basic information on the respondents- (a) gender, (b) age-group and (c) educational qualification.

owners/permanent workers of the hotels/restaurants/resorts, and 23-40 age years in the Hotels/Restaurants/Resorts (Seasonal Workers) dependent livelihood. Except for the travel/tour operator which is a male dominant occupation, the other groups chosen in the study have a relatively good ratio of 21 females over 24 males. Alike the age group, the educational qualification of the respondents has been classified as: up to 10th standard (28%), up to 12th standard (32%), Graduate, and Post Graduate (40%). The range of qualifications expands from a 2nd standard pass to a Masters qualified person including professional courses (5%).

4.2.3.2 Perception of climate change

The responses of the people whose livelihoods depend on tourism-related sectors like - restaurants, souvenir shops, coffee shops, travel/tour operators, hotel owners, permanent employees, and seasonal employees have reported noticing the impact of climate change (long-term changes in rainfall and temperature). They have noticed various impacts- lesser coldness in winter (3.3% respondents), increased infrastructural damage due to heavy rain (10% responses), frequent power cuts, freezing of pipelines during winter, and resulting water supply (18.3%) as shown in Fig. 4.8. Few of the respondents (8.3%) did not observe any impact of climate change or did not understand the concept of climate change's impact on their livelihood. The only impact of climate change on business that the respondents observed was the blockage and damage of roads during winter due to heavy rainfall and snowfall that further leads to delays in the supply of raw materials or products to the district. This is particularly troublesome as most of their products are supplied from the state of Assam or Itanagar- the capital of the state. Apart from the similar pattern of climate change impact like lesser snowfall, heavy rainfall, etc., an important observation that the respondents reported was the breeding of mosquitos in recent years. It is also observed that due to favorable weather conditions over the last 4-5 years, i.e., owing to warmer temperatures, tourist inflow has increased as tourists can now visit Tawang throughout the year instead of for a few months in September-October.

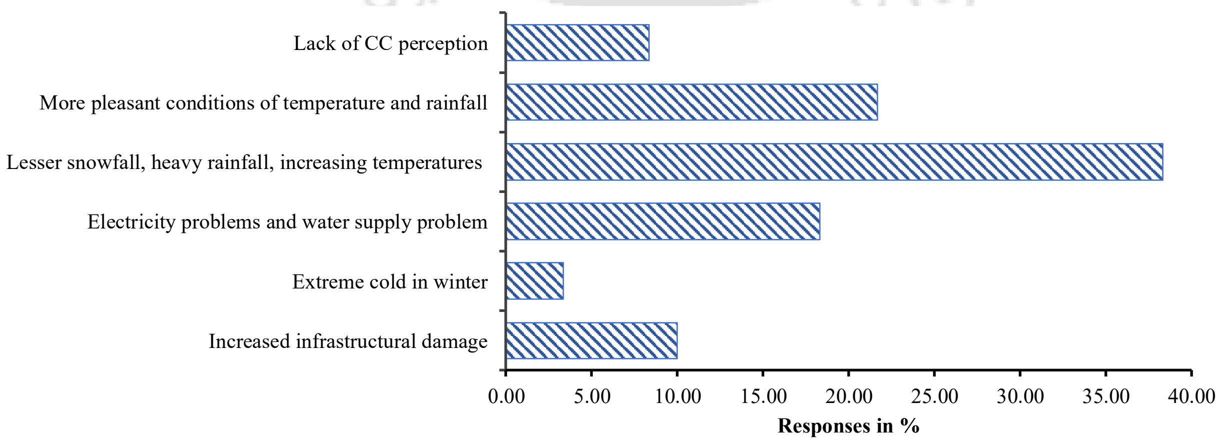

Fig. 4.8 Responses on Climate Change (CC) impact: travel/tour operators, permanent workers: hotel/restaurant/resorts, seasonal workers: hotel/restaurant/resorts, and tourism-dependent livelihoods.

4.2.3.3 Alternate source of income

The participants report they have no other sources of income during the off-season (approximately from March to September). Locals that work in the travel and tour industry have their vehicles and are active during the tourist season. During the off-season (no/minimal tourist inflow), they work on their agricultural land, or as laborers or construction workers. The region has a rich tradition of handicrafts, including weaving, pottery, woodcarving, and jewelry-making. These products are not only sold to tourists, but also to local markets and shops. Both locals (from Tawang and Bomdila) and workers from outside Tawang (tea tribes from Assam) work in the tourism industry, such as in hotels and restaurants, during the busiest months. They return to their respective homes and work in their agricultural fields during the off-season. The majority of hotel owners, permanent employees, and proprietors of gift shops are involved in other businesses, and some of the respondents are also government employees.

4.2.3.4 Awareness of climate change adaptation schemes

Climate change adaptation schemes are measures and strategies implemented to help individuals, communities, and societies cope with the impacts of climate change. The interview results indicate that the locals are not familiar with the idea of climate change adaptation. They only responded that they had no views on the subject when asked if there are any government initiatives or planned adaptation methods in the tourism sector that are affected by climate change. Unfortunately, many people are not aware of these schemes, which can make it difficult for them to adapt to the changing climate. There are several reasons why these people may not be aware of climate change adaptation schemes. Firstly, there may be a lack of education and awareness-raising efforts around the issue of climate change and its impacts. Many people may not understand the severity of the situation and the need for adaptation measures. Secondly, there may be a lack of communication and engagement between policymakers, scientists, and the general public. Climate change is a complex and interdisciplinary issue, and it can be difficult for people to understand the science behind it and the potential impacts it may have on their lives. Thirdly, there may be a lack of resources and funding for climate change adaptation schemes, particularly in the region still in the developing stage. This can make it difficult for governments and organizations to implement effective adaptation measures and raise awareness among the public.

Tourism is a significant contributor to many regional economies. It is a broad and complex industry that includes a wide variety of enterprises and activities such as hotels, restaurants, transportation, entertainment, and so on. Climate change is having a profound influence on the tourism and economic sectors. The amount of both positive and negative climate change effects on mountain tourism is affected, in part, by the investment, operational, and management choices made by tour operators, other tourism sector experts, and the sector's overall strategic adaptability. There are adaptation options available for people in the tourism industry who are financially challenged, but many of them are likely to boost costs and provide only temporary relief (IPCC, 2014). On the other hand, as a result of tourists' interest in spending time in natural settings and their desire to travel, the market for mountain tourism, adventure, and leisure is rapidly developing. As a result, mountain tourist activities like hiking, trekking, camping, rock climbing, mountaineering, mountain biking, wildlife viewing, and many others are in high demand. The respondents and other local people engaged with the tourist sector are uncertain about the unanticipated tourist influx in the scenario for the future. The projection of tourist flow reveals that the tourism sector is expected to grow by 4% annually on average and contribute 10% of the world's GDP within ten years. How tourists will respond to the consequences of climate change is highly unpredictable (Mark Nicholls and Nicholls, 2014).

Although North-East India offers several picturesque locations and significant untapped tourist potential (Prasanta and Bhattacharya, 2008), the region has historically lagged due to insurgency and difficult access (Katyaini et al., 2017). Tourism is vital in north-eastern India because it can drive growth in other economic sectors while also contributing to environmental conservation, socio-cultural enrichment, and rural development. Nowadays, the region's slow and steady development of transportation and other facilities has expanded the scope of tourism (Katyaini et al., 2017).

Results obtained from the analysis of the historical meteorological data reveal (temperature and precipitation) observed impacts of climate change in the last few years such as lesser snowfall, heavy rainfall, and increasing temperatures, etc. In the absence of adaptation strategies, it was observed that the respondents who depend on the tourism sector for their livelihood are coping with the changes by switching to alternative sources of income-termed as livelihood diversification which means adapting to the changes through diversification of their livelihood sources by adopting diverse livelihood options apart from the tourism-based livelihoods. During the off season, agricultural activity (for self-consumption) and construction labour tend to become viable sources of alternate income. Heavy rainfall and snowfall lead to damage or blockage of the roads, thereby causing delays in the supply of products. This is a common and recurrent problem during severe weather conditions, and has significant impacts on local businesses and consumers alike. While heavy rainfall causes landslides, damaging roads and making them impassable, snowfall also results in roads being difficult or impossible to traverse. Consequently, this leads to delays in the delivery of goods and supplies. This can be particularly problematic for businesses that rely on timely deliveries to maintain their operations. To address this issue, it is important to have contingency plans in place for severe weather events. This might involve using alternative transport routes, and the Sela road tunnel can be a possible solution to these obstructions and ensure all-weather connectivity to Tawang in future.

People in the study area were found to be unaware of any government help or scheme for planned adaptation in the sector to climate change. To address this problem, governments, organizations, and individuals need to work together to raise awareness of climate change adaptation schemes and their importance. This can be achieved by educating people about the likely impacts of climate change on the tourism sector and the need for adaptation measures, improving communication and engagement between policymakers and the public, and increasing funding and resources for adaptation efforts. Through a collaborative effort between the government and the stakeholders, more resilient and sustainable communities that are better prepared to face the challenges of climate change can be built.

Earlier Tawang used to receive tourists during the months of September to November, when weather conditions are the most favourable. However, over the past 4-5 years a notable change has been observed in this pattern. Visitors have begun arriving throughout the year due to favourable conditions resulting from an increase in precipitation and temperature. On the other hand, increased precipitation has exacerbated infrastructure damage, such as damage to buildings and roads that are vulnerable to heavy rainfall. The respondents also mentioned issues with the availability of electricity and water, including freezing of water in the pipelines during the winter. The locals, including the respondents, exhibited a lack of any plans for sustaining daily water supply or usage in the face of climate change.

From the analysis of the homogeneity test and trend analysis stated in Chapter 2, Chapter 3, and Sections 3.1 and 3.2 in this chapter, it is clear that the region is experiencing changes in temperature and precipitation pattern, has a reduced snow cover area, and will experience a predicted high runoff in the future. As a result, these changes are altering the natural landscape of mountainous regions, such as melting and retreating glaciers, and a lack of seasonal snow cover is affecting the charm of destinations that depend on these factors. These changes can cause more extreme weather conditions, such as floods, extreme precipitation and associated landslides, droughts, etc., which can damage infrastructure and deter tourists from visiting these destinations. Climate change can also impact water availability in these mountain areas, which would impact the availability of water to tourists during their stay. All these changes may affect tourist behavior, with more travelers seeking out eco-friendly destinations and activities that minimize their carbon footprint. This is leading to an increased demand for sustainable tourism practices. Overall, climate change can have significant economic impacts on the regions tourism industry, including loss of revenue, reduced tourism numbers, and increased costs associated with adapting to changing conditions, thus reducing the livelihood options of the mountain community.

4.3 Conclusions

Tourism is a significant contributor to many regional economies. It is a broad and complex industry that includes a wide variety of enterprises and activities such as hotels, restaurants, transportation, entertainment, and so on. Climate change is having a profound influence on the tourism and economic sectors. The amount of both positive and negative climate change effects on mountain tourism is affected, in part, by the investment, operational, and management choices made by tour operators, other tourism sector experts, and the sector's overall strategic adaptability. There are adaptation options available for people in the tourism industry who are financially challenged, but many of them are likely to boost costs and provide only temporary relief (IPCC, 2014). On the other hand, as a result of tourists' interest in spending time in natural settings and their desire to travel, the market for mountain tourism, adventure, and leisure is rapidly developing. As a result, mountain tourist activities like hiking, trekking, camping, rock climbing, mountaineering, mountain biking, wildlife viewing, and many others are in high demand. The respondents and other local people engaged with the tourist sector are uncertain about the unanticipated tourist influx in the scenario for the future. The projection of tourist flow reveals that the tourism sector is expected to grow by 4% annually on average and contribute 10% of the world's GDP within ten years. How tourists will respond to the consequences of climate change is highly unpredictable (Mark Nicholls and Nicholls, 2014).

Although North-East India offers several picturesque locations and significant untapped tourist potential (Prasanta and Bhattacharya, 2008), the region has historically lagged due to insurgency and difficult access (Katyaini et al., 2017). Tourism is vital in north-eastern India because it can drive growth in other economic sectors while also contributing to environmental conservation, socio-cultural enrichment, and rural development. Nowadays, the region's slow and steady development of transportation and other facilities has expanded the scope of tourism (Katyaini et al., 2017). Apart from the above-mentioned issues, the tourist operators (respondents) showed enthusiasm about promoting tourism in the region by tapping into its natural scenic beauty, strong and unique cultural environment, handicrafts, and festivals, and generate livelihoods. This shows that the district has a high tourist potential and offers a very positive picture. Growth in the tourism sector will have a "multiplier"effect on other businesses as well, boosting the pace of growth. As there is lack of awareness among the local population regarding climate change adaptation schemes of a mountain community. This lack of knowledge and understanding can hinder the community's ability to adapt to the changing climate and implement effective measures to mitigate potential impacts on the tourism sector. Now what next?

In such a scenario, addressing this issue becomes crucial. To ensure the community's ability to adapt to the changing climate and implement effective measures, the following steps may be fruitful if implemented:

1. Outreach: The first step is to launch an extensive education and outreach campaign. This can be done through workshops, community meetings, and informational materials distributed in the local language. The aim is to inform locals about the potential impacts of climate change on their environment and the tourism sector.

2. Local Engagement: Involving the local community in the decision-making process may provide valuable input to solve the issue, as they have a deep understanding of the local ecosystem. Engagement of community leaders, NGOs, and local experts to collaborate on developing adaptive strategies.

3. Customized Solutions: Each community's needs are unique. Tailor climate adaptation schemes to the specific challenges faced by the mountain community. This may involve

strengthening infrastructure against extreme weather events, promoting sustainable practices, or diversifying livelihoods.

4. Capacity Building: Empowering the community with the skills and knowledge needed to implement climate adaptation measures is a one step forward. This can include training in disaster preparedness, sustainable land use, and natural resource management.
5. Monitoring and Evaluation: Establishment of a system to monitor the effectiveness of implemented measures. Regular evaluation helps identify what's working and what needs adjustment, ensuring the long-term success of climate adaptation initiatives.
6. Partnerships: Collaboration with governmental agencies, NGOs, and international organizations of the adaptive measures. These partnerships can provide financial support, technical expertise, and access to best practices from other regions.
7. Raise Awareness: Use of various communication channels to spread awareness, not only within the community but also among tourists is another step towards adaptation measures. Tourists can play a significant role in supporting sustainable practices, making them aware of the community's efforts.
8. Long-term Planning: Climate change adaptation is an ongoing process. The mountain community should have a long-term plan that accounts for future changes in climate and continuously evolves to meet new challenges.
9. Incentives: Providing incentives for community members to actively participate in climate adaptation initiatives is surely an important step that leads to active participation of the local community. Recognize and reward their efforts to create a sense of ownership and commitment.
10. Feedback Loop: Establishment of a feedback loop that allows the community to share their experiences, insights, and challenges shall boost the process. This can help refine adaptation strategies and ensure they remain relevant.

By taking these suggestive steps, the mountain community can overcome the lack of awareness, adapt to the changing climate, and protect its environment and economy, especially the crucial tourism sector, from the potential impacts of climate change. As Agenda 21 of the UN Conference on Environment and Development (UNCED) identified mountain tourism as a crucial element in sustainable mountain development and conservation and indicated that more than half of the world's population may be impacted by the future of the mountains. Working with this industry is essential if we want to create and promote sustainable tourist practices. The greatest way to maintain economic growth is to properly and sustainably utilize this resource from nature through tourism. The findings of this study can be used in planning a tourism-economic development nexus and in implementing sustainable tourism initiatives.

5

Summary and Limitation

5.1 A brief review of the work done

The current study was carried out to examine changes in hydro-climatological variables such as precipitation, temperature, and streamflow, as well as an analysis of the snow cover area in the Tawang river basin (India) in the Eastern Himalayas. This study also examines the influence of climate change on people's livelihoods (tourism sector). Climate data (variables: temperature and precipitation), two different GCMs (RCPs 4.5 and RCPs 8.5) for the two variables, snow cover area from remote sensing data, and ground hydro-meteorological data were used to complete the analysis for the future period 2006-2099. The climate change impact on the tourism sector was carried out using a qualitative sampling technique. In this study, the trend analysis of the precipitation and temperature was done using the Mann-Kendall trend test and Sens slope estimator, and snowmelt runoff modeling was done using the Snowmelt Runoff Model (SRM). Based on the objectives chosen for the current study, this chapter summarises the major findings of the research work presented, along with the limitations associated with the current studies. This chapter also provides scope for future research.

5.1.1 Precipitation and temperature trends in historical and futuristic time series

- This chapter aims to investigate and quantify the trend and homogeneity in total precipitation, T_min, and T_max for the RCP4.5 and RCP8.5 from 1950 2099 using a class of approximately 30-year duration.
- The study was validated using a minimum set of meteorological acquired from the CWC, Govt. of India.
- The three study points fall in the Tawang river basin with a large area covered with snow and glacier, which plays an important role in the Tawang basin's hydrology and

downstream hydrology.

5.1.1.1 *Precipitation trend analysis*

- The historic precipitation trend analysis in the study reveals that there is no significant increasing trend in the annual and seasonal mean precipitation.
- The summer mean precipitation for RCP4.5 (2006-2065) shows a positive trend with a positive rise in precipitation in all the study points.
- The mean annual precipitation statistics show an increase as compared to the historic precipitation for RCP4.5 in 2006-2052 and 2053-2099 at study point 1, which declined for RCP8.5 than the historical mean annual.
- The study points 2 and 3 show an increase in mean annual precipitation for RCP4.5 and RCP8.5 as compared to the historic mean annual.
- Although decreasing in mean annual precipitation in study point 1 is not in agreement with previous reports and studies, the increasing total precipitation in the later years of both RCPs in the study point 2 and 3 looks in agreement with the previous and earlier studies report.

5.1.1.2 *Temperature trend analysis*

- The mean annual T_min statistics in the study reveal a significant increase against the normal increase of T_max in RCP4.5, similar to the precipitation statistics and behavior of study point 1.
- Both RCP scenarios show a uniform increase in T_min and T_max for study points 2 and 3.
- A consistent increase in mean annual T_min and T_max for the three study points. Still, the inter-decadal temperature statistical analysis shows that the increase in mean annual T_min is greater than the increase in T_max, indicating a decreasing trend in DTR (Government of Arunachal Pradesh, 2011; Shivam et al., 2017).

5.1.2 Analyses of the hydrological Snow melt using the Snow Melt Runoff model and future projection

- The snow melt-induced runoff in the Mago Chu sub-basin is simulated using the SRM model based on observed runoff, snow cover area, temperature, and precipitation data.
- The model needs snow cover area as a major input variable, therefore, the cloud-free scenes acquired from MOD10A2 for the years 2007, 2009, and 2013 have been selected as the simulation period- for the calibration period 2007 and 2009 years; and the validation period 2013 year.

5.1.2.1 *Objective summary*

- The results of the two accumulation periods and SCA peaks within the annual cycle are different from some previous studies in the central and western Himalayas but similar to that of a small basin named Nuranang nearby the study basin in the eastern Himalayas.

- A probable explanation for the slightly decreasing trend of snow cover in the basin could be the decreasing trend in winter precipitation and elevation-dependent warming.
- The GCM models used in the study, the average monthly T_max, T_min, and precipitation is projected to rise in the future both for the RCP4.5 and RCP8.5 for the year 2040, 2060 and 2090 as compared to the base year 2007.
- Similarly, the rise in T_min is also observed at both the RCPs for the years 2040, 2060, and 2090 as compared to the base year 2007.
- A similar pattern of high flow is observed in the predicted runoff for the months as compared to the base year, July is the month of highest runoff the highest flow month justified by the wet season.
- In the RCP8.5 predicted runoff shows a unique pattern of highest flow month behavior. The far future year has the highest predicted runoff in May for RCP8.5, thus a clear climate-affected runoff time shifting from the normal highest runoff month of July to May month.
- The average annual runoff for the future years 2040, 2060, and 2090 reports an increase in many folds over the years of assessment for RCP4.5 and RCP8.5 Scenario, the highest runoff being in the year 2090.

5.1.3 Assessment and analyses of climate change impact on the livelihood of the mountain community

This objective is a climate-based socio-economic study that assesses the perception of climate change among the people engaged in tourism industry the Tawang district. The study was conducted among people who are engaged in the tourism sector for livelihood generation.

- Basic information on the age group, gender ratio, and educational qualification revealed that there was a wide range in age group and educational qualification found among the respondents who were engaged in the tourism sector for livelihood generation at the time of sampling. The gender ratio is almost equal showing a women empowerment picture.
- The analysis of the sampling shows that the people in the Tawang district have a clear perception of climate change and its impact that is affecting their livelihood.
- As the main occupation is being a tourist operator, during the assessment it is found that the respondents work as construction or worker in agricultural activities as an alternative during no tourism season or off-tourism season (March-September).
- The analysis of the responses reveals that the respondents are not aware of any Govt. help or scheme for planned adaptation in the sector to climate change. They are coping with the effects of climate change.

5.2 Limitations

While assessing climate change impact in the Tawang basin in the Eastern Himalayas several limitations have been identified which may be taken as the future extension of the present work. Some of the key limitations are described below:

- The study was carried out and verified utilizing a limited set of ground-based meteorological data obtained from the CWC, Government of India, which resulted in uncertainty/limitation in the validation and selection of GCMs for the precipitation and temperature trend analysis. More years of ground-based meteorological data could be used in the future to reduce uncertainty and give more reliable trend analysis.
- Similarly, a comprehensive ground-based daily hydro-meteorological dataset is required for running a hydrological model; however, this study had very restricted temporal data availability, which necessitated the use of reanalysis data, satellite, and model-based outputs. Due to a lack of appropriate data, only three years have been chosen for the SRM simulation period.
- The MODIS MOD10A2 dataset is utilized in this work to calculate snow cover area. When snow is observed in a cell in MOD10A2 on any day of the period, the cell is mapped as snow. If no snow is found, the cell is filled with the most frequent clear-view observation (e.g., snow-free land, a lake, etc.). A pixel size of 500 m in spatial resolution can influence snow cover area mapping. Remote sensing data with finer spatial and temporal resolution might have supplied the exact snow cover area for snowmelt runoff modeling. The use of cloud-free and freely available high-resolution remote sensing data could be a useful future scope for similar studies.
- The snowmelt runoff model was only applied to one small river basin in the Tawang river basin. Similarly, the model can be used to compare other adjacent basins or comparable basins in future studies.
- A total of 60 respondents- those who rely on tourism for a living- were included in the assessment and analysis of climate change's impact on the livelihood of the mountain community in the tourism sector. More respondents can be offered as a future scope of this study, which could lead to a greater comprehension of the study. Qualitative models could be useful as well.

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Appendix I

A. Type and Source of Data used for Analysis of Non-Parametric Trend and Climatic Parameter Homogeneity Tests

Sl. no.	Data	Source
1	Digital Elevation Model (DEM)	Shuttle Radar Topography Mission (SRTM)- 30m United States Geological Survey (USGS)
2	Temperature and precipitation: 2017-2018	Central Water Commission (CWC) discharge site- Muruga Bridge site
3	Temperature and precipitation: 2017-2018	ERA5-Land hourly precipitation
4	Temperature and precipitation: 2017-2018	NASA POWER (Prediction of Worldwide Energy Resources)
5	Precipitation: 2017-2018	Tropical Rainfall Measuring Mission (TRMM)
6	Precipitation: 2017-2018	Global Precipitation Measurement (GPM)
7	General Circulation Models	NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP): 1950-2100

B. Type and Source of Data used for Analysis of Hydrological Snowmelt and Future Projection

Sl. no.	Data	Source
1	Digital Elevation Model (DEM)	Shuttle Radar Topography Mission (SRTM)- 30m United States Geological Survey (USGS)
2	MOD10A2 (Snow cover area)	MODIS- National Snow and Ice Data Center (NSIDC)-NASA
3	Discharge data	Central Water Commission (CWC) discharge site- Muruga Bridge site, Tawang Basin
4	Air temperature maximum and minimum Precipitation	NASA POWER (Prediction of Worldwide Energy Resources) project
5	Climate change scenerios	NEX-GDDP dataset- 2040 (near future), 2060 (middle future), and 2090 (far future), using two GCMs for temperature and precipitation, namely- GFDL-CM3 and CSIRO-Mk3-6-0 respectively, for RCP 4.5 and RCP 8.5.

C. Type and Source of Data Used for Impact of Climate Change on Livelihood in Tawang District

Sl. no.	Data	Source
1	Average maximum temperature (T_max), Average minimum temperature (T_min), Average temperature (T_average), Total Precipitation (TP)	NASA POWER (Prediction of Worldwide Energy Resources) project
2	Domestic tourist visits in Arunachal Pradesh since 2011	Ministry of Tourism, Govt. of India
3	Climate change perception, its influence on tourism, and adaptation of the tourist sector to climate change	Survey-based on open-ended questionnaire (Purposeful Sampling)

Appendix II

Tourism Questionnaire: Hotel/Restaurant/Resorts (Owners/Permanent Workers)

Date: Place:

S.No.	Questions	Responses
1	Name and address of the hotel/ resort/ restaurant	
2	Year of establishment and operation	
3	Name of the owner	
4	Services provided	1.
		2.
		3.
		4.
4	a) Name of the respondent	
	b) Designation of the respondent	
	c) Gender	
	d) Age group	
	f) Home address	
	Year since employed at the hotel/ resort	
6	Have you noticed impact of climate change (long term changes in rainfall and temperature) on tourism in this place and your business?	Yes....................1
		No....................2
		May be...................3
7	Please explain your answer to question 12.	
8	If 'yes' or 'may be' to Qn. No 6-	
	What is the impact of climate change on livelihood?	
9	Scale of operation	No. of permanent employee
		No. of seasonal employee
10	Percentage (%) of rooms occupied per month on an average (from the hotel/ resort records)	1. January
		2. February
		3. March
		4. April
		5. May
		6. June
		7. July
		8. August
		9. September
		10. October
		11. November
		12. December

Date: Place:

S.No.	Questions	Responses
11	Total number of rooms in the hotel/ resort.	No. of rooms
12	Hotel accommodation rates in slabs (Rs.)	1. Standard-Single Rs..................
		2. Standard-Double Rs..................
		3. Deluxe-Single Rs..................
		4. Deluxe-double Rs..................
		5. Suite Rs..................
13	Number of visitors per month (tourists who do not reside in the hotel)	1. January....................
		2. February..................
		3. March......................
		4. April.......................
		5. May.........................
		6. June........................
		7. July........................
		8. August...................
		9. September..............
		10. October..................
		11. November...............
		12. December................
14	Average numbers of days do the tourist stay?	No. of days.....................
15	Any other source of income-	
	a. Autonomous income source	
	b. From owner	
	c. From Govt.	
16	Any plan on using daily water consumption or supply to sustain climate change?	
17	Any Govt. help or scheme for planned adaptation in tourism sector to climate change?	
18	Impact of Covid Pandemic	Yes 1
		No. 2
		May be. 3
19	Is there any sudden flow of tourist after Covid Pandemic?	

Tourism Questionnaire: Hotel/Restaurant/Resorts (Seasonal Workers)

Date: Place:

S.No.	Questions	Responses
1	Name and address of the hotel/ resort/ restaurant	
2	Year of establishment and operation	
3	Services provided	1....................... 2....................... 3....................... 4.......................
4	a) Name of the respondent b) Designation of the respondent c) Gender d) Age group e) Educational qualification f) Home address	
5	Year since employed at the hotel/ resort	
6	For how many months in a year are you employed at the hotel?	
7	Has the number of months for tourism for tourism increased in the past few years?	Yes No
9	If yes, what are the reasons for increase in tourism months?	1....................... 2.......................
10	Is Climate Change a possible reason (more pleasant conditions of temperature and rainfall)?	Yes No
11	What is the alternate source of employment?	
12	Impact of Covid Pandemic	Yes.......................1 No........................2 May be................3
13	Is there any sudden flow of tourist after Covid Pandemic?	

Tourism Questionnaire: Travel/Tour Operator

Date: Place:

S.No.	Questions	Responses
1	Name and address of the travel/tour operator agency	
2	Year of establishment and operation	
3	Services provided	1..................... 2..................... 3..................... 4.....................
4	a) Name of the respondent b) Designation of the respondent c) Gender d) Age group e) Educational qualification f) Home address	
6	Year since employed at the agency	
7	What is the scale of operation of this agency?	No. of vehicles with tourist Permit
8	Has the scale of operation of the agency expanded since it has been established?	Yes..................... No.....................
9	If yes, what are the reasons for expansion?	1..................... 2..................... 3..................... 4.....................
10	What is the approximate expenditure per day by tourists on travel to the place?	Rs...................... per day
11	What are the approximate number of days do the tourist travel?	
12	What are the other modes of travel to the place?	1..................... 2..................... 3..................... 4.....................
13	In which months the inflow of tourists is maximum?	1. January..................... 2. February................... 3. March....................... 4. April......................... 5. May.......................... 6. June......................... 7. July......................... 8. August.................... 9. September.............. 10. October................... 11. November................ 12. December................

Date: Place:

S.No.	Questions	Responses
14	Have you noticed impact of climate change (long term changes in rainfall and temperature) on tourism in this place and your business?	Yes No Maybe
15	Please explain your answer to the question above.	
16	Any other source of income-	
	a. Autonomous income source	
	b. From owner	
	c. From Govt.	

Tourism Questionnaire: Tourism Dependent Livelihoods

Date: Place:

S.No.	Questions	Responses
1	Name and address of the shop/outlet, etc.	
2	Year of establishment and operation	
3	Goods/Services provided	1 ....
		2 ....
		3 ....
		4 ....
4	a) Name of the respondent	
	b) Designation of the respondent	
	c) Gender	
	d) Age group	
	e) Educational qualification	
	f) Home address	
5	Year since employed at the shop/ outlet etc	
6	Have you noticed impact of climate change (long term changes in rainfall and temperature) on tourism in this place and your business?	Yes No May be
7	Please explain your answer	
9	Have there been any changes in the raw material supply for your livelihood in the past 10 years as a result of rainfall?	Yes No May be
10	Please explain your answer	
11	Are you aware of any government schemes and policies to encourage certain raw material usage because they are eco-friendly?	Yes No May be
12	Please explain your answer	

13	Which are the months when the sales are highest?	1. January.................... 2. February.................. 3. March...................... 4. April........................ 5. May......................... 6. June........................ 7. July........................ 8. August................... 9. September.............. 10. October................... 11. November............... 12. December................
14	What is the average monthly/yearly revenue? This is in context of decline in revenue if tourism declines in the area as a result of climate change.	Rs........../month Rs........../year
S.No.	**Questions**	**Responses**
15	Have you noticed impact of climate change (long term changes in rainfall and temperature) on tourism in this place and your business?	Yes No May be
16	Please explain your answer to the question above.	
17	Any other source of income- a. Autonomous income source b. From owner c. From Govt.	
18	Any plan on using daily water consumption or supply to sustain climate change?	
19	Any Govt. help or scheme for planned adaptation in your sector to climate change?	

List of Publications and Conferences

Publications

1. **Devi, J.P.**, Mahanta, C. & Barua, A. (2022) Analysis of non-parametric trend and climatic parameter homogeneity tests in a data-scarce region: a spatio-temporal perspective in the Tawang River basin, Eastern Himalayas. Theor Appl Climatol .
2. **Devi, J. P.**, Barua, A., & Mahanta, C., (2020). Mountain Tourism Adaptation to Climate Change in the Indian Himalayas; Challenges of Resilient and Sustainable Infrastructure Development in Emerging Economies, CRSIDE2020, India, 631-637, ISBN 978-81-954551-0-2. *(Conference Proceeding)*
3. **Devi, J. P.**, Mahanta, C., Barua, A. (2022). Understanding Adaptation Strategies to Climate Change. In: Yadav, B., Mohanty, M.P., Pandey, A., Singh, V.P., Singh, R.D. (eds) Sustainability of Water Resources. Water Science and Technology Library, vol 116. Springer, Cham. *(Book Chapter)*
4. **Devi, J. P.**, Barua, A., & Mahanta, C., Climate Change Perception, its Influence on Mountain Tourism and Local Adaptation Responses: A Case Study in Tawang, Eastern Himalayas. *(Under review)*
5. **Devi, J. P.**, Barua, A., Mahanta, C., & Pivot, F. C., Hydrological Snow melt modelling of the Tawang river (Mago Basin) using Snow Melt Runoff model and future projection of the streamflow for different climate change scenarios. *(Under preparation)*
6. **Devi, J. P.**, Barua, A., Mahanta, C., & Pivot, F. C., Dynamics of High-Altitude Lakes (1990-2020) and identification of potentially dangerous lakes using Remote Sensing data in Mago Basin in the Eastern Himalayas, India. *(Under preparation)*

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1. **International Conference on State of the Cryosphere in the Himalaya: with a focus on Sikkim and Eastern Himalaya**
   Juna Probha Devi, Chandan Mahanta, Anamika Barua. *Snow cover area extraction using multispectral & multi-temporal satellite datasets: the case of Lachung River catchment, Sikkim.* Dept. of Science and Technology and Climate Change, Govt. of Sikkim and ICIMOD. Oral Presentation, Feb 19-20, 2018.
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3. **Issues and Challenges in Water Treatment and Allied Research for Sustainable Environment, Water2020, India**
   Juna Probha Devi, Chandan Mahanta, Anamika Barua. *Inventory and Dynamics of High-Altitude Lakes (19902018) using Remote Sensing data in Mago Basin in the Eastern Himalayas, India.* Indian Institute of Technology Guwahati. Poster Presentation, Jan 23-25, 2020.

4. **Energy and Environmental Technologies for Sustainable Development, Chem-Conflux20, India**
   Juna Probha Devi, Anamika Barua, Chandan Mahanta. *Theoretical aspect of Adaptation strategies to climate change.* National Institute of Technology Allahabad. Oral Presentation, Feb 14-16. 2020.

5. **Challenges of Resilient and Sustainable Infrastructure Development in Emerging Economies, CRSIDE2020, India**
   Juna Probha Devi, Anamika Barua, Chandan Mahanta. *Mountain Tourism Adaptation to Climate Change in the Indian Himalayas.* American Society of Civil Engineers (ASCE), Kolkata. Oral Presentation, Mar 2-4, 2020.

6. **International e-Conference on Water Source Sustainability, Roorkee, India**
   Juna Probha Devi, Chandan Mahanta, Anamika Barua. *Understanding adaptation strategies to climate change.* Jointly organized by Indian Water Resources Society (IWRS) and Department of Water Resources Development and Management, IIT Roorkee. Oral Presentation, June 18-20, 2021.

7. **International e-Conference on Water Source Sustainability, Roorkee, India**
   Chandan Mahanta, Ashim Sattar, Abhishek Dixit, **Juna Probha Devi**, Vishnu U Krishnan, Satheesh Barre, Arup Kumar Sarma, Rajib Kumar Bhattacharjya, Sudip Mitra, Rishikesh Bharti, Archana M Nair, Ajay Dashora, Arindam Dey, Ravi K and T. G. Sitharam. *Status of glacier-stored freshwater sustainability in Arunachal Pradesh.* Jointly organized by Indian Water Resources Society (IWRS) and Department of Water Resources Development and Management, IIT Roorkee. Oral Presentation, June 18-20, 2021.

Biography

Author

Juna Probha Devi, the author, was born in Morigaon district, Assan, India. She completed High School Certificate Examination (10th Standard) in 2002 conducted by the Secondary Education Board of Assam (SEBA), Assam. In 2004, she finished the 12th grade exam administered by the Assam Higher Secondary Education Council, Assam, with distinction marks. She graduated from Morigaon College, Assam, in 2007 and is a gold medalist in Geography (Gauhati University). She completed her Post-Graduation degree in 2009 in *Geography* with a specialization in *Cartography* from Gauhati University, Guwahati, Assam. Further, she qualified for the National Eligibility Test-Lectureship (NET-LS) and State Level Eligibility Test (SLET) for Lectureship (NE region). She was a lecturer in various educational institutes in Assam and Meghalaya. Later, she enrolled in the joint educational programme of ITC, University of Twente, The Netherlands, and Indian Institute of Remote Sensing (ISRO, Govt. of India), Dehradun, for the Post Graduate Diploma (PGD) course in Geoinformation science and earth observation, specialising in Natural Hazard and Disaster Risk Management in 2013. She began working on a Department of Science and Technology (Govt. of India) funded project at the Indian Institute of Technology Guwahati (IIT Guwahati), Assam, in 2014, after completing the PGD programme.

She joined PhD programme in 2017 at the Centre for the Environment, IIT Guwahati. She also received *Shastri Research Student Fellowship (SRSF)-Doctoral fellowship* awarded by the Shastri Indo-Canadian Institute during her PhD. She also received a research fellowship from Ministry of Education, Government of India and the Student Travel Grant (STG) for attending the American Geophysical Union Fall Meeting in 2019 held at California, USA. She appeared for the synopsis seminar (open-seminar) on December 12, 2022 and got permission for thesis submission with constructive remarks.