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Evaluation of Temperature and Precipitation Changes under Climate Change Scenarios in Budhi Gandaki River Basin (BGRB), Nepal

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Abstract

Climate change has posed a solemn threat to the hydrological firmness of mountainous river basins, with broad impressions on ecological systems, water resources, and hydropower development. This study evaluates the future effects of climate change over the Budhi Gandaki River Basin (BGRB) in Nepal using a collaboration of CMIP6 General Circulation Models (GCMs) under Shared Socioeconomic Pathways 2-4.5 and 5-8.5. Quantile mapping, as an advanced bias correction technique, was applied to enhance the models' accuracy in reproducing the past climate pattern, thereby improving the robustness of the future projection. Conferring to the verdicts, significant warming with maximum temperature increases by the end of the 21st century can be expected over a range of 1.18 to 5.08°C. Some other key seasonal changes noticed in precipitation regimes include increased seasonality, increased winter rainfall, and variable monsoon activity. The consequences highlight the urgent need to integrate bias-corrected climate projections into regional progress and climate adaptation plans. It calls for community-based adaptation approaches coupled with strong infrastructure and sustainable water management regulations so that the emerging risks could be reduced. Our work delivers essential new knowledge linked to the regional effects of climate change in high-altitude basins, confirming the urgent necessity for prompt, evidence-based decision-making to foster climate resilience and sustainable development in Nepal's Himalayan region.

Keywords Climate Change: GCMs selection: CMIP6: BGRB: Bias correction.

Introduction

Climate has been demarcated as the average atmospheric condition across a particular region for a specific timeframe. Global climate change phenomenon has impacted every element of human beings including other animals. According to the (IPCC, 2014), Any change in the global climate that is caused by human action direct or indirect and persists for a substantial period is stated to as climate change. The global temperature has amplified by 0.3–0.6℃ in assessment to 1900, and it is projected to increase by 1.4 to 5.8℃ by 2100 (IPCC, 2014). The variation in climate involves the interactions between the atmosphere and other components of the climate system such as land, seas, snow, ice, and hydrological systems. Variations in precipitation and temperature patterns impact the storage of snowmelt in Himalayan regions, which are shielded by snow virtually year-round. The hydrology of perennial Himalayan rivers is allied to the rate of snowmelt (Kumar et al., 2022; Pokhrel and Thapa, 2021; Singh, 2011; Thapa et al., 2021). Climate change is typically detected through studies of temperature and precipitation patterns. Higher Elevation regions are also more susceptible to uncertainty and changes in the global environment (Maskey et al., 2011; Shrestha et al., 2011) as warming is more noticeable in higher elevation regions than in lower elevations. The rate of change of temperature change in Himalayan region is higher than the global average (Goswami et al., 2018; Singh and Goyal, 2016). Effects of climate change, such as variations in temperature and precipitation, are causing floods and droughts to happen more commonly. The broadly held of Nepal's hydropower is Run-off-river type and, can function at full installed capacity during monsoon season only, hence the river basin may see notable seasonal variations and is vulnerable to climate change phenomenon.

Climate change has been a big anxiety globally, regionally, and domestically. One cannot contradict the fact that the earth's temperature has risen by a few degrees Celsius in the last few eras. Universally, according to (IPCC, 2021) the average temperature was 0.87 °C warmer in the decade between 2006 and 2015, 0.93 ± 0.07°C warmer in the decade between 2009 and 2018, and 1.04 ± 0.09 °C warmer during the last five years (2014–2018) with assessment to 1850–1900 period. Also, the projected rate of temperature increase is unevenly 0.2°C for every ten years (IPCC, 2021). In Nepal, the temperature has been intensifying in the last few decades. Also, the general warming leaning, most evidently in the winter months, an increase in the highest recorded temperature of 0.06 °C each year between 1978 and 1994, mainly from higher altitude stations, was noted for Nepal (Shrestha et al., 1999). The upsurge of temperature is directly interlinked with the quantity of carbon dioxide and other greenhouse gases in the atmosphere. Increased evaporation, primary snowmelt, a change from snow to rain, less infiltration, low soil moisture, lessened groundwater recharge value, decreased stream flow amount, and increased inconsistency in precipitation of stream flow are all foreseen in a changing climate. A global circulation model takes the effects of rising greenhouse gas concentrations in the atmosphere which results in the predicted changes in climate. In general, the purpose of such model is to predict future weather patterns. Numerous expectations regarding the rates at which greenhouse gases will be released into and removed from the atmosphere are included in the model which are referred to as emissions situations in the climate model.

Climate models are considered important tools for the analysis of past, present, and future climate conditions. They are useful in understanding climate variability and the projection of future scenarios, which in turn are used in assessing impacts. The Coupled Model Intercomparison Project has evolved from CMIP1 to CMIP6 over time, leading to the development of many Global Climate Models (GCMs) to date. However, with an increasing number of models available, there is also a corresponding increase in uncertainties and biases; hence, the optimal selection of representative GCMs is very critical. This study forecasts climate change scenarios for temperature and precipitation in the Budhi Gandaki River Basin using GCMs selected from previous research through the advanced enveloping method. Model selection is difficult and normally depends on either the model's skill in replicating historical climate or its capability to represent the full range of projected change. Future projections in this study rely on carefully chosen CMIP6 GCMs under different SSP scenarios to estimate possible future temperature and precipitation patterns in the basin. These projections are of paramount importance for future hydrological studies, including streamflow estimation. The study thus provides the essential basis for climate adaptation planning through the quantification of basin-scale climate change and its associated uncertainties. The policymakers can employ these downscaled outputs in support of informed decision-making to formulate effective climate adaptation strategies.

Study Area and Data Collection

Study Area

In central Nepal, the Dhading and Gorkha districts are part of the Budhi Gandaki River Basin (BGRB), which lies between latitudes 27°50' and 29°00' N and longitudes 84°30' and 85°10' E. The Budhigandaki River, total drainage area of roughly 5,000 kilometers, is the site of a proposed 1200-megawatt storage-type hydropower project. Conferring to Figure 1, the terrain is principally rocky and ranges in elevation from 315 to 8,115 meters above sea level. The Mowang Khola from the Ladakh Himal and the Shiar Khola from the Lark Himal are two substantial tributaries. They meet and flow toward the south for about 120 km before joining the Trishuli River at Benighat. Nearly 24 km upstream of this confluence, the Budhigandaki is joined by the Aankhu Khola, another noteworthy tributary that rises in the Ganesh Himal. The BGRB is a constituent of the larger Narayani river system, which drains central Nepal and has five main tributaries: The Kali Gandaki, Budhigandaki, Marsyangdi, Trishuli, and Seti Gandaki Rivers. The lower reaches of the basin are eminent by smooth, sharply carved landscapes that were created by recent Himalayan uplift accelerating active fluvial erosion.

Observed Daily Temperature and Precipitation Data

Historical climate data for 1985–2014 were achieved from the Department of Hydrology and Meteorology

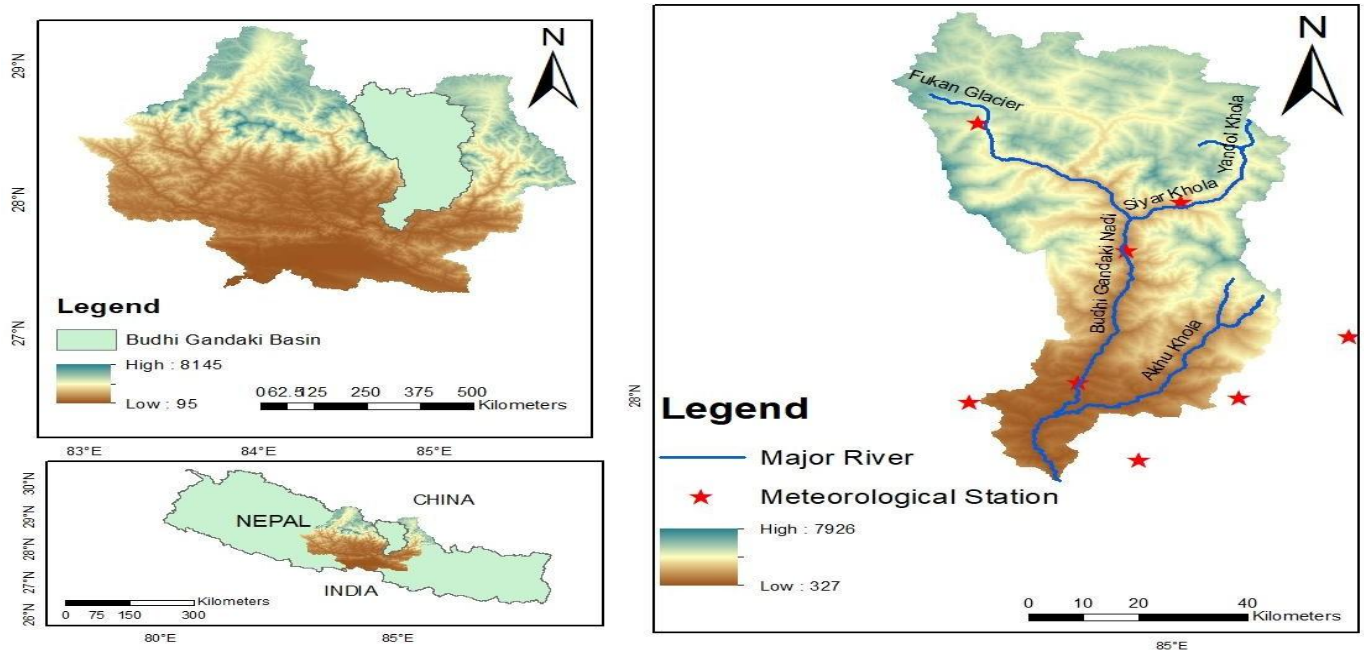

Fig.1 Study Area Budhi Gandaki River Basin

Table 1 List of Meteorological Observed Stations Used in the Study Department of Hydrology and Meteorology (DHM)

Station Name	Lat (°N)	Long (°N)	Elevation(m)	Data Period	Data available
Jagat (Setibas)	28.37	84.90	1334	1990-2014	P
Larke (Samdo)	28.67	84.62	3650	1990-2014	P
Chhekampar	28.48	85.00	3300	1976-2005	P
Arughat Bazar	28.05	84.82	518	1976-2005	P
Dhading	27.87	84.93	1420	1976-2005	P
Thamachit	28.17	85.32	1847	1976-2005	P
Pansaya Khola	28.02	85.12	1240	1976-2005	P
Gorkha (Birenchowk)	28.00	84.62	1097	1990-2014	P,t

(DHM), Nepal. The basin's typical annual maximum, minimum, and mean temperatures are 26.96°C, 15.98°C, and 18.84°C, respectively. June is the hottest month, while January and December are the coldest and driest. July obtains the highest rainfall, with an average precipitation of 384.71 mm. Absent or missing data were corrected using the Inverse Distance Weighting (IDW) method. For steadiness, daily precipitation records from eight places and temperature data from the single available nearby station were used. The concluding dataset for precipitation and temperature (1990–2014) was gathered from DHM for locations within and surrounding the BGRB.

Future Climatic Data

The verification of model runs that passed the criteria of reproducing historical climates was done by using monthly averages of air temperature and precipitation. The model selected from the shortlist was able to reproduce the annual cycle of precipitation and air temperature data for the base period, which is considered as 1990– 2014. The reference climate dataset was obtained from the Department of Hydrology and Meteorology (DHM). Monsoon, winter, and total biases for air temperature were considered. Finally, the models with the lowest cumulative bias-a measure of the GCM's effectiveness relative to the reference data-was selected. The four GCMs that make up the final selection are each linked to a unique ensemble member code r1i1p1f1 where 'r' stands for realization index, 'i' for initialization index, 'p' for physics index, and 'f' stands for forcing index. Based on the total bias of precipitation and temperature for the Warm- Wet (W-W), Warm-Dry (W-D), Cold-Dry (C-D), and Cold-Wet (C-W) corners, respectively EC-Earth3-CC, MIROC6, MPI-ESM1-2-LR, and MRI- ESM2-0 exhibit the smallest total bias values under SSP2-4.5 during the end of the century, demonstrating their high performance in simulating historical climates. IPSL-CM6A-LR, MRI-ESM2-0, GFDL-ESM4, and INM-CM5-0 perform well for the end-of-century climate simulations under SSP5-8.5.

Bias Correction and Uncertainty Quantification

Biases in the selected GCMs were adjusted using the quantile mapping method (QM), which works by aligning the CDFs of modeled and observed data. Bias correction is essential before applying GCM outputs in climate impact studies due to the methodical errors generally found in these model outputs because of model structure, discretization, and spatial averaging (Teutschbein and Seibert, 2012). QM assumes that model biases are constant in time and has been widely applied in previous studies, such as Arnell et al. (2016a), Idrizovic et al. (2020), and Singh et al. (2022). It corrects modeled values statistically, which are linked with observed records. In this research, the QM technique was applied in R-Studio for bias modification of historical temperature and precipitation data of the BGRB to generate dependable future projections. Other revisions underline the need for downscaling to be done to advance the spatial resolution of climate models (Chen et al., 2012; Grose et al., 2023; Kaini et al., 2020; Khadka & Pathak, 2016; McSweeney et al., 2015; Salathé, 2003; Soares et al., 2024; Wood et al., 2004). Lastly, the uncertainties from GCM variability, emission scenarios, and hydrological modeling were represented by using box plots.

The QM technique has been successful in downscaling and correcting local climate signals, and it enhances extreme projections (Belay et al., 2024; Gudmundsson et al., 2012; Song et al., 2025). A mathematical equation that may be demarcated formally as follows and is used to translate distribution functions of the modelled variables with detected ones as part of the statistical alterations to correct the bias of climate model (X_{raw}), the bias point of this QM method is to use observed value (X_{obs}) based on following equation as (Belay et al., 2024).

$$F_{obs}(X_{obs}) = F_{raw}[X_{raw}] \quad (1)$$

Which is equivalent to

$$X_{obs} = F_{obs}{}^{-1}[F_{raw}(X_{raw})] \quad (2)$$

where $F_{obs}{}^{-1}$ is the converse form of the cumulative distribution function (CDF) of observed rainfall and temperature data, F_{obs} and F_{raw} stand for CDFs of observed and model-simulated rainfall data, respectively.

Results and Discussion

Performance of Model for Bias-Corrections

Here in this study, bias-corrected historical precipitation, maximum temperature, and minimum temperature from four selected GCMs were operated to assess the performance of models under four climatic conditions: W–W, W–D, C–D, and C–W. Figs. 2 and 3 present the performance of the bias correction for monthly precipitation and temperature for SSP2-4.5. Figs. 4 and 5 present the corresponding results for SSP5-8.5. In both scenarios, raw GCM outputs significantly overestimate monsoon precipitation, especially for June to August, in the W–W and C–D periods. Bias correction significantly reduces these seasonal peaks and corrects systematic errors to result in outputs that are very close to the observed data. The raw data from the SSP5-8.5 scenario, which undertakes higher greenhouse gas emissions than SSP2-4.5, resulted in even greater overestimates in projected precipitation intensities. Overall, the results specify that bias correction is a necessary process in refining the reliability of the climate projections used in hydrological impact assessments and climate adaptation planning.

Projected Future Climate of BGRB

The prediction of precipitation, maximum temperature, and minimum temperature was made for BGRB for three future periods: NF (2026-2050), MF (2051-2075), and FF (2076-2100) under two different climate change scenarios SSP2-4.5 and SSP5-8.5 and compared with the baseline period (1990- 2014). Both the maximum and minimum temperature are projected to rise under SSP2-4.5 and SSP5-8.5 scenarios for all the selected GCMs until the end of 2100, having relatively higher magnitudes of increase for SSP5-8.5 following continuously increasing trends from the baseline period (1990-2014), as depicted in Figure 6. However, the precipitation drifts are unpredictable.

Table 2 Final selected model of GCM runs with their details from advanced enveloped method

Scenarios	Climate pattern	GCM Name	Institution	Country	Long (°)	Lat (°)
	Warm-Wet	EC-Earth3-CC (Europe)	EC-Earth-Consortium	Europe	0.70	0.70
SSP2-4.5	Warm-Dry	MIROC6 (Japan)	MIROC (Atmosphere and Ocean Research Institute (AORI), Centre for Climate System Research - National Institute for Environmental Studies (CCSR- NIES) and Atmosphere and Ocean Research Institute (AORI))	Japan	1.406	1.406
	Cold-Dry	MPI-ESM1-2-LR (Germany)	MPI-M AWI (Max Planck Institute for Meteorology (MPI- M), AWI (Alfred Wegener Institute))	Germany	1..875	1.875
	Cold-Wet	MRI-ESM2-0 (Japan)	Meteorological Research Institute	Japan	1.10	1.10
	Warm-Wet	IPSL-CM6A-LR (France)	Institute Pierre-Simon Laplace	France	2.50	1.30
SSP5-8.5	Warm-Dry	MRI-ESM2-0 (Japan)	Meteorological Research Institute	Japan	1.10	1.10
	Cold-Dry	GFDL-ESM4 (USA)	Geophysical Fluid Dynamics Laboratory	USA	1.25	1.00
	Cold-Wet	INM-CM5-0 (Russia)	Institute of Numerical Mathematics	Russia	2.00	1.50

Projection of Precipitation in Future

The detected annual average precipitation in the BGRB during 1990–2014 is 1094 mm. Future prognoses under SSP2-4.5 and SSP5-8.5 exhibit irregular annual precipitation in NF, MF, and FF periods. C–D conditions indicate a slight decline in NF precipitation, while W–W exhibits strong increases, specifically under SSP5-8.5. In the FF period, W–W and W–D exhibit the largest rises up to 52.85% and 32.41%, respectively (Figure 7a, b). Seasonal investigation (Table 4) shows rainfall in winter and pre-monsoon seasons has lowered, while there is noticeably higher precipitation during the monsoon and post-monsoon, representing wetter monsoons and drier winters in the future. Winter precipitation remains highly uncertain; some GCMs project declines in MF (−8.13% to −21.06% under SSP2-4.5), followed by increases in FF, whereas others show the opposite. Most GCMs foresee increased monsoon precipitation, ranging from 13.70% to 40.52% (SSP2-4.5) and from −22.87% to 44.17% (SSP5-8.5) in FF, although one model reveals a slight decline in NF. The post-monsoon precipitation will also increase but underwrites less due to low baseline values. The pre-monsoon and winter seasons exhibit the highest inter-model variability and vagueness (Supplementary Table S1).

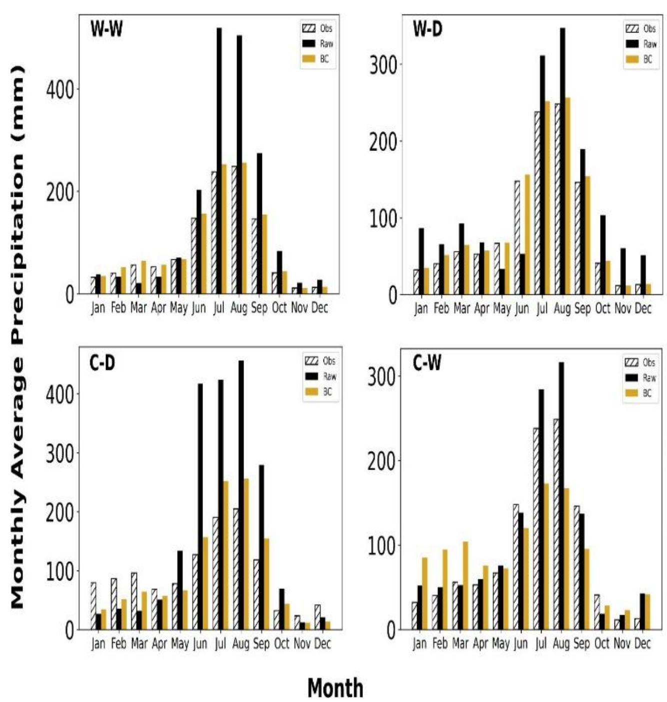

Fig. 2 Comparison of simulated historical precipitation (Raw), observed data (Obs), and bias-corrected (BC) precipitation for selected four corner GCMs on total monthly basis under SSP2-4.5 scenarioon BGRB.

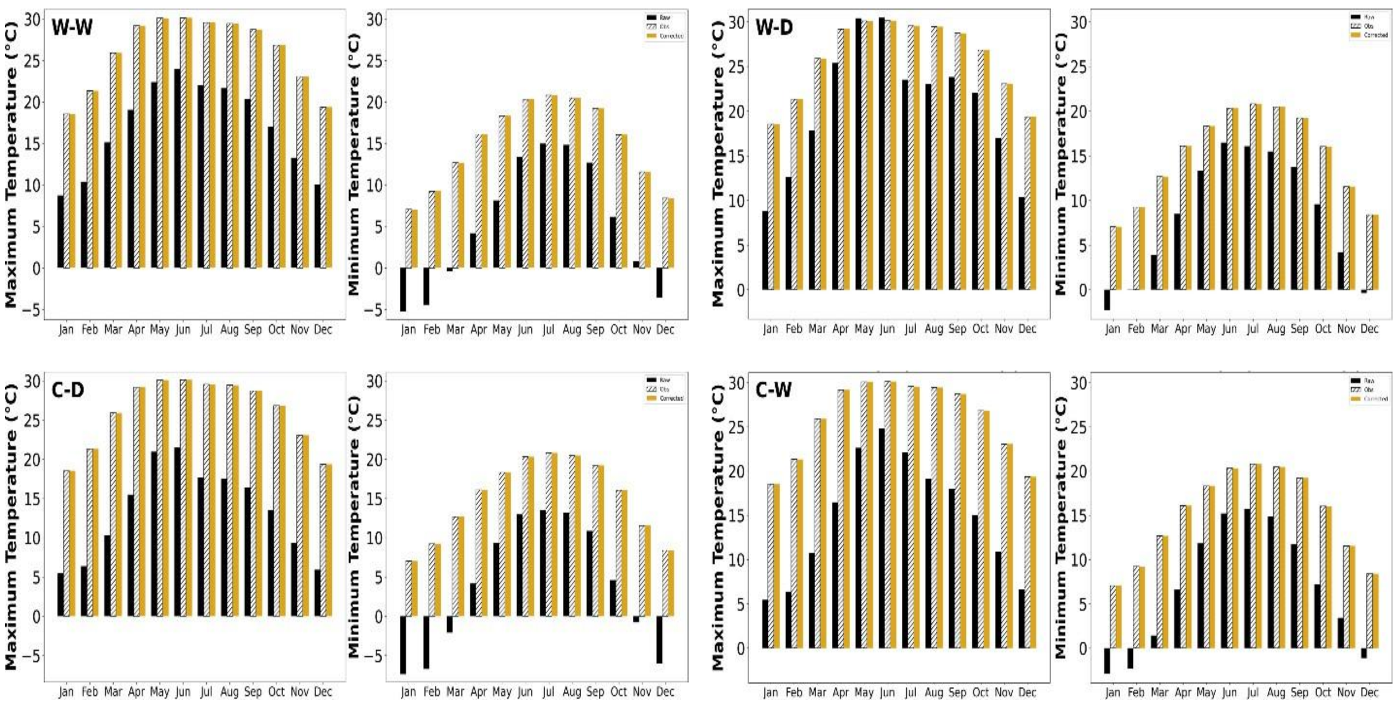

Fig. 3 Comparison of simulated historical precipitation (Raw), observed data (Obs), and bias-corrected (BC) Maximum and Minimum Temperature for selected four corner GCMs on a monthly basis under SSP2-4.5 scenario on BGRB.

Projection of Temperature in Future

The baseline average annual minimum and extreme temperatures in the BGRB are 15.04°C and 26.03°C, correspondingly. Both Tmin and Tmax are expected to rise across all future periods under SSP2-4.5 and SSP5-8.5 set-ups Figure 6 (c, d). By 2100, Tmax is expected to reach 28.32°C under SSP2-4.5 and 31.10°C under SSP5-8.5, while Tmin could increase to 17.63°C and 20.93°C, respectively (Supplementary Tables S2, S3). Notably, the sharpest rise in Tmax under SSP5-8.5 during the FF period is projected by Warm-Wet (5.08°C), followed by W-D (4.37°C), C-D (3.34°C), and C-W (3.01°C) (Supplementary Table S4). These projections specify a dependable warming trend in both minimum and maximum temperatures across GRB throughout the 21st century.

Temperature projections across the BGRB vary and are beset with uncertainty, particularly across seasons and future time edges when compared to the detected reference data. The annual Maximum temperature is projected to rise from NF to FF by 1.18 to 2.30°C under SSP2-4.5 and by 1.35 to 5.08°C under SSP5-8.5. The seasonal trends indicate that winter and monsoon temperatures will rise during all periods. Monsoon temperatures are more uncertain under SSP2-4.5, while winter temperatures are more uncertain under SSP5-8.5. Precisely, it is projected that monsoon maximum temperatures may rise by up to 2.48°C and 4.59°C, respectively, and winter by up to 3.60°C under SSP2-4.5 and 5.43°C under SSP5-8.5.

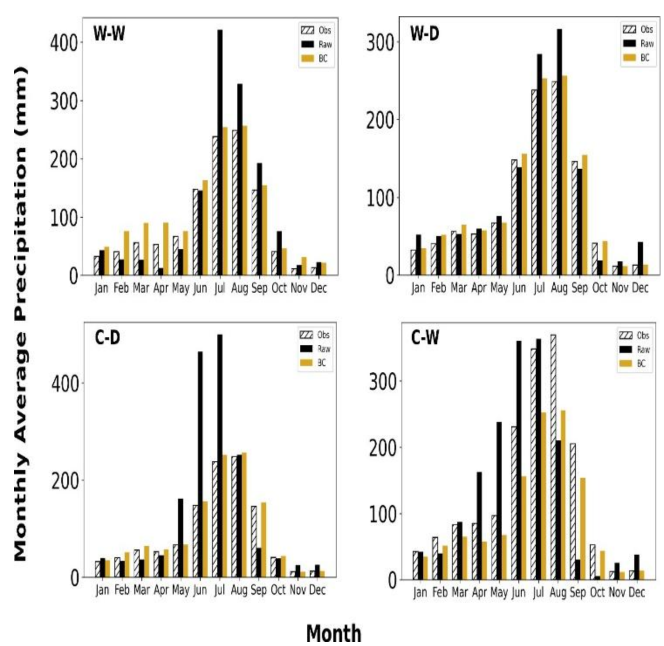

Fig.4 Comparison of simulated historical precipitation (Raw), observed data (Obs), and bias-corrected (BC) precipitation for selected four corner GCMs on total monthly basis under SSP5-8.5 scenario on BGRB.

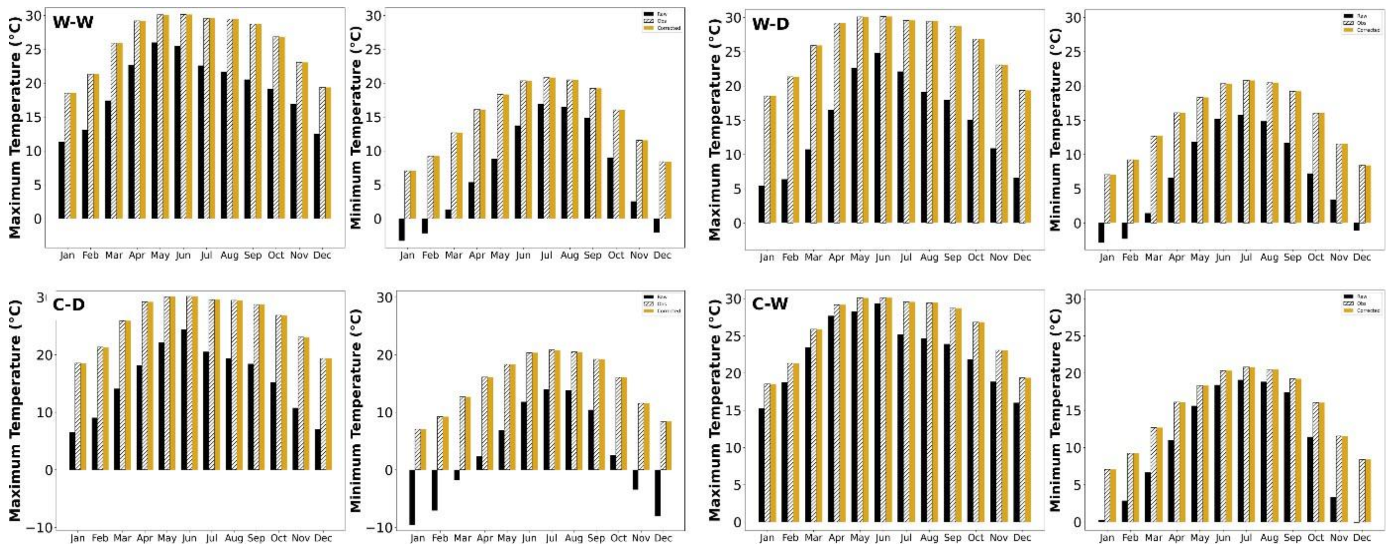

Fig. 5 Comparison of simulated historical precipitation (Raw), observed data (Obs), and bias-corrected (BC) maximum and minimum temperature for selected four corner GCMs on a monthly basis under SSP5-8.5 scenario on BGRB

Uncertainty in Precipitation and Temperature

The use of multiple GCMs and emission pathways naturally increases the spread of climate projections, emphasizing the uncertainty in future precipitation estimates. Figure 7 depicts this variability for SSP2-4.5 and SSP5-8.5 across NF, MF, and FF periods for precipitation and temperature. Precipitation has the most inter-model divergence, with wider interquartile ranges and more outliers than temperature. Under SSP2-4.5, there are considerable increases in NF, with deviations of 35.49% (dry season), 149.68% (post-monsoon), and 40.03% (pre-monsoon). Under SSP5-8.5, the main development in uncertainty takes place during the pre-monsoon, increasing from 103.16% in NF to 172.65% in FF, and in the post-monsoon from 126.94% to309.94%. This pattern is important to highlight the full ensemble mean to obtain reliable assessments of precipitation. For temperature, Figure 7 and Table 3 present that SSP5-8.5 projects a greater eccentricity from the observations than SSP2-4.5, which supports the argument that single-model estimates cannot capture the full range of future climate ambiguity.

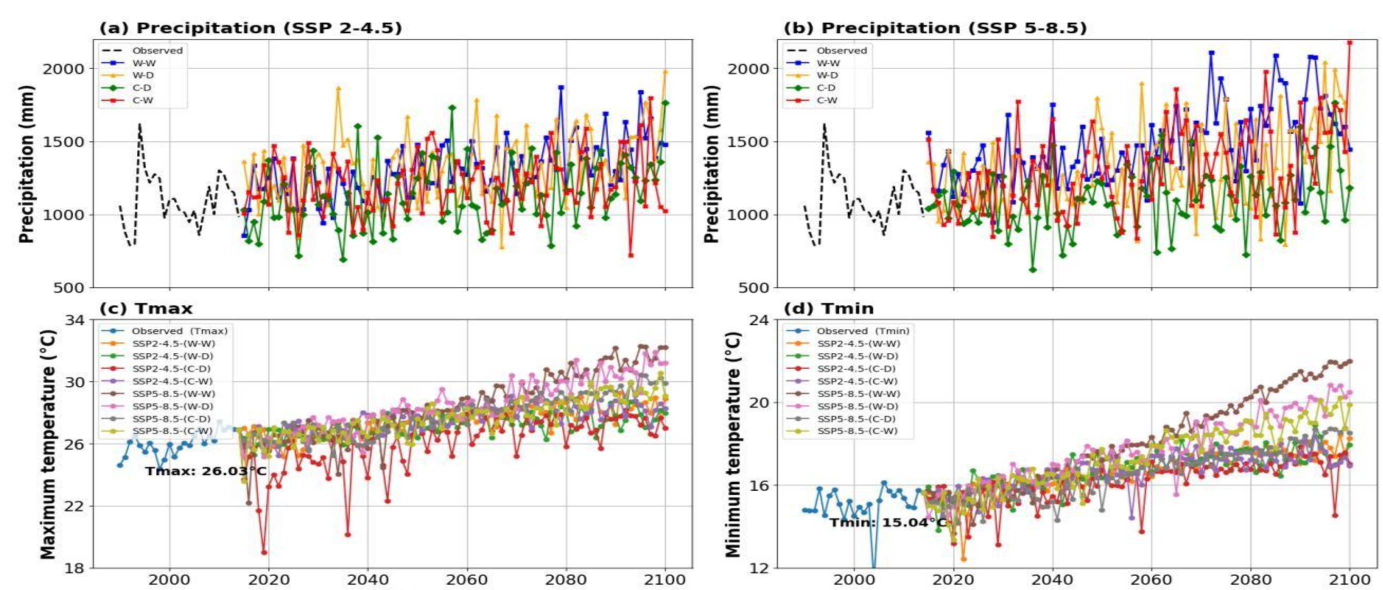

Fig. 6 Projected annual precipitation under SSP2-4.5 (a) and SSP5-8.5 (b) with observed baseline and projected annual maximum temperature Tmax (c) and minimum temperature Tmin (d) under SSP2-4.5 and SSP5-8.5 scenarios between 2015 and 2100 in comparison to observed baseline period of 1990–2014 for BGRB.

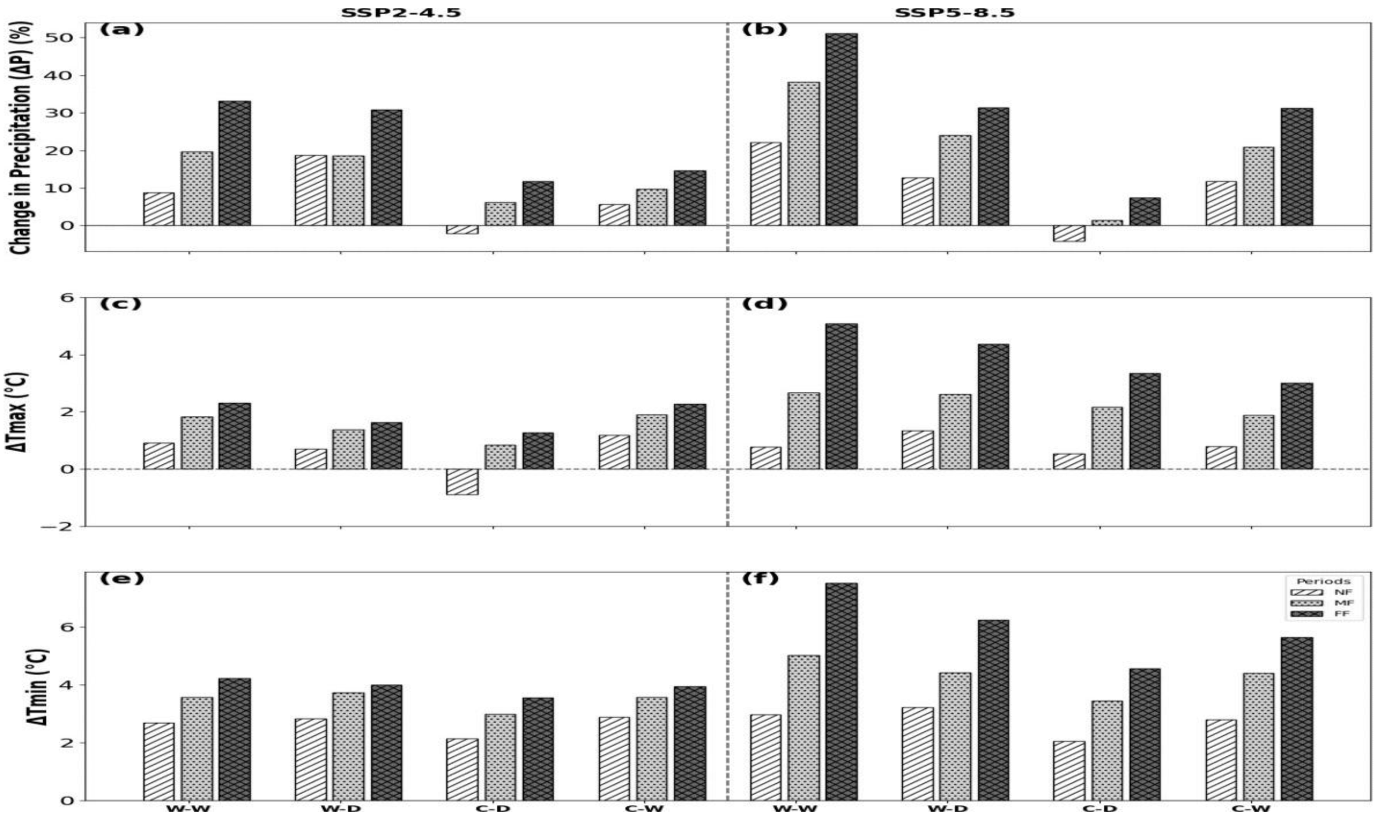

Fig. 7 Relative change in annual average precipitation SSP2-4.5 (a) and SSP5-8.5 (b), absolute change in Tmax SSP2-4.5 (c) and SSP5-8.5 (d), and Tmin SSP2-4.5 (e) and SSP5-8.5 (f) for three future periods for SSP2-4.5 and SSP5-8.5 with an observed baseline on BGRB.

Table 3 Uncertainty in absolute changes in Tmax and Tmin in BGRB as compared to observed data.

		Near Future (2026-2050)		Mid-Future (2051-2075)		Far-Future (2076-2100)	
Scenarios	Annual / Seasonal Temperature	Tmax (°C)	Tmin (°C)	Tmax (°C)	Tmin (°C)	Tmax (°C)	Tmin (°C)
	Annual	-0.90 to 1.19	2.15 to 2.89	0.85 to 1.89	3.00 to 3.73	1.27 to 2.31	3.56 to 4.24
SSP 2-4.5	Winter	1.00 to 2.21	2.60 to 3.09	1.63 to 3.13	3.30 to 3.92	1.96 to 3.61	3.90 to 4.13
	Monsoon	-5.49 to 1.15	1.75 to 2.48	-1.79 to 1.88	2.78 to 3.16	-1.25 to 2.49	3.33 to 3.86
	Annual	0.53 to 1.35	2.06 to 3.23	1.88 to 2.67	3.45 to 5.03	3.01 to 5.08	4.56 to 7.53
SSP 5-8.5	Winter	0.69 to 1.78	2.41 to 3.41	2.43 to 2.92	3.97 to 4.50	4.29 to 5.43	5.17 to7.00
	Monsoon	0.42 to 1.28	1.50 to 2.86	1.53 to 2.49	2.67 to 4.97	2.06 to 4.60	3.30 to 7.43

Table 4 Uncertainty in absolute variations and relative variations in average rainfall in BGRB

	Annual/	Near Future (2026-2050)		Mid-Future (2051-2075)		Far-Future (2076-2100)	
Scenarios	Seasonal Precipitation	Absolute(mm)	Relative (%)	Absolute (mm)	Relative (%)	Absolute(mm)	Relative (%)
	Annual	-23.76 to 205.27	-2.24 to 15.85	67.00 to 215.12	6.32 to 20.30	128.56 to 361.97	12.13 to34.16
	Winter	-11.80 to 26.59	-15.76 to 35.49	-6.10 to 15.77	-8.13 to 21.06	-8.85 to 12.73	-11.81 to17.00

SSP 2-4.5	Pre-monsoon	-32.85 to 66.01	-19.92 to 40.03	-44.50 to 63.16	-26.98 to 38.30	-28.24 to 98.10	-17.72 to 59.48
	Monsoon	-53.88 to 166.45	-6.74 to 20.84	34.69 to 174.83	4.34 to 21.88	109.46 to 323.72	13.70 to 40.52
	Post-monsoon	-12.88 to 31.08	-62.02 to 149.68	-13.60 to 37.59	-65.54 to 181.05	-15.63 to 17.86	-75.31 to 86.02
	Annual	-45.68 to 241.55	-4.31 to 22.80	15.72 to 417.39	1.48 to 39.40	80.55 to 559.95	7.60 to 52.85
	Winter	-12.44 to 58.20	-16.61 to 77.70	-3.79 to 62.01	-5.06 to 82.79	-13.30 to 102.70	-17.77 to 137.10
SSP 5-8.5	Pre-monsoon	-23.07 to 170.15	-13.99 to 103.16	-32.98 to 183.65	-19.99 to 111.35	-44.78 to 284.76	-27.15 to 172.65
	Monsoon	-146.64 to 157.50	-18.36 to 19.72	-152.98 to273.56	-19.15 to 34.24	-182.69 to352.86	-22.87 to 44.17
	Post-monsoon	-14.90 to 26.35	-71.79 to 126.94	-26.73 to 40.80	-128.70 to 196.54	-23.31 to 64.35	-112.28 to 309.94

Conclusions

This study utilizes CMIP6 GCMs under SSP2-4.5 and SSP5-8.5 to evaluate projected climate change impacts on the hydrological and climatic regimes of the Budhi Gandaki River Basin. Bias correction through quantile mapping ensures that model outputs realistically reproduce historical climate patterns, hence engendering confidence in the future projections. The analysis identifies a clear climate change signal that has important implications for water resources, hydropower, agriculture, and ecological sustainability. Results indicate a consistent warming scenario, where at the end of the century, the projected rise under SSP5-8.5 is 1.35-5.08°C for maximum temperature, and 2.06 - 7.53°C for minimum temperature, with stronger warming at higher elevations. Precipitation projections indicate higher seasonal variability, significant rises in winter precipitation (up to 137%), and varied increases in monsoon rainfall (up to 44%, with possible decreases in some models). Substantial inter-model variability indicates that uncertainties in future hydrological response persist. This study underlines the importance of strong bias-correction methodologies to increase temporal and spatial accuracy in the climate impact assessments. Lastly, despite the uncertainties, some of the selected models show reasonably good behavior in replicating the historical climate and thus support their use for future scenario analysis. Continued improvements in observational data sets, integration of local hydrological processes, and refinement of regional climate models will further enhance reliability.

The findings imply that the water-resource management of mountainous basins should be adaptive and resilient from a policy perspective. It includes flood-risk mitigation, ecosystem-based adaptation, climate-informed water management, strengthening hydropower operation, and reinforcement of infrastructure. Embedding climate projections within planning frameworks is key to securing Nepal's hydropower potential and water security in a changing climate. Overall, this study advances understanding of climate change impacts in a critical Himalayan basin and provides a scientific foundation for evidence-based policymaking. Future research should integrate hydrological modeling with socioeconomic analyses to evaluate resilience pathways and optimize resource allocation under evolving climatic uncertainties.

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Data Availability Statement

The datasets generated during the current study are available from the corresponding author on reasonable request.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal

relationships that could have appeared to influence the work reported in this paper.

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